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IN-3

HTS Magnets: Stability; Protection; Cryogenic; Economics; Research Areas

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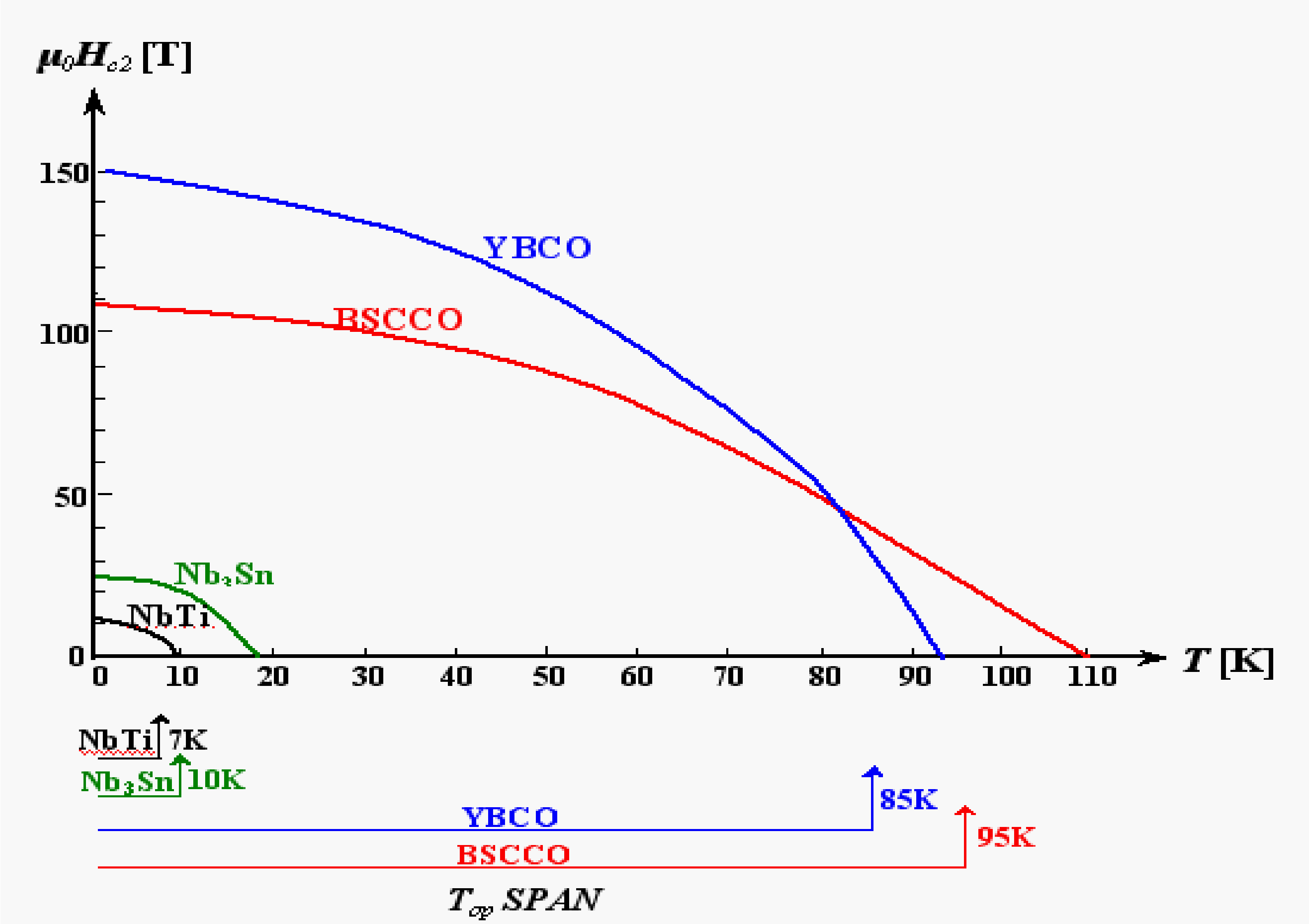
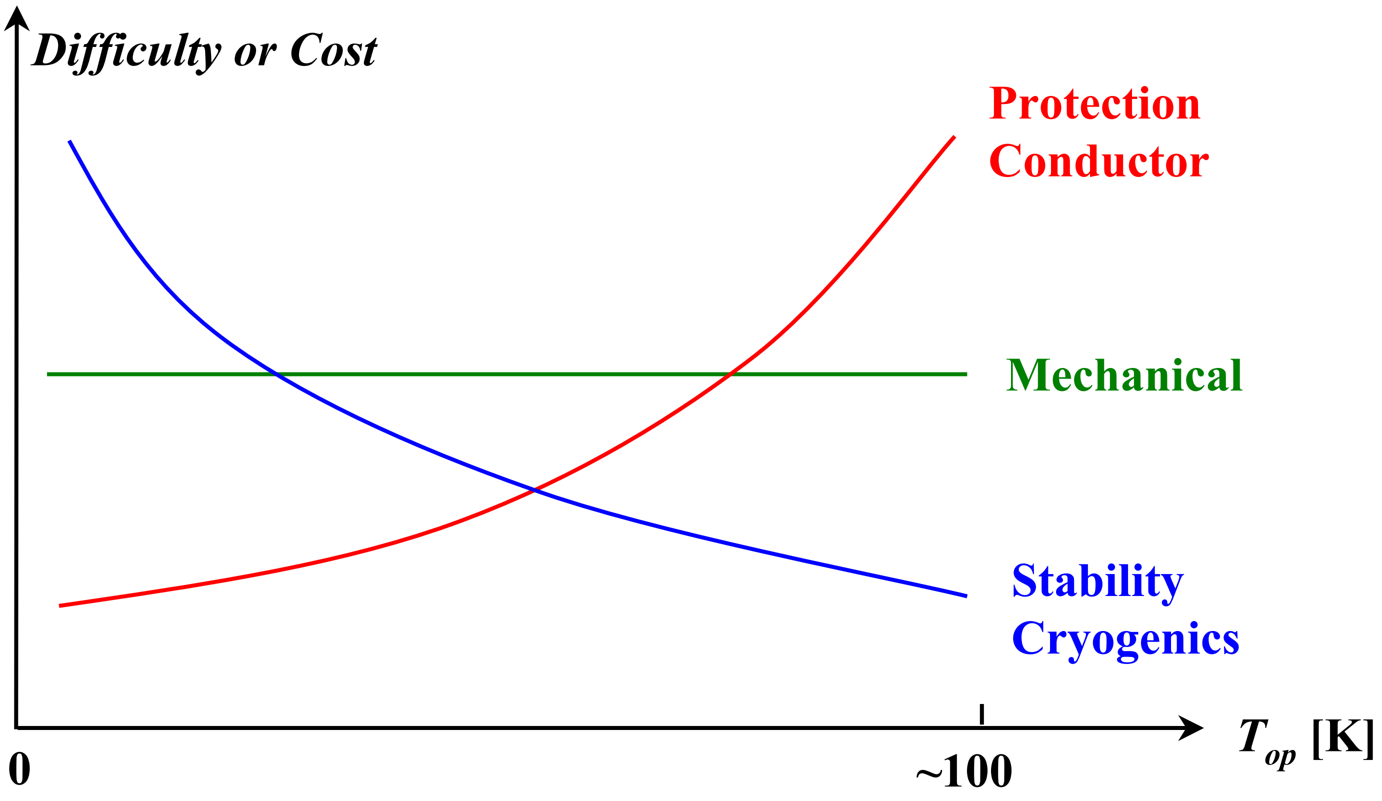
Outline

- Introduction.
  - ☆ Range of T_{op}: LTS *vs* HTS.
  - ☆ Magnet issues.
- Stability.
- Protection.
- Cryogenics.
- Economics of large-scale HTS devices.
- Research areas.
  - ☆ Activities *at FBML*.

Range of T_{op}: LTS vs HTS



Key Magnet Issues vs T_{op}



Stability: LTS vs HTS

LTS: $dT_{op}/dt \approx 0$**---permissible** ΔT_{op} **generally < 1 K.**

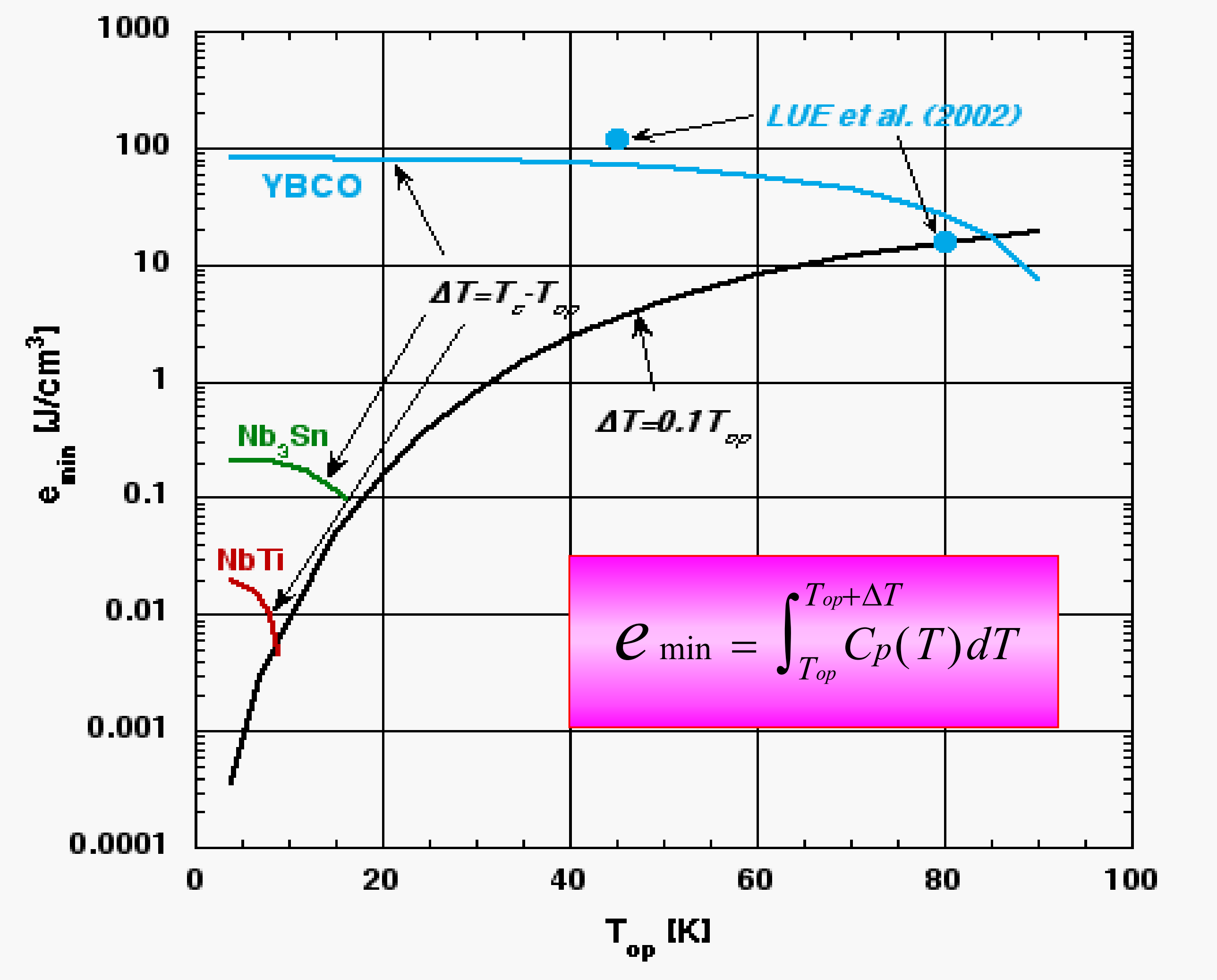
- **Mechanical energy disturbance as small as ~10μJ may induce a quench.**

HTS: **Permissible** ΔT_{op} **can exceed 10 K.**

- **Immune against those disturbances that afflict high-performance (adiabatic) LTS magnets.**
- **May be vulnerable to fault-mode disturbances.**

Minimum Thermal Energy Density

(*C_p*: copper; *T_c*: Superconductor)



$$e_{\min} = \int_{T_{op}}^{T_{op}+\Delta T} C_p(T)\,dT$$

Protection

Probable Causes of Quench in HTS Devices

- **Malfunction, *e.g.*, cryogenics.**
- **Scheduled fault modes, e.g. FCL.**
- **Non-issues: mechanical disturbances; AC losses.**

Key Areas

- **Overheating.**
- **Arcing.**
- **Overstressing.**

Protection (continued)

Magnet Self-Protecting if…

- **NZP velocity "high:" $U_l > 1$ m/s.**
- **Magnet size (a_2-a_1) "small:" (a_2-a_1)/$U_l < \tau_j$.**

Corollary: HTS devices not self-protecting.

- **Overheating: requires normal metal substrate.**
  - ☆ **quench/recovery behavior;**
  - ☆ **detection of hot zones.**
- **Arcing (internal): requires normal metal substrate.**
- **Overstressing: requires reinforcing substrate.**

Corollary: All three tend to reduce J_e.

NZP Velocity & Protection

LTS: In the range >1 m/s.

- **"High" NZP velocities make LTS self-protecting.**
- **For multi-coil magnets---resistor shunting effective.**

HTS: In the range 1-10 mm/s.

- **"Low" NZP velocities make HTS not self-protecting.**
- **Active protection required---detection of a hot zone (though unlikely to be created) important.**

NZP Velocity (Adiabatic Winding)

$$U_t = \frac{J_m}{C_{cd}}\sqrt{\frac{\rho_m k_i}{\Delta T}} \qquad (J_m = 10^8\ \mathrm{A/m^2})$$

LTS (4.2 K): $C_{cd} \sim 10^3\ \mathrm{J/m^3\,K}$; $\rho_m \sim 2\times10^{-10}\ \Omega\ \mathrm{m}$;

$k_i \sim 0.2\ \mathrm{W/m\,K}$; $\Delta T \sim 0.5\ \mathrm{K}$ → $U_t \sim 1\ \mathrm{m/s}$.

HTS (77 K): $C_{cd} \sim 2\times10^6\ \mathrm{J/m^3\,K}$; $\rho_m \sim 2\times10^{-9}\ \Omega\ \mathrm{m}$;

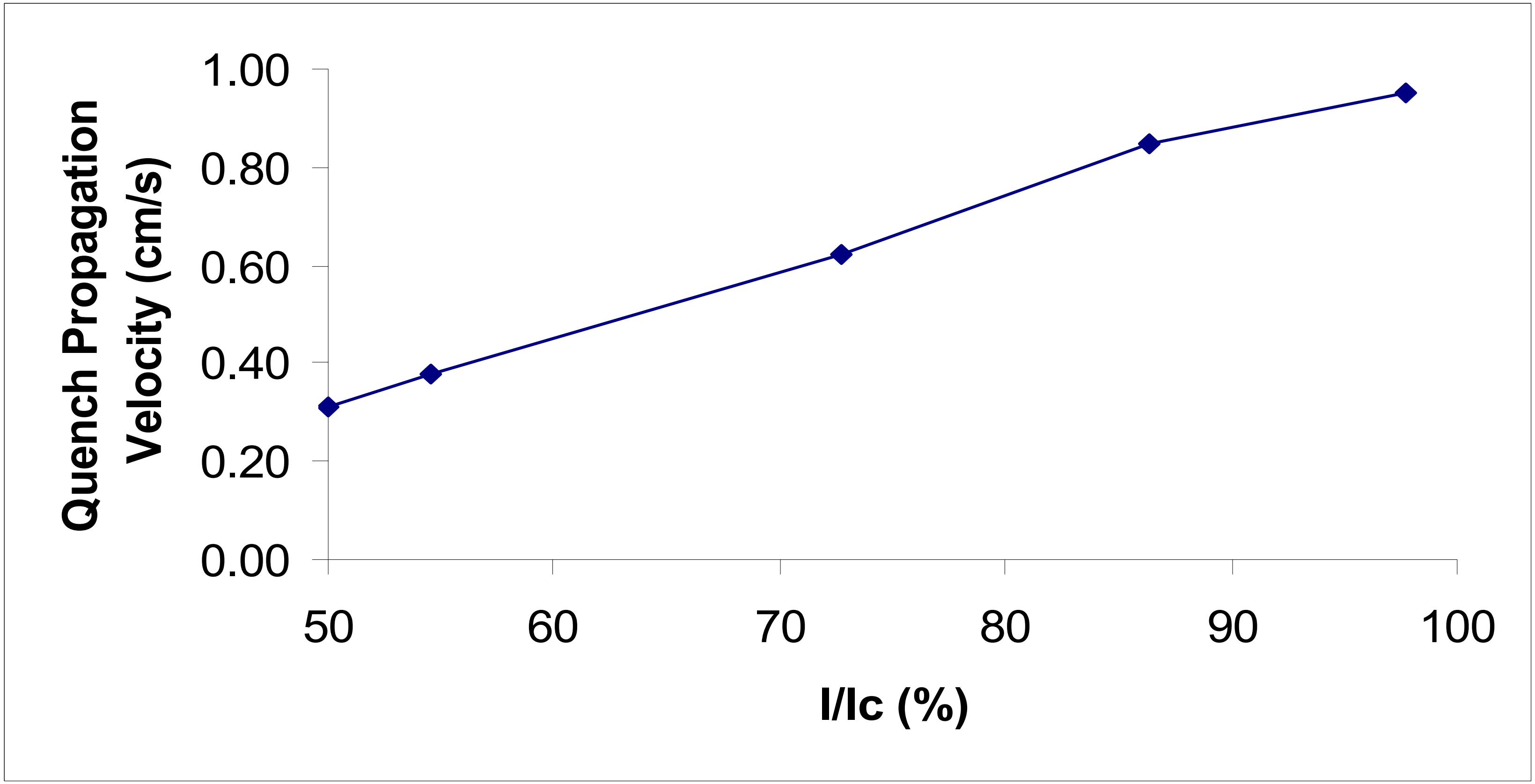
$k_i \sim 0.2\ \mathrm{W/m\,K}$; $\Delta T \sim 10\ \mathrm{K}$ → $U_t \sim 0.3\ \mathrm{mm/s}$.

Schwartz: $J_m \sim 10^9\ \mathrm{A/m^2}$: $C_{cd} \sim 2\times10^6\ \mathrm{J/m^3\,K}$; $\rho_m \sim 2\times10^{-9}\ \Omega\ \mathrm{m}$;

$k_m \sim 400\ \mathrm{W/m\,K}$; $\Delta T \sim 20\ \mathrm{K}$ → $U_l \sim 10\ \mathrm{cm/s}$.

Quench Propagation Velocity vs I/I_c

(Schwartz, 2002)



Cryogenics

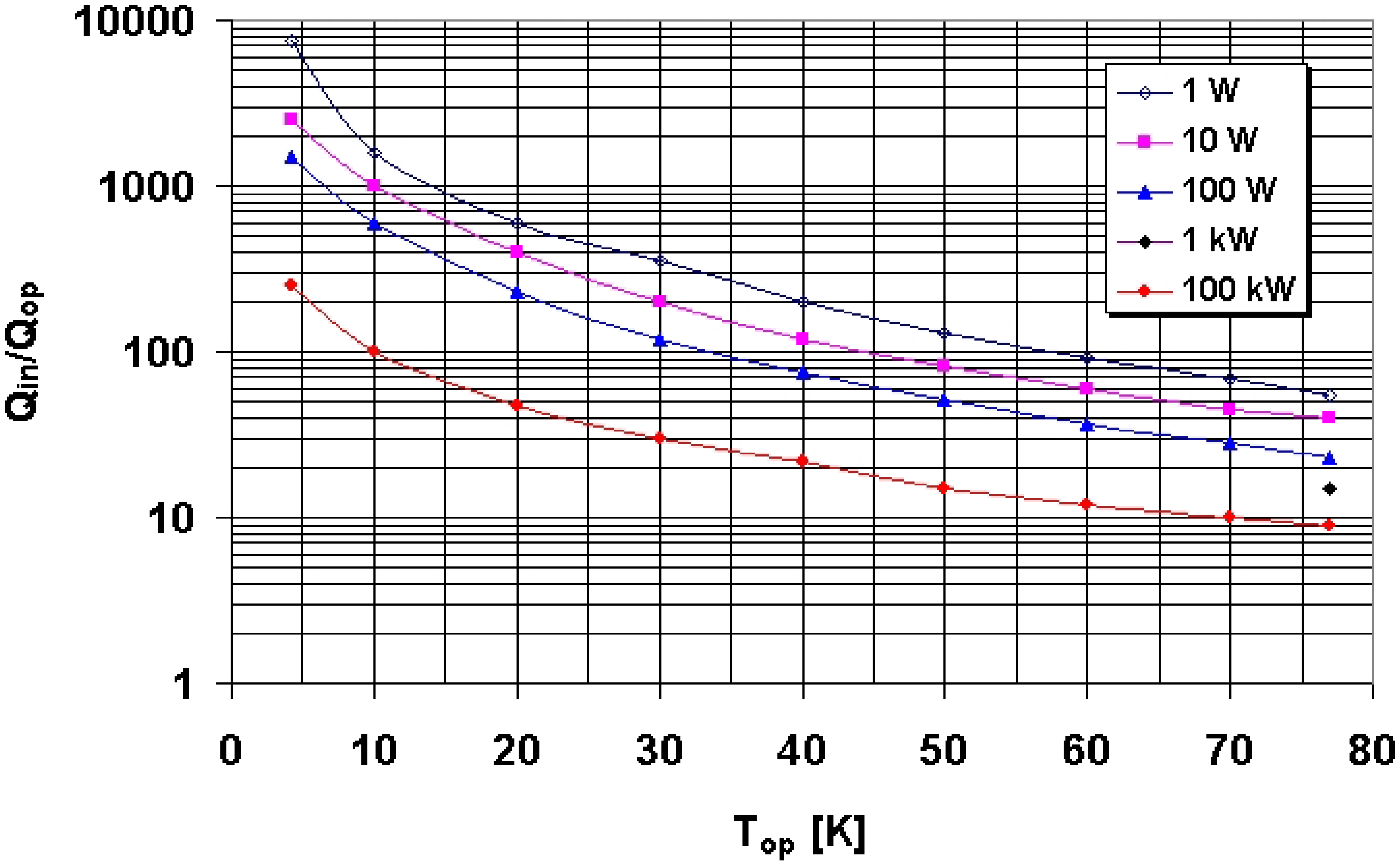
- **Most devices operate at RT.**
  motors; cameras; refrigerators; wrist watches; CD players; pianos; airplanes; automobiles; nuclear reactors---note that some key components operate above but generally not < RT.
- **Prominent exceptions: superconducting & cryogenic devices.**

Operation at Cryogenic Temperature

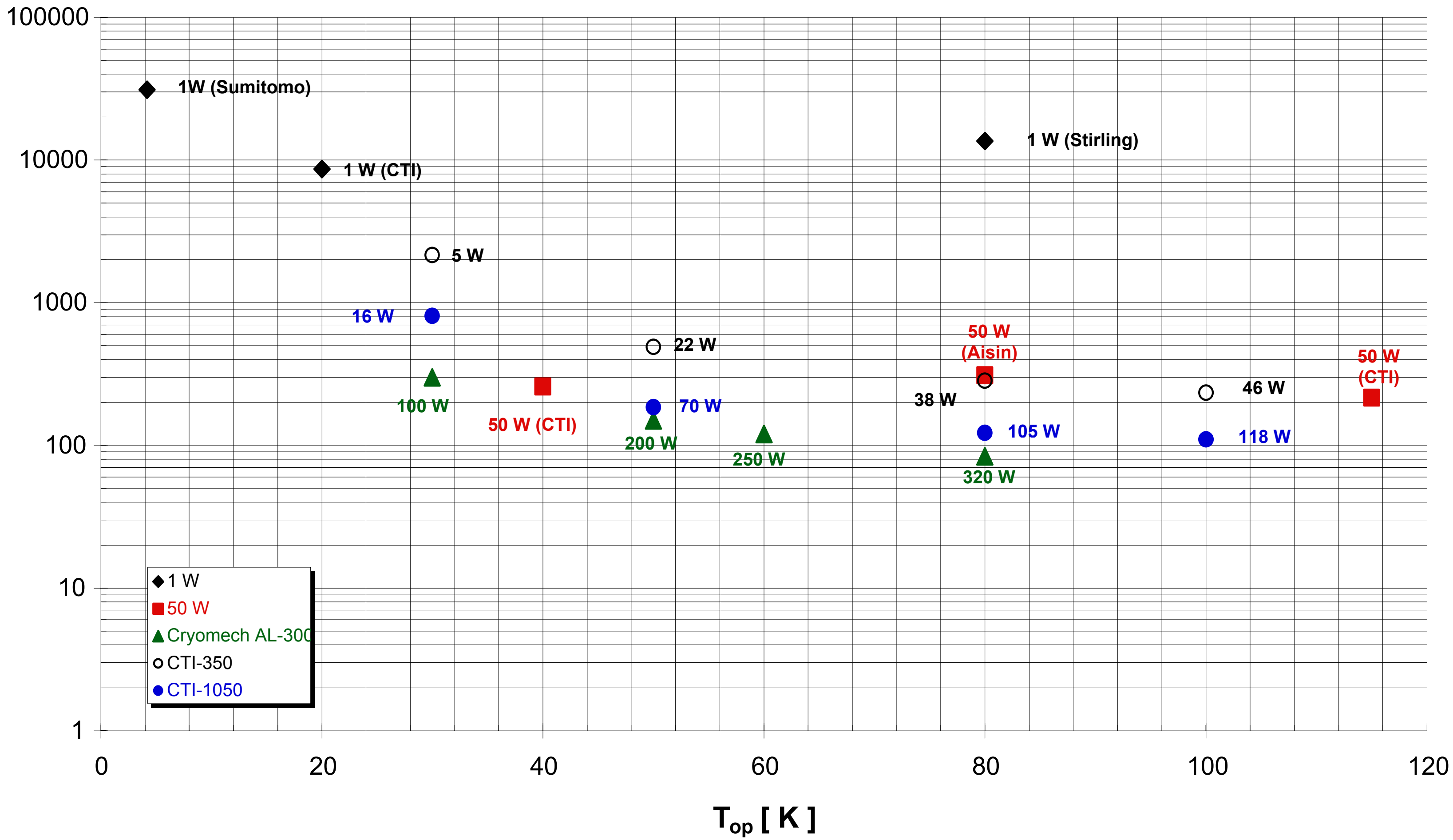
- **Refrigeration and thermal insulation required.**
  - ☆ **Refrigeration power/cost---manageable.**
  - ☆ **Thermal insulation---fundamental hindrance.**
- ***Needed: Quantum innovation in insulation technology***

  ---- akin to Dewar's "Thermos" bottle.

Refrigerator Performance vs. T_{op}



Refrigerator Capital Cost/Cooling Power vs T_{op}



Optimal T_{op} for Minimum Device Cost

Key Parameters

- **Conductor cost (T_{op}; B; Size).**
- **Refrigerator capital cost (T_{op}; Capacity).**
- **Refrigerator operating cost (T_{op}; Capacity).**
- **Stability/protection cost (T_{op}; B; Size)**
  - ☆ **normal metal (stability/peak voltage)**

    → reduced J_e → increased device cost.
  - ☆ **Cooling medium (high voltage): vapor, liquid, solid**
- **Mechanical integrity cost (J_e; B; Size).**

Economics of Large-Scale HTS Devices

Enabling vs Replacing Technology

Technology	*Performance*	*Competition*	*Criterion*
Enabling	**Yes**	**No**	**Performance**
Replacing	**No**	**Yes**	**Cost**

Large-Scale Superconducting Devices

Electricity

- **Fusion; SMES; Generator ; Cable; Transformer; FCT; Motor.**

Medicine

- **MRI.**

Research

- **HEP; NMR/MRI; High-*B* DC Magnets.**

Is Superconductivity Enabling?

Technology	*In General*	*Yes…only*
Fusion	**Yes***	**> 2050**
SMES	**Yes***	**“Large” Wh**
Cable	**No**	**“Large” VA**
Transformer	**No**	**“Compact”**
FCL	**No**	**“Compact”**
Motor/Generator	**No**	**“Compact”**

* ***Not enabling*** **as a power converter or energy storage.**

Is Superconductivity Enabling?

(continued)

Technology	*In General*	*Yes…only*
MRI (medicine)	**Yes**	**> 0.5 T**
HEP	**Yes**	**> ~1 TeV**
NMR/MRI	**Yes**	**> 2 T / > 0.5 T**
High-*B* DC Magnet	**Yes**	**> 2 T**

Development Steps to Commercial Product

- **Step-by-step progression from small to large units.**
- **Continued development likely if the completed unit at each step serves the user.**
- **Desirable if the cost of each upgrade unit is *reasonable, i.e.* $Ms rather than $100Ms or $Bs.**

Minimum Size Serviceable to the User

Technology	*Minimum Size*
Fusion	**100-300 MW**
SMES	**0.1-1 GW h**
Cable	**0.5-1 GW; 1-2 km**
Transformer	**30 MVA**
FCL	**0.1-1 GVA**
Motor/Generator	**1 kHp / 300 MVA**

Minimum Size Serviceable to the User

(continued)

Technology	*Minimum Size*
MRI (medicine)	**> 0.3 T**
HEP	**> 1 TeV**
NMR/MRI	**> 2 T/ > 0.5 T**
High-*B DC* Magnet	**> 2 T**

Fusion (& SMES)

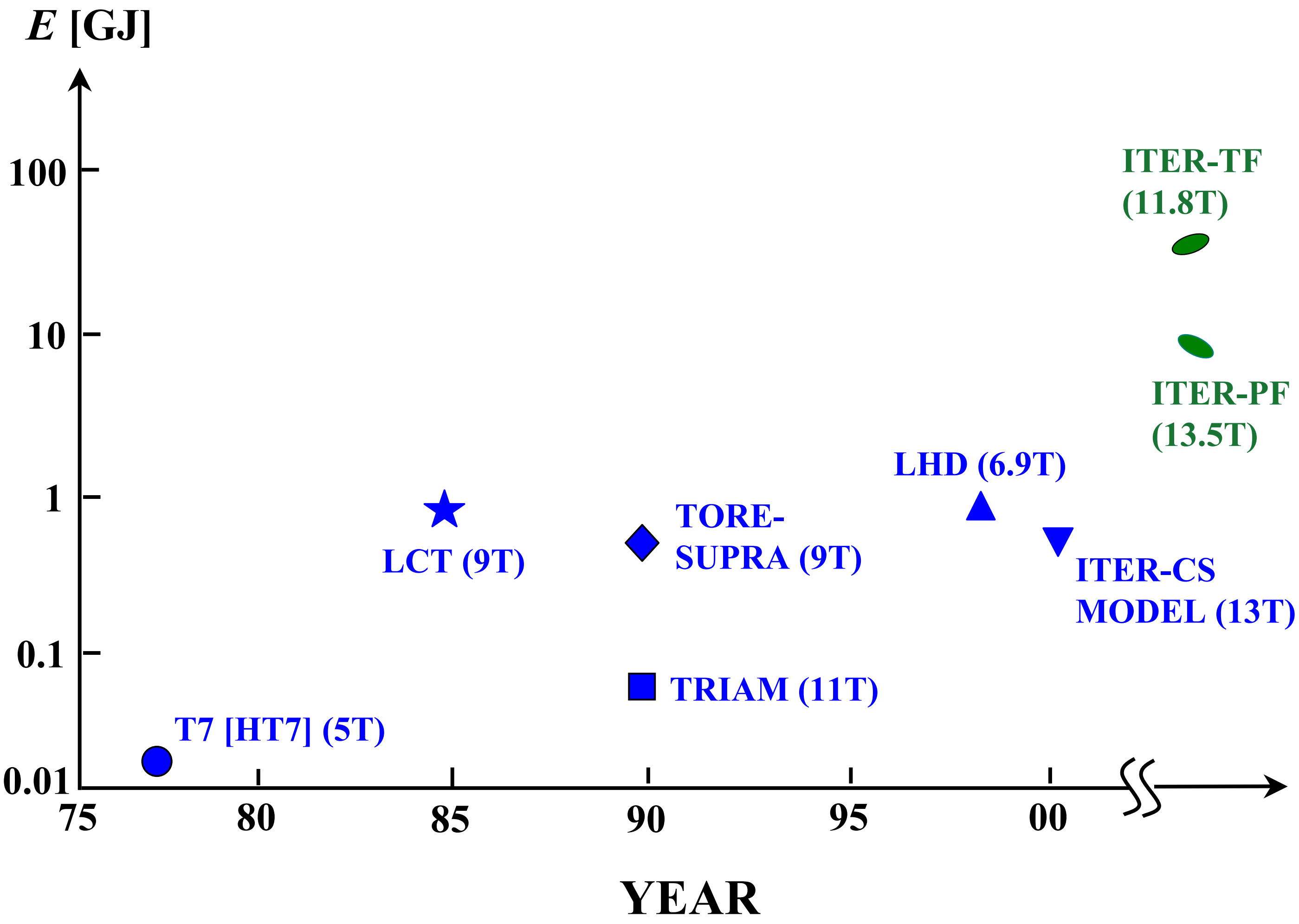
Disadvantages

- **Unit must be huge, *i.e.*, expensive, to serve the user. Even ITER ($10B) still just a demonstration unit. (Essentially the same with SMES.)**

Prognosis

- **May become a necessity, *i.e.*, an enabling power converter, after 2050. (SMES: ~2020 or later.)**

Superconducting Tokamaks



Other Power Electric Devices

Conditions for Market Penetration

- **“Promised” HTS, *i.e.*, much less expensive and with “low” AC losses, must come through.**
- **Cryogenics must become “invisible.”**
  - ☆ **For most “large” devices, cost NOT an issue.**

HEP

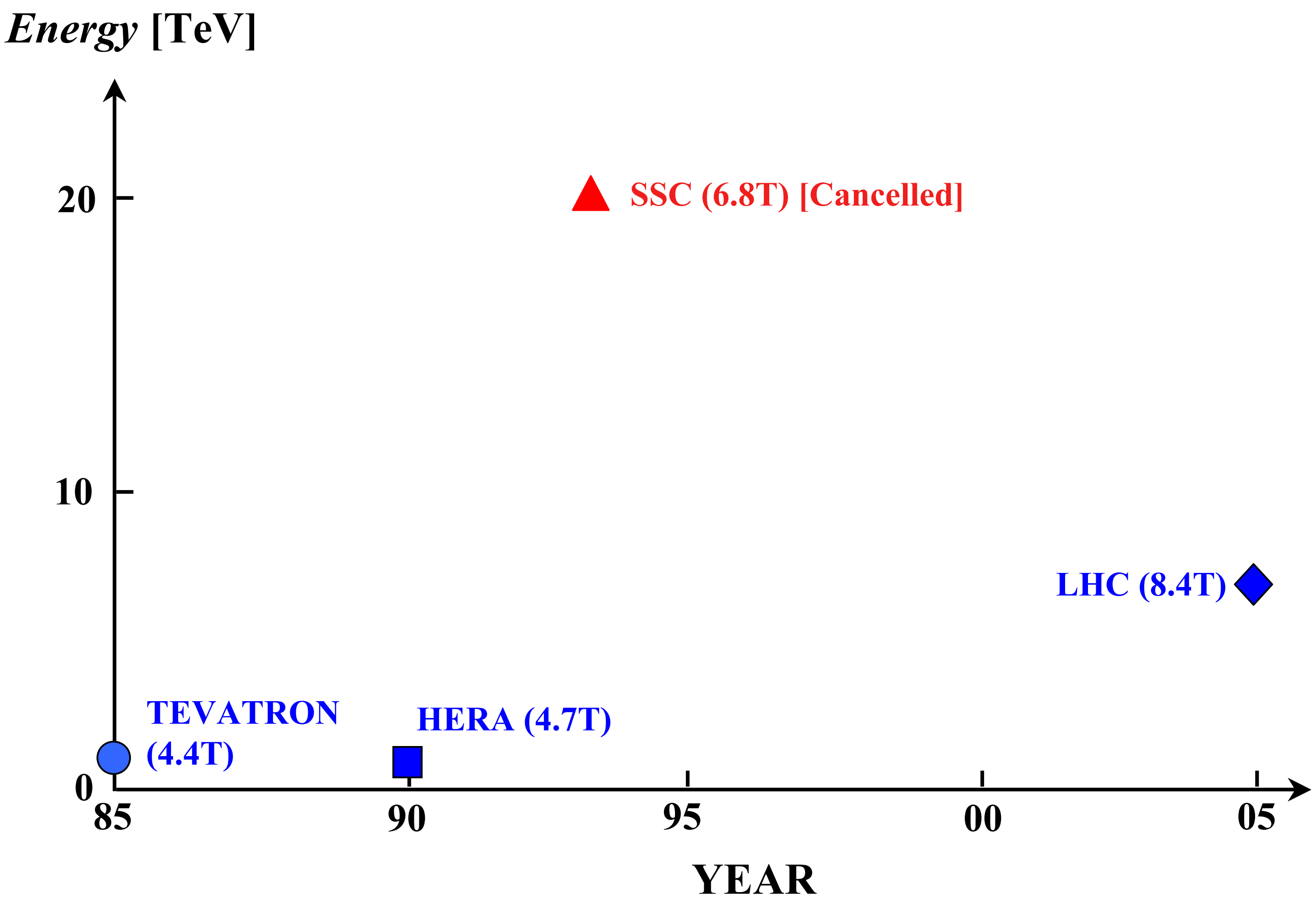
Reason for the SSC demise in 1993

- **Cost overrun, $5B (1986) to ~$15B (1993).**

"Smaller" Accelerators successful

- **Tevatron: πD_{av}=6.3 km (*vs* πD_{av}=87 km for SSC).**
- **LHC: πD_{av}=27 km.**

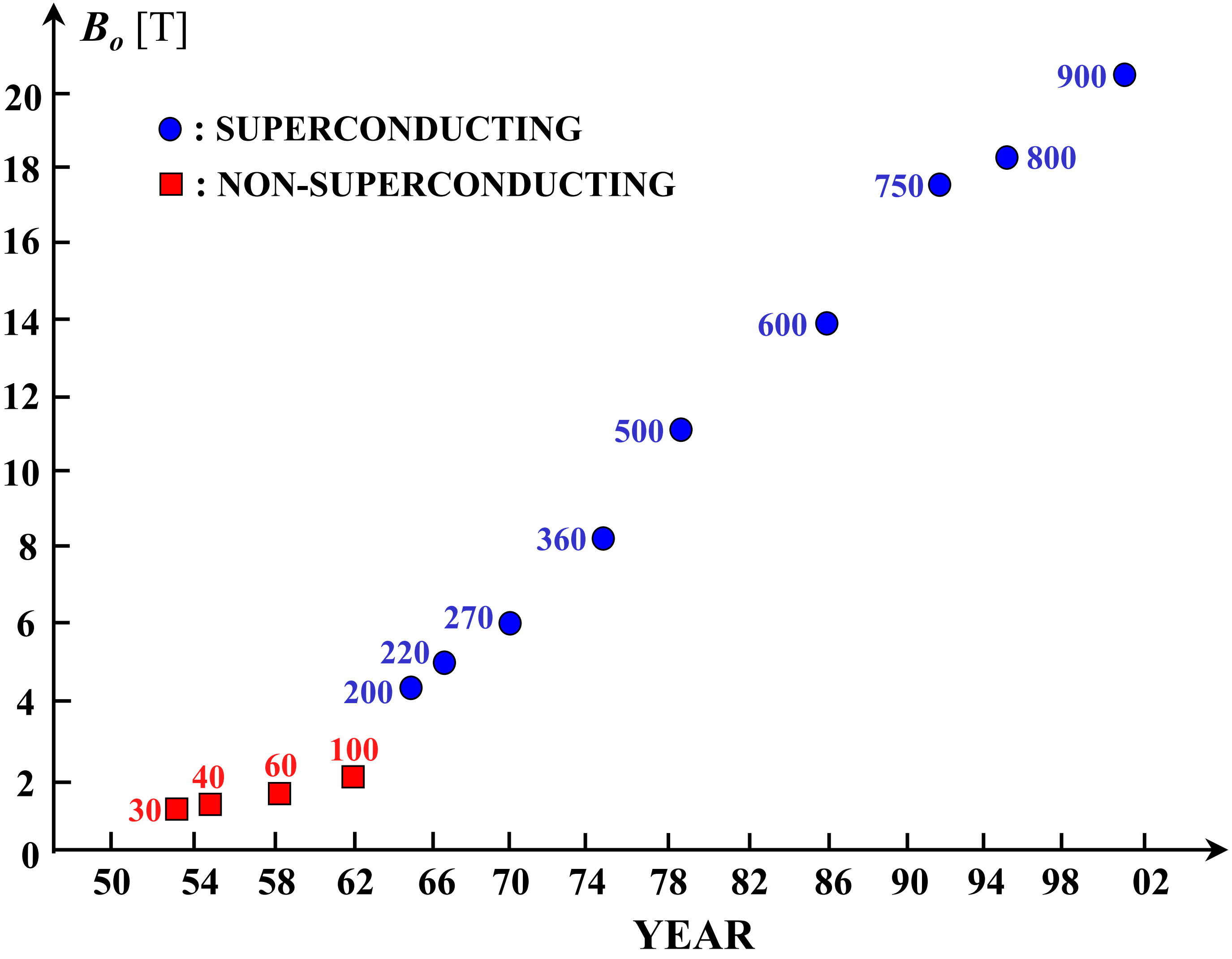
Superconducting Accelerators



NMR/MRI

- **Upward march, through step-by-step upgrading.**
- **Unit at each step serviceable to the user.**
- **Each upgrade $Ms rather than $100Ms to $Bs.**

Progress of NMR



High-B DC Magnets

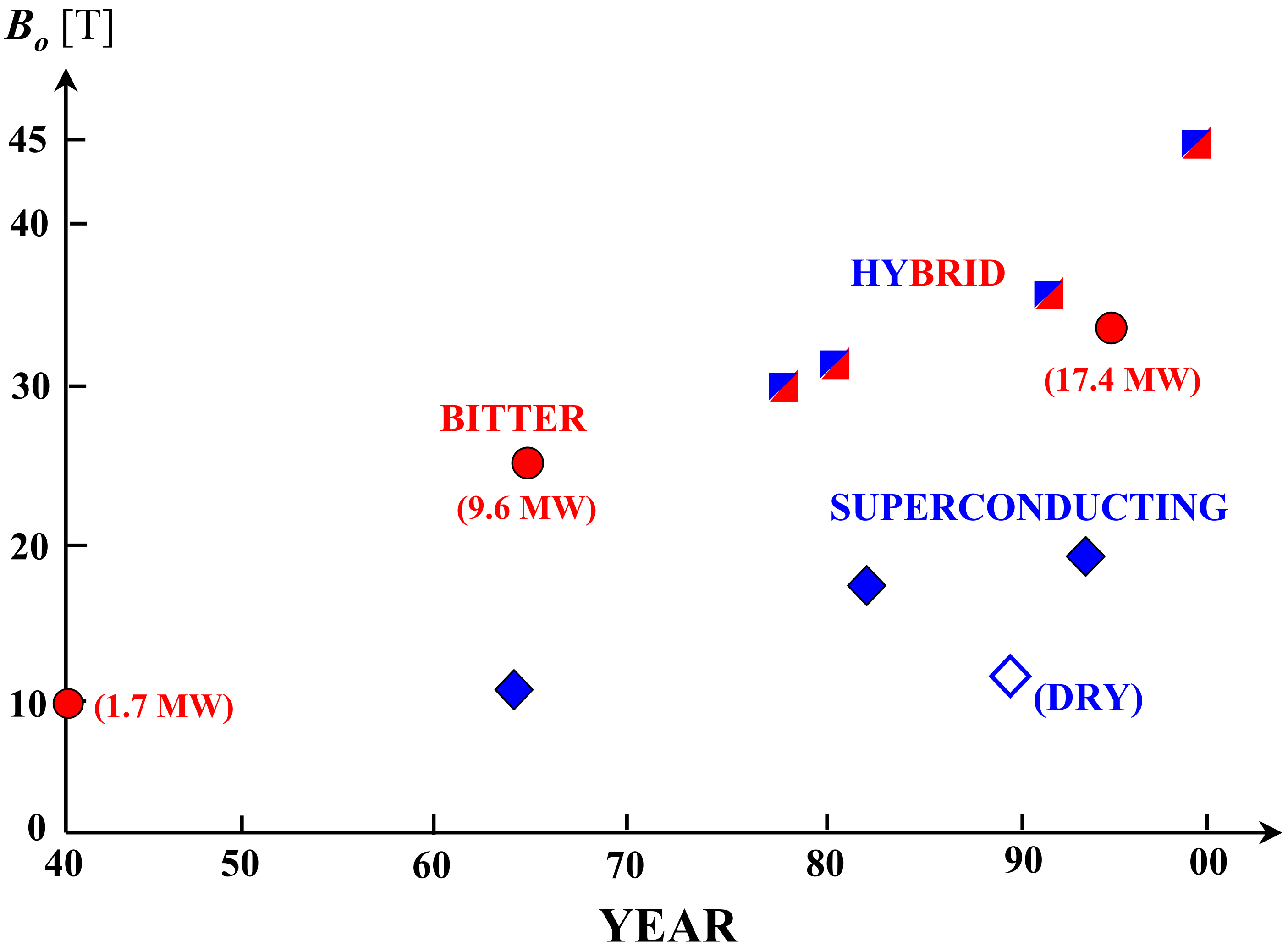
R&D Driven

- **Started initially as "Bitter" magnets (>1930s).**
- **Superconducting magnets (>1960s)**
- **Hybrid magnets (>1970s).**

Commercial

- **Available starting in the 1970s.**
- **Now generally "dry," up to ~10 T.**

High-B DC Magnets



Activities: Past and Present

Technology	*1980s*	*1990s*	*2002*
Fusion	↗	↗	↗
Electrical Devices	→	↗	↗
MRI (medicine)	↗↗	↗↗	↗↗
HEP	↗	↗	↗
NMR/MRI	↗↗	↗↗	↗↗
High-*B* DC Magnet	↗↗	↗↗	↗↗

↗ : R&D; → : Dormant; ↗↗ : Commercial products

Research Areas in HTS Magnet Technology

Stability/Protection

- **Quench/recovery behavior of conductor subject to fault-mode type disturbances---includes e_{min}; NZP velocities.**
- **Detection of a localized hot zone.**

AC Losses

- **Measurement techniques.**
- **Reduction---through conductor fabrication?**

Current Activities at FBML

Stability/Protection

- **Response of YBCO tape to an over-current pulse: LN2 bath and forced-flow cooling.**

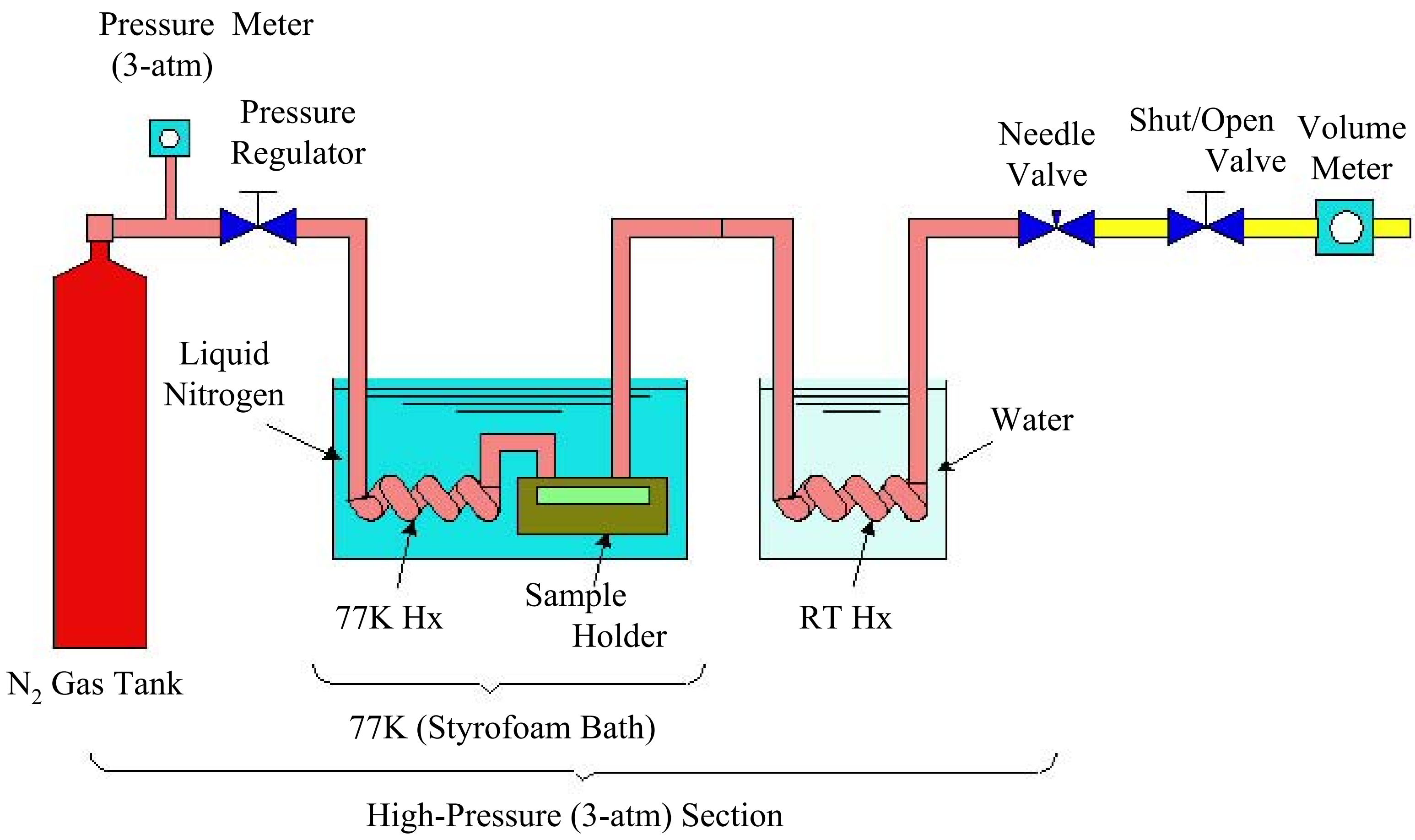
Detection of a Hot Zone

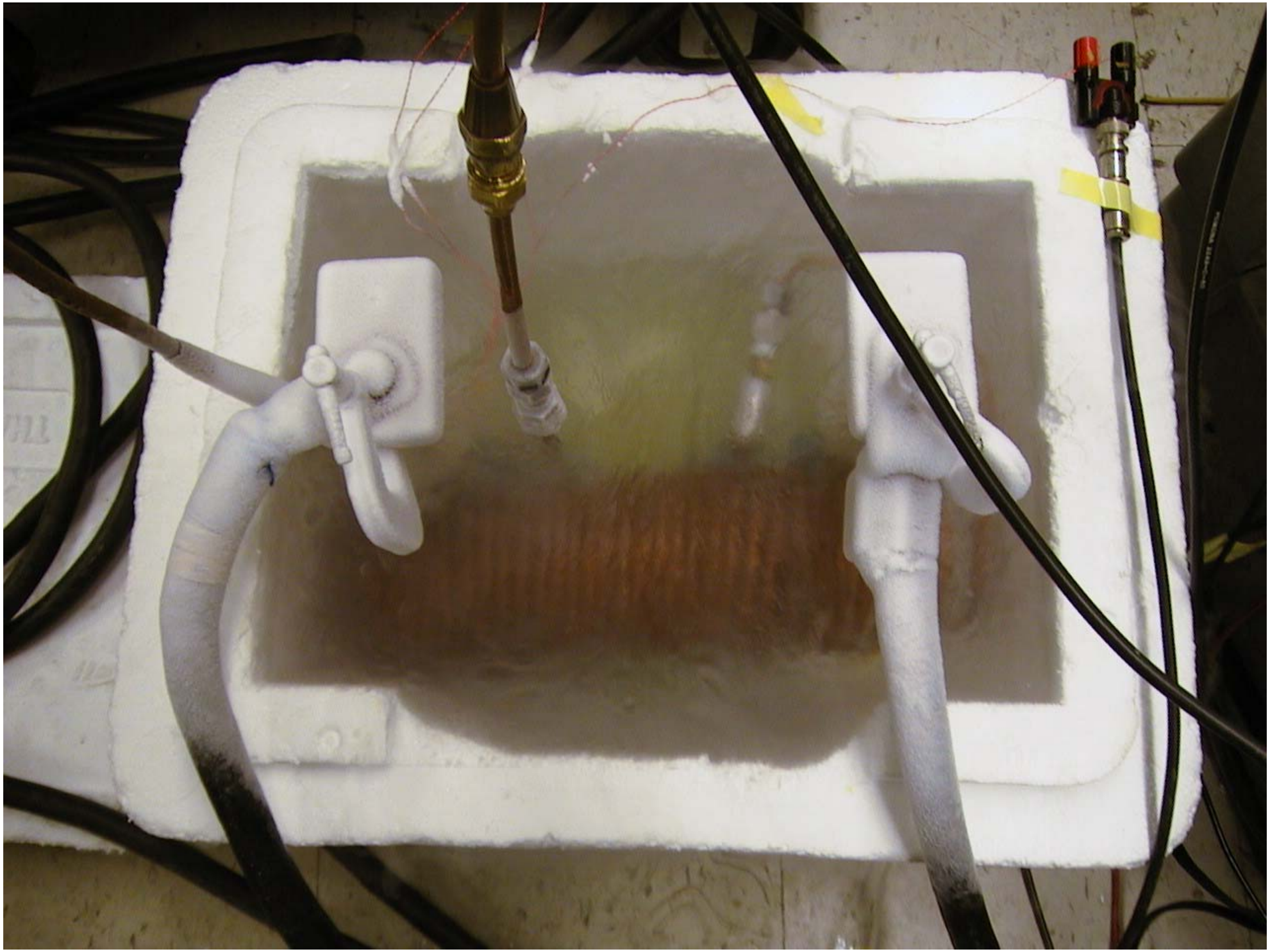
- **AE technique---new activity (08/02 →).**

Quench/Recovery: Experiment & Simulation

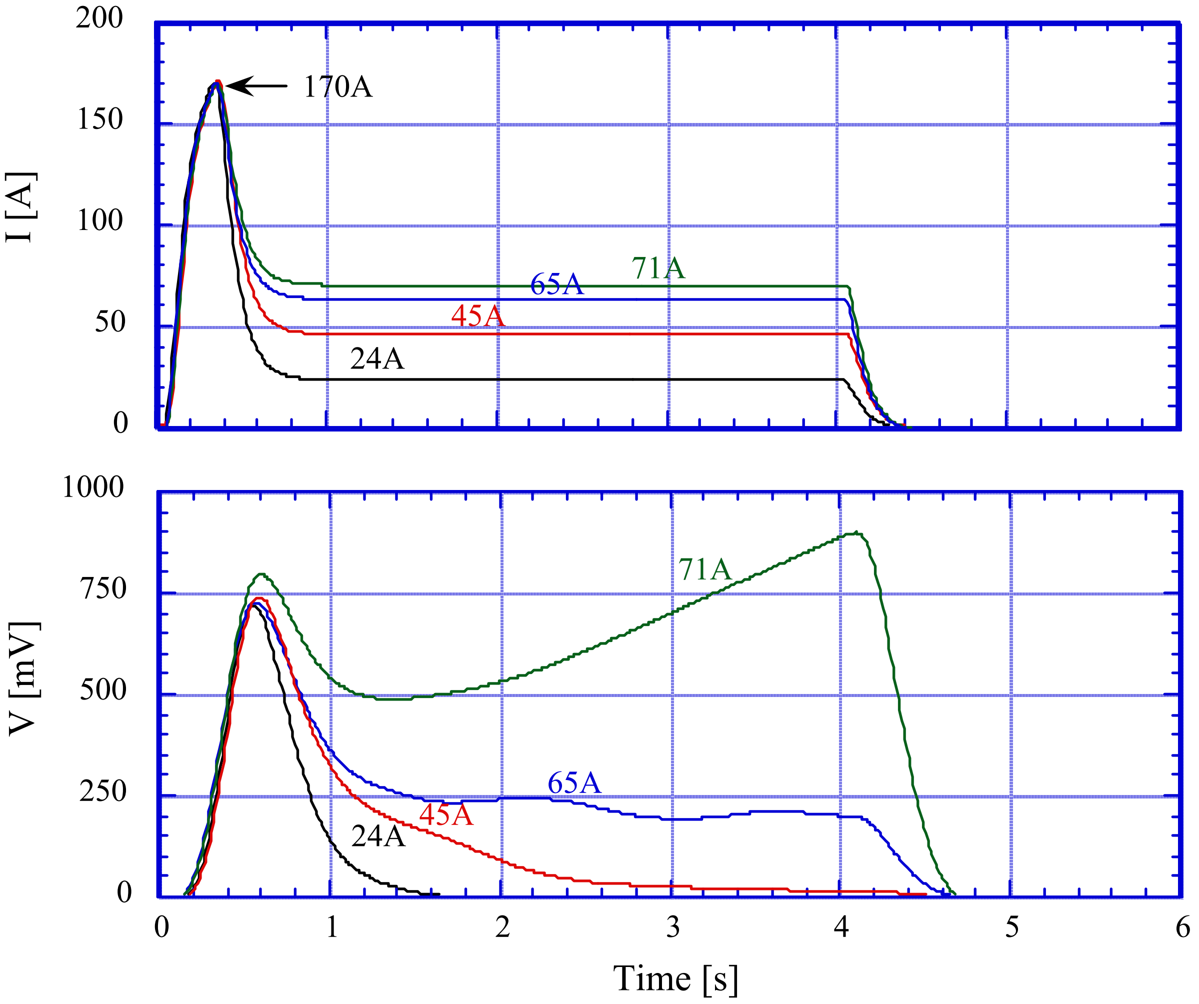
- **Bath cooling @77 K.**
- **Forced-flow cooling @ 2-3 atm 80-81 K.**

Forced-Flow Experimental Setup

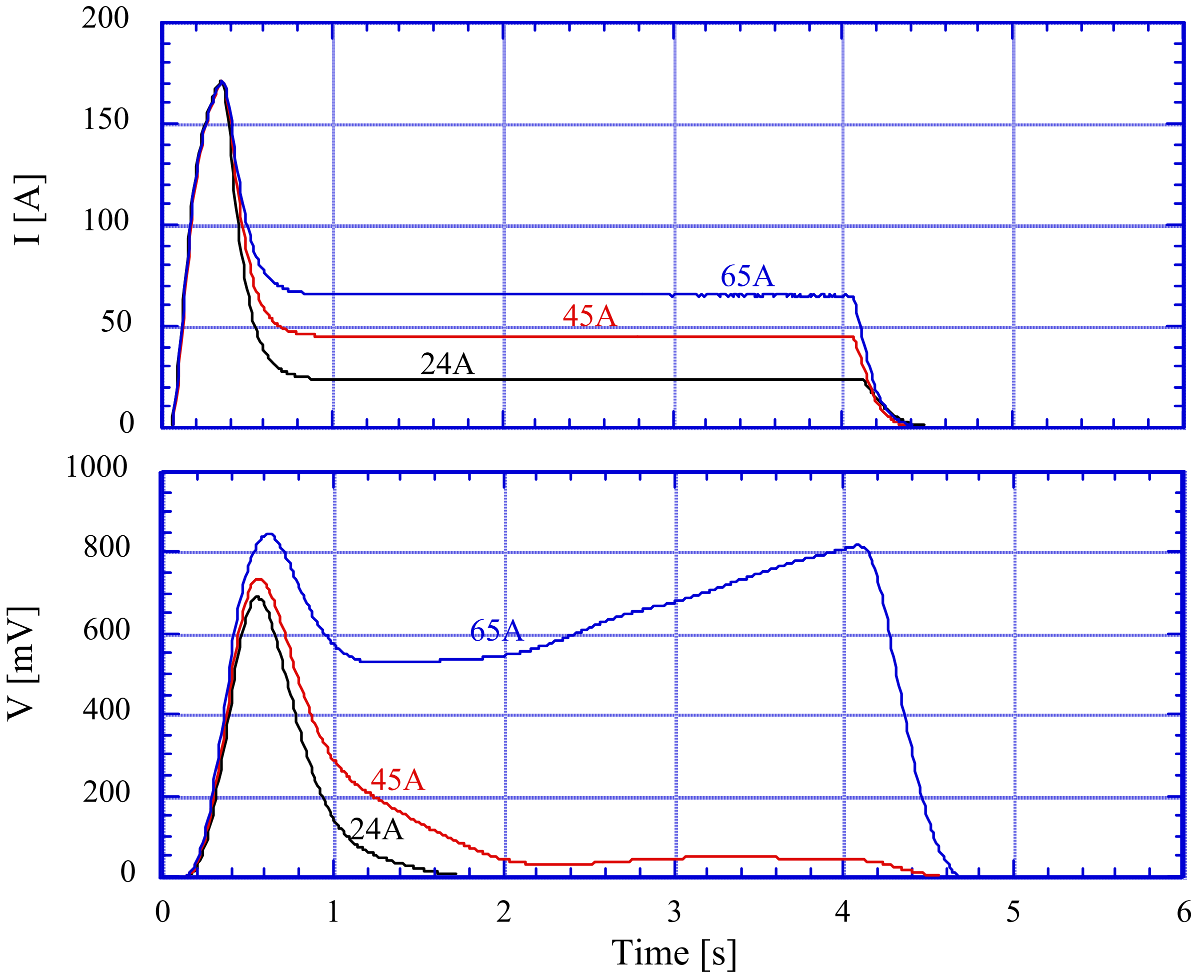




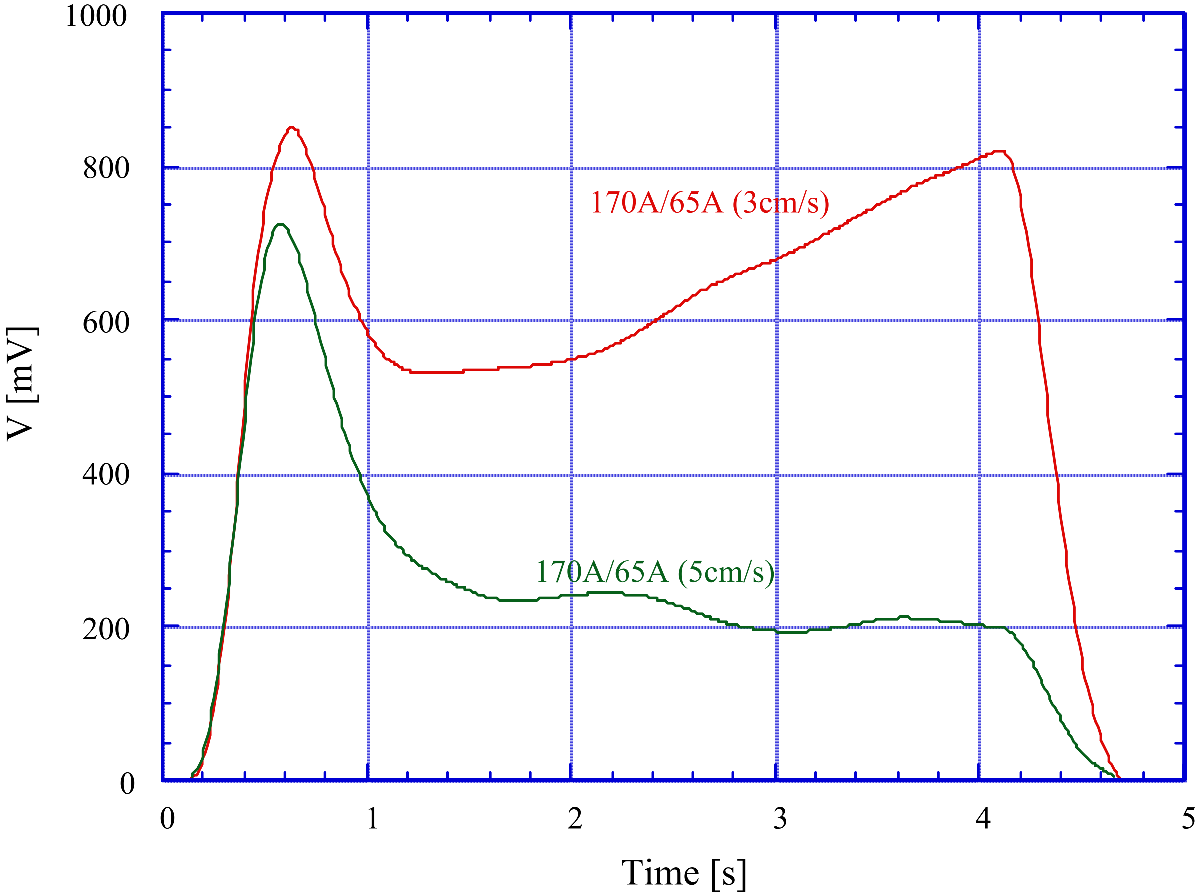
Sample 2: Forced-Flow (~81 K; 5 cm/s)



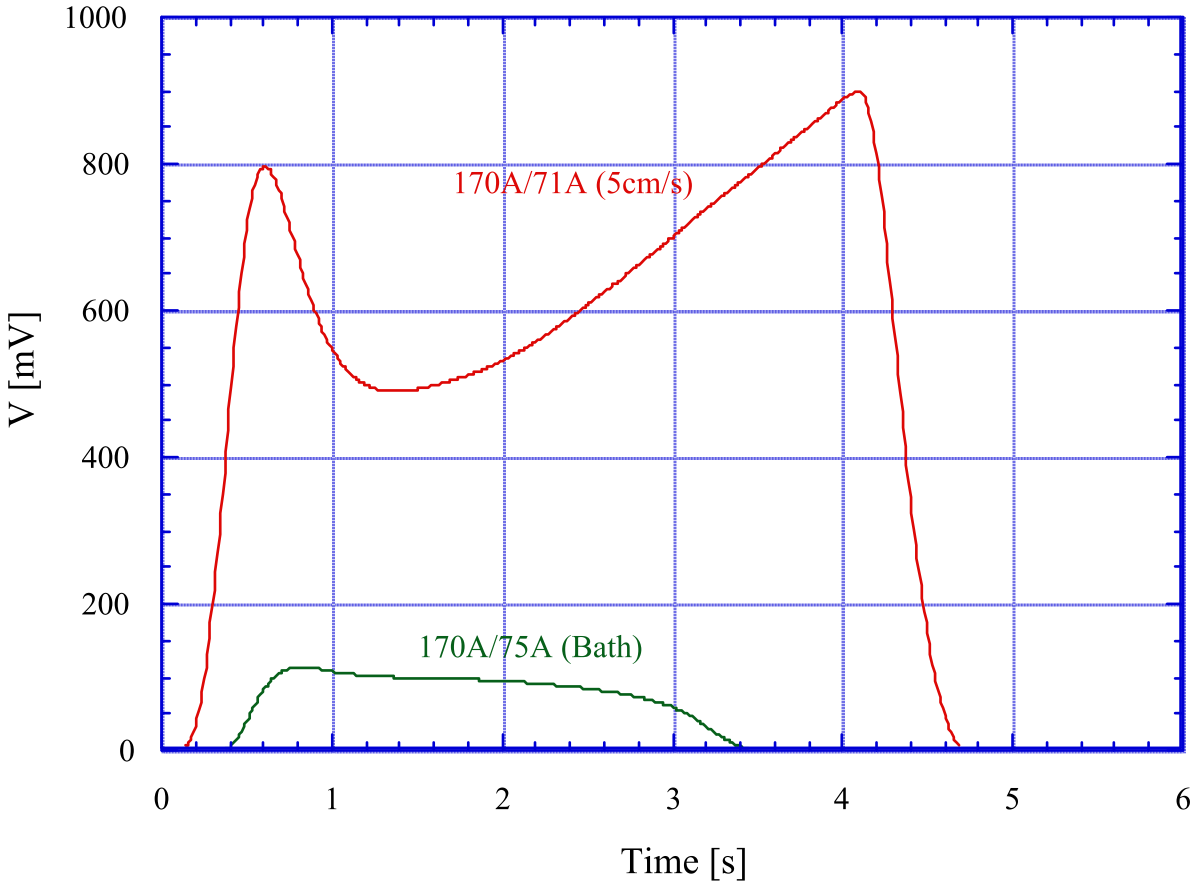
Sample 2: Forced-Flow (~81 K; 3 cm/s)



Sample 2: Forced-Flow (@81 K)



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



Simulation

$$Q = \hbar A_s \Delta T_w = \hbar A_s \left(T_w - T_f\right)$$

$$\hbar = \frac{kNu}{D}$$

$\mathrm{Re} \geq 3000$, turbulent flow

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}$$

$\mathrm{Re} < 3000$, laminar flow

$$Nu = 3.66 + \frac{0.0668\,(D/L)\mathrm{Re}\ \mathrm{Pr}}{1 + 0.04\left[(D/L)\mathrm{Re}\ \mathrm{Pr}\right]^{2/3}}$$

Nitrogen Properties at 2 bar (From Handbook of Cryogenic Engineering, I. G. Weisend II, 1998)				
T(K)	ρ(kg/m³)	Cp(j/kg K)	μ(Pa s)	κ(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}

1-D Power Flux Equation

$$\overline{\delta_{cd}C_{cd}(T)}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[\overline{k_{cd}(T)}\frac{\partial T}{\partial x}\right]+g_j(T)+g_d(t,x)-q_{n2}(T)$$

$$\overline{\delta_{cd}C_{cd}(T)}=\delta_{ag}C_{ag}(T)+\delta_{sc}C_{sc}(T)+\delta_{ic}C_{ni}(T)$$

$$\overline{k_{cd}(T)}=\frac{\delta_{ag}k_{ag}(T)+\delta_{ic}k_{ic}(T)}{\delta_{ag}+\delta_{ic}}$$

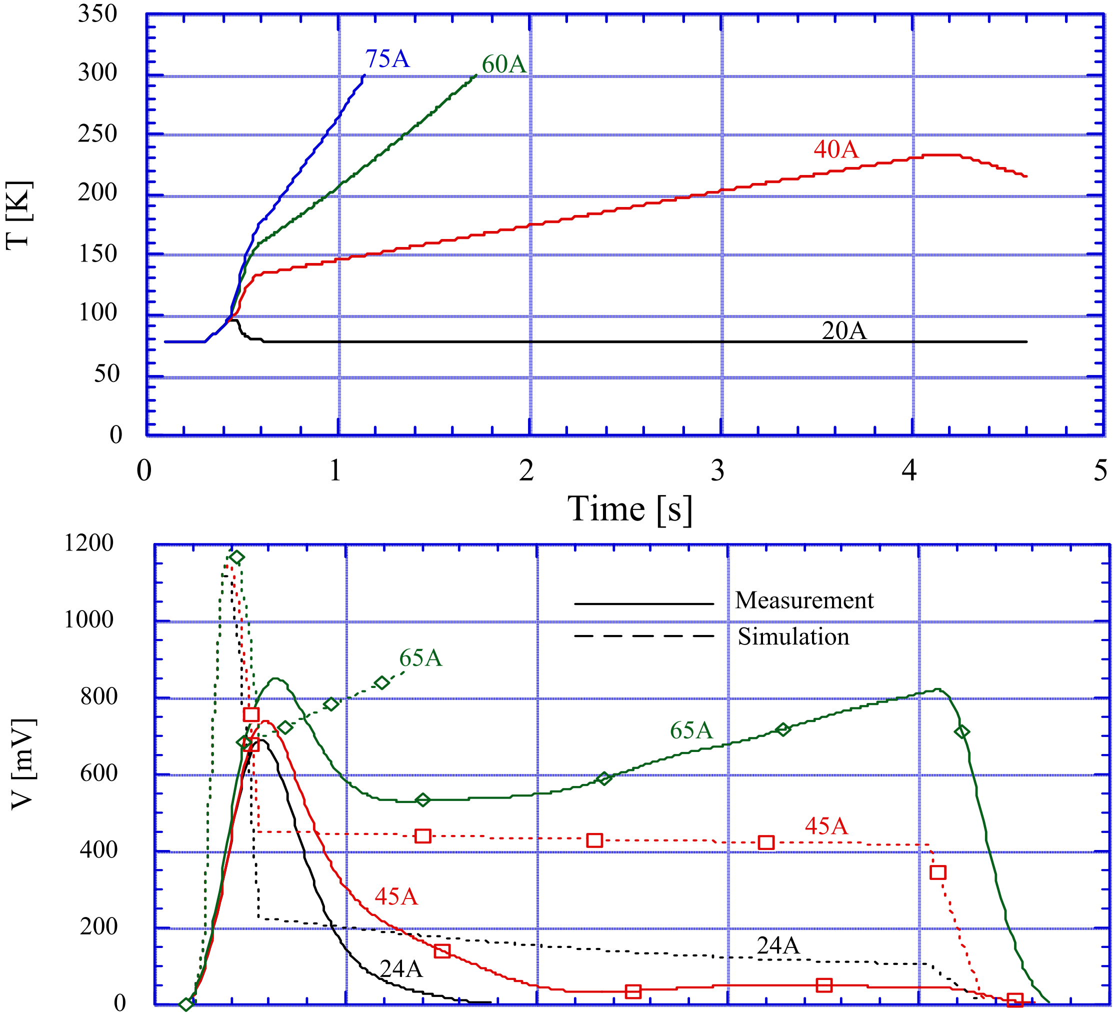
$$g_j(T)=0 \qquad [T_{op}\le T\le T_{cs}]$$

$$=\frac{1}{w^2}\left[\frac{\rho_{ag}(T)\rho_{ic}(T)}{\delta_{ic}\rho_{ag}(T)+\delta_{ag}\rho_{ic}(T)}\right]I_t[I_t-I_c(T)] \qquad [T_{cs}\le T\le T_c]$$

$$=\frac{1}{w^2}\left[\frac{\rho_{ag}(T)\rho_{ic}(T)}{\delta_{ic}\rho_{ag}(T)+\delta_{ag}\rho_{ic}(T)}\right]I_t^2 \qquad [T\ge T_c]$$

$I_c(T)$**: a linear function (100 A @77 K, sf; @**T_c **=93 K).**

Sample 2: Bath @77 K & Simulation



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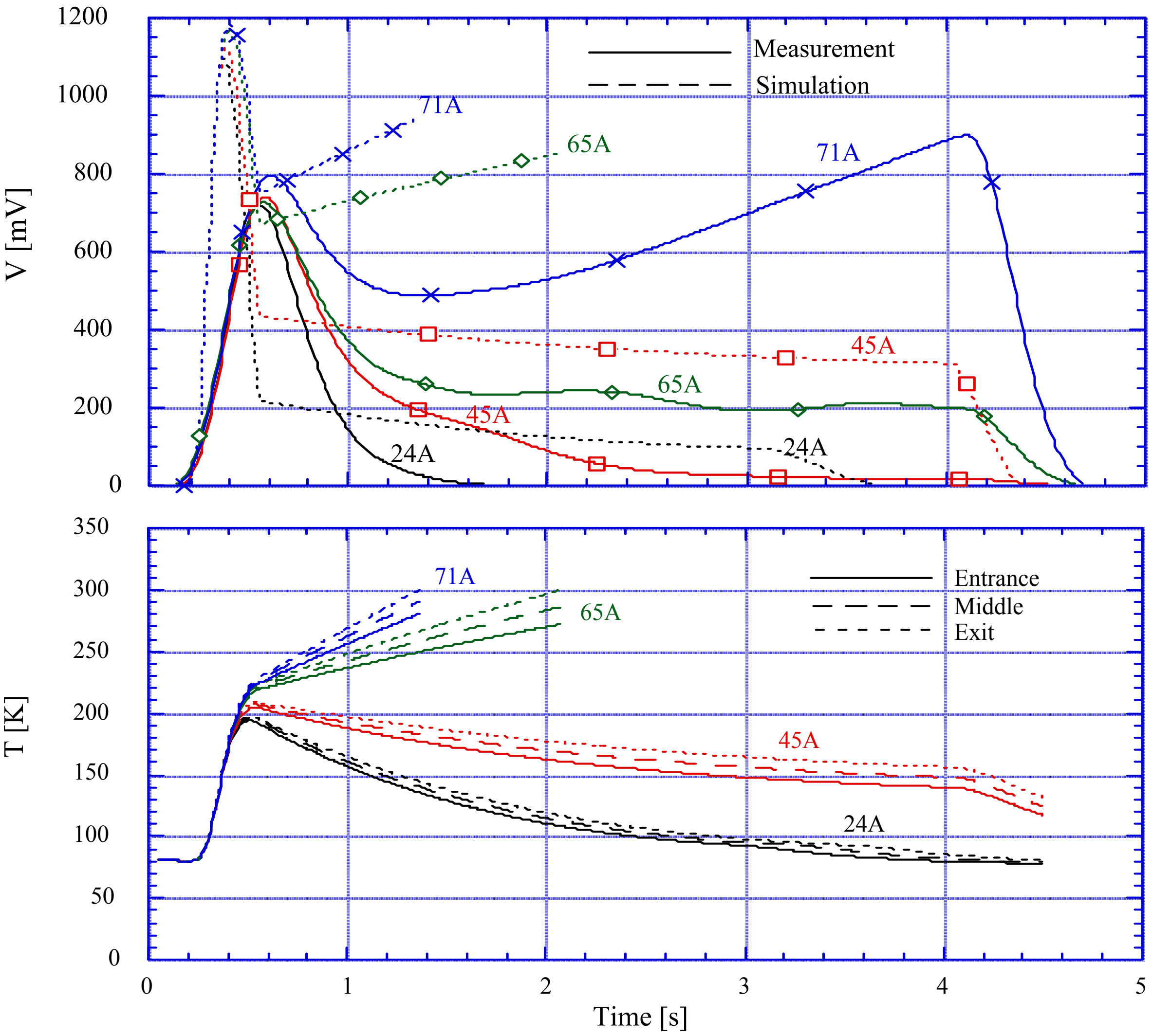
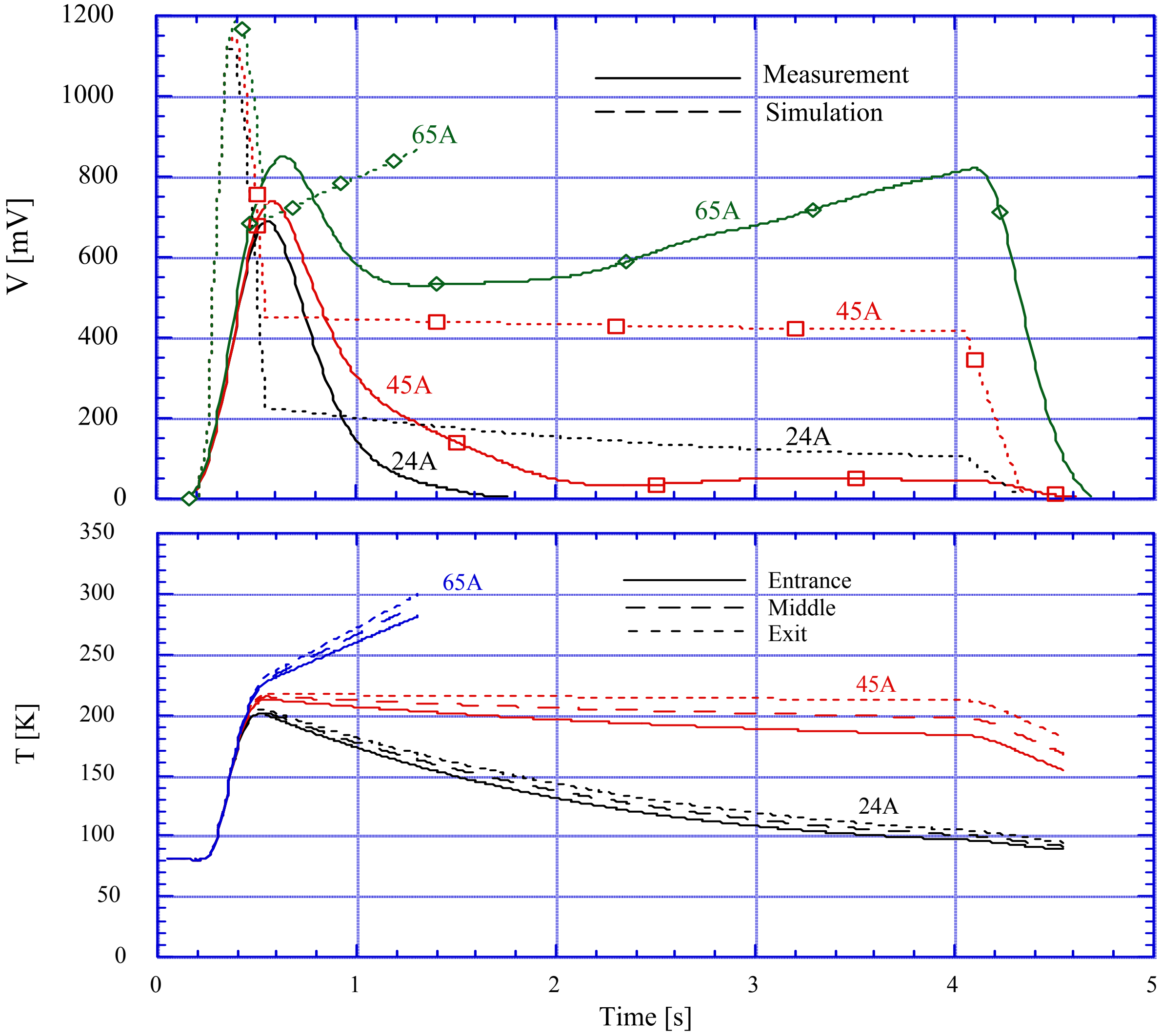
09/18/2002, Karlsruhe, Germany

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



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



Preliminary Conclusions

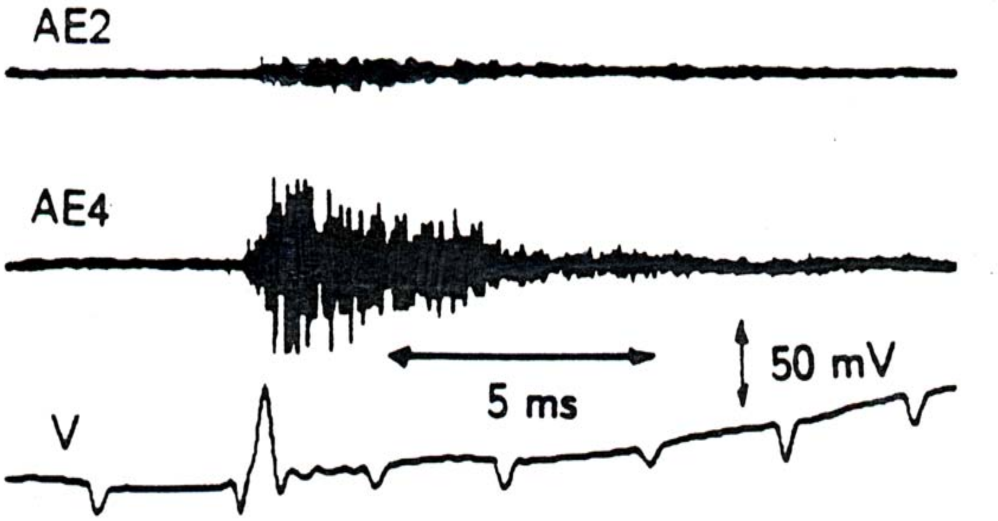
- **Forced cooling (>3cm/s) provides better cooling than bath.**
  - ☆ **Cooling improves with flow velocity.**
- **Simulation requires improvement.**

Detection of a Local Hot Zone with AE

- *AE (Acoustic Emission): Acoustic signals emitted by sudden mechanical events in a body being loaded (stressed) or unloaded.*
  - ☆ **Stress can be of mechanical, magnetic, or thermal.**
- **Proven useful for high-performance (adiabatic) LTS magnets in distinguishing mechanical-disturbance induced quench (AE) from I_c-induced quench (no AE).**

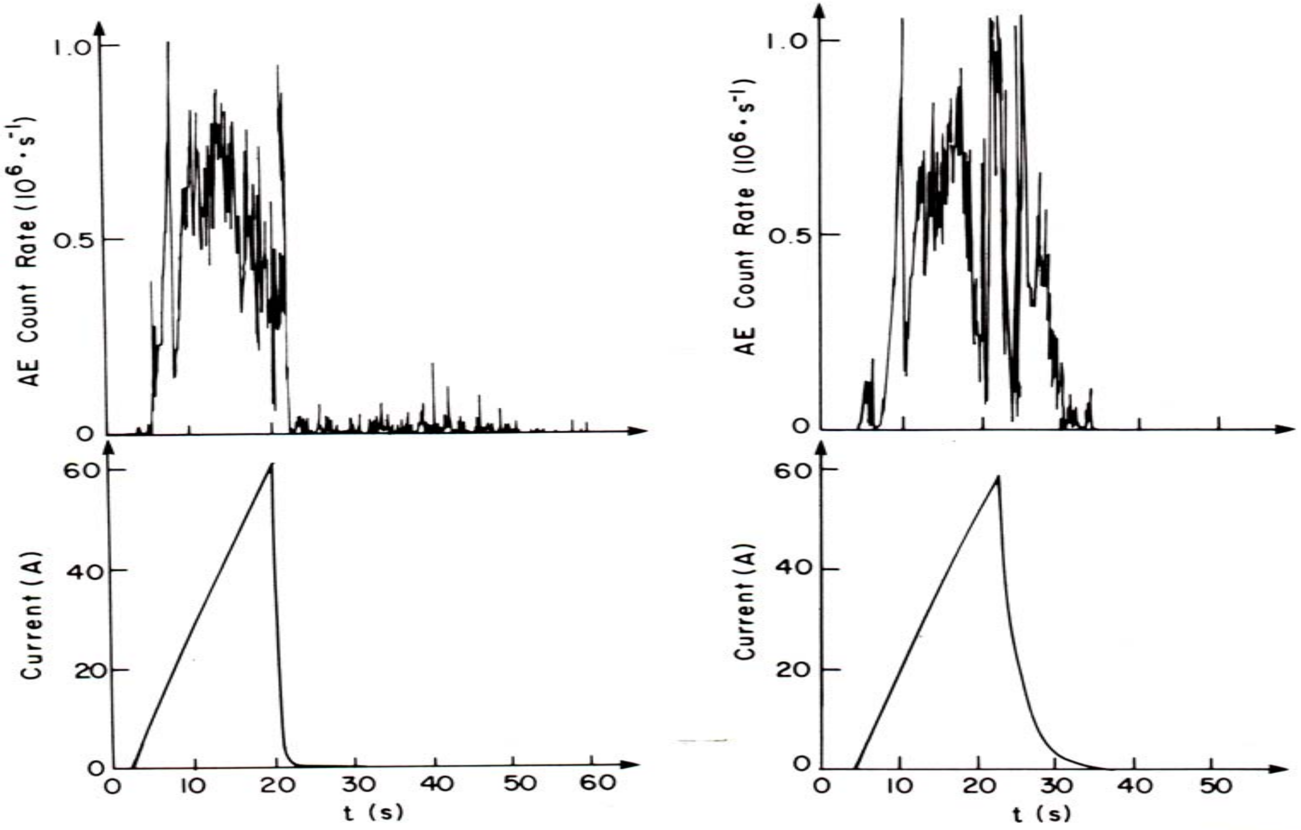
Early (1980s) Examples with LTS (4.2 K) Magnets

1. Conductor-Induced Quench in a Dipole

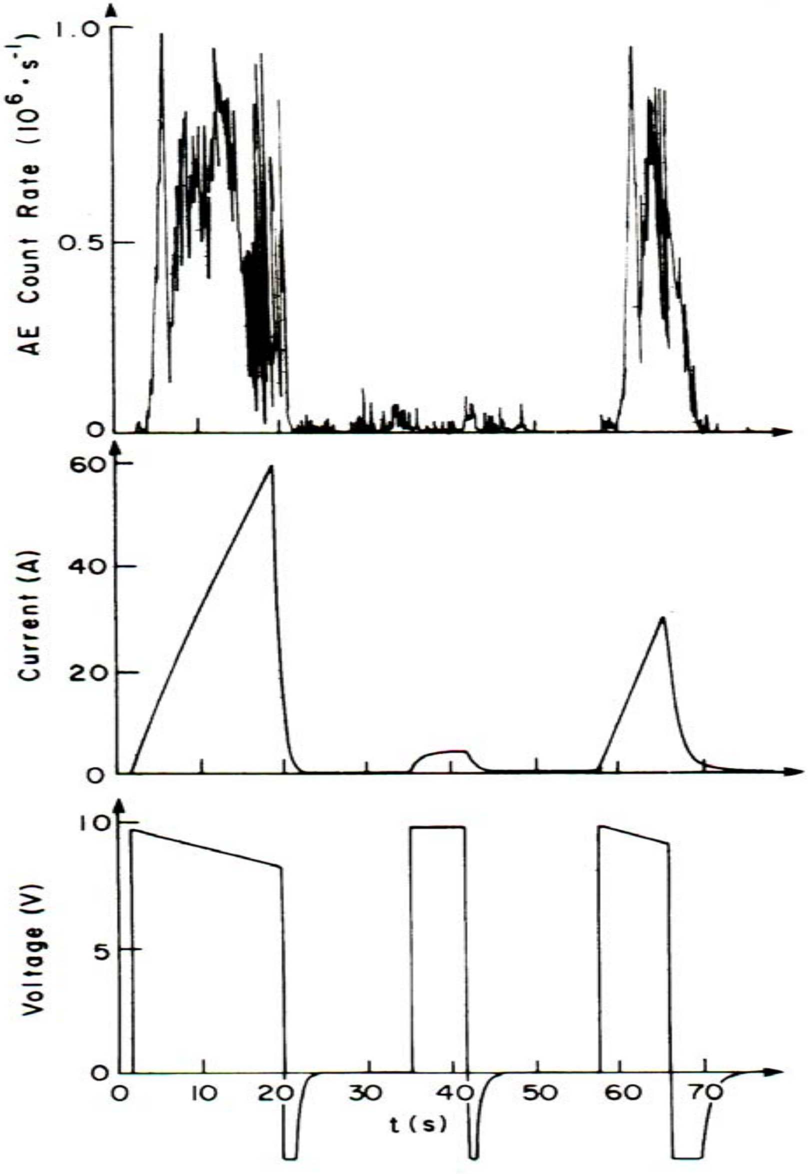


O. Tsukamoto, M.F. Steinhoff, Y. Iwasa (1981)

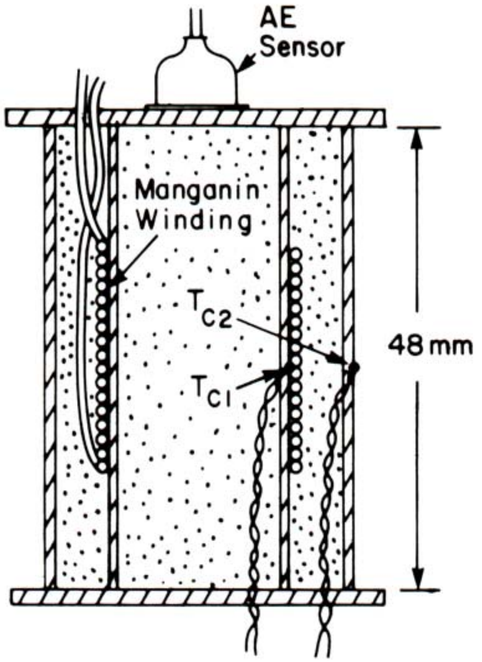
2. ΔT-Induced AE Signals: Magnet Discharge

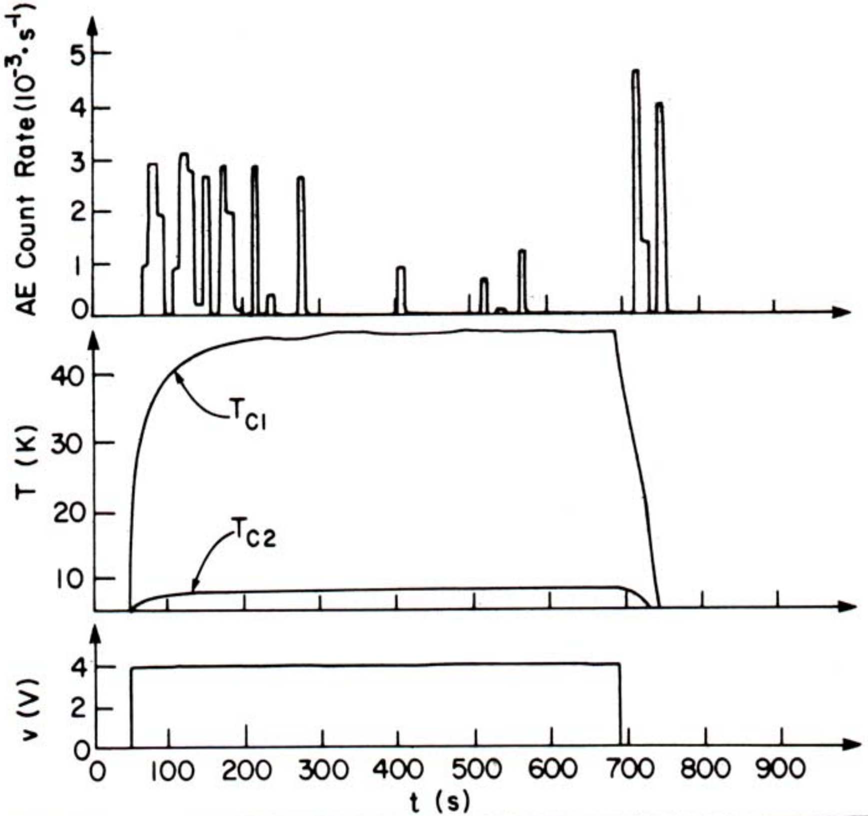


O. Tsukamoto and Y. Iwasa (1984)


1.0
0.5
0
AE Count Rate ($10^6 \cdot s^{-1}$)
60
40
20
0
Current (A)
10
5
0
Voltage (V)
0
10
20
30
40
50
60
70
t (s)

3. ΔT-Induced AE Signals: Heater



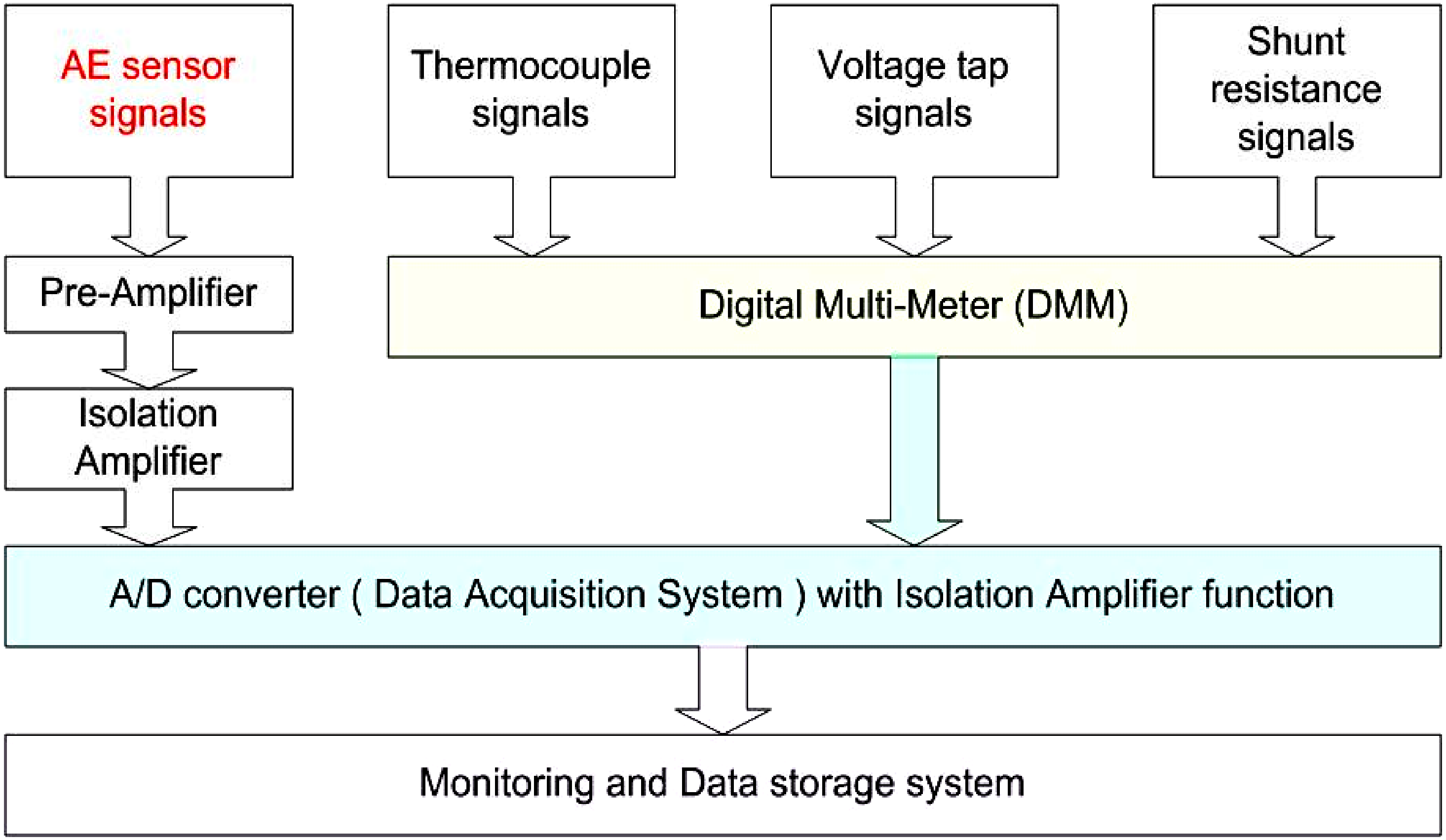


O. Tsukamoto and Y. Iwasa (1984)

Conclusions for LTS & Prospect for HTS

- **Normal zone induced heating generates AE signals.**
  - ☆ **Thermal expansion small at 4.2 K---required ΔT~40 K.**
- **AE signals diminish as $\Delta T/\Delta t \rightarrow 0$.**
- **AE sensitivity increases with T_{op}.**
  - ☆ **AE technique more useful for HTS.**

Signal Processing Block Diagram (2002)



AE sensor signals

Thermocouple signals

Voltage tap signals

Shunt resistance signals

Pre-Amplifier

Digital Multi-Meter (DMM)

Isolation Amplifier

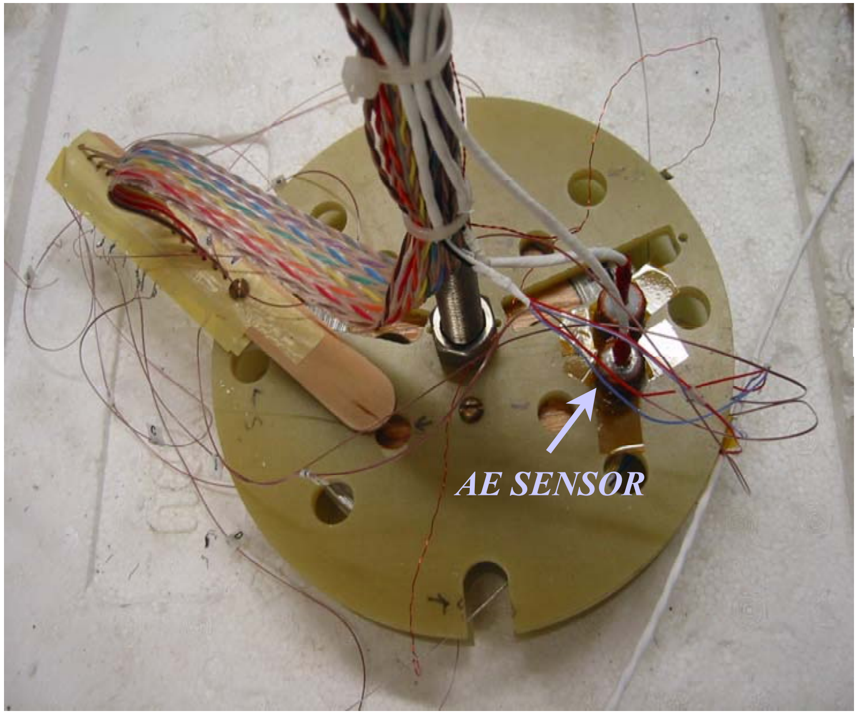
A/D converter (Data Acquisition System) with Isolation Amplifier function

Monitoring and Data storage system

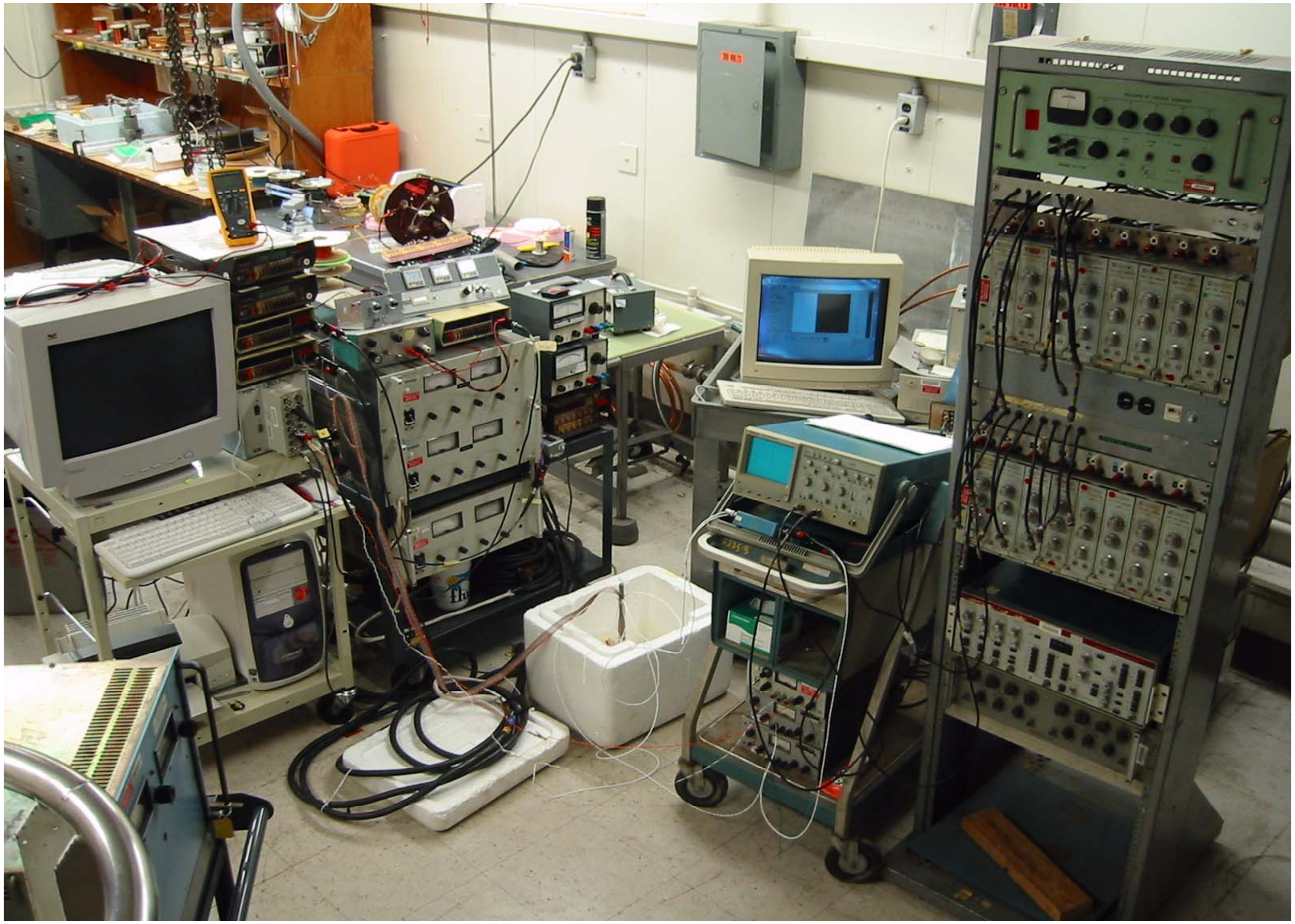
Double-Pancake Test Coil (Bi-2223)

As Wound (o.d.: 12cm)

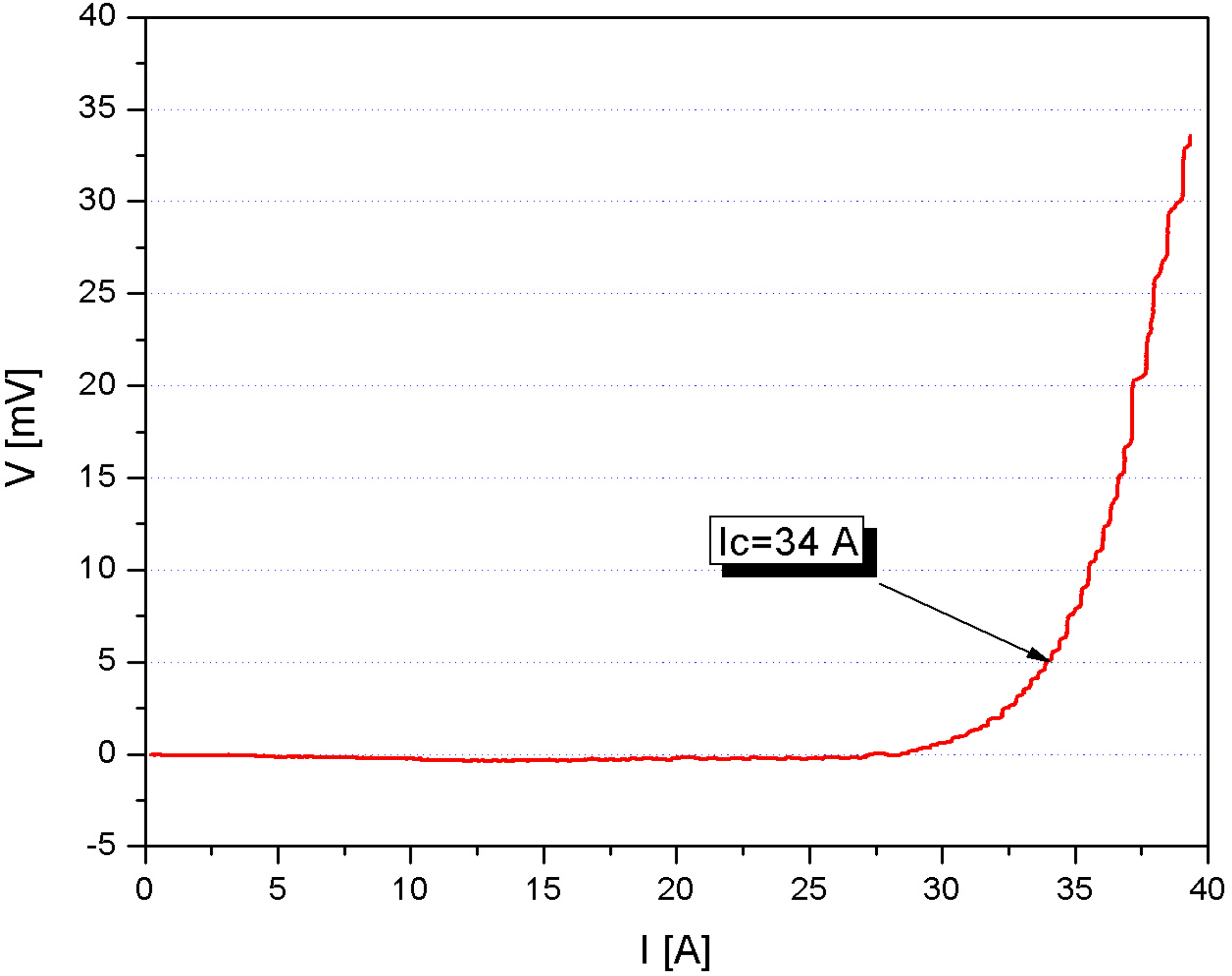
In a Sample holder



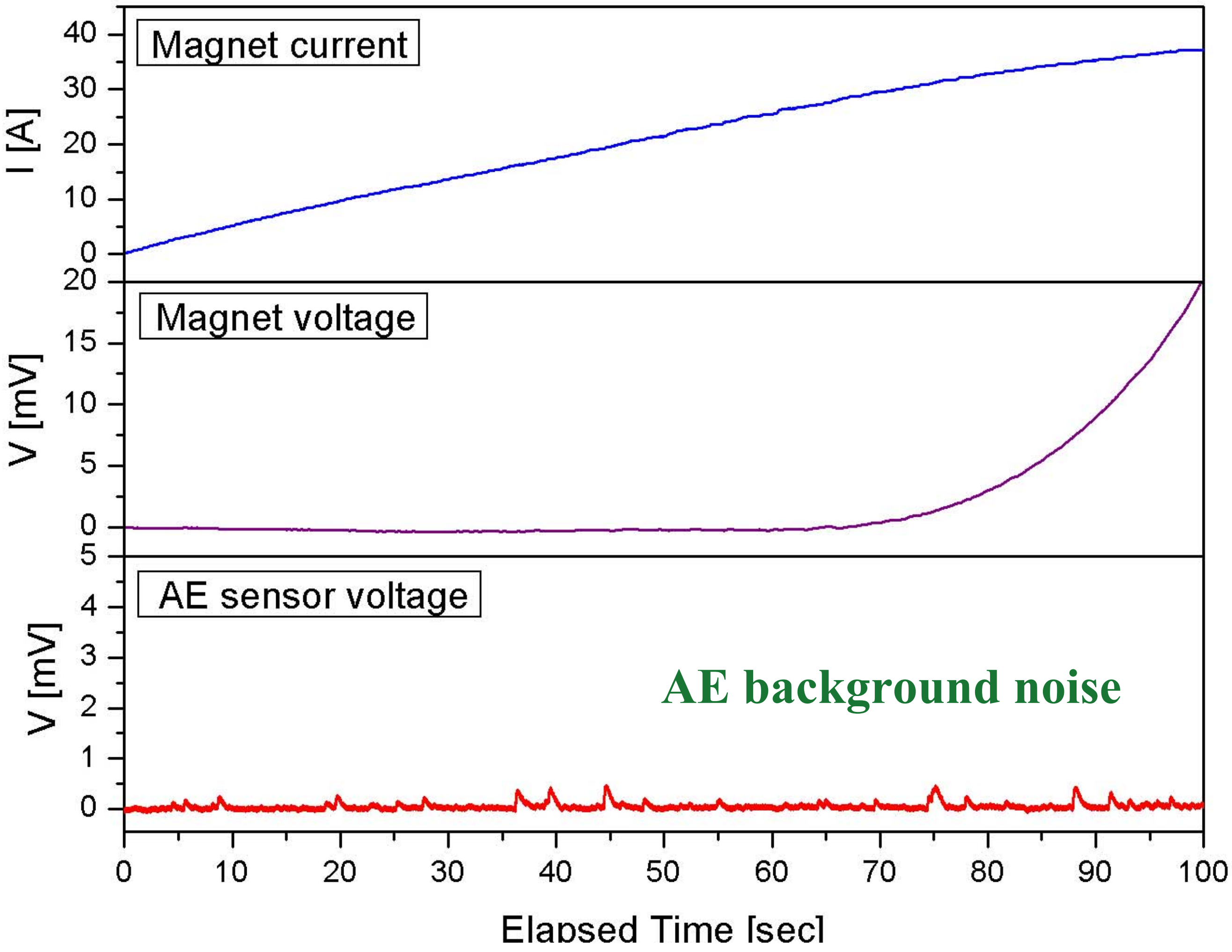
Experimental Setup



V(I) Plot @ 77 K

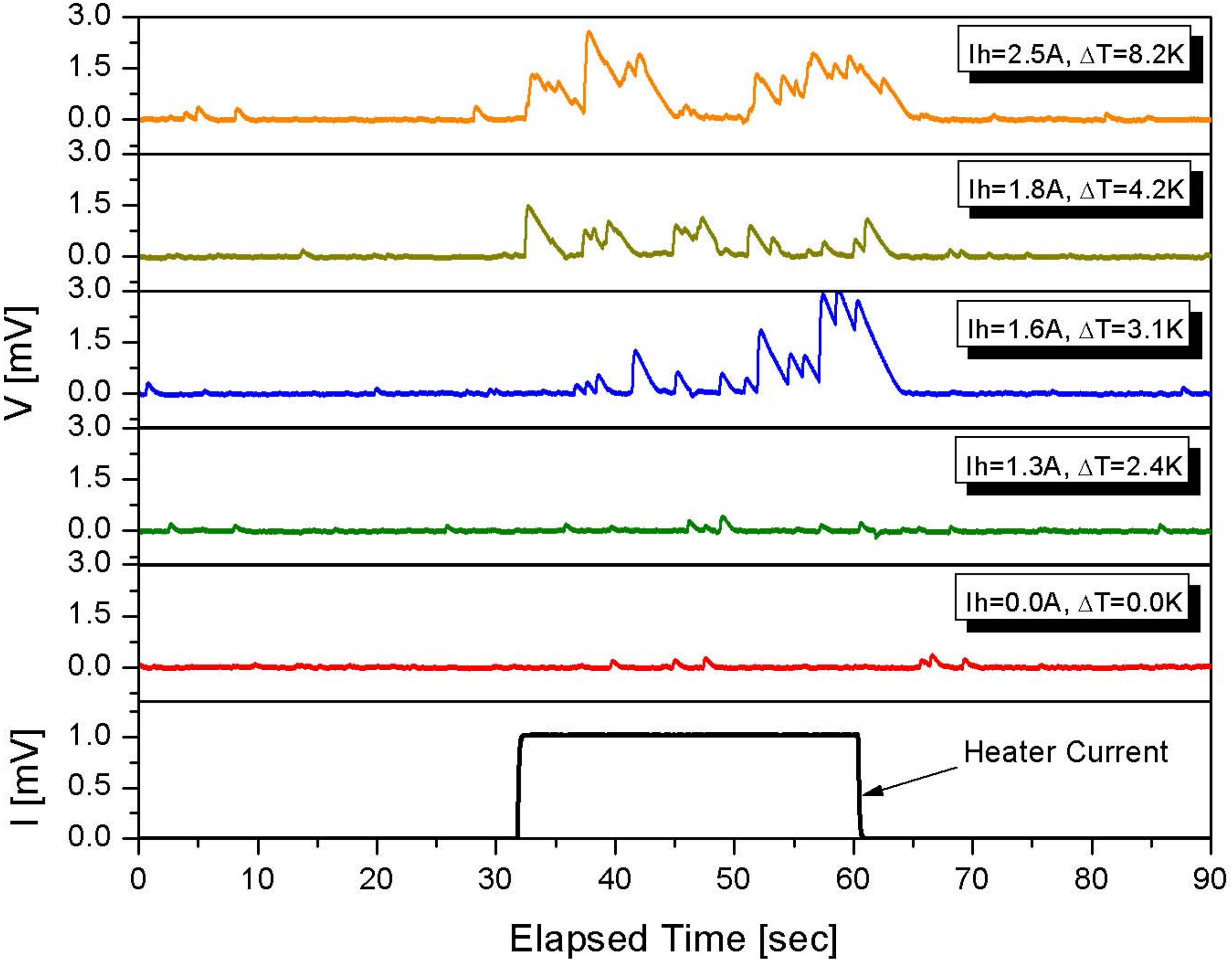


I(t); V(t); and AE(t) Plots @ 77 K

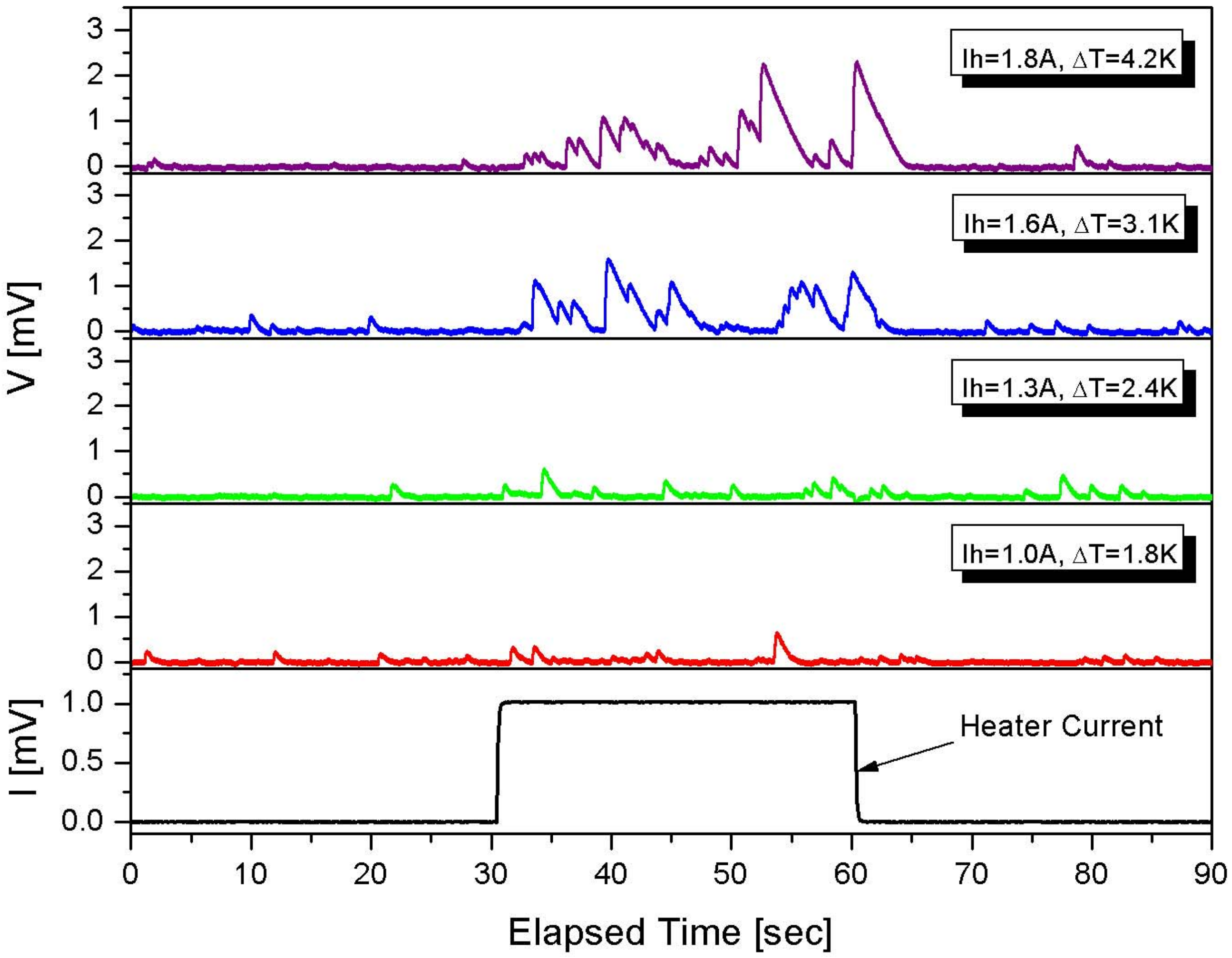


AE background noise

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



Heating-Induced Data: I_{op}=0 A



Preliminary Conclusions on AE Experiment

- I_c **transition does not generate AE signals.**
  - ☆ **May generate AE signals if SC/Cu joint overheated.**
- **Localized heating ($\Delta T \geq 4$ K) detectable with AE signals even with a test coil immersed in LN2.**
  - ☆ ΔT **sensitivity may be enhanced in "dry" coils.**

Conclusions

HTS Magnet Technology

- **Stability: benign under routine conditions, requires further simulation/experimental study for fault-mode events.**
- **Protection: overheating ; arcing; overstressing key issues--- HTS J_e likely no greater than LTS J_e.**
- **Cryogenics: cost likely not an issue; should become more "invisible" with innovative insulation techniques.**
- **Economics: market penetration possible by being competitive in cost (replacing) or performance (enabling).**
- **Research Areas: stability/protection; AC losses.**