Development of Ultra Efficient HTS Electric Motor Systems

Agenda
Help
Summary

2006 Annual Superconductivity Peer Review Meeting

Washington, DC
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Rockwell Automation Superconducting Motor Development

- First investigation started in 1987 with EPRI funded project.
- World's first demonstrations of HTS motors from 1990 through 2005

Largest Motor

1600 horsepower, 1800 rpm Motor Demonstrated in 2001

Largest 2nd Gen HTS Coil Motor

7.5 horsepower, 1800 rpm Motor Demonstrated in 2005

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Superconducting Motor Development

- Technology Drivers
  - Compared to conventional high efficiency induction motors, HTS motors will be . . .
    - more efficient (half the losses)
    - lower in life cycle costs
      - $50,000 per year savings for 5000 hp motor due to efficiency improvement
    - smaller <u>and</u> lighter (half the volume)
- Projected Applications
  - Large motors: greater than 1000 hp
    - Pumps, fans, compressors

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Benefits of HTS Motors

- About 1/3 of US electrical energy is utilized by electric motors rated at 1000 hp and above.

- Energy savings potential of HTS Motors in US alone is $1 Billion per year

Rockwell Automation SPI Program: "Research Topics for the Development of Ultra Efficient HTS Electric Motors"

Program includes eight critical technology research tasks in two key areas:

- **Total cost of ownership reduction (first cost reduction and efficiency improvements)**
  - Alternate HTS motor topologies
  - Eddy current heating in air-core rotating machinery
  - Alternate HTS wire application issues
    - Second generation HTS conductor application
  - Variable Speed Drive integration/shielding for HTS motors
  - Cryogenic persistent current switch for HTS field winding
- **Reliability improvement**
  - On-board refrigeration systems
  - Composite torque tube technology advancement
  - Coil quench detection and protection

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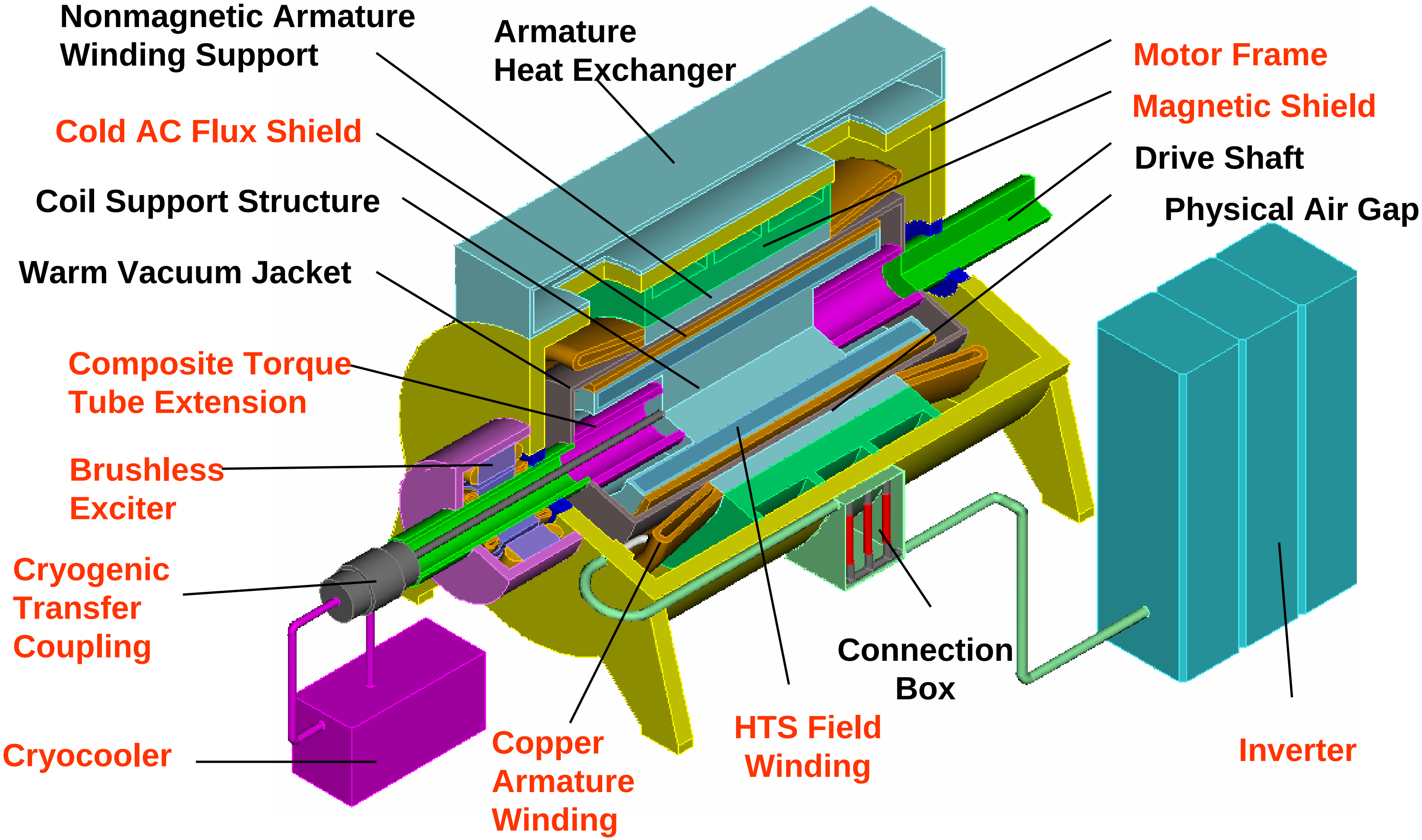
Superconducting Synchronous Motor with HTS Field Winding



Rockwell SPI Phase 3 tasks address these components

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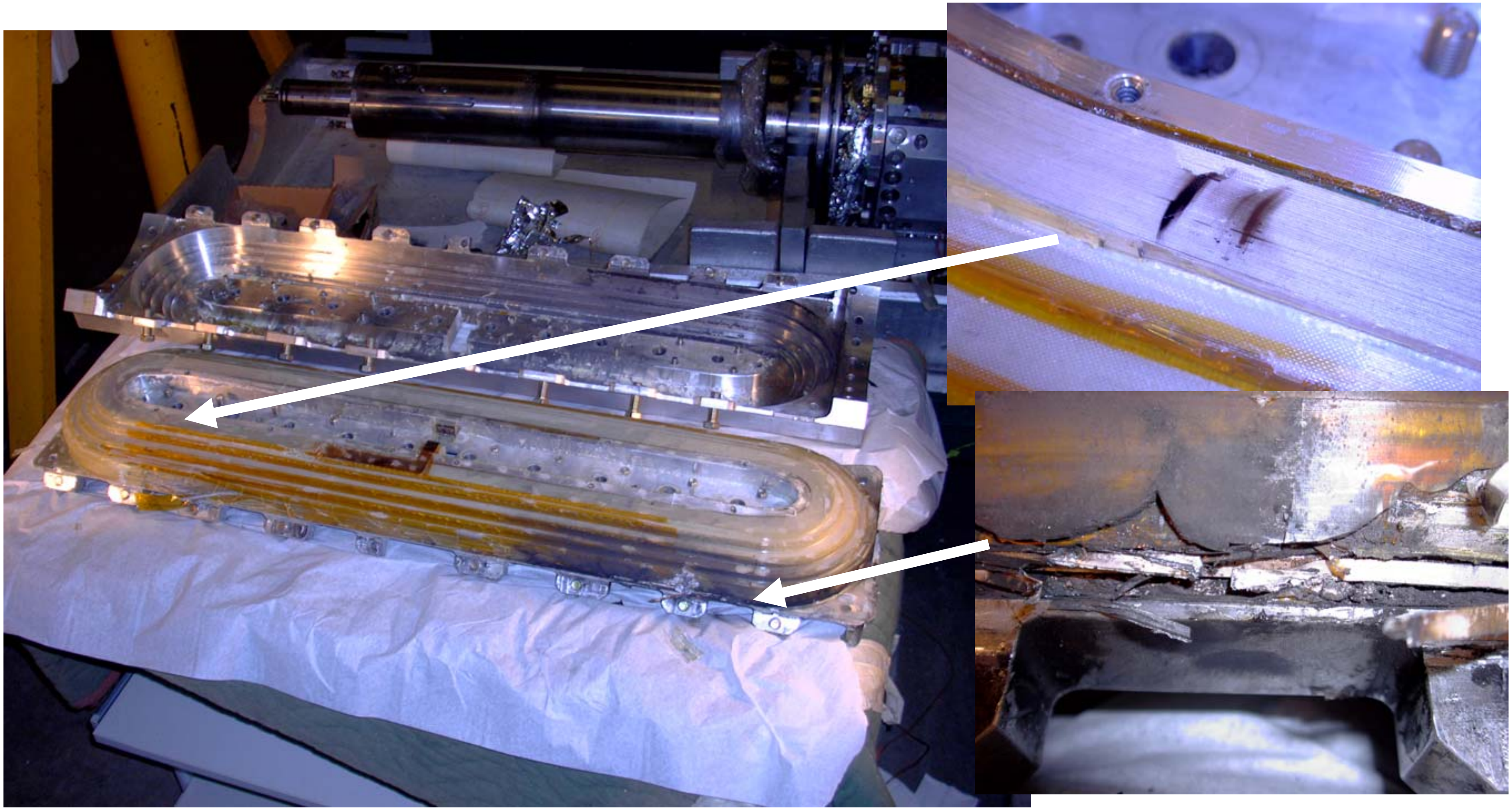
Rockwell Automation SPI Program: "Research Topics for the Development of Ultra Efficient HTS Electric Motors"

- Progress has been made on all 8 tasks
- Quench task results will be reported on, in detail, here
- Summary progress sheets are included at the end of this presentation in the reviewer's handouts

Task 6: Coil Quench Detection and Protection

- Issue
  - HTS coil quench during 1000 hp motor test resulted in coil failure
  - Reliable quench detection and protection methods must be developed for industrial HTS motors.
- FY06 Planned Accomplishments
  - Verify quench models at lower temperature and issue report
  - Demonstrate quench detection / prevention system during testing at ORNL
- FY06 Accomplishments / Progress
  - Quench testing completed on 1G HTS motor coils at ORNL at 30K
  - Quench phenomenon was found to be similar to 77K test results from FY05 and matched models
  - Quench detection and prevention system defined and verified
  - Four technical papers will be published or presented on tests and models
- FY07 Planned Accomplishments
  - Task completed in FY06
  - 2G characterization studies will continue under "Alternate HTS Wire Technology task".

1000 hp motor HTS coil failure



HTS Coil Quench: Definitions

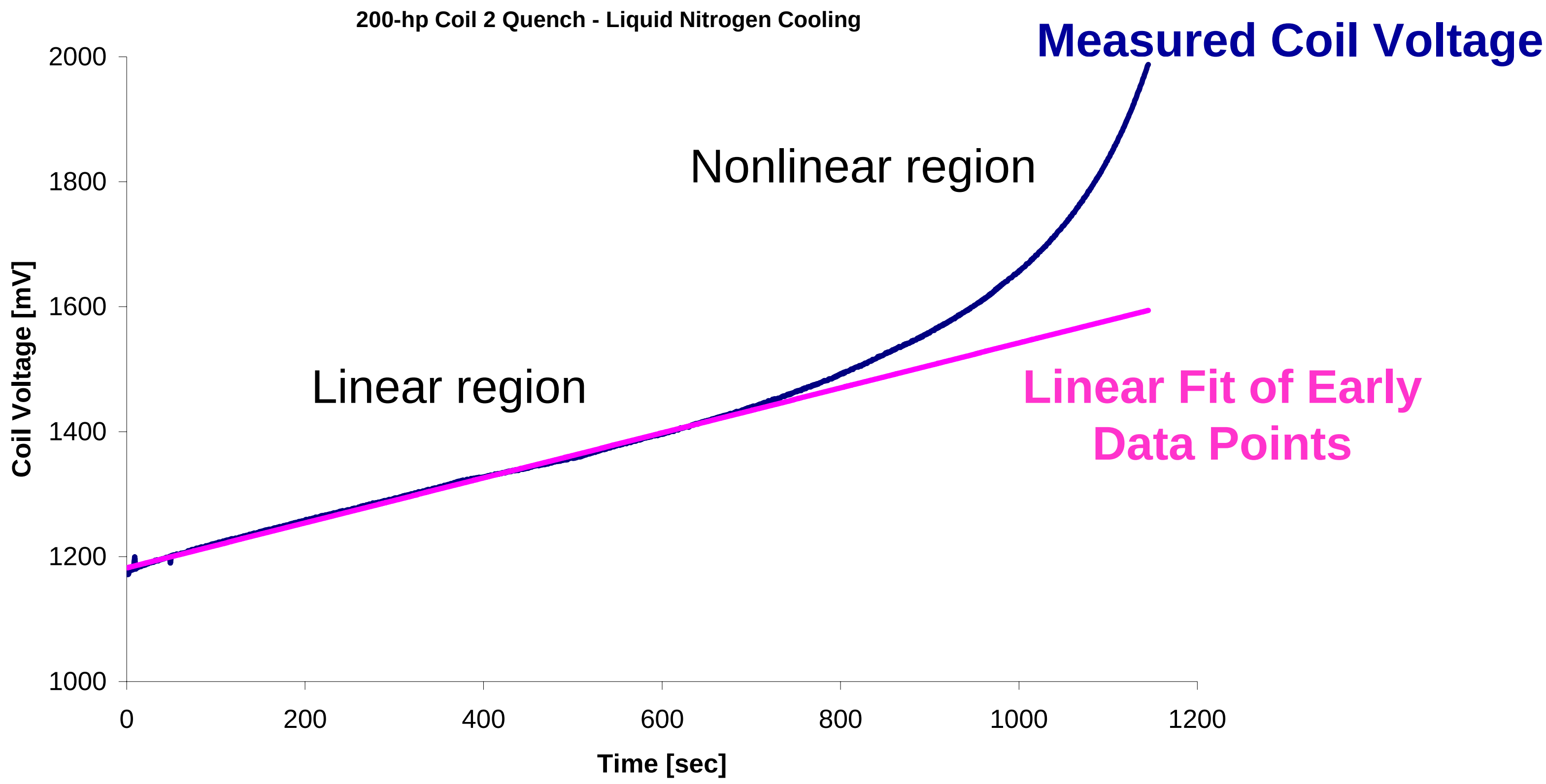
- **Quench:** A condition under which coil voltage/temperature are observed to be unstable (e.g. they increase without bound in spite of constant coil current). This occurs because the coil cooling system is unable to keep pace with the increase in coil heating which occurs as the coil temperature increases.

HTS Coil Quench Observations from 77K Tests in FY05

- Typically quench in superconducting coils is thought of as the propagation of a normal zone –
  - Especially for low temperature superconductors that are perfect conductors
  - This is considered a **true quench** and has been studied extensively for HTS wire in the literature

- In HTS coils the true quench is preceded by a phenomenon that we call “pre-quench instability” which has two steps
  1. Slow increase in coil voltage and temperature that is almost linear vs time. This may last for hours.
  2. Nonlinear rise in temperature and voltage. This may last 10’s of seconds.
- The “pre-quench instability” is, by far, more important for quench detection and protection than the true quench.
  - Quench detection must occur here

Typical test results: constant applied current



Note: Entire test time shown is during pre-quench instability

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Quench Detection and Protection

- 30 K Testing Goals
  - Match cooling conditions of HTS coils in motors
    - Conduction cooled at 30 K
  - Verify expected voltage versus time response of HTS coil before and during quench event
    - Does it match what we saw with 77 K testing?
    - Does it match model results?
  - Characterize current induced quench and temperature induced quench (loss of cooling)
  - Complete testing on 200 hp and 1000 hp motor coils

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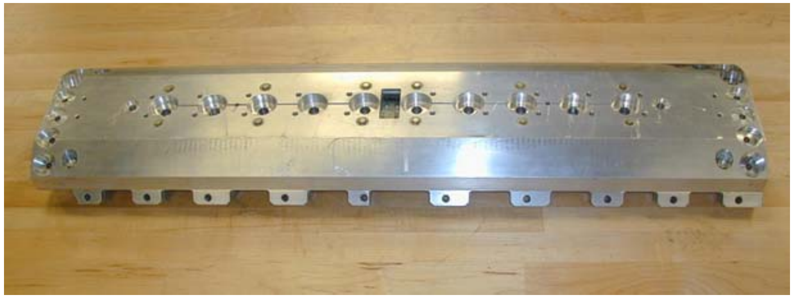
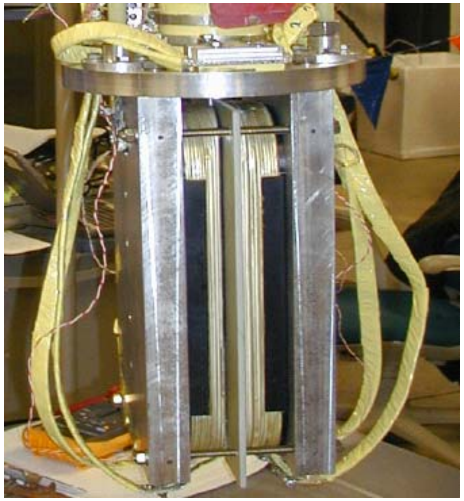
HTS Test Coils and Coil Test Fixtures

200 hp motor coil



1000 hp motor coil



2 coils – mounted back-to-back

Coils Mounted in Test Fixtures for 30 K Testing

Single coil tested at a time

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ORNL CRADA Results

Chris Rey

Oak Ridge National Laboratory

1000 hp Status

Task	Status
Thermal cycle testing	2 (complete)
Multiple-coils	2 (complete)
Quench tests	Complete
Loss of Cooling test	Complete

Experimental Apparatus

1000 hp Test Circuit

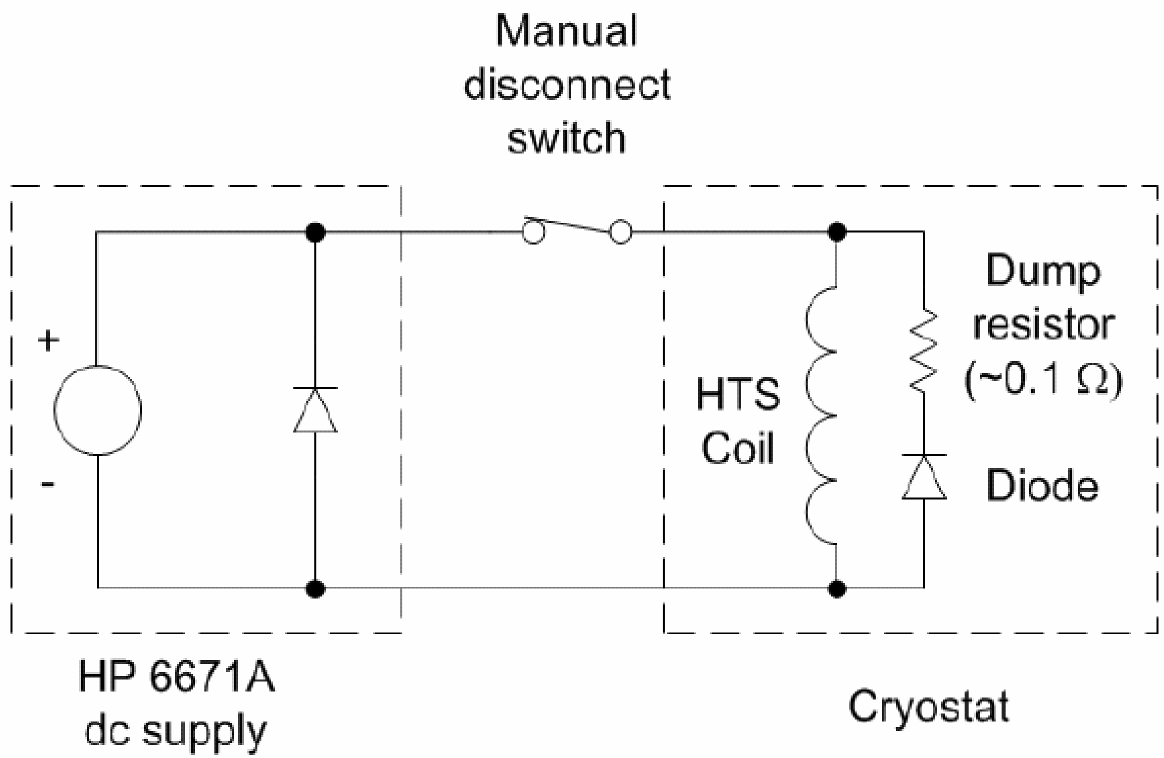
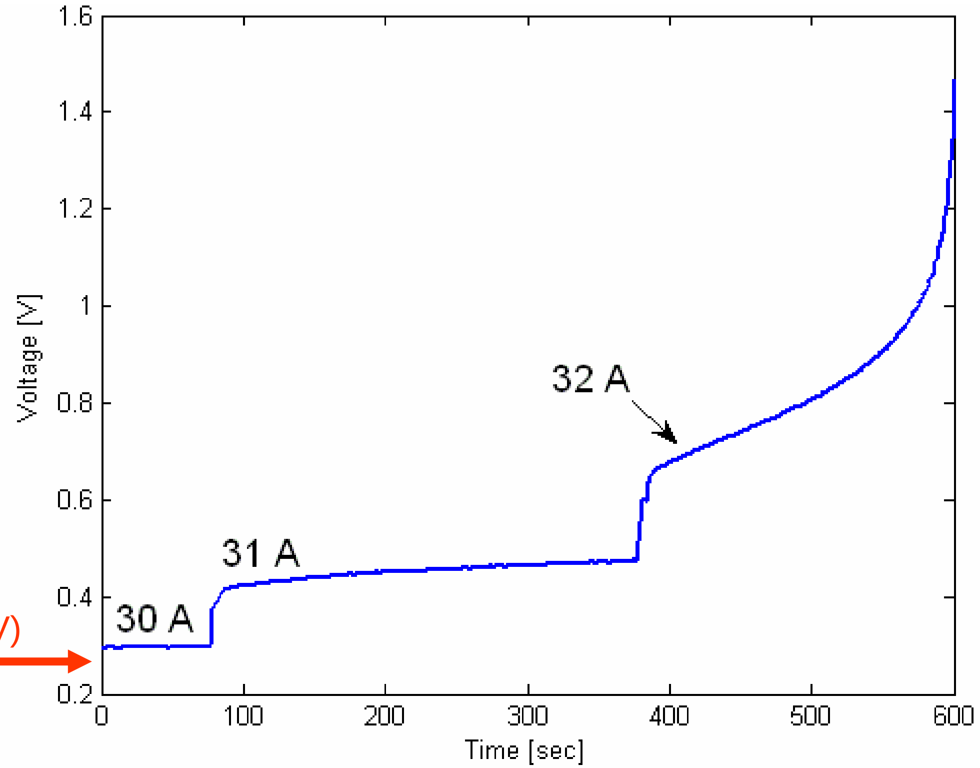


Figure 7: Schematic diagram of the wiring for the 1000-hp HTS coil experiments.

1000 hp 77 K Quench Test

I_c

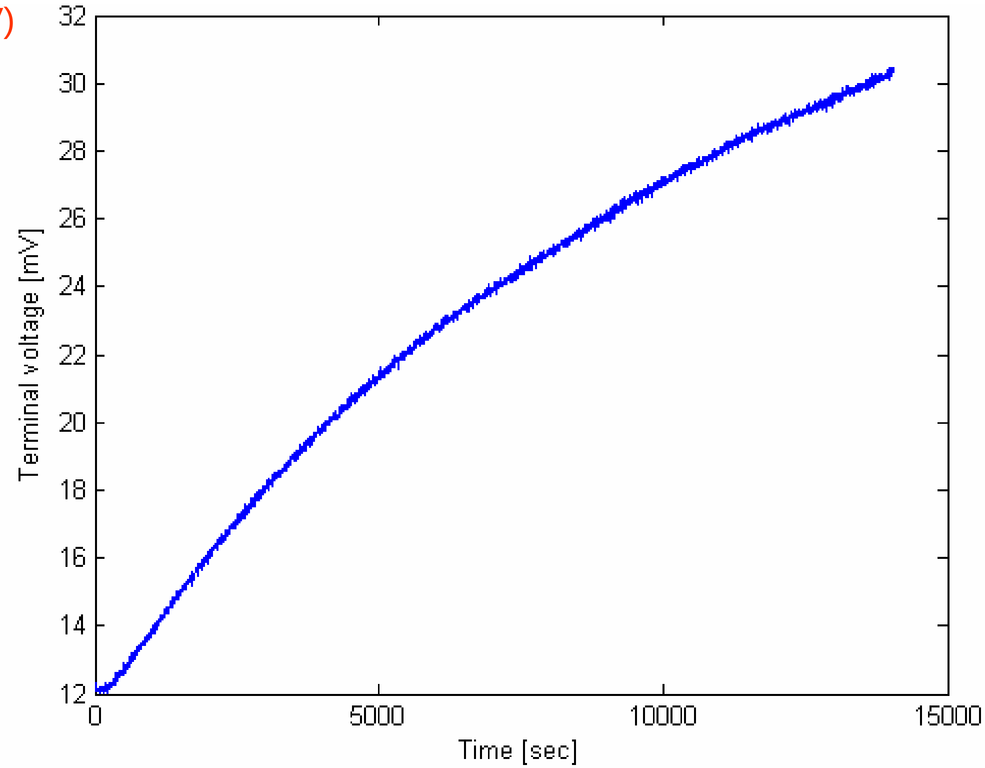
(1 uV/cm ~ 250 mV)



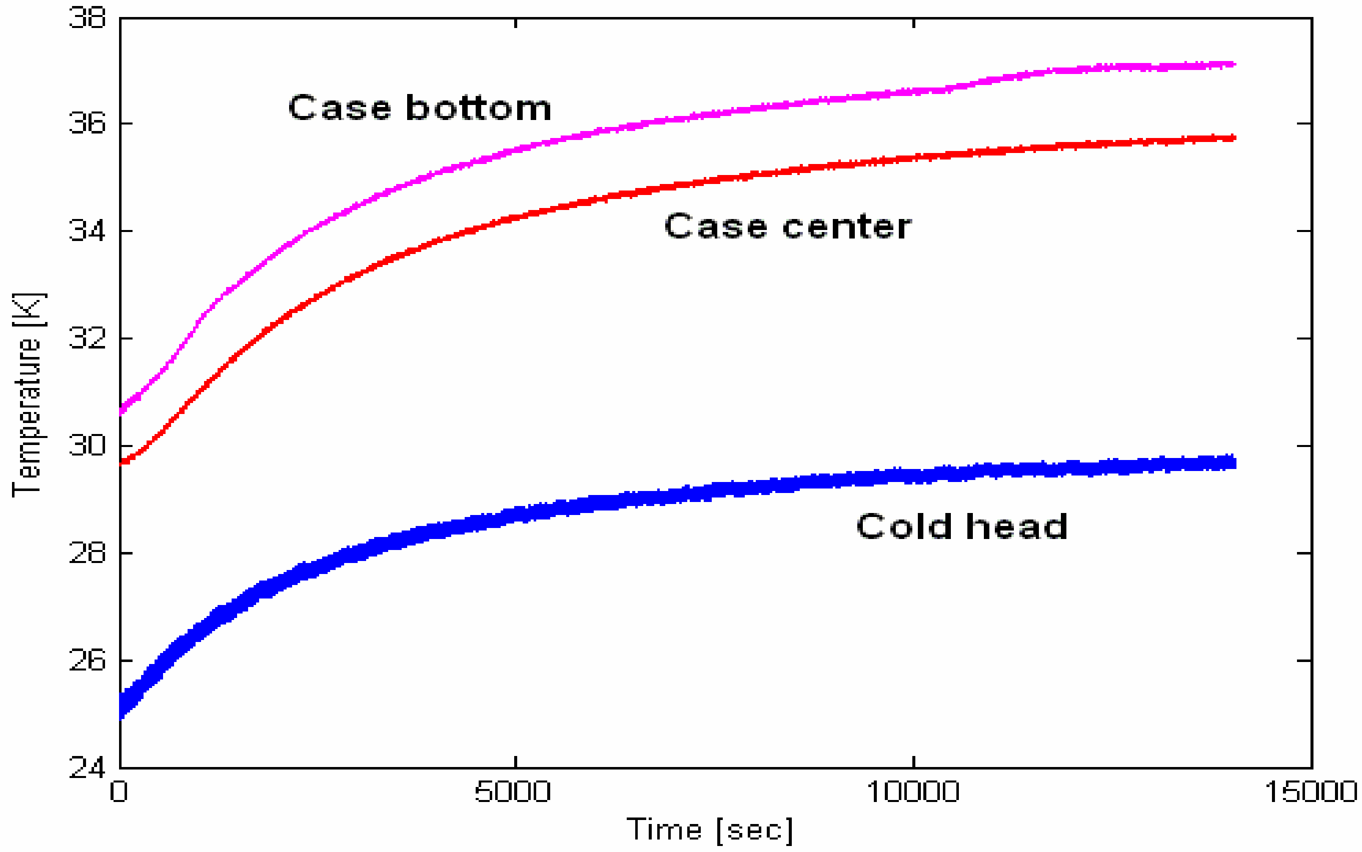
1000 hp 30 K Quench Test, 172.5 A (Stable)

I_c

(1uV/cm ~ 250 mV)



1000 hp 30 K Quench Test, 172.5 A (Stable)

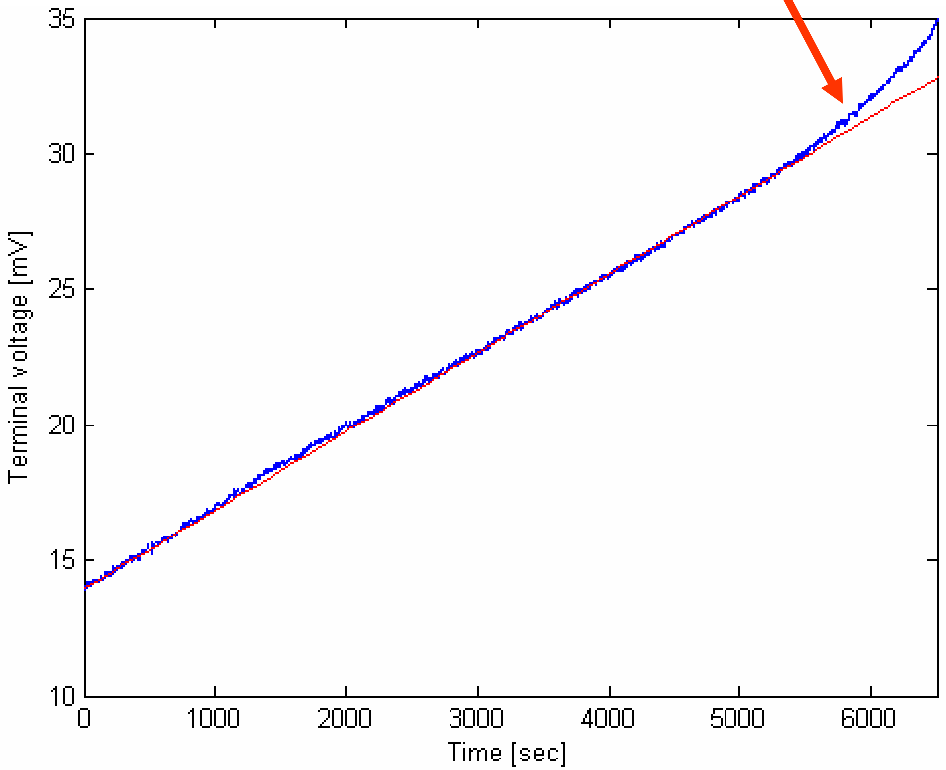


1000 hp 30 K Quench Test, 175 A (Unstable)

I_c

(1uV/cm ~ 250 mV)

(> 5000 s)



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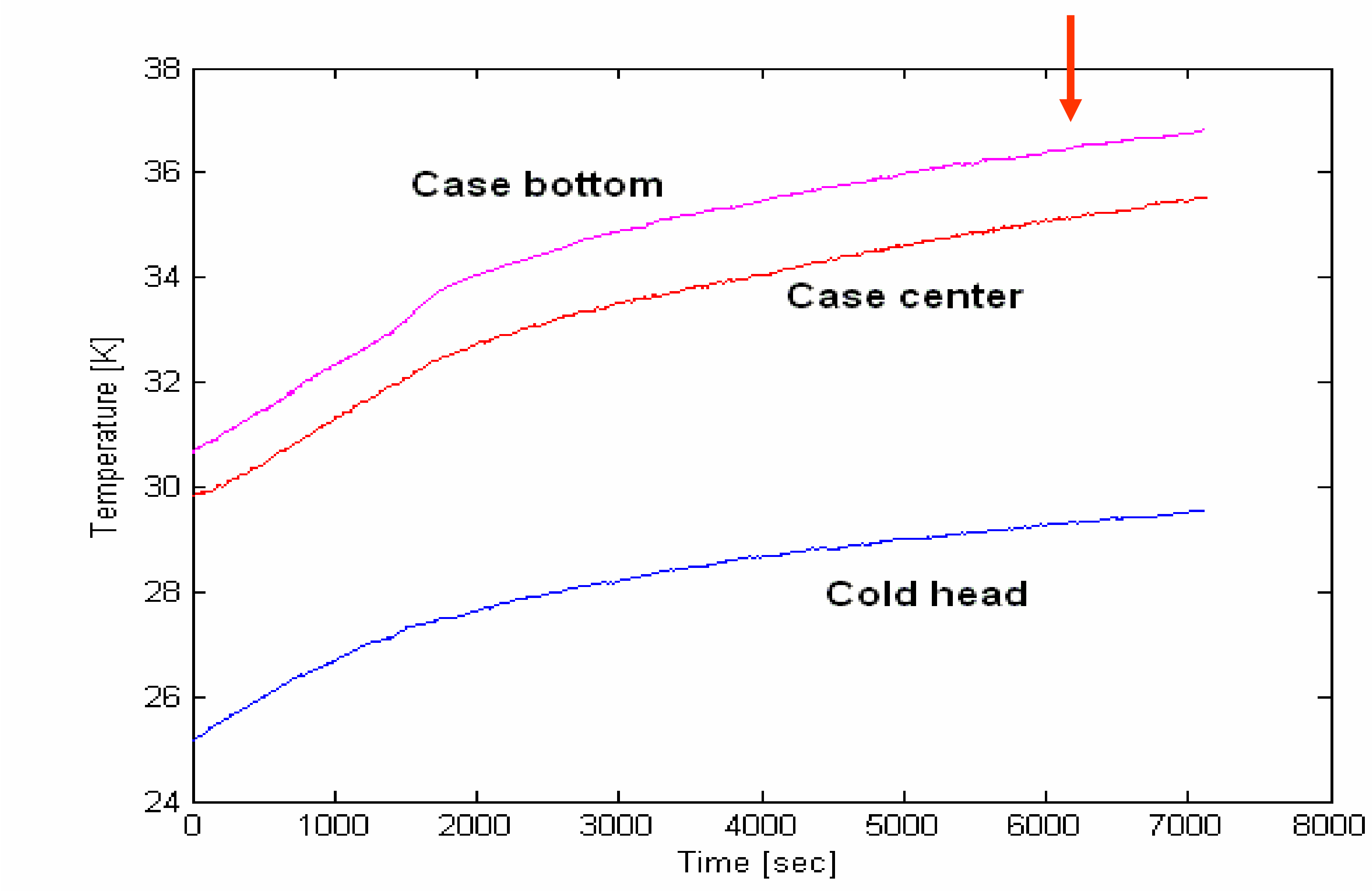
1000 hp 30 K Quench Test, 175 A (Unstable)

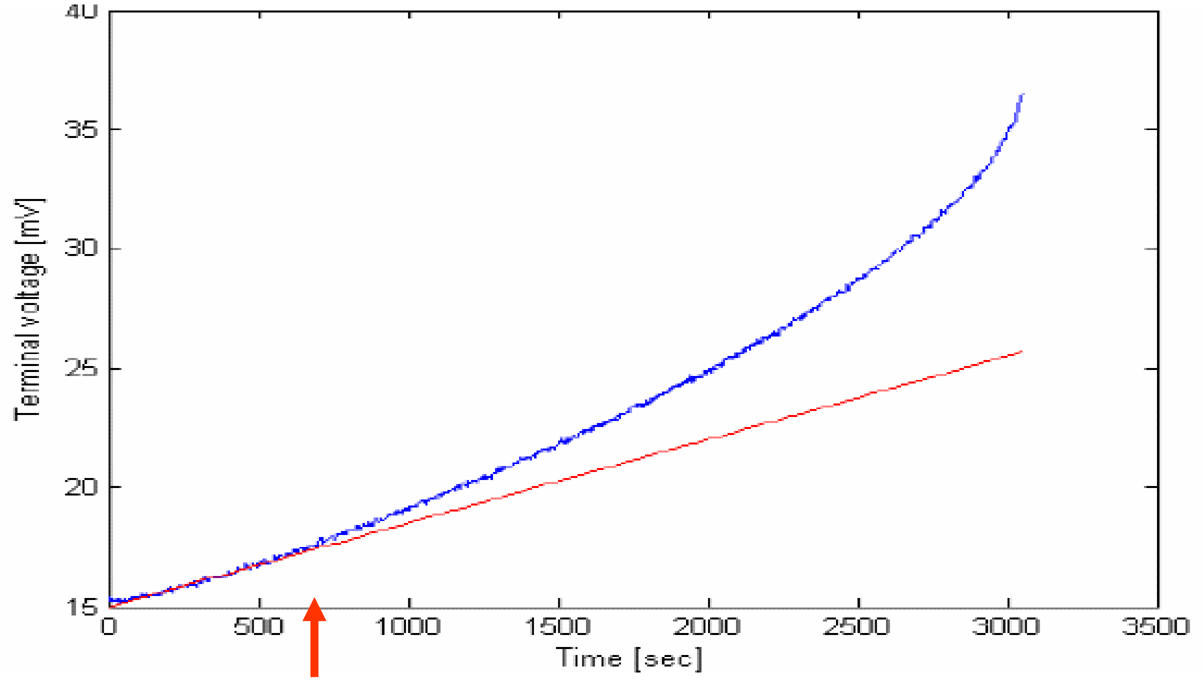
(> 36 K @ non-linear onset)



1000 hp 30 K Quench Test, 180A (Unstable)

I_c

(1uV/cm ~ 250 mV)



(> 600 s)

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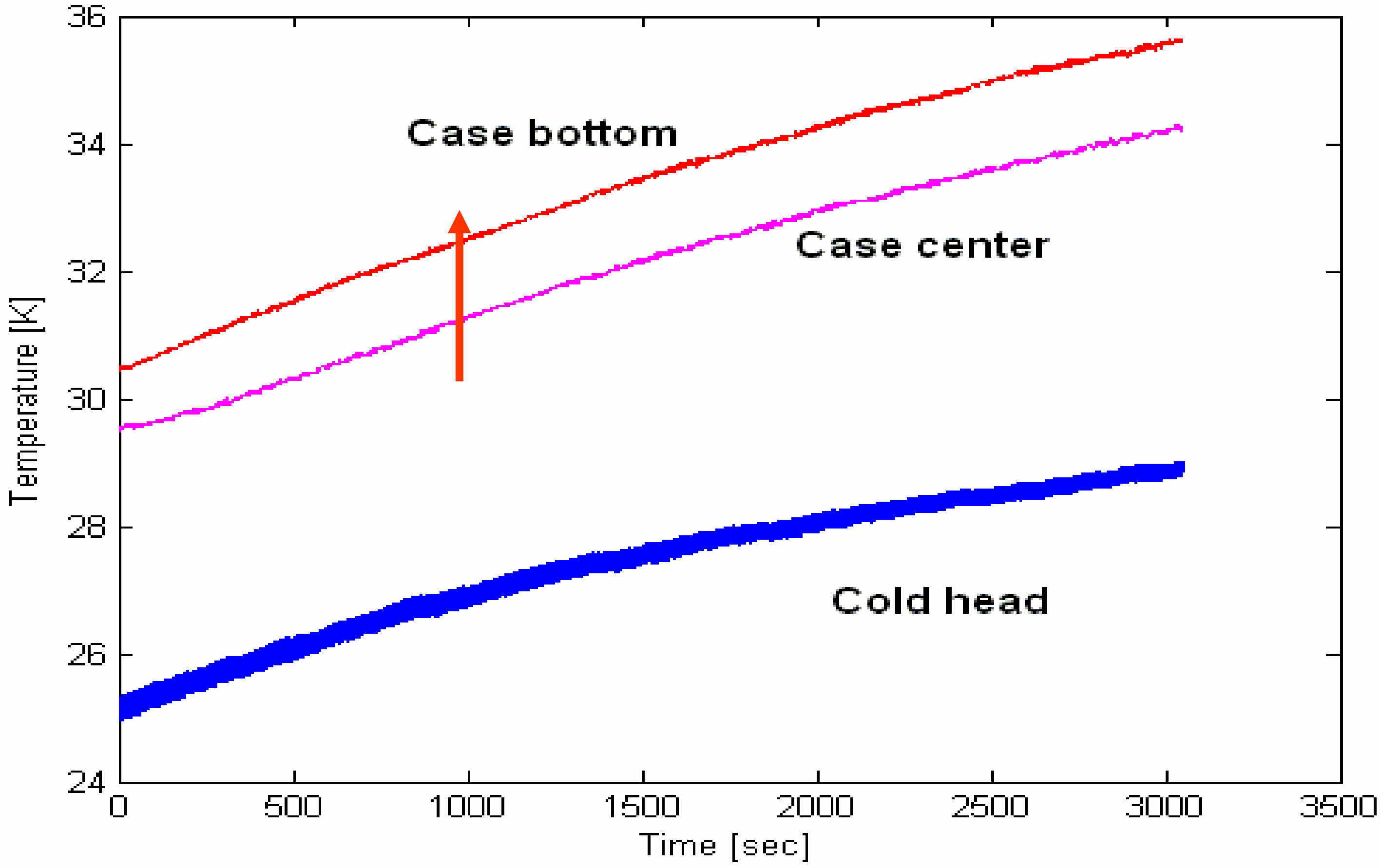
1000 hp 30 K Quench Test, 180A (Unstable)



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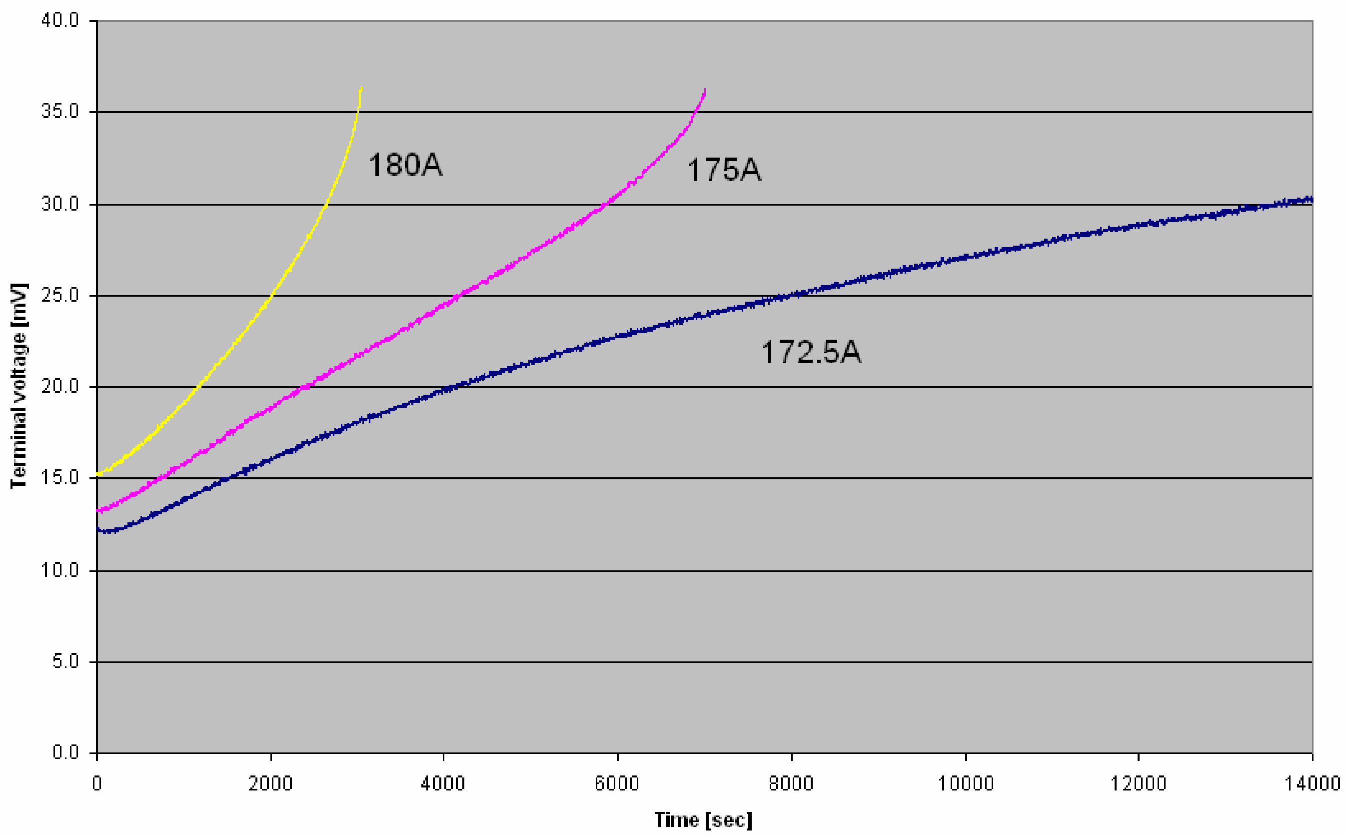
1000 hp 30 K Quench Test (Terminal Voltage)

I_c

(1uV/cm ~ 250 mV)

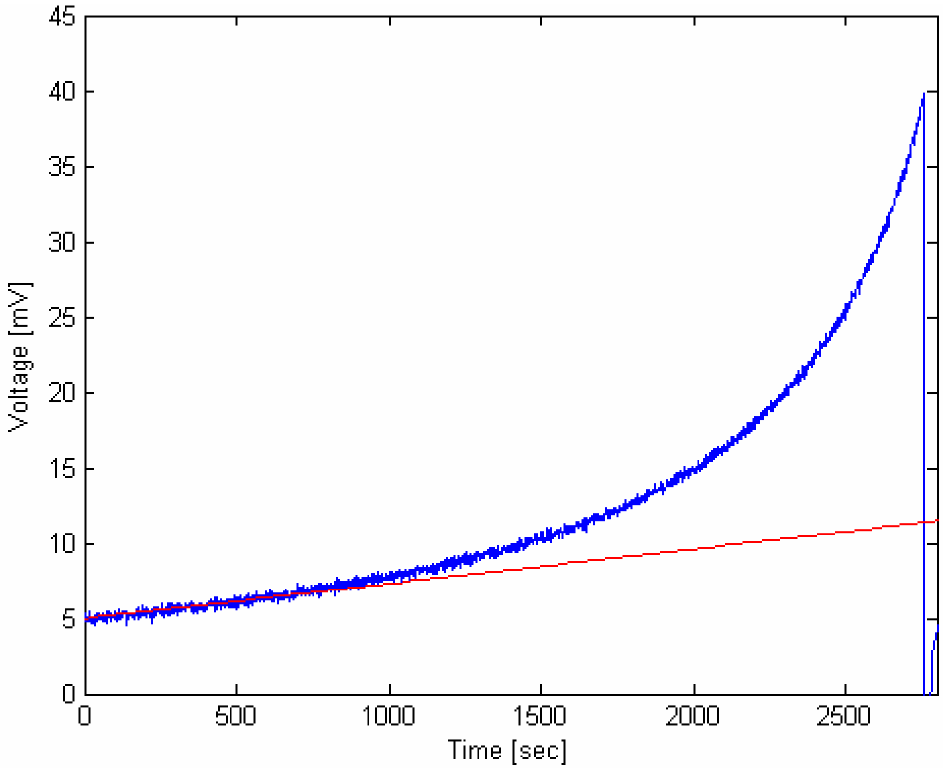


(Stable)

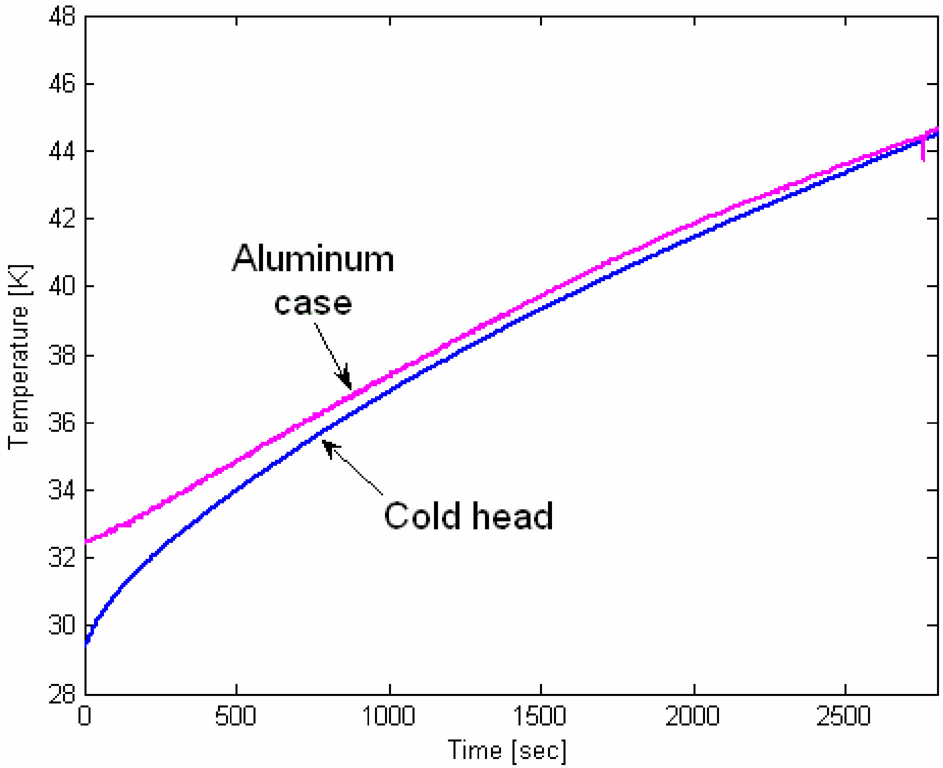
1000 hp 30 K Loss of Cooling Test, 140 A

I_c

(1uV/cm ~ 250 mV)



1000 hp 30 K Loss of Cooling Test, 140 A (Temperature)



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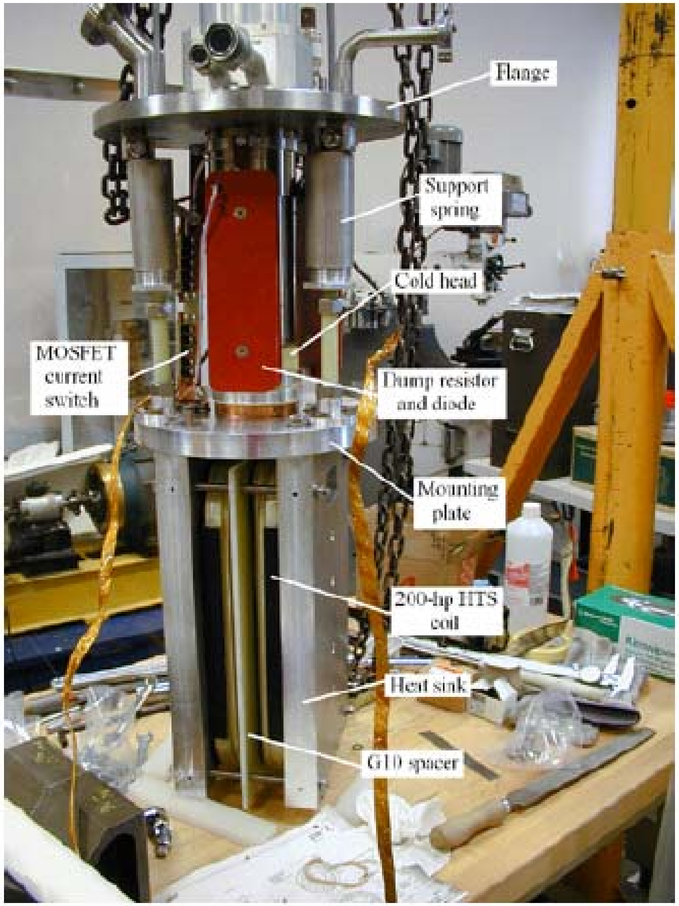
200 hp Status

Task	Status
Thermal cycle testing	2 (complete)
Multiple-coils	2 (complete)
Quench Test	Complete
Loss of Cooling Test	Complete

200 hp Experimental Apparatus



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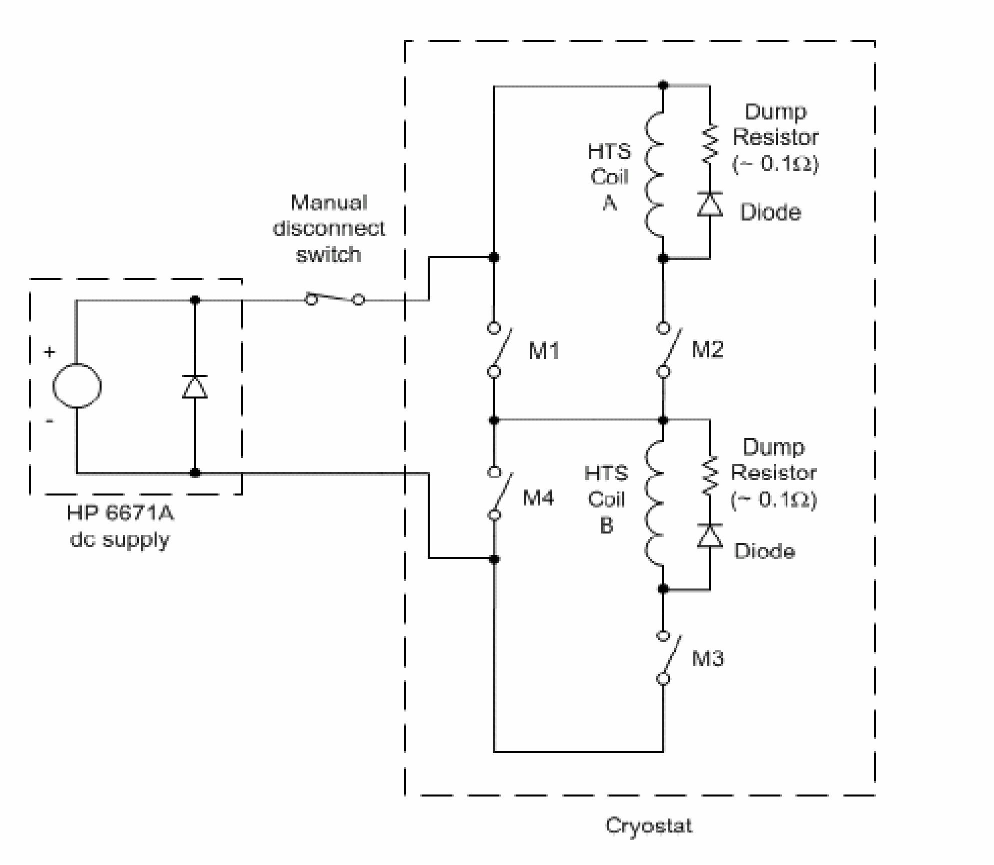
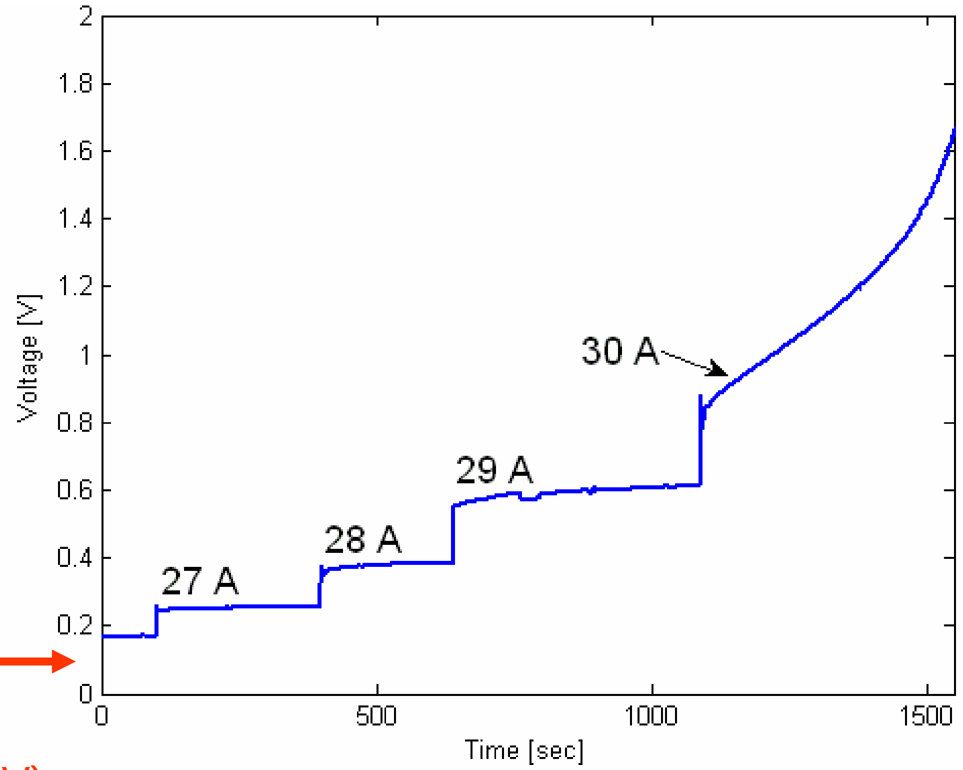
200 hp Test Circuit

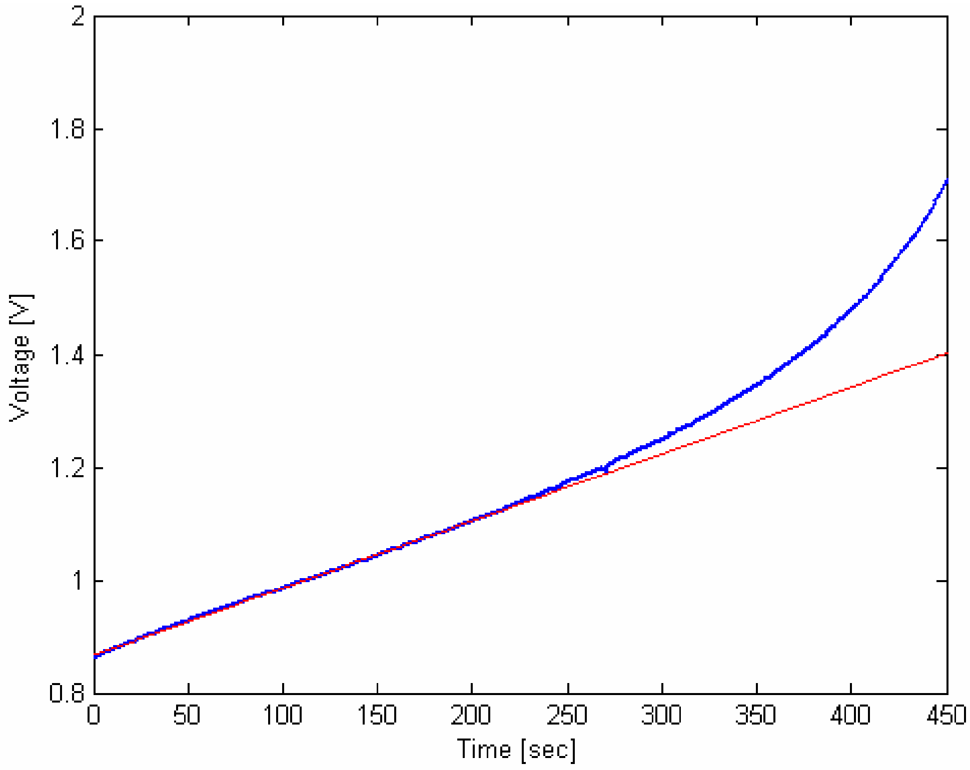


200 hp 77 K Quench Test



I_c
(~ 60 mV)

200 hp 77 K Quench Test, 30 A (Unstable)

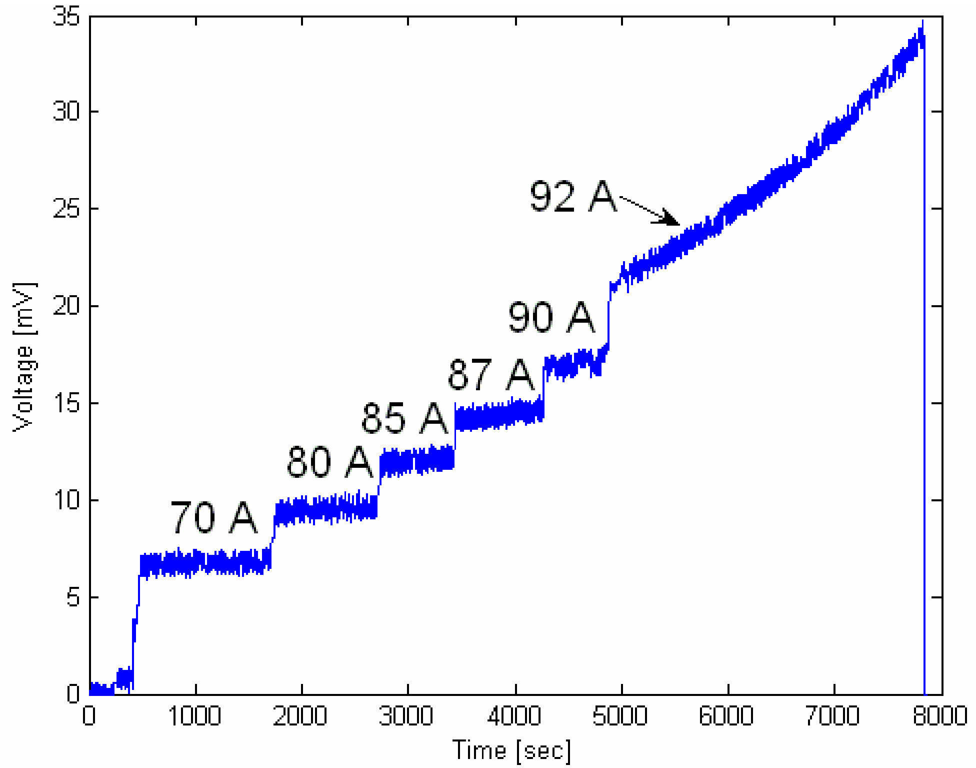


I_c
(~ 60 mV)

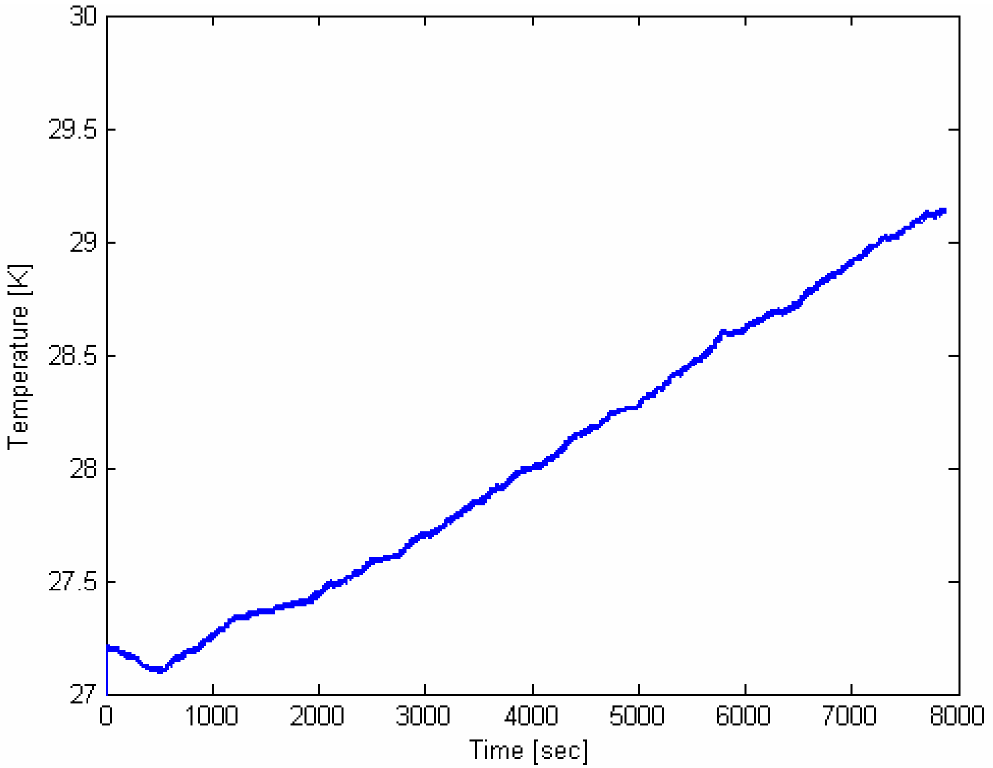
200 hp 30 K Quench Test

I_c

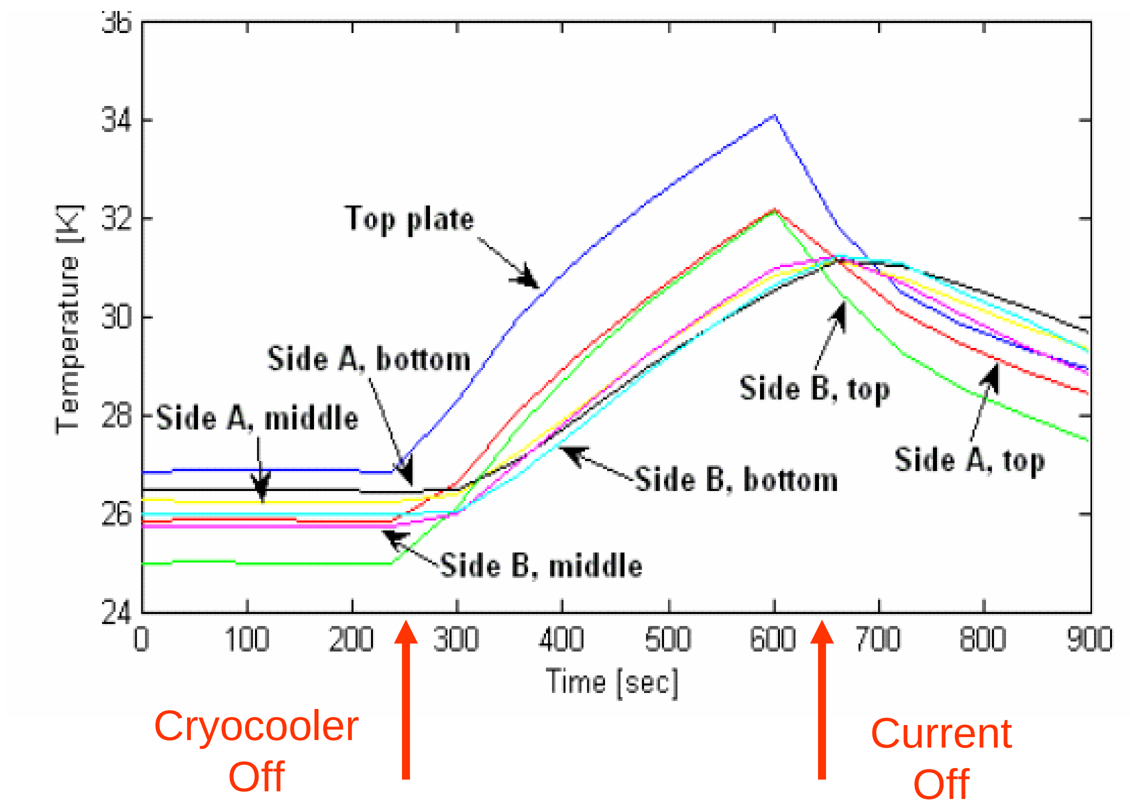
(1uV/cm ~ 60 mV)



200 hp 30 K Quench Test, 92 A (Unstable)



200 hp 30 K Loss of Coolant Test



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Summary

- Conduction cooled (30 K) vs. bath cooled (77 K) gives qualitatively similar features but vastly different quantitative values
- Differences between a quench and a stable condition only ~ 1-2 A apart
- Quench characteristics qualitatively similar between Bi-2223 wire manufactured ~ 5 years apart
- Large temperature rise before quench
- Critical current I_c is an inadequate number for characterizing quench & stability→ must be modeled based upon heating & cooling
- Quench current based upon fundamental non-linear physics

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Quench Modeling

Rich Schiferl
Rockwell Automation

HTS Coil Quench Event Modeling

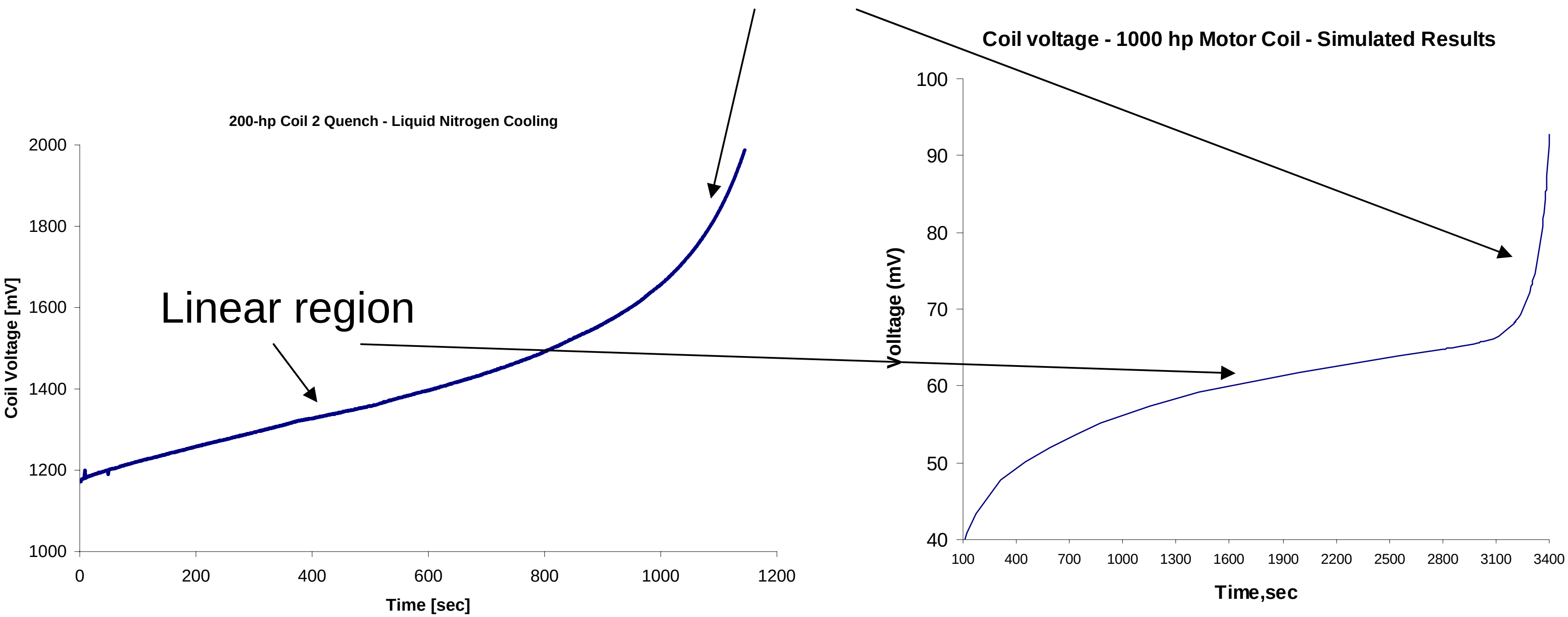
Goal: Determine the coil temperature distribution and terminal voltage as a function of time to provide information for quench detection and protection methods.

Include the following capabilities:

- Current induced quench
- Loss of cooling induced quench
- Impact of localized defects in the coil
- Current sharing between HTS and normal conducting stabilizer
- Applicable to any HTS conductors and coil designs

Quench Modeling Results

Test Data | Nonlinear region | **Model Data**



- 200 hp coil test data
- Voltage vs Time

- 1000 hp coil simulation data
- Voltage vs Time

Model mimics test phenomenon quite well

HTS Coil Quench Event Modeling Method

- Input HTS wire characteristics
  - Voltage drop as a function of current, temperature, magnetic field, magnetic field direction in the HTS
- Solve the static magnetic field problem for the HTS coil to obtain magnetic field distribution throughout the coil
- Solve the transient thermal problem for a given applied current to obtain voltage and temperature distribution throughout the HTS coil
- Post process to obtain temperature and voltage vs time

HTS Coil Quench Observations from Modeling

- Pre-quench instability is followed by the true quench.
- During the true quench, normal zone propagation concepts can be applied

- Both pre-quench and true quench periods are included in our quench models
  - The same model is used

- Quench detection must occur during the pre-quench instability region

HTS Coil Quench Modeling – Wire Characterization

- Quench modeling requires mathematical relationships between coil voltage and current, temperature, magnetic field, and magnetic field direction.
- If these relationships are simple enough, they allow for model implementation and some closed form expressions for coil response during a quench.
- The reduced temperature model has been developed to simplify HTS wire characteristic representation.

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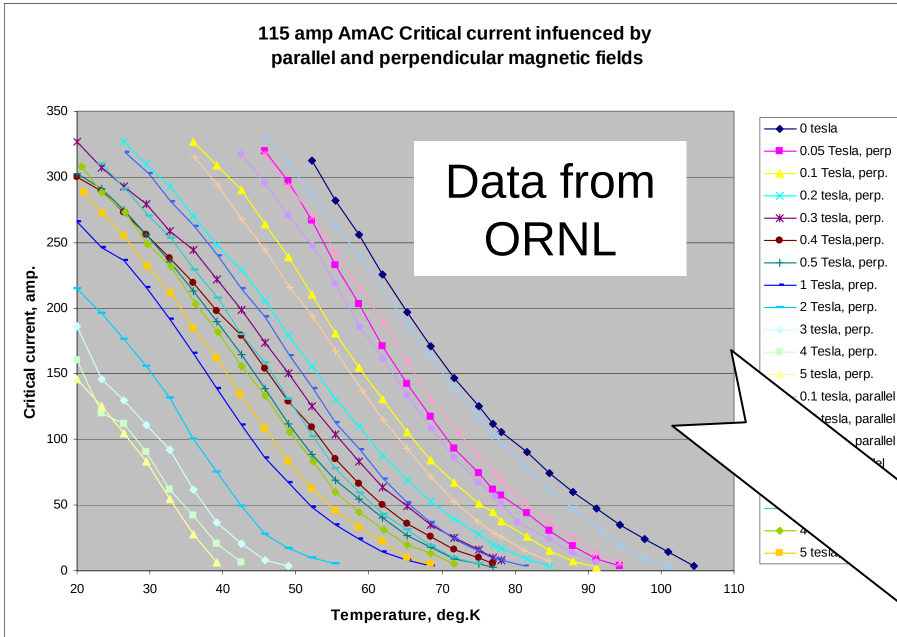
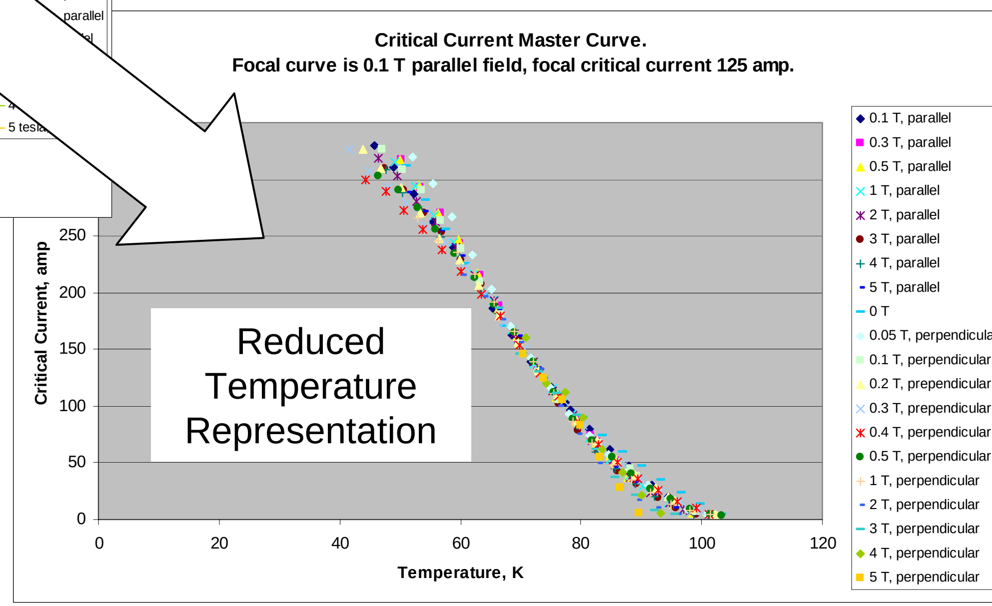
Reduced Temperature Model for HTS Conductor

- Collapses multiple curves to single curve
- Works with 1G and 2G HTS conductors
- Offers opportunity for dramatic reduction in test data to fully characterize HTS wire





Details are described in upcoming technical paper

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HTS Coil Quench Technical Papers

– S. Umans & B. Shoykhet, **"Quench in High-Temperature Superconducting Motor Field Coils: Experimental Results“,** IEEE, IEMDC Conference, May 2005 – IEEE IAS Transactions, July 2006.

– S. Umans, B. Shoykhet, J. Zevchek, C.Rey and R. Duckworth, **"Quench in High-Temperature Superconducting Motor Field Coils: Experimental Results at 30 K“,** Invited paper for the IEEE Applied Superconductivity Conference, August, 2006.

– B.A.Shoykhet, S.D.Umans, **“Quench in High-Temperature Superconducting Motor Field Coils: Reduced-Temperature Modeling of HTS Tapes”,** IEEE Applied Superconductivity Conference, August 2006

– B.A.Shoykhet, S.D.Umans**,”Quench in High-Temperature Superconducting Motor Field Coils: Computer Simulations and Comparison with Experiments”,** IEEE Applied Superconductivity Conference, August 2006.

Future ORNL CRADA Work

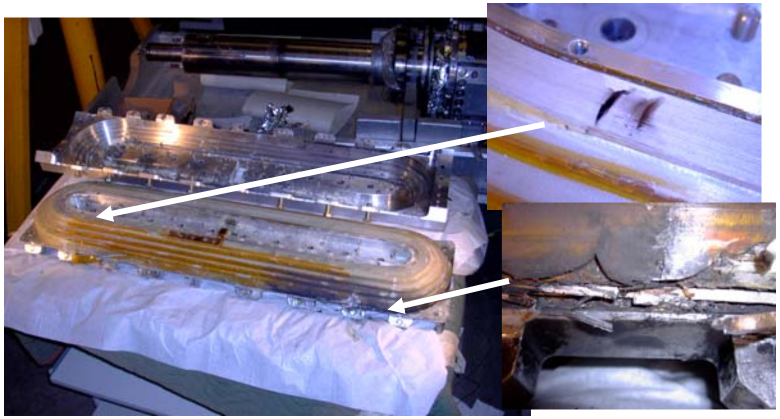
- Second Generation Wire
  - wire characterization tests
  - 2G wire joints characterization
  - performance vs. strain
- 2G HTS coil performance before and after winding
  - highly instrumented coil
  - winding mandrel topology and material investigation
- Quench testing of 2G HTS rotor coil at 30 K

Conclusions: Coil Quench Detection and Protection

- The quench phenomenon on HTS coils is now well understood
  - Test results at 77 K and 30 K show similar characteristics
  - Time is available to detect the onset of a quench and prevent damage coils
- A comprehensive quench model has been developed
  - Utilizes wire characteristic (voltage) data over range of temperatures, magnetic fields, and currents
    - Simply represented using the reduced temperature method
  - The quench model matches the observed quench phenomenon from test
  - A simplified model has been developed that predicts quench current quite accurately
    - A useful tool for use in coil design calculation iterations for HTS machines
  - Model has been applied to 2G coils with success

Conclusions: Coil Quench Detection and Protection

- 1000 hp motor coil that failed was flawed
  - Failure occurred at a joint
  - This was a mechanical failure and not related to quench at all
  - No other tested coil had this type of quench or failure response



Failed HTS Coil from 1000 hp Motor

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  - Alternate HTS wire application issues
    - Second generation HTS conductor application
  - Variable Speed Drive integration/shielding for HTS motors
  - Cryogenic persistent current switch for HTS field winding

- **Reliability improvement**
  - On-board refrigeration systems
  - Composite torque tube technology advancement
  - Coil quench detection and protection

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Research Integration

- National Institute of Standards and Technology (NIST)
  - Rotating (pulse tube based) cryocooler model development
- SuperPower, Inc.
  - Second generation HTS coil development and wire characterization
- Oak Ridge National Labs CRADA
  - HTS coil quench testing and wire characterization data
    - FY06 results reported here
    - FY07 plans concentrate on 2G wire, joint, and coil characterization testing as previously reported

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  - Coil quench detection and protection

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Example from Appendix: Task Summary

Task 1: Alternate HTS Motor Topologies

- Issue
  - Other motor topologies may offer improved performance over HTS synchronous motors
  - Permanent magnet, induced flux, axial gap, all HTS, … topologies should be investigated
- FY06 Planned Accomplishments
  - Complete design trade-off studies of permanent magnet (PM) vs HTS content and issue report
- FY06 Accomplishments / Progress
  - Parametric design study of PM vs HTS motor conducted
    - Preliminary results show PM motor is between conventional motor and HTS motor in size and performance.
- FY07 Planned Accomplishments
  - Continue trade-off studies of PM vs HTS with various ratios

Conclusions – Ultra-Efficient HTS Motors

- Project tasks address key technologies for commercially viable HTS motors for industrial applications
- Substantial progress made in
  - HTS coil quench modeling and test characterization
    - ORNL CRADA has been instrumental
  - Sharing of research task data
    - Five technical papers presented or published in FY06
  - 2G performance and cost targets
- Progress is being made on all tasks toward the future of HTS industrial motors with 2nd Generation HTS field coils
  - Half the losses of conventional motors
- Project will be completed at the end of FY07 within original budget.

The End