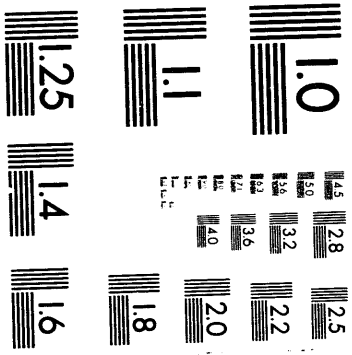
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# Quench Detection & Instrumentation for the Tokamak Physics Experiment Magnets

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# Quench Detection & Instrumentation For The Tokamak Physics Experiment Magnets

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## ABSTRACT

**The design of the Local Instrumentation & Control (I&C) System for the Tokamak Physics Experiment (TPX) superconducting PF & TF magnets is presented. The local I&C system monitors the status of the magnet systems and initiates the proper control sequences to protect the magnets from any foreseeable fault. Local I&C also stores magnet-system data for analysis and archiving. Quench Detection for the TPX magnets must use a minimum of two independent sensing methods and is allowed a detection time of one second. Proposed detection methods include the measurement of; (1)normal-zone resistive voltage, (2) cooling-path helium flow, (3) local temperature in the winding pack, (4) local pressure in the winding pack. Fiber-optic based isolation systems are used to remove high common-mode magnet voltages and eliminate ground loops. The data acquisition and fault-detection systems are computer based. The design of the local I&C system incorporates redundant, fault-tolerant, and/or fail-safe features at all component levels. As part of a quench detection R&D plan, a Quench Detection Model Coil has been proposed to test all detection methods. Initial cost estimates and schedule for the local I&C system are presented.**

## INTRODUCTION

The Tokamak Physics Experiment (TPX), to be built at the Princeton Plasma Physics Laboratory (PPPL) [1], will be the first tokamak with superconducting poloidal-field (PF) and toroidal-field (TF) magnets [2]. Three previous tokamaks, TORE SUPRA [3], T-15 [4], and TRIAM 1-M [5] have superconducting TF magnets and normal-copper PF magnets. On TPX, superconducting cable-in-conduit-conductor (CICC) with forced-flow supercritical helium as the coolant will be used in all PF & TF magnets. With its pulsed magnets and plasma disruptions, the tokamak is a very noisy electrical environment. The previous tokamaks mentioned above, have had difficulty in the quench detection systems with inadequate or marginal noisy rejection in measuring the normal-zone voltage. For TPX the Local I&C for the magnets will provide quench detection; the protection circuits (breakers, dump resistors, etc.) are part of the Magnet Power Systems and handle by C. Neumeyer's group at PPPL.

When a quench occurs in a force-flow-cooled CICC, several distinct phenomena will take place in a very short period of time;

1. A normal-zone (non-superconducting state, resistive) in the conductor and the current flow will cause the local temperature of the conductor and the helium to rise.
2. The heating of the helium coolant causes it to expand, and a local pressure rise occurs.
3. The local pressure rise causes the heated helium to flow away from the initial normal zone in both directions; reversing the inlet flow, and increasing the outlet flow.
4. The warm helium gas expanding from the normal zone heats the adjacent conductor causing the normal zone to expand and propagate through the winding pack.

With the temperature of the conductor rising very fast (greater than 100 Kelvin, in less than 4 seconds for TPX TF magnets) [6], the current in the conductor must be reduced quickly and with little delay to prevent structural damage in the magnet. Table 1 states the defined allowables [7] for magnet protection for TPX.

| Parameter | Allowable | Units |
|---|---|---|
| $V_{(\text{magnet terminals, max.})}$ | 15 | kV |
| $T_{(\text{hot-spot, max.})}$ | 150 | K |
| $t_{(\text{detection, max.})}$ | 1 | s |
| $l_{(\text{detectable normal-zone, min.})}$ | 0.12 | m |

**Table 1 - Magnet Protection Allowables**

The resistive voltage and the flow changes caused by a quench have been used in previous systems for quench detection of a CICC [8],[9], and work very well in "quiet" laboratory experiments. However in a noisy tokamak, these phenomena are very difficult to measure. In TORE SUPRA, the voltage detection system is logically *ANDED* with several other sensing inputs because it would generate numerous false triggers if used alone. The addition of pressure sensing in TORE SUPRA's He-II cooling system has provided the reliability the quench detection system must have. In T-15, the quench detection system is voltage measurement only, and must be disabled during the plasma initiation phase because of coupled noise in the TF magnets; eddy currents in the TF support structure from the PF magnets and plasma startup. In addition, plasma disruptions cause the same problems.

In the PF magnet system, this problem will be considerably worse. The PF magnets and the plasma are much more closely coupled; and are pulsed systems. The magnet currents are out of phase with each other. The charging and discharging voltages for the PF system are in the range of 10 kV, about 100,000 times larger than the 100-200 mV normal-zone voltage that we must extract. This will be very difficult.

For TPX there will need to be multiple levels of noise suppression and quench-sensing techniques. The primary technique will be the use of co-wound voltage-tap wires. With this technique, most of the inductive-coupled signals into the magnet are canceled between the voltage-tap wire pair.

The second level of noise rejection will be the filtering of all high frequency noise that is out of our range of interest. For example, if we assume a data sampling rate of 10 Hz., then the maximum bandwidth of the data acquisition system should not be half, 5 Hz. With this bandwidth limitation, the fast signals predicted by Wang's disruption simulation [10], will be filtered out before sampling and should not be an issue.

The third level of noise rejection will involve the use of noise cancellation algorithms. There have been several different noise reduction algorithms used over the years to detect this normal-zone voltage in the presence of noise. The two under consideration by TPX are;

1. Central-Difference Averaging [11]: where three adjacent voltage taps are used to calculate the normal-zone voltage for the middle voltage tap ($V_{2NZ}$) of the three as follows;

   $$V_{2NZ} = 0.5\,(V_1 + V_3) - V_2 \qquad (1)$$

   This algorithm works well when the coupled noise to the three voltage taps changes linearly across their positions, and could be implemented simply in analog hardware.

2. Active Compensation [12]: where the source of the noises are measured, their coupling is know, and the influence is subtracted from the measured voltage for tap 2 ($V_2$) as follows;

   $$V_{2NZ} = V_2 - (L_2 \cdot \Delta i_2) - (M_{2,3} \cdot \Delta i_3) - (M_{2,n} \cdot \Delta i_n) \qquad (2)$$

   This algorithm could be used to cancel the effects of all coupled noise; the PF magnets, the vertical-positioning magnets, and the plasma. Due to its complexity, this algorithm should be implemented in software.

## SYSTEM DESIGN

The Local I&C System for the TPX Magnets will consist of the following subsystems (see Figure 1);

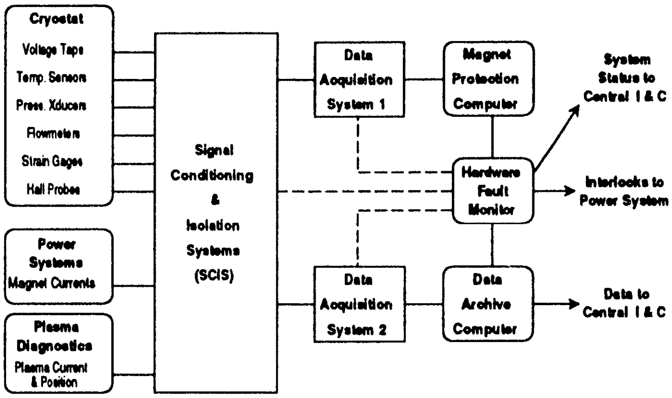

Figure 1 - Block Diagram, Local I&C System

1. Input sensors and signals
2. Signal Conditioning and Isolation System (SCIS)
3. Data Acquisition Systems
4. Computer-based Quench Detector
5. Data Analysis & Archive Computer.
6. Hardware Fault Monitor & Control Interface.

*Input Sensors for Monitoring & Detection*

There are two primary candidates for sensing a quench in the TPX magnets; (1) co-wound voltage taps to sense the resistive normal-zone voltage, and (2) flowmeters to sense the quench-induced flow transients at the inlet and outlet of all cooling paths.

The co-wound voltage taps will be redundant (1 each at 2 locations). The first will be an insulated strip routed between the conductor's sheath (conduit) and the first layer of the insulation pack. This sensor would be attached to the conduit during the insulation phase of the magnet, after heat-treatment. The wire and the magnet insulation must be good enough to prevent partial discharges from occurring. This is the phenomena noted by KfK that is the most difficult problem to deal with when high voltages (> 10 kV) are present in multiple layer (& dielectric strength) magnet insulation.

The second insulated wire will be wrapped around the conductor strands, inside of the conduit. This wire presents a number of challenges also. The wire must be wrapped with the strand before insertion into the conduit. The wire must survive the final compaction and shaping of the conductor.

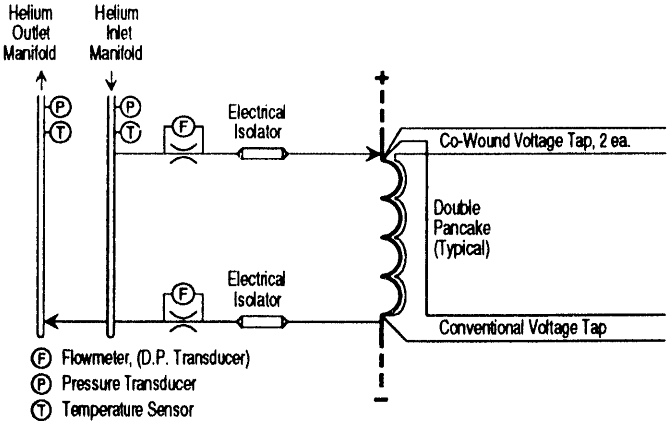

Figure 2 - Magnet Diagnostics

After winding the magnet, the wire now must survive the heat treatment phase. Last, but not least, at the double pancake cooling connections, these wires must be extracted through the conduit with a leak-tight helium-to-vacuum seal, and spliced to a high voltage wire.

*Flowmeters*

The flowmeters will consist of an orifice (or venturi) with a differential-pressure (DP) transducer across it. The orifice will be sized to drop 7-14 kPa (1-2 psid) during normal 5 g/s helium flow. This will keep its pressure drop low (100-300 kPa) during a quench.

The differential-pressure (DP) transducer under consideration, will be a modified commercial unit that uses a 4-active-arm strain gage bridge to measure the deflection of a stainless-steel diaphragm. The transducer will be a low-level type, with no internal electronics. With the units located in the magnet lead boxes, we would not be able to calibrate high-level transducers in this location.

The DP transducer will be thermally anchored to the orifice with short pressure-tap lines to eliminate the thermal-gradient induced pressure oscillations that are common with this type of pressure measurement.

*Temperature Sensors*

Carbon-Glass Resistance (CGR) temperature sensors shall be located at (1) the helium inlet and outlet manifolds in the cryostat, (2) on the magnet cases and support structure, and (3) at the junction of the superconducting buses, and the gas-cooled leads.

The resistance of the magnet winding packs will also be measured during cooldown and warmup to calculate its temperature.

*Miscellaneous Sensors*

The pressure of the helium inlet and outlet manifolds will be monitored with pressure transducers of similar design to the DP transducers of the flowmeters.

Strain gages shall be used on the magnet cases and support structure to determine peak stress levels during cooldown, warmup, and operations.

Hall probes shall be used to measure magnetic field and polarity during magnet testing and configuration.

| Diagnostics from the Cryostat | T F | P F | Usage | | | |
|---|---|---|---|---|---|---|
| | | | Cooldown, Warmup | Magnet Testing | Tokamak Operations | Fault Detection |
| Voltage Taps | 266 | 364 | X | X | X | X |
| Temperature Sensors | 144 | 164 | X | X | X | |
| Pressure Transducers | 4 | 8 | X | X | X | |
| Flowmeters | 100 | 104 | X | X | X | X |
| Strain Gages | 200 | 200 | X | X | X | |
| Hall Probes | 8 | 12 | | X | | |
| Sub-Totals | 722 | 852 | | | | |
| Grand Total | 1574 | | | | | |

**Table 2 - Sensor Summary**

*Signal Conditioning & Isolation System (SCIS)*

The SCIS shall interface all required diagnostic signals to the data acquisition systems in the main control room. The magnet double-pancake voltages could have common-mode levels as high as 15 kV. This will require the use of a fiber-optic-based isolation system. All of the diagnostic signals will require some sort of signal conditioning; i.e. voltage amplification, bandwidth filtering, or voltage clamping.

The SCIS will use individual fiber-optic isolation channels for all voltage taps. All other signals can be routed through 8-to-1 channel multiplexed isolation systems to reduce the fiber count to the control room.

*Data Acquisition Systems*

The two redundant data acquisition systems shall normally serve two functions; (1) acquire quench-sensor data for the quench-detection computer, and (2) acquire data from all sensors for monitoring the magnets' performance and analysis of its operational status. The second system can be substituted for the first (quench detection) in the event of a failure.

"Adaptive" data-sampling techniques [13] shall be used to reduce the data storage needs for the magnets. A simple diagram in figure 3 illustrates the concept of sampling data at a fast rate, but only storing the data at a much reduced rate if no absolute or derivative data limits are exceeded.

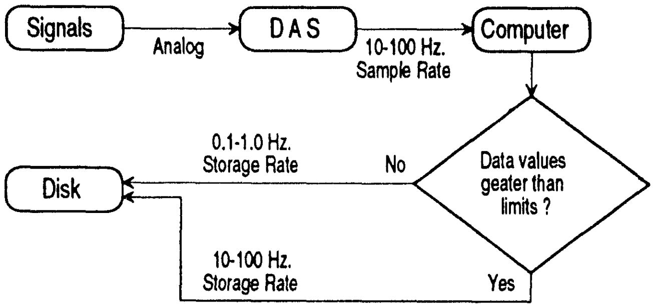

**Figure 3 - Adaptive Data-Sampling Techniques**

*Computer-Based Detection System*

To have flexibility in the use of detection algorithms and in detector calibration, the detection system will be developed in software. The "active compensation" algorithm could be implemented as an "Expert System" that will learn TPX's coupled noise characteristics during initial magnet testing and plasma shots.

*Hardware-Fault Monitor & Control Interface*

This subsystem will monitor the status of the other subsystems, and switch in redundant units when failures or problems occur. Its other function is to provide the fail-safe interlocks to the Magnet Protection Systems for control of the power supplies and breakers.

## MODELING, SIMULATION, & ANALYSIS

Three-dimensional (3-D) electrical, mechanical, and thermal-hydraulic models are being developed and used to simulated the TPX magnets in actual plasma scenarios. These simulations include; (1) noise coupling from plasma initiations and disruptions, (2) normal-zone voltages, temperatures, pressures, and gas flows from worse-case quenches, and (3) initiation-induced gas-flow changes. In addition, SPICE simulations will be used to verify and cross-check a few of the 3-D electrical simulations.

Analysis of the modeling and simulations will lead to initial calibration of the detector algorithms. The algorithms will be incorporated in benchmark codes for testing their "fit" and for evaluating the eventual hardware requirements of the code.

## RESEARCH & DEVELOPMENT

### *Co-Wound Voltage Taps*

A noise injection experiment has been proposed to test the effectiveness of the two types of co-wound voltage taps for noise rejection. The experiment will consist of a sub-scale CICC (possibly without superconductor) wound into 2-3 double pancakes, both types of co-wound voltage taps, and external noise generation sources. There will also be fabrication studies and testing to learn & validate the installation of both co-wound voltage-tap types.

### *Flowmeters*

Candidate flowmeters will be installed on the FENIX Test Facility at the Lawrence Livermore National Laboratory (LLNL) to test the applicability and response time of the flowmeters.

### *Collaborative R&D with ITER*

ITER has proposed a Long-Length Quench Experiment [14] to be performed in '94-'95 at the SULTAN Facility at PSI in Switzerland. The U.S. ITER Home Team has quench instrumentation responsibility for this experiment; and the TPX candidate sensors (co-wound voltage taps & flowmeters) along with novel local temperature & pressure measuring sensors will be included in this experiment.

## SUMMARY

TPX will be the first tokamak with superconducting PF & TF magnets. Quench detection for the TPX magnets will consist of two or more detection sensors (co-wound voltage taps & flowmeters), signal conditioning and isolation systems, data acquisition systems, computer-based detector, and control interface to the magnet protection system. With an aggressive R&D plan, and a detection system designed to deal with the noise environment of a tokamak, the TPX magnets should be fully protected and compatible with the experiment's mission.

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