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SLPX — SUPERCONDUCTING LONG-PULSE TOKAMAK EXPERIMENT

PLASMA PHYSICS LABORATORY

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SLPX – SUPERCONDUCTING LONG-PULSE TOKAMAK EXPERIMENT

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ABSTRACT

The principal objectives of the SLPX (Superconducting Long-Pulse Experiment) are: (1) to demonstrate quasi-steady operation of 3 to 5 MA hydrogen and deuterium tokamak plasmas at high temperature and high thermal wall loading, and (2) to develop reliable operation of prototypical tokamak reactor magnetics systems featuring a toroidal assembly of high-field niobium-tin coils, and a system of pulsed niobium-titanium superconducting poloidal-field coils. This paper describes the status of the engineering design features of the SLPX, with emphasis on the magnetics systems. The toroidal-field coils have an aperture of 3.1 m x 4.8 m, and can operate with a maximum field at the conductor of 12 T. The superconducting poloidal field magnetics system consists of a pulsed NbTi central solenoid, and a set of d.c. NbTi equilibrium-field coils. The entire machine is enclosed in an outer vacuum container equipped with re-entrant ports that provide ambient access to the room-temperature plasma vessel.

1. INTRODUCTION

This report summarizes preliminary design features of a tokamak device equipped with niobium-tin superconducting TF (toroidal-field) coils and niobium-titanium pulsed ohmic-heating coils, and capable of operating at extended pulse lengths (≳ 30 s) with plasma currents up to 5 MA. Called SLPX (Superconducting Long-Pulse Experiment), this machine 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 objectives of the SLPX can be summarized as follows:

- Demonstrate quasi-steady operation of high-temperature (> 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 operation at high thermal power loading.
- Develop and demonstrate high-duty-factor operation of a protocypical 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 x 3.65 m, and an overall coil size appropriate for direct 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 x 4.8 m, and is capable of producing "ignition-level" plasmas in hydrogen. Preliminary results of scoping studies for SLPX-I and II are described in Refs. 2 and 3, and the features of SLPX-I 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: (1) Although NbTi can in principle be used at 9 T or above, there would be practically no margin against temperature excursions such as might be

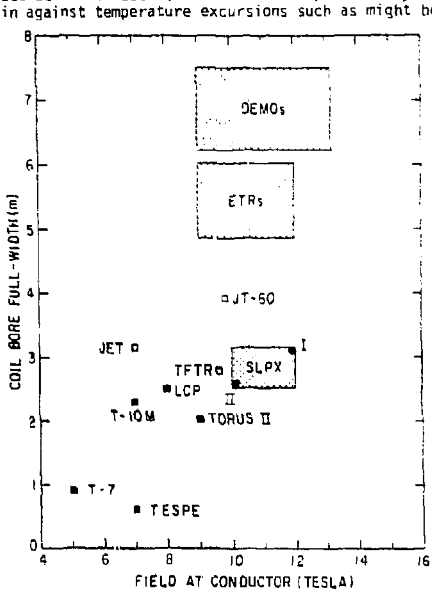

Fig. 1. Comparison of TF-coil bore sizes. TFTR, JET, and JT-60 have normal coils, while all others are superconducting. (ETR≡ Engineering Test Reactor)

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induced by pulsed fields. (2) A practical reactor cannot be expected to operate at the extremes of its component performance, which would be necessary with NbTi TF coils. (3) For $B_{max} \gg 10$ 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.

Several experimental programs have demonstrated that Nb_3Sn magnets can be operated at strains up to 0.2%. 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

Magnetics System. Sufficient space must be provided for adequate build of the TF-coil conductor and structure to support B_{max} up to 12 T. Adequate space must be provided also in the TF-coil throat for the flux swing of a superconducting solenoid which must help establish and maintain a plasma current of 5 MA.

Plasma Size. The plasma radius and attainable pressure should be sufficient to give $\bar{n}\tau_E \geq 2.5 \times 10^{14}$ $cm^{-3}s$ 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 quasi-steady 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 allow ease of access for device maintenance and high-power neutral-beam injection.

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 x 4.8 m. The coil major radius is 3.8 m.

The principal operating parameters of SLPX-I and II are given in Table I.

TABLE I

Parameters of Two SLPX Machines

	SLPX-I	SLPX-II
Plasma major radius (m)	3.60	2.92
Plasma minor radius (m)	0.90	0.77
Plasma elongation ratio	1.5	1.35
TF Coils		
Number	16	16
Conductor	Nb_3Sn	Nb_3Sn
Conductor current (kA)	11.4	15.2
Clear bore (m)	3.1×4.8	2.6×3.65
Max. field at windings (T)	12.0	10.0
Max. J/J_{crit}	0.65	0.65
Max. field at plasma major radius (T)	7.0	5.8
Stored energy (MJ)	6500	2700
Plasma current (MA)	5.0	3.2
Transformer (V-sec)	20	16
Max. field (T)	7.5	7.0
Stored energy (MJ)	± 180	± 60
Beam energy (keV)	100 (H)	80 (H)
Beam power (MW)	40	30
Divertor	single-null poloidal	single-null poloidal
Pulse length (s)	≥ 32	≥ 32
Duty factor	≥ 0.05	≥ 0.05

4. MACHINE LAYOUT

Figure 2 shows plan and elevation views of the SLPX-I, and Fig. 3 shows a perspective view. The machine is constructed in 8 modules, with two TF coils per module. The entire machine is housed in an outer vacuum container (or dewar) with re-entrant holes that provide access to the room-temperature inner vacuum vessel. This outer structure mechanically supports

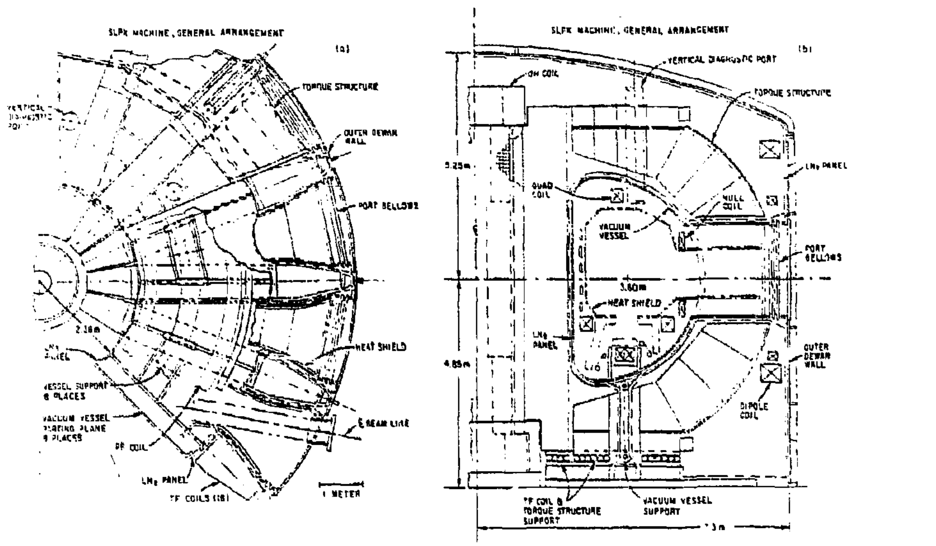

Fig. 2. (a) Plan and (b) elevation views of the SLPX-I machine. (78-6051)

and maintains the superconducting coils at a temperature near 4.2 K. The dewar consists of a stainless steel outer wall, appropriately stiffened, which supports the vacuum loads, and also a low emissivity shield maintained at liquid nitrogen temperature. The lareg re-entrant ports are used for neutral-beam injection, plasma diagnostics, electrical and hydraulic services, and for maintenance of the heat collectors, getter assemblies, and internal PF (poloidal-field) coils.

The plasma vacuum vessel is of thick-wall steel plate construction, and encloses the vacuum-canned internal PF coils. This vessel 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 overpressure loads that may be as large as 5 atmos. for short periods must be sustained.

5. TOROIDAL-FIELD MAGNETS

The first design of the TF coils for the SLPX has been based on the force-flow cooled Nb_3Sn coil to be fabricated by Westinghouse/AIRCO, for testing in the Large Coil Program at Oak Ridge.[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 requires only B_{max}= 8 T, so that aluminum plates can be used, thereby saving cost and weight. However, the SLPX-I requires B_{max}=12T.

Conductor[1]

The compacted Nb_3Sn cable shown in Fig. 4 was selected for the first SLPX design, because this conductor too has been authorized for fabrication and testing. This force-cooled conductor is very similar to the LCP conductor, which is presently being qualified by several laboratories.[3] The cable is fully transposed, thereby minimizing the influence of the pulsed poloidal fields. The cable is made up of six sub-cables of 3^4 superconducting strands wrapped around a central sub-cable.

A cost and operational optimization study[2] indicated that the optimum ratio of J/J_c is 0.65. This value

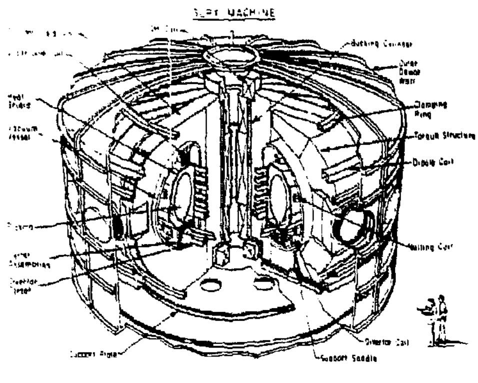

Fig. 3. Perspective view of the SLPX-I machine.

TABLE II

SLPX Toroidal Field Coil Specifications

Candidate Conductor Specifications	
Superconductor	Nb_3Sn
Cable Configuration	3^4 by 7
Total Strands	567
Cu to NonCu Ratio	1.58
Strand Diameter	0.718 mm
J/Jcrit	0.65
Operating Current/Strand (@ 12 T)	24.4 A
Number of Filaments	3500
Filament Diameter	3.5 μ
Length of Conductor	11.7 km
Conductor Cooling Requirements	
Peak Field	12.0 T
Conductor Current	11.8 kA
Helium Void Fraction	0.4
Helium Flowrate/Coil	890 g/s
Helium Pressure Drop	1.43 atm.
Helium Pumpwork, 4.2 K	1,280 W/coil
3.6 K	750 W/coil
Electrical and Mechanical Parameters	
Number of TF Coils	16
I.R. of Central Leg	1.1 m
O.R. of Central Leg	2.17 m
Horizontal Bore (Conductor)	3.3 m
Vertical Bore (Conductor)	5.0 m
Coil Width (Maximum)	79 cm
Number of Turns Per Coil	684
Number of Slots Per Plate	6
Number of Turns Per Slot	6
Number of Plates	26
Number of Segments Per Plate	3
Plate Material	Stainl. Steel
Structure Weight	118,233 kg
Winding Weight	32,476 kg
Stored Energy (B_{max}= 12 T)	6500 MJ

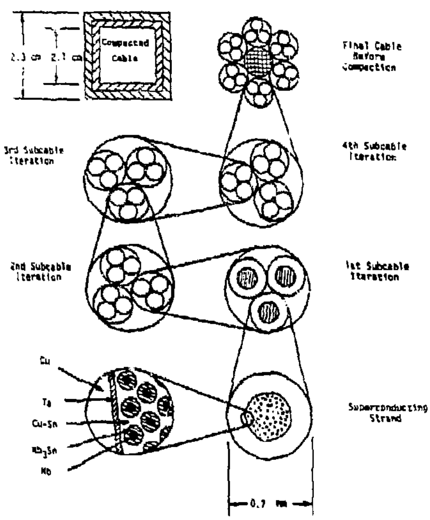

Fig. 4. TF-coil conductor configuration. (78-6053)

simultaneously minimizes both the cost of the conductor and the pumping power required for cryostability. Table II gives both the conductor and coil specifications for operation of SLPX-I at B_{max} = 12 T.

Stress Analysis

A stress analysis of the SLPX-I coil has been undertaken at PPPL, using the NASTRAN version 17 code. Several different finite-element models have been used. Both aluminum and stainless steel plates have been considered. Preliminary results, including only in-plane loads, indicate that the maximum deflection of the aluminum plate at B_{max} = 12 T would be excessive (viz. 6.78 mm). Consequently, we have decided to use stainless steel plates, in which the maximum deflection (due to in-plane forces only) is 2.58 mm, the maximum strain is 0.11%, and the maximum stress is 38,000 psi. 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 eliminate the bucking cylinder used 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 a torque frame together with structural members between adjacent coils (see Fig. 2).

Plasma Disruptions

If the plasma vacuum vessel has no resistive break, then it has been determined that the amount of energy deposited in the TF coils following a total loss of plasma current (i.e., 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-I PF magnetics system has the following components (see Figs. 2 and 3):

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

Pulsed nulling-field coils. Before start-up, these water-cooled copper coils are pulsed to oppose the DC external field to obtain a near-zero starting field, and are then pulsed to provide the correct equilibrium field during plasma current start-up.[5]

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.[5]

Divertor-field coils. A single-null poloidal divertor is established with the lower quadrupole. Two adjacent copper coils pull out the poloidal field lines in order to spread particle and heat fluxes across water-cooled 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 coils. The OH solenoid provides about 60% of the flux swing for plasma current build-up. The OH windings are made with NbTi stranded insulating superconductor operating at a maximum field of 7 to 7.5 T. The overall current density can be kept under 1500 A/cm^2. The maximum dB/dt is 6 T/s. Except for total stored energy (±180 MJ), the OH solenoid specifications are close to those being developed in the pulsed-coil programs at Los Alamos and Argonne.

7. 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 to 20 K for a length of one half turn. This cryostability criterion requires a refrigeration power of 150 watts per coil for SLPX-I at B_{max} = 11.0 T and 4.2 K, and 750 W per coil at 12.0 T and 3.6 K. With a deuterium plasma, 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.

TABLE III

Liquid Helium Refrigeration Requirements
Watts at 4.2 K

Field at conductor ≈	11.0 T	12.0 T
TF Coils	2,400	12,000[a]
TF Leads	500	700
Dipole Coils	100	100
Dipole Leads	500	500
Central OH Coils[b]	4,000	4,200
OH Leads	1,100	1,200
Helium Pump[c]	2,400	8,000
Outer Container	400	400
Total (watts)	11,400	27,100

[a]At 12 T, coils are operated at 3.6 K.
[b]Averaged over operating cycle (600 s).
[c]Based on 60% efficiency.

Table III lists all the liquid helium refrigeration requirements. During charging of the TF coils, an extra 2000 W is required, but this load is non-simultaneous with the larger requirement of the ohmic-heating central solenoid. Three 10-kW refrigeration units are required for 12 T operation, but only 15 kW capacity is needed at 11 T (including D-D neutron loading). The total liquid nitrogen requirements are estimated to be 190 kW.

8. GENERAL

Assuming the use of large-scale manufacturing methods, the estimated cost of the 16 TF coils of SLPX-I is $78 million (1978). The total estimated project cost for SLPX-I, including 30% E.D.I.A. and 20% contingency, is approximately $260 million (1978). All the superconducting and cryogenic elements together account for 60% of the total cost. This estimate assumes that the machine will be sited at PPPL, and will take advantage of the TFTR-site facilities. For timely implementation of this machine, the development of Nb_3Sn conductor must be pursued vigorously, and planned Nb_3Sn coil tests such as in the LCP must remain on schedule or be accelerated.

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