Inertial Fusion Energy Technology: Repetitive Driver-Target Coupling in Hostile Fusion Chamber Environments

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Topical area(s):

Chamber, including first wall, materials, etc
Targets (including manufacture, injection, and survivability)
Drivers (including driver-specific technologies, e.g. final optics)
Reactor engineering and balance of plant (e.g., rep-rates, gains, output powers)

Executive Summary

We propose a program to directly support the development of Inertial Fusion Energy (IFE) for promising Inertial Confinement Fusion (ICF) target designs. Whilst there are necessarily specific issues that need to be advanced for individual targets, there are several common themes and components for any IFE approach that must be developed. These primarily include the ability to rep-rate the driver and reload the target at suitable rates, couple the driver to the target within acceptable parameters, and clear and reset the chamber environment sufficiently following high yield shots to allow the repeatable and predictable performance required for grid implementation. By advancing these topics and developing a body of technical expertise we can be ready to assess the best integrated system to scale for energy generation.

Major magnetic fusion energy (MFE) programs are focused on the specific requirements of bringing fusion energy to the grid, but there are presently no comparable programs for ICF. There is a danger that a successful single-shot ignition target has no feasible path to a repetitively driven energy system, and that other more readily applied systems are underfunded or abandoned before sufficient testing has been carried out. This may severely delay the implementation of fusion energy. One of the primary aims of the inertial fusion energy technology program (IFET) suggested here is to facilitate a well-informed down selection process to a 'point design' IFE plant by its conclusion.

Introduction

The recent data from the NIF represents a significant and exciting step forward in achieving ICF in the laboratory. It should also serve to reinvigorate discussions around transforming successful ICF approaches into energy generation point designs. Inertial Fusion Energy (IFE) was of great interest in recent community planning processes[1-4]. At a very high level, IFE systems consist of: 1) an ICF target, 2) a rep-rated and highly reliable driver[2] (laser[5,6], pulsed power[7,8], heavy ion beam[4,9], or other compression schemes), 3) a method for efficient repetitive driver-target coupling in the hostile IFE chamber environment[5-9,10], and 4) a long-lifetime target chamber and fusion blanket[11-15] compatible with tritium breeding, energy generation, and a steam cycle. Integration of these four sub-systems and other required sub-systems (e.g. tritium breeding and recovery, target production, balance of plant) into a viable IFE system is challenging.

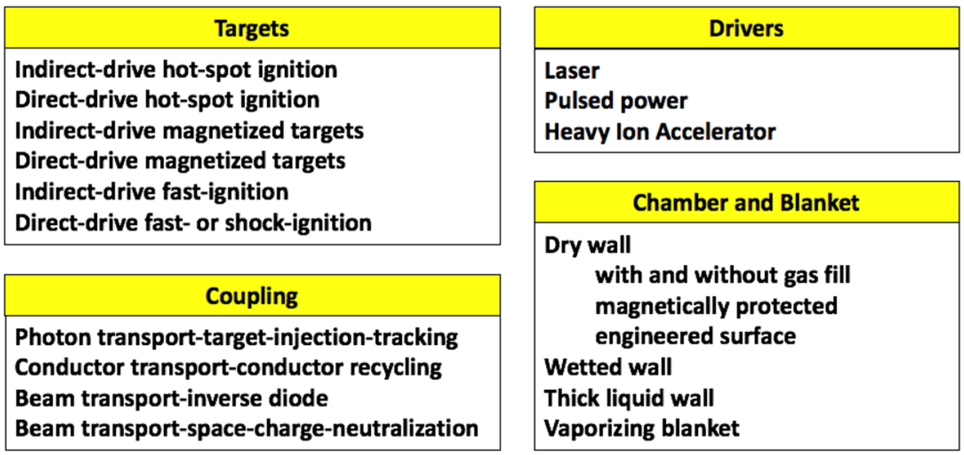

Fig. 1. Example target, driver, coupling, and chamber and blanket options for IFE systems. There are numerous possible systems that could be envisioned by combining different options from each sub-system. Coupling, chamber, and blanket options are commonly tightly-linked to the choice of driver. Target options are often more flexible.

IFE system development cannot lag too far behind ICF progress or there will be a significant delay in implementing IFE. These two must progress in synchronization for a particular target design to allow simulation work to accurately predict performance in rep-rated, full-scale energy producing systems.

A major issue for progress is that many of the previously funded IFE technology programs have been offline for some time, and experienced personnel in the field have necessarily moved to other fields or retired. There have been several IFE system studies in recent decades, but these must be updated and tested for present targets and coupling designs and performances. This timely proposal would boost technological expertise as well as technology to support the development of IFE systems.

Description of the Initiative: Repetitive Driver-Target Coupling in Hostile Fusion Chamber Environments

Driver-target coupling for IFE is a multi-disciplinary topic combining plasma physics, specialized driver physics and technology, material constraints from fusion chambers and blankets, and incorporating relevant environments. What are the physical processes that limit the delivery of energy, often from multiple lines of sight, overlapping on the target to the required degree of precision, in the chamber environment? Can relevantly-scaled experimental demonstrations of repetitive coupling be performed to elucidate these processes? How will the hostile environment in the fusion target chamber alter this coupling at the required rep-rate? This problem needs experimental study and robust multi-physics modeling and simulations that span multiple spatial and temporal scales.

Understanding of repetitive driver-target coupling must be developed with due consideration to the choice of driver, and the compatible chamber, chamber/driver protection, and blanket approaches. This integration makes the problem particularly rich. Creative new ideas are needed.

There have been more than 50 IFE chamber design concepts and power plant studies over the last 40 years[11]. There have also been numerous references to repetitive coupling schemes. We are proposing an initiative that would lead to the creation and integration of:

- sub-scale repetitive driver-target coupling, including target injection, placement, or insertion
- sub-scale repetitive drivers
- sub-scale hydrodyamically-scaled IFE target chamber surrogate environments

The funded work should emphasize creation of integrated experimental and simulation capabilities. Full scale IFE systems will never be built unless there are validated computational models of the repetitive coupling problem in relevant or surrogate environments that can be used to design those very systems. The challenges of this research will also drive solutions for potential IFE systems forward, and will have numerous spin-off applications in standoff, energy projection, repetitive HED experimental capability, and modeling and simulations of hostile environments.

Examples of research topical areas

- **Drivers**: Can we develop sub-scale drivers with suitable repetition-rated operation? These should have all the prerequisites of a full-scale device, and demonstrate clear scalability, as well as compatibility with envisioned coupling technologies. Progress here could have broad benefits beyond IFE.
    - What driver technologies can provide a scaled rep-rate that can be developed and employed for these experiments, and that are on the path to meeting full scale requirements with technology maturation?
    - Can low-maintenance switches required for high energy, high repetition-rate lasers and pulsed power drivers be developed that operate at-scale for millions of shots?

- **Coupling**: What are the approaches to coupling and the chamber environment that should be considered? Approaches should be studied that are expected to viably scale to the yields and rep-rates needed for fusion energy production.
    - What systems are needed for target injection, tracking, laser or heavy ion beam steering, repetitive transmission line placement, in potentially turbulent gas environments? Laser focus compensation methods and adaptive optics? Ion beam focus compensation methods? Adaptive correction for beam steering errors?
    - What chamber and driver protection schemes are compatible with coupling?
    - Can current be delivered down high inductance single replaceable transmission lines that provide standoff? What are the current transport efficiencies, and can these be modeled? What are the limits to current transport, if any?
    - Can pre-pumped vacuum transmission line cassettes be installed without inducing additional current losses due to plasma physics, achieving appropriate vacuum conditions, electrode properties, and current contacts?
    - What is the minimum mass that can be used to transport current to targets in pulsed power systems?
    - Can inverse diodes be utilized to transport current efficiently to pulsed power targets? What simulation capabilities are needed?
    - Can space charge dominated beam transport and charge neutralization methods be explored in the laboratory, that are surrogates for HIB transport in IFE chambers?
    - Can beam overlap be studied experimentally? What simulation tools are needed for beam transport and overlap?

- **Chamber Environment**: What is the environment in the chamber following the previous fusion target event, and is the chamber clear of gas, plasma, or other debris which could interfere with driver coupling? How long will it take to clear the chamber and what is the environment at the time of the next pulse? What is the required environment for proposed targets?
    - What is the laser attenuation in the chamber fill gas? laser plasma instability issues, if any, in the post chamber environment? LPI issues, if any, with the target blow off, or target remains? Beam refraction or steering issues?
    - How does the driver interact with the target blow off plasma and can this be simulated? How could these issues and others be simulated and studied in a surrogate and scaled experimental environment? What are the cross beam interaction issues for IFE systems?

- **Simulations**: The only feasible means to predict behavior at full-scale from sub-scale data is through well-benchmarked simulations. Can IFE chamber environments be simulated in order to provide guidance for suitable environments for scaled driver-target coupling demonstrations? Are there computational models and platforms that are up to the tasks of modeling the target chamber environment? If not, what new simulations tools and algorithms are required?
    - What surrogate experiments can be developed that capture essential aspects of the problem, and that can be used to benchmark high fidelity computational models that can subsequently be used to assess and design full scale systems?
    - Can hydrodynamically-sub-scaled blast clearing environments be created that simulate relevant IFE chamber conditions?
    - The optimal solution for any portion of an IFE system will depend on the choices made for each other section, can simulations aid in assessing these tradeoffs?

Program Cost Estimates

For years 1-5, fund at $4 M/year and potentially ramp to $10 M/year with quality of proposals, and continued progress in national ICF program. For years 6-12 fund at $8 M/year to $20 M/year. Stage gates would be developed pending progress in ICF and in the IFE research, and technology down selects are recommended based on progress and promise of the concepts and technology to scale to capsule yields needed for fusion energy. As the program proceeds, investments into repetitive driver technology development should begin ramp up. The TRL and CRL should advance to levels that enable consideration for full scale systems over the life of the 12-year program. This proposed IFE program allows the eventual application of progress in ICF to IFE energy systems to “keep up” with the national ICF program, with a total funding over 12 years of $80 M to $200 M, expected to be a small fraction of expected costs for a next generation ICF/HED facility.

Cross-Cutting Connections

Rep-rate experiments are anticipated to produce vastly increased amounts of data which offer opportunities in plasma physics, HED, data informed machine learning. Repetitive diagnostics are a challenge, as are data acquisition systems and computing platforms that can handle the huge data streams. High data rates open up opportunities for machine learning and modern data science methods in HED experiments. Simulations and computational platforms have reached new levels, but modeling the environment in IFE chambers is another scale in complexity, scale lengths, and multi-physics that will push that community, as is modeling driver-target coupling physics in that same environment. Multi-scale, and multi-physics simulations capabilities are needed.

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