

Tokamak Physics Experiment (TPX) Power Supply Design and Development

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Abstract: The Tokamak Physics Experiment (TPX) is an advanced tokamak project aimed at the production of quasi-steady state plasmas with advanced shape, heating, and particle control. TPX is to be built at the Princeton Plasma Physics Laboratory (PPPL) using many of the facilities from the Tokamak Fusion Test Reactor (TFTR). TPX will be the first tokamak to utilize superconducting (SC) magnets in both the toroidal field (TF) and poloidal field (PF) systems. This new feature requires a departure from the traditional tokamak power supply schemes. This paper describes the plan for the adaptation of the PPPL/TFTR power system facilities to supply TPX. Five major areas are addressed, namely the AC power system, the TF, PF and Fast Plasma Position Control (FPPC) power supplies, and quench protection for the TF and PF systems. Special emphasis is placed on the development of new power supply and protection schemes.

I. Operational Requirements

The design of the power systems is driven by the baseline requirements, and also by the possibility of several upgrade options which are foreseen.

A. Baseline Requirements

Plasma current	2 MA
Plasma configuration	Double Null
Toriodal Field	4 Tesla
Heating & Current Drive Power	17.5 MW
Max. pulse (burn) duration	1000 seconds
Min. repetition period	4500 seconds
Max. # pulses per 24 hours	10 pulses

B. Single Null Upgrade Option I

The plasma configuration is single null, which requires unequal currents in the upper and lower PF coils.

C. Heating & Current Drive Upgrade Option II

The heating & current drive (H&CD) power deliverable to the plasma is increased to 45 MW from 17.5 MW.

D. Steady State Upgrade Option III

A plasma is generated and driven in a quasi-steady state mode ($\approx 100,000$ sec, ≈ 24 hrs).

II. AC Power Systems

While the use of superconductors permits long pulse operation without undue power and energy demand by the TF & PF magnets, the heating & current drive systems still present a substantial load over a long time period such that energy storage means are impractical, and the load must be taken directly from the utility grid. A summary of the peak values of the major loads is given in Table 1. It is noted that in terms of peak load, Option I is identical to the baseline, and Options II and III are equivalent to each other.

<u>Load</u>	<u>Baseline</u> (MW/MVAR)	<u>Option II/III</u> (MW/MVAR)
PPPL Facilities	5/3.75	5/3.75
TPX Aux Sys	20/15	20/15
TPX PF (ramp)	75/*	75/*
TPX PF (burn)	10/*	10/*
H&CD (burn)	66/34	197/102

* = reactive power set by converter configuration

Table 1 - Summary of Peak Loads

The existing TFTR power systems include two powerful (475 MVA, 2.25 GJ) motor-generator (MG) sets which deliver power to a large (1.8 GVA (pulsed) installed capacity) thyristor rectifier system. Analysis of the various options for powering the magnet power supplies and the heating and current drive systems¹ led to the conclusions that 1) the TF loads could be serviced through the existing substation transformers and a new rectifier, 2) the PF loads could be serviced by the TFTR MG systems and associated rectifiers, and 3) that the H&CD systems require a new substation and distribution system located immediately adjacent to the facility for the long pulse, high power load. Figure 1 shows a simplified one-line diagram of the AC power system.

The composite load imposed on the grid for the various stages of operation is summarized in Table 2.

<u>Load</u>	<u>Baseline</u> (MW/MVAR)	<u>Option II/III</u> (MW/MVAR)
Base	31/24	31/24
Pulsed	66/34	197/102
Peak	97/58	228/126

Table 2 - Composite Load On Utility Grid

Preliminary calculations performed in conjunction with the local public utility indicate that 50 MVAR of reactive compensation will be required for Options II, and Option III may require the reconductoring of the transmission line spur which feeds the main 138 kV PPPL substation.

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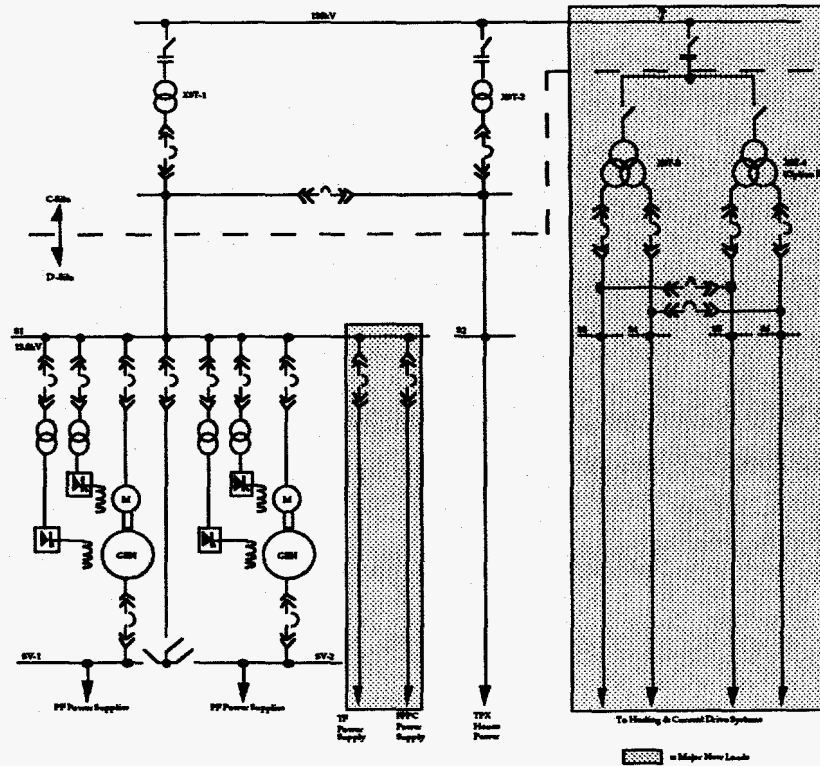


Figure 1 - Simplified One-Line Diagram of TPX AC Power System

III. TF SYSTEM

The main parameters of the TF system are:

Maximum current (continuous)	33.5 kA
Field @ max. current, $r=2.25m$	4.0 Tesla
Inductance	1.8 Henries
Stored energy @ max. current	1.0 GJoule
Current ramp up/down interval	600 seconds
Maximum fast discharge voltage	15kV
Full load voltage (ramp)	110 volts
Full load voltage (hold)	10 volts

The TF system will nominally remain energized over the full operational day, but will occasionally be de-energized between pulses to permit glow discharge cleaning; this need dictates the ramping interval. Once the current is established, only the small voltage drop associated with the DC bus and rectifier semiconductor impedances needs to be provided. The fast discharge is obtained by resistor insertion and is reserved for emergency situations such as magnet quench events.

A schematic of the TF circuit is given in Figure 2.

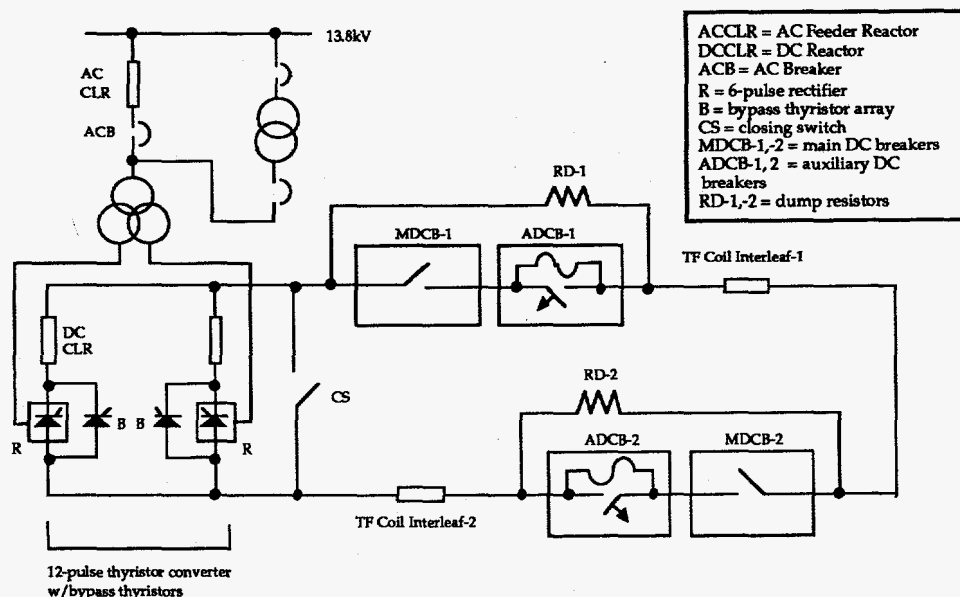


Figure 2 - Simplified Schematic of TF System

A. TF Rectifier Converter

A 12-pulse thyristor converter with fully rated bypass thyristor array, operable in the freewheeling mode, is envisioned. The reduction of primary voltage during current hold via AC bus transfer to an intermediate feeder transformer is being considered. This feature would reduce the reactive power and harmonics consumed by the converter during constant current (hold).

B. Interleaving

The DC circuit is divided into two interleaves to reduce voltage to ground during the 15kV fast discharge event to +/- 3.75kV nominal, +/- 7.5kV fault.

C. Converter Protection

A pulse rated closing switch is included to provide a reliable discharge path for the magnet current in case the converter bypass thyristors in the rectifier converter become faulty. If this switch is closed, the fast discharge of the magnets must be invoked.

D. Quench Protection

In each interleaf a pair of DC circuit breaking devices, in parallel with an energy dump resistor, are provided. The main device provides the first line of defense for quench protection (QP) while the auxiliary device is a back-up. If a slow discharge is desired, then only one of the two resistors can be inserted; however this requires that each resistor be rated for the full energy.

IV. PF SYSTEM

The PF system consists of 7 pairs of coils with symmetry about the horizontal mid plane of the tokamak. For double null, the currents are identical in the upper and lower coils, whereas to create a single null, an asymmetry in the current is required in the PF-4, -5, and -6 coil pairs. Maximum parameters of the seven circuits are as follows:

Maximum current (instantaneous)	27.9 kA
Maximum current (1000 seconds)	27.9 kA
Stored energy @ max. current	96.5 MJoule
Maximum fast discharge voltage	6kV
Full load voltage (ramp)	1.4 kV
Full load voltage (burn)	0.18 kV

During a pulse the PF coils are precharged, and then a resistor is inserted for the fast discharge for plasma initiation (PI). Once the plasma is established it is ramped to its flat-top value and the "burn" phase commences. During burn, conditions are relatively quiescent; additional volt-seconds for plasma current drive are provided by the H&CD systems and plasma bootstrap effects. However, it is still necessary to provide power supply capability for control of plasma fluctuations as follows.

1) Loop voltage fluctuations

A one volt-second margin is to be reserved for inductive control of the plasma current. This requirement can be translated into a power supply requirement via a hypothetical scenario whereby I_p is imagined to vary in a triangular fashion.

Assuming a plasma inductance of $5\mu\text{H}$, the corresponding ΔI_p equates to 200kA. Allowing an average $I_p = 2.0 - 0.2 = 1.8\text{MA}$, the plasma current can be assumed, for power supply design purposes, to fluctuate between 1.6 and 2.0MA in a triangular fashion around an average value of 1.8kA. A 20 second fluctuation period has been suggested, so that dI_p/dt equates to 40kA/second, which is roughly 1/10 of that during initial plasma ramp up.

2) Vertical Field Fluctuations

The outer PF coils will need to relieve the internal (FPPC) coils following a 50% drop in plasma stored energy; they need to transition to a new equilibrium point with reduced vertical field, while maintaining shape constraints.

3) Strike Point Fluctuations

The strike point on the divertor target will need to be varied over a +/- 5 cm range with a sweep rate still to be determined.

Thus the PF power supply voltage and power requirements during plasma burn are determined to be as summarized in the following table:

	V control	I _{max} burn	V bus	V _{max}	Power
	V	kA	V	V	MW
PF1	66	24.792	7	73.1	1.8
PF2	47	23.385	8	54.6	1.3
PF3	24	16.117	6	30.7	0.5
PF4	18	12.283	4	22.3	0.3
PF5	5	27.875	6	11.2	0.3
PF6	169	19.492	9	178.4	3.5
PF7	79	18.214	7	85.6	1.6
				Total....	9.2

The PF power demands are nearly one order of magnitude less during the plasma burn ($\approx 10\text{MW}$) as compared to the ramping ($\approx 75\text{MW}$). Two design approaches for the PF power supply have been identified to provide for this large variation in demand:

Baseline Approach

Enough thyristor rectifier sections are available from TFTR so as to permit the supply of the PF system using anti-parallel connected strings of rectifiers, with a sufficient number in parallel in the direction of current flow during plasma burn to supply the current for 1000 seconds². With the TFTR MG sets as a power source the AC voltage impressed on the converter transformers can be controlled via control of the excitation of the generator field winding. Using this feature the full voltage and power capability is available during the ramping phase, while the voltage can be reduced during the burn phase to better match the rectifiers to the requirements of the load.

HCLV Approach

Although the TFTR power supply sections exist in ample quantity, the use of new High Current, Low Voltage (HCLV) power supplies during the plasma burn phase may be a better solution. The TFTR equipment was designed for pulsed

operation (24kA-6 seconds every 300 seconds), so that many parallels are required to conduct the current for 1000 seconds. The connection costs might exceed the cost of the HCLV supplies, and control would certainly be more complex.

Besides, the HCLV supplies could be rated on a continuous basis and support the steady state upgrade option.

A simplified schematic the PF circuit concept showing both approaches is given in Figure 3.

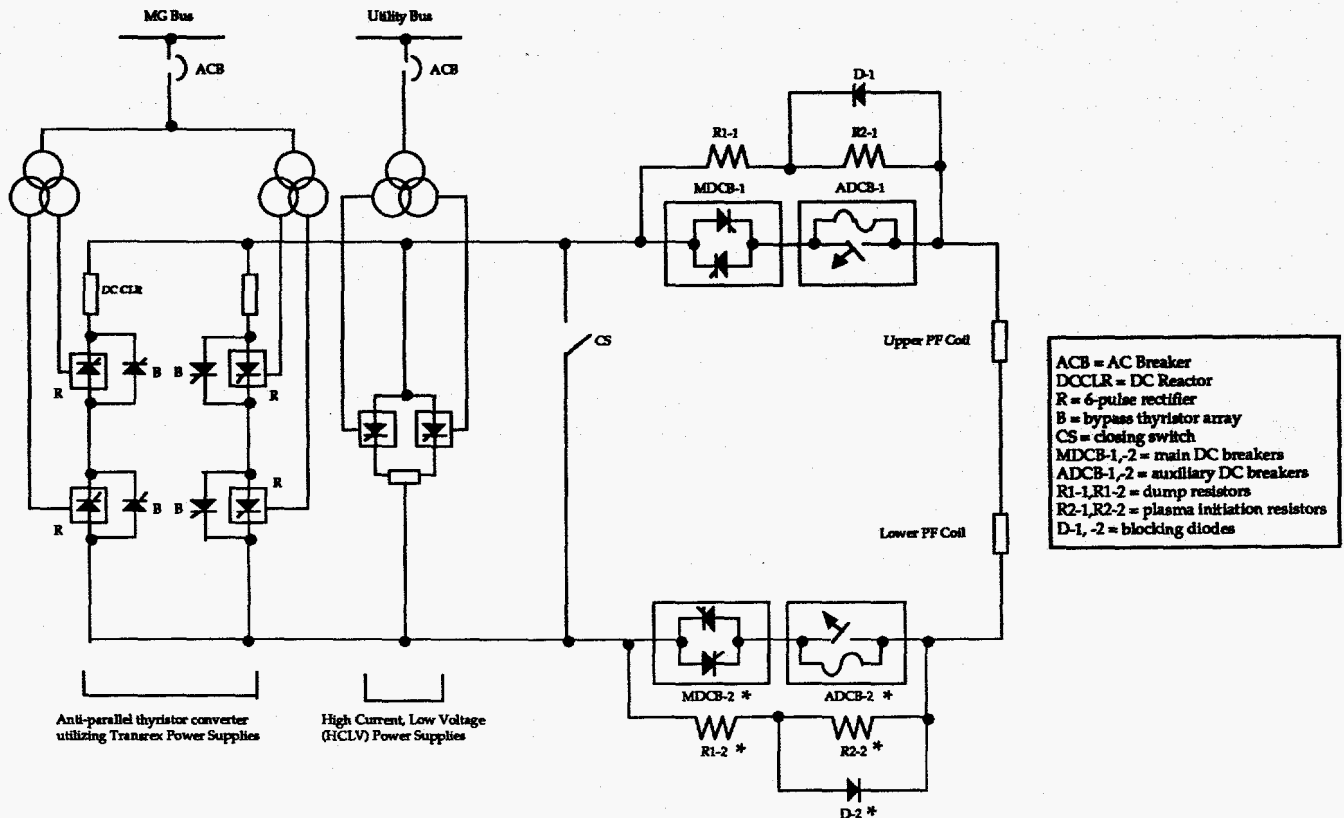


Figure 3 Simplified Schematic Diagram of Typical PF Circuit

A. PF Rectifier Converter

An antiparallel connection of the TFTR rectifiers is provided for bipolar currents. The number of parallels in each current direction is tailored to the ampacity requirement of each circuit. The number of series layers is at least two, but in some cases (PF6 and PF7) four. Only a single parallel is required in the forward direction. Without the HCLV option the number of parallels in the plasma burn (negative) current direction is typically four. With the HCLV option a single parallel is sufficient.

B. HCLV Power Supplies

The HCLV power supplies, if used for the baseline or for the steady state upgrade, would be suppressed while the main converter ramps the plasma current, then commutated into the circuit for the plasma burn duty. They must be rated to block the voltage produced by the main converter.

C. Converter Protection

A pulse rated closing switch is provided to provide a reliable discharge path for the magnet current in case the converter bypass thyristors become faulty. If this switch is closed, the fast discharge of the magnets must be invoked.

D. Plasma Initiation and Quench Protection

In each circuit one or two sets of DC circuit breaking devices, in parallel with an energy dump resistor, are provided, two sets in the case of those circuits with the midpoint connection. The main device operates each pulse for PI, and provides the first line of defense for QP. The auxiliary device is a backup. It is noted that, in the event of a QP event, all seven PF circuits are simultaneously discharged.

E. Blocking Diodes

Blocking diodes are connected across a fraction of the dump resistor in those circuits whose maximum (-) current exceeds the maximum (+) current; in this way the maximum fast discharge voltage is limited to the PI value.

V. FPPC System

The D-shaped TPX plasma is vertically unstable and therefore requires active feedback control on a time scale much shorter than can be accommodated by the main PF coil system. In addition, active feedback of the radial position of the plasma on a fast time scale is required to maintain tight coupling with the RF antennae under fluctuating plasma equilibria conditions and to recover the plasma radial position after minor disruptions. This control is to be achieved on TPX using a pair of coils located inside the TPX vacuum vessel which in combination can provide the vertical and radial poloidal field components required for control of the radial and vertical position of the plasma. The radial and vertical position control

requirements will be additive in one coil and subtractive in the other. Power supply design requirements were generated by assuming that the worst case addition of the two requirements and are described in terms of the voltage and current profiles shown in figures 4 and 5.

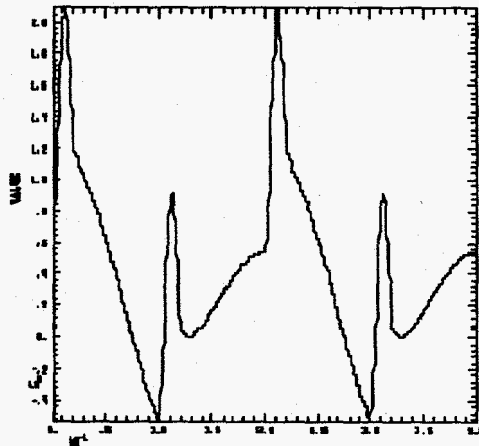


Figure 4 FPPC Current (Amps vs. Seconds)

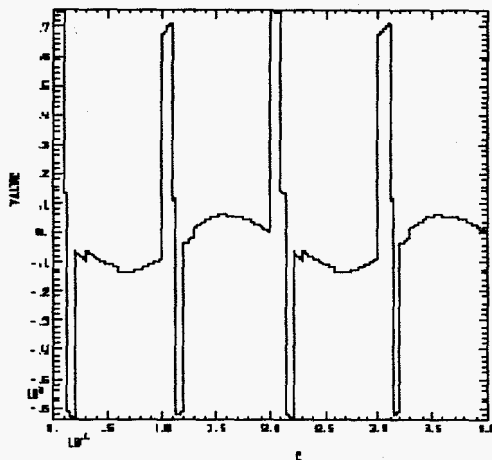


Figure 5 FPPC Voltage (Volts vs. Seconds)

Peak current is $\approx 20\text{kA}$, and peak voltage $\approx 750\text{V}$. The period of the waveform is 200 mS. The bursts of power correspond to roughly 10MW and each contain about 0.1MJ of energy. Two approaches are under consideration.

Circulating Current Converter

Antiparallel connected thyristor rectifiers (from the inventory of TFTR equipment) can be implemented to provide four-quadrant control as required. A preliminary study indicates the required frequency response can be achieved by oversizing the voltage rating somewhat so that the normal range of operation is near $\alpha = 90$ degrees where the dV/dt is maximized.

The advantage of this scheme is the utilization of existing equipment. The disadvantage is the large reactive power consumption which cannot be easily supplied unless the MG sets are used as the power source. Since it is desired to use only one of the two MG sets, and since the PF baseline would require the variation of the MG voltage, the viability of this option is linked to the decision on the HCLV option in the PF system.

Chopper

The use of a multi-phase four-quadrant chopper³ is being considered, with a DC link capacitor as an energy storage device to provide the intermittent pulses of energy. This type of device is based on a Pulse Width Modulation (PWM) type of control using Gate Turn Off (GTO) thyristors. Previous implementation of GTOs for similar duty⁴ has been limited to lower currents with two parallel devices at most, due to the inherent difficulties associated with direct paralleling of the GTOs.

Because of the complexity of the plasma shape control on TPX, and the need to use simple coils inside of the vacuum vessel with a small number of turns, the currents are quite high.

However, as shown in figure 6 (one current direction only) the multi-phase chopper scheme isolates the individual GTO parallels via reactors and the commutation of each device with its related diode is accomplished with little influence from the other devices. A small rectifier rated for the average power demand charges a DC link capacitor used as an energy storage element to supply the large pulses of power.

The final selection of approach will be made in conjunction with the decision for the PF system and will involve more detailed feasibility studies and cost estimates related to the multi-phase chopper option.

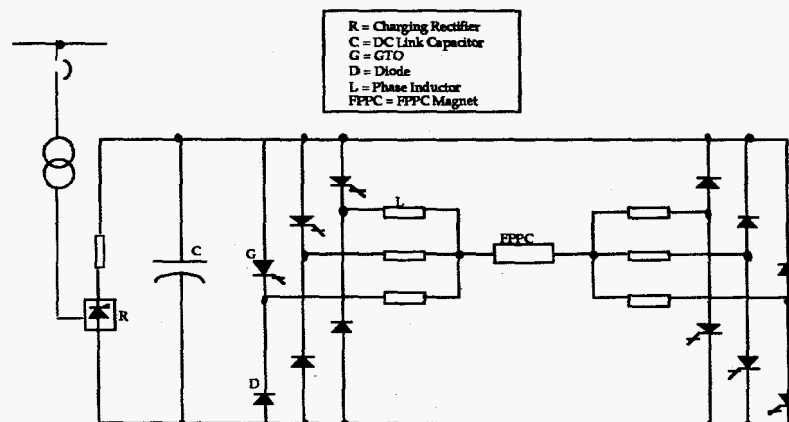


Figure 6 Multi-Phase Chopper Approach

V. QUENCH PROTECTION

Quench protection (QP) is a crucial function in both the TF and PF systems.

The reliability requirement (≈ 1 failure allowed per 50,000 operations) for this equipment is at least an order of magnitude higher than that achievable by traditional technologies used for DC circuit interruption, such as counterpulsed vacuum breakers or thyristor arrays. Various means have been considered for satisfying these requirements^{5,6}. An alternate technology which, due to its inherent simplicity, has the potential for achieving the requisite reliability is the explosively actuated DC breaker. However, this class of devices is not practical for repetitive operation. In the TF system, operation of the DC breaker will be required not only for quench events but also for the fast discharge of the circuit under other fault conditions. In the PF the plasma initiation event takes place every pulse. Therefore, to achieve the required reliability and to support repetitive operations a series combination of a repetitively operable device and the explosively actuated class of device is foreseen.

In the TF system, since relatively few operations are expected, a high current switch in parallel with a pair of series connected mechanical DC breakers will be connected in series with the explosively actuated device in each interleaf. This system is available at a relatively low cost compared to the counterpulsed devices. In the PF system a counterpulsed thyristor breaker will be connected in series with the explosively actuated device. Due to the absence of moving parts the thyristor breaker is most suitable for maintenance free repetitive operation.

An R&D program has been initiated to obtain and test several prototype devices from several manufacturers. These devices will be sub-scale with a rating of 10kA continuous and 7.5kV interruption voltage. Heat run tests will be performed to confirm ampacity and interruption tests will be performed to investigate operating characteristics.

In addition to the DC breaker challenge, the energy rating of the TF dump resistor is rather large. Since either of the two resistors could be subject to the dissipation of the full coil energy, two units with ratings of about 1 GJoule are required. Several options ranging from liquid rheostat to steel cable⁶ resistor are under consideration.

Conclusions

TPX will be the first tokamak to utilize superconducting TF and PF magnet systems. This, along with the nature of the existing facilities to be used, strongly influence the design approach. Special challenges exist as follows:

- matching the TF and PF power supplies to the superconducting magnets which have dramatically different demands when ramping the current and holding the current
- providing ultra-reliable quench protection for the superconducting magnets
- providing cost-effective dump resistors of very large capacity
- providing fast plasma position control at high current

A baseline approach to the TPX design has been identified which addresses all of the above issues. Several alternatives are still under study, along with an R&D program to demonstrate the feasibility of the explosively actuated DC breakers.

Acknowledgments

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