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SLPX — SUPERCONDUCTING LONG-PULSE EXPERIMENT

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SUMMARY

The principal objectives of the SLPX — Superconducting Long-Pulse Experiment — are to demonstrate quasi-steady operation of 3 to 5 MA hydrogen and deuterium plasmas at high temperature and high thermal wall loading, and to develop reliable operation of a prototypical reactor magnetics systems featuring a toroidal assembly of high-field niobium-tin coils. This report summarizes the results of an engineering scoping study for the SLPX. A range of sizes has been investigated, from a TF (toroidal-field) coil aperture of 2.6 m × 3.65 m, to an aperture of 3.1 m × 4.8 m, and with a maximum field at the Nb_3Sn conductor of 10 to 12 Tesla. The poloidal-field magnetics system utilizes superconducting ohmic-heating and d.c. EF coils located outside the TF coils, together with normal-conducting EF and divertor coils located inside the TF coils. For the largest embodiment, the D-shaped plasma in hydrogen operation has major radius = 3.6 m, half-width = 0.90 m, elongation $\lesssim$ 1.5, and B = 7.2 T. Maximum plasma current of 5.0 MA can be maintained for a 30-s flat-top when $Z_{eff} \sim 1$. A single-null poloidal magnetic divertor disposes of particles and heat diffusing out of the current channel, thereby helping to insure the feasibility of quasi-steady operation.

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1. INTRODUCTION

This report summarizes preliminary design features of a tokamak device equipped with superconducting toroidal-field coils and other advanced magnetics features, and capable of operating at extended pulse lengths ($\geqslant$ 30 s) with plasma currents up to 5 MA. Called SLPX (Superconducting Long-Pulse Experiment), this facility is intended to provide the technological and operational experience with advanced magnetics systems and long-pulse high temperature plasmas that is required before embarking on a tokamak power reactor program. The steady-state TF (toroidal-field) system will permit long-pulse operation ($\geqslant$ 30 s) in which the problems of quasi-steady fueling, impurity control, and especially heat removal from the plasma, first wall, and particle collection systems can be addressed for the first time, in a machine of high thermal energy density and high thermal wall loading.

The objectives of the SLPX can be summarized as follows.

- Demonstrate quasi-steady or steady-state operation of high-temperature ($\gtrsim$ 10 keV) hydrogen and deuterium plasmas of 3 to 5 MA size.

- Demonstrate effective heat removal from the plasma, the first wall, and divertor particle collection systems in quasi-steady or steady-state operation at high thermal power loading.

- Develop and demonstrate high-duty-factor operation of a prototypical tokamak reactor magnetics system in a working tokamak environment (i.e., with pulsed fields and plasma disruptions).

- Develop and demonstrate optimal maintenance and assembly procedures for a large superconducting tokamak.

A range of sizes for the SLPX has been investigated. This range is bounded at the lower end by the SLPX-II, which has a TF-coil aperture of 2.6 m × 3.65 m, and an overall coil size appropriate for testing in the Large Coil Test Facility at Oak Ridge [1]. The upper end of the range is bounded by SLPX-I, which has a TF-coil aperture of 3.1 m × 4.8 m, and is capable of producing "ignition-level" plasmas in hydrogen. The SLPX machines have the same basic design features, and differ principally in geometric dimensions and plasma current. Preliminary results of scoping studies for SLPX I and II are described in References [2] and [3], and are summarized in the present paper.

2. MOTIVATION FOR NIOBIUM-TIN COILS

The magnetic fields that have been specified in recent conceptual designs of tokamak reactors have generally fallen in the range of B_{max} = 9 to 13 T (at the TF coil windings), as indicated in Fig. 1. Thus a prototypical reactor magnetics system should be capable of operation at B_{max} up to at least 10 T. Niobium-tin with its high critical field and high critical temperature has been chosen as the conductor material for the following reasons:

- Although NbTi conductor can in principal be used at 9 T or above, there would be practically no margin against temperature excursions such as might be induced by pulsed fields.

- A practical reactor cannot be expected to operate at the extremes of its component performance. The need for reliability is more critical than the ability to operate under extreme conditions, which would be necessary with NbTi.

- For $B_{max} \geqslant 10$ T, Nb_3Sn coils are actually cheaper than NbTi coils because much more NbTi conductor is required to keep J/J_c at a sufficiently low value.

Thus we have chosen Nb_3Sn coils for the SLPX by extrapolation to future reactor needs, and because such coils are feasible.

3. MACHINE PARAMETERS

The principal considerations that have resulted in the present range of TF coil sizes are the following:

Magnetics System. The TF coil design should be similar to that of a reactor, and sufficient space must be provided for a reactor-grade magnetics system, including adequate build of the TF coil conductor and structure to support $B_{max} \geqslant 10$ T. The minimum coil size that satisfies the prototype requirement is probably that of the LCP (Large Coil Program) [1]. Adequate space must be provided in the TF-coil throat for the flux swing of a superconducting solenoid which must help establish a plasma current in the 3 to 5 MA range, and which sustains that current for at least several tens of seconds.

Plasma Size. The plasma radius and attainable pressure should be sufficient to give $\bar{n}\tau_E \geqslant 2.5 \times 10^{14}$ cm^{-3}s at $I_p > 3$ MA in hydrogen operation (i.e., "ignition-level" confinement).

Vertical Bore. The vacuum vessel must have sufficient vertical extent to accommodate a particle and heat exhaust system.

TF Ripple. The TF-coil horizontal bore should be sufficiently large so that the ripple at the edge of the largest plasma is 2% or less.

Access. The number of TF coils should be sufficiently small to permit high-power neutral-beam injection, and to allow ease of access for device maintenance.

As a result of these considerations, the number of TF coils has been chosen as 16, and the aperture for SLPX-I has been established as 3.1 m × 4.8 m. The aperture for SLPX-II, the smallest size machine, is jsut slightly larger than that specified for the LCP coils, and a prototype SLPX-II coil would fit in the Large Coil Test Facility of the LCP. The coil major radius is 3.8 m in SLPX-I and 3.0 m in SLPX-II. However, SLPX-II is unlikely to satisfy the above criterion for Plasma Size.

Figure 1 compares the bore sizes and maximum fields of authorized superconducting-coil systems with those of future reactors. Figure 2 compares the coil apertures of SLPX-I and II with those of the Soviet T-7 and T-10 M devices. The TORUS-II device, under design in France, also has circular coils with an aperture just slightly smaller than that of T-10 M. The crucial problem of quasi-steady heat removal cannot be addressed in either T-10 M or TORUS-II with their relatively short pulse lengths. Among these machines, only the SLPX would address the following critical issues:

- Operation of a high-field Nb_3Sn toroidal magnet assembly in a real tokamak environment.
- Control of high throughput levels of particles and heat for pulse lengths of at least several tens of seconds.
- Maintenance of temperature and density profiles and plasma purity in high-energy-density plasmas, for pulse lengths of at least several tens of seconds.

The principal operating parameters of SLPX-I and II are given in Table I, and compared with the parameters of the TFTR [4]. The maximum plasma current of 5.0 MA for SLPX-I and 3.2 MA for SLPX-II can be maintained for a 30-s flat-top when $Z_{eff} \sim 1$ and $\bar{T}_e \gtrsim 5$ keV, with a duty factor of at least 0.05. A current of at least 60% of the maximum value can be maintained for at least 100 s, with a duty factor of 0.15 or more.

4. MACHINE LAYOUT

Figure 3 shows plan and elevation views of the SLPX-I, and Fig. 4 shows a perspective view. The machine is constructed in 8 modules, with two TF coils per module. The primary vacuum vessel is of thick-wall steel-plate construction, and encloses the vacuum-canned internal PF coils. The entire machine is housed in an outer vacuum container with re-entrant holes that provide access to the room-temperature inner vacuum vessel. The principal requirement for access ports is to provide sufficient throughput for neutral-beam injectors. In the SLPX, neutral beams heat and fuel the plasma throughout the pulse. Attempts will also be made to drive at least part of the plasma current with neutral beams, an application which calls for quasi-tangential injection.

The magnetic limiter is activated with the lower quadrupole coil, and the center line of the plasma is raised about 30 cm above the horizontal midplane of the machine. Heat removal from the plasma is performed by water-cooled targets in the divertor chamber, and by a gas-cooled heat shield surrounding the plasma. Particles are removed by a high-capacity, electrically heated getter system in the divertor chamber.

5. TOROIDAL-FIELD MAGNETS

The first design of the toroidal field coils for the SLPX has been based on the forced-flow cooled Nb_3Sn coil to be fabricated by Westinghouse/AIRCO for testing in the Large Coil Program at ORNL [1]. This coil is the only large Nb_3Sn TF coil presently authorized for fabrication and testing in the U.S. or Europe during the next several years. The Westinghouse LCP coil utilizes a modular approach with a plate type support structure. The segmented, laminated structure limits pulsed-field eddy current losses while keeping conductor strain low.

The LCP coil is designed only for B_{max} = 8 T. Stress analyses at PPPL have indicated that for $B_{max} \geq 10$ T, the coil structure should be stainless steel, rather than the aluminum used in the LCP coil. The stainless steel plates may also allow the use of arch-supported coils (i.e., wedging at the inner legs) without exceeding desirable stress levels at the support bolts. This technique can permit the elimination of the bucking cylinder in the present design, thereby allowing more space for the central ohmic heating solenoid. Resistance against torque set up by the poloidal fields is provided by structural members between adjacent coils (see Fig. 3).

If the primary vacuum vessel has no break, then the amount of energy deposited in the TF coils following a total loss of plasma current (a major "plasma disruption") is sufficiently small so that the coils will remain superconducting. The maximum resistance of the vacuum vessel so that this condition is still satisfied is presently under investigation.

6. POLOIDAL-FIELD MAGNETICS SYSTEM

The SLPX poloidal field magnetics system is illustrated in Fig. 3. The components of this system are the following:

Superconducting external dipole coils generate the principal steady-state vertical field.

Pulsed nulling-field coils. These water-cooled copper coils are pulsed to first oppose the DC external field to obtain a near-zero starting field, and then pulsed to provide the correct equilibrium field during plasma current buildup. These coils also supply about 40% of the flux for plasma current startup.

Pulsed equilibrium-field coils. A pair of water-cooled coils inside the TF coil bore provides a time-dependent quadrupole field which gives the proper curvature to the equilibrium vertical field.

Divertor-field coils. A single-null poloidal divertor is established with the lower quadrupole. Two adjacent copper coils are used to pull out the poloidal field lines in order to spread particle and heat fluxes across target collection systems.

Superconducting ohmic-heating coils. The OH coils are located in the TF-coil throat with a field-compensating portion outside the TF coil. These coils provide about 60% of the flux swing for plasma current buildup, and all of the flux swing required to sustain the plasma current. The OH windings are made with NbTi stranded insulated superconductor operating at 7 to 7.5 Tesla maximum field. The overall current density can be kept under 1300 A cm^{-2}.

The interior placement of the copper coils makes possible their use in initiating the plasma current [2]. The nulling and quadrupole coils are initially rapidly pulsed in opposition to one another to induce a voltage in the plasma for resistive breakdown. Subsequent to this operation, the quadrupole coils are ramped to their final currents while the null current is reduced to zero. The internal coils are wound in place, and then canned in vacuum-tight containers.

Figure 5 shows a magnetic flux plot with the divertor null activated, for an SLPX-I plasma with I_p = 5.0 MA and $\langle\beta\rangle$ = 0.03.

7. VACUUM CONTAINMENT SYSTEM

The SLPX vacuum vessel is illustrated in Fig. 6. It consists of a thick wall single curvature shell which is stiffened with poloidal ribs that also serve as the support for canned poloidal field (PF) coils. The vessel, which is designed for room temperature operation, also serves as the inner wall of the dewar which encloses the TF coils, and is thermally isolated by copper LN_2-cooled panels hung just inside the dewar space. Under normal operation the vessel shell and frame structure support the electromagnetic loads of the PF coils and the combined gravity loads of the coils, vessel, and other structures. During plasma disruptions, inwardly directed over-pressure loads that are estimated to be as large as 5 atmospheres for short periods must be sustained.

Reentrant ports are provided for neutral beam access, electrical and hydraulic services, and for scheduled maintenance of the collectors and getter assemblies. The large ports are also used to remove internal PF coils, and to rewind new ones.

The low wall resistance of the vacuum vessel poses a particular problem during startup. The primary transformer action provided by the null, quadrupole, and divertor coils induces voltages in the vacuum vessel as well as in the plasma. A low-resistant vacuum structure has the advantage that during plasma disruptions the vacuum vessel inhibits the induction of large voltages across the superconducting coils. However, the vessel resistance must be increased somewhat in order to facilitate the startup of plasma current.

Up to 25% of the plasma heat outflux will be incident on the first wall structure of the upper section (above the divertor coils) of the vacuum vessel. A barrier wall consisting of titanium alloy tubing or corrugated sheet is interposed between the structural wall and the plasma.

This tubing carries high pressure helium which acts as the coolant medium. The diverted plasma impinges on water-cooled swirl-tube heat collectors. The particles reflected from the heat collectors are trapped by an array of zirconium-aluminum getter assemblies. The getter systems are electrically heated to maintain an operating temperature of 400°C, and for regeneration are heated to 700°C.

A structure must be designed to mechanically support and maintain the superconducting coils at a temperature near 4 K, while at the same time the plasma vessel, beam injectors, and plasma diagnostic instruments remain at ambient temperature. Figure 3 shows the outer vacuum container which performs this function. It consists of a stainless steel outer wall, appropriately stiffened, which supports the vacuum loads, and a low emissivity shield maintained at liquid temperature. The vacuum container is covered by an elliptical dome. The vacuum vessels and TF coils are divided into 8 removable modules, as illustrated in Fig. 4.

8. REFRIGERATION REQUIREMENTS

The thermal stability criterion for the SLPX TF coil is that the conductor should recover the superconducting state after an energy input sufficient to raise the conductor temperature above its critical temperature for a length of one half turn. This cryostability criterion requires a refrigeration power of 81 W per coil for SLPX-II at 10 T and 4.2 K, and 750 W per coil for SLPX-I at 12 T and 3.6 K. With a deuterium plasma in SLPX-I, 40 cm of shielding must be inserted to protect the TF coils from neutron irradiation [2]. As much as 300 kW of fusion-neutron power could be produced in deuterium, but the neutron power load on the TF coils would be 3 kW or less.

The central OH coils have a refrigeration load of 4200 W and 3200 W for SLPX-I and II, respectively, when averaged over the 600-s operating cycle. The total specified refrigeration capacity for SLPX-II is 10 kW, which provides a comfortable margin even with modest deuterium operation. For SLPX-I, three units of this size would be required for 12-T operation with the present TF-coil design, but only 15-kW capacity is needed at 11 T.

The neutral-beam injector requirements are 40 MW at 100 keV (H°) for SLPX-I, and 30 MW at 80 keV (H°) for SLPX-II. Important development needs are improved injector efficiency, such as could be obtained with direct energy recovery, and an operating pulse length of at least 30 s.

9. USE OF PPPL FACILITIES

The SLPX would be located in a new test cell at the TFTR complex, adjacent to the TFTR test cell, as shown in Fig. 7. This building would be large enough to accommodate the SLPX device, neutral beam injectors, and close-in power supplies, and would hold a powerful bridge crane. The SLPX basement annex adjoins the west wall of the TFTR Test Cell and serves as the interface between the two installations. All services for the SLPX Test Cell enter through the annex.

The SLPX would make maximum usage of the equipment and facilities that will be available both at the TFTR site and other installations at PPPL. This equipment includes power supplies, machine controls, water and liquid nitrogen coolant systems. The sharing of common facilities by TFTR and SLPX would be similar to the present PLT/PDX arrangement, or the previous ATC/ST arrangement at PPPL.

10. COST AND PROGRAM PLAN

The total estimated project cost, including 30% EDIA (engineering/design/inspection/administration) and 20% contingency, is approximately $260 million for SLPX-I and $160 million for SLPX-II. These estimates are in 1978 dollars, and assume that the machine will be sited at PPPL. The TF-coil set of SLPX-I accounts for 46% of the estimated cost of the total installation, while all the superconducting and cryogenic elements together account for 60% of the total cost.

The development of the superconducting TF coils is the "critical-path" item in determining a time scale for commissioning the SLPX. For timely implementation of this machine, the development of Nb_3Sn conductor must be pursued vigorously, and the LCP coil tests must remain on schedule or even be accelerated. In an optimistic program plan, conceptual design of the SLPX would start October 1978, and a contract would be placed with both the industrial prime contractor and the architect/engineer in October 1979. Under this plan, the machine embodiment with LCP-sized coils (SLPX-II) would begin plasma operation in December 1984, while the largest machine (SLPX-I) would begin operation in March 1986.

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Table I.

COMPARISON OF PARAMETERS OF TWO SLPX MACHINES AND THE TFTR

	SLPX-I	SLPX-II	TFTR
Plasma major radius (m)	3.60	2.92	2.48
Plasma minor radius (m)	0.90	0.77	0.85
Plasma elongation ratio	1.5	1.35	1.0
TF Coils			
Number	16	16	20
Conductor	Nb_3Sn	Nb_3Sn	Copper
Conductor current (kA)	11.4	15.2	73
Clear bore (m)	3.1×4.8	2.6×3.65	2.8
Max. field at windings (T)	12.0	10.0	9.7
Max. J/J_{crit}	0.65	0.65	—
Max. field at plasma major radius (T)	7.0	5.8	5.2
Stored energy (MJ)	6500	2700	1400
Plasma current (MA)	5.0	3.2	2.5
Transformer (V-sec)	20	16	13
Max. field (T)	7.5	7.0	5.0
Stored energy (MJ)	± 180	± 60	± 39
Beam energy (keV)	100 (H)	80 (H)	120 (D)
Beam power (MW)	40	30	≳ 20
Divertor	single-null poloidal	single-null poloidal	none
Pulse length (s)	≳ 32	≳ 32	1-3
Duty factor	≳ 0.05	≳ 0.05	≲ 0.01

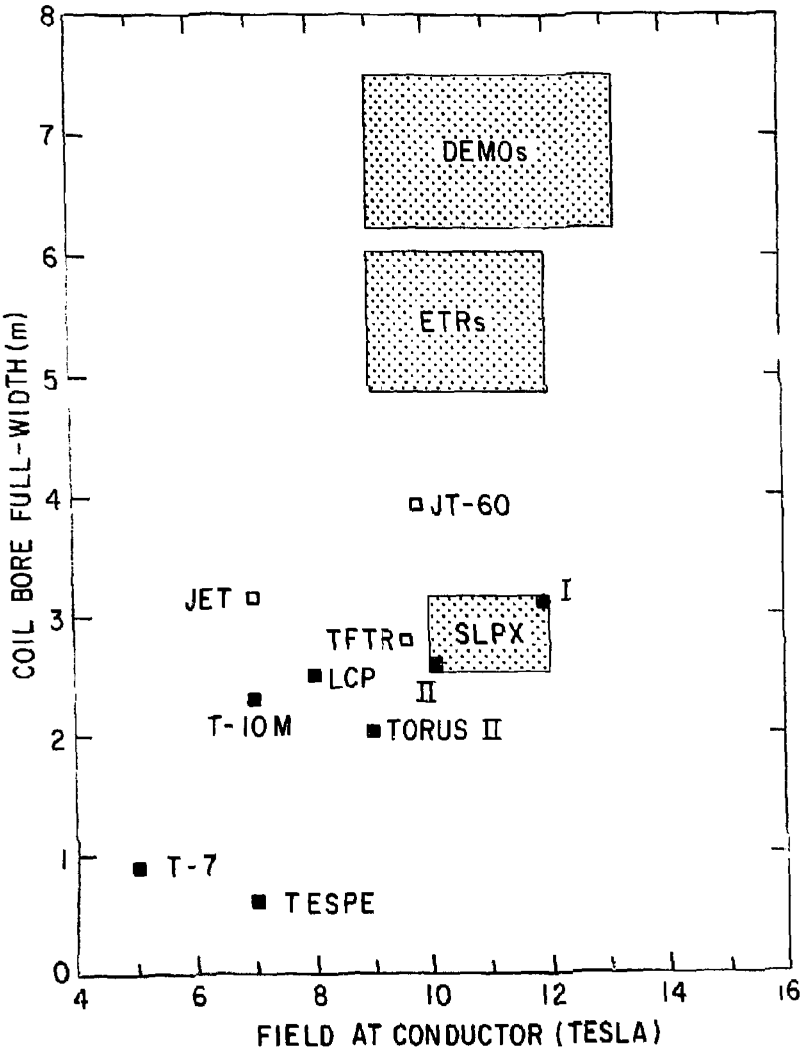

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Fig. 1. Comparison of TF-coil bore sizes. TFTR, JET, and JT-60 have normal coils, while all others are superconducting. (ER ≡ Engineering Test Reactor)

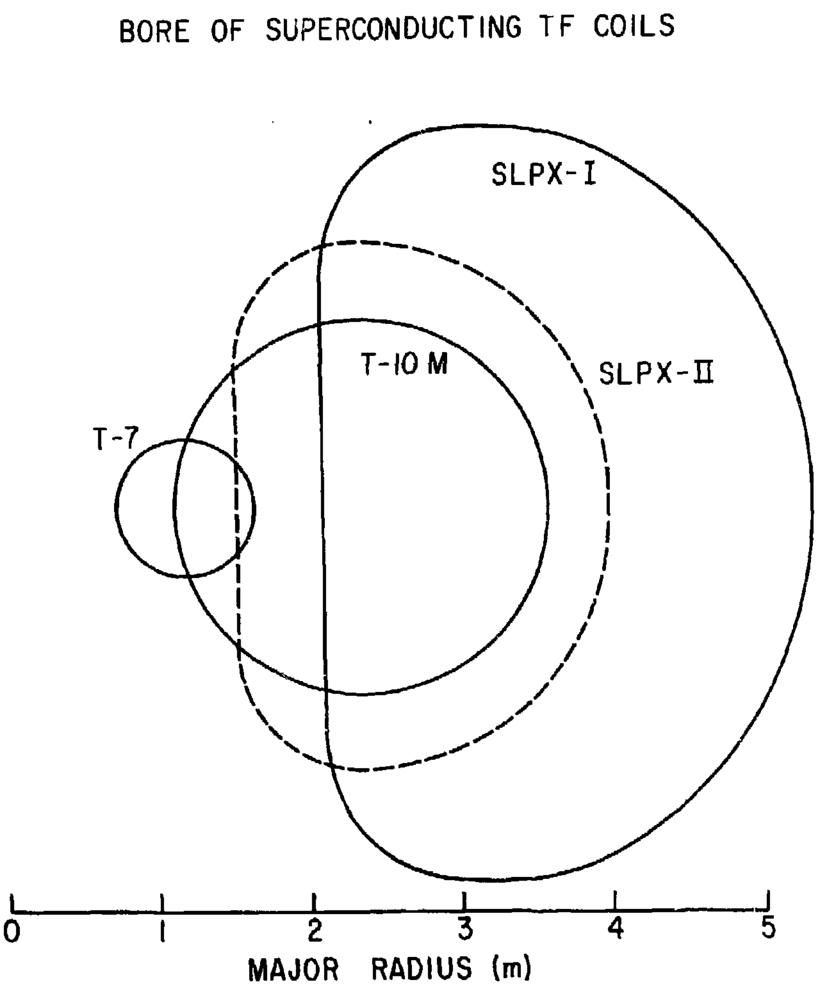

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Fig. 2. Elevation view of the internal bores of the toroidal-field coils for the superconducting T-7 and T-10M machines at Kurchatov, and for the largest and smallest SLPX machines.

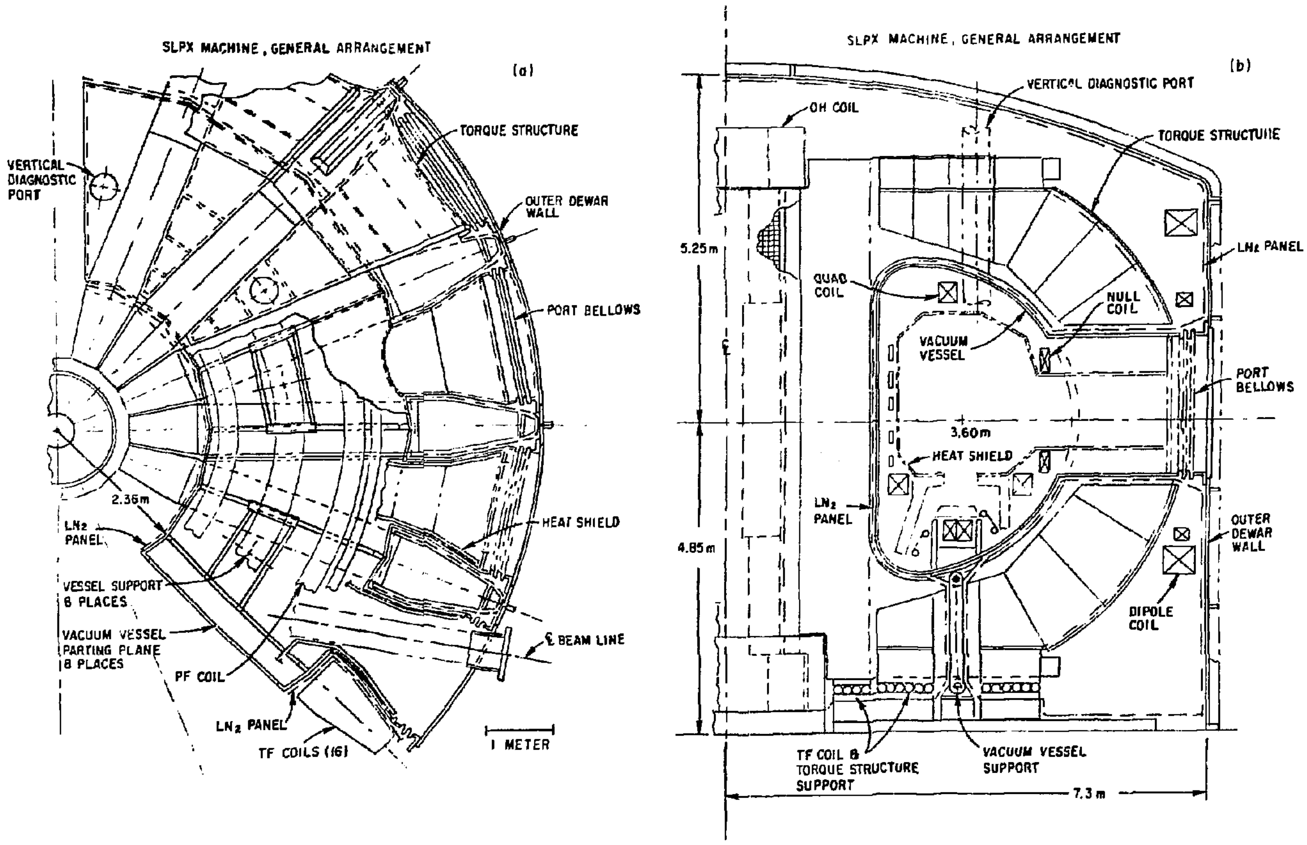

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Fig. 3. (a) Plan and (b) elevation views of the SLPX-I machine.

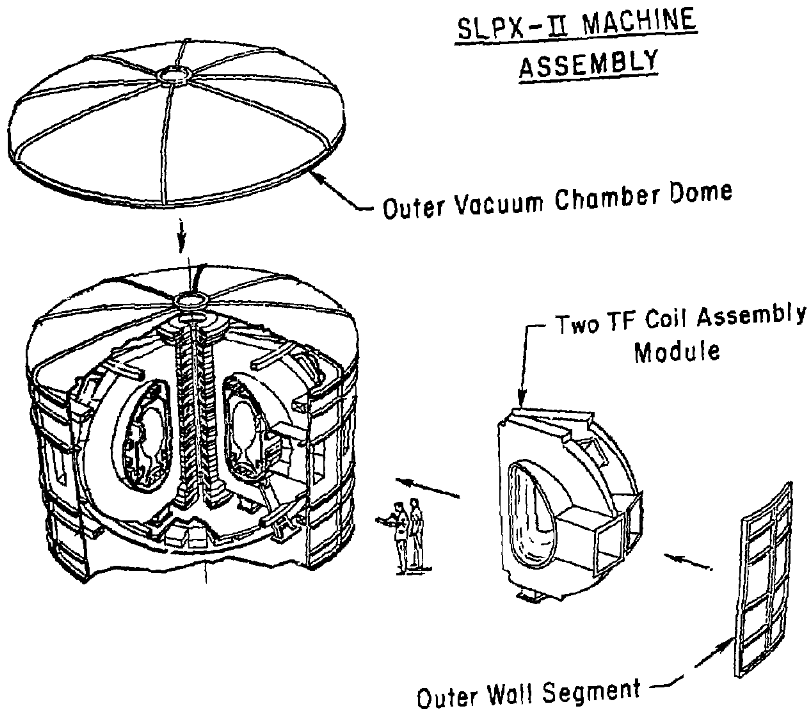

Fig. 4. Perspective view of the SLPX-II machine.

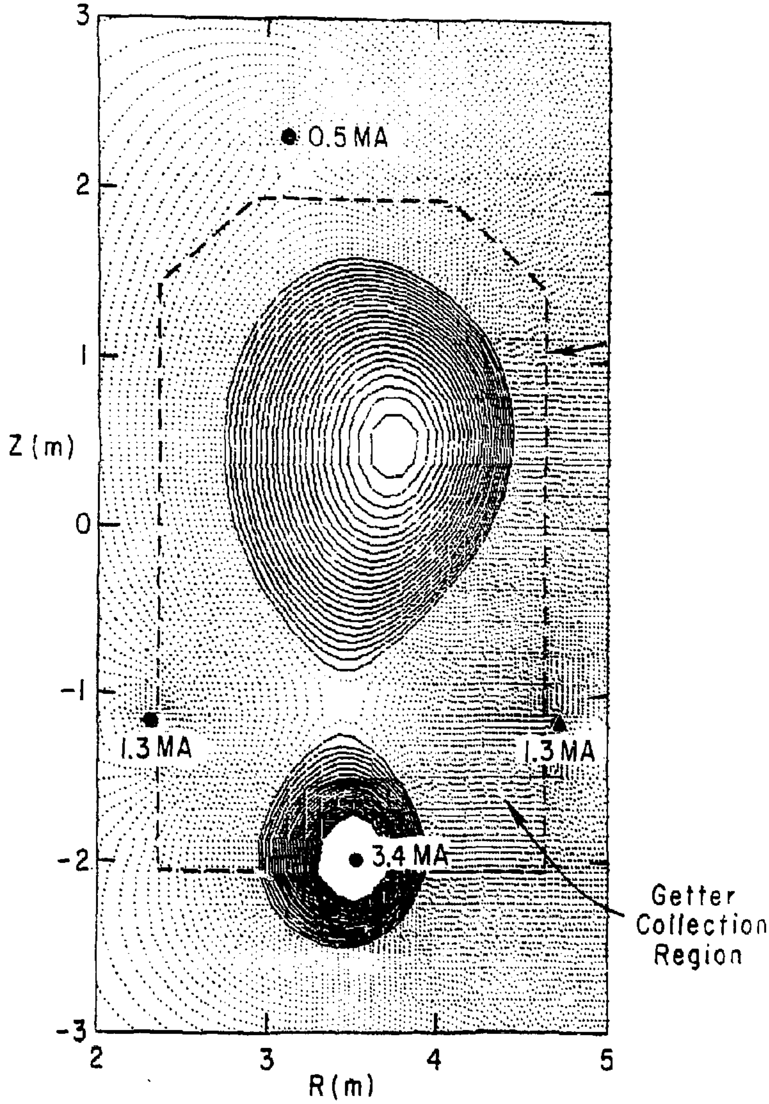

Fig. 5. Flux surfaces for an illustrative 5-MA SLPX-I plasma with the divertor coils activated. Coil currents are indicated.

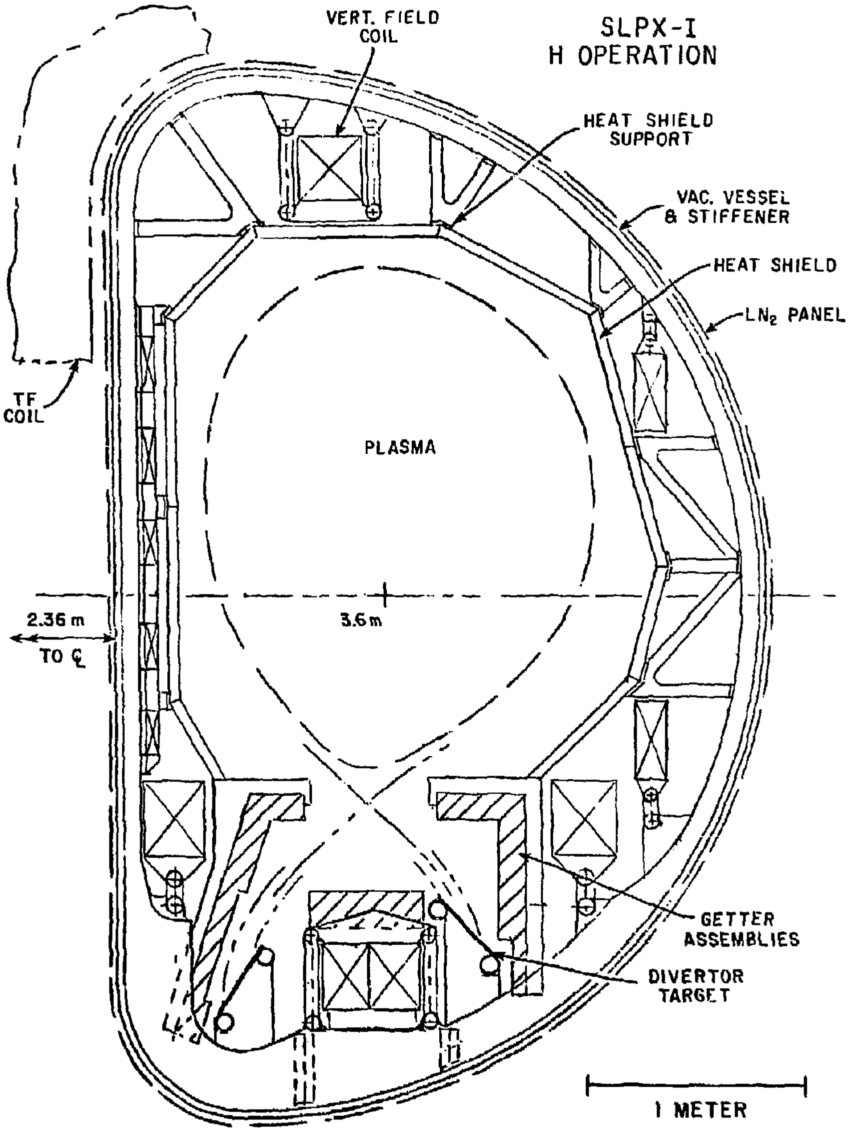

Fig. 6. Elevation view of the components of SLPX-I internal to the toroidal-field coils.

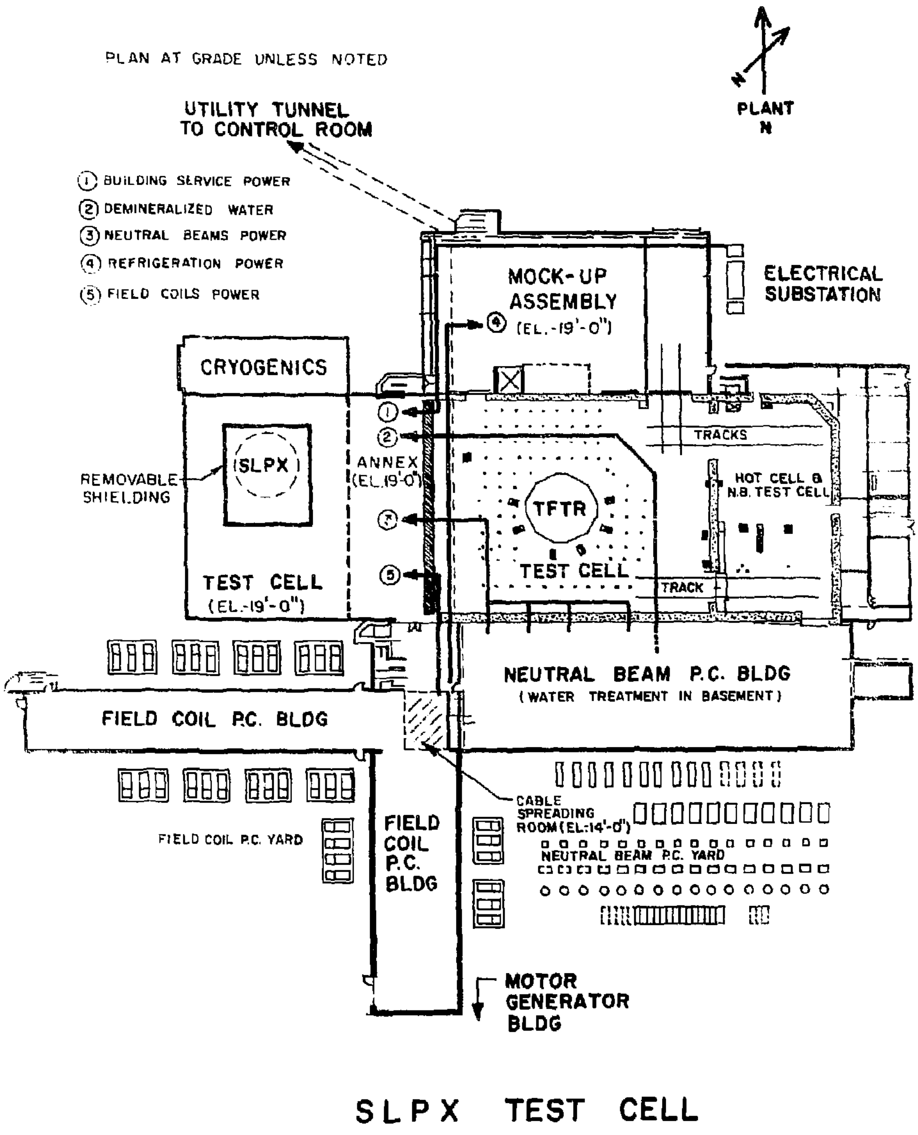

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Fig. 7. Plan of TFTR and SLPX facilities.

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