

# Research and Development Assessments for Prometheus Heavy Ion and Laser Driven Inertial Fusion Energy Reactor Designs

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## ABSTRACT

Research and development assessments for two inertial fusion energy (IFE) reactor design concepts developed in the Prometheus study are presented in this paper. The assessment here focuses on resolving the technical issues identified for the critical components unique to IFE: target, driver, and cavity/first wall. The two designs considered are based on heavy-ion and laser drivers.

## INTRODUCTION

Two commercial central station electric power plants have been conceptually designed and analyzed in the Prometheus[1] study led by McDonnell Douglas Aerospace. These plants use inertial fusion energy (IFE) technologies by employing the latest advances in KrF excimer laser (Prometheus L) and heavy ion (Prometheus H) drivers.

The research and development (R&D) assessment carried out for Prometheus serves three purposes: (1) provide input for a comparison study between the Heavy-Ion and Laser-driven reactors, (2) provide programmatic-decision makers with a list of important R&D tasks that need to be conducted, and (3) identify areas of R&D that are common to inertial and magnetic fusion energy. The assessment has not attempted to develop a comprehensive R&D plan for IFE. Rather, this effort has focused on identifying the R&D required to resolve the key issues identified during the development of these two designs.

In this paper, R&D requirements are summarized for the critical components unique to IFE: the target, driver, and cavity/first wall protection system. Additional requirements for the blanket, shield, tritium systems, safety and environment were omitted due to space limitations, but can be found in Ref. [1]. A much greater level of detail and breadth also are found in [1] for all of the R&D tasks.

## RESEARCH AND DEVELOPMENT REQUIREMENTS FOR TARGETS AND DRIVERS

*A. Target/Driver R&D Interrelationship:* The majority of the most urgent research and development requirements of IFE targets and the two types of drivers are inextricably

linked together. Some of the most difficult issues having exclusively to do with the drivers involve the demonstration of the generation and delivery of high energy pulses; these same high energy pulses from the driver are requirements for solving significant issues associated with target design and development. A long R&D program involving experiments and analyses associated both with drivers and targets must be established. This would permit the development of a series of DT target designs of increasing scale, beginning at our present stage of understanding, and proceeding in an orderly manner to IFE target ignition and beyond, with the desired optimum reactor targets having yields of the order of hundreds of MJ. This orderly series of target/driver interaction experiments is crucial to the success of an IFE reactor development program because there are a variety of competing processes to efficient thermonuclear "burns" of the DT fuel which have unique scale lengths. These competing processes can lead to anisotropies in target compression, preheating of the cryogenic DT fuel, generation of plasma instabilities, etc. As target dimensions increase, many of the strengths of these competing processes can grow exponentially. Frequently, variations of one or more parameters in target or driver design can check the growth or otherwise control an undesirable competing process, thereby permitting continued progress toward achieving ignition, thermonuclear break-even, and eventual demonstration of optimized target/driver designs for cost-effective IFE reactor operation.

*B. R&D For Feasibility of Laser Driven Direct Drive Target System:* Designs for direct drive (DD) laser driven IFE DT targets have been anchored on experiments conducted on miniature DD targets illuminated with only a few kJ of laser energy. Large reactor sized, multi-MJ DD targets may require different illumination conditions making use of recent technological innovations in laser beam propagation and apodization. For reactor operation, the DD targets must also be accurately injected into the target chamber in coordination with a tracking/alignment system capable of meeting the illumination uniformity requirements discussed in Reference 1.

Two general types of R&D experiments are required to solve the problems identified above. Those include: (1) DD

target irradiation experiments at  $> 1$  MJ delivered in approximately 60 beamlines with a  $\sim 1\%$  illumination uniformity, and (2) Realistic DD target injection, tracking, and alignment experiments to assure that the static DD target irradiation specifications can be met.

*C. R&D For Feasibility of Laser Driven Indirect Drive Target System:* The current designs for reactor-scale indirect drive (ID) laser driven IFE DT targets have been anchored on experiments conducted on miniature ID targets illuminated with less than 1% of the laser energy required for the IFE reactor laser drivers. Furthermore, reduction or elimination of the transparencies[2] of the hohlraum entrance apertures may be an issue.

As was the case also for the direct-drive targets, for IFE reactor operation, it must be demonstrated that the reactor-scale ID targets can also be accurately injected into the target chamber with tracking/alignment system capable of meeting the illustration requirements. R&D experiments required to solve these problems include: (1) Gradual scale up to full-scale ID target irradiation experiments (Indirect-drive target irradiation experiments at  $> 100$  kJ to 1 MJ) and (2) Brassboard laser driven ID target injection, tracking, and alignment experiments to assure that the static ID target irradiation specification can be met.

*D. R&D For Feasibility of Heavy Ion Driven Indirect-Drive Target System:* The primary problems associated with the feasibility of heavy ion indirect-drive (HI ID) targets have to do with space-charge-limited heavy ion beam transport and accurate focusing onto the moving HI ID target. Another HI ID target problem is associated with fabricating the HI ID target to be economical, mechanically robust to withstand launch accelerations, and capable of meeting the precise target design requirements for efficient implosion.

Recommended R&D efforts include:

*1. Acceleration and Transport of HI Beams:* Demonstration that  $\sim 12$  to 18 lead HI beams can be accelerated to an energy of 4 GeV, injected and ejected efficiently from the storage rings in timed, synchronized, and bunched prior to injection into the triplet focusing magnets.

*2. Focusing of Bundled HI Beams to 3 mm Radius Spot:* Demonstration that the 4 GeV (in a +2 charge state) can be focused down to a spot having a radius of 3 mm.

*3. Injection of Focused HI Beams into Pre-formed Channel:* Demonstration that the focused HI beam will enter a preformed channel (formed by either a precursor ion beam or UV laser beam).

*4. Propagation of Self-Pinched HI Beams Parallel to Precursor Beam:* Demonstration that the self-pinched beam will self-focus and follow the preformed channel with an angular accuracy of  $\sim 10$  microradians.

*5. Demonstration of Efficient Conversion of 3 MJ 4 GeV HI Beams to Soft X-rays:* Efficiently convert the  $\sim 6$  MJ of HI beam energy to soft X-rays in the target.

*6. Demonstration of Self-Pinched HI Beam Insensitivity to Deflection:* Demonstration that all return currents can be conducted without significant HI beam deflection or misalignment.

*7. HI ID Target Tracking and Performance Verification:* Demonstration that launched HI ID targets can (a) be directed accurately into the HI ID target firing zone, and (b) meet target robustness requirements.

There is some indication that HI ID target irradiation performance may be improved by single-sided HI ID target irradiation geometries but with the condition that the delivered HI beam energy (and hence the number of HI beams) may need to be reduced.

*E. Target Physics & Engineering-Related R&D:* The following tasks cover below a significant R&D effort within the target physics and engineering-related areas.

- Target implosion on a low adiabat - Experiments to demonstrate efficient compression without excessive preheat before ignition.
- Test of target designs - Experiments to prove that high gain can be achieved with proposed target designs.
- Proof of ability to model plasma physics correctly - Experiments with high gain targets to establish agreement with computer models.
- Central spark ignition and propagating burn - Experiments to prove that bootstrap heating by fast alpha particles can generate an outward-propagating burn wave leading to efficient thermonuclear burn.
- Studies of development of hydrodynamic instabilities and target break up/mixing for reactor size targets - Experiments to show that growth of Rayleigh Taylor and other instabilities agrees with predictions for reactor-size targets, and that symmetric implosions can be achieved.
- Significant gain for low mass targets - Experiments to prove that economically attractive gain can be achieved with 1-10 MJ drivers.
- Hohlraum physics - Experiments to show agreement with predictions of computer models.
- Non-LTE radiative transfer. Demonstrate agreement of code-predicted radiative transfer with experiments for reactor-size indirect drive targets.
- Target injection and tracking/beam steering - Experiments to show that targets can be injected reliably and tracked with sufficient precision.
- Illumination symmetry and laser light absorption for reactor size targets - Experiments to demonstrate sufficiently smooth beam profiles with correct apodization and laser light absorption in agreement with computer models.
- Accurate pulse shaping - Experiments to show that pulses can be shaped with sufficient accuracy to implode targets on a low adiabat and, at the same time, generate shocks sufficient to ignite a small, central hot spot (spark plug).

*F. Reliability and Cost Reduction Strategy For Heavy Ion Driver:* Although the HID basic accelerator technology is well developed, the beam physics is tractable, and existing accelerator systems have exhibited 25-year lifetimes with 95% availabilities, there are a number of unanswered questions associated with improving known weak links in the HID. Unlike the laser system, failure of almost any single component of the HID is likely to provoke a complete shutdown of the IFE reactor. A major lifetime problem has to do with analyzing to what extent redundant systems could be implemented to prevent HID failure and consequent reactor shutdown. Five types of experiments are required to solve the HID reliability problems:

1. Development of a reliable, high brightness, doubly charged lead ion source.

2. Demonstration of a highly reliable (possibly redundant) helium refrigeration system, serviceable cryostats, dependable magnets.

3. Development of cost effective techniques and demonstrations of space charge-limited transport of a bunched heavy ion beam through an accelerator: It is necessary to demonstrate transport at high  $\omega_0$  (undepressed tune), low  $\omega_0$  (depressed tune), continually bunching the HI beam to increase current as voltage increases.

4. Development of cost effective techniques and design of high current storage rings for heavy ion beams: Experiments to demonstrate that a HI beam of the required intensity can be stored in a storage ring for the requisite time, typically on the order of 1 to 2 milliseconds.

5. Minimization of Metglas losses to raise the accelerator efficiency: The important physical parameter associated with the eddy current losses is the thickness of the Metglas ribbon and the shape and amplitude of the waveform used. Presently Metglas thicknesses of the order of 35  $\mu$  are being employed, although successful experiments have been carried out with Metglas thicknesses as small as 20  $\mu$ . By optimizing the voltage waveforms used to drive the beam and to reset the cores, the pulsed power requirements can be minimized.

*G. R&D For Demonstration Of High Laser Driver System Efficiency.* The R&D program involving experiments associated with the elements of KrF driver(1):

1. R&D investigations of promising (efficient and reliable) designs of both electron beam excited excimer lasers (EBEELs) and electric-discharge excimer lasers (EDELs). These include: Characterization of the optimum pulse duration and gas mixture to achieve efficient neutral channel excimer excitation with a matched, efficient, pulsed power system; Sensing and prevention of the formation of arcs in the discharges caused by consumption of fluorine, impedance changes, etc; Extension of the operating lifetimes of the amplifiers to reach levels of  $10^9$  to  $10^{10}$  amplifier firings between failures; and Control of color center formation and chemical attack of amplifier windows during the  $10^9$  to  $10^{10}$  shot operational periods.

2. R&D for the Raman Accumulator. Experiments are to deal with issues associated with single pulse and high repetition rate involving: Demonstration of efficient rotational Raman conversion in  $H_2$  (or  $D_2$ ); Demonstration of an effective (correlated) rotational Raman Stokes seed generator; Demonstration of intensity averaging and beam quality enhancement for crossed Raman accumulator geometries; Coherent, large aperture beam synthesis; Control of diffraction and egg-crate damage by image relay optics for single pulse; and experiments to deal primarily with the gas circulation problems to remove the phonon heat from the  $H_2$  (or  $D_2$ ) gas without adversely affecting the accumulator beam quality with high repetition rate.

3. *R&D for Stimulated Brillouin Scattering (SBS) Pulse Compressor:* The SBS pulse compressor R&D needs to be divided between single pulse proof-of-principle experiments and high average power experiments dealing with control of thermal effects. These experiments need to be performed at both sub-scale and full scale levels. The sub-scale experiments involve full scale physical lengths of the SBS cell ( $L_{\text{cell}} = c \text{ pump} / \omega_0$ ) but, to reduce costs, subapertures of perhaps 1/20 full aperture may be employed. These include the following tasks: Demonstration of high pulse conversion efficiency using a self-seeded, "chirped" input Stokes SBS seed[3]; Demonstration of versatile SBS pulse compressor output pulse shapes by using a ramped "chirped" Stokes SBS seed; and Demonstration of the operating principles of an electro-optical "switchyard" involving fast Pockels cells to tailor the undepleted pump pulse into an 80 ns long precursor pulse. These experiments could be carried out at convenient apertures (~5 cm) using pulse energies of 250 J and 250 ns durations.

In order to conduct the full scale SBS pulse compressor R&D experiments, it would require large aperture pump beams containing ~100 kJ. Although a relatively large 1 m aperture of the MDA IFRDS SBS Pulse Compressor design can be synthesized from an array of smaller optics supported in an "egg-crate" structure. These full scale experiments would require the feature that transverse SBS parasitics could be investigated as a potential problem.

The primary purpose of the high average power SBS pulse compressor R&D experiments is to investigate the influence of phonon-induced thermal effects in the  $SF_6$ -filled SBS cell.

4. *Computer Control and Alignment R&D Experiments :* The computer control and alignment R&D experiments need to demonstrate all aspects of computer control and optical alignment of the MDA Prometheus laser driver system.

## **R&D FOR THE CAVITY FIRST WALL PROTECTION**

A basic test plan for the first wall protection system has been devised, in which a number of parallel near-term tests are performed on separate or multiple issues, followed by a

facility in which integrated cavity responses are simulated. Near-term R&D tasks are best classified by the types of facilities required. The main tasks areas include:

1. *Film flow*: In the Prometheus designs, a thin liquid metal film wets the first wall in order to prevent the solid structures from rapidly degrading due to the extremely high instantaneous heat and particle loads. The film thickness must be relatively uniform in Prometheus because the surface power conducts through the film. The local film thickness determines the local surface temperature, which strongly influences the condensation rate. Even for very thin films, the flow becomes turbulent, and instabilities are likely to develop. Therefore, a better understanding of the nature of instabilities and possible remedies is critical. Good wetting between the solid surface and liquid film is very important. The problem of wall protection with films near inverted surfaces is particularly difficult.

Experiments should demonstrate that adequate wall coverage can be attained to prevent first wall structure damage. This includes studies of film stability, development of effective injection and drainage systems, and film thickness control studies. Some specialized tests are needed. For example, the concept of MHD guiding to protect inverted surfaces should be explored. Transient response in the porous wall also requires study.

2. *Cavity Vapor Response to Blast and Clearing Demonstration*: Calculations for Prometheus indicate the cavity pressure drops below 1 mtorr before the next shot, which is adequate for propagation of targets as well as laser and heavy ion beams. However, the actual physics of energy and mass transport and vapor recondensation is very complex under the extremely dynamic conditions following a target explosion. The cavity gas is partially ionized and subject to highly time-dependent processes such as hydrodynamic shock waves.

A key to successful testing is to simulate the energy release characteristics from the target explosion. Without this, the responses may bear little resemblance to a real reactor. The experiments should measure the major responses, including time-dependent temperature, pressure, and heat and mass fluxes to the surface. Ideally, one would measure spatial variations in these parameters. The tests should demonstrate that the time to clear the cavity allows for high repetition rates in a reactor.

3. *Cavity Structure Mechanical Response to Blast*: Tests must measure stress and strain in the structures, and run to enough cycles to identify major problem areas. Locations where stresses are highest should be more highly instrumented to ensure the design limits are not exceeded anywhere in the structures. The structure geometry should be as close to prototypic as possible, including the mechanical support system. Scaling of the tests may be possible, but ultimately a full scale experiment should be performed. The most important environmental condition to simulate is the pressure loading at the front of the wall. Methods to obtain prototypic impulsive loading without fusion explosions should be explored.

## SUMMARY

Although the Prometheus reactor designs appear attractive on paper, many critical technical issues were identified. Resolution of these issues will require a substantial program of R&D. An in-depth assessment of the R&D needs led to the following conclusions. 1. The heavy-ion driven reactors appear to have a small advantage in R&D requirements over their laser-driven counterparts; however, the differences are small and future results of R&D could change the ranking. 2. The amount of time and effort required to develop components for an IFE DEMO are very large. Target and driver R&D programs should be enhanced and an aggressive technology development program must be initiated immediately if there is to be any hope of achieving the national energy strategy goal of a DEMO by the year 2025. 3. IFE can share R&D tasks with the MFE program, depending very much on the design choices for IFE cavities. In many cases, minor additions to existing or planned activities in MFE can provide substantial benefits to the IFE program.

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