STATUS OF FUSION ENERGY

Impact & Opportunity for Alberta

Volume II

Appendices

 

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TABLE OF CONTENTS

Page

Page

Appendix B: Assessment of an Alberta Role in Fusion
(potential for enhancing R&D and diversification of Alberta economy)

LIST OF ACRONYMS

CEA – Commissariat a l'Energie Atomique et aux Energies Alternatives (France)
DEMO – demonstration fusion reactor to follow ITER
DPSSL – diode pumped solid state laser
ELECTRA – KrF laser system at NRL
FI – fast ignition
GA – General Atomics (USA)
GW – gigawatt
HQP – highly qualified personnel
ICF – inertial confinement fusion
IFE – inertial fusion energy
ILE – Institute for Laser Engineering (Japan)
ITER – international tokamak project based in Cadarache, France
JET – Joint European Tokamak based in Culham, UK
HAPL – high average power laser, program based in US
HiPER – high power laser experiment, European proposal
KrF – krypton fluoride (gas laser medium)
LCOE – levelized cost of electricity
LIFE – Laser Inertial Fusion Energy, LLNL inertial fusion power plant design
LIFT – laser inertial fusion test, ILE fast ignition inertial fusion power plant design
LLE – Laboratory for Laser Energetics (USA)
LLNL – Lawrence Livermore National Laboratory (USA)
LMJ – Laser MegaJoule – laser system at CEA, Bordeaux
MCF – magnetic confinement fusion
MJ – megajoule (~the energy to heat 2.4 litres of water from 0 to100 degrees)
MTBF – mean time between failures
MW – megawatt
MFE – magnetic fusion energy
NIF – National Ignition Facility – 1.8MJ laser system at LLNL
NIKE – KrF laser system at NRL
NNSA – National Nuclear Security Administration
NRL – Naval Research Laboratory (USA)
OMEGA – laser system at LLE
ORNL – Oak Ridge National Laboratory (USA)
PDD – polar direct drive
RF – radio frequency
SI – shock ignition
ST – spherical tokamak

Physics symbols:

α – alpha (helium)	B – boron	D – deuterium	He – helium
T – tritium	n – neutron	n – density	p^+ – proton
p – pressure	ρ – density	τ – time	

keV – kiloelectron volt (11,600,000 degrees)

Page

List of Figures:

Page

APPENDIX A

ASSESSMENT OF MAJOR GLOBAL FUSION TECHNOLOGIES

1.0 Context - Global Energy Demand

1.0.1 Foreword

While carbon fuels will remain paramount for the next few decades, environmental impact, finite resource constraints and unequal distribution of assets will ultimately limit their useful lifetime as “burnable” fuels. Of increasing importance are the attendant environmental and health costs - build-up of green house gases, impact on fresh water supplies, toxic emissions and fallout of particulates. The explosive growth in nations such as China and India implies even greater energy demands than heretofore – meeting the world’s energy demands will require all clean alternative energy sources available. Indeed, these influences and the desire of nations to become less vulnerable to external energy supplies are driving profound changes in international energy strategies. Paramount will be sustainable alternatives to provide the clean energy “currencies” needed for the future, i.e., process heat, electricity and hydrogen. Fusion energy has such prospects and Alberta/Canada will not be immune to these developments.

The ever-increasing demand for energy and its associated impact on the environment are key issues internationally. Since fossil fuel energy sources are finite, non-renewable and carbon dioxide emitting, all nations are turning to renewable and alternative energy sources to provide sustainable clean energy supply. While there are no magic bullets and all major energy technologies will require 20-year time frames for commercial implementation, the sheer scale of energy demand coupled with finite resources compels accelerated development of alternative technologies.

Each energy source has its benefits and its drawbacks and it is wise to have a multiplicity of choices. Unfortunately, few sources have the capability to provide for long-term, large-scale green-house-gas (GHG) free energy needs. Fusion energy is one of them and inevitably, will be an important source for our long-term energy security (large energy reserves, no long-lived radioactive products as for fission, no possibility of reactor runaway, no green house gas emissions, suitability for central heat and electrical power plant operation). Controlled fusion for power generation is a challenge but will be transformative when the difficulties are surmounted.

Indeed, the challenge is great - to heat fuel (isotopes of hydrogen) to high temperature (100,000,000 C) and confine it long enough for sufficient fusion reactions to result in significant energy yield. Fusion energy has long been characterized as the most technologically demanding R&D to be undertaken by mankind and progress during the past 60 years has at times appeared to be frustratingly slow. **It is therefore important to recognize that demonstration of fusion energy by both major approaches, inertial fusion energy (IFE) and magnetic fusion energy (MFE) will be realized in the near future (National Ignition Campaign, USA and ITER, France)**. These dramatic proof-of-principle experiments are destined to become front page news and to have a profound impact on the pace of development of fusion power systems – triggering a worldwide drive to commercialize fusion energy.

As a leading energy province, Alberta is particularly conscious of the importance and impact of energy supply. The Alberta government is also aware of the need to diversify its economy to become less reliant on revenues from non-renewable resources and address associated environmental issues. Fusion research and development offers a special opportunity to address these issues by building a future economy yielding benefits in energy, environment and technology, at the same time creating a more diversified economy with accompanying highly skilled occupations.

Over the next 25 years, fusion energy will become a reality and specifically, for IFE:

- Within 2 years, proof-of-principle experiments in the USA are expected to demonstrate fuel ignition and burn in laser induced fusion reactions
- During the next 10 years, parallel developments in lasers, targets, materials, etc. will advance the enabling technologies needed to design and build a prototype power plant
- Within 15 years, the first demonstration power reactor for electricity generation is feasible and it may be anticipated that commercial exploitation will follow rapidly.

Meeting the world growth in energy demand implies significant economic opportunities as well as overcoming issues of resource limits of fossil and nuclear fission fuels. Non-renewable fuel sources – primarily coal, petroleum liquids and natural gas – provide the bulk of current energy supplies but will decline as a percentage of the energy mix during this century. Alternative energy sources – primarily renewable, fission and fusion – will therefore become essential to power the increasing demands of nations. This will provide two major benefits: 1) multi-trillion dollar economic opportunity and; 2) reduced environmental impact. Fusion energy will be a key component of this energy future.

1.0.2 Energy Trends

Energy and economic development have historically shown a remarkable relationship; the energy consumption per capita in developed countries is many times that for less-developed countries. Global consumption trends, however, are changing rapidly as industrialization proceeds throughout the world. This accounts for increased demands – and further limits non-renewable fuels as sources of adequate energy in the future.

Electric power is essential for modern economies, supplying clean energy for industrial, commercial and residential applications. We would not enjoy our modern conveniences and labor saving devices without it. Large-scale electric energy demands, however, can only be met by central power plants, ideally located nearby to avoid costly transmission. This will become more common as the transportation industry moves to electric and hydrogen powered vehicles. Indeed, hydrogen generation in the future will require even more electricity than heretofore as steam reforming of hydrocarbons is supplemented and replaced by electrolysis of water. In addition, large-scale desalination will be an important application of electricity for production of clean drinking water.

World-wide electric power generation has been growing[1] at ~2.8%/year for a period of ~25 years. Moreover, the rapid industrialization and electrification of countries such as China and India has created substantially greater growth rates for the most populated countries (7.9% and 5.8% respectively for a period of ~25 years)[2]. More recent projections suggest world-wide growth of ~2.2% over the next 30 years. Extrapolating a 2.2% growth to mid-century, reduced to 2% thereafter, the anticipated power demand is 13 (35) TWe in 2050 (2100). This implies construction of more than 35,000 power plants of 1GWe =1,000 MWe capacity in this century – an investment exceeding $100 trillion. Fusion systems will play a significant role in the world's power generation beyond 2050, thereby gaining a significant fraction of this business.

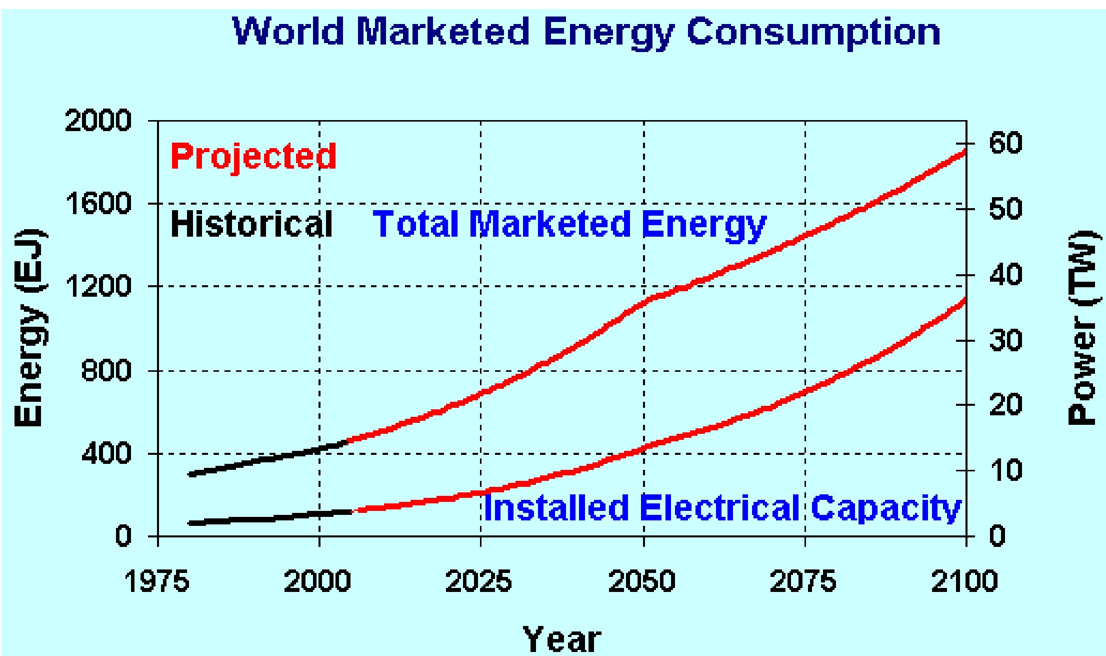


Fig. 1.1: World trends in power consumption: (a) world marketed energy consumption; (b) world total installed electrical generating capacity. (1 EJ = 10^{18} joules = 0.95 Quads)

In 2005, the total U.S. energy expenditures amounted to >$1 trillion and American energy consumption was ~100 Quad (10^{20} joules), of which ~40 Quad was electric (including losses). In comparison, the world total consumption of energy for 2005 (2010) was approximately 450 (524) Quad and has been increasing at an annual rate of ≥2% for a period of ~30 years. Indeed, energy consumption in non-OECD countries is growing more rapidly than in the mature economies and surpassed that of the OECD countries by 2010. The estimated cumulative requirements for energy and electric power generation are summarized in Fig. 1.1.

The dramatic increase in energy and electricity demand for non-OECD countries is highlighted in the following figures (Figs. 1.2, 1.3), taken from recent EIA data[3].

Fig. 1.2 World energy consumption, 1990-2040 (Quad)

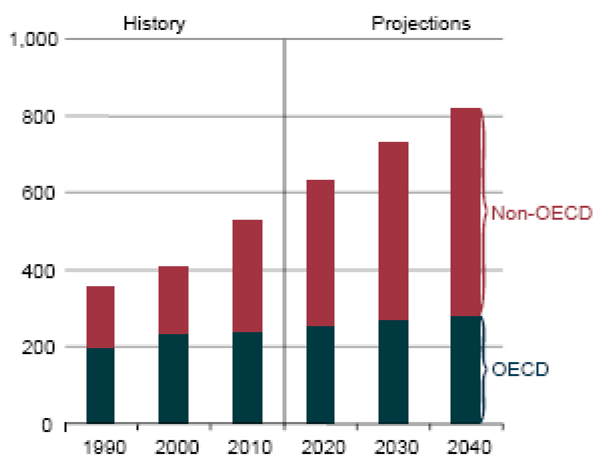
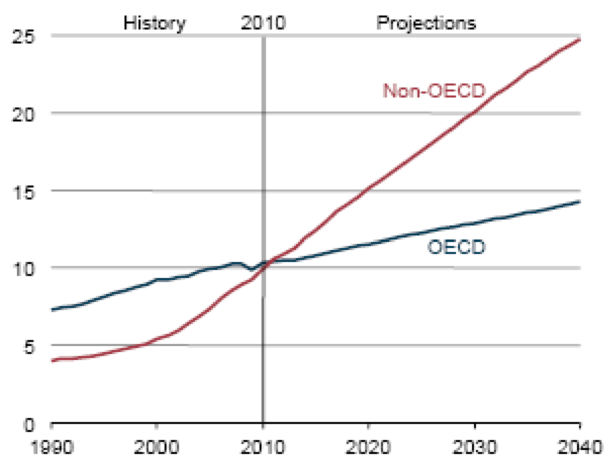


Fig. 1.3 OECD and non-OECD electricity generation, 1990-2040 (trillion kWh)



1.0.3 Energy From Fusion Reactions

The global interest in fusion is motivated by:

- the inexhaustible energy reserves of fusion
- the absence of radioactive fusion reaction products
- the impossibility of a reactor “runaway”
- the lack of GHG emissions from fusion
- the scalability of fusion for central power plant operation
- the ability to operate year round in northern, grey-sky climates

No other energy source offers this combination of attributes.
Energy reserves are inherently large since each fusion reaction produces several million times the energy release of a chemical reaction (such as burning coal or natural gas). The initial fuels of interest for fusion are deuterium (D) and tritium (T), isotopes of hydrogen, and the products are helium and neutrons (Fig. 1.4). Fusion reactions require high particle energy (high temperature ~100 million degrees for D,T) to overcome the natural Coulomb repulsion of the positively charged nuclei. The required heating can be supplied by lasers or particle beams for inertial fusion energy (IFE) and by electromagnetic waves and particle beams for magnetic fusion energy (MFE).

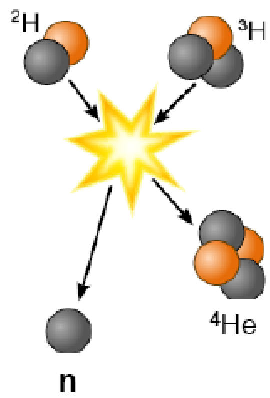


Fig. 1.4 Fusion of isotopes of hydrogen (D,T) yields neutrons and helium + large energy

The relative scale of energy released can be appreciated by comparing the fuel requirements of a 1,000 MW electric power plant for 1 year of operation:

- a coal-fired power plant requires approximately **26,000 train carloads** (each containing 100 tons) of fuel
- a fusion-fired power plant can be supplied with **one truckload** of fuel.

This intrinsic high energy density of fusion fuel is highlighted in Fig. 1.5 which provides a relative comparison of the material to be processed and handled as waste for coal, fission and fusion fired power stations.

Fig. 1.5 Fuel comparison for coal, fission, fusion

Daily fuel consumption & waste production for 1GWe plant

	Coal plant	Fission plant (U)	Fusion plant (D,T)
Fuel	~ 10,000T	~77kg	~ 0.27kg D ~ 0.82kg Li^6 (0.41kg T)
Waste	~ 30,000T CO_2 ~ 600T SO_2 ~ 40T NO_x ~ 600T fly ash	~77kg	~ 1.09kg He ("ash") **(advantage fusion)**

Hopper filled with coal – 10-20 min fuel
Filled with fusion targets – 7 years fuel

The basic fuels (deuterium and lithium – used to breed tritium) are widely dispersed on land and sea; this implies availability for all countries – unlike fossil fuels that are not equally distributed. With universal fuel availability and their environmental, health and safety advantages, fusion reactors could locate anywhere.

World reserve estimates of lithium (Li) are ~1.2×10^7 metric tons on land and 2.3×10^{11} metric tons in seawater and for deuterium ~4.6×10^{13} metric tons. This implies more than a billion years of D fuel and more than 10,000 years of Li fuel. While the initial aim is to harness D,T fusion because the ignition temperature is much lower than for D,D reactions, eventually maturing fusion energy systems will be able to work with D,D (and other fuels), avoiding the need for T fuel production.

Since tritium has a short half life of 12.3 years, it is not available as a natural fuel but must be produced. The neutrons generated in fusion reactions can be used for capturing heat (carrying 80% of the net fusion energy yield) and for producing tritium via the reaction Li (n,T) He. Consequently, a circulating liquid metal alloy containing Li used for transporting heat to the external thermal loop would be processed to extract the tritium generated by the neutrons in the reaction chamber.

Tritium processing and handling is a mature technology but must be carefully carried out since tritiated water (HTO) is a biological hazard. Fortunately, the amount of T to be handled in a day is less than a kg and therefore a limited hazard. Studies have shown that a release of the T in a major fusion power plant accident would pose little hazard to the environment beyond a kilometer square plant site. Indeed, there is a very high premium on capturing and using the T generated for fuel pellet fabrication and strict controls will be in place to avoid any tritium release from an operating plant. The tritium hazard is estimated to be less than for coal ash and the contribution to total radiation exposure is much less than for radon, cosmic rays, medical x-rays.

While the fusion products themselves (neutrons and helium) are not radioactive, there is a potential hazard associated with neutron activation of chamber wall materials. This depends on the structural materials and varies widely. Fig. 1.6 shows a comparison of radioactive waste decay for some possible materials.

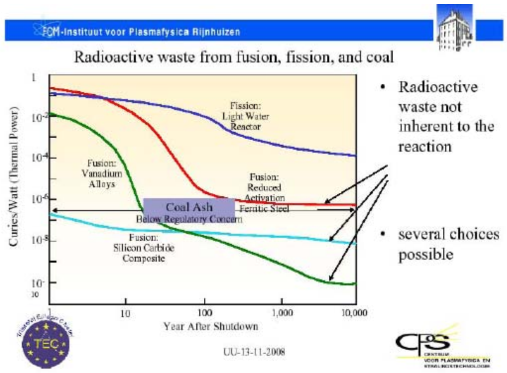


Fig. 1.6 Radioactive waste comparison

Clearly, a chamber made of silicon carbide poses no hazard whereas steel structures (containing iron) have varying activation levels depending on type of steel. Note that the decay times are far less than for fission systems implying that the inventory decreases rapidly and the material can be processed and reused after a finite storage time of the order of 20 to 100 years.

1.1 Major R&D Approaches to Fusion Energy

1.1.1 Introduction

The basic science of nuclear fusion was discovered in the late 1930's and it is the source of energy in the sun, which is the primary source of energy harvested on earth. However, harnessing a controlled continuous release of fusion energy on earth has been difficult to achieve, spawning decades of research work since the 1950s. It was recognized that the reacting species (deuterium and tritium in the simplest case) required a very high temperature ionized state (electrons stripped off the nuclei and freely roaming among ions), a state called plasma[4] (the fourth state of matter). In the 1950's and early 1960's there was initial enthusiasm that such plasma systems could readily be developed to confine the high temperature species long enough for significant fusion burn and energy yield to occur in a controlled fashion.

Most of these early approaches were based on the use of magnetic fields where it is well known that charged particles will orbit in tight loops around the magnetic field lines as seen in Fig. 1.7(a). A typical configuration is a magnetic mirror machine with two powerful field coils as shown in Fig. 1.7(b). However, it was quickly discovered that interactions between the charged particles led to collective motions causing bunching, drifting and twisting of the particles and field lines, rapidly destroying particle trapping (Fig. 1.7(c)). This motivated the investigation of plasma instabilities which continues to be one of the major hurdles to overcome in any approach to controlled fusion energy.

Techniques using a magnetic field for confinement of the fuel are referred to as magnetic confinement fusion (MCF) and for energy systems as magnetic fusion energy (MFE) systems. In the 1960's, with the discovery of the laser it was recognized that an alternative technique of instantaneously heating a fuel pellet up to reacting conditions might be possible but these approaches remained classified in the USA until 1972 when it was announced as a possible route to controlled fusion energy at the International Conference on Quantum Electronics in Montreal. This technique is now commonly referred to as laser fusion energy (LFE). Because this technique relies solely on the inertial mass of the system to hold it together for a very brief instant in time before it disassembles, this technique is also referred to as inertial confinement fusion (ICF) and for energy producing systems as inertial fusion energy (IFE).

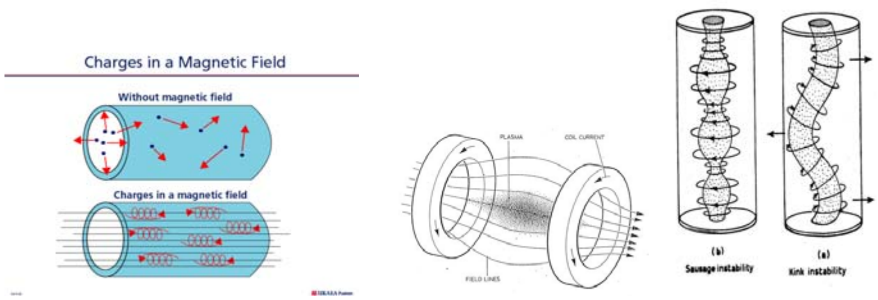


Fig. 1.7 (a) Guiding of particles by magnetic field lines, (b) mirror machines and (c) plasma instabilities

In order to determine how well a given technique approaches the conditions for breakeven, where more energy is released than utilized in heating and confining the plasma, various criteria have been developed to characterize the performance of a given system. The original criterion first outlined by Lawson[5] in 1957 was that the product of plasma density (n) and energy confinement time (τ) be greater than a certain product given by:

$$n\,\tau > 2 \times 10^{20} \quad m^{-3}\, s$$

In addition, in order for fusion reactions to occur, the energy of the particles must be extremely high, on the order of 10 keV or greater per particle which corresponds to a plasma temperature of the order of 100 million degrees. Because the plasma temperatures are so high, a different temperature scale given in electron volts (eV) per particle is normally used, where a temperature of 1 eV corresponds to 11,600 C. A combined criterion has been developed incorporating the plasma temperature (T_i) given as

$$n\,\tau\, T_i > 2 \times 10^{21}\, m^{-3}\, s\ keV$$

where T_i is the required plasma temperature in keV. An alternative way of writing this requirement is by combing the product of temperature and density to give pressure (p); resulting in the requirement of

$$p\,\tau > 10 \text{ atm s}$$

All three criteria are approximately equivalent and are used in order to judge how close a given experimental technique is to achieving net fusion energy.

The goal of any reactor system is to achieve large output energy and thus any fusion reactor should operate sufficiently above this threshold condition to achieve much larger output power than invested in heating and confining the plasma. The ratio of net fusion output power to input power is called the Q factor. It is expected that typically reactors should operate with Q values of 20 to 200 to operate economically (depending on the specific system details).

A large range of possible operating parameters can be envisaged from very low densities (close to vacuum) with long confinement times (10's of seconds); to extreme densities (100's of times normal solid densities) and very short confinement times (picoseconds = 10^{-12} seconds). The former regime is that of standard MFE fusion approaches and the latter for IFE approaches.

1.1.2 Fusion Reactions & the Fuel Cycle

The basic fusion reaction with the lowest threshold for energy production is that involving isotopes of hydrogen, namely tritium and deuterium given by:

$$D + T \rightarrow He + n + 17.6 \text{ MeV energy}$$

Where D is deuterium (hydrogen with an added neutron), T is tritium (hydrogen with 2 added neutrons), n is a neutron and He is natural helium, also called an alpha particle in nuclear reactions (see Fig. 1.4). The energy released in the reaction is 17.6 MeV which is equivalent to 3×10^{-12} J per reacting particles, approximately 4 million times greater than that released per reacting particles in burning carbon (4eV). This is one of the major advantages of fusion energy; the energy released per unit of fuel is ~4 million times greater than for carbon fuel, requiring <250kg of DT fuel per year for a 1 GW electric power plant with the release of 400kg inert helium as the waste by product.

Deuterium exists naturally in heavy water molecules in all lakes and oceans making up 1 part in 6500 of all hydrogen on earth. Tritium does not exist naturally in any quantity since it decays radioactively with a half life of 12.3 years. Trace amounts of tritium do exist naturally produced by cosmic rays hitting hydrogen atoms and water molecules in the upper atmosphere and more recently produced by above ground nuclear weapons tests in the 1950's and 1960's. The largest amount of tritium currently in the atmosphere is principally that left over from weapons tests. Tritium is also produced in small quantities in nuclear fission reactors when neutrons bombard heavy water such as in Candu reactors, and is extracted from the heavy water on a regular basis. Because

Canada, the developer of the Candu reactor, is the leader in the world on heavy water reactors we have some of the world leading expertise in the extraction and handling of tritium. However, the total inventory of commercial tritium in the world is of the order of only a few kilograms which is enough for scientific research experiments but insufficient to run a fusion reactor. Consequently, tritium must be generated on site for any fusion reactor system for use as fuel[6]. This can be done very effectively by the reaction of neutrons with lithium which produces tritium in the two reactions:

$$Li^6 + n \rightarrow He^4 + T^3 + 4.8 \text{ MeV energy}$$

$$Li^7 + n + 2.5 \text{ MeV energy} \rightarrow He^4 + T^3 + n$$

Lithium exists naturally in the two isotope states, Li^6 (7.5%) and Li^7 (92.5%) and thus a lithium containing blanket surrounding the reactor core can produce a surplus of tritium that would be extracted chemically from lithium (primary heat loop in a fusion reactor) on an ongoing basis. In fact, other reactions of neutrons with beryllium or lead can be used to multiply the number of neutrons by a factor of 2 per reaction allowing for enhancement of the neutron numbers. This permits breeding of tritium at a breeding ratio significantly greater than unity allowing for the manufacture of excess tritium to start newly built reactor systems.

Not all the tritium fuel is burned up in one pass through fusion reactions. It is estimated that the burnup fraction for MFE will be of the order of 6% while that of IFE reactors would be on the order of 30%. Thus a large amount of tritium must also be recovered from the reactor vessel and reprocessed as fuel for use in subsequent fueling cycles. Estimates of the reactor inventory of tritium at any given time are of the order of 6 kg for optimized MFE reactors and 1kg for IFE reactors for 1 GWe (gigawatt electric) plant. The latter is comparable in magnitude to the tritium inventory in present day Candu reactors and does not represent a large radioactive risk to the general public. Both MFE and IFE systems will require that the tritium be reprocessed into fuel pellets on site with a fuel or target manufacturing plant. It is not likely that regulatory agencies will allow large scale shipments of tritium off site for reprocessing and then shipment back to the reactors for fueling. There is a consensus of opinion that such a fuel breeding and extraction cycle is quite feasible to implement.

Other fusion reactions based on deuterium-deuterium or deuterium-helium-3 reactions are possible given by the following reactions:

$$D^2 + D^2 \rightarrow T^3 + n + 4.0 \text{ MeV energy}$$

$$D^2 + D^2 \rightarrow He^3 + p + 3.3 \text{ MeV energy}$$

$$D^2 + He^3 \rightarrow He^4 + p + 18.3 \text{ MeV energy}$$

However, the cross-sections for these reactions are much lower and the required particle temperatures are much higher than for the DT reaction and thus make these more difficult to achieve. The latter two reactions are of interest since they do not produce neutrons and thus can lead to much lower radioactivation and material damage to the reactor vessel and components. These reactions are often used in deuterium fueled surrogate experiments to determine the reaction conditions, temperature, density etc. in the development of fusion approaches.

In both IFE and MFE systems a similar scaling of efficiency with size is expected. For magnetic confinement systems the losses scale as surface area while the power generated scales as internal volume. As the reactor size increases the ratio of power generated to that lost scales approximately as the size of the system. Thus, one expects to reach threshold conditions just by increasing the size of the system. In fact this has been the approach to date; the next generation ITER system currently under construction, which is expected to reach ignition, is 10 times the volume and over 2 times larger in linear dimension than the previous largest system, the JET system in Europe.

Similarly, apart from chamber dimensions to absorb the IFE yield, for inertial fusion systems the same holds true. This can be understood as the confinement time scaling linearly with the size of the fuel pellet with the compressed density remaining the same; consequently, it is expected that one can reach threshold for ignition and burn by increasing the fuel pellet size and the laser system energy. The current 1.8MJ NIF laser system at Lawrence Livermore National Laboratory in California is expected to reach ignition and burn conditions with modest gains of Q ~ 1-10 in the next few years (2014-2017). Once the NIF results and the future ITER results (2027-2030) are assessed, this will give a firm scaling point from which a GWe demonstration reactor system (DEMO) can be designed.

1.1.3 IFE Approaches to Fusion

1.1.3.1 Introduction to IFE

The main approach to inertial fusion energy pursued to date is based on laser drivers. There is a possibility that large scale reactor systems in the future could be driven by pulsed heavy ion beams generated in large scale particle accelerators. However, such high energy (10’s of Megajoules per pulse) pulsed ion sources will require major development work and would probably only be considered when more readily available drivers such as pulsed laser sources have demonstrated the operating regimes for inertial fusion systems. Thus the main approach to IFE relies on lasers.

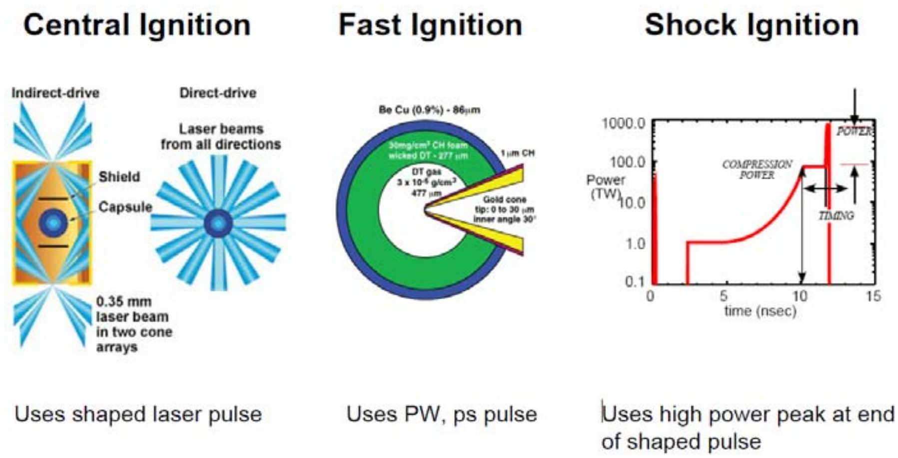


Fig. 1.8 Basic Concepts of (a) indirect drive and (b) direct drive IFE and advanced techniques of (c) fast ignition and (d) shock ignition

The basic concept for inertial fusion system is shown in Fig. 1.8 for two alternate approaches: (i) indirect drive, as pursued in the NIF Project at LLNL[7,8,9,10,11,12,13,14] and the LMJ project in France, and; (ii) direct drive approach as pursued at the OMEGA facility at the University of Rochester, the Institute of Laser Engineering in Japan and in the proposed HiPER project in Europe. In both approaches, a hollow spherical fuel capsule composed of an outer shell (plastic, beryllium or diamond as a few options) with a frozen DT fuel layer on the inner surface is employed. In the direct drive approach, Fig. 1.8(b) the outer surface is directly irradiated by powerful laser beams which vaporize and ionize the thin surface layer which acts like a rocket engine propelling the inside of the shell inwards at an accelerating rate. The imploding material collides when it reaches dead center compressing the inner fuel to extreme densities and converting the kinetic energy of motion into heat. This compression results in a very hot and dense fuel region at the center of the target called the ignition spot.

If the conditions in the ignition spot reach the threshold Lawson criteria listed earlier, then fusion reactions will start and initiate a burn wave through the fuel similar to ignition and burn in a combustible fluid but at a much more rapid pace[15]. In the case of fusion reactions, the propagating burn occurs due to energy deposition from the helium ions, also called alpha particles, produced in the fusion reaction. These helium ions rapidly slow down in the surrounding region of the fuel converting their kinetic energy into thermal energy in the surrounding fuel layer. The 3.5 MeV initial energy per helium particle is sufficient to heat 350 tritium and deuterium ions to 10keV energy so that they reach fusion threshold conditions creating more heated neutrons and alpha particles and the cycle continues until the burn wave propagates through the complete compressed fuel mass.

A burn fraction of approximately 30% is expected in an IFE system. The assembled and compressed fuel mass must have a minimum product of density times radius in order to ensure an efficient burn. This product is called the ρR or rho-R product for the assembled fuel and typically values of greater than ~3 g cm^{-2} are required for efficient burn which is one of the first requirements for an IFE system. Because the compressed fuel mass is fairly small, on the order of 100 microns in diameter, the required densities are on the order of 300 g cm^{-3} which is why extreme fuel compression is required to ~1000 times normal liquid density of DT which is 0.2g cm^{-3}. This technique is called central hot spot ignition[15].

Extreme densities required can only be achieved if the fuel is compressed uniformly from all sides so that all fuel arrives at the center at exactly the same time. This is another major requirement of an IFE system - to have irradiation uniformity of the order of a percent throughout the compression phase, which typically lasts 10 to 20 nanoseconds.

Due to compression of the heavy shell by the less dense high temperature ablation plasma, the fluid interface between these regions is subject to various hydrodynamic instabilities such as the Rayleigh Taylor instability (heavier fluid over a lighter fluid). This causes any initial non-uniformity in laser drive or target thickness to grow exponentially in time over the brief acceleration period. The growth of such instabilities has been studied for many years in the context of IFE systems and is fairly well characterized and understood at this time. This instability is one of the reasons that leading laboratories have pursued the indirect drive approach to fusion.

For indirect drive, Fig. 1.8(a), the laser radiation is first converted to x-rays by irradiating the inner side of a cylinder made of a high atomic number material, creating a dense plasma emitting most of its energy as soft x-rays which are then absorbed in the outer surface of the fuel capsule to vaporize and ionize the outer layer driving the inward implosion of the fuel. The soft x-ray radiation fills the entire volume of the cylinder, called a hohlraum, and just as for heat in an oven, leads to uniform heating of the outer wall of the fuel capsule. The x-ray generation process introduces an extra stage of energy conversion and inefficiency into the process. At the same time, the much shorter wavelength of the soft x-ray drive and the extra uniformity obtained leads to increased efficiency compared to direct laser drive and this in part makes up for extra conversion losses.

One of the key variables measured to determine the performance of a given implosion experiment is the neutron yield compared to what is calculated for a perfect spherical 1D implosion with the same target and laser parameters. This parameter is referred to as the yield over clean, YOC parameter for a given experimental shot. If there were no asymmetry in the implosion and the physics was correctly modeled then the YOC value should be unity. In reality, the values are often less than unity, becoming much less as the operating parameters are pushed into regions where plasma instabilities start to appear.

One of the experimental indicators of how close a system is to achieving ignition and the start of burn is the ignition threshold factor experimental, ITFX parameter or generalized Lawson parameter, GLP which is the pressure times confinement time[16,17]. This parameter is determined from the experimentally measured parameters such as ρR, peak implosion velocity and neutron yield. Thus, YOC determines how well a given experiment performed versus expectations from the known physics of the interaction while the ITFX or GLP parameters determine how close the experiment is to achieving the final goal of ignition and net energy production.

Another important issue for all laser driven IFE systems is the generation of a number of plasma instabilities which can lead to back reflection of the laser light and conversion of some of the laser energy into high energy electrons accelerated towards the fuel core. The back reflected light has a number of deleterious consequences including non uniform heating of the target surface if the backscattering is non uniform, plus potential damage to the laser system if large quantities of radiation are backscattered into the laser amplifier chain. The forward accelerated energetic electrons, with energies of the order of 50 to 200 keV, referred to as hot electrons, penetrate into the cold fuel prior to the final compression, preheating the fuel. Even a small amount of preheat can lead to much higher drive energy requirements in order to compress the fuel. For present systems it is expected that the generation of such hot electrons must be kept below ~ 1% of the absorbed laser energy. These plasma instabilities have been studied for four decades now and there is a fairly good understanding of the scaling laws for these processes. In particular, the strength of these interactions tends to scale with the target irradiation intensity, I times the square of the laser wavelength λ ($I\lambda^2$). Thus, shorter wavelength lasers are strongly preferred as laser drivers in order to minimize these processes for a given driver intensity delivered to the target.

The choice of laser system and wavelength play a significant role in the design of an IFE system. The first requirement of any laser system is to have a high operating efficiency, typically around 10% or better. This would require a gain of about Q=25 to just power the laser system from the output power of the reactor assuming a conversion efficiency of heat energy into electricity of 40%. Consequently, practical laser fusion energy systems will require operating gains of Q=50 to 200.

Recently there have been great strides in improving the efficiency of laser systems based on the use of semiconductor laser diodes which can operate at an electrical to optical energy conversion efficiency of 60% to 80%[18,19]. The quality and characteristics of such lasers are not suitable to drive laser fusion systems directly but they can be used as high efficiency sources to pump high quality, rare earth doped laser media.

A second significant development in the past several years has been the advent of rare earth doped ceramic laser materials[20,21] which can be manufactured at relatively low cost and scaled to large apertures of 50 cm square as required for high energy laser drivers. It is expected that diode laser pumped ceramic slab lasers suitable for laser fusion drivers can operate at electrical to optical efficiencies in the range of 10% to 20%.

Such systems are called diode pumped solid state lasers (DPSSL).

Unfortunately, the available high efficiency laser materials operate at an output wavelength of approximately 1060 nm in the infrared wavelength range. This wavelength is not optimum for laser fusion due to the high level of plasma instabilities stimulated at the required interaction intensities. Thus, optical crystals are used to convert the laser light to a shorter wavelength (third harmonic of the incident laser light) at 353 nm. This process can be carried out at efficiencies of 70%[22] and thus overall laser performance can be in the 7% to 14% in optimally designed systems, meeting the 10% system efficiency required. To build such systems requires very sophisticated state of the art optical engineering. The construction and operation of the current NIF laser system shown in Fig. 1.9 is a demonstration that such sophisticated laser engineering can be achieved in practice.

Fig. 1.9 NIF 1.8MJ laser system (left) & photos of laser bay, target chamber (right)

An alternative laser system that has been investigated for several decades is the krypton fluoride (KrF) gas laser system. Its projected operational efficiency could approach 7% which is less than the usual 10% desired for laser fusion drivers[23]. However, the KrF gas laser has the significant advantage that the laser wavelength is even further in the ultraviolet spectral region at 248 nm and thus would be a very efficient driver for high gain direct drive laser fusion systems.

1.1.3.2 Indirect Drive

The most developed approach to IFE is based on the indirect drive technique as outlined above. The largest laser system in the world, the National Ignition Facility (NIF) at 1.8 MJ per pulse, has been built at the Lawrence Livermore National Laboratory (LLNL) in order to demonstrate ignition and net energy gain by means of laser driven fusion. Operation of the system started in 2009 and now NIF scientists are actively pursuing an experimental program studying ignition and gain[7,8,24]. A similar system, Laser Megajoule (LMJ) is being built near Bordeaux, France and will start ramping up to full scale operation in 2015 (about 8 years behind LLNL)[25]. Both NIF and LMJ have targeted indirect drive as the most straight forward approach with the highest probability of success to implement laser fusion in the near term. Because of the inefficiency of converting laser light into x-rays which then acts as the ablation driver, indirect drive systems will have lower gains for a given laser driver energy. Typical calculations of expected scaling of gain as a function of laser driver energy are given in Fig. 1.10 for direct and indirect drive. It can be seen that laser energies of over 2.5MJ probably will be required for the indirect drive approach to achieve gains of Q = 50 or more.

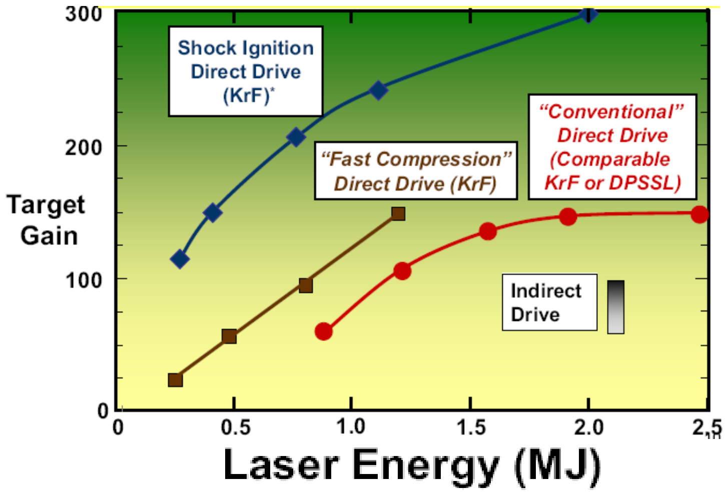


Fig. 1.10 Scaling of predicted gain vs laser energy for different approaches to laser

The typical irradiation configuration requires a number of conical rings of laser beams as shown in Figure 1.11. The axisymmetric design with laser cones from each end of the target simplifies reactor design to some extent since the entrance holes in the reaction chamber wall for the laser beams are localized at the two ends of the chamber allowing for easier shielding and utilization of the equatorial plane for the tritium breeding blanket.

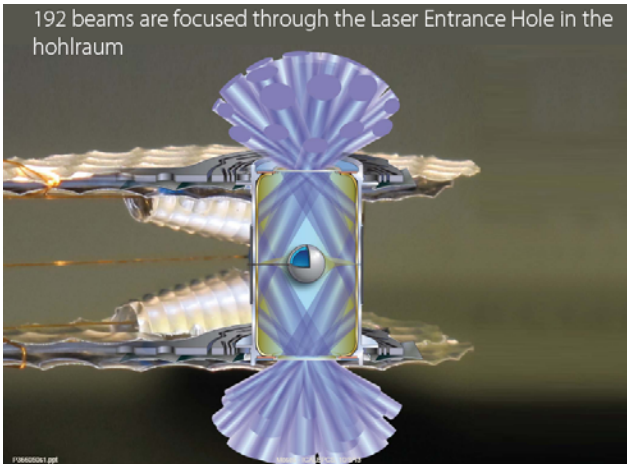


Fig. 1.11 Irradiation configuration for indirect drive fusion using 3 cones of beams from each side

1.1.3.3 Direct Drive

The most efficient use of laser drivers involves direct irradiation of the target surface with the laser beams. This requires a large number of laser beams and careful design of beam overlap in order to achieve the percent level irradiation uniformity required. Such designs have been developed and implemented with the largest operating direct drive system in the world which is the 60 beam, 30kJ OMEGA laser facility at the University of Rochester[11,12]. Beam energy balance on the order of 1% is routinely achieved in this system. Scaling experiments have only been carried out to an energy level of about 5% of what would be required for ignition and significant burn of the fuel. The key variables measured are the ρR product, the peak density, the peak pressure and the neutron yield compared to what is calculated for a perfect spherical 1D implosion with the given target and laser parameters, i.e., the yield over clean, YOC parameter. If there were no asymmetry in the implosion the YOC value should be unity but in reality the values are less than unity, becoming much less as the operating parameters are pushed into regions of higher intensity or for very thin shell targets where plasma instabilities start to appear and growth rates for Rayleigh Taylor instability become large.

Tests are carried out on scaled target designs, taking into account that the laser energy is less than optimum but trying to reproduce the drive intensities and scaled target shell acceleration of the equivalent full energy system. The experiments also mainly use deuterium filled targets in order to avoid the more stringent handling requirements of radioactive tritium. In these cases the neutron yields are calculated for the deuterium fuel only, due to DD reactions (much lower yield than DT fuel) and then the neutron yield under the same conditions using DT fuel is predicted based on numerical code simulations. It is found that thick shell targets, which generate lower core pressures, perform very close to prediction since they are fairly robust against the effects of instabilities. In these cases YOC values approaching unity can be obtained.

Thin shell targets are found to perform more poorly - the thinner the shell thickness - because of increased sensitivity to plasma instabilities and breakup of the shell before completion of the implosion. In addition to poor compression, mixing of cooler plastic and metal ablator layers with the fuel cause large amounts of bremsstrahlung radiation cooling, quenching fusion reactions. The direct drive approach using the modest energy OMEGA laser facility has achieved results, when scaled to 1.8MJ laser drive, would correspond to an ITFX parameter of ~0.23 while the NIF indirect drive approach has recently achieved an ITFX parameter[26] of the order of 0.65. The main difference is due to the much smaller laser drive energy for direct drive experiments to date. In both cases YOC values close to unity have been demonstrated on more robust targets.

The expected scaling of fusion yield versus driver energy as shown in Fig. 1.10 indicates that target gains of 50 to 150 should be achievable for optimized direct drive systems with drive laser energies of 1 to 2.5 MJ. These are significantly higher by about a factor of three compared to the expected gains for an indirect drive laser reactor system at comparable laser energies. However, scaling of the direct drive physics to ignition conditions still needs to be demonstrated, particularly control of uniformity and suppression of instabilities.

1.1.3.4 Fast Ignition

One of the more recent developments in IFE concepts is the idea of separating the fuel compression from fuel ignition. By utilizing a separate laser pulse for ignition the requirements for fuel compression can be reduced considerably. The first pulse can be used to assemble a large high density fuel mass but not generate the high temperature, high pressure central hot spot to self ignite. A second laser pulse can then be introduced to create a high temperature hot spot which will serve as the ignition point for fusion reactions. This is similar to a spark plug in an internal combustion engine. This concept, as illustrated in Fig. 1.12, is called fast ignition (FI), and was first introduced in the mid 1990's. This reduces energy requirements of the main compression laser considerably[27,28] (approximately 500kJ to 1 MJ) and also allows for more tolerance for non-uniformity. In order to achieve ignition, a separate high intensity laser pulse with a duration of 20-40 ps and energy of ~200 kJ would be required. Only in the last two decades has laser technology advanced sufficiently to generate such laser pulses and the leading systems in the world are approaching the level of 10kJ with such operating parameters.

The compression phase physics is well understood and there is a very high probability of achieving the fuel compression required for this scheme. However, the physics of creating a fast ignition hot spot is still a matter of significant scientific research. The high intensity ignition laser pulse cannot penetrate to the high density fuel core directly since it is absorbed in the lower density outer regions of the plasma surrounding the compressed core. Various schemes for providing an access channel to the core have been proposed, including either a physical cone embedded in the target or laser drilling of a hole as shown in Fig. 1.12(a) and (b). In either case, the there is a region of ~100 microns of high density plasma which must still be penetrated to get to the edge of the very high density compressed fuel region. To do this the laser energy must be converted into MeV energy electrons or protons[29] in order to couple the energy across this gap into the edge of the compressed fuel.

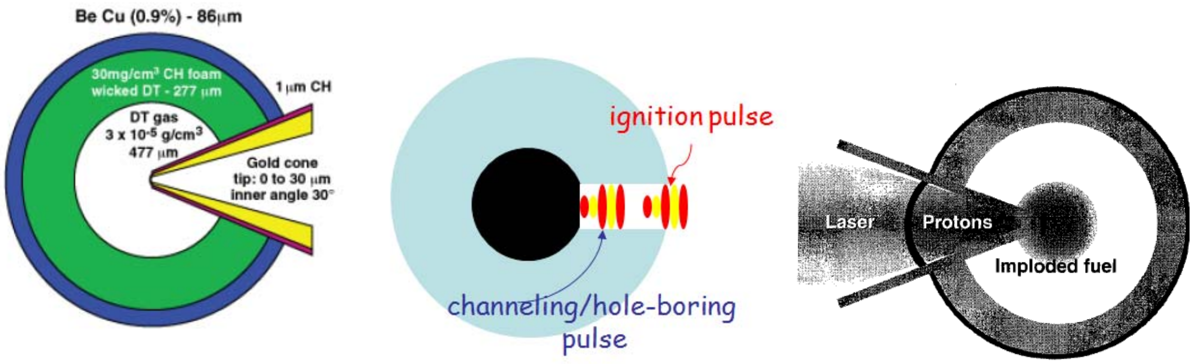


Fig. 1.12 Schematic diagrams of a cone guiding and laser boring to bring the fast ignition laser beam close to the compressed fuel core and proton cone guiding

The ignition spot requires approximately 20kJ of deposited energy. Experiments to date have indicated coupling efficiencies into the required MeV electrons of ~10-30%[30,31,32] and coupling efficiencies into protons of ~5-10%. The major issue yet to be accomplished is the guiding of electrons or protons to the 40 micron diameter hot spot on the side of the compressed fuel core. For electrons, magnetic guiding using both externally driven and laser driven megaguass magnetic fields is currently being pursued (see Fig 1.13) and for protons, ballistic and electrostatic focussing geometries are being investigated. If an overall coupling efficiency to the core hot spot of 10% can be achieved then a 200 kJ laser driver would be sufficient to drive the ignition process.

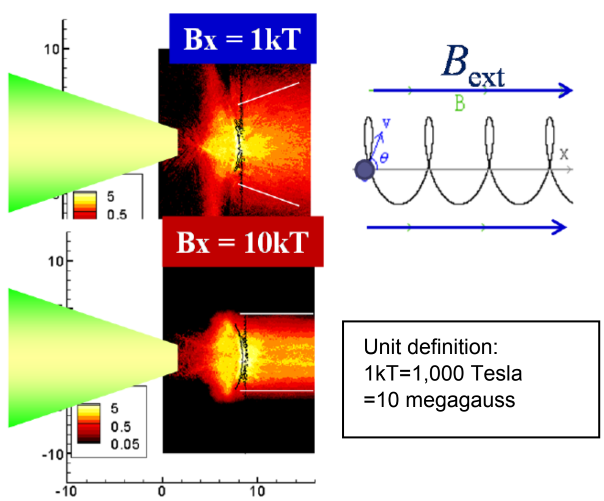


Fig. 1.13 Computer simulation of magnetic field guiding of electrons from cone tip towards the high density fuel core at two field strengths of 1kT and 10 kT . (courtesy of ILE Japan)

The investigation of fast ignition is at an early stage at the moment but the rewards in terms of smaller scale size reactor systems are quite attractive. As seen in Fig. 1.14, the scale size of a high yield reactor system with a gain of over 100 can be less than a megajoule. Assuming a 10 Hz system at a total laser energy of 1MJ operating at a gain of 100, with an electrical generation efficiency of 40%, an output thermal power of 1,000MWth and an electric output power to the grid of 300MWe would be achieved (100MWe recirculated to power the laser). The smaller scale size, compared to indirect drive or direct drive systems, would allow for more rapid development cycles and the fielding of smaller but still highly efficient reactor systems. Thus the development of such next generation systems can lead to significantly decreased reactor scale size and significantly increased cost efficiency.

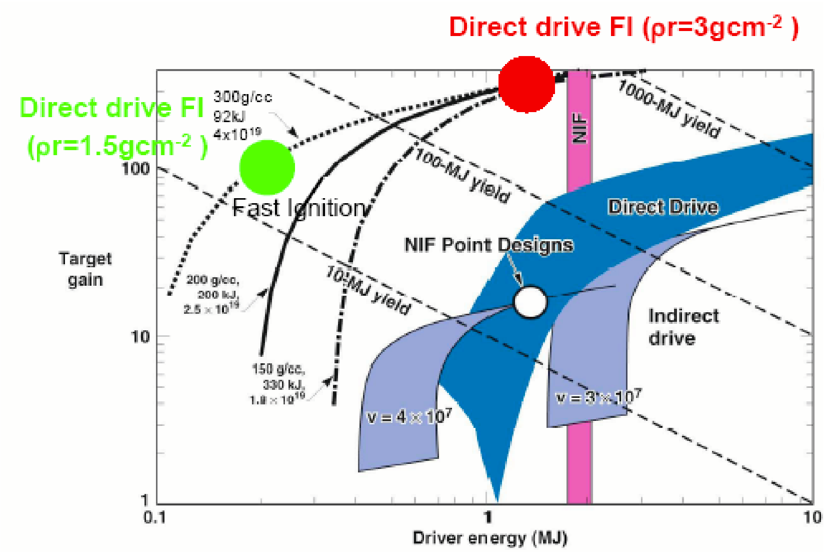


Fig. 1.14 Scaling of target gain versus laser system energy for fast ignition

1.1.3.5 Shock Ignition

Another advanced approach using a separate laser pulse to create the ignition event proposed in 2006 is through shock ignition[33,34], SI. In this case a higher intensity laser spike is focussed from all sides onto the target in a similar fashion to the main compression pulse. With careful engineering this laser pulse can be generated using the same laser amplifiers as the main compression pulse by injecting a high intensity seed pulse at the end of the main compression pulse as shown in Fig. 1.15.

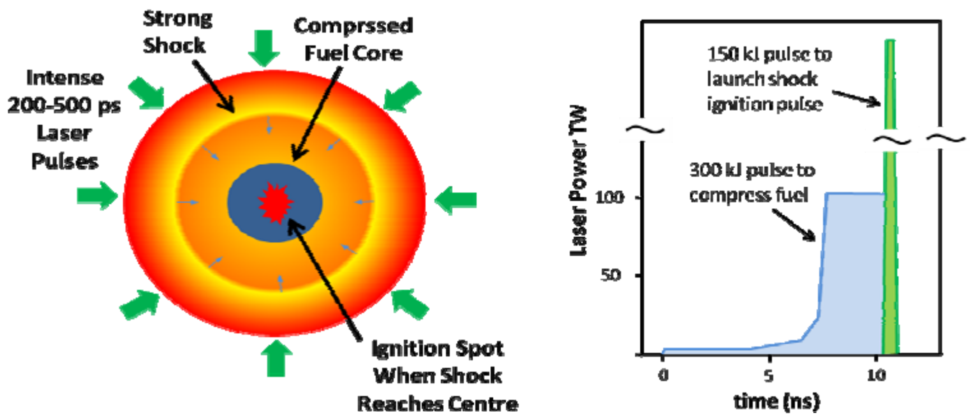


Fig. 1.15 Shock ignition pulse shape and concept

The intensities required, $5x10^{15}$ to 10^{16} W cm^{-2}, are an order of magnitude above those considered for the normal compression pulse since it is well into the regime of exciting plasma instabilities. However, the novel idea here is that at the late time of this ignition pulse the imploding fuel is no longer as sensitive to such instabilities. Hydrodynamic simulations indicate the plasma core is so dense at this late time that only electrons above approximately 150 keV in energy can penetrate inward to cause fuel preheat. In addition, the late time shock is hydrodynamically more stable against Rayleigh Taylor type instabilities[35]. The large hot plasma cloud surrounding the high density core acts a high thermal conductivity blanket helping to smooth out non-uniformities of laser irradiation and simulations show that shock ignition could potentially be achieved even with non uniform polar irradiation predominantly from two sides of the compressed fuel pellet.

It is early in the investigation of this technique but initial scaling experiments at the OMEGA facility have indicated positive results[36]. The overall effect of shock ignition, like fast ignition, would be to reduce the laser driver requirements from the multi-megajoule level to around the megajoule level for an operating system. Scaling laws for expected target yield versus laser system drive energy are shown in Fig. 1.16. Again, these predicted yields are much higher than equivalent yields from indirect drive or direct drive systems alone. Given that such laser pulses can be generated by the main laser system itself there is no requirement for an additional high intensity short pulse laser system. Because of its attractive features, shock ignition has become the favoured approach for the proposed HiPER laser fusion demo project in Europe[37,38] and will be explored in some of the direct drive experiments planned for the LMJ laser facility in France and potentially at NIF later this decade.

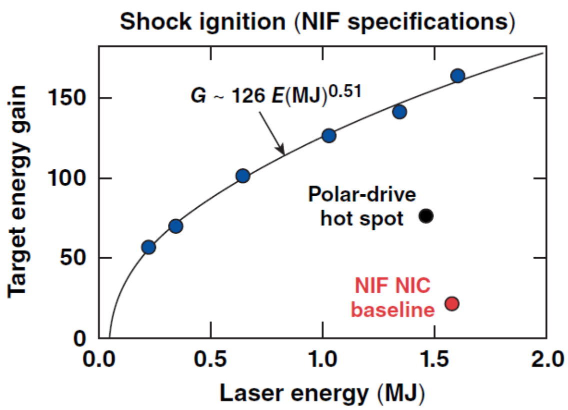


Fig. 1.16 Shock ignition yield versus laser energy

The key physics issues which need to be resolved for this approach include determination of actual plasma instability levels, amount of target preheat induced, efficiency of coupling energy into the shock wave, and efficiency of heating and igniting the core by the shock spike.

1.1.3.6 IFE Power Reactor Systems

The most developed approach to IFE is based on the indirect drive technique as outlined above and LLNL has used this technique as a basis for a detailed power reactor design called LIFE or laser inertial fusion engine. There are a number of less developed conceptual design studies in the past including the HAPL study[39] in the USA and Koyo and Koyo-FI for fast ignition in Japan[40]. There are numerous significant issues in the design of complete reactor systems which will challenge existing technology and push it forward. While challenges exist, it appears that there are acceptable near term solutions and potentially much better long term solutions to most of these challenges. The list of critical design issues for IFE includes:

- long time survival of laser components against optical damage
- fabrication of robust 10% efficiency pulsed laser systems
- mitigation of down time from laser failures
- degradation of final optics facing the target
- erosion of inner vacuum vessel wall from x-ray flash and target debris
- degradation of structural materials from neutron bombardment
- neutron activation of reactor structures
- tritium breeding, recycling and containment
- target fabrication, injection and tracking of cryogenic DT targets

For all these issues there are near term solutions envisaged including:

- preconditioning and annealing of optics at high fluence and dust free enclosures

- high efficiency diode pump lasers
- line replaceable laser modules which can be robotically hot swapped without shutdown
- grazing incidence final metal mirrors replaced every year or so
- liquid metal alloy inner shower wall, matrix of ceramic liner tiles, magnetic shielding to deflect ions, and/or replacement of liner materials and reactor vessel every few years
- use of radiation damage resistant steels plus replacement of reactor vessel every few years
- use of low activation steels, alloys and materials
- breeder blankets containing lithium with additional lead or beryllium for neutron multiplication, metal alloy recirculation systems with continuous extraction of tritium, and multilayer containment vessels to prevent tritium leakage
- mass production of targets using microelectronics and MEMS type foundries, high precision optical measurement and tracking techniques coupled to high speed computer analysis of final target position for a given shot, millisecond response time acousto-optic steering of all laser beams to hit the projected target spot, protective sabot carrying the target most of the way to the center of the reactor chamber to avoid premature melting and vaporization of the cryo DT fuel layer

Many of these issues can benefit from development of advanced state-of-the-art materials such as erosion resistant surface coatings for the reactor vessel, refurbishing techniques such as laser melting or re-cladding of the inner chamber wall, the use of advanced ceramic materials such as silicon carbide for low neutron activation, improved optical materials with no inclusions which can seed optical damage, and advanced coating mixtures for high performance fuel targets.

LLNL has expended considerable effort in completing an initial comprehensive analysis of all steps required to build an operational reactor system[41] based on the indirect drive approach and have reached the conclusion, based on current experience, that construction of such a system is feasible using a mixture of existing technologies (59%), extensions to existing technologies (28%) and the development of new technologies (13%). They envisage an aggressive 5 year program focussed on technology demonstration concurrent with a ten year building phase for a LIFE demo system. The previous HAPL program was carried out at a more conceptual level with a few small scale technology development and demonstration projects but with the same focus on how to build a reactor today. Near term solutions to all the technical challenges were proposed in that project.

1.1.3.7 Modeling Codes

One of the key reasons that approaches to fusion energy have advanced significantly in the past two decades is the rapid development of sophisticated computer modeling codes giving accurate insight into the very complex nonlinear processes occurring in these systems. However, even with today's most powerful computers, modeling is still compartmentalized to look at a particular part of the physics at a time. For laser fusion modeling there are three levels of codes predominantly being used.

The first are hydrodynamic codes tracking the energy absorption, implosion dynamics, fusion reactions and fusion burn. A number of independent versions of such hydrodynamic codes exist to date, many with the capability of modeling full non-uniform 3D compression physics. These include the Livermore Lasnex code (classified), the French Chic code (classified), Hydra (commercial but restricted), Draco (Rochester), Multi (open source), Japanese (in house), Russian (in house) and Chinese (in house) modeling codes. In addition, there has been significant development of the open source code called Flash, funded by NSF in the USA for modeling of astrophysical systems, towards applications in laser fusion.

Inter-comparisons of such codes indicate that the basic physics of hydrodynamic compression and fusion yield can be modeled to the several percent level accuracy, if the compressibility and material behaviour is known accurately. The latter material specific response data is referred to as the equation of state (EOS) for a given material. However, for many of the mixtures of materials being employed, the equation of state at the extreme temperatures and pressures is not well known, though many approximate models exist. This is a region of current study and, in fact, this knowledge is currently being updated as part of the current experiments at NIF. To a large extent the basic hydrodynamic behaviour of the target ablation and compression process is well understood and can be modeled in full detail using such 3D simulations. However, discrepancies in high yield experiments to date give YOC significantly below unity, indicating that some of the physics of the growth of hydrodynamic instabilities and of the material behaviour are still not fully understood. Full 3D simulations still tax the most powerful supercomputers at LLNL and elsewhere today and only a limited number of full 3D runs are done each year, whereas many full 2D runs are carried out each year. It is expected that full 3D runs will become more commonplace as the power and availability of supercomputers increases every year.

The second set of codes are detailed particle in cell (PIC) codes. They model the plasma at the particle level using billions to 100's of billions of representative electron and ion particles to mimic a tiny piece of the interacting plasma, primarily focussed on the modeling of coupling of the laser to the plasma at high intensities, excitation of plasma instabilities, generation of high energy particles and propagation of these high energy particle in the plasma. These codes are applied to a zoomed in region where the laser light is interacting with and being absorbed by the plasma and can be calculated in 2D or full 3D systems, depending on the computer resources available. The physics of such codes is entirely based on well established fundamental laws of mechanics for acceleration of particles in microscopic electromagnetic fields and the propagation of electromagnetic wave energy (both from the incident laser radiation and induced magnetic and electric fields from the particles) based on Maxwell's equations. Currently, in house codes exist in all major laboratories of the world and, in addition, there are a few open source codes, particularly OSIRIS, originally from UCLA and a commercial code, LSP. When such PIC codes are compared in bench marking exercises, agreement is found to approximately the ten percent level if the same physics, same interaction conditions and same degree of accuracy are used.

The third level of codes is used to calculate the intermediate scale interaction of high energy particle propagation and transport of energy by such particles over larger distance scales than can be done with PIC codes. These so called kinetic codes look at the evolution of the statistical velocity distribution function of the particles as a function of position and time. Energy in the form of high energy particles propagates as perturbations to the normal Maxwellian thermal velocity distribution function and the propagation is calculated by solving the coupled equations for particle motion based on these distribution functions and the electromagnetic equations over macroscopic distance scales. Such codes are used to calculate nonlinear effects on heat transport and target preheat from energetic electrons. Most groups have their own specialized kinetic codes for such calculations and comparisons of predictions between codes for the same conditions generally agree within the tens of percent level. Some PIC codes have the ability to calculate the same propagation of energetic particles over longer ranges and these are called hybrid PIC codes. LSP is a commercial code with this capability.

At the end of the day, the codes are benchmarked against experimental data which is a key goal of current experiments.

1.1.4 MFE Approaches to Fusion

1.1.4.1 Introduction

All the MFE approaches to fusion require the use of powerful magnetic fields generated by electric or superconducting field coils to confine, guide and trap the reacting particles. Typically fields of ~10 tesla are required. Such magnetic fields produce mechanical forces on structures of the order of ten's of atmospheres requiring significant reinforcement of the large reactor vessel structures in addition to requirements for clean non-ablating materials facing the high energy plasma bombardment from the reactor (inner liner and diverter plates for collecting escaping plasma). These field coils generally occupy a large fraction of the structural geometry. A significant parameter for all magnetic confinement reactors is the ratio of plasma thermal pressure to magnetic trapping pressure defined as the beta parameter:

$$\beta = 2 \mu_o n_{e,i} k_B T_{e,i} / B^2$$

Where $n_{e,i}$ is the plasma density, k_B is Boltzmann's constant, $T_{e,i}$ is the plasma temperature, μ_o is the permeability of free space and B is the magnetic field strength. Typically β is of the order of 10% in order to maintain stability of the plasma. One of the goals of magnetic fusion systems is to make the beta parameter as large as possible, thereby reducing the size and cost of the magnetic field coils and the overall reactor system.

1.1.4.2 Tokamaks

In the late 1950`s the idea was developed in Russia of using a toroidal (donut shaped) configuration where the ions and electrons will orbit around the circular magnetic field lines indefinitely until they suffer collisions and drift sideways out of the plasma region. The first attempts to utilize this configuration ran into difficulties because of the combination of magnetic field gradient and electric fields generated caused the plasma to drift across the magnetic field lines. The net result caused the plasma to drift outwards until it hit the outer plasma wall. Russian researchers then proposed that passing a current through the circular ring would induce an additional magnetic field which would twist the plasma rapidly and stabilize the outward drift. They called this device a tokamak. This approach has received the most investment in research to date and is closest to demonstrating net power production for magnetic approaches.

The confinement of the plasma is illustrated in Fig. 1.17. There are a number of coils required for such a system including the main toroidal magnetic field coils (in green)

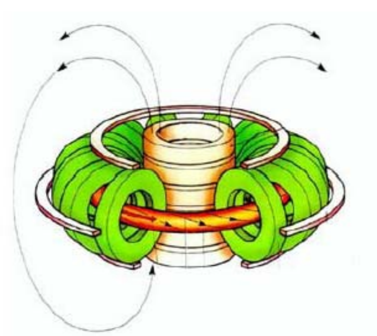


Fig. 1.17 Tokamak concept

that will have to be superconducting coils to minimize electrical costs and excess heat generation. These create the main guiding magnetic field going around the donut shaped loop. On the top, middle and bottom of the machine there are additional poloidal coils to help adjust the plasma height and position. Finally there is a transformer winding in the middle of the device in order to induce the toroidal current around the ring which is the distinctive feature of the tokamak design. This current generates the additional magnetic field which will twist the field lines in a spiral around the torus and thus scramble any net outward drift motion.

Unfortunately, a transformer cannot generate continuous DC current as would be required for a reactor and thus additional means of current drive must be employed for long pulse operation. As the plasma heats up above 1keV in temperature it becomes virtually a perfect conductor and the heating from the transformer induced current ceases to be effective. Auxiliary techniques to both heat and drive current through the plasma - high energy particle injection and directional RF heating - are required. Both of these techniques will deposit momentum into the plasma which can continue to drive plasma current after the transformer action has terminated. Thus, it is expected that operational tokamak systems will require high power RF and particle injection systems capable of delivering of the order of 50 to 100 MW of continuous heating power into the plasma during operation.

One of the major issues with achieving net power output is to avoid excessive radiation cooling of the plasma. Just as a stove element, the plasma radiates a large amount of its energy away as thermal radiation called bremsstrahlung. The radiated power scales as $Z^2 n_e n_i T^{1/2}$. Such radiation losses have been taken into account in estimating the Lawson threshold criteria for ideal deuterium-tritium plasmas (Z=1). However, since the radiation scales as the nuclear charge Z^2, any contaminant species such as carbon or metal ions from the reactor vessel walls which makes it into the plasma will radiate power by factors of 36 times or more compared to hydrogen isotopes. This will quickly cool the plasma below the threshold conditions required for net energy gain. Consequently, all fusion reactor systems require that the main reacting volume contain as little contaminant species (<<1%) as possible. In order to minimize the contamination of the reacting volume the reacting plasma is designed with an outer layer called the scrape off layer which is diverted to intersect special plates called diverter plates; this provides for a continuous flow of plasma from the plasma core out to the diverter plates. The plasma core itself will be refueled by a continuous stream of injected DT fuel pellets.

The diverter is typically located in trough like regions well above or below the main plasma volume so that higher atomic number materials such as metal ions hitting it can be pumped away and not enter the main reactor volume. These diverter plates, where most of the escaping plasma is deposited, are one of the critical components of a tokamak reactor since the incident power density is extremely high - on the order of 10 MW m^{-2}. Suitable designs to withstand this power load with limited erosion are a major point of materials development still required for operational MFE reactor systems.

Fueling of an operational reactor would be accomplished by firing frozen deuterium-tritium (DT) fuel pellets into the plasma interior at several pellets a second. Such injectors would probably use pressurized gas guns. An alternative proposed scheme involves fueling with compact toroid plasma balls which are formed in a plasma gun and accelerated via electromagnetic forces into the main reactor volume. This technique gives more control over the fuel condition entering the reactor but the density of such plasma spheroids is much smaller and whether a sufficient fueling rate can be obtained and whether sufficient penetration of the magnetic field can be achieved remain ongoing questions.

Tokamaks can operate in different plasma stability regimes. The regime which has been favoured most recently is the H-mode of operation because it allows operation at a relatively high value of beta of around 10%. In this mode of operation there is a continuous pulsation of the plasma out to the walls and then a relaxation inwards called ELM oscillations. Each pulsation gives a burst of escaping plasma on the diverter plates. If left to occur at their natural rate the peak pulsed energy fluence on the diverter plates would exceed their operating capabilities. In order to minimize the peak energy flux the oscillations are artificially stimulated at a much higher rate in a controlled fashion so that each burst by itself is within the expected tolerance of the diverter plates.

One of the outstanding issues for an operational tokamak is a major disruption where the plasma becomes unstable and suddenly arcs to the chamber wall, dumping all of its stored energy (multi-gigajoules) to one spot - like a lightning strike - that can cause the spot to melt and potentially puncture the vacuum vessel wall. If the vacuum vessel is punctured then the reactor must be shut down for repair, a lengthy and expensive procedure. Such disruptions are due to unexpected major fluctuations of an operating parameter such as sudden failure of one of the heater beams or control coils or if a piece of debris falls into the plasma from the reactor wall. Plasma monitoring systems can detect such an event in its early stages; to mitigate damage, the current solution is to immediately inject a large block of frozen gas such as neon which very rapidly vaporizes and quenches the plasma. Such systems have been an operational feature on current research systems but will need significant scaling to quench hotter, more energetic plasmas in a power reactor.

To date, tokamak systems have achieved both the high temperatures above 10 keV and high densities typically above 2×10^{20} particles/m^3 but not both conditions at the same time. Also, energy confinement time has reached several seconds, somewhat less than required for continuous reactor systems. The best result obtained to date has been a power output from fusion burn of 16 MW in the Joint European Tokamak (JET) project, while heating the plasma with a deposited power of 24 MW for a Q = 0.65 and for a period of time of approximately 0.6 seconds. The JET facility and a sketch of the next generation ITER facility are shown in Fig. 1.18. Some tokamak references[42,43,44,45] provide useful summaries of past performance and projections for ITER – designed as an international experimental project to demonstrate a fusion output power of 500MW.

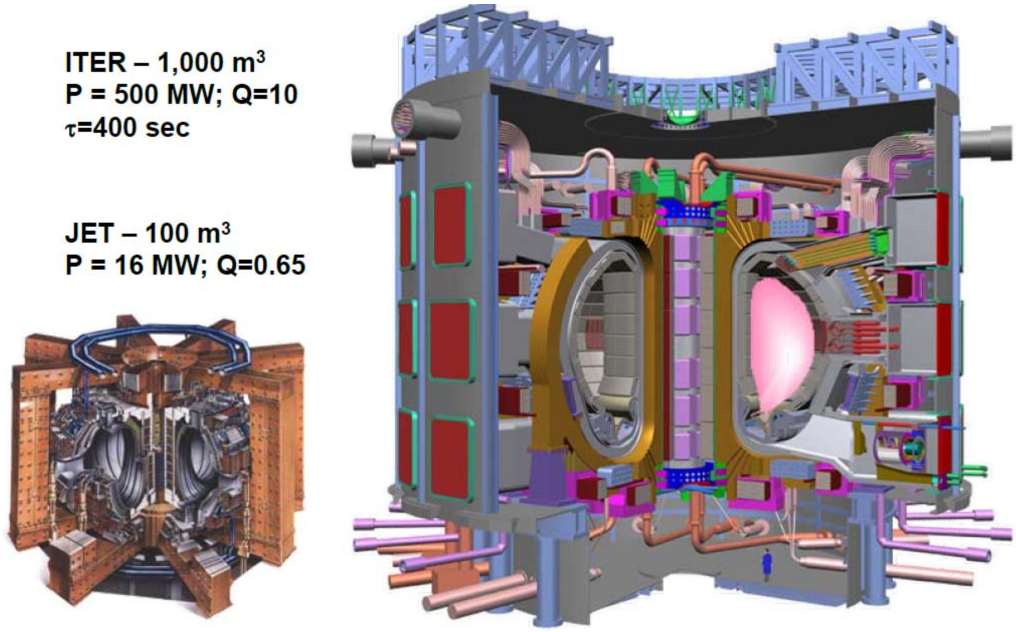


Fig. 1.18 JET tokamak and ITER tokamak facilities

1.1.4.3 Solenoids and Mirror Machines

A number of the original attempts to confine plasma under fusion conditions were based on linear plasmas with strong pinching magnetic fields at each end to reflect and trap the plasma - called linear solenoids or mirror machines, Fig. 1.7(b). However, these devices suffered from excessive losses from plasma leaking out the ends or from pinch and kink instabilities, Fig. 1.7(c) where the plasma would break up or twist into highly distorted figures very quickly (microsecond to millisecond time scales), thus breaking into small pieces, destroying plasma confinement. Most of these schemes have been abandoned as routes to fusion reactor systems.

1.1.4.4 Compact Toroids: Spherical Tokamaks, Spheromaks & Reversed Field Pinches

Further refinements of the tokamak include the Compact Toroid, Spheromak and Reverse Field Pinch configurations as illustrated in Fig. 1.19. In this case the center transformer column and inner conductor of the toroidal field coils of the tokamak are shrunk in size or removed entirely with the required plasma currents generated in part or in whole by self consistent electric fields in the plasma controlled by external means. In the case of shrinking the center column, the devices are called Spherical Tokamaks since the dead region in the middle becomes very small and the overall shape starts to look spherical.

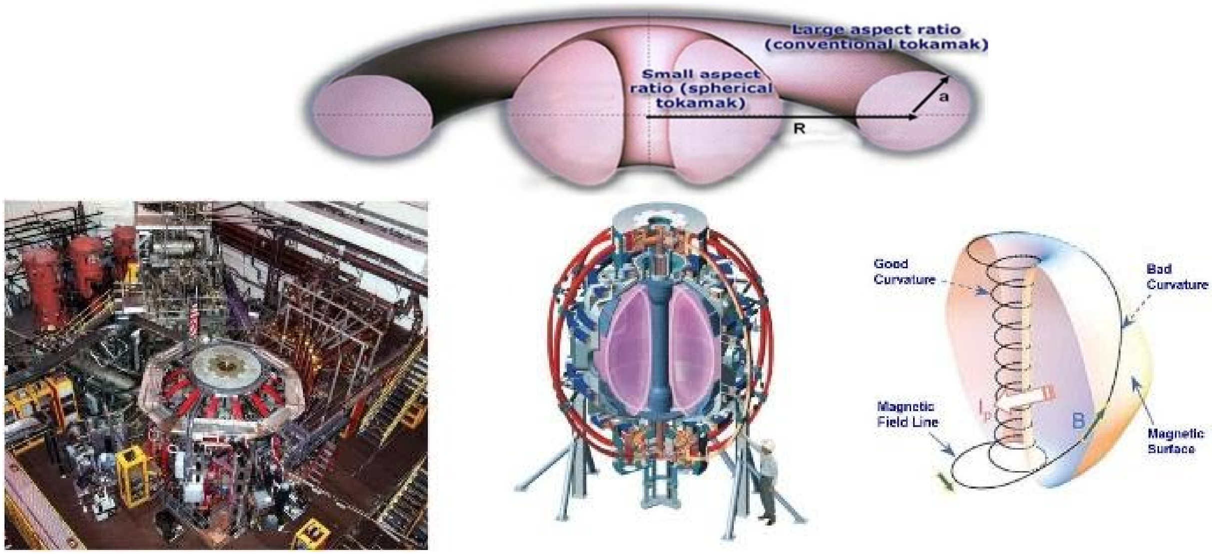


Fig. 1.19 Compact Spherical Tokamak and NSTX Compact Torus at Princeton

Such systems are being investigated at Princeton University (NSTX)[46], Culham Centre for Fusion Energy in the United Kingdom (MAST)[47] and several other places in the world. One advantage of such systems is that they are inherently more stable against plasma instabilities and can operate at much higher beta values of up to β = 30% and thus could be smaller than equivalent tokamak systems. However, they are much less developed and all the operational issues of scaling to full size reactor systems are not well established yet. At present, the Princeton program is undergoing an upgrade and the UK program is also scheduled for an upgrade. There are proposals to use such compact high beta toroidal systems as fusion neutron sources in order to carry out testing of materials and components under high neutron fluxes in order to develop long lifetime materials for future reactor systems.

1.1.4.5 Stellerators

The stellerator, Fig. 1.20, is an alternative to the tokamak. In this case, plasma stability is maintained by generating a twisted magnetic field line configuration in the magnetic coil design rather than adding a transformer current through the plasma. The virtue of the stellerator[48] is that it can operate in a completely steady state configuration with no pulsing transformer current to activate the plasma current. However, to build such a system requires a precision 3D layout of magnetic field coils to ensure that all the twisted magnetic field lines connect properly around the torus and that no open field lines exist where the plasma could escape.

Large stellerators have been designed in Germany and Japan - the Wendelstein and the Large Helical Device (LHD), respectively. The latest Wendelstein 7-X system will start operation in 2015 and the HPD system has been operating for a few years. The results to date have been encouraging but it is expected that operating reactors based on such systems may be larger than equivalent tokamak systems. Scaling to scientific breakeven test machines, Q > 1, will require at least one more generation of development beyond the current machines now being investigated.

Fig 1.20 Stellerator magnetic field coils and plasma

1.2 Alternative Approaches to Fusion Confinement or Fusion Applications

1.2.1 Foreword

While this report primarily responds to a request for assessment of major fusion technologies - highlighting IFE with its options and potential for economic deployment and including an outline of MFE development - a brief survey of private sector initiatives is included here for completeness.

In addition to the mainline approaches in IFE and MFE, there are a number of alternative schemes and/or alternative applications being pursued internationally. Since we have not reviewed all possible enterprises, only more prominent ones will be mentioned here. Generally, these alternative approaches seek to find a niche that is outside the more traditional programs. Moreover, these exploratory concepts are generally funded by the private sector as compared to public funding of the mainline approaches. The motivation of the private venture companies is to discover a faster or cheaper route to practical fusion systems for power or other applications – a laudable but difficult goal. Indeed, there is a long history of such attempts, so far without success. In view of the major commitment and funding required for fusion R&D, generally beyond the reach of smaller companies, it may be the neutron or radiation applications achievable with smaller sub-systems that will eventually provide commercial success for them.

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The alternative approaches are based on variations of: (i) the known fusion fuel reactions; (ii) possibility for direct electric conversion (vs steam turbine cycle) and/or; (iii) confinement regime determined by the Lawson parameter requirement ($n\tau \geq 10^{20}$ m^{-3} sec).

In addition to the principal fusion reactions, some others include:

$n + Li^6 \rightarrow He^4 + T$ + 4.8 MeV energy
$D + He^3 \rightarrow He^4 + p$ + 18.3 MeV energy
$p^+ + B^{11} \rightarrow 3\,He^4$ + 8.7 MeV energy

The latter two reactions result in charged particles. Depending on reaction cycle, the required "ignition" temperature varies considerably. Ignition is associated with self-heating of the fuel and minimizes the triple product $n\tau T_i = p\tau$, where T_i = the fuel temperature, p = pressure and τ = confinement time. The D,T reaction has the lowest optimum temperature of 13.6keV; D,D is 15keV; p,B is 123keV. At these temperatures, the reactivity varies considerably and so too the power density for a given fusion reaction relative to D,T (factors of 70 and more).

In reality, even higher temperatures are needed for D,D (500keV) and p^+,B (300keV) fusion to optimize fusion power compared to inherent bremsstrahlung radiation losses - for this reason, the D,T cycle has been the focus of all major international programs. With experience gained in D,T fusion, later generation systems could proceed to advanced fuel cycles requiring higher temperatures.

1.2.2 Some Private Sector Companies in Fusion R&D

Tri-Alpha Energy was founded in 1998 and is located in Rancho Santa Margarita, California. Private funding of the project appears to have exceeded $100 million up to 2010 and perhaps double that by now.

The initial Tri-Alpha goal was to pursue the p^+,B reaction that produces fusion energy in charged alpha particles rather than yielding neutrons as in the D,T reaction. This avoids both radioactivity issues and inefficiencies in electrical power generation by avoiding the conversion of heat to steam. Little information has emerged on its progress with p^+,B but work on deuterium fusion has been reported. It is not clear whether this is an intermediate step enroute to p^+,B fusion or whether their plans have changed.

Tri-Alpha designs are based on a field reversed configuration in which accelerated proton and boron beams are injected into a solenoidal confinement magnetic field. These magnets and the magnetic fields established by the plasmas themselves cause the plasmas to rotate inside the cylinders in a field reversed configuration.

Proton-boron collisions lead to a fusion reaction producing carbon-12 that decays to three helium-4 (alpha) particles. The alpha ions generated would be ejected and collected in a decelerating field coil to produce electricity; proton and boron fuel would be injected to maintain the reaction. The proton-boron reaction is subject to severe bremsstrahlung radiation losses.

A more advanced experimental configuration being developed by Tri-Alpha - based on colliding compact toroids - is shown in Fig. 1.21. Since Tri-Alpha has not been publishing their work, the current status of their R&D is unknown.

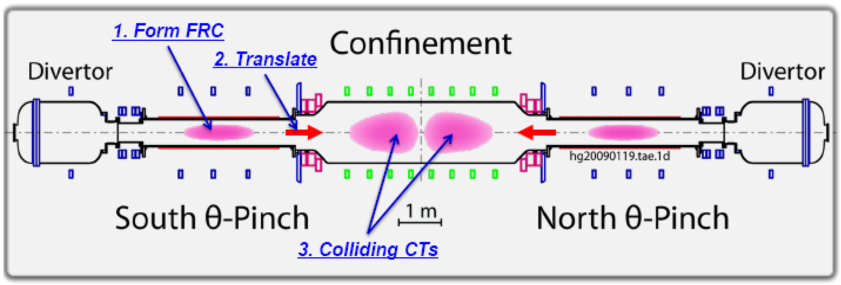

Fig. 1.21 Tri-Alpha compact toroid

Lawrenceville Plasma Physics is another company interested in pursuing the p,B reaction for fusion energy but this time employing a dense plasma focus (initially with deuterium). A schematic of the focus device is shown in Fig. 1.22; the accelerated plasma collapses in the center electrode.

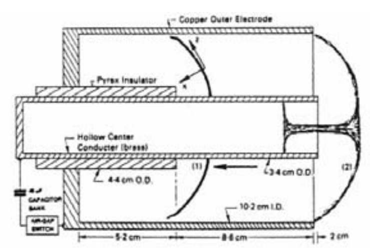

Fig. 1.22 Plasma focus

There has been considerable experimental work on the plasma focus (over many decades) with the conclusion that while dense plasmas as radiation and neutron sources are feasible, they are not scalable to fusion power generation.

In addition to magnetic confinement approaches, there have been experimental programs using **electrostatic acceleration and confinement** (Farnsworth-Hirsch fusor, **Polywell Fusion**, **Energy/Matter Conversion Corporation-EMC2**). The basic concept of the fusor involves an electrical grid (spherical) near the center of the device with a negative charge into which a positively charged ion beam of fusion fuel would be accelerated from a spherical grid at larger radius. The high energy ions (>10keV) would pass through the inner grid and undergo oscillations in the central region resulting in collisions and fusion reactions. Unfortunately, the grid structure degrades the ion energy and also fails due to heating. While the technique is capable of producing neutrons, it is not scalable to fusion power production. Variations to potentially improve confinement include using magnetic cusp geometry.

Yet another approach uses **magnetized target confinement**. This technique is a hybrid of inertial and magnetic confinement and was first explored at the US Naval Research Laboratory (NRL) using steam driven pistons to mechanically drive shock waves to compress a magnetically confined plasma. The objective was to take advantage of highly developed pulsed power technologies (electric, magnetic, mechanical) in the microsecond-millisecond time domain that could potentially compress fusion fuel to densities (10^{26} m^{-3}) substantially below those required for IFE (10^{31} m^{-3}) but well above those required for MFE (10^{20} m^{-3}). [Recall the Lawson criteria: $n \tau > 2 \times 10^{20}$ m^{-3} s]

A variation is the magnetized liner inertial fusion concept that uses a 100 nanosecond pulse of electricity to create an intense Z-pinch magnetic field to inwardly crush a fuel filled cylindrical metal liner through which the electric pulse runs. Prior to cylinder implosion, a laser preheats the fusion fuel held in the cylinder contained by a magnetic field. Sandia National Labs is currently exploring the potential of this method for fusion reactions. The cylinder and electrode connections are destroyed each shot and so the scheme is not directly amenable to steady state power production.

General Fusion is a Canadian company based in Burnaby, BC that was founded in 2002 to pursue magnetized target fusion with newer technology than was available to NRL in the 1970s. It has had private sector and other funding of ~$55 million up to 2013. The basic concept includes a liquid lithium-lead (Li-Pb) vortex flow forming a cylindrical cavity into which separately formed plasmas are injected from each end and, at which point, mechanically driven acoustic waves compress the liquid liner and plasma inside to high density and temperature to ignite fusion reactions. The neutrons would be absorbed in the lithium-lead blanket that is then transported outside to produce tritium and extract heat for electric power generation. A schematic of the device is shown in Fig. 1.23.

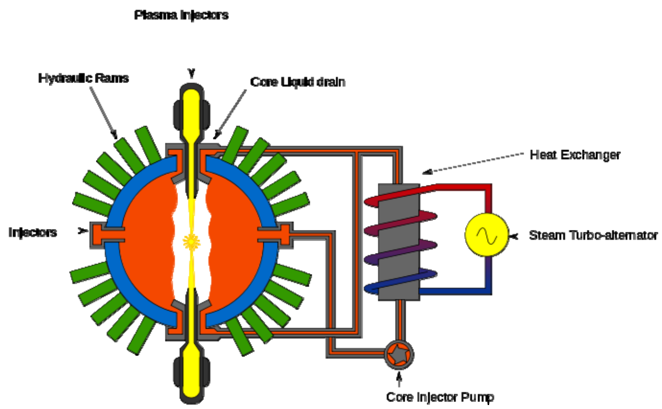

Fig. 1.23 General Fusion magnetized target experiment

The status of this R&D is summarized under the required elements outlined above. The first task is to produce compact toroid (CT) plasmas of the right density (~10^{23} m^{-3} and temperature (>100eV) for injection into the Li-Pb vortex. This has been difficult to achieve because of the observed in-flight losses (density, temperature) of the accelerated plasmas formed in the injectors. Modeling indicates highly turbulent magnetic fields and anomalous transport losses as the problem. A recent experimental modification has been to add a sustaining current to the CT plasma that appears to reduce turbulence, leading to a more quiescent state and lifetime increase of 5-6 times; however, the density remains too low. In addition, they are investigating staged magnetic acceleration of the plasmas in the injector to maintain the density for injection into the Li-Pb vortex. Such modifications will be essential to overcome the initial density limiting barrier in the plasma injectors.

Due to limited hardware available for piston driven compression studies, the approach has been separated into two tasks: a) using chemical explosives to study compression of plasmas in separate instrumented experiments and, b) testing piston driven shock propagation timing and shock stability. Explosive tests are necessarily destructive with turn-around times of months between shots. Limited compression of plasmas (2-3 x) has been observed to date but improved performance is expected, based on knowledge gained from initial shots. A goal for 2014 is to generate substantial neutron yield in compressed plasmas using chemical explosives as a driver.

In the separate experiment, piston driven shocks of the required speed (50m/s) and timing accuracy (5-10μs) have been successfully demonstrated. The task of producing Li-Pb vortices has yet to be accomplished but compression studies of a 20cm Pb vortex in a spherical chamber of 1m diameter with14 pistons have begun. Experiments show non-uniform droplets injected rather than a smooth inner surface due to the non-uniform drive (limited number of pistons). Calculations for symmetric drive indicate limited growth of fluid instabilities (Richtmyer Meshkov and Rayleigh Taylor).

Once the separate tasks are successfully completed, the next stage would be to combine plasma injector, Li-Pb vortex flow and 200 piston drivers in a full system experiment.

How these results will extrapolate to plasma fusion conditions is unknown. High temperature plasmas are difficult to control (instabilities and transport) and, inevitably, new questions will arise in this intermediate density state. Issues of boundary transport between core plasma and the Li-Pb vortex will emerge. Survivability of materials will become a major concern. It is too early to fully assess all issues that would arise in an integrated power plant design. In summary, prospects for the General Fusion scheme as a potentially viable approach to fusion energy is at an early stage of development.

Tokamak Solutions is a UK based company that has the objective of building smaller tokamaks than are conventionally pursued (see ITER) – the configuration is called a spherical tokamak. Since performance scales with size and magnitude of magnetic field, the smaller size requires significantly higher magnetic fields. Eventually this requires high temperature super-conducting coils to make magnetic confinement economically attractive. Tokamak Solutions is an early-stage company initially building table-top tokamaks with conventional magnetic field coils. They have a partnership with Oxford Instruments to fabricate novel high temperature super-conducting magnets for next generation spherical tokamaks.

The initial company objectives are to sell small tokamaks as neutron sources and as experimental machines to an R&D market. Neutron production is less demanding than power production in a fusion device. Possible applications envisaged include: testing components for future fusion power plants; transmuting problem wastes from existing fission power stations; production of tritium; production of medical isotopes and; using them as the core of a hybrid fusion/fission power plant. A representative Tokamak Solutions device is shown in Fig. 1.24.

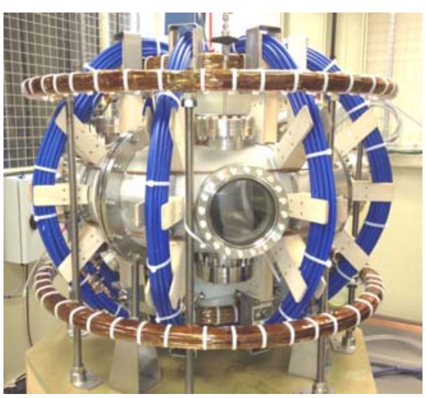

Fig. 1.24 Tokamak Solutions spherical tokamak shown with conventional magnets

Hamamatsu Corporation is a large photonics company based in Japan that is owned by the Hiruma family (father and son). The elder Hiruma is in failing health but is a person with a passion for IFE and related technologies. His son continues this passion and is carrying on with the objectives first set by his father. Hamamatsu has played a significant role in the Japanese IFE program (primarily based at Osaka University) but is now constructing experimental facilities at their corporate research laboratories.

The broad objective is IFE based on “fast ignition” with colliding foils. As outlined previously, this technique could, in principal, provide higher gain with less laser drive energy. Their strategy envisages applications of neutrons for medical and industrial uses at modest laser (~1kJ) and fusion energies (~100J), enroute to fusion power with higher energy lasers at a later stage.

As outlined in the site visit report (see Appendix), Hamamatsu has made impressive strides in their experimental program. They have built a low energy laser system and demonstrated several key aspects of the fast ignition concept including targeting, laser synchronizing, repetitive firing and neutron production. As a photonics manufacturing company, they have the resources to develop and fabricate high power solid-state lasers, as shown in Fig. 1.25 and they are designing new laboratory facilities to scale up the experiments. The Hamamatsu chronological roadmap is shown in Fig. 1.26.

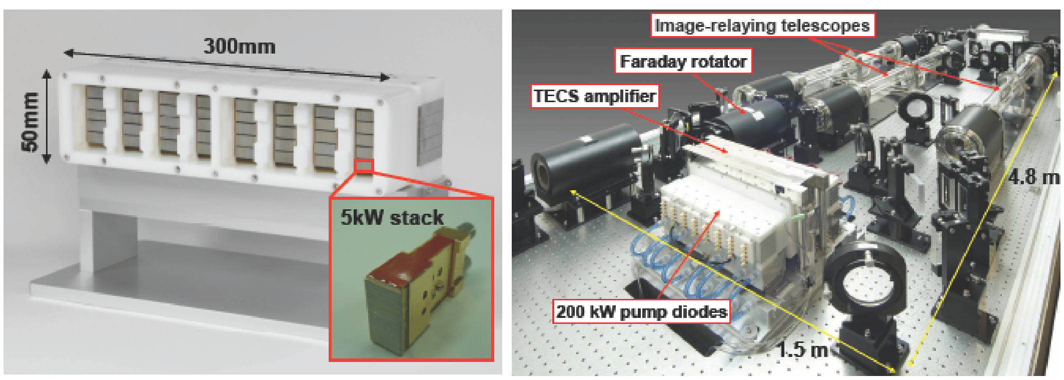

Fig. 1.25 Hamamatsu high power solid state laser system

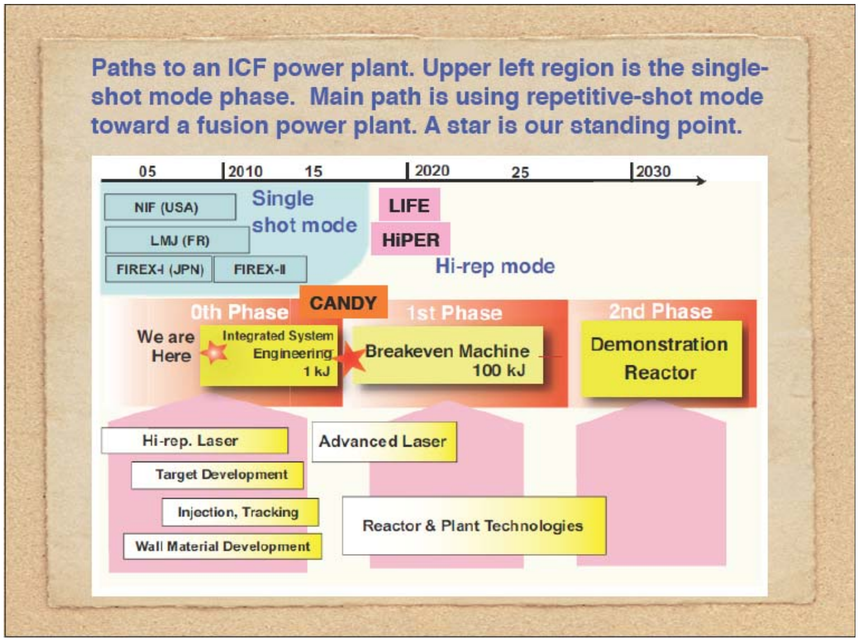

Fig. 1.26 Hamamatsu IFE roadmap

1.3 Progress and Status of Major Fusion R&D Programs

1.3.1 Foreword

Both IFE and MFE have shown significant progress and expectations are high for achieving energy/power demonstration in the near future. This is not to gloss over the significant technological hurdles (including scale up of manufacturing) that exist and will take time and ingenuity to overcome but to indicate that sufficient progress has been achieved to expect a successful realization of fusion energy in both approaches.

While there are many large fusion R&D facilities throughout the world, this summary will focus on two leading initiatives – ITER and primarily NIF - as representative of the overall progress and status of fusion energy development in magnetic and inertial confinement. Brief comments will be added regarding other national activities in fusion development. More detailed notes and summaries are to be found in site visit reports in Appendix III.

Insofar as ITER is the culmination of the MFE approach after 60+ years of independent and collaborative research among the international communities, many of the separate national programs have re-oriented their activities to provide support roles for the major undertaking at ITER. Though this is generally true, a few nations, particularly China and Korea, have made fusion a national priority (China in the case of their 2020 Vision and Korea through legislation placing fusion explicitly on the national agenda) and consequently are pursuing major programs in their national laboratories in parallel with their large commitment to the ITER project.

For IFE the situation is slightly different. This approach to harnessing fusion did not commence until after the invention of the laser (1960) and effectively got started with design and construction of laser systems capable of higher energies in the 1970's. Lawrence Livermore National Laboratory (LLNL) was an early proponent and, as a major US national laboratory for science and engineering, was able to garner significant financial support through DOE defense appropriations to initiate a comprehensive capability. As a consequence, this center has made the greatest strides forward in science, technology, computer simulation and systems engineering. This has been a credit to the energy and drive of a dedicated group of people and major program funding, and a significant benefit to international activity, resulting in rapid progress of IFE development.

1.3.2 Progress & Status of Indirect Drive IFE

The National Ignition Facility (NIF), shown previously in Fig. 1.9, comprises a 192 beam, 1.8MJ laser system; target chamber and; associated instrumentation - designed for experiments to achieve fusion fuel ignition. NIF is a precision laser with programmable features in temporal pulse shape, power and energy - able to deliver beams focused with temporal and spatial resolution of 20psec and <50 microns rms. It is modular in construction for line replacement of laser and optical components with all robotic maintenance.

NIF is a remarkable laser engineering achievement - demonstrating a critical precision technology capability for success in IFE.

The hohlraum-target for indirect drive IFE is shown in Fig. 1.27. Briefly summarized, the achieved (**required**) target parameters for IFE to date are: compressed core 500-800g/cc (**1000**); hot spot 50g/cc (**100**) at 5keV; pressure 150Gbar (**350**); fuel ρR 1.3g/cm^2 (**1.5**); implosion velocity 310km/sec (**350**). The triple product, $p\tau$, is still too small for full ignition by a factor of approximately 2.

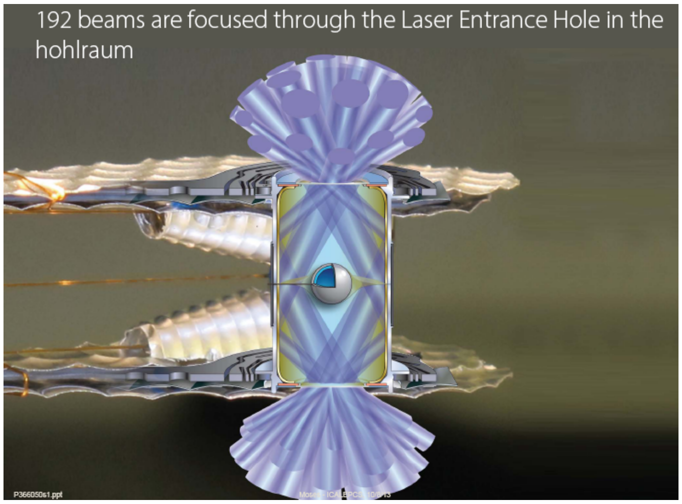

Fig. 1.27 LLNL cryogenic indirect drive target

Significantly, core ignition has been successfully demonstrated, i.e., fusion energy output from the core clearly showing alpha particle heating. This is a critical first step as shown in Fig. 1.28, where in a recent experiment, the total yield of 26kJ exceeds the compression yield of 12kJ; the need is now to ignite the entire pellet through sufficient alpha energy deposition in the outer layers.

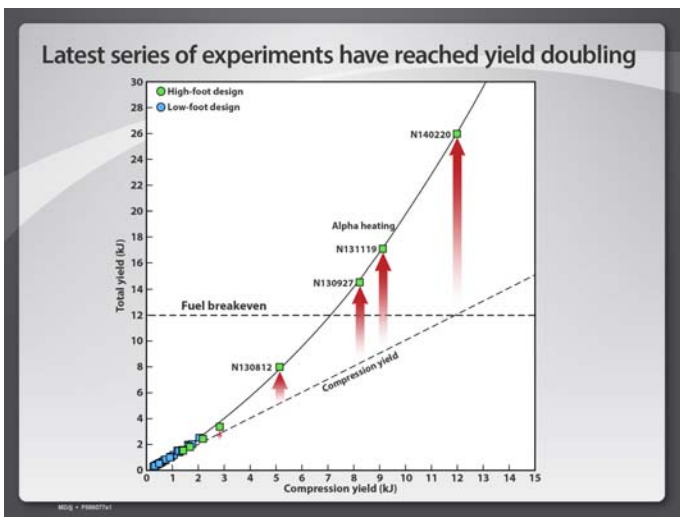

Fig. 1.28 Confirmation of core ignition (alpha particle heating)

Principal issues in these initial experiments include low order asymmetry and fuel mixing in the implosion. Under low adiabatic conditions (ultimately needed for shock compression), they observe strong fuel mixing compared to little mixing for high adiabatic conditions. Given the complexity of such a first ever system (192 high power laser beam propagation, hohlraum conversion to x-rays, target irradiation uniformity and absorption, hydrodynamics, fuel mixing, etc.), surprises are to be expected and consequently the need for a systematic investigation of parameter space is required.

As recommended by a National Academy of Sciences review[49], such an experimental plan is in progress to optimize conditions for ignition. Potential solutions include modified targets and changes to the hohlraum. A gas filled diamond shell under low compression has yielded a new record in neutron yield and agreement with 1-D calculations. While ignition of such a target is predicted with only 1.3MJ, doping of diamond is difficult. Further experiments with plastic, diamond and beryllium targets are planned. Future experiments will also explore thinner shells for higher implosion velocity. To address asymmetry, the cavity length is being changed slightly to modify laser energy deposition on the hohlraum wall and the pellet supporting web is being reduced. Gold coated uranium hohlraums with higher opacity will be explored. Another option is an elliptical vs cylindrical cavity as proposed by the LMJ group in France. There are many such permutations that can influence target performance and will have to be explored.

While reduced efficiency is inherently associated with indirect drive (conversion of laser energy to x-rays in the hohlraum), an additional reduction of 15% in x-ray coupling to the core is found for gas filled hohlraums compared to the gas-free case. Net drive efficiency is therefore reduced and target designs have to compensate for this.

Nonetheless, remarkable progress has been achieved. The **status of inertial fusion research** is summarized in Fig. 1.29, highlighting progress towards achieving burning plasma (the condition in which alpha particles produced from fusion reactions are able to self-heat the plasma to maintain fusion reactions). Overall performance is estimated to be within a factor of ~2 required for pellet ignition.

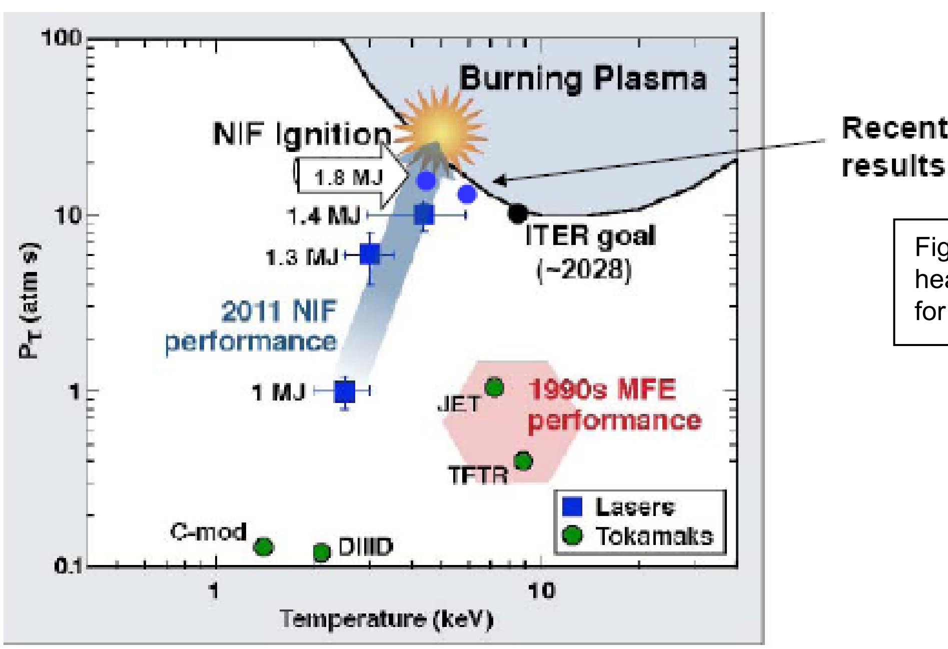

Fig. 1.29 Progress in heating and confinement for IFE (and MFE)

It should be noted that, since inertial fusion ignition is a threshold event, the energy gain increases nonlinearly with drive; therefore, target size and drive energy can be increased to achieve ignition and burn.

1.3.3 Planning for Inertial Fusion Power

The question becomes – what next? How will single-shot experiments be scaled to demonstrate continuous fusion power production? One answer is LIFE[41] proposed by LLNL. LIFE (for laser inertial fusion energy) has been planned by LLNL as a full scale IFE power plant demonstration unit based on indirect drive.

LLNL makes a strong case for “this or nothing in the next 10 years”. The argument is made that the direct drive approach and the KrF laser driver are far less advanced than the indirect drive approach and solid-state lasers, and the alternative approach is therefore not ready for a first demonstration. [Note: the KrF laser may be more applicable for a direct drive scenario in any case.]

While a first plant demo LIFE design was envisaged for 400MWth, second and future plants would be ~1GWe or more; eventually spanning 400-1,600Mwe. Future plants are envisaged to have a 4 year build, 18 year amortization and 60 year lifetime (with chamber liner replaced every 4 years). The LIFE design is based on indirect drive (using the hohlraum to protect the cryo-fuel and reduce helium damage to the chamber wall) using chromium steel for low activation. It assumes 15% efficient lasers at 20Hz, 44% efficient Rankine cycle (future 60% turbines), target gain of 65, resulting in 2,900MWth for a 2.3MJ driver. The laser system would have 384 beamlines with 5,000 hours MTBF. Projected COE is $70-105/MWh for 925MWe-1.6GWe.

Diode-pumped solid-state lasers (DPSSL) are a key enabling technology for IFE and LLNL has invested considerable resources in advancing the state-of-the-art. Their experience and preference is to stay with glass based rather than the new ceramic based laser materials. LIFE would require 10^{10} shot lifetime at 10-20Hz. The LIFE design incorporates 384 beam modules at 5.7kJ/ beam using APG-1 glass with turbulent He gas cooling. The factory built self-contained modules would be truck size for transport to the fusion plant.

The economic case for LIFE would include desalination as well as electric power generation. Desalination is growing 18% per year and therefore represents a potential new market for fusion plants. LLNL has analyzed such systems and projected a decrease in COE from $75/MWh to $50/MWh by the 10^{th} of kind plant (initial plant cost ~$5B).

An artist rendition of a LIFE power plant is shown in Fig. 1.30 and additional detail enabling early deployment illustrated in Fig. 1.31.

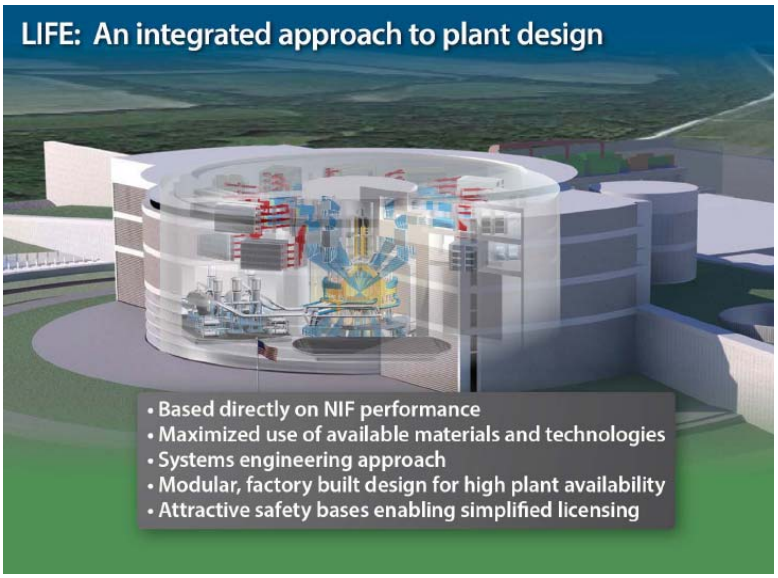

Fig. 1.30 Conceptual LIFE power plant

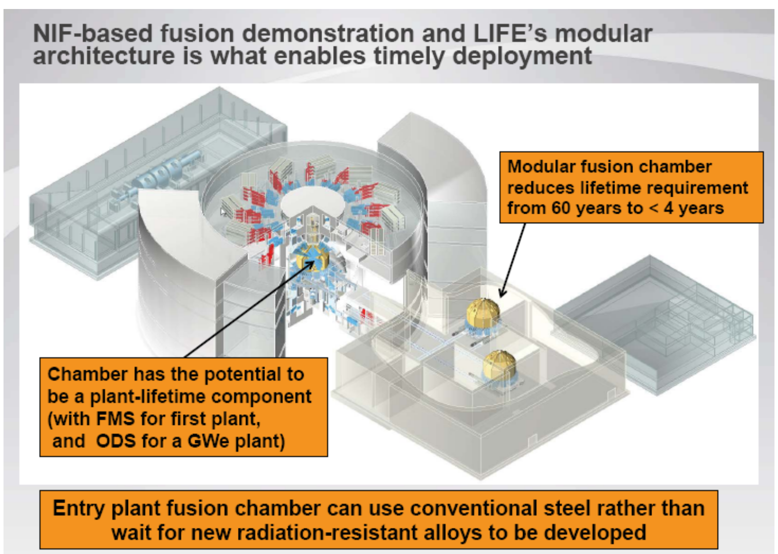

Fig. 1.31 Modular design of LIFE power

In summary, key issues determining the ultimate acceptability of LIFE as a power plant include:

1) NIF achieving full pellet ignition and burn to show net energy gain
2) durability of fusion chamber and optics
3) low cost fuel system delivery and tritium processing
4) safety and licensing

5) high availability plant operations

As for timing of a LIFE plant, the result of a detailed engineering design and risk analysis of a demonstration unit suggests ~10 years following NIF ignition experiments. This short time represents a major shift in prospects for commercial fusion.

Additional discussion is provided in section 3 on heat and electricity applications and the LLNL report referenced therein.

1.3.4 Progress in Direct Drive IFE

As summarized above, the LLNL indirect drive approach is the most advanced concept. Direct drive in contrast is less well developed but offers some advantages for commercial energy applications, primarily through increased coupling efficiency and ability to employ options such as zooming plus fast ignition or shock ignition for higher gain. Three laboratories figure prominently in this approach – Laboratory for Laser Energetics (LLE) at the University of Rochester; Institute of Laser Engineering (ILE) at Osaka University and US Naval Research Laboratory (NRL) in Washington. Summaries of site visits to these centers are provided in Appendix III and so only highlights will be summarized here.

The LLE program emphasizes laser smoothing techniques to ensure uniform target coupling of the laser beams thereby increasing overall efficiency in direct drive. ILE emphasizes direct drive with fast ignition to potentially increase overall drive efficiency even further. NRL emphasizes direct drive with KrF gas lasers rather than solid state lasers as at LLE and ILE. A virtue of the KrF system is an intrinsic ability of this gas medium to achieve superior beam smoothing plus implement zoom focusing to increase target coupling as the implosion proceeds.

LLE In the 40+ years since LLE was founded, it has been a lead lab for direct drive inertial fusion R&D in the USA. In that period, significant progress has been made in devising and demonstrating techniques for beam smoothing of high power solid state lasers required for direct drive. LLE has been a source of innovation in optical sciences, laser hardware, instrumentation, target drive concepts, theory and computer modeling. Major laser facilities include OMEGA: a 60 beam, 30kJ, multi-ns system and; EP: a 4 beam, ~1kJ, ~1ps system. Successful campaigns have been conducted investigating target compression and neutron yield, fast ignition, shock ignition, control of laser-plasma interactions, growth of hydrodynamic instabilities, as well as developing specialized diagnostics for target implosion measurements. Best compression figures achieved are fuel densities of ~200 gm/cm^3 , ρr~0.3 gm/cm^2 and neutron yields of ~$3X10^{13}$, albeit limited by the laser driver energy available that restricts target sizes and therefore net neutron yields.

LLE provides operational support for the US inertial fusion programs at LLNL and other international centers. A recent example is the polar direct drive (PDD) approach that has been proposed by LLE for a future LLNL upgrade to improve irradiation uniformity[50]. They suggest the combination of shock ignition, focal zooming and PDD would reduce the laser energy required in NIF to less than a MJ for target gains of ~60. LLE work on related laser-plasma instabilities at relevant intensities is ongoing. Mass production of cryo targets is also an active area of investigation and LLE is pursuing a variety of concepts and methods for scaling target production.

In summary, LLE has developed a broad capability[51,52] in laser fusion science - laser hardware, target concepts, experimental technique, theory and analysis. It will continue to play a central role in direct drive IFE. Success in demonstration of PDD and SI would have a major impact on future commercial exploitation of IFE. The OMEGA laser facility showing a layout diagram of the 60 beam direct drive irradiation facility and a photograph of the laser amplifier chains is shown in Fig. 1.32.

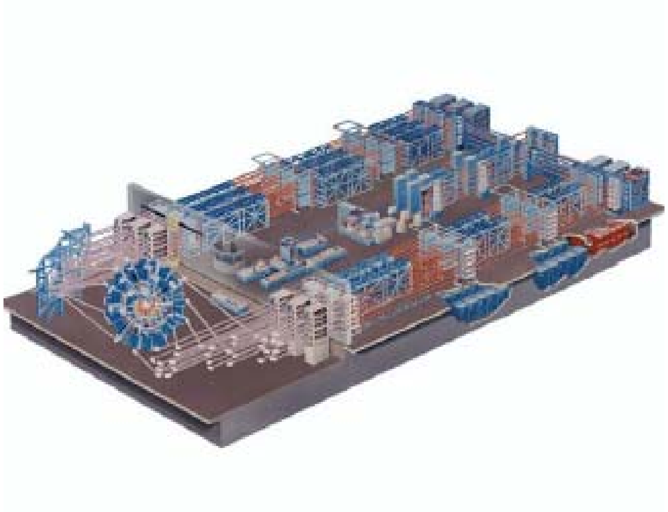

Fig. 1.32 OMEGA Laser facility

NRL This lab has also been engaged in laser-plasma science and direct drive inertial fusion for more than 40 years. Their program is broadly based in experiment, theory, simulation and reactor systems technology and, particularly in KrF laser development. KrF is attractive as an IFE driver for many reasons including laser scalability, target simplicity, coupling efficiency and potential for high gain targets. NRL innovations in KrF laser technology continue to advance the state-of-the-art and increase its prospects for direct drive IFE[23,41]. Significant progress has been achieved in KrF technology with major improvements in electrical pulse power, materials, gas handling and modeling of excitation and energy extraction.

New high gain target designs have been proposed to take advantage of the KrF laser properties, particularly with focal zooming and shock ignition. The conceptual designs incorporate low aspect ratio targets for hydrodynamic stability. NRL has developed 3-D codes, including radiation transport, to model the hydrodynamics of implosions, addressing symmetry and stability issues.

The next step for application of KrF lasers to IFE is the need to demonstrate scaling to multi-kJ, rep-rated systems. Here too, success could have a major impact on the implementation of high gain, direct drive IFE.

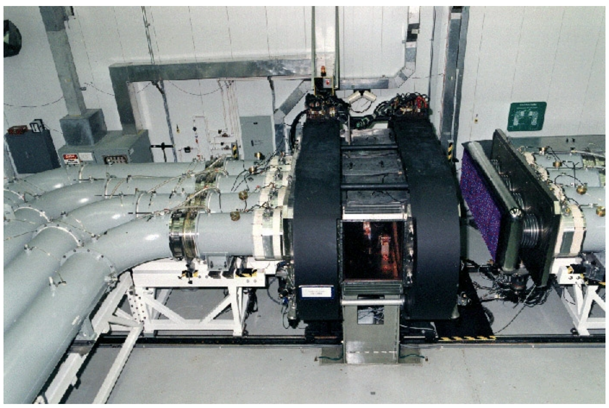

Fig. 1.33 NRL NIKE KrF laser system

ILE The Institute was established in 1972 and has been one of the leading laser fusion labs internationally. The 12 beam laser system, GEKKO-XII, operational since the early 1980s has been a very productive laser facility for research on target compression and neutron yield, hydrodynamic instabilities, laser-plasma instabilities, alternative target concepts, etc. Unfortunately, the laser has degraded over 30 years of operations - the net output energy is reduced substantially - and is in need of an upgrade.

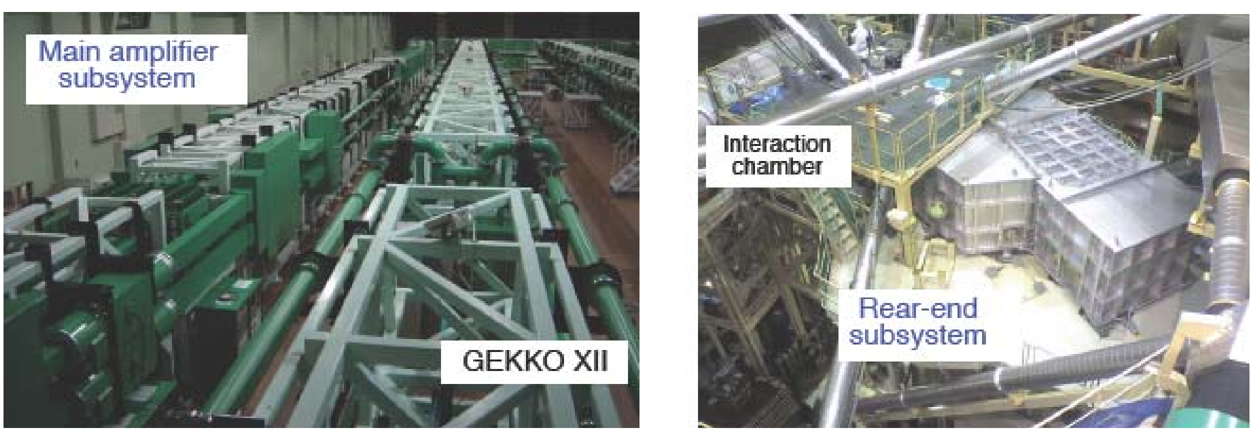

Fig. 1.34 ILE GEKKO-XII and fast ignition (LFEX) laser facilities

For the past decade, emphasis has been centered on fast ignition[7,30] as a way forward for IFE, combining fuel compression using GEKKO-XII with hot spot ignition using a petawatt laser (under construction). This is a key demonstration project that, if successful, will influence the future of FI as a viable approach to commercial IFE.

A fusion demo plant, LIFT, has been designed in a phased progression over a twenty year time frame to demonstrate key capabilities of a fast ignition plant. The design incorporates the latest solid state diode laser technology, ceramic optics, liquid Li-Pb cascade wall for the primary heat loop, fueling technology, together with chamber/blanket material evolving over time. It is based on a target injection rate of ~2/sec and fusion gain of 100, with output power up to 180 MWe.

In summary, the direct drive programs are an important contributor to the development of IFE and hold the promise of higher gain and more efficient systems for commercial applications. They are widely investigated (primarily in academic laboratories) but at a much lower level of funding than indirect drive (located in national laboratories).

1.3.5 Progress & Status of Tokamak MFE

MFE has been actively pursued for more than 60 years in major national laboratories with marked advances in theory, computational simulations and experiments (hardware and diagnostic instrumentation). Consequently there is a vastly improved understanding of magnetically confined plasma, particularly with regard to fusion power systems. This brief summary will highlight status but not include the considerable work done over the decades in many international laboratories that would take more than a thesis to cover. Other large programs continue to be started worldwide; noteworthy are the ambitions of China, India and Korea to pursue development of fusion power as a base load electrical supply on a shorter timeframe.

A large number of tokamaks have been built over the years to explore different parameter regimes. As a result of increased theoretical and experimental capability, there is now an ability to control collective drifts, plasma instabilities and turbulence to project confinement time τ at least adequate for fusion power production. This is achieved by scaling to large magnetic field B_T and device size R. This accounts for the large ITER size of R=6.2 m and B_T = 5.3 Tesla at R=6.2 m, requiring a large central column current to initiate a plasma discharge. Auxiliary heating is then employed to reach ignition and burn.

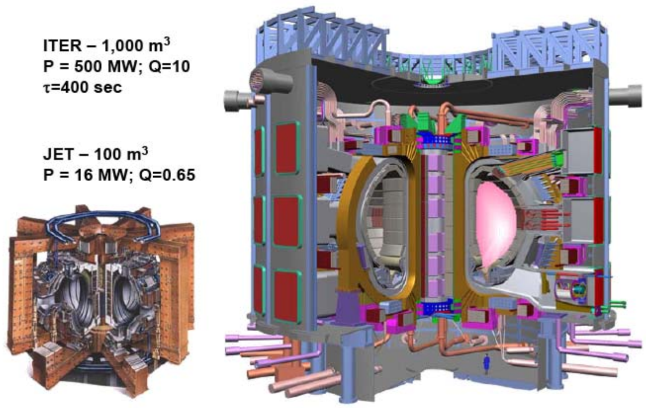

Fig. 1.35 ITER is the most advanced tokamak

ITER is a scale up from the earlier generation of tokamaks, particularly JET that previously had generated the largest fusion power (16 MW) up to 1997. To date, the leading tokamak facilities have achieved confinement parameter ($n\ \tau$) of up to 0.2 x 10^{20} m^{-3} s at fusion temperatures of 20 to 40 keV and 1.5 x 10^{20} m^{-3} s at temperatures of 1-2 keV. JET is a continuing experiment and working platform for testing materials, scaling of heating, studying confinement, divertors, new diagnostics, etc. in preparation for ITER.

Plasma confinement is a major concern for ITER both through "edge localized modes" (ELMs) that could dump a large amount of energy on the walls leading to damage and to disruptions resulting in runaway electrons that could lead to beam-like damage of walls. To avoid such damage, once sensed, ITER incorporates additional field coils and a pellet injector to quench the high temperature plasma by injecting a frozen pellet of neon approximately the size of a wine cork. **ITER has been conservatively designed to avoid potential damage and thereby enable a long experimental working lifetime.** It will operate in a pulsed mode with a very low duty cycle compared to an operational reactor which requires a duty cycle of unity.

Wall materials are a special issue given the high fluxes of high energy radiation, charged particles and neutrons. Impurities sputtered from the walls, including divertor, that could penetrate the plasma would lead to large radiation losses and so have to be avoided. A variety of materials, including beryllium, tungsten and carbon will be employed for testing in critical areas of the device, for eventual implementation in next generation tokamaks.

Auxiliary heating via neutral beam injection of deuterium (33MW, that also provides fueling) and electromagnetic waves (20MW, 170GHz for electron heating and 20MW, 40-55MHz for ion heating) are included in the ITER design to achieve ignition. The use of particle injection and electromagnetic waves will be essential for ultimate success in fueling and current drive for steady state operation of tokamaks. ITER will provide an important test bed for auxiliary heating and fueling of large tokamaks for power production.

Procurement arrangements (that will be fulfilled by the nations contributing to ITER) are essentially in place for delivery of all components of ITER. The nominal commissioning date is 2022 with plasma experiments planned for ~6 years before fueling with D,T for fusion power demonstration.

Fig. 1.36 summarizes the progress in confinement and heating towards ignition and burning for MFE. ITER is projected to result in 500MW of fusion power at a Q=10 for periods up to 400 seconds. Since ITER is a scaled up confinement experiment, it will not generate electricity and so another machine, DEMO, is planned to be constructed in the 2040-2050 period to demonstrate fusion power to the electrical grid. Results from ITER experiments will guide the path for DEMO and beyond.

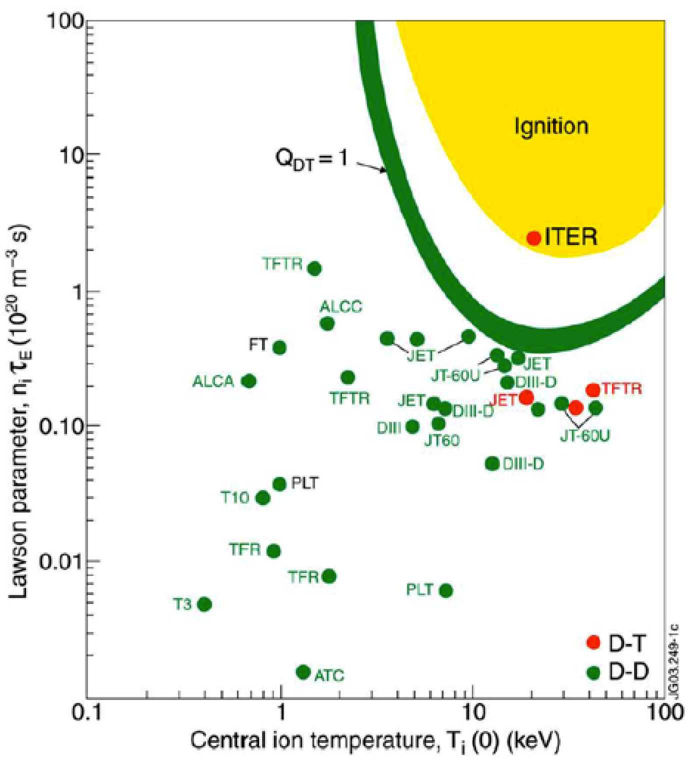

Fig 1.36 Progress in heating and confinement for MFE; results from many tokamaks

1.4 Safety and Regulatory Issues for Fusion

Fusion energy is inherently safe as far as large central power station options are concerned, without the danger of catastrophic failure or the generation of dangerous waste products. There is no large inventory of fuel in the reactor which can continue to release energy after the energizing source (lasers for IFE, neutral beams and electromagnetic waves for MFE) are shut off. There is no radioactive waste product stream. The tritium fuel is generated and consumed within the reactor site itself with no off site emission or transport of tritium. With proper design all the reactor vessel and materials can be buried and disposed of in low activation landfill sites after a decommissioning period of less than 100 years. All operations are designed to be carried out safely well within the radiation exposure safety limits of normal radiation workers. However, fusion reactors will have nuclear and chemical systems which must be closely monitored, controlled and regulated.

Because the Canadian nuclear industry is based on the CANDU heavy water reactor which produces tritium on an ongoing basis, Canada has world leading expertise in the safe handling and processing of tritium which will be critical for fusion reactors. In addition, regulations and guidelines for safe handling of tritium are already established within our nuclear regulatory framework administered by the Canadian Nuclear Safety Commission (CNSC), unlike most other jurisdictions in the world. Thus, Canada is in an ideal position to quickly establish a fusion energy program involving tritium fuel.

The major hazards related to an IFE power plant are:

- tritium leaks from the plant
- long term activation of reactor vessel and the plant
- fire in liquid lithium loop of a plant and tritium release

The tritium is generated and contained in the liquid metal breeding and cooling loop which may be either pure lithium, lead-lithium or some other lithium containing alloy. The lead lithium alloys have relatively low melting temperatures and flow like molten solder and thus are fairly easy to pump through heated systems. Pure lithium is much lighter and has a melting temperature of 180.5 C and thus also is easy to pump in heated pipes. It also has the advantage of high affinity for tritium reducing the diffusion rate of tritium through the chamber and plumbing walls. It is expected that a second heat exchange loop will be employed in between the primary liquid alloy system and the high temperature steam system to avoid any leakage of tritium into the water system. It is expected that any residual leakage will be minute, well below the CNSC current regulations for operating CANDU reactors, 7000 Bq/m^3.

The activation of the reactor vessel made of low activation steel has been analysed in the LIFE reactor scenario and the approach taken is to use currently available steels rather than wait for future longer lifetime steels with even lower activation currently being developed. With the currently available steels the reactor vessel can be replaced every few years just like an industrial boiler. It will be stored on site and after a cool down period of a year or more can be disposed of on site by burial. If a reactor vessel with sufficient long lifetime mechanical properties is developed from the low activation steel alloys such that it could remain in service for the plant lifetime, then the activation level would be such that it would need to be stored on site for the approximately 100 years and then could be disposed of in low level radioactive waste burial. Ultimately and, especially with smaller size advanced systems employing FI or SI, silicon carbide walls would eliminate activation and simplify systems even further (Fig. 1.37).

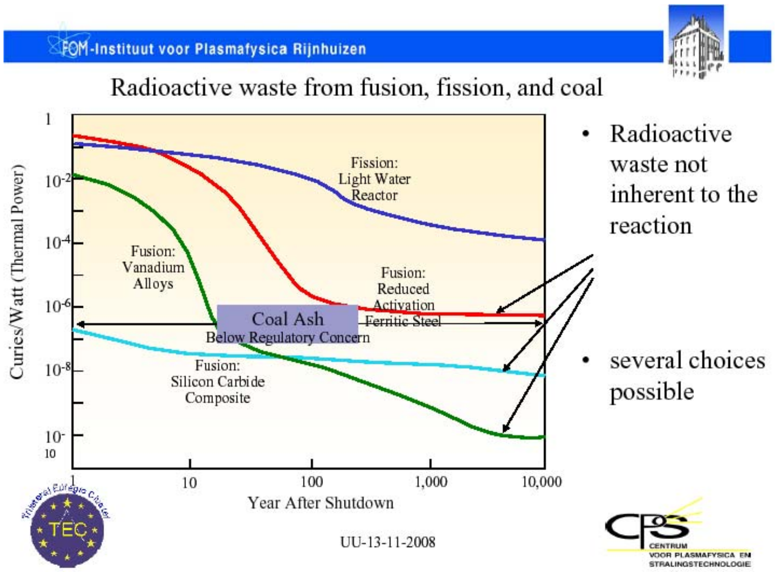

Fig. 1.37 Radioactive waste comparison

Liquid lithium has a very high chemical reactivity with oxygen, air and water. Such liquid metal systems have been studied with regards to applications to high temperature nuclear reactors, in particular breeder reactors. Primary safety systems consist of inert gas filling of reactor vessel housings, avoidance of any water near the reactor vessel, and passive gravity fill dump tanks for any accidental spill. Lithium has a high affinity for tritium and thus will contain most of the tritium without release even in the event of a partial burn up of lithium in a fire. The analysis carried out for the LIFE reactor indicates that even in the case of the worst industrial accident, breakage of main pipes and escape of liquid lithium inside or outside the reactor vessel with a fire, a low release of tritium would result (within the safety limits of the general public outside of the reactor site) and therefore not require evacuation of the general population.

The Canadian Nuclear Safety Commission already has regulations for the safe operation of CANDU reactors including regulations regarding the handling, monitoring and maximum emission levels of tritium into the environment. Many other countries in the world do not have such regulations in place yet and would require years of study before introducing such regulations. In addition, it appears that fusion power plants are already classified as class 1A nuclear facilities and the procedures for approval of a plant are similar to a current nuclear facility proposal. Thus Canada does have an advantage in that the regulations can immediately be applied to a proposal for a fusion demo plant without having to develop new regulatory procedures. Finally, because of Canada’s long history in developing nuclear reactors the Canadian nuclear licensing process is simpler and shorter than in many other nations of the world. Overall, Canada is in a good regulatory position to be the site of a first demonstration fusion power plant.

1.5 Summary Comments

From the foregoing material, the following observations are presented:

1) governments worldwide consider fusion to be a strategically important future energy source and are investing to realize its potential
2) private sector visionaries are seeking to obtain strategic positions in emerging fusion energy technologies
3) both IFE and MFE will be developed; IFE offers the possibility for a simple, accessible plant design and technologies associated with IFE appear to offer more opportunities for new entries, both R&D and commercial
4) while advanced systems based on direct drive and FI or SI must be pursued for next generation IFE systems, the experience obtained in building a LIFE demonstration plant (based on the maturity of indirect drive) would be incalculable

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APPENDIX B

ASSESSMENT OF AN ALBERTA ROLE IN FUSION
(potential for enhancing R&D and diversification of Alberta economy)

2.0 Fusion as an Overarching Driver of Technologies

2.0.1 Foreword

Fusion energy in whatever form it takes will challenge many of the existing technologies in order for it to become a commercial reality. It will act as driver for technology development giving those groups who pursue reactor technologies a leading edge in next generation technological solutions which in the long run will have a spill over effect into other industrial and resource sector needs. While better performance will be required in many technology areas and new solutions must be found in some areas, in all cases there are one or more proposed solutions and no show stoppers are currently seen.

The required mix of technologies is different for magnetic and inertial fusion approaches. The magnetic fusion approach needs high power particle driver and RF driver systems, superconducting magnets and significant advances in high temperature materials for the chamber inner walls and especially the divertor plates. The key requirement is for materials that can withstand continuous bombardment of high energy plasma, including neutron irradiation and alpha particle injection at high load power density. Since the primary request in this assessment report concerns inertial fusion, MFE opportunities for R&D will not be discussed separately except to note there is overlap in many areas.

For inertial fusion there are the driver technologies (the main one being laser drivers); target fabrication, target injection and tracking technologies and; chamber and optical materials. These and other major technology sectors such as robotics and computing required for laser fusion energy systems are discussed below.

2.0.2 Laser & Photonics Opportunities

The photonics sector which includes all applications of light, lasers and optics, is expected to be the fastest growing technology sector in the 21st century. The use of light and all its various applications has already penetrated all business sectors (manufacturing, communications, defense, energy, health) from precision laser welding in many different industries to fiber optics communications and BluRay players. The use of lasers and optical applications will continue to expand as the industry matures just as the microelectronics industry was a dominant industry in the 20th century. As shown in

Fig. 2.1, the overall worldwide photonics industry[1] was on the order of $490B per year in 2011 and is expected to grow at a rate of approximately 6.5% per year, at 1.5 times the predicted GDP growth rate, to a world market of approximately $860B by 2020. This economic growth is accompanied by creation of highly skilled jobs at a rate of approximately 1 job per $240,000 of economic activity.

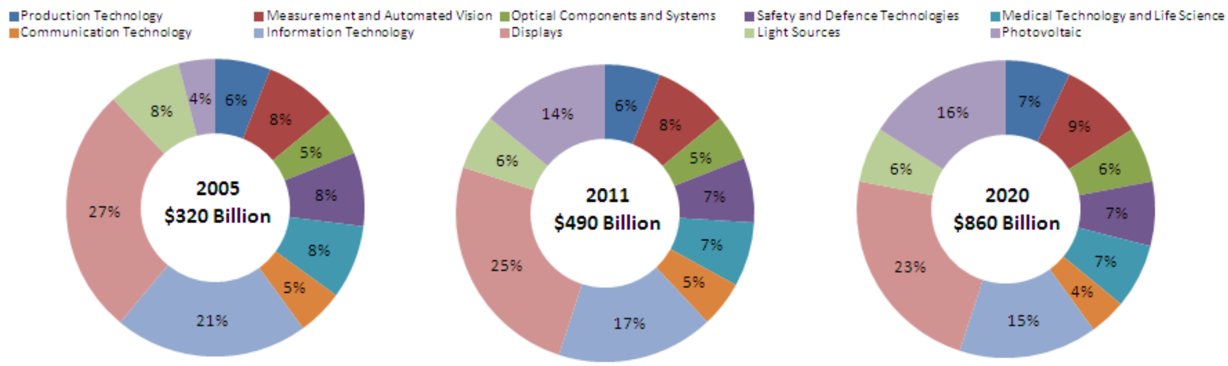

Fig. 2.1 Growth in World Photonics Industry (from Ref. 1 at 1.4 US$ per Euro)

Laser fusion has been one of the major drivers in the development of very high energy, high power laser systems and the future development of laser fusion energy reactor systems will open up a huge new market for such laser systems. It is estimated that approximately 25% of the capital cost of 1GWe fusion reactors will be in the cost of the overall laser system opening up new opportunity for those who develop the technology and manufacturing plants for such systems. Currently there is no such manufacturing base and most systems have been built as in-house research systems from scratch. By mid century, envisaging 10 initial reactors being built, this already exceeds a $10B market in itself which will then start to double every few years. The number of reactors built beyond that will grow exponentially until the end of the century when on the order of 200 reactors a year will be built, giving a growth curve similar to that for personal computers and the internet in the past several decades.

Specifically, there are many individual component sectors involved in the manufacture of complete laser modules which will be designed as self contained units that can be hot-swapped into the operating reactor systems. Typical beam sizes in the amplifier sections will be on the order of 50 cm by 50 cm. On the order of 400 beams will be required and on the order of 20 large optical components per beam giving 2000 m^2 of optical components required. The most expensive component will be the diode pump lasers which currently are manufactured in microelectronics nanofabs and custom optoelectronic packaging centers. Current techniques involve hand assembly and testing of each diode laser stack, in 1 cm^2 surface area modules, at considerable manpower expense.

One fusion reactor will create a demand greater the current total annual demand for such diode pump lasers and spur the development of automated assembly plants similar to microelectronic fabrication facilities today. Alberta has considerable strength in nanofabrication techniques and with an investment in R&D activity and the development of new automated manufacturing and packaging techniques could become an important player in this market. In addition, the basic electronic power supplies to drive the diode lasers require high power electrical driver circuits which are similar to much of the high power electrical power circuits used in the resource industry today. Developing this niche area would immediately penetrate one of the most lucrative opportunities in laser fusion drivers. Such diode pump lasers are required in virtually all other applications of lasers in industry and thus this expertise can subsequently be marketed in many different areas beyond laser fusion driver systems.

Other major areas within photonics are the optical mirrors and lenses, normally referred to as optical components. These must be state of the art components able to withstand laser intensities well beyond most standard industrial applications. About 1500 m^2 of such components (about 50% of the components being transmitting optics) will be required for one laser driver system. In order to achieve such high performance specifications requires very advanced finishing and inspection techniques such as computer controlled magneto-rheological polishing, super-polishing techniques to give ultra-smooth surface finishes and ultra-clean vacuum coating plants to manufacture defect free multilayer mirror coatings. A key requirement is the avoidance of any trace absorbing materials and defects down to the sub-micron level which can lead to incubation of an optical damage site in or on the optical component when it is put into continuous high power operation. Thus, automated high precision inspection techniques and complete pre-testing of components under the required irradiation conditions (burn in) will be required. Techniques for laser melting, removal and reforming of minor surface defects will also be necessary to fix any residual defects after manufacturing. Many of these techniques are similar to techniques already used in microfabrication and inspection systems such as in the nanofab and surface science centers in Alberta.

Another key component in the laser system is the actual ceramic or glass laser media itself which converts the diode pump laser energy into the shaped short pulse required to implode the fuel capsule. The manufacture of these rare earth doped glass or ceramic laser slabs require advanced ceramic or glass growing facilities. Glass growing facilities with the required specialty glass mixes, impurity free conditions and capability of uniformly doping the glass with the actual rare earth lasing species are very specialized and only exist in a few of the leading glass manufacturers in the world such as Schott, Corning or Hoya. However, the ceramic laser materials which also show great promise are relatively new. Currently there is only one commercial manufacturer and a number of research groups making such materials. They require special techniques for preparing very uniform, very pure micron sized nano-crystalline powders as precursors for making the slurries which are cast into laser disks. Considerable expertise is required in the preparation and sintering of these materials to produce optical quality laser disks and only a few places in the world are developing this technology. Alberta with strengths in materials, nanomaterials and chemical technologies could become a leader in this area by investing in an intensive R&D campaign.

In addition, there are many more specialized components such as large electro-optic crystals, inspection tools, beam monitoring and diagnostic systems, and optical alignment systems, to name a few, which will be required. As can be seen from the Routes des Lasers program accompanying the Laser Megajoule project in France there is opportunity for numerous start-up companies to enter these specialty areas, developing the expertise by working on current large scale laser system projects. These specialty optics and tools are applicable to many other application areas of lasers which will give a continuously growing market place for several decades to come.

All of these technologies can be exploited outside of the laser fusion driver area in new application areas of laser manufacturing, processing and sensor systems. Some of the applications are in laser cutting and welding in traditional areas of auto, aerospace and ship building industries where high efficiency, high power lasers are required. Numerous specific applications can benefit from high repetition rate high energy per pulse (>100J per pulse) laser systems to give more effective cutting or processing of large pieces. Such high efficiency laser systems are not commercially available at present.

One technology area that has already been identified for 100J per pulse lasers is in laser shock hardening of metal surfaces. This is similar to traditional techniques of hardening of metals using ball peening except that the pressure pulse is generated by firing a short high energy laser pulse on the surface which creates a strong shock wave penetrating into the surface. The use of lasers allows more control and a much greater range of parameters for carrying out such hardening; the availability of high efficiency, high energy lasers would allow large surface areas of many metres square to be treated effectively. Such laser peening, as it is called, is already used for specialized parts such as jet engine turbine blades and inside cylinder heads of high performance cars. With high efficiency short pulse lasers in the 100 to 5,000J per pulse range it would become possible to treat very large parts to a significant depth, e.g., the extraction buckets for oil sands scoops and other components in oil sands processing to extend part lifetimes by a factor of 2 to 3 times, cutting expensive maintenance and down time. There are many other resource industry applications where extension of tool lifetime would lead to significant cost savings, thus leading to a new industry of laser hardening of large scale size resource industry tools.

Another major future technology area will be in laser cutting, welding and processing of carbon fiber reinforced plastic materials. With mass production it is expected that carbon fiber reinforced materials will become the building material of choice in the future starting from small scale applications in automobiles, airplanes and trucks and eventually penetrating into large scale structures such as buildings and corrosion resistant bridges. Lasers will be one of the dominant tools to manufacture, cut, shape and join such materials. In addition, this will give a huge market for much higher value added use of carbon and plastics derived from the large reserve of hydrocarbons in Alberta.

By spawning a new photonics industry, Alberta can diversify the economy and tie in to one of the fastest growing technology sectors this century.

2.0.3 Target Fabrication Opportunities

Fuel pellets are the major consumable in a fusion reactor. In the case of laser fusion, these would be high precision millimetre size targets which are consumed at a rate of 10 to 20 per second leading to a demand of the order of 1 to 2 million targets a day. Since one of the fuel elements, tritium, is radioactive, and in fact is generated in a tritium breeding blanket in the reactor, it is planned that operational plants will have a tritium extraction, processing and target manufacturing plant on site. This avoids any safety issues of continuously transporting tritium offsite for processing elsewhere. Tritium will be extracted from the liquid metal cooling loops of the reactor in an ongoing basis and it is expected that by immediately processing the tritium into new fuel pellets that the total inventory within the whole reactor complex can be maintained at a low level of the order of 1kg. This will require an automated, very specialized large scale nanofabrication facility to manufacture a continuous stream of precision nanoshell targets, fill them with DT gas or liquid and then form a frozen cryogenic layer on the inside of the fuel pellet shell just before injection into the target chamber. This will also require very sophisticated complimentary optical and x-ray inspection facilities, most likely with nano-precision laser repair operations to take care of any defects noted.

All these operations are currently carried out by hand at significant cost and in the future the whole process must be automated in a nanofab facility. This requires techniques such as microfluidic formation of perfect target shells with oil-polymer mixtures, flow through batch processing in coating plants and high pressure filling chambers, cryo cooling to freeze the inner DT layer, flow through inspection stations, laser repair and sorting stations and final packaging in a launch capsule for injection into the target chamber. Throughout, great care must be taken in the handling of tritium in the cycle. The investigation of automated processes for target fabrication is just beginning in a few of the major target preparation facilities in the world, e.g. General Atomics in California and Rutherford Labs in England. Canada has some of the world leading expertise in the handling and processing of tritium and Alberta has world expertise in microfluidic, nanofabrication and process automation technologies.

Even after pellets have been manufactured their injection to the center of the target chamber so that they can be hit to within 20 to 50 microns accuracy by all of the approximately 400 laser beams will require very sophisticated optical tracking, midcourse corrections (via laser ablation or magnetic steering) and then final tracking to predict exactly when and where the target will exactly be within a millimeter region of the chamber center. At this point all laser beams will be steered electronically in a millisecond to make the final pointing corrections to hit the predicted target point to the required 20 to 50 micron accuracy. This state of the art sensing, tracking, high speed computing and control systems will require significant development and it is expected that only a few specialty companies will develop such expertise and market these systems world wide.

2.0.4 Robotics & Maintenance Systems

The continuous inspection and maintenance of the plant operation will require very sophisticated sensor and monitoring systems interrogating all aspects of optical component damage, reactor wall degradation, liquid metal alloy heat transfer system conditions and tracking of any minute radiation leaks. Due to the high radiation environment around the main reactor vessel, most maintenance will be carried out under remote control with clean robotic systems. Even replacement of laser modules will occur with mobile robotic dollies which can dismount the defective laser and mount the new laser module, similar to Walmart warehouse restocking systems. Because of the activation of the chamber by neutrons all inspection and maintenance of the reactor chamber must be done robotically. There will be significant areas of opportunity for such smart robotic inspection and maintenance systems. Alberta has considerable expertise in systems automation and growing expertise in robotics.

2.0.5 Reactor Chamber & Large Project Engineering

One of the critical elements is the reactor chamber – the fusion engine. Its inside wall must withstand ongoing pulsed bombardment of ions, neutrons and x-rays, heating it to melting or near melting temperatures with each pulse if a solid wall is used or vaporizing some material if a liquid wall is used. At the same time, the solid support structures and vacuum vessel walls will be bombarded with neutrons at a rate of several 10's of DPA's (displacements per atom) per year causing embrittlement and changes in material properties. Finally, the escaping helium ions, called alpha particles, will embed themselves in the surface layer of the wall and eventually resulting in microscopic pockets of entrapped helium gas causing further embrittlement and stress. Many mitigation strategies are proposed to address these issues including modest background gas fills to slow down ions and alpha particles, magnets lining the chamber walls to repel ions and alpha particles, liquid metal walls to avoid erosion, replaceable protection tiles lining the inside chamber and the development of radiation resistant steels and eventually much more radiation resistant non metallic materials such as silicon carbides.

Manufacturing large reactor structures with such non metallic materials is a brand new area and will require the development of new large scale forming and manufacturing techniques for these difficult to work materials. Again, high power lasers with their capabilities to deliver heat and pressure in custom controlled fashion could play an important role in such manufacturing. Current expectations are that the initial reactor vessels will be replaced on a routine basis every several years with the plan that the reactor lifetime will improve over time with ongoing advances in reactor vessel materials and technologies. Other techniques such as laser melting, refurbishing and recladding of the inner reactor vessel surface, or nanotextured heat and erosion resistant surfaces are also possible alternative strategies to extend the lifetime of the reactor vessel.

One of the advantages of laser fusion based reactors over magnetic fusion systems is that the reactor vessel itself is decoupled from the expensive laser driver, optical beam line and target injection systems and it is relatively easy to swap out and refurbish the reactor vessel on a routine basis. This is not the case for magnetic fusion reactors where the whole system must be disassembled like a jig saw puzzle and rebuilt again if the reactor vacuum vessel needs to be replaced. Thus the development of operational magnetic fusion reactor systems must wait until proven materials and structures have been found to guarantee minimum operational lifetimes of a decade or more to start.

As an overall project a fusion power plant represents a multi billion dollar facility, which in terms of overall project management and civil engineering aspects is similar to large scale projects that the Albertan oil industry is used to today. The complete power system chain from liquid metal to high temperature steam heat exchangers, high efficiency generation of electricity from higher temperature steam generator systems and power station infrastructure are similar to large power station engineering today. Alberta has leading expertise in this area and would be capable of managing such major projects both within Canada and around the world.

2.0.6 Materials Engineering

One of overriding areas required for many of the required technology developments is that of advanced materials. All the areas of optical components, target fabrication and reactor vessel engineering will require advanced materials engineering. This includes the full range of technologies from nanomaterials, nanostructures, advanced materials mixtures, ceramic and refractory materials, specialty optical materials and avoidance of micro-impurities and inclusions and radiation resistant materials. It will also include advanced techniques for material characterization at all levels from atomic and nanoscale to large structural scale.

Included in this will be advanced state of the art modeling of materials properties, degradation, damage and erosion in order to optimize any one material application. In order to carry out such development, considerable testing of new materials under highly stressed simulated reactor conditions will be required to match against the modeling.

Testing large samples requires large, expensive high power test facilities which are then tied up for a considerable amount of time per sample. Such test facilities themselves do not yet exist at full operating fluences expected for reactor conditions and the development and deployment of such test facilities is a first step to the development of improved materials.

Given the limited availability of current and future test sources, it is highly desirable to test many micro and nano sized samples and then characterize them using nano-characterization tools. The microscopic properties can be compared directly with computer modeling and long term macroscopic behaviour can be predicted by extending the material behaviour to larger scales using advanced computer modeling. Such nanotesting of materials is an emerging area of nanotechnology at present. It is particularly relevant to neutron and radiation damage testing of samples, since once the samples are irradiated at high neutron doses they become highly radioactive and require expensive and awkward remote handing procedures in radioactive hot boxes. However, if only a micron sized sample is irradiated, while highly radioactive, the amount of the material is so small that it can still be safely handling in a standard laboratory environment using lead containers and special handling precautions. This new area of irradiating and testing micro sample is a new approach just starting in a number of the materials testing facilities today (ORNL, Rutherford Labs).

2.0.7 High Power Computing & Systems Modeling

For all areas from plasma physics modeling to optical design and particularly in the development of advanced materials, high power, large scale computing is required to connect fundamental equations governing the microscopic behaviour to the overall system behaviour. There will be tremendous requirements for high power computing and modeling during the development and initial improvements in reactor design and operation. This will require the development of modeling programs and expertise over a full spectrum of techniques from fundamental particle kinetics, electromagnetics, fluid hydrodynamics to Monte Carlo and quantum molecular dynamics simulations. In addition, detailed testing verification and characterization against experimental data will be required to make these models accurate. Thus a combined development of the modeling programs, materials benchmarking and the building of detailed materials data bases is required to make such computing tools effective and will be difficult for others to duplicate with high accuracy.

2.1 Link to Existing Provincial Initiatives

2.1.1 Foreword

The broad range of technologies required for fusion energy outlined in the previous section can build on many existing strengths and initiatives already existing in Alberta. In fact, there is a remarkably good fit between existing strengths and a number of the required technology developments which can act as a powerful driver to keep Alberta at the forefront of emerging technology areas, help diversify into new application areas and build a strong team of highly skilled workers in the province. It has been estimated in the LIFE reactor design of LLNL that 59% of the required technology is off the shelf, 28% will require relatively straight forward extrapolations of present technology and 13% will require the development of new technologies. Thus there is an ideal opportunity to build on current strengths, extend current strengths and initiate new diversified technology thrusts within Alberta.

There is a good match between technology needs and Alberta strengths cut across various technology needs in each case. In particular, the needs can build on current strengths in large project engineering, nano-technology, materials technology, information technology and large scale computing. The opportunity exists to use fusion as a driver for moving these areas to a higher level of strength and scale of activity in the province and to diversify the focus of these activities and market the skills around the world. In the end, the markets for these specialized skills will be in the 10's of billions of dollars, similar to today's nuclear fission based industries, primarily located in Ontario and Quebec.

There is an opportunity to extend our current strengths into new application sectors as required for fusion reactor systems. These include the photonics sector (which cannot be ignored as one of the highest growth technology sectors for this century), high performance materials engineering and associated high performance computer modeling of reactor plasmas and materials. Our major engineering companies could become the developer of choice in overall project management marketing their skills a round the world.

If Alberta becomes a major player in the field the overarching goal would be to design and sell complete power stations. It is expected that in the second half of this century, once initial fusion plants are proven, that the dominant part of energy production for electricity, heat and transportation will come from fusion power plants - directly or indirectly through the manufacture of synthetic fuels such as hydrogen. This would require an installed base of the order of 35,000 plants of 1GWe (Fig. 1.1) with a 50 year lifetime and replacement rate of 700 per year. At ~$5 billion per power plant this represents a replacement market of $3.5 trillion per year and an ongoing maintenance and operation cost market of about the same per year. Since such power system will be very complex it will be difficult and expensive for new players to enter the market place. As one of the leaders in the field, Alberta could expect to capture on the order of 5% of the world market which would represent $175 billion of sales a year plus probably an equal amount in ongoing maintenance and refurbishing contracts per year. Such leadership has been shown in the past when Canada developed its own unique Candu heavy water fission reactor system that was a major player in fission reactor sales in world in the 1970's and early 1980's. The nuclear fission reactor industry still represents a significant fraction of the advanced manufacturing and technology industries in Ontario even after reactor sales stopped in the early 1980's due to world wide resistance to further development of nuclear fission.

The link to Alberta areas of strengths are outlined in more detail below.

2.1.2. Nanotechnology

Nanotechnology will play a major role in the following areas:

- Large scale automated fabrication of targets (~$73M targets required per year per reactor)
- Large scale automated fabrication of laser pump diodes (~$1B pump diodes required per reactor)
- development of optimum nanopowders and sintering techniques for fabrication of ceramic laser materials (~$100M laser disks per reactor)
- Heat and erosion resistant coatings for the inner reactor vessel walls (~$100M per reactor vessel liner)
- Materials development and testing on a micro and nano scale and scaling to macroscopic properties
- Advanced optical and x-ray characterizaton techniques for inspection, certification and qualification of targets and optical components

The key players in Alberta who can contribute to this thrust are NINT (nanotechnology), Micralyne (microfluidics and MEMS), Norcada (target fabrication), Applied Nanotools (advanced x-ray diagnostics), the University of Alberta and the University of Calgary. World leading research and manufacturing facilities already exist in the state-of-the-art nanofacilities at NINT, the nanofabs at the University of Alberta and University of Calgary, the Alberta Surface Science Centre at the University of Alberta, the Alberta Centre for Advanced MNT Products and the MEMS manufacturing facilities at Micralyne.

2.1.3 Materials Technology

Materials technology will play a major role in the following areas:

- Advanced target capsule designs using new combinations of layered materials
- Inclusion free ultra high purity materials for damage resistant optical components
- Inner wall of the reactor vessel to make it resistant to plasma and pulsed heating erosion

- Long lifetime structural materials that are resistant to radiation damage such as non metallic refractory materials
- Nanotesting of materials in high stress environments and subsequent characterization
- Low tritium diffusion rate barrier materials for lithium alloy to high temperature steam heat exchanger systems
- Tritium reprocessing technologies

While Alberta does not have groups working directly on these areas it has considerable strength in materials metallurgy and technologies in general focused to a large degree on the resources industry. This expertise and testing facilities would primarily be those at NINT, the University of Alberta and University of Calgary Chemical Engineering, Physics and Chemistry Departments, and Alberta Innovates Technology Futures facilities.

2.1.4 Information Technology

Such complex reactor systems will require very extensive sensor and monitoring systems. The expertise for such extensive information gathering and analysis systems can come from both process engineering monitor systems currently deployed in projects throughout industry and from expertise in the information technology sector. Such monitoring and control will be carried out in many subsystems of a reactor including the following:

- Target injection, correction and tracking
- Laser system steering and firing
- Implosion imaging and characterization
- Target fabrication and quality control
- Monitoring and control of tritium recycling, reprocessing and leak detection
- Design and optimization of laser and optical systems

Current sensor technology, information technology and information management and decision making groups are located at the Alberta Innovates Centre for Machine Learning, and the Universities of Alberta, Calgary and Lethbridge Engineering and Science faculties. This is an area where considerable growth is possible in the various sensor technologies required.

2.1.5 Large Scale Computing

Large scale computer modeling will be core to almost every technology area for a fusion reactor system including:

- Plasma physics modeling for target design and optimum yield
- Laser system modeling
- Materials modeling from the atomic to the macroscopic scale
- Overall plant operations and health monitoring

The province of Alberta has a major strength in large scale computing and its applications. The University of Alberta already has world leading expertise in plasma physics modeling in the Department of Physics and in laser development and modeling in the Department of Electrical and Computer Engineering. There is a large core of expertise in materials modeling at NINT and in the Departments of Physics, Chemistry and Chemical Engineering at the Universities of Alberta and Calgary. The Computer Science and Computer Engineering groups at the Universities of Alberta and Calgary and Alberta Innovates Centre for Machine Learning have leading experts in the area of information acquisition, decision making strategies, data mining and data storing. There are numerous companies involved in seismic exploration, modeling and analysis of oil deposit reserves who could start developing expertise in the new areas required. There are also a few companies directly involved in high power computing system architecture such as YottaYotta. The province and Canada also have a large computing infrastructure available for such high power computing in the Westgrid and Compute Canada computer networks.

2.1.6 Large Project Management

Such complex reactor systems will require experienced large project management teams both at the overall project integration level and also at the major subsystem level. These various project and sub project levels include:

- Complete project integration
- Laser system integration
- Target manufacturing system integration
- Heat exchanger and power plant integration
- Provision of civil infrastructure

Large engineering companies in Alberta such as Stantec and PCL are very experienced in project engineering and could take the lead in such projects.

2.2 Expected Benefits & Economic Impact

An anticipated 35,000 gigawatt class power plants needed by 2100 to supply the rapidly increasing need for electrical power globally will result in enormous economic opportunities for those able to meet the demand. Based on recent advances in fusion technology it is conceivable that more than a third of those power plants would be based on fusion as the world transitions to a low carbon economy. This section outlines the potential benefits available to Alberta/Canada if a decision is made to take a leadership role in laser fusion and gain first mover advantage not only in fusion but also in the associated R & D spin-offs.

2.2.1 The Market

As highlighted in this report, laser fusion R&D around the world - led by NIF at LLNL - is rapidly closing in on ignition and fuel burn. Once ignition is achieved, commercialization of fusion energy becomes feasible and will proceed rapidly resulting in a fleet of laser inertial fusion energy (LIFE) power plants.

As envisioned by LLNL, the first step following ignition would be the design and construction of a gigawatt class market entry plant (MEP) where engineering challenges would be tackled and a template for future plants developed. Based on the lessons learned from the MEP, a first of its kind gigawatt class electrical plant would be constructed followed by a series of commercial plants incorporating the lessons learned from its predecessors.

In a November 2012 report “The Economic Impacts of LIFE” by Oxford Economics[2], MEP pre-construction is expected as soon as ignition is achieved with construction starting 2-years later, taking 6-years including procurement and commissioning. Assuming a doubling time of 10-years as a lower bound and 5-years as an upper bound, Oxford Economics predicts between 50 and 136 plants could be built in 35 years. It should be noted that a 5 year doubling rate is in line with the initial growth of fission power plants in the 1960’s and 1970’s.

Year	**Lower Bound (10-year)**		**Upper Bound (5-year)**	
	Construction	**Total**	**Construction**	**Total**
2024	1	1	1	1
2029			2	3
2034	2	3	4	7
2039			8	15
2044	4	7	16	31
2049			32	63
2054	8	15	64	127

Table 2.1 Plant roll out scenarios for North American Plants (Oxford Economics)

Assuming ignition is achieved in 2016, construction of the MEP could start as early as 2018 and begin operation in 2024 with the first of a kind starting construction in 2024 and commercial operations in 2029. With continued investment the North American market could have 127 operating plants by 2054. Using a 4:1 ratio of global to domestic

(North American) plants, this number increases to 508 plants by 2054.

This is a significant market to be captured by the right players. In general terms the design and construction of the MEP is comprised of 59% off the shelf materials and technologies such as the site, building, utilities, project management, etc., 28% technologies that can be found in other sectors such as precision controls, computer modeling, tritium handling, etc. and 13% to be developed specific to the fusion process. The latter has spin-off possibilities to other sectors such as photonics, industrial applications of lasers, advanced high performance materials, high precision MEMS and nanotechology, etc.

To benefit from each of these market opportunities it is important for Alberta/Canada to establish a framework that clearly defines the role of government, research institutions and private sector stakeholders in leveraging a first mover advantage.

2.2.2 Post Ignition Opportunities

As fusion moves from science to commercial applications - much like fission did 50-years ago - it is important for industry to be engaged from the beginning. A planned transitioning from public to private funding of a fusion energy program can nurture small and medium companies to stimulate technical innovation.

Based on the ITER and LMJ experience there are many traditional and start-up companies required just to develop a large facility such as the LIFE demo proposed for Alberta. Initially these companies would supply the needs of the market entry facility and the successful ones will grow with the fusion industry as more plants are built worldwide and new markets are found.

Off-the-shelf services and materials include:
- Engineering – civil, mechanical, electrical, electronic
- Building materials – concrete, steel, equipment, etc.
- Commissioning
- Operating and Maintenance services

Related technologies include:
- Computer modeling and analytics
- Power supplies
- Coils and magnets
- Vacuum vessels and systems
- Nuclear systems – tritium handling
- Lasers – including high performance diode pump lasers
- Control systems

- Remote handling and Robotics

Fusion specific technologies include:

- Chamber design and construction
- Heat blanket design and construction
- Fuel handling and delivery
- Plasma technologies
- Advanced neutron resistant materials
- Micro fabrication

There will be tremendous requirements for high power computing and modeling during the development and initial improvements in reactor design and operation.

Spin-off industries include:

- Investment and Venture Capital
- Photovoltaic systems and processes
- Lasers - optical materials, diode pump lasers, fiber sources, process machining
- Non-destructive testing - laser shock hardening of materials
- Healthcare imaging equipment
- Advanced laser driven particle accelerators for radioisotope, cancer treatment and security applications
- Scientific instrumentation
- Advanced sensor technologies – optical, x-ray, nuclear
- High precision, mass production MEMS and nanotechnology
- Large laser facilities

Many of the industries associated with the fusion specific technologies are not currently large enough to support the increased demand that would result from a global rollout (Oxford p11). The development of a commercial scale – gigawatt class – MEP will result in additional R&D spending of $593 million per annum (Oxford p17). Pre-construction spending is estimated to generate a total GDP impact of $2.5 billion over the entire pre-construction period. This spending will result in a total labour impact of 2,690 jobs ($1.8 billion of labour income) during an average year of the pre-construction phase.

This offers Alberta a “first mover” opportunity to capture a significant share of the global fusion capital investment expected after ignition is achieved. By hosting the MEP, Alberta will leapfrog to a leadership position in the fusion industry, gaining access to the $7.3 billion worth of research conducted between 1992 and 2012 (Oxford p17). As a leader, Alberta/Canada would be ideally positioned to take advantage of intellectual property (IP) generated and expertise required and developed as the fleet of commercial fusion plants are rolled out globally.

There is a small window of opportunity before demonstration of ignition to plan Alberta’s approach to harvesting the R&D investments and participating in the commercial and spin-off benefits of fusion.

Alberta has leading expertise capable of managing large and complex construction projects both within Canada and around the world.

A model that can be explored is Routes des Lasers

TM (Figs. 2.2 and 2.3) which is a high tech industry cluster created to diversify the primarily agricultural economy of Bordeaux by taking advantage of the expertise and technology associated with Laser MegaJoule (LMJ), a facility similar to NIF. In this model the LMJ megaproject becomes the pull for developing the unique fusion related technology solutions needed for laser fusion such as photonics, instrumentation, materials, data analytics, etc. that, for Alberta, will have spill-over effects in other industries such as manufacturing (laser cutting and welding), resource (material hardening of tools), oil & gas (instrumentation and diagnostics), computing (big data, analytics and robotics), etc. By building on Alberta's current industrial and technology strengths, the Province can create a fertile environment for Small and Medium Enterprises (SME) to flourish.

> *There will be significant areas of opportunity for such smart robotic inspection and maintenance systems. Albert has considerable expertise in systems automation and growing expertise in robotics.*

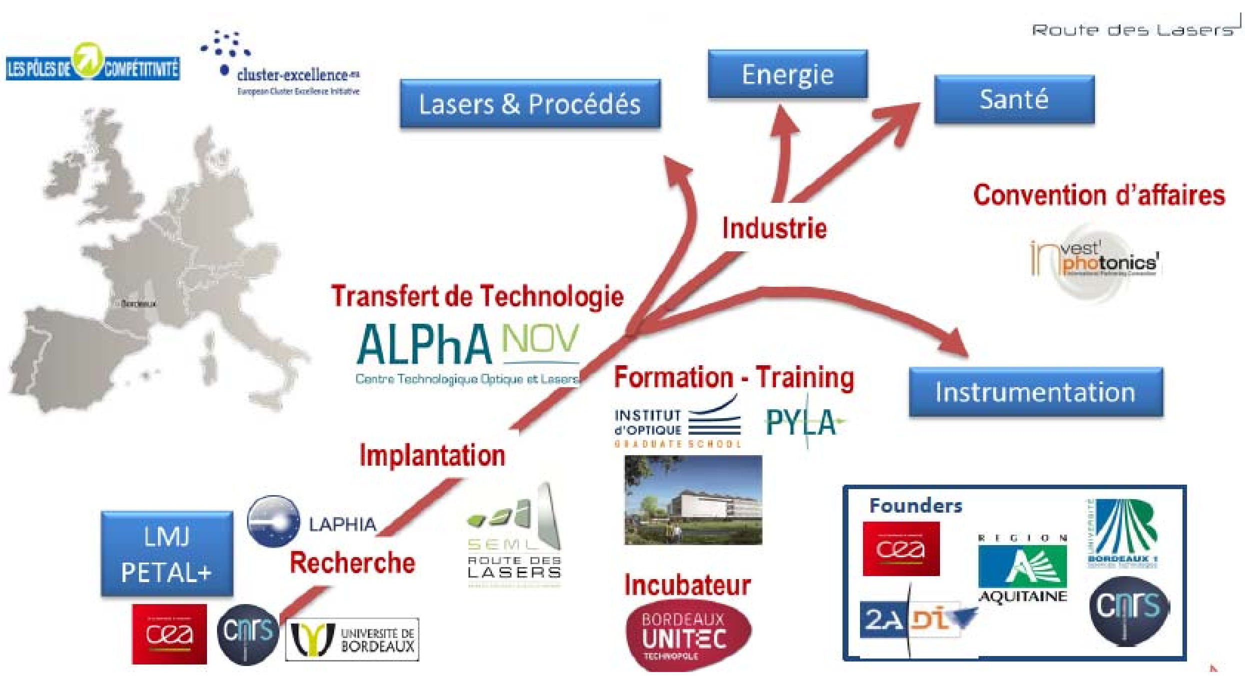

Fig. 2.2 Commercialization model of Routes des Lasers

Fig. 2.3 Potential market sectors for spinoff technologies from LFE

Other examples of private sector companies engaged in fusion R&D include: 1) Hamamatsu Corporation; a Japanese photonics company developing lasers for fusion, sub-threshold laser fusion reactors for diagnostic and materials testing neutron sources and, laser cutting and welding technologies for the automotive industry (looking towards carbon fibre to replace steel) and; 2) General Atomics in California, which is a major supplier of fuel pellets and specialized technology to industry.

> *Currently the overall worldwide Photonics industry is on the order of $400B per year and is growing at a rate of 8% per year. This rate of growth is expected to continue for at least several decades.*

It is important to provide a nurturing environment for emerging technologies and start-up industries. Much like nurturing a seedling, one cannot pull its stem to make it grow faster or pull it out of the soil to see if the roots are developing, however, you can provide the right amount of light, water and nourishment to set it up for success. Even then, not all will survive. Ultimately an industry knowledge ecosystem will emerge and like a mature forest will be sustainable. The Routes des Lasers approach associated with the French LMJ project is taking this approach. Similarly, developing industry clusters around an MEP, networked with other clusters around the world, will position Alberta/Canada as a leader and diversify our economy not by funding individual companies but by providing an environment of opportunities.

2.2.3 Anticipated Benefits

Should Alberta decide to invest in the fusion sector there are a number of expected medium and long term benefits including:

Economic

- $500 million plus R&D investment, much from outside of the province
- First mover advantage in the roll out of 127 plants in North America (508 globally)
- Increased exports of expertise, knowledge and machinery
- Attracting high quality personnel & companies
- Global leader in managing a smooth transition to a post-carbon economy, benefitting Alberta's energy and distribution sectors

Alberta with strengths in materials, nanomaterials and chemical technologies could become a leader in this area by investing in an intensive research and development campaign.

Environmental

- Avoidance of negative environmental impacts – carbon dioxide, carbon monoxide, nitrogen oxides, sulphur oxides, particulate matter, and mercury – that contribute to climate change and localized health impacts
- Reductions in the use of carbon fuels – coal and natural gas – that can be repurposed into value added materials and products, e.g., carbon to replace steel
- Transition to a low carbon economy with sustainable alternative

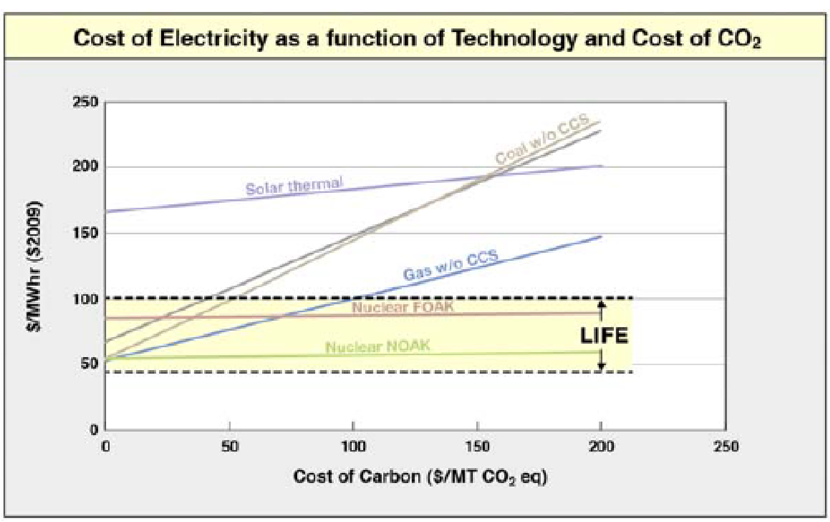

Fig. 2.4 Comparative costs of electricity (Oxford Economics, Nov 2012, p19)

Geopolitical

- Energy Stability - fusion fuels are widely available and evenly distributed – reducing potential for conflict
- As a traditionally neutral nation, Canada has the credibility to facilitate collaboration among countries and institutions.
- Canada is ideally positioned as a bridge between Asia and Europe and has excellent relations with the US to spearhead a joint Market Entry Plant initiative

High efficiency, high energy, short pulse lasers make it possible to harden very large parts to a significant depth such as the extraction buckets for oil sands scoops and other components in oil sands processing to extend part lifetimes by a factor of 2 to 3 times, cutting expensive maintenance and down time.

Regional

- The commercialization of fusion is ultimately a multi-year mega project, attracting leadership and warranting collaboration on such a scale as to define, or redefine, a region
- Alberta – opportunity to rebrand by using some profits from carbon fuels to develop a clean energy technology for the world and simultaneously diversify its economy by creating opportunities for its HQP and technology start-up companies
- Canada – opportunity to lead the world in creating the low carbon economy by transitioning its resource exports to value added knowledge exports
- Global – opportunity for developing nations to use safe fusion energy technologies to meet the increasing energy demand required to grow their standard of living to that enjoyed by developed nations with minimal impact on the environment

With mass production it is expected that carbon fiber reinforced materials will become the building material of choice in the future starting from small scale applications in automobiles, airplanes and trucks and eventually penetrating into large scale structures such as buildings and corrosion resistant bridges. Lasers will be one of the dominant tools to manufacture, cut, shape and join such materials

2.2.4 Assessing the Opportunities

In order to compare the merit of different energy strategies, four scenarios are presented for transitioning towards a low carbon economy:

- **Status Quo** – this scenario assumes no significant investment is made in either fusion or renewables and the technology is purchased at some time in the future

- **High Renewables** – this scenario assumes a significant investment in renewable generation capacity from solar, wind, biomass, etc. and no new coal or nuclear plants are constructed

- **Fusion "Canada Arm"** – in this scenario Alberta makes a significant investment in fusion but focuses on a limited technology sector such as photonics, analytics, nanofabs, etc. and is incorporated into the final plant built by another jurisdiction or consortium

- **Fusion "All-in"** – in this scenario Alberta invests in the hosting, design and construction of the MEP thus leapfrogging to the front of laser fusion technology

2.2.4.1 Scenario: Status Quo

This scenario assumes that no significant investment is made in either fusion or renewables and the technology is purchased at some time in the future.

Economic

Economic benefits would continue to come primarily from the extraction of fossil fuels – oil, gas and coal – until the market declines. Pricing of these commodities is dependent on global demand and can be very volatile. As a landlocked province it is challenging to ship our natural resources to a diversified market leaving the industry vulnerable to the US market.

Environmental

The burning of fossil fuels is one of the major contributors of carbon emissions, a cause of global warming. These resources are finite. Alberta has already exhausted its supply of conventional oil and alternative sources such as the oil sands consume large quantities of water, disturb habitat and generate large quantities of waste that are currently stored in tailings ponds.

Geopolitical

Alberta and the oil sands have been branded by environmental groups around the world as the "dirtiest" oil in the world, which makes it challenging to sell our resources at global market prices or even to build transportation networks that will get these resources to new markets. The European Union's move to label Alberta oil as dirty and US problems in getting the Keystone XL pipeline approved are recent examples.

Benefits

By continuing to narrowly focus on fossil fuel extraction Alberta will continue to reap the profits of a valuable global commodity as well as export our expertise and equipment around the world. Fracturing is a good example of a technology refined in Alberta and now used around the world.

Risks

Focusing on a single product leaves the industry vulnerable to market swings and decisions made by others that adversely affect oil and gas exports. In addition, threats can come from a new found respect for the environment and concerns over climate change or countries concerned about their own energy security and exploring alternatives.

There is a significant risk that the demand for fossil fuels will decrease to the point of leaving these assets stranded along with the industry focussed on its extraction.

2.2.4.2 Scenario: High Renewables

This scenario assumes a significant investment in renewable generation capacity from solar, wind, biomass, etc. and no new coal or nuclear plants constructed.

Economic

The total investment in renewable energy in 2012 was $244 billion (Global Trends in Renewable Energy Investment 2013, Bloomberg) and in the likeliest scenario grows to $630 billion by 2030. Alberta can take advantage of this emerging market to reduce its carbon footprint and diversify its economy and energy mix. The Alberta Government can stimulate this emerging market by reinvesting some of its royalties collected from fossil fuels into renewables.

Environmental

Renewable energy generation will reduce the amount of carbon and other emissions into the atmosphere thus reducing its heavy carbon footprint.

Geopolitical

Reducing Alberta’s carbon footprint will improve its brand as a “dirty” energy producer, which will make it easier for Alberta to do business in the global market place.

Benefits

A focus on renewable energy production will significantly reduce carbon emissions, add resiliency to the grid, and diversify the economy by building a renewable energy industry.

Risks

If renewables fail to achieve critical mass and associated economies of scale they may not provide enough energy to offset the fossil fuels.

2.2.4.3 Scenario: Fusion ("Canada Arm" or "All-in")

In this scenario Alberta makes a significant investment in fusion as a clean, abundant energy source for the future, either focused on a limited technology sector or "all-in".

Economic

Investing in fusion as an energy source Alberta will start the transition towards a low carbon economy without disruption of the fossil fuel industries for several decades. Indeed, fusion could provide clean energy for oil sands extraction and processing in the future.

There are two ways to benefit from an investment in fusion. The first is a "Canada Arm" strategy where Alberta/Canada focuses on a limited technology sector such as photonics, analytics, nanofabs, etc. to be incorporated into the final fusion plant built by another jurisdiction or consortium. This would have the benefit of diversifying the economy by attracting some high tech companies and highly qualified people to Alberta.

The second approach is for Alberta to go "all-in" and invest in the hosting, design and construction of the MEP thus leapfrogging to the front of laser fusion technology. This approach would garner the benefits of the Canada Arm in space plus have the additional benefits of local construction worth billions and leveraging billions of dollars of R&D already completed.

Environmental

Fusion is inherently a clean energy source that will replace carbon and its emissions generated in coal and gas fired power plants. It is the highest energy density fuel and reduces the environmental impact of mining, transporting and burning in a power plant; additionally, it has no long term radioactive wastes.

Geopolitical

Many countries are pursuing fusion as an ultimate energy source. Canada could play a role in bridging the initiatives in Europe and Asia and build upon its historical relationship with the US. Combining a demonstration plant based on LIFE with an R&D program on advanced technologies, Canada will benefit from the most promising developments.

Benefits

As the host, Alberta will develop relationships with the international partners that would lead to future trade. The MEP will attract external investment and the facility will use local architecture, engineering and construction capabilities that will in turn develop expertise that can be exported as more plants are constructed globally.

Risks

There are two major, but alternate, risks: 1) an inability to resolve engineering challenges that make fusion plants commercially feasible and; 2) fusion roll-out happens quicker than anticipated, making the technology a threat to the fossil fuel industries.

At the present time only a qualitative assessment of the impact of the various scenarios can be given. A more detailed study would be required to assess these scenarios in more depth.

2.3 Summary Comments

Fusion energy development offers Alberta/Canada significant benefits well into the future and would mitigate the risks associated with a status quo approach that depends on a single commodity.

By investing a portion of revenues from fossil fuels in fusion energy development and, by becoming a center of the emerging fusion industry, Alberta will assure its future as a leading global energy supplier. This would be analogous to the $2 billion Alberta invested in establishing a Carbon Capture and Storage program aimed at reducing the carbon footprint and the AOSTRA investment decades earlier. Unlike CCS, however, fusion will develop into a growing global industry and improve Alberta's brand around the world.

In contrast to the renewable energy industry, which depends on foreign technologies and manufacturing capabilities, many of the technologies needed for a commercial fusion plant can be developed in Alberta and expertise exported.

One approach would be for Alberta to focus on one or more of the enabling technologies needed for a commercial plant and become a supplier to international consortiums. It would then leverage the spin-offs derived from fusion energy technologies such as lasers, photonics, materials, analytics, etc. This is a viable strategy for diversifying Alberta's economy and improving its brand as a source for creative ideas. However, this is likely to require significant government support and the question must be asked: why under the umbrella of fusion? Why not just become a laser center of excellence?

Alternatively, by hosting the MEP after ignition, Alberta would leapfrog to the front of the fusion industry thereby leveraging billions of dollars of R&D investment and become a global focal point for something other than the oil sands. Alberta is an ideal location to build the MEP jointly with the USA and, as an energy province, has the experience to build and operate large energy projects and supporting infrastructure.

Given its small population of 4 million people Alberta does not provide a large market for fusion plants. However, hosting the MEP and harnessing the expertise and technologies that inform the design, construction and project management of future plants around the world will provide significant economic benefits to the Province.

There are many aspects of this roadmap that need to be explored further and the creation of an Alberta Center for Fusion Energy is an important first step to plan for positioning this Province at the center of an emerging industry in the new economy.

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APPENDIX C – SITE VISITS

Executive Summaries of site visits for assessment of fusion technologies

Site Visit #1 – May 14-17, 2013

- **Institute of Laser Engineering (ILE)**
- **Hamamatsu Corporation**

ILE at Osaka University in Japan is a major center for IFE research and development and has now specialized in the advanced concept of “fast ignition”. The current program, called the fast ignition realization experiment (FIREX-I) is based on demonstrating fuel pellet heating to a temperature of 5keV. This would be followed by FIREX-II to demonstrate fuel ignition and burn. The first phase objective is to build a 4 beam, 4kJ, 1 ps (originally 10kJ/10ps) pulse laser system as an addition to the original 12 beam GEKKO ns laser facility.

Three aspects of the program were covered in the assessment site visit: 1) the operational status of the laser system; 2) results from preliminary heating experiments and; 3) planning for fusion power plants based on fast ignition. In addition, an MOU between Osaka University and the University of Alberta was agreed to that updates earlier ones signed in 1988 and 2007.

An overview of the ILE inertial fusion program was presented by Hiroshi Azechi, H. Shiraga, T. Norimatsu, Hideo Nagatomo, Junji Kawanaka. The achievement of high power ultra-short pulses requires stretching of low power beams to longer pulses in order to amplify them without damaging the laser optics and then re-compressing to generate the desired high power ps pulses. Stretching and compressing is achieved using optical gratings in vacuum. This requires precision fabrication of large, high quality gratings and ensuring damage thresholds are not exceeded. Progress in fabrication has been slow and expensive for the FIREX system; consequently, the 4 beam capability has been delayed awaiting production of gratings. In the meantime, a 2 beam facility has been completed and preliminary experiments initiated. Grating damage thresholds are not yet known but should exceed 1J/cm^2.

It was also found that operation of the laser system at full kJ energy/beam results in large electromagnetic noise interfering with neutron measurements; this has limited initial experiments to be operated at lower energy (400J). Consequently, the current status of the FIREX facility combines 9 beams of the GEKKO-XII laser for compression of targets with 2 beams of 400J, 1ps laser pulses to study heating.

The laser-target coupling uses a cone imbedded in the fuel pellet to deliver the high intensity pulse and fast electrons closer to compressed fuel core. Earlier experiments (2002) have demonstrated heating from 0.4keV (compressed target only) to 0.8keV (compressed with 0.5PW heating). This led to a 1,000 fold increase in neutron yield. Recent experiments with 2 beams (400J, 1ps) have resulted in neutron yields exceeding the previous results.

The 4 beam facility (4x1kJ, 1ps) is expected to be completed early next year and, with other experimental refinements, should lead to increased performance and neutron yield.
The objective is to realize an ion temperature (Ti) of 5keV in 2014.

Experiments-to-date have shown higher Ti for fast rising heating pulses (<1ps) but eventually longer pulses of ~10ps will be required to deliver ~10kJ of heating. Pre-plasma generation in the cone (associated with slow-rising pulses) results in lower energy coupling efficiency and undesirable heating to higher electron temperatures than optimum for coupling to the core. Means of reducing such effects as well as improving transport of the desirable “fast” electrons (~1MeV) are under study; they include using low-Z materials for the cone tips and magnetic fields (~1kT) for guiding fast electrons. Additional developments include double cone targets to improve coupling efficiency and cryogenic solid deuterium filled targets to replace deuterated polystyrene targets.

The proposed next phase is an integrated system called laboratory inertial fusion test (LIFT) to be followed by KOYO-F, a demonstration power plant. Key components of a fusion power system include: laser driver; target fabrication/delivery system, fusion chamber and heat cycle. All aspects are under study by ILE and their collaborators (nationally and internationally). This includes items such as pellet injection and in-flight tracking; solid and liquid walls to capture fusion products; stability of liquid flow; tritium permeation and safety; clearance of the chamber gases between shots and; final optics.

The laser system for LIFT is highlighted here as one of the key enabling technologies. LIFT design parameters include 2 laser systems for fuel compression (400kJ) and heating (200kJ), with a 1Hz repetition rate. For a target gain of 100, a power of 60MWth and 24MWe (40% thermal efficiency) would be produced. One quarter of the electricity would be required to run the laser system if it operated at10% efficiency.

With new technology developments in laser diodes and ceramics, this efficiency can be achieved. Flash lamps have been the traditional pump source for glass based lasers but this combination suffers from 2 major defects: spectral broadness resulting in poor coupling efficiency to the narrow absorption bands of the glass laser host and heating of both flash lamp and glass laser media limiting the repetition rate. The spectral emission of laser diode pumps can match the laser absorption line to vastly improve both efficiency and repetition rate. Moreover, modern ceramics, with much higher thermal conductivity than glass, can replace the glass host.

Long-life, high efficiency, high repetition rate has been demonstrated in the HALNA-20 system at ILE (10J, 10Hz and 10% efficiency) and successfully run for 8 years without diode failure when operated intermittently at lower repetition rate and reduced energy. It does not have ceramic crystals. For high power, a collaboration of ILE and Hamamatsu has developed a reactor scale diode-pumped solid-state laser system of 200kW in a 5cm x 30cm package. The key is cost/watt of diode pump for eventual application and this is primarily a function of market size.

Hamamatsu has made significant progress since a last visit in 2007. They have mounted a substantial civilian project in IFE, emphasizing key technologies for an eventual reactor – lasers, targets, materials and system engineering. Overall manpower commitments, laboratory facilities and experimental progress are impressive. In addition, they have the participation of Toyota Central R&D Laboratory scientists in their laser fusion program. Plans include: a near-term 4kJ, 10Hz facility (CANDY) to demonstrate integration of system technologies including tritium recovery; a 100kJ breakeven demonstration plant by 2025 and; power reactor demonstration by 2035. The CANDY facility can provide a neutron source for materials analysis and medical applications and is expected to cost ~$200 million.

In summary, ILE and Hamamatsu are making steady progress using ultra-short pulse lasers for development of fusion energy systems. They have comprehensive programs to address basic R&D together with engineering planning for IFE systems. They are working on the key issue of demonstrating efficient coupling of laser energy-to-electrons-to fuel core needed for ignition. If successful, this should lead to lower fusion energy modular systems and lower capital costs. We will learn more when the completed FIREX-I system is available for experiments in the coming year.

Site Visit #2 – June 17-20, 2013

- **Oak Ridge National Laboratory (ORNL)**
- **Naval Research Laboratory (NRL)**

Oak Ridge National Laboratory (ORNL) is a major center for materials science research and development and is the headquarters for the US engagement with the ITER project. ITER is a $20+ billion international magnetic confinement fusion project based in Cadarache, France; its objective is to build a large conventional Tokamak to demonstrate self-heating of fuel accompanying fusion reactions and power production in a sustained operating mode (with a planned run time of 400s). The system design parameters include achieving an ion temperature T_i=28keV and electron temperature T_e=10keV using electric current ohmic heating, radio-frequency and microwave heating as well as particle beam injection fueling and heating.

Three aspects of the ORNL program were covered in the assessment site visit: 1) ORNL materials science R&D for fusion systems; 2) overview and details of the US contributions to ITER; 3) tour of facilities supporting fusion R&D, including neutron sources. General observations of the international programs in magnetic confinement fusion were also solicited.

An overview of the ORNL and USA non-ITER fusion program elements was presented by Don Hillis, Jurgen Rapp, Bill Wiffen and Lance Snead. ORNL is the largest DOE open science lab with 4,000 people and annual funding of $1.6B. There are 60-80 staff engaged in fusion technology ($20M/yr) and materials ($10M/yr), participating in programs throughout the world as well as in-house. This includes Tokamaks and stellerators in Europe, Asia and the USA.

The power levels and particle fluxes for ITER in operation will require materials capable of withstanding very high thermal (~10M/m^2) and neutron loading (~5MW/m^2). This implies material erosion rates of up to 50dpa/yr. Moreover, helium embrittlement and swelling limit the lifetime of materials exposed to the fusion environment. Materials being studied for application to fusion systems include oxygen dispersion strengthened steel, reduced activation ferritic metals, vanadium alloys, silicon carbide, etc. ORNL facilities include a plasma materials test source (MPEX), Vortek plasma arc lamp, Lambda microwave source, high flux fission reactor (HIFER) and spallation neutron source (SNS). While important work can be done with such smaller systems, eventually high energy fusion systems will require new test facilities with larger volumes for neutron and particle irradiation of materials.

With respect to present and future facilities, it was noted that Japan, Korea and China were already planning for demonstration systems. Indeed, China has identified fusion as one of the 5 priorities in their 2020 vision and Korea has legislated a fusion energy mandate. Europe/Japan have already initiated a joint materials test facility (IFMIF-Light) that will enable neutron irradiation inducing transmutations at a level of ~1 dpa/yr. At ORNL a fusion simulation program ($15M/yr for 10 years) has been initiated to link the predictive capabilities of various international existing codes. Planning for a multi-billion US$ Fusion Nuclear Science Facility (FNSF) to study materials damage at ~2dpa/yr will proceed following the ITER capital funding commitment phase (and likely built at ORNL).

The USA ITER fusion program was presented by Dave Rasmussen. ITER has been designed in a conservative fashion to ensure operational reliability since the Tokamak will be subject to various instabilities (sawtooth, ELMs, tearing, disruption, runaway electrons, etc.) that can inflict damage to the device. ORNL is the US headquarters for ITER contributions, including: 8% of toroidal field coils and 100% of central solenoid; pellet injection; electrical network, vacuum and cooling water systems; disruption mitigation; exhaust processing system; ion and electron cyclotron transmission lines;

diagnostics. Startup heating requirements are 73MW (33MW neutral beams, 20MW electron cyclotron heating and 20MW ion cyclotron heating). Tritium processing will be handled by Savannah River. Current and projected annual expenditures for ITER by the US are $105M (2013) and $225M (2014).

The building phase of ITER should be completed by ~2022 and subsequently operated as an experimental device by 2026 before turning to D-T fuel burning in 2028 to achieve fusion. With auxiliary heating of 50MW after startup, the projected fusion output power =500MW (Q=10). These parameters significantly exceed those of any existing Tokamak and will provide a test facility for studying a myriad of issues - fueling, fusion neutron irradiation of materials, tritium production and processing, instabilities affecting performance, etc. By comparison, the joint European torus (JET), currently in operation, has produced 16MW of fusion power for ~0.5s with 27MW of auxiliary heating. In contrast to JET which mitigates against disruptions by massive gas injection, ITER will inject neon ice pellets approximately the size of a wine cork.

In addition to the construction phase activities underway, there is a separate physics organization for ITER that is involved with theory, computer modeling and planning for experiments.

Following ITER, a first generation fusion power plant is projected for 2040 and an advanced power plant by 2050.

Stellerators are seen as alternatives to Tokamaks for magnetic confinement fusion devices. The large helical device (LHD) in Japan and Wendelstein VII-X in Germany are the largest such facilities currently in operation. They have achieved either high density or high temperature modes of operation but not both simultaneously. They offer the possibility of true steady-state operation but would be larger again than Tokamaks.

Tokamaks have had the benefit of decades of development worldwide - continuing improvements in theory, computer modeling, diagnostics and technology (vacuum, materials, magnetics, etc.) - and so are a leading fusion technology. ITER is the culmination of the steady progress. ORNL will continue to play a major role in fusion materials science and Tokamak development.

The US Naval Research Laboratory (NRL) is focused on direct drive laser fusion and has been a major center for developing krypton fluoride (KrF) lasers as a potential driver for IFE systems. NRL has been a significant player in laser/plasma science and fusion R&D for more than 40 years, introducing ideas such as: first flash-lamp pumped Nd:glass laser disk amplifiers (John Emmet, who subsequently became director of LLNL laser fusion); induced spatial incoherence (ISI); zooming of laser beams and; myriad KrF laser technology refinements.

Four aspects of the NRL program were covered in the assessment site visit: 1) direct drive physics approach to IFE (theory, experiments); 2) current status of KrF laser development; 3) IFE technology issues addressed by the HAPL program (coordinated by NRL); 4) tour of lab and particularly KrF laser facilities.

An overview of the NRL fusion program was presented by Steve Obenschain. The laser/plasma/fusion group is a division in the US Naval Research Laboratory, Washington, DC (overall 2200 employees and an annual budget of $800M). The virtue of the KrF laser lies in its short wavelength. Compared to frequency tripled Nd:glass lasers (351nm) - the majority of high energy systems world-wide - the 248nm wavelength of the KrF laser provides for higher target absorption and hydrodynamic efficiency, reduced laser/plasma coupling instabilities, increased ablation rate, etc. In the event that scaling of KrF drivers to the requisite energy required for IFE can be realized, it holds the promise of inertial fusion systems with simpler targets, higher energy gain and better economics. NRL target designs combining shock ignition with zooming of laser beams predict gains of >100 at drive energy ~500kJ, a significant improvement to indirect drive (e.g., LIFE gain ~60 for 3MJ of drive). He summarized NRL activities, highlighted and contrasted aspects of direct vs indirect drive targets that could impact compression and fusion energy gain and, argued for the positive attributes of KrF laser drivers for IFE.

A summary of directly-driven shock ignition target designs was presented by Andy Schmitt. These designs incorporated low aspect ratio (for hydrodynamic stability), variable mass, focal spot zooming and shock ignition - indicating the potential for very high gain, even over conventional direct drive with KrF lasers. Issues such as hydrodynamic stability, implosion symmetry and laser/plasma instabilities were addressed. Trade-off between compressor and ignitor power levels; intensity and aspect ratio were discussed as well as aspect ratio scalings for energy, implosion velocity and yield. In order to pursue this research, NRL has developed 3-D hydrodynamic codes including radiation transport. The summary highlighted variances in fusion performance as a function of laser (wavelength, intensity) and target (size, aspect ratio, etc.) parameters. In a subsequent lab tour, experiments on growth of hydrodynamic instabilities using ultra-smooth KrF laser beams were reviewed.

Development of KrF laser and other technologies needed for IFE was presented by John Sethian. This included NRL activities and elements of the High Average Power Laser (HAPL) program coordinated by NRL that involved many academic, industry and government laboratories for a period of ~8 years (funded by a Congressional vote of ~$25M/yr). Proceeding to IFE from single-shot fusion experiments will require systems operating efficiently and reliably at 5-10 Hz for hundreds-of-millions of shots. For KrF lasers, excitation requires electron beams with voltages >500kV and currents ~500kA in gas volumes of ~1m^3. This places demands on pulse power conditioning and delivery, gas handling, structural materials, optics, etc. NRL has demonstrated advances in durable electron emitters and rib-foil structures with embedded cooling to withstand the thermal loading of such electron beams. In addition, they have increased foil lifetime dramatically (>100,000 shots) by eliminating voltage reversal on the E-beam diodes and demonstrated an all-solid state switch to replace spark-gaps which have limited material lifetimes. A comprehensive KrF physics code has been developed to model electron energy deposition, optical excitation and extraction, plasma chemistry, etc. for the amplifiers. This leads to a projection of an overall wall-plug efficiency of η >7%, for which a fusion gain G>140 would satisfy a minimum IFE requirement of ηG >10. NRL has proposed a phased KrF laser technology program to demonstrate scaling to the 20kJ level appropriate to fusion driver modules.

The HAPL program addressed a variety of issues for IFE power plants including laser systems, reaction chambers (materials, chamber clearing, final optics), targets (fabrication, injection, tracking), tritium breeding, etc. Studies in the various centers generated and some cases “bench tested” solutions for most key components (final optics survivability, mass production of foam shells, injected target survivability and engagement, chambers with “engineered” walls or magnetic intervention of particle fluxes, material recycling). Comparison of systems based on direct and indirect drive identified distinct differences in materials requirements and therefore chamber options (e.g., x-ray heating of walls); also, in quantities of material to be recycled. A possible solution to the issue of helium retention and exfoliation was identified – “nano-engineered” armor using tungsten fibers or “magnetic intervention” using cusp fields (this option eliminates the helium retention/heat load challenge allowing smaller chamber and SiC walls for better neutron resistance). Power plant system efficiency was studied for Brayton cycle electric generation and hydrogen production. This short summary gives some idea of the comprehensive studies pursued in the HAPL program.

In summary, NRL has a competitive program with alternate technologies for IFE, particularly “direct drive”. In addition to KrF laser development expertise, they have a comprehensive capability in theory, modeling and experiments. The principal issue for application of KrF lasers to IFE is demonstrating scaling to multi-kJ, rep-rated systems with concurrent reliability. The pieces are in place; the next level of investment is required.

Site Visit #3 – July 24-26, 2013

- **General Atomics (GA)**
- **Lawrence Livermore National Laboratory (LLNL)**

General Atomics (GA) is a private corporation based in San Diego, California that is a major center for both inertial and magnetic confinement research and development. GA is contracted by DOE to operate the Doublet-III Tokamak as an international user facility for magnetic fusion R&D and is engaged as a developer and supplier of technology for

US contributions to the ITER project. In addition, GA is contracted by DOE to develop and supply targets to the national ignition facility (NIF) at LLNL as well as other centers involved with laser fusion R&D. They also have the largest program in target manufacturing, injection, tracking and engagement for eventual fusion power applications.

Three aspects of the GA program were covered in the assessment site visit: 1) overview and details of GA fusion activities; 2) target fabrication, characterization, injection, tracking for IFE applications; 3) tour of target production facilities and Doublet-III.

An overview of the GA fusion program was presented by Dan Goodin. GA began as a think tank for General Dynamics in the 1950s, subsequently produced nuclear reactors and then branched out to fusion and other energies. It was owned by Gulf and Shell until the 1980s when it went private, diversifying into defense and commercial activities (currently 40% defense, 30% energy, 30% commercial). They are a leading supplier of electronic systems, sensors and UAVs ("predator" drone) and are broadly involved with nuclear technology (both fission and fusion). Their history of involvement with fusion goes back 50+ years – designing, building and operating magnetic fusion devices. GA involvement with inertial fusion began in the 1990s and has grown rapidly, focusing on target manufacturing, injection, tracking and engagement. Of the ~350 fusion personnel, 100 are engaged with IFE (25% PhD). GA has extensive development and fabrication infrastructure, including precision equipment and metrology. They are developing automated assembly systems for large-scale target manufacturing for all IFE approaches - as they put it, "a difficult but manageable task".

The GA magnetic fusion program was presented by Mickey Wade. It may be summarized under 3 themes: 1) scientific leadership (develop scientific basis for optimized approach to fusion – experiment & theory); 2) MFE technology & components (deliver high quality components for next-step fusion devices); 3) fusion energy (play a lead role in defining/executing a path to fusion energy). Motivation for their involvement in fusion energy includes the high energy density of fusion fuels compared to carbon fuels (add figure) and the large supply of fusion fuels compared to existing nuclear fission + carbon sources (add figure). GA expenditures include their own money as well as contract funds from DOE.

The GA interest in Tokamaks derives from its capabilities to confine hot plasmas and demonstrate scaling to fusion power levels (11MW in TFTR, 1994; 16MW in JET, 1997). ITER is designed to produce a power of 500MW. The D-III Tokamak is the largest such device in the USA and is operated as a flexible research facility. It includes magnetic field shaping coils, neutral beam and cyclotron heating as well as current drive, diverter and wall conditioning, plus a comprehensive suite of diagnostics. GA will contribute to ITER in a variety of ways, initially by training manpower and building the superconducting central solenoid and cyclotron transmission lines.

The GA inertial fusion program was summarized by Neil Alexander and Dan Goodin. It is primarily concerned with ICF target fabrication and support to both indirect and direct drive programs at LLNL, LLE, ILE, GPI, NRL. Their role is to develop target fabrication and characterization techniques, provide targets and target cryogenic systems. Through this collaboration, they furnish several 1,000s of unique targets per year. Of ~100 staff, one-quarter are PhDs.

GA has started in-house development of beryllium targets in anticipation of demand by LLNL. They are also fabricating high density diamond targets, however, the diamond shells are obtained from the Fraunhofer Institute in Germany and they are having trouble doping the shells. Current investment on target fabrication is ~$20M/yr ($15M/yr from DOE and $5M/yr in-house). The cumulative investment is ~$440M.

We toured their facilities that include clean rooms, drop towers, foam fabrication, coaters, laser machining, computer controlled machining, x-ray equipment, microscopes (optical and electron) and interferometers. They have an extensive program for automating assembly of targets using robots for course positioning, piezo drive for fine positioning, laser illumination for mass characterization, etc. In the last year, GA has started the development of robotic assisted production to reduce the cost and increase target throughput to ~1,000 per day compared to hand production of a few per day. Their ultimate goal is mass production target facilities for IFE. Their estimate for simple direct drive targets is one-half the cost of indirect drive targets (~$0.20 each when mass produced).

GA has been a prime developer of technology for injecting, tracking and engaging targets for IFE plants. They have started developing an advanced electromagnetic target injector with electromagnetically induced spin to stabilize hohlraum targets and accelerate up to 175m/s without destroying the target. Final testing is on hold requiring additional funding. Target engagement using acousto-optical steering of mirrors is under investigation.

Lawrence Livermore National Laboratory (LLNL) is a US government laboratory engaged in a number of strategic science and technology missions related to national security (energy, defense, computing, photonics, life sciences). Its facilities include the National Ignition Facility (NIF) - a 192 beam, 2MJ laser system; target chamber; associated instrumentation - designed for experiments to achieve fusion fuel ignition. From the 1970's to the present, they have been in the forefront of high energy laser development motivated by the theoretical possibility of demonstrating fusion ignition. NIF – a truly remarkable laser engineering achievement - is the culmination of progress in this scientific endeavour.

Four aspects of the LLNL program were covered in the assessment site visit: 1) progress and status of the National Ignition Campaign; 2) current status of LIFE for power production; 3) solid-state laser technology developments; 4) advanced ignition concepts as recommended by the National Academy of Sciences report. Additional comments were sought and acquired on US and international perspectives for fusion energy.

An overview of the LLNL fusion program was presented by Mike Dunne. A strong message of “this or nothing” was made, arguing that NIF was the only near-term facility close to fusion reactor conditions, upon which a power plant could be built (LIFE is the design proposed by LLNL). By comparison, magnetic fusion requires a 10x step (ITER), to be followed by a demonstration power reactor (planned for mid-century). He also noted the large difference in tritium (T) inventory as a major issue: < 1kg for IFE compared to as much as 70kg for MFE.

NIF is a precision instrument with programmable features in temporal pulse shape, power, energy; able to deliver beams focused with temporal and spatial resolution of 20psec and 10 microns. It is modular in construction for line replacement of laser and optical components with all robotic maintenance. The facility can be operated by a small staff, as was evident in our lab tour. He briefly touched on the main issues believed to be limiting compression (and core ignition) and modifications to targets, assembly and hohlraums to overcome the limitations. A key issue will be the limited number of shots with new cryogenic targets due to budget restrictions.

A review of progress towards ignition was presented by John Edwards. In summary, the achieved (required) parameters to date are: compressed core 500-800g/cc (1000); hot spot 50g/cc (100) at 5keV; pressure 150Gbar (350); fuel ρR 1.3g/cm^2 (1.5); implosion velocity 310km/sec (350). The net (pressure-confinement time) product is still too small for ignition. Principal issues include low order asymmetry and fuel mixing in the implosion. Adjustments to the cavity length and capsule support membrane are planned to improve symmetry. Under low adiabatic conditions (ultimately needed) for shock compression, they observe strong fuel mixing compared to little mixing for high adiabatic conditions. New targets are being pursued. A gas filled diamond shell under low compression has yielded a new record in neutron yield and agreement with 1-D calculations. While ignition of such a target is predicted with only 1.3MJ, doping of diamond is difficult. Further experiments will be conducted with plastic, diamond and beryllium targets. Yet another issue is that the amount of x-rays coupled to the core is reduced by 15% for a gas filled hohlraum compared to the gas-free case.

There is optimism but concern over the budget cut to the program limiting shots since a National Academy of Sciences review is scheduled for 2015.

An overview of LIFE was presented by Mike Dunne. LIFE has been planned by LLNL as a full scale IFE power plant demonstration unit based on indirect drive. In view of the detailed design, involvement of engineering and supply vendors, risk management analysis, etc., he makes a strong case for “this or nothing in the next 10 years”. The claim is made that the alternative KrF laser driver is far less advanced than solid-state lasers and therefore not ready for big-time. [Note: the KrF laser may be more applicable for a direct drive scenario in any case.] While LIFE is a first plant demo at 400MWth, a second and future plants would be ~1GWe or more; eventually spanning 400-1,600MWe. Future plants are envisaged to have a 4 year build, 18 year amortization and 60 year lifetime (with liner replaced every 4 years). The market would target desalination as well as electric power generation. The LIFE design is based on indirect drive (using the hohlraum to protect the cryo-fuel and reduce helium damage to the chamber wall) using chromium steel for low activation. It assumes 15% efficient lasers, 44% efficient Rankin cycle (future 60% turbines), a target gain of 65, resulting in 2,900MWth for a 2.3MJ driver. The laser system would have 384 beamlines with 5,000 hours MTBF. Projected COE is $70-105/MWh for 925MWe-1.6GWe.

Diode-pumped solid-state (DPSS) technology scaling for LIFE was presented by Andy Bayramian. This is a key enabling technology for IFE and LLNL has invested considerable resources, manpower and money, in advancing the state-of-the-art. Their experience and predilection is to stay with glass based rather than the new ceramic based laser materials. LIFE would require 10^{10} shot lifetime at 10Hz. The LIFE design incorporates 384 beam modules at 5.7kJ/ beam using APG-1 glass with turbulent He gas cooling. The factory built self-operating modules would be truck size for transport to the fusion plant. A gigashot optical laser demonstration (GOLD) - a 200J, 10Hz system - has been funded for next fiscal year.

The economic case for LIFE was briefly discussed by Wayne Meier. He pointed out that desalination was growing 18% per year and therefore represented a new market for fusion plants. LLNL has analyzed such systems and projected a decrease in COE from $75/MWh to $50/MWh by the 10th of kind plant (initial plant cost $5B).

Polar direct drive and advanced ignition was presented by Mike Key. These studies are a direct consequence of the recommendations in the National Academy of Sciences review of the National Ignition Campaign. The concepts are: polar direct drive (PDD), fast ignition (FI) and shock ignition (SI). PDD has been suggested as a possible way to improve target irradiation uniformity starting from the end-on beam delivery to hohlraum targets. The study results indicated that, in principal, significantly more energy could be deposited in the target leading to higher fusion gain but; 1) the required optical modifications (modulators, phase plates, polarization plates) would need an investment of $100-200 M and; 2) there are worries that laser-plasma interactions would re-distribute the energy delivered and produce hot electrons that would negate the gains. Additional data in other experiments are required to establish accurate scaling. The FI concept is attractive but to this point is beset with highly divergent electrons resulting in poor heating. If this cannot be overcome, the study indicates that ~2MJ of laser energy would be required, too large to be worthy of implementation. Similar consideration of SI suggests higher fusion gain but the scheme requires focal zooming to half size (an optics problem) and the worry remains of enhanced laser-plasma interactions.with the same issues as for PDD. More work is required to determine the efficacy of these schemes on NIF

A short discussion of US and international perspectives was led by Mike Dunne. With respect to the NAS review, he commented that the NNSA, expecting that the energy application was much longer, was surprised that NAS called for IFE to be pursued as part of the national energy strategy. It was also noted that President Sarkozy in 2010 stated that LMJ would be an energy research facility (a point also mentioned in our visit to LMJ in August). We learned that President Putin signed a letter in 2012 approving the building of a high energy 3MJ laser system for inertial fusion research to be completed by 2020. China is particularly active with several centres (Beijing, Mianyang, Shanghai) and high energy laser systems for inertial fusion research. Laser systems include SG-II (24kJ) operational, SG-III (180kJ) nearing completion and SG-IV (1.4MJ) to be completed by 2020. They are pursuing fast ignition and magnetic guiding of electrons with a PW laser. We were told that when Prof. Li was asked how long to build a fusion power plant, he replied that a design was needed by 2015 and built by 2025. Interestingly, Korea has passed legislation to deliver magnetic fusion energy (MFE) with a commitment of $1B to build K-STAR and $1B for a demo plant K-DEMO to be completed in the 2030's; this in addition to their ITER commitment. He observed that Japan has the capability but is divided; power needs to shift to Tokyo to establish major program. HiPER is in a standby mode until NIF succeeds; moreover, it is now more tied to LMJ planning.

In summary, the NIF program at LLNL is well founded, if not well funded. With results from initial shots, the complexity of the laser-hohlraum configuration has raised physics issues – LPI, x-ray conversion efficiency and target illumination symmetry, hydrodynamics and fuel mixing – that has forced a reassessment of laser-hohlraum coupling and compression drive. These issues are not intractable and LLNL has the capability and motivation to find solutions.

Site Visit #4 – August 3-10, 2013

- **Central Laser Facility (CLF) at Rutherford Appleton Laboratory (RAL)**
- **Culham Centre for Fusion Energy (CCFE)**
- **Laser MegaJoule (LMJ) and Centre Lasers Intenses et Applications (CELIA)**

RAL is a UK government funded lab based in Didcot, Oxfordshire. Operating under the Science & Technology Facilities Council (STFC), it houses a number of major facilities, including the Central Laser Facility (CLF). In turn, CLF houses a number of laser systems supporting physics, chemistry and biology research for RAL and academic staff from the UK and Europe. CLF is a major centre for laser/plasma/fusion science and operates the Vulcan 8 beam system (both high energy and petawatt (PW) modes) for ultra-high intensity experiments. RAL scientists have collaborated actively with ILE scientists in Japan to pursue "fast ignition" and have provided leadership to the HiPER program in Europe. HiPER is planned for a next stage demonstration of IFE energy, following ignition at LLNL.

Three aspects of the CLF program were covered in the assessment site visit: 1) general status of IFE at RAL including HiPER program planning; 2) high average power laser development and; 3) tour of laser and target fabrication facilities.

An overview of the status of IFE was presented by Peter Norreys and Robert Bingham. There is no formal inertial fusion energy program in the UK at this stage but this would change once NIF demonstrates ignition. The attitude is one of "everybody must put their shoulder to the wheel to make NIF work". Discussion of principal issues such as fuel mixing needs additional diagnostics but is expected to be solved by going to carbon vs plastic shell. There is optimism that NIF will achieve ignition in the next year. It was pointed out that Vulcan is currently operating at 60% capacity (~ £7M /yr, training ~175 students/yr). An empty target area of 150-200 m^2 could become a Canadian target area for ~£1M. Planning for an upgrade to >10PW to cost £25M is not yet funded. HiPER planning has a team of ~5 people at RAL but is primarily in a holding pattern until NIF ignites.

The HiPER program planning was presented by Mike Tyldesley. Context for IFE was presented as: 1) UK coal and nuclear end of life coming up 2015 to 2025; 2) biomass footprint (45km x 45km), solar/wind area (1/4 of biomass), fusion (1km x 1km). The HiPER mainline approach has shifted from fast ignition (FI - British led) to shock ignition (SI – French led) as an advanced alternative to direct/indirect drive only. The issue of coupling efficiency for high energy electrons in FI is still believed to be solvable using magnetic field guiding. Concern was expressed about filamentation as a possible problem for SI. HiPER is an ambitious project (€5B) with subsequent demo (€5-10B in the 2025-2030 period) and fleet roll-out 2035-2045. It is envisaged as a two-phase program with two chambers – one for testing ignition, target tracking & engagement and the other a 10-15 Hz rep-rated power production chamber of ~20MWe to test operating system issues (neutronics, heat load on materials, etc.).

The Center for Advanced Laser Technology & Application (CALTA) was discussed by Justin Greenhalgh. Dipole is a laser development program (£1M /yr) to demonstrate 10J, 10Hz operation at high efficiency. It combines liquid N2 cooling, cryo pumping, turbulent He flow and Yb:YAG optical slabs. The European funded HiLASE contract (£10M) for the Czech ELI project has an objective of 100J, 10Hz and ends in 2015. It has achieved 25% optical efficiency and 12-18% electrical to optical efficiency without cryo operation. Applications include laser annealing, security and laser peening.

A tour of some CLF laser facilities was conducted by Peter Norreys and Mike Tyldesley. The Vulcan area has ~35-40 staff. All facility costs and targets are provided for successful user applicants. Target fabrication and machine shop is provided with 1 day turnaround support. Dipole and HiLASE developments were among the viewed facilities.

CCFE is the UK Atomic Energy Authority laboratory for fusion research located in Culham, Oxfordshire. The site houses the UK national MAST experiment (a spherical Tokamak) funded by the Engineering and Physical Sciences Research Council and the European funded JET experiment (the largest operating conventional Tokamak in the world). There are ~150 staff on the MAST project and ~500 on the JET project. Visiting European scientists number ~350. The site is also home to an innovation centre for start-up high tech companies. JET is being used as a half scale test bed for ITER designs. It holds the current record for fusion power output - 16MW for 0.5 sec - and a new campaign is planned for 2016-2020 to achieve 20MW for 5 sec. For this campaign, they will purchase 60gm of tritium from Canada.

Three aspects of the CCFE program were covered in the assessment site visit: 1) progress and status of JET; 2) issues and timescale for ITER; 3) tour of facilities. Additional comments were sought and acquired on international perspectives for fusion energy.

An overview of the magnetic fusion program was presented by Steve Cowley and Lorne Horton. The fusion roadmap will progress from JET to ITER to DEMO. JET has been operational since 1983 and has achieved many milestones, including the world record for fusion power burning D-T fuel (16MW for 0.5 sec). Since it is effectively a half scale size ITER, it has provided an important test bed for ITER design and construction. A divertor was incorporated in 1993 and operation as an ITER-like configuration was started in 2006. An ITER-like metal wall (beryllium and tungsten) was subsequently installed at a cost of £100M. JET has been operated as a remote handling facility since 1998, as will ITER.

Magnetic confinement of plasma in JET is accomplished with a 3.5T magnetic field (toroidal and poloidal coils) and field induced by a 5 MA current that also provides heating. Auxiliary heating and fueling is provided by neutral beam injection (34MW), ion cyclotron resonance heating (10MW) and lower hybrid current drive (7MW). Pellet injection provides for re-fueling and mass gas injection for plasma disruption.

ITER is planned for plasma operation beyond 2020 and D-T burn beyond late 2027. While a power output of 500MW is expected, this will not be tied to an electric grid. DEMO, as the next step in the period 2040-2050, would be the first fusion plant supplying electric power to the grid. In terms of heat, the ITER divertor will handle an exhaust of a few MW/cm^2 compared to $10MW/cm^2$ for DEMO and eventual power plants. DEMO is intended to be the last step paid for by Europe, private investment to follow. It was noted that the Chinese are more aggressive, aiming for a national demo by 2030, well ahead of the ITER-DEMO sequence. It was also noted that China built a superconducting Tokamak in 3 years without having built one before.

Materials issues were highlighted. Materials in full power systems will experience high heat, particle and neutron loads, approaching displacements of 20dpa/yr or more. Consequently, the world strategy calls for a neutron materials testing facility and the UK has mounted a strong computational effort on molecular dynamics calculations. Small irradiated samples (micron and nanometer size) were emphasized in order for them to be handled in normal facilities for materials testing. CCFE is working with Oxford University on nanoscience collaboration ($5M government funding).

The International Fusion Materials Irradiation Facility (IFMIF), at a cost of €2B, was conceived to investigate such material physics at levels of 150 dpa/yr. A less expensive version, IFMIF Light, will provide 20dpa/yr testing capability for a few €100M. The validation and engineering phase includes a facility in Japan using spallation – (D, Li) n stripping reaction using accelerated D and a flowing Li target.

Other comments: China is very serious about fusion since fission fuel is limited and 12 year breeding times of fast breeders is too long for China growth. Fusion is one of the 5 priority programs in their 2020 Vision. Korea has also emphasized fusion through legislation and prioritizing the development time scale. We also learned that Australia and Brazil are asking how to become a partner in ITER.

MAST (for mega amp spherical tokamak) at Culham is one of a few spherical tokamaks being investigated worldwide. These are complementary to conventional Tokamaks and are of interest as potentially more compact devices for economic fusion power – achieved by obtaining higher plasma pressure for a given confining magnetic field. The Culham MAST is a 3m diameter chamber with 1.3MA in a 1 sec pulse producing ~2keV core temperatures. MAST is implementing a £30M upgrade to increase the pulse length to 10 sec, add heating to achieve higher temperature and thereby a capability to test advanced heat exhaust divertors. ST's are at a relatively early stage of development as fusion power systems but could be test facilities for blanket materials, neutronics, magnetic field geometries, etc. on the pathway to fusion.

A tour of the JET control room and MAST compact torus concluded the visit. A meeting with Alan Costley at CCFE led to arranging a visit the following morning with Alan Sykes, a retired Culham scientist. He has started a new company, Tokamak Solutions, with 1/3 funding from Lord Wolfson, to accelerate development of fusion reactors based on the compact torus. The initial niches identified include: 1) high temperature superconducting magnets with scaling to very high B fields and therefore power output; 2) compact torus D-T neutron source, similar to proposed US program; 3) selling small tokamaks to new players (interest already expressed by 2 potential purchasers).

Commissariat à l'énergie atomique et aux énergie (CEA) is a French government funded technological research organization that operates 10 laboratories throughout

France and employs 16,000 staff of which 30% are in basic research, including low carbon energies (~4,000 people, €1.8B). CEA has missions with energy, health, security and defense applications with an annual budget of €4.3B. LaserMegaJoule (LMJ) is an inertial fusion technology project of CEA based in the Bordeaux region (CESTA). Simulations are a major part of the program with large scale computers (2 petaflops at present).

The status and progress of LMJ were presented by Pierre Vivini, Charles Lion and Francis Kovacs. LMJ is a laser system comparable to NIF at LLNL with some technical differences. The number of laser beams is 176 (44 quads in 2 cones) vs 192; the energy is 1.2MJ (third harmonic) vs 2MJ; final focusing optics are gratings rather than lenses and; the point design for the hohlraum is rugby shaped rather than cylindrical as in the national ignition campaign at NIF. Total cost to date is €3.4B over 15 years. 250 companies are directly involved with more than 1,000 support companies – it is the biggest project in Europe at the moment but will be eclipsed by ITER in due course (also in France).

LMJ is a high precision laser facility with 50μm pointing accuracy, 15ps timing accuracy, 3% eventual beam balance, employing spectral modulation to avoid optical damage problems and phase plates to avoid high intensities and LPI. LMJ was designed with larger beam angles to reduce cross-beam energy transfer and LPI, expecting it to be the major problem rather than hydro instabilities as assumed in NIF. Incident energy is half each in 33 degree and 49 degree drive cones. Initial targets are CH but pure C is expected to be better in the future. Targets are 2.4mm sphere with 310μg of D-T at 18 deg K; gas filled rugby hohlraums with predicted gain of G=10 and perhaps optimized to G=30. Point design for ignition is 860kJ and 260 TW drive, substantially lower than for cylindrical hohlraums. The potential for increased efficiency of the rugby hohlraum was confirmed in comparison experiments conducted at LLE - 50% additional x-ray conversion, higher radiation temperature and 10x increase in neutron yield over the cylindrical hohlraum. The French program is accompanied by comprehensive computer simulations to analyze experimental results thereby enabling laser/target optimization.

LMJ is planned for 5-10 years to achieve ignition, taking a systematic approach on physics issues – 6 month cycle for experiment, analysis and changes for new experiment. The LMJ schedule calls for a first quad experiment by December 2014 with other quads brought online annually thereafter. LMJ in operation will be a 20% user facility. A petawatt laser, PETAL, will come online with LMJ for use as a backlighter.

Attention was given to the issue of direct and indirect drive, France as a policy emphasizing that fusion as an energy source must be based on direct drive since indirect drive is too close to weapons physics. It is not understand why NIF is promoting LIFE based on indirect drive. In contrast, strong support was expressed for international coordination to increase the effort on IFE using direct drive and thereby raise the profile for IFE as has been accomplished for MFE by international cooperation on Tokamaks.

The significant industrial links to LMJ were presented by Herve Floch, General Manager for Routes des Lasers (RDL), a competitive cluster of companies at LMJ. The philosophy of RDL is to develop industrial applications and scientific research around LMJ. Routes des Lasers is a major thrust of the province of Aquitaine, encouraging start-up and existing companies in a wide variety of photonics applications - lasers, optics, materials processing, metrology, instrumentation, health, etc. The cluster has one of the highest concentrations of scientific expertise in photonics in Europe - initiated by LMJ as a scientific flag for international visibility. It has links to the University of Bordeaux through a new Institut d'Optique d'Aquitaine. ALPhNOV: "Routes des Lasers" is a new optics and technology transfer platform with 40 scientists and engineers on staff to support companies from ideas to products. PYLA: "Routes des Lasers" is an optics and lasers training platform for providing 2-8 day training courses. SEML: "Routes des Lasers" provides shared services and resources in dedicated real estate to support business and technology sites suited to industrial needs. Other services help to give visibility to photonics and facilitate meetings between entrepreneurs, investors and analysts. There are now 80 companies and 115 members in the cluster. Since 2000, 20 new SME's have been created and 1,400+ highly qualified new jobs. Some 146 collaborative projects (50% success rate) have been funded totalling €274M (€132M public funds); company formation was slow for the first 8 years but rapid for the past 4 years.

An overview of the Centre Lasers Intenses et Applications (CELIA), University of Bordeaux was presented by Vladimir Tikhonchuk and Francis Kovacs. CELIA was formed in 1999 to make a bridge between large laser facilities such as LMJ, LIL and PETAL at CESTA and the university community, providing academic support for inertial fusion science, industrial applications of optics and lasers, basic research and training on lasers and plasmas. There are 34 permanent researchers and total staff of ~70. The annual budget is €1.3M, excluding salaries. There have been 8 spin-off companies since 1999. CELIA is structured as a joint research unit among the University of Bordeaux, Centre National de Researche Scientifique (CNRS) and Commissariat à l'Energie Atomique et aux Energie (CEA). Low energy pulsed lasers are available at CELIA and high energy lasers are available through links with CESTA and international labs. A wide variety of collaborative experiments, augmented by theory and computer simulations at CELIA have been pursued. Considerable computer resources are available to CELIA. Fast ignition and shock ignition are two subjects extensively investigated due to their relevance in HiPER planning and a lively discussion followed on many of the relevant physics issues. CELIA also directly supports "Routes des Lasers" objectives in innovation, technology transfer and economic activity.

In summary, France has generated an impressive breadth and depth in inertial fusion R&D; moreover, with LMJ as a catalyst, a solid foundation of advanced technologies - lasers, optics, photonics, systems engineering, computational capability, etc. – has been fostered and transferred to industry. The combination of NIF at LLNL and LMJ at CESTA increases confidence in achieving fusion fuel ignition and setting mankind on the path to fusion energy production.

Site Visit #5 – August 27-30, 2013

- **Laboratory for Laser Energetics (LLE)**
- **Canadian Nuclear Society (CNS) Fusion Workshop**

LLE is a University of Rochester laboratory funded by the US government as an educational centre for laser-plasma science, inertial fusion R&D, training of scientists and development of new concepts and technologies. It came into existence in 1970 and has an annual operating budget of ~$60M. There are more than 200 professional staff and more than 100 graduate and undergraduate students engaged at LLE. LLE provides operational support for DOE and NNSA inertial fusion science. It is the lead lab in the US for direct drive ignition.

Five aspects of the LLE program were covered in the assessment site visit: 1) polar direct drive (PDD) ignition campaign and relation to NIF experiments; 2) experimental plasma physics campaign; 3) theoretical physics program; 4) shock ignition; 5) mass production of targets. A tour of facilities was included in the visit. Additional comments were sought and acquired on US and international perspectives for fusion energy.

An introduction to the LLE fusion program was presented by John Soures. He highlighted opportunities to: 1) invest in the PDD campaign that requires a variety of optical components, coatings, phase plates, cryo hardware and; 2) collaborate with development of mass target fabrication. This was followed by reports on program components by Craig Sangster, Dustin Froula, Jason Myatt, Ken Anderson and David Harding. Sam Morse and John Soures conducted a facility tour.

The polar direct drive campaign through FY2015 was presented by Craig Sangster. It includes 8 shots on NIF in each of 2014 and 2015. This is a result of the recommendations in the National Academy of Sciences review of the National Ignition Campaign. Polar direct drive (PDD) has been proposed as a possible way to improve hohlraum target irradiation uniformity. The optical requirements and costs of implementing PDD were discussed together with technical issues accompanying cryo injection and physics issues such as laser plasma interaction (LPI), cross-beam energy transfer (CBET) and generation of hot electrons. PDD symmetry and dydro stability will be studied at LLE in the 2014 fiscal year. The merits of lower intensity conditions for direct vs indirect drive configurations were highlighted. There is a severe problem with reduced neutron yield for low adiabat shots ($\alpha < 4$). This is critical for NIF that has a point design of $\alpha = 2.4$.

The experimental plasma physics campaign was discussed by Dustin Froula. He emphasized the factor of ten reduction in single beam focused laser intensity for LLE design compared to that for NIF. This has consequences for ease of modeling as well as reduction in hot electrons resulting from laser/plasma instabilities. He reported on a variety of advanced diagnostics including Thomson scattering and Fresnel refractometry to enable validation of code predictions for target parameters such as density and temperature. Target designs appear to be optimum with beryllium included in the ablator (higher ablation rate, velocity and pressure). Currently, there is no budget for the cryo fill tube for handling beryllium. It was noted that beam zooming could help considerably in avoiding CBET.

The theoretical plasma physics program was presented by Jason Myatt. He discussed various 1-D, 2-D and 3-D codes that have been validated with experiments at LLE. He particularly emphasized the importance of collisional damping that localizes Langmuir waves and the reduction of hot electrons for higher effective atomic number Z (obtained by mixing Si with CH).

The case for shock ignition (SI) was presented by Ken Anderson. It was noted that implementing PDD on NIF would require 1.5MJ for ignition. In contrast, their calculations suggest SI with PDD and zooming will yield a target gain of 58 for 700kJ total laser energy. Moreover, the yield is reasonably robust to variations in target smoothness. They have investigated the important laser/plasma instabilities at relevant laser intensities to determine scattering levels and generation of hot electrons with a view to benchmarking experiments.

Mass production of targets for IFE systems was addressed by David Harding. This continues work initiated under the HAPL program stimulated by David White at MIT. The work is primarily pursued as small student projects. It was noted that LIFE as a working system would have to turn around the entire tritium inventory every day. Technical issues such as slow freezing for quality control, thermal barriers (e.g., neon) for target injection survivability and facility size were briefly discussed.

The laboratory tour of facilities was conducted by Sam Morse and John Soures. The main laser system, OMEGA, is a 60 beam, 30kJ facility that delivers ~1,200 shots per year on a 3 day/week, 2 shift/day schedule. The petawatt facility, EP, enables advanced concepts such as fast ignition (FI) to be studied and can deliver up to15 shots per day. External users such as Atomic Energy of France (CEA) pay $100k/day for facility access. The target cryo fab facility has a cumulative investment of ~$35M and requires a staff of 8 persons to operate. Full target preparation time is 36 hours. LLE has an annual budget of $60M.

We enjoyed a lunch discussion with senior staff including Bob McCrory (LLE Director), David Meyerhofer and John Soures. A critique of the NIF indirect drive program at

LLNL included comparison with direct drive (DD) at LLE and the potential for ignition (DD higher but not feasible on NIF), that LIFE is premature, the need to keep options open and carry out basic science, but that demonstration of ignition is critical for moving forward.

Canadian Nuclear Society fusion workshop. Synchronizing the LLE visit with the August date of the meeting permitted attendance at a 1 day CNS workshop in Oshawa. Since the demise of the national fusion program in the 1990’s and subsequent retirement of senior researchers, the Canadian activity has been limited to university involvement and a modest private sector effort. Consequently, the 1 day workshop had the virtue of bringing together interested parties to re-engage and stimulate discussion of fusion in Canada.

Presentations included: Dr. Zheng, Hope Innovations; Mr. Delage, General Fusion; Prof. Fedosejevs, University of Alberta; Prof. Xiao, University of Saskatchewan; Mr. Carle, Queen’s University; Dr. Shahani, Norax Canada; Mr. Barnes, ANRIC Enterprises; Dr. Boniface, AECL Chalk River Laboratories; Dr. Davis, University of Wisconsin. The subjects ranged over magnetic, inertial, beam and magnetized plasma approaches; materials science and plasma diagnostics.

APPENDIX D – FUSION FORUM & WORKSHOPS

Executive Summary of Fusion Energy Forum (Edmonton – November 25, 2013)

Forum International Guests

- Dr. E. Moses, Lawrence Livermore National Laboratory (LLNL), USA
- Prof. W. Zhang, Inst of Applied Physics and Computational Mathematics (IAPCM), China
- Prof. H. Shiraga, Institute of Laser Engineering (ILE), Japan
- Dr. C. Edwards, Rutherford Appleton Laboratory (RAL) & European HiPER, UK
- Dr. J. Parmentola, General Atomics (GA), USA
- Dr. H. Floch, Délégué Général ALPhA, Routes des Lasers, France
- Prof. R. Li, Shanghai Institute of Optics and Fine Mechanics (SIOM), China
- Dr. S. Zou, Inst of Applied Physics and Computational Mathematics (IAPCM), China

Introduction: The one year fusion technology assessment underway has 4 important components: 1) international site visits; 2) workshops for the Alberta technology community; 3) fusion forum for leaders in government, industry and R&D institutions; 4) final report of findings and recommendations. The site visits and workshops have been completed. This is a brief summary of the fusion forum just concluded.

The objective of the forum was to bring international leaders of major programs to Alberta as a means of communicating the breadth and depth of activity in fusion development, especially inertial confinement. The invited speakers represented Asia (China and Japan), Europe (France and UK) and the USA (government and industry). Moreover, the presentations included current R&D (progress and status), advanced concepts, enabling technologies & early stages of industry involvement, and preparing for fusion power generation. Other countries could have been invited since Russia and India also have made large commitments to developing fusion energy. Given the constraint of presenting the story in one working day - to reduce the time burden on senior people with busy schedules - the number of speakers was purposefully limited to enable six comprehensive presentations plus a panel discussion within the time limitation.

USA: Dr. Moses, as the previous Director of the National Ignition Facility (NIF) at LLNL, and now head of Laser Inertial Fusion Energy (LIFE) planning, gave the opening presentation. LLNL is a premier centre for fusion R&D - theoretical concepts, experimental facilities, computational and engineering capabilities. This is demonstrated by the 192 beam highly engineered NIF laser system with detailed pulse shaping ability, beam energy balance and reliability as particularly noteworthy features. NIF was constructed over a period of more than 10 years and is the highest energy laser system in operation in the world today.

In addition to reporting on progress with NIF experiments, his talk highlighted contributions of scientists from other institutions and cutting edge instrumentation that has been developed and implemented on the target chamber to measure key parameters of laser driven targets. These capabilities are backed by sophisticated computer codes that incorporate relevant physics to model energy absorption, transport and target hydrodynamics.

The NIF laser system has an output energy up to 2 megajoules that is expected to achieve target ignition and demonstrate net energy gain in fusion fuel. The approach is that of "indirect drive" in which laser beams heat the interior surface of a cylindrical "hohlraum", thereby converting laser energy to x-rays with which to more uniformly implode the target fuel at the centre of the hohlraum. Ultimately, the goal is to convert the energy of the imploding target into heating a central hot spot to a temperature of ~10 keV (100,000,000 ºC). Following core ignition, the energetic alpha particles resulting from fusion would provide additional self-heating to sustain fuel burning.

Dr. Moses reported on the progress of recent campaigns in which neutron yields and energy produced from the ignited core have unambiguously shown alpha particle heating which is the primary goal of fuel burning by self-heating. **The hot spot has produced ~14 kilojoules of fusion yield, exceeding the nominal core heating of ~8 kilojoules. As he highlighted, this achievement successfully demonstrates hot spot ignition and fuel burn, the first step to complete fuel ignition.** Since this is very much a threshold phenomenon, the planned experiments over the next 2 years will seek to establish full ignition and propagating burn via alpha particle heating in outer layers of the compressed fuel that should result in megajoule energy yields. The yield depends sensitively on laser/target characteristics such as laser power profile, total energy, uniformity of target irradiation, target materials and hydrodynamic stability – parameters that will be systematically investigated on NIF.

This capability has motivated the consideration of scaling to a demonstration reactor. LLNL has initiated a parallel program of engineering design, costing and risk analysis of a scale up to a fusion power plant called Laser Inertial Fusion Energy (LIFE). This will be summarized in a later section of this report.

China: Prof. Zhang, as the current Director of the equivalent institution to LLNL in China, gave the second presentation. His talk summarized the plans and progress in China for fusion energy development, highlighting the issues of global warming in the context of fossil fuels, instability of supply in the case of renewables and radioactive wastes in the case of nuclear fission. This motivates China's strong interest in and commitment to developing fusion energy.

His talk summarized the sequence of laser systems constructed since the 1970's and China's plans for larger systems to reach megajoule energies. He spoke of the parallel development in computer simulation capabilities, instrumentation and experiments to benchmark the codes. The Chinese program has an overall objective similar to that of LLNL but also includes alternative approaches (direct drive plus fast ignition, shock ignition) to the intensively studied central core ignition via indirect drive. The program is taking a systematic approach to understanding target physics enroute to ignition. They are developing a comprehensive capability in numerical simulation to model laser/plasma interaction, radiation transport, hydrodynamic instability and fuel ignition and burn. He briefly described some of the x-ray diagnostics employed and results of experiments to verify x-ray drive in hohlraum capsules.

A sketch of future plans was outlined including developments in solid state laser drivers, high damage threshold & large aperture optical glasses and crystals, and megajoule class laser systems for inertial fusion energy. He also discussed a laser driven sub-critical system (LDS) in a fusion/fission hybrid scheme that would provide fast neutrons from fusion to induce fission of U238 or Th232 in a blanket around the fusion chamber (thereby enhancing energy gain as well as burning non-fissile fuels). In conclusion, he presented an IFE roadmap that included an objective of demo reactor design and construction in the 2030's.

Comment: It should be noted here that the French LaserMegaJoule (LMJ) facility in Bordeaux and the now approved plan to build a similar megajoule class laser in Russia will bring very large laser facilities to a total of 4 in the next few years. In addition, other large, 10 to 100kJ class laser systems in existence or planned include those of China, EU, Japan, Korea, UK and USA. Inertial fusion is receiving considerable attention worldwide.

The subject of the forum then turned to alternative advanced concepts that may provide higher gain with reduced laser driver energy. Two schemes, in particular, are receiving attention: 1) fast ignition and 2) shock ignition. The former utilizes a powerful short pulse laser to generate high energy electrons that could be used to ignite a pre-compressed fuel and the second approach adds an intense laser spike at the end of the main laser driver pulse to shock ignite the pre-compressed fuel.

Japan: Japan has made a major commitment to fusion energy development – historically, especially to magnetic fusion that has been pursued since the 1950's. Inertial fusion research began after the invention of the laser in 1960 and specifically in the 1970's in most countries, including Japan, as high energy laser technology emerged. Japan has traditionally espoused the direct drive approach in which laser beams are used to irradiate the target directly rather than through conversion to x-rays. Their current work employs direct drive with fast ignition.

Prof. Shiraga presented the work at ILE on fast ignition as an alternative route to commercial IFE – making the case that the compactness of this approach will accelerate fusion energy development. As he points out, two virtues are potentially lower capital cost compared to central ignition and less sensitivity to hydrodynamic instabilities.

The ILE program is called FIREX for Fast Ignition Realization Experiment. The first phase, in process, is to demonstrate heating to 5 keV (50,000,000 ºC). The second phase, FIREX-II to follow, would be to demonstrate fuel ignition and burn. A complex optical architecture is required for generating high power short laser pulses and ILE is highly involved in this technology. He presented their campaign roadmap, reported on current heating experiments to 1 keV with partial beams and discussed target coupling issues. ILE expects all 4 beams to be available next year. The strategic objectives include FIREX-II by ~2020 and experimental fusion power test facility by ~2030.

He then proceeded to outline development of key enabling technologies for reactor systems. Japan is pursuing laser diode pumping to replace flash lamps for increased efficiency, rep rate and heat suppression. Since higher thermal conductivity enables high rep rate operation, they are also pursuing ceramics to replace glass materials for laser substrates. Additional studies are concerned with fueling systems – mass production of targets, injection and tracking. They have demonstrated reliable target acquisition and laser firing. A conceptual design committee for their Laser Inertial Fusion Test (LIFT) facility has been organized with key sub-groups working on associated specifications. This experimental project would include 3 phases to realize burning fuel physics, electric power to the grid and tritium breeding and materials testing at up to 180 MWe. Laser driver architecture, liquid wall chamber and other design features have been incorporated on the basis of largely using existing technology and materials.

Prof. Shiraga also presented material prepared by Dr. Kitigawa on IFE developments proceeding at the Hamamatsu Corporation. Hamamatsu is a photonics company and is pursuing laser driver technology as well as schemes based on fast ignition to generate fusion neutrons for other applications. This is significant since we see a totally private company engaged in scaling laser technologies to generate and utilize inertial fusion neutrons with a roadmap including medical and industrial applications from small to full power plants. It is also noteworthy that the automobile manufacturing company Toyoto has become engaged in IFE through association with Hamamatsu.

UK, EU and HiPER: Continuing with advanced concepts for IFE, Dr. Edwards presented the planning for a pan-European program in inertial fusion called HiPER. It was conceived as the next step to laser fusion following ignition demonstration at NIF. The physics design is based on direct drive and shock ignition with a test of concept using LMJ in France ~2022. The roadmap is built upon the continuing knowledge base developed at NIF and LMJ and seeks to develop and exploit technology opportunities enroute to full fusion power production. A key decision point would be 2030 for the HiPER construction.

Major funding agencies in Europe and many other partners are involved. Current technical work is funded on a national basis and the E.C. is expected to fund future work under the Horizon 2020 program now under discussion in Europe. The HiPER design includes 2 target chambers – one for R&D experiments and the other as a power generating unit. This would allow for continuing upgrades as the knowledge base expands.

His presentation contrasted the differences in footprint for power generation using various energy sources, highlighting the large space requirements for renewables that would have a large impact on small countries such as the UK.

The following presentations addressed the technological base and ways in which industry is becoming involved.

USA: Dr. Parmentola of General Atomics discussed the global issue of energy supply and opportunities that places a premium on fusion compared to other sources, especially when total resource, as well as utilization issues, are considered. He then turned to GA involvement in addressing IFE fuel fabrication and delivery, namely the need for low cost mass production of targets coupled with injection, tracking and laser beam engagement.

General Atomics is currently a supplier of targets to LLNL and other programs and is working on scaling the technology to mass produce targets. He noted that, even while target complexity has increased, efficiency has reduced the cost. Additionally, new models of production are being devised for mass production of hohlraums and targets. Likewise, super-accurate injection, tracking, final aligning and driver beam engagement methods are being worked on. His talk suggested that, while difficult, no show stoppers stood in the way of achieving the required solutions.

GA is also involved in magnetic fusion and, indeed, operates the largest Tokamak in the USA for the Department of Energy. As a consequence they are involved with supplying technology to the ITER project in France. This includes such items as the central current conductor and rf heating. He showed an interesting slide demonstrating improvement by a factor of more than 1 trillion in fusion power output for magnetic confinement devices over the past 4 decades.

France: The following speaker was Herve Floch, General Manager for Routes des Lasers, a competitiveness cluster established by the French central and Aquitane regional governments to generate spin-off commercial activity and particularly photonics capability stimulated by the LaserMegaJoule national facility. Its goals include research, training and technology transfer.

He highlighted that photonics is one of the key enabling technologies in this century impacting energy, life sciences, industrial automation, consumer electronics, automotive, aerospace and defense, inspection, etc. with large sales & market growth, manpower employment, R&D investment.

The photonics cluster in Routes des Lasers links basic research and industry through access to facilities, materials, laser sources, equipment, metrology, etc. A comprehensive plan supports the research/industry link. A new Institut d'Optique d'Aquitaine (IOA) brings together talents and resources in photonics and optics in the Bordeaux region and links industrialists and researchers in collaborative projects. LaserMegaJoule, a €3 billion investment for inertial fusion R&D, is the scientific flag for international visibility. PETAL is a physics demonstrator for fast ignition. ALPhANOV-Routes des Lasers is a transfer platform with up to 40 scientists and engineers providing expertise to support companies from ideas to products. PYLA- Routes des Lasers is an optics and laser training platform providing over 40 training courses or specialized sessions on request. SEML- Routes des Lasers provides dedicated real estate – business and technology sites - suited to industrial support. Invest in Photonics is an international partnering business convention for photonics that facilitates meetings, opportunities, current issues, visibility, etc.

He summarized the impact of Routes des Lasers thus far as follows (in the 13 years since formation): 83 member companies; 340 certified projects (€525M) with 146 funded (€274M, public funding part €132M); 26 startup companies created; >1,400 jobs created.

USA: The final speaker of the forum was Dr. Moses who reported on the technical progress of LIFE and its context in global energy supply. His introductory comments highlighted mankind's voracious energy needs and increased GHG emissions accompanying; pointing to the requirement of 10 thousand new GW power plants in this century as the grand challenge in project management.

He then described LIFE as an attractive energy solution with features of universally abundant fuel, negligible toxic emissions, minimal water and land use, safety; in addition to being CO_2 free. LIFE can be used for myriad applications including clean electricity generation, desalination, hydrogen fuel production and process heat.

LIFE is an integrated approach to plant design, based on NIF, using systems engineering, maximizing use of existing materials & technology and modular factory built design for high plant availability, with safety features enabling simplified licensing. End-user consultation was used to determine the requirements (utility, industry, economics, social policy). Key challenges addressed included: performance validation (using NIF); chamber survival (modular, unsealed using conventional steel); safety & licensing (high burn efficiency, liquid lithium metal heat transfer & tritium breeding blanket and flexible low inventory tritium processing); plant availability (modular line replaceable unit design); fuel manufacture (scaled from present manufacturing processes). The modular reactor vessel architecture reduces lifetime requirement from 60 years to 4 years and permits existing materials to be employed. LIFE incorporates a detailed cost and economics model integrated with technology performance. Based on vendor cost assessment, the levelized cost of electricity is competitive with other fuel sources.

He mentioned independent studies of the economic impact of LIFE by several organizations. In the Oxford Economics study, it was found that the job impact in the US alone would be comparable to employment in machine shops, aircraft manufacturing and semiconductor manufacturing.

Summary: The presentations by the international leaders at the Fusion Energy Forum highlighted significant progress in the science of inertial fusion energy (IFE); planning for advanced concepts for next generation fusion; rapid development of enabling technologies and industrial capacity to supply fusion systems and; detailed planning for first generation IFE power systems. In view of this progress, it is conceivable that an experimental fusion power test facility based on LIFE or LIFT could be deployed in 20 years or less. Such a development would have a profound impact on future clean energy sources for heat and power applications.

FUSION WORKSHOPS SUMMARY

Alberta Fusion for Energy Workshops
October 25th - Calgary and October 26th - Edmonton

The Alberta Council of Technologies hosted two Fusion Energy Workshops on October 25th at Alberta Innovates Technology Futures site in Calgary and on October 26th at the site in Edmonton. Attendees had been informed through email that the objectives of the workshops were to provide highlights of:

- Our study team's visits to fusion research sites in Asia, Europe and the USA
- Associated pre- and post-ignition research and commercial opportunities.

Registered to attend were 37 attendees for Calgary and 51 for Edmonton, Attendees participated in discussions for identifying pre-and post-research and commercial opportunities for Alberta and the socio-economic impact of fusion for energy. Each of the registrants received a Notes Sheet – Attachment A, that they were asked to return at the workshop's wrap-up. Note Sheets were received from 21/30 attendees (70%) in Calgary and 14/46 attendees (30%) in Edmonton. Results now follow.

EXECUTIVE SUMMARY

VISION
Alberta as a leader in advancing the commercialization of fusion for energy technologies as a clean energy supplement and a future alternative to carbon energy

PROPOSED PROJECTS
An Alberta Centre is warranted as an international broker of information, sustaining interest, building capacity, advising on research/commercial priorities and maintaining international relations

ALBERTA's OIL & GAS INDUSTRY
Fusion's impact is speculative for: USAGE as near- term heat benefit and TIMING of long term displacement

RESEARCH & COMMERCIALIZATION
Align and enhance Alberta's public research and commercial capacities in: materials science, lasers, tics, photonics, instrumentation and computer modeling.

CHALLENGES
Increasing competition especially from Asia and project costs among fusion ignition options and the promise of fusion energy are elevating interest in timing. Uncertainties prevail on timing and priorities, partnering and the socio-economic implications of fusion energy

LEADERSHIP
Alberta should stake out leadership - promoting international collaboration and bridging of research and emerging technologies, commercialization and socio-economic policy.

Summary of Fusion Workshop Discussion Sessions (Calgary, Edmonton) – Oct. 25-26, 2013

- Robert Fedosejevs

1. What do we need to know about the production and impact of fusion energy?

- Need reliable and trustworthy sources of information
- Need a roadmap to fusion with various alternatives
- Identify the Alberta/Canada advantage - why Alberta and Canada should pursue fusion energy
- Economics – need cost estimates and compelling case for public funding
- Timelines for development of the different approaches and relevant technologies
- Technical risks, challenges and barriers
- Scalability to produce smaller modular systems
- How much research still required: Plasma Physics, Lasers and optics, Material Science, Instrumentation, neutronics, reactor design, etc.
- Identify nanotechnology applications – targets and material science

2. What should be done to get ready for fusion as a commercially viable energy source?

- Public/Societal awareness and acceptance - education in school system and for general public
- Map key issues and requirements onto current knowledge and skill base in Alberta and Canada
- Identify near term and long term payoffs
- Development of a regulatory framework for reactor construction
- Engage the industrial, educational and research sectors
- Partner with key international players
- Set a challenging goal to stimulate development of advanced technology
- Position Canada as the neutral "Switzerland" of fusion, coordinating international activity

- Lock up some IP – requires moving quickly

3. What can you and others you may know offer to advance the application of fusion energy in Alberta?

- Provide leadership: technical, political, economic
- Raise public, government and industrial awareness through forums and personal interactions
- Build on the Alberta vision of being an Energy Leader
- Tap into government sources initially but have a business plan to transition to the private sector
- Tap into the CCEMC (Climate Change and Emission Management Corporation) funds
- Encourage private sector investment – General Fusion an example already
- Increase training of highly qualified personnel in Universities and Colleges
- Propose an International Centre for Fusion Energy - act as an international information hub and hold an annual conference to build international relations
- Establish award for the leading local and leading international developments in the science and technology of fusion energy each year