

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DEPARTMENT OF NUCLEAR ENGINEERING

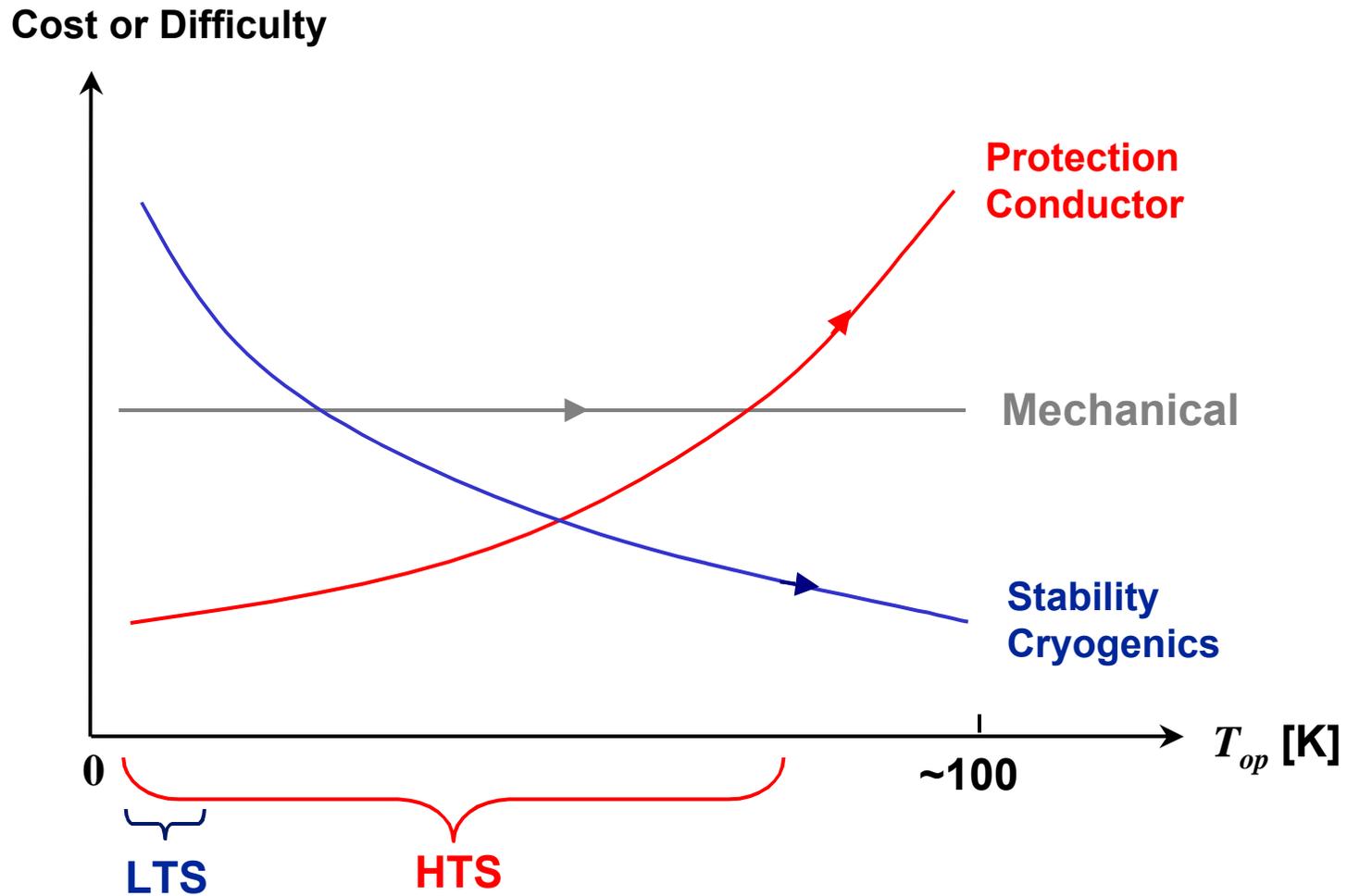
2.64J/22.68J Spring Term 2003

May 8, 2003

Lecture 10: Protection & HTS Magnets

- **Key magnet issues vs. T_{op} ; Areas of failure in superconducting magnets**
- **Key problems: overheating; high voltage; overstressing; over pressure**
- **Protection against overheating: self-protecting magnets; normal zone propagation; active protection; detection of quench**
- **High voltage — driven mode & persistent mode; overstressing**
- **Over pressure—bath cooled & CICC**
- **HTS Magnets & Issues**
- **Bi-2223/Ag Data**
- **YBCO composite**
- **$J_c(B)$ data @ 4.2, 10, and 20 K of superconductors**
- **1-D NZP of YBCO: Energy margin & NZP velocity (FSU/NHMFL)**
- **Stability experiment & simulation of YBCO at 77 K (MIT)**
- **1-D NZP of YBCO: Energy margin & NZP velocity (ORNL)**

Key Magnet Issues vs T_{op}



Areas of Failure in Superconducting Magnets

In the order of decreasing reported incidents.

- **Insulation**
- **Mechanical**
- **System performance**
- **Conductor**
- **External system**
- **Coolant**

Key Quench-Induced Problems

- **Overheating**
- **High voltage**
- **Overstressing**
- **Over pressure**

Overheating

Energy Conversion

$$\frac{B_0^2}{2\mu_0} = h_{cu}(T_m) - h_{cu}(T_{op}) = 5.2 \times 10^9 \text{ J/m}^3$$

\uparrow \uparrow
1356 K **4.2 K**

$$B_0 = 115 \text{ T}$$

- For a uniform energy conversion over the entire winding, a quench-induced T_{max} will remain <100 K, an upper limit to keep the differential thermal expansion stresses negligible.

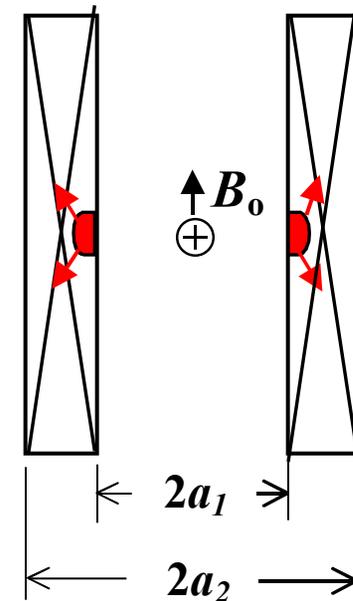
Protection Against Overheating

1. Self-Protecting Magnets

- **Normal zone propagation** speed, U_{nzp} , fast enough to spread normal zone over **most of the winding volume** from a localized “hot spot” initially created. Specifically, a self-protecting magnet must satisfy:

$$\tau_{decay} > \sim \frac{a_2 - a_1}{U_{nzp}}$$

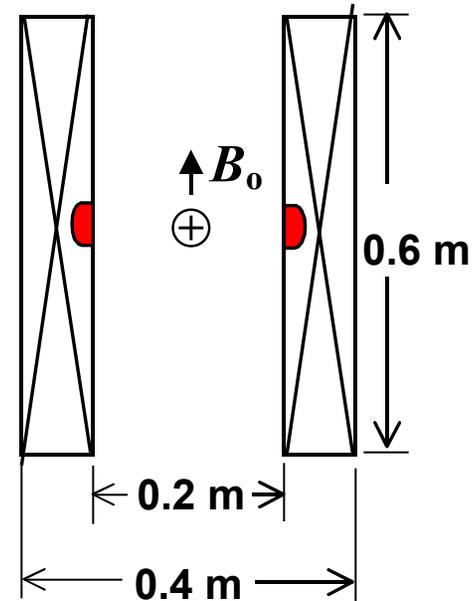
- **“Large”** magnets are **not** self-protecting.
- $[U_{nzp}]_{HTS} \ll [U_{nzp}]_{LTS}$: **HTS** magnets **not** self-protecting.



An Example

- $B_0 = 8 \text{ T}$
- $E_{mg} = 10^6 \text{ J}$
- Winding volume = 0.06 m^3 ($\sim 2 \text{ ft}^3$)

Winding % Absorbing E_{mg}	T_f [K]	Remarks
100	55	Well below 100 K
50	70	< 100 K
10	130	Barely acceptable
1	580	Unacceptable



Normal Zone Propagation Velocity

Along Wire Axis--No Matrix

$$C_n \frac{\partial T_n}{\partial t} = \frac{\partial}{\partial z} \left(k_n \frac{\partial T_n}{\partial z} \right) + \rho_n J^2 \quad \text{(normal state)}$$

$$C_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \left(k_s \frac{\partial T_s}{\partial z} \right) \quad \text{(Superconducting state)}$$

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial z} \frac{\partial z}{\partial t} = -U_\ell \frac{\partial T}{\partial z} \quad (U_\ell: \text{longitudinal velocity})$$



$$-C_n U_\ell \frac{dT_n}{dz} = \frac{d}{dz} \left(k_n \frac{dT_n}{dz} \right) + \rho_n J^2$$

$$-C_s U_\ell \frac{dT_s}{dz} = \frac{d}{dz} \left(k_s \frac{dT_s}{dz} \right)$$

Assume k_n , k_s , and $d^2 T_n / dz^2 \approx 0$ near $z = 0$

$$C_n U_\ell \frac{dT_n}{dz} + \rho_n J^2 = 0 \quad (z < 0)$$

$$k_s \frac{d^2 T_s}{dz^2} + C_s U_\ell \frac{dT_s}{dz} = 0 \quad (z > 0)$$

$$T_s(z) = A e^{-cz} + T_{op} \quad C = \frac{C_s U_\ell}{k_s}$$

$$\text{At } z = 0 \quad T_s(0) = T_c$$

$$T_s(z) = (T_c - T_p) e^{-(C_s U_\ell / k)z} + T_{op}$$

$$\text{At } z = 0 \quad k_n (dT_n/dz) = k_s (dT_s/dz)$$

$$-\frac{k_n \rho_n J^2}{C_n U_\ell} = -C_s U_\ell (T_c - T_{op})$$

$$U_\ell = J \sqrt{\frac{\rho_n k_n}{C_n C_s (T_c - T_{op})}}$$

$$C_s = C_n = C_0$$

$$U_\ell = \frac{J}{C_0} \sqrt{\frac{\rho_n k_n}{(T_c - T_{op})}}$$

- $U_l \propto J$
- $U_l \propto 1/C_0 \Rightarrow [U_l]_{hts} \ll [U_l]_{lts}$

In the presence of normal metal matrix:

$$U_\ell = \frac{J_m}{C_{cd} \sqrt{\frac{\rho_m k_m}{(T_{cs} - T_{op})}}}$$

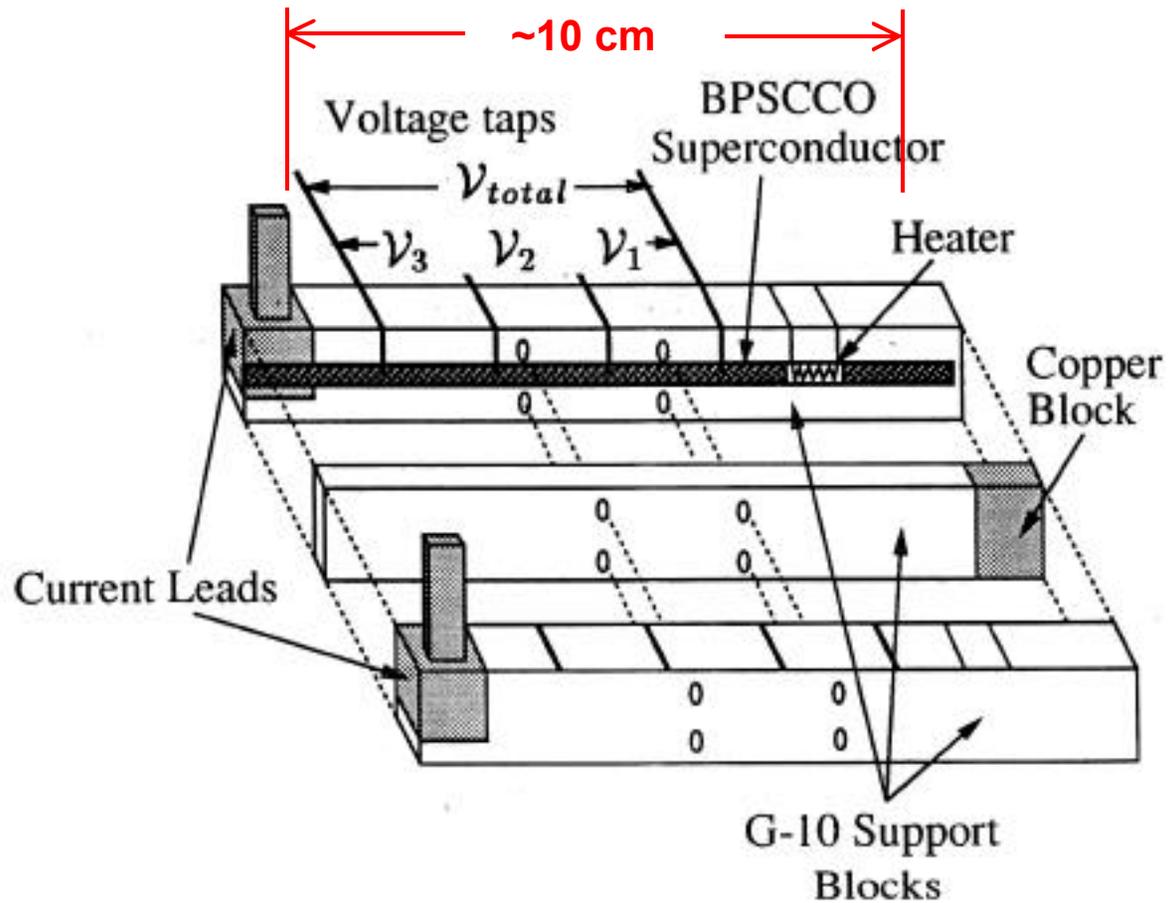
Note that $T_{cs} = T_t$

With $C_n(T)$, $C_s(T)$, $k_n(T)$:

$$U_\ell = J \sqrt{\frac{\rho_n(T_{cs})k_n(T_{cs})}{\left[C_n(T_{cs}) - \frac{1}{k_n(T_{cs})} \frac{dk_n(T)}{dT} \Big|_{T_{cs}} \int_{T_{op}}^{T_{cs}} C_s(T) dT \right] \int_{T_{op}}^{T_{cs}} C_s(T) dT}}$$

Note that $T_{cs} = T_t$

1-D “Adiabatic” NZP—Experimental & Simulation Results



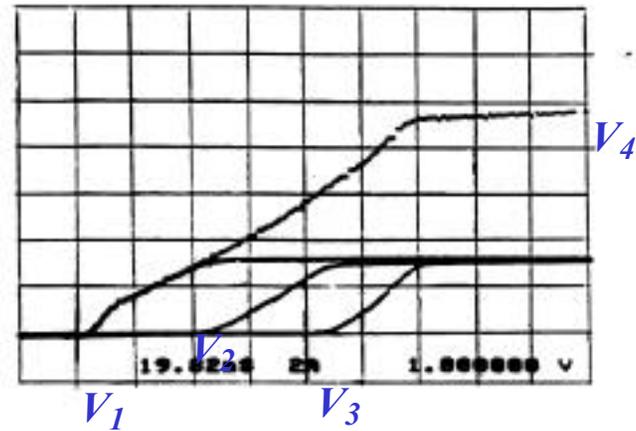
Slides 13-15: from R.H. Bellis and Y. Iwasa (*Cryogenics*, Vol. 34 1994)

Y. Iwasa (05/08/03)

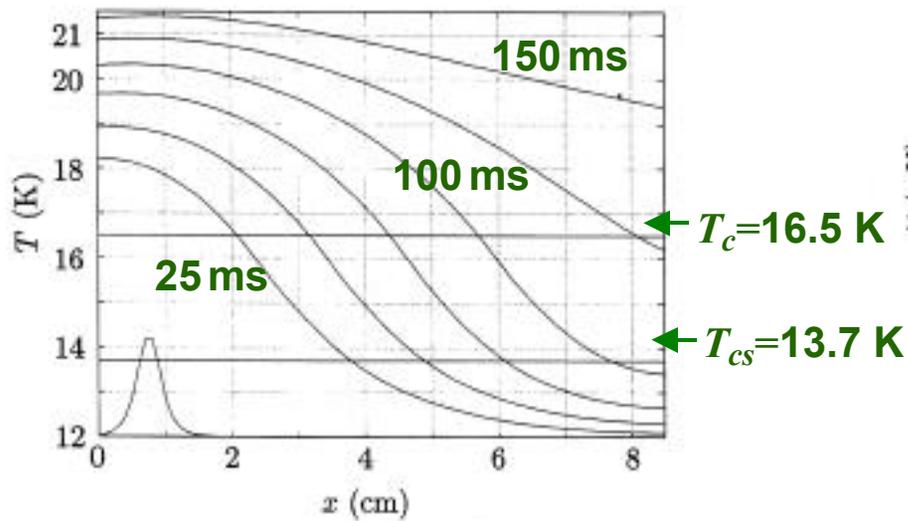
Nb₃Sn Tape @ 12 K & 225 A

$U_1 = 50$ cm/s

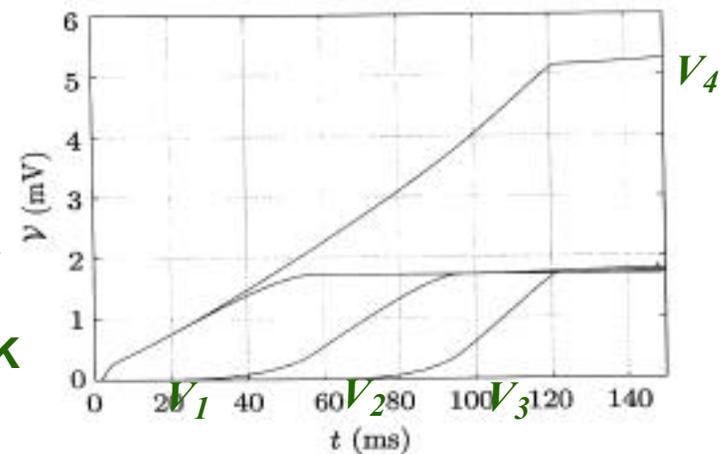
Experimental



Temperature Simulation



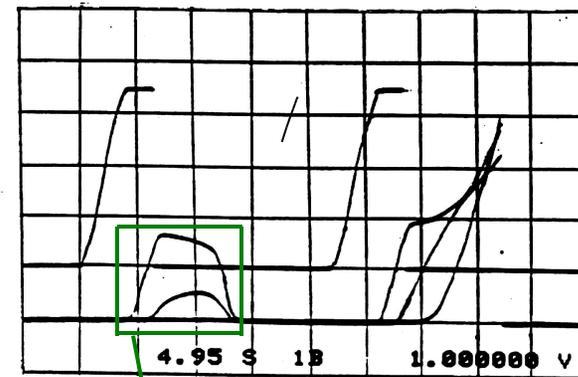
Simulation



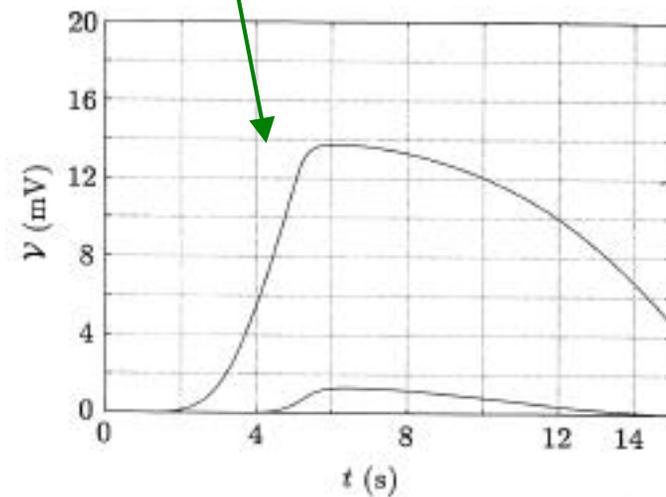
Bi-2223/Ag Tape @ 14 K & 100 A

$$[U_l]_{hts} = 1 \text{ cm/s} \ll [U_l]_{lts}$$

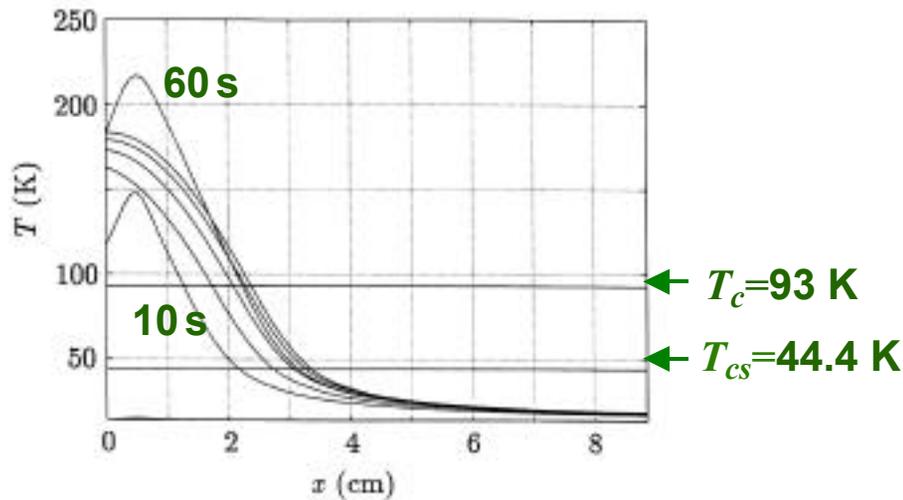
Experimental



Simulation



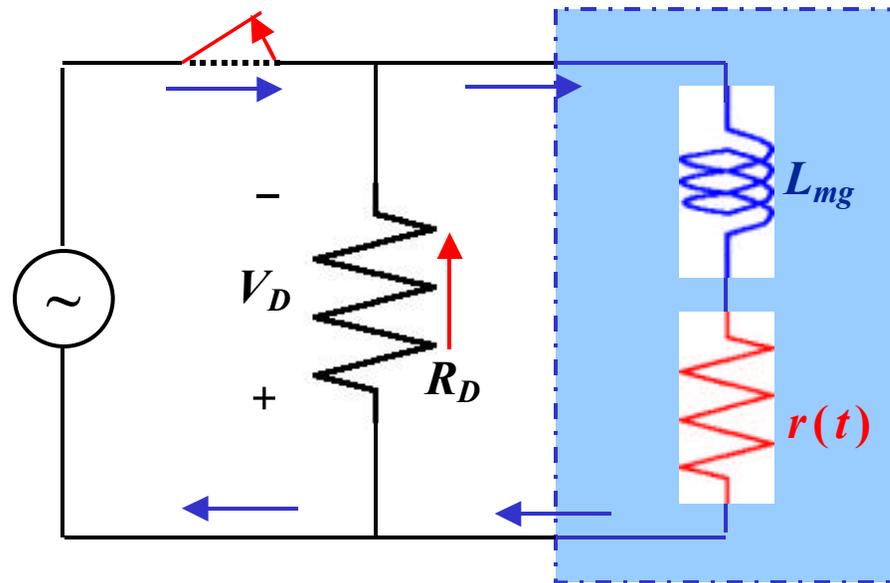
Temperature Simulation



2. Active Protection

“Detect-and-Dump”

- Widely used in large magnets.
- Dissipates most of the stored magnet energy into a “dump resistor” connected across the magnet terminals.
- A “hot spot” heated only over a “brief” period of current decay.
- Leads to another criterion for operating current density.



$$L_{mg} \frac{dI(t)}{dt} + [r(t) + R_D] I(t) = 0$$

For $r(t) \ll R_D$:

$$L_{mg} \frac{dI(t)}{dt} + R_D I(t) = 0 \Rightarrow I(t) = I_\phi \exp\left(-\frac{R_D t}{L_{mg}}\right) \Rightarrow J_m(t) = [J_{op}]_m \exp\left(-\frac{R_D t}{L_{mg}}\right)$$

With $g_k = g_d = g_q = 0$:

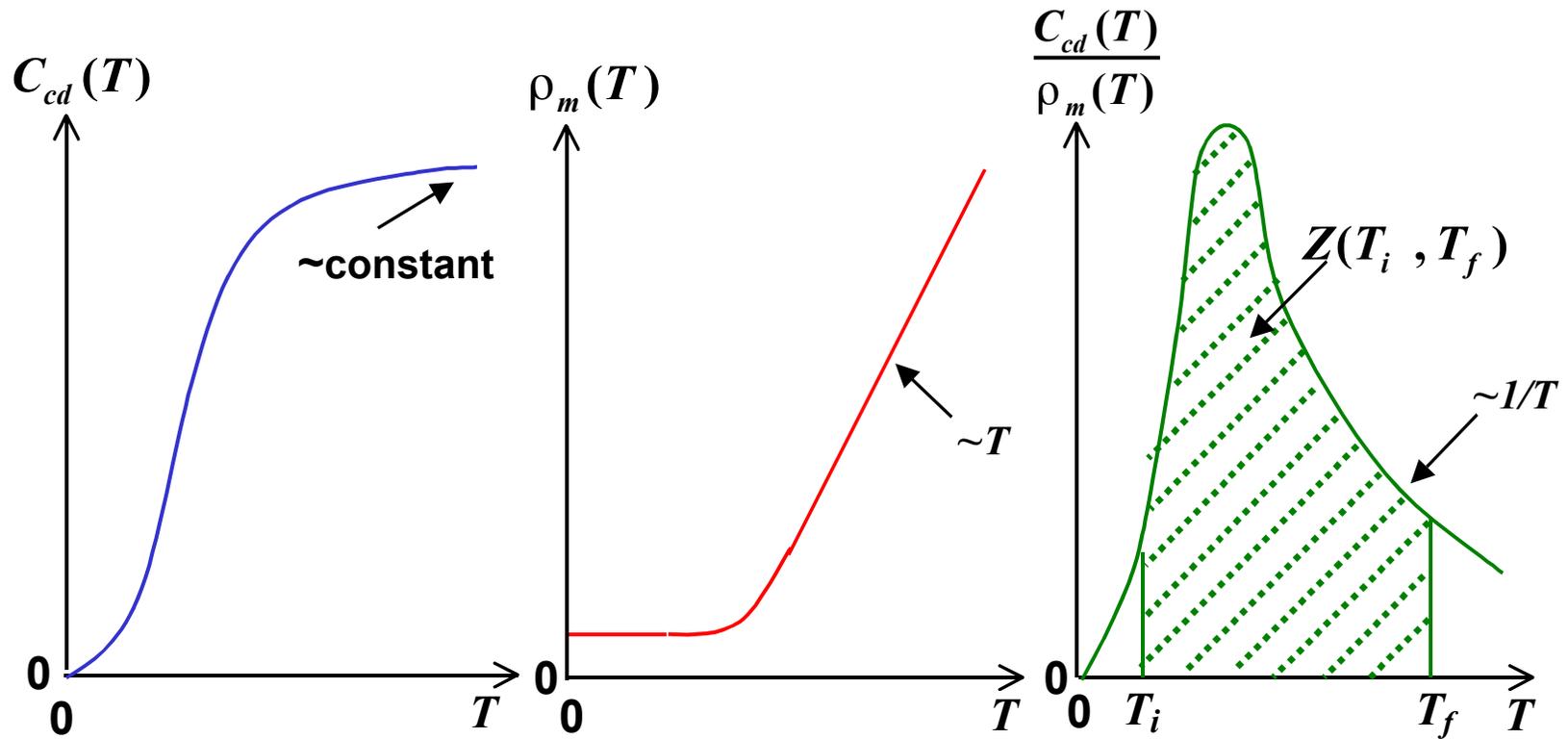
$$A_{cd} C_{cd}(T) \frac{dT}{dt} = \frac{\rho_m(T)}{A_m} I^2(t) \Rightarrow C_{cd}(T) \frac{dT}{dt} = \rho_m(T) \left(\frac{A_m}{A_{cd}}\right) J_m^2(t)$$

$$\frac{C_{cd}(T)}{\rho_m(T)} dT = \left(\frac{A_m}{A_{cd}}\right) [J_\phi]_m^2 \exp\left(-\frac{2R_D t}{L_{mg}}\right) dt$$

$$\int_{T_i}^{T_f} \frac{C_{cd}(T)}{\rho_m(T)} dT \equiv Z(T_i, T_f) \geq \left(\frac{A_m}{A_{cd}}\right) [J_\phi]_m^2 \int_0^\infty \exp\left(-\frac{2R_D t}{L_{mg}}\right) dt = \left(\frac{A_m}{A_{cd}}\right) [J_{op}]_m^2 \frac{L_{mg}}{2R_D}$$

$$Z(T_i, T_f) \geq \left(\frac{A_m}{A_{cd}}\right) [J_{op}]_m^2 \frac{L_{mg}}{2R_D} = \left(\frac{A_m}{A_{cd}}\right) [J_\phi]_m^2 \frac{2E_{mg}/I_\phi^2}{2V_D/I_\phi} = \left(\frac{A_m}{A_{cd}}\right) [J_{op}]_m^2 \frac{E_{mg}}{V_D I_\phi}$$

$$Z(T_i, T_f) \equiv \int_{T_i}^{T_f} \frac{C_{cd}(T)}{\rho_m(T)} dT$$



$Z(T)$ Functions:

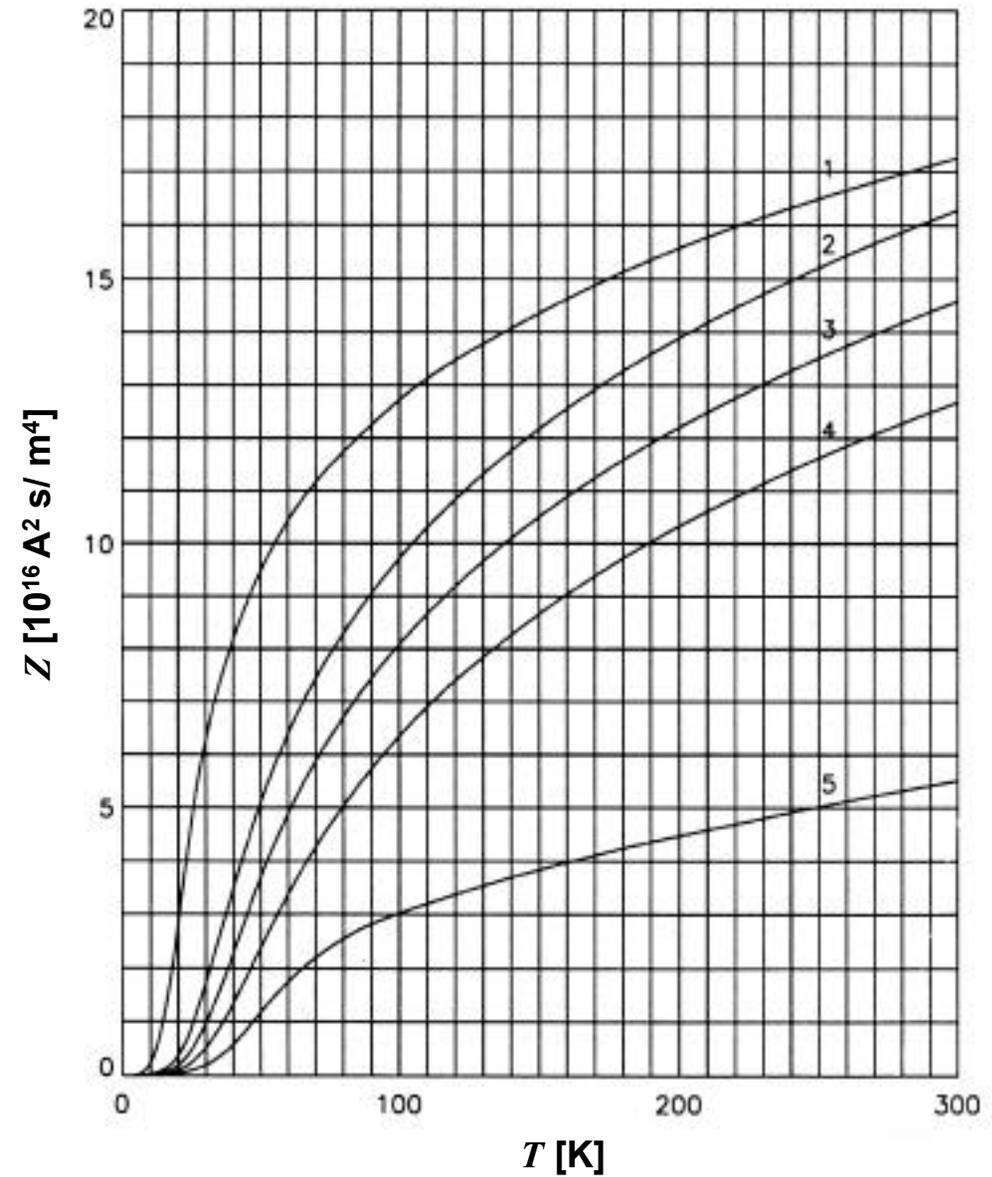
1: Ag (99.99%)

2: Cu (RRR 200)

3: Cu (RRR 100)

4: Cu (RRR 50)

5: Al (99.99%)



“Protection” Criterion

$$[J_{op}]_m \leq \sqrt{\left(\frac{A_{cd}}{A_m}\right) \frac{V_D I_{op} Z(T_i, T_f)}{E_{mg}}}$$

“Cryostable” Criterion

$$[J_{op}]_{cd} \leq \sqrt{\frac{f_p P_{cd} A_m q_{fm}}{\rho_m (A_s + A_m)^2}}$$

***Detect-and Dump* : Options to improve $[J_{op}]_m$**

1. Increase I_{op}

- ⊖ Larger conductor; more expensive for given kA-m**
- ⊖ Larger current leads--greater heat input**
- ⊖ Larger ($I \times B$) force**
- ⊖ For a given power rating VI , higher I more expensive**

2. Increase V_D

- ⊖ Increased danger of voltage breakdown, particularly > 800 V in helium environment**

3. Increase $Z(T_f)$

- ⊖ Better to keep T_f below ~ 100 K-150 K**
- ⊖ Cu better than Al**

4. Reduce E_{mg}

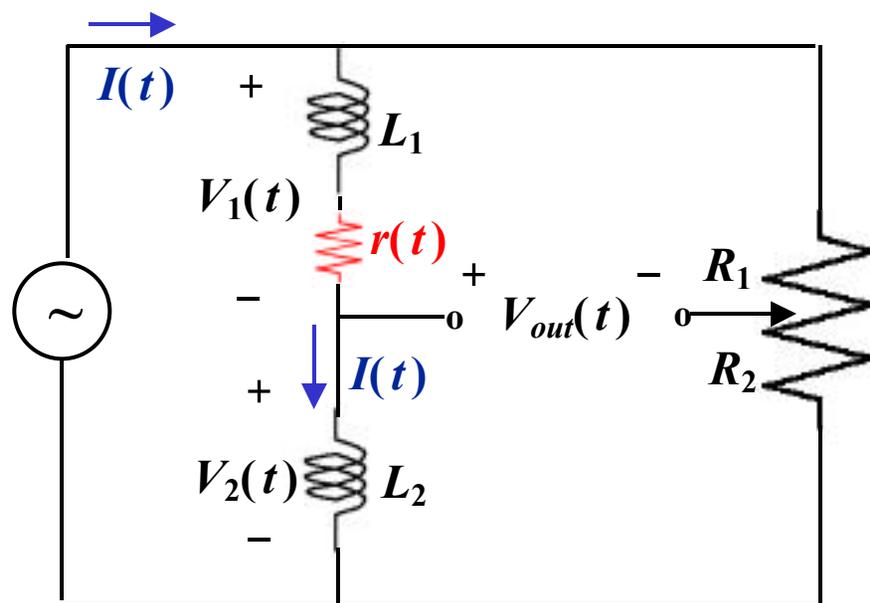
- ⊖ Subdivision—common practice with HEP & Fusion magnets**

Detection of Non-Recovering Quench

$$V_1(t) = L_1 \frac{dI(t)}{dt} + r(t)I(t) \quad V_2(t) = L_2 \frac{dI(t)}{dt}$$

$$V_{at}(t) = V_2(t) - V_1(t)$$

$$R_2 L_1 = R_1 L_2 \Rightarrow V_{out}(t) = -\left(\frac{R_2}{R_1 + R_2}\right)r(t)I(t)$$



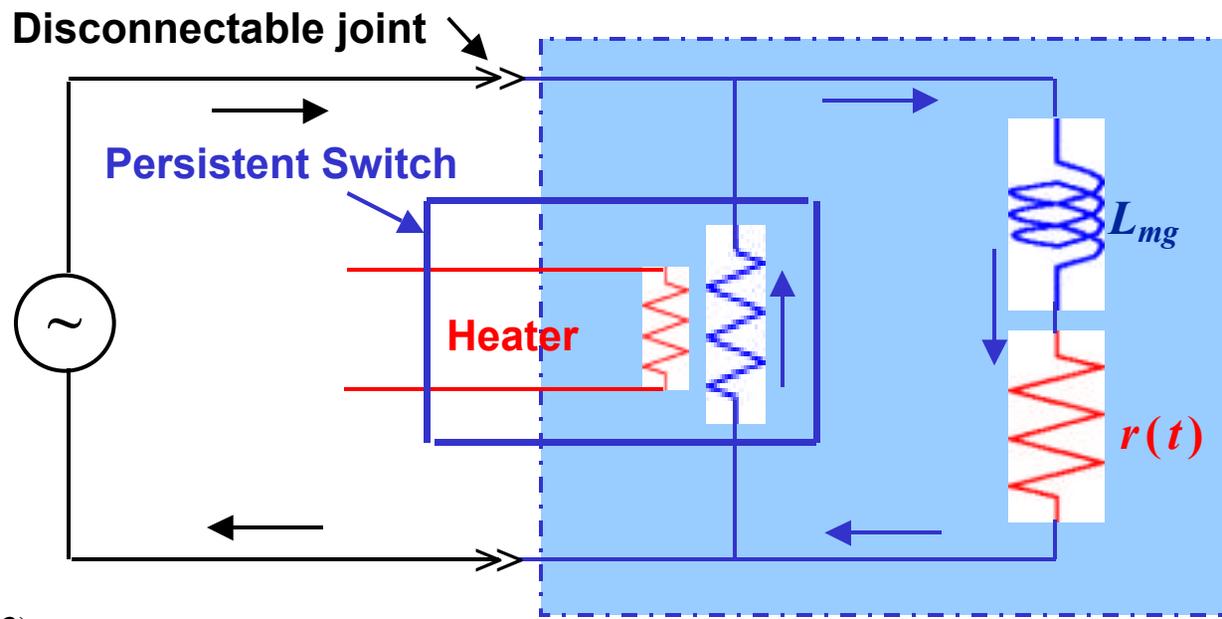
High Voltage

- **Driven mode magnet, i.e., operated with its power supply generally connected, except during a dump.**
 - **High voltage, i.e., V_D , appears across the magnet terminals.**
- **Persistent mode magnet, i.e., operated with its power supply removed, except when the magnet is being charged.**
 - **Terminal voltage is *zero*; high *internal* voltage may be induced.**

Persistent Mode Operation

Operation Steps

1. With persistent switch (PS) **resistive (heater on)**, energize the magnet.
2. Turn off the heater; PS becomes **superconducting**; slowly bring the supply current back to zero.
3. Disconnect the current leads from the magnet terminals.
4. Magnet now operates in “persistent mode.”



Persistent Mode Operation (Continued)

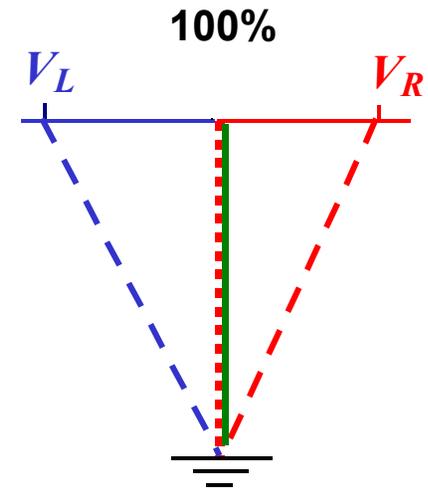
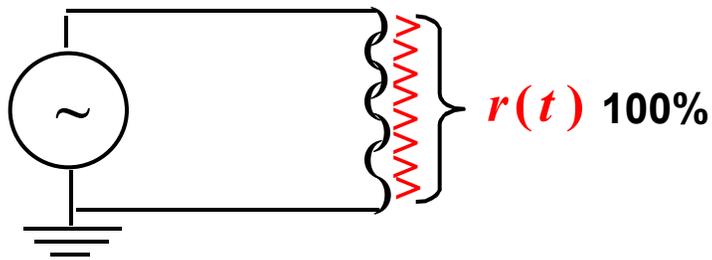
r(t) represents:

- 1. quench-induced *variable* resistance; may lead to a high internal voltage *OR***
- 2. “small” *constant* resistance by imperfect splices; causes a “slow” field decay (time constant= L_{mg}/r) in NMR & MRI magnets:**

$$B(t) = B_0 e^{-(r/L_{mg})t} \cong B_0 \left(1 - \frac{r}{L_{mg}} t \right) \quad (\text{for } L_{mg}/r \ll 1 \text{ hr})$$

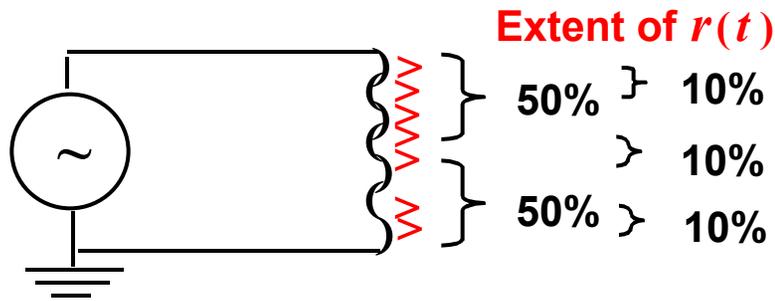
Internal Voltage In Persistent Mode Magnet

- No internal voltage in a uniformly (100%) resistive magnet.
- Internal voltage in a partially resistive magnet.
- Large voltages can occur when a resistive zone confined to a small section.

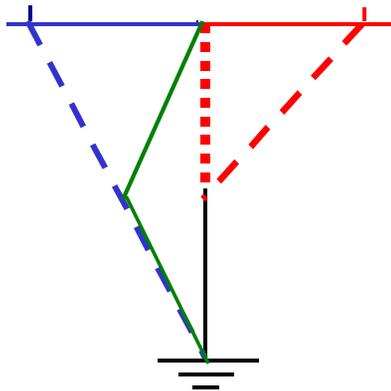


No internal voltage

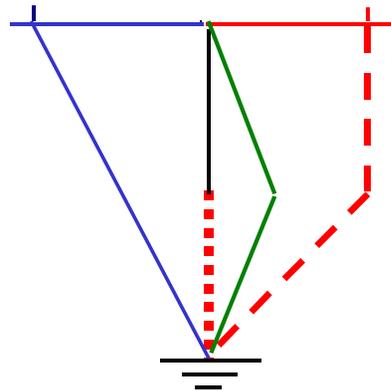
Internal Voltage in Persistent Mode



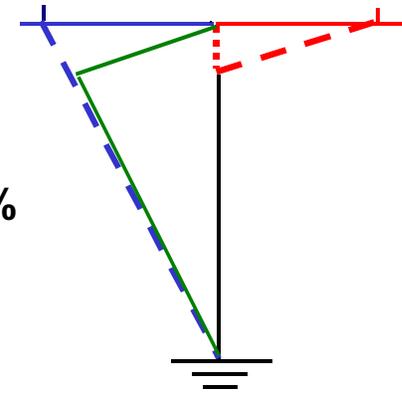
Top 50%



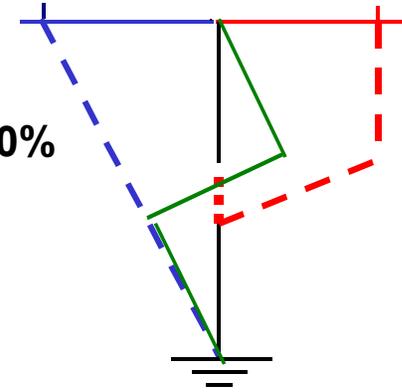
Bottom 50%



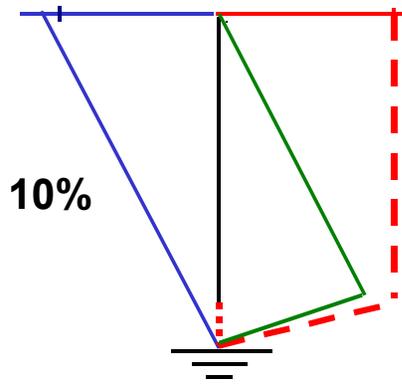
Top 10%



Middle 10%

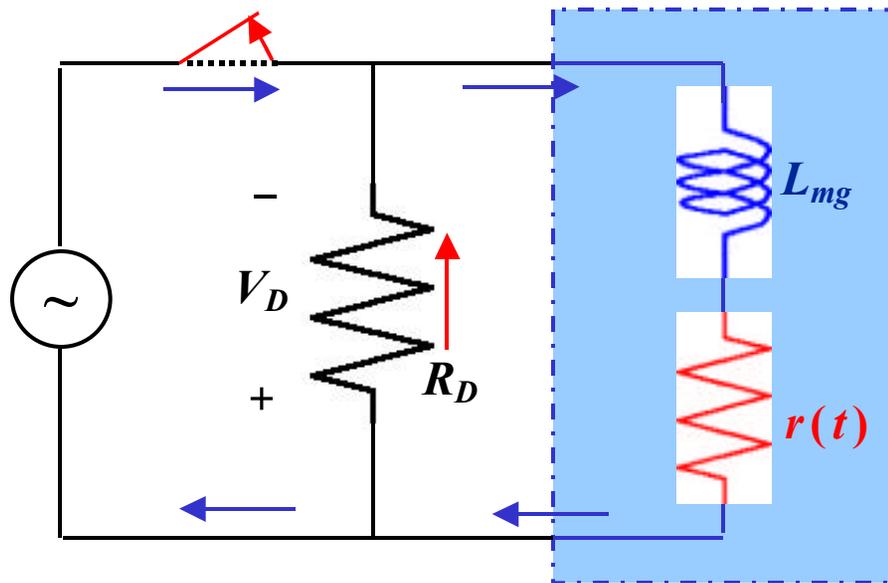


Bottom 10%

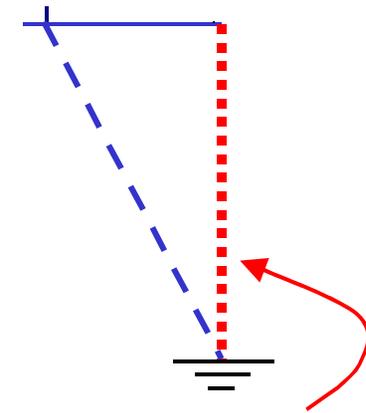


Internal Voltage In Driven Mode Magnet

- For $R_D \gg r(t)$, internal voltage is essentially due to the inductive voltage. The maximum inductive occurs at $t=0$ and it is equal V_D .



$$V_L \cong V_D (R_D \gg r)$$



Effect of $r(t)$ is neglected.

Overstressing

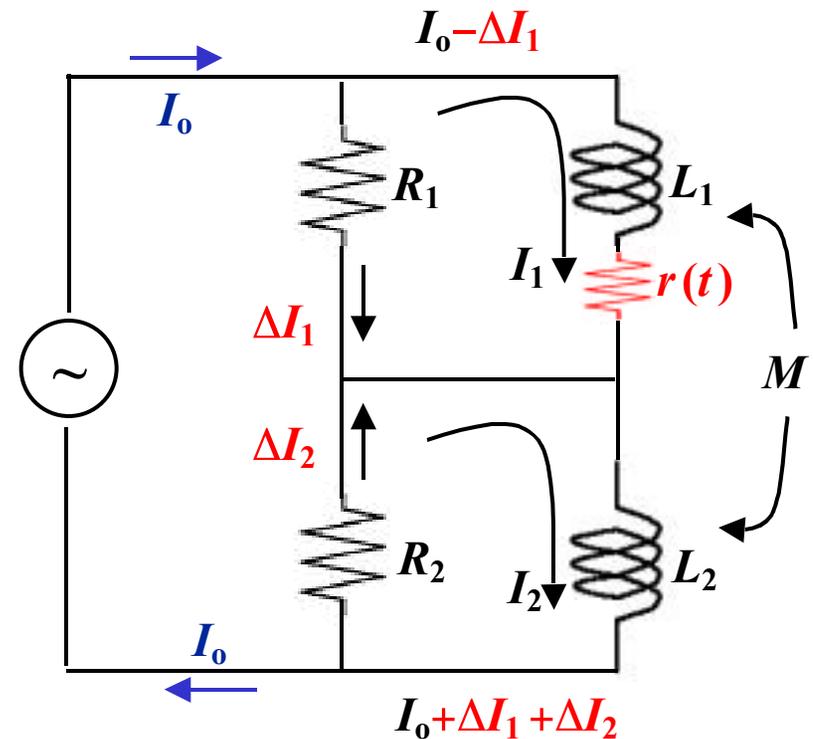
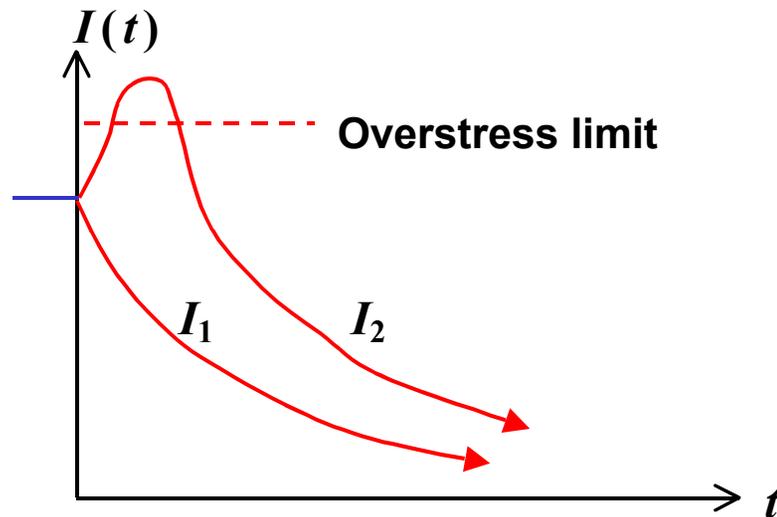
- **Overstressing generally occurs in a multi-coil system.**
 - **A quench in one coil increases the current in the rest of the coils—this is good for PROTECTION, because this increased current accelerates spreading of normal zones in the rest of the coils by inducing quenches in these coils.**
 - **This increased current may also cause overstressing in these coils.**

Overstressing (& Protection)

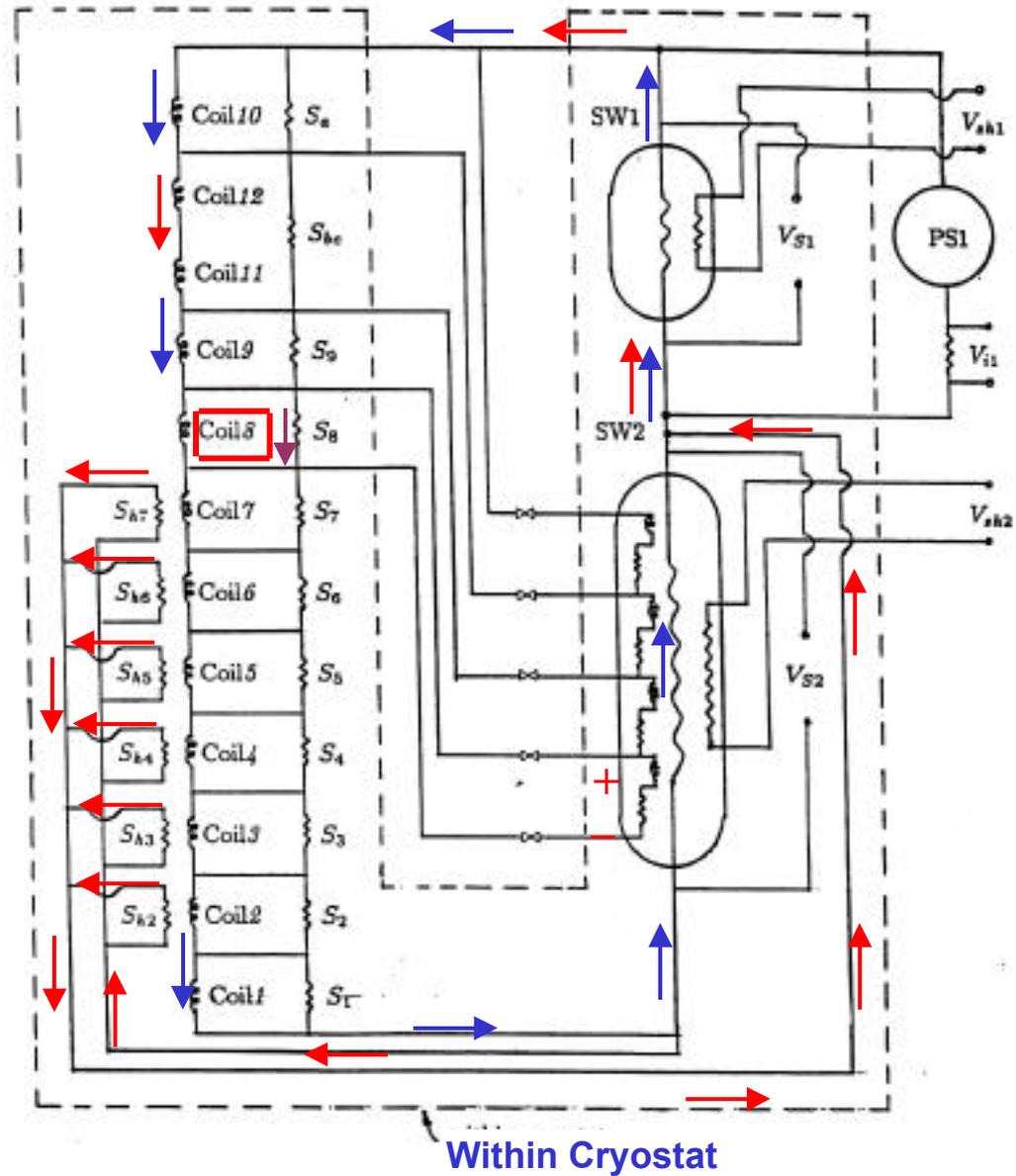
Example: 2-Coil System

A quench in Coil 1 induces an extra current in Coil 2.

1. Helps spreading out normal zone faster and over a large volume.
2. May overstress Coil 2



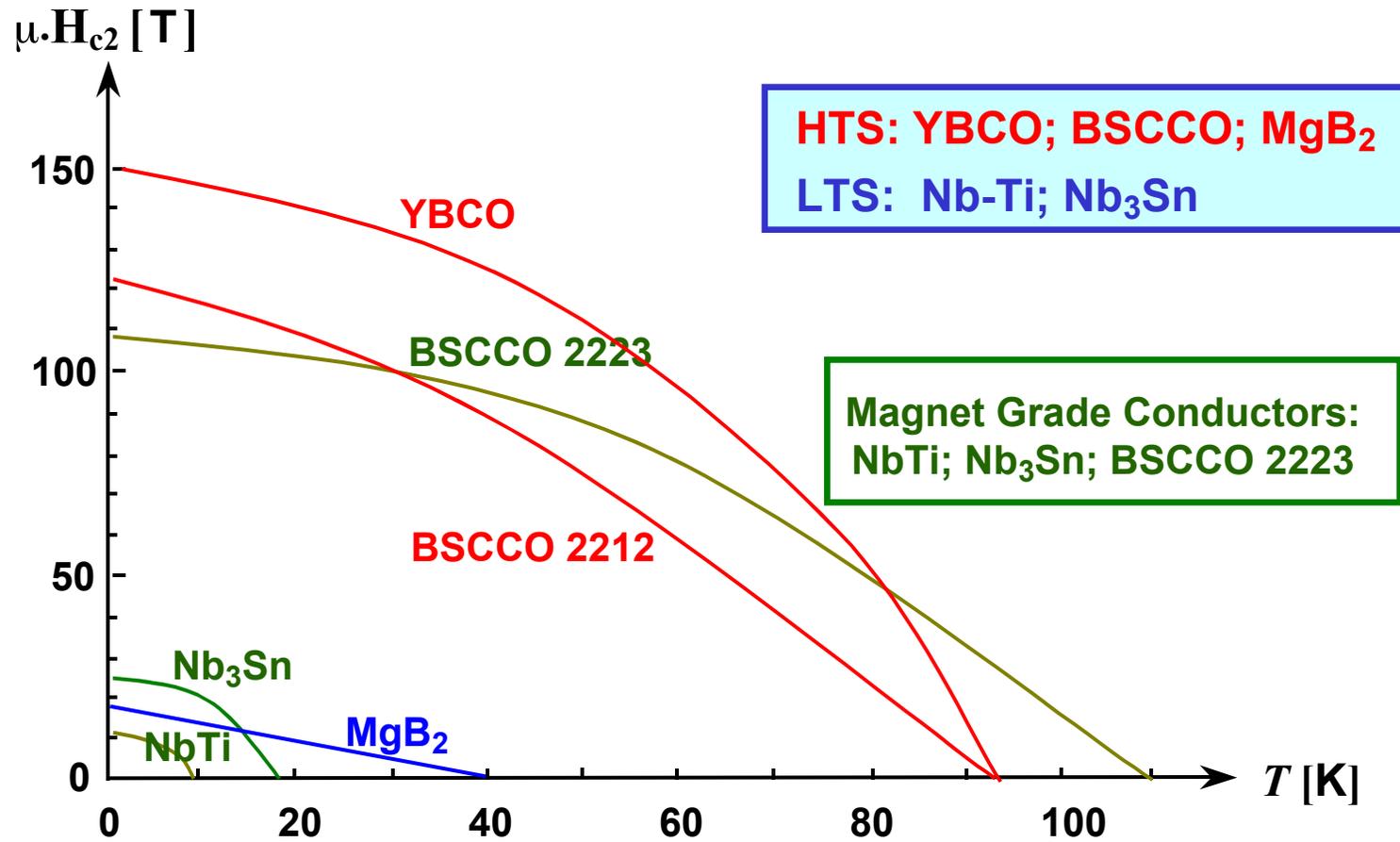
Protection Circuit for an NMR Magnet



Over Pressure

- **In every superconducting magnet system, driven, persistent, in which coolant is cryogen (helium, nitrogen), a quench generally causes generation of vapor within the cryostat, raising the cryostat pressure above a safe limit (no greater than $\sim 1/3$ atm).**
 - **Cryostat must be equipped with a relief valve or a “burst” disk to permits a rapid release of the vapor from the cryostat.**
- **For CICC there is another problem of having to estimate the internal pressure generated in CICC.**
 - **Conduit thickness and vent line diameter must be sized according to the maximum quench-induced internal pressure.**

HTS Magnets & Issues



HTS

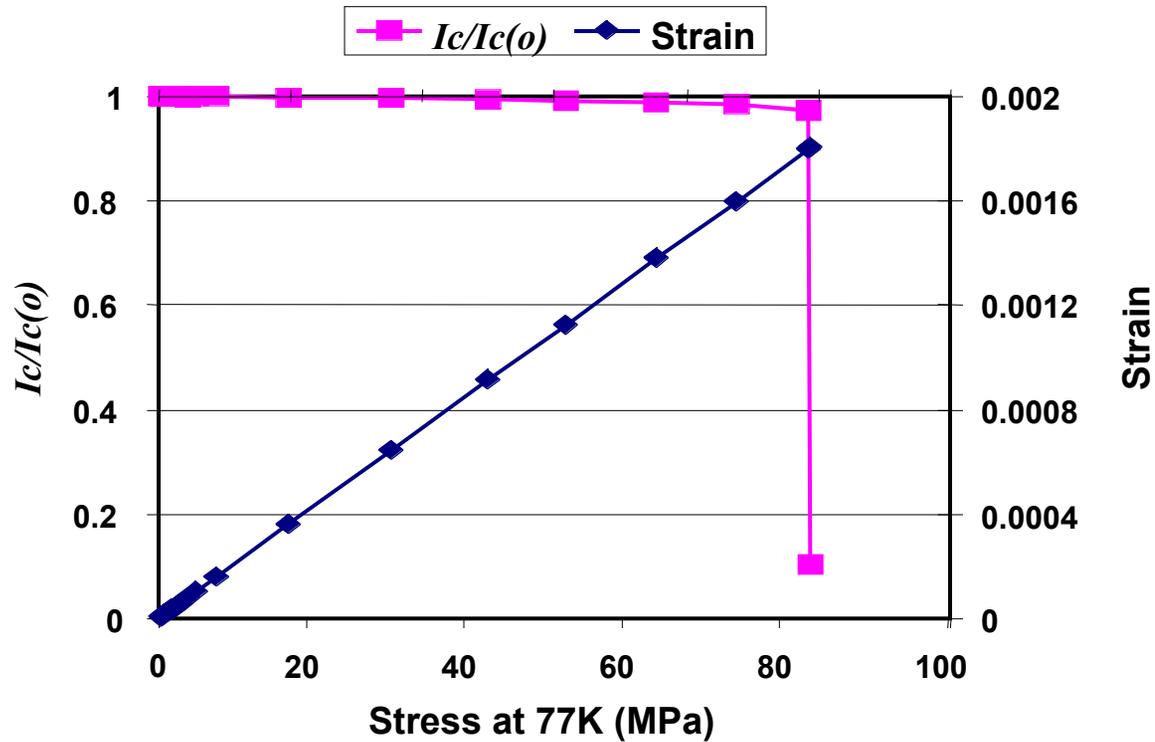
- **BSCCO 2223 currently available as “magnet grade conductor.”**
 - **Powder in Ag tube**
- **BSCCO 2212 being developed but not easily available.**
- **YBCO, compared with BSCCO, regarded more promising for electric power devices.**
- **MgB₂ also regarded promising, because of its low cost.**

Bi-2223 High Current Density Wire: Non-Reinforced

Thickness (avg): 0.21 (+/-0.02mm)
Width (avg): 4.1 (+/- 0.2mm)
Min. Critical Stress: 75 MPa
Min. Critical Strain: 0.15%
Min. Bend Dia: 100 mm

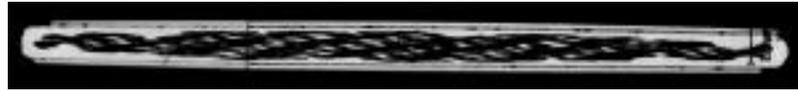


Variable Specifications:
Min. I_c : 115 A—135 A
Piece Length: 100 m —200 m



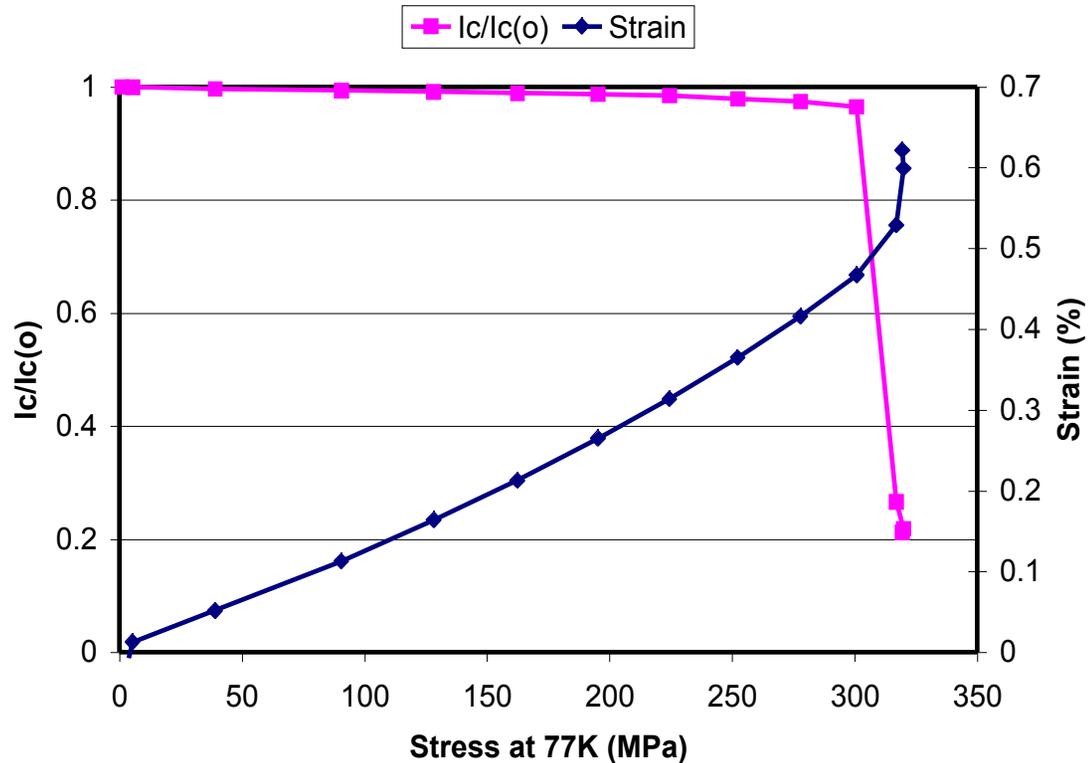
Slides 35-39: Based on American Superconductor Corp. Data Sheets

Bi-2223 High Strength Reinforced Tape

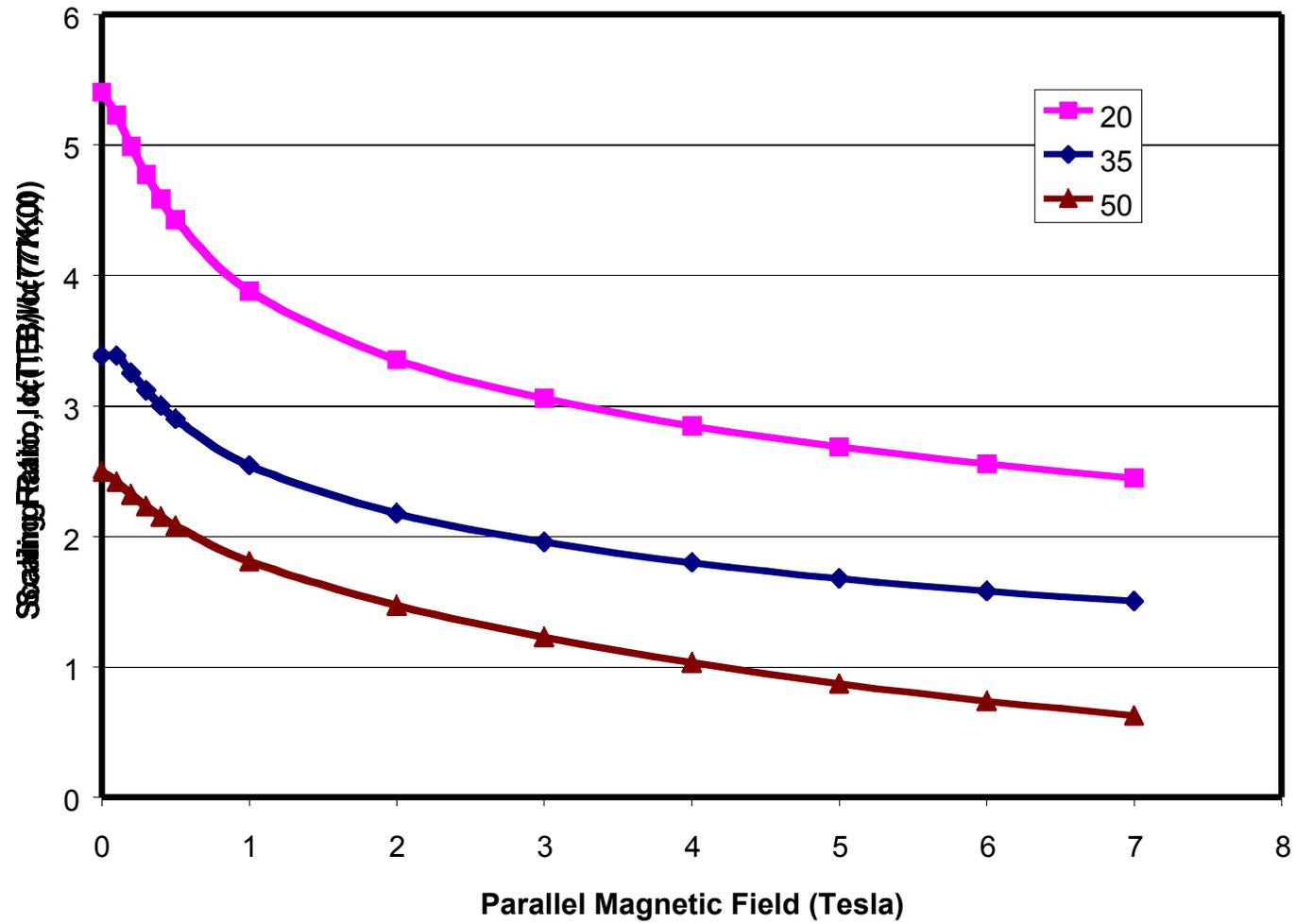


Thickness (avg): 0.31 (+/-0.02mm)
Width (avg): 4.1 (+/- 0.2mm)
Min. Critical Stress: 265 MPa
Min. Critical Strain: 0.4%
Min. Bend Dia: 70 mm

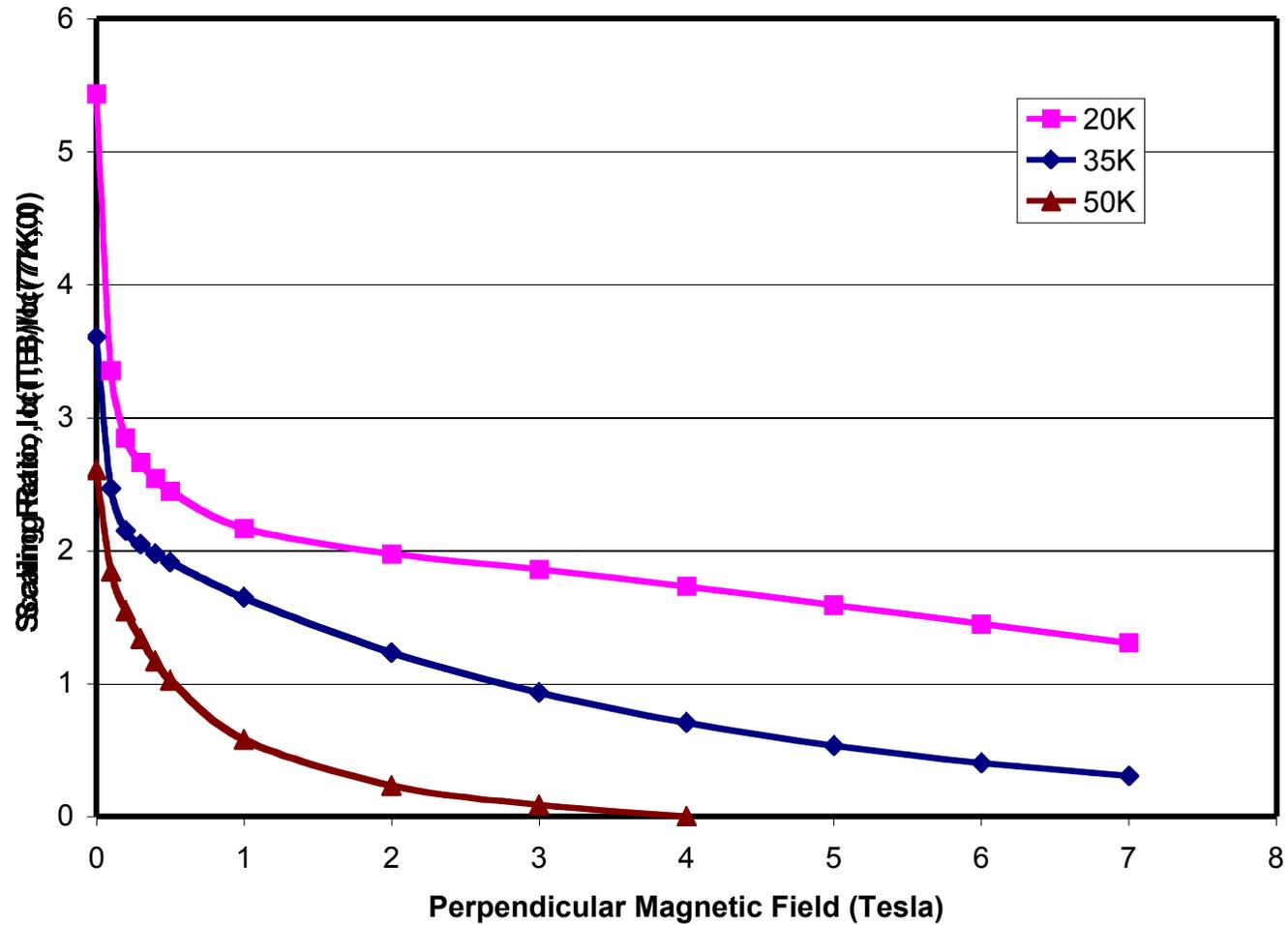
Variable Specifications:
Min. I_c : 115 A—135 A
Piece Length: 100 m —300 m



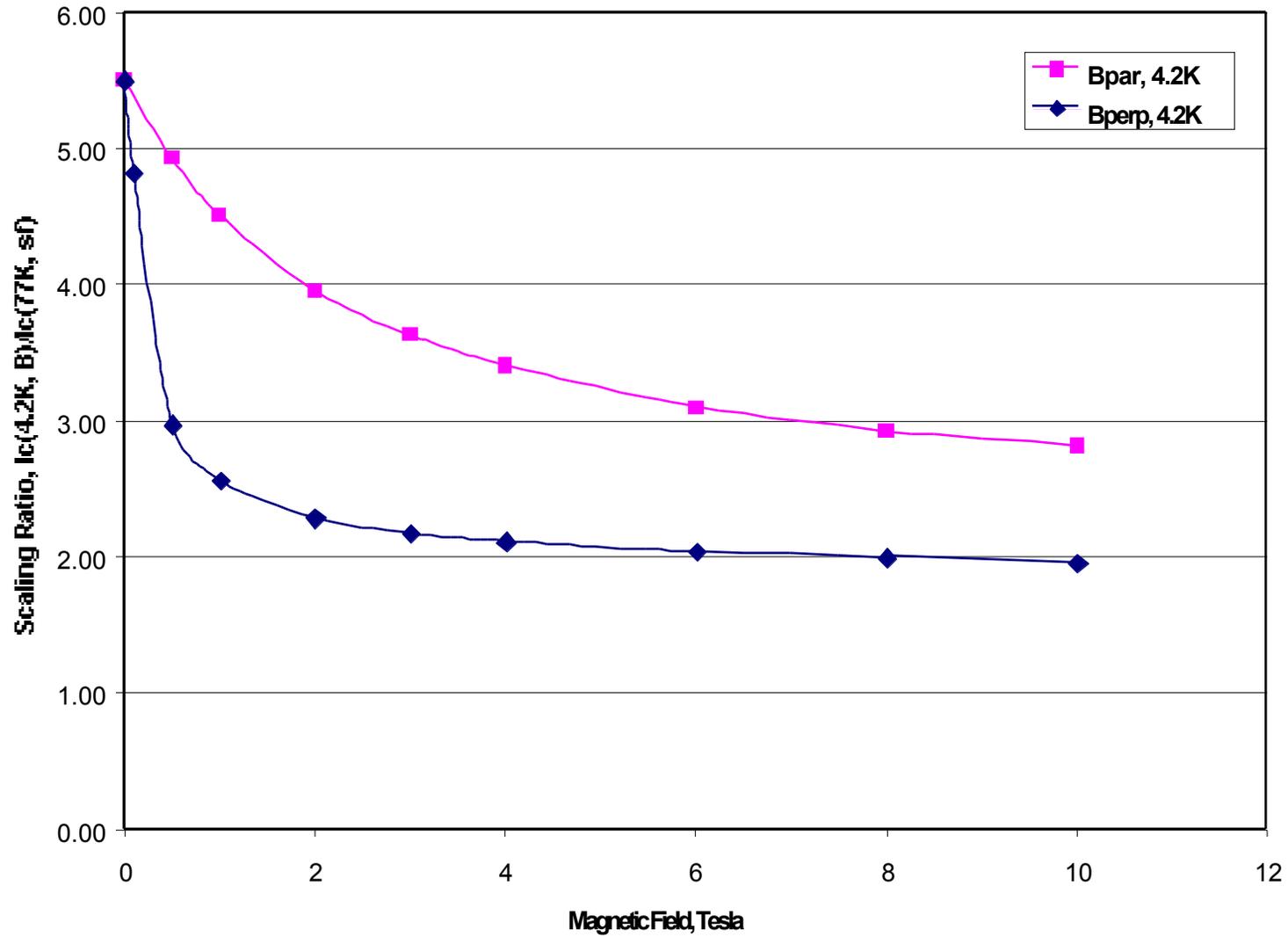
Scaling Ratio to 77K (self-field) in // External Field



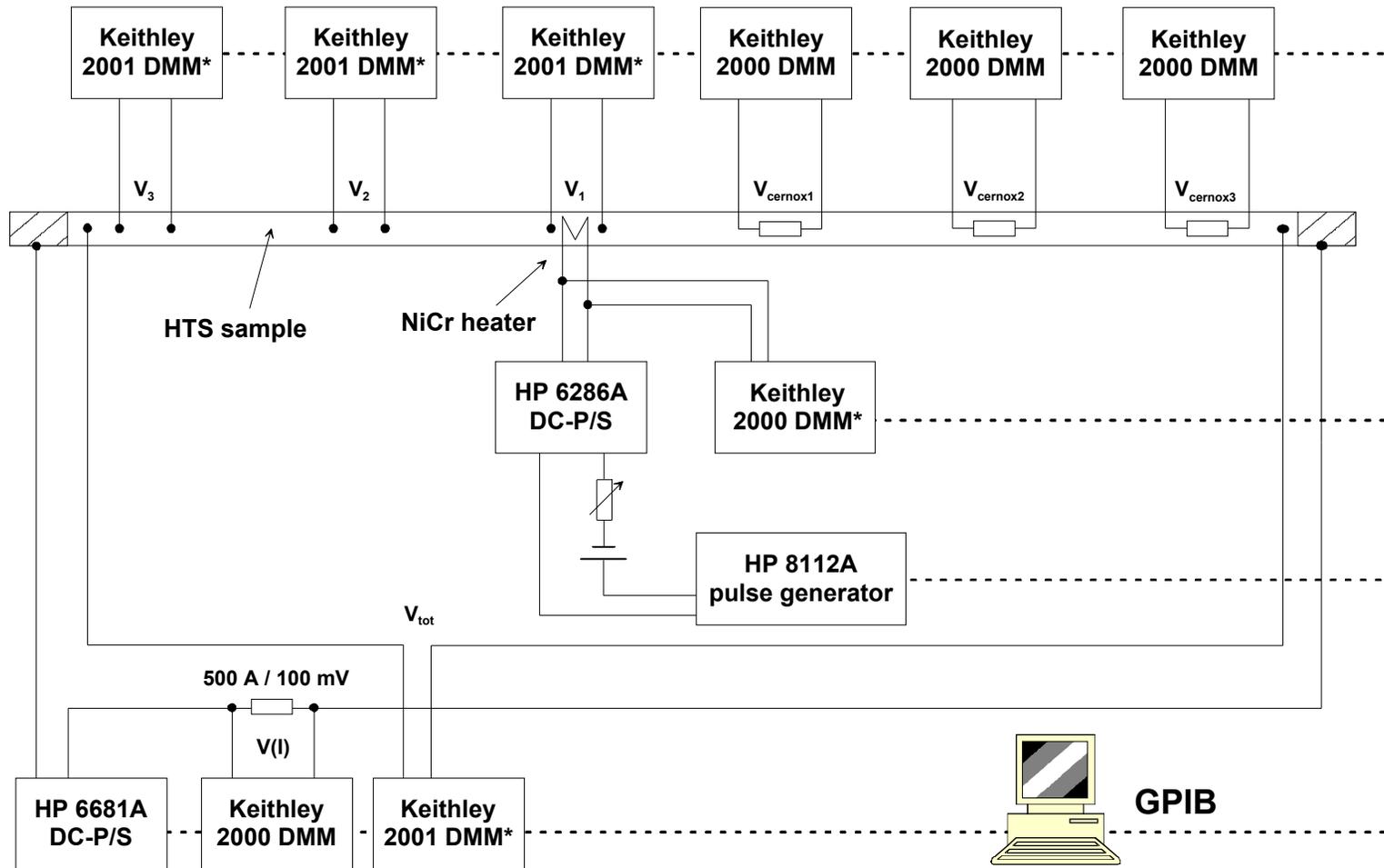
Scaling Ratio to 77K (self-field) in \perp External Field



Scaling Ratio, 77K to 4.2K



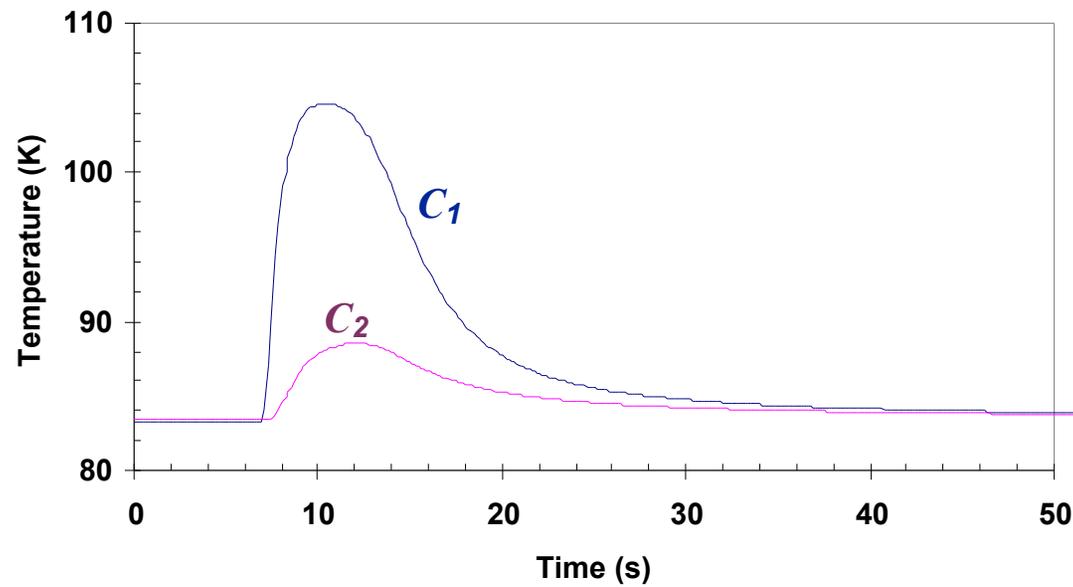
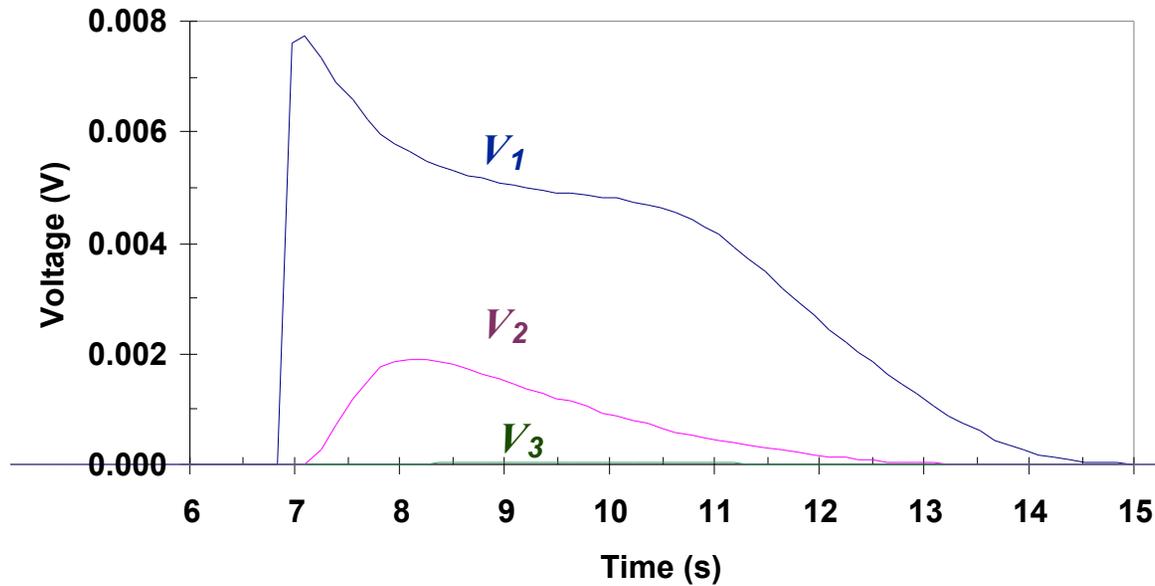
1-D NZP in YBCO Composite—Energy Margin & NZP Velocity



*set on buffer read for increased speed/resolution

Slides 45-51: Based on Justin Schwartz (DOE Meeting July 2002)

Bi2223 tape: Recovery

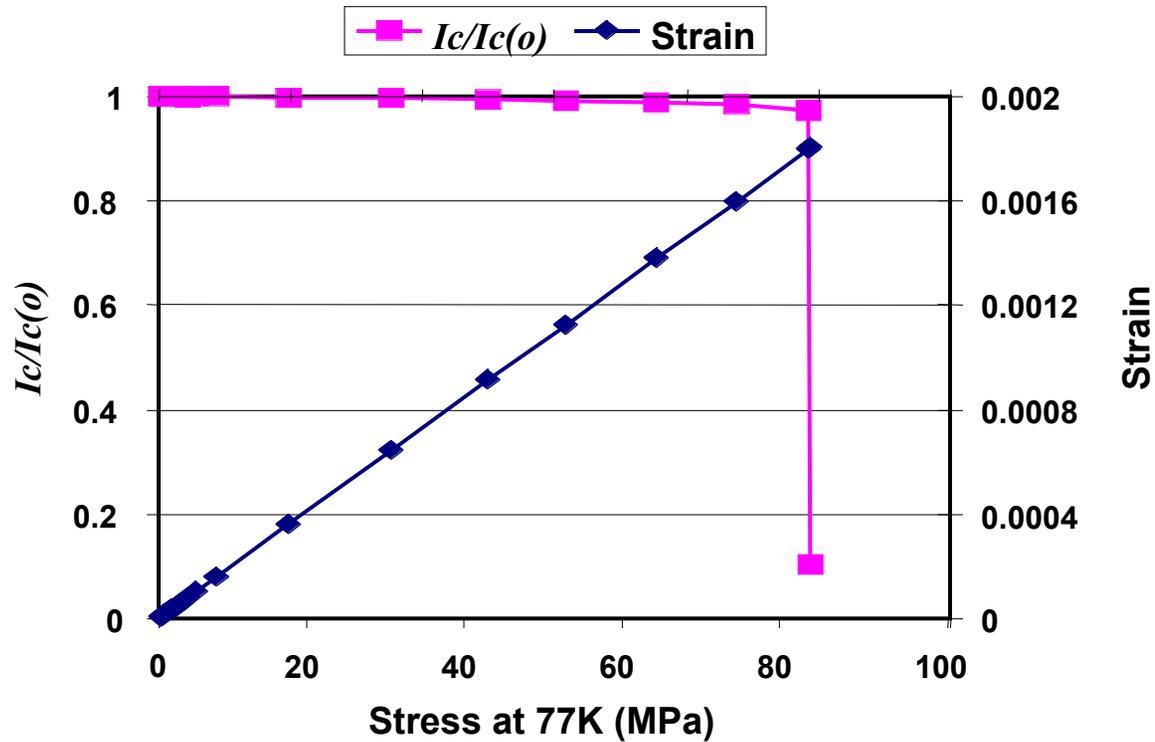


Bi-2223 High Current Density Wire: Non-Reinforced

Thickness (avg): 0.21 (+/-0.02mm)
Width (avg): 4.1 (+/- 0.2mm)
Min. Critical Stress: 75 MPa
Min. Critical Strain: 0.15%
Min. Bend Dia: 100 mm

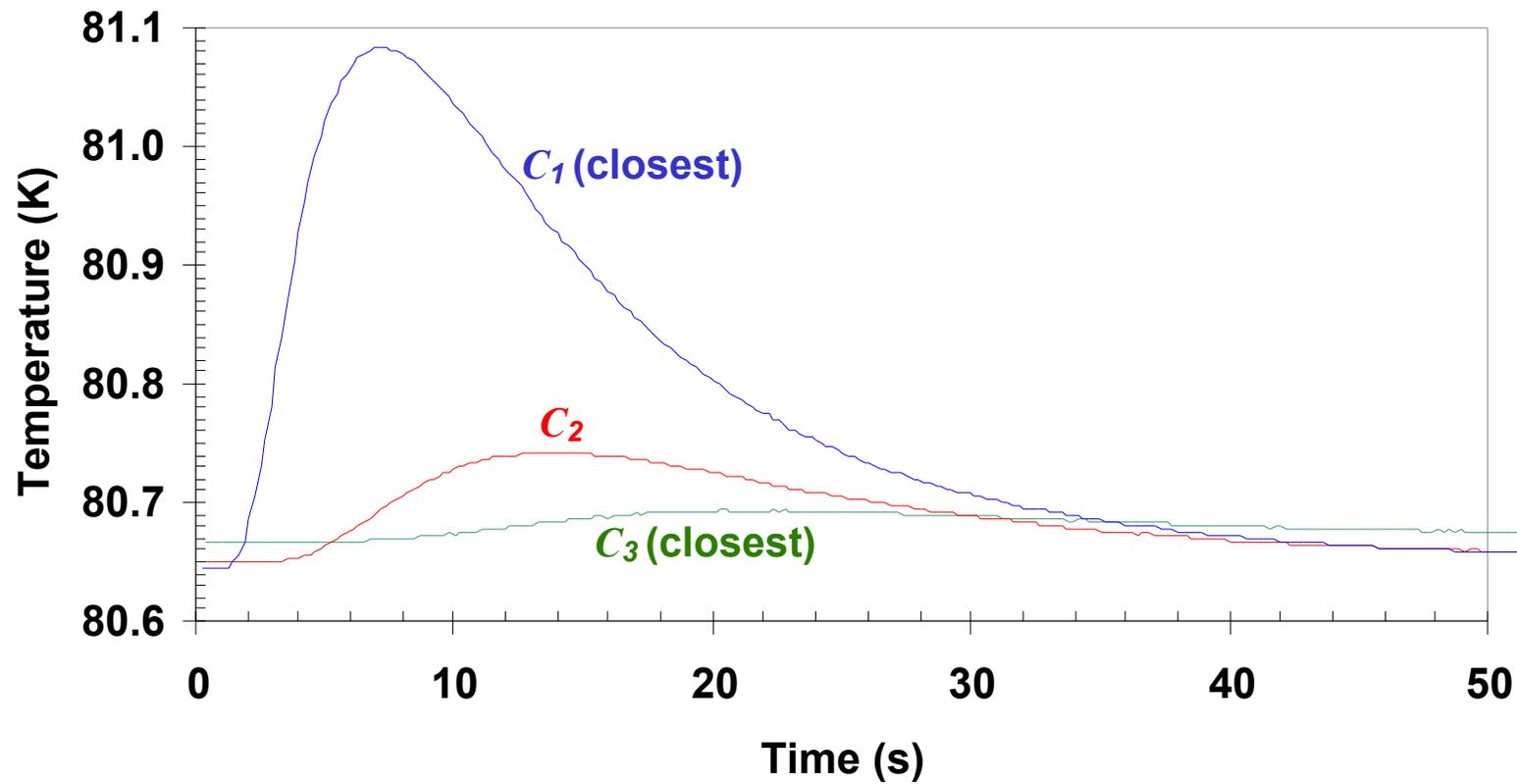


Variable Specifications:
Min. I_c : 115 A—135 A
Piece Length: 100 m —200 m

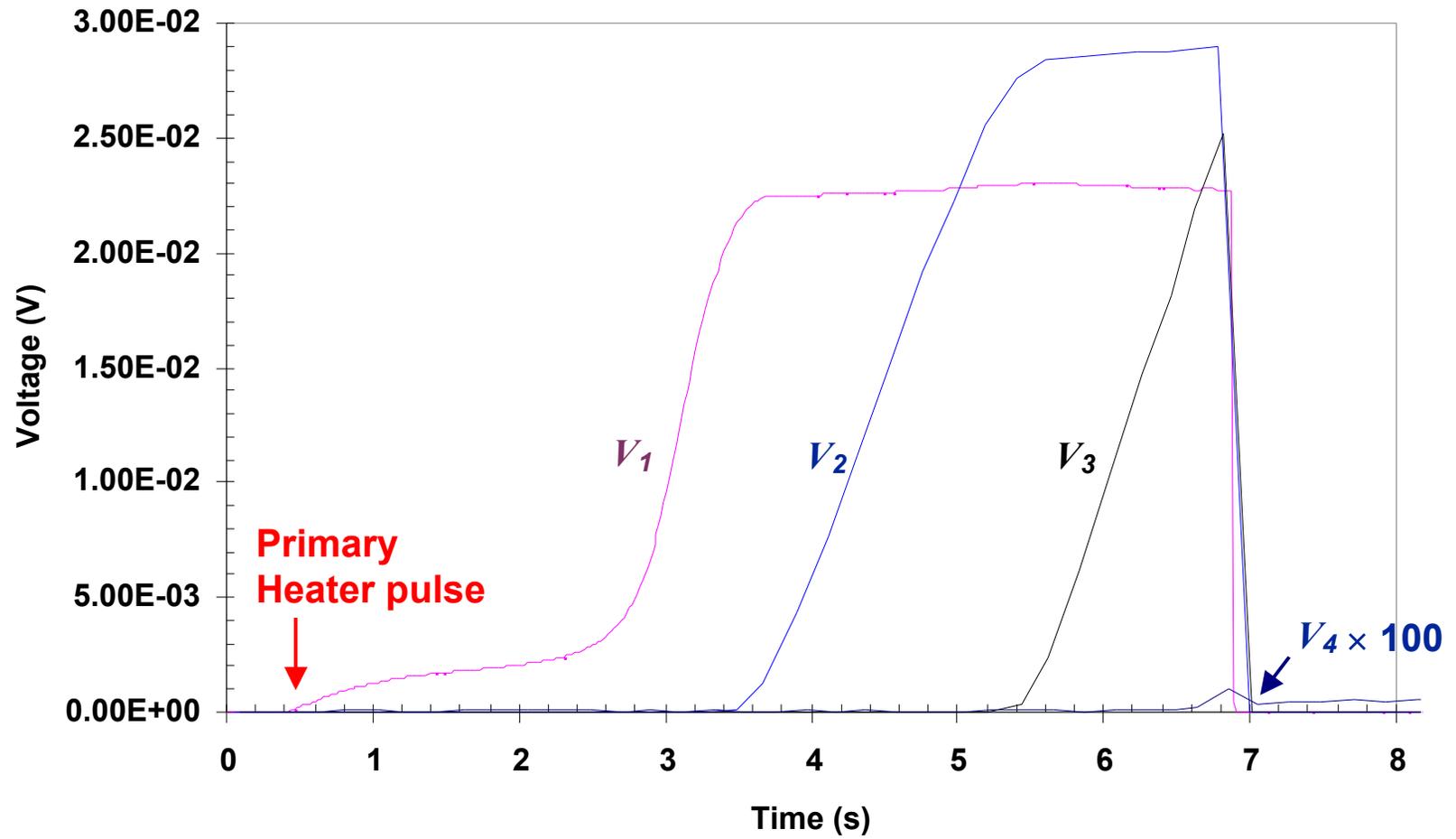


Slides 36-40: Based on American Superconductor Corp. Data Sheets

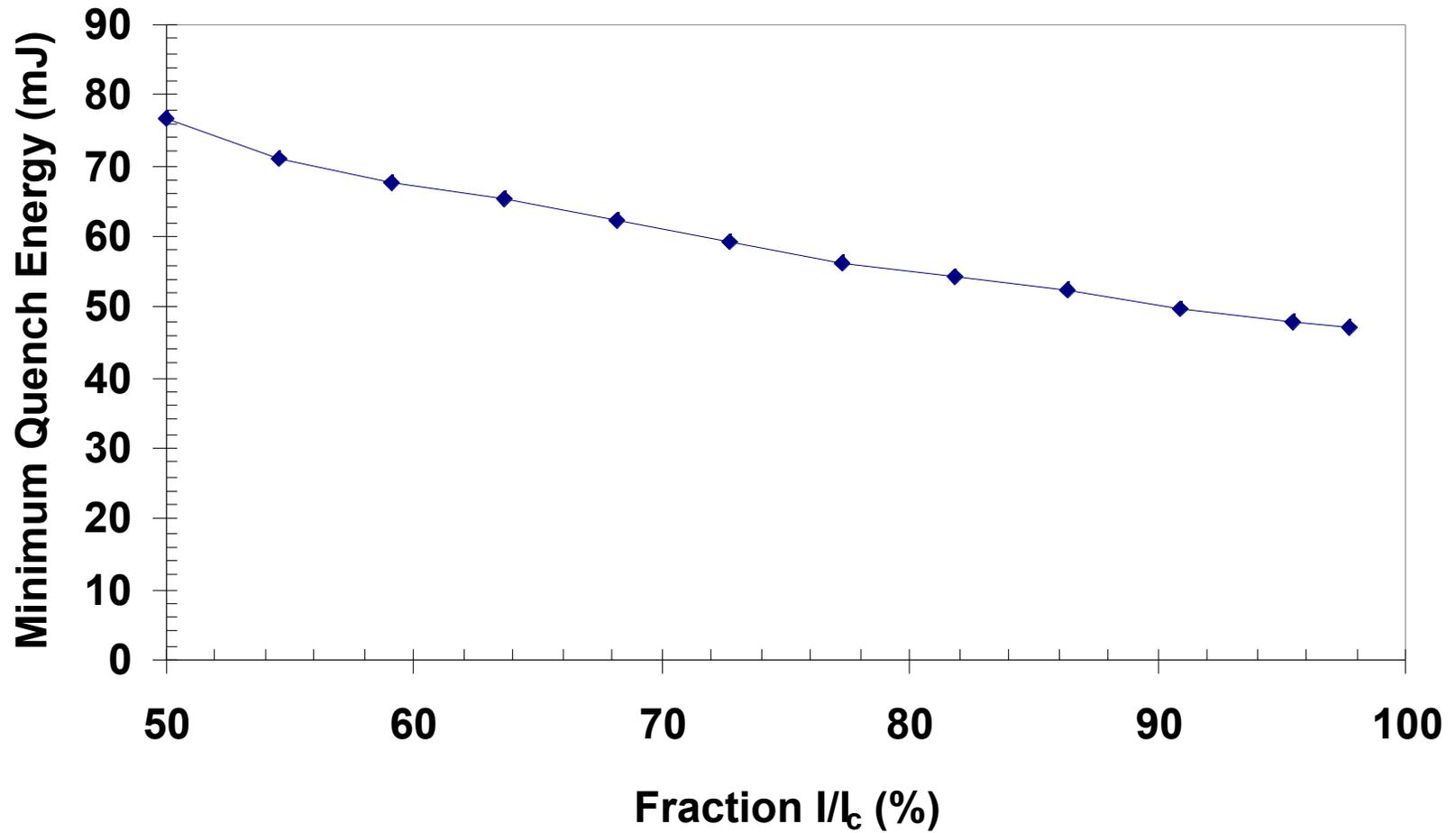
$I_{op}=19\text{ A}; I_c=22\text{ A}$



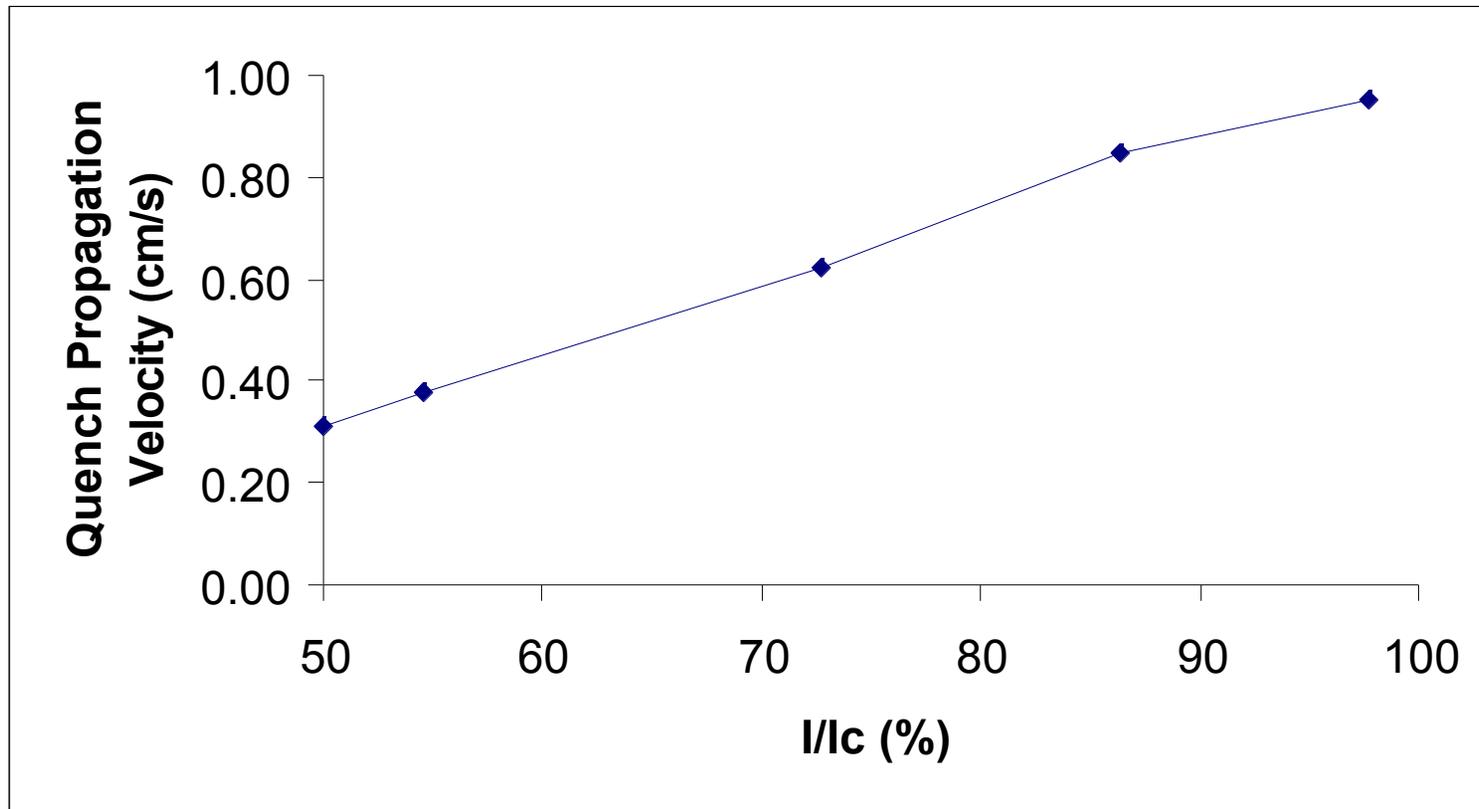
NZP @ 19 A & 80.6 K



Energy Margin vs. I/I_c ($I_c = 22 A @ 80.6 K$)



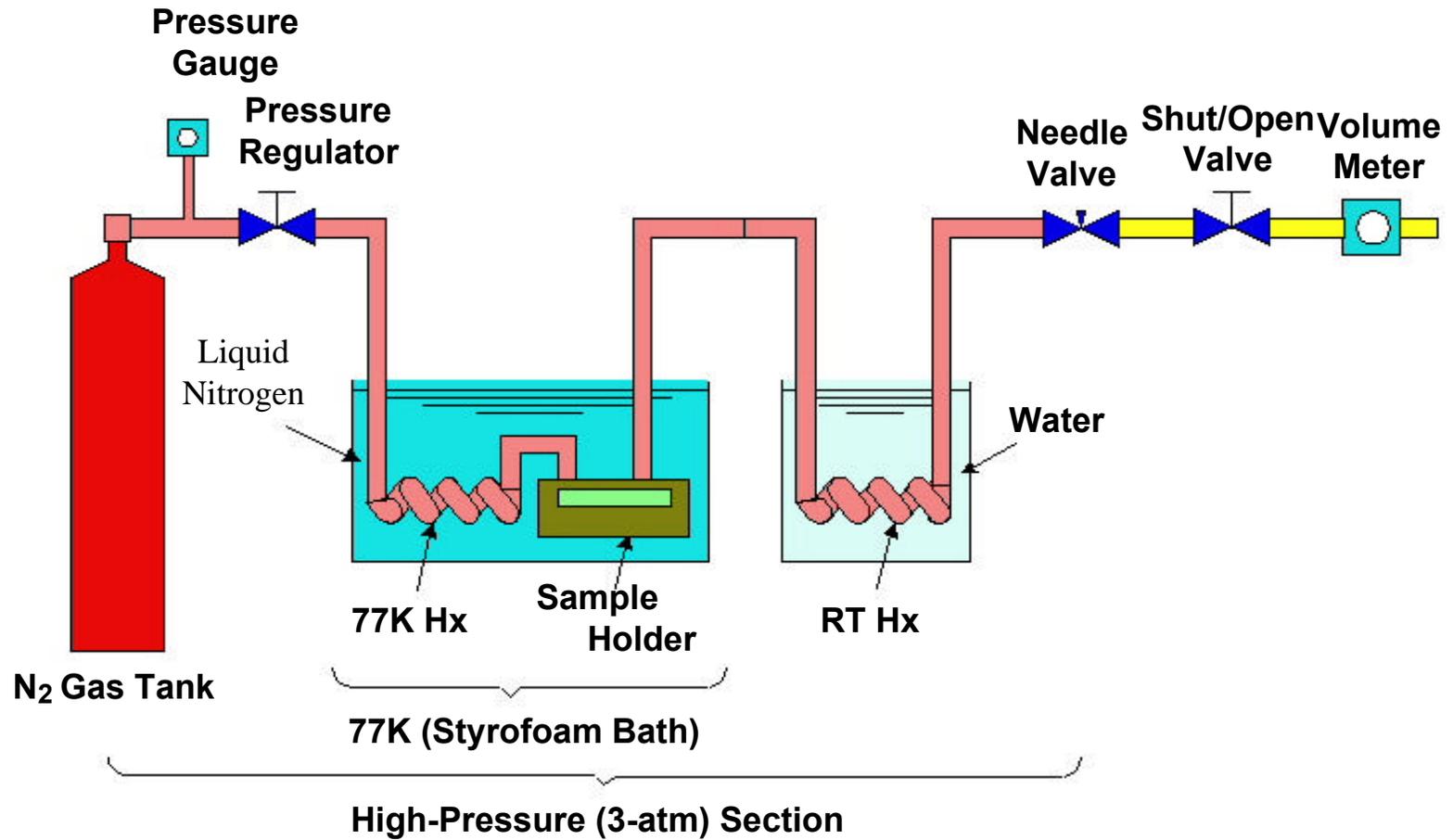
NZP Velocity vs. I/I_c



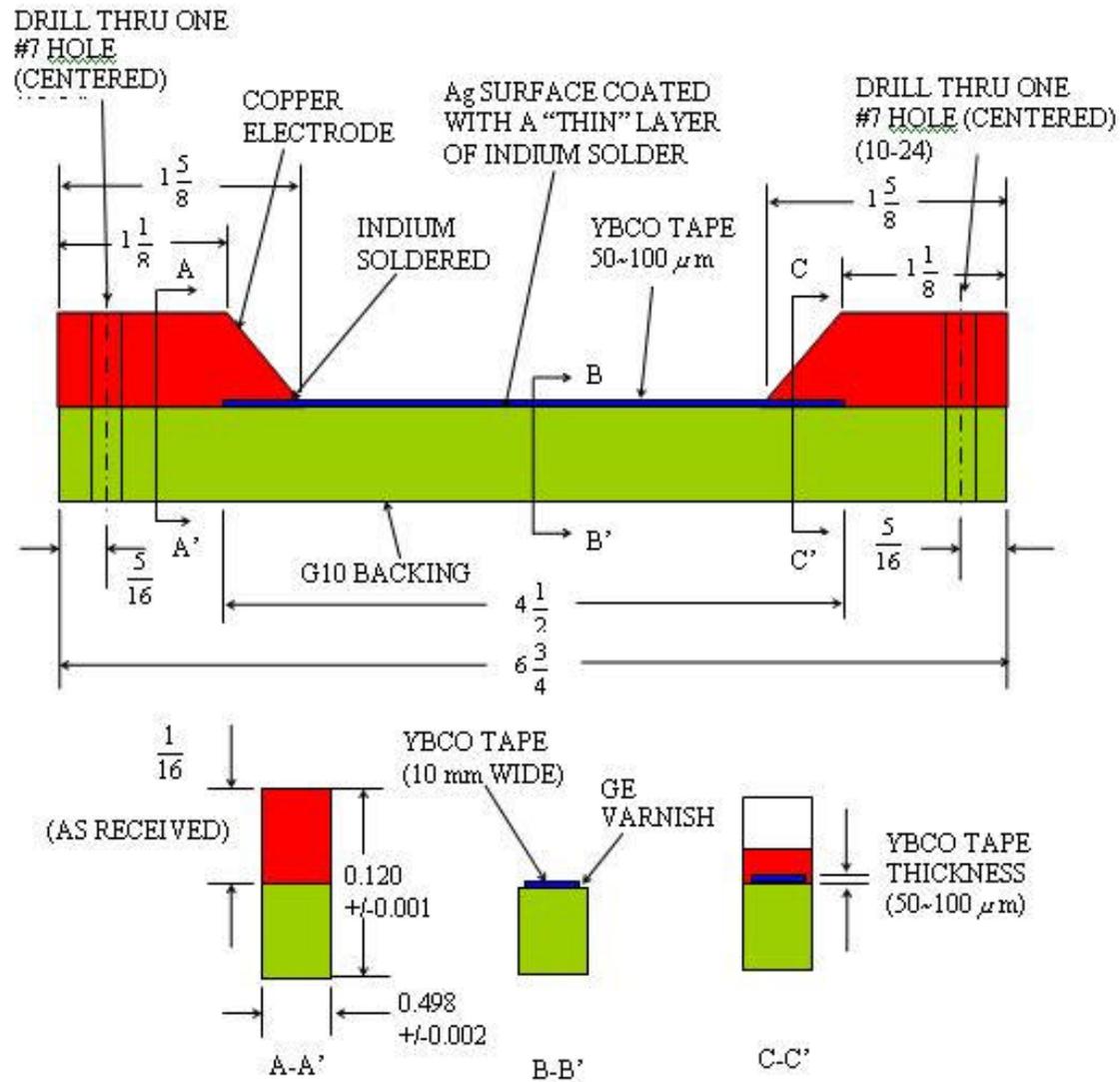
Quench/Recovery Experiment & Simulation

- **Bath cooling @77K**
- **Forced-flow cooling @ 2-3 atm 80-81K**

Forced Flow Experimental Setup

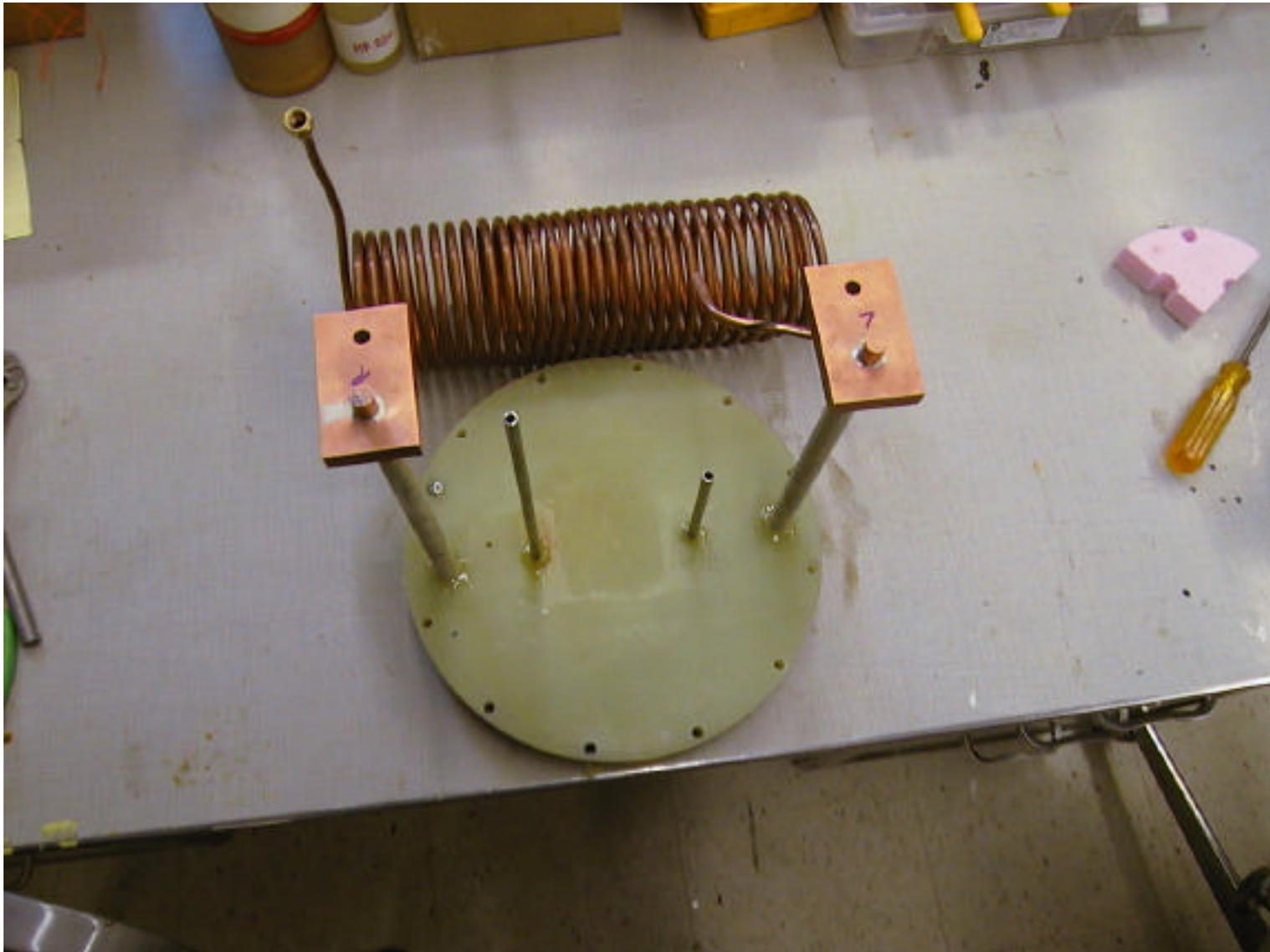


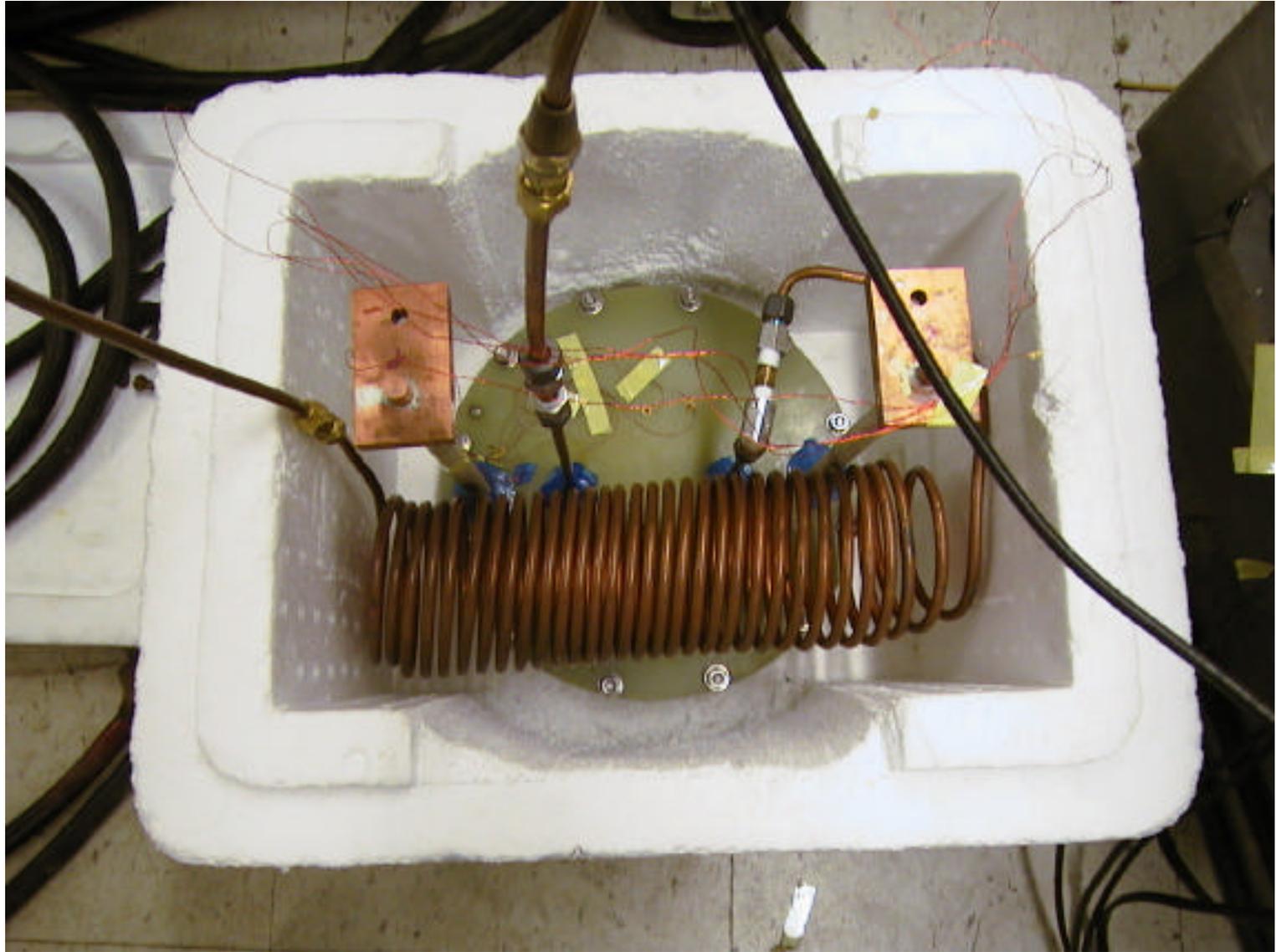
NOTE: VERTICAL SCALE IS ≈ 10 TIMES ACTUAL;
HORIZONTAL SCALE \approx ACTUAL



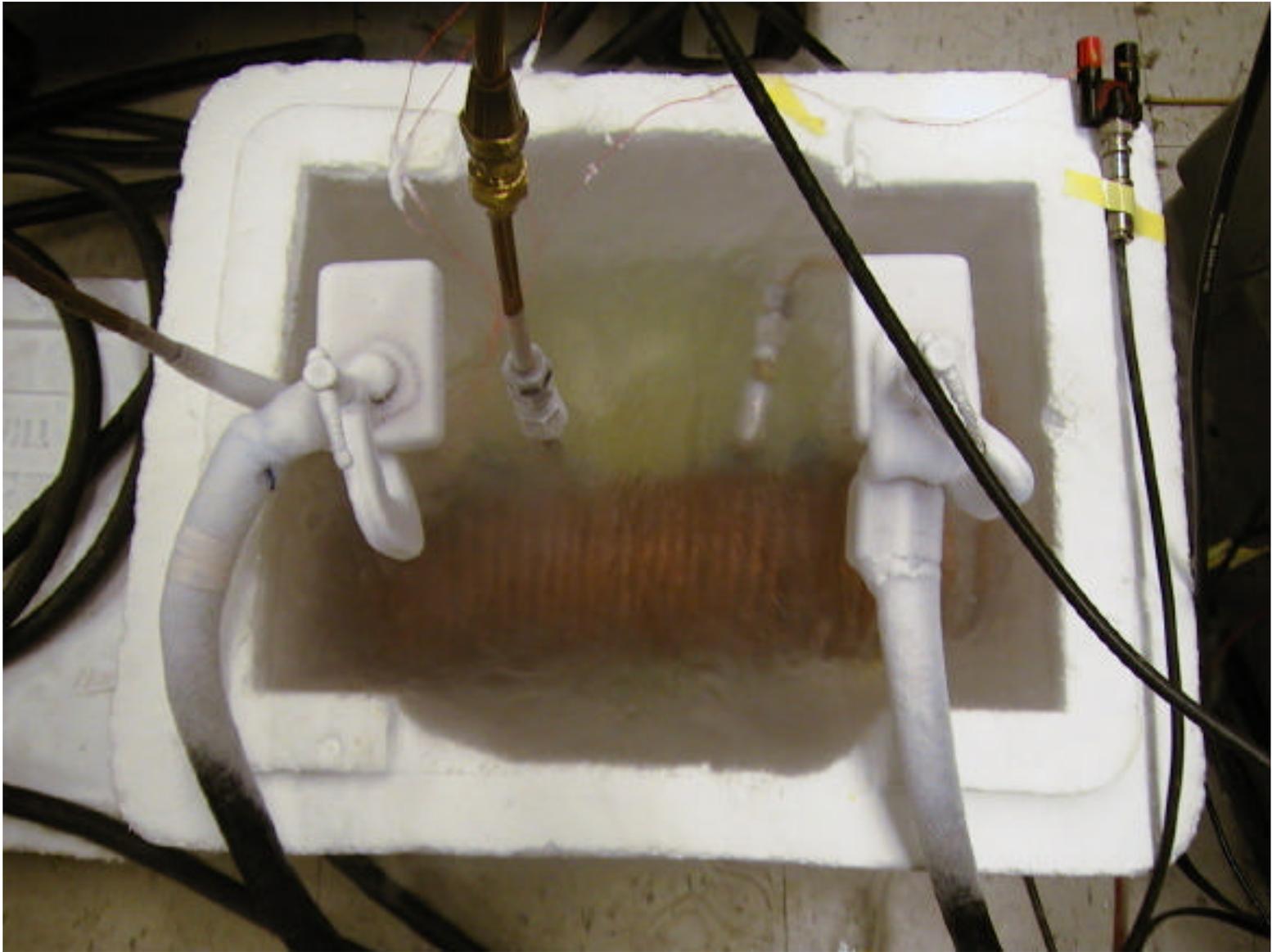
New Forced-Flow Sample Holder



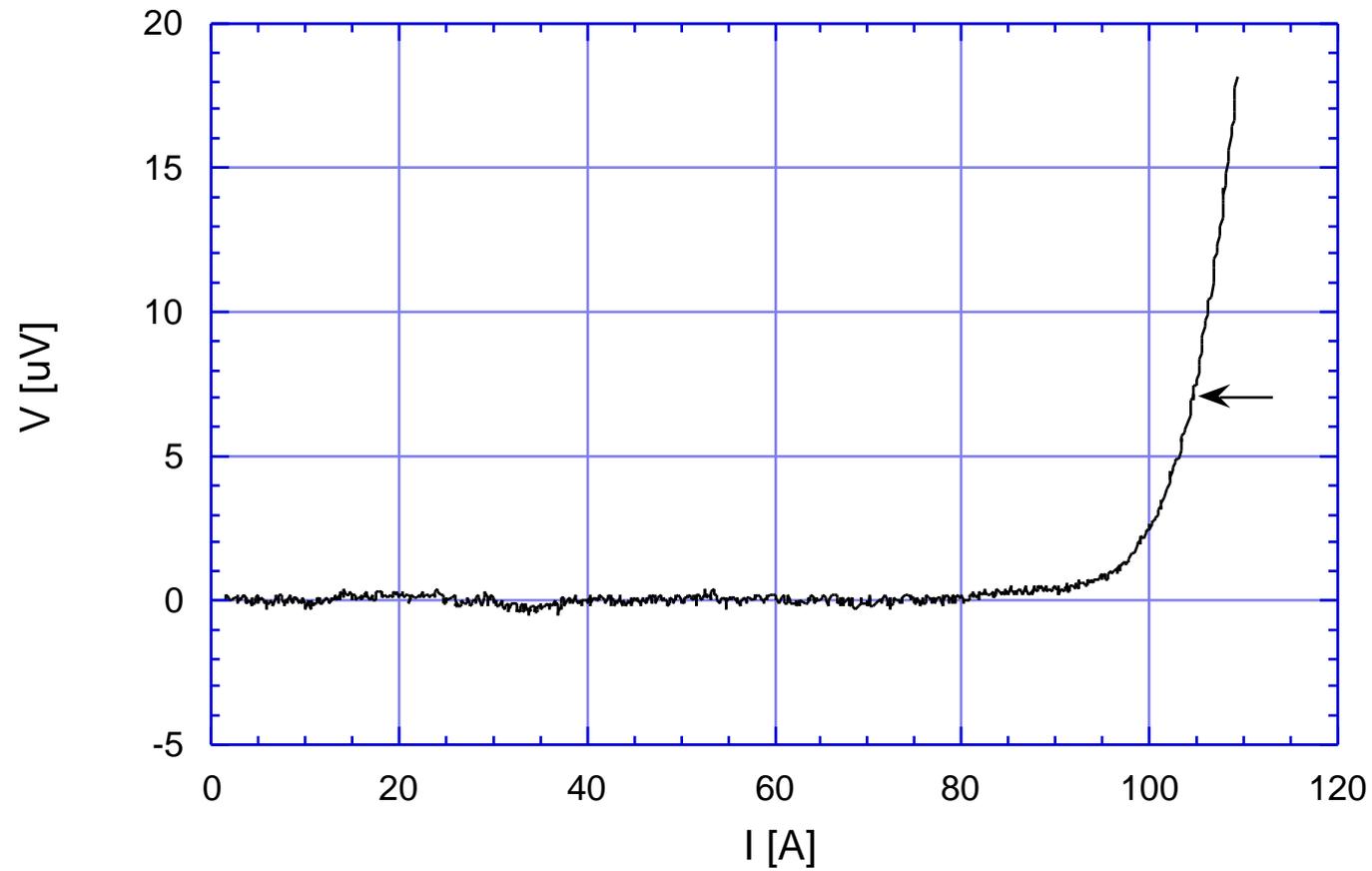




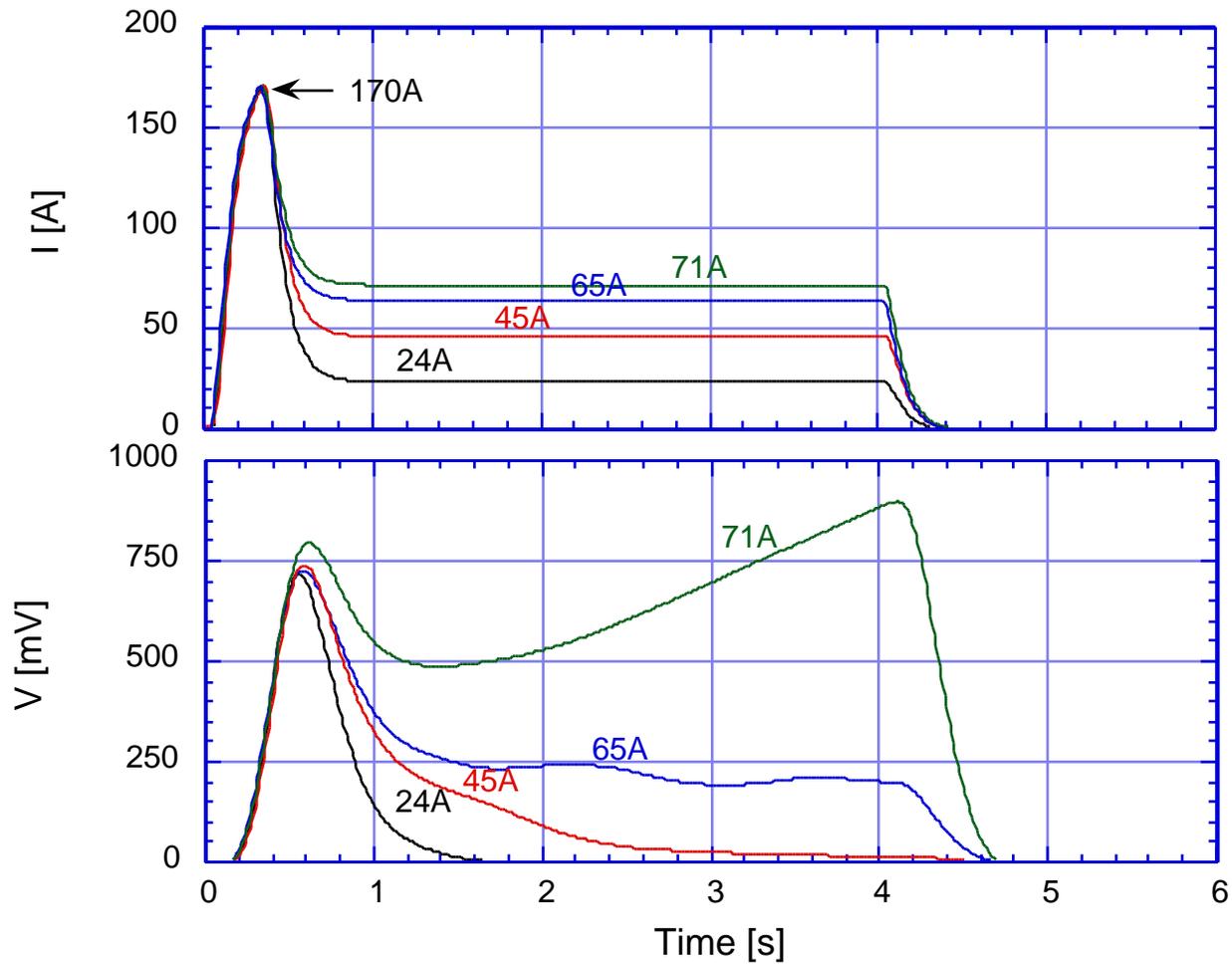




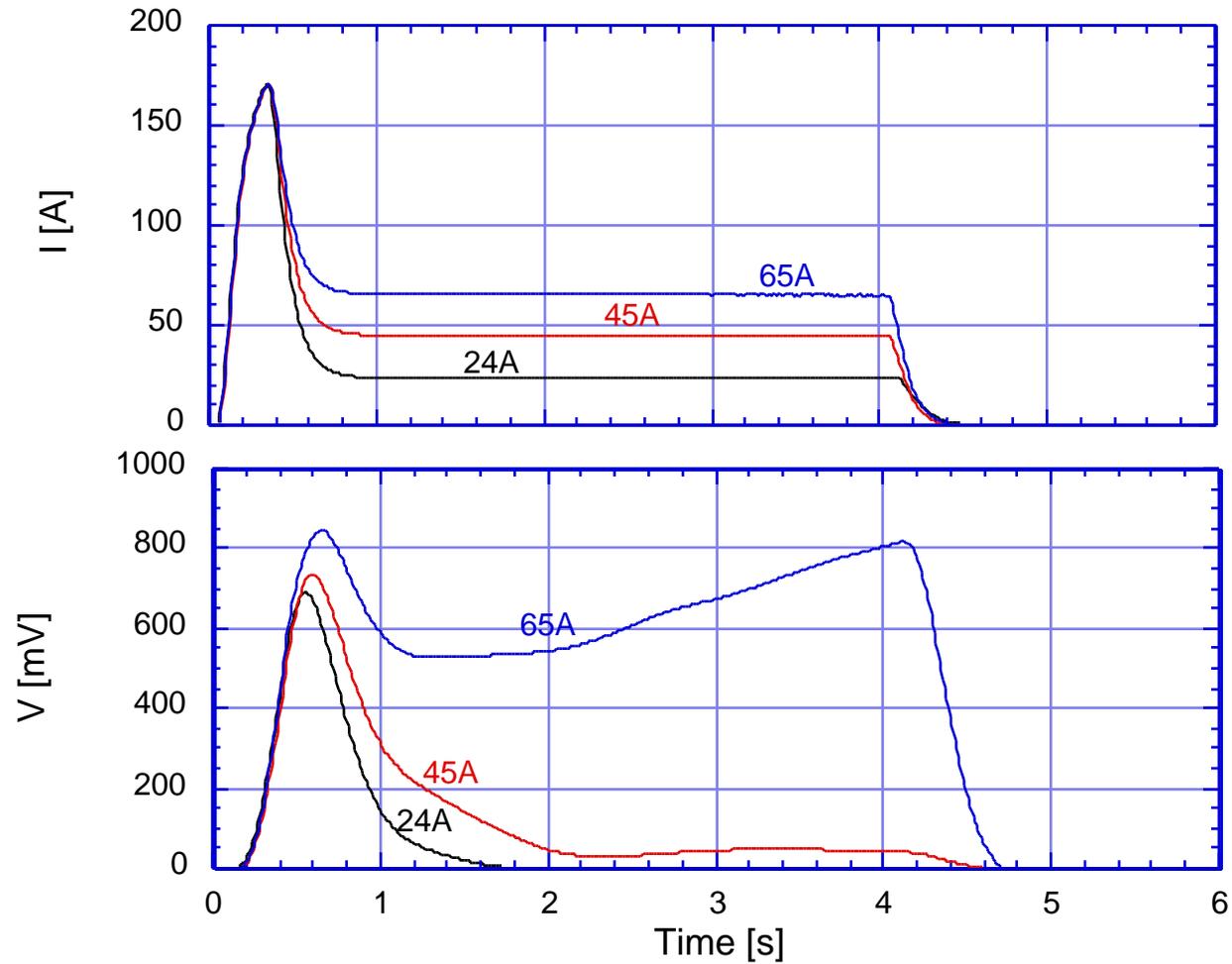
Sample 2: $V(I)$ Plot @77K [$I_c=105A$]
[Source-Measured $I_c > 100A$]



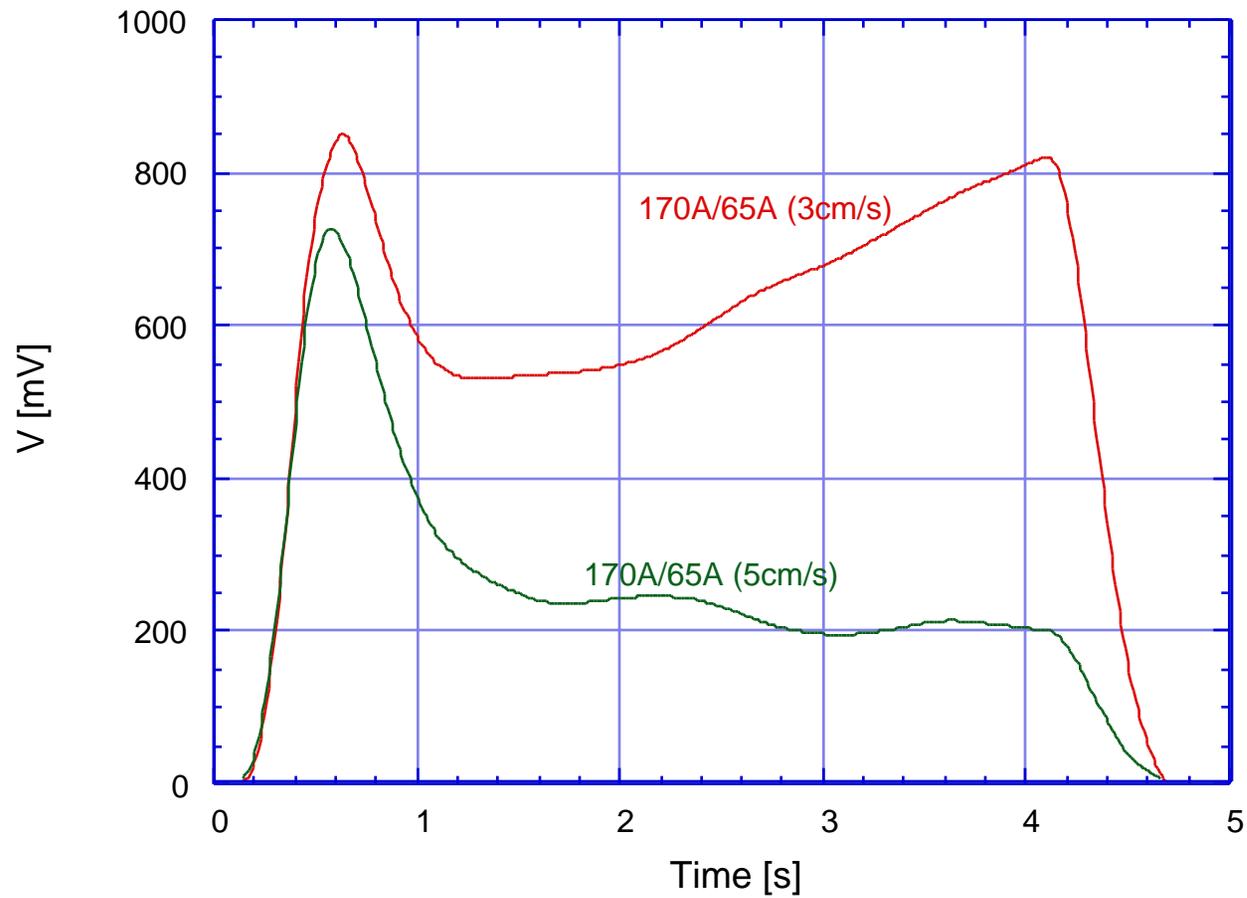
Sample 2: Forced-Flow ($\sim 81\text{K}$; 5cm/s)



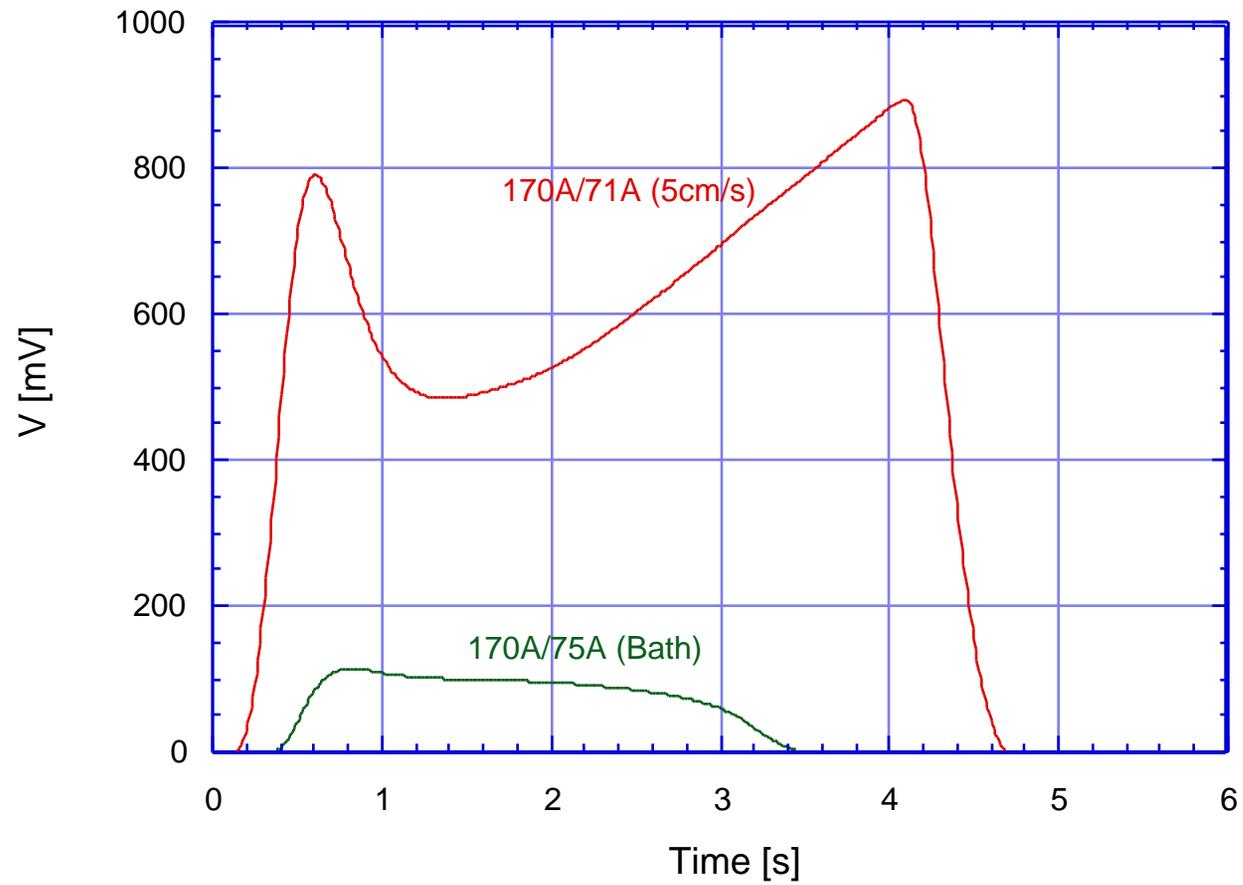
Sample 2: Forced-Flow ($\sim 81\text{K}$; 3cm/s)



Sample 2: Forced-Flow (@81K)



Sample 2: Forced-Flow (5cm/s) & Bath



Simulation

$$Q = h\Delta T_w = hA_s(T_w - T_f)$$

$$h = kNu/D$$

Re 3000 , turbulent flow

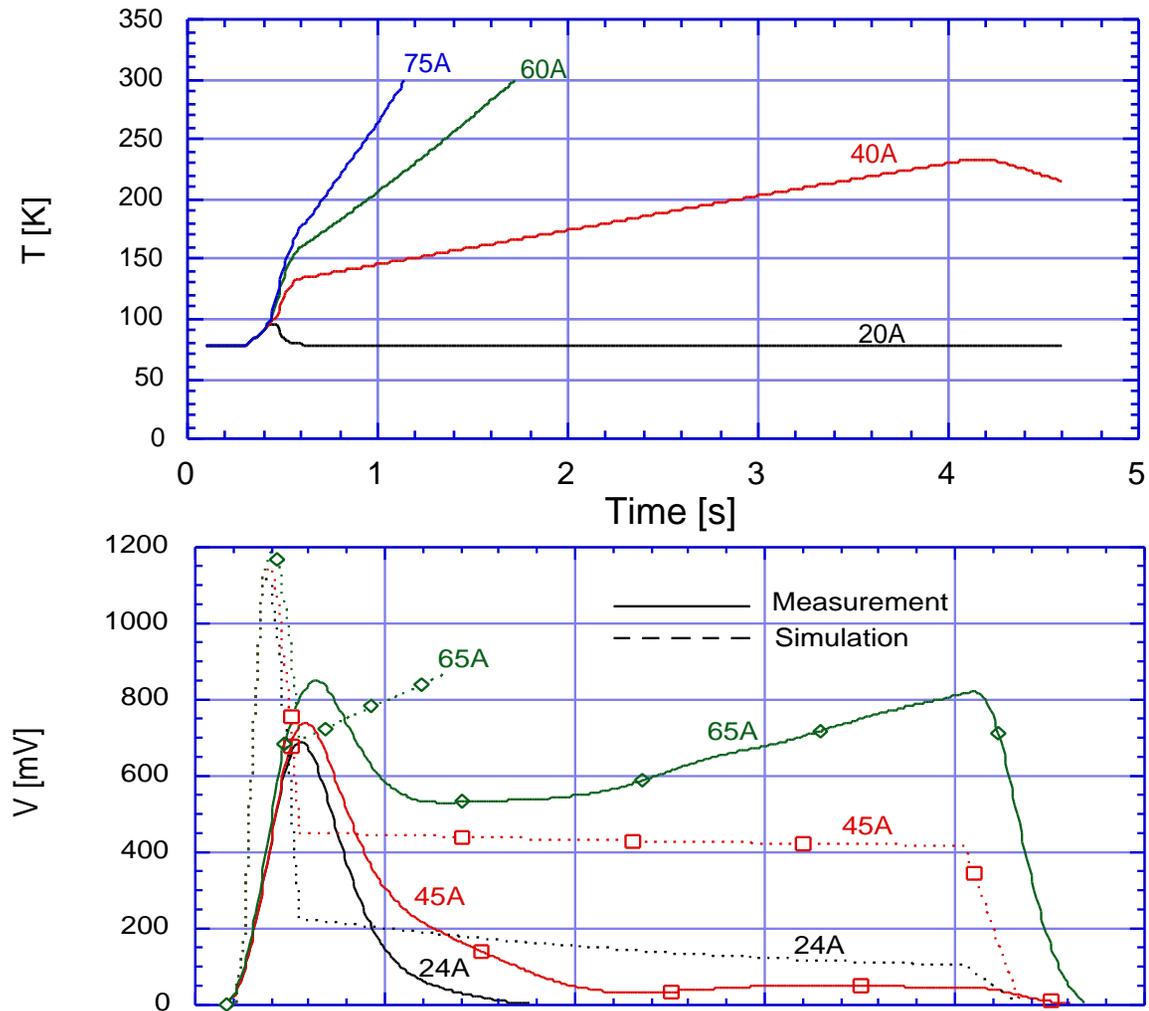
$$Nu = 0.023 Re^{0.8} Pr^{0.3}$$

Re < 3000, laminar flow

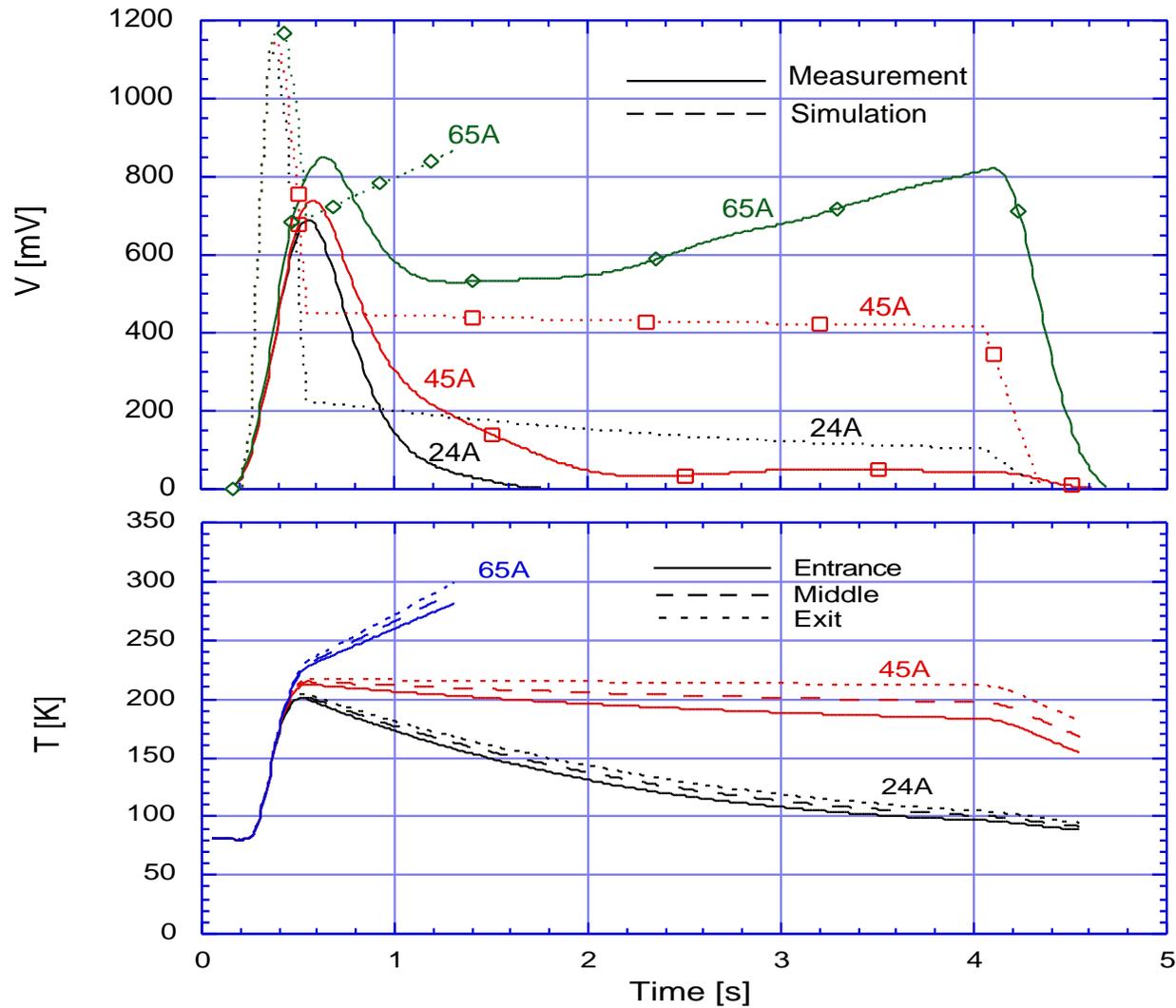
$$Nu = 3.66 + \frac{0.0668(D/L)RePr}{1 + 0.04[(D/L)RePr]^{2/3}}$$

Nitrogen Properties at 2 bar (From Handbook of Cryogenic Engineering, I. G. Weisend , 1998)				
T(K)	(kg/m ³)	Cp(j/kg K)	μ(Pa s)	(W/m K)
83.0	779.9	2079	0.1228°10 ⁻³	0.1247
84.0	8.628	1376	0.5791°10 ⁻⁵	0.849°10 ⁻²

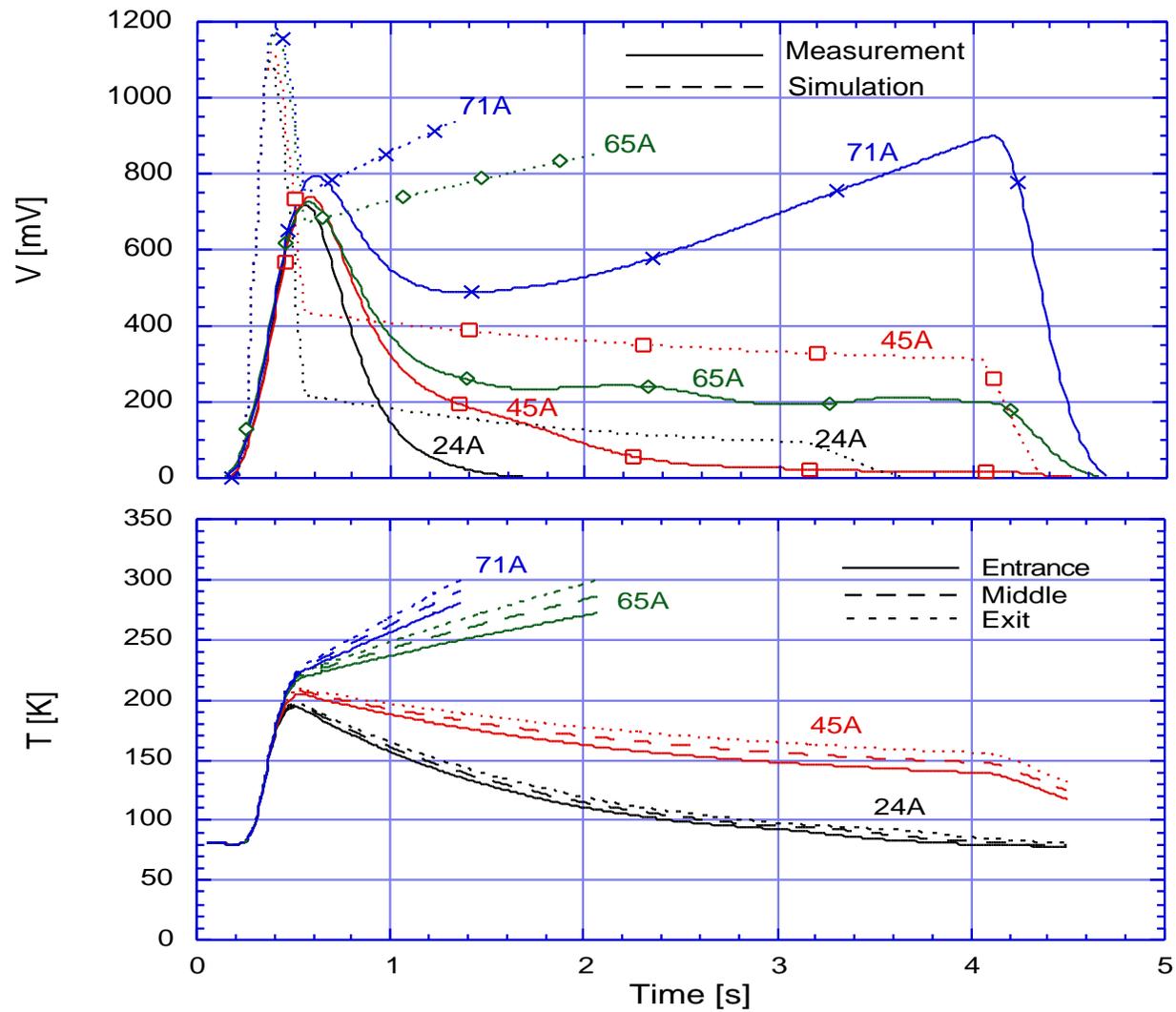
Sample 2: Bath @77 K & Simulation



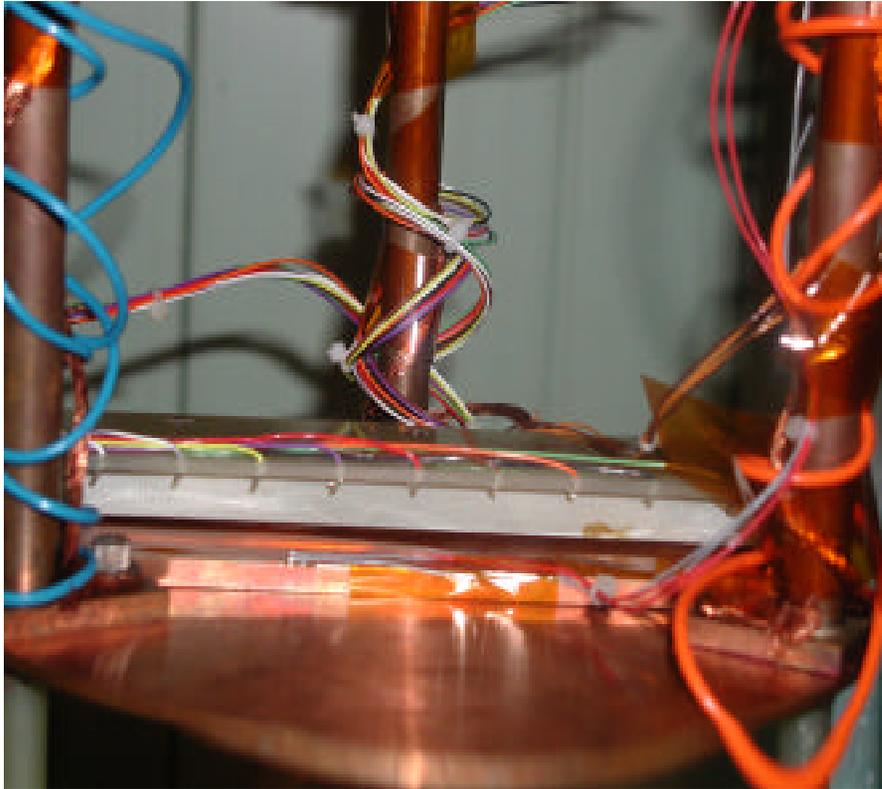
Sample 2: Forced-Flow (3 cm/s) & Simulation



Sample 2: Forced-Flow (5 cm/s) & Simulation



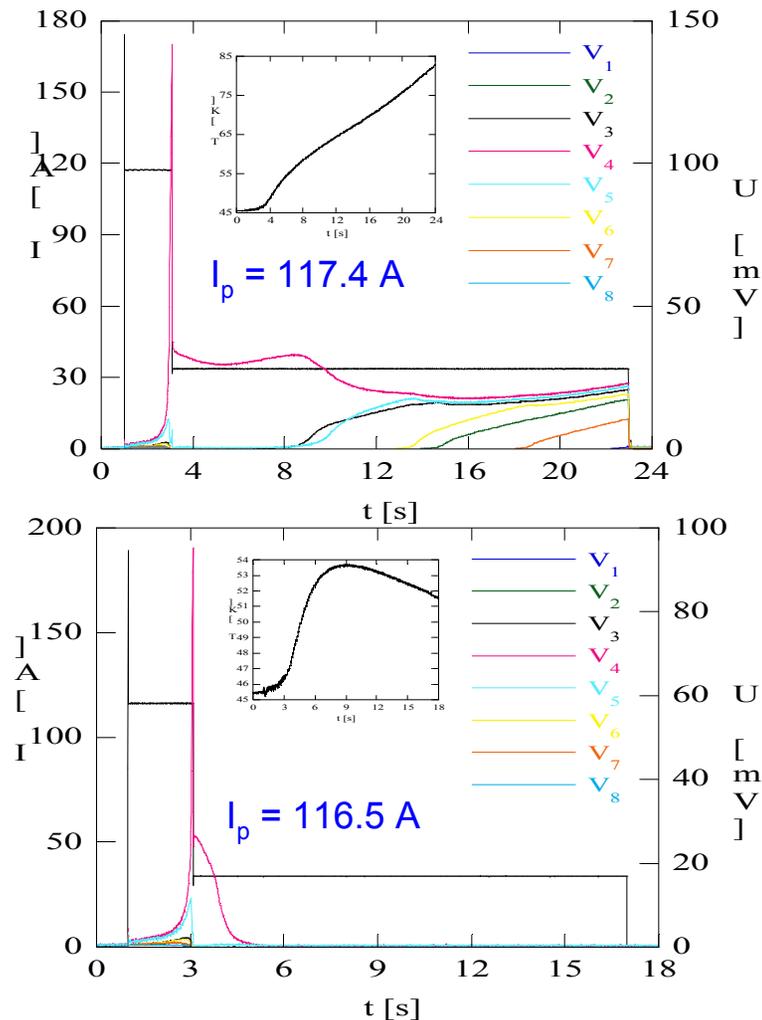
YBCO Samples in a Conduction Cooling Setup



- The sample was mounted between a Kapton-tape-insulated Cu-block and a G-10 block.
- It was affixed to the first-stage cold-head of a Cryomech GB-37 cryocooler for conduction cooling to about 40 K.
- **A copper shield was added around the G-10 block to ensure a better uniform temperature of the tape.**
- A heater was affixed to the copper base, and three PRT Thermometers are placed on the YBCO top surface.

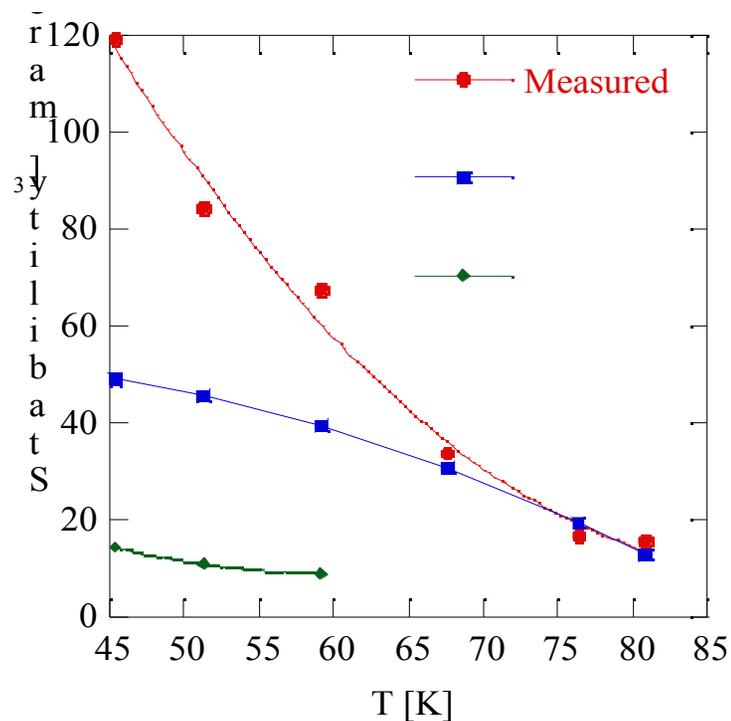
Slides 69-78: Based on Winston Lue (ASC2002, August 2002)

Over-Current Pulse Induced NZP



- At each operating current, I_{op} an initial over-current pulse was applied. 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 2-s over-current pulse duration, an I_p of 117.4 A caused a quench while 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.

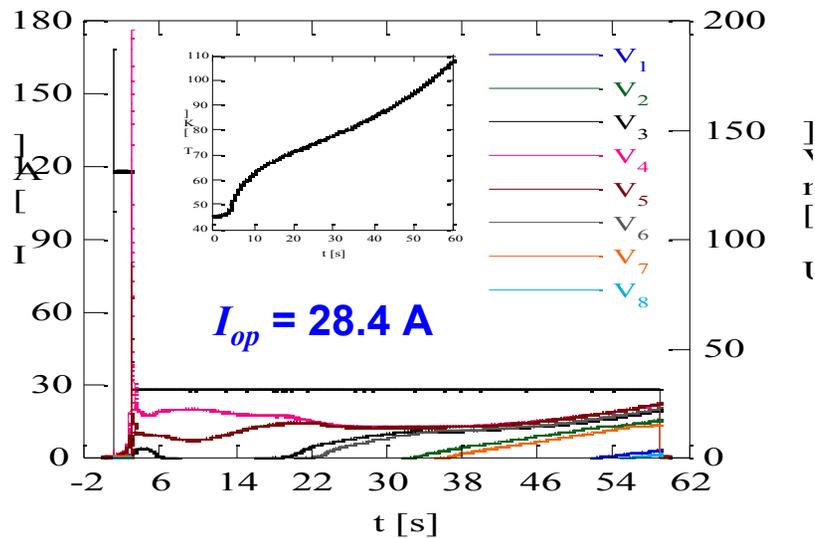
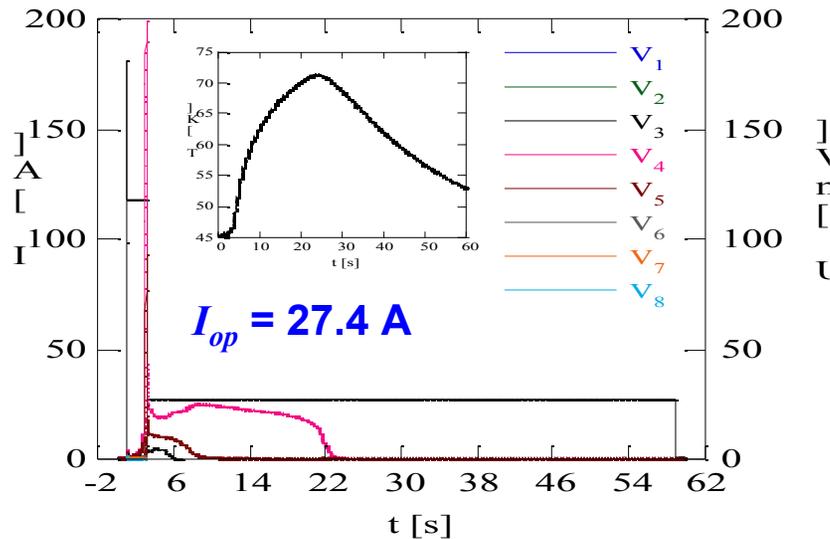
Stability Margins in the Range 45—80 K



- To measure the stability margin, the operating current was set near the lowest zone I_c at a particular temperature.
- 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 ranged from 16 to 120 J/cm³ as temperature lowers from 80 to 45 K.**
- Comparison with the specific heat integrals indicated better fit to T_c than to T_{cs} for the HTS tapes.
- The higher margins measured at lower temperatures are attributed to the higher conduction cooling.

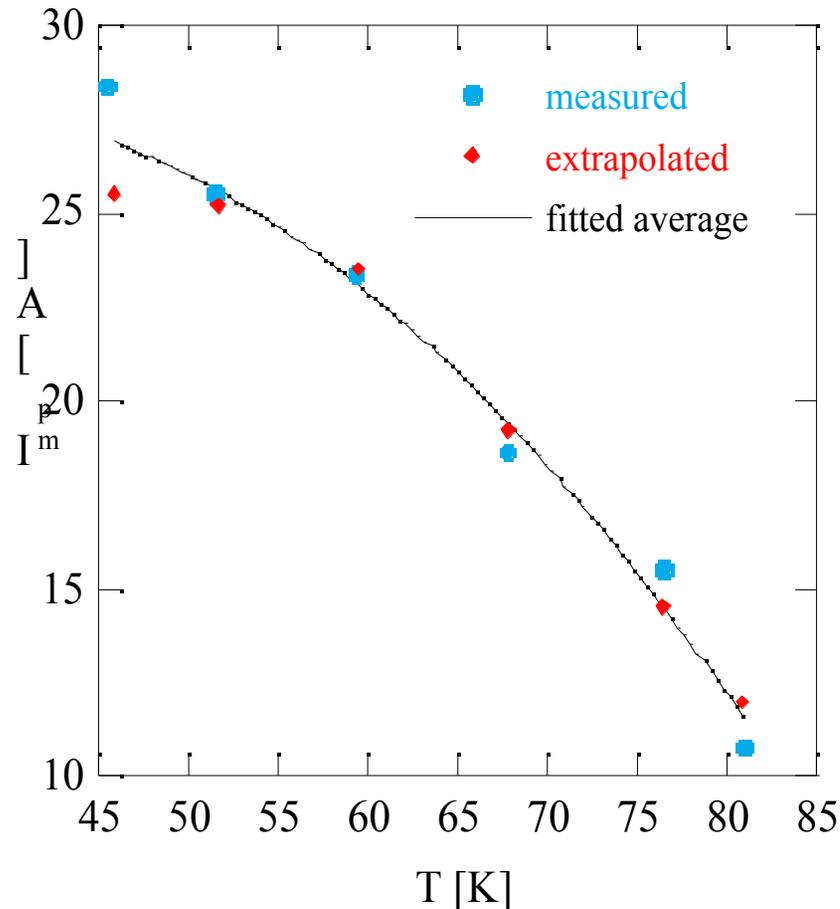
$$T_{cs} = T_{op} + (T_c - T_{op}) \left(1 - I_t / I_{cop} \right)$$

Minimum Propagation Currents



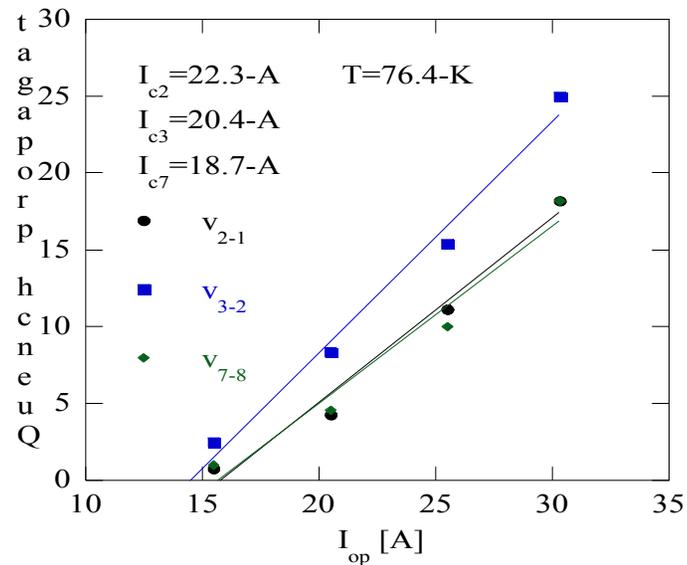
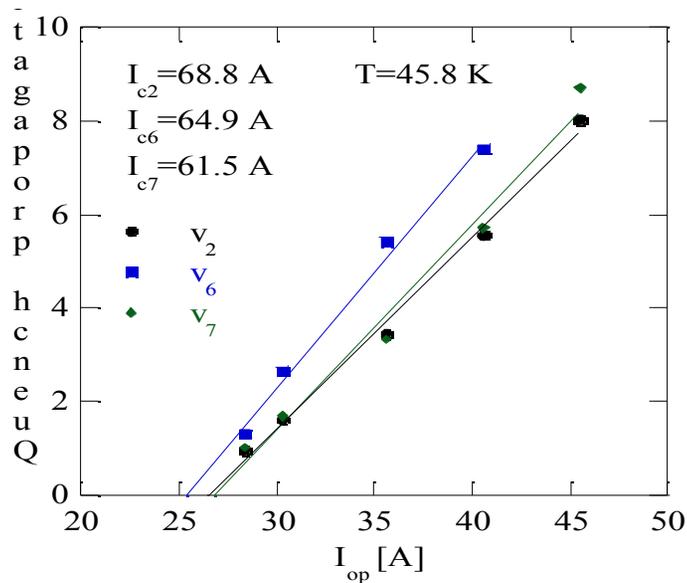
- At 45.4 K, the sample was subjected to an initial over-current pulse of 118 A for 2 s while increasing the operating propagation in 1 A steps.
- The figures show recovery at an operating current of 27.4 A and propagation at 28.4 A - a minimum propagation current.
- The initial heat input to zone 4 was about 4.6 J or 350.4 J/cm^3 - about 3 times the stability margin.

Minimum Propagation Current vs. Temperature



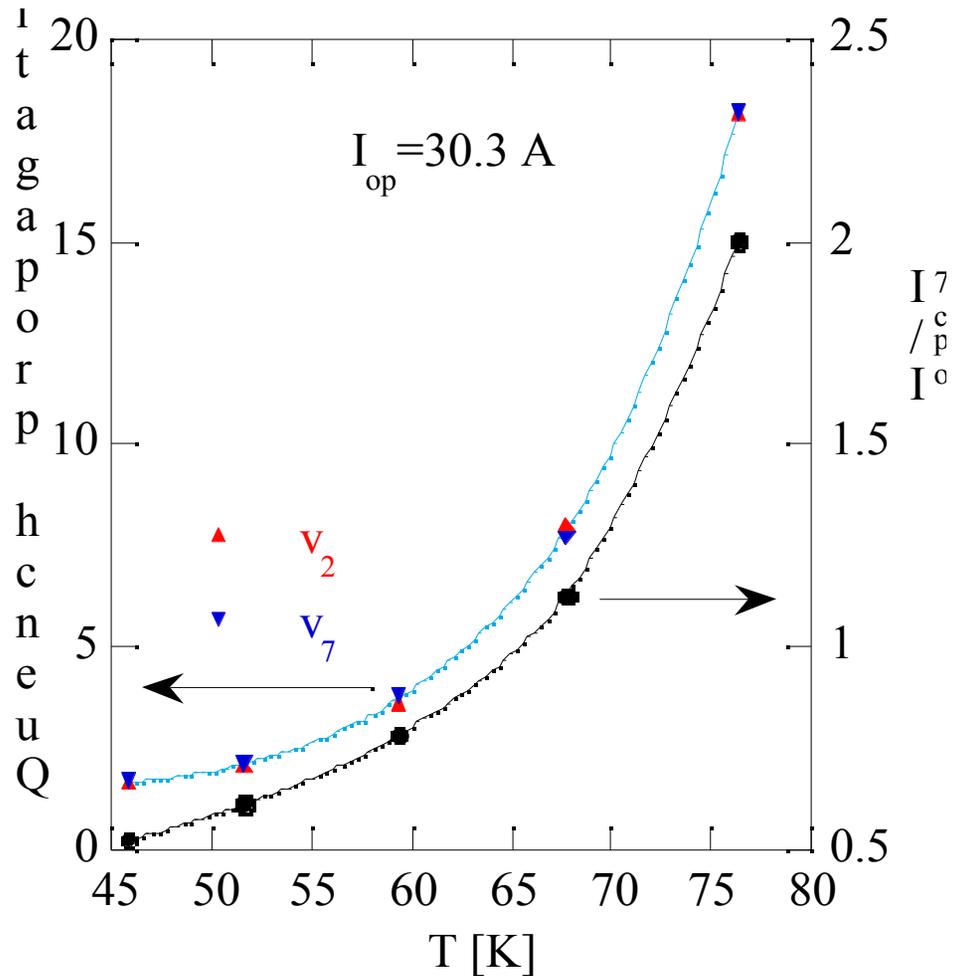
- **Minimum propagation currents were also determined by extrapolating the velocity versus current plots to zero velocity.**
- **Minimum propagation currents of 12 to 27 A were observed at 80.8 to 45.4 K.**
- **The existence of minimum propagation current is thought to be the result of conduction cooling.**

NZZ Velocity vs. I_{op}



- NPZ always starts from the middle (zone 4) of this sample.
- NPZ velocities were found to be increasing linearly with the current.
- **No more than 20 mm/s of NPZ velocity was measured when I_{op} was set below I_c .**
- **The outer zones which received better cooling resulted in lower NPZ velocity and higher minimum propagation current.**

NZP Velocity vs. Temperature



- **NZP velocities were measured at five different temperatures.**
- **NZP velocities at an operating current of 30.3 A were found at the different temperatures and plotted in the figure.**
- **NZP velocity vs. temperature shows a similar dependence as the ratio of operating to critical current.**

Modified Adiabatic Theories of NZP Velocity

1. Constant material properties (Dresner)

$$v_A = \frac{(I - I_{mp})}{A \cdot C_p} \sqrt{\frac{k\rho}{T_c - T_\phi}}$$

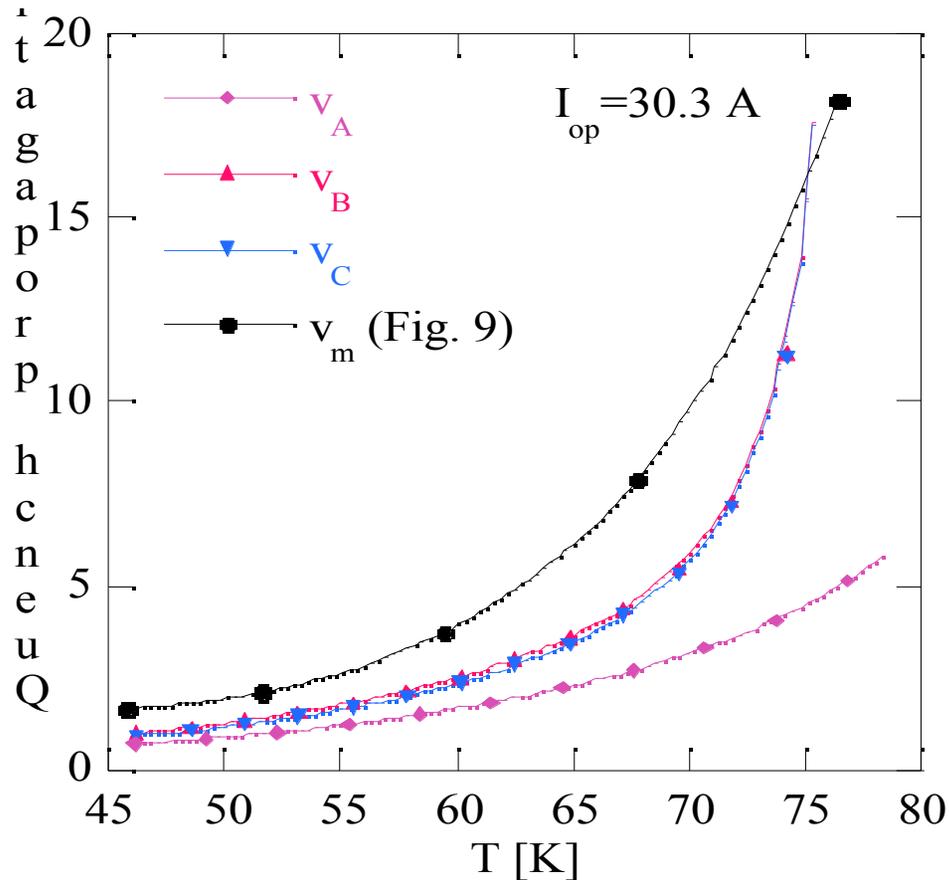
2. Variable material properties (Zhao and Iwasa)

$$v_B = \frac{(I - I_{mp})}{A} \sqrt{\frac{k_n \rho_n}{\int_{T_p}^{T_c} C_s dT \left(C_n + \frac{1}{k_n} \frac{dk_n}{dT} \int_{T_{op}}^{T_c} C_s dT \right)}}$$

3. Constant material properties with a different transition temperature (Bellis and Iwasa)

$$v_C = \frac{(I - I_{mp})}{A} \sqrt{\frac{k_n \rho}{C_n C_s (T_t - T_\phi)}} \quad T_t = T_{cs} + \frac{1}{2} (T_c - T_{cs})$$

NZP velocities: Experiment & Modified Adiabatic Theories



- Inclusion of a minimum propagation current is necessary to achieve better agreement with the data.
- The agreement of the two Iwasa's theories indicated the validity of a new transition point for HTS,
- **Fair agreement is found between the data the modified theory of Iwasa.**

ORNL Conclusion

- **Stability margins ranged from 16 to 120 J/cm³ as temperature lowers from 80 to 45 K.** Comparison with the specific heat integrals indicated better fit to T_c than to T_{cs} for the HTS tapes.
- **Distinctive NZP in YBCO was observed at each of the measured temperatures.**
- **Minimum propagation current as a function of temperature was measured. Its existence is thought to be the result of conduction cooling.**
- **NZP velocities of no more than 20 mm/s were measured. Velocity vs. temperature data show a similar dependence as the ratio of operating to critical current and agrees with a modified adiabatic theory.**