3rd Workshop on Accelerator Magnets in HTS (WAMHTS-3)

HTS magnet quench criteria

thibault.lecrevisse@cea.fr

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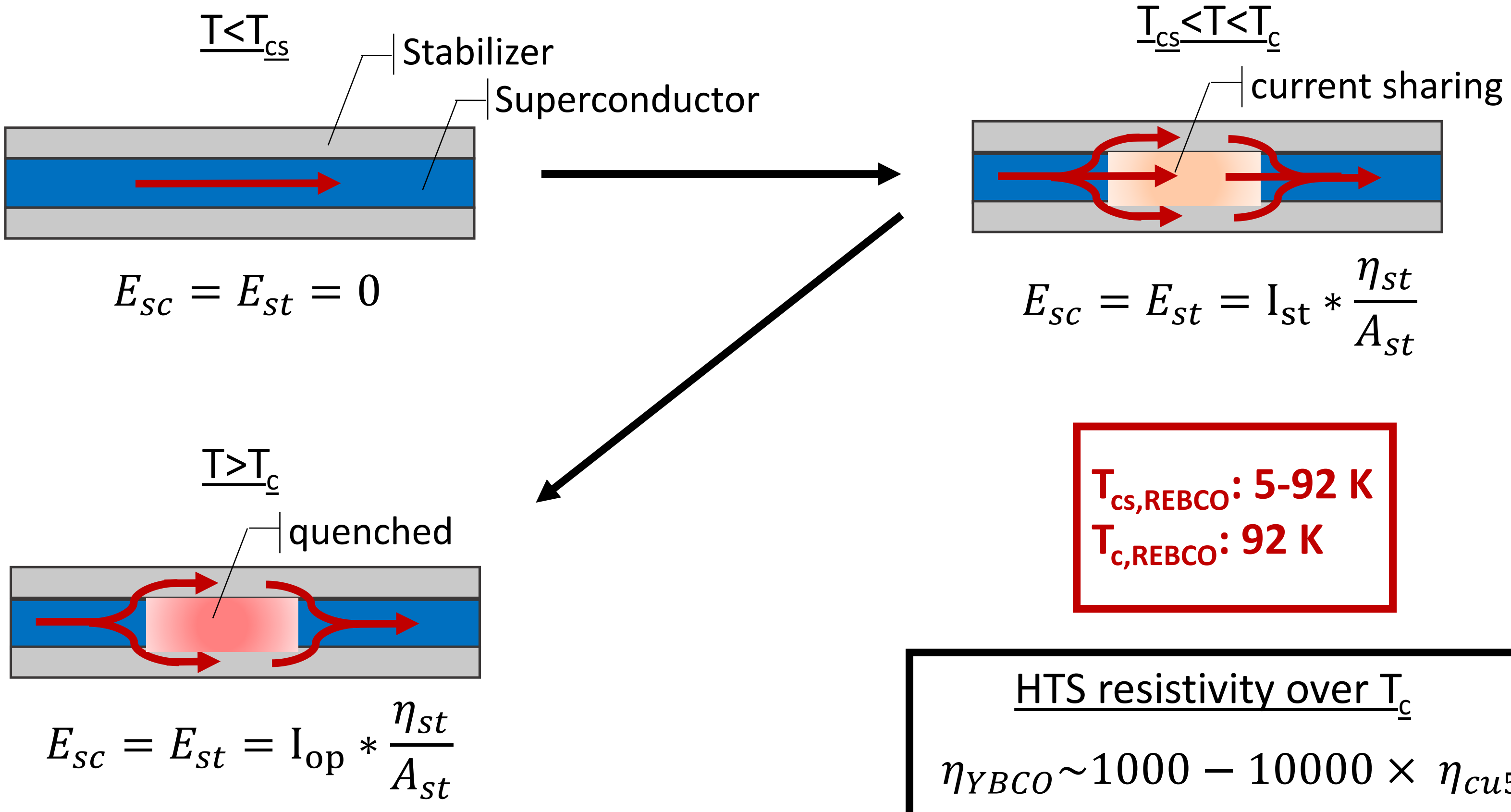
Overview

1. Physics of a Quench
    1. Principle
    2. "Danger"
    3. Issue with HTS
2. HTS Quench protection criteria
    1. Heat balance and adiabatic hot spot
    2. "quench capital" vs "quench tax"
    3. Increase the quench capital
    4. Lower the quench tax :
        1. Fast detection
        2. Accelerate the dump
        3. Winding adaptation
3. Conclusion

Physics of quench: Principe

Definition of a quench: resistive transition in a superconducting magnet leading to appearance of voltage, temperature increase, thermal and electromagnetic forces (and cryogen expulsion).



$$E_{sc} = E_{st} = 0$$

$$E_{sc} = E_{st} = \mathrm{I}_{\mathrm{st}} * \frac{\eta_{st}}{A_{st}}$$

$$E_{sc} = E_{st} = \mathrm{I}_{\mathrm{op}} * \frac{\eta_{st}}{A_{st}}$$

$T_{cs,REBCO}$: 5-92 K
$T_{c,REBCO}$: 92 K

HTS resistivity over T_c

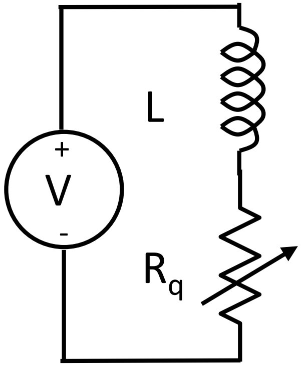
$$\eta_{YBCO} \sim 1000 - 10000 \times \ \eta_{cu50}$$

Physics of quench: “Danger”

Why is it a problem ?

The magnetic energy is transformed in heating through the resistive volume

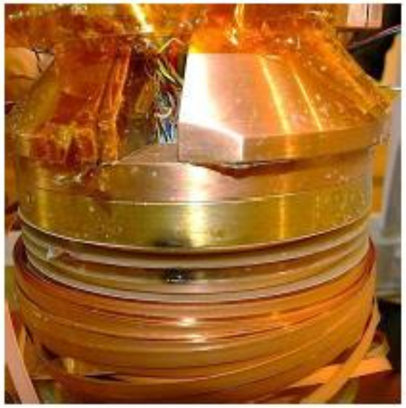
$$E_m = \int_V \frac{B^2}{2 * \mu_0} dv = \frac{1}{2} L I^2$$ is converted in $R_q I^2$



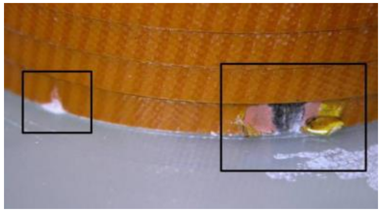
Not a problem up to ~ 40 T <u>*if it happen uniformly*</u> *in all the winding.*
(REBCO tape from 4 K to 300 K : E_m= 7·10^8 J/m^3 B_{max} = 41 T)

BUT : it does not happen uniformly (low quench velocity) and less than 1 % of the total magnet mass might absorb the total energy → **large damage potential**

BSCO impregnated pancake, by courtesy of P. Tixador and A. Badel



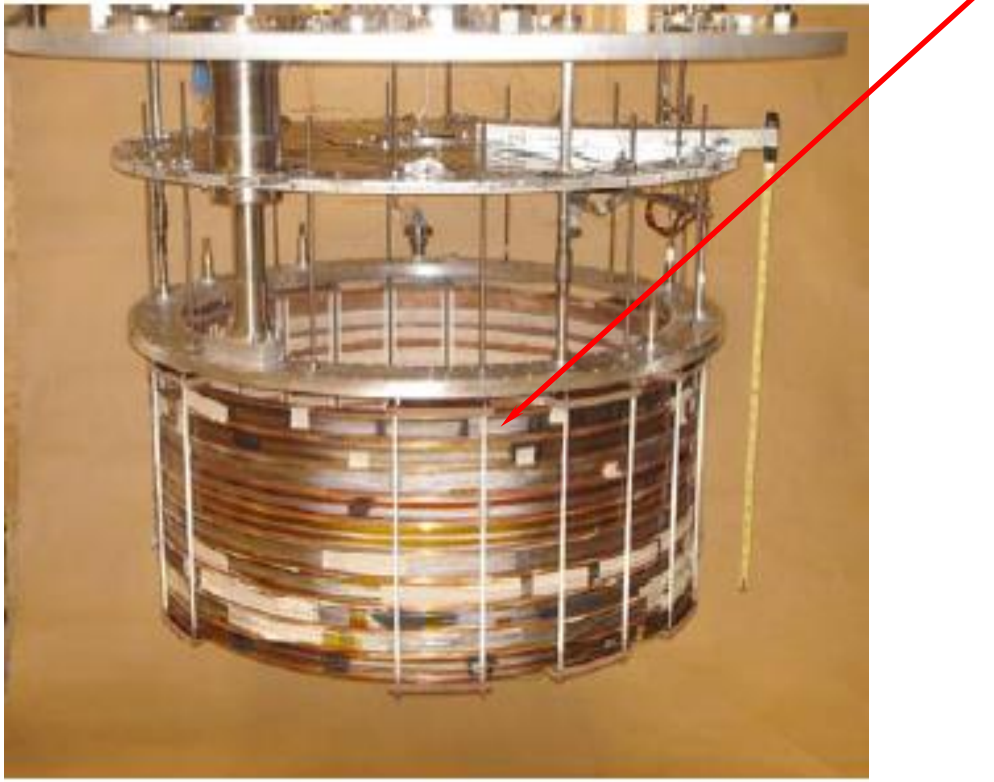
REBCO dry wound coil



S. Matsumoto et al., IEEE Trans. Appl. Supercond., vol. 22, no. 3, pp. 9501604, June 2012

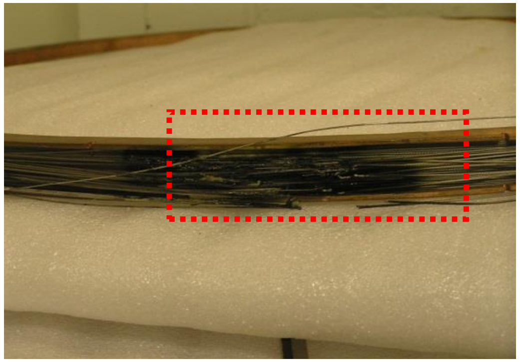
Physics of quench: “Danger”

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



An unscheduled quench (top coil)

⇒ Permanent damage



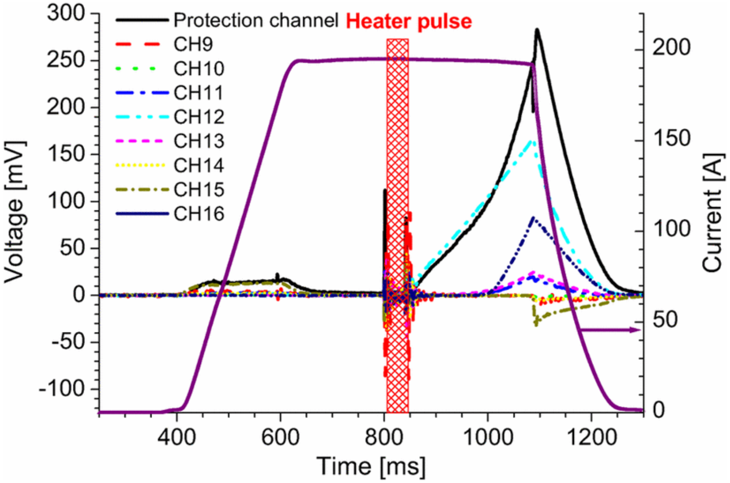
MgB_2 coil, by courtesy of Yukikazu Iwasa (FBML, 2007)

Physics of quench: Issue with HTS

Issue with HTS:

→ Very low quench propagation in a winding **typical few tens of mm/s** (2-3 order of magnitude lower than LTS) → Small volume dissipating E_m

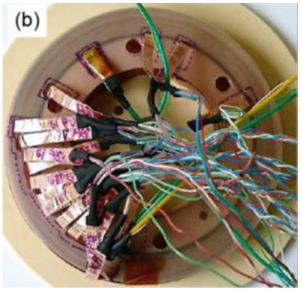
→ **Need an Active protection or another dumping method.**

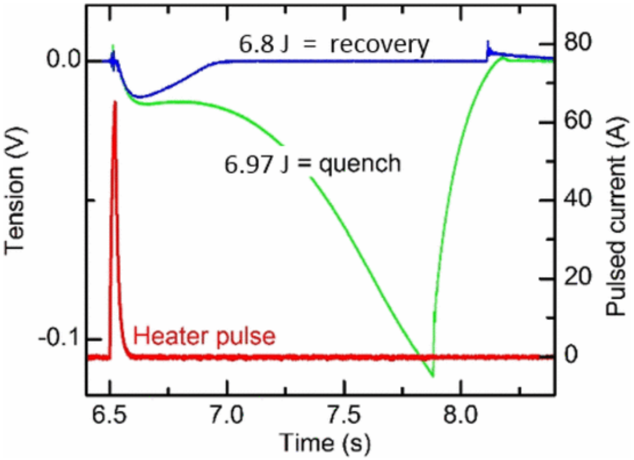


4.2 K; 17 T; 196 A (515 A/mm²) :

$$u_l < 80\ mm/s$$

T. Lécrevisse et al., IEEE Trans. Appl. Supercond., vol. 23, no. 3, June 2013





10 K; 8 T; 280 A (286 A/mm²) :

$$u_l \sim 45\ mm/s$$

Y. Miyoshi et al., IEEE Trans. Appl. Supercond., vol. 25, no. 3, June 2015

Physics of quench: Issue with HTS

Issues to be considered (LTS/HTS):

- **Temperature increase** and **temperature gradients** (thermal stresses)
- **Voltages within the magnet**, and from **magnet to ground** (whole circuit)
- **Forces caused by thermal and electromagnetic loads** during the magnet discharge transient
- **Cryogen pressure increase** and expulsion (liquid cooling)

A quench invariably requires detection and, in case of HTS, definitively needs actions to safely turn-off the power supply and discharge the magnet.

HTS Quench protection criteria: Heat balance and adiabatic hot spot

$T_{\text{hot-spot}}$: **< 200 K, Safe** ; **<300 K, risky** ; >300 K, very risky *(*, pp.470)*

Heat equation *(*, pp. 352):*

$$\boxed{\bar{C}(T)\frac{\partial T}{\partial t}} = \boxed{\xcancel{\nabla\cdot\left(\bar{k}(T)\nabla T\right)}} + \boxed{\bar{\eta}(T)J^2(t) +} \boxed{\xcancel{g_d(t)}} - \boxed{\xcancel{\frac{f_p P_D}{A_{cd}} g_q(T)}}$$

Conductor's thermal energy

Thermal conduction into the conductor

Joule heating

non-Joule heat generation

Cooling by cryogen

→ **adiabatic heat balance** (simplest and conservative approach) :

$$\boxed{\bar{C}\frac{dT}{dt} = \bar{\eta}J^2}$$

$\bar{C} = \sum_i f_i \rho_i c_i$ Average heat capacity

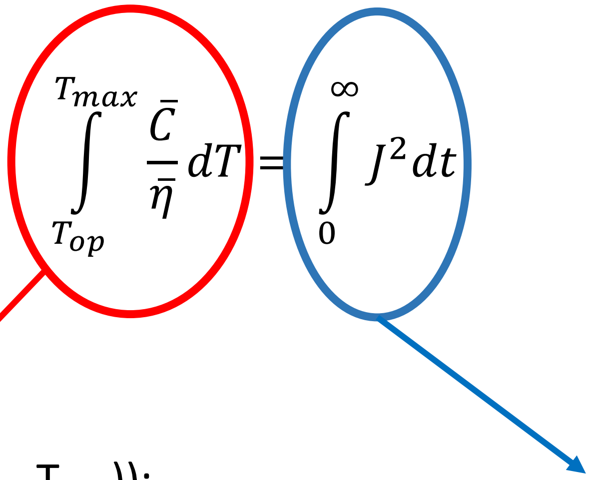
$\bar{\eta} = 1/(\sum_i \frac{f_i}{\eta_i})$ Average resistivity

**Yukikazu Iwasa, Case Studies in Superconducting Magnets, Second Edition, Springer, 2009*

HTS Quench protection criteria: “quench capital” vs “quench tax”

$$\boxed{\bar{C}\frac{dT}{dt} = \bar{\eta}J^2}$$

Can be integrated:



$$\int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}}\,dT = \int_0^{\infty} J^2\,dt$$

$\boldsymbol{\Gamma(T_{op}, T_{max})}$ (or $Z(T_{op}, T_{max})$):

“Quench Capital”*

(conductor/winding property)

$$\int_0^{\infty} \mathbf{J_{op}^2 dt = J_{op}^2 t_{quench}}$$

“Quench Tax”*

(circuit linked)

** L. Bottura, Magnet Quench 101, WAMSDO CERN proceedings 2013*

HTS Quench protection criteria: “quench capital” vs “quench tax”

“Quench Capital”*
(conductor/winding property)

“Quench Tax”*
(circuit linked)

$$\int_{T_{op}}^{T_{max}} \frac{\overline{C}}{\overline{\eta}}\, dT \quad = \quad \int_{0}^{\infty} \mathbf{J}_{\mathbf{op}}^{2}\, \mathbf{dt} = \mathbf{J}_{\mathbf{op}}^{2}\, \mathbf{t}_{\mathbf{quench}}$$

- Winding (shunt ratio)
- Materials

- what t_{quench}?

→ Detection
→ Protection

Enhance the protection by either **increasing the quench capital** and/or **lowering the quench tax.**

HTS Quench protection criteria: Increase the quench capital

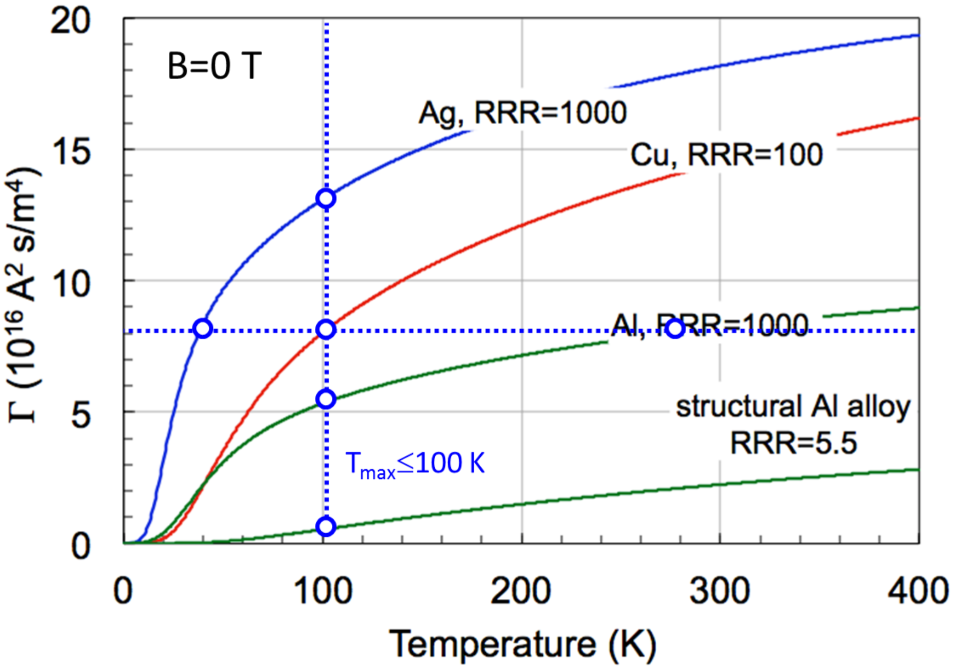
Quench Capital

$$\boldsymbol{\Gamma(T_{op}, T_{max}) = \int_{T_{op}}^{T_{max}} \frac{\overline{C}}{\overline{\eta}} dT}$$

Lower the resistivity $\overline{\eta}$

→ Add more shunt

→ Use purer materials



L. Bottura, Magnet Quench 101, WAMSDO CERN presentation

Issue: $V_{NZ} = \int_{L_{NZ}} \bar{\eta} j_{op} dl$

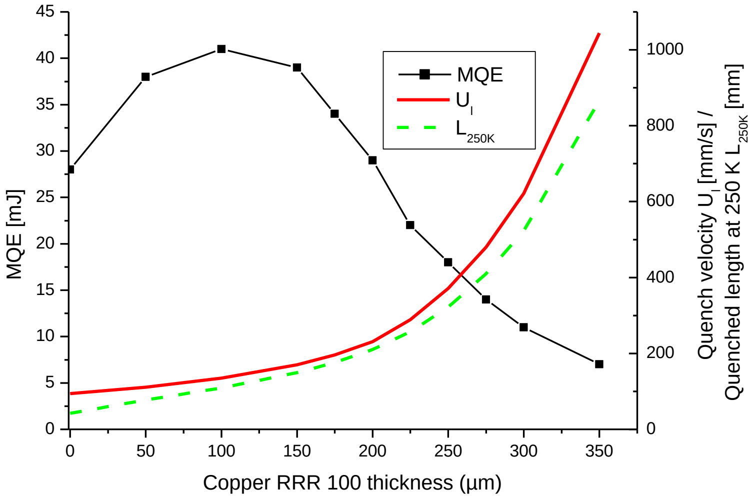
Lower $\overline{\eta}$ → **lower voltage** (increase $t_{detection}$)

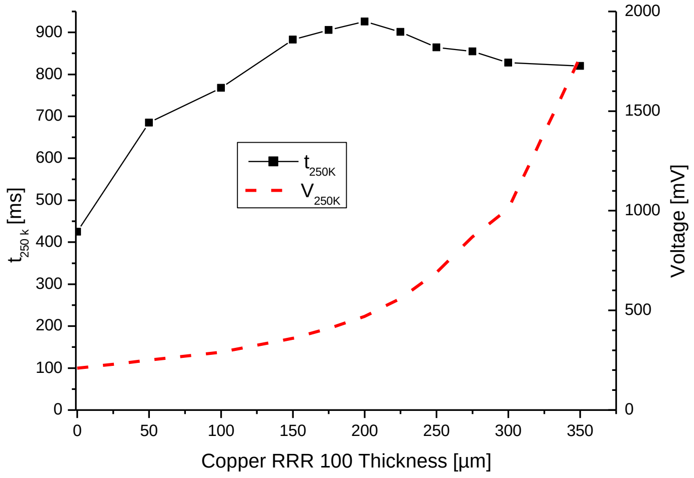
HTS Quench protection criteria: Increase the quench capital

Increasing the quench capital by adding some low resistance shunt

Simulation (SCS4050-AP with 2x20 µm Cu)

If only adiabatic longitudinal propagation: 4.2 K, 14 T (// ab), 340 A/mm²





→ Voltage at $T_{hot\text{-}spot}$= 250 K > 200 mV
→ Time at $T_{hot\text{-}spot}$= 250 K > 400 ms

→

OK but are we able to detect and dump in 400-800 ms?

→

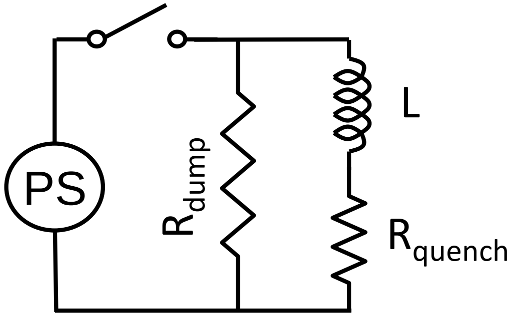
$V_{detection}$?
$t_{detection}$?
t_{dump}?

(Quench Tax)

T. Lécrevisse et al., IEEE Trans. Appl. Supercond., vol. 23, no. 3, June 2013

HTS Quench protection criteria: protection enhancement by lower the "quench tax"

<u>Constant external dump:</u> $\boxed{R_{dump} \gg R_{quench}}$



$$t < t_{discharge} \qquad J = J_{op}$$

$$t \geq t_{discharge} \qquad J = J_{op} e^{-\frac{t - t_{discharge}}{t_{dump}}}$$

$$\int_0^\infty J^2 dt = J_{op}^2 \left(t_{discharge} + \frac{t_{dump}}{2}\right) = J_{op}^2 t_{quench}$$

$$t_{dump} = \frac{\boxed{L}}{\boxed{R_{dump}}} = \frac{2E_m}{V_{max} I_{op}}$$

$$\boxed{t_{quench} = \left(t_{discharge} + \frac{t_{dump}}{2}\right)}$$

$$t_{discharge} = \boxed{t_{detection}} + t_{delay} + t_{switch}$$

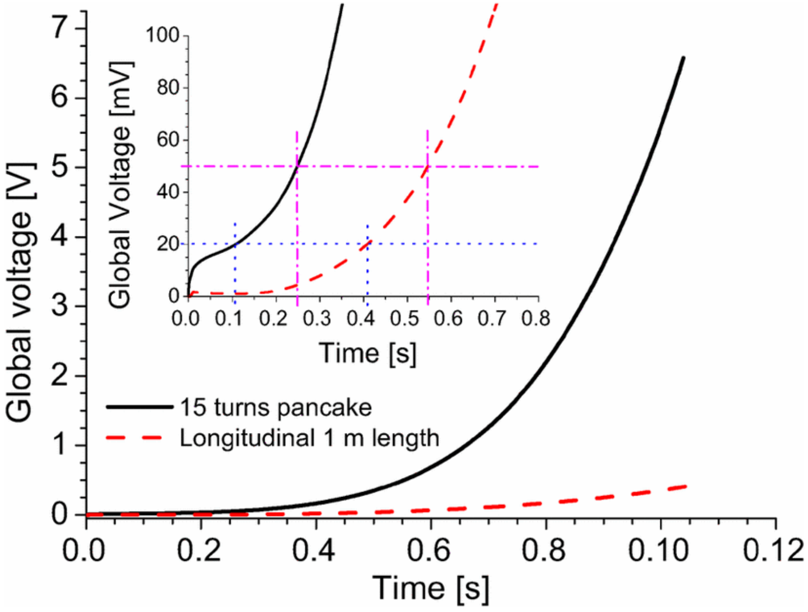
<u>Protection can be enhanced by:</u>

- a **fast detection**
- a **large R_{dump}** (but limited by $V_{max} \sim 500 - 1000V$)
- a **low inductance** (HTS cables)

HTS Quench protection criteria: Fast detection

Simulation (SCS4050-AP with 2x20 µm Cu)

SCS4050-AP, 4.2 K, 14 T (// ab), 150 µm Cu added, 20 µm Mylar insulation, 340 A/mm²



T. Lécrevisse et al., IEEE Trans. Appl. Supercond., vol. 23, no. 3, June 2013

$$t_{quench} = \left(t_{detection} + t_{delay} + t_{switch} + \frac{t_{dump}}{2}\right)$$

$t_{250K,\ pancake}$ = ~**900 ms**

$t_{detection,\ 20mV}$ = **100** ms

$t_{detection,\ 50mV}$ = **250** ms

t_{delay}= 10 ms ; t_{switch}= 30 ms

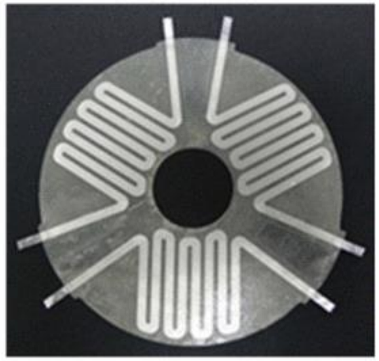
t_{dump}/2 ~620-770 ms (pancake 50 mV-20 mV)

- **Improve the turn to turn thermal contact *** → increase the voltage
- **Develop fast detection system**
- Be careful: Simulation is a **very simple case** (same // field, same I_c, adiabatic, …)
- 250 K is an high $T_{hot\text{-}spot}$ for protection

** H. Bai et al., IEEE Trans. Appl. Supercond., vol. 23, no. 3, June 2013*

HTS Quench protection criteria: Accelerate the dump

Active Protection Heaters (NHMFL)



Heater spacer

32 T magnet : 52 disks

f_{heater}~45 %

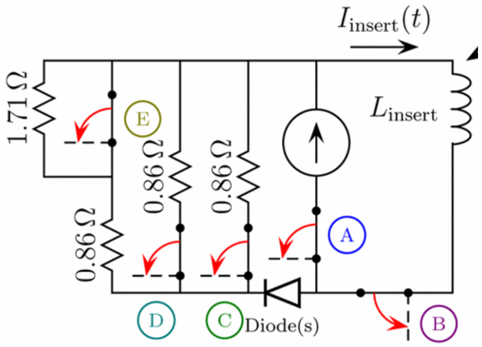
P_{heater}=50 kW

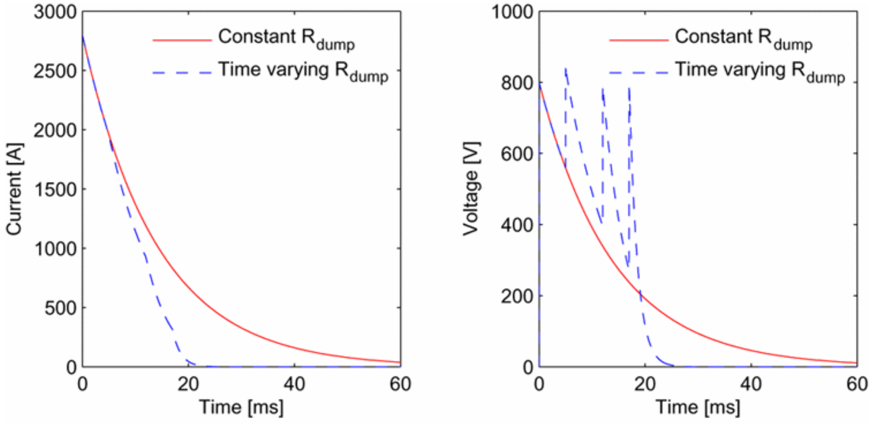
heating time : ~0.8 s

quench delay: ~0.1-0.6 s

H.W., Weijers et al., IEEE Trans. Appl. Supercond., vol. 24, no. 3, pp. 1-5, June 2014

Variable R_{dump} (EUCARD HTS insert study)

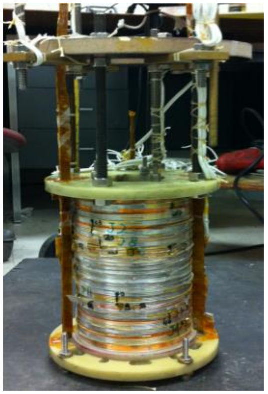




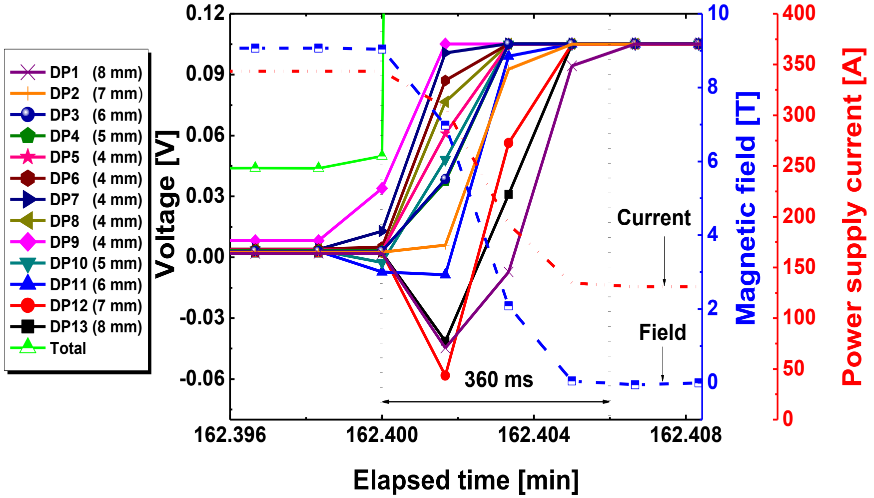
E. Haro et al., IEEE Trans. Appl. Supercond., vol. 23, no. 3, pp. 4600104, June 2013

HTS Quench protection criteria: Winding adaptation

No-Insulation Multi-Width: self-protection



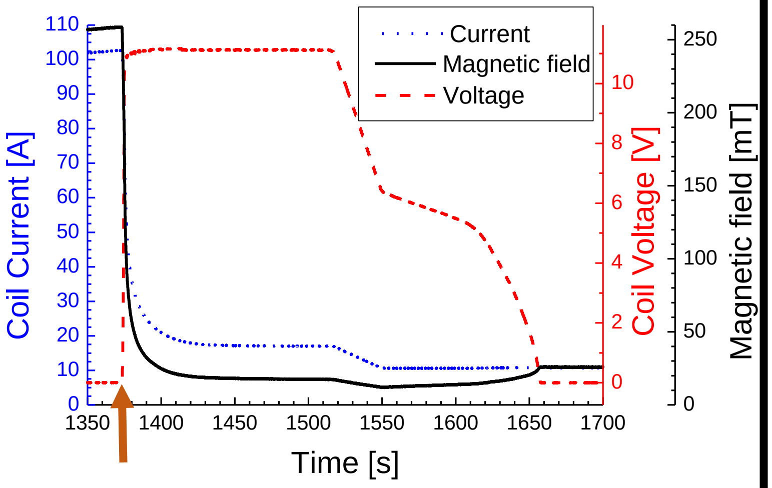
- → When a quench occurs in DP9 ($\sim 900\ \mathrm{A/mm^2}$) , **all DPs** quenched in ~**400 ms.**
- → All Energy **(> 30 kJ**) is discharged under constant voltage mode (PS limitation) **in ~360 ms**.
- → **NO protection, NO damage.**



Y. Song et al., "Over-Current Quench Test and Self-Protecting Behavior of a 7-T / 78-mm Multi-Width No-Insulation REBCO Magnet at 4.2 K," to be published in Supercond. Sci. Technol., 2015.

Metal-as-Insulation

Metal tape co-wound with REBCO tape during a quench at 77 K, PS constant voltage mode.



T. Lécrevisse, Y. Iwasa, "A(RE)BCO Pancake Winding With Metal-as-Insulation", presented at EUCAS2015

Conclusion

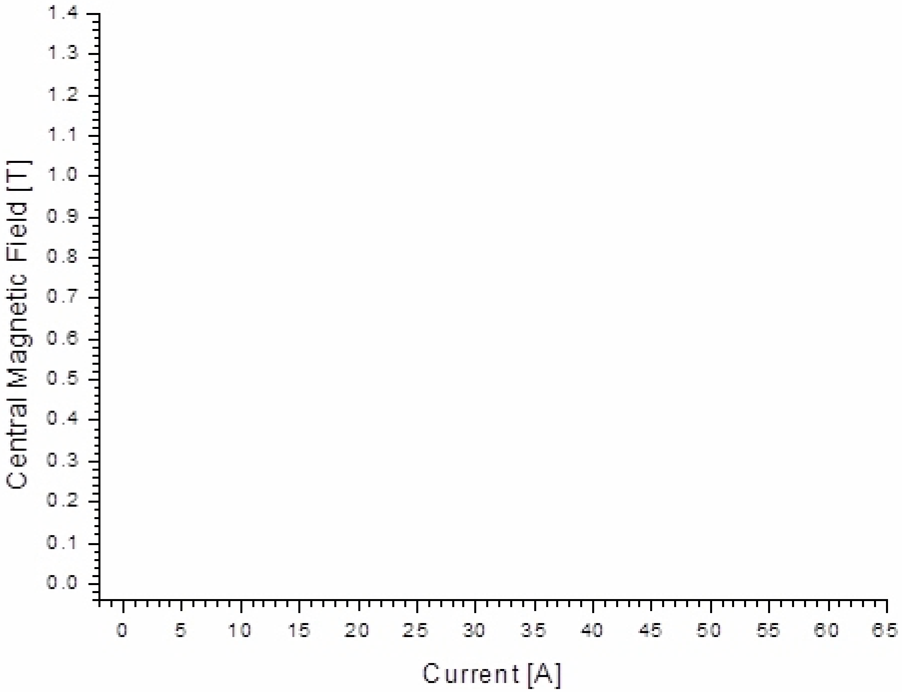
→ HTS magnet can be protected BUT it is not so easy:

- → Key issue remains the detection : **What is the most efficient method to detect a quench? How to increase the voltage/NPZV * ?**
- → Once detected, energy dump ($\sim 0.5\ s$) can be done.
- → **Low inductance** is for a better protection.
- → **What protection scheme suitable ? Dump ; heaters ; subdivision …**

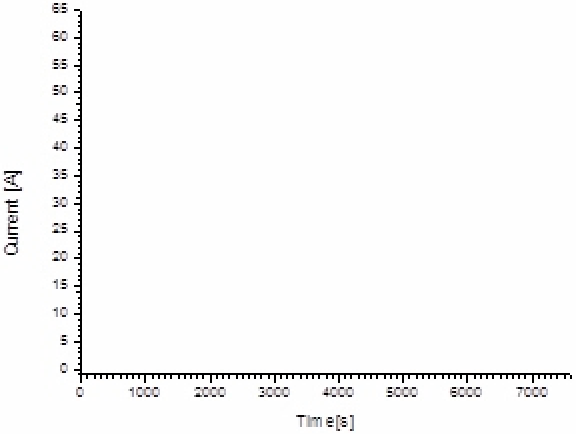
→ Winding might be optimized for the protection:

- → **Stabilizer ratio and properties**
- → **Insulation**
- → **New winding** with **No, Partial, or Metal-as-Insulation**: allows the current to bypass the hot-spot → lower $T_{\text{hot-spot}}$ and higher quench capital (higher t_{quench}).
  - → *See S. Hahn presentation on NI technique tomorrow*

** C. Lacroix and F. Sirois, "concept of a current flow diverter for accelerating the normal zone propagation velocity in 2G HTS coated conductors," vol. 27, 035003 (10pp), 2014*


Central Magnetic Field [T]
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Current [A]

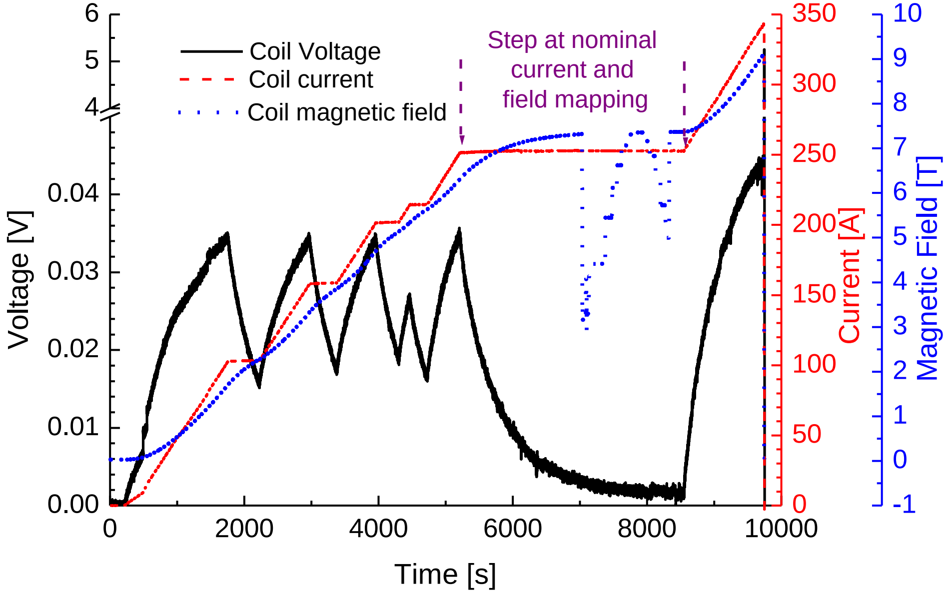
0 s


Current [A]
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Time[s]

Thank You

Back-up slides

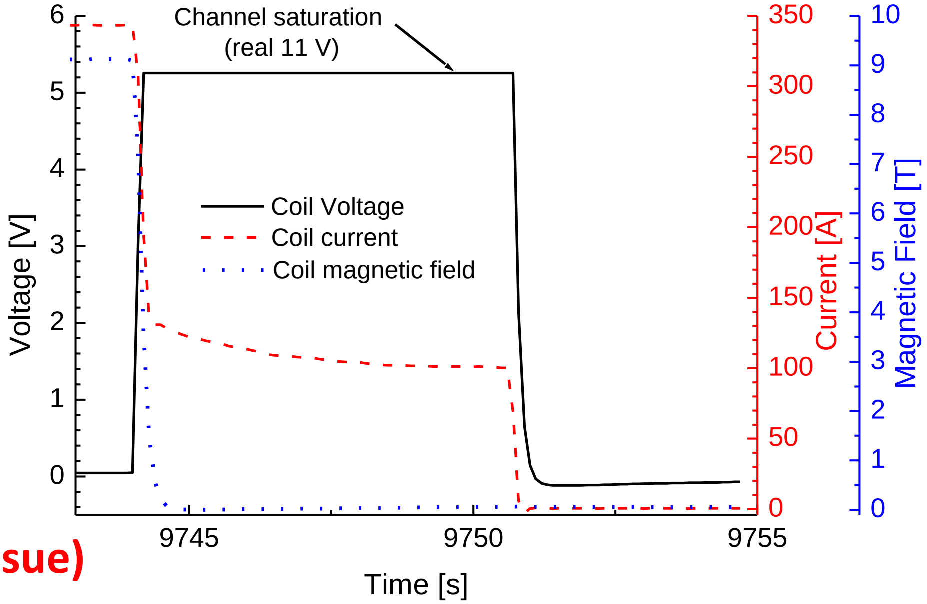
NI-MW



Protection by :

- Bypassing current
- PS constant voltage mode

Constant voltage mode

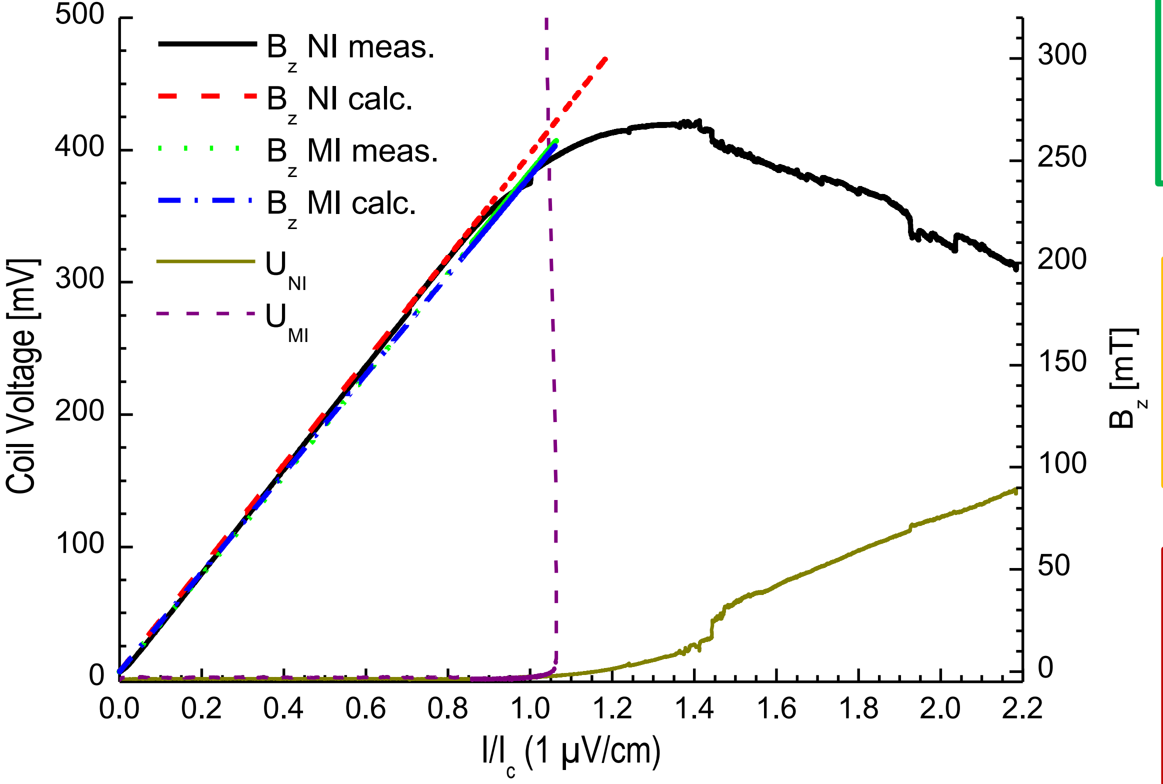


BUT : low resistance and still high current

→ **need to shut down the PS (not an issue)**

NI-MI

- *Over-current behavior*

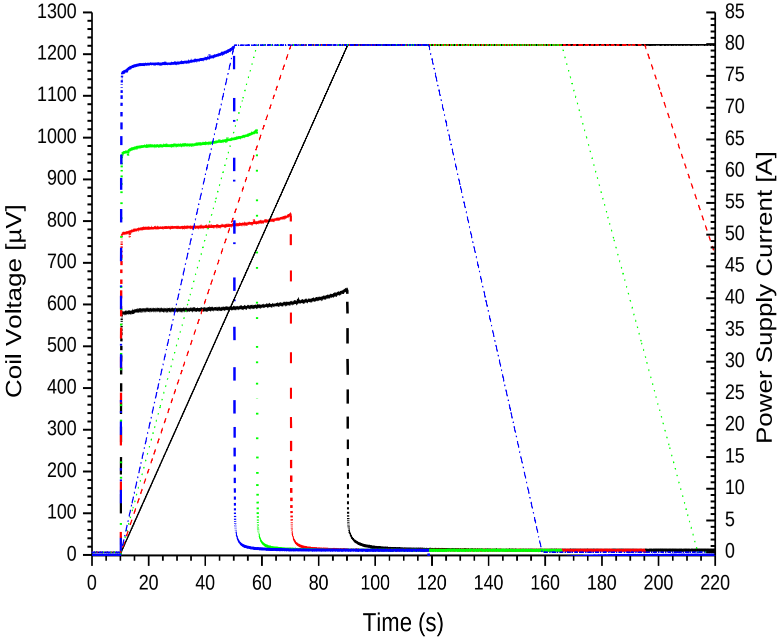


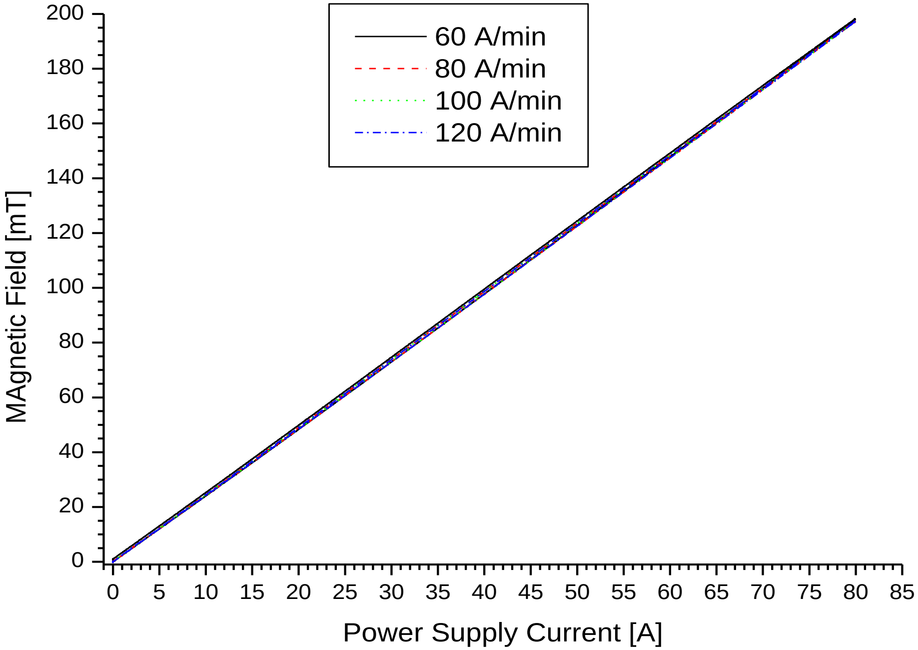
Below I_c :
- low (NI) and almost no (MI) I_R.
- beginning of Field saturation (NI)

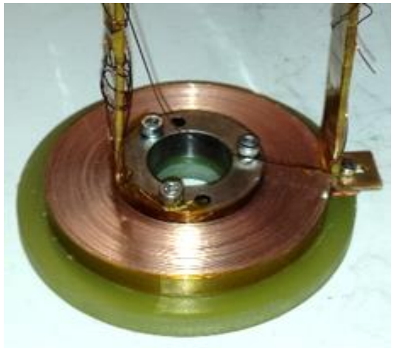
NI near and over I_c:
- I_R increase (over $0.5 \cdot I_{coil}$ at $2.2 \cdot I_c$)
- "Low" voltage

MI quench at "low" over current:
- Quench at about $1.06 \cdot I_c$
- No Field saturation up to the quench.
- almost no (MI) I_R

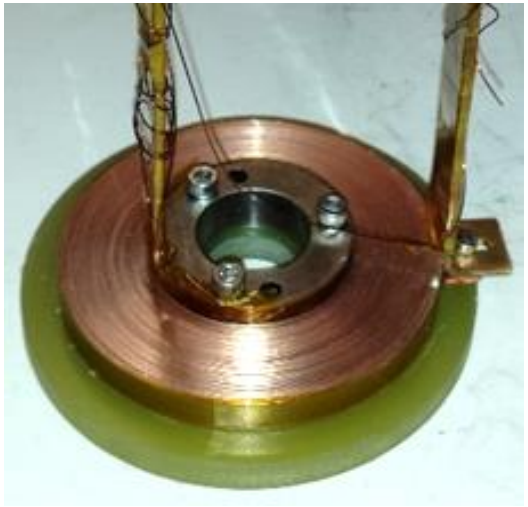
Metal-as-Insulation

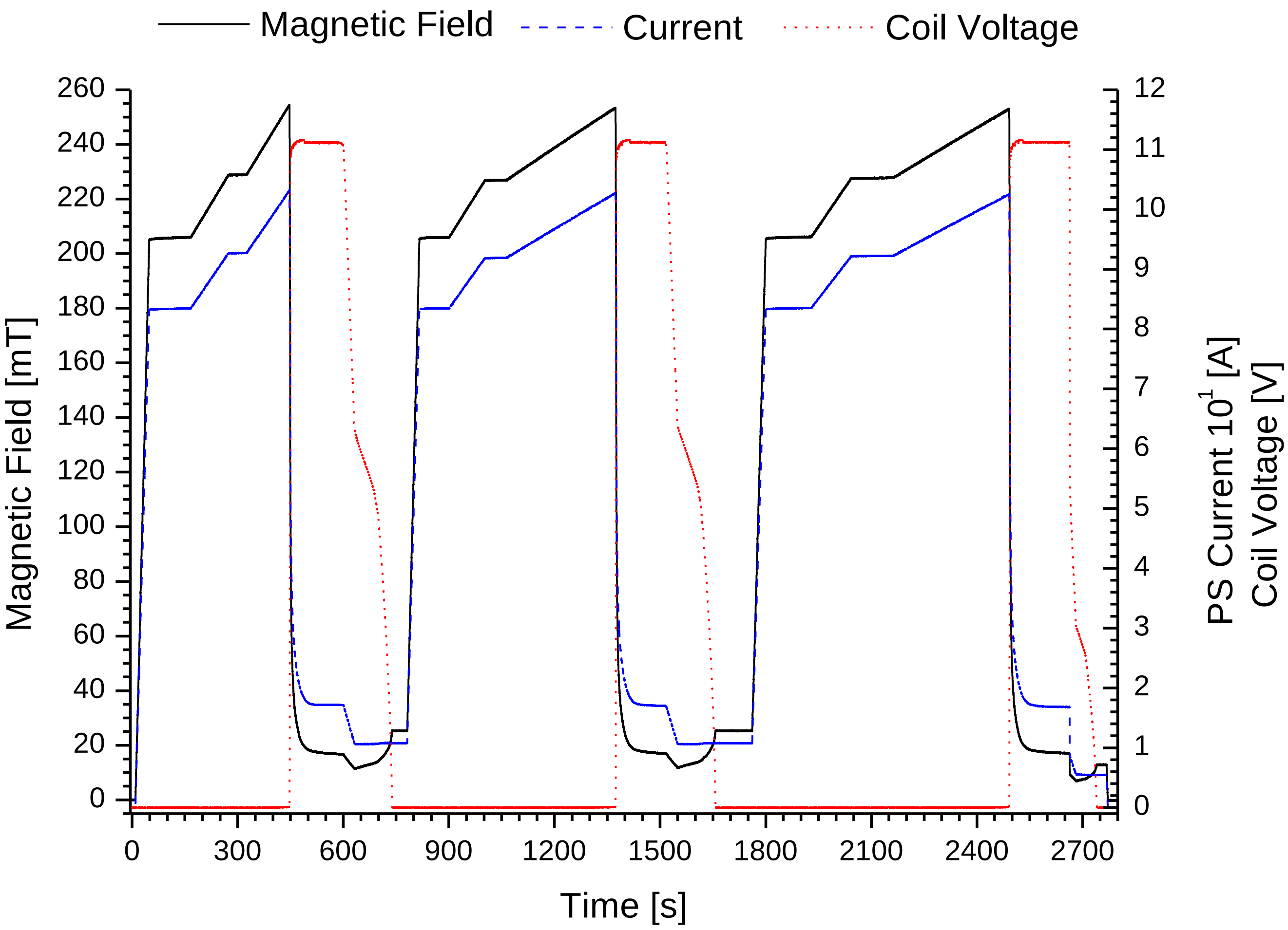




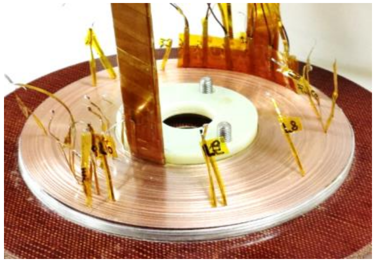


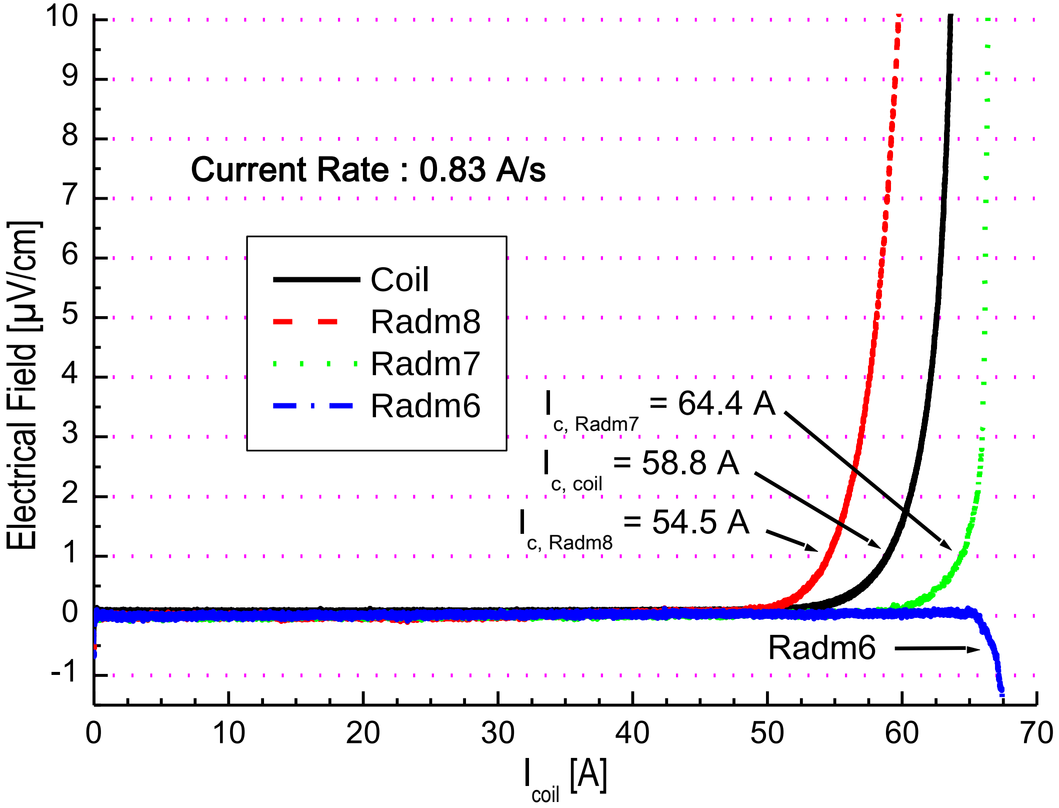
Metal-as-Insulation





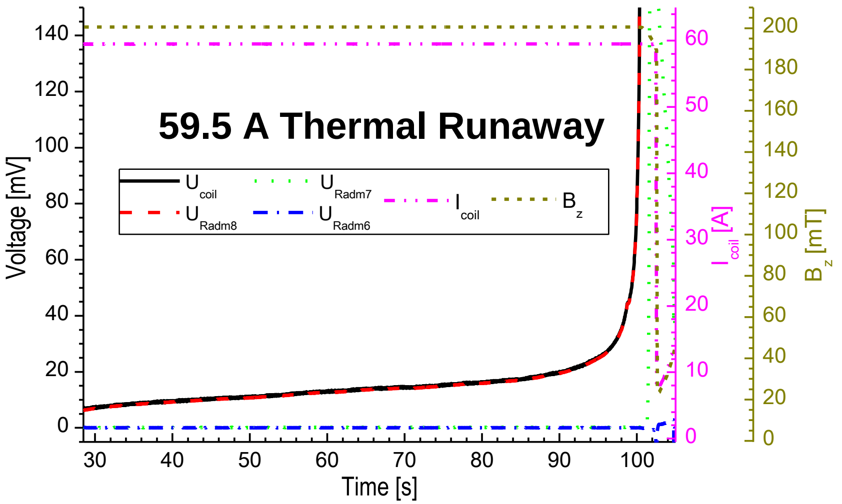
Metal-as-Insulation

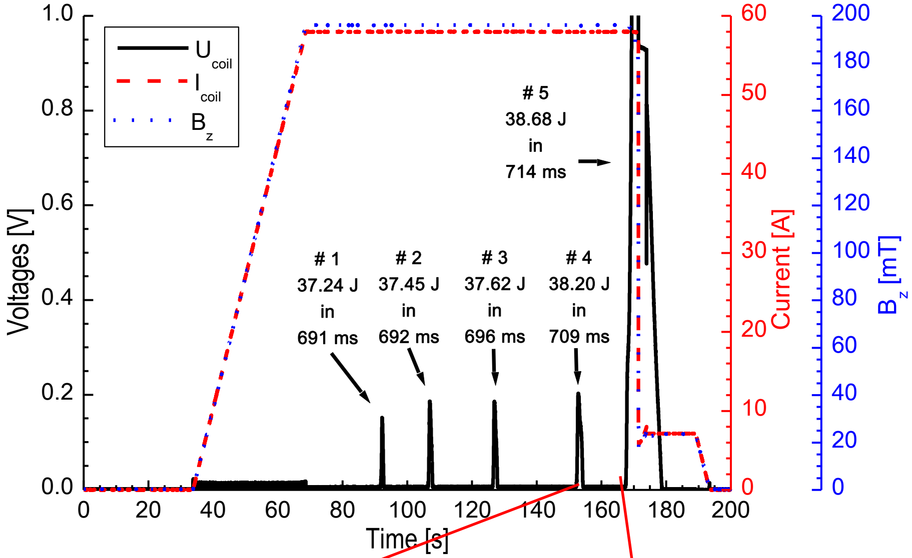


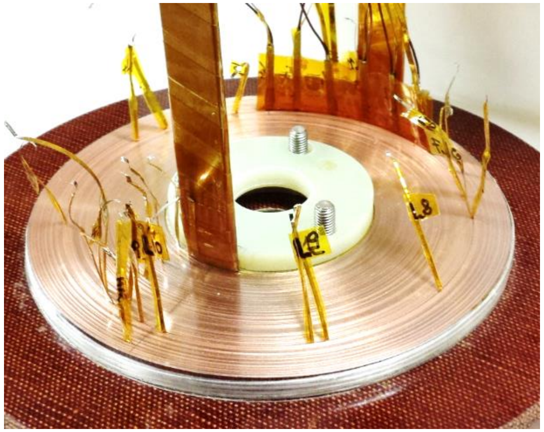


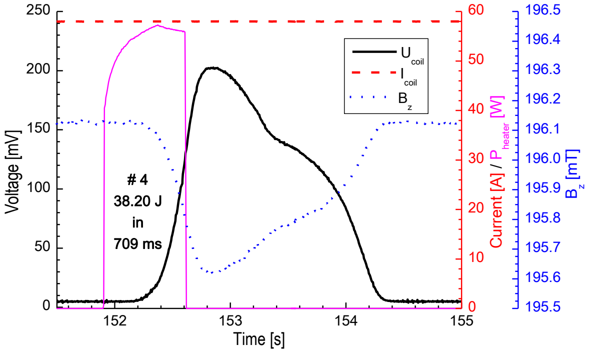
Voltage name	Turns number	Conductor length [cm]
Radm8 (inner part)	40	709
Radm7	40	863
Radm6	30	748
Radm5	20	547
Radm4	5	143
Radm3	5	145
Radm2	5	147
Radm1	4	120
Heated Turn	1	30
RadP1	10	307
RadP2	30	978
RadP3 (outer part)	16.5	575
Coil	206.5	5312

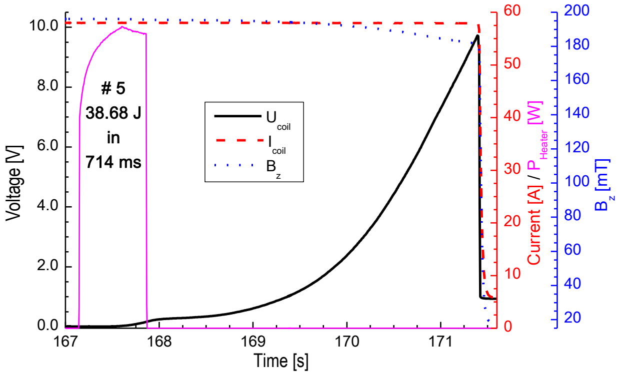
Metal-as-Insulation











T. Lécrevisse, Y. Iwasa, "A(RE)BCO Pancake Winding With Metal-as-Insulation", presented at EUCAS2015