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# THE TPX MAGNET R&D PROGRAM

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## ABSTRACT

A unique feature of the magnet system for the Tokamak Physics Experiment (TPX) is that all the magnets are superconducting. With the exception of the outer poloidal coils, the magnet system uses Nb3Sn cable-in-conduit conductor; the outer poloidal coils use Nb-Ti cable-in-conduit conductor. A Research and Development program is needed to ensure that the materials, processes, and systems are available to support the fabrication and operation of these magnets. We describe our plans for R&D in the areas of: conductor strand and sheath development, insulation materials and configuration, conductor forming, curing, and impregnation techniques, and quench detection methods and techniques. Since a significant portion of the TPX magnet system design and fabrication will be done in industry, a division of the magnet R&D effort between industry and the National Laboratories is proposed. A close liaison is maintained with the ITER magnet R&D program, and TPX will make use of ITER results whenever possible.

## INTRODUCTION

The Tokamak Physics Experiment (TPX), an advanced steady state plasma physics machine to be built at the Princeton Plasma Physics Laboratory [1], will be the world's first Tokamak with a complete set of superconducting main coils [2]. Figure 1 depicts the magnet set as presented at the Conceptual Design Review[3,4]. An overview of the TPX Magnet System is presented by Schultz et al.[5] elsewhere in this conference. All of the TPX coils will use cable-in-conduit-conductors (CICC) cooled with flowing supercritical helium. The Toroidal Field (TF) coils will require a Nb3Sn superconductor with a copper to noncopper ratio of about 2:1, the Central Solenoid (CS) and Poloidal Field (PF) 5 will use a Nb3Sn superconductor with a copper to noncopper ratio of about 3.5:1, and PF 6 and PF 7 will use Nb-Ti superconductor with a copper to superconductor ratio of about 6:1. The conduit material for the Nb3Sn conductors will be Incoloy 908, a ferromagnetic material developed especially for this purpose to survive the Nb3Sn reaction conditions and to match the thermal contraction of the superconducting composite[6]. The Nb-Ti superconductor will be sheathed with 316LN material, an austenitic stainless steel alloy well suited for cryogenic applications[7].

Because of space constraints and reliability considerations, no joints are envisioned within any of the coils - there will only be joints between coils and between coils and their superconducting bus. Continuous lengths of the sheathed superconductor (0.8 to 2.4 km, depending on coil) will be wound, then in the case of the Nb3Sn coils reacted, insulated and finally vacuum-pressure impregnated. In the TF coils, the insulated and potted windings will be encased in a welded 316LN case structure, and there will be a massive intercoil structure, also fabricated out of 316LN, to safely react the electromagnetic loads. In the PF and CS coils there is no case structure to eliminate induced eddy currents during the pulsed operation. The fiberglass-epoxy insulation in the PF coils must be resistant to cracking during cryogenic and pulsed field operation by proper materials selection and process development and control.

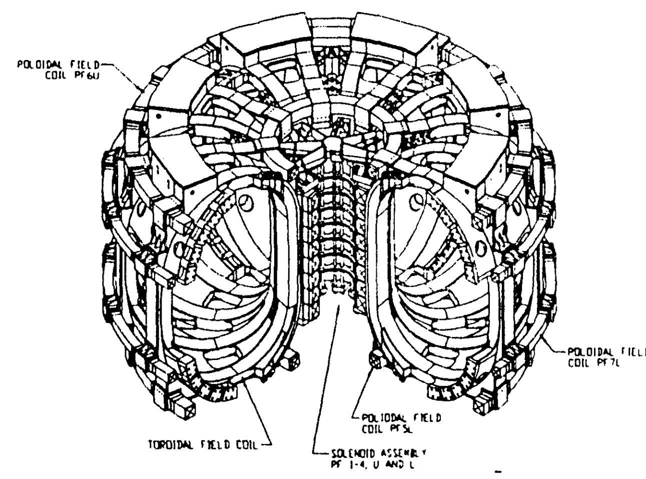


Fig. 1. TPX Magnet System

The present TF electrical configuration has all 16 TF coils connected in series to minimize the amount of electrical switch gear and minimize the possibility of unbalanced electromagnetic forces. This, coupled with the compact winding pack, results in a TF discharge voltage of 15 kV to limit the hot spot temperature in case of a quench to 150 K. Since the PF coils will be rapidly pulsed to initiate the plasma, the voltages required for normal operation will in general be only slightly less than the 15 kV required for TF protection [5].

A planned program of research and development (perhaps more development than research) is needed to ensure that the TPX design and fabrication decisions result in a system that meets the machine requirements. Since a major portion of the actual design and fabrication will be done in industry, the R&D effort must be shared between industry and the National Laboratories. The main areas of R&D are: conductor development (including ramping rate studies), process development, and quench detection and protection.

## CONDUCTOR DEVELOPMENT

### A. *Strand Development and Evaluation*

The compact TF coil winding pack design, coupled with a machine requirement to deal with nuclear heating from fusion-produced neutrons and eddy current heating from the vertical stabilizer coils, leads to a rather small design window for the $Nb_3Sn$ conductor. The TF coil design is still being finalized, but the final set of TF strand requirements will be close to those shown in Table 1. The preliminary requirements for the PF strand are presented in Table 2.

The superconducting strand will be developed by industrial superconducting wire manufacturers to the TPX specifications, with testing being performed by both industry and the appropriate National Laboratories. This effort will be led by personnel from LLNL and MIT, with assistance from our industrial magnet contractor(s), once they are under contract. Although the requirements on the superconducting strand material appear to be rather modest, the copper fraction required is somewhat higher than what is currently produced commercially for both the $Nb_3Sn$ and Nb-Ti. Therefore, a development program is needed to:

- define strand requirements that are achievable in production,
- predict magnet performance under the TPX operating conditions, and
- obtain vendors qualified to produce the strand at the rates required.

Initial procurements of $Nb_3Sn$ material produced from small, say 25 kg, billets will be made to allow superconductor manufacturers to produce material on a short time scale and give us an early delivery of strand for evaluation. After performing the evaluations on this material, orders for production-type material will be placed to allow the superconductor manufacturers to scale up their processes. If the scale-up is unsuccessful, the fallback position would be to use the process originally used to produce the smaller billets.

The planned $Nb_3Sn$ strand evaluation tests include:

- Photomicrographs to allow a visual assessment of strand morphology and a determination of copper fraction.
- Measurement of critical current at a sensitivity of 0.1 μv/cm on 1 to 2 m long barrel samples at 4.2 K, 5 K, and 6 K.
- Measurement of critical current as a function of strain at 4.2 K.
- Measurement of upper critical field as a function of temperature.
- Measurement of the residual resistivity ratio..
- Measurement of hysteresis loss over a ± 3 T and ± 7 T cycle, using the dc magnetization technique.
- Measurement of the effective coupling time constant and hysteresis loss using calorimetry at zero field and at full field.

The Nb-Ti strand development will proceed in a slightly different manner since the uncertainty in production process is probably not as great as it is for the $Nb_3Sn$ case. We will

Table 1. TF Strand Requirements

| Conductor Type | $Nb_3Sn$ |
|---|---|
| Total mass, Mg | ~ 30 |
| Peak field, T | 9 |
| Peak temperature, K | 7 K |
| Operating strain, % | -0.3 |
| Diameter, mm | 0.78 |
| Noncopper $J_c$ A/mm$^2$ @ 9 T, 4.2 K | 1000 |
| Copper : noncopper ratio | 2:1 |
| Cr plating, μm | 1 |
| Final RRR | 75 |
| Twist Pitch, mm | < 8 |
| Hysteresis loss, ± 3 T, mJ/cc (noncopper vol.) | 460 |

Table 2. PF Strand Requirements

| | CS | PF 5 | PF 6 & PF 7 |
|---|---|---|---|
| Conductor type | $Nb_3Sn$ | $Nb_3Sn$ | Nb-Ti |
| Total mass, Mg | 5 | 2.5 | 4 |
| Peak field, T | 7.6 | 5.3 | 5 |
| Peak temperature, K | 5.5 | 5.25 | 5.25 |
| Operating strain | -0.3 % | -0.3 % | na |
| Diameter, mm | 0.78 | 0.78 | 0.78 |
| Noncopper $J_c$, A/mm$^2$ @ peak field, 4.2 K | 1300 | 1850 | 2075 |
| Copper : noncopper ratio | 3.5:1 | 3.5:1 | 6:1 |
| Cr plating, μm | 1 | 1 | 1 |
| Final RRR | 75 | 75 | 150 |
| Twist pitch, mm | < 8 | < 8 | < 8 |
| Hysteresis loss, ± 3 T, mJ/cc (noncopper volume) | 460 | 460 | 150 |

proceed initially with a 250 kg Nb-Ti billet, which would probably be close to the actual production size. The Nb-Ti strand evaluation tests will be similar to those above, with the elimination of the measurement of the strain effect on critical current.

In the above procurements, the vendor will be responsible for obtaining the Cr plating, but a parallel study of the effect of Cr plating on the RRR will be carried out because of uncertainties in the effect of the plating on RRR.

*B. Subcable Evaluation*

measurements will be made for steady-state, slow field-ramp, and fast current ramp (80 kA/s) conditions. In addition, measurements of the stability margin of the full-size cable will be made using pulsed coils which induce quenches in the high-field region of the sample, and current sharing temperature measurements will be made with heaters on the helium feed lines. The joints to be tested include the TF interconnection joints, the TF conductor to Nb-Ti bus joints, the PF1-5 conductor to Nb-Ti bus joints, and the PF6-7 Nb-Ti bus joints. In these tests, the voltage drop across the joint is intimately connected with the actual fabrication the subcontractor(s) will have to do and are needed to select the materials and design and specify the equipment. As mentioned above, both dummy as well as early prototype conductor will be provided to the magnet subcontractor(s) as soon as it is available for their use in carrying out these tests. Included in these process development tasks are:

- Conductor bending and forming tests to determine the factors and limitations are needed to be able to wind the continuous lengths of sheathed conductor without pancake joints
- Ensuring a uniform $Nb_3Sn$ reaction over the entire winding pack cross section, how to meet the environmental conditions required to retain good properties of the Incoloy 908 sheath, and sheath cleaning procedures if any are needed
- Materials selection and process development for the coil insulation and impregnation, including tests to ensure that the material and process meets the electrical and mechanical requirements
- Development of reliable helium connections to the sheathed conductor, and tests to demonstrate the suitability for use in TPX.

## QUENCH DETECTION DEVELOPMENT

The quench detection development program is very important to the TPX magnet system because: 1) computer simulations indicate that the conventional quench detection technique of differential voltage thresholds between adjacent voltage taps will not be able to distinguish between coil quenches and plasma disruptions in time to satisfy peak hot spot temperature allowables, 2) an ongoing review and analysis of existing methods and systems so far indicates that existing techniques are marginal or inadequate for TF coils. Quench detection in the PF system is expected to be more difficult, because of the much higher unbalanced voltage levels there, and 3) several new sensor techniques that have not yet been used in superconducting magnet systems have been proposed as solutions. These require serious design and analysis effort before they can be tested.

The quench detection devices presently proposed for TPX include:

- conventional voltage taps connected to every other pancake at the outer diameter of the coil,
- noninductive voltage taps outside the conduit,
- noninductive voltage taps inside the conduit, and
- helium flowmeters on every cooling channel.

Several other quench sensors have been proposed and rejected for TPX, but fiber optic temperature sensors, wound continuously in the cable space and extracted every 2 pancakes, remain a tantalizing option for the Nb-Ti coils which don't require a post-winding heat treatment.

The overall TPX quench detection R&D plan consists of the following:

- Continue design and analysis studies of the proposed methods to understand their virtues and faults,
- prepare a set of quench detection requirements by which our effort can be assessed,
- fabricate and test small conductor samples to demonstrate the survivability of the noninductive voltage taps to coil fabrication, heat treatment and operation.
- gain operating experience with cryogenic differential pressure sensors (flowmeters) in the FENIX facility at LLNL
- carry out noise rejection experiments at LLNL on the various voltage taps
- participate in the upcoming ITER quench tests on long lengths of CICC conductor in the SULTAN facility in FY94, and
- monitor the performance of the novel techniques such as fiber optic sensors, pressure relays, and microwave cavities as proposed by ITER.

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