FUSION 2030

ROADMAP FOR CANADA

Alberta/Canada
Fusion Technology Alliance

UNIVERSITY OF ALBERTA

UNIVERSITY OF SASKATCHEWAN

CANADIAN NUCLEAR SOCIETY
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generalfusion

Executive Summary

Climate change, clean technology and innovation are now identified in provincial and federal agendas as major issues facing Canada's (and the world's) future. The central questions are threefold: 1) how do we satisfy the large future energy requirements of the developed and especially developing countries; 2) how do we do this in a sustainable, environmentally acceptable way and; 3) how do we ensure suitable economic opportunity for our children, grandchildren and future generations in an energy dependent society? Associated issues include: how does this fit into the international scene and, where does Canada want to position itself in this new energy future?

We are aware that the fossil fuel era will be short-lived (centuries, not millennia) due to both supply and environmental constraints. There are long-term energy solutions that do not depend on carbon fuels:

- fission (sustainable with fuel breeding - but has radioactive waste to manage);
- intermittent renewables such as wind and solar (sustainable - but constrained in application due to factors such as availability and variability);
- steady renewables such as hydro and geothermal (sustainable, but limited growth potential and/or geographic constraints);
- fusion (sustainable - and environmentally acceptable).

Fusion is the energy source that powers the sun and all stars. Apart from having the highest energy density of any source, fusion has the best energy payback ratio (EPR) and carbon life cycle footprint of any source (including solar, wind and fission).

Fusion, as a primary energy source is particularly suited for industrial scale heat, electricity and hydrogen production. Fusion will be especially important for generating electricity - comprising an increasing proportion of energy used to support a growing demand in mobile and stationary applications (think of mid-century autos running exclusively on electricity or hydrogen fuel cells).

Moreover, the small fuel requirements of a fusion power plant ensure the smallest environmental footprint (and the "exhaust" is helium – a safe and inert gas). Indeed, the fusion fuel needed for one full year's operation of a 1,000 Megawatt electrical power station, comparable to BC Hydro's Site C dam, could be delivered in the back of a pickup truck. With minimal fuel requirements and environmentally acceptable operation, fusion power plants represent a significantly reduced radiation hazard compared to conventional nuclear plants, providing more flexibility for siting; this, in turn, reduces the need for expensive "not-in-my-back-yard" transmission lines.

The long-term economic implications are significant - the projected worldwide demand for new electricity generation in this century will require in excess of $100 trillion investment beyond that required for the replacement of existing plants. In addition, fusion - as a clean, available on-demand energy source - can be used for industrial heat processing, desalination of water, production of hydrogen, etc. for higher value added applications. Since fusion energy systems intrinsically employ very sophisticated technology, the associated value added is very high indeed.

The prospect of fusion satisfying worldwide demand motivates the large international effort to harness this clean, sustainable energy source. Given that the countries involved represent over half the world’s population, it can be anticipated that fusion will become an important energy source by mid-century or sooner. This energy technology will have a transformative positive impact on the world’s energy strategies (virtually inexhaustible, environmentally acceptable, and universally available).

This prospect underpins the large international effort to harness fusion. Two major approaches to fusion - magnetic fusion energy (MFE) and inertial fusion energy (IFE) - and several alternative approaches (including that of General Fusion) - are being pursued worldwide. In all approaches, the challenge is to create conditions similar to those in the interior of the sun to enable "burning" of the fuel (isotopes of hydrogen). This is not a trivial task, as it requires both high fuel temperature and containment of the hot fuel long enough to generate more output energy than that required to heat it to "ignition" in the first place.

Development of the MFE approach has been an international collaborative effort since the late 1950’s and the largest undertaking is the ITER project in France - funded by the EU, China, India, Japan, Korea, Russia and the United States. This $20+ billion project is expected to be commissioned in the mid-2020s and demonstrate fusion power (~500MW), but not electrical production, by 2030.

Apart from the ITER cooperation, various countries individually are supporting large national MFE programs. Particular examples include China, that has identified fusion as one of the 5 priorities in their 2020 vision, and Korea, that has passed legislation formally including fusion as a line item on its national agenda. The steady but cumulatively large progress in MFE R&D can be seen in Figure 1 and Figure 2, lending support to the 2030 timeline for design and deployment of a demonstration prototype fusion power plant.

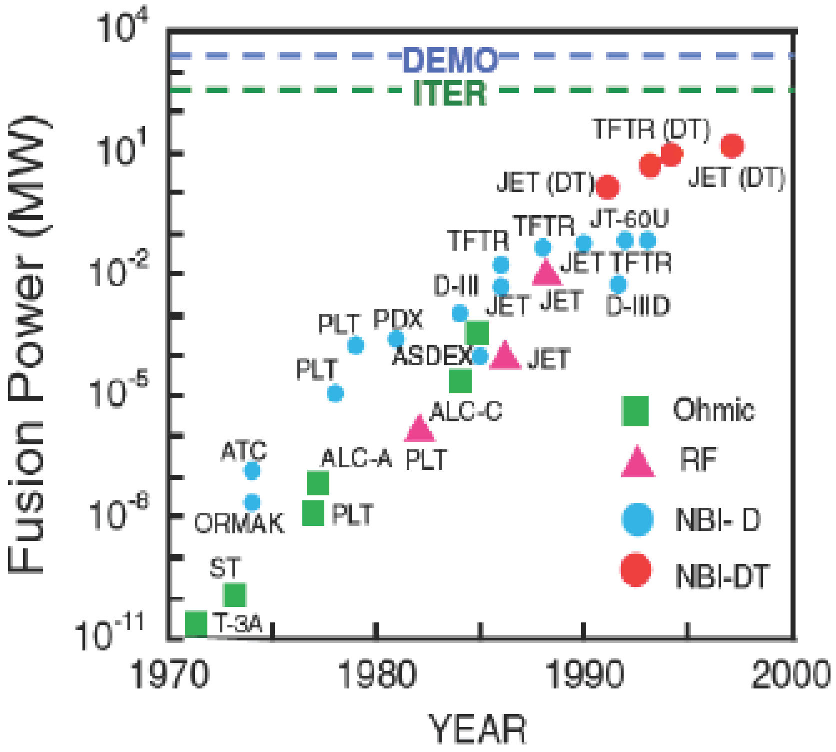

Figure 1. Historical progress in MFE towards achieving ignition/burn

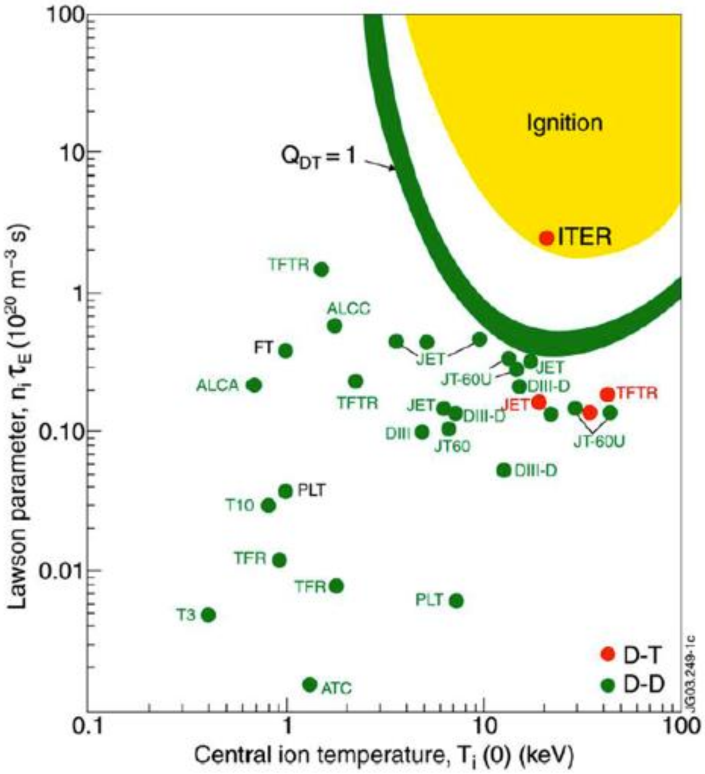

Figure 2. Historical progress in MFE based on key measures

IFE, a distinctly different approach from MFE, began theoretical research following the invention of the laser in 1960 and then experimental research by the mid-1970's, when the first high energy laser systems were built. Scientific and engineering progress has been rapid due to a combination of factors: i) large defense investments, particularly in the United States and France, and; ii) the involvement of many researchers in academic and national labs throughout the world - stimulated by the science and prospect of potentially simpler IFE power systems.

Two high energy laser facilities – the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in the United States (Figure 3, now operational) and Laser MegaJoule (LMJ) in France (in the final stages of construction) - have been built to achieve fusion fuel ignition. NIF has already shown fuel core ignition (although not yet full pellet ignition). The progress in IFE R&D can be seen in Figure 4. The achievement of full ignition in an IFE experiment will profoundly influence energy strategies worldwide and have an impact on Canada. Performance factor improvements (Q-values) of less than 10 are needed for both MFE and IFE to reach demonstration phase.

Figure 3. The National Ignition Facility (NIF)

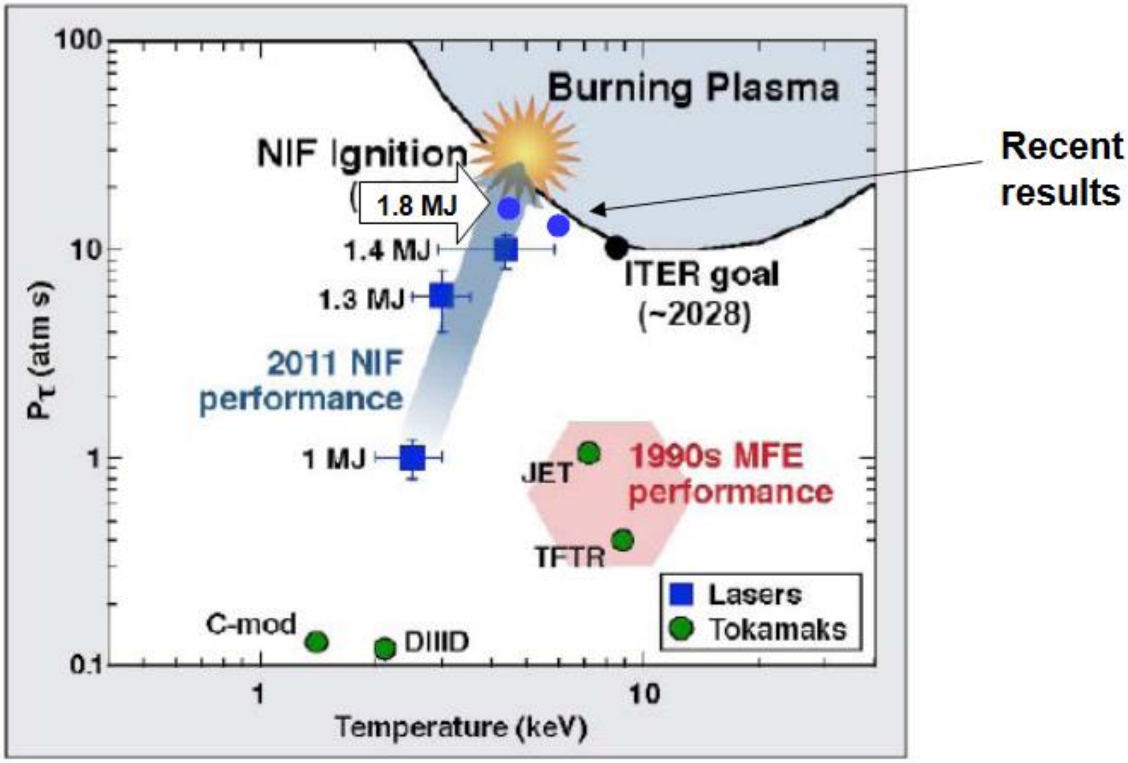

Figure 4. Metrics of fusion performance to date for inertial and magnetic fusion approaches. The vertical axis is pressure times time and the horizontal axis is temperature in units of kev (1 kev = 10,000,000K).

In addition to the major national efforts, and as a consequence of international progress in fusion science and technology, a number of private sector companies are emerging to pursue alternative concepts to the two major approaches. Examples may be found in Asia, Europe and North America, e.g., General Fusion in Burnaby, BC. While at a much earlier stage of development, these companies contribute a growing body of engineering expertise. With the critical assets of highly qualified personnel and technology in hand, gained from public and private investment, it may be expected that the cumulative knowledge will enable a transition to practical fusion energy systems far more quickly, once ignition has been demonstrated.

What happens following the demonstration of fusion ignition and burn? The answer is clear - fusion offers the prospect of sustainable, abundant, clean energy for the world and will be so deployed. In addition to growth in energy demand in developing countries, there is a need for replacing existing power plants with non-carbon fuels in the developed countries. There are already preliminary designs for demonstration power plants based on MFE and IFE. The projected delivery time of a 400MW IFE demonstration plant is 10 years following ignition and approximately the same for MFE. It is anticipated that the year 2030 will be a transition point for fusion energy.

Perhaps surprisingly, Canada is the only developed country without a dedicated national fusion program. It is hoped that this proposal will help to change this situation. A consortium of postsecondary institutions and industries engaged in R&D, in five provinces, has begun working to position fusion on the national agenda and prepare Canada for the fusion future that is coming.

A proposed fusion roadmap for Canada is provided in greater detail in the following document. The initial 5 year phase is concerned with “Capacity Building” - both highly qualified personnel (HQP) and technology. This phase would be accomplished by expanding both university programs and industry collaborations. It would include technology development in magnetic, inertial and alternative fusion approaches as part of the core training and buildup. Specific international opportunities include the offer of collaborations that would leverage national investment, bootstrap the learning curve for Canadians and build long term working relationships. The goal is to position Canada as a world player in 5 years and a leader in 10 years.

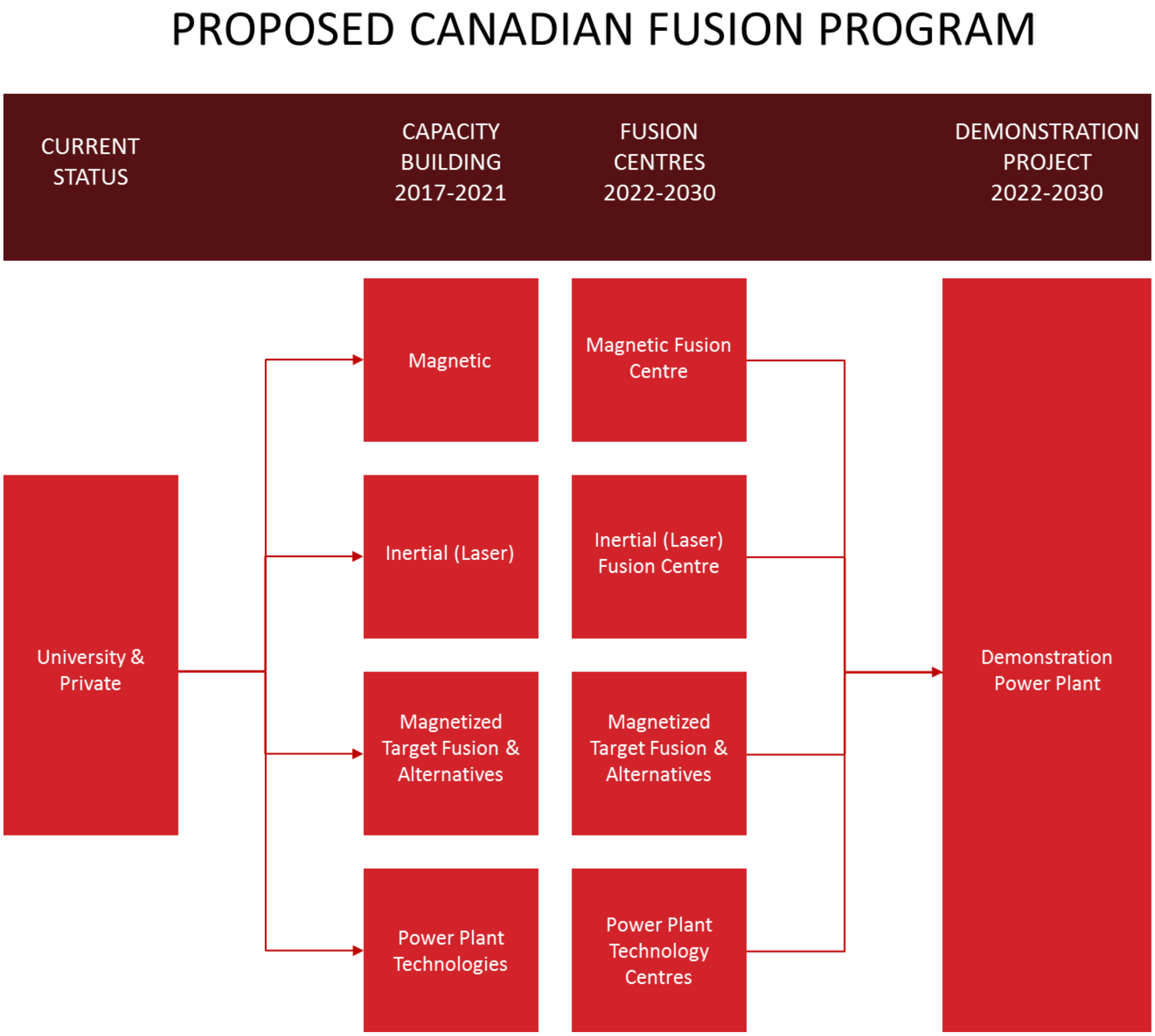

Figure 5. Proposed Fusion 2030 Program

Since the ultimate objective is to participate in any demonstration power plant - design, construction and operation – based on a breakthrough that is anticipated to occur by 2030, this roadmap provides a focus to build a strong capability in enabling technologies and advanced fusion power systems. Important technologies, with wide areas of application, include lasers, optics, photonics, materials science, targets, robotics, sensors, computing (controls, data, analytical methods), additive manufacturing, fusion systems engineering, etc. Deuterium and tritium production, storage and handling technology for fueling fusion power plants is another key area of Canadian expertise that can be exploited. Materials, subject to irradiation by high energy fusion plasmas (particles and radiation) will be one of the key technology areas, offering scope for a wide variety of Canadian contributions by private companies and public institutions such as Canadian Nuclear Laboratories (CNL), TRIUMF, and the National Institute for Nanotechnology.

As a consequence of long respected involvement internationally, the Canadian fusion initiative has strong support from the leaders of the programs in the United States, Europe and Asia and invitations to collaborate on fusion development (including posting of Canadian researchers to their labs). The University of Alberta and the University of Saskatchewan are particularly known for their international engagement. This provides an opportunity to rapidly build expertise and develop even stronger working relations with our partners in fusion energy domestically, through private companies such as General Fusion, and internationally, such as with China.

The advanced technologies associated with fusion systems offer an overarching driver for economic diversification. As a strategic priority, fusion would nicely complement and considerably amplify current efforts to build strength in energy, nanotechnology and computer modeling 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 highlighted above.

Our Fusion 2030 roadmap calls for a revitalized Canadian National Fusion Program, in concert with provincial initiatives, to prepare Canada for the coming fusion era. A three phase program of capacity building and technology development is described, culminating in construction of demonstration fusion power plants and the establishment of a multi-billion dollar fusion energy industry in Canada. Preparedness and participation are the key attributes of the strategy. When tasked with “big issues”, Canada has repeatedly demonstrated the capability to adapt, innovate and achieve. Sustainable, clean base-load energy to replace carbon fuels is the paramount issue of this century and fusion is a major part of the solution. Canada needs to be involved.

Signature Page

The undersigned support the above proposal for a Canadian National Fusion Program and the proposed roadmap.

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1. Introduction

Fusion energy has the potential to transform the world's energy supply. As a clean, safe and abundant source of energy, it presents an opportunity to combat climate change while still meeting the world's growing energy needs. With fusion development accelerating worldwide, there is a desire and commitment amongst Canadian researchers to build a strong Canadian fusion program that is internationally competitive, and to put Canada back at the forefront of fusion development.

This document outlines the roadmap for a Canadian fusion research program culminating in the establishment of a demonstration fusion energy power plant. It will provide context on recent developments at both a Canadian and international level, and propose a program of research and development that will expand Canadian cleantech innovation and expertise while building the country's capacity to meet its climate change mitigation targets.

2. World Context:

We are currently in an exciting new era in the development of fusion energy worldwide. There are high profile national programs in most advanced nations in the world, developing a variety of different approaches. In addition there a dozen or more private ventures pursuing alternative concept routes to fusion energy, including one of the leading ones, General Fusion, here in Canada. Most of the current activity is at the stage of scientific proof of principle but also there is a growing emphasis on investigating engineering and technical issues which need to be addressed in the implementation of future fusion reactors. We are on the brink of demonstration of net energy gain on a large scale both with the magnetic fusion energy (MFE) approach and the inertial fusion energy (IFE) approach. The former will be demonstrated by the international ITER project under construction in France at present and the latter at the National Ignition Facility in Livermore California within the next few years. In parallel, a number of directions are being pursued to improve on the design of these approaches to lead to more compact and more economic power plant designs, which is the basis of most national fusion programs around the world.

In all these approaches a number of benchmarks are used to assess the performance, the most important being the energy output versus energy input to heat the fuel, the so called Q parameter. From the scientific side the advancement towards net energy gain can be assessed in terms of the product of density and confinement time of the fuel, the so called Lawson Criterion. At the same time, a minimum temperature on the order of 50 to 100 times that at the centre of the sun must be achieved in order for the fusion reactions to occur. This leads to a triple product of density, temperature and confinement time or pressure and time as a metric to compare the status of various different approaches to fusion.

To put this in context the annual investment in fusion research and development exceeds US$4B per year around the world. Initial planning is already starting towards Engineering Demonstration systems for net power production on an intermediate scale to develop the advanced systems and materials to withstand long term operation of power plants. The construction of such systems will likely start in the period of 2025 to 2035. Such demonstration plants will target net energy returns of 20 to 100 times. A brief outline of current international activity and timelines is given in the following subsections.

A. Magnetic Fusion

Magnetic Confinement Fusion research aims to develop a fusion power plant where a fusion plasma is confined in a “magnetic bottle”; using powerful, steady-state magnetic fields generated from external coils. These systems, including tokamaks, stellarators, and reverse field pinches, are toroidal in shape, with the tokamak configuration being the most widely studied.

Construction is underway at the ITER project (Figure 6) [MF1] in France, a collaboration of many countries (the EU, China, India, Japan, Korea, Russia, and the USA), with first operation expected in 2025. The mission of the ITER project is to demonstrate the feasibility to ignite a fusion reactor with a net energy gain.

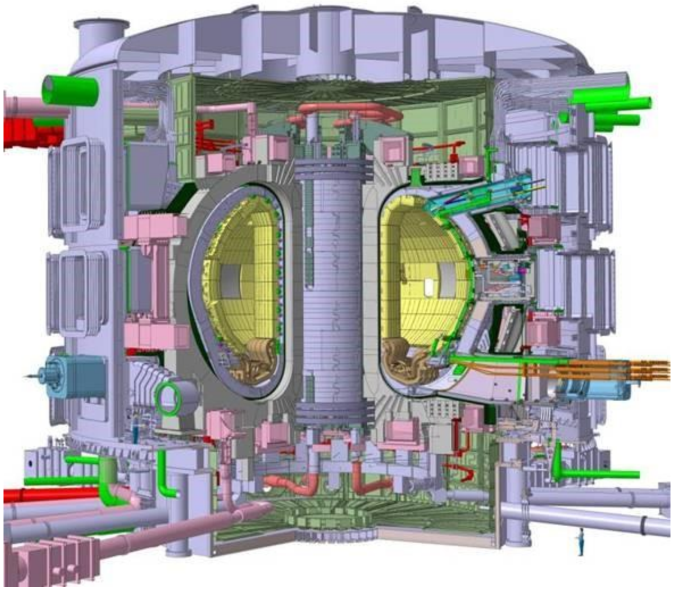

Figure 6. 3D CAD image of the ITER tokamak [MF2]

Significant progress has been made towards tokamak reactors. The Joint European Torus (JET) machine has set the world record of Q=0.6 in the 1996 [MF3]. Extrapolating from deuterium plasma performance in the JT-60 tokamak, the device achieved an equivalent of Q=1.25, indicating that break-even conditions would have been surpassed had a deuterium-tritium fuel mix been utilized [MF4]. In China, the EAST tokamak recently set records for high temperature (70 million degrees), long pulse operation. The Japanese are constructing a new superconducting tokamak, JT-60SA, and in Europe, the Joint European Torus (the world record holder for fusion power) is gearing up for a major tritium-fueled campaign. The progress in the development of tokamak-based Magnetic Fusion is shown in Figure 7 showing better exponential improvements in performance over the past 4 decades than that in the semiconductor industry, a benchmark referred to as Moore's law.

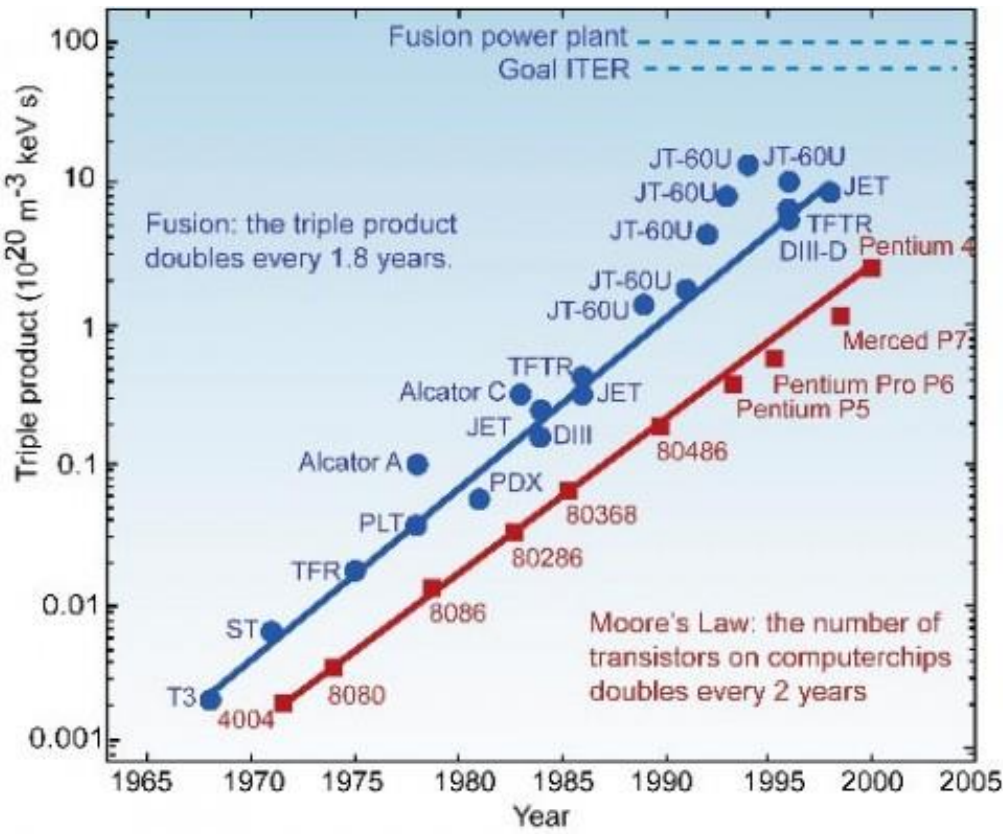

Figure 7. Progress in tokamak-based Magnetic Fusion compared to Moore's law for semiconductors

Recent years have seen some major advances in other magnetic fusion configurations, both in science and in technology. In Germany, the Wendelstein 7-X stellarator [MF5] recently began scientific operations (Figure 8), and quickly demonstrated record performance for this type of system, reigniting interest in stellarators as fusion power plants. Another major stellarator is LHD [MF6].

Figure 8. The Federal Chancellor of Germany, Dr. Angela Merkel, switched on the first hydrogen plasma in Wendelstein 7-X on February 3, 2016.

Spherical tokamak (Figure 9) [MF7] is a type of tokamak with low aspect ratio (a fat torus). Active research has been carried out in MAST in the UK [MF8] and NSTX-U in the USA [MF9]. The key advantages of spherical tokamaks include improved plasma stability and potential to build compact fusion reactors with lower capital investment.

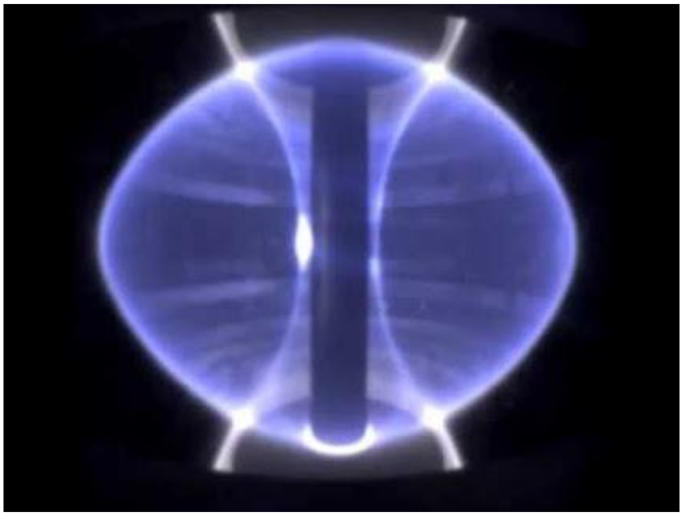

Figure 9. Image of plasma in the MAST Spherical Tokamak Experiment at the Culham Laboratory in the U.K [MF10]

At the same time, a new wave of innovation in high temperature superconductors is leading to concepts at MIT, Princeton, and in the UK that would make for smaller, lower cost fusion power plants, and the potential for an accelerated commercialization program.

B. Inertial Fusion

The main approach to inertial confinement fusion (ICF) energy relies on using very high power laser pulses to compress and heat the fuel to the point of ignition and burn (somewhat analogous to a diesel engine). As shown in Figure 7, there are number of configurations currently being explored, from traditional indirect drive and direct drive approaches to advanced schemes using a separate laser pulse to produce the actual ignition the fusion reactions (like a match lighting fuel). Once ignited the fuel will burn extremely rapidly in a fraction of a nanosecond (1 ns = 1 milli-microsecond).

The *indirect drive* approach [IF1] has to date been the most developed. With the construction of the largest laser system in the world, producing 1.8 MJ pulsed energy, the multi-billion dollar National Ignition Facility (NIF) [IF2] at the Lawrence Livermore National Laboratory (LLNL) in California is a test platform for this concept. This approach, which converts laser light into a burst of X-rays inside a small canister which then irradiates and compresses the fuel capsule, has the advantage of being very robust and has been pursued as the mainline approach by the USA and France to date.

The next most investigated approach is the *direct drive* approach [IF3] using the laser beams to directly irradiate the fuel pellet. This approach is energetically more efficient, should lead to ignition at lower overall laser system energies, and achieve higher gains for a given laser energy. The largest laser system in the world pursuing this approach is at the Laboratory for Laser Energetics (LLE) in Rochester [IF4] with a peak laser pulse energy of 40kJ.

The most advanced ICF approaches currently proposed would use a two-stage approach for compression and ignition (somewhat analogous to a gasoline engine). A first laser pulse is used for the initial compression stage. A second laser is then used to create an ignition spark. This two-stage laser approach would reduce the requirements of the primary laser pulse which only needs to compress the fuel to a high density ready to burn. There are a variety of such approaches, including Fast Ignition with electrons [IF5], Fast Ignition with protons [IF6], and Shock Ignition [IF7]. These approaches have the advantage of being more efficient, yet would lead to much higher gain at significantly lower overall laser energies than the single pulse approaches. The variety of approaches is illustrated in Figure 10 and the scaling of net energy gain versus overall laser pulse energy is shown in Figure 11.

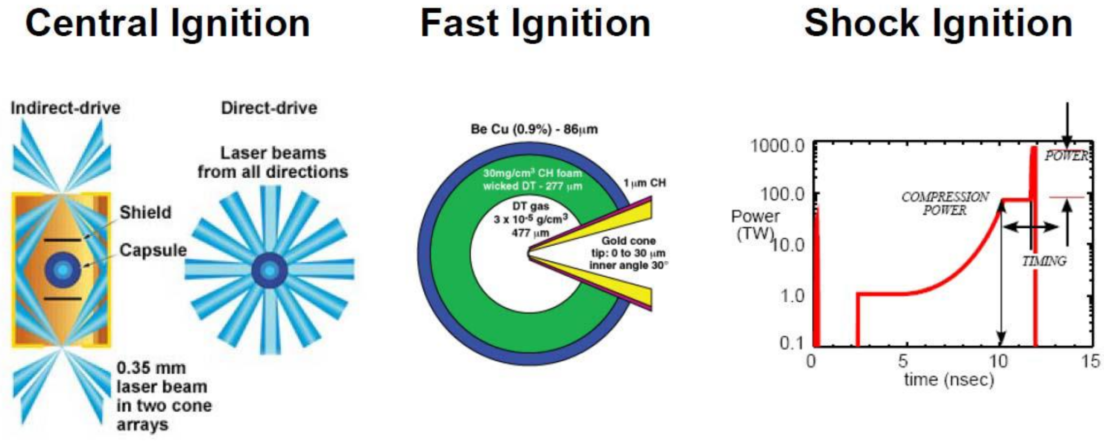

Figure 10. Various approaches to laser fusion energy, from left to right: Indirect Drive, Direct Drive, Fast Ignition and Shock Ignition

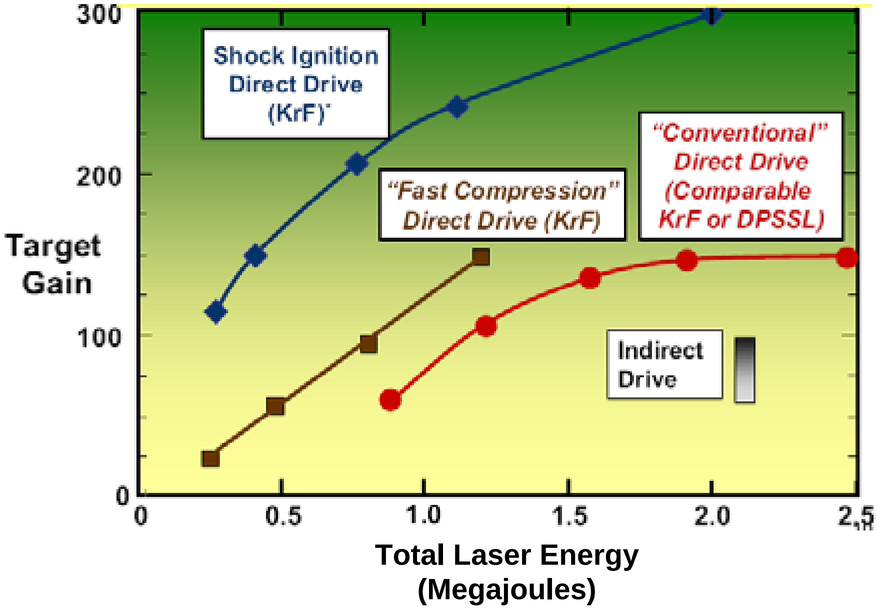

Figure 11. Calculations of net energy gain, defined as fusion energy produced divided by laser energy used for various approaches to laser fusion energy as a function of total laser energy in Megajoules.

At present, a number of the largest nations of the world have built or are building large laser systems to explore indirect drive fusion with the option to convert to direct drive if, in the end, the direct drive approach looks more promising. These facilities include the 1.8-MJ NIF facility in the United States (Figure 12), the 2-MJ LMJ facility in France, the 600-kJ Shenguang IV facility in Mianyang China, and a Megajoule-class facility in Russia. In addition, there are smaller laser facilities investigating various aspects related to laser fusion including direct drive and advanced ignition. These include the 40-kJ laser facility at the Laboratory for Laser Energetics (LLE) in Rochester, NY, United States; the 12-kJ laser facility at the Institute of Laser Engineering (ILE) in Osaka, Japan; the 6-kJ laser facility (Orion) in Culham, England; the 2-kJ Central Laser Facility at Rutherford Appleton Laboratories (CLF RAL) in England; the 1-kJ class laser facilities in Paris, France (LULI), Shanghai China (Shenguang II), and the United States (JLF at LLNL, and NRL in Washington, DC).

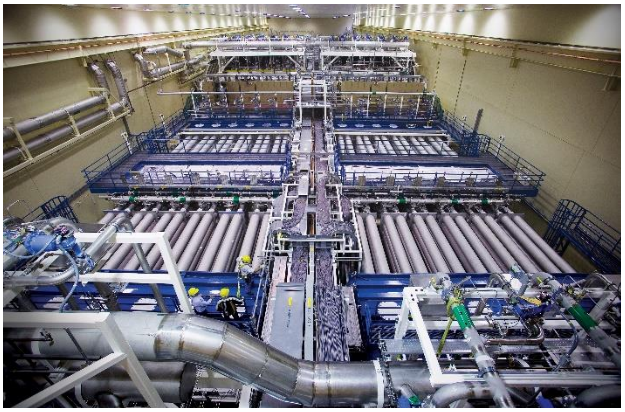

Figure 12. Photo of 1.8MJ laser bay of the National Ignition Facility at Lawrence Livermore National Laboratory.

The best result achieved to date has been at LLNL using the indirect drive approach with the production of net energy gain of 17 kJ fusion energy production from 10kJ energy invested in the ignition hot spot of a laser fusion pellet [IF8]. This value is within a factor of 2 of ignition at which point the fuel would ignite and start to burn releasing Megajoules of energy. Current experiments at LLE for the direct drive approach if scaled to the 1.8 MJ laser driver energy indicate that this approach would yield 120kJ of fusion energy [IF9] and thus are very similar in status to the indirect drive approach. Current experiments still have a number of technical issues which can be improved including the uniformity of the implosion and further shielding of the target fuel from preheat before compression. These are the subject of investigations funded by the Department of Energy (DOE) in the USA with the goal of reporting in 2020 [IF10] on the understanding of all technical issues related to achieving laser fusion ignition, and a recommendation of a route forward for achieving ignition.

At the same time, many of the smaller laboratories are studying the technical issues related to implementing advanced ignition techniques. The study and implementation of these advanced ignition techniques is envisaged in a number of the large laser facilities currently under construction including LMJ in France and Shenguang IV in China. Two planning studies for Engineering Scale Demo systems have already been prepared: the LIFE system for Indirect Drive Fusion [IF11] at LLNL and the HiPER system [IF12] using advanced ignition techniques in Europe. These proposals for building demonstration ICF fusion power plants will be put forward once ignition and fuel burn has been demonstrated at one of the current facilities.

C. Alternative Fusion Concepts

The last ten years has seen a surge in surge in the investigation of alternative approaches and technologies for fusion energy. Advances in plasma physics, electronics and digital controls, computer simulation, and materials have opened up new avenues for developing fusion power plants. In some cases, this work is building on old concepts originally developed decades ago, but with some modifications and innovations making use of new technologies and new knowledge. In other cases, completely new ideas are emerging based on modern understanding of plasma physics. Beyond science and technology, new business models and strategies for research and development have also emerged, with private companies attracting tens and even hundreds of millions of dollars, building world class teams and research centers working closely with publicly-funded institutions.

i. Magnetized Target Fusion / Magneto-Inertial Fusion

Many innovative new approaches lie in a branch of fusion research called Magneto-Inertial Fusion or Magnetized Target Fusion (MTF). [MTF1] Magnetic Fusion (MF) systems are typically envisioned as low density, steady-state systems, where the cost of confining large plasmas dominates. Inertial Fusion (IFE) systems have very small plasmas, but are dominated by the cost of the very high power driver systems (such as lasers). In both cases, recent advances are leading to opportunities to significantly reduce those costs.

MTF spans the intermediate regime between MF and IFE, using small plasmas confined by magnetic fields and rapid compression for heating to fusion conditions. The aim is power plants where both the cost of confinement and the compression driver can be dramatically lower, as illustrated in Figure 13. [MTF2]

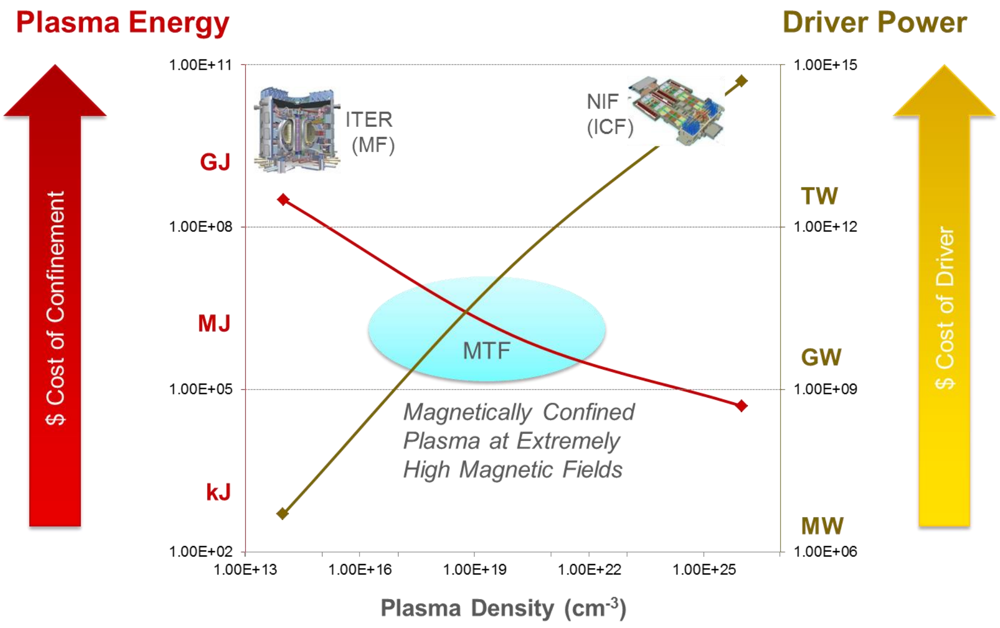

Figure 13. Magnetized Target Fusion compared to Inertial and Magnetic Fusion

MTF concepts trace back to research first undertaken in the 1970s, however the science in this regime remains less explored than MF or IFE. Recent efforts are aiming to close this gap. [MTF4], [MTF5]. In Canada, the world leader in MTF research, General Fusion, is undertaking pioneering research to explore the behaviour of compressed magnetized plasmas. And in 2015, in the USA, the Department of Energy's Advanced Research Projects Agency for Energy (ARPA-E) launched their ALPHA program, funding nine different groups pursuing variations of MTF and supporting science. ARPA-E grant recipients include private companies such as Helion Energy in Seattle, national laboratories such as Los Alamos National Lab, and universities such as Swarthmore College and the University of California. Sandia National Laboratory, also a recipient of ARPA-E funding, is researching another approach to magneto-inertial fusion using an extremely large pulsed magnetic field to compress the fuel, called Magnetic Liner Inertial Fusion (MagLIF). [MTF6]. Research efforts on these concepts are also underway in China.

ii. Other Alternative Fusion Concepts

Alternative concepts for fusion energy have been proposed periodically over the past decades, but have generally received little support [AC1], [AC2]. Recently, however, a diverse range of fusion concepts have emerged and attracted meaningful investment in both the private and public sector. [AC3], [AC4], [AC5] These alternative concepts share a common theme of accepting risk from the application or exploration of new science and technology with the goal of developing a commercially-viable fusion power plant in the near future. These include Tri Alpha Energy (Irvine, California) studying a unique Field-Reversed Configuration, Figure 14, Lockheed Martin's Skunkworks (USA) division developing a new magnetic fusion configuration, EMC2 (USA) studying a magnetic fusion configuration called the Polywell, and First Light Fusion (UK) pursuing a new inertial fusion concept.

Figure 14. Picture of Tri-Alpha Fusion Research Device

D. Fusion Power Plant Technologies

Since the beginning of research and development of fusion reactors in the 1950s, there have been several science and technology topics investigated that have relevance to all fusion reactor concepts, including both mainstream and alternative concepts. These include:

- Interaction between the fusion plasma and the first wall of the surrounding structural component [PP1].
- Modeling and assessment of neutron and photon (gamma rays, X-Rays) transport and interactions outside the fusion plasma region. This topic includes the interactions of neutrons and photons with various materials and components, such as coolants, breeding materials, shielding, support structures, field magnets, and others [PP2].
- Performance of structural materials and components under high radiation environments (neutron, gamma, X-rays), along with the impact of the cycling of thermal heat and mechanical force loads, which may cause fatigue and damage [PP3].
- Production, handling and storage of fusion fuels (such as deuterium and tritium), and the interactions of deuterium and tritium with various materials [PP4], [PP5].
- Behavior of fertile and fissile nuclear materials, if the fusion reactor is being used as a neutron source to drive a sub-critical fission reactor blanket [PP6], [PP7].
- Design and operation of the balance-of-plant, which is used to convert the heat from the fusion plasma into electricity [PP8], [PP9].
- Overall safety analysis and environmental assessment of the fusion power plant, which generates high radiation fields (in the form of high-energy neutrons, X-rays, and gamma rays) while in operation [PP10], [PP11].

The operating parameters of a fusion reactor place many of the materials under severe stress, and thus materials development, engineering and testing is a critical necessity for the eventual implementation of fusion reactors. Test facilities with sufficient neutron, photon and charged particle flux, and the correct mix of high-energy particles and photons do not exist today and plans are underway for the construction of such test facilities. All of the above generic fusion reactor issues are being studied at research facilities globally, including the United States, Russia, China, Korea, Japan, and Europe. However, significantly more effort is required to develop materials and sub-systems for prototype demonstration fusion power plant facilities (Engineering Demo) and this effort in turn will allow more rigorous lifetime testing of the various subcomponents under real operating conditions.

E. Summary

There is presently significant global activity in fusion energy development, with the advanced inertial confinement and magnetic fusion concepts now within striking distance of breakeven energy production.

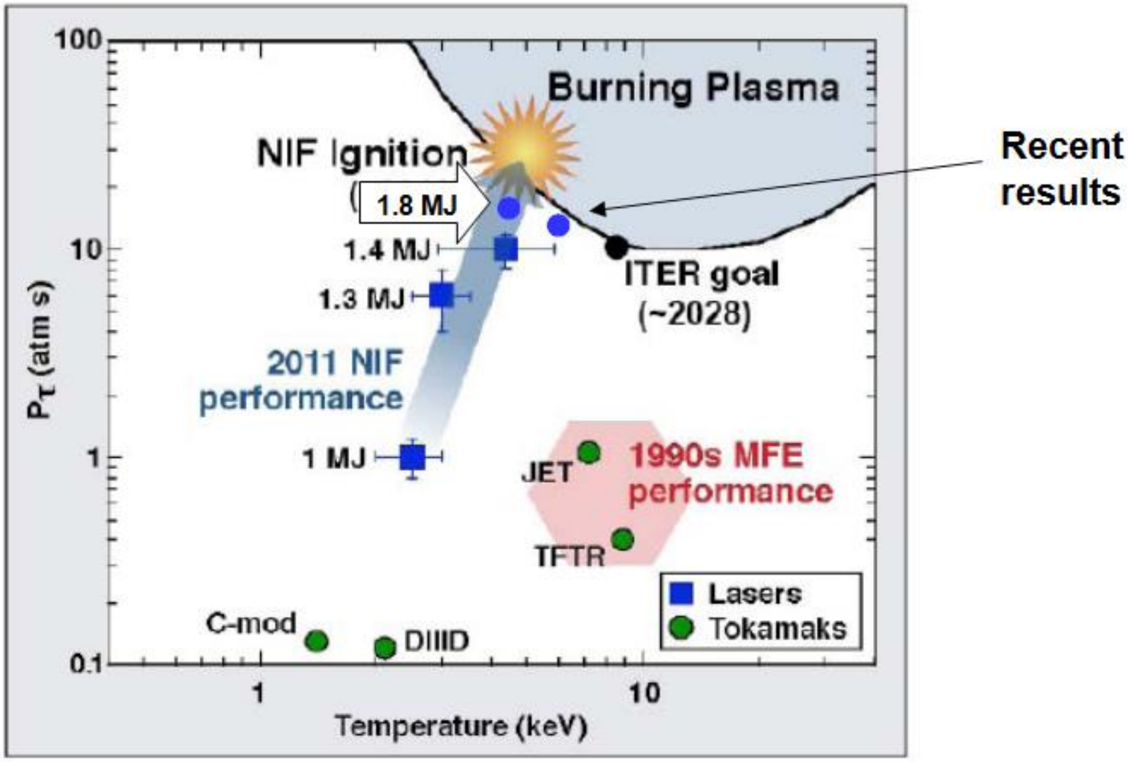

Figure 15. Metrics of fusion performance to date for inertial and magnetic fusion approaches. The vertical axis is pressure times time and the horizontal axis is temperature in units of kev (1 kev = 10,000,000K).

Two metrics are critical to achieving net energy production: sufficient confinement time (as given by the product of pressure and time (Lawson Criterion); and appropriate temperatures to achieve a sufficient energy production rate. These are shown as the two axes on the plot above. The region where net energy production can be achieved is shown in the upper right region of the curve (the Burning Plasma region).

Studies by the IAEA, European Union, and USA have outlined roadmaps to power plant systems. At the current rate of progress it appears very likely that scientific demonstration of the conditions required for net energy production by fusion energy will be reached fairly soon. A roadmap of project timelines and expected progress from various sources is summarized in Figure 16.

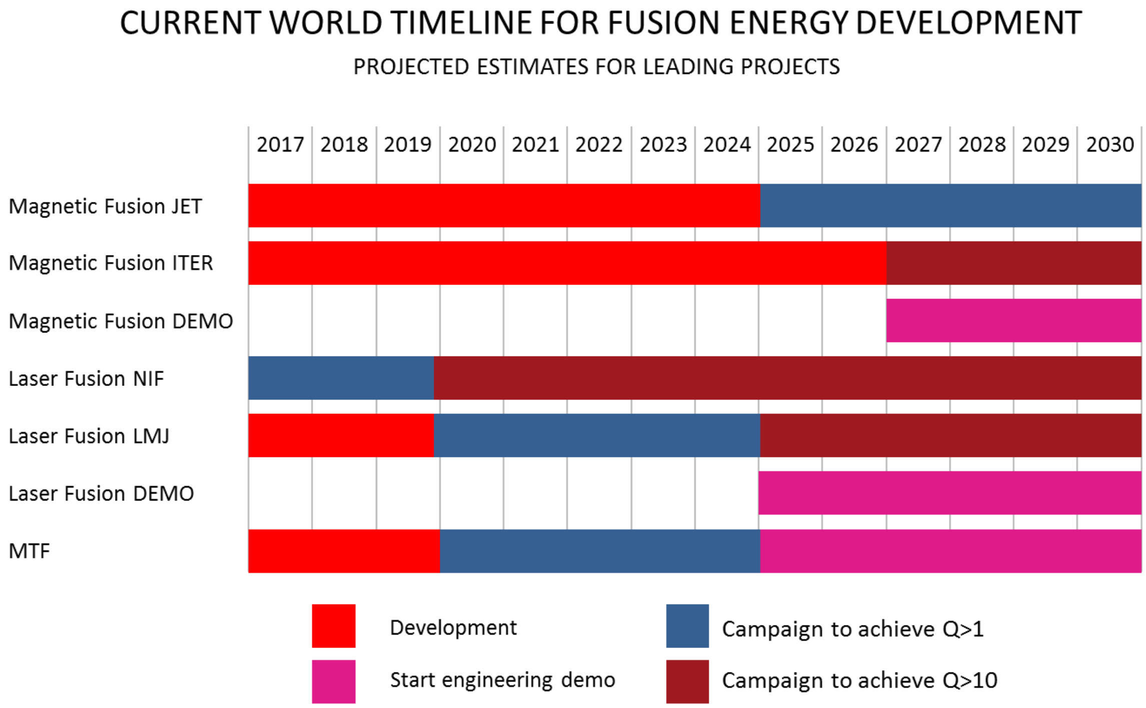

Figure 16. International progress and estimated timelines of major fusion programs till 2030.

3. Canadian Current Context:

Canada has a long history of research and development in fusion energy, but the activity has shrunk considerably over the past two decades after the termination of the Canadian National Fusion Program in the late 1990’s [G1], [G2]. In the 1960’s, recognition of the potential of fusion energy led to the establishment of a number of groups studying plasma physics and fusion energy, particularly at the Universities of British Columbia, Alberta, Saskatchewan, Toronto and Institut National de la Recherche Scientifique (INRS) in Montreal. All of these were major players in the field in the 1970’s and 1980’s. In addition, the Laser-Plasma group at the National Research Council (NRC) became a significant player in laser fusion related studies during this period. These activities eventually led to the establishment of a Canadian fusion energy program in the 1980’s with the construction and operation of the Tokamak de Varennes (TdeV) in Quebec and the Canadian Fusion Fuels Technology Project (CFFTP) in Ontario, led by Ontario Hydro (the provincial electric power utility) and Atomic Energy of Canada Limited (AECL). Canada was also an initial member of the development group for ITER.

In the mid-1990s, during an era of government austerity, the Canadian government cancelled the national fusion energy program. This led to the demise or redirection of a number of the programs. However, there is still significant core expertise remaining in a few of the groups which now can be used to start a new effort to finally achieve fusion energy. The current status in various areas is summarized below.

A. Magnetic Fusion

Magnetic fusion research is being carried out in Canada in both public and private sectors. Fusion research has been underway in the Plasma Physics Laboratory (PPL) at the University of Saskatchewan since late 1950s. For more than half a century, PPL has been making experimental and theoretical contributions to the study of controlled nuclear fusion. The first Plasma Betatron began operating in the early 1960s. Following the most promising technological path, University of Saskatchewan researchers, along with the majority of the world’s plasma physicists, have worked mainly with tokamaks. The University of Saskatchewan's tokamak, STOR-M, has been in operation since 1987 and is currently the only active tokamak in Canada. There have been constant upgrades, improvement, and additions to STOR-M. Over the years, U of S researchers at the PPL have made several significant and original contributions to tokamak research on fueling technology, confinement improvement, and novel tokamak operation scenarios including quasi-continuous alternating current operation and feasibility studies of plasma start up with a small iron core in spherical tokamaks. University of Saskatchewan PPL maintains close collaboration with international fusion groups and has actively participated in the IAEA (International Atomic Energy Agency) Coordinated Research Project “Utilization of the Network of Small Magnetic Fusion Devices for Mainstream Fusion Research”. STOR-M has also been an excellent facility for training students, young scientists and engineers and continues to attract a large number of students and post-doctoral fellows (PDFs).

In addition, theoretical work is also carried out in PPL to study waves, instabilities and other important topics related to fusion plasmas. There are collaborations between the PPL and General Fusion on theory, modeling and diagnostics for their MTF program outlined below.

PPL has currently 3 professors, 2 emeritus professors and a dozen other staff and students including a PDF, a research assistant, and a number of graduate students. Currently, there is a search on for a tenure-track professor in experimental plasma physics at University of Saskatchewan. In 2011, the Province of Saskatchewan funded the Sylvia Fedoruk Canadian Centre for Nuclear Innovation which is now a focal point for nuclear research and development activity from medical sciences to fusion technology. This gives an ideal platform for the initiation and operation of an expanded fusion program at the University of Saskatchewan.

B. Inertial Fusion

Inertial confinement fusion research in Canada has focused exclusively on laser-driven fusion. Research was initiated in a few groups at the NRC in Ottawa, INRS in Montreal and the University of Alberta, almost immediately after the approach was first publically disclosed at an IEEE Laser conference in Montreal in 1972.

Canada had also recently invented the highly efficient pulsed atmospheric Carbon Dioxide discharge laser (CDDL) at the Defense Research Establishment at Valcartiers (DREV), and initially this was seen as a potential driver for laser fusion systems giving Canadian groups a potential advantage in development of such fusion systems.

However, during the 1970’s it became clear that long wavelength lasers such as the Carbon Dioxide were poor drivers for laser fusion systems and were abandoned by 1980. This shifted the thrust to short wavelength lasers and one of the leading candidates was an ultraviolet laser system based on Krypton Fluoride. This led to the establishment of a significant project at the University of Alberta funded by the Albertan government Energy Resources Research Fund (ERRF). This project was a contributor to the development of techniques for efficiently extracting and compressing laser pulses and studies of laser-plasma interaction physics leading to the strong conclusion that ultraviolet wavelength drivers were ideal for laser fusion drivers.

Smaller projects also developed at the University of British Columbia and University of Toronto during the 1980’s. However, with the shutdown of the Canadian Fusion Program in the 1990’s most programs focused on new directions or shrank away. The University of Alberta group remains the only group active in laser fusion research today.

As shown in the summary table (Table 1) at the end of this section, there are 3 academic researchers (2 experimental and 1 theoretical) directly involved in laser fusion research at the University of Alberta, with another 5 working in the general laser or plasma experimental and theoretical area. In fact, all of these other five were trained in fusion energy related programs in the past. There is also on the order of $1.5M worth of laser systems and diagnostic systems for laser-plasma related studies at the University of Alberta. The University of Alberta has one of Canada’s leading nanofabrication facilities (necessary for target fabrication and characterization), and the National Institute for Nanotechology (NINT) for materials development. Other laser-plasma research groups exist at the University of Toronto, University of Ottawa (with a major new photonics thrust), and INRS in Montreal. Additional laser development groups exist at the University of Laval and University of Manitoba.

The industrial sector is already involved and well positioned to take advantage of opportunities in laser fusion targets and instrumentation. Local Microelectromechanical Systems (MEMS) companies in Edmonton such as Norcada and Applied Nanotools have already delivered targets for laser-plasma experiments to research groups around the world. Applied Nanotools has also become a world leader in x-ray optics (a key diagnostic component for studying hot plasmas) with contracts around the world. There is significant MEMS manufacturing capacity and expertise in the Edmonton area which can be expanded to serve the future needs of an inertial fusion program and subsequent industry.

C. Alternative Fusion Approaches

i. Magnetized Target Fusion / Magneto-Inertial Fusion

General Fusion is a private company based in Burnaby, British Columbia pursuing the science and technology to develop a commercially viable fusion energy source based on principles of magnetized target fusion. It is a world leader in this area. General Fusion's R&D team includes over 50 scientists, engineers, and technicians, including 12 with PhDs in physics and engineering, and trains many co-op students (up to 13 at a time). The expertise at General Fusion covers plasma physics theory and simulation, magnetized plasma experimentation and diagnostics systems, mechanical and electrical engineering, materials, control systems, pulsed power and fluid dynamics. They operate world class compact toroid sources (Figure 17), a pulsed plasma compression program, the largest pulsed power facility in Canada, a flowing lead power plant technology platform and a 256 node computer cluster. This is the second largest privately-funded fusion science research program in the world.

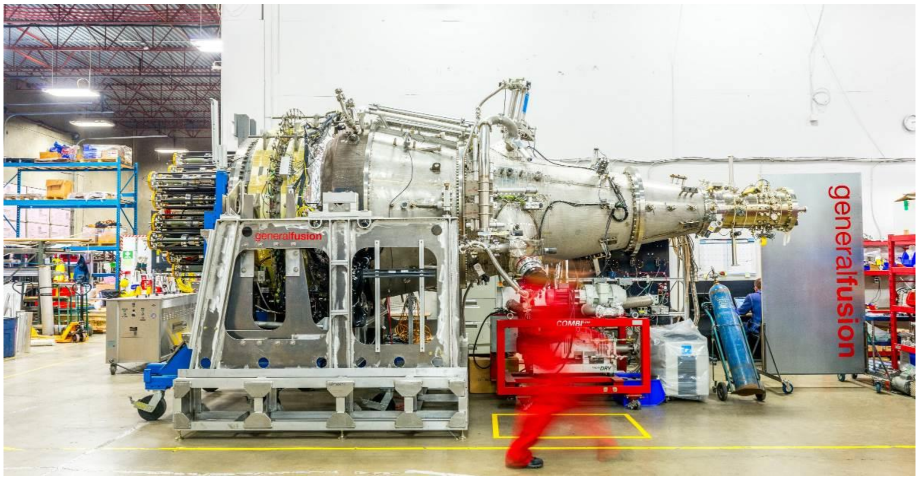

Figure 17. Plasma Injector at General Fusion for the MTF project

General Fusion is funded primarily from an international syndicate of private investors including Cleantech venture capital, Cenovus Energy, Jeff Bezos, and sovereign wealth funds, with over $100M invested to date. An additional ~$20M of capital has been received through Canadian government funding programs including Sustainable Development Technology Canada (SDTC), the Scientific Research and Experimental Development Tax Incentive Program (SR&ED), and the Industrial Research Assistance Program (NRC-IRAP).

Since 2014, General Fusion has invested over $350,000 in university researchers and students, leveraging federal programs to result in over $500,000 in funding. Universities and institutions involved with these collaborations include the University of Saskatchewan, Simon Fraser University, McGill University, University of Sherbrooke, TRIUMF (BC), Princeton University (in NJ, U.S.A.) and Queen Mary University (London, UK). Other formal and informal research collaborations involved professors and scientists at Queen's University (General Fusion sponsored a PhD student who has since joined General Fusion as a research scientist), Los Alamos National Laboratory (LANL, in Los Alamos, NM, U.S.A.), Defence Research and Development Canada (DRDC), Lawrence Livermore National Laboratory (LLNL in Livermore, CA, U.S.A.), the University of Washington, and Massachusetts Institute of Technology (MIT, in Cambridge, MA, U.S.A.).

ii. Other Alternative Concepts

The University of Saskatchewan has recently constructed a Dense Plasma Focus system for materials testing. A 2kJ prototype device has been built and will be soon upgraded to a 20kJ device. Dense plasma focus is a candidate for boron fusion reactor without neutron emission.

In Ontario, Hope Innovations, is in the early stages of exploring a concept based on multiple intersecting plasma arcs, stemming from research into the nature of high-current plasma discharges [AC6]. HOPE is continuing to develop its theoretical basis and has undertaken some preliminary experiments aimed at proving the concept.

D. Fusion Power Plant Technologies

Historically, Canada had been involved at a small scale in carrying out supporting research for both mainstream and alternative fusion reactor concepts [G1]. However, since the early 1970s [PP12], [PP13] and continuing through the 1980s until 1997, researchers across Canada were contributing to broad-purpose fusion energy science and technology development through the previous Canadian National Fusion Program [G1], which included the Canadian Fusion Fuels Technology Project (CFFTP) [PP14], [PP15].

Canadian researchers have focused their efforts in the area of fusion fuels including technologies for the production, handling and storage of deuterium and tritium, evaluating breeder blankets [PP16], [PP17], understanding how deuterium and tritium interact with materials [PP4], [PP18], and the investigation of separating deuterium and tritium from water [PP19]. Other studies have involved investigating the interaction of plasmas with first wall materials and components [PP14], [PP15], and evaluating fusion-driven sub-critical systems for producing power and breeding fissile fuels, involving neutronics analyses [PP13]. Current activity is focused on deuterium production and tritium handling [PP4], with some exploratory computational neutronics studies on hybrid fusion-fission reactors [PP7]. There are also continuing Canadian university research activities on plasma-material interactions [PP20], [PP21], albeit on a small-scale.

In terms of plasma materials interactions, which are of significant importance for the first wall lifetime in fusion reactors, a number of university groups in Saskatchewan, Alberta, Ontario and Quebec have studied such interactions for decades. In addition, a private research company in

Montreal, Plasmionique (operating since 1999) has been working on developing and providing plasma source systems of various specifications for applications in plasma processing. The work being done by Plasmionique could potentially be adapted for fusion research applications.

E. Summary

As seen above there is a very strong base of knowledge and expertise within Canada that can be used as a platform to initiate a renewed drive towards the goal of fusion energy. An inventory of current personnel and research facilities across Canada summarized in the Table 1 below.

Institution	Professors	Researcher Scientists and Engineers	PDFs	Graduate students	Present Value of Related Facilities
					$M
University of Alberta	5	1		10	2
University of Saskatchewan	4	1	1	15	5
University of Ontario Institute of Technology	1				
Other Universities	3			3	
General Fusion		50			20
Canadian Nuclear Laboratories		2			2
Totals	13	54	1	28	29
Other Potential Resources					
Materials Science Researchers	4			4	
NINT	4			4	
Other related programs (Plasma, Optics, neutronics etc.)	10			10	
Overall Totals	31	54	1	46	29

Table 1. Summary of personnel numbers and infrastructure in existence in Canada today plus complementary resource facilities such as NINT, CNL, other University groups, etc.

4. Canadian Proposed Program:

It is strategically important for Canada to rejoin the international community in the area of fusion energy science and technology after a nearly 20-year hiatus. The development of fusion energy as a viable power source will help support international efforts to increase long-term energy security and sustainability. The use of fusion energy would also help protect the environment and mitigate global climate change through reduction in the emissions of air pollutants and greenhouse gases.

By contributing its expertise and capabilities to international efforts, Canada can have a significant impact in accelerating the progress of the development of fusion energy, while also ensuring that Canada is a future player in what will be a dominant energy industry, with all the associated economic, environmental and social benefits. The accelerated implementation of fusion energy will help reduce air pollution and greenhouse gas emissions, while also allowing growth in the use of energy. This development path is particularly important, as developing and third-world nations become more industrialized and increase their energy usage, standard-of-living, and quality-of-life.

An investment in the development of fusion energy can have a much larger impact towards reduction in long-term air pollution and greenhouse emissions than other smaller programs in Canada to reduce domestic emissions. As outlined below, it would be strategically advantageous for Canada to pursue a bold new program with a vision of becoming a significant world player within a five-year time period, and a world leader by the year 2030.

A new Canadian National Fusion Program would require an initial investment of approximately $25M per year over the first five years from the federal government, matched by additional provincial contributions. It would lead to an initial assessment review in 2020 to determine the path forward to an engineering "demo" fusion system, to be operational by 2030. This effort could involve Canada's participation in one or more international demo projects or a project that Canada would lead. This effort would likely require an investment on the order of $100M per year of federal funding from 2022 to 2030, potentially supplemented by contributions by provincial governments and private sector investors.

A. Magnetic Fusion

It is very likely that demonstration of a burning plasma with net energy gain will be made in ITER. However, commercial viability of an ITER type high aspect ratio tokamak reactor is questionable because of its large size, complexity and capital cost. It operates at a relatively low-beta, the ratio of the thermal energy density to the magnetic energy density, which increases the size of its magnets and adds substantially to capital costs. This problem can been resolved in a Spherical Tokamak (ST) which is characterized by small aspect ratio and larger plasma current. The low aspect ratio and the D-shaped plasma cross-section of spherical tokamaks provide strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature. The key advantages of spherical tokamaks include high beta operation with improved plasma stability.

However, in spite of high beta, spherical tokamaks suffer from low plasma pressure due to the drastic change in the magnetic field across the plasma volume. Increasing the plasma pressure would require strong magnetic field which can be achieved by installing superconducting magnets. Despite the challenges STs may face as full scale fusion reactors, they have great potential to become compact fast neutron sources [MF11] for various applications including studies of neutron-material interactions and hybrid fusion-fission reactors.

A program is proposed for research on such ST systems and can be divided into two phases. The first phase is the near-term capacity building phase followed by the establishment of the Canadian Magnetic Fusion Research Center. Such a Centre would require a new spherical tokamak system, and an opportunity exists to acquire such a tokamak. The device, called ST-40, is available from a private fusion R&D company in UK called Tokamak Energy, and could be brought to the University of Saskatchewan. The ST-40 (Figure 18) is a modern spherical tokamak which has many benefits including a compact size with lower initial capital investment and higher efficiencies. In particular, ST will use high temperature superconducting coils producing unusually high magnetic fields to confine plasma in a compact geometry. ST-40 will replace the nearly 30 year old STOR-M tokamak to significantly enhance our research capabilities and to train personnel for future fusion research.

Future research topics on the ST-40 tokamak will focus on physics and engineering issues related to tokamak reactors, including better understanding of confinement physics and a novel fuel delivery technology based on compact torus injection. It should be pointed out that the ST design includes a D-T fuel option with the potential to be a fast fusion neutron source. Communication with Tokamak Energy has started for potential relocation of the ST-40 to the University of Saskatchewan began in August 2015. The associated costs of implementing this system at the University of Saskatchewan would be of the order of $25M. Annual budget for operation and research is estimated to be $5M with the following personnel: 5 PDF/RA, 5 PhD (RA), 2 Res. Eng. , 3 Technologists, Students (Total salaries ~$1M/yr).

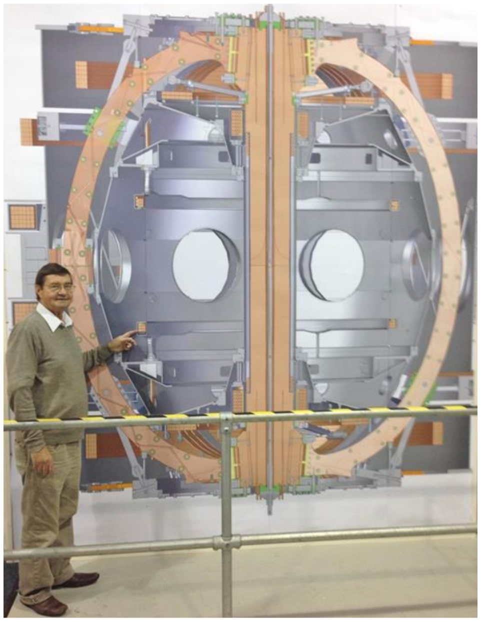

Figure 18. Life-sized diagram of the ST-40 tokamak

The second phase involves the design and construction of a spherical tokamak STOR-U as shown in Figure 19, with emphasis on the following aspects: (1) simplified tokamak design by removal of central solenoid and coaxial helicity injection for current start-up, (2) steady state operation through quasi continuous AC operation, (3) innovative technology development including Lithium coating of plasma facing components and fueling based on compact torus injection. STOR-U will be a medium-size tokamak and estimated cost will be in the range of $40M (for the hardware alone) and $100M (including building the axillary heating). The annual operating and research budget will be around $20M.

This facility will be sufficiently large to become a national facility, with the involvement of groups across Canada, and would allow Canada to make significant contributions to magnetic fusion research, drawing significant international collaborations from other countries.

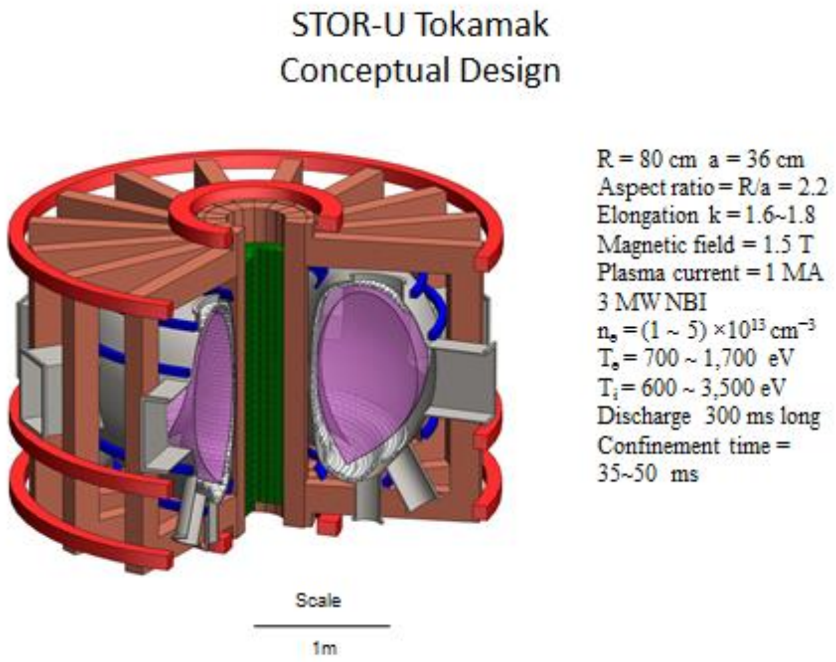

Figure 19. Conceptual design of the STOR-U tokamak

B. Inertial Fusion

The University of Alberta, ABCTech and the Alberta/Canada Fusion Technology Alliance have carried out a number of studies of the status of fusion energy development, and laser fusion energy approaches in particular, for the Government of Alberta over the past several years [IF13, IF14]. These have culminated in proposals for a 5 year capacity building fusion program followed by the development of a scale laser-fusion research institute in the following 5 year time scale. The capacity building program is focused on knowledge transfer from other leading research programs around the world and will lead to 3 new University Professor positions, 5 Research Associates and Post Doctoral Fellows, and training of 15 graduate students on an ongoing basis. The strategy will be to hire and place people in a number of the leading research programs around the world to investigate various approaches to laser fusion primarily focused on advanced ignition techniques, and train Canadian-based High Quality Personnel (HQP) in the state of the art research. Only a small amount of infrastructure would be funded in order to have a small resource base at the University of Alberta for laser and diagnostic development.

Based on the expertise built up, a world leading program can be developed in laser fusion research and development. At the same time, the USA will be reviewing the status of their laser fusion program and thus this would be a key assessment period. This gives the opportunity for Canada to take the lead in developing an international consortium to build a demo laser fusion reactor system since the laser fusion programs in many of the leading countries are tied to their weapons programs and thus are not applicable to an international civilian program. The European HiPER project proposal, the Livermore LIFE proposal and the Japanese LIFT proposal are three concept proposals, currently sitting on the shelf, for such a civilian program but without any specific decision on the exact approach to be employed. Of these, the HiPER proposal focused on advanced Shock Ignition appears to be the most promising currently.

In order to be in a position to take a lead role in a civilian laser fusion program, Canada needs to rapidly build up its base of expertise in lasers, laser-plasma physics, inertial fusion physics and target development. The $25M proposal for capacity building will be submitted to the Albertan government in the next month by the Alberta/Canada Fusion Technology Alliance (ACFTA). The University of Alberta already has recognized the urgency in spearheading the laser-fusion effort by announcing the funding of four new academic professor positions in support of this area with advertising for hiring already under way. However, a major buildup of infrastructure and a targeted development program are also required in order for Canada to be major player in this area. Three immediate areas are required: a major laser development project to acquire the capabilities to build the required kilojoule class driver lasers; a significant laser-plasma interaction facility allowing the study of critical advanced ignition physics under real high energy plasma conditions; and a targeted program in shock ignition which currently appears to be the most favorable in terms of advanced ignition concepts.

A laser development program could target the development of a high-efficiency 100-J, 10-Hz diode pumped laser system based on Yb:YAG ceramic laser disks. Such systems look promising for achieving overall wallplug efficiencies of greater than 10% as laser drivers, and also would be useful for high energy industrial applications such as shock hardening of metal tools and surfaces. Scaling to the 1kJ pulse level at a low repetition rate avoids large engineering costs in high efficiency cooling systems and high continuous power supplies. Such a five year program would cost around $15M and employ 4 research scientists, 2 support personnel and train 2 graduate students per year. It is expected that this project would have a large potential for spin off applications in laser technology and applications generating many highly skilled jobs in the process.

A laser plasma interaction facility (LPIF) is a necessary component of any internationally visible laser-fusion program. Such a facility requires both a high energy laser to form the high temperature and high density plasma conditions similar to real fusion implosions, together with an intense short pulse laser to interact with and probe the plasma. This would allow studies of the advanced ignition schemes of Fast Ignition and Shock Ignition for laser fusion energy. A kilojoule laser and building expansion to house it would cost around $7M and the short pulse interaction laser would cost around $10M for a total project cost of around $26M. This would be a leading world class facility for such studies and employ 6 researchers, 3 support personnel and train an additional 3 graduate students per year.

A targeted program with worldwide collaborations to accelerate investigations of Shock Ignition would require on the order of $5M funding over 5 years. The goal would be to participate in an international project to demonstrate Shock ignition using polar direct drive implosions on the LLNL NIF laser facility. Such scaling studies at high laser energies should verify the physics understanding and scaling models under development at present, giving confidence on predictions scaled to full reactor systems. Such a project would involve 2 researchers, 2 support staff and train an additional 2 graduate students.

It is expected that the founding of large scale programs in fusion energy will lead to the engagement of NINT in the areas of reactor materials, optical materials, X-ray microscopy systems and target fabrication. This involvement would require redirection of some of their funding resources into these directions.

All these projects will involve the researchers and graduate student already funded by the Alberta capacity building project and will lead to an internationally visible critical mass of activity. It would give a firm platform for a recommendation on participation or initiation of future expanded programs in the laser fusion area. Many of the other groups in the country involved in laser-plasma studies could also join in these activities.

These projects could also create opportunities to develop many spinoff application areas, particularly in industry and medicine. The experience in similar high-technology projects around the world has shown that once a critical mass of activity is reached, spinoff companies can develop and prosper in the technological support base that has been established, leading to many valuable highly skilled jobs and the founding of new companies, some of which will grow to be technology leaders in their field in the future. The long term economic payback from developing laser fusion energy has been assessed in an economic impact study for the LLNL LIFE power plant concept [IF15] showing large economic return on investment and growth in high technology jobs with the creation of a fusion energy industry.

C. Alternatives

i. Magnetized Target Fusion / Magneto-Inertial Fusion

General Fusion is a world leader in magnetized target fusion research, and since 2009, has built a world-class fusion research team and facilities, Figure 20 and Figure 21. However, the lack of a Canadian national fusion program and supporting research ecosystem has proven to be a significant handicap. The last 20 years has seen a significant loss of capacity in fusion and plasma physics research in Canada, and consequently a major reduction in the potential for research collaboration and the training of highly qualified personnel.

Figure 20. Prime Minister Trudeau visiting General Fusion

The lack of vigorous fusion research programs in Canadian universities means that even where funding programs (such as NSERC and MITACS) exist to help support research collaborations between universities and private sector companies or other government institutions, the university researchers do not exist or the necessary facilities are not available in order to undertake the research work relevant to General Fusion. Hiring of highly qualified individuals has also proven difficult. Generally hiring has to be done outside of Canada. However, many experienced scientists are well supported in academia in other countries and the risks of relocation, cultural differences, and the loss of benefits such as academic tenure compound to make it difficult to attract them. In the last twelve months, General Fusion has hired physicists from the USA and Russia, and continues to work to secure a senior plasma scientist to help lead General Fusion's research program.

A vibrant, healthy fusion research infrastructure and community in Canada is thus a critical element of the research ecosystem that a private company such as General Fusion depends upon in order to succeed. National leadership and government funding to support academic research and educational programs in fusion energy could support multiple initiatives that are directly relevant to magnetized target fusion research. Examples of initiatives include:

- Additional faculty positions and new experimental and/or theoretical research centers at Canadian universities, with particular interest in compact toroid plasmas and the compression of magnetized plasmas.
- Positions for post-doctoral researchers and graduate level students
- Collaborative research partnerships between Canadian university researchers and private sector fusion research, including support for research sabbaticals in the private sector
- Collaborations between Canadian researchers, both public and private sector, on international fusion research teams

Figure 21. Research and Development team at General Fusion

Support

General Fusion is ready to contribute to this initiative. Through Fusion 2030, General Fusion will continue to provide opportunities for researchers and students to work at its research facilities and look for opportunities to sponsor relevant research at Canadian universities.

To accelerate the expansion or establishment of advanced plasma physics laboratories, particularly where relevant to magnetized target fusion, General Fusion will consider contributing equipment, technology and expertise, including compact toroid plasma systems, diagnostics, data analysis and control systems, and pulsed power technology.

General Fusion continues to build an Open Innovation program which includes research collaboration visits by experts individually, as well as for group workshops and crowdsourcing challenges. Later in 2016, General Fusion will launch Aurora, a portal for research collaborators to access and analyze experimental data from General Fusion's plasma systems.

ii. Other Alternative Concepts

In Ontario, HOPE Innovations plans to explore a concept based on multiple intersecting plasma arcs, stemming from research into the nature of high-current plasma discharges [AC6]. The company will be collaborating with researchers at the University of Ontario Institute of Technology on this project. HOPE sees a significant benefit arising from access to improved modeling and test facilities, as well as access to qualified staff to assist the company with further theoretical and experimental development of its concept. To date, much of its preliminary development work has been accomplished through collaborations with researchers in China.

D. Fusion Power Plant Technologies

While it is expected that Canada would make use of fusion energy science and technology developed within the international community, it is also anticipated that Canada could make very valuable contributions that build upon its historical experience and current expertise in relevant technologies. Such technologies include those pertaining to fusion fuels (deuterium and tritium), fusion blankets, and potentially hybrid reactor technologies.

In terms of capabilities, Canadian nuclear research facilities, such as Canadian Nuclear Laboratories (CNL) have several capabilities that could be harnessed to make advances in fusion technology. Examples of CNL capabilities and facilities include the following:

1. Expertise in hydrogen isotopes (hydrogen, deuterium and tritium), including production, storage and handling.
2. Specialized, licensed facility dedicated to handling tritium and tritiated water.
3. Licensed nuclear fuel fabrication and testing facilities that could be adapted for research on fusion blanket materials and components.
4. Expertise in computational neutronics and radiation transport modeling.

A major area of strength and proposed area of activity is in all aspects of tritium, production, extraction, storage, and material interactions. Canada is a world leader in many of these areas at present, but much work needs to be done specifically for aspects related to fusion reactors. Because Canada does not have a national fusion program and has no formal linkages to ITER, Canada has limited access to the significant market for supplying tritium and tritium handing expertise to the ITER. Groups in other countries, many trained by scientists from Canada, are taking over this leadership role. It is very important that a new initiative should be established to ensure that Canada maintains its leadership in this area.

Other areas of strength include the development of improved processes for extraction and recovery of deuterium. CNL is working to commercialize new processes for this at present. CNL is also exploring options for harnessing the energy available in thorium, a fertile nuclear fuel that is nearly three times as abundant as uranium. Hybrid fusion-fission reactors (HFFR) are a technology that could be used to convert thorium into fissile nuclear fuel for use in conventional nuclear reactors, for enhanced long-term energy security.

The area of plasma-material interactions is very important for the successful development of future fusion reactors operating over long lifetimes. These interactions range from plasma bombardment to radiation damage of materials. The CNL expertise in neutron and radiation damage, combined with the expertise in plasma-materials interactions at various Canadian universities, could be exploited to tackle this area. Test facilities of various sorts will be required, such as neutron sources at CNL, traditional plasma sources such as those produced by Plasmionique in Quebec, high energy density plasma particle sources as proposed by the University of Saskatchewan and laser-based high-energy plasma and particle sources as proposed by the University of Alberta. The development and testing of materials can be accelerated considerably if multiple small samples are exposed at once to test conditions. The analysis of response and material changes in such samples could be carried out using the diagnostic and analytic tools of nanotechnology, as exists in NINT, and extrapolating to macroscopic behavior with the development of robust analytic and numerical materials models. The current level of investment in hydrogen isotope technology at CNL is approximately $5M to $8M per year with 15 to 20 scientific staff working in the field. The level of work in the areas of fusion blanket technology, and fusion reactor neutronics and radiation transport are non-existent. Effort related to hybrid reactor technology in relation to the use of thorium-based fuels is minimal, amounting to ~$100k, or 1/3 of a person-year. Additional resources would be required at other institutions to develop the plasma materials testing capabilities

Doubling the current investment in hydrogen isotope technology from $8M to $16M per year would move the program substantially forward and allow for more focused support for fusion. An additional sustained investment of $16M per year for at least 5 years would permit dedicating up to 40 scientific staff to focus efforts on fusion fuel blanket technology and hybrid reactor technology.

E. Summary

As can be seen above, there is a desire, commitment and a plan amongst Canadian researchers to build a strong internationally competitive program in fusion energy within Canada and put it back at the forefront of fusion energy development in the world. A program to do so is shown in Figure 22 below. This would require a combined commitment on the order of $25M per year over five years from federal funding, with expected matching from provincial sources to build and support programs in four key areas of Magnetic Fusion technology, Laser Fusion technology, Magnetized Target Fusion, and Alternative approaches to fusion and Power Plant technologies. This would lead to an establishment of a fusion energy demonstration project, likely in collaboration with international partners, which would build to a demo plant starting operation around the period of 2030.

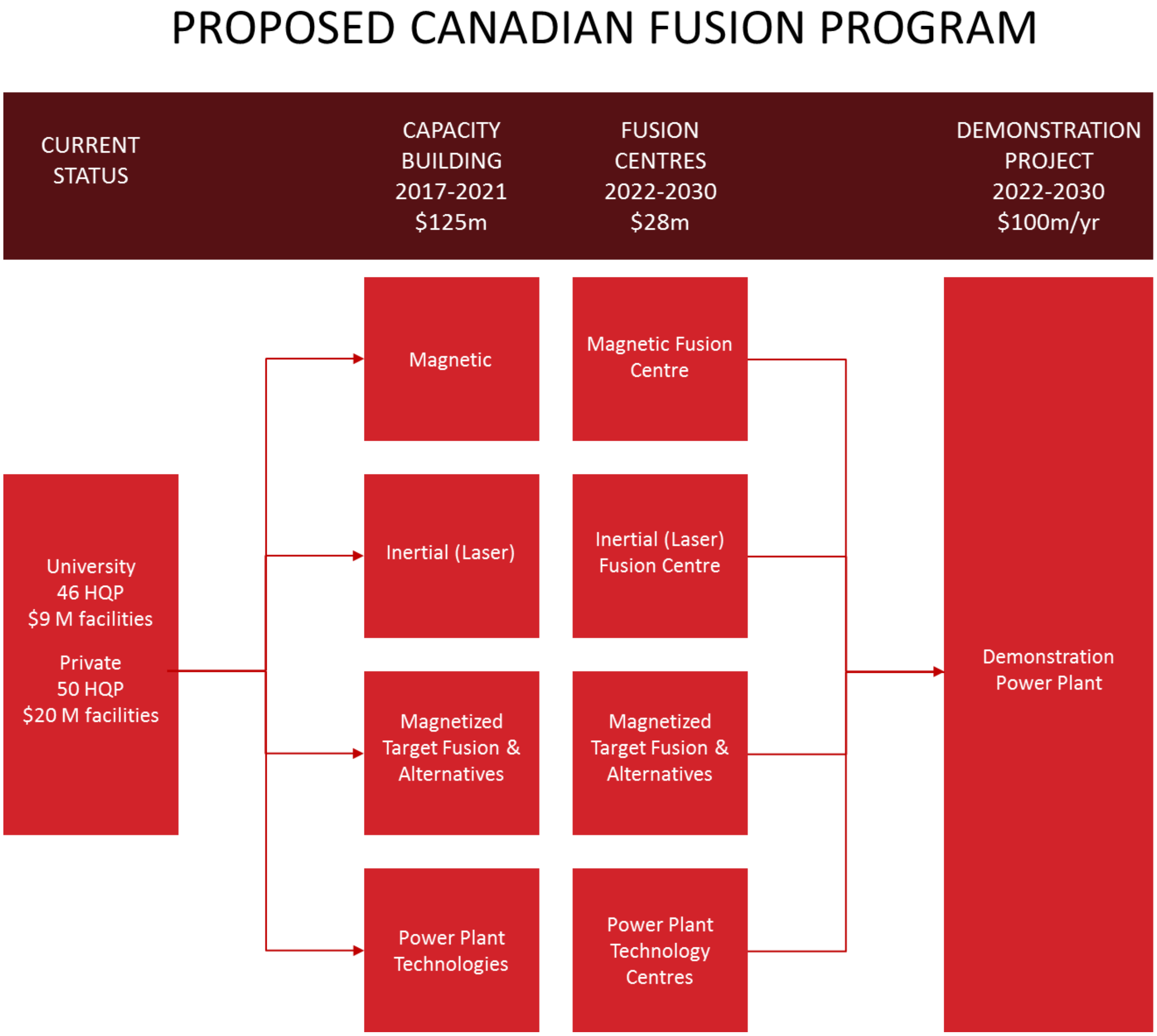

Figure 22. Proposed Fusion 2030 Program

5. Summary and Call for Action:

The world is moving forward to developing and exploiting fusion energy at an accelerating pace. Other countries, particularly the newly emerging Asian economies, are starting to “up their game”, while Canada is still on the sidelines. Canada is approaching a critical decision point, where it must decide if it wants to be a player in a future multi-trillion dollar clean-energy industry, or risk missing that opportunity while continuing to rely predominantly on its fossil fuel resource industry.

Canada has always had the capacity to be an innovation leader and it should be using that capacity to build a new leadership role in fusion energy. Some encouraging evidence of this capacity for innovation is seen with the current efforts by General Fusion in British Columbia. At the same time, a key group of expertise still exists in magnetic fusion and laser fusion energy technologies in Saskatchewan and Alberta respectively. World leading expertise on tritium technology, fusion fuels, and neutron-material interactions exists in Ontario at the Canadian Nuclear Laboratories and various universities. Smaller pockets of expertise exist on plasma diagnostics and on plasma-material interactions in a number of Canadian universities (such as the University of Toronto). Major expertise exists in supporting areas such as materials and nano-materials development, including several universities and NINT, laser and photonics in numerous programs, particularly in Quebec and Ontario, and in large infrastructure project management in the private sector. Thus, the foundation that Canada needs to build upon into a significant and effective national fusion program exists.

As can be seen above there is the strong desire and commitment amongst Canadian fusion researchers to build a strong and competitive national fusion program. This program would start with a capacity building phase of approximately 5 years to position Canada with basic expertise and facilities in the key areas currently advancing in fusion energy. This visionary investment will ensure that Canada will have highly qualified people trained, and ready to participate and grow businesses in the international fusion areas. This proposed initial investment will also help provide Canada with the necessary expertise to assess and advise on the next steps to expand this program. The next steps could lead to significant participation by Canada in an international engineering demonstration fusion reactor. It is estimated that an initial investment by the federal government on the order of $125M over five years ($25M per year), with a matching amount of provincial funding will be required.

The second phase of the program would be ramping up to the participation in a demonstration reactor project. It is too early to say at this point what this project would look like and a critical assessment review in 2020 would be carried out to assess the route or routes to follow based on the Canadian and International expertise at that time. It is expected that a number of options for fusion energy will still be viable in the long run so during this phase it is still important to continue a core capability in the various main areas of fusion research including international scale facilities and training programs. It would be expected that of the order of 1,500 highly qualified graduate degree personnel and an equal number of technical support personnel would be trained in the process. At the end point it is expected that private companies will start building commercial reactors with all the knowledge gained in the demonstration reactor system leading to the growth of a multi-billion industry for Canada. Many of the people involved will also pursue new application areas of spin off technologies which has always accompanied the growth of a new high technology sector. Normally, such spin off technology sectors are economically as important as the main goal of a given focused project in a new technology area.

Through this process Canada will build world leadership in a number of areas and build strong international linkages in the integrated high technology economy of the future. Most importantly, Canada will help accelerate the process of developing fusion energy with Canadian knowledge and expertise, contributing to ensuring long-term energy sustainability and security, while also protecting the environment, minimizing the emissions of greenhouse gases and air pollutants, and mitigating the effects of global climate change.

6. References

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Fusion Science and Technology Spin-offs

Fusion energy research is a frontier of science that draws upon a number of fundamental and applied science fields, ranging from several physics sub-disciplines to high performance computing and materials research. Advances in these areas have in turn led to new developments and technologies in fields such as medicine and manufacturing, as well as areas of research that are science, technology and innovation priorities for Canada. [1]

[The figure below] illustrates some of the potential areas for science and innovation that are particularly relevant to Canada and Canadians, and assessments of technologies and applications that have come from fusion energy research.[2]

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[1] Canada's science, technology and innovation priorities include: environment, natural resources and energy, health and life sciences, and advanced manufacturing. Innovation, Science and Economic Development Canada *Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation,* 2014. Section 4.0, pp. 19-22.

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Spin-offs include:

Fuels: Fusion reactors run on the hydrogen isotopes deuterium and tritium, which are obtained from heavy water or 'bred' from lithium. Canada has a long history of expertise in the synthesis, storage and handling of deuterium and tritium as part of its domestic heavy water reactor technology program, and the successful deployment of the CANDU (CANada Deuterium Uranium) reactor in both Canada and internationally. The same type of expertise is also being applied to developing the use of hydrogen as a transportation fuel. In addition, hydrogen produced from the electrolysis of water, using high-temperature heat and electricity provided by fusion reactors, could also be used to create relatively clean and practical synthetic hydrocarbon fuels (such as methanol), using various types of carbon-based feedstocks (such as woody biomass from the Canadian forest industry, bitumen from Alberta's oilsands, and coal from reserves in Saskatchewan and Nova Scotia).

Policy: Fusion, as with any other major energy or complex infrastructure project, will require innovations in the public policy arena including public consultation and engagement, siting, safety and regulatory affairs. The potential for fusion as a sustainable, high-density energy source will also have an impact on energy economics.

Materials: Fusion research is a driving force in materials sciences and advanced manufacturing, making use of plasmas to develop novel materials, coat surfaces to improve their durability and strength, synthesize nanomaterials, and laser technology. Plasma science, for example, is a key component of the semiconductor industry. A fusion reactor will require advances in material sciences that will lead to other innovations in materials, micromachining, resurfacing and manufacturing.

Medicine: Research and innovation related to lasers and plasmas has led to (and can lead to further) new imaging methods, ways to treat cancers using radiation, methods of sterilizing medical equipment, and the use of lasers and plasmas as tools for ablative surgery. Fusion research is also at the forefront of applying superconductor technology, which underpins the modern MRI diagnostic systems that have become pervasive in medicine.

Health: Spin-offs from fusion research have included disposing of hazardous waste through high temperature vitrification that essentially turns waste into rock, as well as methods of protecting food from spoiling, and purifying water. There are also the potential options of using a fusion reactor as a neutron source for irradiating specially-designed targets for producing medical isotopes, and also for destroying or transmuting radioactive minor actinides and long-lived fission products from spent nuclear fuel into stable or short-lived radio-isotopes for use in medicine.

Computing: The modelling and calculations required for simulating the behaviour of plasmas push the boundaries of computing power, leading to faster computers, new methods to simulate phenomena and techniques to handle large amounts of data. Along with meteorology, fusion science and plasma physics simulation has been a driving force in advancing scientific computing and supercomputing applications for decades. The techniques developed have advanced computational modeling in fields from aerospace to biochemistry.

Engineering: A fusion power plant will drive advances in almost all fields of engineering and applied science, including automation and control systems, construction, and heat transfer for power and industrial applications.

Other Technology: Fusion energy research is already leading to innovations in a variety of other fields including lasers and photonics, robotics, sensors, prosthetic joints and aerospace systems (satellite protection, propulsion).

Summary: The development of fusion energy will be a driver for leading-edge innovation in virtually all of the industrial sectors of importance to Canada. An investment in fusion will pay dividends in maintaining Canada’s position as one of the world’s leading technology developing nations.