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MAGNETIC AND INERTIAL FUSION STATUS AND DEVELOPMENT PLANS*

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ABSTRACT

Controlled fusion, pursued by investigators in both the magnetic and inertial confinement research programs, continues to be a strong candidate as an intrinsically safe and virtually inexhaustible long-term energy source. We describe the status of magnetic and inertial confinement fusion in terms of the accomplishments made by the research programs for each concept. The improvement in plasma parameters (most frequently discussed in terms of the $Tn\tau$ product of ion temperature, T, density, n, and confinement time, τ) can be linked with the construction and operation of experimental facilities. The scientific progress exhibited by larger scale fusion experiments within the U.S., such as Princeton Plasma Physics Laboratory's Fusion Test Reactor for magnetic studies and Lawrence Livermore National Laboratory's Nova laser for inertial studies, has been optimized by the theoretical advances in plasma and computational physics. Both TFTR and Nova have exhibited ion temperatures in excess of 10 keV at confinement parameters of $n\tau$ near $10^{13}\text{cm}^{-3}\cdot\text{sec}$. At slightly lower temperatures (near a few keV), the value of $n\tau$ has exceeded $10^{14}\text{cm}^{-3}\cdot\text{sec}$ in both devices. Near-term development plans in fusion research include experiments within the U.S., Europe, and Japan to improve the plasma performance to reach conditions where the rate of fusion energy production equals or exceeds the heating power incident upon the plasma.

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1. INTRODUCTION

Although it occurs naturally in the sun and other stars, the fusion process continues to present technical challenges in the laboratory environment where it is being explored as a candidate energy source. The technical challenges of fusion energy encompass questions of scientific, engineering, and, in the long term, economic feasibility. The commercial viability of fusion energy will be fully known only with the complete systems integration of fusion power plants, which includes satisfying the public's concern over environmental and safety issues associated with any form of energy (fossil, fission, or fusion).

In this paper, we focus on the status and development plans for fusion science research while fully realizing that the issues of nuclear technology and materials may determine the timetable for fusion research to be accepted as a means to commercial fusion energy. These acceptance issues are covered in a separate paper, "Understanding and Accepting Fusion as an Alternative Energy Source," presented at this conference by D. A. Goerz.

The generic approaches of magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) have both improved the $Tn\tau$ scientific criterion of plasma temperature, density, and confinement time, by a factor of 100 in the last 10 years alone. Designs representing each of the two approaches are in place for the next major experimental facility: the Compact Ignition Tokamak (CIT) for MCF and the Laboratory High-Gain Facility (LHGF) for ICF. Each facility would verify the scientific feasibility of high gain (fusion energy output many times the plasma energy input, with breakeven defined as output equals input), and, researchers hope, the ultimate scientific goal of controlled fusion ignition (fusion energy produced at such a rate that the plasma is self sustaining, that is, no steady-state power input is required).

2. MCF STATUS AND DEVELOPMENT PLANS

As defined[1] by the Department of Energy (DOE), there are four key technical issues for MCF: (1) magnetic confinement geometry, (2) burning (ignited) plasmas, (3) nuclear technology, and (4) fusion materials.

Issues (3) and (4) are beyond the scope of this paper but were recently reviewed[2] by the Office of Technology Assessment. The DOE addressed issue (2) by requesting funds to start building the Compact Ignition Tokamak.[2,3] The CIT is designed to ignite and burn plasmas for periods up to 3.7 sec and represents the next major significant step in the MCF program within the U.S. The remaining part of this section will discuss issue (1), that is, various aspects of the status of present MCF confinement geometries.

Perhaps the latest summary of plasma ion temperatures, T, and product values for the parameters plasma density and confinement time, $n\tau$, in various magnetic geometries is given in Ref. 2 and reproduced here as Fig. 1. Because of budgetary constraints set by U.S. fiscal policy, the DOE decided in 1986 to concentrate its major research efforts in MCF on the toroidal geometry (rather than the dual approach of toroidal and/or linear geometry). Data similar to that in Fig. 1 influenced that decision, along with the total data base that defines the level of development of each geometry. There is now a worldwide consensus in the MCF community that the toroidal tokamak can lead to a viable commercial power plant. Without discounting the fact that other

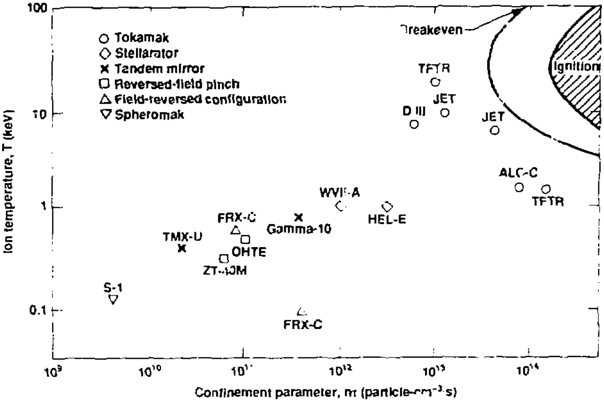

Fig. 1 Plasma parameter values achieved by various confinement concepts. (Graph by courtesy of the Office of Technology Assessment; see Ref. 2.)

geometries might have characteristics preferable for a MCF power plant, we present the current performance of tokamaks and the associated physics issues in the remainder of this section.

Worldwide, the major tokamaks operating today are the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory; the Doublet III-D (DIII-D) at GA Technologies, Inc., San Diego, CA; the Joint European Torus (JET) at Culham Laboratory, United Kingdom; and the JT-60 in Japan. Figure 2 gives comparison numbers for the plasma minor radius, a; the major radius, R; the plasma column vertical elongation (vertical height/horizontal width); the toroidal magnetic field, B; and the plasma ohmic heating current, I. The drawing shows the relative size of these four major tokamak experiments.

Both TFTR and JET have achieved $n\tau$ values of 10^{13} ($\mathrm{cm}^{-3}\cdot\mathrm{s}$) at ion temperatures near $T = 10$ keV and higher $n\tau$ values at lower values of T near 2 to 3 keV (see Fig. 1). The two TFTR data points of Fig. 1 are representative of the variations in T, n, and τ observed when various amounts of neutral-beam heating and pellet-injected fuel are added to the standard ohmically heated, gas-fueled plasma.

	JT-60	TFTR	JET	DIII-D
a (m)	1.0	0.85	1.3	0.67
R (m)	3.0	2.5	2.8	1.67
Vertical elongation	1.0	1.0	1.5	2.0
B (T)	5.0	5.2	3.5	2.2
I (MA)	3.0	3.0	>5.0	5.0

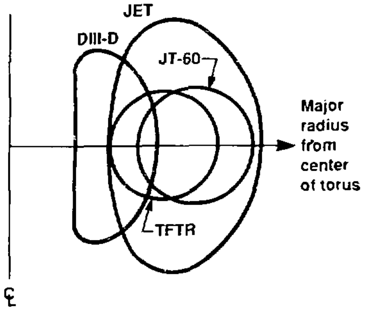

Fig. 2 Comparison of various dimensions and other values for large tokamaks.

Within the U.S. MCF community, the confinement geometries and their plasma physics issues have been reviewed in the Technical Planning Activity (TPA) Plasma Science Final Report.[4] This report lists five general tokamak issues, each of which includes several subordinate issues. The five issues listed are: (1) macroscopic equilibrium, (2) transport, (3) wave-plasma interactions, (4) particle-plasma interactions, and (5) composite issues associated with sustained plasma equilibrium in tokamaks. These five issues, expressed (perhaps simplistically) in terms of parameters, translate into (1) plasma beta, $\beta \propto nT/B^2$; (2) $n\tau$; (3) ion heating, ΔT; (4) control of impurity, Z_{eff}, and density profile, $n(r)$; and (5) plasma pulse length. Issue (4) also includes ion heating from neutral-beam injection. Although supported by theoretical interpretation of the plasma physics, the improved performance in many of these parameters has benefited from the empirical scaling within the substantial data base from all tokamak experiments. An example of a multiple-machine data base is given in Fig. 3 where β is

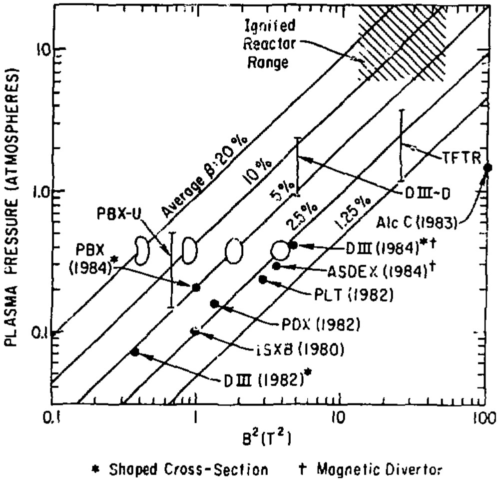

Fig. 3 Recent progress of toroidal experiments toward beta conditions for an ignited reactor. The illustrative cross sections indicate theoretical beta limits for aspect ratios of about 3. (Graph reproduced from Ref. 4.)

plotted against the square of the toroidal magnetic field in tesla. Note that a plasma density of $n = 10^{20}$ m^3 at an ion temperature $T = 10$ keV is equivalent to 1.6 atmospheres of pressure (1 atmosphere $= 10^5$ J/m^3). The value of β is significant in the economics of a MCF commercial power plant because the fusion power production scales as $n^2 \propto \beta^2 B^4$ for fixed values of T determined by fusion cross sections.

Another important factor in tokamak designs for commercial power plants is the pulsed nature of the inductively driven, toroidal-plasma current required for heating and for generation of the poloidal magnetic fields. Noninductive, steady-state current drive from rf power has been a seriously investigated experimental issue. The current-drive efficiency for rf lower-hybrid heating[4] in terms of nRI/P ($10^{20} m^{-2}$ A/W) is approximately 0.1 from both Alcator-C and Princeton Large Tokamak (PLT) experiments. Estimates[4] of the 0.1A/W for the *maximum* tolerable recirculating-power demand of current drive in a tokamak commercial power plant translate for power plant parameters of $n \sim 10^{20} m^{-3}$ and $R \sim 5$ m to $nRI/P = 0.5$. Expected improvement at higher electron temperatures for lower-hybrid heating or current drive with the aid of neutral beams should produce much of the required improvement in nRI/P

Electron-cyclotron heating is also being investigated, at Lawrence Livermore National Laboratory (LLNL), as a possible way of generating noninductive plasma currents. The Alcator-C tokamak, originally at the Massachusetts Institute of Technology, was moved to LLNL for this investigation. The experimental facility at LLNL links this tokamak with the Experimental Test Accelerator II and an advanced wiggler structure (the two main components of a free-electron-laser, or FEL) to study microwave heating of electrons within the tokamak geometry. Experiments will be carried out to demonstrate that the Alcator-C tokamak and FEL-generated microwaves can be used for both electron heating and steady-state current drive in tokamak plasmas.

The five general tokamak issues listed in the <u>TPA Plasma Science Final Report</u> will continue to be investigated in existing facilities with many of the commercial power plant parameters at breakeven conditions to be attained in TFTR and JET within a few years. The planned construction and operation of CIT will allow the MCF community to study the physics issues associated with ignited plasmas, such as alpha particle heating. This valuable experience will aid in the design of the International Thermonuclear Experimental Reactor (ITER),[4] a multinational effort that represents the MCF test for economic viability of a fusion commercial power plant.

3. ICF STATUS AND DEVELOPMENT PLANS

The goal of the ICF program is to demonstrate the scientific and economic feasibility of inertial confinement fusion for both military and civilian applications.[5] The near-term applications and benefits of ICF are in the military arena, including studies for weapons physics, nuclear effects testing, and other applications. In the long term, the ICF community has very strong convictions that ICF can be a candidate for commercial energy production.

There are three significant milestones to developing ICF for commercial power production. The first is to show scientific feasibility and develop the science and technology base for both driver and target, to define what it takes to obtain high gain (1000 MJ of fusion energy from a target driven with about 10 MJ). The second milestone is to build a Laboratory High-Gain Facility, to achieve high gain, and to conduct experiments to optimize driver-target performance. The third milestone is to develop those specific technologies needed for a commercially competitive power plant.

For almost 15 years, a series of increasingly powerful neodymium-glass laser systems at LLNL have been used to conduct ICF experiments. Figure 4 shows this progress. It is this progress that assures the ICF community that a 10-MJ laser could be built for high-gain demonstration.

Neodymium-glass lasers produce infrared light at a wavelength of about 1 μm (1000 nm). One of the very important discoveries made in laser-plasma interaction physics is that the infrared wavelength is a bit too long to optimally couple to and drive ICF targets. Using a somewhat shorter

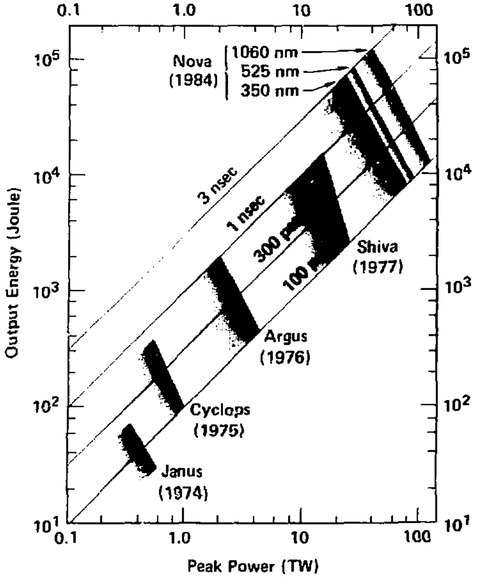

Fig. 4 The peak power and energy capability of neodymium-doped-glass lasers has progressed rapidly to the point that it is technically assured that multi-megajoule solid-state lasers can be built.

wavelength in the visible or ultraviolet portion of the spectrum is much more effective. The success achieved by using shorter wavelength has been one of the fundamental breakthroughs in the last few years that has resurrected the technical credibility of ICF. The rate of advancement in ICF in the last few years is a ramification of the improvements obtained with the shorter wavelengths.

At the Nova facility[4] at LLNL, the frequency of the laser light can be converted by using arrays of crystals to change the wavelength from the fundamental infrared frequency to the second harmonic (green, 1/2 µm) or the third harmonic (blue, 1/3 µm). So far, Nova experiments have operated with up to 20 kJ of green or blue light. Platinum impurities in the neodymium-doped glass laser disks that make them damage-prone at higher energy levels have limited the operation of the laser to below the 50 kJ level in the infrared (corresponding to about 20 kJ of third harmonic blue light on target). By installing new laser glass, Nova will be able to meet or exceed the original specifications and deliver 50 to 80 kJ of green or 40 to 70 kJ of blue light to targets in 2.5-ns pulses.

Since Nova's completion in 1984, two classes of implosion experiments using 20 kJ of blue light have been performed. The first was a very simple, directly driven target designed for the specific purpose of providing a burst of neutrons as a source to aid neutron diagnostics development. The target was directly irradiated with 20 kJ of blue light delivered in 1 ns. The fuel reached an ion temperature of about 10 keV and produced 2×10^{13} neutrons. However, simple, direct-drive targets of this type (exploding pusher, high-entropy implosion variety) do not necessarily scale to high gain for reasonable laser direct-drive power uniformity on target.

The second class of Nova experiments involves an indirectly driven target. The laser energy is absorbed and converted to x rays; the x rays are contained in a hohlraum-like environment and drive the implosion with a pressure pulse generated from the absorption of x rays by the capsule. The main advantage of the indirect-drive approach is that the necessary high degree of pressure uniformity required by the capsule can be more easily generated with fewer laser beams. In addition, the high degree of laser-beam symmetry and uniformity required for directly driven targets is not necessary for indirectly driven targets. To achieve high gain, the requirements on the target implosion are stringent. The deuterium-tritium fuel must be compressed to a density of about 200 $g/cm,^3$ and the mass density-radius product (ρr) must be greater than about 3 g/cm^2 for efficient burn. To reach these conditions requires a capsule convergence ratio of about 40 to 45.

To allow a practical driver energy, the driver/target coupling must be very efficient. In addition, the capsule must be driven uniformly so that instabilities do not spoil the compression. Together, these requirements place specific constraints on the target geometry. To limit the impact of instability growth, it is advantageous to gradually accelerate the pusher during the entire implosion. In order to accomplish this it is desirable to control the temporal shape the drive pulse. (Nova's recent success at reaching the high convergence value of 35 [see Fig. 5] was something of a surprise because instabilities had been expected to degrade the performance since the driver pulse had not been ideally shaped.) In the past, the measured neutron yields could fail to meet theoretical predictions by as much as a factor of 100, depending on the specific target and the amount of convergence. Now, the experimental values for neutron yields have improved so much that they agree with calculations to within a factor of two or so, as the data in Fig. 5 indicate. This significant improvement is attributable to a combination of enhanced experimental capabilities, the inherent advantages of the relaxed target physics for indirect drive, and the shorter wavelengths provided by Nova, together with a better understanding of the relevant physics and an improved modeling capability.

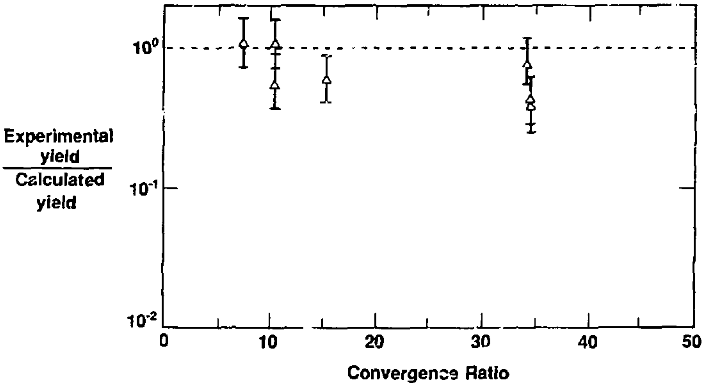

Fig. 5 Indirect-drive experiments have produced convergence ratios near 35, and results closely match one-dimensional calculated predictions.

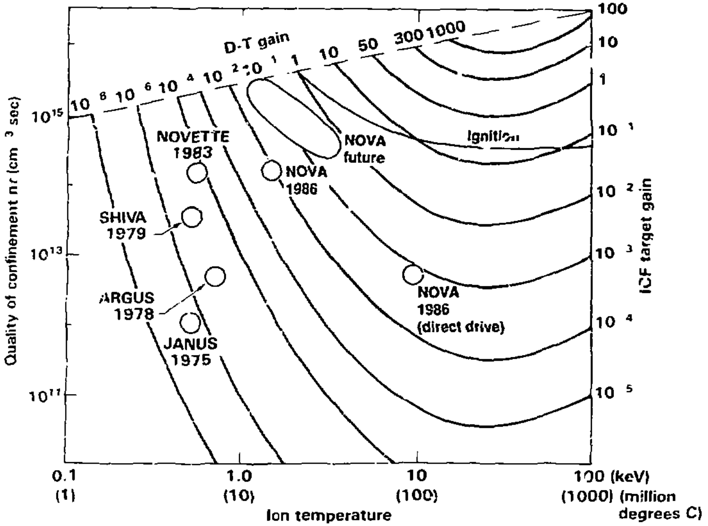

Fig. 6 The data base for several laser fusion facilities at LLNL shows that ICF is approaching the goal of high energy gain.

Data from Nova experiments where the ion temperature was 1.7 keV, measured from broadening of neutron time-of-flight spectra, are given in Fig. 6. Additional neutron diagnostics were able to determine fuel density. These experiments yielded a fusion confinement parameter $n\tau$ in the range of about 2 to 3 X 10^{14} cm^{-3}sec. Plans call for these results to be extended into the regime indicated in Fig. 6. This will come about through experimental iteration of target designs, improvements in Nova's performance to the 50 to 70 kJ level with new laser glass, the use of temporally shaped laser pulses to allow lower entropy implosions, and new experimental techniques resulting from insights gained with new diagnostics. Researchers expect Nova to come quite close to ignition conditions but probably not to reach them.

The next significant step in ICF is to construct a high-gain facility employing, for example, a short-wavelength laser at about 10 MJ that will be capable of driving ICF targets to high gain. The ICF community is confident that after three to five years of experiments with such a facility it could demonstrate moderate- to high-gain fusion microexplosions. Such a next step will demonstrate the scientific feasibility of ICF. It would produce specific payoffs on the near-term applications of ICF and allow the optimization that can pave the way to development of ICF for commercial power production.

4. CONCLUDING REMARKS

Both MCF and ICF have made steady progress towards achieving fusion energy. The graph shown in Fig. 7 supports that claim by plotting the $Tn\tau$ scientific criterion for each year since 1975 Many other scientific and engineering milestones have been reached, and many more are planned for the next decade.

Design studies in fusion research programs are directed toward economical, reliable electricity from a fusion power plant. Two examples are the *International Thermonuclear Experimental Reactor*,[8] a test reactor using the magnetic confinement approach; and the Cascade reactor,[7] which uses the inertial confinement approach.

The ITER involves the United States, Japan, the European Community, and the Soviet Union in an effort to design an experimental reactor. The design study will provide information towards a decision about whether to build and test it. The ITER is designed to operate under conditions close to those of the commercial fusion power plant of the future. It will be used to study many aspects of physics and engineering that are important for a full-scale, commercial, fusion power plant.

The Cascade reactor, introduced at LLNL, uses fusion energy produced by the inertial confinement process. The released fusion energy is deposited in a blanket of lithium aluminate granules that line the interior wall of a rotating, double-cone shaped fusion chamber. These granules (which have minimal activation characteristics) slide along the walls of the rotating chamber, held there by centripetal force.

As with most scientific endeavors, the great challenges also hold the greatest promise. Fusion is one of today's most challenging and promising areas of energy research. Recent scientific and technological advances have shown that fusion is indeed ready for accelerated development. The scientific feasibility of fusion is virtually certain--a claim that could not have been made a decade ago--and the virtues of fusion energy have withstood the scrutiny of increasingly sophisticated engineering analysis.[8,9]

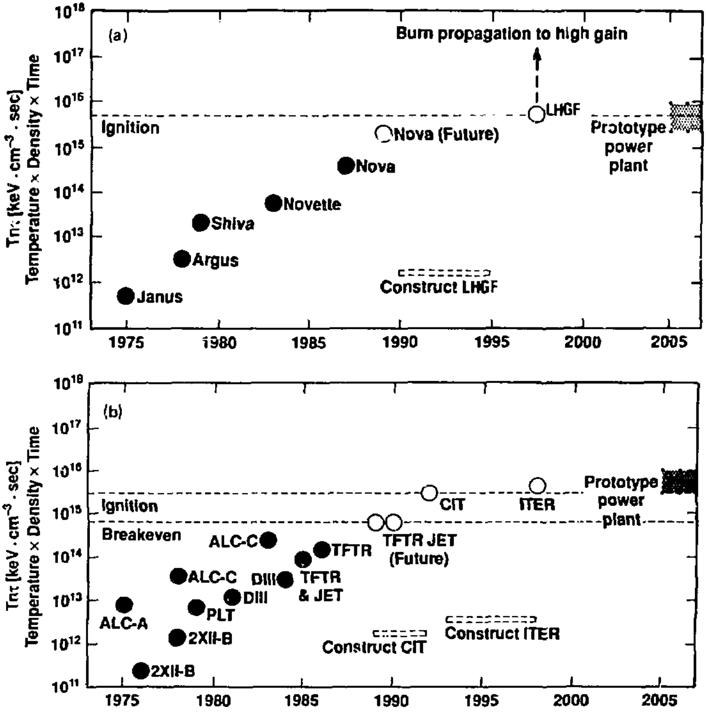

Fig. 7 Both the ICF and MCF approaches have made steady progress toward achieving the necessary conditions for fusion energy: (a) data for ICF progress and (b) data for MCF progress.

ACKNOWLEDGMENTS

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