Quench Protection for Very High Field Magnets using HTS Conductors

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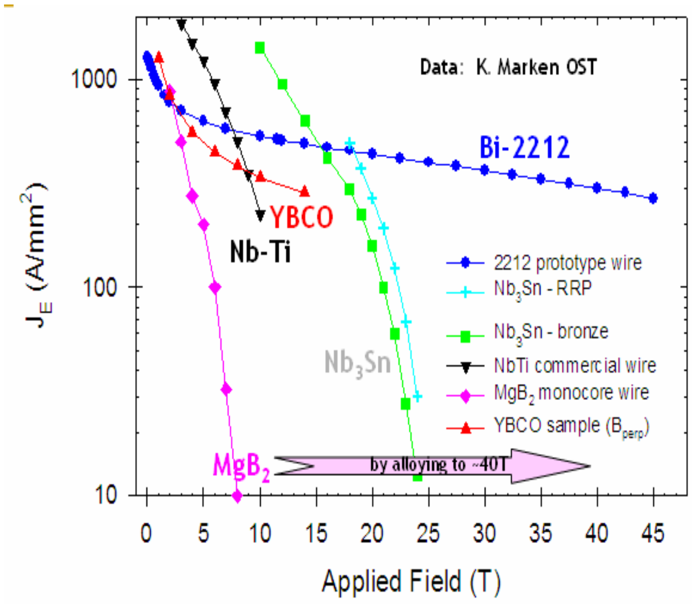
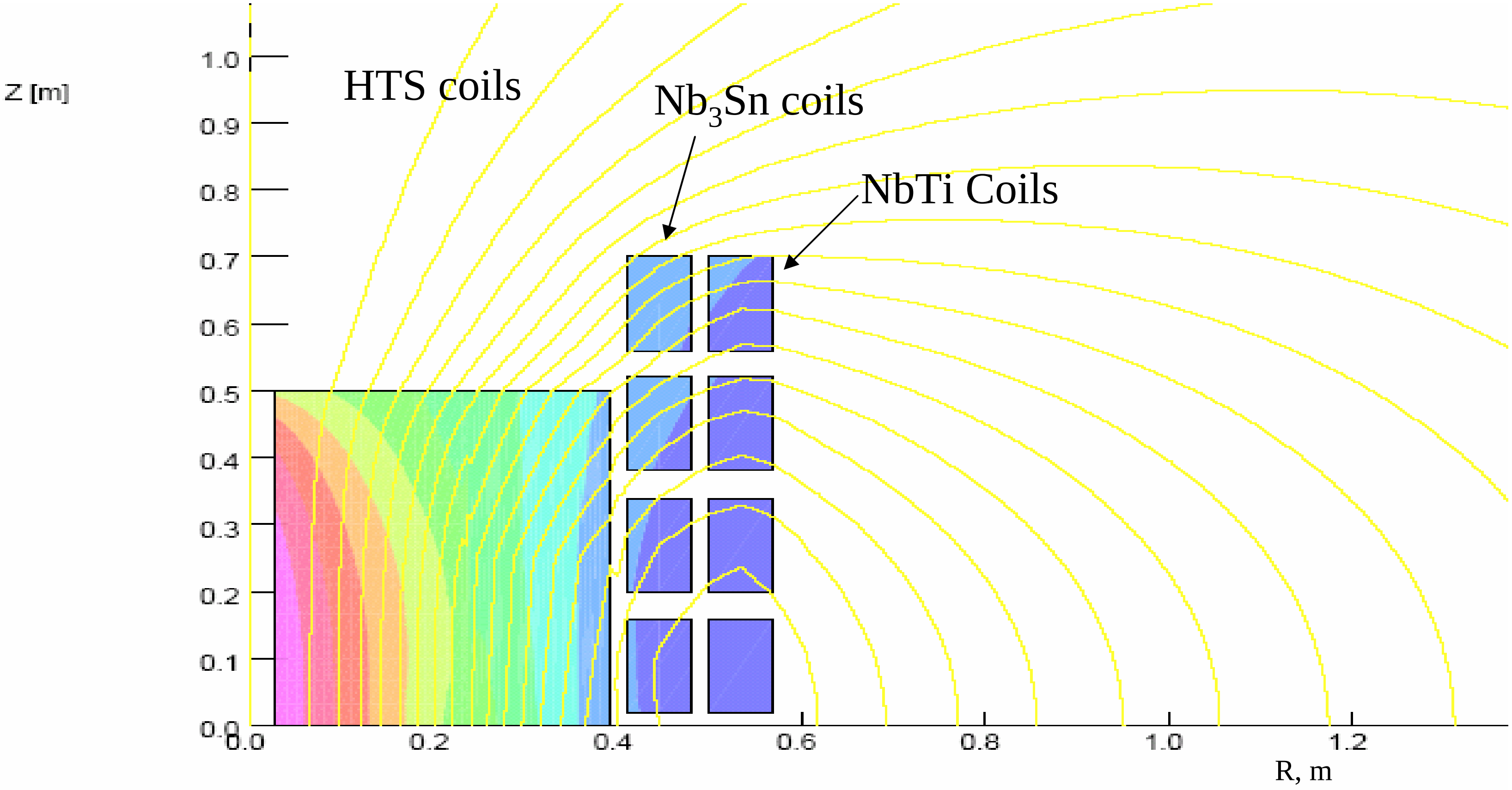
HTS Magnet Protection—Why is this different from normal Quench Protection?

- In our scenario for a muon collider we (casually) use very high field magnets that can not be achieved using normal Niobium superconductors.
  - The NbTi alloy is a ductile material that has reasonably decent mechanical properties.
    - Reasonable current to 7T at 4.2 K
  - Nb_3Sn superconductor is a more brittle material. Fields to ~17 T.
  - It has been demonstrated that HTS conductor can carry significant current at fields as high as 45 T
    - HTS conductor is very brittle. There is a major concern about damage from strain.



Recent Model of 50 T Solenoid (LTSW06)



HTS coils

Nb_3Sn coils

NbTi Coils

Comparison of High Field Solenoid Parameters

Quantity		EPAC06	LTSW06	NHMFL (Insert)
Central Field		50 T	45 T	25 T
Insert Field Contribution		50 T	30 T	5 T
Outer Insert Radius		23 cm	39 cm	4.8-8.2 cm
Outer Radius		23 cm	58 cm	
Total Energy	$U=\pi\int rB\cdot H ds$	20 MJ	229 MJ	16 MJ
Total Insert Energy	$U=\pi\int rA\cdot J ds$	20 MJ	51 MJ	10 kJ

Two Concerns with HTS Magnets

- One concern is how to remove this large amount of energy from the magnet in case of an incident.
- The second concern is that the quench propagation velocity for HTS is very slow. The superconductor can heat up significantly before the quench energy can spread.
  - This can cause local irreversible damage to the magnet.

Conductor and Insulator Description

- The conductor is BSCCO 2223 which is 30% HTS filaments and 70% Ag matrix and Ag-Mg sheath (for strength). We assume the matrix/sheath is all Ag for the calculation.
- The insulator is assumed to be the Stainless Steel interleaving. A minimum thickness (0.07 mm) is used since we are describing the inner layers.
  - In practice we will likely add a ceramic coating or kapton wrap as insulator. This will inhibit the transverse quench propagation.

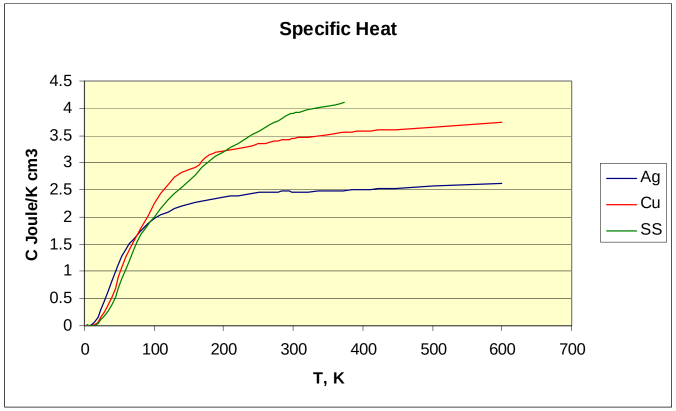
Component	Area	Fraction
HTS conductor	0.3483 mm^2	0.238
Ag matrix/sheath	0.8127 mm^2	0.556
SS Insulator	0.301 mm^2	0.206

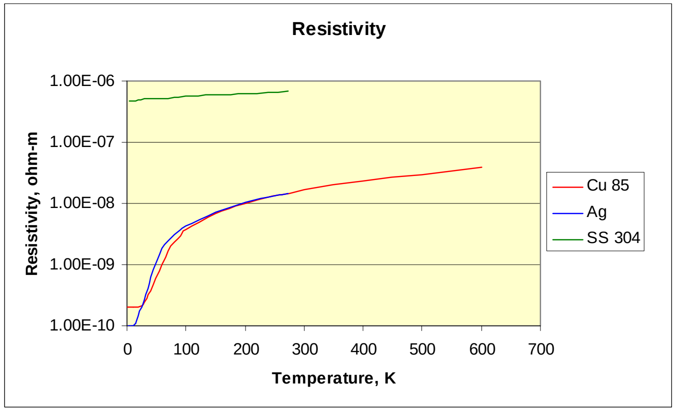
Conductor Material Properties Necessary for Quench Protection

- We need the material properties of all the components of the conductor and insulation.
- The important properties are
  - Heat capacitance (Specific Heat)
  - Resistivity
  - Thermal conductance
    - Obtained from resistivity with Wiedemann-Frantz law.
- C_V and ρ are parameterized as in up to four temperature ranges:

$$\rho = A \cdot T^{a} + B \cdot T^{b}$$

$$C_V = D \cdot T^{d} + E \cdot T^{e}$$





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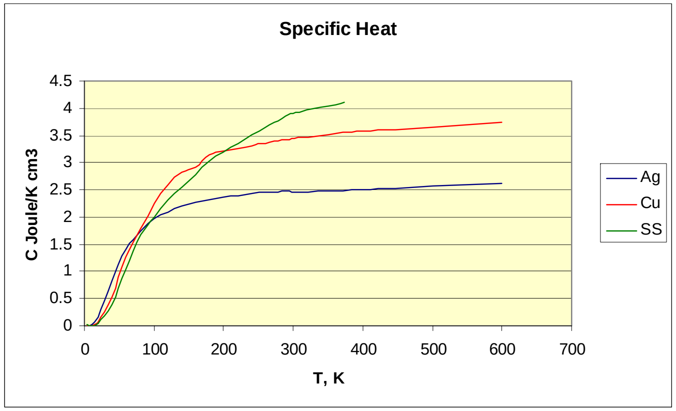
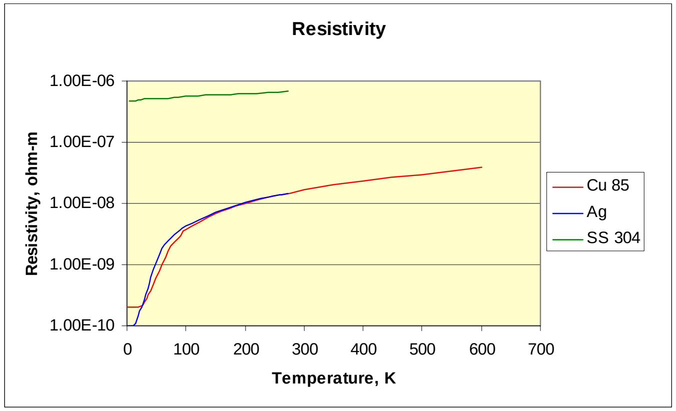
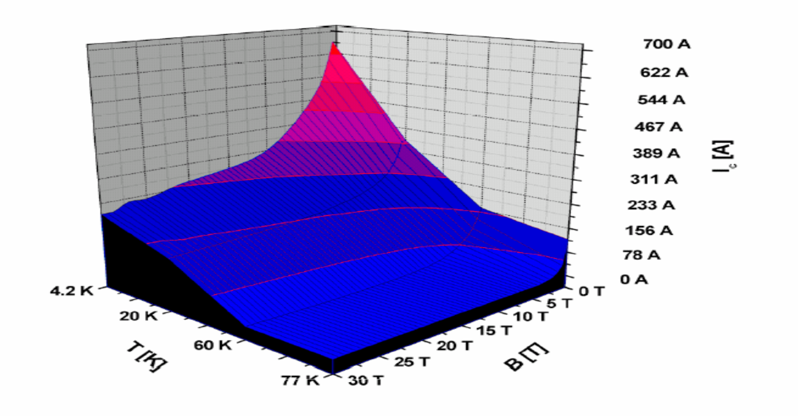
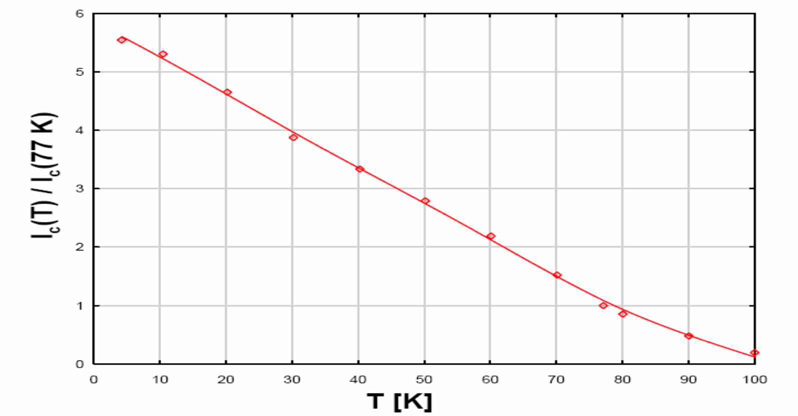
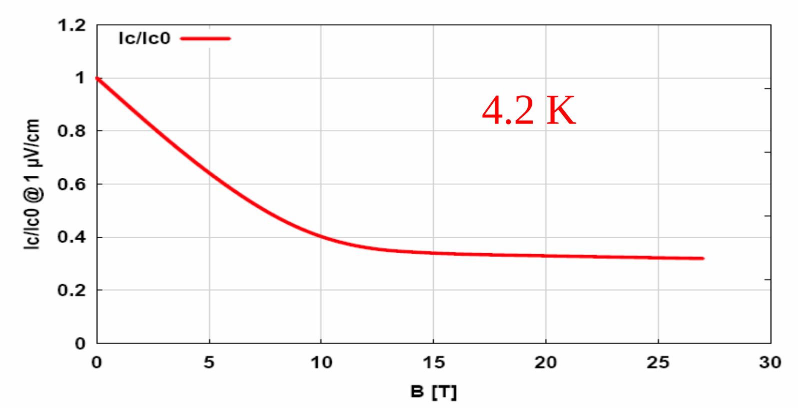

Specific Heat


Resistivity

Critical Current, Field, and Temperature Measurements on BSCCO 2223 Conductor







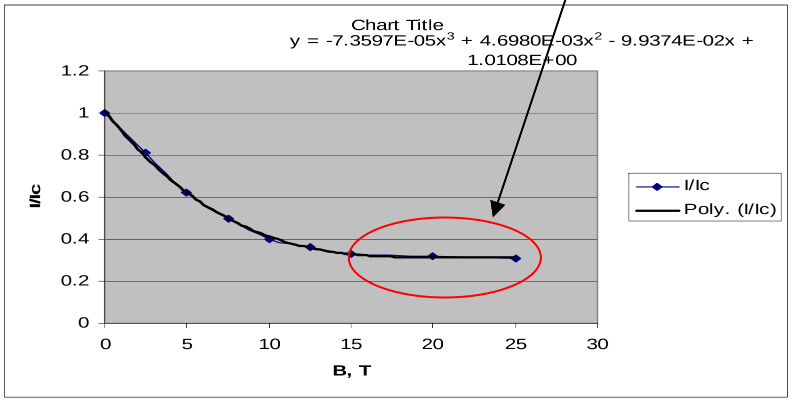
Data from EHTS Bi-2223 Data Sheets.

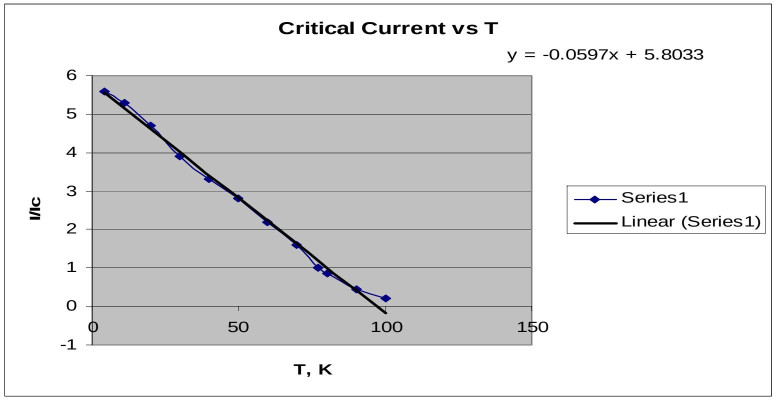
Measurements were performed at GHMFL, France.

Critical Current Measurements

- Measurements of critical current as a function of B and temperature are from EHTS (another provider of BSCCO 2223).
- The measured data is used to determine parameters of the following equation:

Used only high field part of data to determine B_{c20}

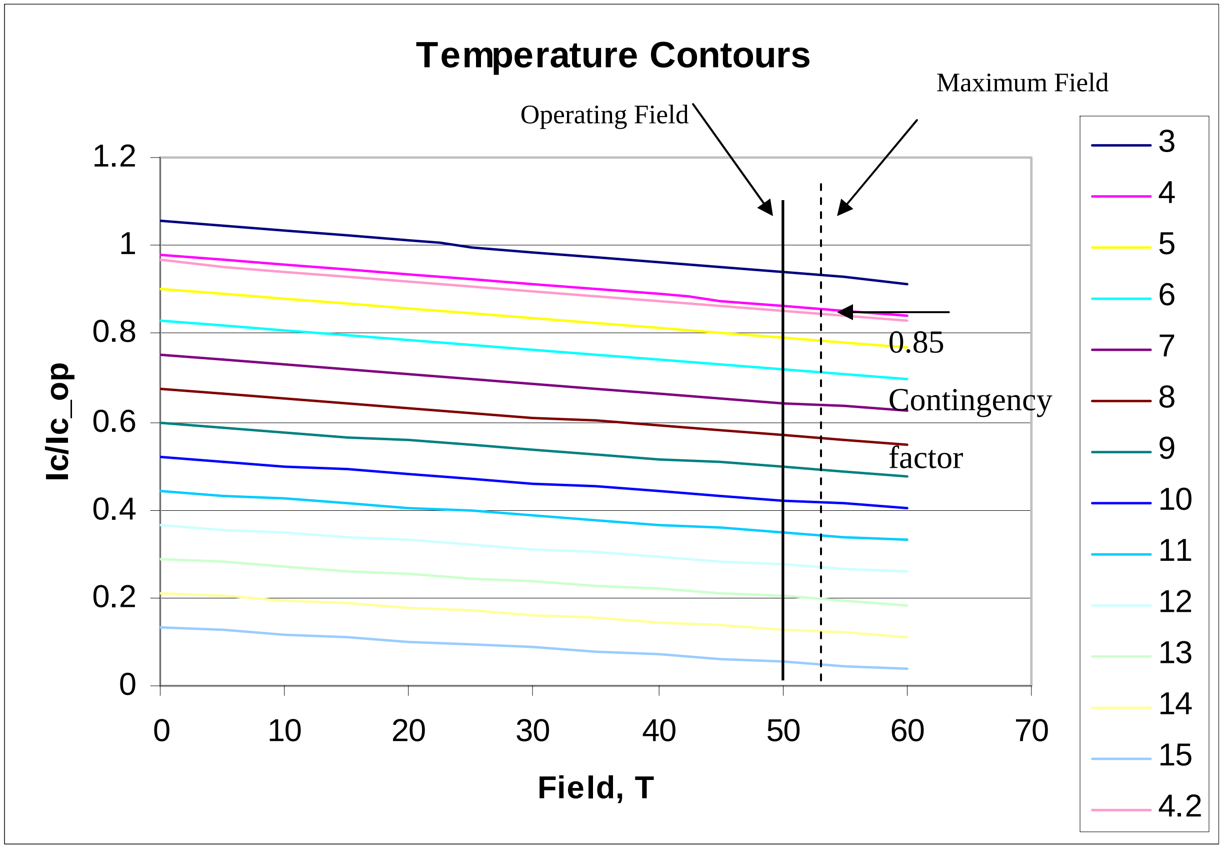




$$T_c(B,J) = \left[1 - \frac{J}{J_{00}\left(1 - \frac{B}{B_{c20}}\right)}\right] T_{c0}\left(1 - \frac{B}{B_{c20}}\right)^{0.59}$$

This formula is used for NbTi and Nb_3Sn. Is it valid for HTS??

HTS Characteristics: J_C vs. B for Constant T



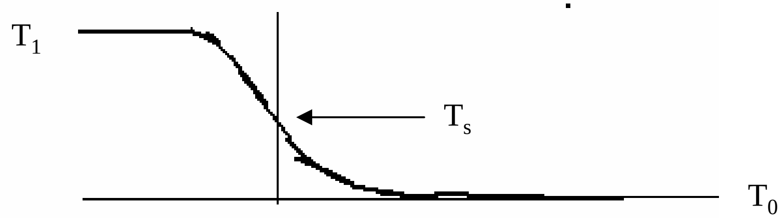
Quench Propagation Velocity

- Quench protection calculations depend on the *quench propagation velocity.*
- The quench propagation velocity can be calculated from the formula below.
  - – This is what I did.
  - – Experience for NbTi shows that the formula does not reproduce the measurements.
    - Typically the experimentally determined value is used.
      - – We need to measure this for HTS.
  - – One of the weaknesses of the velocity calculation is that the specific heat (ρC_V) varies as T^3 and is rapidly varying at the quench front.

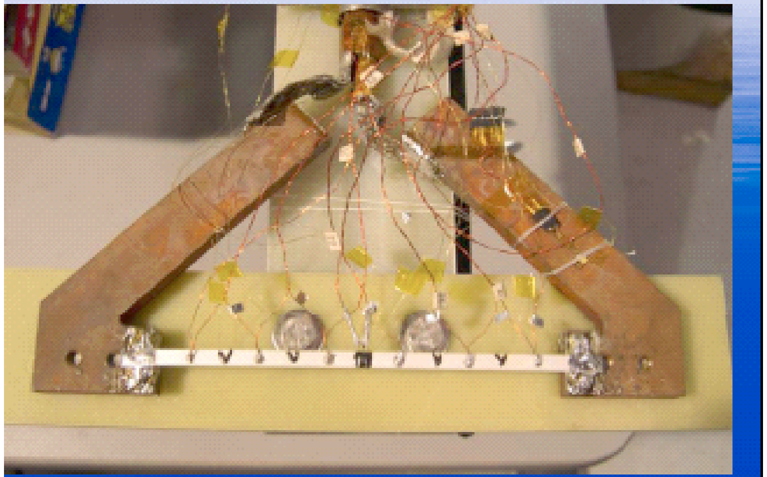
$$v_{quench} = \frac{I}{A_{cond}\,(\rho C_V)_{Ave}} \sqrt{L_0 \frac{T_S}{(T_S - T_{Op})}}$$

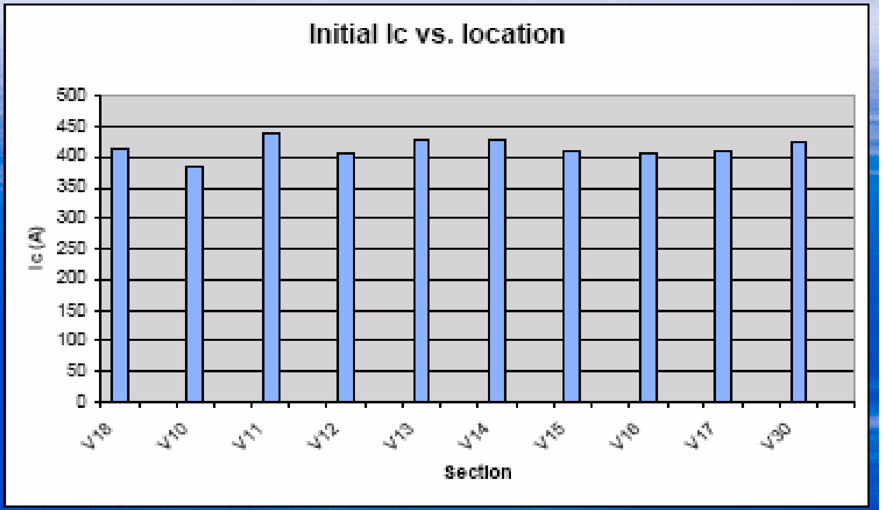
$$T_S = \tfrac{1}{2}(T_{\max} - T_{crit})$$

Lorentz Number



Wiring configuration & sample homogeneity

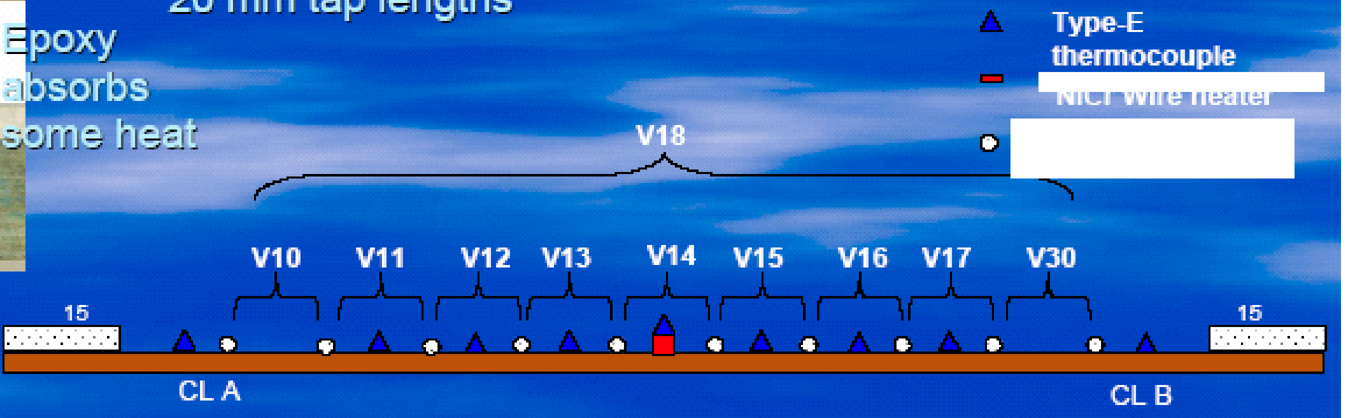




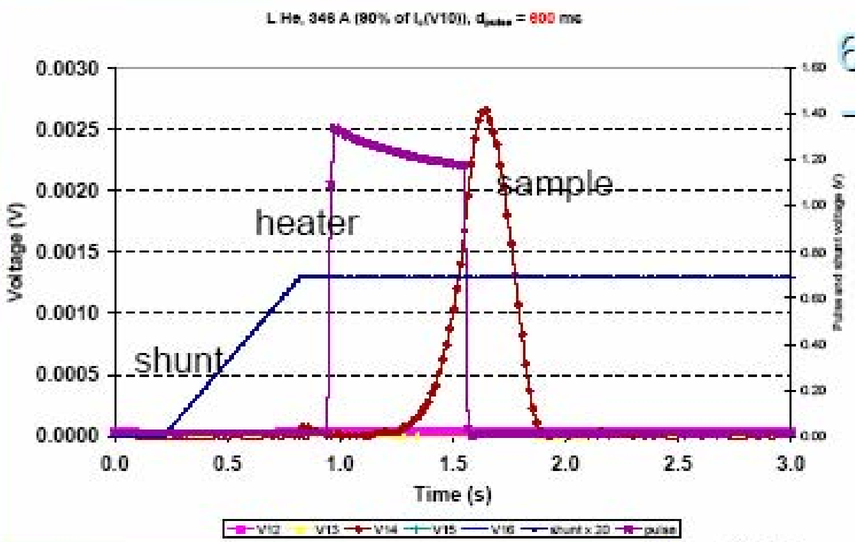
NiCr heater

Epoxy absorbs some heat

20 mm tap lengths



Bi2212 conductor quenches

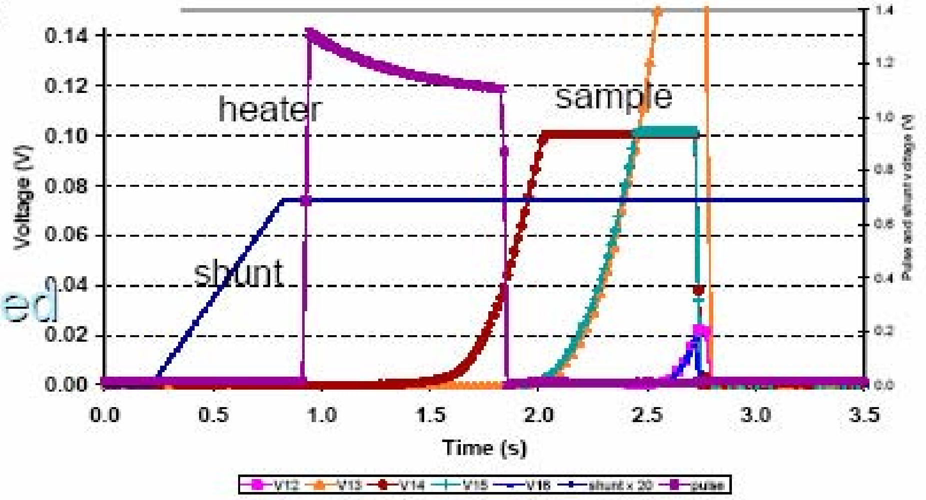


600 ms heat pulse (1.27 J)
→ stable

4.2 K, s.f.

900 ms heat pulse (1.72 J)
→unstable; sample destroyed
→**NZPV ~ 46, 36 mm/s**

L He, 346 A (90% of I$_c$(V10)), d$_{pulse}$ = 900 ms



Comments on Quench Velocity Measurements

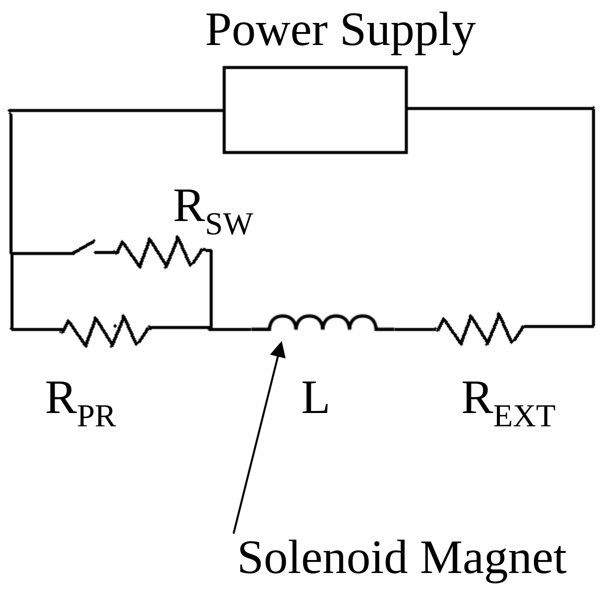
- The quench propagation velocity in this experiment is ~4 cm/sec. In NbTi it is approximately 1 m/sec.
  - If a quench occurs and the heat can not be dissipated, the local area will heat up to a very high temperature. It can be destructive.
- The slow propagation velocity is largely due to the fact that at 4.2°K most of the SC is far away from the critical temperature.
  - The closer we are to the critical condition, the faster the quench velocity.
- Restated: A conservative design with a large safety factor built-in against quenches occurring could be self-destructive if a quench does occur.
- The typical approach used with NbTi and Nb_3Sn of firing heaters to make the magnet go normal faster *won't work.*
  - It takes too much external energy to make the magnet go normal and would likely increase the destruction.

Preliminary Calculations

- I am presenting some preliminary calculations using the quench calculation program QUENCH.
  - This program was written by Martin Wilson at Rutherford Lab in the 1970's. The current version of the program is marketed by B. Hassenzahl of Advanced Energy Analysis. BNL has a license to use it.
- There are other codes available:
  - QUENCHPRO at FNAL Technical Division.
  - SPQR from CERN.
  - QLASA from INFN-Milano.
  - QUABAR.
  - Vector Fields is developing a quench propagation code.
    - Being beta tested now.

Circuit for Quench Energy Extraction

- Quench circuit components:
  - Solenoid represented by inductance L. Also there is an internal resistance (not shown) which is about 10 ohm.
  - R_{PR} represents the energy extraction resistance. This will take the large share of quench energy.
  - Switch will be activated by quench detection system.
    - Could even be a diode system.
  - R_{EXT} represents the resistance associated to leads, power supply, etc.

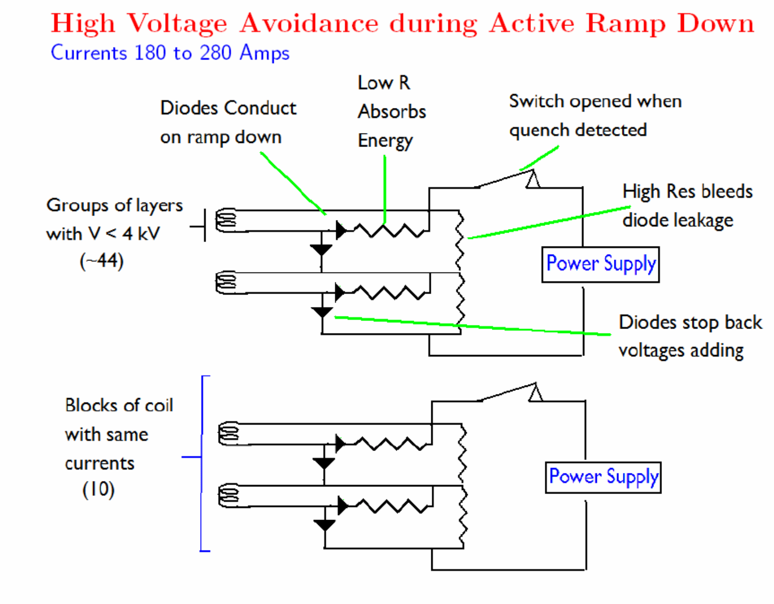


Circuit Parameters

- QUENCH treats the whole magnet. It does not provide for segmenting the magnet into separate coupled systems.
  - This means that the current has the same time-dependence throughout.
  - We shall ignore the Nb_3Sn outer coils.
    - We assume that they are sufficiently away from critical that they won't quench. Also that the Nb_3Sn coils will not affect the HTS (this may be a bad assumption).
  - The total inductance can be calculated from the stored energy:
    - $U=\frac{1}{2}LI^2$ where U=66 Mega-Joules and I=129 amps is the single turn current.
    - There are 672 layers × 250 turns/layer = 167821 turns.
    - This gives 8000 henrys (big!)
  - The resistance associated with 61 km of Ag is 8 ohms.
- We certainly will need to trigger an external resistance into the circuit with a quench is detected.

Quench Simulation

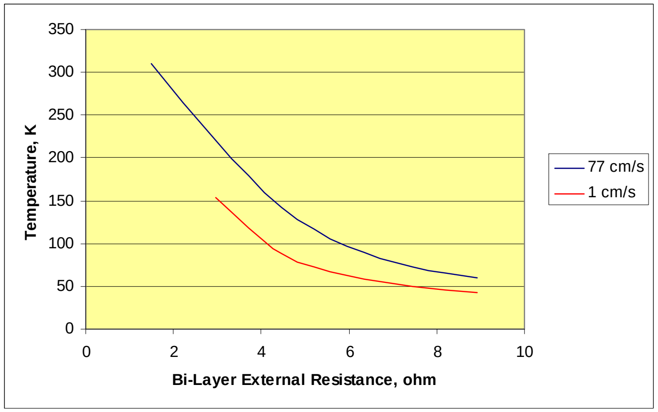
- We want to ramp the magnet down with a single time dependence. (This is all that *Quench* can do) we would like to segment the magnet into separate circuits with diodes.
  - This provides greater sensitivity to quench incidents.
  - This will prevent unreasonably large voltages across external resistances.
- Each sub-circuit consists of two adjacent conductor layers.
  - Quench detection circuitry can be put on one end of the magnet.
  - IGBT switches to include external resistance circuit when the quench is detected.

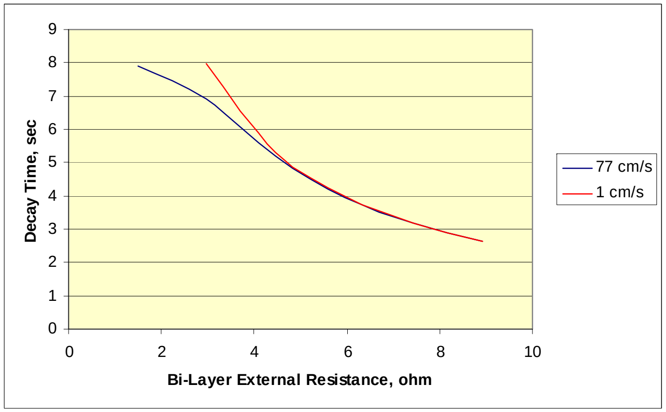

High Voltage Avoidance during Active Ramp Down

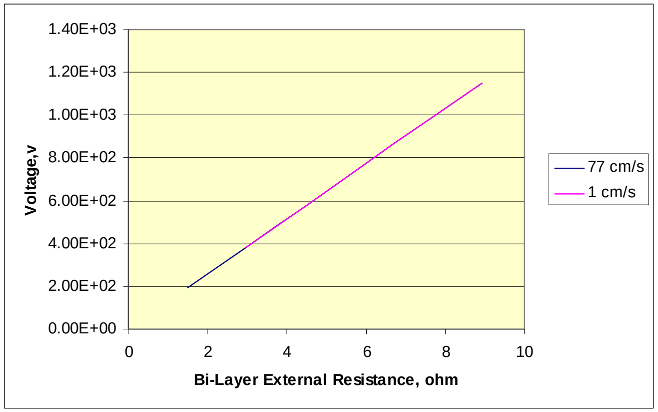
Currents 180 to 280 Amps

Quench Parameters as a Function of External Resistance

- The figures show the following parameters as a function of an external resistance for energy extraction.
  - Maximum temperature on conductor
  - Time constant for decay
  - External voltage on external resistance
- Note that as one increases the external resistance one decreases temperature, but increases the external voltage.



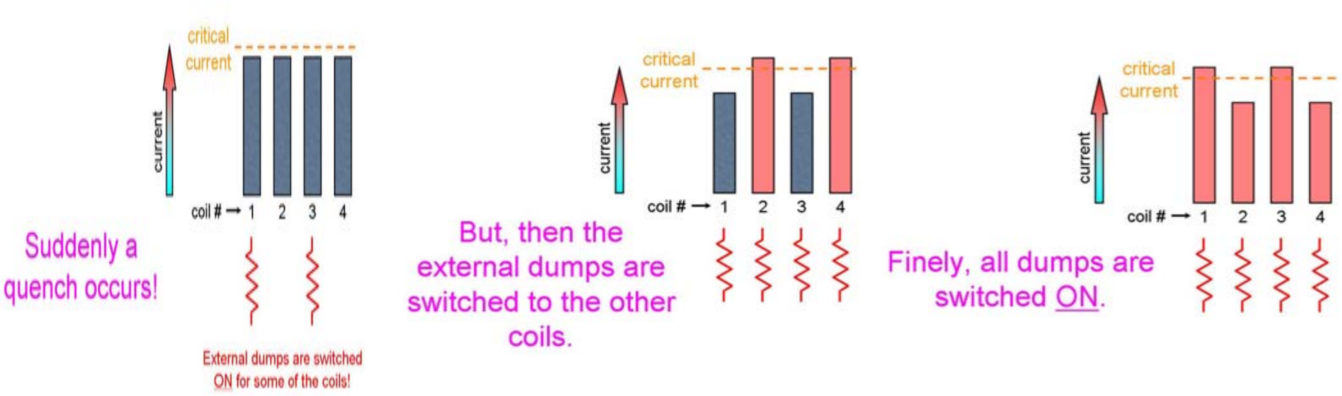




Quench Detection

- Typical quench detection circuits used for LHC and the 25 T NHMFL Solenoid(with HTS insert) trigger at 200-250 mV.
  - This corresponds to ~4 cm of "Ag resistance" or 1 sec detection time.
  - A "back of the envelop" calculation of ΔT gives ~150°K.
    - Caveat: C_v varies as T^3 so one needs to do a proper integration over time which can change this significantly.
  - We would like to keep $\Delta T < 200°K$ if possible to avoid potential damage to the conductor (from micro-cracking)
  - If we can detect a quench at 0.1 sec (trigger at 10-25 mV) we would gain significantly.
    - We anticipate that the time constant to remove the field to be ~1-10 sec.

An Alternate Approach to Remove Energy



Suddenly a quench occurs!

External dumps are switched ON for some of the coils!

But, then the external dumps are switched to the other coils.

Finely, all dumps are switched ON.

This idea was suggested by R. Flora.

- When a quench occurs, the detection circuit triggers *some* of the dump resistors.
- Energy is transferred to adjacent coils inductively such that they will induce a quench in those coils.
- The dump resistors of the remaining coils are turned on.
- This approach would spread the quench throughout the magnet without adding energy from external sources as heaters. This should permit a faster ramp-down of the magnet in a controlled manner.

A Program to Study Quench Protection for HTS Magnets

- Muons Inc has submitted an SBIR proposal with Fermilab to study protection of HTS magnets.
    - We would like to setup a test station to study quench detection of HTS magnets.
    - We would like to investigate techniques to detect quenches in ~10 ms with amplitudes of ~10 mV.
- It is clear from this initial calculation that some parameters are not well known. We should try to measure them.
    - Electrical resistivity and heat capacity of HTS conductor as a function of temperature. This should be done above critical current.
    - Same measurements of Silver as a control.
    - Determine $I_c(B)$ at high field. Verify that the critical current relation that we used (which was developed for NbTi, Nb_3Sn) works for HTS.
    - Measure the quench propagation velocity. This is important.