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HIGH-DENSITY TOKAMAK DESIGN STUDIES FOR TFTR-II

D.L. Jassby, H.P. Furth, P.J. Reardon
Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey,

D.R. Cohn, J.E.C. Williams
Plasma Fusion Center,
Massachusetts Institute of Technology,
Cambridge, Massachusetts,
United States of America

Abstract

A joint Princeton-M.I.T. design program for large tokamak devices is examining possible configurations for a copper-coil Ignition Test Reactor (ITR) and a superconducting-coil Long Pulse Experiment (LPX), two machines whose combined performance will provide the plasma physics and technology bases for an optimal experimental power reactor. The basic features of the ITR and LPX design approaches are described.

1. INTRODUCTION

The purpose of the PPPL/MIT prototypical reactor design program is to identify the optimal large tokamak devices for construction in the U.S.A., following commissioning of the TFTR, and to develop preliminary conceptual designs of these machines. For the purpose of minimizing costs, special attention will be paid to installation of these large devices in the TFTR facility now under construction at the Princeton Plasma Physics Laboratory.

The primary goal of the 1980s tokamak development program is an experimental power reactor, which must deliver net electrical energy in each pulse. As indicated in Fig. 1, we believe that the plasma physics and machine requirements for an EPR can be developed in two smaller, less expensive, and less

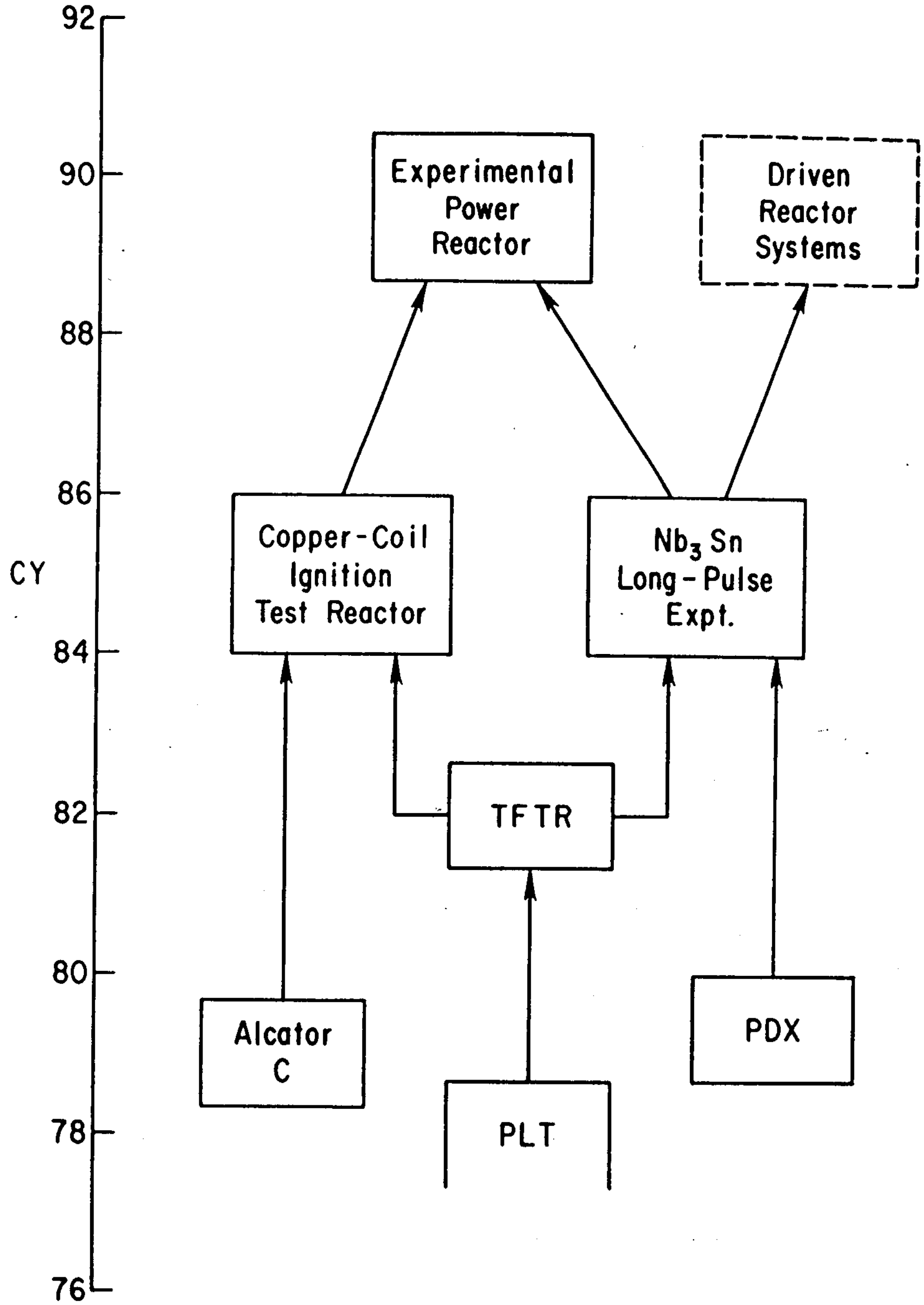

Figure 1. Outline of possible scenario for development of a tokamak Experimental Power Reactor.

risky machines: a copper-coil ignition test reactor (ITR), and a superconducting-coil long-pulse experiment (LPX). This report discusses the rationale for this approach, and indicates the major characteristics of the two devices.

2. RATIONALE FOR ITR/LPX APPROACH

An experimental power reactor (EPR) will be equipped with a thermal energy conversion blanket and will produce net electrical energy over a pulse length of the order of 50 s or longer. An EPR should operate at ignition, or near-ignition conditions, use superconducting TF (toroidal-field) coils, and have effective long-time control over fueling, thermal stability, impurity build-up, and plasma heat removal for the 50-s burn period. An EPR of reasonable cost must employ special techniques that allow start-up and control of an ignited plasma in a machine of practical size. To maximize the success of an EPR, these techniques must be introduced and tested as soon as possible in smaller, less expensive, and less risky devices. In addition, there may be undue risk in assuming that a device of the magnitude and importance of the EPR can be the first in the U.S. program to use superconducting coils (bore size ~ 5 m × 8 m), especially if high fields are required, as appears to be the case.

The approach in the TFTR-II design study is to examine two less ambitious and less costly machines, whose combined performance will provide the necessary plasma physics and technology information for building the most successful EPR (see Fig. 1). The first device, an Ignition Test Reactor (ITR), will demonstrate the attainment of thermonuclear ignition in a relative small copper-coil machine that has minimal shielding and a burn length as short as 5 s. The plasma size (i.e., $\bar{n}\cdot\bar{a}$) will be intermediate between those of the TFTR and an EPR, while the plasma current will be in the 3 to 6 MA range, or sufficient to confine fusion alpha particles. The second device, the Long-Pulse Experiment (LPX), will have a plasma that could be as large as EPR size, with a variable shape to maximize beta. It will obtain "ignition-level" parameters in a hydrogen plasma, and will demonstrate all the features required of a quasi-steady-state burn in the EPR (with the exception of thermal stability). This beam-sustained device will utilize high-field niobium-tin

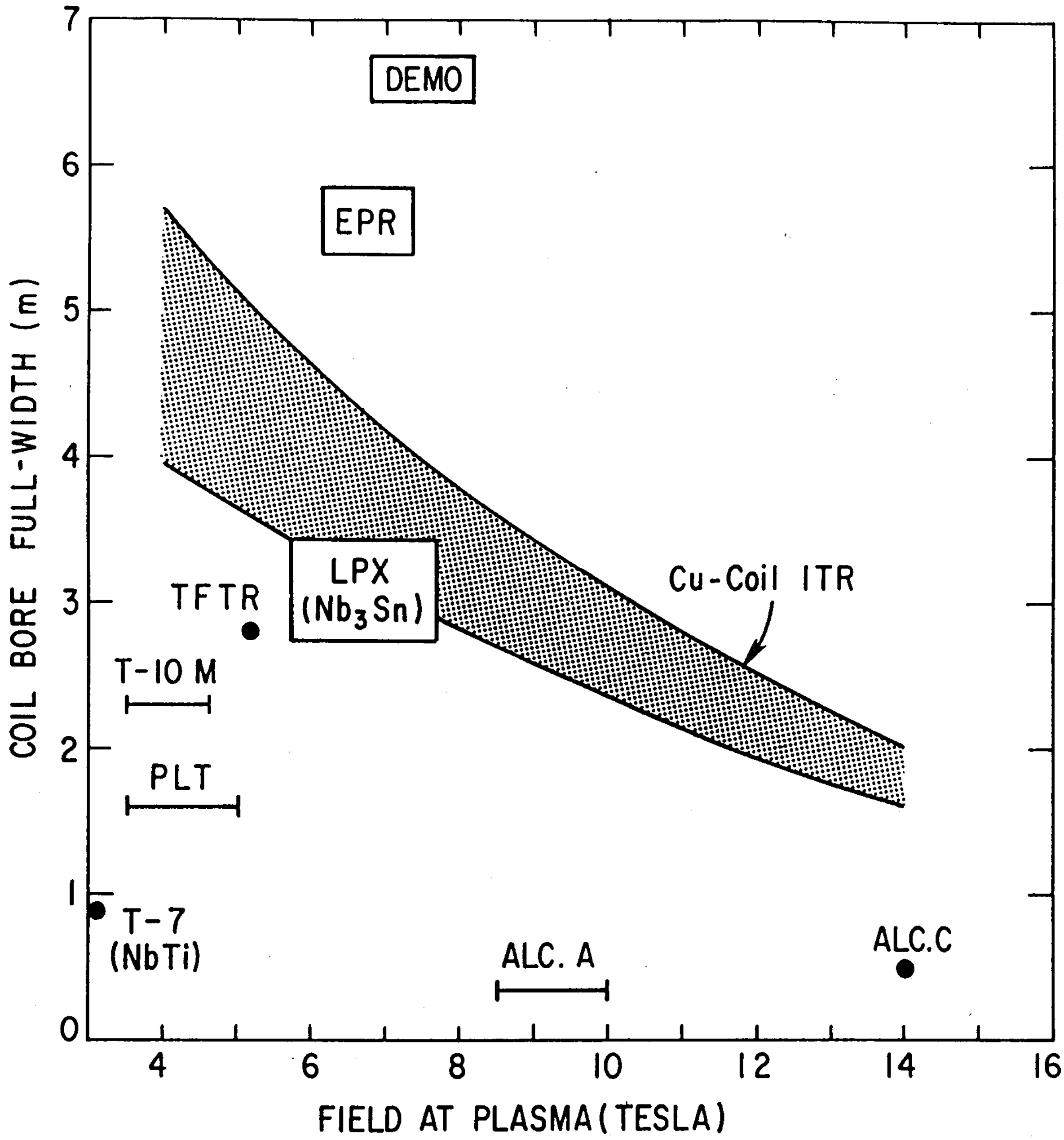

Figure 2. Full-widths of toroidal-field coil bores for the range of possible copper-coil Ignition Test Reactors (ITR) and a Long-Pulse Experiment (LPX). The bore sizes of some present tokamak devices and future power reactors are also shown.

superconducting coils, with bore size much smaller than that of an EPR, since no neutron shielding is required. The major radius is about 3.5 m, and the toroidal-field coil size (~ 3 m × 5 m) seems a more reasonable first step for a superconducting tokamak in the U.S. program. Figure 2 compares the range of coil size of possible copper-coil ITRs and a superconducting LPX with the sizes of some present tokamak coils, as well as those expected in future reactors.

3. IGNITION TEST REACTOR (ITR)

The principal goals of the ITR are the following:

(i) Demonstrate an ignited thermonuclear burn of at least 5-s duration.

(ii) Demonstrate an optimized prototypical plasma for power reactor design and operation.

(iii) Demonstrate effective heat removal from the plasma and from the first wall throughout the burn.

(iv) Demonstrate remote maintenance and assembly of a tokamak device subject to repetitively pulse ignited operation.

A number of design options for the ITR using various magnetic configurations have been identified for detailed investigation. All these options aim for large plasma density ($\bar{n} \gtrsim 2.5 \times 10^{14}$ cm^{-3}), since it is clear from present tokamak experiments and theoretical analyses that high density affords the largest $n\tau_E$, the highest fusion power density, and the smallest impurity ion content. For any given β limit (β = plasma pressure/magnetic field pressure), maximum density is achieved by maximizing the toroidal magnetic field. Hence the use of Bitter-type copper coils providing $B \gtrsim 9$ T at the plasma center with $\beta \sim 0.03$ is one attractive possibility for an ITR that our program will investigate. This HFITR (High-Field Ignition

Test Reactor) represents an extrapolation of the Bitter-magnet Alcator devices, and will be pursued by MIT. At the other extreme is a new concept for a very small aspect-ratio device ($R/a \sim 2$) with moderate elongation and $\beta > 0.06$, thereby affording high plasma pressure at moderate field ($B \sim 4$ T). This SMARTOR (Small Aspect-Ratio Torus) class of devices will be investigated by PPPL. Both types of ITRs have major radii ~ 2.5 to 3 m. The principal means of plasma heating is expected to be an optimized combination of low-energy and high-energy neutral beams, with some major-radius compression.

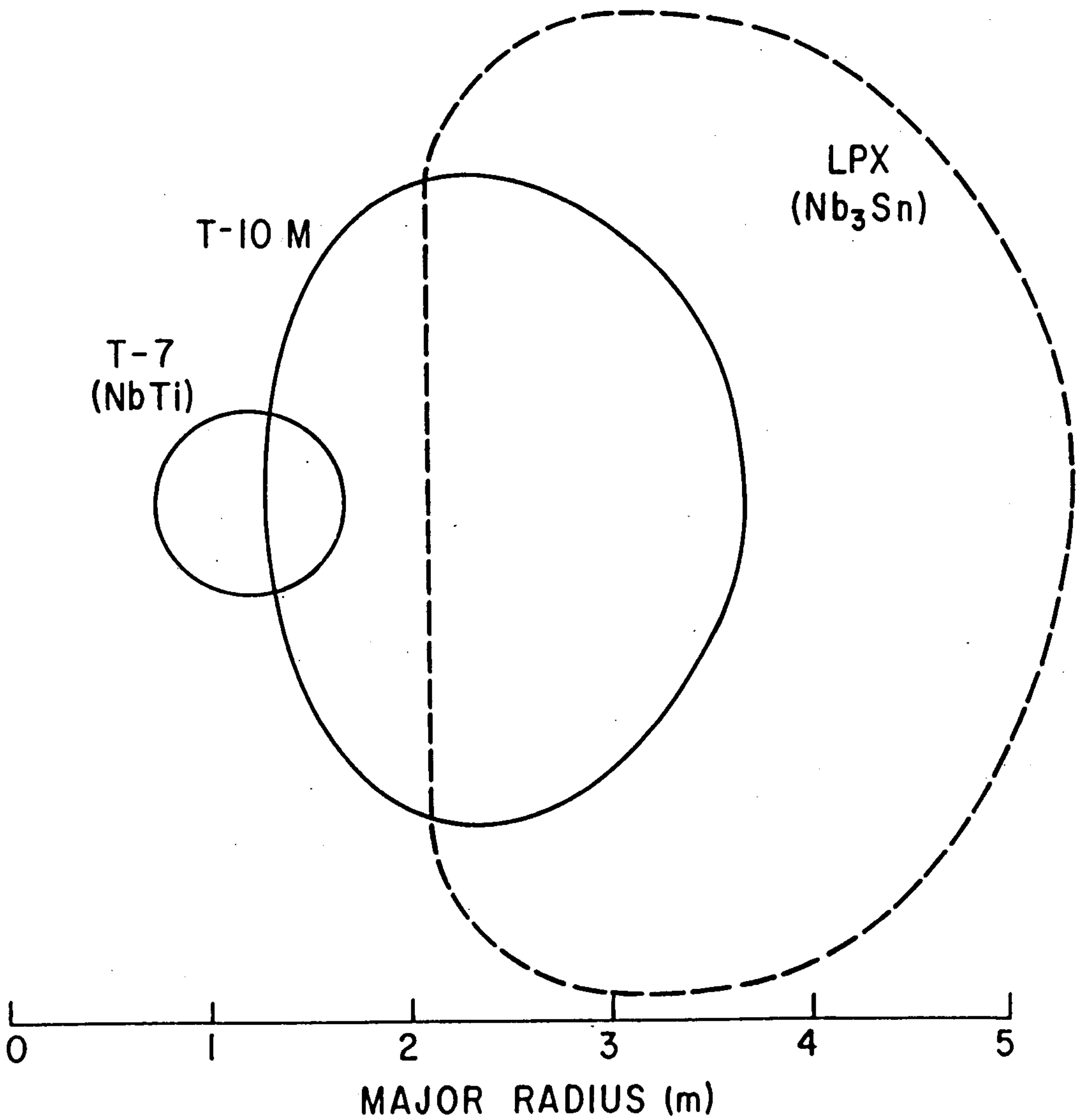

Figure 3. Internal bore of the toroidal-field coils for the superconducting T-7 and T-10M devices at Kurchatov, and an illustrative LPX device.

A wide range of parameterization in β, B, and size is required by uncertainties in the beta limit of tokamak plasmas, in the scaling of energy confinement with temperature, and in impurity control. The MIT approach utilizes very high field and nearly circular plasmas in order to operate at beta-values, plasma configurations, and collisionality that are only modestly different from those of present-day tokamak plasmas. Impurity control by a dense cold plasma layer will presumably be similar to that which works so effectively in Alcator A. Possible draw-backs of the very-high-field approach are difficulties in beam access, remote handling, and pulse length.

The lower-field, higher-beta PPPL approach encounters fewer problems with beam access or remote handling, and is capable of long pulse lengths, but the extrapolations in plasma configuration and beta from present practice are quite large. The vacuum vessel is of thin-wall, multilayer, titanium-alloy construction, with continuous flow cooling between layers. A bundle divertor is specified for impurity control during the initial beam-heating phase.

By the end of 1978, the most attractive features of each design approach will be incorporated into the preferred conceptual design of the ITR.

4. LONG-PULSE EXPERIMENT (LPX)

The principal objectives of the LPX are:

(i) Demonstrate reliable operation of a toroidal assembly of Nb_3Sn coils (B_{max} = 10 to 13 T) of the same design as EPR coils — except for size — in a working tokamak environment.

(ii) Demonstrate long-pulse (≳ 30 s) quasi-steady operation at high density and temperature of a hydrogen or deuterium plasma of nearly EPR size and current (~ 5 MA).

The LPX will utilize Nb_3Sn coils with a bore size somewhat larger than that to be tested in the Large Coil Program (LCP) at ORNL (2.5 m × 3.5 m), but will be based on the same design as the force-flow-cooled Nb_3Sn coil to be fabricated for the LCP. The coils to be tested in the LCP will have a bore similar to that of T-10M, which is illustrated in Fig. 3. This figure also shows the relative size of a 3.1 m × 4.8 m coil (labelled LPX), which would be adequate for containing a 5-MA plasma, without neutron shielding, with a field of 7.2 T at the plasma center. This value corresponds to a field of 12.0 T at the coil winding.

The poloidal-field magnetics systems of the LPX is based on the design of the MIT/PPPL demonstration power reactor, and utilizes superconducting OH, field-shaping, and dc EF coils, located outside the TF coils, together with normal-conducting nulling and quadrupole coils, located inside the TF coils. The equilibrium-field system can support $\bar{\beta}$ up to 8% at maximum toroidal field.

Because the LPX is to demonstrate solutions to the plasma physics and engineering issues associated with quasi-steady-state operation (e.g., impurity control, heat removal, particle exhaust) a poloidal divertor is tentatively included in the design. In addition to the usual issues of plasma physics and methods of particle collection, careful attention will be paid to the impact of the divertor on machine size, cost, and ease of disassembly.

5. USE OF TFTR SITE

An important step in minimizing the cost of either the ITR or LPX is to strive for the maximum possible usage of equipment and facilities that will be provided at the TFTR site. Either of the new machines would take advantage of TFTR buildings, power supplies, controls, neutral beams, coolant systems, and remote handling equipment. The ITR would have to be installed in a new containment building adjacent to the central utilities tunnel, while the LPX would be installed in the Mock-Up Assembly area. A possible upgrade of the site power source would include the installation of a 900-MVA, 500-kV power line, which would power the toroidal-field coils of a normal-coil ITR. The basic TFTR power supplies would be sufficient to meet the needs of all the TF and PF coil systems of the LPX. Modification of the TFTR neutral beam injectors with higher quality ion sources and direct energy recovery systems would permit a doubling of the neutral-beam power to 40 MW (D°) at 150 keV.