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ORIGINAL PAPER

The Rationale for an Expanded Inertial Fusion Energy Program

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Abstract The rationale for an expanded effort on the development of inertial fusion as an energy source is discussed. It is argued that there should be a two-pronged, complementary approach to fusion *energy* development over the next two to three decades: (1) Magnetic Fusion (MFE) via ITER and the supporting magnetic domestic program and (2) Inertial Fusion (IFE), a credible, affordable approach that exploits unique US strengths and current world leadership. IFE is only a few years away from demonstration of single-shot ignition and fusion energy gain via NIF. Enhanced funding for IFE R&D is needed in the near-term in order to prepare to expeditiously proceed beyond NIF to the energy application of inertial fusion.

Keywords Fusion energy · Inertial confinement

Introduction

Since the 1950s, scientists and engineers around the world have worked to make a dream come true: creating and harnessing for use on earth the fusion reaction that sustains the Sun and other stars. The potential payoff for success is considerable: the promise of a source of energy that is essentially unlimited, safe, environmentally benign and based on affordable fuels readily available to all nations. After 50 years of research and development, the paths to success are becoming increasingly apparent.

There are two fundamentally different major approaches to fusion energy, equally promising: magnetic confinement (MFE) and inertial confinement (IFE). In magnetic confinement, seven international Parties, including the US, have embarked on the construction of the tokamak-based 500 MWth fusion experimental reactor called ITER, that is envisaged as the final stepping stone to a fusion demonstration power plant. Operation of ITER is projected around 2016, with full deuterium-tritium operation after 2020.

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In inertial confinement, construction of the laser-based National Ignition Facility (NIF) is nearing completion in the US (as is a similar facility, LMJ, in France) to demonstrate the ignition of small pellets containing fusion fuel. The "ignition campaign" is slated to begin in the US in 2010. In addition, innovative programs are underway in the US and Japan, and in the planning stage in Europe, aimed at exploiting the potential benefits of petawatt lasers to reduce the size and cost of lasers required for IFE.

Both magnetic and inertial confinement are based on years of research on the fundamental processes governing their physics and the development of required technologies. Sufficient progress has been made on both approaches to allow high confidence in success.

While NIF and LMJ are currently the "flagship" inertial fusion facilities under construction, it is important to note that the current readiness of inertial fusion to take on an energy mission is based on the cumulative achievements of many groups and other facilities, both in the US, and in the world, over many years. Confidence in attaining the ignition goal rests on broad-based theoretical and experimental understanding of the fundamental physics of inertial fusion attained in a multi-institutional effort spanning several decades. The database includes decades of thermonuclear weapons research, IFE-related underground test experiments of the 1980s and an extensive implosion database on both direct and indirect-drive targets, including comparisons with sophisticated computer codes.

The scientific and technological achievements of the inertial confinement fusion program over the past several decades are immense and include: high-density implosions of ignition-scaled cryogenic fusion capsules to densities in excess of 500 times liquid density (required for ignition on NIF), the development of sophisticated diagnostic instrumentation to probe matter at the extremes of density and pressure ever attained on earth in the laboratory, the development of ultra-high power laser technology; the development of sophisticated multi-dimensional computational capsule design codes; and the development and construction of NIF, a laser capable of demonstrating ignition within the next 5 years.

The United States has invested more than any other nation in developing the underpinnings of inertial fusion. NOW is the time to plan and implement a program to take full advantage of these achievements to develop inertial fusion as an energy source.

In this paper, the rationale for an expanded effort on the development of inertial fusion as an energy source is addressed.

Advantages of Inertial Fusion Energy

An energy source based on inertial fusion has several inherent advantages:

- The driver, the most expensive and complex part, is either modular, or composed of modular parts. This allows development on a small scale before replication to produce a full scale system.
- The principal components are physically separated from one another, allowing them to be developed individually before integration into a full system. In a power plant, this separability should lead to lower operational costs and facilitate incremental improvements.
- The underlying target physics can be established on a single shot basis using existing or soon to be completed facilities.
- Most, if not all, of the fusion nuclear science and technology can be developed and demonstrated on one repetitively pulsed facility. This includes the target physics, the driver/final optics, the target fabrication and injection, materials and components, and the chamber architecture.

The above advantages result in very affordable development costs for an IFE power plant.

Rationale for an Expanded IFE Program

The rationale for proceeding with an inertial fusion energy program now, (aside from the virtually immediate global need for a clean, plentiful energy source) is to capitalize on the momentum produced by significant recent technical advances. The US has invested heavily in the physics of inertial fusion through the Department of Energy's National Nuclear Security Administration's (NNSA) Science-Based Stockpile Stewardship program. The primary focus of that program has been on indirect drive with lasers, and this is the technical basis for the National Ignition Facility. But the US program has also developed designs with the higher gain needed for the energy application. Among the more mature are those based on direct drive with lasers, indirect drive with Z-pinches, and indirect drive with heavy ions. More advanced approaches such as fast ignition, shock ignition and direct drive with heavy ion beams are also under investigation. In addition to the US program, there are significant international efforts in IFE, particularly in fast ignition and solid state laser development.

Significant advances also have been made in the fusion nuclear science and technologies needed for IFE. This work has been carried out under the High Average Power Laser program, the Z-pinch fusion program, and the Heavy Ion Fusion Program. For example, two durable and efficient laser drivers have demonstrated long duration, high energy per pulse, rep-rate runs, and have a credible path to realizing the required efficiency. Meaningful advances have been made with Z-pinch and heavy ion based drivers as well. Outside the driver arena, experiments and design studies have shown that it should be possible to mass-produce targets with the precision and cost required for IFE, and that these can be tracked into the reaction chamber. Several chamber concepts have been identified, backed with experiments for all the main approaches to inertial fusion.

When NIF achieves ignition and fusion energy gain circa 2010–2012, world attention will be focused on inertial fusion and its potential as an advanced, carbon-free energy source with unlimited fuel reserves. This landmark event will be about a decade ahead of the projected operation of ITER with fusion fuel. To prepare for this event, a focused R&D research plan should be implemented now in advanced targets, advanced drivers, chambers, associated science, and associated technologies such as materials, target fabrication and target injection. This will require expanded current and future IFE budgets directed to these ends. A detailed R&D plan should be prepared, targeted towards the following principal questions:

What is the IFE roadmap and major IFE facilities that follow/accompany NIF?
What is the near-term (3–5-year) national IFE program to be prepared for NIF ignition?
What should be the projected funding profile—near term (next 3–5 years) and post-NIF-ignition—and What is the proposed balance between DOE-NNSA, DOE-OFES and other programs?

An Expanded IFE Program should be Focused on Power Plant Competitiveness

The IFE program should be focused on ensuring that IFE power plants will be fully competitive in the US energy marketplace.

In IFE, the target design dictates the driver requirements and chamber geometry. Consequently, the biggest leverage in reducing the size, cost and complexity of the power plant embodiment, lies in the potential of advanced targets and associated advanced driver systems. In short, for an attractive, competitive IFE power plant we need coordinated effort encompassing:

- Robust high gain targets
- A driver concept that is affordable, durable and has high efficiency (ideally >10%)
- Practical target chamber concepts with radioactivity low enough to avoid the need for active safety systems or high-level waste disposal
- Mass-produced, low-cost targets, together with a target injection system that can deliver high gain targets to the chamber center at the required rates
- Combined high reliabilities and lifetimes for driver, chamber, final optics and target fabrication/injection that translate to overall plant availabilities of >95%
- An affordable development path based around a next-step high-average-fusion-power device

Accordingly, the optimal “roll-back” IFE program should be directed to these ends.

The overarching motivation for developing IFE now is, of course, that the energy industry of the 21st century will approach a 100-trillion-dollar market with a significant demand for non-carbon-emitting fuels.

The Major IFE Facility Following NIF should have High Average Fusion Power

NIF and other inertial fusion facilities will demonstrate the science of inertial fusion ignition/burn. However, because of low rep-rate, these facilities are inherently low average fusion power facilities. A fusion power plant will be a high average power facility. Accordingly, for IFE to maintain its momentum post-NIF-ignition, it should aim for construction of a high average fusion power facility as soon as the preparatory R&D permits a high confidence of success.

Such a facility would be comprised of several key elements that must work together:

- High gain targets
- Acceptable illumination geometry
- Efficient high rep-rate driver(s)
- Long-lasting chambers and optics
- Mass manufactured targets and repetitive delivery system at 0.1–10 Hz

This high-average-power fusion facility must demonstrate that inertial fusion can make sustainable fusion power in steady state operation. A facility of this class has gone by several names over the years (Integrated Test Facility, Engineering Test Facility and, most recently, NRL’s Fusion Test Facility), but the essential objectives are consistent with what has traditionally been called a pilot plant, namely, it will:

- integrate, for the first time, all the required subsystems,
- establish at low cost and scale (i.e., low power) technical feasibility, and
- provide the basis for scale up of technologies to a demonstration power plant.

It does not have to demonstrate the economic viability of IFE but must convincingly demonstrate the scaling to a competitive power plant.

In addition, it should be possible to use the IFE pilot plant for accelerated radiation damage testing of materials by placing samples closer to the fusion source (chamber center) than the chamber first wall. This is not an option for MFE, where the plasma extends to the boundary layer immediately adjacent to the first wall.

The IFE pilot plant may progress through several stages and could be designed to test various target and chamber concepts. Typical characteristics might be target gains of 10’s–100’s, rep-rates of 0.1–10 Hz and average powers of $\sim$25 MW_{fus} (early stages) up to 100’s MW_{fus} (final stages). It would be configured with one of the several driver types now under development but would accommodate various high-gain target variants that have been pre-qualified on NIF and other facilities.

Enhanced Near-term and Intermediate-term IFE Programs are Essential to Prepare for Initiation of a High Average Power Facility

In the near and intermediate terms, R&D is required in four major thrust areas:

- High efficiency, high rep-rate drivers
- High gain targets
- Chambers, materials and final optics
- Supporting technology (target fabrication and injection systems, conceptual power plant design, etc.)

Programs on rep-rated drivers (lasers, heavy ion and z-pinch) are essential in order to be prepared to capitalize on NIF success

Nike, Omega-EP, ZR and NDCX are key facilities for testing advanced IFE targets and for developing predictive target modeling capabilities. Such target types include:

- Direct drive
- Fast ignition
- Shock ignition
- Asymmetric 2-sided drive
- Indirect drive at 2ω (green light)
- Designs that give gain and yield at 1ω (red light)
- Designs that employ deeper UV light
- Other advanced concepts

By 2010–2012, we should be poised to take full advantage of NIF ignition with proposals for credible designs of such advanced targets that could be fielded on later phases of NIF. Thus, prior to that time, it is important to perform the supporting design and preparation work, including experimental support on existing facilities. These facilities are already engaged in research relevant to IFE. An expanded IFE program would enhance these activities and provide data essential in determining the future direction of the IFE program. Such an effort would include activities to:

- Establish plausible designs of a variety of advanced target concepts
- Evaluate their performance with state-of-the-art 2/3D rad-hydro-burn codes
- Define and conduct supporting experiments on existing facilities
- Develop and test advanced targets on various facilities, including NIF
- Advance the power plant concepts with design and system studies to demonstrate the value of information of the advanced target and driver concepts on the competitiveness of the IFE power plant.

NIF could also pre-qualify beam injection, tracking, beam slewing requirements for such targets. It might also entertain the fielding and igniting of targets in “burst-mode”, e.g., several targets injected on the fly at a few Hz. This would complement the target injection efforts planned by the high average power laser program on smaller high-rep laser systems.

Robust Conceptual Power Plant Designs are Necessary to Assess Competitiveness

An expanded IFE program should be focused on competitiveness of the prospective power plant. Accordingly, one important program element that must be adequately funded is conceptual power plant studies. The objective is not to position each nut and bolt in an engineering design but rather to assess how the advanced program elements—drivers, targets, energy cycles, etc.—contribute to the commercial viability of the future commercial power plant and to delineate their minimum performance requirements. In addition, such studies should assess the potential of:

- Means to reduce the development time and cost of IFE power plants
- Advanced energy conversion
- The ability to employ thick-liquid-wall chambers with two(one?)-sided drive
- Plant sizes larger than the traditional 1,000 MWe
- Multiplexed plants where one high-rep-rate driver drives several separate target chambers.
- Multiplexed IFE plants devoted to energy missions in addition to electricity, e.g., desalination and hydrogen fuel production
- Hybrid IFE plants devoted to supporting the fuel cycle for advanced fission burner reactors (that is fission fuel breeding and actinide/fission-product burn up)

We Must Prepare Now for NIF Ignition

In order to be prepared to capitalize on NIF ignition in a timely manner, a research *and development* program is required now. The Department of Energy needs to assign responsibility for IFE development, *as an explicit mission*, to either an existing or new Office within the agency.

The DOE Office of Fusion Energy Sciences (OFES) is presently focused on fusion science and not on fusion energy development and, additionally, OFES funding is almost totally devoted to magnetic fusion (MFE). Although OFES has a small program in relevant high energy density laboratory physics (HEDLP), its scope at present does not encompass the energy-oriented technology development required to capitalize on NIF ignition.

The DOE National Nuclear Security Administration (NNSA) funds IFE-relevant work aimed at single-shot ignition. It could also conduct advanced target demonstrations on NIF that are duel use—i.e., good for both stockpile stewardship and for IFE. NNSA could be the funding and management vehicle for inertial fusion energy development, provided Congress and DOE explicitly add energy-related inertial fusion to the “mission” of NNSA as a national security responsibility.

If neither OFES nor NNSA can take on the inertial fusion energy *development* mission, DOE could establish an IFE program within its energy programs or in the newly created ARPA-E.

Summary

IFE is a credible approach to fusion energy in a realistic timeframe and has an affordable development path. The programs required to prepare to capitalize on NIF ignition are, however, beyond those currently envisaged for the science-oriented program in high-energy-density-laboratory-physics (HEDLP).

There should be a two-pronged, complementary approach to US fusion *energy* development over the next two to three decades: (1) MFE via ITER and the supporting US magnetic domestic program and (2) IFE, a credible, affordable approach that exploits unique US strengths and current world leadership, and is only a few years away from demonstration of ignition and fusion energy gain.

In view of the rapid approach of NIF operation, an enhanced effort for near-term IFE R&D has become urgent. It is important that the US government review and evaluate this situation.

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