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Beyond the physics and demonstration of ignition

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Fusion holds the promise of providing growing world energy demand with a carbon-free power source having a universally available fuel source and attractive safety and environmental characteristics. A significant global effort has been underway for over 50 years aimed at the achievement of fusion by inertial confinement. The effort to date has necessarily emphasized understanding the physics of compressing and heating a small amount of fusion fuel to the high densities and temperatures required for ignition and energy gain. Though steady progress has been and is still being made to achieve the required physics understanding and energy gain, those goals have not yet quite been met. It is timely to put progress toward fusion power by inertial confinement into perspective by developing an updated roadmap. Preparing a roadmap from present achievements to the ultimate goal of commercial fusion power requires formally identifying and implementing complementary efforts on a number of fronts. These include the choice, development and demonstration of high repetition rate compression drivers (e.g. lasers) to succeed present day single-pulse sources; design, fabrication and testing of high gain targets (gain of order 100); development of mass production, cost-effective, target fabrication and delivery systems capable of inserting targets into the reaction chamber several times per second, and demonstrating ability to accurately hit and efficiently compress those targets to reliably produce the required fusion yields; design and demonstration of reaction chambers capable of handling energy yields and target debris clearing at the levels required for achieving high power plant reliability with low induced radioactivity. A robust ongoing effort on competitive power plant conceptual design is necessary to guide the implementation of a

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roadmap, including the timing and level of effort on the 'beyond ignition' demonstrations.

This article is part of the discussion meeting issue 'Prospects for high gain inertial fusion energy (part 1)'.

1. Introduction

The threat of climate change from continuing reliance on carbon-based energy sources, in a world of growing energy demand, highlights an urgent need for carbon-free energy sources. Fusion holds the promise of providing growing world energy demand with a carbon-free power source having a universally available fuel source and attractive safety and environmental characteristics. The primary fuel deuterium (an isotope of hydrogen) can be inexpensively obtained from water and hence is universally available. The other hydrogen isotope used for fusion, tritium, can be produced *in situ* in the fusion power plant from lithium, an abundant natural resource.

Compared to fossil energy, fusion has no chemical combustion products, no greenhouse gas emissions, no large-scale mining and transportation requirements and no large volume of long-lived waste products. Compared to fission, fusion has no possibility of 'criticality' or reaction 'runaway' leading to 'meltdown' and shorter-lived, less biologically hazardous radioactivity, and no weapons grade fissionable material. Compared to solar and other non-hydro renewables, fusion has less mining and use of toxic material, no susceptibility or dependence on cloud cover or weather, no requirement for energy storage, is more compatible with large-scale generation and has greatly reduced land requirements.

In addition to the promise of providing electricity for the foreseeable future, fusion has other potential applications, including production of hydrogen as a fuel for transportation or for fuel cells, desalination of water, destruction of radioactive wastes, production of fuel for fission reactors if needed, production of special isotopes for medicine and for food sterilization. Fusion research, being at the cutting edge of science and technology, also has many 'spinoff' commercial applications, including fabrication of micro-miniature integrated circuits, deposition of anti-corrosion coatings, superconductivity, ultraviolet light sources, laser and high-energy beam applications in industry and medicine, X-ray lithography, welding, printing of polymer films, production of high-performance ceramics, surface cleaning of materials, and precision optics and diagnostic equipment.

2. Requirements

To produce fusion energy, a gas or solid containing deuterium and tritium must be raised to a high temperature and sustained for a sufficient length of time to produce a useful amount of energy. The length of time it must be sustained depends inversely on the density of the hot fuel, i.e. the higher the density, the shorter time is needed to release a given amount of energy. In a 1955 Atomic Energy Research Establishment classified report (later unclassified and published in 1957), British scientist John D. Lawson estimated the minimum conditions required to produce fusion energy for use in a power plant [1]. He found that a minimum ion temperature of 50 million degrees C was required and that the needed product of density and confinement time was approximately 10^{14} cm-3sec (figure 1). This became known as the Lawson Criterion and has been sought by experimental fusion efforts as a feasibility goal since that time. Though both the temperature required and the product of density-confinement time have been reached separately in experiments, they have not yet quite been met simultaneously.

Progress toward achieving the Lawson Criterion is frequently charted by multiplying the temperature by the product of the density and confinement time. This has come to be called the Lawson Triple Product or Lawson Parameter. Progress was steady from the 1960s until around the year 2000. Further progress was hampered by the lack of new, more advanced facilities. New

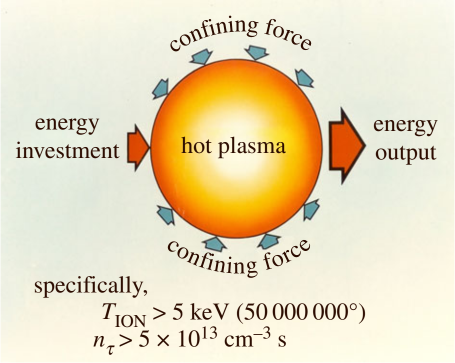

Figure 1. Lawson Criterion. (Online version in colour.)

facilities, like the National Ignition (laser) Facility (NIF)[1] and the International Thermonuclear Experimental Reactor (ITER)[2], are aimed at reaching and surpassing the Lawson Triple Product.

Historically two main technical approaches to fusion energy have been pursued: magnetic fusion energy (MFE) and inertial fusion energy (IFE). More recently a third approach, magneto-inertial fusion (MIF), historically a subcategory of MFE, has emerged and is being pursued with increasing vigor. These three approach categories vary in density by twelve orders of magnitude and hence vary considerably in the technologies used to explore their physics and technology basis. MFE fusion concepts typically operate at densities about a million times less than atmospheric density (essentially in vacuum). IFE fusion concepts typically operate at densities about a million times higher than atmospheric density (or a thousand times the density of solids). MIF concepts operate about half way between these two extremes, i.e. at or around atmospheric density.

To reach the desired temperature, the fuel assembly must be raised to the required 50 million degree or higher temperature by injecting energy into the fuel assembly by some means. For most magnetic fusion schemes (e.g. tokamaks and stellarators), this is typically done by a combination of high-energy neutral particle beams and radiofrequency power; for inertial confinement this is typically done using high energy, high power lasers; for magneto-inertial confinement this is typically done by rapidly increasing the strength of a surrounding magnetic field.

The status and plans for MFE were discussed at a previous (2018) Royal Society meeting and later published [2] and are not the subject of this paper. A European Research Roadmap to the Realisation of Fusion Energy was prepared by EUROfusion and has been published [3]. That Roadmap was confined to the prospects for MFE and did not include a roadmap for IFE. A Discussion Meeting on Prospects for High Gain Inertial Fusion Energy was held at the Royal Society March 2–3, 2020, aimed at informing plans for preparing an IFE roadmap. This current paper is based on a talk given at that Discussion Meeting[3].

3. Inertial confinement

As soon as or shortly after the laser was invented in 1960, scientists (mostly at nuclear weapons laboratories) began to consider whether a laser could ignite a very small capsule of fusion fuel, creating a 'microexplosion' [4]. Much of that research was conducted as 'classified' since the geometry was similar to that of a hydrogen bomb. Calculations showed that the lasers of the

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[1] https://lasers.llnl.gov.

[2] https://www.iter.org.

[3] https://royalsociety.org/science-events-and-lectures/2020/03/inertial-fusion-energy/.

1960s were not sufficient for such ignition; but in the 1970s, a series of ever higher energy, higher power lasers were developed, tested and used to compress fuel capsules to sub-ignition conditions. The development of higher power lasers continued in the 1980s and by the early 1990s a consensus had emerged that a high power laser with a capacity of 1–2 Megajoules should be able to ignite targets. That laser, called the National Ignition Facility (NIF), was proposed to Congress in 1995 as part of President Clinton's FY 1996 budget. The facility was built at the Lawrence Livermore National Laboratory in the U.S. and began operations in 2009, with a goal of achieving ignition around 2012. With ignition seemingly within reach, more attention was being given to the prospects of ICF for an energy mission [5]. Though ignition has still not yet been achieved, it remains a necessary condition for an inertial fusion energy source.

Pursuing an energy source based on inertial confinement has several inherent features that make its development path attractive:

- The underlying physics of compressing the fuel can be established on a single-pulse basis.
- The principal components of the power plant are physically separated from one another, allowing them to be developed individually before integration into a full system. In a power plant, this should lead to lower maintenance costs and facilitate incremental improvements.
- Most, if not all, of the fusion nuclear science and technology can be developed and demonstrated on one repetitively pulsed facility. This includes mass production target fabrication, delivery and targeting, driver and final optics performance, chamber architecture, materials evaluation, and components integration and performance.

It is highly advisable to develop various post-ignition power plant subsystems within the context of a top-level overall power plant conceptual design. This avoids sub-optimization of component systems, drives timely delivery, substantially reduces overall development cost and allows balanced investment decisions based on mission need and residual technical risk [6].

4. Roadmap

A roadmap for inertial confinement fusion should be focused on power plant competitiveness. Robust and continually updated conceptual power plant designs are necessary to assess competitiveness in a developing marketplace. The main line (backbone) of the roadmap should show the stepping stone major facilities envisaged from present day to a power plant. A high-average power ignition test facility is almost certainly a major facility on the roadmap. The roadmap should also show a selection of the major subsystems requiring development and their needed relationship in time to the major facilities. An issue to decide in preparing a roadmap is how many subsystems to include in the top line roadmap. Some may be grouped. Details of these subsystems can be discussed in accompanying text. Major subsystems may include:

- Repetitively pulsed driver development
- Target fabrication mass production facility and delivery system
- High gain target design and fabrication
- Final optics development and evaluations
- Power plant chamber architecture design and development
- Power plant overall systems conceptual design
- Systems analysis on topics such as safety, licensing, costing and plant availability

Inertial Confinement Fusion efforts to date have focused heavily on the physics of compression aimed at eventually achieving ignition in single pulses. The roadmap should indicate this expected achievement. How, when and where can be discussed in the text of the report. It has long been assumed that NIF would provide this milestone. Currently that assumption is in doubt.

Power plants will require ignition of many targets per second. This requires the development and use of high repetition rate drivers combined with mass produced target fabrication and delivery systems. Current candidates for such a laser driver include diode-pumped solid-state lasers (DPSSL) and Argonne-Fluoride (ArF).

Most likely, the first demonstrations of ignition will have modest gain per pulse (perhaps in the 10–30 range). Inertial confinement fusion power plants will likely need energy gain per pulse of order 100. How and when this is to be achieved will need to be addressed, e.g. by design, fabrication and testing of high gain targets.

Target chambers for power plants will be considerably more complex than those in use for ignition experiments and will involve many new issues, such as clearing the chamber of target debris between pulses, chamber wall protection, energy conversion of fusion energy to heat and coupling to the electricity system, and choice of materials that have long life and also keep induced radioactivity low.

Other considerations in preparing a roadmap include whether or how to include a timeline and costs. Some roadmaps have used a range of dates. The EUROfusion roadmap for magnetic fusion, for example, uses Short Term, Medium Term and Long Term to define the timeline and provides no costs. Past experience has shown that timelines with specific dates turn out to be overly optimistic especially when the funding and facilities required to accomplish the goals described on the timeline are not provided [7]. Top-level roadmaps necessarily show a simplified structure, with detail on subsystems and supporting systems covered in the accompanying report.

5. Magneto-inertial fusion

As indicated earlier a third approach, magneto-inertial fusion (MIF), historically a subcategory of mainline magnetic fusion (MFE), has gained renewed interest; but it is being pursued at relatively small scale. For the most part, these efforts use pulsed magnetic fields to compress the fuel to densities intermediate between those used in MFE and inertial confinement (IFE). However, the essential feature of this category is to use a pulsed driver, not necessarily provided by a pulsed magnet. One such example is the work at General Fusion in Canada that uses steam driven compression of a liquid metal liner to compress an injected magnetized plasma[4].

Some of the earliest MFE fusion experiments (now in the MIF category) called ‘pinches’ passed a strong current through the fuel gas (plasma) which generated a magnetic field that compressed and heated the plasma [8]. Perhaps the best known of these early experiments was Zeta in the U.K. that operated in the late 1950s [9]. Since that time, beginning in the late 1960s, the bulk of world magnetic fusion effort shifted to the tokamak concept, which uses a steady magnetic configuration to contain a plasma of fixed density heated by external energy sources. As a result, the level of effort and interest in pulsed magnetic approaches (i.e. MIF) waned but never vanished.

Currently, there is a resurgence of interest in pulsed approaches, in part spurred by a 2009 paper by Lindemuth & Siemon [10]. One claim in that paper asserted that fusion power plants in this intermediate density regime should have lower capital equipment costs than either MFE or IFE. There are now numerous relatively small efforts in MIF, with considerable configuration variations, some of which are supported by private capital and also by the U.S. Department of Energy’s Advanced Research Projects Agency (ARPA-E). One of the largest of these efforts is Magnetized Liner Inertial Fusion (MagLIF) at Sandia National Laboratories [11]. Another significant-sized effort, previously mentioned, is at General Fusion in Canada (see footnote 4). In addition to funding MIF efforts, ARPA-E is also supporting a variety of fusion topics and approaches [12].

In preparing an IFE roadmap, the preparers should consider whether or not to include MIF to be with their scope.

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[4] https://generalfusion.com.

6. Summary

IFE provides a credible approach to fusion power. EUROfusion did not include IFE in its Roadmap. Consequently a Roadmap describing a path for IFE is both timely and necessary.

The IFE Roadmap must indicate the necessity of achieving single pulse, and eventually repetitive pulse ignition. Beyond ignition, the Roadmap must incorporate complementary efforts on a number of technologies required for commercial power plants. In addition to repetitively pulsed high-energy drivers like lasers, these include cost-effective mass production of high gain targets and associated delivery and targeting systems, efficient power plant chambers and associated energy conversion systems, tritium systems and integrated conceptual designs of competitive power plants.

Magneto-Inertial Fusion has a smaller, but growing constituency. The IFE Roadmap should consider whether or not to include MIF in its Roadmap.

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Competing interests. I declare I have no competing interests.

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