STATUS OF FUSION ENERGY

Impact & Opportunity for Alberta

Volume I

Summary

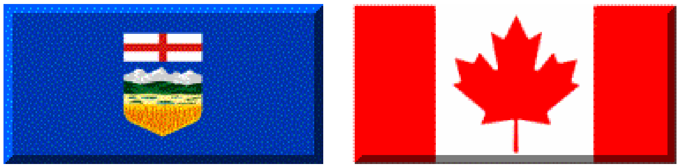

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TABLE OF CONTENTS

Page

Section: (A*) denotes in Appendix A only

1. Assessment of Major Global Fusion Technologies – Summary

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

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

Page

List of Figures:

EXECUTIVE SUMMARY

MOTIVATION: Energy from fusion will be demonstrated by both inertial confinement (ICF) and magnetic confinement (MCF) approaches in the near future. This occurrence will trigger one of histories most significant economic events, heralding the post-carbon economy. Alberta, as a leading energy supplier of carbon fuels, has the chance to anticipate fusion, get engaged in the transition and capitalize on the opportunity to become a leader in this future clean energy with multi-trillion dollar economic impact.

CURRENT STATUS: The accompanying report includes an assessment of the major fusion technologies and how close they are to achieving net energy gain; of how inertial fusion could impact Alberta R&D and help to diversify the economy and; how fusion may be applied for oil sands extraction and processing. Alberta is poised to take a leadership position for advancing fusion energy in Canada and partner worldwide, specifically through inertial fusion energy (IFE) and its advanced technologies.

RECOMMENDATION:

- That Alberta establish an **Alberta Fusion Energy Directorate** and from this base, using our established working relations internationally, develop a plan for our province's engagement in fusion energy and related technologies as part of an economic diversification strategy, with the objective of building the world's first inertial fusion energy (IFE) demo plant jointly with the USA, in Alberta

RATIONALE:

- Fusion offers a long term solution to the world's need for clean energy sources and, as such, is the focus of a large international effort
- Progress in both ICF and MCF development will likely result in fusion energy systems by mid-century or sooner
- Laser inertial fusion energy (LIFE) is favorably positioned to be the next step in inertial fusion energy (IFE) - the world's first fusion market entry plant, potentially within 10-15 years
- Canada is the only developed country without a fusion program but Alberta leadership could change that, leveraging the cumulative international investment
- Alberta has the support of program leaders in the USA, Europe and Asia
- Coupling an R&D program on advanced IFE concepts to the demo unit in collaboration with international partners would catapult Alberta/Canada into a world leading center
- There are numerous attendant benefits (economic, environment, political) and Alberta would benefit significantly from an associated economic diversification strategy in new high growth technology areas
- There is an opportunity to build a comprehensive new business model aligning private, academic and government sectors to develop this energy source and its associated technologies – a high tech industry cluster model similar to Routes des Lasers ^{TM}

BACKGROUND: This report was prepared after extensive consultations in Asia, Europe and USA and with support from Alberta Energy, Stantec, Alberta Council of Technologies and the University of Alberta. The findings were discussed in workshops with Alberta industry and R&D institutions to assess commercial and socio-economic opportunities.

1. ASSESSMENT OF MAJOR GLOBAL FUSION TECHNOLOGIES - SUMMARY

1.1 Major Approaches to Fusion Energy

This section is a brief summary of key points on the status of fusion research and development (R&D) with additional detail in Appendix A for those seeking more in-depth background on fusion R&D. **Note that reference material is provided only in the Appendices.**

In view of the rapid progress in inertial confinement fusion (ICF) development and planning for inertial fusion energy (IFE), primary attention is devoted to controlled fusion based on this approach. At the same time, the continuing advances in magnetic confinement fusion (MCF) and planning for magnetic fusion energy (MFE) based on tokamaks warrant attention as a major international thrust and so are incorporated here. Appendix A also includes a brief discussion of alternative approaches, including private sector involvement.

1.1.1 Introduction

Two conditions must be satisfied for producing energy from fusion:

1) the particle energy (equivalent to temperature) must be sufficient to overcome the natural Coulomb repulsion of the positive charged nuclei – this varies with fusion fuel and is found to be ~10keV (~100,000,000 C) for the easiest one to implement. At such high temperatures, all matter is ionized (the state of matter is called plasma) and so **magnetic** fields can be used as one **confinement** approach (MCF). Another is to initiate and complete fuel burn up in a time shorter than the hot plasma would disassemble under its own pressure, **inertial confinement** (ICF).

2) the required confinement condition for breakeven – where more energy is released than expended in heating and confining the plasma – is given by the Lawson criterion: $\mathbf{n \tau > 2 \times 10^{20}\ m^{-3}\ s}$**;** where n=plasma particle density and τ=energy confinement time. Combining the required plasma temperature T_i~10 keV (~100 million degrees) with the Lawson criterion gives: $n\ \tau\ T_i > 2 \times 10^{21}\ m^{-3}$ s keV or, noting the product of temperature and density is just pressure (p), equivalently $\mathbf{p\ \tau > 10}$ **atm s.**

This criteria permits a large range of possible operating parameters from very low density (close to vacuum) with long confinement times (many seconds or continuous) to extreme density (100's of times normal solid densities) with very short confinement times (picoseconds = 10^{-12} seconds). The former regime is that of standard MCF approaches and the latter for ICF approaches.

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

1.1.2 Fusion Reactions & the Fuel Cycle

The fusion reaction with the lowest threshold temperature for fusion reactions is that involving isotopes of hydrogen, namely tritium (T) and deuterium (D) given by:

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

Where n is a neutron and He is helium, also called an alpha particle in nuclear reactions (Fig. 1.4, Appendix A). The energy released in the reaction is approximately 4 million times greater than that released in burning carbon. **The high energy density is one of the major advantages of fusion as an energy source - much less fuel is required (and inert helium is the waste by product)**. The dramatic contrast with other fuels is highlighted in Fig. 1.5, Appendix A.

The fuel cycle is discussed in more detail in the appendix including breeding of tritium from lithium in the primary cooling loop. 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 a 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. There is a consensus of opinion that such a fuel breeding and extraction cycle is quite feasible to implement.

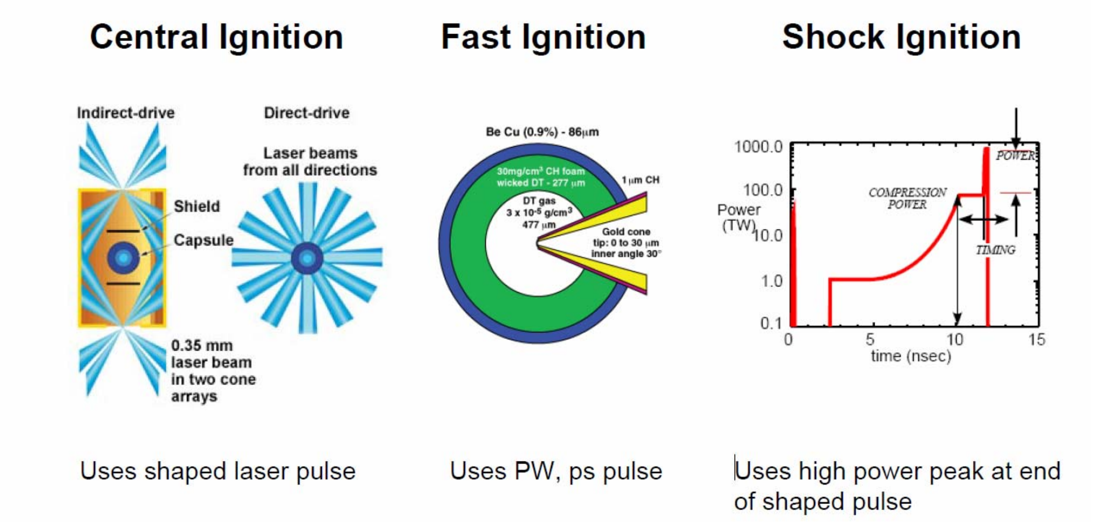
It should be noted that tritium is produced in small quantities in Candu fission reactors and is extracted from the heavy water on a regular basis. Because Canada, the developer of the Candu reactor, is the leader in the world on heavy water reactors we have some of the world leading expertise in the extraction and handling of tritium.

1.1.3 IFE Approaches to Fusion

1.1.3.1 Introduction

The main approach to inertial fusion energy (IFE) pursued to date is based on laser drivers. The choice of laser is determined by requirements of drive laser intensity, laser efficiency and scaling of target parameters such as energy absorption, energy conversion, hydrodynamic efficiency, instabilities, etc. These considerations place a premium on short wavelength lasers. Inertial fusion research is presently based on the use of older flash lamp pumped laser technology that is inefficient and permits only single shot experiments. Practical IFE systems will require laser pulses at repetition rates of ~10/sec. Recent developments in solid state lasers and optical materials offer considerable promise for commercial IFE systems (efficiency, reliability, power handling, footprint size). An alternative laser driver under development is the krypton fluoride (KrF) gas laser with an even shorter wavelength (248 nm).

The basic concept for inertial fusion is discussed in Appendix A and is shown in Fig. 1 for two alternate approaches: (i) indirect drive and; (ii) direct drive. The basic principals of fuel compression, central core ignition and propagating burn generated through self heating by helium produced in fusion reactions are described in the appendix. Advanced concepts of fast ignition and shock ignition, also illustrated, hold the promise of higher gain but are at an early stage of investigation.


Central Ignition

Fast Ignition

Shock Ignition

Uses shaped laser pulse

Uses PW, ps pulse

Uses high power peak at end of shaped pulse

Fig. 1 Basic Concepts of (a) indirect drive and (b) direct drive IFE and advanced techniques of (c) fast ignition and (d) shock ignition

To satisfy the Lawson criteria and ensure an efficient burn through helium self-heating, the compressed fuel mass must have a minimum product of density times radius; the ρR or rho-R product for the assembled fuel must typically exceed ~3 g cm^{-2}. 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}, requiring extreme fuel compression to more than 1000 times normal liquid density of DT (0.2g cm^{-3}).

1.1.3.2 Indirect Drive

The most developed approach to IFE is based on the indirect drive technique 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 (Fig.

2). Operation of the system started in 2009 and NIF scientists are actively pursuing a systematic study of ignition and gain. A similar system, Laser Megajoule (LMJ) is being built near Bordeaux, France and will start ramping up to full scale operation in 2015. Both NIF and LMJ have identified 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.

Fig. 2 NIF 1.8MJ laser system (left) & photos of laser bay (center), target chamber (right)

Typical calculations of expected scaling of gain as a function of laser driver energy are given in Fig. 3 for direct and indirect drive. It can be seen that laser energies of over 2MJ probably will be required for the indirect drive approach to achieve gains of Q = 50 or more.

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 on the largest operating direct drive system in the world which is the 60 beam, 30kJ OMEGA laser facility at the University of Rochester. Beam energy balance on the order of 1% is routinely achieved in this system.

The expected scaling of fusion yield versus driver energy as shown in Fig. 3 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 up to 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 has to be demonstrated and this will require higher laser energy than existing lasers such as OMEGA can deliver.

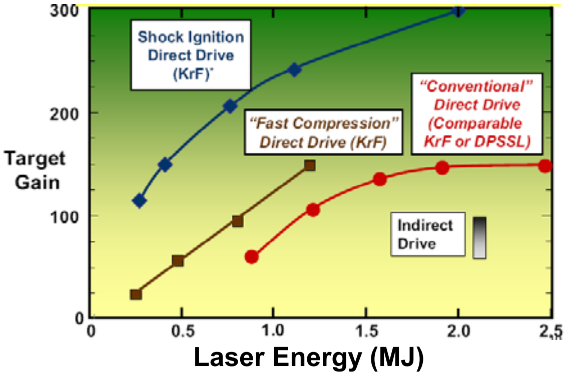


Fig. 3 Scaling of predicted gain versus laser energy for different approaches to laser fusion energy

1.1.3.4 Fast Ignition

One of the more recently developed concepts is the idea of separating fuel compression from fuel ignition (see Appendix A). By utilizing a separate laser pulse for ignition the requirements for fuel compression can be reduced considerably. The first pulse is used to assemble a large high density fuel mass and a second laser pulse is introduced to create a high temperature hot spot to ignite fusion reactions. This is analogous to a spark plug in an internal combustion engine. This reduces energy requirements of the main compression laser considerably (approximately 500kJ to 1 MJ) and also allows for more tolerance in irradiation non-uniformity.

The investigation of fast ignition (FI) is at an early stage but the rewards in terms of smaller scale size reactor systems are quite attractive. As seen in Fig. 4, the scale size of a high yield reactor system with a gain of over 100 has the potential to be less than a megajoule (MJ). 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 could lead to significantly decreased reactor scale size and significantly increased cost efficiency.

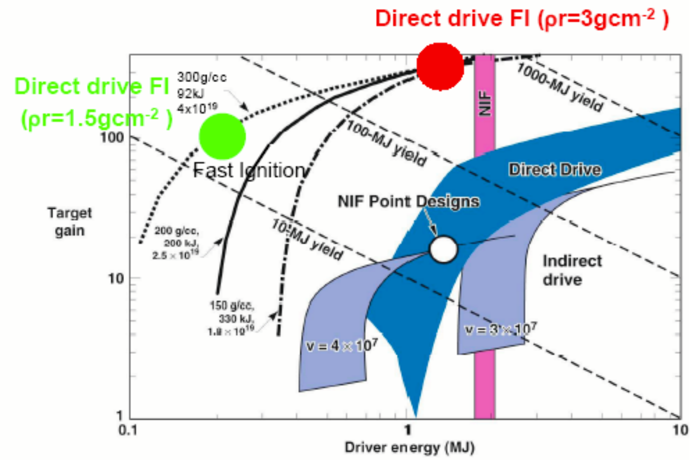


Fig. 4 Scaling of target gain versus laser system energy for fast ignition

1.1.3.5 Shock Ignition

Another advanced approach using a separate laser pulse to create the ignition event is through shock ignition (SI). In this case a higher intensity laser spike is added to the main laser pulse and focussed onto the target. With careful engineering this laser spike can be generated using the same laser amplifiers as the main compression pulse by injecting a seed pulse at the end of the main compression pulse.

Details of shock ignition are discussed in Appendix A. 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. 5. 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, as in fast ignition. Because of its attractive features, shock ignition has become the favoured approach for the proposed HiPER laser fusion demo project in Europe 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.

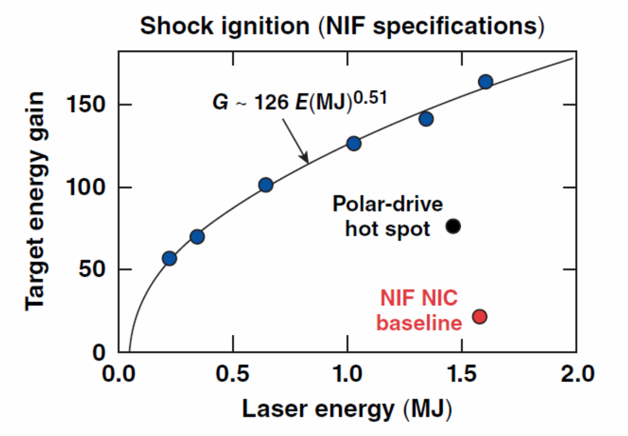


Fig. 5 Shock ignition yield versus laser energy, courtesy of LLE

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 technology as a basis for a detailed power reactor design called **LIFE** (for laser inertial fusion engine). There are a number of other conceptual design studies including the HAPL study in the USA and Koyo and Koyo-FI for fast ignition in Japan. While there are numerous significant issues in the design of complete reactor systems which will challenge existing technology (and move it forward), it appears that there are acceptable near term solutions and potentially much better long term solutions to most of these challenges. Critical design issues for IFE include: materials, optics, laser systems, chamber wall and, target fabrication & delivery.

Technical solutions include: annealing optics, diode pumped solid state lasers, hot swapping of line replaceable units, replaceable grazing incidence optics, chambers with liquid metal wall or ceramic liner tiles or magnetic shielding or few year replacement cycle, choice of materials, microelectronics fabrication techniques.

LLNL has expended considerable effort in completing an initial comprehensive analysis of all steps required to build an operational reactor system based on the indirect drive approach and has 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 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.

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 one particular part of the physics at a time.

For laser fusion modeling there are three levels of codes predominantly in use. The first level are hydrodynamic codes tracking the energy absorption, implosion dynamics, fusion reactions and fusion burn. The second level 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. The third level - so called kinetic codes - are 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.

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 can be carried out yearly. It is expected that full 3D runs will become more commonplace as the power and availability of supercomputers increases.

1.1.4 MFE Approaches to Fusion

1.1.4.1 Introduction

All MFE approaches 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 large mechanical forces requiring significant reinforcement of the large reactor vessel structures. 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, β. 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 β as large as possible, thereby reducing the size and cost of the magnetic field coils and the overall reactor system. In addition, clean non-ablating materials are required to withstand the high energy plasma bombardment from the reactor (inner liner and diverter plates for collecting escaping plasma).

A variety of magnetic configurations (Appendix A) have been investigated; many have been abandoned and outside of the mainline tokamak approach, the stellerator and spherical tokamak (ST) concepts remain as two that are actively pursued in countries such as Germany, Japan, UK and USA. One advantage of ST systems is that they are inherently more stable against plasma instabilities and can operate at much higher beta values of up to $\beta = 30\%$ and thus could be smaller than equivalent tokamaks. However, they are much less developed and all the operational issues of scaling to full size reactor systems are not yet well established. The virtue of the stellerator 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. It is expected that operating stellerators 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.

1.1.4.2 Tokamaks

The tokamak is a Russian invention of the 1950's that has proved to be the most successful magnetic confinement device to date; its success is due to having both large toroidal and poloidal magnetic fields to force particle orbits that, analogous to stellerators, cancel out drifts in simple toroidal geometry. The tokamak, described more fully in Appendix A, has received the most research investment to date and is closest to demonstrating net power production for magnetic approaches.

The confinement of the plasma (orange ring) is illustrated in Fig. 6. Key features include: main toroidal magnetic field coils (in green) that will have to be superconducting to minimize electrical costs and excess heat generation; poloidal coils to help adjust the plasma height and position (top, middle and bottom of the machine); transformer winding (beige) in the middle of the device to induce a toroidal current around the ring to produce additional magnetic field for confinement.

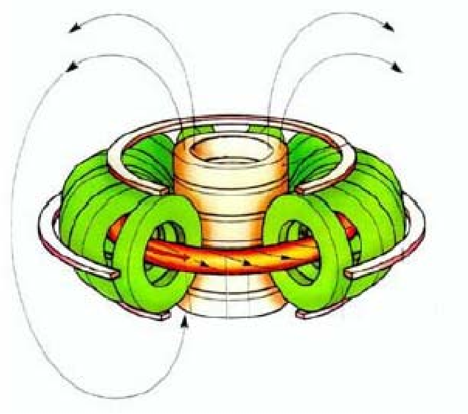


Fig. 6 Tokamak concept

Following the transformer initiated toroidal current, auxiliary techniques to both heat and drive current through the plasma - high energy particle injection and directional radio frequency (RF) heating - are required. Operational tokamaks will require 50 to 100 MW of continuous heating power by high power RF and particle injection.

To minimize radiation cooling of the plasma to below Lawson threshold conditions required for net energy gain, contaminant species such as carbon and metal ions from the chamber wall have to be controlled from entering the hot plasma. This requires an outer plasma scrape off layer which is diverted to intersect special plates. 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 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 use pressurized gas guns or perhaps an alternative scheme of fueling with compact toroid plasma balls which are formed in a plasma gun and accelerated via electromagnetic forces into the main reactor volume.

Tokamaks can operate in different plasma stability regimes. The so-called H-mode regime allows operation at relatively high value of beta, ~10%. In this mode, there is a continuous pulsation of plasma out to the walls and then a relaxation inwards called edge localized modes (ELM). These oscillations have to be controlled to prevent escaping plasma overloading and damaging the diverter plates or walls.

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 to one spot - like a lightning strike. This can cause the spot to melt and potentially puncture the vacuum vessel wall necessitating a lengthy and expensive repair. Plasma monitoring systems can detect such disruptions at an early stage; to mitigate damage, the current solution is to inject a large block of frozen gas such as neon which very rapidly vaporizes and quenches the plasma. Such techniques are an operational feature on current research tokamaks 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 x 10^{20} particles/m^3 but not both conditions at the same time. Also, energy confinement time has reached several seconds but is still less than required for power reactor systems. The best result obtained to date, in the Joint European Tokamak (JET) project, has been a power output from fusion burn of 16 MW for a period of approximately 0.6 seconds, obtained under conditions of heating the plasma with a power of 24 MW. Robotic control has been implemented for accessing and maintaining the facility.

ITER is a 35 nation tokamak scaling experiment underway in France - designed to produce a fusion output power of 500MW by 2028. Sketches of JET and ITER facilities are shown in Fig. 7.

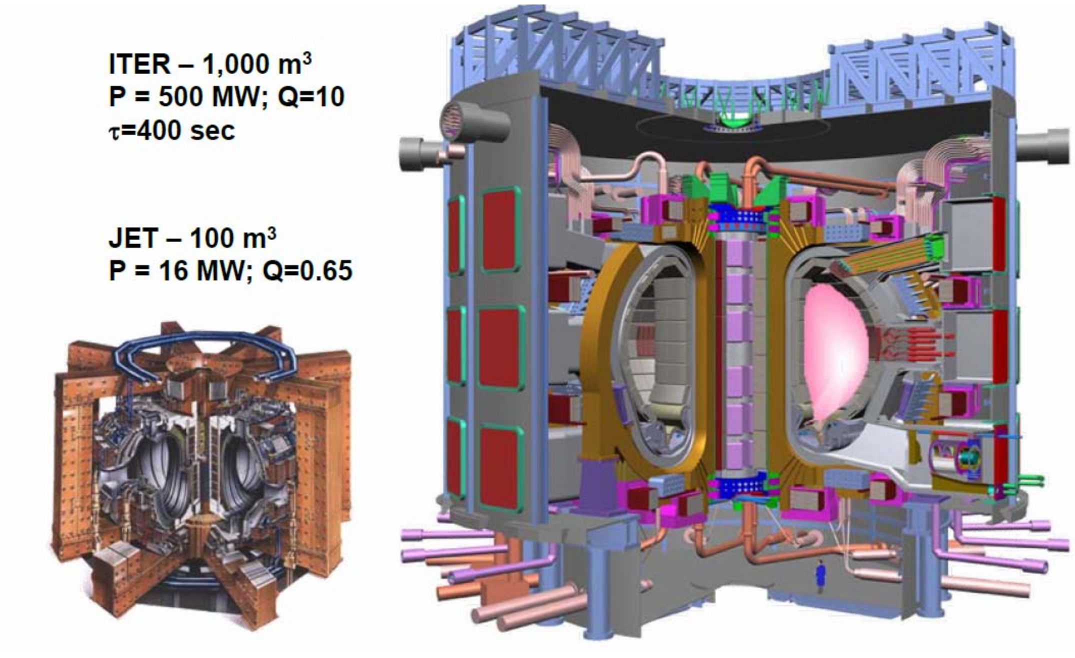


Fig. 7 JET tokamak and ITER tokamak facilities

1.2 Alternative Approaches to Fusion Confinement or Fusion Applications

This material is presented in Appendix A.

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 are provided in the appendix regarding other national activities in fusion development and more detailed notes and summaries are to be found in site visit reports in the appendices.

Insofar as ITER is the culmination of the MFE approach after 60+ years of both independent and collaborative research in the international community, 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 directly 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 talented and dedicated group of people plus major program funding, resulting in rapid progress in IFE development - a significant benefit for all.

1.3.2 Progress & Status of Indirect Drive IFE

The National Ignition Facility (NIF), shown previously in Fig. 2, 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 technology capability for success in IFE. The next generation of diode pumped solid state lasers will benefit from and improve on this standard, particularly in efficiency, reliability and repetition rate capability.

The hohlraum-target for indirect drive IFE is illustrated in Fig. 1 (see Fig. 1.11, Appendix A for more detail). 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**); temperature 6keV (**10**). These values, however, have been obtained in separate experiments, not all simultaneously. The product, pτ, is still too small for full target ignition by a factor of approximately 2.

Significantly, core ignition has been successfully demonstrated, i.e., fusion energy output from the core clearly showing alpha (He) particle heating. This is a critical first step as shown in Fig. 8, 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 (He) energy deposition in the outer layers.

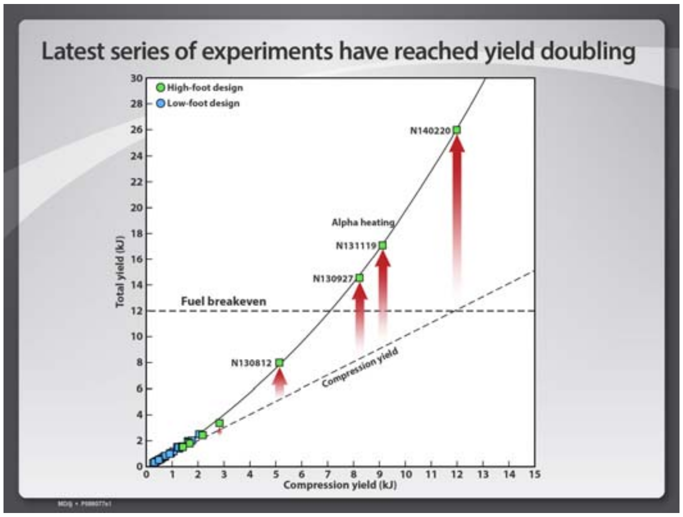
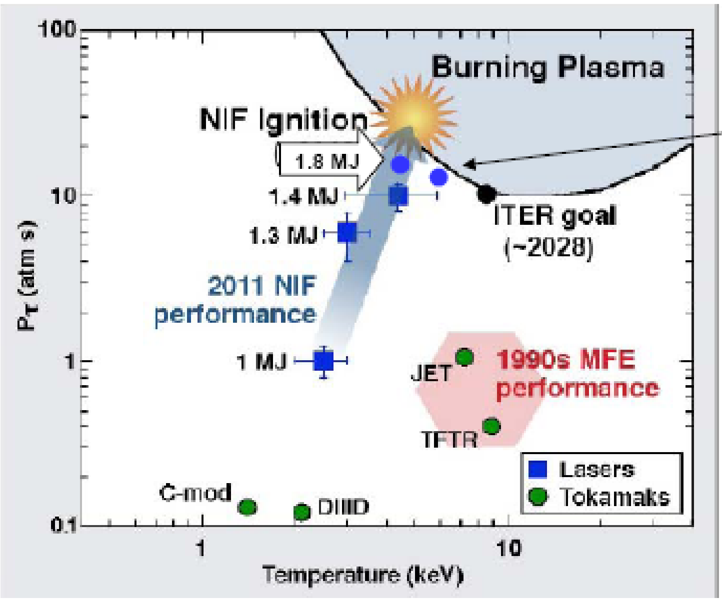


Fig. 8 LLNL data confirming core ignition (alpha particle

Principal issues in these initial experiments include low order asymmetry and fuel mixing in the implosion. Given the complexity of such a first ever system (multiple driver laser beams, hohlraum conversion to x-rays, target irradiation uniformity and absorption, hydrodynamics, fuel mixing, etc.), surprises are to be expected. A systematic experimental plan is in progress to explore and optimize parameter space - targets (materials, coatings, dimensions, etc.), hohlraum (shape, coatings, dimensions) and laser temporal profile.

Nonetheless, remarkable progress has been achieved. The current status of inertial fusion research is summarized in Fig. 9, highlighting NIF 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 approximately two of that required for complete pellet ignition.

It should be noted that, since inertial fusion ignition is a threshold event, the energy gain increases nonlinearly with drive; based on current results, ignition and burn could be achieved by increasing target size and drive energy which would require a slightly higher energy laser system than the present NIF facility. Current optimization experiments are focused on bringing the threshold ignition energy down below the 1.8 MJ level which can be generated in the current NIF laser system.



Recent results

Fig. 9 Progress in heating and confinement for IFE (and MFE)

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 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 and diode pumped solid state driver lasers.

LLNL makes a strong case for “this or nothing in the next 10 years”. The argument is made that the direct drive approach, advanced ignition approaches and the KrF laser driver are far less advanced than the indirect drive approach and solid-state lasers.

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 1.6GWe-925MWe.

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 laser 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 cost of electricity (COE) from $75/MWh to $50/MWh by the 10th of kind plant (initial plant cost ~$5B).

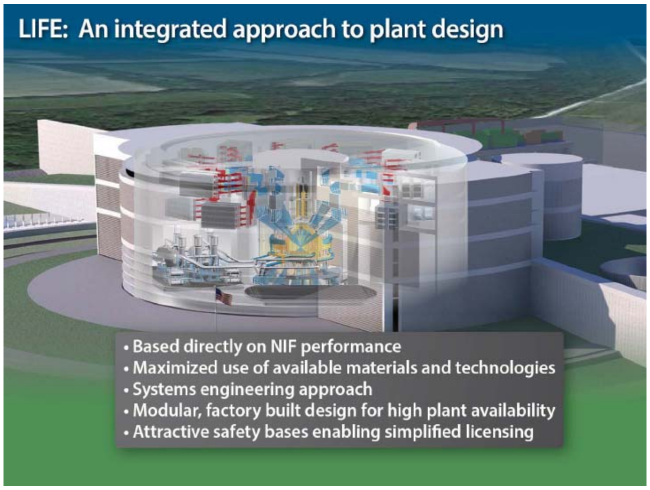
An artist rendition of a LIFE power plant is shown in Fig. 10 and additional detail enabling early deployment illustrated in Fig. 11.

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

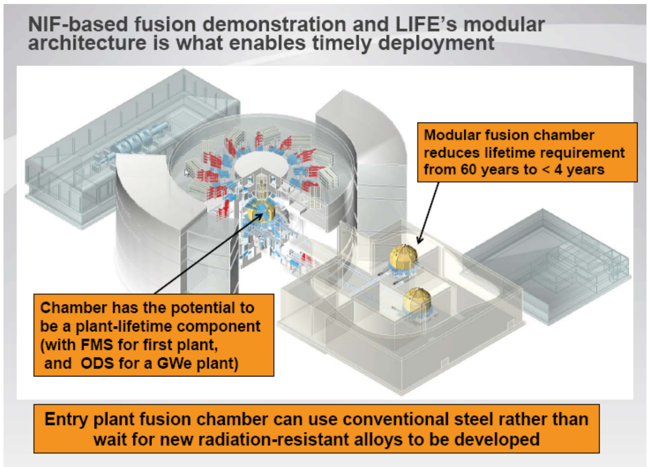
As for timing of a LIFE plant, the result of a detailed engineering design and risk analysis of a demonstration unit suggests ~10 years following NIF ignition experiments. **This short time span represents a major shift in prospects for commercial fusion.**

A key feature of fusion energy systems is the small amount of fuel required and acceptable cost. Additional discussion is provided in section 3 and the LLNL report referenced therein.


LIFE: An integrated approach to plant design

- Based directly on NIF performance
- Maximized use of available materials and technologies
- Systems engineering approach
- Modular, factory built design for high plant availability
- Attractive safety bases enabling simplified licensing

Fig. 10 Conceptual LIFE power plant


NIF-based fusion demonstration and LIFE's modular architecture is what enables timely deployment

Modular fusion chamber reduces lifetime requirement from 60 years to < 4 years

Chamber has the potential to be a plant-lifetime component (with FMS for first plant, and ODS for a GWe plant)

Entry plant fusion chamber can use conventional steel rather than wait for new radiation-resistant alloys to be developed

Fig. 11 Modular design of LIFE power plant

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 zoom focusing plus fast ignition or shock ignition for higher gain.

Key technical concepts for direct drive that have been proposed and/or experimentally verified by LLE, ILE and NRL include: effective laser beam smoothing techniques, polar direct drive (PDD), fast ignition, shock ignition and KrF gas laser technology. Progress in such direct drive techniques could carry over to enhance gain of indirectly driven targets. For example, LLE has suggested 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. Likewise, a demonstration of scaling KrF lasers to multi-kJ, rep-rated systems could have a major impact on the implementation of high gain, direct drive IFE. ILE is embarked on a key demonstration project that, if successful, will influence the future of fast ignition as a viable approach to commercial IFE.

A fusion demo plant, LIFT, has been designed by ILE as a phased progression over a twenty year time frame to demonstrate key capabilities of a fast ignition fusion 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 simulation and experiment (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. 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 primarily a function of scaling to large toroidal 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.

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.

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 continuous operation. Given the concerns of ELMs that could dump a large amount of energy and damage the walls as well as disruptions resulting in runaway electrons that could lead to beam-like damage of walls, ITER incorporates sensors and 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 will provide an important test bed for materials as well as heating and fueling of large tokamaks. 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 (that also provides fueling) and electromagnetic waves (for electron and 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.

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 DT for fusion power demonstration in late 2027 or early 2028.

Fig. 12 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.

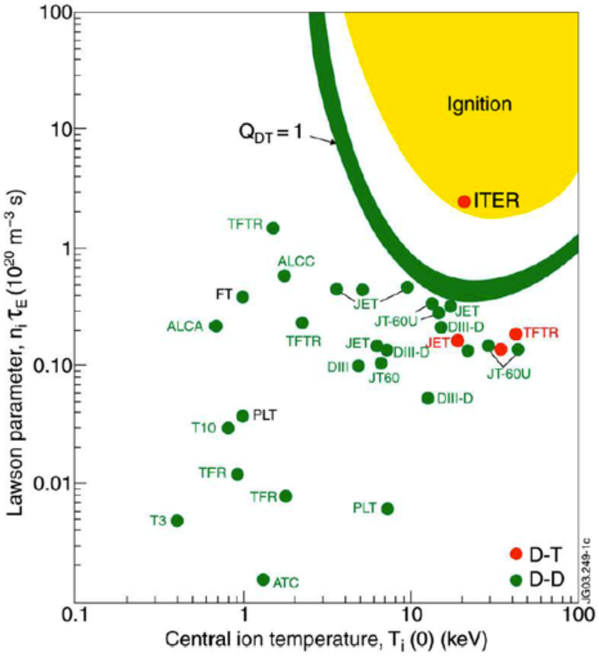


Fig. 1.12 Progress in heating and confinement for MFE (tokamaks)

1.4 Safety and Regulatory Issues for Fusion

A more complete discussion is presented in Appendix A. The key takeaways: fusion offers intrinsic safety, no long lived radioactive waste products, no possibility of reactor runaway, in addition to inexhaustible fuel supply and no green house gas emissions.

1.5 Summary Comments

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**

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

2.0 Fusion as an Overarching Driver of Technologies

Fusion energy will act as driver for technology development which will have a spill over effect into most other industrial and resource sectors. Key requirements are for high efficiency laser drivers; high damage threshold optics; precision target fabrication, injection and tracking; tritium fuel handling; advanced materials resistant to plasma ablation and neutron damage and; advanced 3D simulation and modeling capabilities for all scientific and engineering aspects (from basic physics to modeling fusion energy systems).

2.0.1 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 just as microelectronics was in the past century. The use of light and all its various applications has already penetrated all business sectors (manufacturing, communications, defence, energy, health) from precision laser welding in many different industries to fiber optics communications. As shown in Fig. 2.1, the overall worldwide photonics industry 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.

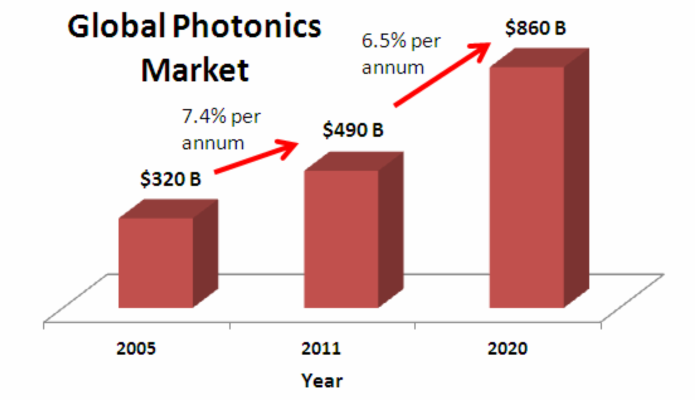


Fig. 13 Growth in World Photonics Industry (from Appendix B at 1.4 US$ per Euro)

Laser fusion has been one of the major drivers in the development of very high energy, high power laser systems in particular and optical technology in general. 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 to develop the technology and manufacturing plants for such systems. By mid century, envisaging 100 initial reactors being built, this already exceeds a $100B 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. Note that the growth predicted in Fig. 2.1 does not include this additional demand.

The most expensive component will be the diode pump lasers. One fusion reactor will create a demand greater than 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 expanded investment in R&D activity and the development of new automated manufacturing and packaging techniques could become an important player in this market. Other opportunities exist in the manufacturing of thousands of optical components, lenses, mirrors, and windows, which require 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. Many of these techniques are similar to techniques already used in microfabrication and inspection systems such as at the Nanofab and Surface Science Centers in Alberta.

Another key component in the laser system is the ceramic or glass laser media itself which converts the diode pump laser energy into the shaped short pulse required to implode the fuel capsule. Alberta with strengths in materials, nanomaterials and chemical technologies could become a leader in the new area of ceramic laser materials by investing in an intensive R&D campaign.

All of these photonics technologies can be exploited in many other areas of laser manufacturing, processing and sensor systems. One technology area that has already been identified for 100J to 1000J per pulse lasers is in laser shock hardening of metal surfaces. 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, high-energy short pulse lasers it would become possible to treat very large parts to a significant depths such as the extraction buckets for oil sands industry extending part lifetimes by factors of 2 to 3 times. 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 participate in one of the fastest growing technology sectors this century.

2.0.2 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. 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. Alberta has world expertise in MEMS-, microfluidic-, and nano-fabrication techniques and could easily develop the required technologies to be a world leader in this area. Canada also has world leading expertise in the handling of tritium which would be required in filling the fuel capsules. State of the art sensing, tracking, high speed computing and control systems will also be required to inject these targets at 10 to 20 times per second with 500 micron accuracy into the reactor vessel.

2.0.3 Other Opportunities

Alberta companies have world leading expertise in the construction of multi billion dollar mega-projects and associated technologies. Many aspects of a fusion reactor system can build on these areas of expertise. In particular, opportunities exist in:

- Civil infrastructure and large project engineering
- Reactor chamber fabrication, maintenance and replacement
- Robotic maintenance systems
- Materials engineering for extreme operating environments
- High power computing & systems modeling

2.1 Link to Existing Provincial Initiatives

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.

The predicted installed base of the order of 35,000 plants of 1GWe (Fig. 1) with a 50 year lifetime and replacement rate of 700 per year would represents a replacement market of $3.5 trillion per year and an ongoing maintenance and operation cost market of about the same per year. As an early mover in the field, Alberta could expect to capture on the order of 5% of the world market (as Canada did with CANDU fission reactors in the past) which would represent $175B of sales a year plus probably an equal amount in ongoing maintenance and refurbishing contracts per year.

2.1.1 Nanotechnology

Nanotechnology, MEMS and packaging will play a major role in the following areas:

- Automated fabrication of targets (~$73M targets required per year per reactor)
- Automated fabrication of laser pump diodes (~$1B pump diodes per reactor)
- Fabrication of ceramic laser materials (~$100M per reactor)
- Reactor vessel fabrication (~$100M per reactor vessel liner)
- Micro and nano scale materials testing
- Advanced optical and x-ray characterizaton techniques for inspection,

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 Alberta Centre for Advanced MNT Products, the Universities of Alberta and Calgary.

2.1.2 Materials Technology

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

- Advanced target capsule designs
- High purity materials for damage resistant optical components
- Erosion resistant inner wall of the reactor vessels
- Neutron damage resistant reactor materials
- Nanotesting of materials in high stress and high radiation environments
- Low tritium diffusion rate barrier materials
- Tritium reprocessing technologies

While Alberta does not have groups working directly on these areas it has considerable strength in materials metallurgy and technologies in. Current expertise exists at NINT, the University of Alberta and University of Calgary, and Alberta Innovates Technology Futures facilities, and in various industrial R&D laboratories.

2.1.3 Large Scale Computing & Information Technology

Complex reactor systems will require very extensive large scale computing modeling, sensor and monitoring systems. 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 and 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 (now EMC). The province and Canada also have a large computing infrastructure available for such high power computing in the Westgrid and Compute Canada computer networks.

Alberta already has extensive information gathering and analysis expertise in process engineering 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. Alberta's data analytics and associated sensor technologies are also rapidly growing as a commercial extension of computing science and business programs at the various universities. This is an area where considerable growth is possible.

2.1.4 Large Project Management

Such complex reactor systems will require experienced large project management teams and large engineering companies in Alberta such as Stantec and PCL, both very experienced in project engineering, could take the lead in such projects.

2.2 Expected Benefits & Economic Impact

2.2.1 The Market

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. In the report “The Economic Impacts of LIFE” by Oxford Economics, it is predicted that a market entry plant (MEP) would take 2-years for pre-construction engineering and 6-years to build, including procurement and commissioning. Assuming a doubling time of 5-years (in line with initial growth rates for fission reactors) 136 plants could be built in 35 years.

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. The North American market could have 127 operating plants by 2054 with 508 plants world wide. To benefit from 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

According to the Oxford Economics Study 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. The development of a commercial scale – gigawatt class – MEP will result in additional R&D spending of $593 million per annum. 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 creation of 2,690 jobs ($1.8 billion of labour income) during 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. 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.

A successful model to catalyze this growth already exists: Routes des Lasers TM (Fig. 2.2) which is a high tech industry cluster engaging private, academic and government sectors to diversify the economy and bootstrap a new photonics industry in Bordeaux based on the Laser MegaJoule project.

Other examples of private sector companies engaged in fusion R&D include: 1) Hamamatsu Corporation, a Japanese photonics company and 2) General Atomics in California, a major supplier of fuel pellets and specialized technology to industry.

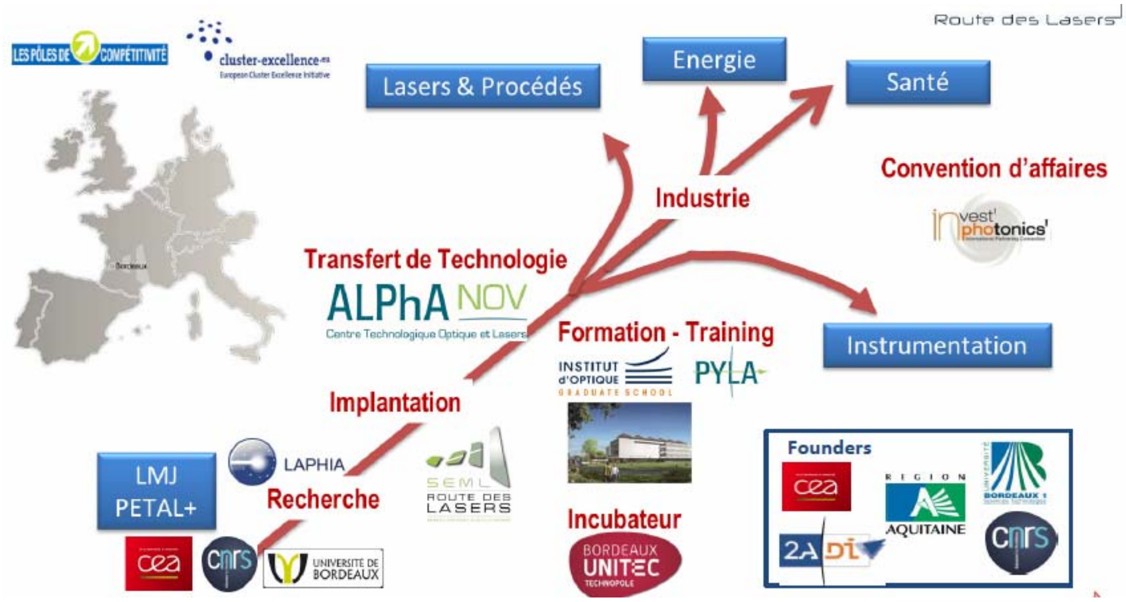


Fig. 14 Commercialization model of Routes des Lasers around the LMJ project

2.2.3 Anticipated Benefits

By deciding to invest in the commercialization of fusion, 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 N. 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

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, cost competitive alternative

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

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 highly qualified personnel (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

2.2.4 Assessing the Opportunities

In order to compare the merit of different energy strategies, a range of scenarios can be assessed for transitioning towards a low carbon economy ranging from Status Quo to full investment in a Market Entry Plant (MEP). Given the unique window of opportunity at the moment, the option with the highest positive impact by far would be hosting the Marker Entry Plant. As outlined in the Oxford Economic Study of the impact of a LIFE reactor project there would be billions of dollars of immediate benefit followed by tens and eventually hundreds of billions of dollars of future business activity by being a leading player in the field together with 100’000’s of highly skilled jobs.

2.3 Summary Comments

By hosting the MEP after ignition, Alberta would leapfrog to the front of the fusion industry thereby leveraging billions of dollars of past worldwide R&D investment and become a global focal point for something other than the oil sands. Alberta is an ideal location to build the market entry plant jointly with the USA and, as an energy province, has the experience to build and operate large energy projects and supporting infrastructure. Such an investment will pay handsome dividends in diversifying the economy and tapping into the most rapidly growing technology sectors in this century. An investment in fusion energy NOW complements other initiatives intended to bridge the transition to a knowledge economy by advancing the commercialization of emerging technologies. Such an investment capitalizes on Canada's international relationships, Alberta's rich research and applied research infrastructure and addresses environmental challenges to reduce the oil sands carbon footprint.

3. FUSION ENERGY (HEAT & ELECTRICITY APPLICATIONS)

3.0 Alberta Energy Context

Alberta is a large consumer as well as producer of energy. This is attributable to the strong economy and the nature of energy use, particularly electrical, for industrial, commercial, oilsands and residential consumption. Electrical power demand (generation) now amounts to ~11GWe (~14GWe) and is projected to grow to ~16GWe (~20GWe) in the next decade, tapering off thereafter. This is not too surprising, given that oilsands production appears likely to double in the same period, inferring related activity will increase substantially.

In addition to electrical energy, heat demand is significant for all components of the economy and particularly for the growing needs of the oilsands for extraction and processing. Energy consumption for the SAGD process varies from 0.1 to 0.25 MJ per MJ of bitumen and refining of heavy oil can add another input of 0.1MJ per MJ of product. The heat needs of the oilsands are currently met primarily by burning natural gas. This is accompanied by significant GHG emissions.

As the world transitions from fossil to renewable and nuclear fuels by mid-century or sooner, Alberta could choose to build a future in fusion energy that, in turn, would serve world markets in fusion energy systems and, at home, supply the heat and electricity needs for extracting and processing the carbon rich oilsand deposits for value added products.

3.1 LLNL Report of Findings for Potential Application to Electricity & Oilsands

Since a more complete report is available, only a short summary will be provided here. The full report prepared by Lawrence Livermore National Laboratory, titled “Laser Inertial Fusion Energy for Oilsands and Electric Power Production”, can be accessed through Alberta Innovates Technology Futures.

http://www.albertatechfutures.ca/NewsRoom/PublicationsReports/FusionEnergyReport.aspx

Apart from the virtues of fusion as a sustainable, environmentally acceptable energy source, there are additional features of note for oilsands applications. It offers the possibility of transmitting high temperature heat over long distances from a central plant. Moreover, it can be operated in a co-generation mode to supply steam at the required quantities and pressures as well as electricity at the several hundred MWe level. In addition, because fusion is a “threshold” effect, there are strong economies of scale for larger plants, therefore able to provide power at low breakeven prices. Indeed, it may be possible to recover capital costs of the plant through electricity sales alone, while producing steam for oilsands recovery.

Since coal fired plants in the US are being phased out by ~2060, LIFE was historically designed - as a principal mission - for electric power generation at the GWe level to integrate with baseload requirements for established power grids. A noteworthy feature is that a LIFE plant has the flexibility for load following since power can be increased or decreased on the time scale of hours.

A detailed delivery plan for a LIFE power plant has been developed in conjunction with Parsons Engineering and a large number of vendors. A first market entry plant is estimated to take 10 years for delivery and a mature plant 4 years for delivery.

Specific plant configurations, together with a thermal and economic assessment, are presented in the report to meet requested Alberta applications of LIFE to electric power generation, steam assisted gravity drainage (SAGD), mining operations and integrated operations. The report shows that LIFE can support all scenarios.

Technical details of the LIFE power plant are summarized in the report, including: operating parameters; fuel manufacturing, injection, tracking, engagement; chamber materials; heat transfer and; tritium fuel cycle. Operational, safety and environmental characteristics are addressed with regard to risk and waste management.

The option of supplying stand-alone electrical power for Alberta at the GWe level was analyzed for a system based on a primary lithium loop (carrying the fusion heat), secondary molten salt loop to provide radiological and chemical isolation from the primary loop and tertiary water loop for superheated steam generation (high temperature Rankine cycle). Multiple turbines, steam reheater loops and feedwater preheating stages are incorporated to maximize overall thermal efficiency.

For in-situ (SAGD) operations supporting multiple sites of 30,000 barrels per day, LIFE can deliver the required steam for long distance transport. In this case, thermal energy from the molten salt loop is used to generate superheated steam at high temperature and pressure and, eventually electricity and process steam in a Rankine cycle. A detailed schematic of the “process steam loop” is described to accomplish this objective. Similar descriptions are included for the mining only operation, integrated mining and steam only options. The steam only option can be accomplished at less capital cost (but higher cost per unit of steam) because expensive Rankine cycle components for electricity generation are not required.

The regulatory assessment of a LIFE plant is discussed, contrasting the US and Canadian situations. While there are similarities, there are also significant differences. The Canadian Nuclear Safety Commission regulations would appear to have some advantages since CNSC regulations already include: (i) language specific to commercial fusion facilities, (ii) tritium hazards since it is generated in CANDU reactors and, (iii) the Canadian nuclear licensing process is simpler and shorter.

Capital and operating cost estimates are presented for each option using LLNL's Integrated Process Model (IPM). From the specified operating characteristics, the IPM calculates plant performance, structures and components, generating a bill of materials and associated costs. Resulting cash flow streams and plant costs are iterated to achieve desired cost of electricity (COE) or performance.

In the absence of a specific site location, the study incorporated cost adjustment factors from the 2006 Alberta Bitumen Processing Integration Study to compare the Alberta site with a US based site (Houston). Capital costs were scaled from the Parsons Engineering reference plant and other costs, including labour, from relevant data sources. Annual operating costs, including plant organizational structure, were taken from an operations evaluation by Parsons Engineering and LLNL.

The various scenarios were analyzed using a reference electrical output of 1GWe, reflecting Alberta grid constraints. For co-generation cases, the thermal output was increased to generate the required steam for oilsands operations.

Results are presented for the various scenarios, ranging from LCOE of $67/MWHr for the all-electric option, to variable prices for steam depending on particulars of the option. The co-generation option, with electricity sold at the LCOE price, provides the lowest steam unit costs slightly larger than $2.00 per 1,000 lbs.

3.2 Summary Comments

While inertial fusion is potentially an attractive energy source for Alberta requirements in electricity and heat, it is not immediately available. Under a scenario of 10-15 years for a demonstration plant, however, and the world aggressively pursuing fusion thereafter, IFE offers a very attractive way forward in meeting Alberta needs related to extracting and processing oilsands (for upgraded carbon applications) for the long term plus providing engineering and commercial services to international markets for heat/electricity/hydrogen /desalination based on fusion energy systems.

4. ALBERTA FUSION STRATEGY AND IMPLEMENTATION

4.0 Motivation

Progress in ICF (IFE) and MCF (MFE) development will lead to application of this technology by mid-century or sooner. Since fusion offers a sustainable solution to the world's need for clean energy sources, it will become a dominant source for baseload energy eventually. This will, in turn, transform stationary and mobile transport using electric batteries and fuel cells with fusion as a primary energy source.

The largest MCF project is ITER, located in Cadarache, France, funded by 35 nations representing more than half the world's population. Its scientific goal, by 2028, is to demonstrate a fusion output power of 500MW, ten times the input power used to heat and sustain the fuel. This facility will be followed by a full scale power plant, DEMO, generating electricity for the grid by the 2040s.

The largest ICF project is NIF, located in Livermore, California, funded by DOE. Its goal is to demonstrate fuel ignition using lasers in support of the NNSA mission at LLNL. Anticipating future civilian energy applications, a power plant called LIFE has been designed by LLNL and a new Center for Fusion Energy Science and Applications established at the University of California Berkeley to interface with public utilities and other organizations. As with ITER and DEMO, LIFE is favorably positioned to be the next step in IFE after ignition - planning for the world's first fusion demonstration plant, potentially within 10-15 years.

Alberta has the option of standing aside or joining the large international effort to harness fusion. While the timing is subject to uncertainty (>10 years) and the investment is substantial, fusion energy will have a multi-trillion dollar economic impact in this century. For an energy province, such a scenario should receive serious consideration.

Enroute to the energy payoff with attendant benefits (economic, environment, geopolitical), Alberta will gain from capacity building in associated high technology areas as part of an economic diversification strategy. There is an opportunity to build a comprehensive new business model aligning industry, education and R&D institutions with this future energy vision and its associated technologies. Such a model, "Routes des Lasers", is being established in conjunction with the ICF project in France.

The potential for value added spinoffs associated with laser fusion energy systems is very high and offers an overarching driver for economic diversification in Alberta. As a strategic priority, fusion would nicely complement and considerably amplify current efforts to build strength in energy, nanotechnology, computer modeling and systems engineering, as well as launch lasers and photonics as a new high-tech sector - a compelling combination of sustainable energy/environment/ economy components providing long-term economic growth in myriad technologies.

Canada is the only developed country without a fusion program but, with Alberta leadership, we have the chance to change that. The challenge is to build a development capability and get industry involved in fusion energy system technologies. This requires government leadership since the time scale is greater than 10 years; presently, all major international programs are government funded. The objective should be to become a world player in fusion energy in 5 years, and a world leader in 10.

The Alberta initiative has support from the leaders of programs in the USA, Europe and Japan and invitations to collaborate on fusion development. In particular, our link with LLNL through the newly formed Center for Fusion Energy Science and Applications (CFESA) at the University of California Berkeley, opens the door to building the first IFE demo plant in Alberta. This would provide a strong focus for commercialization and economic diversification. Moreover, coupling an R&D program on advanced IFE to the demo unit would catapult Alberta/Canada into a world leading center.

The Alberta Council of Technologies and its advisory, the Alberta/Canada Fusion Energy Program, recommends that this province embrace such a vision. A way to proceed is briefly outlined below; detailed planning and negotiations would follow a mandate to proceed.

4.1 Proposed Implementation

Note that an announcement of fuel ignition/burn demonstration will galvanize countries worldwide to capitalize on fusion energy. This implies a limited window of opportunity to pre-position Alberta. Discussions would proceed through the Center for Fusion Energy Science and Applications (CFESA) that has been established to separate the inertial fusion energy civilian goals from the NNSA security mission at Lawrence Livermore National Laboratory.

The first step:

- seed funding for a start up phase to initiate an IFE program in Alberta and engage in discussions with: 1) CFESA and other US organizations regarding prospects for a joint LIFE demo and; 2) international organizations regarding collaboration on advanced concepts such as HiPER

It is proposed that Alberta establish an **Alberta Fusion Energy Directorate** (AFED) and from this base, using our established working relations internationally, develop a plan for our province's engagement in fusion energy and related technologies. In a 3 year ramp up, AFED would accomplish or develop: 1) Alberta as a recognized center for fusion technology development and coordination in Canada (and internationally); 2) a core group of highly qualified personnel (HQP) with fusion technology expertise (obtained through postings of staff to international labs); 3) comprehensive working relations with international centers and local industry; 4) an Alberta base for myriad technologies and applications in addition to fusion energy; 5) plans for a national fusion energy program (with Alberta as a coordinating center) that would include a program of public education; 6) plans for the possibility of a first generation IFE heat/power demonstration plant jointly with the USA and; 7) collaborations with international partners on advanced concepts such as HiPER.

Importantly, implementation of a provincial fusion energy policy could be incorporated eventually in the National Energy Strategy. Planning would leverage international R&D links, capitalize on Canada's industrial capacity and forge provincial and national links. The opportunity for a prototype demonstration heat/power plant (joint with the USA) in Alberta as the underpinning of an integrated fusion strategy should be evaluated and, if promising, terms negotiated with the USA for proceeding. A business development strategy would accompany this phase.

This ramp up phase would require a non-profit organization to be established with appropriate personnel for scientific management, planning, government liaison, business development and administrative management and a board of directors representing government, industry and R&D institutions.

The budget for the ramp up phase would be determined by the number of tasks to be accomplished and resources required for each. With Step 1 implemented, funding from other existing sources could be leveraged, both provincial and federal.

The advent of fusion energy will trigger one of histories most significant economic events, heralding the post-carbon economy. Alberta has the chance to anticipate fusion, get engaged in the transition and capitalize on the opportunity. This is a rare opportunity for leadership.