HTS Conductor Design Issues Including Quench and Stability, AC Losses, and Fault Currents

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Oak Ridge National Laboratory

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Program objective and technical approach

- The purpose of this collaborative R&D project is an investigation of HTS conductor design optimization with emphasis on stability and protection issues for YBCO wires and coils applied to electric power devices.
- Work by MIT and FSU is supported via ORNL subcontracts.
- ORNL has conducted studies in thermal stability and quench propagation of cryo-cooled YBCO tapes.
- ORNL is also studying 2nd generation conductor design issues such as ac loss optimization, copper stabilization layers, tape joining techniques and impact of insulation on burn-out heat fluxes.

Motivation/background

- Stability and protection are crucial issues for HTS tapes and coils applied to electric power devices.
  - Both in normal operation (for example, conductor motion during a transient, conductor hot spot)
  - From an external event such as a short circuit or loss of cooling
- Minimization of AC losses is a key issue for the economic argument for HTS AC applications like cables and transformers.
- Conductor design is important to optimize several diverse parameters such as cost, performance and reliability (protection, stabilization).

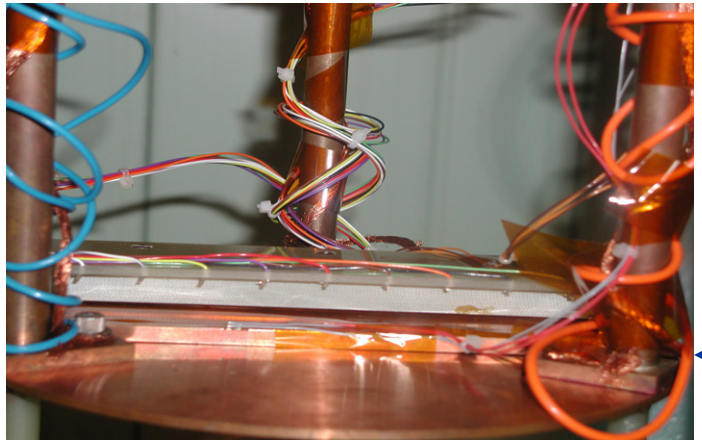
Outline of ORNL program

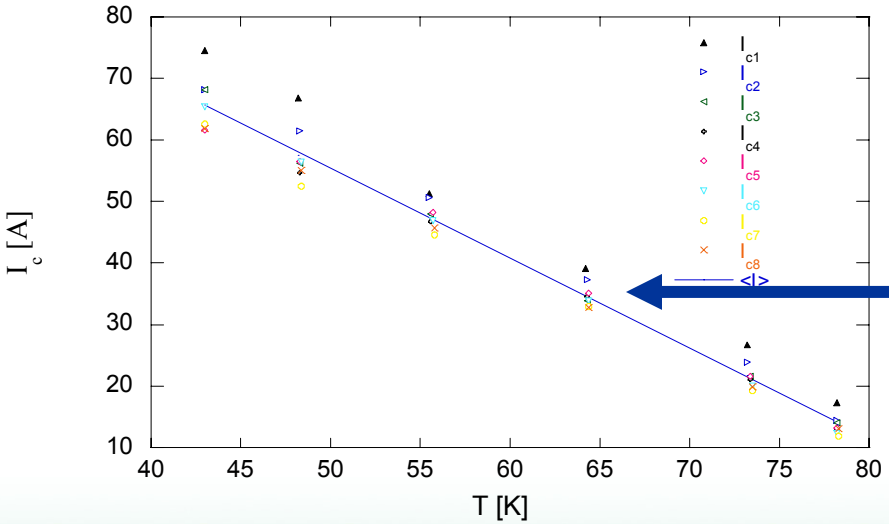
✓Program objectives and technical approach

- Accomplishments/results since last peer review
  - Normal zone propagation (invited paper at ASC 2002)
  - Stability margins
  - AC loss measurements in YBCO tapes
  - YBCO cable
  - Burn-out and fault current testing of HTS tapes
- FY 2004 Plans
- Research Integration

➢Talks by Profs. Iwasa and Schwarz will follow this ORNL presentation.

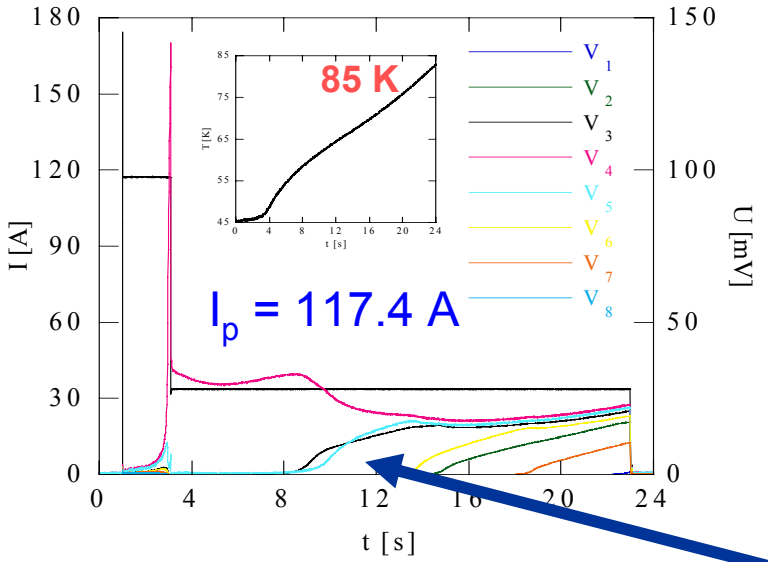
Stability and quench experiments are performed in a conduction-cooled environment

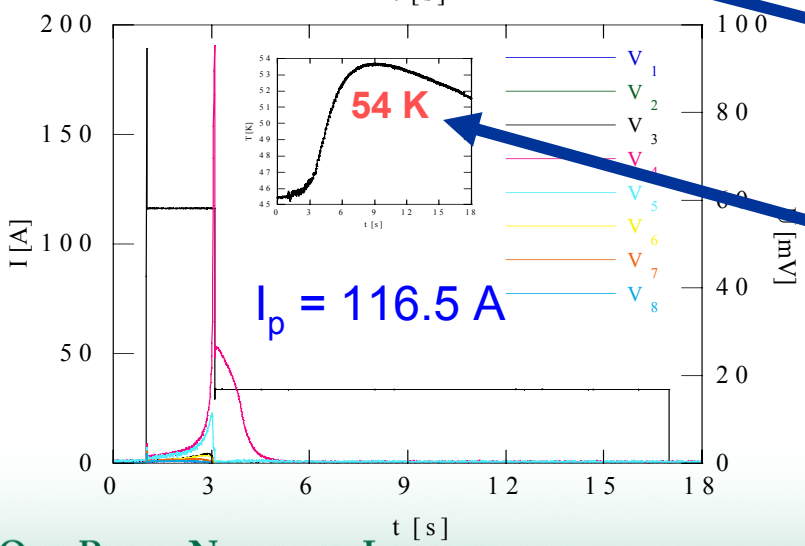




- YBCO (circa 2002) on nickel RABiTS substrate (3 μm of Ag, 50 μm Ni)
- The 20-cm YBCO tape sample was mounted between an insulated Cu-block and a G-10 block as shown on the left.
- A fairly uniform distribution (in the eight ~ 2-cm long zones) of critical currents from 12-17 A were measured at 78 K, and from 62-75 A were measured at 43 K.
- Critical currents increase linearly as the operating temperature decreases.

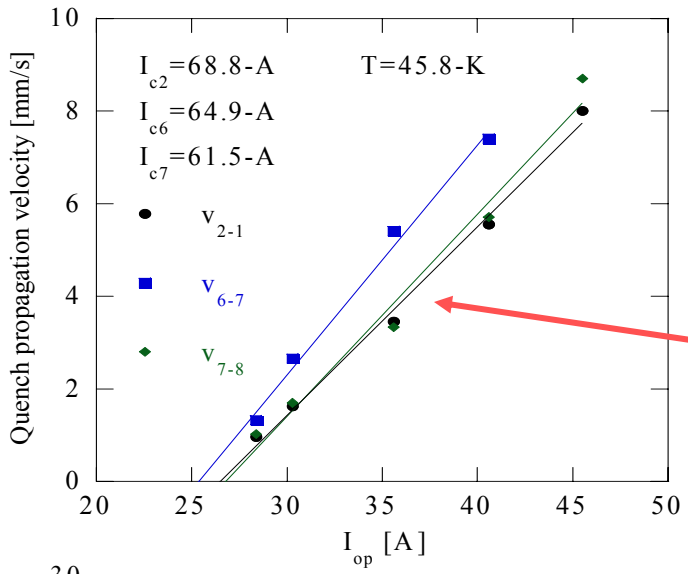
To study the quench behavior, an over-current pulse was applied to create a normal zone

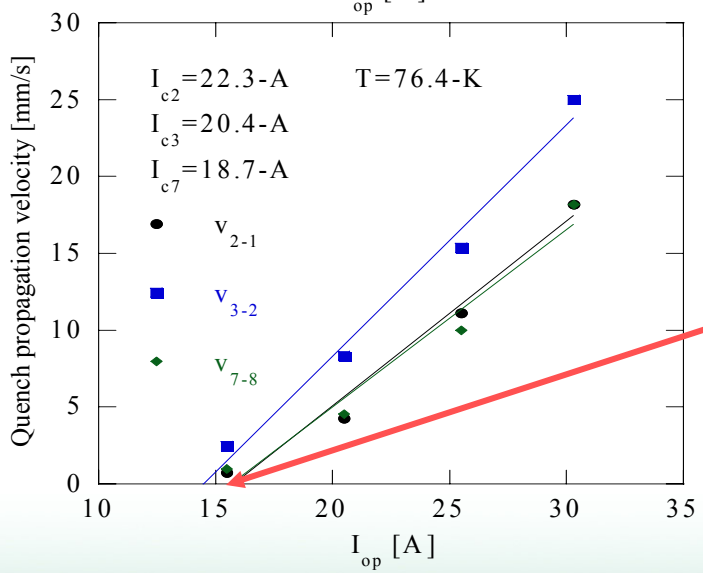




- The transient pulse energy was varied by changing the magnitude, I_p or the duration of the pulse.
- The figures show at T= 45 K and at an I_{op} of 33.7-A and a 2-s over-current pulse duration:
  - an I_p of 117.4 A caused a quench
  - an I_p of 116.5 A did not.
- Distinctive normal zone propagation was observed when there was a quench.
- The inserts show the temperatures measured by a PRT at the center of the sample.

Propagation velocities were measured from 45-80 K





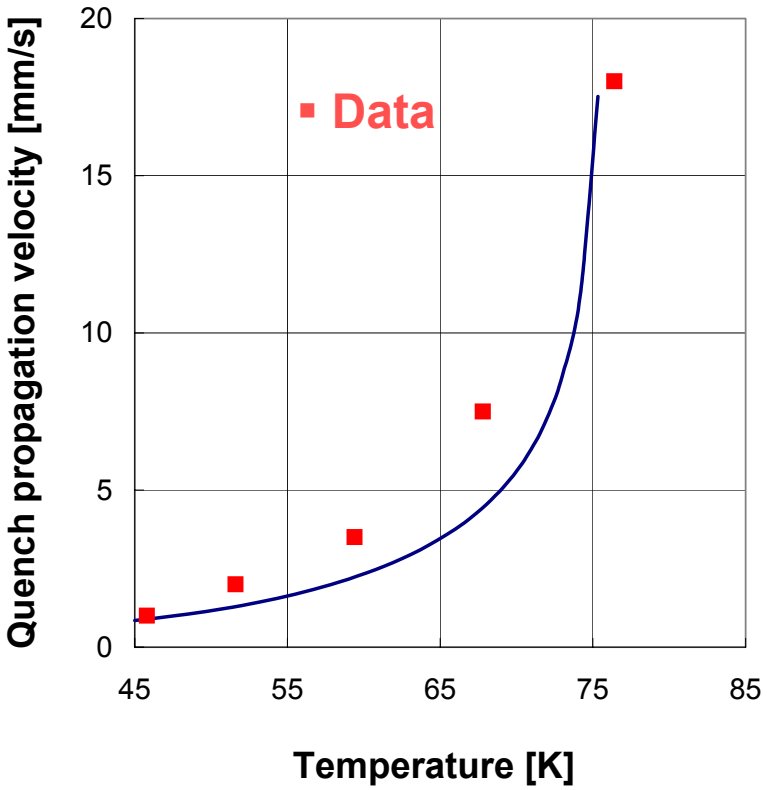
- Normal zone propagation always starts from the middle (zone 4) of this sample.
- Normal zone propagation velocities were found to increase linearly with the current.
- No more than 20 mm/s propagation velocity was measured when I_{op} was set below I_c.
- A minimum propagation current was found at each temperature, which is attributed to the conduction cooling.

Normal zone propagation speeds measured from 40-80 K

- **Agrees with modified traveling wave theory expression at a fixed current**

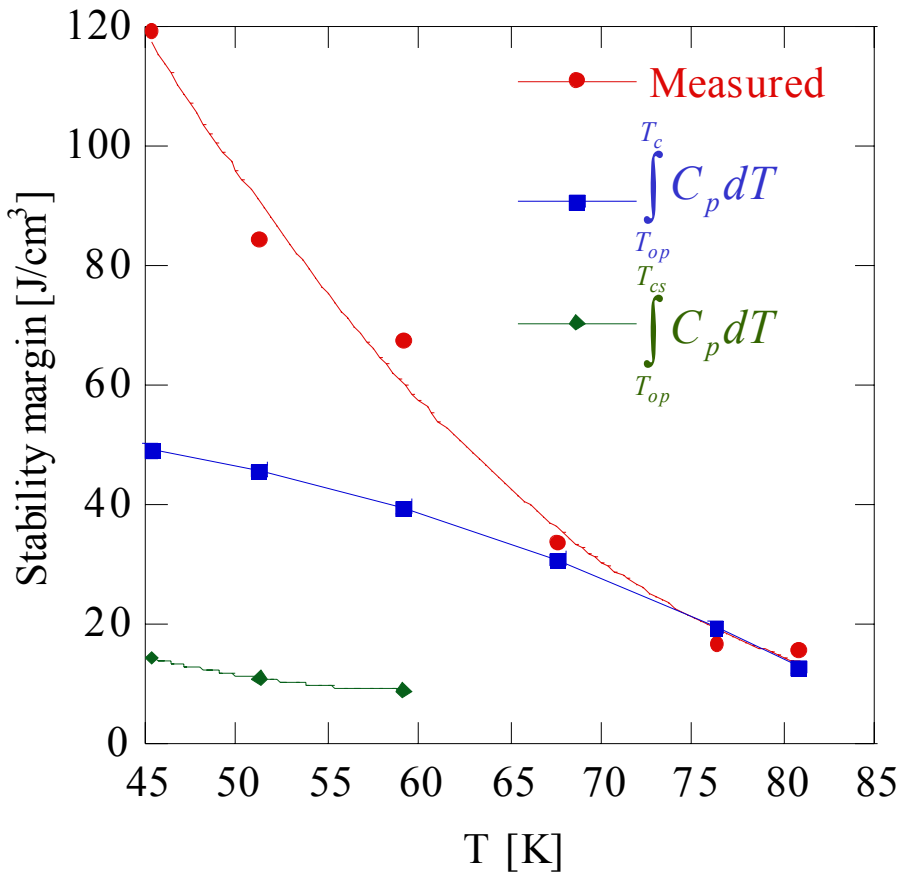
$$V = \frac{\left(I - I_{mp}\right)}{A}\sqrt{\frac{k_n \rho}{C_n C_s \left(T_t - T_{op}\right)}}$$

- **Propagation is on the order of 1-20 mm/s (LTS ~10 m/s)**



Stability margins

- Measured by increasing the current pulse followed by a fixed operating current below the lowest I_c of the tape.
- At the highest recovery pulse current, the V-I product integrated over the initial pulse divided by the zone volume is used to estimate the stability margin.
- The measured stability margins increased from 16 to 120 J/cm^3 as the temperature was lowered from 80 to 45 K.
- Comparison with the specific heat integrals indicates a better fit to T_c than to T_{cs} for the HTS tapes.
- Typical values for LTS are few-100 mJ/cm^3

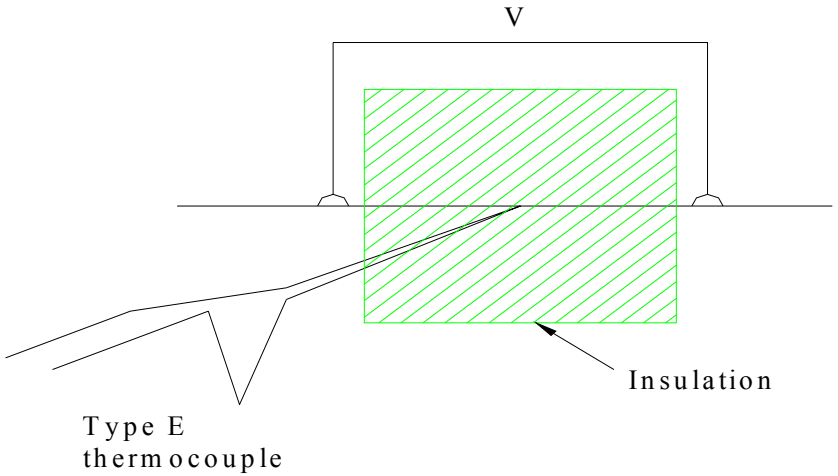


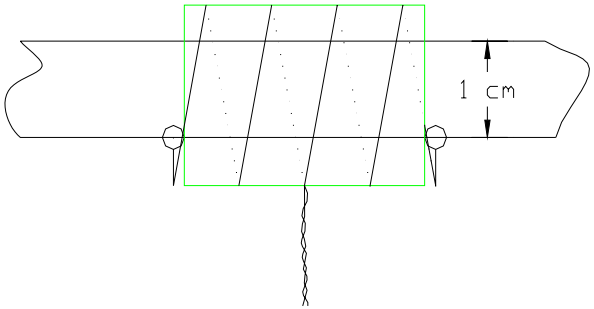
Stability and quench protection of YBCO conductors

- Stability margins of YBCO conductors are very high – there should be no concern against transient heat loading such as wire motion in a winding.
- Normal zone propagation velocity is low in HTS conductors – a localized thermal runaway is a distinct possibility.
- Events such as a local bad spot, over-current, and loss of cooling should be anticipated.
- Stabilizer must be added to the YBCO conductor to lower the heat production and prolong the time before thermal runaway
  - a normal state resistance no more than 5 mΩ/m @ 77 K for a 100 A/cm-width conductor is suggested.
- Electrically shorting the already existing Ni-substrate to YBCO is a possible approach to reduce normal state resistance.
  - less effective for Ni-alloy substrates
  - but more recent R&D on Cu substrates
- Uniformity in the stabilizer, as well as in the I_c is imperative.

AC losses (transport current only)

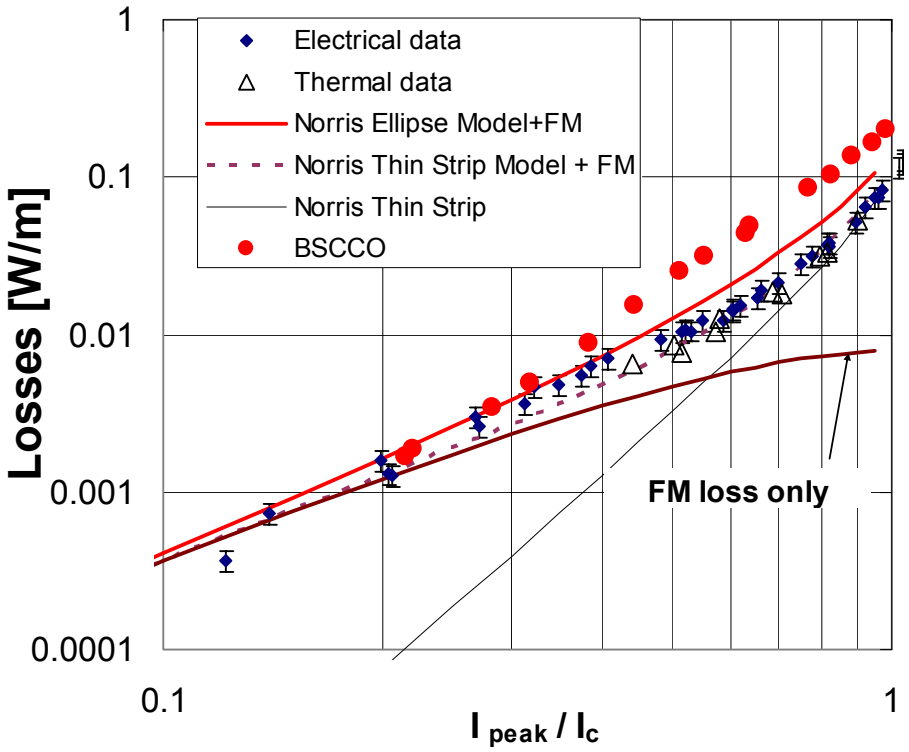
- Sample characteristics
  - Ni 5%W 75 μm substrate
  - Critical current of 110 A
  - YBCO thickness of 1 μm
- Thermal measurement
  - Comparison of thermocouple response from AC current to known heat input
- Electrical Measurement
  - Spiral voltage tap configuration
  - Q = I V cos(Θ)





AC loss (cont'd)

- Norris thin strip model + ferromagnetic loss from Ni-5at%W provided good agreement with both thermal and electrical data
- Ferromagnetic loss measured experimentally at T = 95 K > T_c for Ni-5at%W substrates
- For $I_{peak}/I_c < 0.5$, ferromagnetic loss fraction is greater than 50%

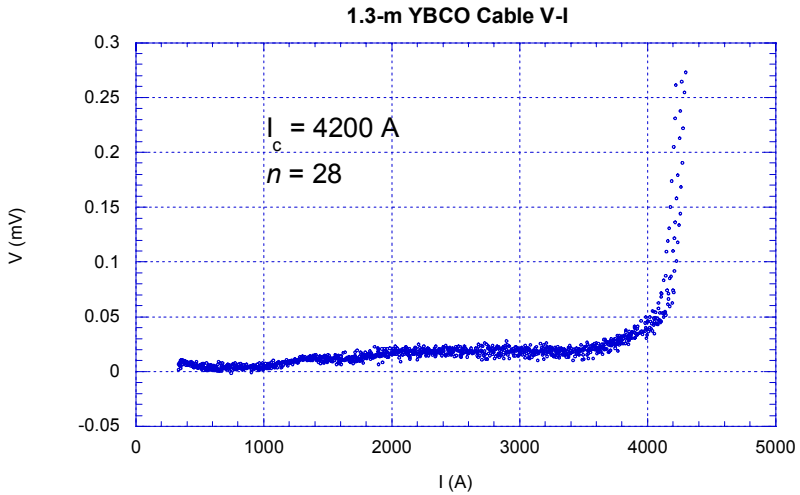


BSSCO I_c = 145 A, YBCO I_c = 110 A

Submitted to Supercond. Sci. Tech (to be published)

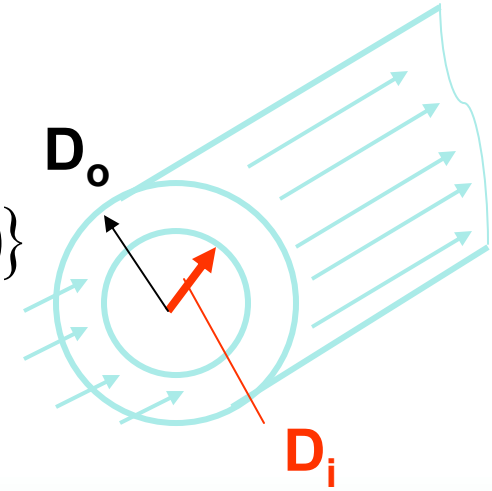
1.25 m YBCO cable

- Commercial-grade demonstration YBCO cable, I_c ~4.2 kA, I_{ac} ~ 2 kA_{rms}
- Copper-coated YBCO conductors
  - 50 μm of copper laminated to silver-coated YBCO conductor from American Superconductor
  - Average critical current >170 A over 24 tapes of 1.5 m in length
  - Tapes were quite robust
- Advantages of YBCO for electric devices
  - Potentially lower ac loss relative to BSCCO
  - Potential lower cost
  - Higher performance in field



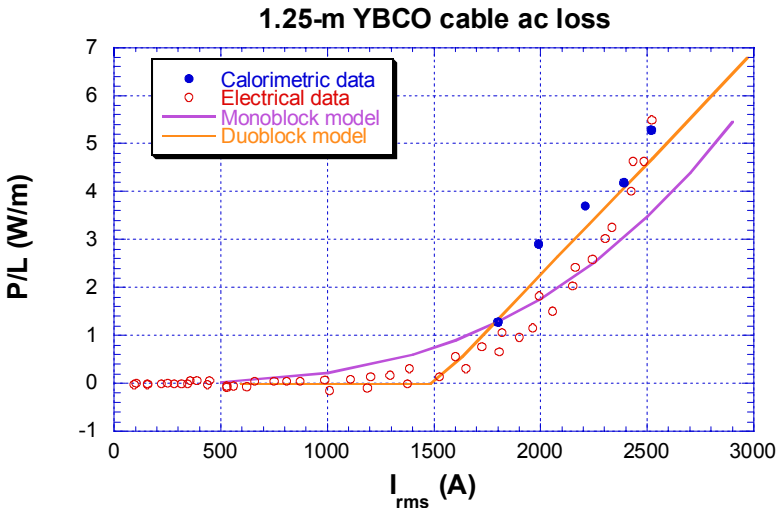
$$Q = \frac{\mu_o f I_c^2}{2\pi h^2}\left\{\left(2 - Fh\right)\cdot Fh + 2\cdot\left(1 - Fh\right)\ln\left(1 - Fh\right)\right\}$$

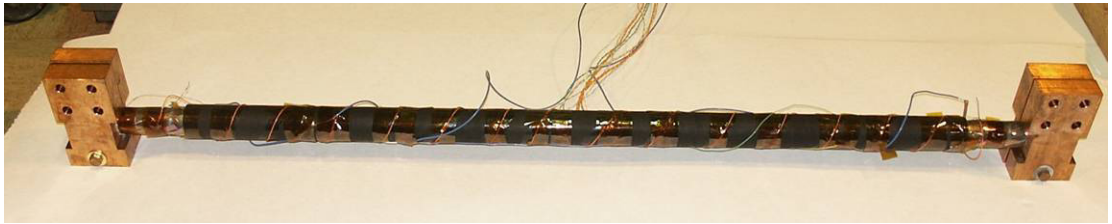
$$h = \frac{D_o^2 - D_i^2}{D_o^2} \qquad F = I_{peak} / I_c$$



1.25 m YBCO cable –AC losses

- **Successful operation at up to 2500 A_{rms}**
- **AC loss was measured electrically and thermally to be about 2 watt/m at 2000 A_{rms}, corresponding to $I_{peak}/I_c \sim 0.67$**
- **Loss is enhanced due to large gap between YBCO conductor layers of order 600-700 microns.**
- **Need 3-5 mm wide tapes to reduce radial build in multi-layer cables**

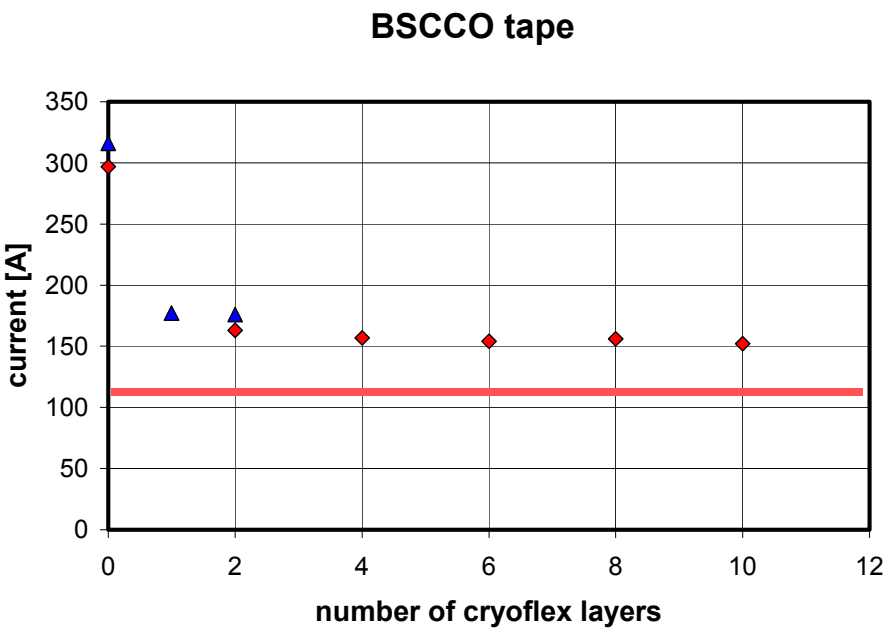


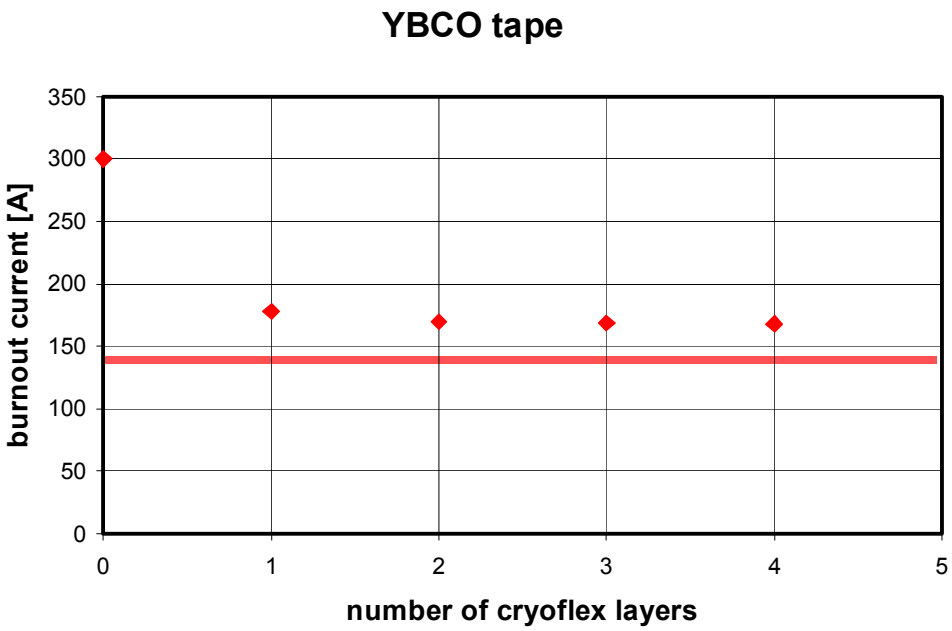


An HTS prototype cable was burned out during a test in Europe

- The cable was made of Ag-alloy matrix BSCCO tapes
- The cable was burned out during an open bath ac loss measurement when I_{peak}/I_c was set to 1.6.

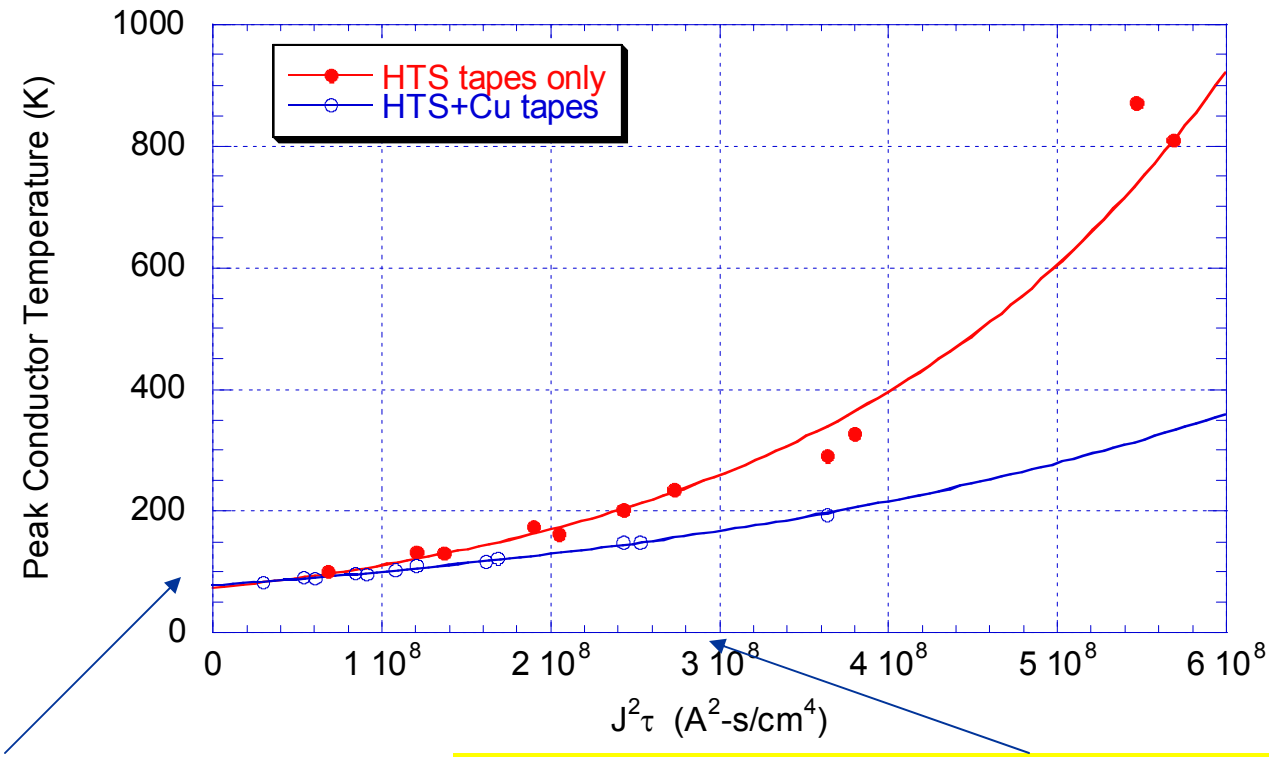
Burn-out tests of AMSC Ni/Cu plated BSCCO and YBCO tape (current on for 60 sec)





Critical current at 77 K

Fault current magnitude and duration determine required Cu stabilization for given peak conductor temperature



What is appropriate transient temperature limit?

Typical 4.5 mm x .25 mm tape at 60 A operating current, 10x fault current for 6 cycles

FY 2004 plans

- Impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerance will be studied (in collaboration with AMSC).
- In addition, normal zone propagation and stability margins will be measured in a series of copper-stabilized, YBCO coated conductors
  - with different copper thicknesses and joining techniques.
- A 1-Tesla HTS coil will be made with YBCO conductor and tested to determine operating envelope and stability margins.
  - similar to a study with a BSCCO coil in 1994: “Stability measurements of a 1-T HTS magnet,” J. W. Lue, R. E. Schwall et al.
- Plan to make a YBCO cable with ~ 4-mm wide 2G tape.

Research integration

- There is coordinated internal interaction between ORNL/MIT/FSU
- There is also a close interaction with the 2nd generation HTS wire developers.
- All three institutions presented papers at the 2002 Applied Superconductivity Conference including an invited paper by ORNL.
- Dr. Iwasa, MIT and Dr. Trociewitz, FSU attended the Workshop on Thermohydraulic Transients in Superconductors, September 2002
  - published articles based on their talks on HTS magnet stability and protection in *Cryogenics* (Vol. 43).
- The FSU team presented a talk on YBCO normal zone creation and propagation at the DOE 2003 Wire Workshop.
- ORNL and FSU were on a coated conductor applications panel at the MURI workshop in June 2003.
- ORNL is working to communicate the relevant YBCO results to the SPI teams interested in YBCO replacement of BSCCO:
  - a test of a 1.25-m cable made with YBCO tapes is in progress.

U.S.Department of Energy Energy Efficiency and Renewable Energy
SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS
2003 Annual Superconductivity Peer Review

MIT/FBML-FSU/NHMFL Joint Project

Stability and Quench Protection of YBCO Wires and Coils

MIT/FBML Activities

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MIT Francis Bitter Magnet Laboratory
Cambridge, MA 02139-4208

July 25, 2003
L'Enfant Plaza Hotel, Washington, DC

MIT/FBML "Year 3" (01/01/03-05/31/04) Programs

xperimental and analytical study of quench/recovery of YBCO samples
are" and Cu-laminated, cooled by LN_2, subjected to over-current pulse

ask 1: Stability enhancement with solid N_2.

ask 2: Quench/recovery with LN_2 bath cooling.

ask 3: Detection of "hot spots" with acoustic emission (AE) technique.

ersonnel: *Y. Iwasa*; *J. Jankowski*; H. M. Kim; H. Lee; J. Bascuñán

est Sample Sources

AMSC (Alex Malozemoff; *Steve Fleshler*)

IGC (Venkat Selvamanickman; *Jodi Reeves*)

sk 1: Stability Enhancement with Solid N_2 (09/01/03-05/31/04)

ability *enhancement* by using $C_p(T)$ of solid N_2 in the range 20-50K.

ability *enhancement* diminishes "protection-initiated" system disruptio

s Proposed

-cm long YBCO test samples subjected to an over-current pulse or loca ating, either with or w/o a thin (~0.5mm) layer of solid N_2. $T_{initial}$: 30-50

***1-m long tape available*, a 3-turn YBCO coil.**

sk 2: Quench/Recovery (01/01/03-05/31/04)

- **AMSC & IGC test samples, under over-current pulse, LN_2 bath 77K**

Variations from Year 2:

- **Samples laminated with a Cu strip (50–76 μm);**
- **Surface insulated from LN_2.**

sk 3: "Hot Spot" Detection with AE Technique (08/15/03-05/31

- **Development of "hot spots" detection technique based on acoustic emission (AE) signals for HTS coils in the temperature range 30-77K**

Technology Integration

- **Presentation at GE Global Research Center, Niskayuna, NY on 10/16/2002: *"HTS Magnets: Stability; Protection; Cryogenics; Economics; Protection/Stability Research Activities at FBML"* (Included MIT's tasks to be proposed for FY2003).**
- **Presentation at IGC-SuperPower, Schenectady, NY on 10/17/2002: *"HTS Magnets: Stability; Protection; Cryogenics; Economics; Protection/Stability Research Activities at FBML"* (Included MIT's tasks to be proposed for FY2003).**
- **Presentation at AMSC, Westborough, MA on 11/22/2002 *"Stability and Protection of YBCO Tapes and Coils: 'Year 3' MIT-FSU Program (01/01/03-05/31/04)-- Tasks Proposed by MIT"***

Technology Integration (Cont.)

- **1-2 hour group meetings at MIT with Steve Fleshler of AMSC to discuss the MIT experiment and review results: 12/17/02; 02/27/03; 04/01/03.**

Publications

- **Y. Iwasa, H. Lee, J. Fang, and B. Haid, "Quench and recovery processes of YBCO tape: Experimental and analytical results," *IEEE Trans. Appl. Superconduc*. Vol. 13, 1772-1775 (2003).**
- **Y. Iwasa, "HTS magnets: stability; protection; cryogenics; economics; current stability/protection activities at FBML," *Cryogenics* 43, pp. 303-316 (2003).**

sk 3: Performance Results (08/15/02-12/31/02)

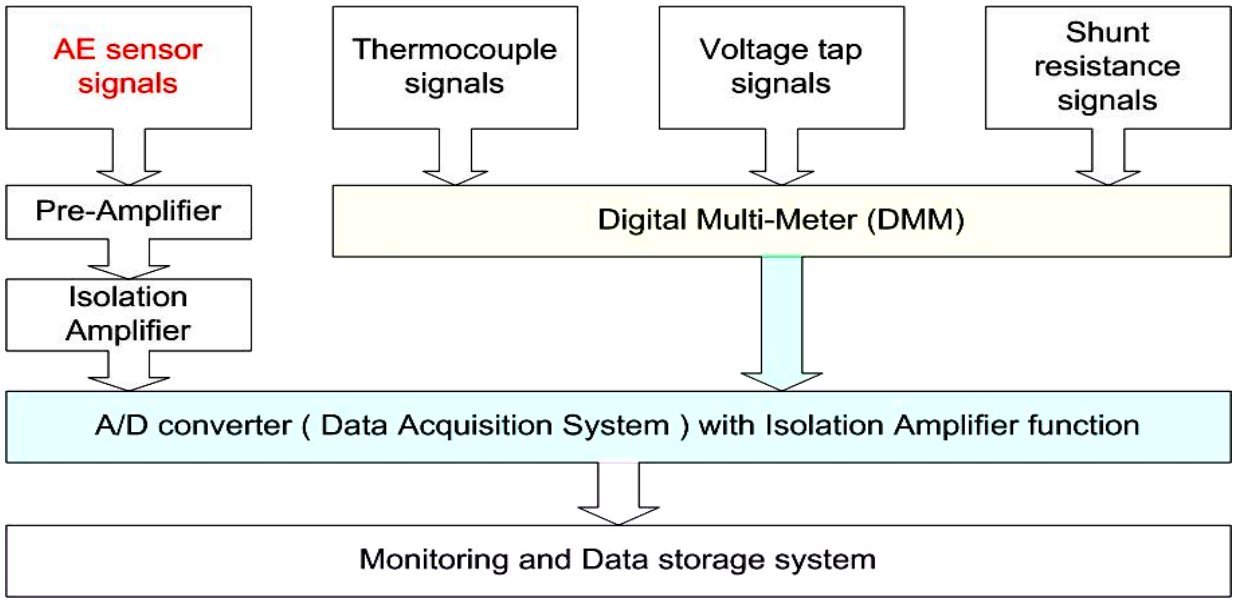
reliminary study of AE detection of "hot spots" in HTS coils.

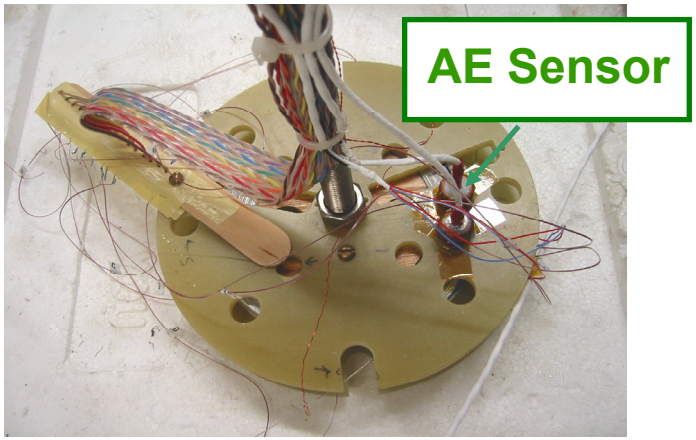
etection of a Local Hot Zone with AE Signals — A Review

AE: Acoustic signals emitted by sudden mechanical or thermal events in a body being loaded/unloaded & heated/cooled.

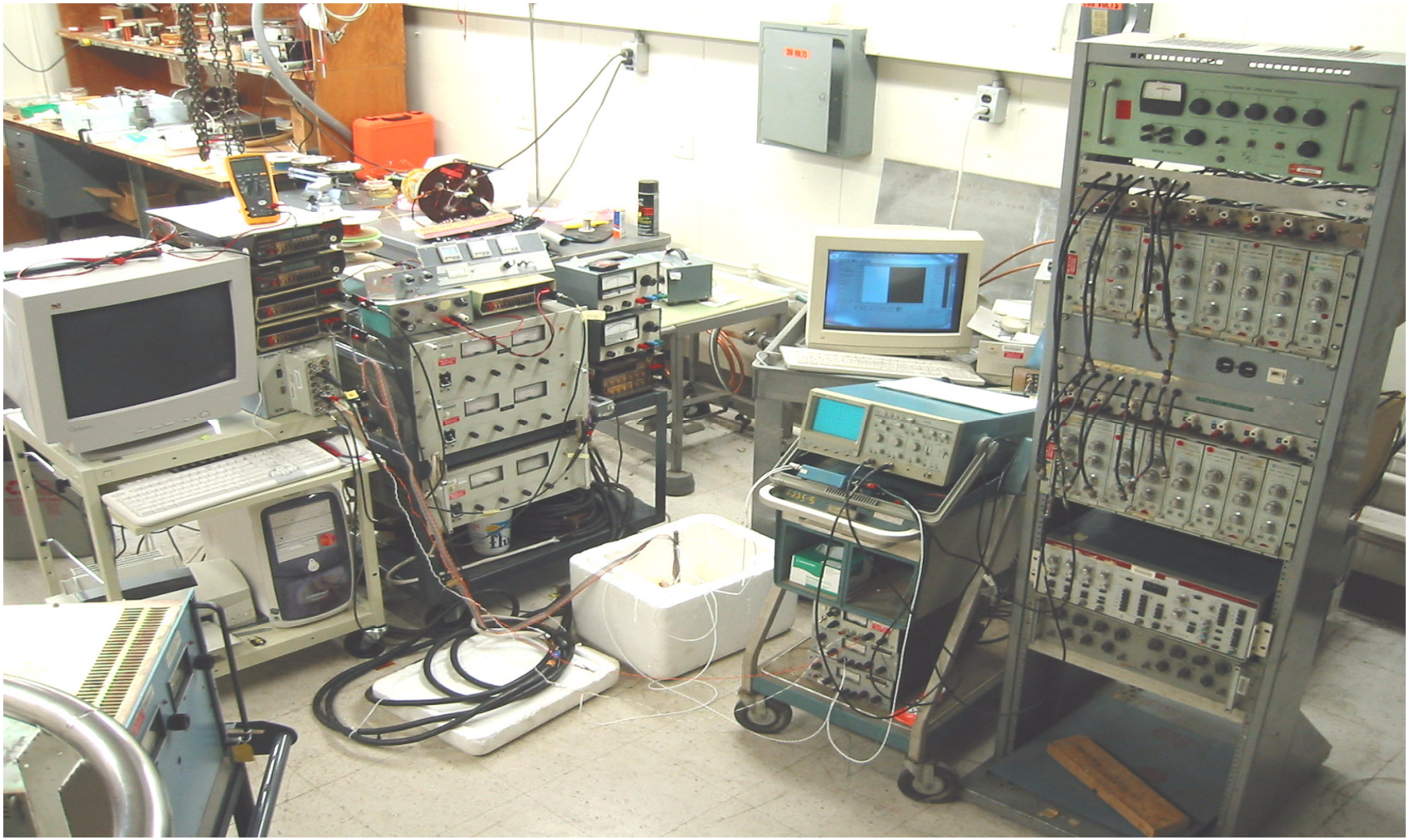
Used in high-performance LTS magnets to distinguish quenches by mechanical disturbances (AE) from those at I_c (no AE).

ignal Block Diagram & Double-Pancake Bi2223 Test Coil (20

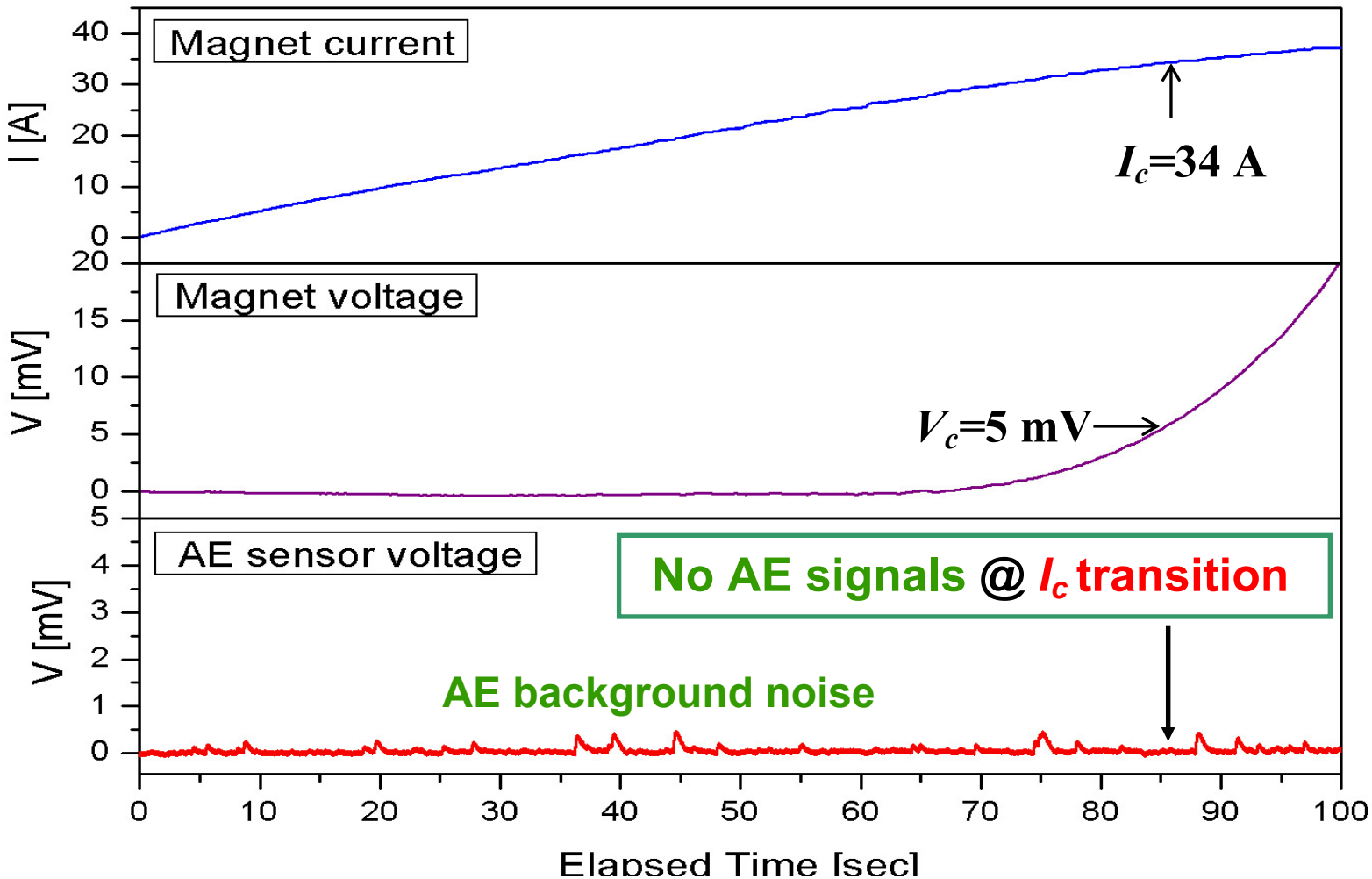




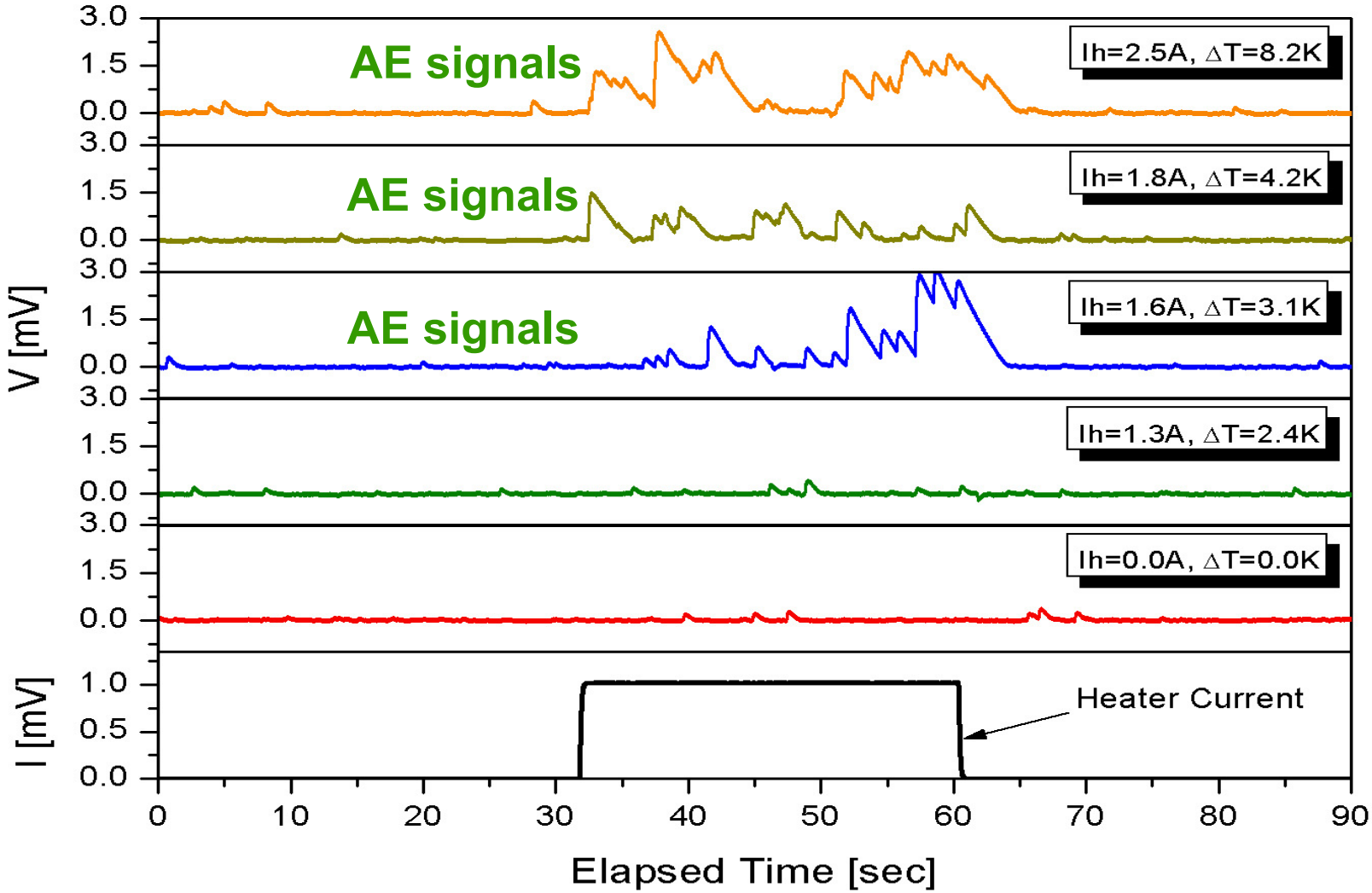
Experimental Setup



I(*t*), *V*(*t*), and *AE*(*t*) Plots @ 77 K

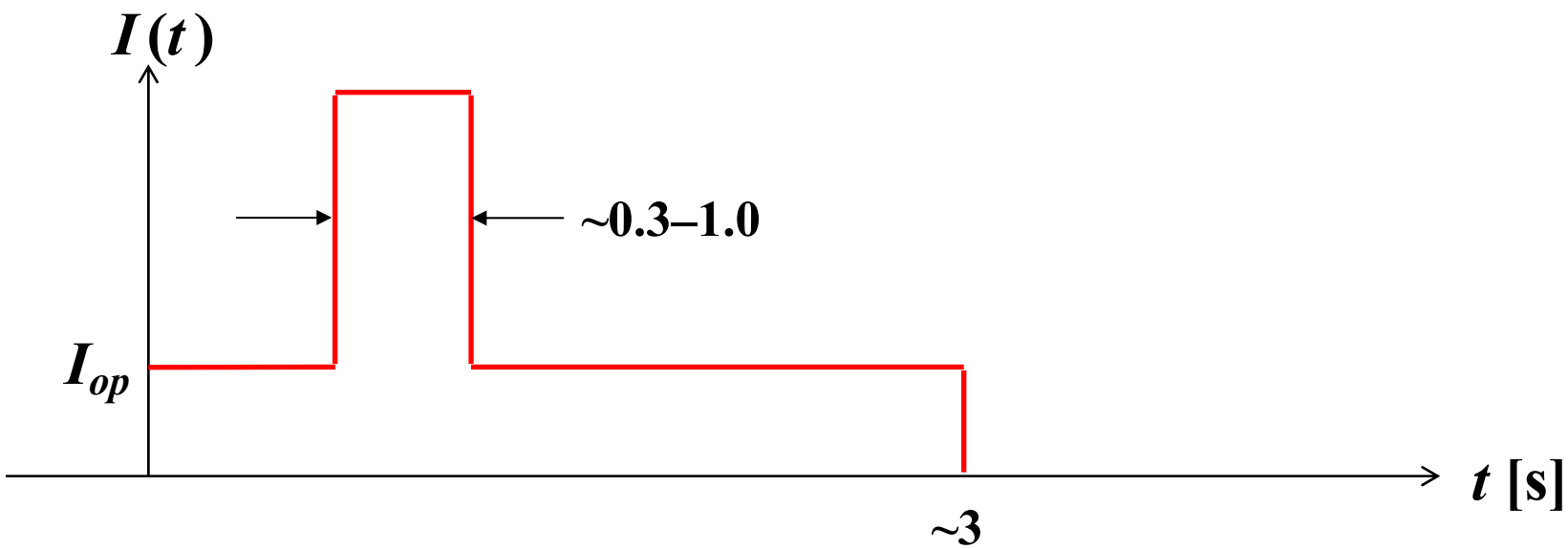


Heating-Induced Data: I_{op}=15 A

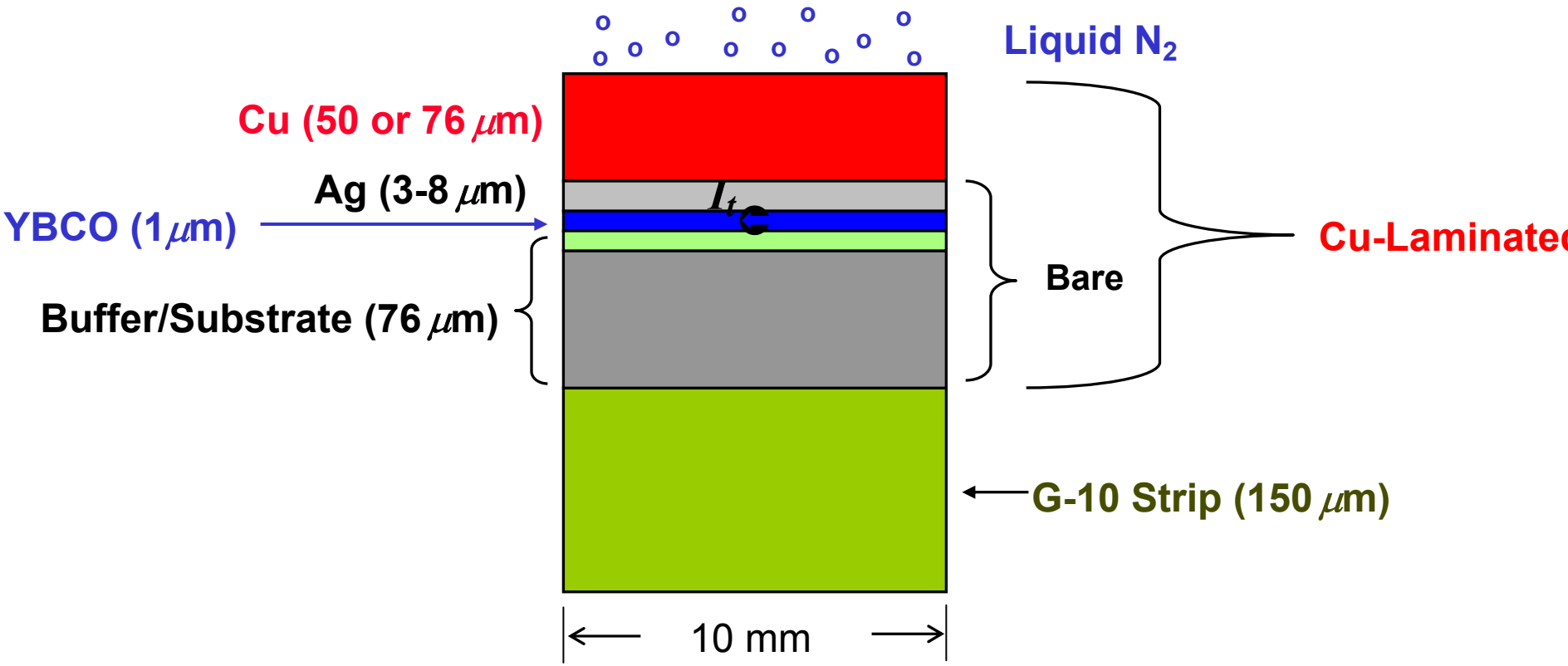


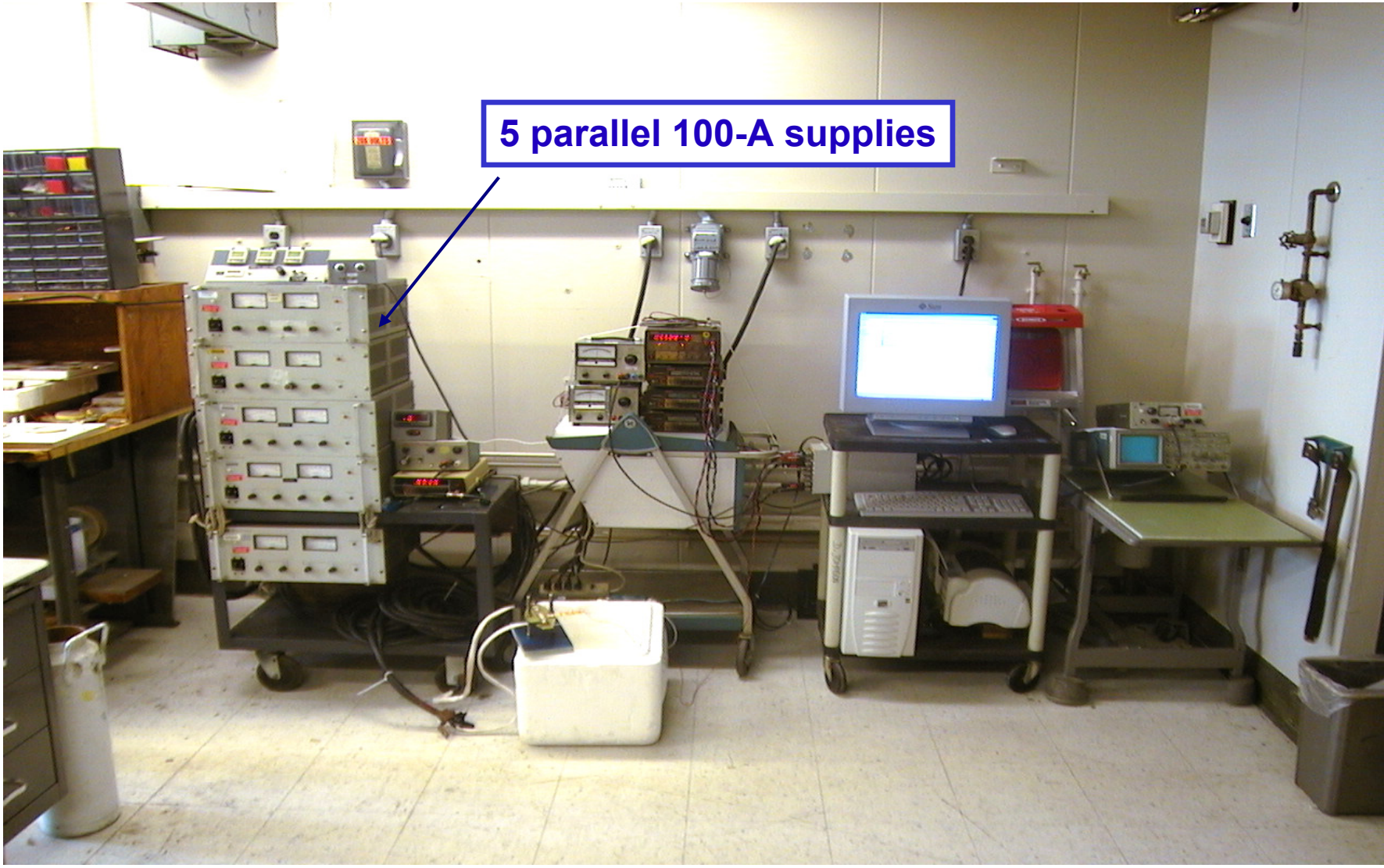
Tasks 2 & 3: Experimental Results (01/01/03-06/30/03)

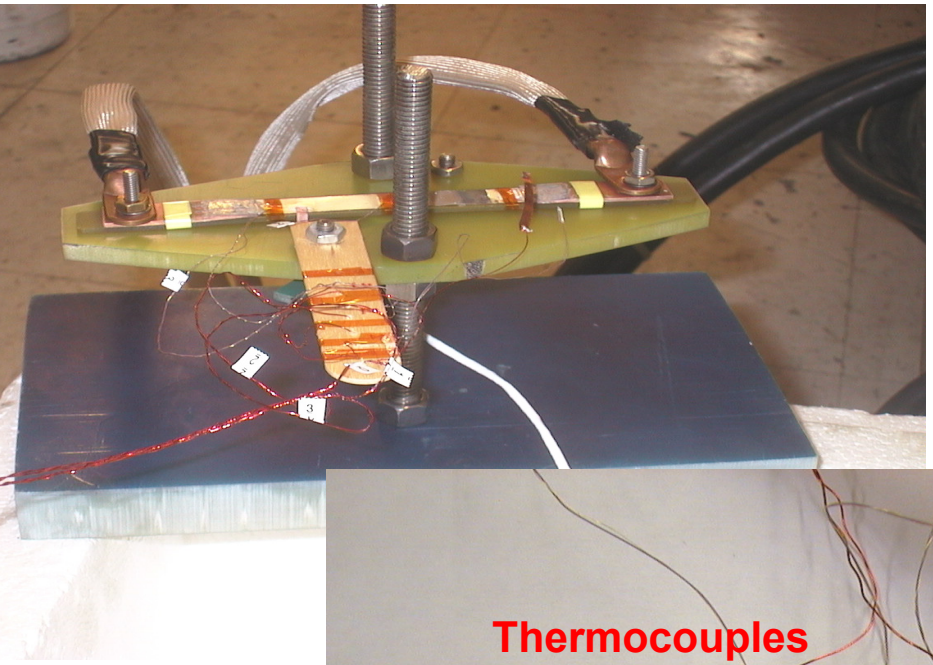
- **AMSC samples, bare (Ag only) & Cu-laminated; 10-cm long**
- **I_c (77 K, self field; measured by AMSC): >110 A**
- **Subjected to an over-current pulse (3-5× I_c) while carrying steady-state DC current (~0.9I_c)**

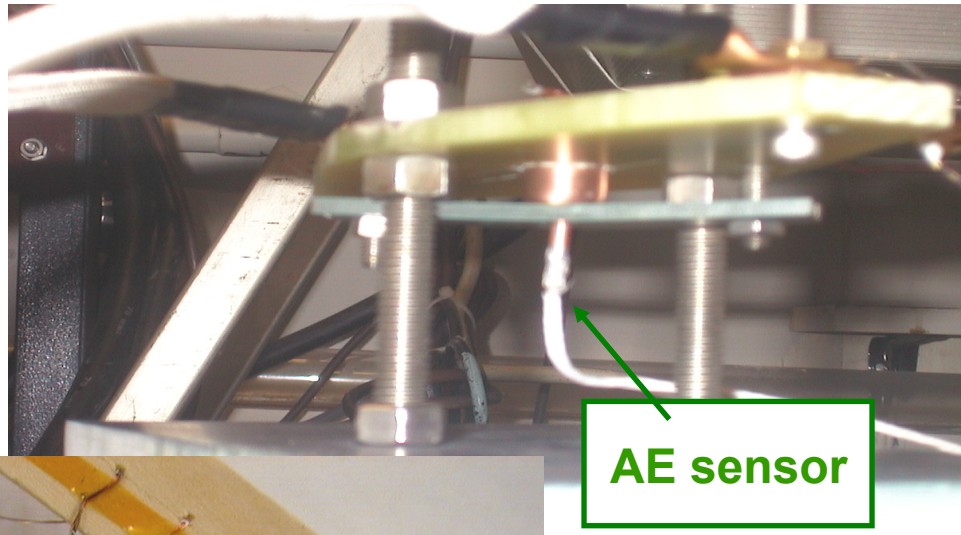


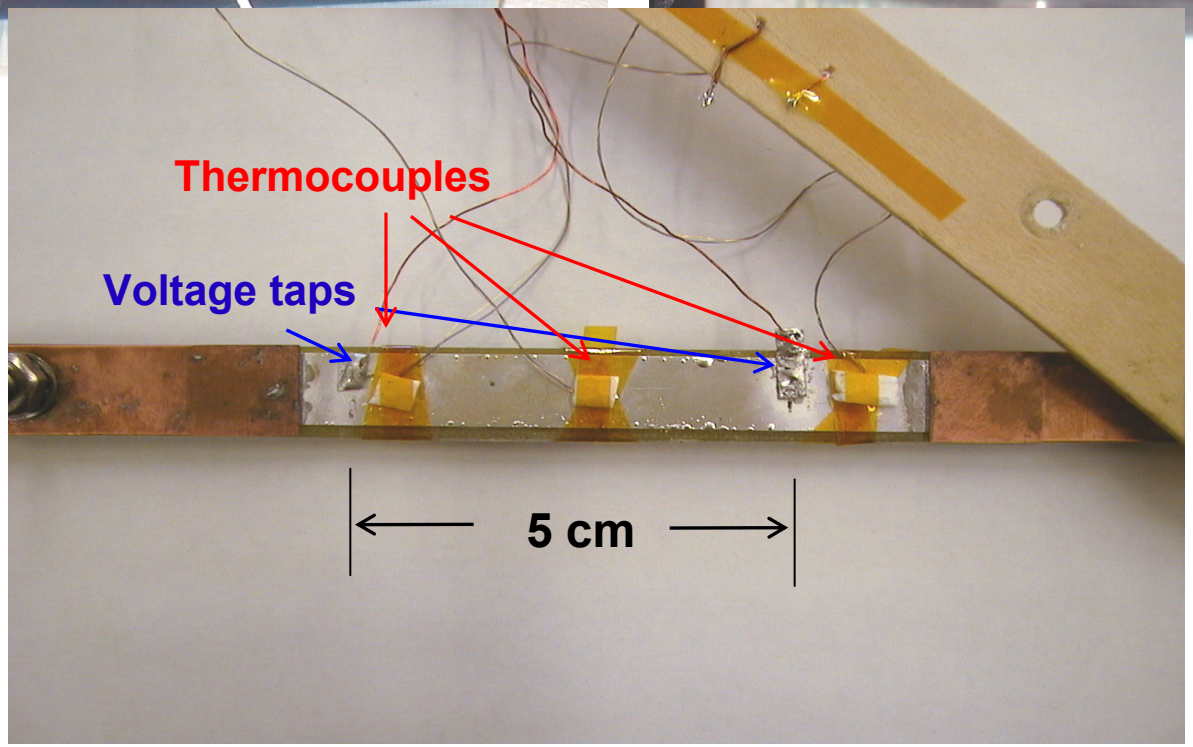
YBCO Composite Front Cross Section View

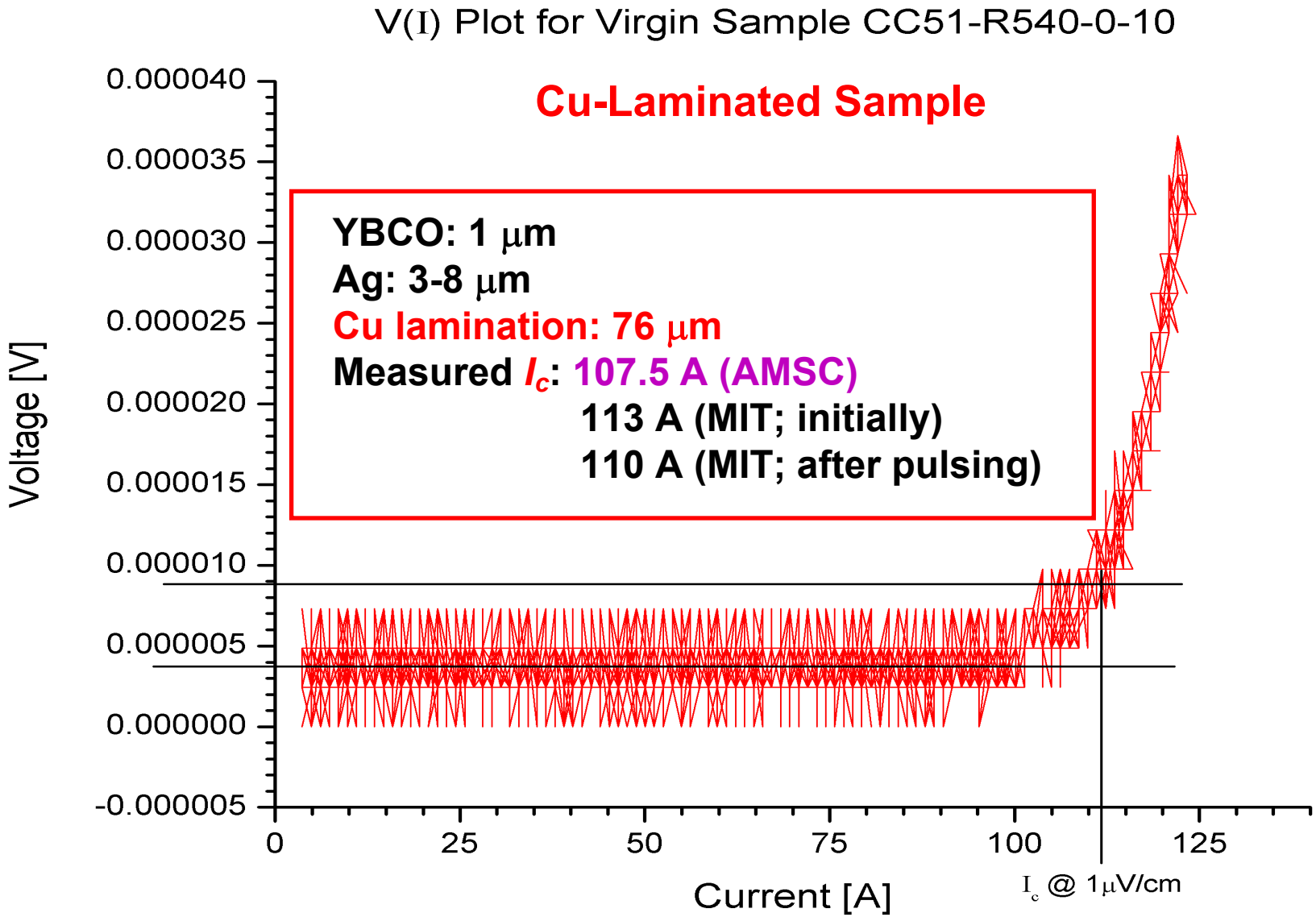



5 parallel 100-A supplies

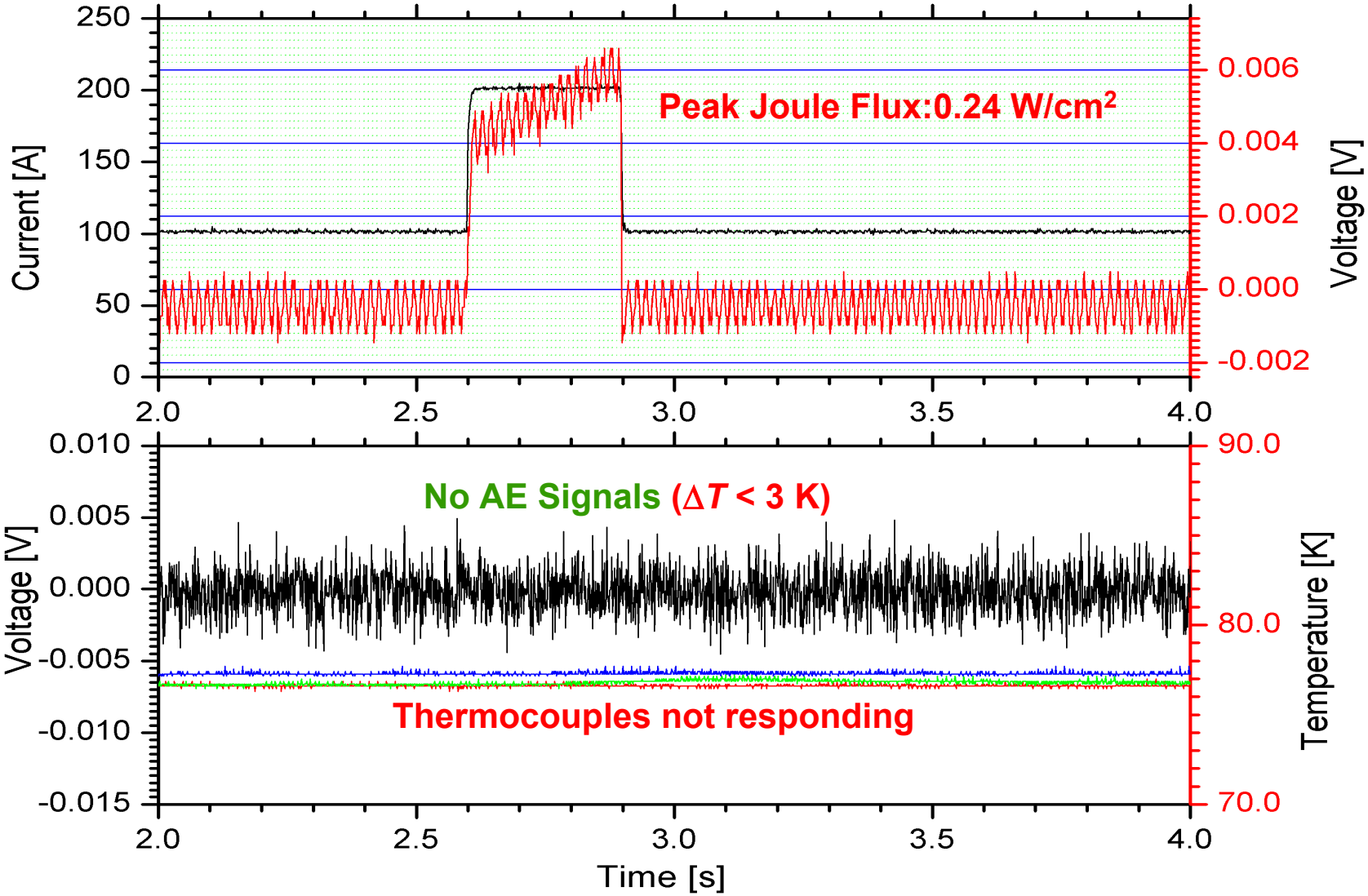


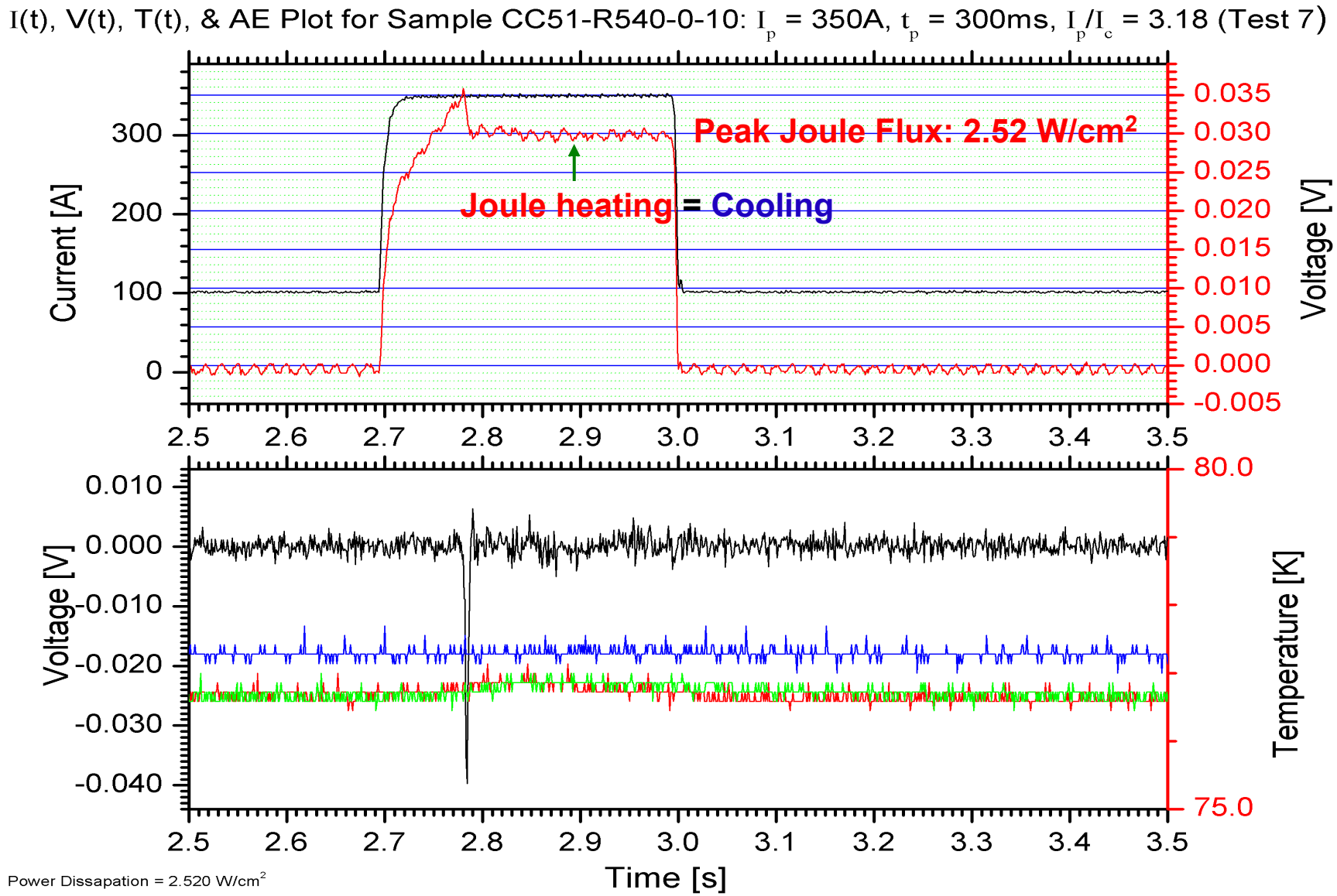

AE sensor

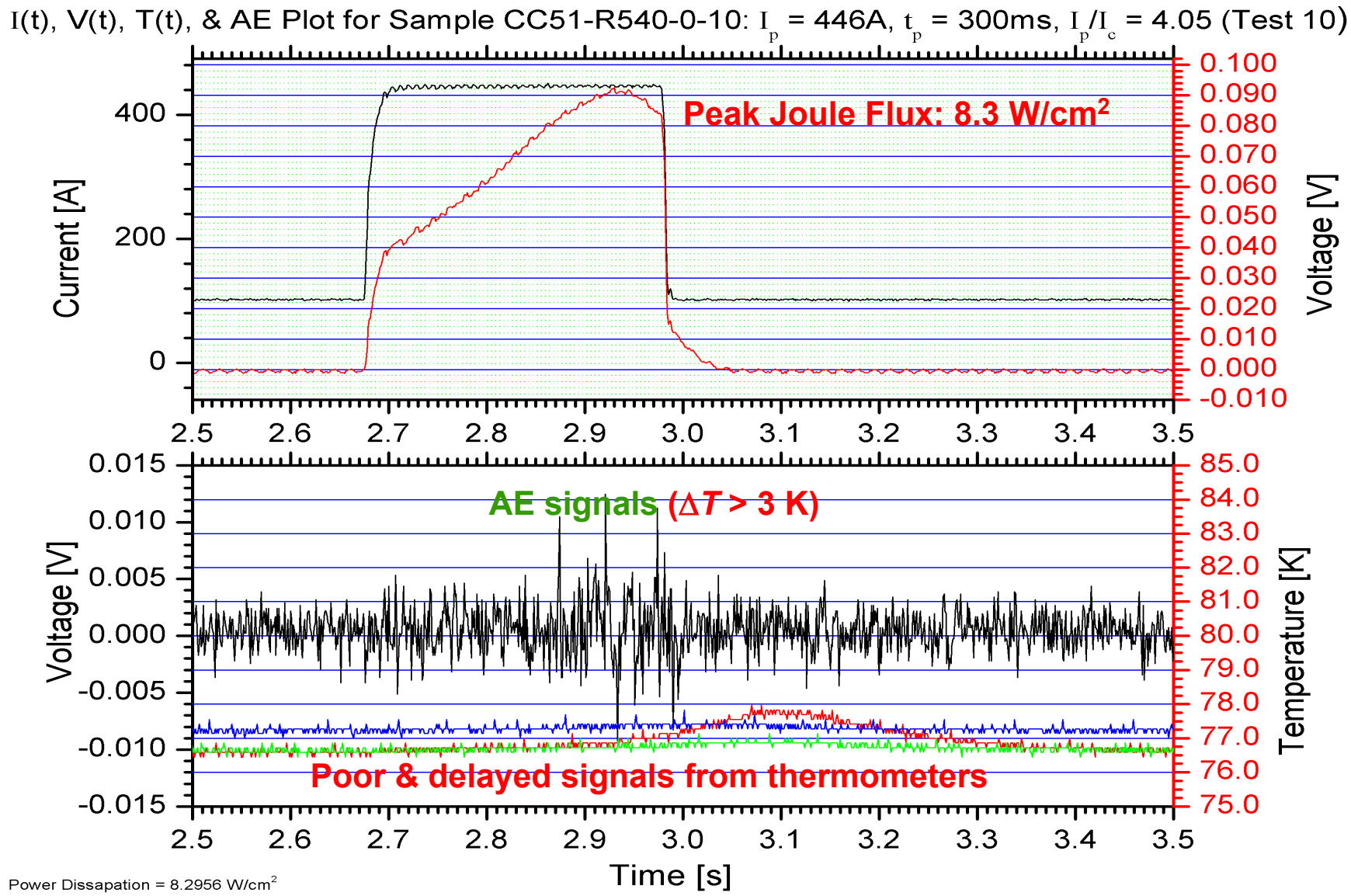

Thermocouples
Voltage taps
5 cm

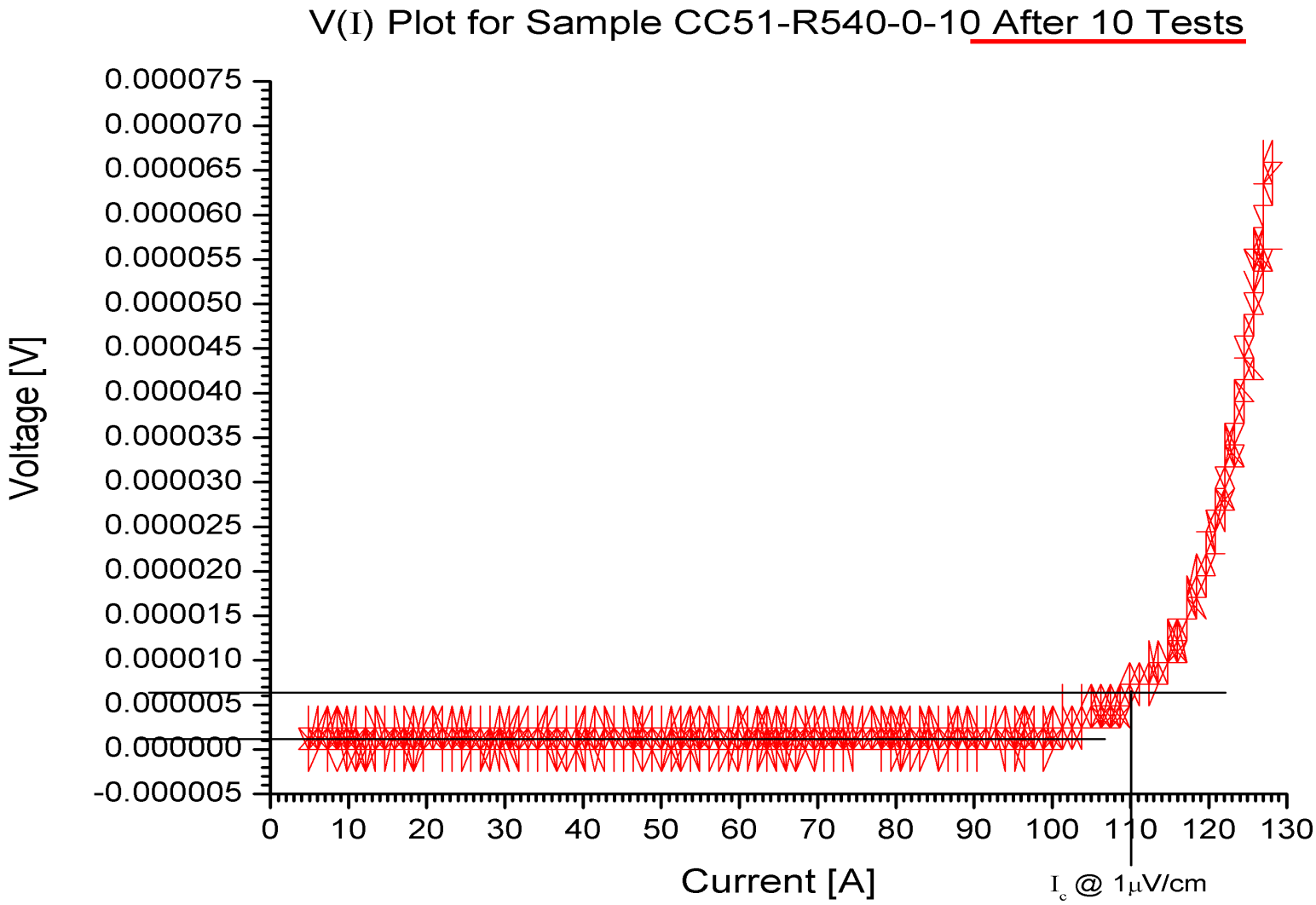

V(I) Plot for Virgin Sample CC51-R540-0-10
Cu-Laminated Sample
YBCO: 1 μm
Ag: 3-8 μm
Cu lamination: 76 μm
Measured I_c: 107.5 A (AMSC)
113 A (MIT; initially)
110 A (MIT; after pulsing)
Voltage [V]
0.000040
0.000035
0.000030
0.000025
0.000020
0.000015
0.000010
0.000005
0.000000
-0.000005
0
25
50
75
100
125
Current [A]
I_c @ 1μV/cm

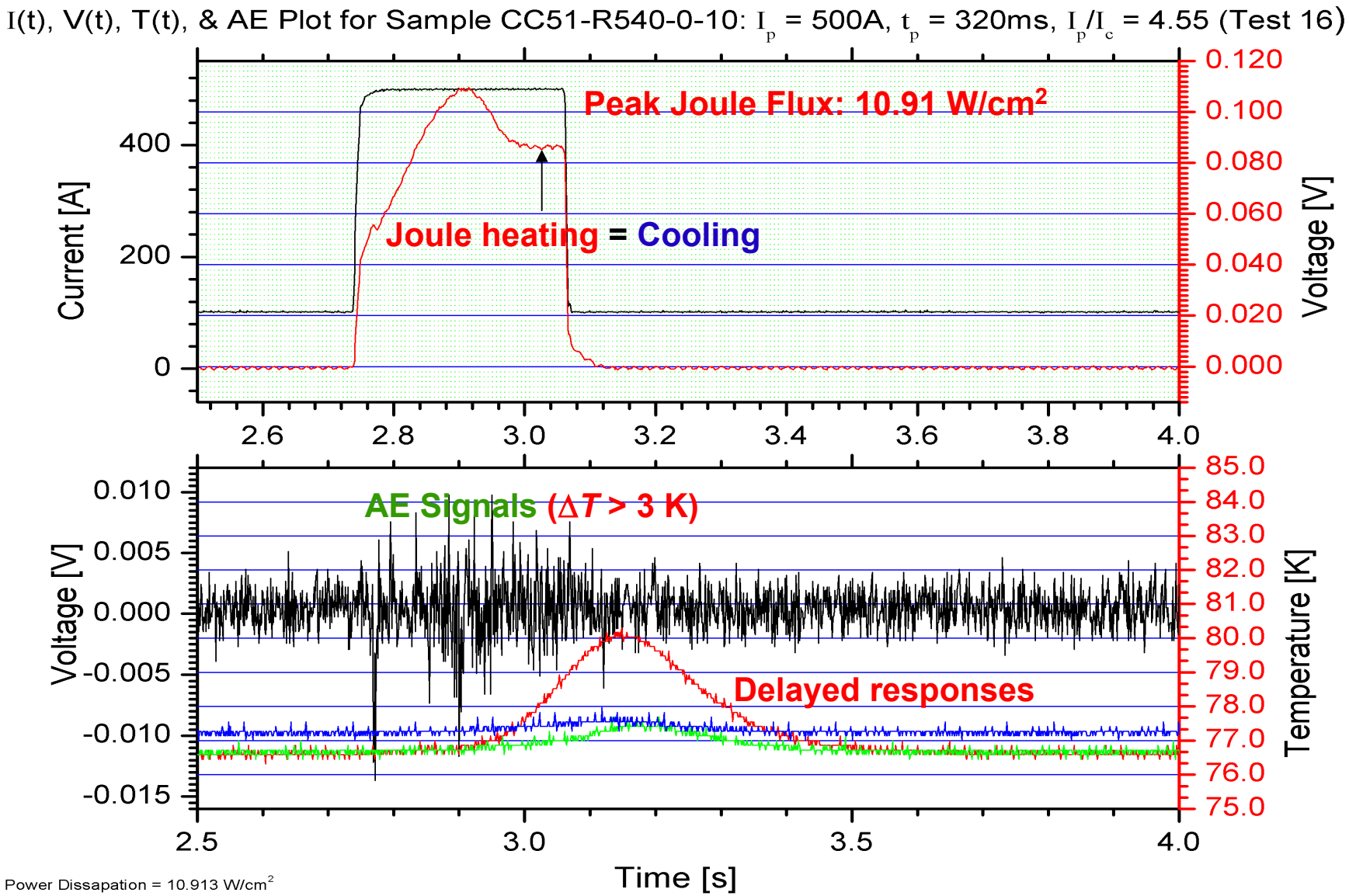
I(t), V(t), T(t), & AE Plot for Sample CC51-R540-0-10: I_p = 201A, t_p = 300ms, I_p/I_c = 1.83 (Test 2)

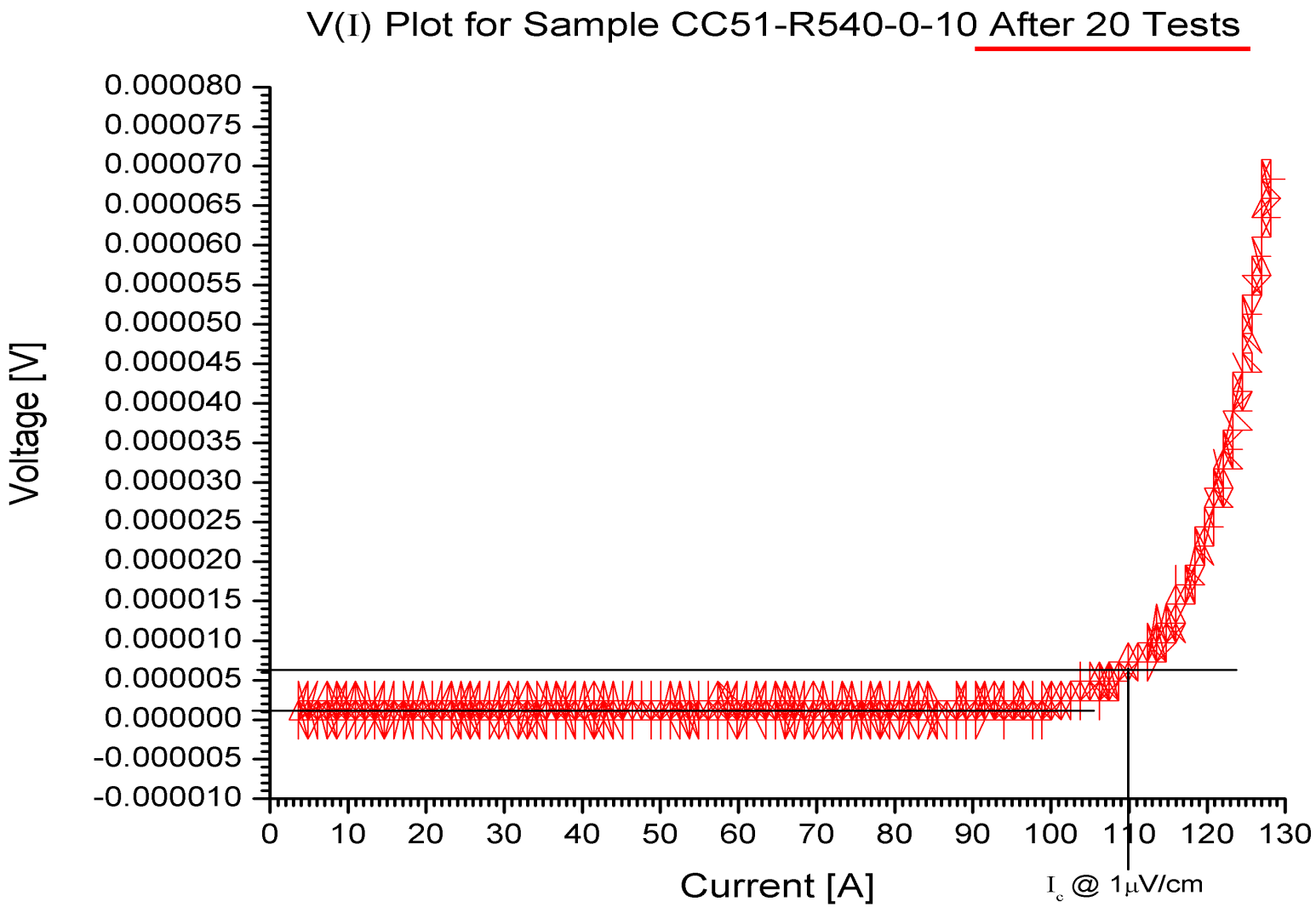


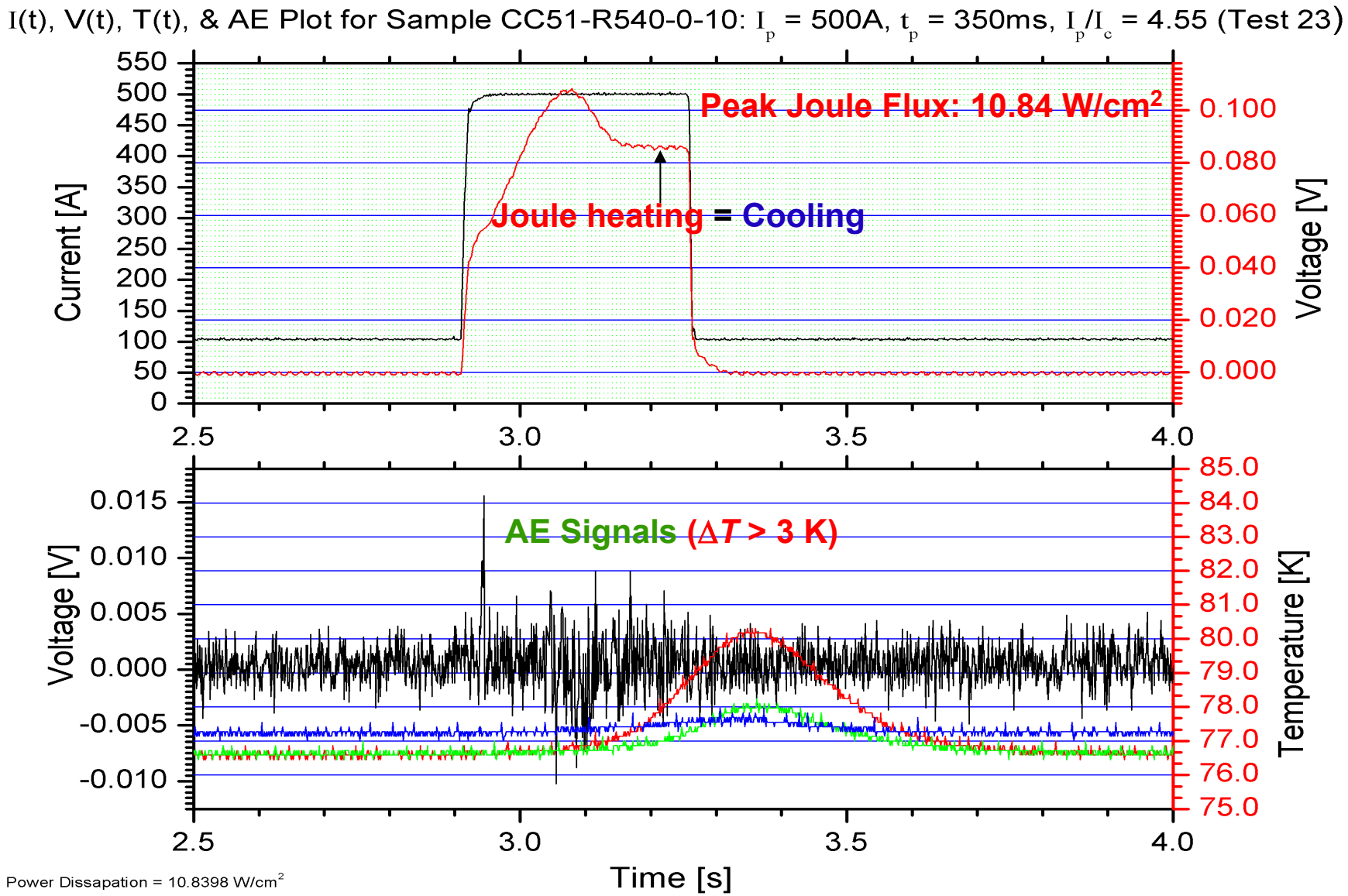

I(t), V(t), T(t), & AE Plot for Sample CC51-R540-0-10: I_p = 350A, t_p = 300ms, I_p/I_c = 3.18 (Test 7)
Peak Joule Flux: 2.52 W/cm²
Joule heating = Cooling
Current [A]
Voltage [V]
Temperature [K]
Time [s]
Power Dissapation = 2.520 W/cm²

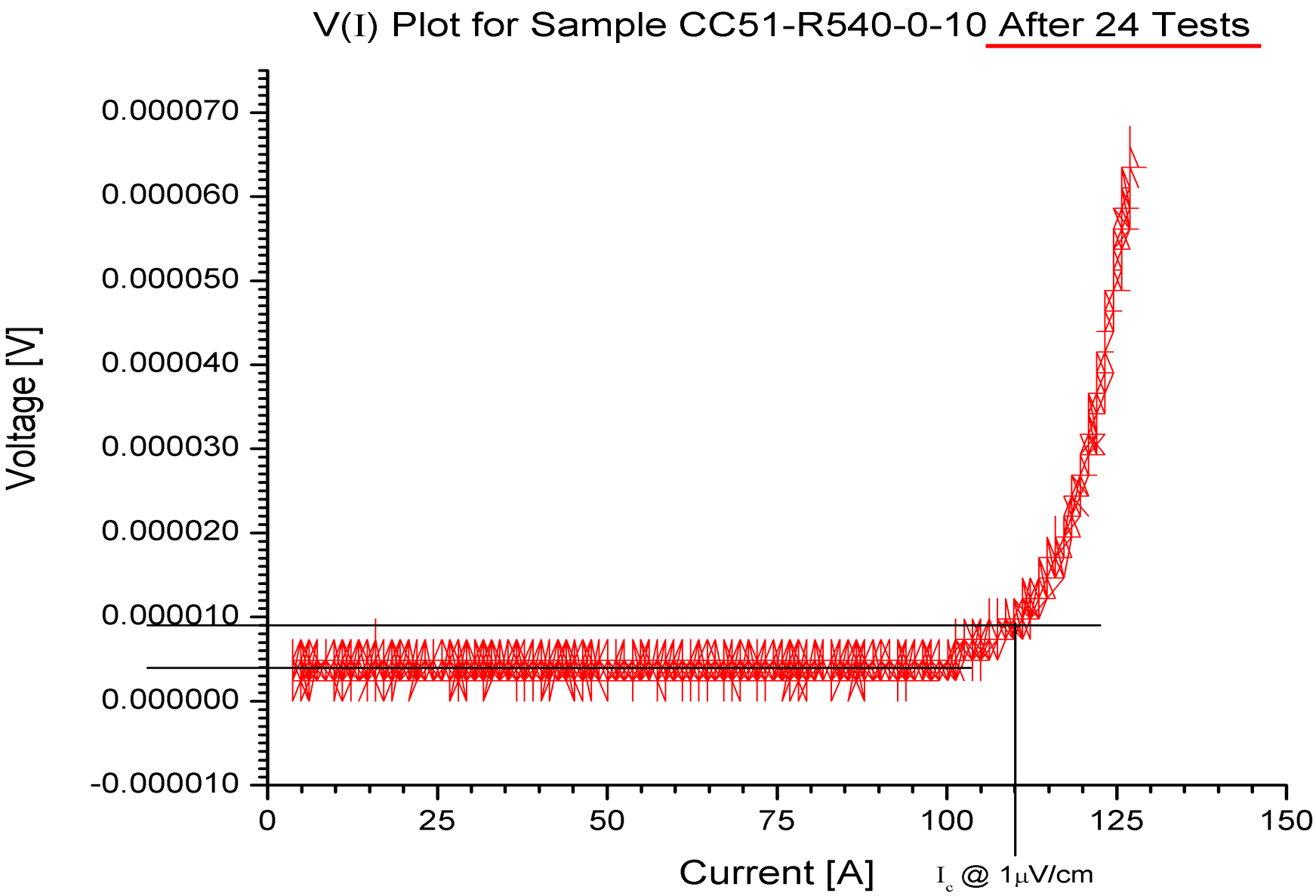

I(t), V(t), T(t), & AE Plot for Sample CC51-R540-0-10: I_p = 446A, t_p = 300ms, I_p/I_c = 4.05 (Test 10)
Peak Joule Flux: 8.3 W/cm²
Current [A]
Voltage [V]
AE signals (ΔT > 3 K)
Poor & delayed signals from thermometers
Temperature [K]
Time [s]
Power Dissapation = 8.2956 W/cm²


V(I) Plot for Sample CC51-R540-0-10 After 10 Tests
Voltage [V]
0.000075
0.000070
0.000065
0.000060
0.000055
0.000050
0.000045
0.000040
0.000035
0.000030
0.000025
0.000020
0.000015
0.000010
0.000005
0.000000
-0.000005
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Current [A]
I_c @ 1μV/cm


I(t), V(t), T(t), & AE Plot for Sample CC51-R540-0-10: I_p = 500A, t_p = 320ms, I_p/I_c = 4.55 (Test 16)
Peak Joule Flux: 10.91 W/cm²
Joule heating = Cooling
Current [A]
Voltage [V]
AE Signals (ΔT > 3 K)
Delayed responses
Temperature [K]
Time [s]
Power Dissapation = 10.913 W/cm²


V(I) Plot for Sample CC51-R540-0-10 After 20 Tests
Voltage [V]
0.000080
0.000075
0.000070
0.000065
0.000060
0.000055
0.000050
0.000045
0.000040
0.000035
0.000030
0.000025
0.000020
0.000015
0.000010
0.000005
0.000000
-0.000005
-0.000010
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Current [A]
I_c @ 1μV/cm

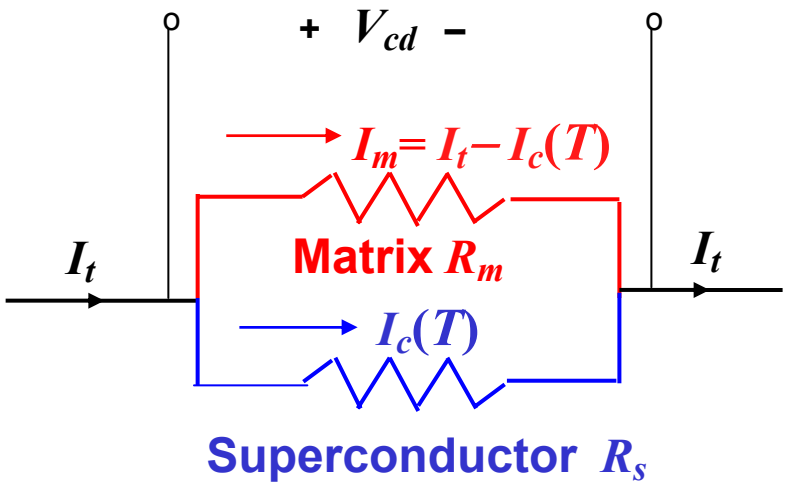

I(t), V(t), T(t), & AE Plot for Sample CC51-R540-0-10: I_p = 500A, t_p = 350ms, I_p/I_c = 4.55 (Test 23)
Peak Joule Flux: 10.84 W/cm²
Joule heating = Cooling
Current [A]
Voltage [V]
AE Signals (ΔT > 3 K)
Temperature [K]
Time [s]
Power Dissapation = 10.8398 W/cm²

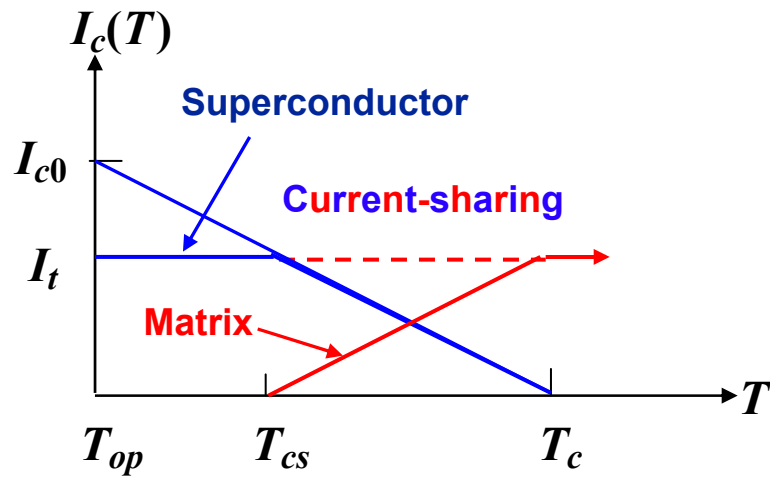

V(I) Plot for Sample CC51-R540-0-10 After 24 Tests
Voltage [V]
0.000070
0.000060
0.000050
0.000040
0.000030
0.000020
0.000010
0.000000
-0.000010
0
25
50
75
100
125
150
Current [A]
I_c @ 1μV/cm

Task 2: Simulation Results (05/01/03-06/30/03)

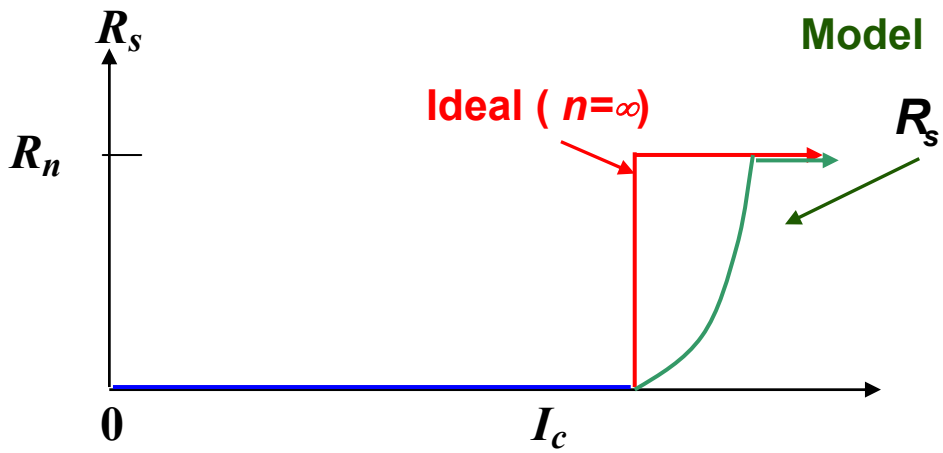
$$C_{cd}(T)\frac{\partial T}{\partial t} = \rho_{cd}(T)J_{cd}^2 - \frac{f_p P_{cd}}{A_{cd}}q(T)$$

- **Circuit model: matrix resistor (R_m) // superconductor resistor (R_s).**
- **Cooling: nucleate boiling.**





perconductor Resistance Model



$$R_s = \frac{\partial V}{\partial I} = n\left(\frac{V_c}{I_c}\right)\left(\frac{I}{I_c}\right)^{n-1}$$

$$= n\frac{V_c}{I_c(T)}\left[\frac{I}{I_c(T)}\right]^{n-1}$$

atrix Resistance Model

$$R_m(T) = \frac{R_{Ag}(T)R_{Cu}(T)}{R_{Ag}(T) + R_{Cu}(T)} \qquad R_{Ag}(T) = \frac{\rho_{Ag}(T)l}{w_{Ag}\delta_{Ag}}; \qquad R_{Cu}(T) = \frac{\rho_{Cu}(T)l}{w_{Cu}\delta_{Cu}}$$

$$R_m(T) = R_o + \alpha(T - 77\text{K})$$

Parameter Values for Cu-Laminated Sample #CC51-R540-0-1

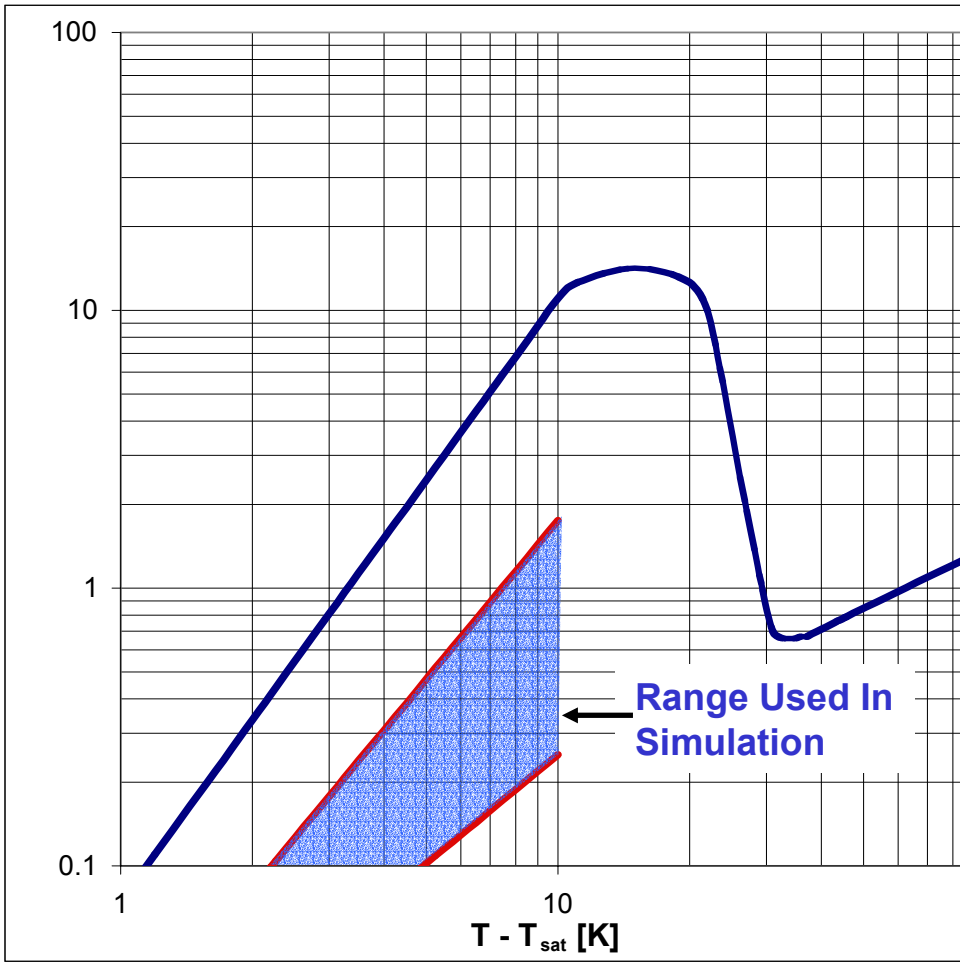
perconductor

V_c=5 μV (voltage taps, : 5 cm)
I_c(77 K, self field)=110 A
n = 18.5.

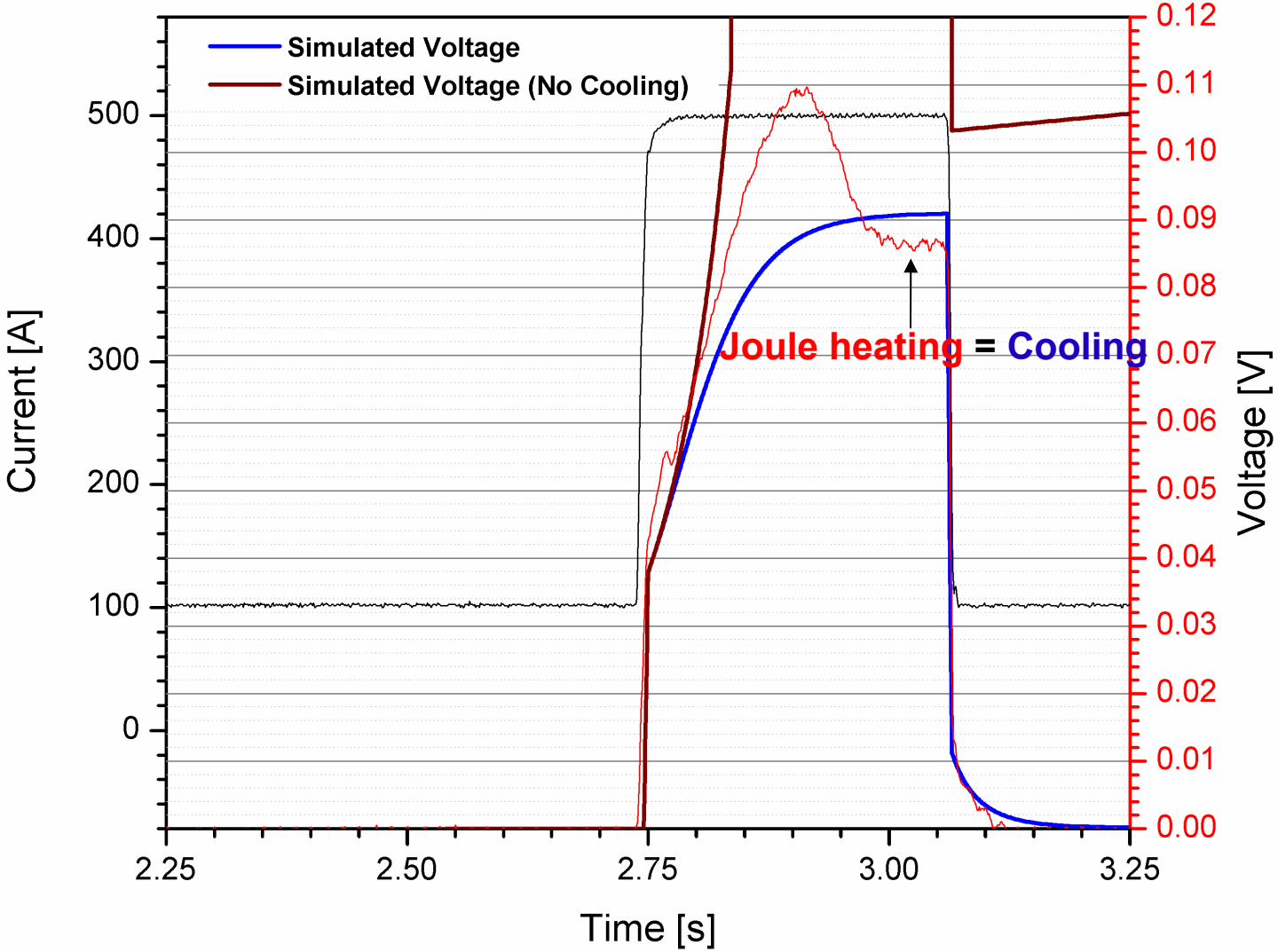
atrix: ($T \geq 77$ K)

$(T) = 0.100 + 0.007 \times (T - 77\ \text{K})\ \text{m}\Omega$

- *Cooling*



I(t) & V(t) Plot for Sample CC51-R540-0-10: I_p = 500A, t_p = 320ms, I_p/I_c = 4.54 (Test 16)



Task 2 Conclusions on Results (01/01/03-06/30/03)

Cu lamination *definitely* enhances conductor stability.

At least with a 76-μm thick lamination, it was not possible to quench th sample with a max. pulse current of 500 A (~5× I_c): heating = cooling.

No degradation of I_c even after repeated over-current pulsing.

Lamination optimal thickness likely to depend on over-current amplitu and duration—to be investigated.

"No cooling" *simulation* shows 76-μm thick lamination insufficient aga a 500-A over-current pulse.

Simulation: "apparent" nucleate boiling cooling fluxes, based at least o one laminated test sample, *below* an "accepted" cooling curve.

Thermal resistance (sample surface/temperature sensors) too high.

Task 3 Conclusions on Results (08/15/02-06/30/03)

- **I_c transition does *not* generate AE signals.**
- **Localized heating ($\Delta T \geq 4$ K) detectable with AE signals even with a test coil immersed in LN_2.**
- **Low AE signal detectability.**
- **AE signals observed—so far "small" because ΔT small; large ΔT expected in non-recovery and thus AE signals.**

Plans (08/30/03-05/31/04)

Task 1: Experiment with 1—3 turn YBCO coils with or w/o solid N_2.

Task 2

- **Use 4-mm wide, 15-cm long samples to force quenching with a 500 A**
- ***Insulate* the cooling surface.**
- ***Improve* thermal resistance between sample surface & sensors.**
- **Continue with simulation work.**
- **Simulate selected FSU/NHMFL results.**

Task 3: Install AE sensors in Tasks 1 & 2 experiments.

- **Improve signal detectability.**

U.S.Department of Energy Energy Efficiency and Renewable Energy
SUPERCONDUCTIVITY PROGRAM FOR ELECTRIC POWER SYSTEMS
2003 Annual Peer Review

MIT-FSU/NHMFL Joint Project

Stability and Quench Protection of YBCO Wires and Coils

FSU Activities

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FSU National High Magnetic Field Laboratory
Tallahassee, FL 32310

Personnel: F. Trillaud[1], H. Weijers[2], U. Trociewitz[2], A. Caruso[3], J. Barrow[3]
[1]visiting graduate student from Saclay
[2]not supported by this contract
[3]undergraduate research assistants (Dept. Mechanical Engr)

July 25, 2002
L'Enfant Plaza Hotel, Washington, DC

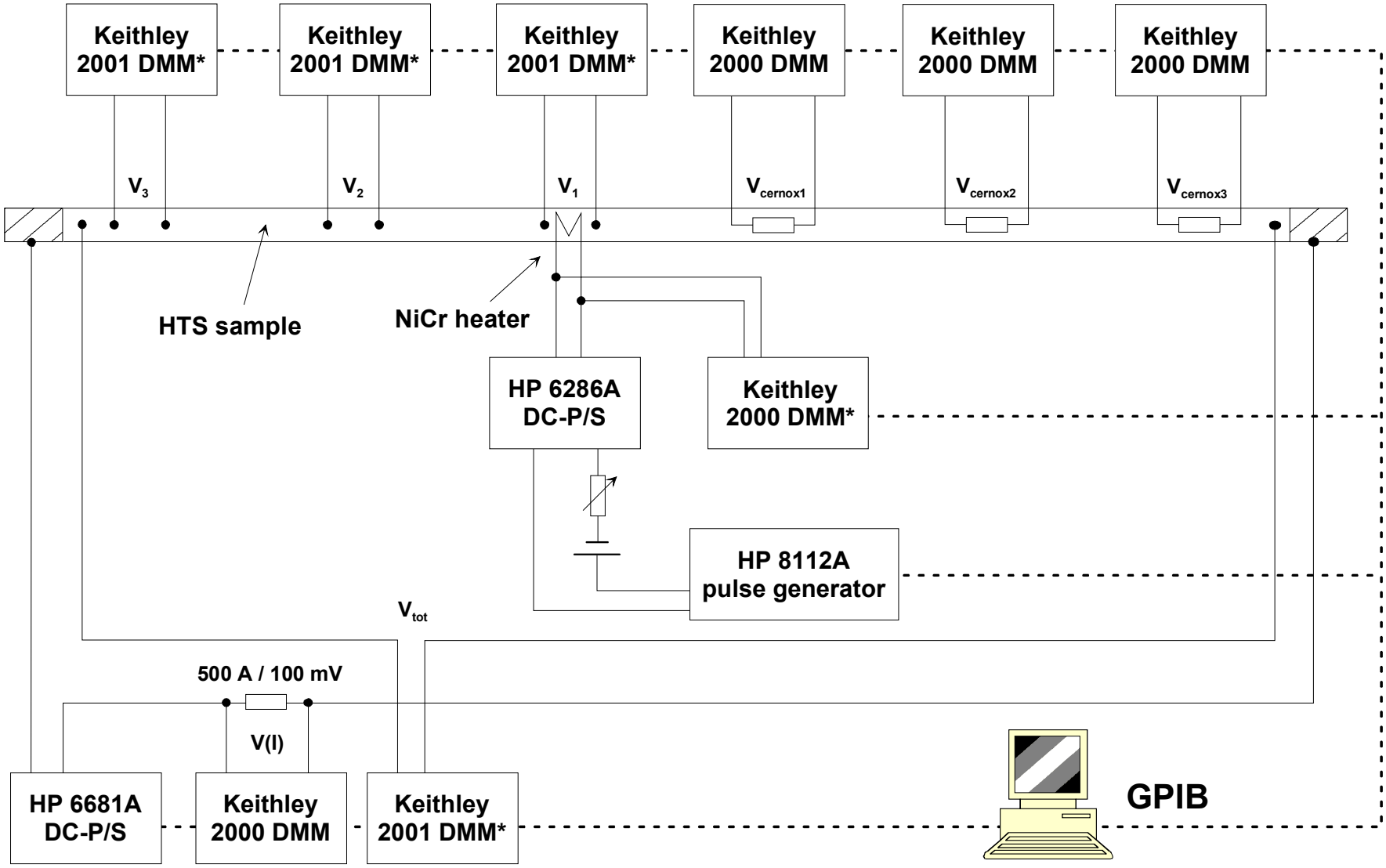
Outline for today's presentation

- Brief review of last year's results
- FY03 plans
- FY03 results
- Plans for remainder of FY03 and FY04
- Research integration

Quench Nucleation & Propagation Experimental Details

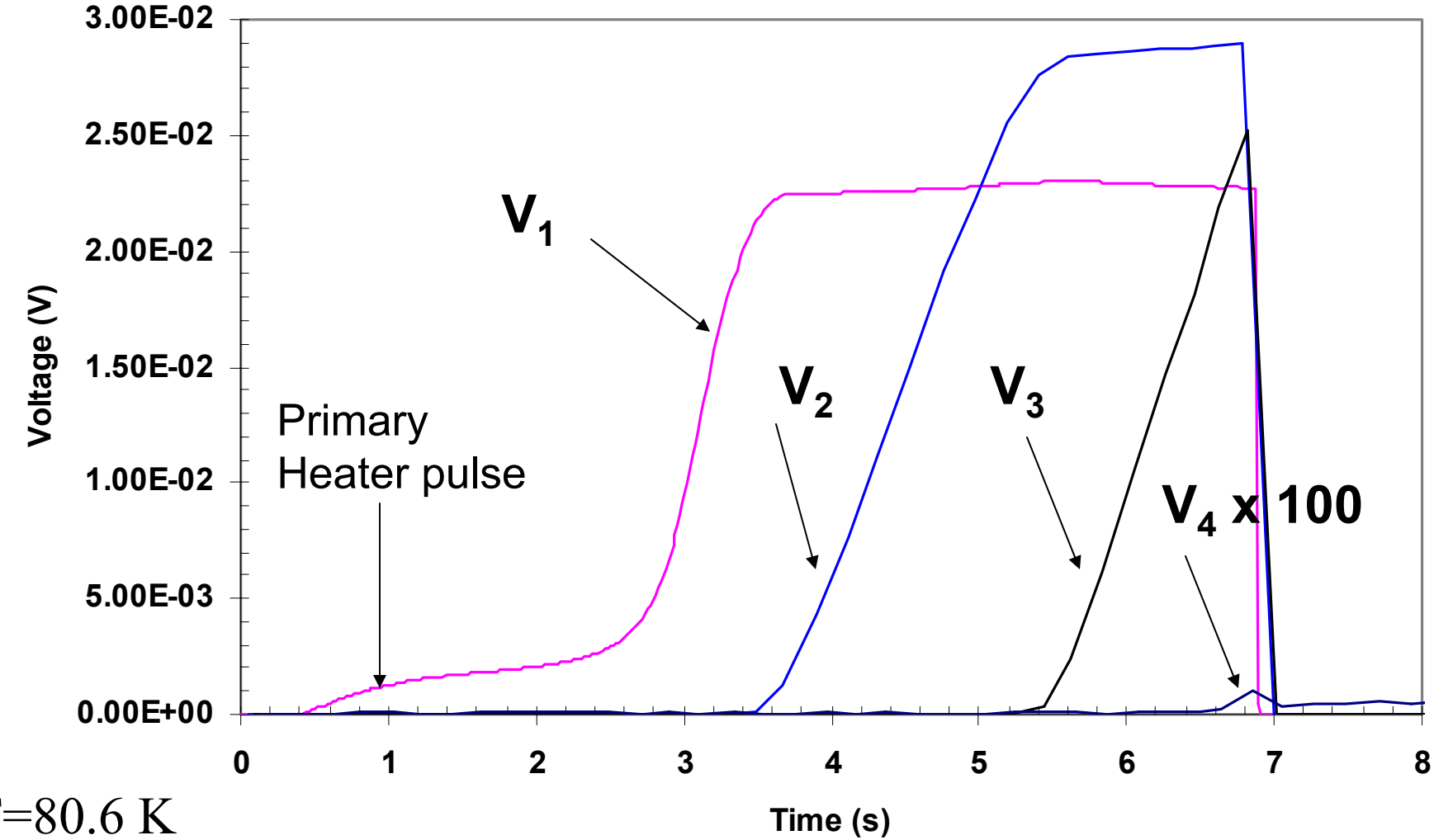
- **Experimental procedures**
  - Sample mounted and instrumented with multiple voltage taps, Cernox temperature sensors
  - ***Localized*** heat pulse supplied by NiCr wire driven by a power supply and pulse generator
  - Heat pulse amplitude or duration increased until quench occurs (vs. I/I_c)
- **Last year:**
  - AMSC YBCO, 50 A@77 K (circa Fall 01)
  - Sample cooled by N_2 gas convection (~81-83 K)
- **This year:**
  - AMSC YBCO, ~140 A@77 K (circa Aug 02)
  - Sample cooled by cryocooler

Wiring Schematic Quench Experiments (07/02)



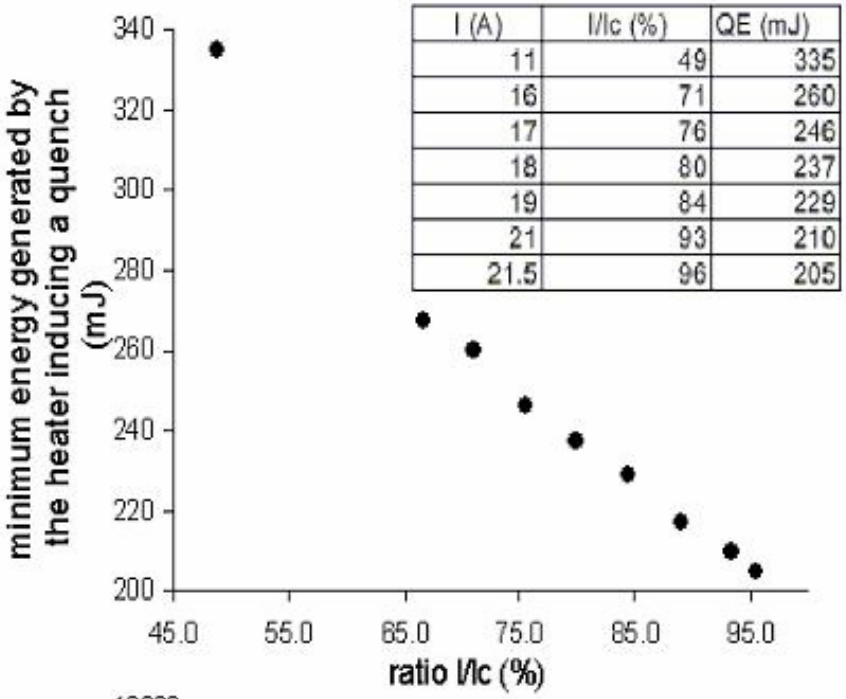
*set on buffer read for increased speed/resolution

Voltage-time-location during quench at 19 A (07/02)

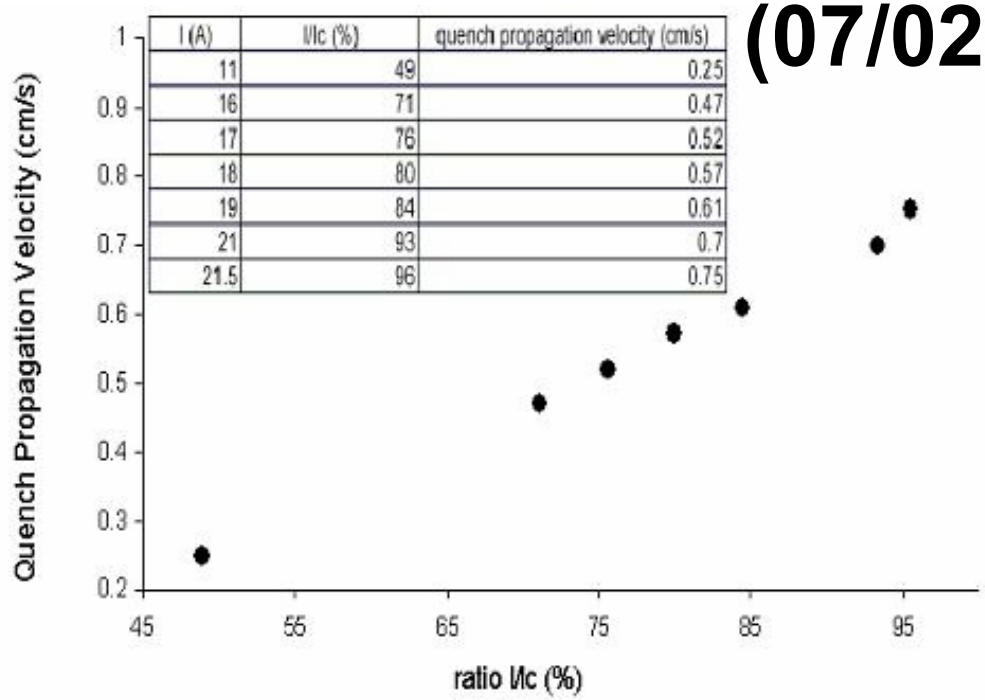


T=80.6 K

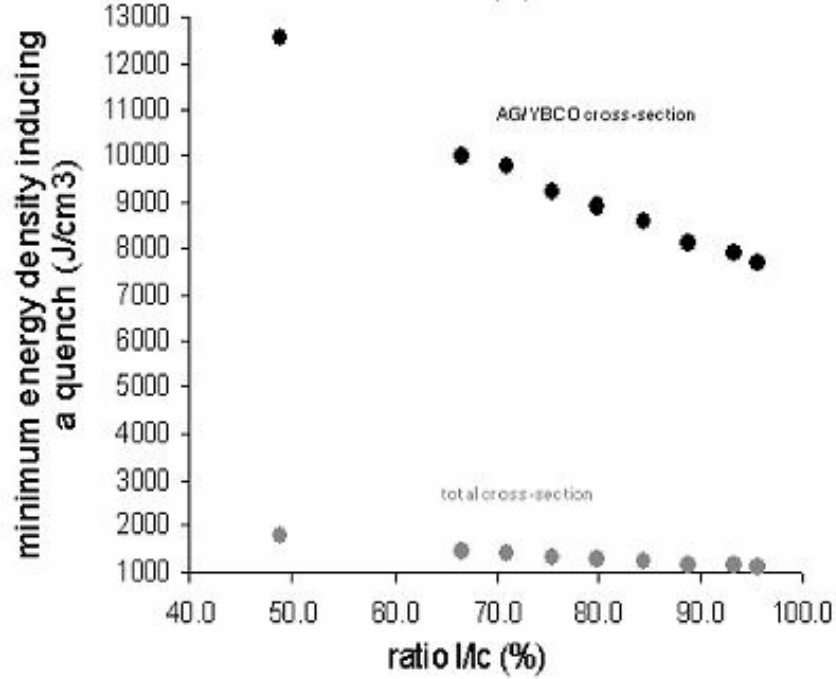
(07/02)

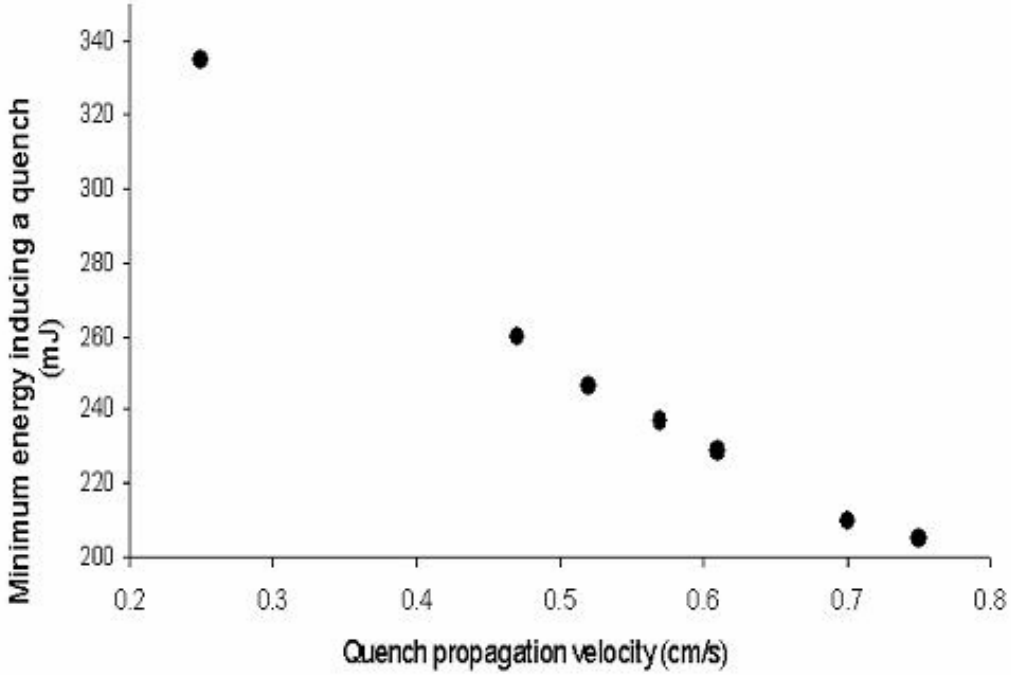


I (A)	I/Ic (%)	QE (mJ)
11	49	335
16	71	260
17	76	246
18	80	237
19	84	229
21	93	210
21.5	96	205



I (A)	I/Ic (%)	quench propagation velocity (cm/s)
11	49	0.25
16	71	0.47
17	76	0.52
18	80	0.57
19	84	0.61
21	93	0.7
21.5	96	0.75





FY03 Plans

- ※ I_c– B – T characterization, including high field data
- ※ Sample homogeneity measurements
  (for propagation velocity studies)
- ※ Modifications to experimental approach
  - ※ cryocooled environment for lower temperature
  - ※ higher I_c sample
    →Significantly higher currents (~15-25X)
  - ※ additional voltage monitoring
- ※ MQE and QPV experiments

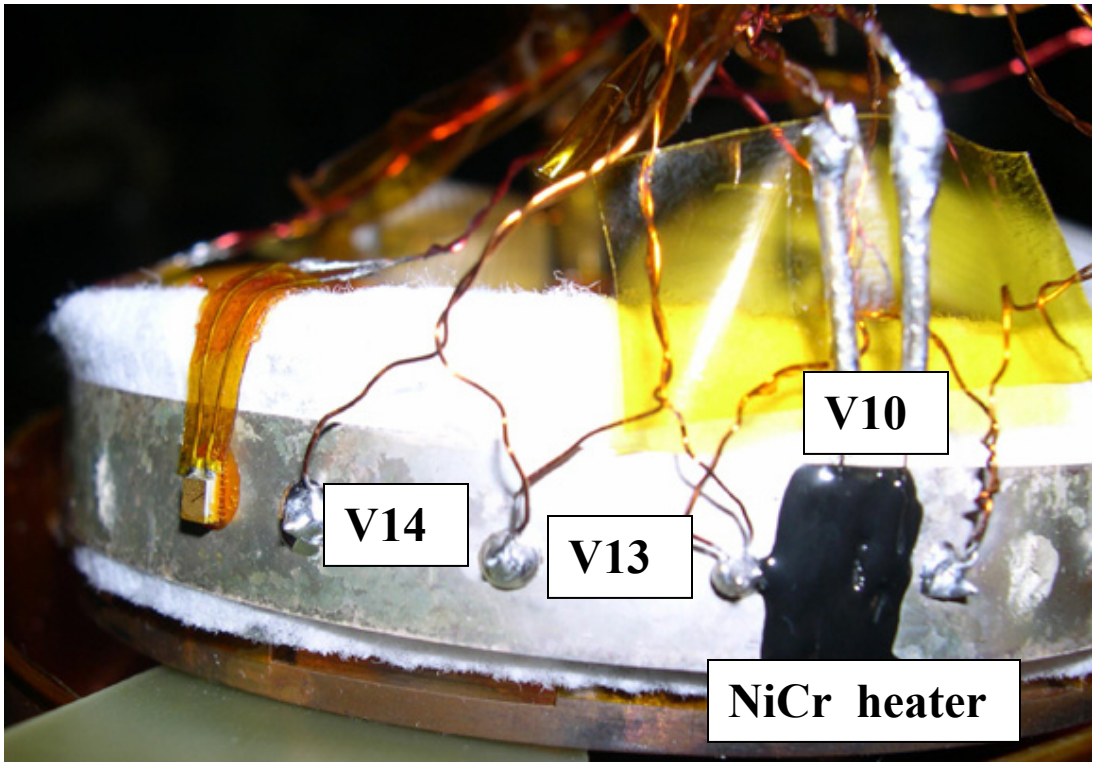
FY03 Progress & Results

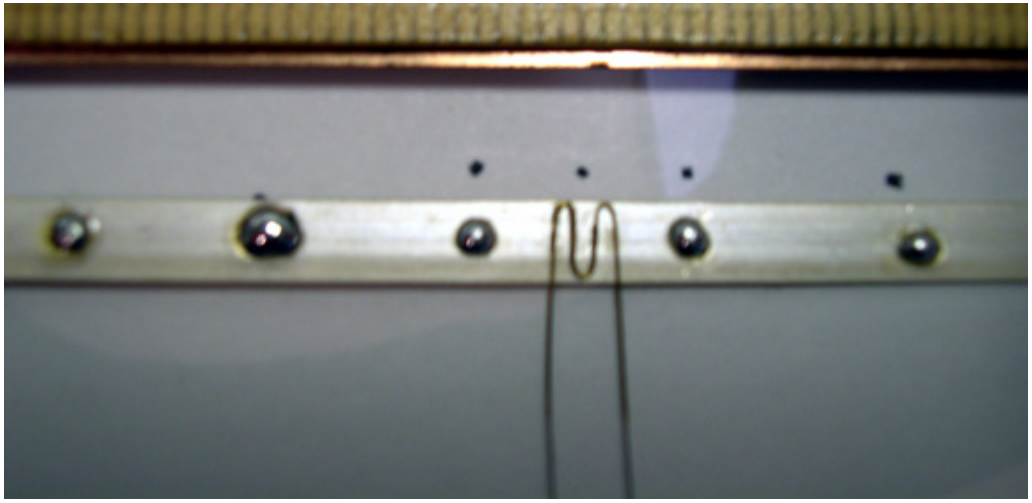
Aug 02 – May 03

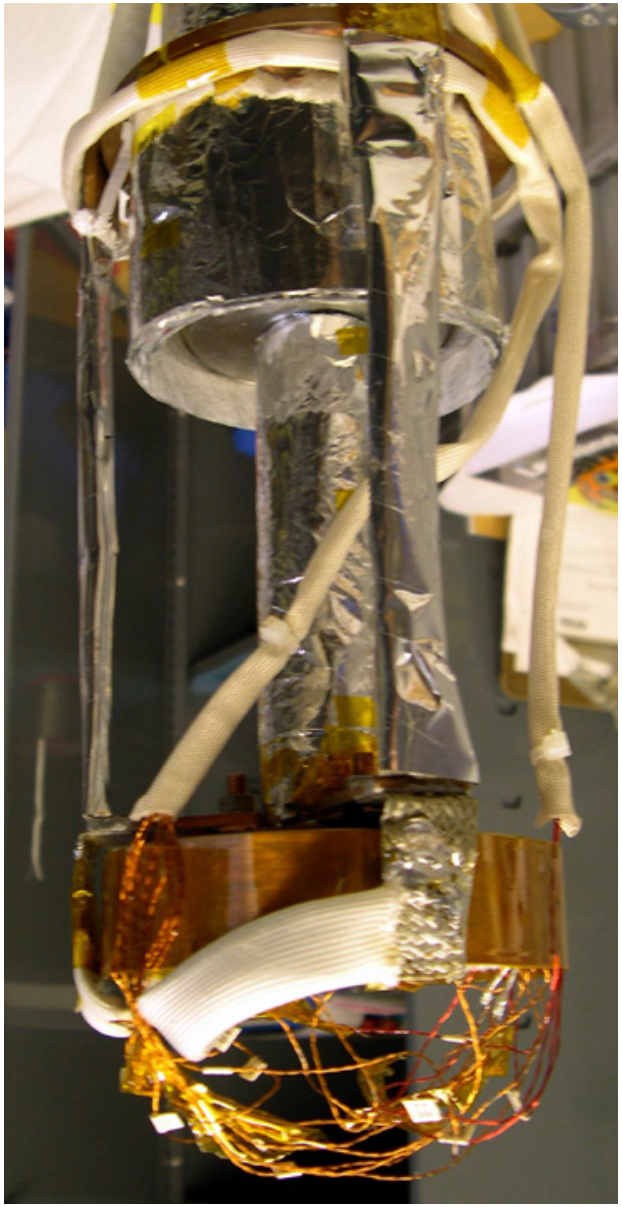
- Completed runs at ~81K in N_2 gas and analysis of results
- Presented results at ASC ’02, CHATS, publ. in *Cryogenics*
- Installed facilities for cryocooler from MIT
- Designed, procured & tested cryostat for cryocooled operation
- Designed & constructed sample holder for cryocooled operation
- I_c-B measurements at high field
- Modified LabView software for new hardware and anticipated
- N.B. Proposal for FY03 funds requested & submitted in Mar03

May 03 – Jul 03

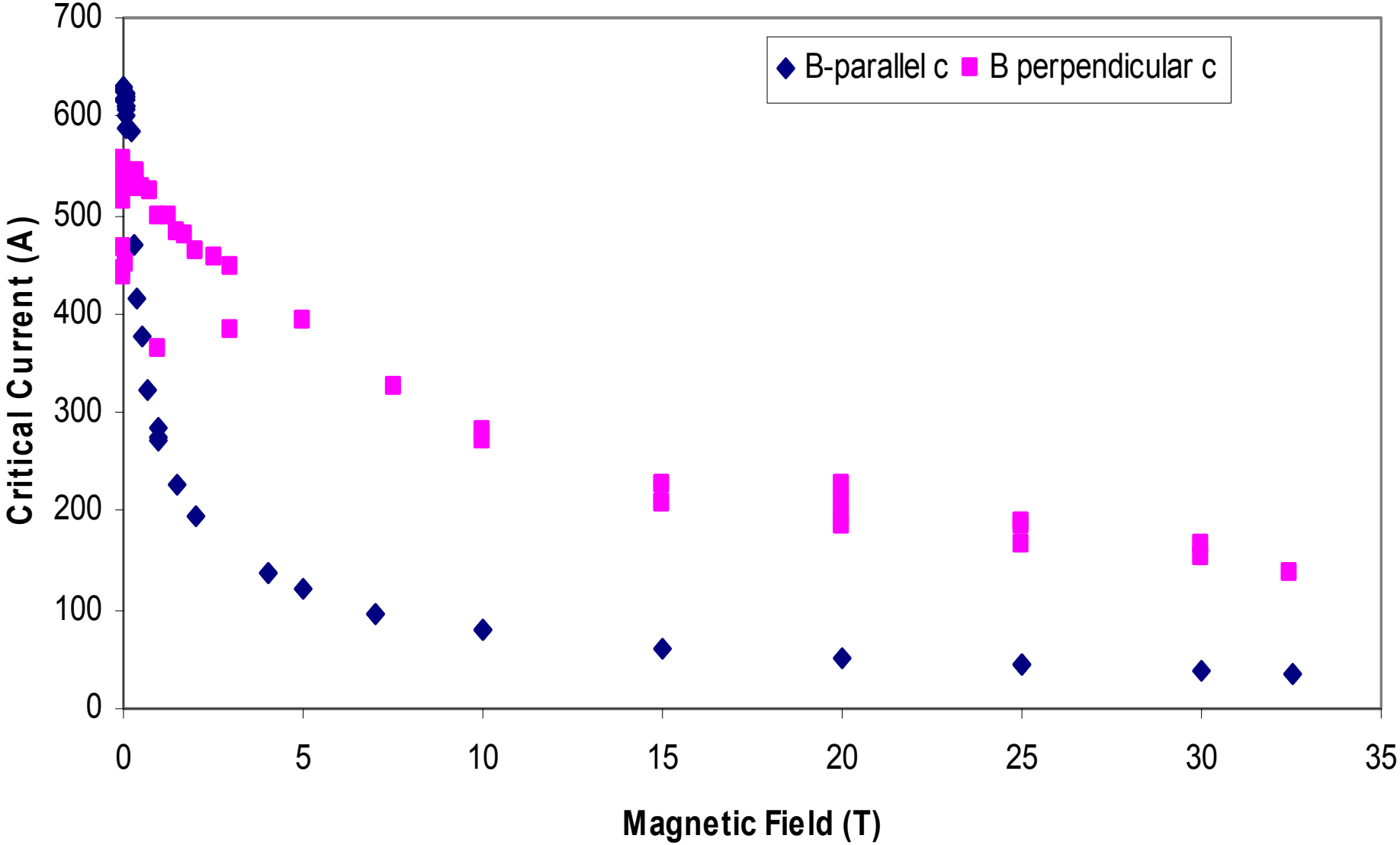
- New funding received (~35k$ of FY03$ spent)
- Additional hardware acquired
- System integration and testing
- First runs on YBCO CC sample


V10
V14
V13
NiCr heater

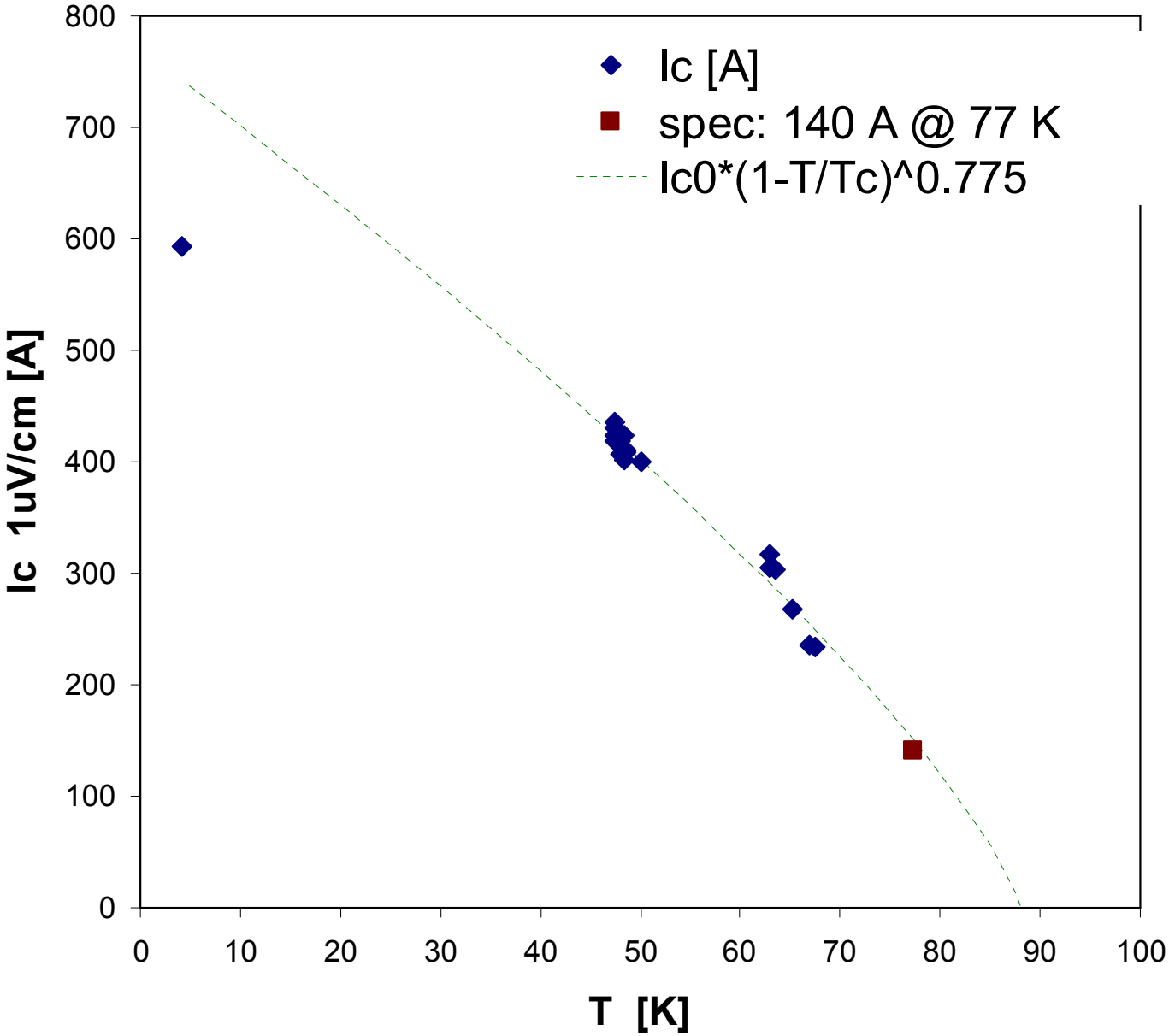




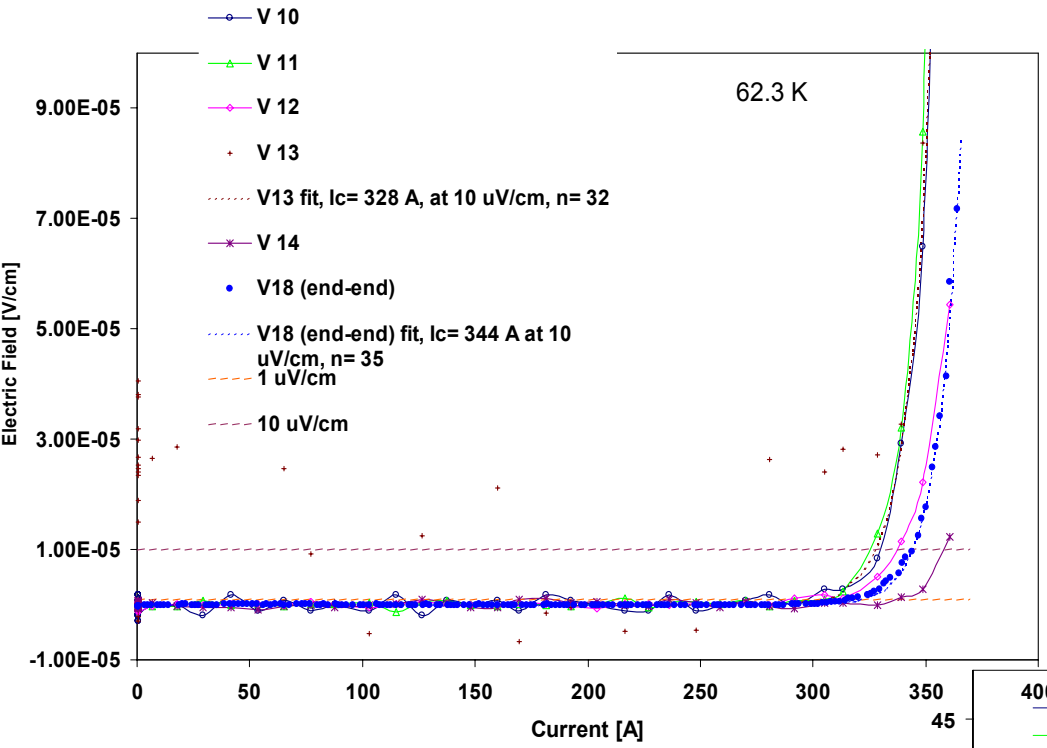
Short sample I_c(4.2 K, B) up to 33 T

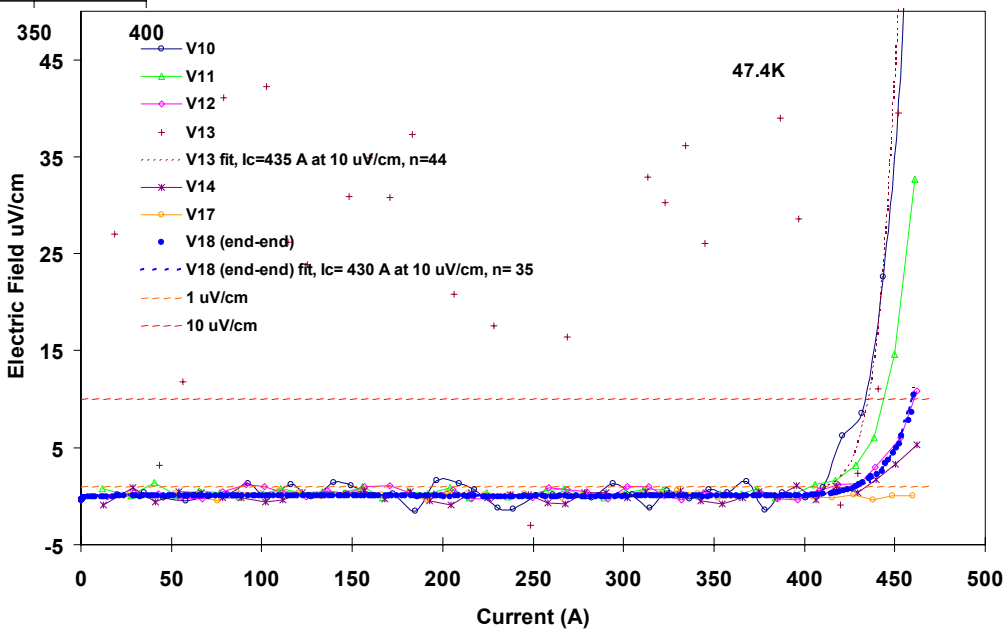


Short sample $I_c(T, s.f.)$

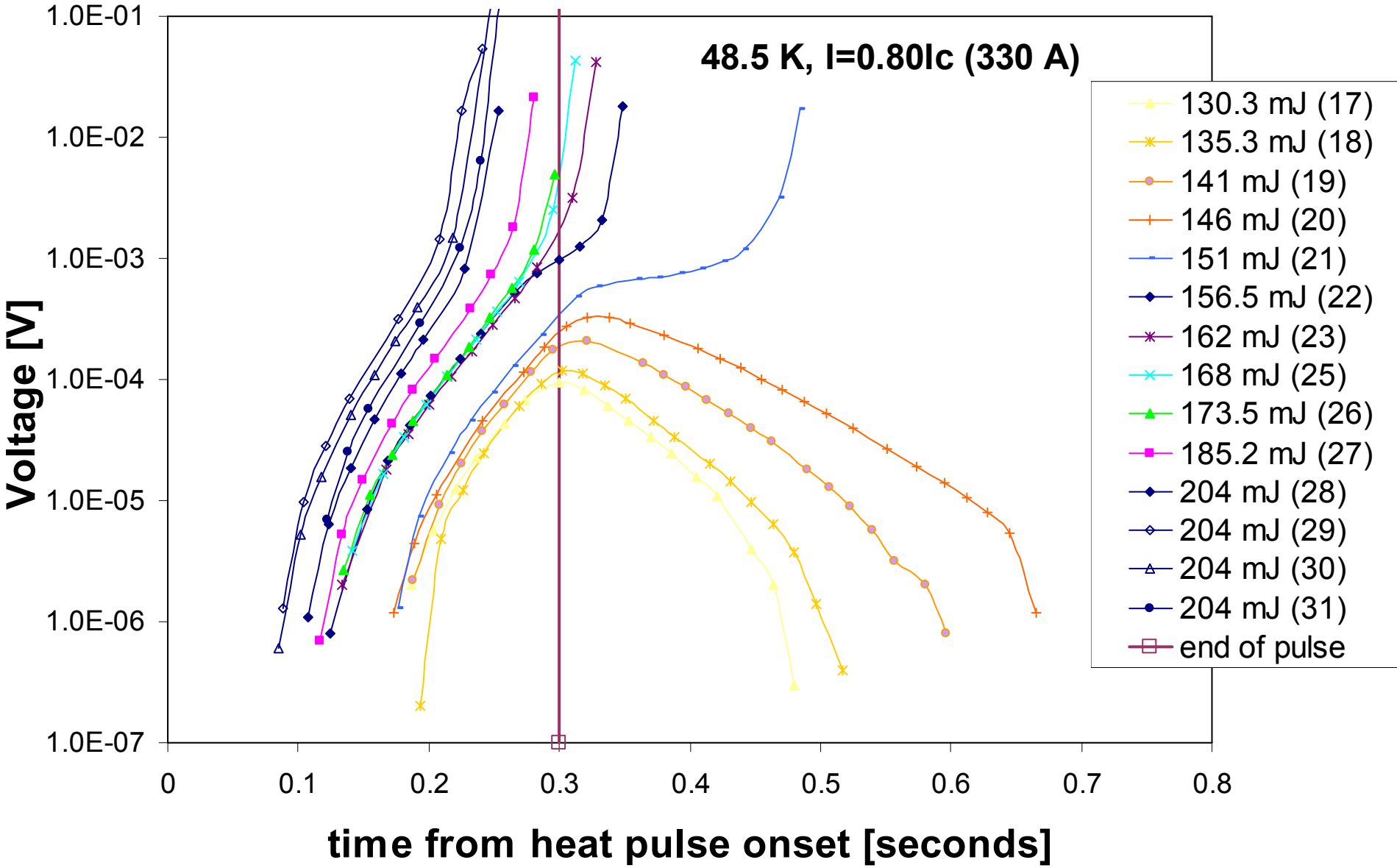


Short sample I_c homogeneity

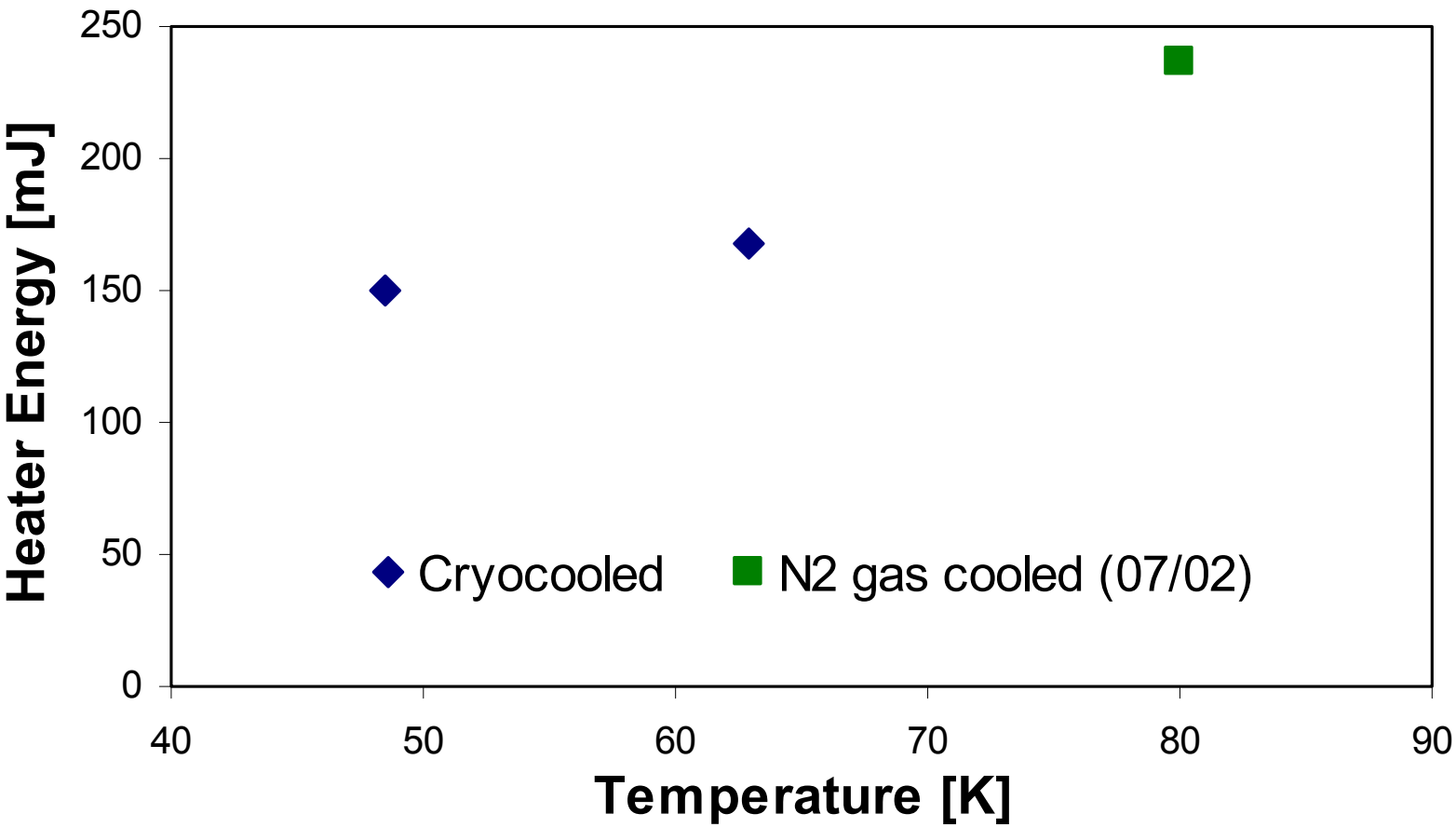




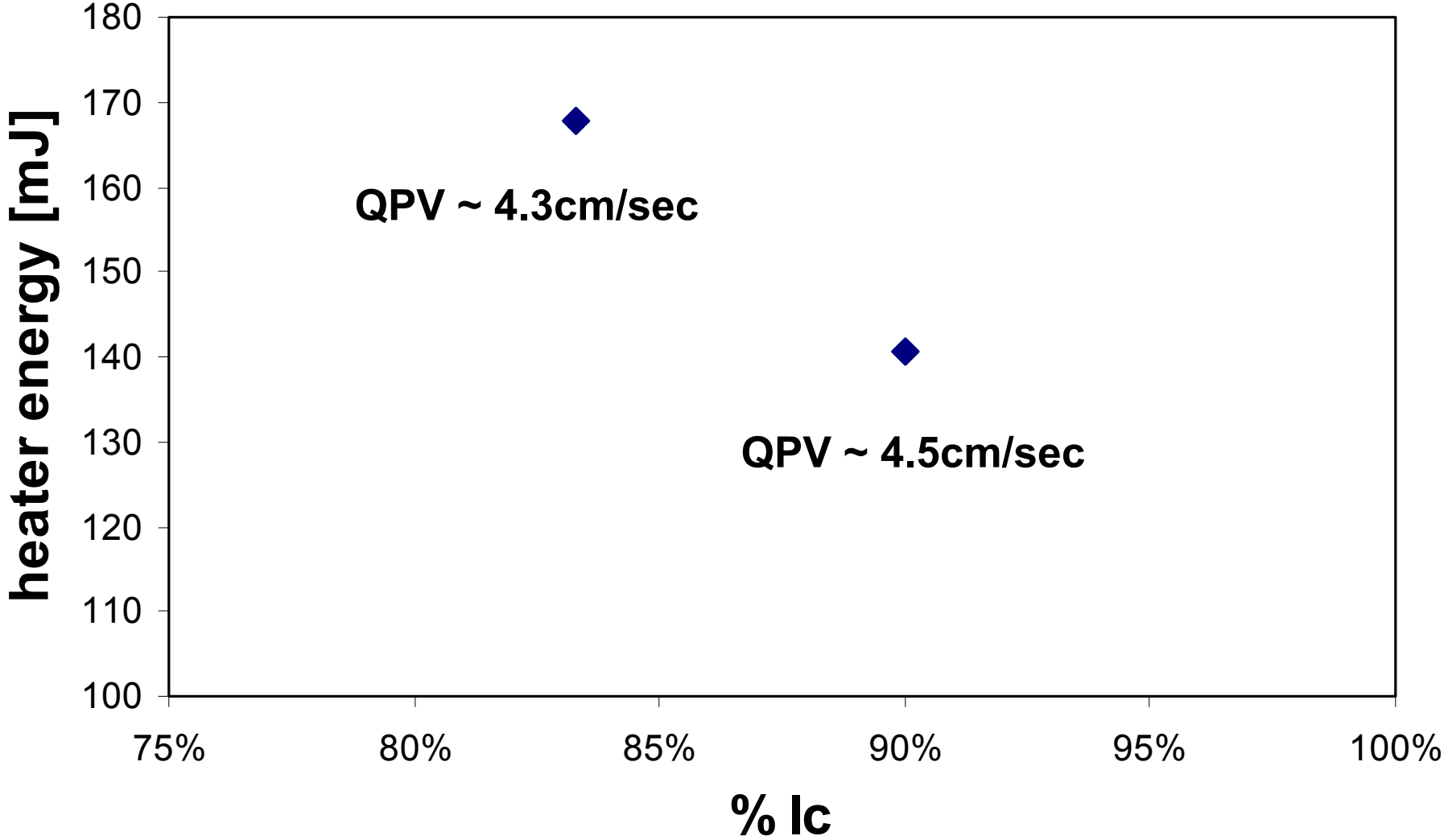
V – time – heat input



Minimum Quench Energy @ 80%I_c(T)



Minimum Quench Energy v. I/I_c @ ~65 K



N.B.: QPV~order of magnitude higher than 81K, N_2 gas cooled

New found experimental issues to address

- Measuring propagation more difficult than last year
  - reduced temperature & improved sample quality →increased I_c significantly

  Increased I →increased V during quench →power supply trips before quench propagates sufficiently to determine QPV
- Temperature gradient (steady-state) ~ 4 K along sample
- Temperature gradient after pulsing – leads to heater coming off of sample (but did NOT damage the sample)

Plans for remainder of FY03 and FY04

- Complete on-going measurements
- Temperature variation via heater on sample block
- I_c variation using magnetic field
- I_c variation using slit samples
- I_c variation using “latest and greatest” samples
- Monitor voltage on Ni-side to assess current sharing
- Identify maximum hot-spot temperature via energy to degrade sample (and causal mechanisms)
- Expand variety & geometry of sample types (manufacturer, buffer layer architecture, AMSC’s NA, ...)
- Expanded heater length
- Additional experiments responsive to community needs

Research Integration

Publications & Presentations

- F. Trillaud, H. Palanki, U.P. Trociewitz, S.H. Thompson, H. W. Weijers, J. Schwartz, "Normal Zone Propagation Experiments on High Temperature Superconductor Composite Conductors," *Cryogenics* 43(3-5) 271-279 (2003)
- "*Stability and Quench Propagation of HTS Conductors*," 2002 CHATS Workshop, Karlsruhe, Germany (Sept. 2002)
- *"Normal Zone Creation and Propagation in YBCO Coated Conductors*," U.S. DoE Coated Conductor Workshop, St. Petersburg, FL (January 2003)
- "*10 Things I Hate About Coated Conductors*," MURI Coated Conductor Workshop, Madison, WI (June 2003)
- Abstracts submitted to 2003 EUCAS, CEC/ICMC, and MT

Graduate Student Theses

- Ms. H. Palanki, M.S. Mechanical Engineering, completed December 2002, "Critical Current Variability and Thermal Quench Studies on High Temperature Superconducting Tapes" Currently w/ Florida Power & Light
- Frederic Trillaud, Ph.D., Saclay, in progress