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OBJECTIVES OF THE TOKAMAK MAGNETIC FUSION PROGRAM*

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Introduction

The demonstration of reactor-like temperatures in the Princeton Large Torus (PLT) tokamak at Princeton Plasma Physics Laboratory (PPPL) is the most recent step in a continuing series of dramatic steps in plasma confinement and heating that began with the development of the tokamak in the Soviet Union in the 1960's. The progress in plasma confinement brought about by the development and refinement of the tokamak system has raised the confidence of researchers in the magnetic confinement community that the national program in magnetic confinement is following a sound path toward the development of a fusion reactor. This confidence is reflected in the extensive program in magnetic confinement that is directed toward tokamak optimization and related technology development. This session will describe two large tokamak research programs, the Impurity Study Experiment (ISX) tokamak program at Oak Ridge National Laboratory (ORNL) and the Poloidal Divertor Experiment (PDX) tokamak program at PPPL. Although neither of these devices will advance the product of energy confinement time and plasma density, they will nevertheless explore issues vital to demonstrating that a tokamak can be made to work as a reactor and that there are ways to make such a reactor economically viable. This paper will briefly describe the tokamak program in the national magnetic confinement program and primary areas where these two tokamaks are contributing to this program.

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Tokamak Fusion Reactors

A tokamak belongs to a family of magnetic plasma confinement devices in which the confining magnetic field is produced by currents flowing within the plasma itself. The tokamak is a toroidal device in which the plasma acts as the secondary of a large transformer where the toroidal plasma current is inductively produced by a set of primary windings. To stablize the plasma against instabilities, a large toroidal magnetic field (3-15 T) is added. The plasma current has the added bonus of heating the plasma to about 10 million degrees Kelvin. Unfortunately, this resistive heating effect drops as the plasma temperature rises. To exceed the ignition temperature of about 40 million degrees Kelvin, some form of external heating will probably be required. The development of high power ($\gtrsim$1 MW of power delivered) neutral beam injectors pioneered by ORNL for heating toroidal systems has led to the reactor-like temperatures in PLT. Other heating methods, most notably rf heating systems, are also being tested. Once the plasma reaches the ignition temperature $\geq$ 5keV (50 million degrees Kelvin), the alpha particles produced by the D-T reactions deliver energy to the plasma. An additional requirement is that the plasma energy production-confinement quality factor ($n\tau$), which is the product of the plasma density and the energy confinement time, must exceed $\sim 10^{14}$ s/cm^3 for a pure D-T plasma. Once these conditions are met, the plasma can maintain the burning condition until either its fuel is exhausted, its power production is reduced to the critical level by helium or impurity buildup, its energy confinement is spoiled by impurity buildup, or the flux swing limit of the transformer core is reached.

Magnetic Confinement Tokamak Research Program

The national research program in tokamak fusion reactor development is a broadly based, multifaceted program designed to rapidly verify the tokamak plasma confinement path to a fusion reactor. At the same time, in order to provide an economically attractive and practical reactor, broadly based research is being conducted in tokamak optimization, auxiliary heating methods, wall/material interactions, magnet development, and blanket development for tritium breeding. This program is intended to produce by the early 1990's a device, the Engineering Test Facility (ETF), that will produce an ignited D-T plasma with all the components necessary for a practical, economically feasible fusion reactor.

The next major milestone in verifying the plasma confinement-temperature scaling for tokamaks beyond PLT and the ALCATOR tokamak at the Massachusetts Institute of Technology (MIT) will be the Tokamak Fusion Test Reactor (TFTR) presently under construction at PPPL. In addition to extending plasma confinement verification to more reactor-like regimes, TFTR is expected to be the first controlled fusion device to produce more fusion power than its uses to heat the plasma:

One of the major problems of a fusion reactor will be control of impurity ions in the D-T plasma. Impurities reduce the plasma energy confinement time by enhancing radiation losses from the plasma and reduce fusion power output by displacing fuel ions. Next to the scaling of plasma confinement, control of impurities is believed to be the most serious potential roadblock to an ignited tokamak plasma. PDX is testing a poloidal magnetic divertor as a means of controlling particle flow both into and out of the plasma. ISX is studying various nonmagnetic impurity

control methods and plasma/material interactions and will soon add a toroidal bundle divertor to test plasma particle control.

Beyond the questions that will determine whether or not a tokamak reactor will work at all are the questions pertaining to the practicality and economic feasibility of tokamak reactors. Included in this category are the questions of plasma power density, pulse leng[illegible] ıgnet design, and blanket design for breeding tritium.

The power density available in a reactor is the primary factor in determining reactor size, which in turn is a major factor in the capital cost of a reactor. In magnetic confinement systems, the quality factor for power density is β, the ratio of plasma pressure to magnetic field energy density (average β's in excess of 5% are required for fusion power reactors). Ohmically heated tokamaks are basically low β devices with $\beta \leq 0.5\%$. With the addition of massive neutral beam heating, ISX has already increased the β obtained in tokamaks by more than a factor of 3. PDX will be adding large amounts of neutral beam power, and both ISX and PDX, together with Doublet III at General Atomic (GA), will study the limits of plasma β as a function of plasma shape.

The development of large superconducting magnets is being pursued by means of the Large Coil Test Facility (LCTF) at ORNL and its associated magnet development programs. Development of neutral beam heating systems is being pursued at ORNL and Lawrence Berkeley Laboratory. Auxiliary heating by rf power is being pursued at PPPL, GA, and MIT. Materials development for blankets and first walls is underway at numerous labs.

The one area short of the ETF device that appears to have an inadequate experimental program is the question of tokamak pulse length and the control of the plasma configuration at high β impurity levels and

the ability to handle reactor level power density during extended pulse operation. Tokamaks are inherently pulsed devices due to the inductive production of the plasma current. However, pulse lengths of at least one hour appear feasible under reactor conditions, and, in the final analysis, this is simply another factor to be included in total device optimization. Experiments to verify the ability to maintain high quality plasma for extended pulse operation have been proposed by GA, ORNL, and PPPL.