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High-Field Conductor Testing at FENIX Facility

S.S. Shen, M.R. Chaplin, B. Felker,
W.V. Hassenzahl, K.I. Kishiyama,
and J.M. Parker

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Lawrence
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Lawrence Livermore National Laboratory
Livermore, CA 94551

Abstract

The Fusion ENgineering International eXperiments (FENIX) Test Facility,[1] which was commissioned at the end of 1991, is the first facility in the world capable of testing prototype conductors for the International Thermonuclear Experimental Reactor (ITER) superconducting magnets. The FENIX facility provides test conditions that simulate the ITER magnet operating environment; more importantly, it also accommodates specific experiments to determine the operational margins for the prototype conductors.

The FENIX facility generates magnetic fields close to 14 T and transport currents over 40 kA for testing the prototype conductors. This paper describes an experimental program that measures critical currents, current-sharing temperatures, forced-flow properties, and cyclic effects.

INTRODUCTION

In the current design of the ITER machine, the Nb_3Sn cable-in-conduit conductor (CICC) has been chosen for both the toroidal and central solenoid systems. For the ITER magnet research and development program, the fabrication and testing of short lengths of such conductors are of prominent importance. The FENIX facility was designed and constructed for meeting the urgent needs of the ITER conductor development program.

Construction started in 1989, and the facility was completed in early 1991. After a series of checkouts and modifications, the facility was commissioned for conductor testing in December 1991 (Fig. 1). The major operation parameters are listed in Table 1.

FACILITY OPERATION

Both the FENIX-magnet cryogenic systems and test-sample cryogenic systems are operating well and can fully simulate ITER operating conditions. The 14-T

Samples under test in FENIX are cooled by forced-flow helium. Room-temperature helium flows to the test well, passes through a counterflow heat exchanger in the upper part of the well, and then passes through a helium bath. Just past the bath, for each leg of the conductor sample, a heater is provided for each cooling circuit to control temperature. Flow returns from each leg to the counterflow heat exchanger and then exits with flow instrumentation and control. The instrumentation and control scheme, as shown in Fig. 2, is designed for

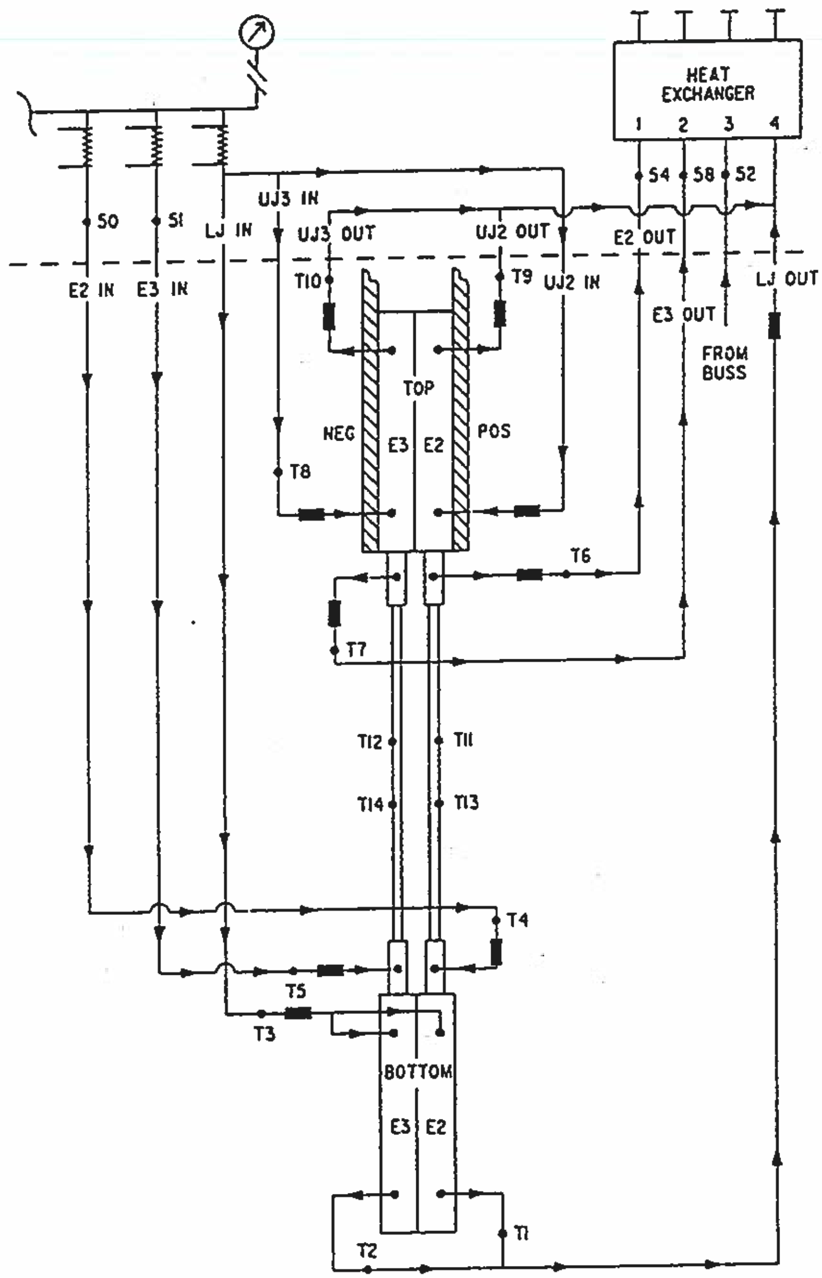


Fig. 2. Schematic of cryogenic instrumentation and control for typical FENIX sample conductor assembly.

CONDUCTOR TESTS AND RESULTS

In 1992 four sample conductors were tested in the FENIX facility through the ITER collaboration. The design features of each sample are summarized in Table 2. In Fig. 3, three European Community's/ITER sample cross sections are shown. An extensive test program was developed and executed to characterize these samples. Following is a summary of the test results of some specific experiments.

All sample conductors are designed for stable operation at 12.5 T and 40 kA. The FENIX facility not only validated the design parameters but also tested the conductors to the limits of temperature where current sharing takes place. Typical results of three EC samples are illustrated in Fig. 4, where the fitting to the results indicated that the effective strain on the strand was about -0.5%, which is considerably lower than expected for CICC conductor using stainless-steel sheath. This encouraging result also suggests that any degradation during the conductor fabrication process was minimal. Another major result is shown in Fig. 5, where the effect of forced-flow cooling on the performance of such large CICC conductor is illustrated by its current-sharing curves, measured by sample voltage versus temperature. The signatures of such effects are clearly seen on samples with different designs. The cyclic effects were also studied by pulsing a 40-kA current at 12.5 T field The induced average transverse stress on the cable was estimated to be about 15 MPa. No degradation was detected after 6000 current cycles.

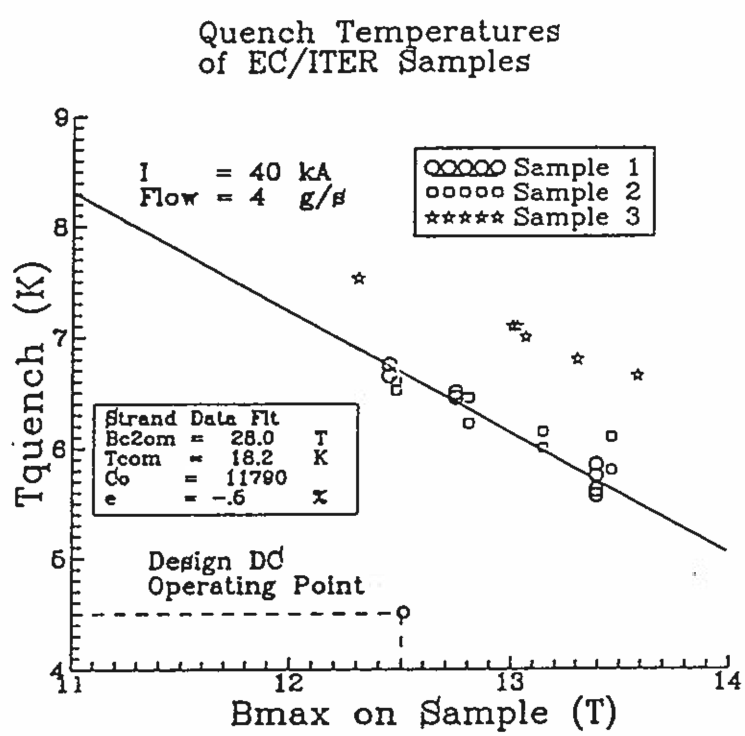
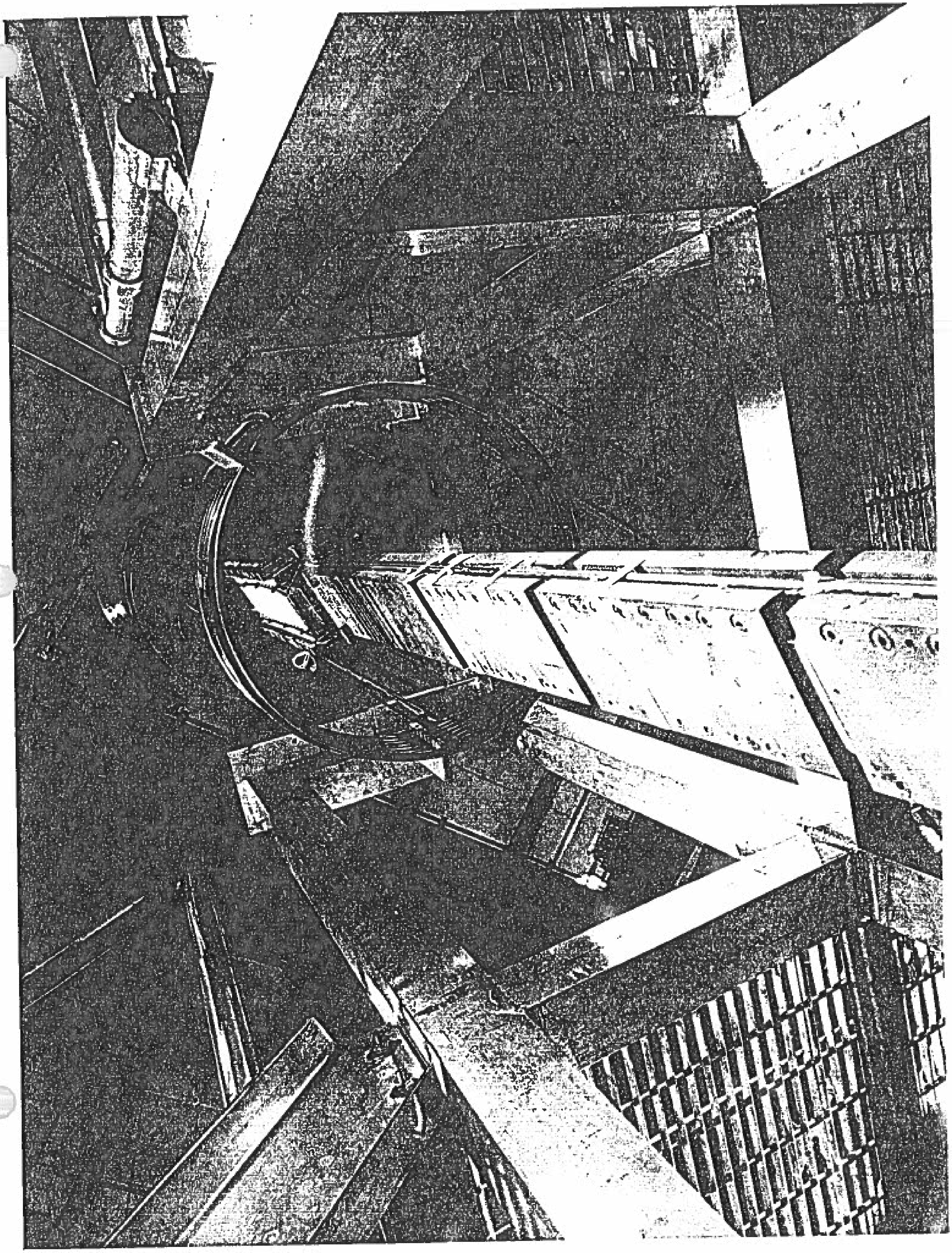
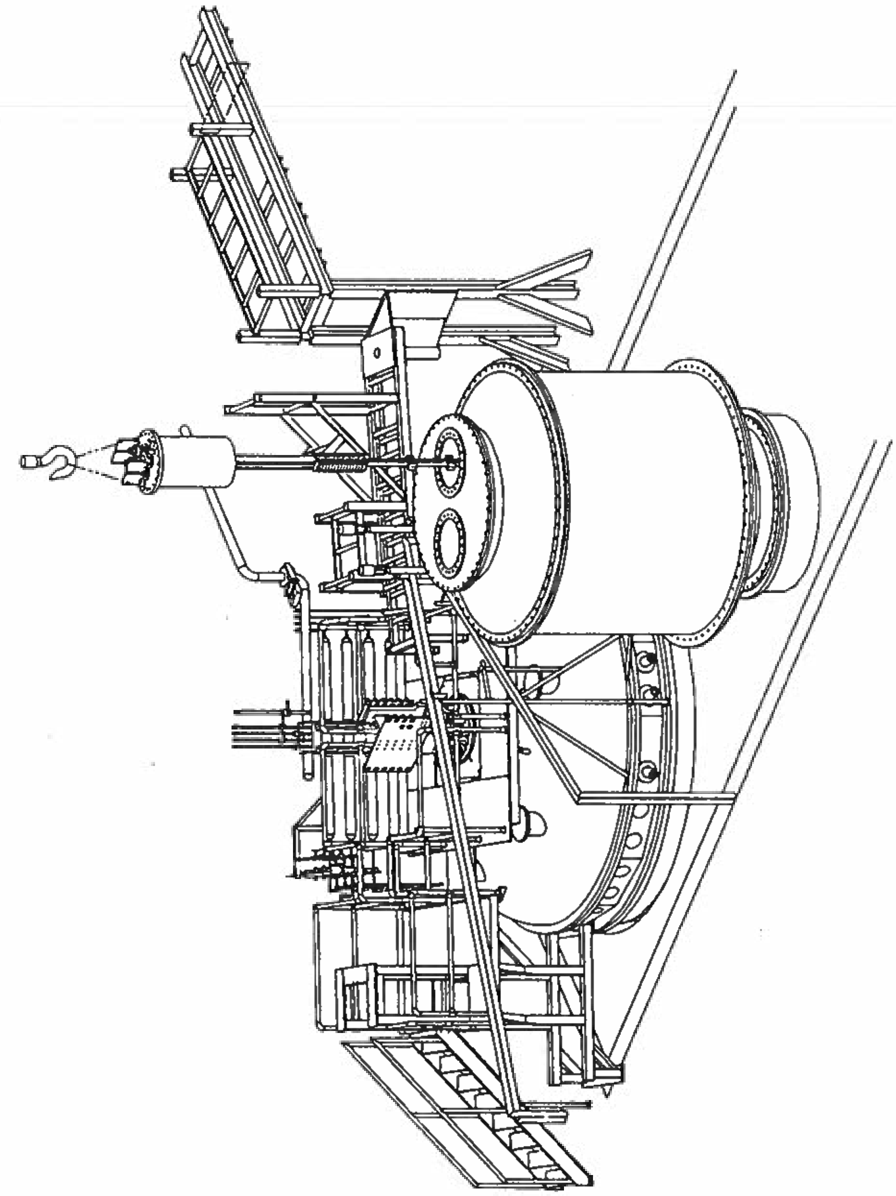


Fig. 4. Measured quench temperatures of EC/ITER samples





High-Field Tests of ITER Prototype CICC

Stewart S. Shen
Applied Superconductivity Group
Lawrence Livermore National Laboratory

Presented at

CICC Workshop
Victoria, Canada
September 24, 1993

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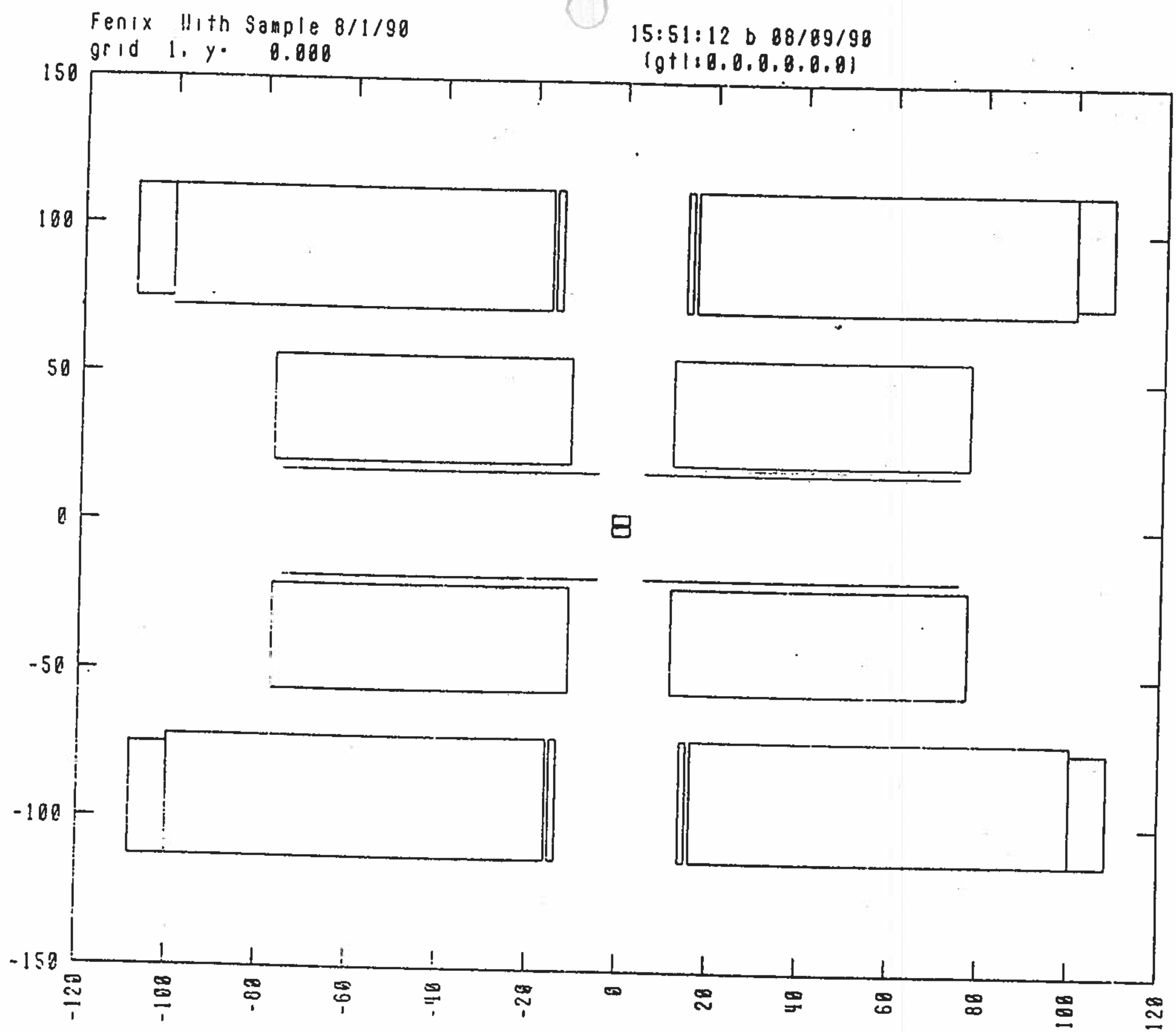
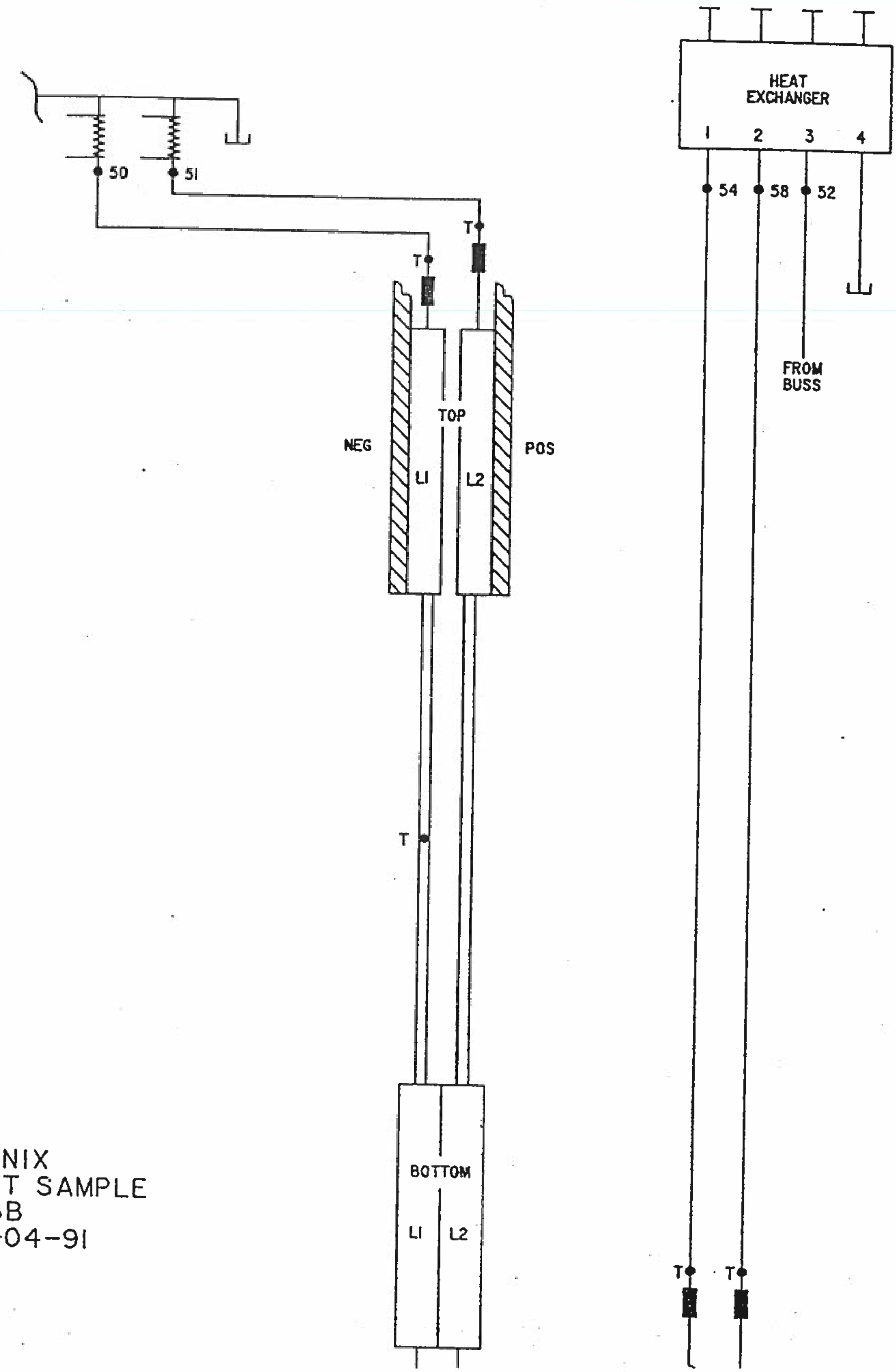
TABLE 1

MAJOR PARAMETERS OF FENIX CONDUCTOR TESTS

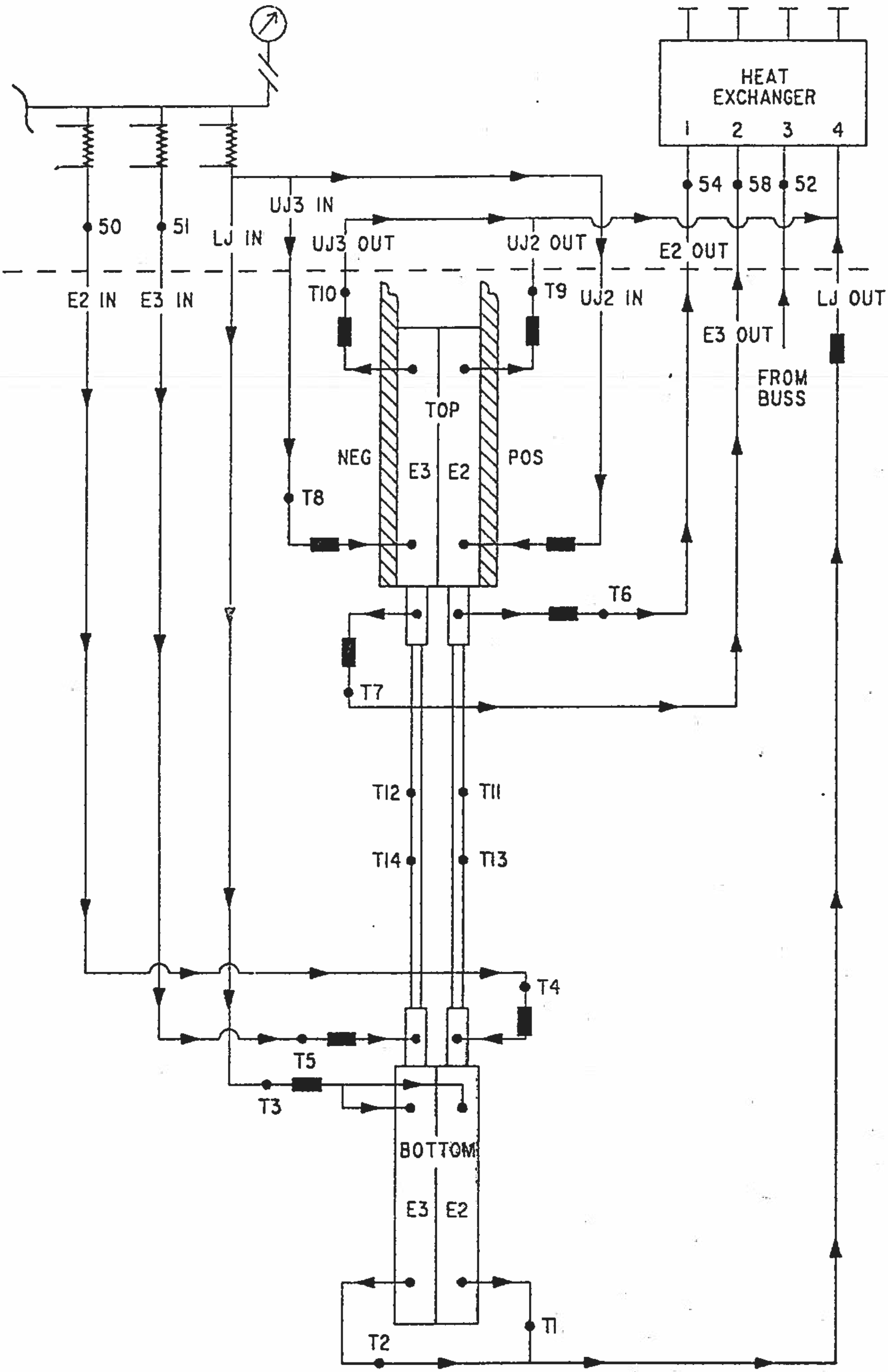
Maximum field	(T)	14
Maximum current	(kA)	50
Maximum conductor length	(m)	4.7 * 2
Uniform high-field length	(m)	0.4
Conductor forced cooling		
Number of paths		2
Inlet pressure	(MPa)	0.5 to 2.5
Maximum total flow rate	(g/s)	10
Conductor bath cooling		
Bath temperature	(K)	4.2 to 4.4

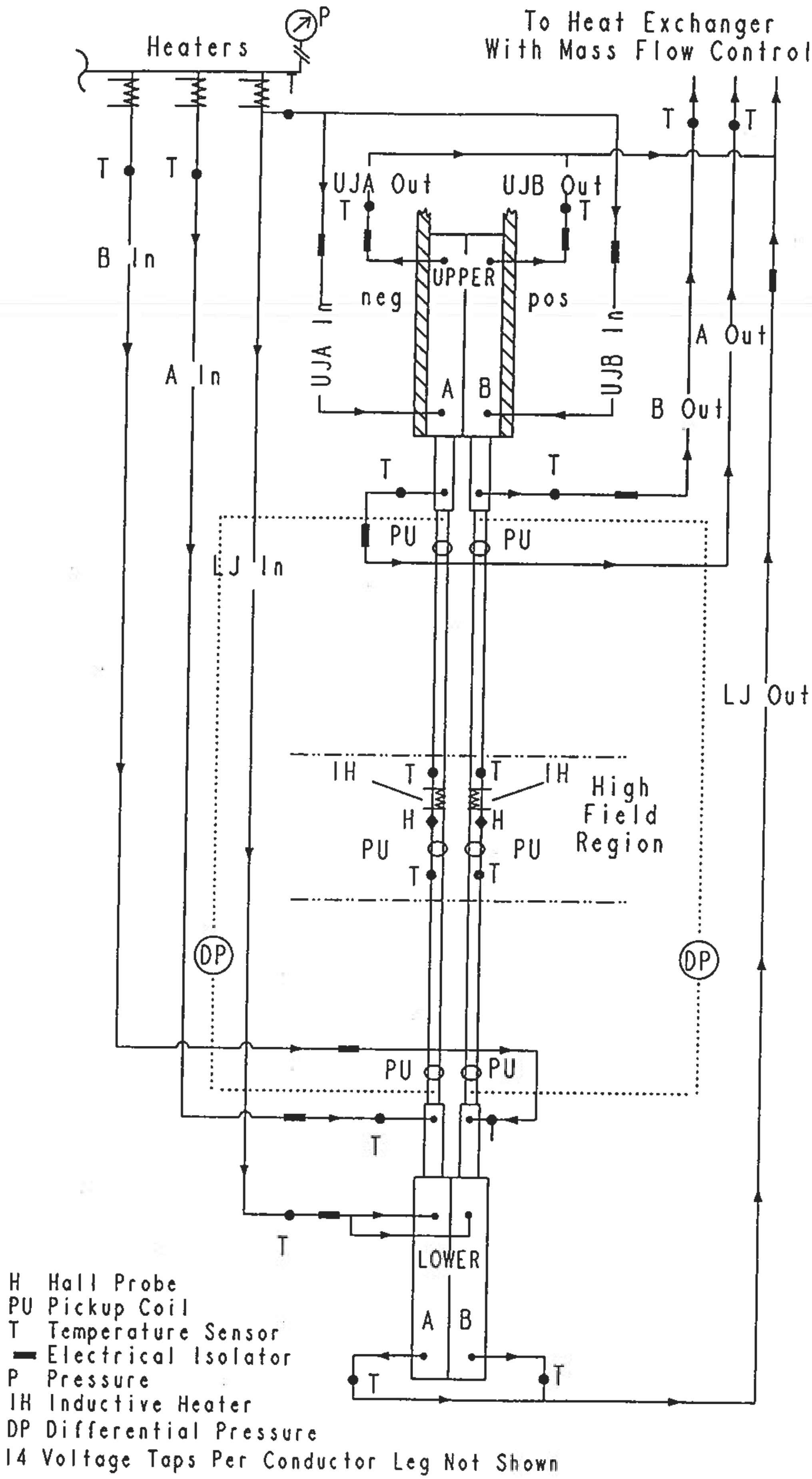


FENIX (with sample)



FENIX
NET SAMPLE
ABB
3-04-91


HEAT
EXCHANGER
1
2
3
4
54
58
52
50
51
UJ3 IN
LJ IN
UJ3 OUT
UJ2 OUT
E2 OUT
E2 IN
E3 IN
T10
T9
UJ2 IN
LJ OUT
E3 OUT
FROM
BUSS
TOP
NEG
POS
E3
E2
T8
T6
T7
T12
T11
T14
T13
T4
T5
T3
BOTTOM
E3
E2
T1
T2


Heaters
P
T
To Heat Exchanger
With Mass Flow Control
T
B In
A In
LJ In
UJA Out
UJB Out
UJA In
UJB In
neg
pos
UPPER
A
B
A Out
B Out
PU
High
Field
Region
IH
H
DP
LJ Out
LOWER
H Hall Probe
PU Pickup Coil
T Temperature Sensor
Electrical Isolator
P Pressure
IH Inductive Heater
DP Differential Pressure
14 Voltage Taps Per Conductor Leg Not Shown

FENIX Conductor Testing

Main Objective

To obtain the following properties of the ITER prototype conductor:

— Critical current and T_{cs} for field up to 14 T

— Forced-flow properties

— Cyclic fatigue effect

— Residual resistance ratio

— Stability tests by inductive heaters

and

— Joints

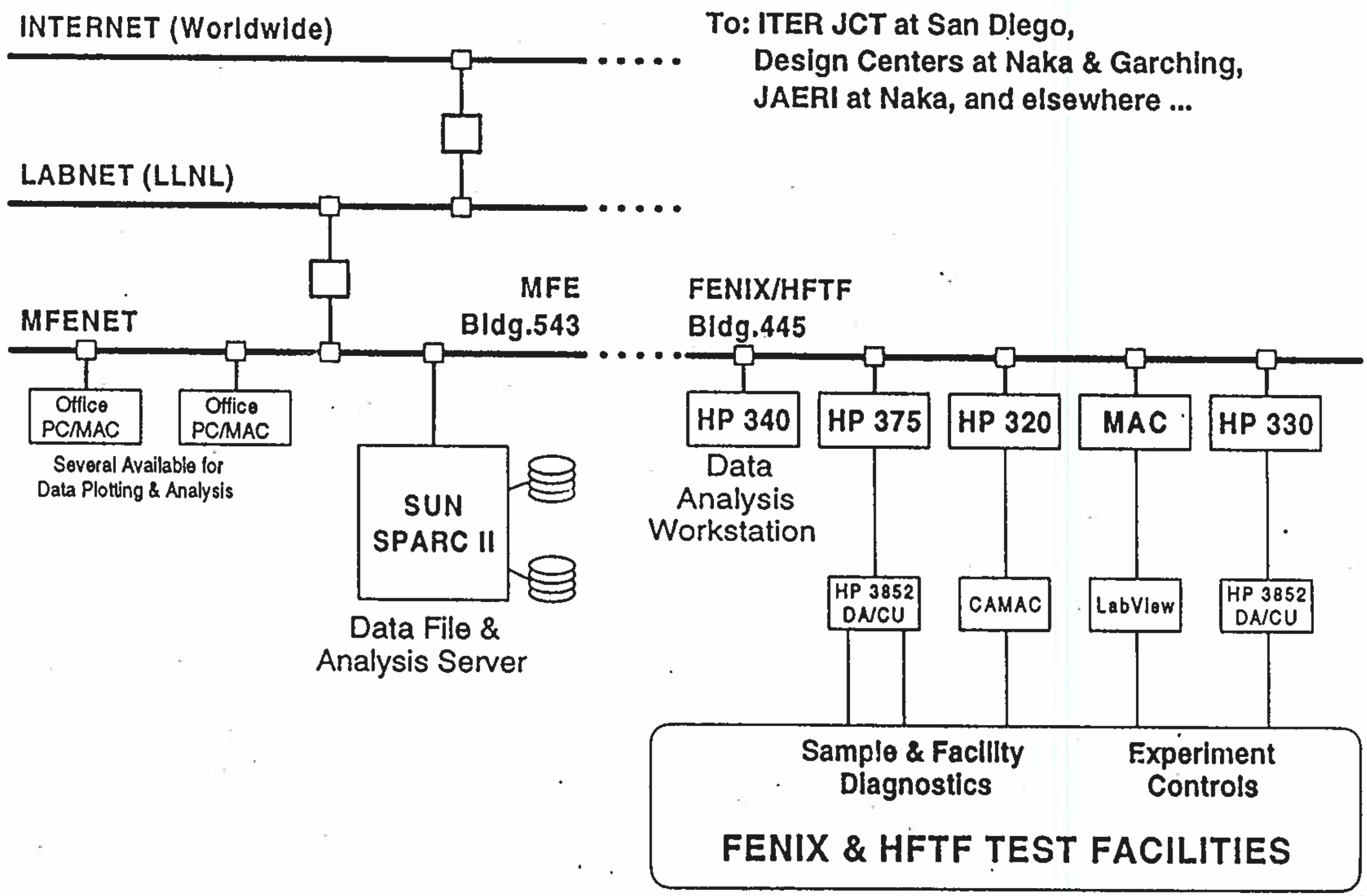
— Quenching properties

— Pulsed-field effects.

Major CICC Design Parameters

Parameters	Descriptions	FENIX Experiments
Cable configurations	Cable patterns Cable composition (Cu) Voids arrangements (dual flow)	T_{CS}, stability T_{CS}, stability Flow, T_{CS}, stability
Cable insulations	Cr or alternatives	Ac losses, fatigue, stability
Superconductors	Nb_3Sn, Nb_3Al,NbTi	T_{CS}
Sheath materials	Incoloy, Ti and SS	T_{CS}
Joints	Butt, praying hands, shaking hands	T_{CS}, dc, and ac tests, stability, ac losses

FENIX Data Systems & Network



Viewgraph No.

NET-LMI Sample, B=12.8T, FENIX Run # 453

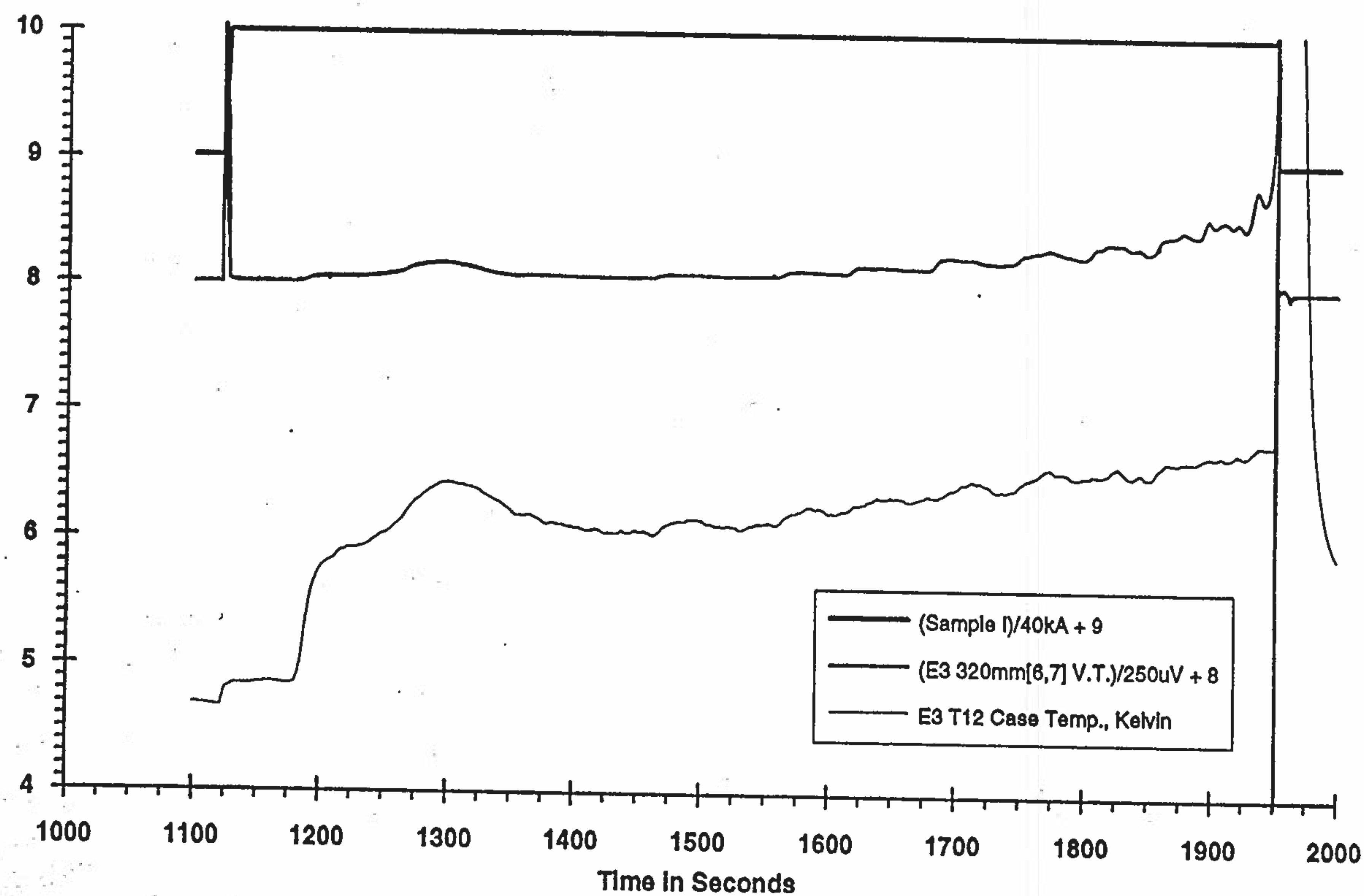
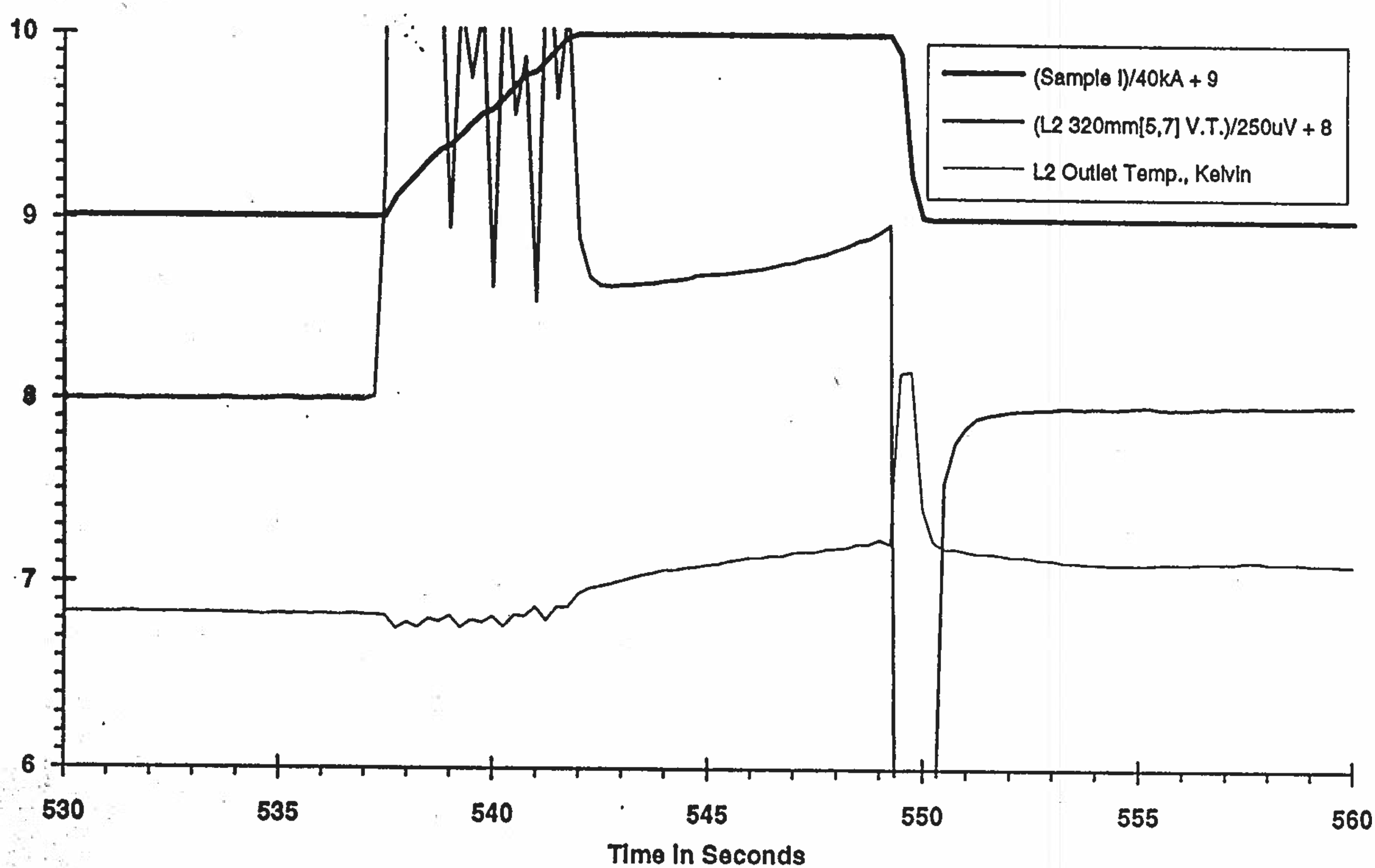
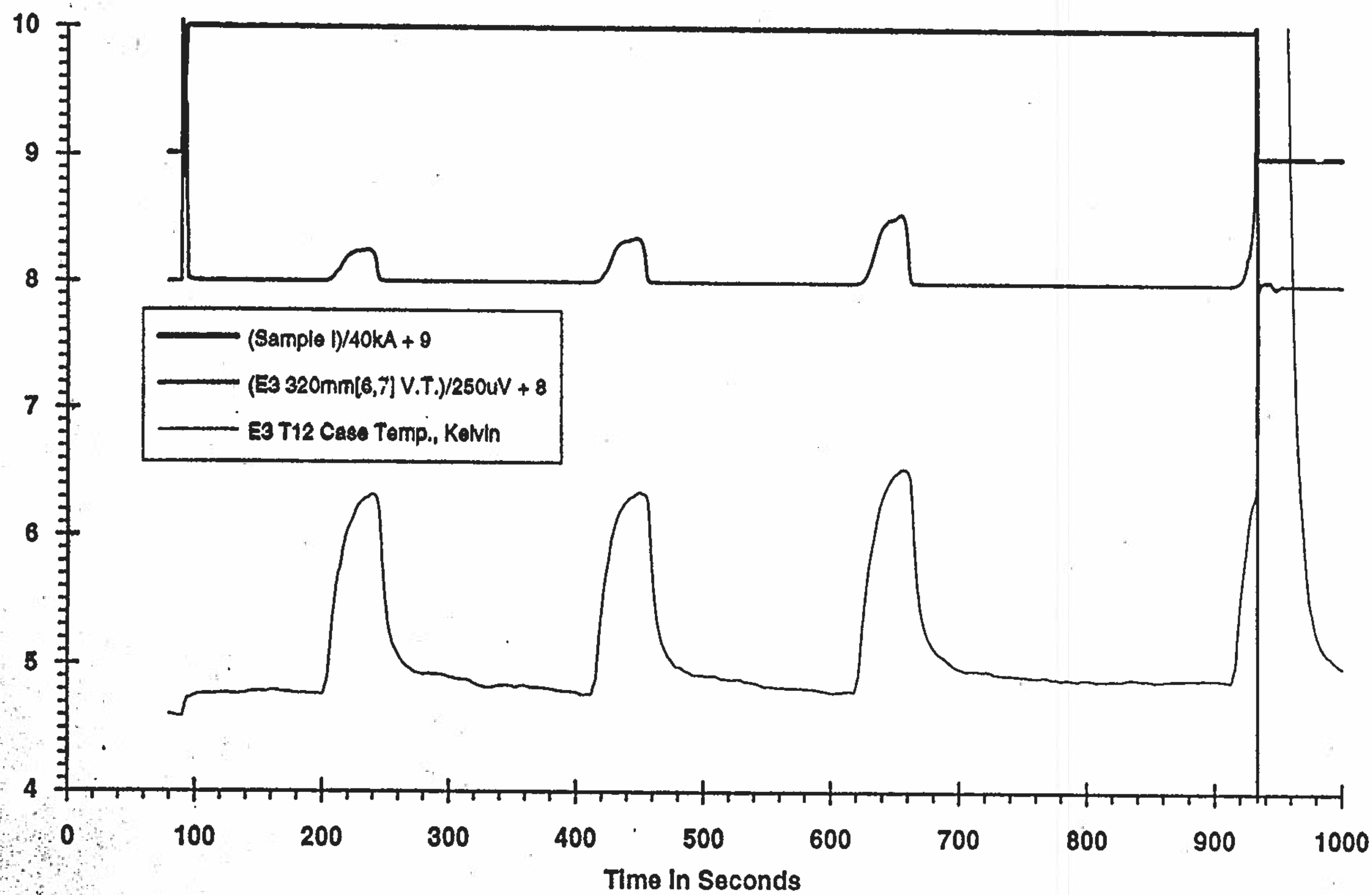
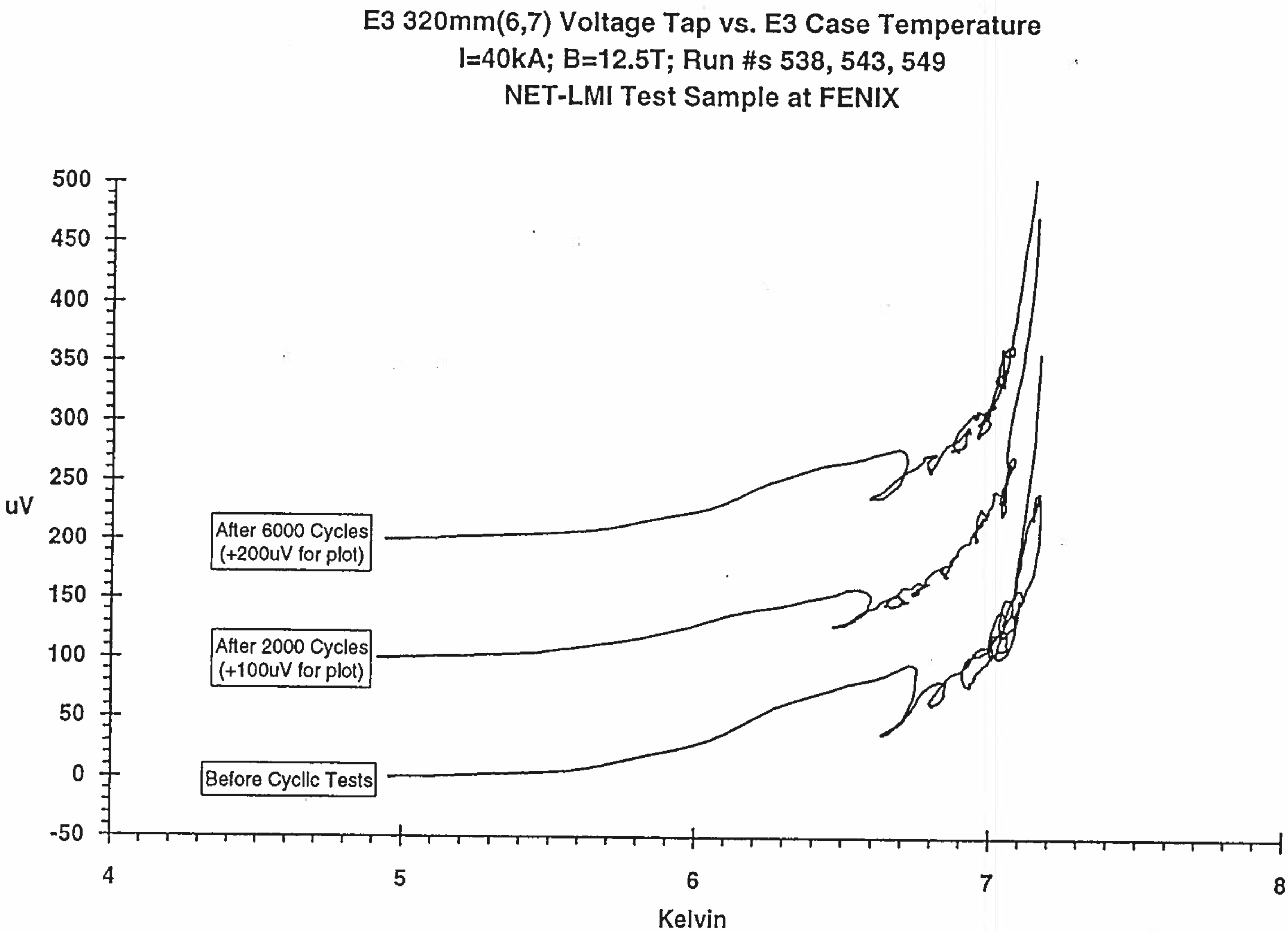


ABB-braided, B=11.8T, Run # 295
NET L1, L2 Sample at FENIX



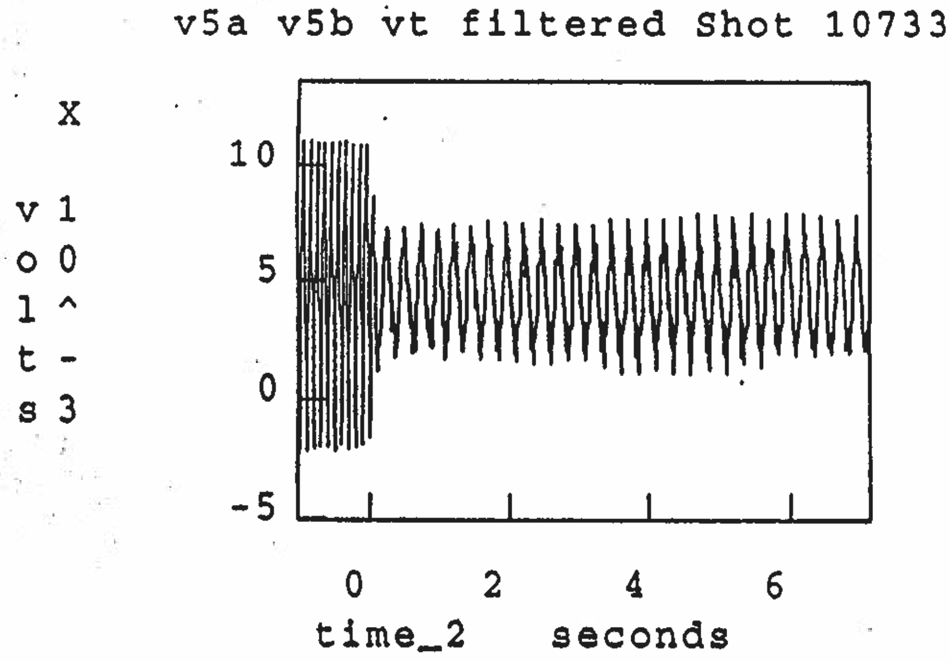
NET-LMI Sample, B=12.8T, FENIX Run # 453

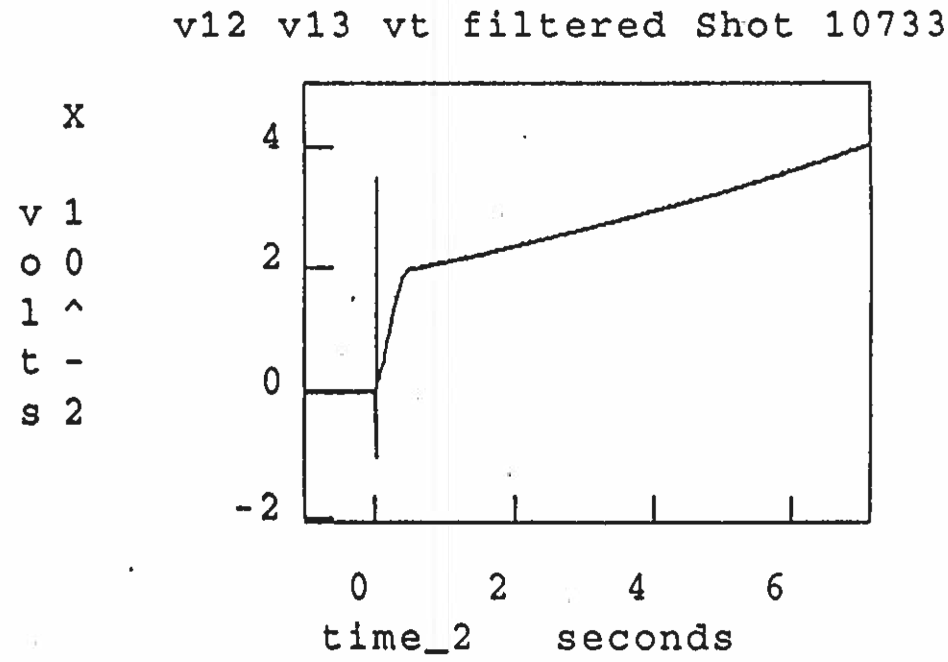


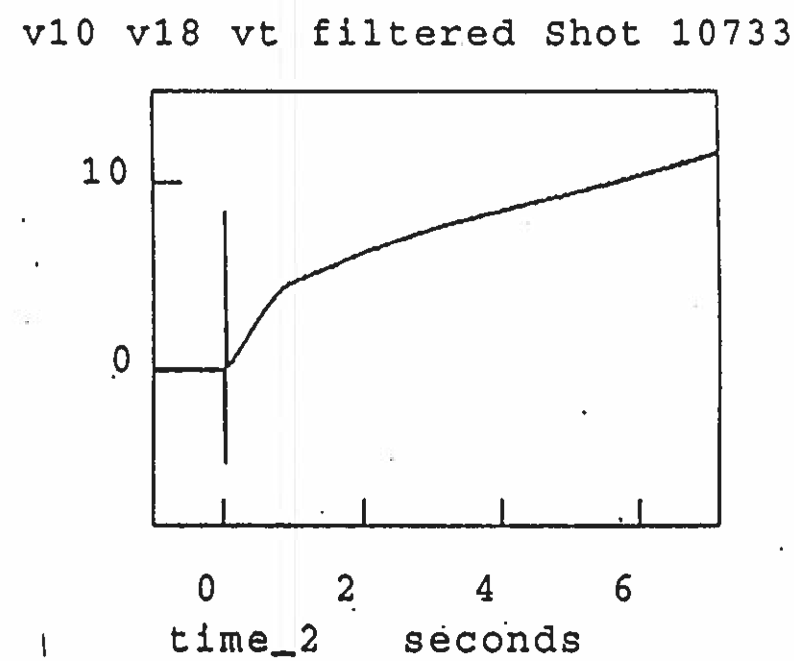

E3 320mm(6,7) Voltage Tap vs. E3 Case Temperature
I=40kA; B=12.5T; Run #s 538, 543, 549
NET-LMI Test Sample at FENIX
uV
500
450
400
350
300
250
200
150
100
50
0
-50
After 6000 Cycles (+200uV for plot)
After 2000 Cycles (+100uV for plot)
Before Cyclic Tests
4
5
6
7
8
Kelvin

Full-Size Conductor Tests

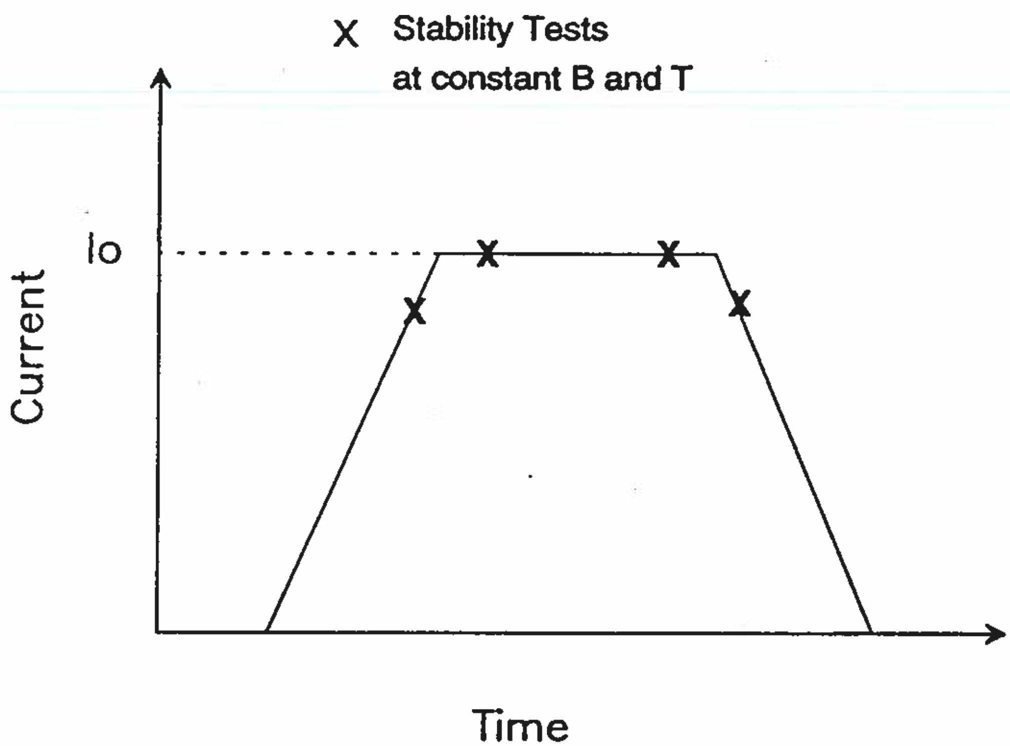
- Stability Experiments
  - Stability margin
  - Ramp-rate limits
  - Current distribution
- RRR Measurements



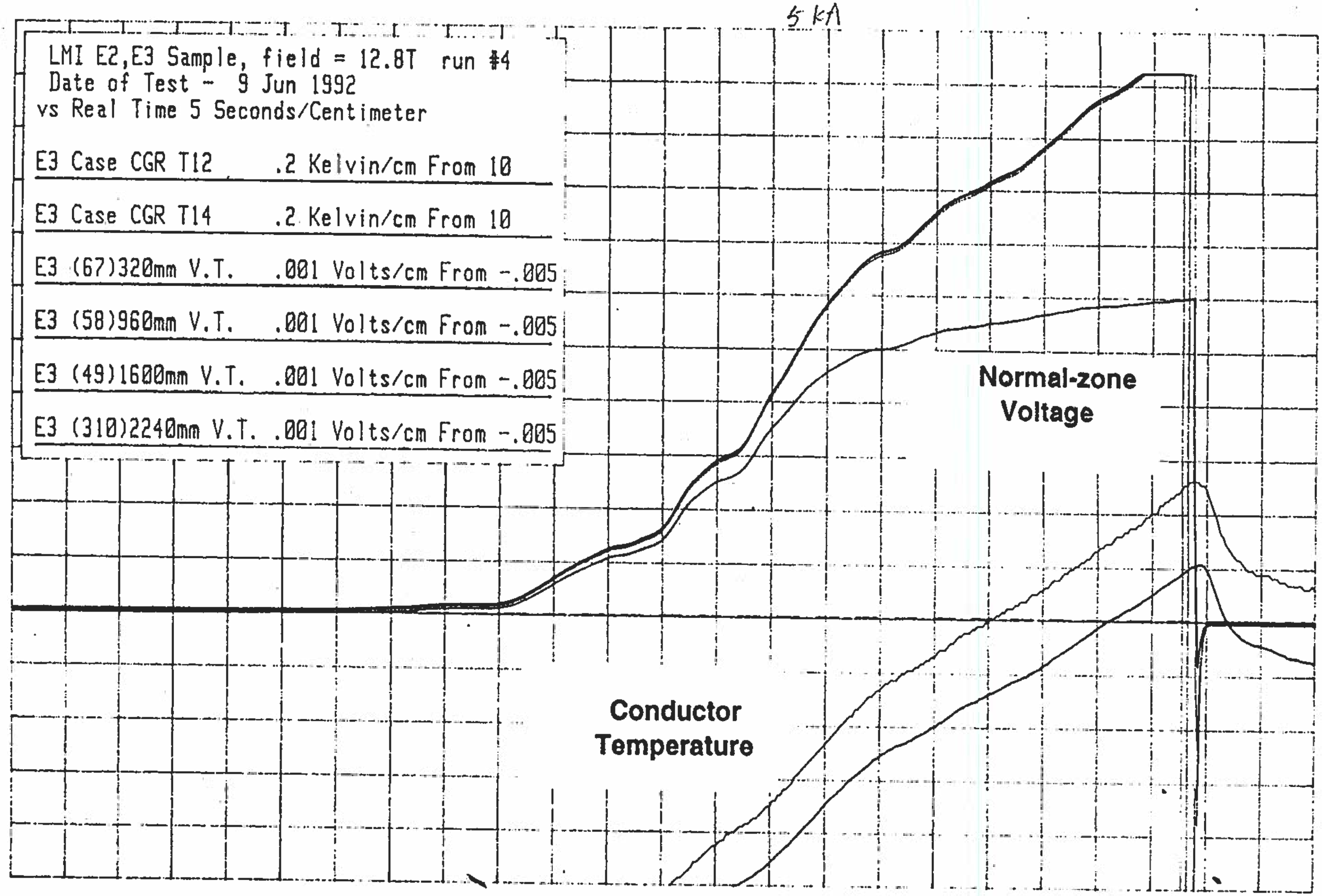




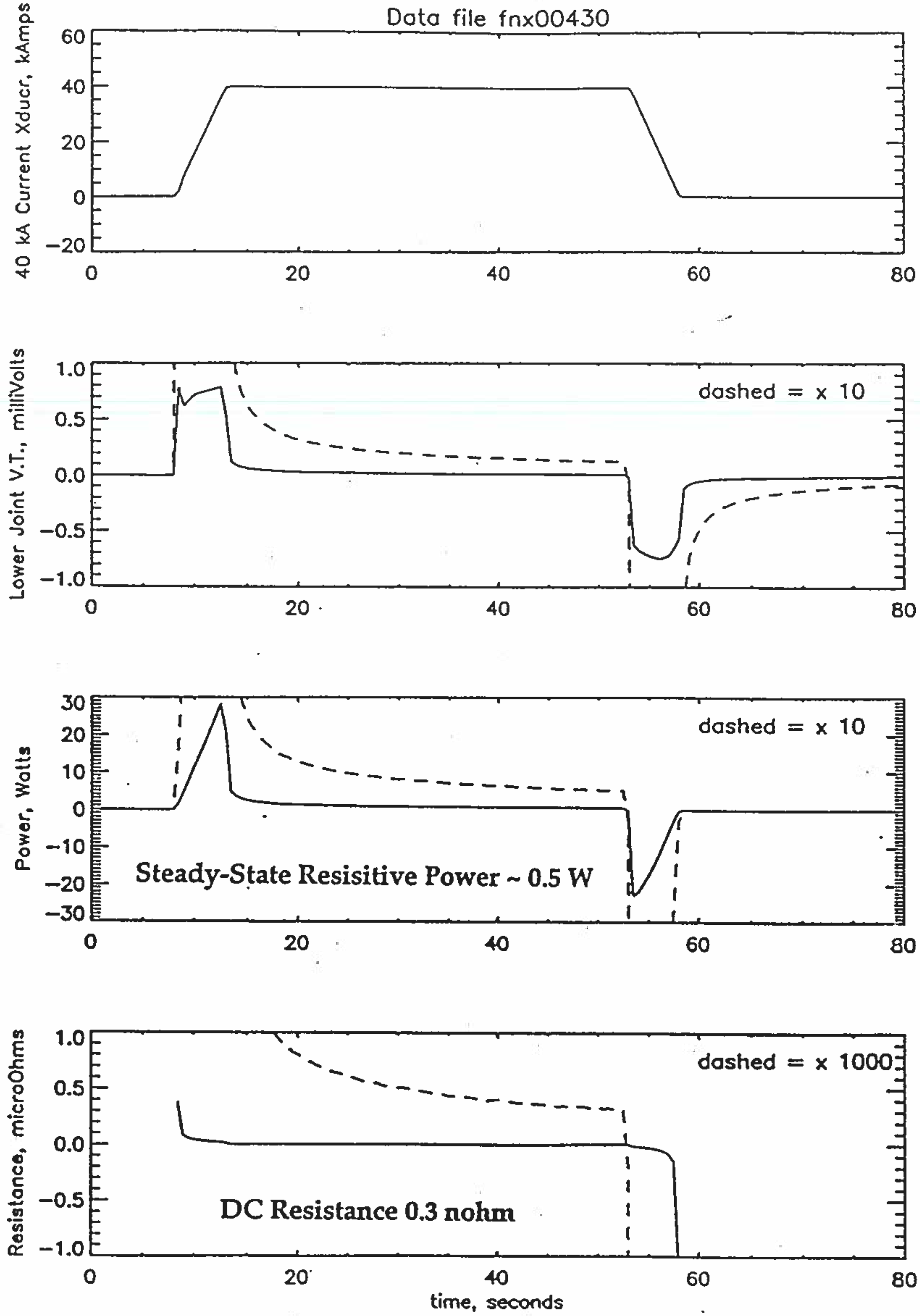
Normal-zone Voltage Measured After A Conductor Quench Induced By Inductive Heater Pulse @ High Field (12 T) and Constant Transport Current (30 kA)



Dynamic Stability Tests



Normal-Zone Resistance Measurement @ 5 kA and 12.8 T



Performance of a 40-kA Lap Joint Measured @ FENIX Facility

B ~ 1T

Need for a Pulsed Test Facility

FENIX tests verify capabilities of CICC:

Flow properties
Current-sharing temperatures
Fatigue caused by cyclic current tests
Stability
Current distribution
Quench properties (normal-zone voltage, RRR)
Quench detection
Ac losses (time constant)
Joint dc tests

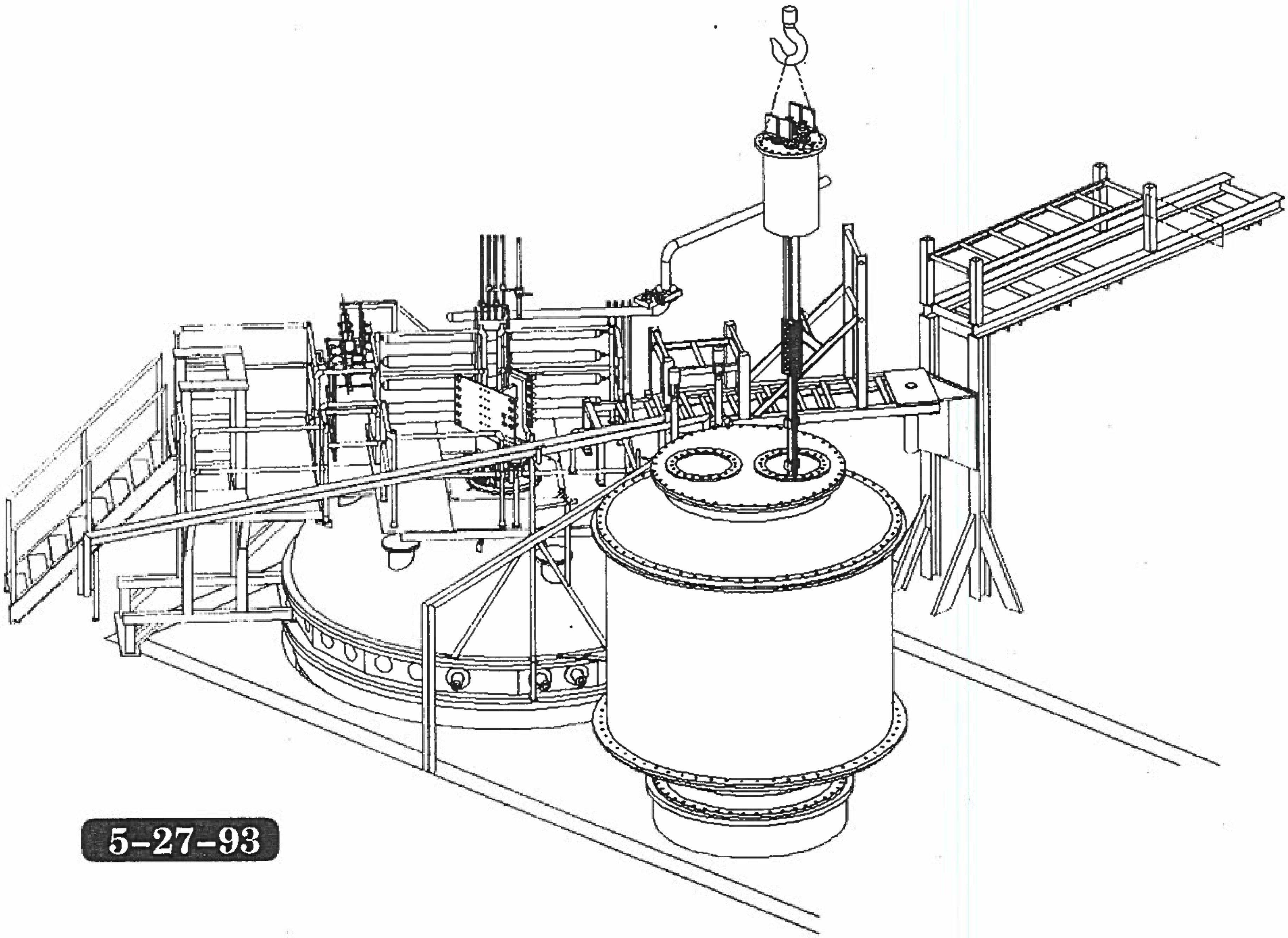
Additional tests required to certify conductor and joints for ITER operation:

- AC conductor
- Joint

FENIX and PFT

- The Pulse-Field Test is designed to test the same FENIX CICC sample, including the joint, under an ac magnetic field.
- Ac properties of the CICC and the joint can be measured, including ac losses. The sample is subject to a peak field of about 6 T with a rate change up to 12 T/s.

PULSE FIELD TESTING OF FENIX SAMPLE



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ITER PROTOTYPE CONDUCTOR SAMPLES FOR FENIX

Specifications/Descriptions	JA/ITER 2		JA/ITER 3	US/ITER 1
	Leg F	Leg H		
Strands				
Manufacturer	Nb3Sn	Nb3Sn	Nb3Al	Nb3Sn
Process	Furukawa	Hitachi Cable	Sumitomo	TWCA
Diameter (mm)	Bronze	Bronze	Jelly-Roll	Jelly-Roll/Internal-Tin
	0.92	0.92		0.78
Ic @ 13 T (A)	155	161		110
CICC				
Manufacturer	Furukawa	Hitachi Cable	Sumitomo	BIW / INCO
Sheath Material	Ti	Ti	Ti	Incoloy 908
No. of strands (n)	765	675		1350
Diameter (mm)	33	33		46
n*Ic @ 13 T (kA)	119	109		149
Cooling design	conventional	conventional	ITER with center hole	ITER with center hole
FENIX Sample with Terminations and Joint				
Manufacturer	Mitsubishi Electric	Hitachi	Fuji Electric	Westinghouse