Inertial Fusion Energy - Research at the University of Alberta and a Proposed Alberta/Canada Program

R. Fedosejevs, A.A. Offenberger, S. Singh and Y.Y. Tsui
University of Alberta, Edmonton, Alberta, Canada

Abstract

Fusion Energy is being pursued internationally using a number of different approaches from magnetic confinement energy to inertial confinement fusion (ICF). Recently there has been significant advancement in inertial confinement fusion using laser drivers with the expectation of the demonstration of large fusion yield within the next year or two opening the path to engineering of fusion reactors based on high energy laser drivers. The Laser Plasma Research group at the University of Alberta has been involved in inertial fusion energy (IFE) research for the past few decades. The current status of IFE and the activities of the University of Alberta Research group in this area is reviewed. Funding of IFE related research in Canada has been very limited and Canada has fallen behind in this area. Given the major developments occurring internationally it is time to increase activities in Canada. A plan for an expanded Alberta/Canadian program in IFE in the near future is discussed.

1. Introduction

Inertial Fusion Energy (IFE) is one of a few approaches being pursued towards the goal of building operating fusion power systems to supply an essentially limitless greenhouse gas free source of energy to the world. Recent advances in laser technology, computer modelling capabilities and in large scale experiments are leading to a more rapid advancement of this technique as compared to other approaches such as magnetic fusion energy (MFE).

The fusion reaction with the largest cross-section and thus easiest to initiate is the fusion of deuterium and tritium. Thu most current approaches to fusion energy target this reaction. The basic concept of the laser driven fusion approach is to implode a fuel capsule containing deuterium and tritium to very high densities (300-700 g cm^{-2}) in a short time scale of several nanoseconds and ignite the fusion reactions by producing a high temperature hot spot in the centre of the fuel from the stagnation of the inward kinetic energy which ignites the fusion reactions. Due to the deposition of the energy from the alpha particles produced further layers of fuel are heated and a fusion burn wave passes through the entire fuel pellet. Typical conditions for high energy gain might require of the order of several MJs of incident laser energy which would in turn release on the order of 100MJ of output energy per interaction. These interactions would occur inside a vacuum reactor vessel at repetition rates of 5 to 20 Hz.

It is expected that in the next year or two that the large National Ignition Facility (NIF) located in the Lawrence Livermore National Laboratory (LLNL) in the USA will demonstrate larger energy gain from laser heated and compressed targets. This will be accomplished with megajoule class laser and target system which have been built over the past decade. A key component of this goal will be the achievement of ignition in the centre of the compressed fuel capsule to initiate the fusion burn of the fuel and, in fact, the current experimental campaign is called the National Ignition Campaign (NIC) on account of this goal. With this demonstration it is expected that IFE will become a much stronger contender amongst the various approaches to controlled fusion energy and the door will be open to the next stage development of an engineering test reactor facility.

A number of technological developments also play a significant role in the rapid advancement of this area. The key technology required is a robust laser system in the 100kJ to 1MJ energy per pulse class operating at a repetition rate of 5 to 20 Hz. Recently a new class of ceramic based laser materials has been developed which have high optical quality, high damage thresholds, are relatively inexpensive to fabricate and are scalable to metre scale size slabs as required for such a laser system. At the same time, high efficiency, long lifetime diode pump lasers are now available to pump these laser materials. In conjunction with this, the availability of powerful 3D numerical modelling of the complex plasma processes has enabled scientist to understand and control the various processes and instabilities which are inherent in such a highly non-linear and dynamic system. Various reactor concepts have been proposed from dry wall to liquid wall systems capable of surviving the impact of energetic particles and x-rays from the exploding fuel pellets and converting the energy into heat which is eventually transferred to a high temperature steam cycle.

Further improvements to the current central hot spot ignition approach are already being proposed with the possibility of bringing the required laser energy for a full reactor system down from the several megajoule regime to the order of hundreds of kilojoule which would significantly further accelerate the advancement of the IFE approach. These include a variety of Fast Ignition techniques (using a second ultra-intense laser to ignite the fusion reactions at the side of the compressed fuel core) and a secondary shock ignition technique which uses a strong second spherically imploding shock wave to initiate the ignition. The former techniques have the additional advantage of using non symmetric compression of the fuel and allow for non uniform doping such as having a DT ignition spot followed by a DD burn region reducing the required amount of tritium breeding and recovery required.

2. The development of Inertial Fusion Energy Research to Date

The viability of inertial fusion energy has been demonstrated in the first successful testing of the hydrogen bomb in 1952. This demonstrated that indeed deuterium and tritium could be compressed and heated to the point where ignition of the fusion reactions occurs and that a burn wave can then propagate through the fuel. However, to accomplish this a large amount of mass was required to give enough inertial confinement time for the reactions to proceed before the fuel dissembled leading to the release of an enormous and uncontrollable amount of energy. With the invention of the laser in 1960 it was immediately apparent to researchers in Lawrence Livermore National Laboratory (LLNL) that lasers might allow the precise injection of sufficient energy to compress and heat a small, millimetre scale, fuel pellet to ignition conditions and release a controlled amount of energy which could be contained in a reactor vessel. This initial concept and early design calculations at LLNL were classified and only as other groups in the world started to come up with similar ideas was the approach declassified in 1972 as presented at the International Quantum Electronics Conference that year in Montreal. A number of groups around the world started to pursue this concept developing laser systems and target interaction facilities for such research. In Canada, there were research groups at NRC, INRS, the University of Alberta, and the University of British Columbia who initiated such research. Over the years steady progress has been made with the initial discovery of a number of plasma and hydrodynamic instabilities which limit the available operating window for such a scheme leading to the abandonment of the CO_2 laser driver approach which, with its 10 μm laser wavelength, stimulated a high degree of plasma instabilities at the required laser intensities. Canada, had been one of the leaders using CO_2 lasers, with the discovery of the Transverse Electric Atmospheric (TEA) laser a few years earlier by the Defence Research Board at Valcartier Quebec. In the 1980's most research programs shifted to short wavelength lasers moving into the ultraviolet region with the third harmonic wavelength (355nm) of glass laser output and Krypton Fluoride excimer lasers (248nm). Most of the University programs in IFE in Canada shrank during this period except for that at the University of Alberta where a new project on the use of Krypton Fluoride laser drivers was initiated, funded by the Alberta Energy Resources Research Fund. This major program developed new techniques for compressing the pulses to nanosecond pulse durations and studied the scaling laws for the interaction of the short pulse lasers with plasmas at intensities relevant to laser fusion.

During the 1980's the NOVA laser facility was built at LLNL with the capability of focussing approximately 60kJ of short wavelength laser light on target for fusion scaling studies. Based on the results obtained, a larger laser was proposed to reach ignition and energy gain which is the current NIF laser at LLNL. Smaller facilities were also built at the Rochester Laboratory for Laser Energetics (LLE), the Central Laser Facility (CLF) at Rutherford Labs in the UK, Laboratoire pour l'Utilasatoin des Lasers Intense (LULI) and at the Institute of Laser Engineering (ILE) in Japan. The results from the investigations in all these facilities have led to a strong understanding of the laser interaction process at the necessary intensities to drive a fusion fuel capsule leading to strong confidence in the expectation that NIF will indeed exceed energy breakeven and demonstrate large energy gains of the order of 20 or more.

In 1995 a new technique to ignite the fusion pellet was proposed using the new method for generating ultrashort high intensity laser pulses, called chirped pulse amplification (CPA), which had recently been invented. This technique relied on the rapid heating, in a matter of 20 ps, a hot spot on the side of the fuel pellet which leads to the ignition and launching of a self propagating burn wave through the compressed fuel core. This technique was called Fast Ignition (FI) and holds the promise of reliably igniting fuel pellets with overall laser system energies of the order of 500kJ, considerably smaller than the few megajoulse required for high gain reactors operating using central hot spot ignition traditionally proposed. Such a reduction in the required laser size would lead to a considerably reduced capital cost for a reactor but equally importantly would lead to a much more rapid building cycle for demonstration prototypes and reactor systems. However, while conceptually simple the laser light itself cannot penetrate into the high density fuel core and the energy must be carried in by an intermediary agent such as 1-2 MeV energy electrons or 15 MeV ions, which in turn is a whole new regime of relativistic laser plasma interaction physics which currently is being investigated. Thus, in parallel with the mainline central hot spot ignition experiments, many laboratories around the world are investigating the scaling laws and issues related to the fast ignition concept. In fact a major proposal has been put forward in 2005 in Europe to build a system to demonstrate high energy gain using the fast ignition approach. This project is called HiPER which stands for High Power Laser Energy Research Facility. Design studies are currently under way for this system in a number of European groups in a collaborative interaction.

There is also a new idea even for the central hot spot ignition technique which includes the use of a high energy spike at the end of the laser compression pulse to give a sudden pressure and temperature spike just when the fuel is optimally compressed. This technique is called Shock Fast Ignition. It also would lead to a reduction in overall laser driver energy and higher target gains. This technique appears to benefit from some reversal of some of the Rayleigh Taylor instability due to the late time high intensity shock running through the already compressed regions. These effects are seen in modelling simulations and there is some evidence that there is a positive effect in the initial experiments reported to date from LLE at Rochester.

During the period from 1990 until 2005 the activity level in IFE in Canada dropped to a very low level due to lack of targeted funding available for laser fusion research. However, in 2005, with the rapid rise internationally in interest in the fast ignition approach and the new HiPER proposal in Europe, the University of Alberta group started to pursue a larger scale laser fusion program again. University of Alberta researchers attended the initial planing meetings for HiPER and are officially recognized as international collaborators on the project. The University of Alberta group obtained joint funding from the University of Alberta and the Province of Alberta to develop a proposal for an inertial fusion energy program to carry out research and to develop expertise in the technology areas required for eventual reactor systems. A proposal for a 5 year initial program with the development of an independent research facility was developed with an approximate cost of $200M over the five years to be split between the province of Alberta and the Federal Government. Due to the economic downturn and shortage of funding to start such a large scale project a smaller 3 year, $22M start up program was developed to ramp up the manpower training and expertise in the area by collaborating with existing international research programs. The goal at the end of three years was to allow for a critical assessment of the laser fusion approach and allow for a decision on whether to commit to a full research program. More details on these proposals are given below.

3. Current Research at the University of Alberta

Since 2005, the University of Alberta research group has initiated interactions with the HiPER project design groups, the Lawrence Livermore National Laboratory and renewed a long standing memorandum of understanding with ILE in Japan for research collaboration. At the same time new Strategic Grant funding was obtained form NSERC specifically to collaborate on fast ignition experiments at LLNL. We have collaborated for the past four years on such experiments and have built up a number of diagnostic capabilities and are training an increasing number of graduate students in the area.

The main focus of the study is to better understand the generation and transport of MeV electrons from the high intensity fast ignition heating pulse. In collaboration with investigators from LLNL, Ohio State University, MIT, UCSD, General Atomics and a number of European groups the interaction of the high intensity pulses with planar foil and cone tip geometries has been investigated. Conversion efficiencies for energy form the laser pulse into forward directed fast electrons on the order of 10 to 20% have been obtained but in cone angles of the order of 60 to 100 degrees. Such large source divergence can in principle be collimated by self generated magnetic fields and current investigations are aimed at better understanding the transport process in heated plasma configurations. There is also some investigation of the fast ion approach using protons to carry the energy from the laser interaction region to the fuel core.

The University of Alberta group has contributed to this effort by developing a number of diagnostic tools including a Kirkpatrick-Baez x-ray imaging microscope, Bragg crystal imagers for k-alpha x-ray line emission form copper tracer layers in the interaction target, high efficiency x-ray spectrometers and electron magnetic spectrometers. Last year the University of Alberta group proposed and obtained beam time to carry out the first experiments at the LLNL TITAN high power laser facility using frequency doubled light at 527 nm instead of the 1054 nm fundamental wavelength used in all experiments previously. Currently the fast ignition scaling experiments are operated at less than 10% of the final intensity which will be required for fast ignition driver lasers. Already, the electrons generated are about the correct temperature for optimal coupling to the core but with higher intensities may become too hot. With the second harmonic laser pulse the temperatures are reduced by the expected intensity times wavelength squared scaling, the so called, $I\lambda^2$ scaling. Thus the same electron temperature would be achieved for four times higher intensity. A second major advantage obtained by using frequency doubled laser pulses is that the doubling efficiency scales as intensity and thus low energy prepulses on the laser waveform are eliminated in the second harmonic pulse. Given, that typically a few millijoules of prepulse laser energy exists on the typical fundamental laser pulses used today, the main pulse interacts with an extended plasma region of tens of microns rather than a steep target surface. Thus experiments at the second harmonic wavelength will lead to virtually prepulse free conditions and thus should approach ideal conditions that have been computing in the modelling of the fast ignition process.

In a four week experimental campaign last August the electron generation and transport was measured using these second harmonic pulses under the same conditions and using the same diagnostics as previous measurements at 1054nm. A reduction in electron temperature was observed for similar intensities while a similar source divergence for the initial electrons was also observed. These are in fact some of the highest intensity interaction experiments carried out with second harmonic laser pulses to date under these clean, prepulse free laser conditions. Peak intensities of the order of 5×10^{19} W cm^{-2} were obtained on target. One key result demonstrated was the ability to frequency double the pulse at 60% conversion efficiency which bodes well for the application of this technique in practice.

A few typical results obtained in the experiment are shown in Figures 1 to 3, showing, the measured electron energy distribution function for a planar target shot, the measured increase in spot size into a thick planar target observed in images of a buries copper tracer layer and a KB microscope image of the heating and transport of MeV electrons along a copper wire in a cone-wire target geometry.

(Figures 1 to 3 to be added here)

A full analysis of the data and extensive 2D modelling is under way in order to determine the best scaling laws for second harmonic interactions. Further experiments are planned this year also at the TITAN laser facility. With these results we should be able to assess the relative trade offs in benefits and disadvantages of introducing frequency doubling into proposed fast ignition fusion schemes in the future.

4. A proposal for an Alberta/ Canada Laser Fusion Energy Program

With funding from the Province of Alberta and the University of Alberta a proposal was developed for the establishment of a critical mass research centre for laser fusion energy in Canada. The Alberta/Canada Fusion Energy Institute was set up in order to develop this proposal. As part of the proposal a new research facility would be built as illustrated in Figures 4 and 5.

(Figs 4 and 5 - Research facility building and layout to be added here)

The program would include research in all major areas related to laser fusion energy from laser development to some reactor design studies. Initially people would be trained by secondment to other major facilities in the world. A large number of graduate students would also be involved in all aspects of the program in order to start training the next generation of researchers and engineers who will be require dot make fusion energy a reality.

This proposal was presented at two special symposiums, one in Alberta in 2007 and one in Ottawa in 2008 in order to inform government and industrial decision makers about the current status of IFE and the new opportunities for fusion energy reactors systems. A good turn out was obtained in both symposiums and a large cross-section audience wa sin attendance. Discussions have also been carried out with high level minsters and government officials at both the provincial and federal level.

Based on the feedback form initial discussions a smaller start up plan involving a three year ramp up of manpower at a cost of $22M was also drafted and proposed to the Province of Alberta. This plan would lead to the initial training of core researchers in various leading international laboratories in the field and gather information for a major decision point at the end of the three year build up phase. This would allow for a critical assessment to be made at that point as to whether the prospects were favourable and a major program should be pursued.

<more details will be added to this section in the final manuscript>

5. Conclusion

These are exciting times for IFE research and rapid advancements are currently occurring after years of slow steady progress in developing a better understanding of all the complex interaction processes which play a role in the interaction of powerful laser beams and matter. Parallel developments in lasers and computer modelling and control systems are equally important in being able to engineer full reactor systems with a high reliability of operation as required. Canada has played a significant role in the past research towards laser fusion energy particularly in the understanding of laser-plasma interactions and demonstration of advantages of short wavelength laser drivers. Currently, Canada has a small research based program based at the University of Alberta, participating in the exploration of the Fast Ignition approach to enhanced IFE architectures. However, if Canada wishes to be a player in the future fusion energy technologies and have a self sufficient capability to supply its own clean energy needs in the future it is essential that Canada launch a vigorous program of research and development to take advantage of the new wave of IFE fusion technologies. The window of opportunity may close fairly rapidly in the next few years. Thus it is vitally important that Canada carry out a critical assessment of the rapid advances currently occurring in the IFE area and respond to the opportunities which will arise from these developments.

6. References

[1] Too be added