Lecture #4

Stability and Protection

Yukikazu Iwasa

Francis Bitter Magnet Laboratory,
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139-4208

CEA Saclay

July 5, 2016

Outline

- Stability
  - Cryostable vs. adiabatic windings
  - Current-sharing temperature; disturbances; energy margins
  - Acoustic emission (AE) technique
- Protection
  - Self-protecting magnet
  - Normal zone propagation (NZP) velocities
  - Active protection techniques
- Conclusions

Two Types of Stability: Cryostable & Adiabatic

Cryostable

- Conductor over most of the winding well-cooled to enable Cooling to balance Joule heating

Adiabatic

- Conductor, except over the winding surface, not exposed to cooling

$$C_{cd}(T)\frac{\partial T}{\partial t} = \nabla\cdot[k_{cd}(T)\nabla T] + \rho_{cd}(T)J^2_{cd_\circ}(t) + g_d(t) - \left(\frac{f_p\mathcal{P}_D}{A_{cd}}\right)g_q(T)$$

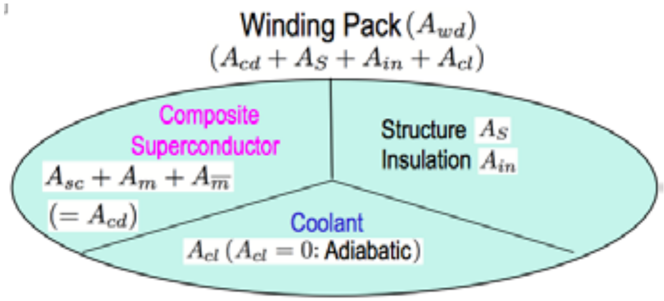
Storage *Conduction* *Joule heating* *Disturbance* *Cooling*

Adiabatic (Also Known as High-Performance) Magnet

- Elimination of coolant within the winding:
  - Enhances the overall current density, λJ;

$$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd}+A_S+A_{in}+\cancel{A}_{cl}} \uparrow$$

  - Makes the winding pack structurally robust
- High-performance magnets: MRI; NMR; HEP
- Susceptible to quench, by a "minute" (but $> \Delta e_h$) disturbance energy



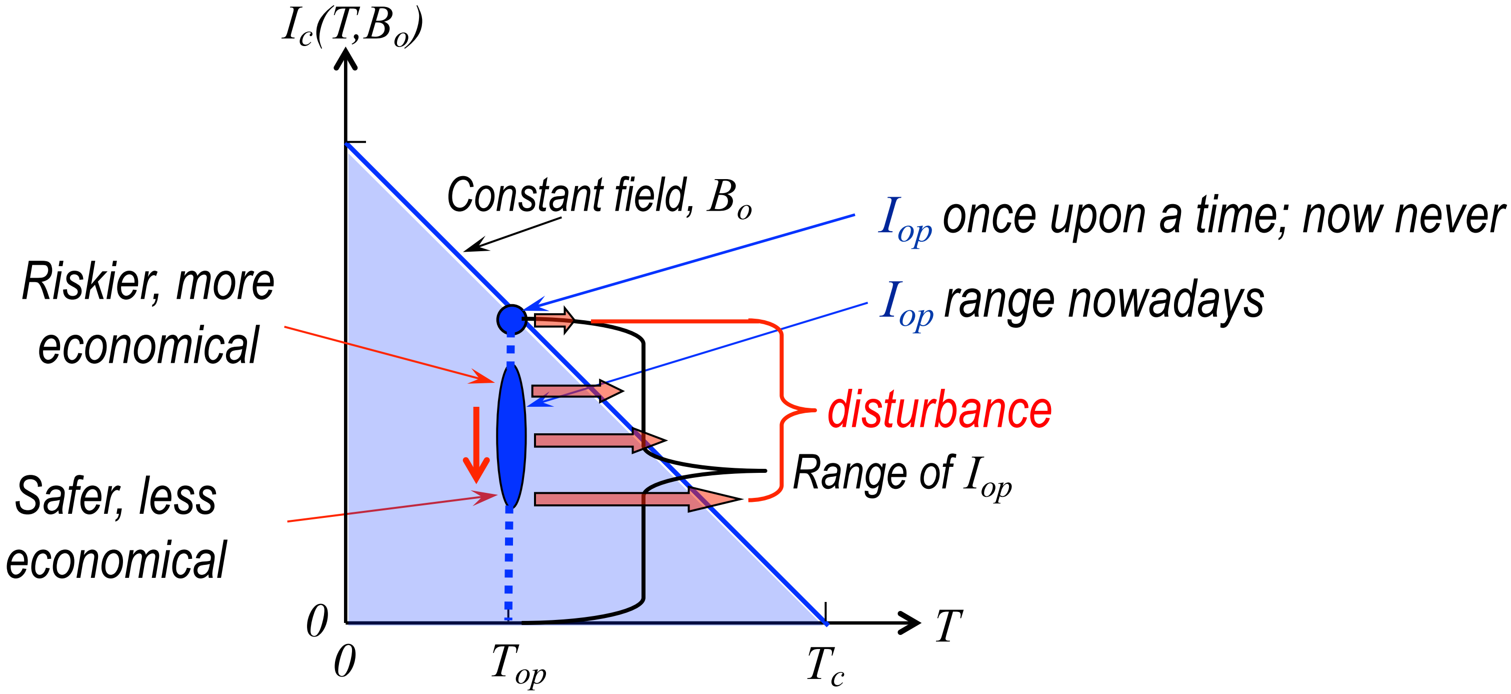
Why fusion magnets "cryostable," i.e., $A_{cl} \neq 0$?

Huge mechanical reinforcement within the winding, $A_S >> A_{cl}$:
A_{cl} *little impact* on λJ, i.e., a negligible sacrifice on magnet efficiency
Let's guarantee *stability* by making the winding *cryostable*, i.e., $A_{cl} \neq 0$

For "small" magnets like MRI, NMR, HEP,
$A_{cl} = 0$ enhances λJ enough to permit "reduced" stability

Stability

Stability (Operation Reliability)
Stable operation of a superconducting magnet in the superconducting state
despite the presence of disturbances that may drive
a section of or the whole magnet into the normal state

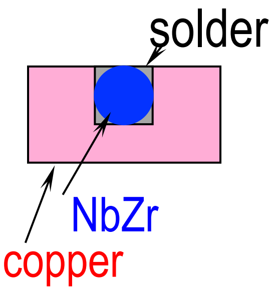


Composite Superconductor

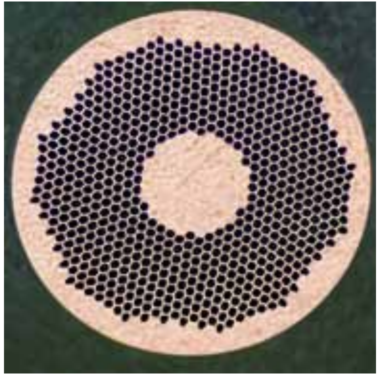
- First formulated and developed in 1964-1965 by Z. John Stekly: because $\rho_{non\text{-}super} >> \rho_{copper}$, superconductor shunted by electrically conductive normal metal like copper

Material @4.2 K	Resistivity [nΩ m]
Copper	0.15
Stainless steel	540
NbTi (normal state)	600

Stekly (1964-1965)

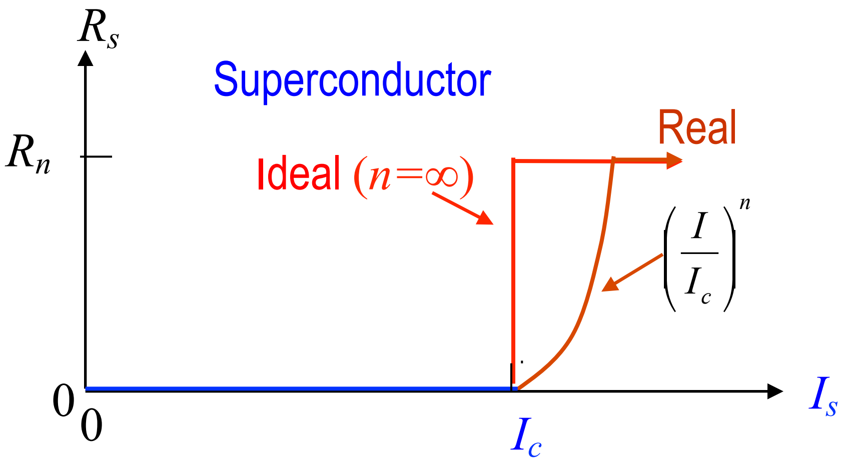


Multifilamentary NbTi



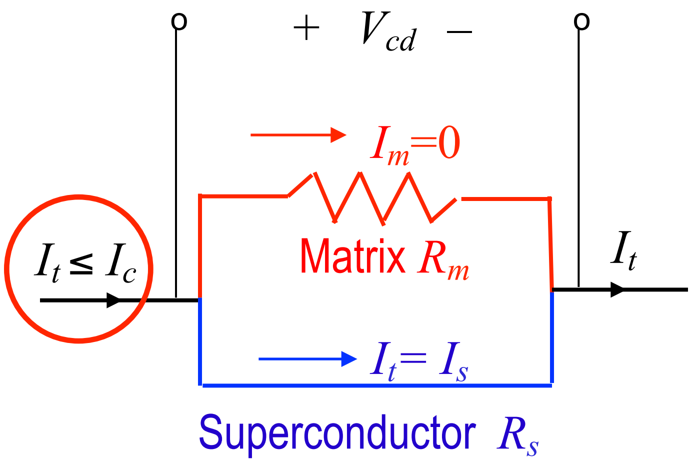
Diameter:	1.03 mm
# Filaments:	642
Filament dia.:	30 μm
Cu/NbTi:	1.1

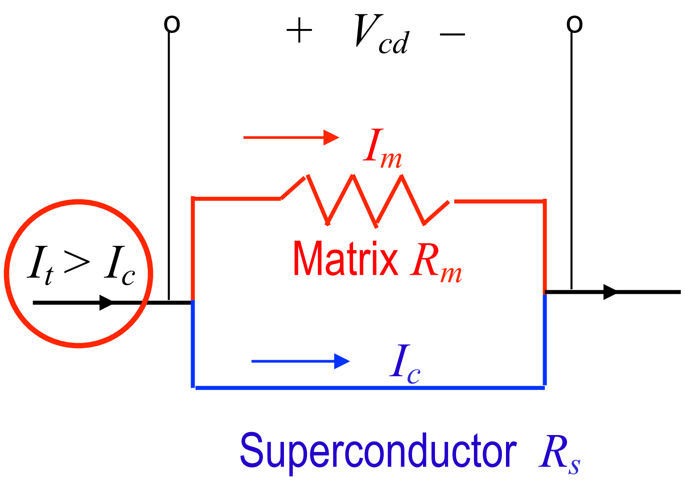
Circuit Models for Composite Superconductor



n: Index

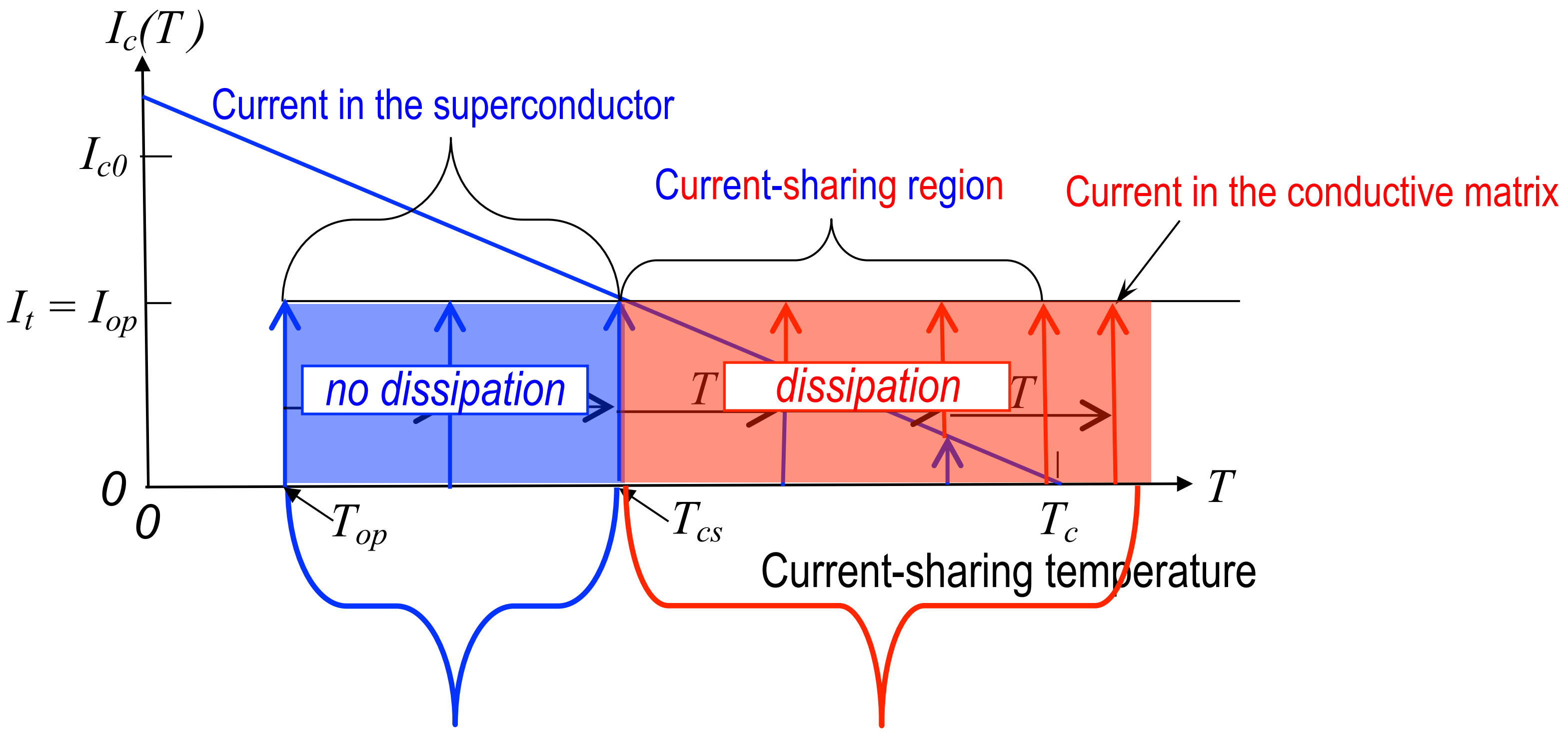
- $n > 30$: LTS
- $n < 30$: HTS
- $n = \infty$: Ideal superconductor





Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

Current Sharing in Composite Superconductor



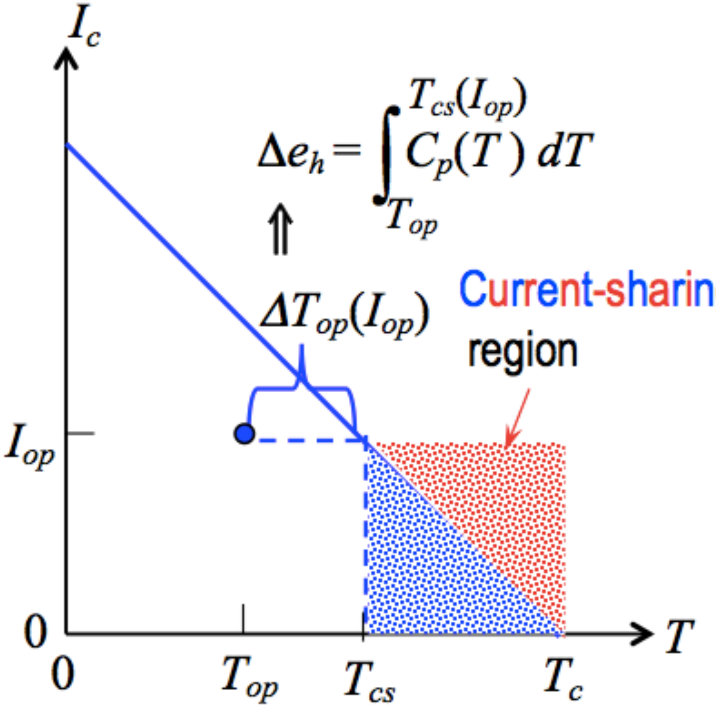
Permissible for any magnet,
even an "adiabatic" magnet

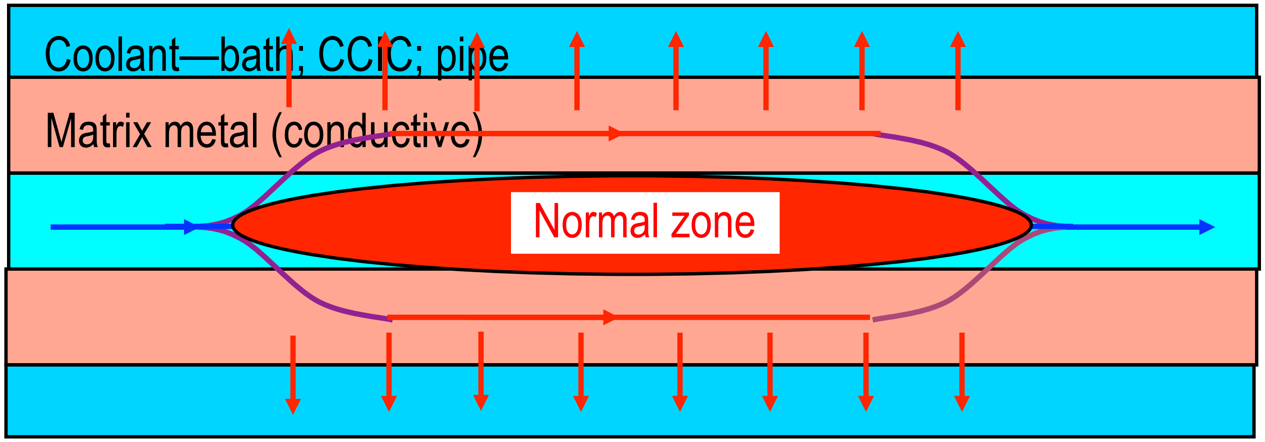
Permissible only for
"cryostable" magnets

Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

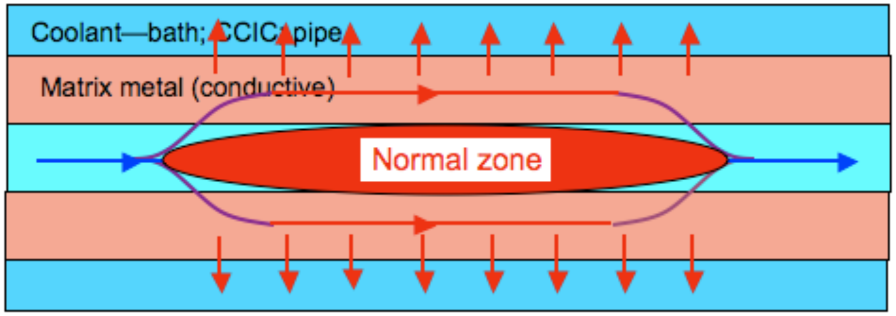
Cryostable Magnet

- Disturbance energy density, $g_d\,(t)$, can exceed Δe_h





Key Issues for Cryostable Magnet

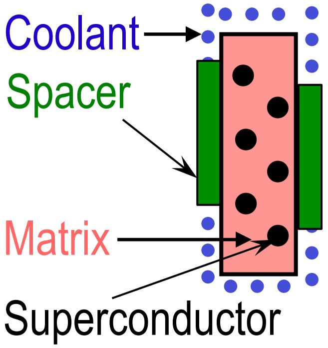


- Dissipation (Joule heating) density:
  - Matrix metal electrical resistivity, ρ_m : the lower the ρ_m the better
  - Matrix metal current density, $J_{mo} \Rightarrow A_m$: the greater the A_m the better
- Cooling:
  - Coolant, e.g., helium (ordinary; superfluid; supercritical)
  - Heat transfer data (natural or forced convection)
  - Conductor design, e.g., monolith; Rutherford; CICC

Cryostability

Stekly's cryostability

- Joule heating / unit length = cooling flux / unit length



$$\frac{\rho_m I_{m_\circ}^2}{A_m} = f_p \mathcal{P}_D q_{fm} = \rho_m A_m J_{m_\circ}^2$$

  - ρ_m: matrix resistivity; A_m: matrix cross section
  - f_P: fraction of $\mathcal{P}_D$, conductor perimeter exposed to cooling

$$[J_{m_\circ}]_{sk} = \sqrt{\frac{f_p \mathcal{P}_D q_{fm}}{\rho_m A_m}}$$

Cryostable operation, $[J_{m_\circ}]_{sk} << J_c$

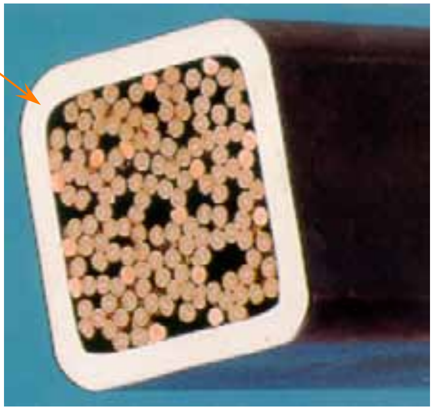
Cryostable Magnets

Key Features

- $[J_{m_o}]_{sk}$ determined by parameters other than J_c :

$$[J_{m_\circ}]_{sk} = \sqrt{\frac{f_p \mathcal{P}_D q_{fm}}{\rho_m A_m}}$$

- LHe within the winding makes the cryostable winding "spongy"
- CICC used for "large" magnets, e.g., ITER, requiring a robust winding
- For "large" magnets in which structural materials occupy a significant fraction of the winding pack, making the condition $[J_{m_o}]_{sk} << J_c$ not as important as for adiabatic magnets.

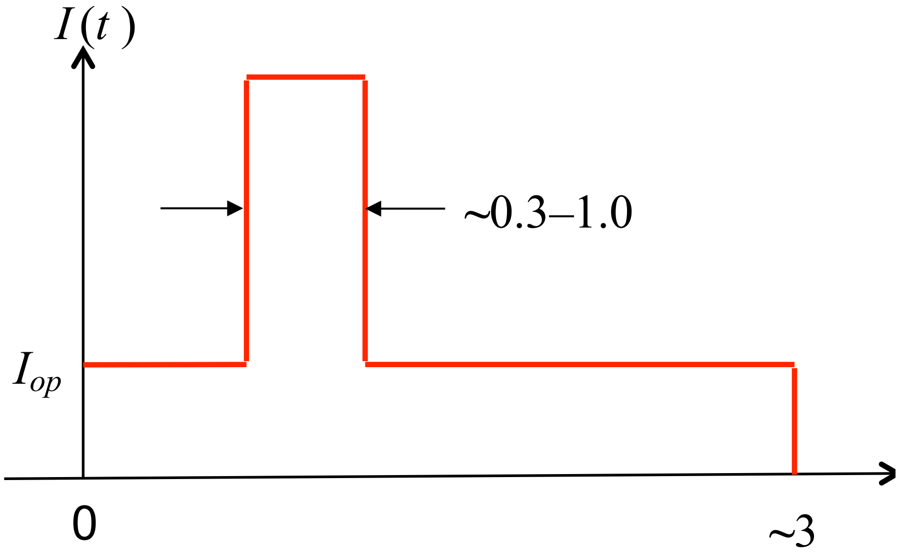


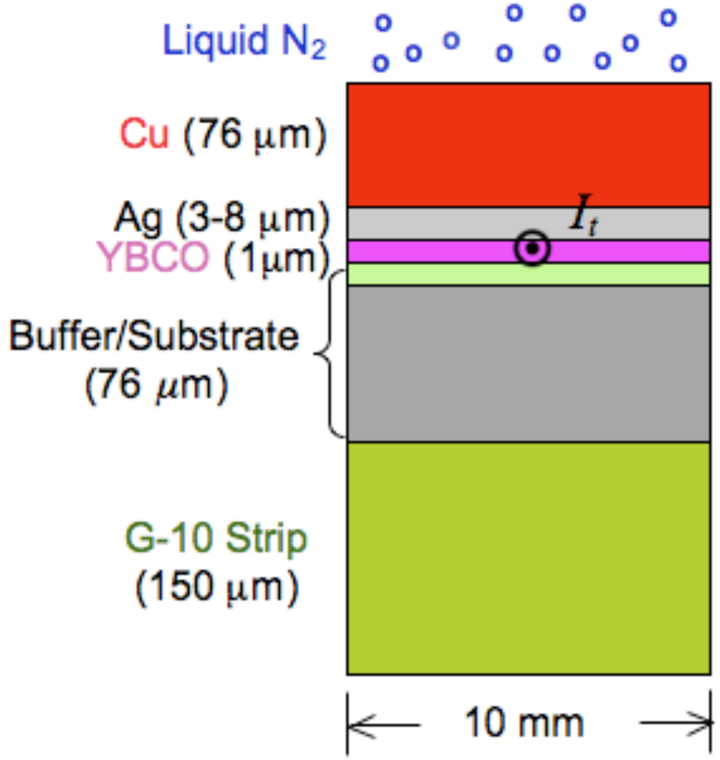
CIC conductor (CICC)

An Experimental Illustration of *Cryostability*

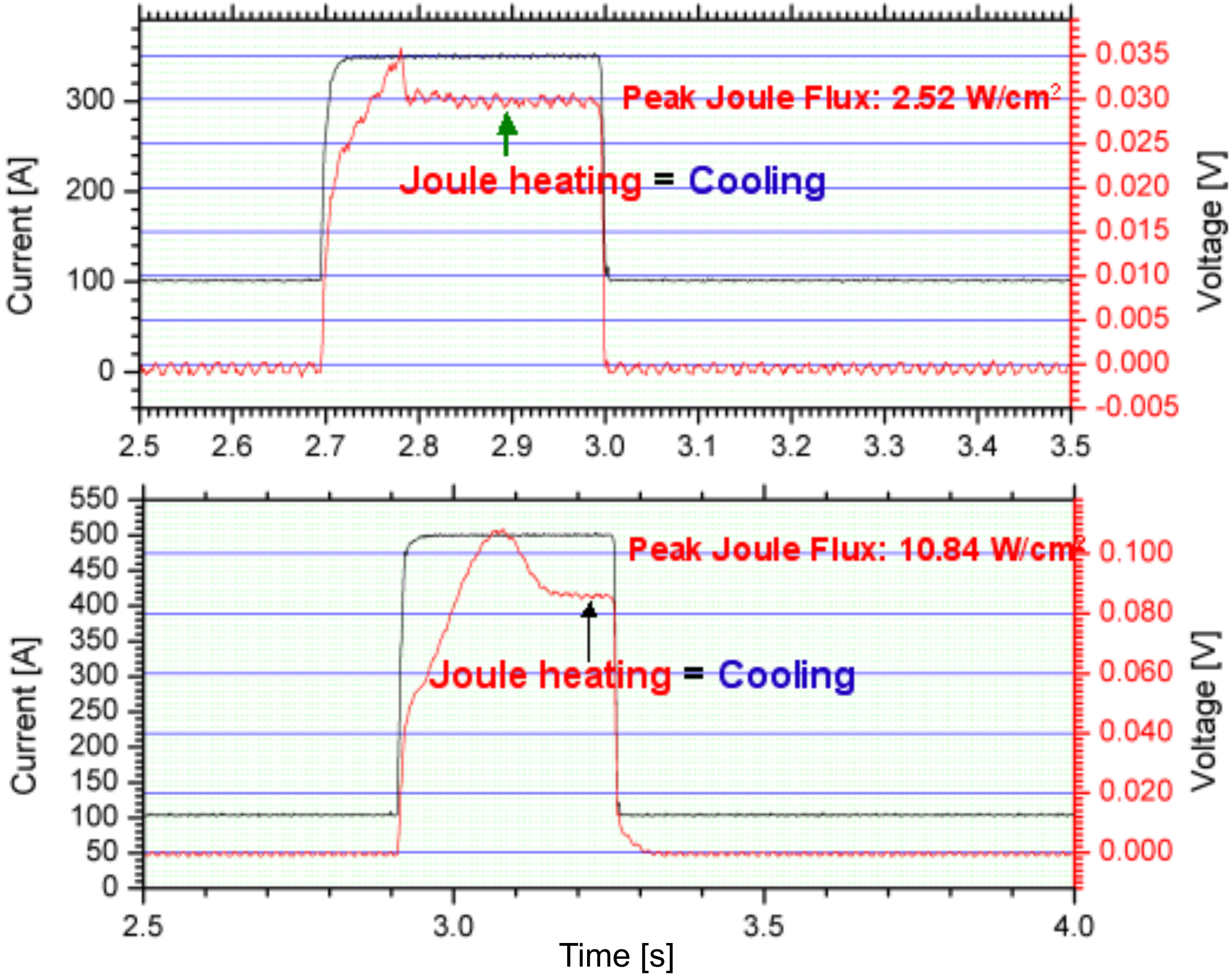
Experiment: *Liquid N_2 Cooled*, “Composite” YBCO Tape

- Composite YBCO, 10-cm long; I_c (77 K, self field): >110 A
- A current pulse (3-5 × I_c) applied over a steady-state DC current (~0.9I_c)



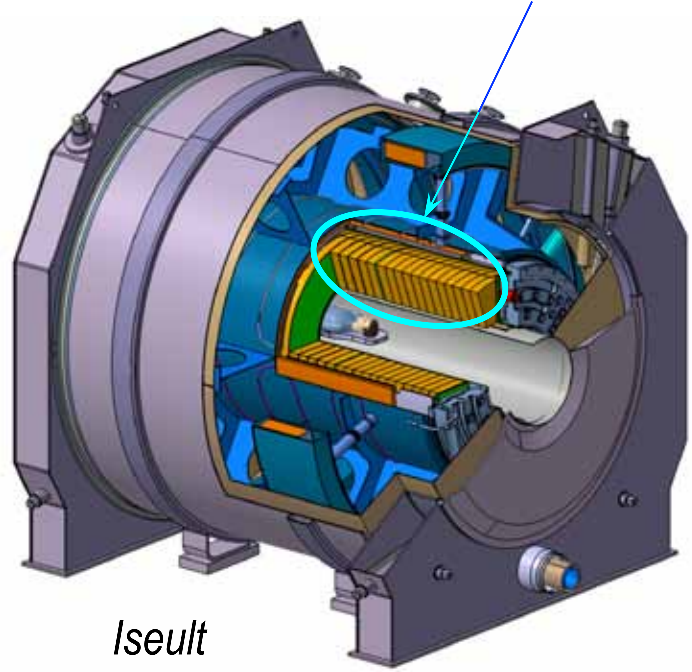


An Experimental Illustration of *Cryostability*



Cryostable Magnets: Current Trend

- Up to ~1980 magnets were mostly cryostable
  - *Success* much more important than *efficiency*
- Since ~1980, *cryostability* restricted to "large" magnets, e.g.,
  - ITER coils: forced supercritical helium through CICC
  - *Iseult*: a large MRI magnet (500 MHz/ 900 mm RT bore) nearly completed in France

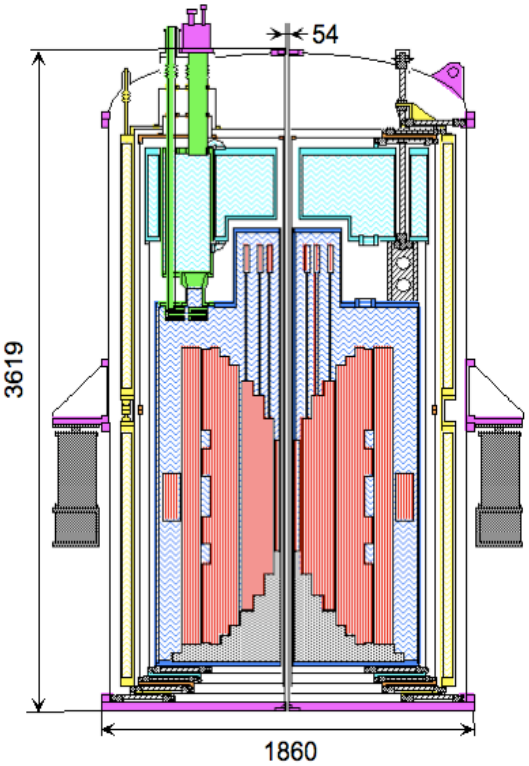


Iseult

Adiabatic Magnets

- Since ~1980, adiabatic* ("high-performance") magnets prominent chiefly because of efficiency (lower cost), e.g.,
  - Magnet *always* requires cooling but its winding not necessarily exposed directly to the coolant
    - HEP dipole and quadrupoles
    - NMR/MRI magnets
    - Most "research" magnets

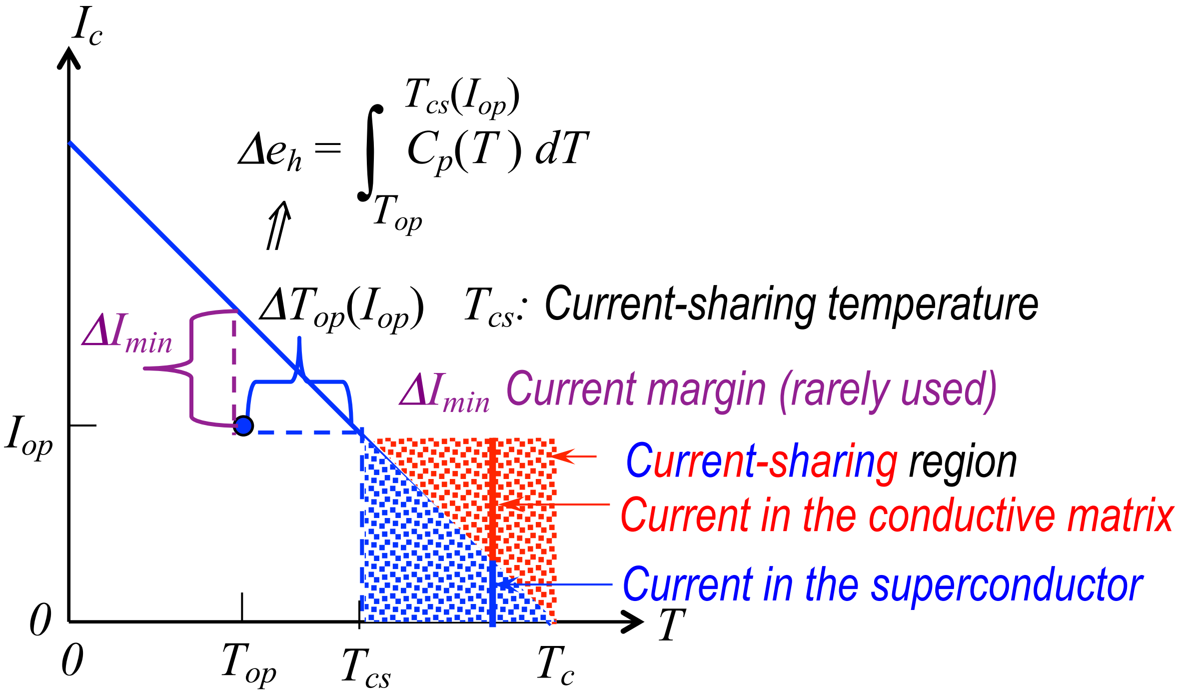
LHC dipole



920 MHz (21.6 T) NMR magnet

Stability Margin: Energy Δe_h or Temperature $\Delta T_{op}(I_{op})$

- Minimum energy density (or energy) or temperature rise that drives a part of the winding out of the superconducting state
  - $\Delta T_{op}(I_{op})$ easier than Δe_h to quantify in the design stage; ΔI_{min} also easier than Δe_h but less used than $\Delta T_{op}(I_{op})$



$$\Delta e_h = \int_{T_{op}}^{T_{cs}(I_{op})} C_p(T)\, dT$$

T_{cs}: *Current-sharing temperature*

ΔI_{min} *Current margin (rarely used)*

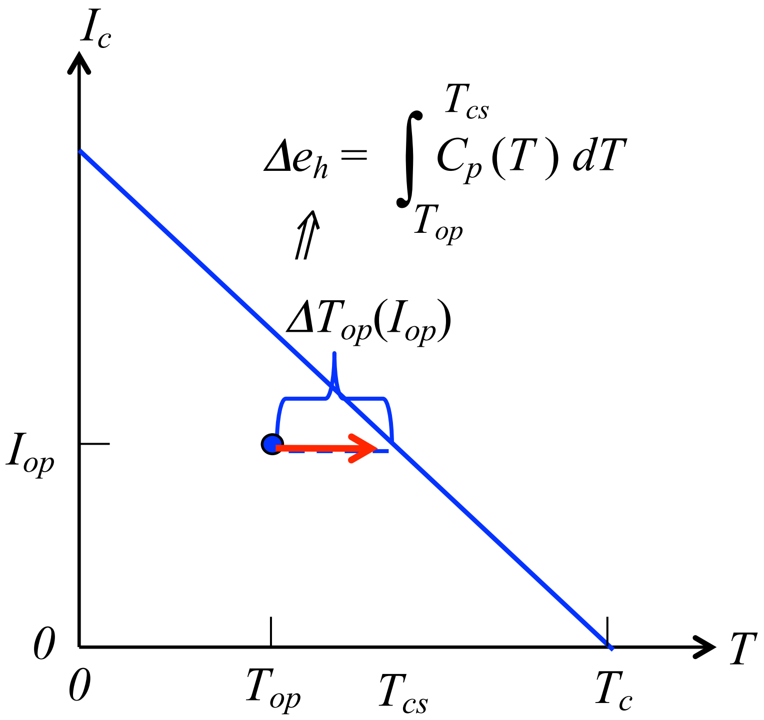
Current-sharing region

Current in the conductive matrix

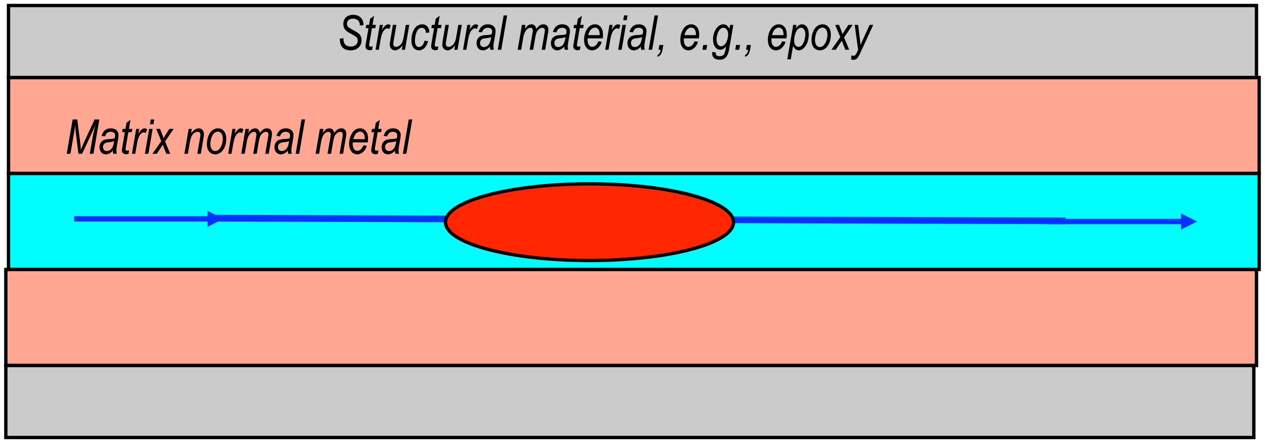
Current in the superconductor

Adiabatic Magnet

- Disturbance energy density, $g_d\,(t) < \Delta e_h$

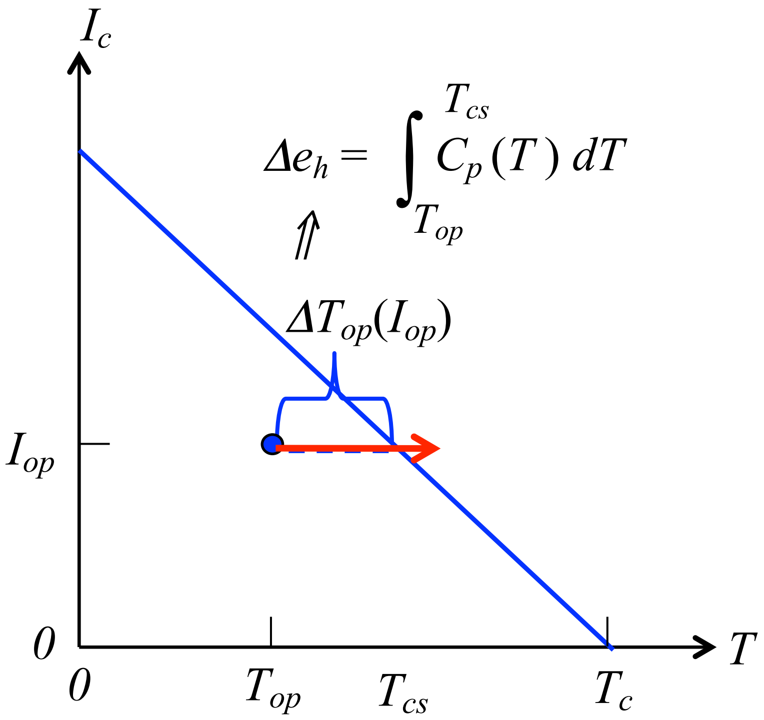


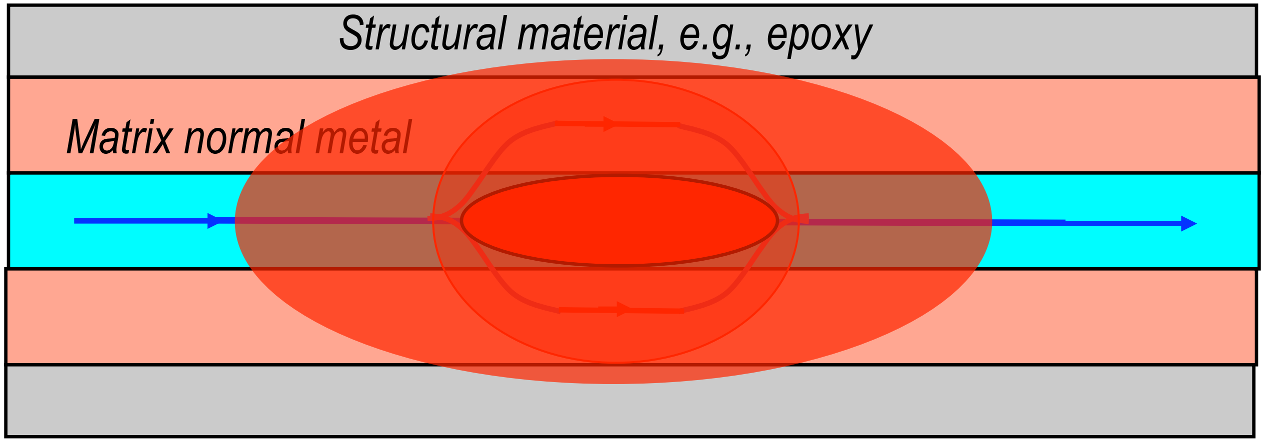
$$\Delta e_h = \int_{T_{op}}^{T_{cs}} C_p(T)\,dT$$



Adiabatic Magnet (cont.)

- $g_d\,(t) > \Delta e_h$: a quench



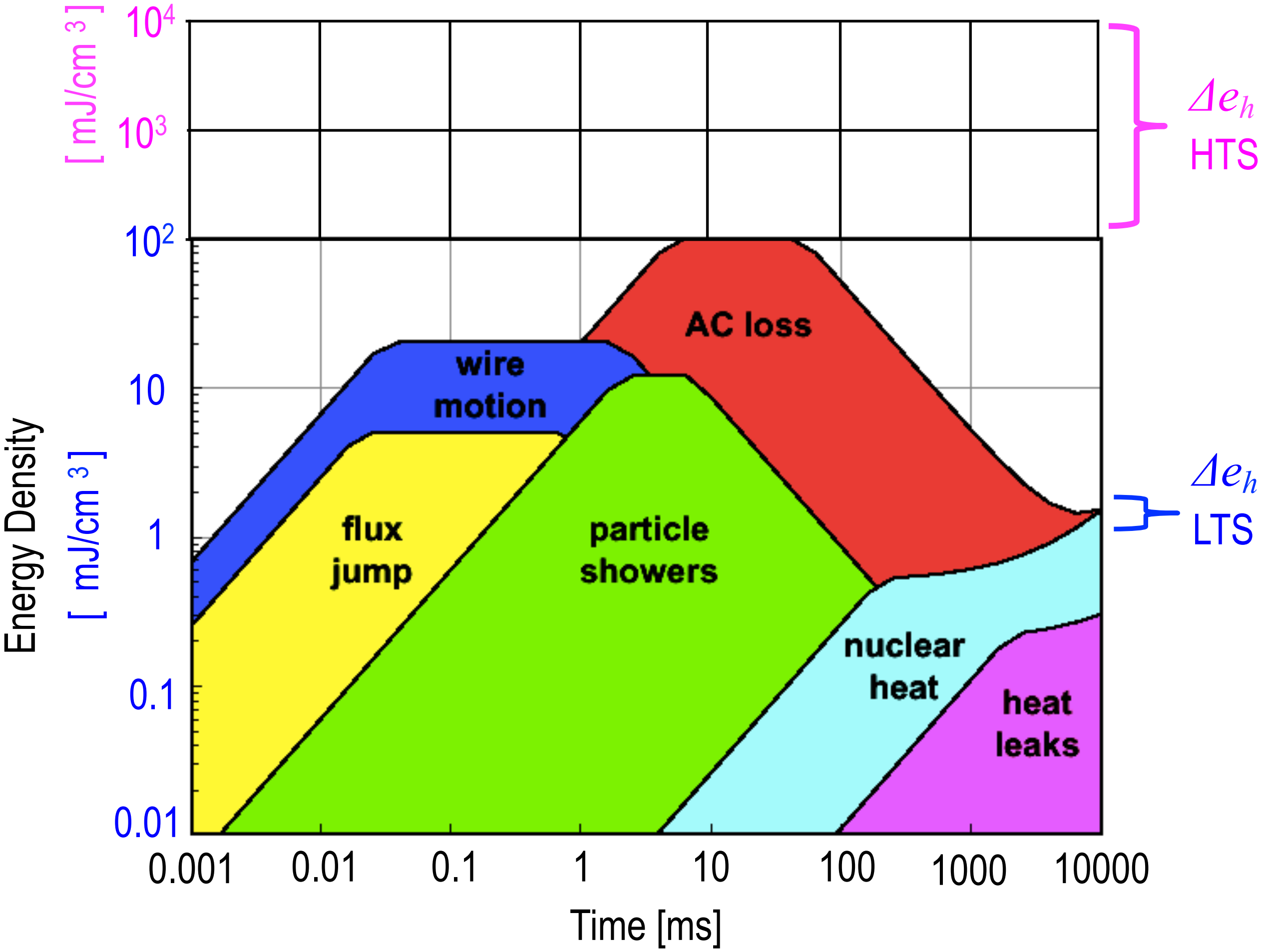


Sources of Disturbance

$$\underbrace{C_{cd}(T)\frac{\partial T}{\partial t}}_{\text{Storage}} = \underbrace{\nabla\cdot[k_{cd}(T)\nabla T]}_{\text{Conduction}} + \underbrace{\rho_{cd}(T)J^2_{cd_\circ}(t)}_{\text{Joule heating}} + \underbrace{g_d(t)}_{\text{Disturbance}} - \underbrace{\left(\frac{f_p P_D}{A_{cd}}\right) g_q(T)}_{\text{Cooling}}$$

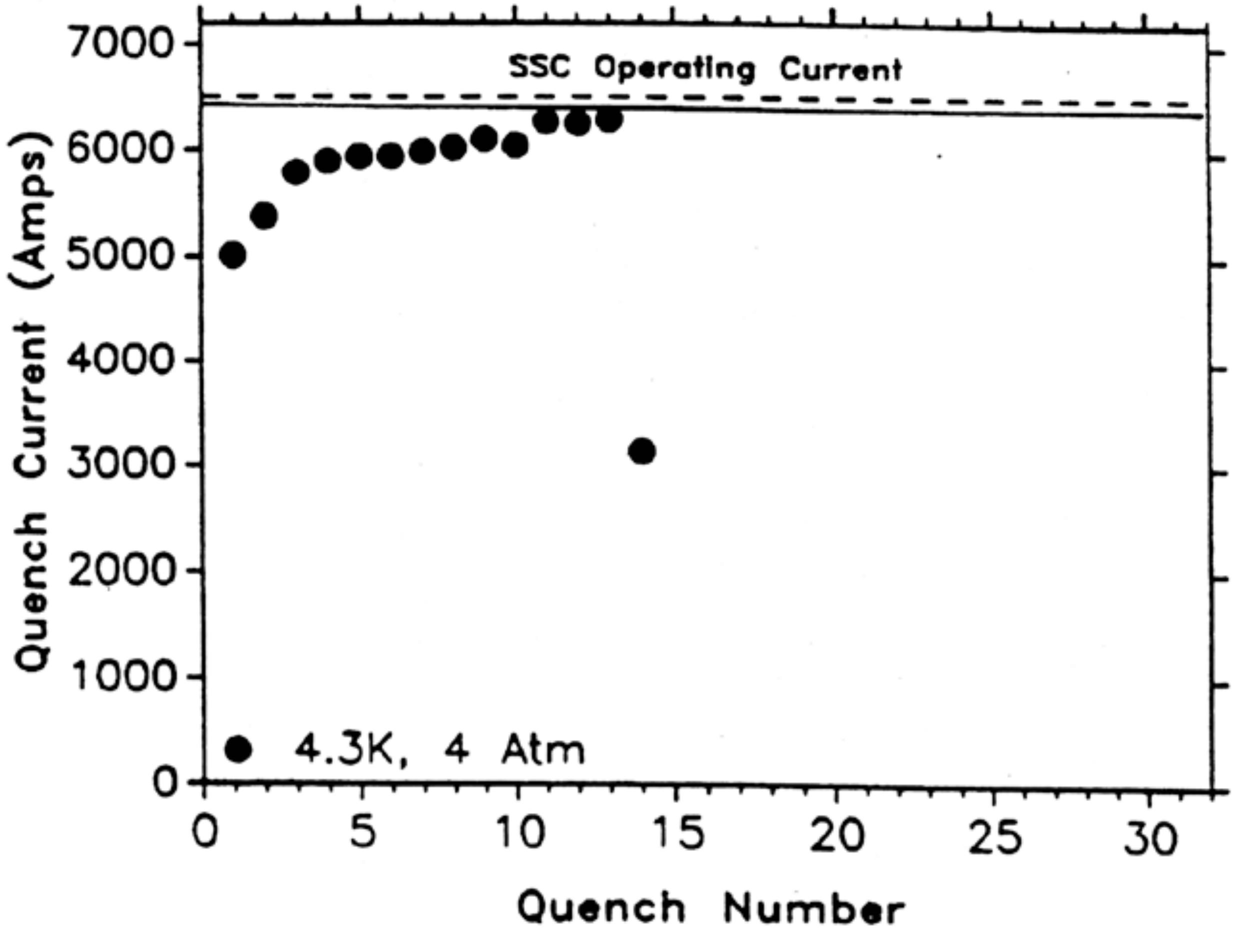
- Mechanical
  Lorentz force; thermal contraction
  - Wire motion / “micro-slip”
    - ▪ Remedy: Impregnate winding with epoxy or other filler
  - Structure deformation
  - Cracking epoxy; debonding
    - ▪ Wire motion remedy can become another disturbance
- Electrical/magnetic
  —Time-varying current/field
  - Current transients, includes AC current
  - Flux motion, e.g., flux jump
  - Field transients, includes AC field
- Thermal
  - Conduction, through leads
  - Cooling blockage (poor ventilation)
- Nuclear radiation
  - Neutron flux in fusion machines
  - Particle showers in accelerators

Disturbance Energy Density Spectra



HTS magnets free of disturbances that afflict adiabatic LTS magnets

An Example of Training in an SSC* Dipole



* Superconducting Super Collider (US program launched in 1986 but canceled in 1993 because of cost overrun). SSC (vs. LHC): 20 TeV (7 TeV); 6.8 T/87 km (8.4 T/27 km)

[S. Ige (MIT ME Dept. Ph.D. Thesis, 1989)]

AE Technique

Acoustic signals emitted by sudden *mechanical events* in a body *being* loaded or unloaded, e.g., a magnet being charged or discharged; useful for detection and location of a premature quench caused by *conductor motion* or *epoxy fracture* event in *adiabatic magnets*

The technique used extensively in the 1980s at FBML to: 1) understand the nature of these disturbances; 2) develop a new technique to minimize the detrimental effects of these disturbance and improve magnet performance, i.e., minimize the premature quenches

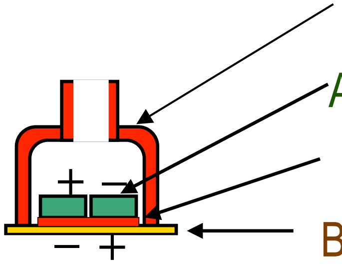
Piezoelectric Effect: The coupling of mechanical and electric effects in which a strain in a certain class of crystals, e.g., quartz, induces an electric potential and vice versa; *discovered by P. Curie in 1880*

Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

AE Sensor

- Commercially available sensor: expensive ($500-$2000); and even those built for use in “low temperature”generally fail
- Home-made (FBML) differential sensors: reasonable cost (~$50/AE disk + labor); withstands 4.2 K - RT cycles.

Differential Sensor



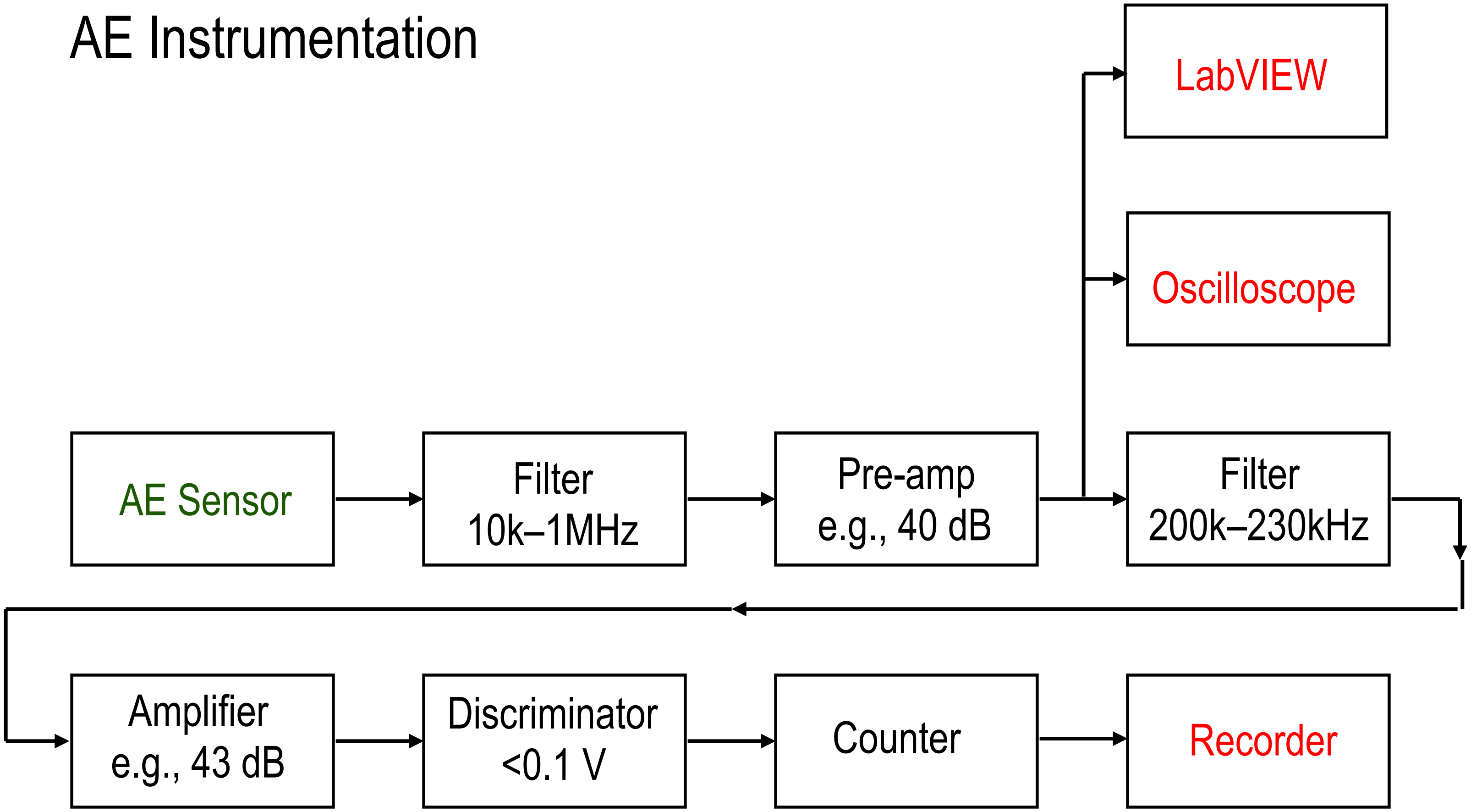
from Copper pipe cap

AE disk: two half-disks

Cu foil (~25 μm)

Brass foil (~75 μm)

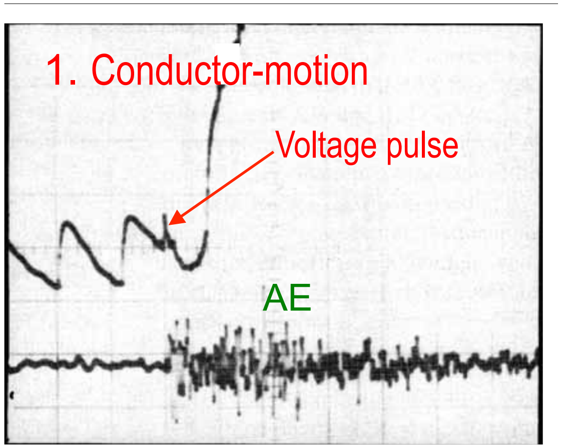
AE Instrumentation

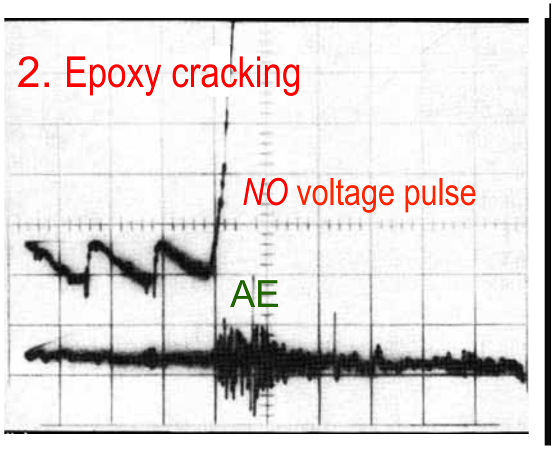


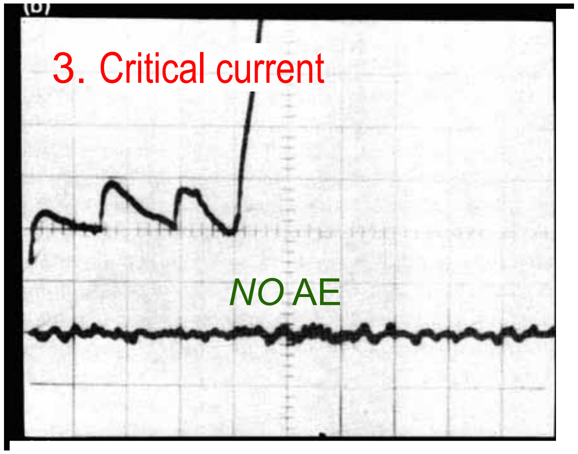
Identification of Quench Causes by AE Technique

A combination of voltage & AE monitoring permits identification of 3 *distinguished* causes of a quench in adiabatic magnets

1. Conductor motion: a *voltage spike* & the start of *AE* signals
2. Epoxy fracture: *no voltage spike* but *AE* signals
3. Critical current: *no voltage spike nor AE* signals



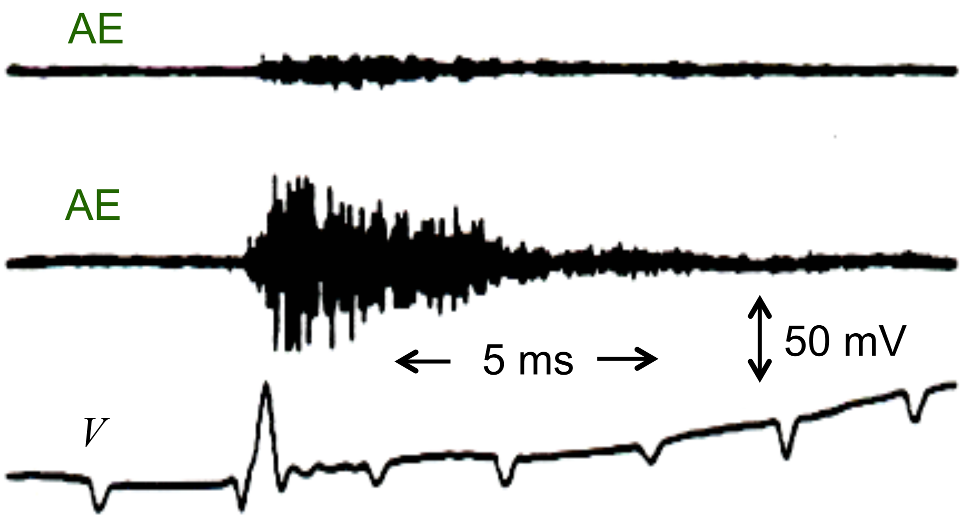




[O. Tsukamoto, J.F. Maguire, E.S. Bobrov, and Y. Iwasa, *Appl. Phys. Lett.* **39**, 172 (1981)]

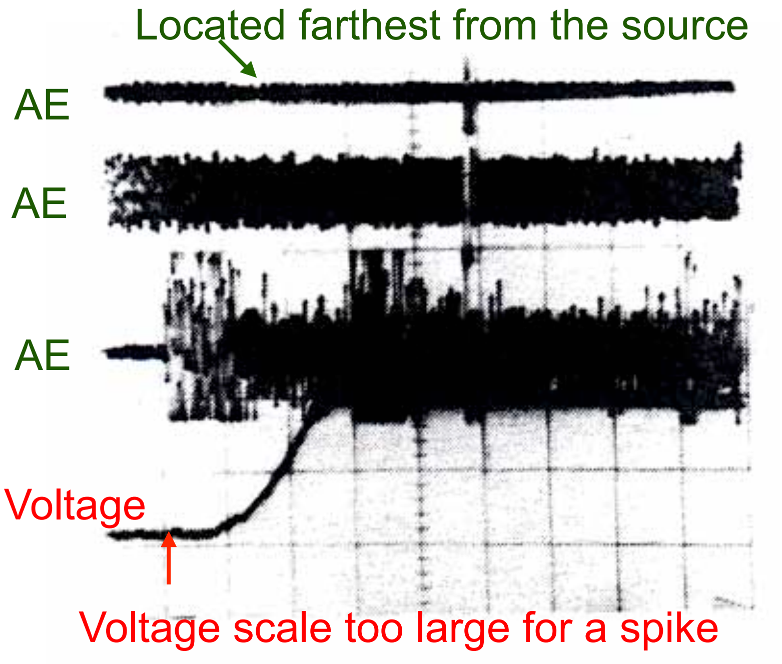
A Conductor-Motion Induced Quench

— *Isabella Dipole* (BNL, c. 1981)



[O. Tsukamoto, M.W. Sinclair, M.F. Steinhoff, and Y. Iwasa, *App;. Phys. Lett*. **38**, 718 (1981)]

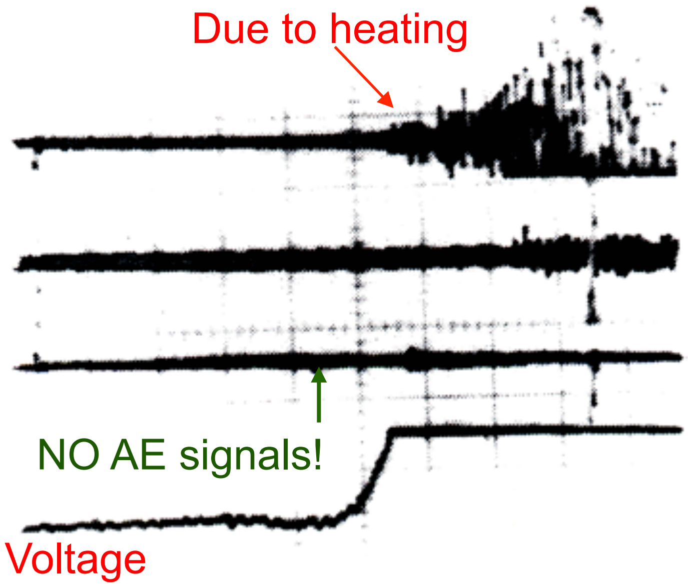
Conductor-Motion Induced & Critical-Current Quenches — An SSC Dipole



Located farthest from the source

Voltage scale too large for a spike

$I_q = 6510$ A



Due to heating

NO AE signals!

$I_c = 6828$ A

[S. Ige (MIT ME Dept. Ph.D. Thesis, 1989)]

Conductor Motion

- Frictional heating energy release, e_f, due to a Lorentz-force induced conductor motion ("slip") of Δr_f:

$$e_f = \mu_f f_{Lr} \Delta r_f = \mu_f J_\theta B_z \Delta r_f$$

With $\mu_f = 0.3$, $J_\theta = 200 \times 10^6\ \text{A/m}^2$, $B_z = 5\,\text{T}$, and

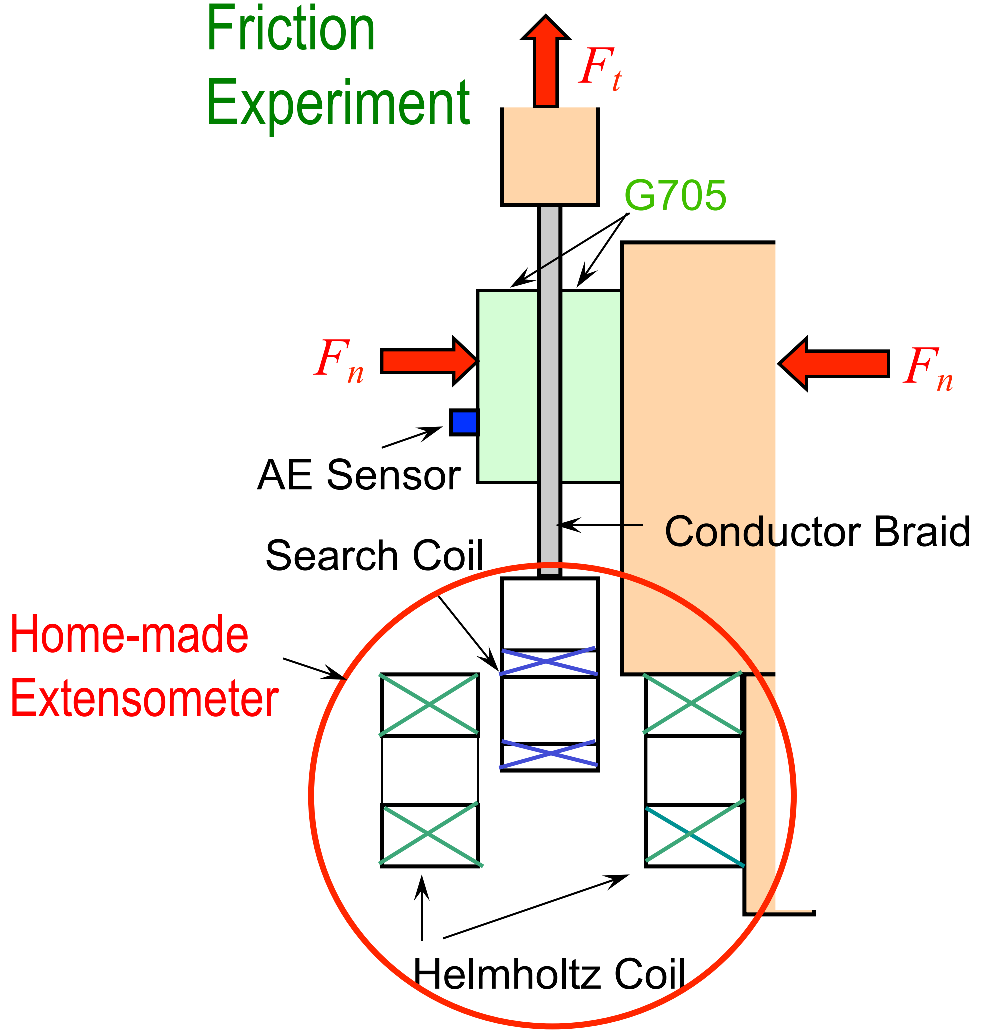
$$e_f = h_{cu}(5.2\text{K}) - h_{cu}(4.2\text{K}) = 1300\,\text{J/m}^3:$$

$$\Delta r_f = \frac{e_f}{\mu_f J_\theta B_z} = \frac{(1300\,\text{J/m}^3)}{(0.3)(200 \times 10^6\ \text{A/m}^2)(5\,\text{T})} \cong 20\,\mu\text{m}$$

- Actually a conductor slip as small as ~1 μm ("microslip") can drive a short length of the conductor to the normal state, inducing a premature quench

Friction/Quench Experiments

Friction Experiment



F_t

G705

F_n

F_n

AE Sensor

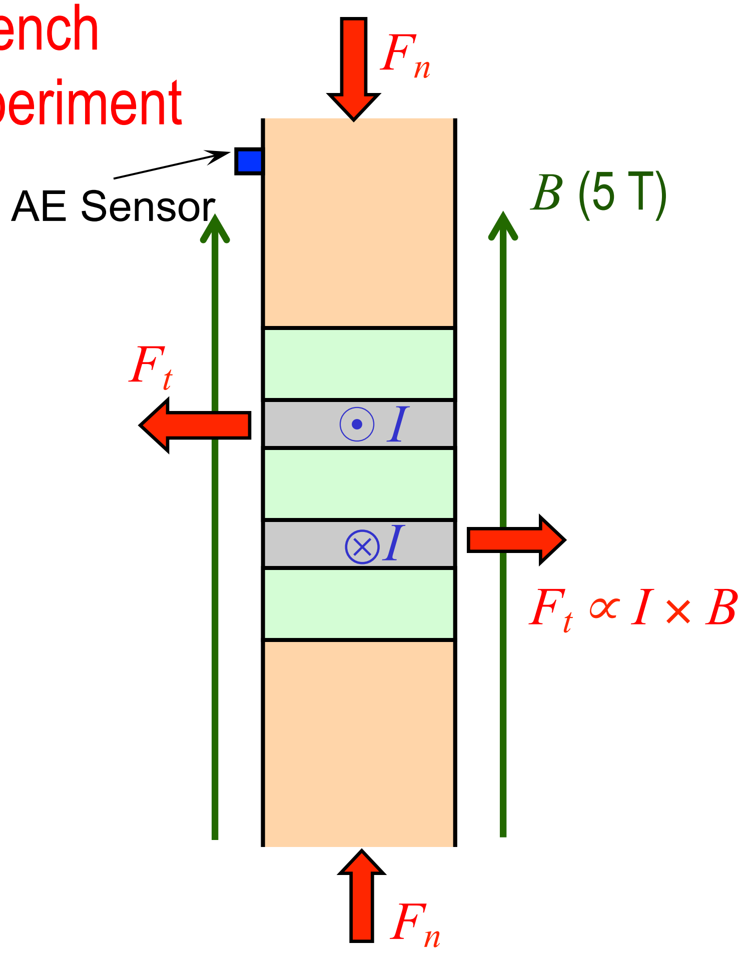
Conductor Braid

Search Coil

Home-made Extensometer

Helmholtz Coil

Quench Experiment



F_n

AE Sensor

B (5 T)

F_t

$\odot I$

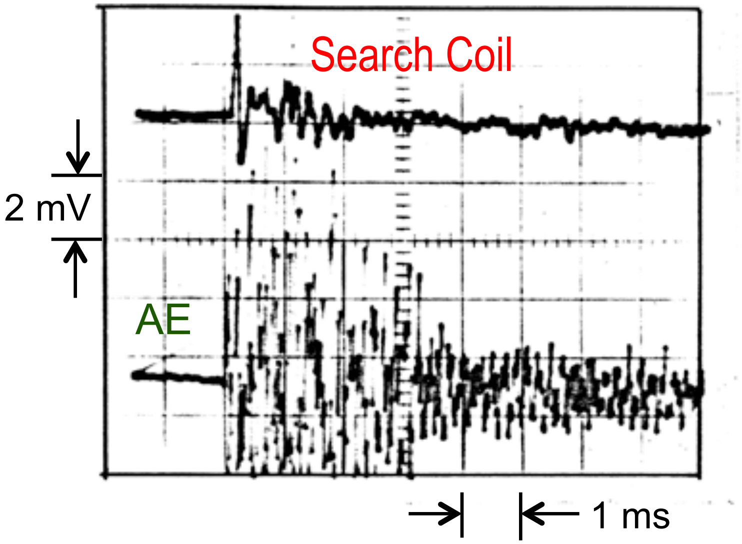
$\otimes I$

$F_t \propto I \times B$

F_n

Based on O. Tsukamoto, H.Maeda, and Y. Iwasa, Appl. Phys. Lett. **39**, 918 (1981)

Friction Experiment

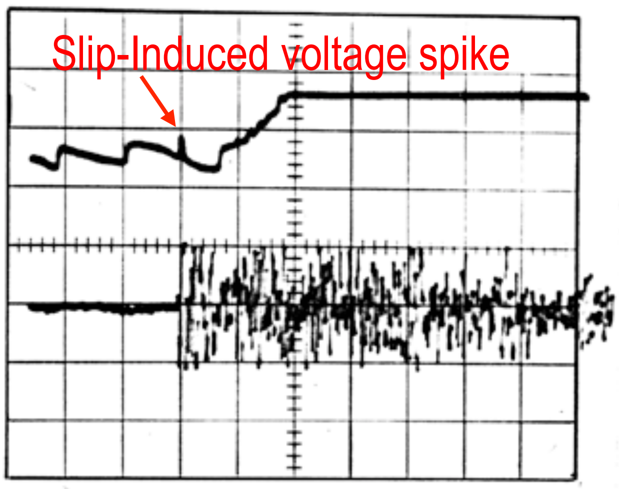


Slip distance: ~1μm

Peak slip velocity: ~ 1 cm/s

F_n=2000 N; F_t~400 N

Quench Experiment



Slip distance: ~1μm

Peak slip velocity: ~ 3 cm/s

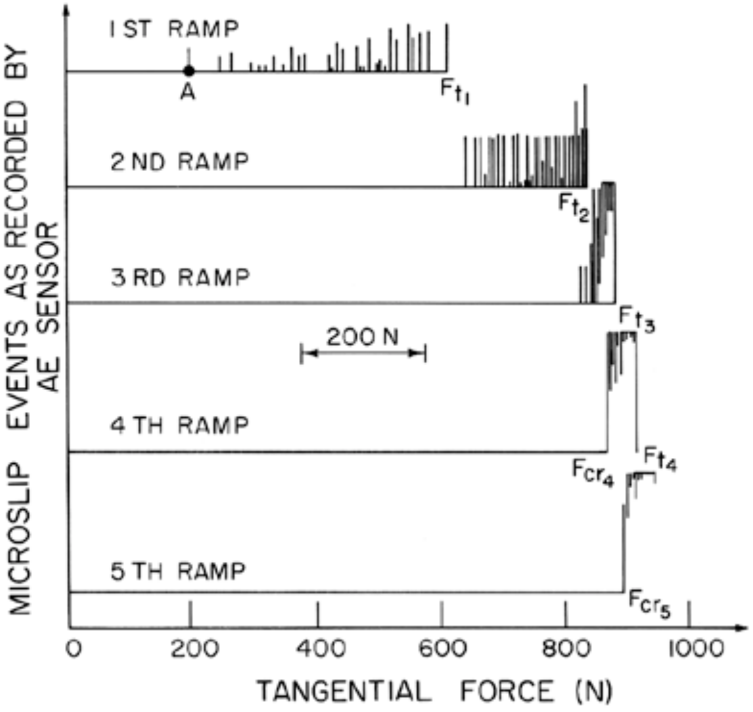
F_n=2000 N; F_t=500 N

[=(0.025 m)(4000 A)(5 T)]

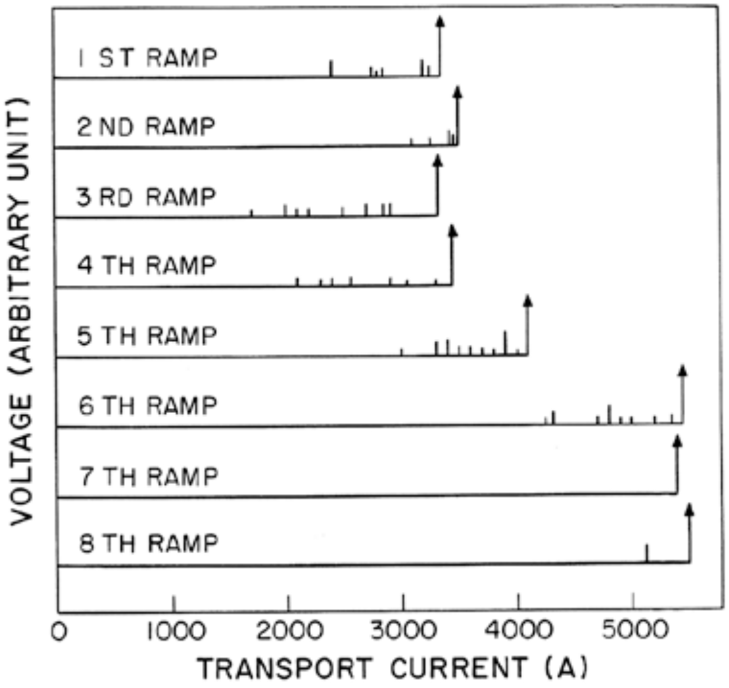
[O. Tsukamoto, H. Maeda, and Y. Iwasa, *Appl. Phys. Lett.* **39**, 918 (1981)]

Observation of Kaiser Effect, i.e., Training

Friction Experiment



Quench Experiment



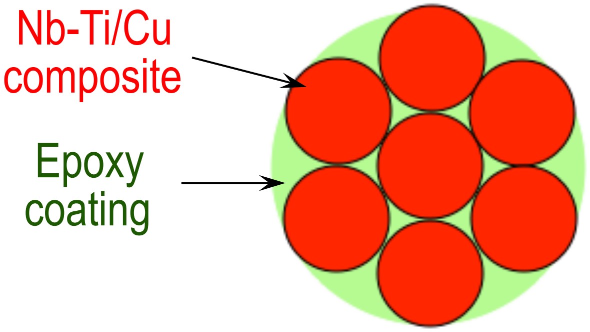
[H. Maeda, O. Tsukamoto, and Y. Iwasa, *Cryogenics* **22**, 287 (1982)]

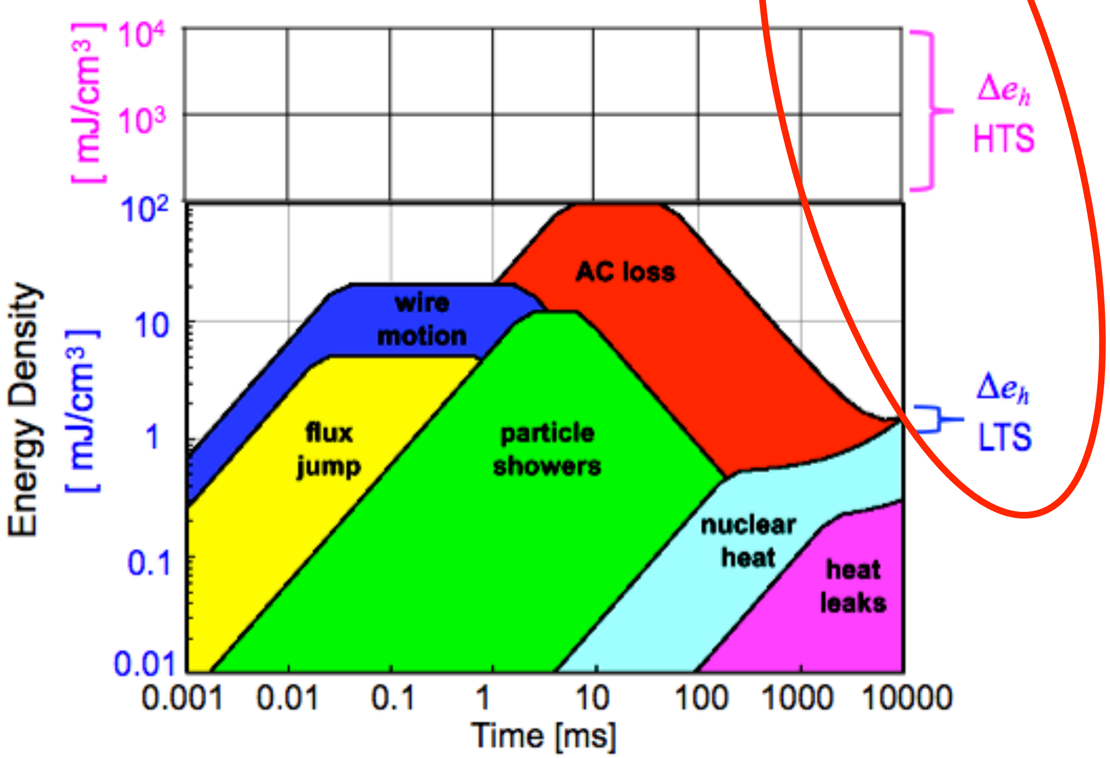
Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

Epoxy Fracture Inducted Heating

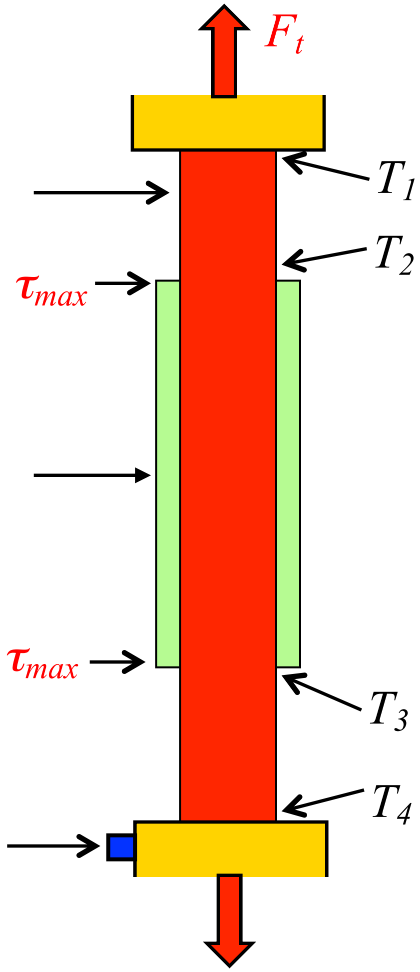
Stored elastic energy density, $\varepsilon_{el,}$ typical epoxy resin:

$$\epsilon_{el} = \frac{\sigma_{el}^2}{2E} \simeq \frac{(15 \times 10^6\,\mathrm{Pa})^2}{2(10 \times 10^9\,\mathrm{Pa})} = 11{,}250\,\mathrm{J/m^3} \sim 10\,\mathrm{mJ/m^3} \gg [e_h]_{mx}$$





Epoxy Cracking Inducted Heating — Experimental Results



Nb-Ti/Cu composite

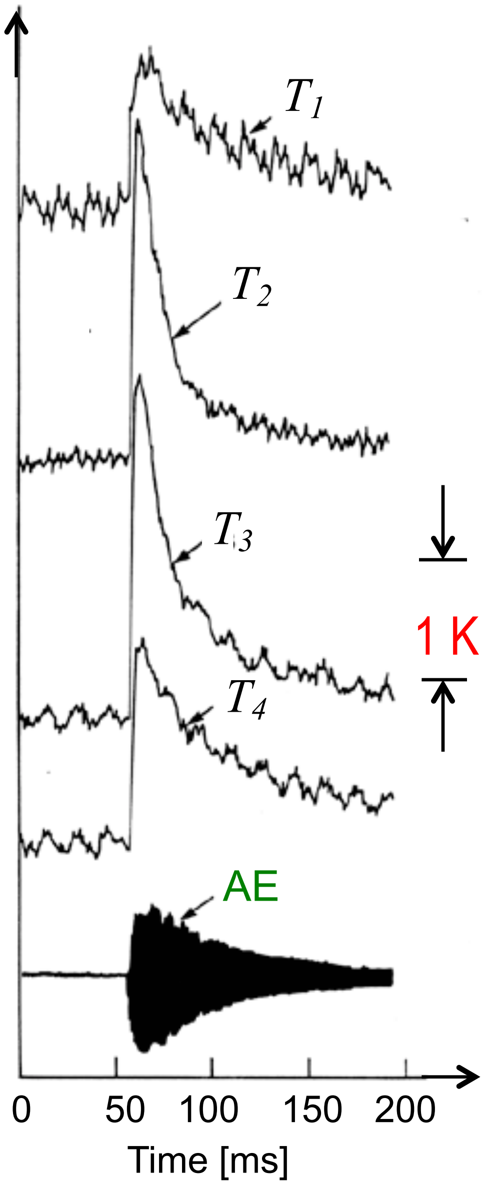
τ_{max}

Epoxy coating

τ_{max}

AE Sensor

[Y. Yasaka and Y. Iwasa, *Cryogenics* **24**, 423 (1984)]



Properties (at 4.2 K) and Energy Densities of Selected Filler Materials:*
Epoxy, Cynate Ester, Vinyl Ester, Polyester, and Others

Manufacturer / Trade Name or #	E [GPa]	σ_{ul} [Mpa]	e [mJ/cm^3]
Hercules / 3502	9.5	66	229
Shell / 9310	9.5	86	389
Dow Chemical / Tactix 123	8.3	102	627
Composite Technology Development / 102	8.1	95	557
Ciba-Geigy / 179	7.5	85	482
Shell / DPL 862	7.0	128	1170
Rhone-Poulenc / REX-378	6.8	117	1007
ICI / 954-3	6.4	69	372
Composite Technology Development / X700	9.4	62	204
Composite Technology Development / X800	7.5	130	1127
Dow Chemical / Derakane 8084	5.8	139	1665
Owens Corning / 701	7.4	95	610
NHMFL 61**	7.5	141	1325
Paraffin+	(assume 6)	21	37

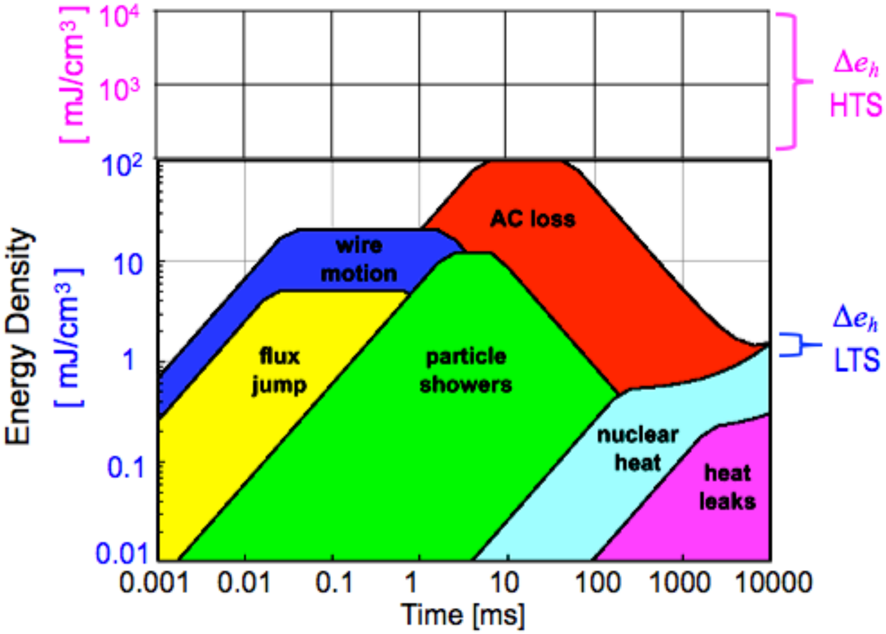
* [D. Evans and J.T. Morgan (Rutherford and Appleton Lab., early 1980s0)]

** [W.D. Markiewicz, I.R. Dixon, J.L. Dougherty, K.W. Pickard, and A.B. Brennan (ICMC/CEC, 1997)]

\+ [P.F. Smith and B. Colyer, *Cryogenics* **15**, 201 (1975)]

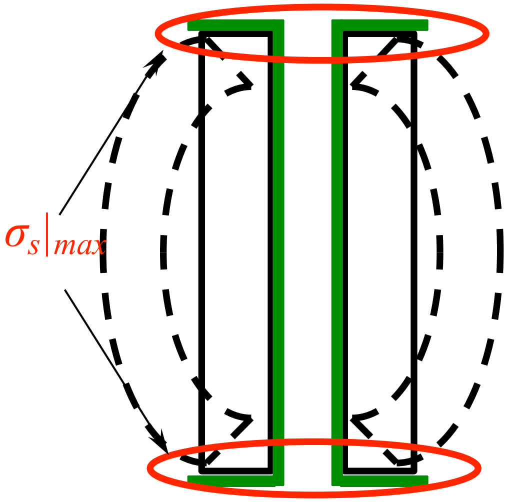
Observations on Filler Materials

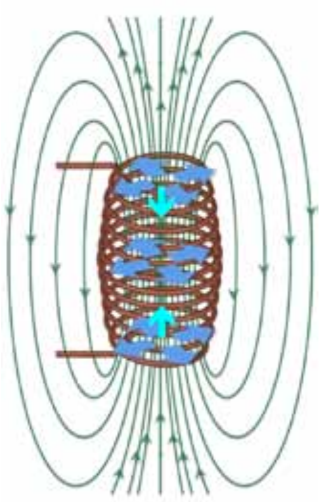
- Filler materials generally release a fracture energy density (> 200 mJ/cm^3)
  - A fracture incident likely to cause a premature quench in *LTS* magnets
  - Still, paraffin-filled magnets suffer least incidents of premature quench
- HTS magnets unlikely to suffer from filler fracture
- HTS magnets unlikely to suffer from conductor motion
  - Filler material *not* required to prevent conductor motion



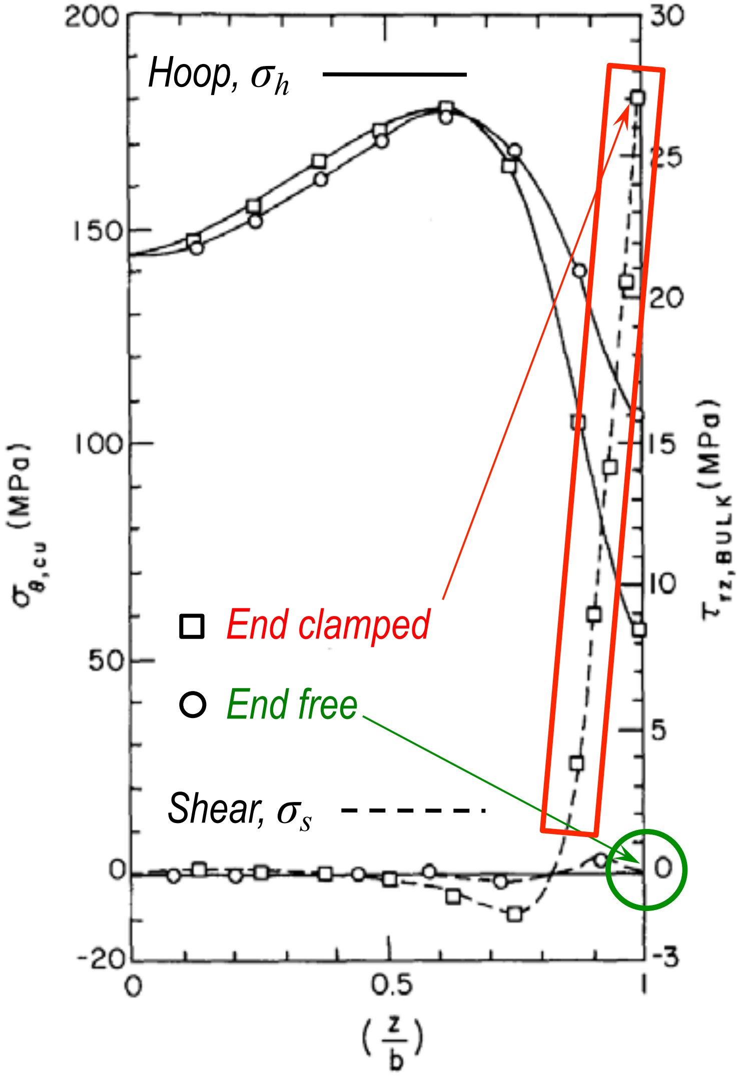
Epoxy-Fracture-Inducted Heating

- Epoxy-impregnated winding anchored to the coil form at both ends by epoxy
- When energized, the winding becomes barrel-shaped
- Large shear stresses appear at the coil ends, causing epoxy fracture, which in turn induces premature quenching



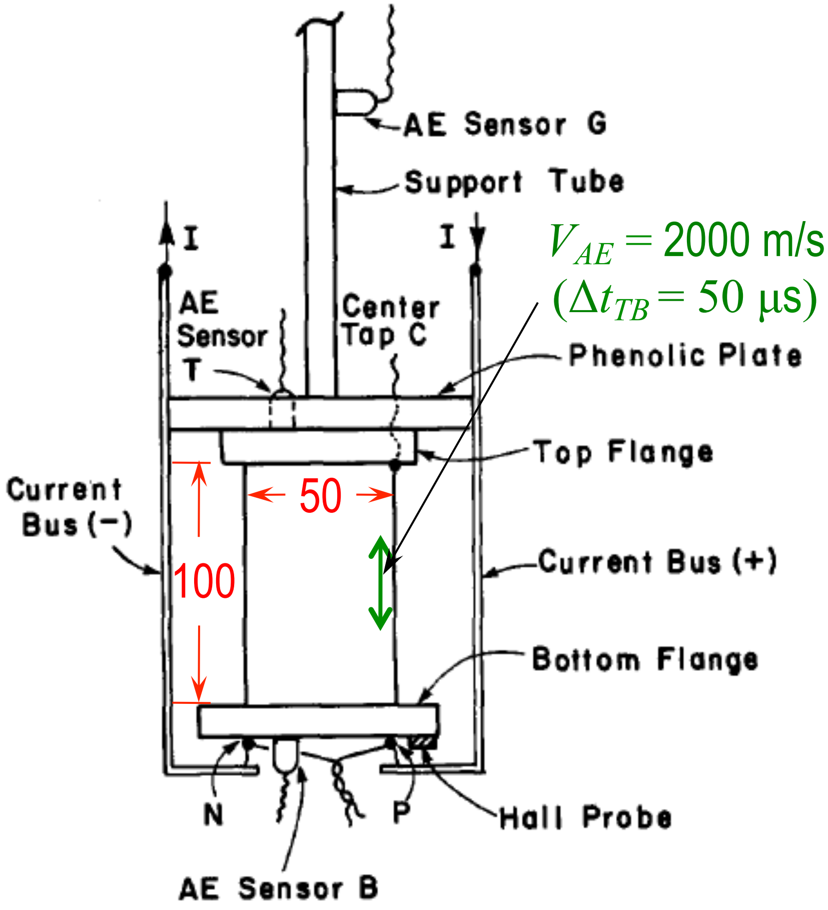


Barrel-shaped (Overly exaggerated)

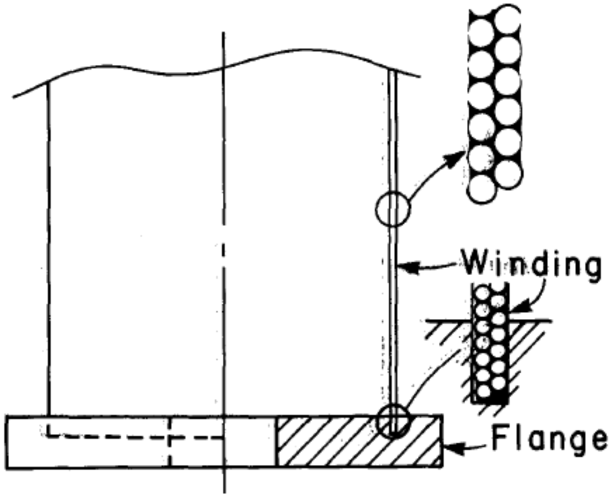


[E.S. Bobrov, J.E.C. Williams, and Y. Iwasa, Cryogenics **25**, 307 (1985)]

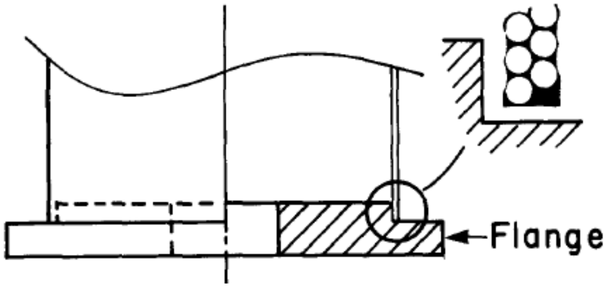
An Experimental Confirmation of Shear-Stress Induced Epoxy Fracture



$V_{AE} = 2000$ m/s
($\Delta t_{TB} = 50$ μs)



End clamped

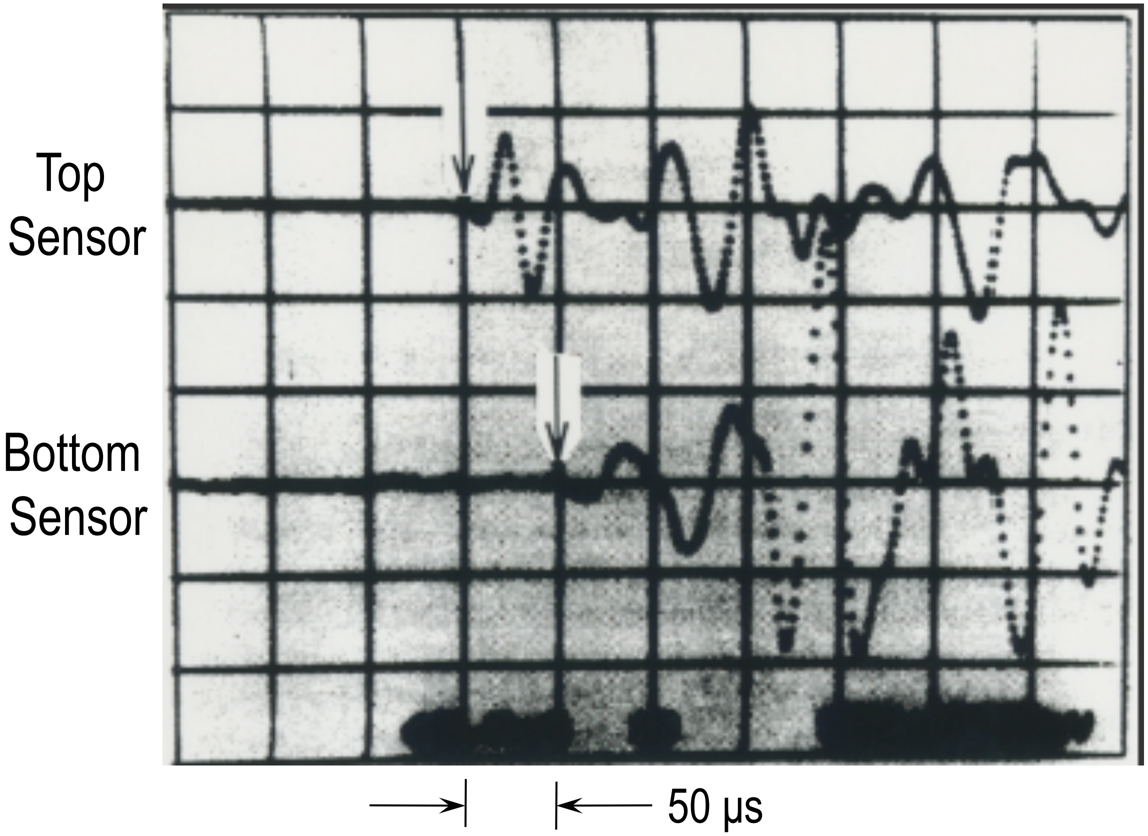


End fee

[Y. Iwasa, E.S. Bobrov, O. Tsukamoto, T. Takaghi, and H. Fujita, *Cryogenics* **25**, 317 (1985)]

An Experimental Confirmation of Shear-Stress Induced Epoxy Fracture (cont.)

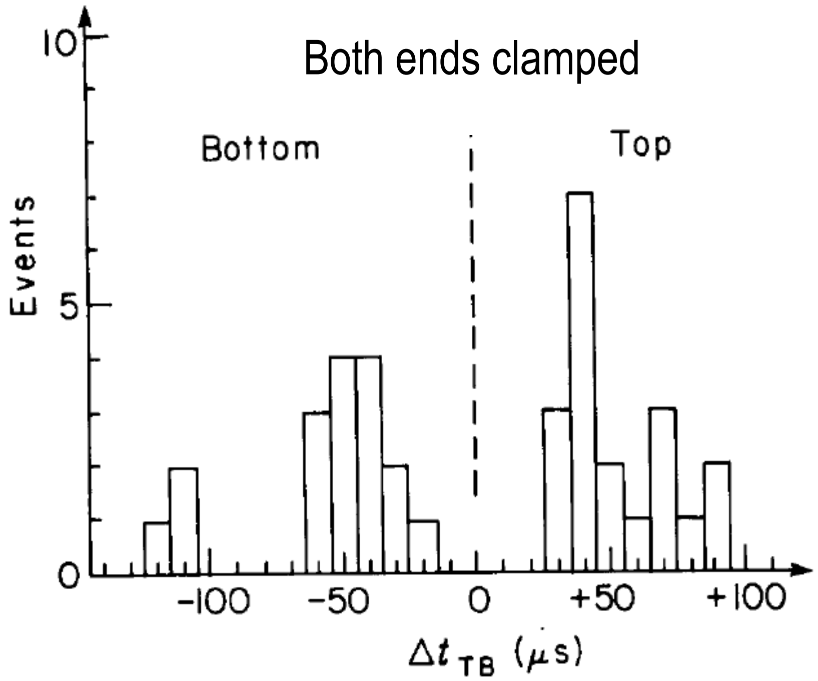
Oscillogram from Top and Bottom AE Sensors



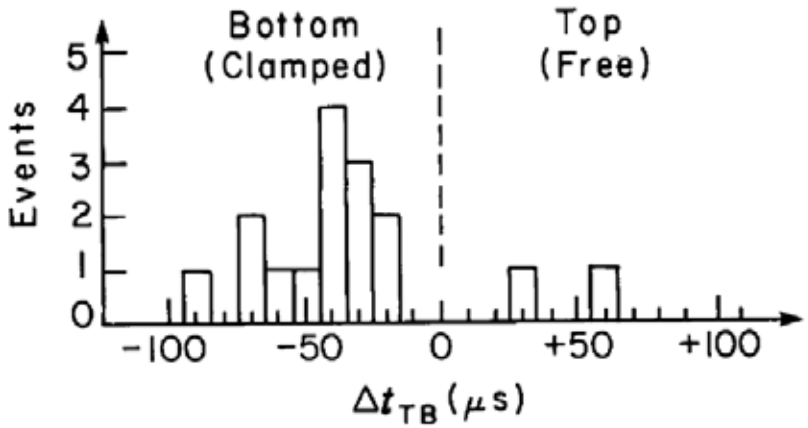
[H. Fujita, T. Takaghi, and Y. Iwasa, *Cryogenics* **25**, 325 (1985)]

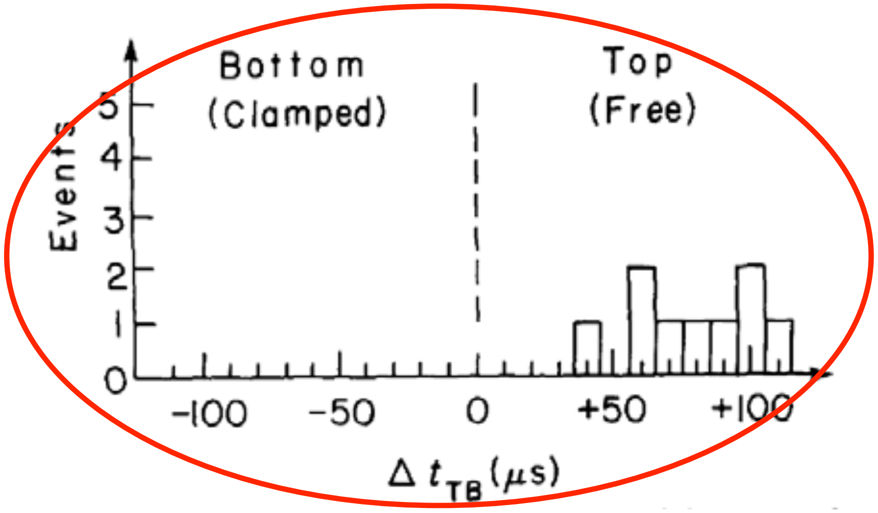
An Experimental Confirmation of Shear-Stress Induced Epoxy Fracture

Both ends clamped



In a 7-T background Field





The test coil positioned slightly below the magnet midplane; when the test coil was gradually energized, the coil moved upward and the winding rubbed against the free end, creating non-quench (current still too low) mechanical events picked up by the upper AE sensor

[H. Fujita, T. Takaghi, and Y. Iwasa, *Cryogenics* **25**, 325 (1985)]

“Floating” Coil Winding Technique

- Developed at FBML in the 1980s to minimize epoxy (or more broadly filler) fracture induced premature quenches
- The technique now widely, if not universally, used for MRI magnets, which for commercially made, are all LTS-based
- The technique proven successful *most* of the time but *not always*, particularly when the winding is impregnated with a high-strength filling material (for winding reinforcement)

Summary on Stability

LTS Magnet

- Cryostable: Disturbance energy can exceed Δe_h
    - ➢ Joule dissipation ≅ Cooling

  Goal: Maximum stability, i.e., reliability, that money can buy

- Adiabatic: Disturbance energy cannot exceed Δe_h
    - ➢ Dissipation energy within the winding ≅ 0 ($\leq \Delta e_h$)

  Goal: Efficiency (➘ cost)

HTS Magnet

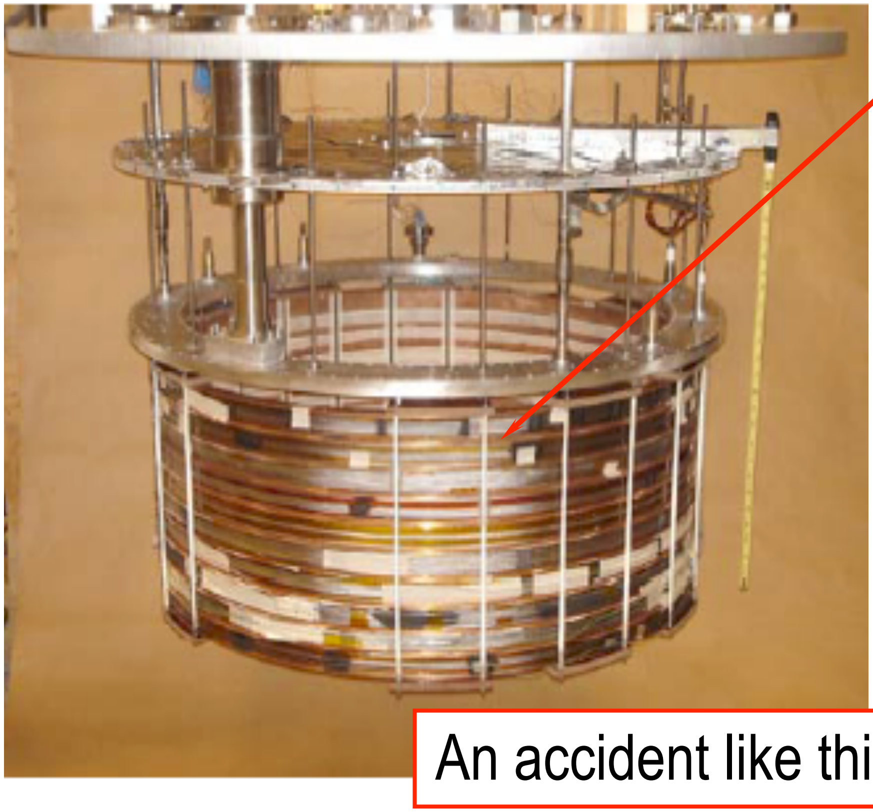
- Stability not a key issue

All HTS magnets should be adiabatic

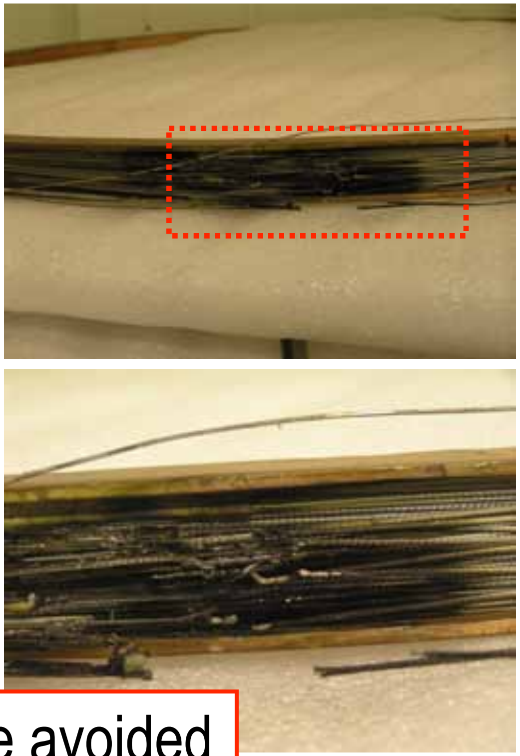
Protection

Objective: To protect the magnet from permanent damage
in the event of an unscheduled quench

A 0.5 T / 773-mm Cold Bore MgB_2 Magnet
(FBML, 2007)



An unscheduled quench (top coil)
⇒ *Permanent damage*



An accident like this must be avoided

[W. Yao, J. Bascuñàn, W-S Kim, S. Hahn, H. Lee, and Y. Iwasa, *IEEE Trans. Appl. Supercond*. **18**, 912 (2008)]

Two Approaches to Protection

Passive: applicable to "self-protecting" magnets, like LTS MRI;
critically dependent on normal zone propagation (NZP)

- Single coil: relies solely on NZP ⇒ size limitation
- Multiple coils: shunt resistors across each coil
  - Transfer of magnetic energy between coils, reducing the energy dissipated in the *hot spot*
  - Built-in heater energized by the magnet itself, rather than by an external source —"passive-activate-the-heater"

Active: applicable to non-self-protecting magnets

Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

Protection

Sources of damage

- Overheating
- High voltage
- Overstress (and overstrains)
- Over pressure, in a system with liquid cryogen

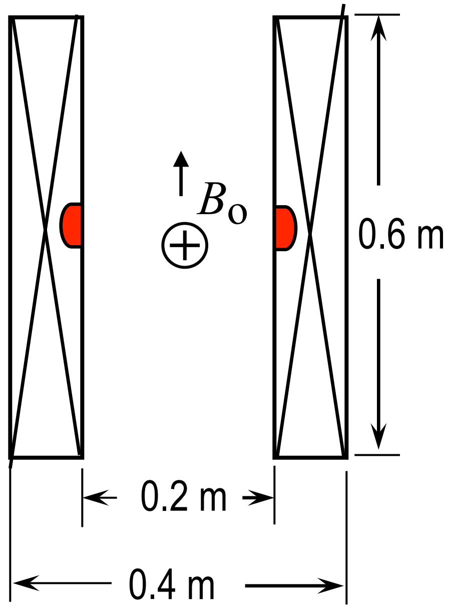
Best Protection Approach**:** Minimize quench events

Overheating

Example

- B_o = 8 T; E_{mg} = 10^6 J
- Winding volume = 0.06 m^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



- *"Fast"* Normal Zone Propagation (NZP) velocity required to spread out normal (i.e., energy absorbing) zone within the winding
- Self-protecting magnet relies on fast NZP velocities

Normal Zone Propagation (NZP) Velocity

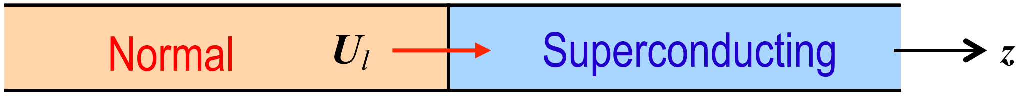
Along conductor axis (longitudinal)—No matrix

$$C_n(T)\frac{\partial T_n}{\partial t} = \frac{\partial}{\partial x}\left[k_n(T)\frac{\partial T_n}{\partial x}\right] + \rho_n(T)J^2$$ (normal)

$$C_s(T)\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left[k_s(T)\frac{\partial T_s}{\partial x}\right]$$ (superconducting)

$$\frac{\partial T_n}{\partial t} = \frac{\partial T}{\partial z}\frac{\partial z}{\partial t} = -U_\ell \frac{dT}{dz}$$ ($\boldsymbol{U_l}$: longitudinal velocity)

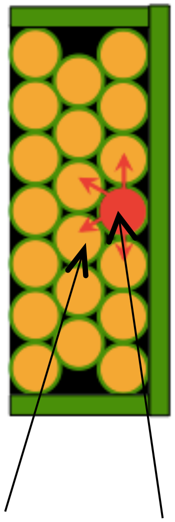
$$U_\ell = J\sqrt{\frac{\rho_n k_n}{C_n C_s (T_t - T_{op})}}$$



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

Protection & Normal Zone Propagation (NZP)

- “Small” LTS magnets rely on “fast” *NZP* velocity to spread out the normal zone to keep the “hot spot” from overheating
- “Large” LTS magnets rely on “subdivision” (by shunt resistors), but the subdivision technique too relies on “fast” NZP velocity
- In HTS magnets, NZP velocities (U_l, longitudinal & U_t, transverse) very slow, compared with those in LTS magnets: if relied only on NZP, an HTS hot spot overheated

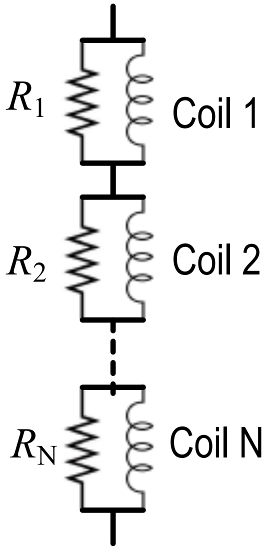


NZP “Hot spot”

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

for HTS $C_{cd}(T)$ very large ⇨ $U_{l_{HTS}} << U_{l_{LTS}}$

Also for HTS, $U_t(T) < 0.1U_l(T)$



Y Iwasa (MIT)
Iwasa@jokaku.mit.edu

Protection & Normal Zone Propagation (NZP)

Selected Measured Longitudinal NZP Velocities (U_l)

Superconductor	B_{op} [T]	T_{op} [K]	J_m [A/cm^2]	U_l [mm/s]	Group (Year)
Nb_3Sn	0	12	70,300	511	MIT (1993)
	5	5.5	46,875	526	MIT (1993)
Bi2223	0	40	22,700	1.9	MIT (1993)
YBCO	0	46	1,000–1500	2–8	ORNL (2002)
	0	77	300–1500	3–10	NHMFL (2002)
	5	60	20,000	1	Waseda (2004)
	8	10	28,570	45	Grenoble-Saclay(2013)

HTS magnet must rely on active protection or

be a self-protecting assembly of NI coils*

* No-insulation (NI) winding technique—not discussed here

See, S. Hahn, D.K. Park, J. Voccio, J. Bascuñàn, and Y. Iwasa, *IEEE Trans. Appl. Suipercond*. **22**, 430405 (2012)

Hot-Spot Temperature (T_f)

$$C_{cd}(T)\frac{\partial T}{\partial t} = \nabla\cdot[k_{cd}\xcancel{(T)}\nabla T] + \rho_{cd}(T)J_{cd_\circ}^2(t) + \xcancel{g_d}(t) - \left(\xcancel{\frac{f_p\mathcal{P}_D}{A_{cd}}}\right)g_q(T)$$

Storage Conduction Joule heating Disturbance Cooling

Compute T_f under adiabatic condition & other assumptions

$$A_{cd}C_{cd}(T)\frac{dT}{dt} = \frac{\rho_m(T)}{A_m}I_{op}^2(t) \quad \text{[W/m]}$$

$$I_{op}/A_m = J_{m_\circ} \qquad C_{sc}(T) \approx C_{\overline{m}}(T) \approx C_m(T) \qquad \gamma_{m/s} \equiv A_m/(A_{sc}+A_{\overline{m}})$$

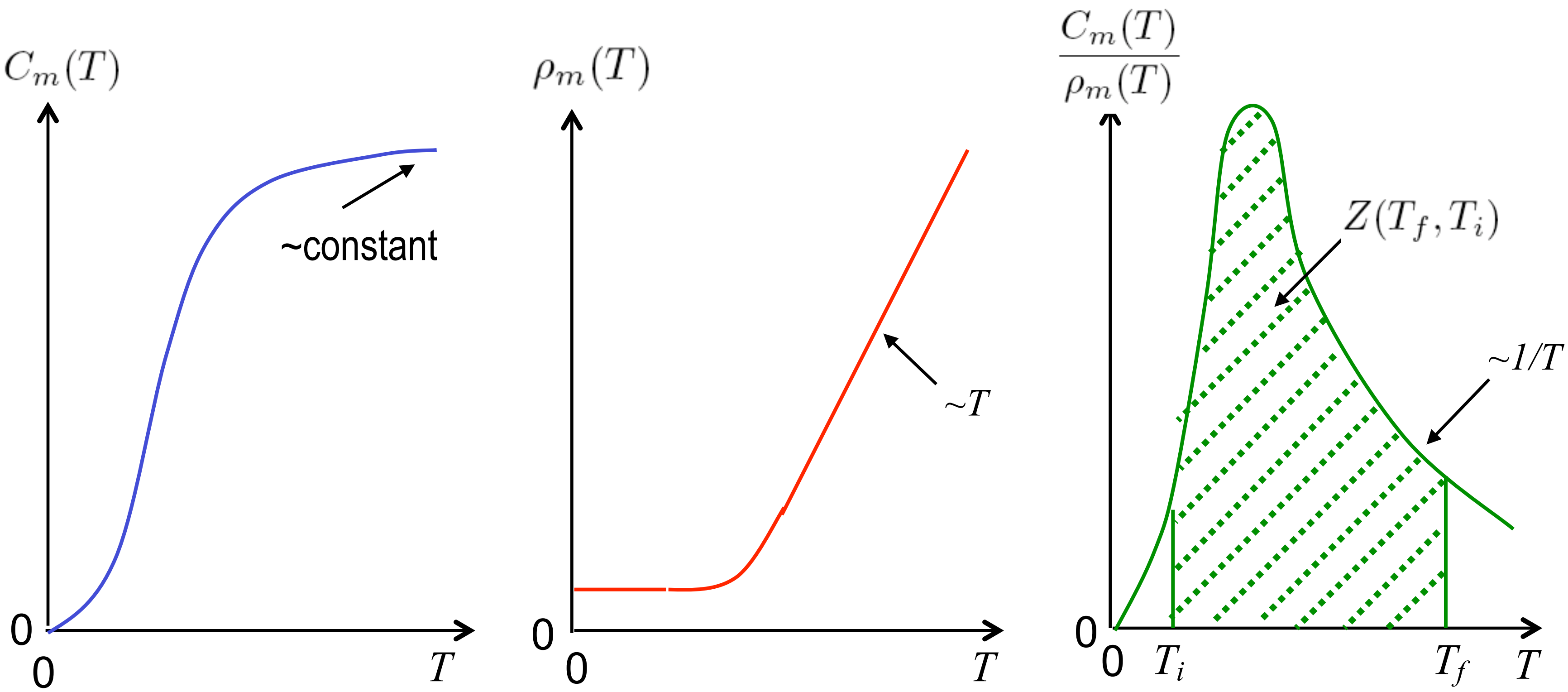
$$C_m(T)\frac{dT}{dt} = \left(\frac{A_m}{A_{cd}}\right)\rho_m(T)J_{m_\circ}^2 = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}}\right)\rho_m(T)J_{m_\circ}^2$$

$$\int_{T_i}^{T_f}\frac{C_m(T)}{\rho_m(T)}\,dT = \left(\frac{A_m}{A_{cd}}\right)J_{m_\circ}^2\tau_{ah} = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}}\right)J_{m_\circ}^2\tau_{ah}$$

Hot-Spot Temperature

Z Function

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



Hot-Spot Temperature (continuation)

- For a given combination of T_i (e.g., 4.2 K) & T_f (e.g., 200 K), and matrix material (e.g., copper of RRR100), $Z\,(T_f,\ T_i)$ is determined:

$$Z\,(200\ \text{K},\ 4.2\ \text{K}) = 12.5 \times 10^{16}\ \text{A}^2\ \text{s/m}^4$$

- Then for a given $\gamma_{m/s}$ the product $J^2_{m_\circ}\tau_{ah}$ is fixed

Example 1

$\gamma_{m/s} = 1$

$J_{m_\circ} = 100\ \text{A/mm}^2 = 10^8\ \text{A/m}^2$

$\tau_{ah} = 25\ \text{s}$ ⇒ plenty of time

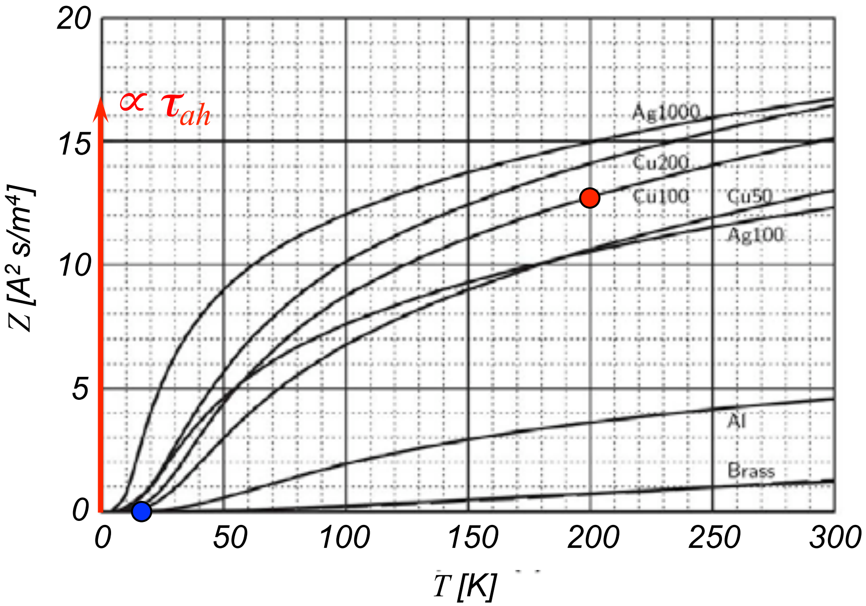
Example 2

$\gamma_{m/s} = 1$

$J_{m_\circ} = 1000\ \text{A/mm}^2 = 10^9\ \text{A/m}^2$

$\tau_{ah} = 250\ \text{ms}$ ⇒ too short

$$Z(T_f, T_i) \equiv \int_{T_i}^{T_f} \frac{C_m(T)}{\rho_m(T)}\,dT = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}}\right) J^2_{m_\circ}\tau_{ah}$$



Active Protection

Generally applied to “large” magnets, mostly driven, but also isolated (persistent-mode)

Active Protection Techniques

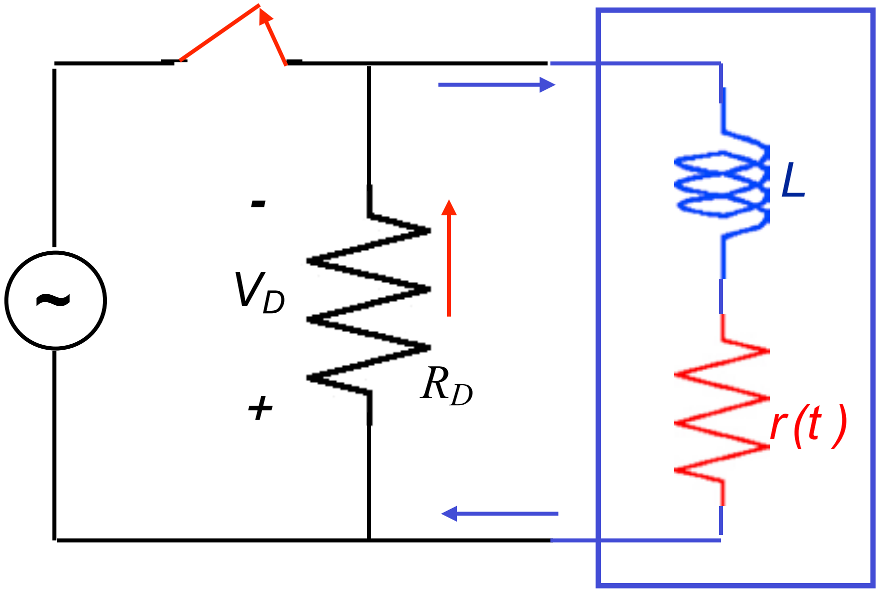
- Detect-and-Dump
- Detect-and-Activate-the-Heater or *Detect-and-Heat*

Key Issues

- Quench detection
- Time delays

Detect-and-Dump

- Dissipates most of the stored magnet energy into a “dump resistor” R_D
- Hot spot heated only for a “brief” period
- Leads to another criterion for operating current density



Detect-and-Dump

J_m criterion from Detect-and-Dump protection

$$J^D_{m_\circ} = \frac{A_{cd} V_D Z(T_f, T_i)}{E_m}$$

This J_m criterion is *different* from Stekly cryostability

Let us estimate $J^D{}_{m_\mathrm{o}}$ for ITER TF magnet

$V_D \approx 25$ kV; $E_m = 41$ GJ; $A_{cd} \approx 25\ \mathrm{cm}^2 = 0.0025\ \mathrm{m}^2$;

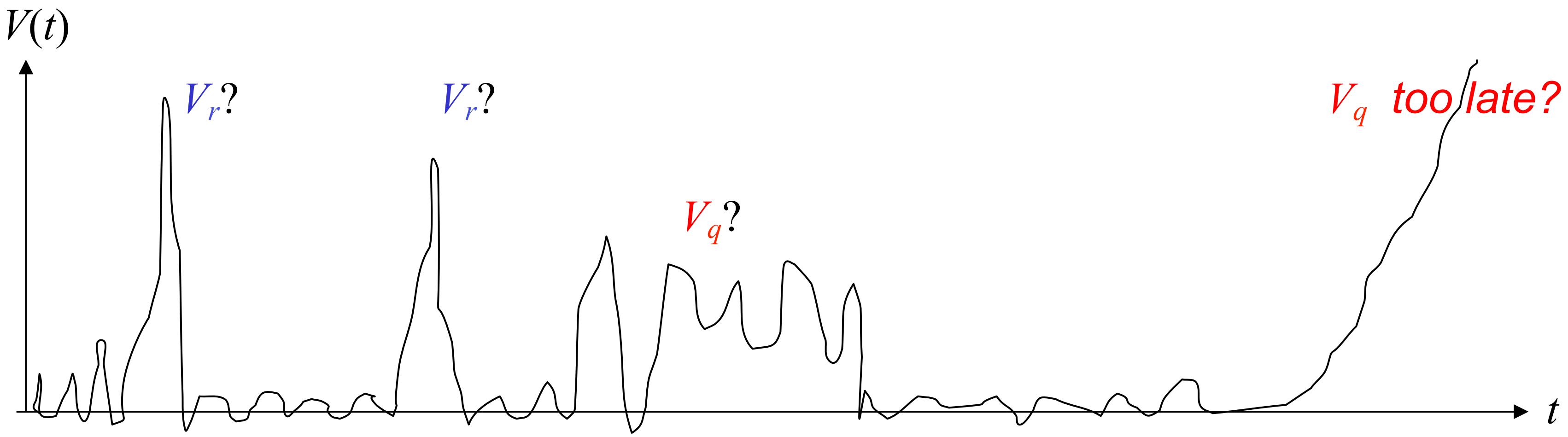
Z (200 K, 4.2 K) $=14 \times 10^{16}\ \mathrm{A}^2\ \mathrm{s/m}^4$:

$J^d{}_{m_\mathrm{o}} \approx 2 \times 10^8\ \mathrm{A/m}^2 = 200\ \mathrm{A/mm}^2$ ⇒ reasonable(?)

Quench Detection

Voltage

- Most directly related to a quench; quickest detection
- Often difficult to distinguish between a *recovering-quench* voltage, V_r , (i.e., *no dump required*), and a *genuine quench* voltage, V_q (i.e., *dump required*)



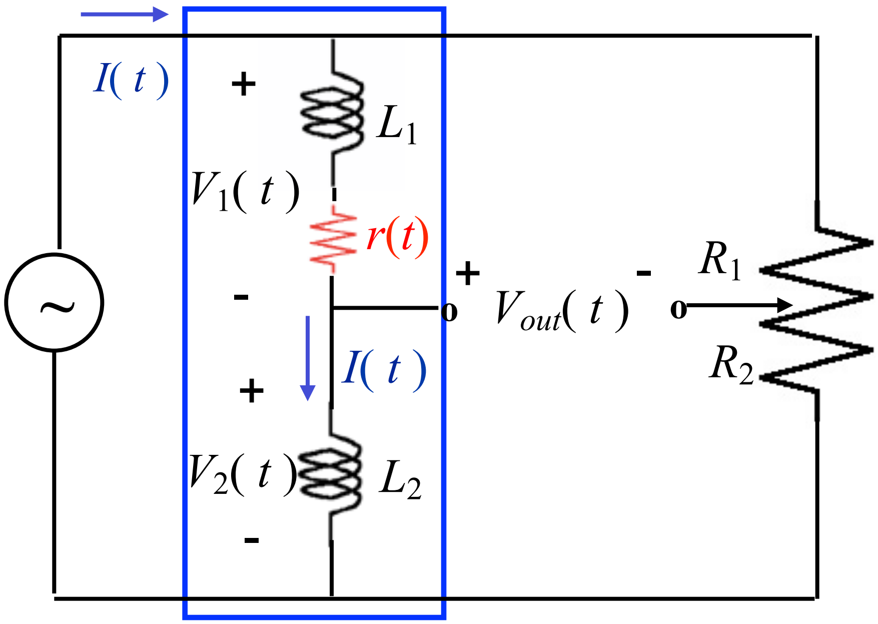
- Sometimes a criterion, $\int V(t)\,dt >$ threshold value, used

Basics of Voltage Method

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

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

$$R_2L_1 = R_1L_1 \quad \Rightarrow \quad V_{out}(t) = -\left(\frac{R_2}{R_1+R_2}\right) r(t)I(t)$$



A Critical Issue in Quench Detection for Detect-and-Dump

- Time delay, τ_{dl}, between Quench Initiation ($t = 0$) and Quench Detection, and finally opening of the Switch at ($t = \tau_{dl}$)

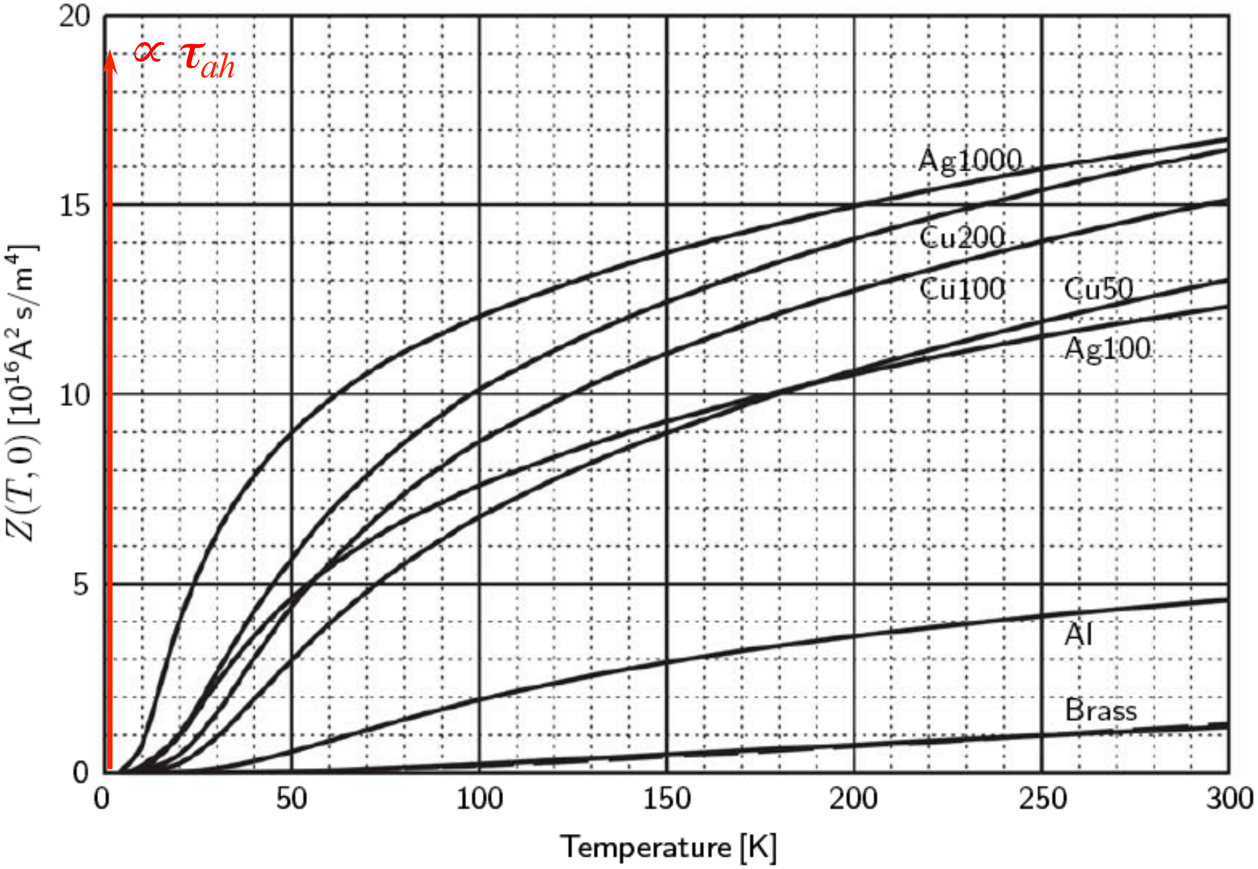
$$Z(T_f, T_i) = \left(\frac{A_m}{A_{cd}}\right)\left(J_{m_\circ}^2 \tau_{dl} + \frac{1}{2} J_{m_\circ}^2 \tau_{dg}\right)$$

Constant-current heating

- The greater the time delay, the smaller will be the matrix current density $\Rightarrow$ smaller $\lambda J \Rightarrow$ *less efficient magnet*

$t\,(T)$ from $Z(T)$ Function

$$Z(T) = \left(\frac{A_m}{A_{cd}}\right) J_{m_\circ}^2 \times t$$



$$t(T) - t(T_i) = \frac{Z(T,T_i)}{(A_m/A_{cd})J_{m_\circ}^2} = \frac{Z(T,T_i)A_{cd}}{I_{op}J_{m_\circ}} \propto \frac{1}{J_{m_\circ}}$$

Lower the matrix current density, it takes longer to reach T

Quench Detection

Temperature

- T sensor must be at or vicinity of the *hot spot*
  - Otherwise, its response time may be “slow”

Pressure

- $T_{hot\text{-}spot}$ must reach LHe through “nonconductive” winding
  - Its response time may generally be “slow”
  - Not applicable to “dry” (no liquid) magnets

Neither a primary method but may complement V method

Quench Detection

Field

- *Mutual coupling effects* (more than one coil) may keep $B_{center} \cong$ constnat during the *critical initial* period

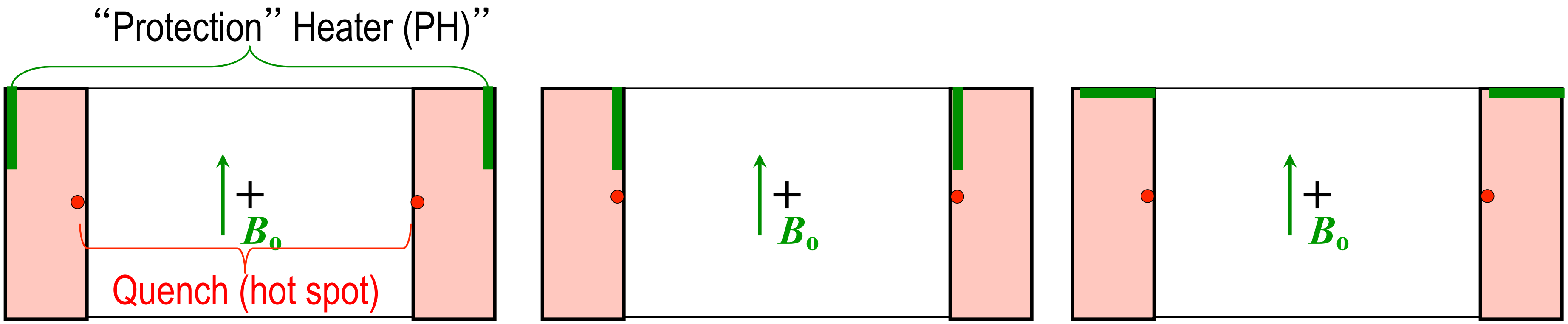
Current

- In a *driven-mode* magnet, the supply may keep $I_{op} \cong$ constant during the *critical initial* period
- In a *persistent-mode* magnet, the PCS may keep $I_{op} \cong$ constant during the *critical initial* period
  - ▪ Thus, the response time of each method may be "slow"

Neither a primary method but may complement V method

Detect-and-Heat (DAH)

- Activate a heater ("protection" heater) to drive the *minimum winding volume* normal to keep $T_f \leq \sim$300 K
  - Protection" heater needs not cover the entire winding
  - Heater size *independent* of the hot-spot size
- "Protection" heater location *not* critical
  - Place the heater at "convenient" locations



- DAH suitable for HTS magnets (slow NZP)
- Also, for "large" LTS magnets, e.g., NMR, dipoles

Conclusions

- Stability continues to be a critical issue for LTS magnets;
  Non-issue for HTS magnets
- Protection well-established for LTS magnets;
  A huge challenge for HTS magnets
  - NI (for "DC") winding technique promising for HTS magnets
- Mechanical issue perhaps the greatest issue for high-field magnets, LTS and HTS

Rendez-vous demain!