Systems Studies, Accelerator Design, Target Design and Enabling Technologies for Heavy Ion Fusion

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Executive Summary

System studies and driver design codes have guided the Inertial Fusion Energy (IFE) Program since its inception 50 years ago. These activities remain critically important if IFE is to be developed as a commercial energy source. Thirty years ago these studies indicated that, compared to other IFE options, heavy ion fusion (HIF) was particularly attractive [1, 2]. But, since the early 2000's, the HIF program has been a small, science oriented program with little emphasis on driver technology or commercial power production. A renewed interest in IFE, and particularly HIF, as a commercial energy source requires the development of new, state-of-the-art systems and accelerator design codes to guide the program and to reassess the promise of HIF [3].

Although in recent decades there has been little effort on HIF as an energy source, there have been revolutionary developments in related fields of science and engineering. These developments include dramatic advances in computers and the simulation tools required for studies of ion beam dynamics. On the experimental side, the FAIR heavy ion facility being constructed in Germany also offers opportunities for HIF research [4]. Current research on the miniaturization of accelerator components for multiple beams at LBNL could lead to significant cost reduction for high power beams. Moreover, important advances in high power switches, superconducting science and technology, and automated (robotic) assembly lines have opened new possibilities that plausibly lead to a greatly improved vision for HIF. These developments are discussed in the other white papers in this group [5, 6, 7]. This paper discusses proposed systems and design studies needed to coordinate and guide the other program elements.

Introduction

Heavy ion fusion (HIF) was first proposed by A. W. Maschke in 1975. Maschke observed that the conventional accelerator technology of that time already had many of the characteristics needed for inertial fusion energy production (IFE). Specifically, accelerators were reliable and efficient. They could be fired at high pulse repetition rates and they had useful lifetimes of several decades. Heavy ions, rather than the more common electron or protons, were appropriate because their short range in matter was necessary to provide the high energy densities needed for IFE.

One particularly important characteristic of accelerators is the transport of beams in vacuum. The beams are accelerated and focused by electromagnetic fields so there is no medium that can deteriorate with repetitive use. This is particularly important for final focusing onto a target since the final focusing elements must survive in a harsh fusion environment, and the electromagnets themselves can be shielded from the direct line of sight from the target explosion.

All these characteristics of accelerators led nearly all IFE review committees to conclude that HIF was the most promising approach to IFE [8-12]. Moreover, in about 1992, the Department of Energy commissioned studies showing that the HIF had favorable economics compared to the leading laser option of that period [1, 2]. Nevertheless, the various magnetic fusion, laser fusion, and pulsed-power fusion programs were already well established and it was difficult to develop the political support necessary to fund an aggressive HIF program. Undoubtedly one problem was the high cost of any fusion driver (> $1B in 1990 dollars if one were realistic). Perhaps more importantly, the advent of the National Ignition Facility (NIF) led to a "wait-and-see" attitude regarding IFE. In particular, the HIF program for energy production was largely placed on hold.

The promising results on NIF have now opened the possibility of a renewed IFE program. But the situation involving HIF has changed. There has been remarkable progress on solid state lasers, excimer lasers, and pulsed power as well as on the magnetic approaches to fusion. So HIF faces a more competitive environment than it did 30 years ago. The new important question is: Can HIF still compete?

The proposed program in systems and accelerator modeling and design, in connection with the activities described in accompanying white papers [5, 6, 7], will address this critical question. If the answer is affirmative, the studies will guide and define the program necessary for HIF to be a success. Preliminary results show promise.

Some of the key fusion parameters under consideration are shown in Table 1.

Parameter	Value	Reference
Target fusion gain	50 - 300	[13, 14, 15]
Driver pulse energy	1-10 MJ	[15, 3]
Driver wall plug efficiency	30-50%	[16]
Power output	0.3 to > 2 GW (switchyard, multiple chambers)	
Pulse repetition rate	5-10 Hz	[3]
Ion mass	40-238 amu, Ar - U	[3]

Table 1: Main fusion parameters under consideration for the proposed research.

The Technical Situation

Figure 1 shows a section of a typical induction accelerator for HIF. It consists of an induction core made of magnetic material (made of the low-loss, metallic glass ribbon used in commercial transformers) surrounding a cluster of beams transported in vacuum and confined to the beam pipe by arrays of superconducting quadrupole magnets. Basically, an induction driver is a transformer in which the beam(s) are the secondary "winding". That is the reason that these drivers can be very efficient. Major cost centers for such an accelerator are the magnetic material in the cores, the pulsers to drive these cores, and the beam transport system.

The most recent study of an HIF power plant was completed about two decades ago [17]. This point design (called the Robust Point Design or RPD) had the following features:

1. An indirectly driven target requiring a driver energy of approximately 6 MJ.
2. A reactor protected by thick liquid streams of molten salt — leading to long life.
3. Current state of the art switch (pulser) technology to drive the acceleration modules.
4. Current state of the art superconductors for the magnetic beam transport system.
5. Current state of the art methods for magnet fabrication and magnet precision.
6. Magnetic final focusing lenses not corrected for known 2nd and 3rd order aberrations.

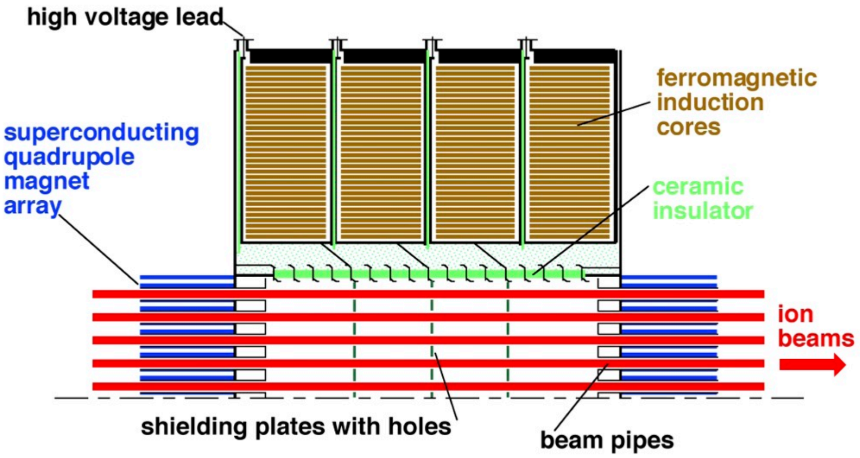

Figure 1: Schematic of one-half of a lattice period in a multi-beam induction accelerator [18].

Putting these parts together in a self-consistent, optimal way requires complex systems codes. The codes of that period were extremely useful; but, partly owing to the limitations in computing power, they usually relied on simple approximations for important scientific and engineering details. And, more importantly, they seldom had the capability to optimize the entire system. Nevertheless, the features listed above appeared to be remarkably self-consistent.

First consider the target. Early simulations of directly driven targets for HIF [14] typically showed an energy gain of 100 - 300 at an input energy of 1-2 MJ. For that matter, directly driven laser targets still do. But these targets had some disadvantages. Some of these, such as stringent beam alignment specifications and stringent beam quality requirements are shared by directly driven targets for all drivers. But, critically, there was no HIF facility to develop these targets. Therefore, as a programmatic, but not necessarily scientific matter, the HIF program chose indirect drive as a base case. This meant that much of the target physics could be done by lasers. HIF had only to provide an appropriate radiation environment. In addition, the two-sided illumination geometry needed for indirect drive was compatible with thick-liquid wall protection for the chamber.

Thick liquid walls solve many of the problems associated with the activation and deterioration of other chamber options. On the negative side, thick liquid walls also limit the pulse repetition rate. But, since the indirectly driven targets require a lot of driver energy, and produce a lot of yield per shot, they are compatible with thick liquid walls. In summary, using indirectly driven targets, high driver energy, and liquid walls leads to a robust program with an attractive chamber. But the cost is in the driver scale that is required to drive the assumed targets. This was not considered an independent problem because items 3 to 6, in the above list, also seemed to require large scale. In particular, the thyratron switches of that era were relatively slow compared to modern standards. The slower switches are compatible with large induction cores requiring large quantities of magnetic materials. The existing superconductors and magnet fabrication techniques also favored large beams that are compatible with the large induction cores. And, unless one was willing to develop systems to correct for magnet fabrication and alignment errors, one needed large magnets anyway. Finally, target scaling is such that required beam energy decreases rapidly as the beam focal spot radius decreases; but, since the other considerations had already dictated large systems, it didn't appear necessary to design corrected optics.

In summary one question that is currently important is whether one can develop a self-consistent picture of a system that is much smaller in scale, and in cost [19]. An affirmative answer to this question would lead to an attractive development path — and make HIF far more competitive with other fusion options. The high efficiency of HIF drivers may decisively tilt the IFE program toward HIF if the current IFE target calculations are optimistic. Developing this self-consistent picture, and guiding the research needed to achieve it, are the goals of this proposed new effort in systems studies and accelerator design. We estimate that the computational part of this effort is small, probably 2 FTEs. But, in conjunction with the other proposed activities, it could have a profound effect. We discuss this more in the next section.

Outlook

Consider each of the six items listed above. Before the HIF program was put on hold, Callahan and Tabak had designed [13] indirectly driven targets that required about half the energy of the RPD design. And, as noted above, direct drive, with or without things like shock ignition or fast ignition, might lead to even lower energy requirements. Smaller yields would require higher pulse repetition rates than the larger targets. This might require the use of chambers that are similar to the ones commonly proposed for lasers, but it is an option that should be evaluated. Another interesting option is to use multiple chambers. Large accelerator complexes, before the advent of colliders, were often designed with beam switchyards to serve multiple experiments at once. During development one would start with a single chamber or multiple chambers of differing types. This is another avenue that should be explored as it leads to an attractive development path, particularly for reactor systems.

In order to design an attractive accelerator for lower target energies, other changes are desirable. There has been good progress in fast switches for induction linacs. This progress enables the new Scorpius induction accelerator [20] for radiography to operate at pulse durations of 50 ns compared to say the 200 ns that has been typical of previous HIF designs. But the new switches are still more expensive (per watt) than the older thyratrons, so cost reduction is of critical importance.

For a given acceleration gradient using 50 ns rather than 200 ns would allow the difference between the outer radius and inner radius of the induction cores to be reduced by a factor of four Since the amount of magnetic material scales more rapidly than linearly in this difference, the reduction in core material is more than a factor of four. But, for a given target energy, shorter pulses mean higher beam current through the cores. The allowable current per beam scales approximately as Ba where B is the magnetic field and a is the beam radius. Since the area of the beam scales as a^2, one can transport more current and/or reduce the inside radius of the induction cores by increasing B and/or by using a larger number of smaller beams. Previously existing superconductors limited B and placed a practical lower limit on the bore radius and therefore a. Both constraints appear to have been obliterated in the last two decades by the development of superconductors that allow both very high fields and very high electrical current densities. But, as noted above, the cost of fabrication and the difficulty of building small magnets with the required tolerances have strongly pushed designs in the direction of fewer, larger beams — leading to large inner radii for the induction cores. The tolerance issue can be addressed with a system that accurately senses the beam position and corrects for imperfections. But in the past fabricating such a system and processing the enormous quantities of data presented formidable difficulties. The cost of the materials for such systems is low, but the fabrication costs have been assumed to be high. Modern automated production of the parts appears to be capable of lowering the fabrication cost for both the magnets and the sensing and correcting systems. And any small modern computer can easily handle the data analysis.

Robotic production of magnets was being explored by Rainer Meinke before the HIF program was placed on hold [21]. Work in this area will need to be revived. Finally, with targets requiring less energy, it may become more important to develop corrected optics. This will be one of the goals of the beam physics simulation program. Corrected optics will also become more important if we choose to increase the beam current density by increasing B rather than reducing a.

In summary, there are several new technologies that, when used in tandem, appear capable of greatly improving the economics of HIF drivers. The use of modern computers and new systems and design codes will guide and evaluate the development needed to adapt these new enabling technologies to HIF.

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