Advances in Commercial ICF Technology Since 1986

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ADVANCES IN COMMERCIAL ICF TECHNOLOGY SINCE 1986

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ABSTRACT

Progress in the march toward commercial ICF fusion reactors has been uneven in the past few years. Considerable advances have been made in the area of light ion beam fusion through the development of rep ratable drivers (i.e., HERMES-III technology) and diodes (i.e., applied B configuration with renewable Li surfaces). Significant progress in the development of lasers to compress targets has also been made through the KrF Aurora program. The possibility of lowering the cost of glass in the advanced solid state lasers has been given serious consideration. The development of the Induced Spatial Incoherence (ISI) technique to improve the uniformity of the laser beam has allowed physicists and engineers to once again contemplate the use of symmetric illumination. This would reduce the driver energy required to achieve high gains but it also introduces difficulty in the reactor design. Relatively little progress in commercial heavy ion beam drivers has been made over the past few years aside from an indepth study (HIFSA) of the desirable operating regimes to be pursued. Other areas where little progress has been made are conceptual reactor studies, target declassification and specific experimental programs to address commercial ICF reactor technology needs.

INTRODUCTION

The use of inertial confinement to produce fusion reactions has been studied for over 25 years.[1] From a civilian standpoint, the objective has always been to produce electricity and the original concept of using laser light to compress a DT mixture was expanded to include electrons in 1968,[2] light ions in 1971,[3] and heavy ions in 1975.[4] It took ten years from the first ICF studies before a conceptual fusion reactor was proposed.[5] During the 1970's and early 1980's there was a considerable amount of activity with respect to commercial reactor concepts and the unique technology required to build such reactors. The object of this paper is to review the state-of-the-art in commercial fusion technology since the 7th Topical Meeting on The Technology of Fusion Energy held in Reno, Nevada in 1986. This paper will not address the work in physics nor the progress in present day experiments. Neither will it address the proposed next step for the U.S.-ICF program, the Laboratory Microfusion Facility (LMF). Instead, it will concentrate on those aspects of ICF technology that contribute directly to commercialization even though some aspects of an LMF type facility may indirectly impact on ICF reactors.

REACTOR STUDIES

Up to the 7th Topical Meeting in 1986, there had been 39 conceptual commercial reactor studies performed around the world.[6,7] Since 1986 only two studies have been published (SIRIUS-M[8] and LIBRA[9]). The number of these studies are grouped in 5 year periods (except for the 1986-88 period) in Fig. 1 starting from 1971 through the present time (1988). It can be seen that the majority (27) of the studies have had to do with lasers while there have been 8 electron or light ion beam (LIB) investigations and 6 heavy ion beam (HIB) designs. Roughly 80% of the studies have been done in the U.S. with 20% being done in Japan or Germany.

The striking feature about Fig. 1 is that the design activity had been steadily increasing through 1985 but in the past 3 years (roughly since the start of the LMF study) only two commercial reactor designs have been reported. It is also worth noting that while there were 6 HIB conceptual designs in the 10 year period from 1975-85, none have been reported in the past three years and, to the knowledge of the author, only one is in the planning stage.

The precipitous drop in the commercial ICF reactor area is counter to the steady progress being made from the current laser and ion beam experimental facilities. However, this pattern is similar to that observed in the magnetic fusion program when the major design teams were focussed on "next step" facilities in the period from 1980 to the present time. It is possible that the same teams which produced the 39 commercial designs from 1970-1985 will be turned toward the LMF[10] in the late 80's and early 1990's.

One bright note in this otherwise sober situation is the recent indication by the U.S. DOE that it intends to devote 4 M$ (or ~ 25 person years) to ICF design in the 1989-91 period. This may help to reverse the trend shown in Fig. 1.

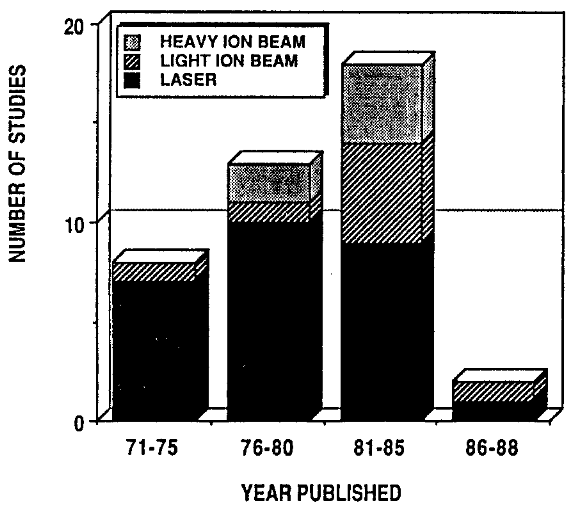


Fig. 1. Summary of commercial ICF reactor studies over the past two decades.

DRIVER TECHNOLOGY

There have been two recent (1988) publications that summarize the state-of-the-art in ICF driver technology.[11,12] The first is a report on the "Status of Candidate Drivers for a Laboratory Microfusion Facility"[11] and the second is the "Proceedings of the Third Inertial Confinement Fusion Systems and Applications Colloquium".[12] Both of these reports cover the laser, light ion and heavy ion approaches.

Commercial Laser Drivers

There are now two major laser programs that could provide drivers for commercial fusion reactors: the KrF program at LANL[13] and the glass laser program at LLNL.[14] The KrF program is currently engaged in bringing the Aurora laser on line at the 10 kJ level in the 1989-90 period.[15] The major advantages of this laser are: its short wavelength (248 nm), the potential for wall plug efficiencies in the 10% range, its rep ratability, and scalability to multimegajoule levels.

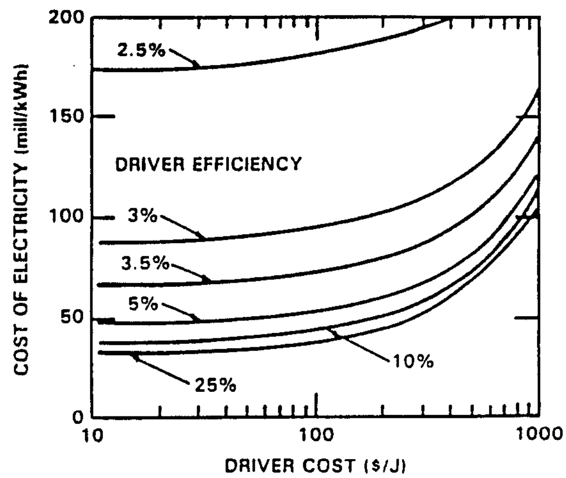


Fig. 2. Effect of driver efficiency and driver cost on the cost of electricity from an ICF power plant with a target gain of 100 and a target energy of 5 MJ.[15]

The importance of driver efficiency on the cost of electricity and the allowable driver cost is shown in Fig. 2.[15] Assuming that drivers for laser induced fusion of non-symmetrically illuminated DT targets require at least 5 MJ, it is easy to see why driver costs have to be < 100 $/J in order to compete with other energy sources. Figure 2 also illustrates why driver efficiencies must be above 5% to keep the COE below the 40-50 mills/kWh considered now to be the long range target for electricity generation. While there is no current funding to demonstrate large scale (~ 0.5-1 MJ) KrF operation, designs for such facilities are currently being studied at Los Alamos.

Glass lasers were traditionally viewed as the mainstay of the current ICF experimental program but not extrapolatable to a commercial system because of 1) system efficiencies, 2) the difficulty of rep ratable operation, and 3) cost of the glass. Within the past few years these views have changed due mainly to the efforts of LLNL scientists. Advances in rare gas flashlamps and 2-D AlGaAs semiconductor laser diode arrays (LDA) have raised the anticipated wall plug efficiencies considerably. It is now anticipated that wall plug efficiencies of 10-11% can be achieved with the rare gas flashlamps.[16] The LDA's have been used to pump Nd lasers with wall plug efficiencies of 16% and 25% is anticipated in 1988 using recently available 60% arrays.[17,18]

The rep ratability of a glass laser system depends mainly on the rate at which waste heat can be removed from the lasing medium while preserving optical quality. Brewster slab amplifier geometry[19] cooled with nitrogen or helium gas has already demonstrated the ability to remove more than 2 W/cm^2 while maintaining high beam quality.[20] Indications are that 5-10 Hz rep rates will be feasible from multi-MJ advanced glass lasers.

The high cost of laser glass has also been addressed by LLNL scientists. While the actual cost of glass per cm^3 dropped by more than a factor of 5 between the Shiva and Nova facilities (see Fig. 3);[21] LLNL scientists are projecting another factor of 10 drop for a multi megajoule laser. These and other modifications to a large multi megajoule glass laser system are also projected by LLNL scientists to bring the cost of the driver to 50$ per joule. While such a projection is controversial at this time, verification of that number for the LMF could have a very large impact on the potential of glass lasers for commercial ICF reactors.

Commercial Light Ion Drivers

Significant advances in the past few years have increased the possibility of testing multi-MJ rep ratable drivers for light ions. Specifically, the HERMES-III technology[22] (Fig. 4) has

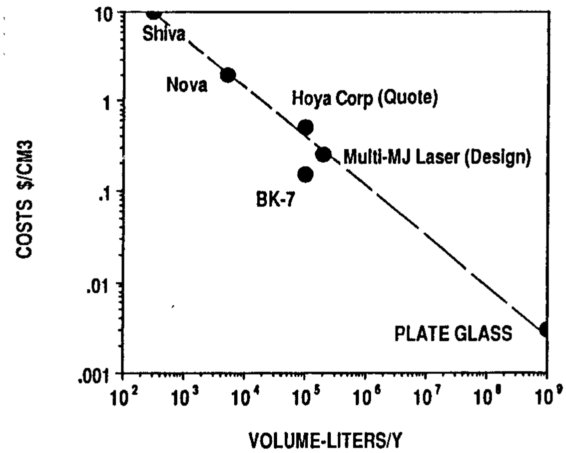


Fig. 3. Reduction of the cost of laser glass as the production volume increases.[21] Quote by Hoya Corp. from Reference 35.

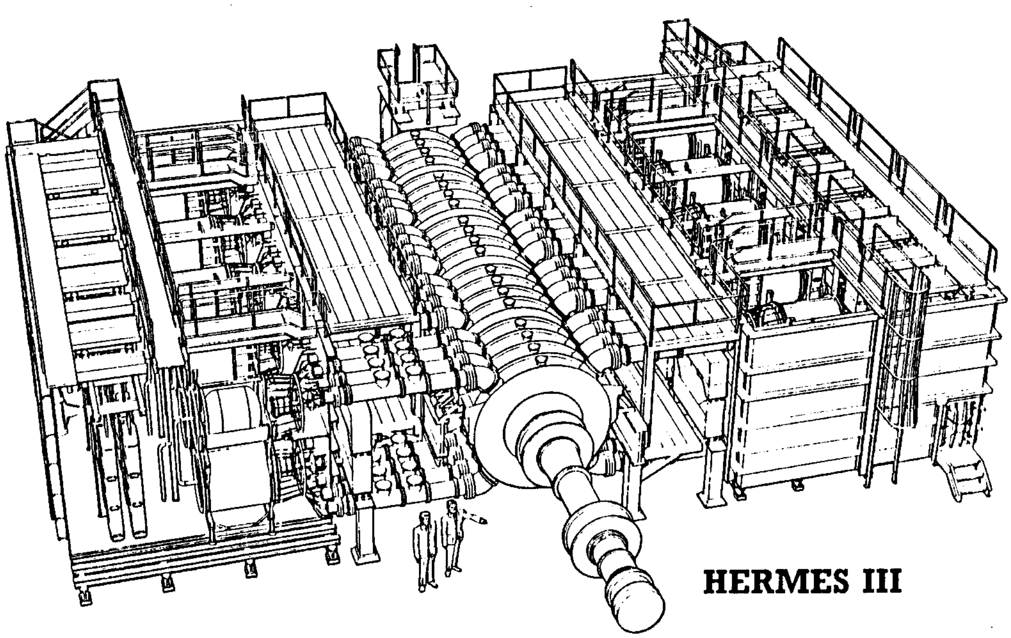


Fig. 4. Schematic of the HERMES-III Pulsed Power Facility at Sandia National Laboratory - first shot February 1988. This driver technology could be extrapolated to a commercial power facility.

already been demonstrated with electrons (first shot Feb. 1988) at 20 MV, 730 kA, and a 40 ns pulse width. By late 1988 the facility has demonstrated that it could be discharged with a 20 minute shot sequence and it will be configured positively in the near future for experiments with Li^+ ions.

It is possible to envisage rep ratable operation by replacing the water dielectric switches with magnetic (saturable reactor) switches like those developed at LLNL.[23] This technology has been chosen by Sandia National Laboratory as the basis for their LMF design and by commercial reactor designers for the LIBRA reactor.[9] While the experimental verification of good focussing with such switches remains to be demonstrated, this coupling of existing facilities with concepts which could be used in commercial reactor studies has greatly strengthened the connection between the present day experimentalists and the designers of future civilian applications.

Commercial Heavy Ion Fusion Drivers

The situation for commercial drivers in HIB fusion has not progressed much over the past two years. This probably stems from the low funding level of this area and because the cost to build even a demonstration sized reactor appears to be prohibitive. A comprehensive assessment of the merits of both RF and linac accelerator systems was recently published.[24] While the report favored the U.S. approach (induction linac's), there is sufficient uncertainty that the RF accelerator approach followed by the Europeans, Japanese, and the USSR cannot be ruled out at this time. One thing that is clear is that rep ratable operation in any HIB driver is not an issue.

The main research effort on HIB fusion in the U.S. is at the Lawrence Berkeley Laboratory (LBL) which has been operating the Single Beam Transport Experiment (SBTE) since 1983 and the MBE-4 facility since 1987.[25] The next step is a device called ILSE[25] which would scale the injector technology to 2 MV and increase the number of beams from 4 to 16. It would also study transverse stacking, magnetic focussing of carbon in the 4 to 10 MeV range, study drift compression physics, and focus the beam to a few mm in size. The energy of the beam would be 100 J compared to the 10 MJ required for a reactor. This device has not been funded yet.

Other efforts in HIB research[26] are being conducted at Darmstadt in Germany which is completing the GSI synchrotron and in Japan which is operating the TARN-II accelerator. In the USSR a prototype module for the first section of an RF linac for ICF is in operation.

It is clear that there is a long way to go in driver development for HIB fusion and at the present rate of effort, it will be well into the 21st century before anything approaching a commercial driver can be contemplated.

TREND TOWARD SYMMETRIC ILLUMINATION

It has been thought for some time that symmetric illumination of a target would not only require less energy to achieve a given yield (see Fig. 5) but that it would also allow the use of unclassified, relatively simple targets to be considered. The problem has always been that the requirements on the uniformity of irradiation were so strict (to achieve implosion stability) that it was thought to be nearly impossible to achieve those conditions. Another problem lies with the geometry of the reactor cavity that has to accommodate 10's of beams at nearly equal angles. This precludes the conventional forms of first wall protection (e.g. flowing streams of liquid metals, rotating solid particle beds, etc.) and may require graphitic first walls or porous walls coated with thin films of liquid metal. Therefore the wisdom of the 1970's and early 1980's was that asymmetric illumination (see Fig. 6) and classified targets would be needed for ICF reactors.

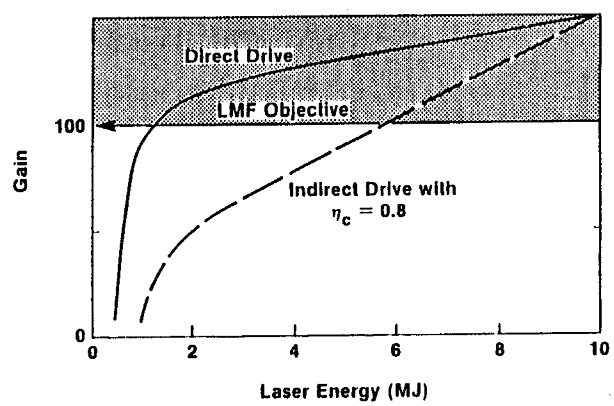
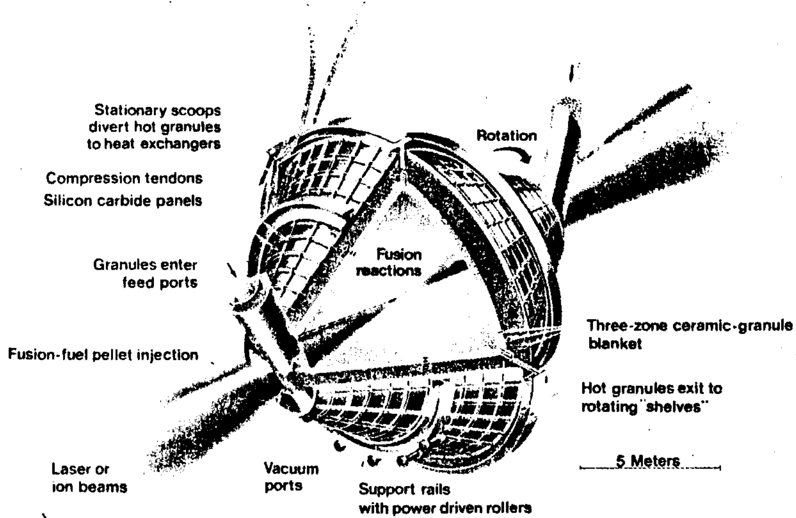
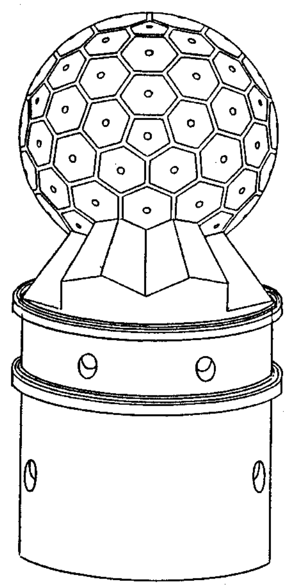


Fig. 5. The effect of direct drive (or symmetric illumination) on the gain of ICF targets (1986 Laser Annual Report, UCRL-50021-86, November 1987).

Significant progress has been made at NRL[27] and the University of Rochester[28] in the demonstration of high quality uniform laser beams on targets. The development of the Induced Spatial Incoherence (ISI) technique to smooth the beam has allowed physicists to seriously consider symmetrical illumination as a method to achieve high gains (see Fig. 5). Several recent reactor designs have used the symmetrical illumination concept for power production,[29] materials testing[8] and the production of tritium.[30] Future experiments on the Omega laser at Rochester at 10-20 kJ will be critical to show that this concept has the potential for reducing the energy of a commercial laser from 10 MJ or more to ~ 1 MJ.



a)



b)

Fig. 6. Example of laser reactor cavities for (a) non-symmetric illumination (CASCADE) and (b) symmetric illumination (SIRIUS-T).

REP RATABLE DIODES FOR LIGHT ION BEAM FUSION

In addition to a commercial light ion driver that can fire 1-10 times per second, it is imperative that sources for the ions be developed at an early time. Researchers at Sandia National Laboratory have recognized this critical research area and are developing a Li ion source that can be fired on a repetitive basis. The applied B diode[31] (see Fig. 7) appears to have the renewable features required for rapid firing and this source will be tested in the near future. Two methods of renewing the lithium surface are now being tested: the electrohydrodynamic (EHD)[32] and the Bolvaps/Libors approach.[33] Designers of LIB reactors have already included such concepts in the LIBRA study[9] and, in contrast to a few years ago, have developed more credible reactor scenarios ranging from the driver (HERMES-III) to the diode (applied B with renewable Li surfaces). Areas still in doubt are the method of propagating the beam to the target (e.g., ballistic or channel transport) and obtaining the required brightness on the target.

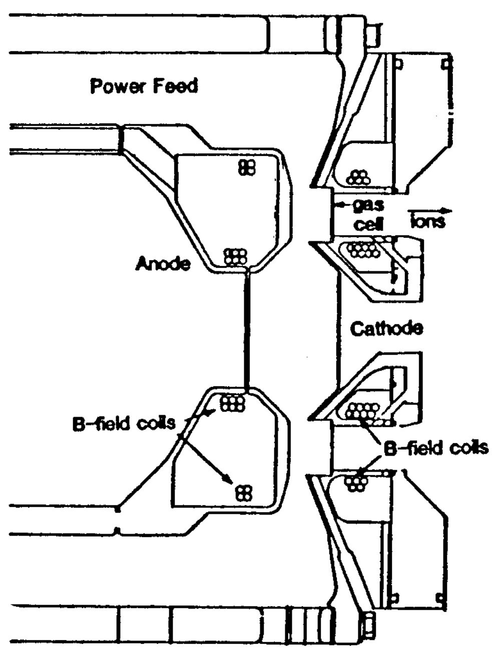


Fig. 7. Extraction applied B diode.[31]

COMMERCIAL ICF TARGET ANALYSIS

This is an area where little has been accomplished at least as reported in the open literature. Commercial reactor designers must continue to base their designs on such simple targets as reported by Bangerter[34] in 1976. The knowledge of the target spectra (x-rays, ions and neutrons) as well as the target debris is vital to the design of the reactor cavity and the power conversion schemes. Until targets are actually irradiated and demonstrate significant yields, there is little hope that such conditions will change.

A second important issue related to commercial reactors is the cost of ICF targets. Obviously, if one doesn't have a design, it is difficult to estimate how much it will cost to make the target. In the past, the target factories have been costed at a canonical "100 million dollars". A more detailed recent study by Pendergrass, Harris and Dudziak (p. 1.2-1 in Ref. 24) reveals that the cost of targets could range from 0.1 to 0.4$ per target depending on whether the targets are for direct or indirect drive, single or double shell, etc. The best estimate is that targets could contribute 5 to 10 mills per kWh to the cost of electricity. Such estimates are useful at this time but cannot be more than first order approximations until real targets are used in a reactor environment.

CONCLUSIONS

There have been some notable advances in the drive to commercialize ICF and some disappointing omissions in the past few years. Perhaps the brightest accomplishments, from the commercialization aspect, have been in the field of light ion beam (LIB) technology. The development and operation of the HERMES-III facility is particularly important because of its voltage, energy and power delivering capability with technology that could be extrapolated on a rep ratable basis. The construction of the applied-B diode with at least two approaches to generating renewable Li beams also could solve a long standing problem.

The laser program will get a boost with the successful operation of the KrF laser, Aurora, at LANL and the demonstration of a wall plug efficiency approaching 10%. The potential for reduction in the cost of laser glass may keep solid state lasers alive for commercial applications and the advances in beam uniformity afforded by the use of the ISI techniques may bring symmetric illumination back as a possible reactor configuration.

Slow progress in the heavy ion beam fusion area is mainly attributable to low funding levels and the lack of declassification of targets (for all ICF concepts) continues to hamper progress toward commercial power plants. The next few years will require substantial financial investments in the next round of ICF drivers and by the mid 1990's a reassessment of all three approaches will be very important to the future of this energy source.

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