What are bulk superconducting magnets?

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5a Escuela de SUPERCONDUCTIVIDAD
Desde la Ciudad de México

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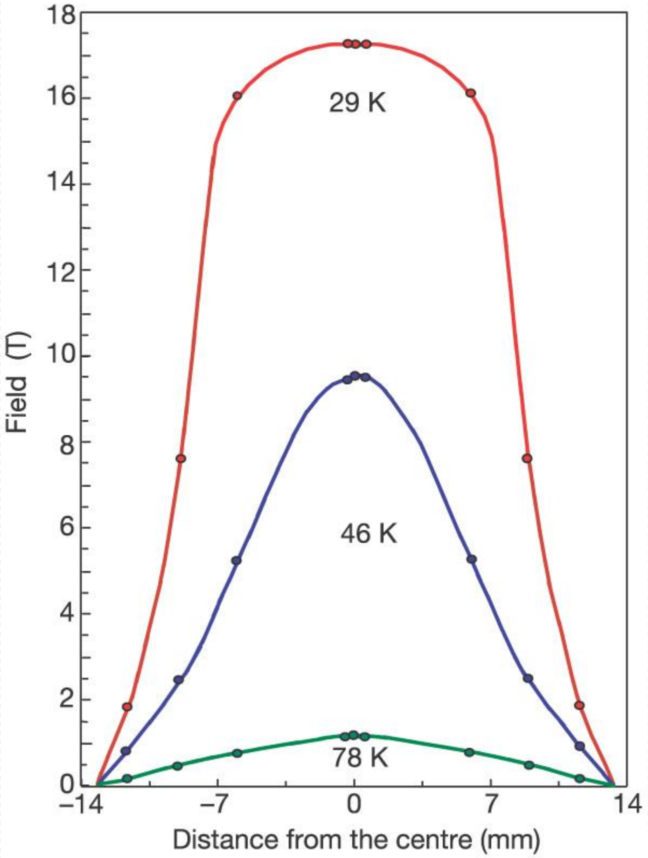
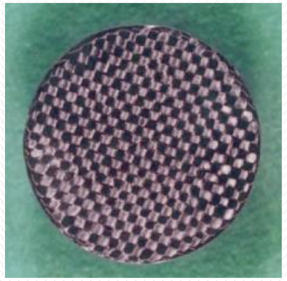
Why are bulk superconducting materials interesting?

[M. Tomita et M. Murakami., « High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K », Nature 421, pp. 517-520, 2003.]

- They can 'trap' or 'screen' large magnetic fields > 17 T (between a stack of 2 disks)
  - Allowing a considerable increase in the power density of electric motors
- We anticipate that they are the key to a major technological breakthrough
- Replacing the classic NdFeB permanent magnets…





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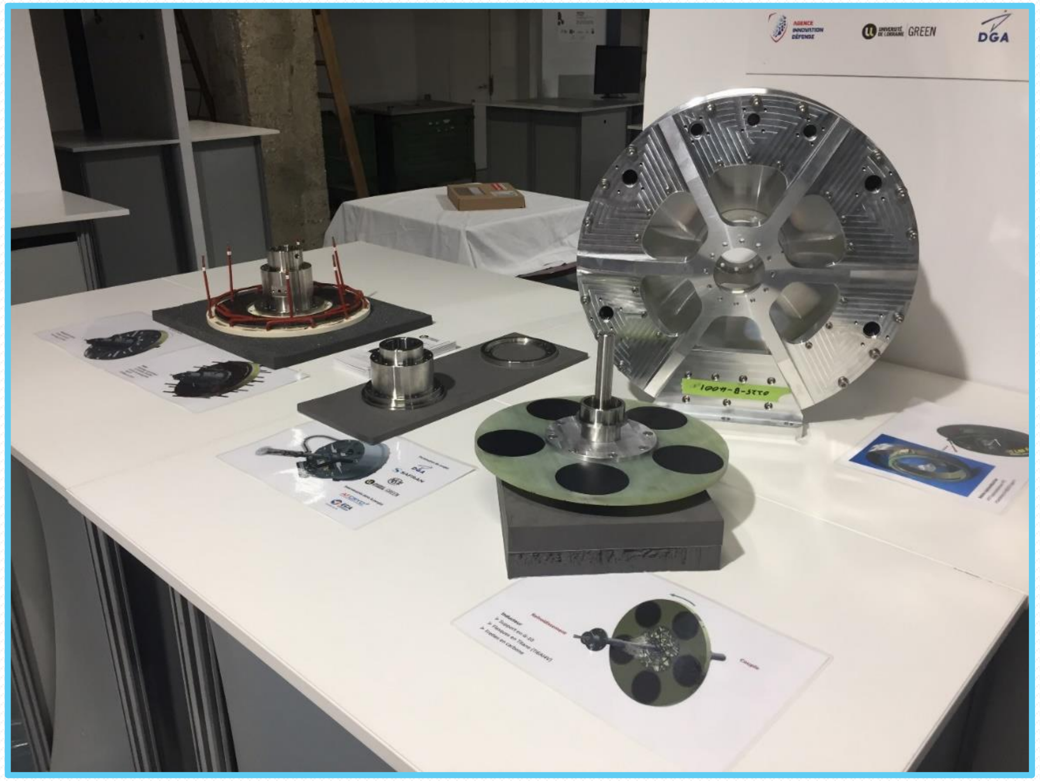
Bulks HTS synchronous motors

50 kW, 5000 rpm @30 K (still under test @ GREEN)



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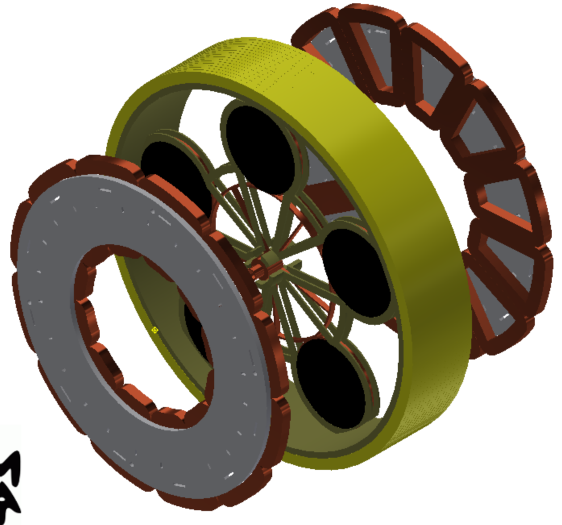

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Presentation Outline

- Superconductivity basics
- Bulk High-Temperature Superconductors (HTS)
  - Types of bulk materials, fabricating, characterizing, magnetization

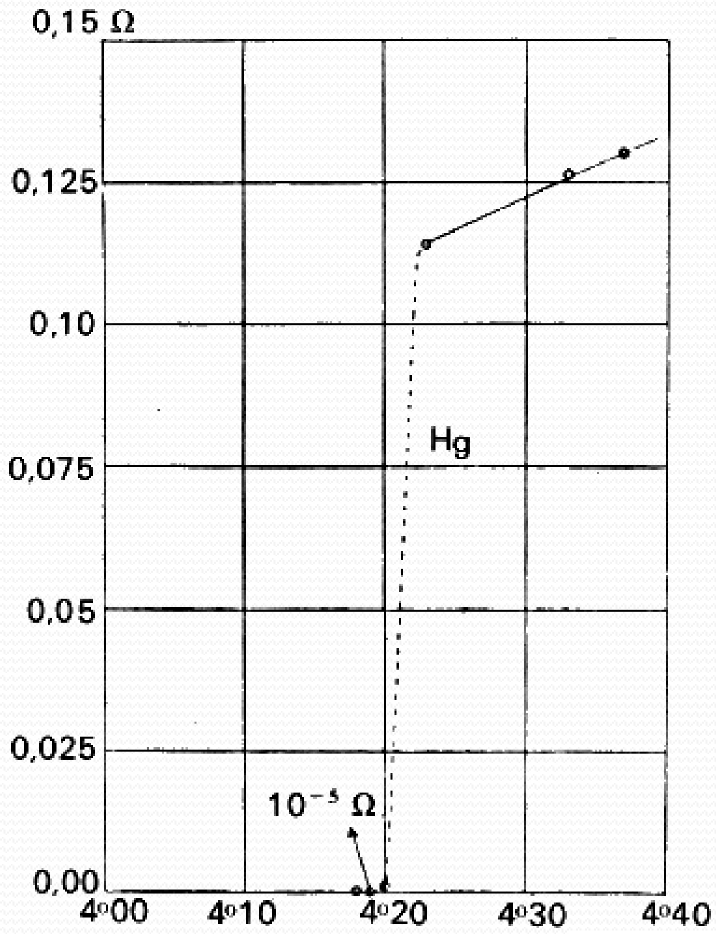
- How does Pulsed Field Magnetization process work?
  - In real life cases

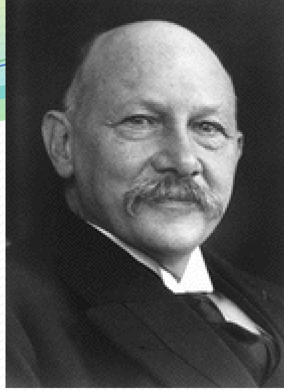
Superconductivity basics

- Zero resistance

Discovered at the university of Leiden in 1911 by Kamerlingh Onnes who was working on the resistivity of Mercury.

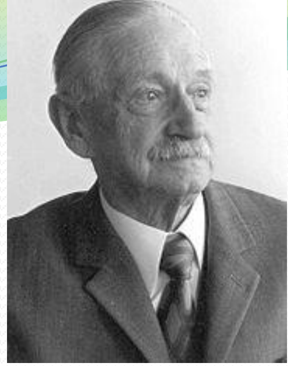
- T_c: Critical temperature concept



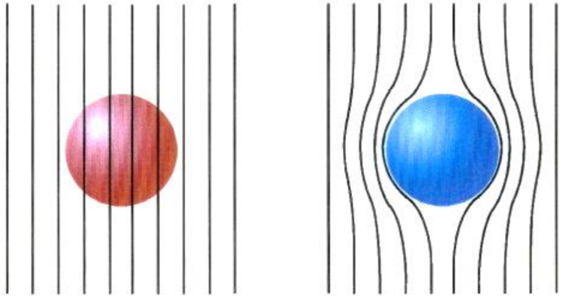


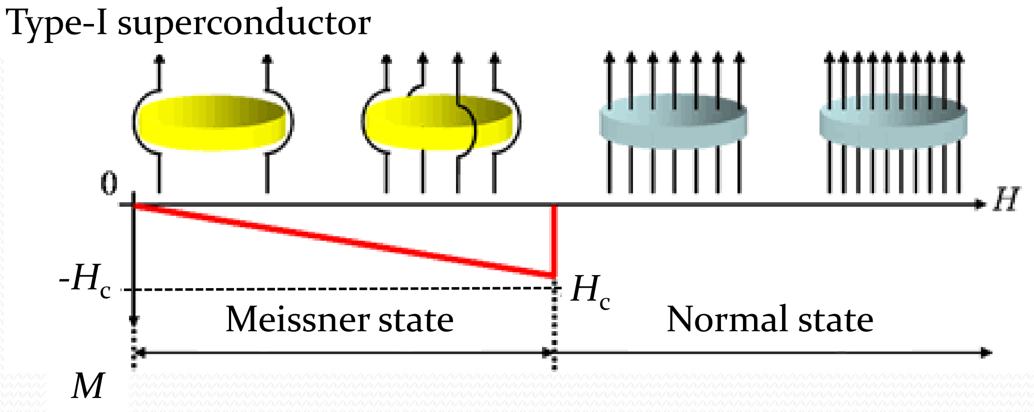
Heike Kamerlingh Onnes

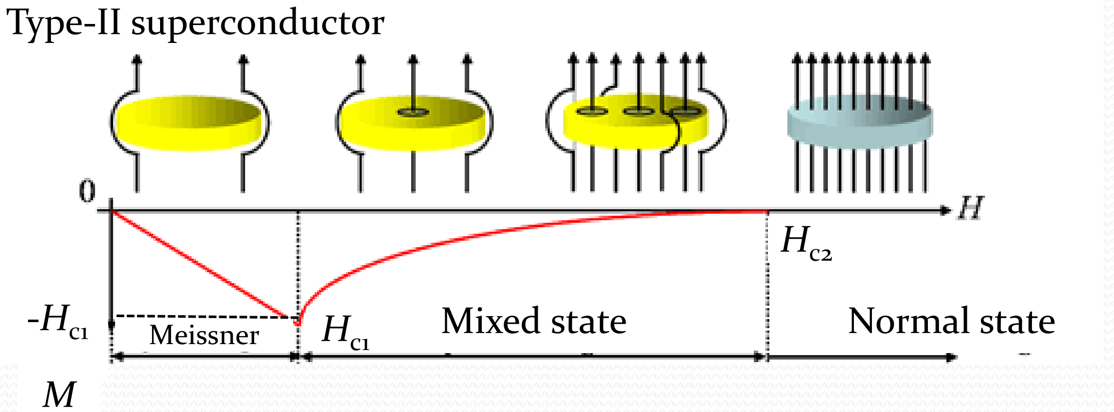
Superconductivity basics


Walter Meißner

- Meissner effect (1933)
  - Characterized by a perfect diamagnetism (B = 0)
  - Below critical field H_c (or first critical field H_{c1})



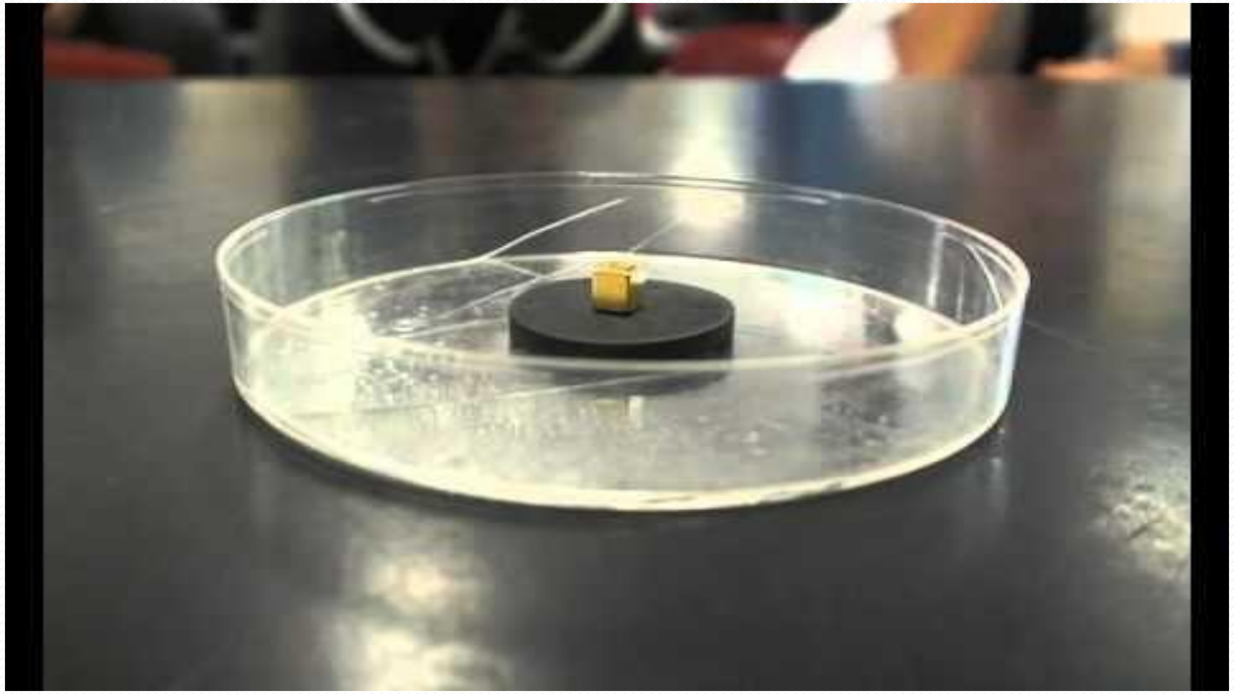




Walter Meißner

Superconductivity basics

- Levitation by Meissner effect ≠ Flux pinning effect
  - https://youtu.be/JIjzJKnpahA



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Superconductivity basics

Walter Meißner

- Meissner effect
  - Eddy currents flow on surface of superconductor to maintain internal B = 0

    {Ref.} Brandt, E. H., & Mikitik, G. P. (2000). Meissner-London currents in superconductors with rectangular cross section. *Physical review letters*, *85*(19), 4164.

    - These currents are reversible (related to B or not dB/dt)
    - The typical size of these currents corresponds to the London's penetration depth λ

Type	Material	T_c [T]	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
I	Pb	7.2	0.080	-	-	48
II	Nb	9.2	0.200	0.170	0.4	40
II	Nb3Sn	18	0.540	0.050	30	85
II	NbN	16.2	0.230	0.020	15	200
II	MgB2	40	0.430	0.030	3.5	140
II	YBCO	93	1.400	0.010	100	150

Superconductivity basics

- Mixed state
  - Only practical operating state possible for superconductors
  - Above first critical field Hc1 (a few mT for HTS)
  - Below second critical field H_{c2} (from a few T to a hundred T)
  - The magnetic field penetrates the material in multiples of flux quantum $\Phi_0 = 2{,}067\,833\,667 \times 10^{-15}$ Wb
  - The fluxons (or vortices) are not independent, they form a triangular network, known as the Abrikosov network

$$a = \left(\frac{2\Phi_0}{\sqrt{3B}} \right)^{1/2}$$

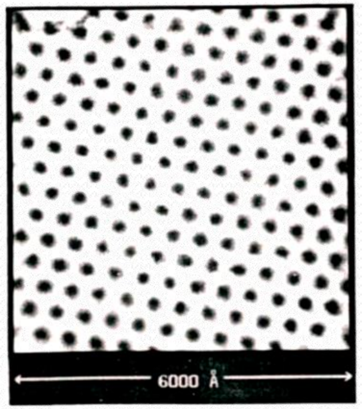
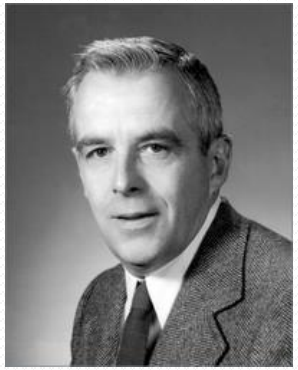


FIG. 2. Abrikosov flux lattice produced by a 1-T magnetic field in $NbSe_2$ at 1.8 K. The scan range is about 6000 Å. The

Superconductivity basics

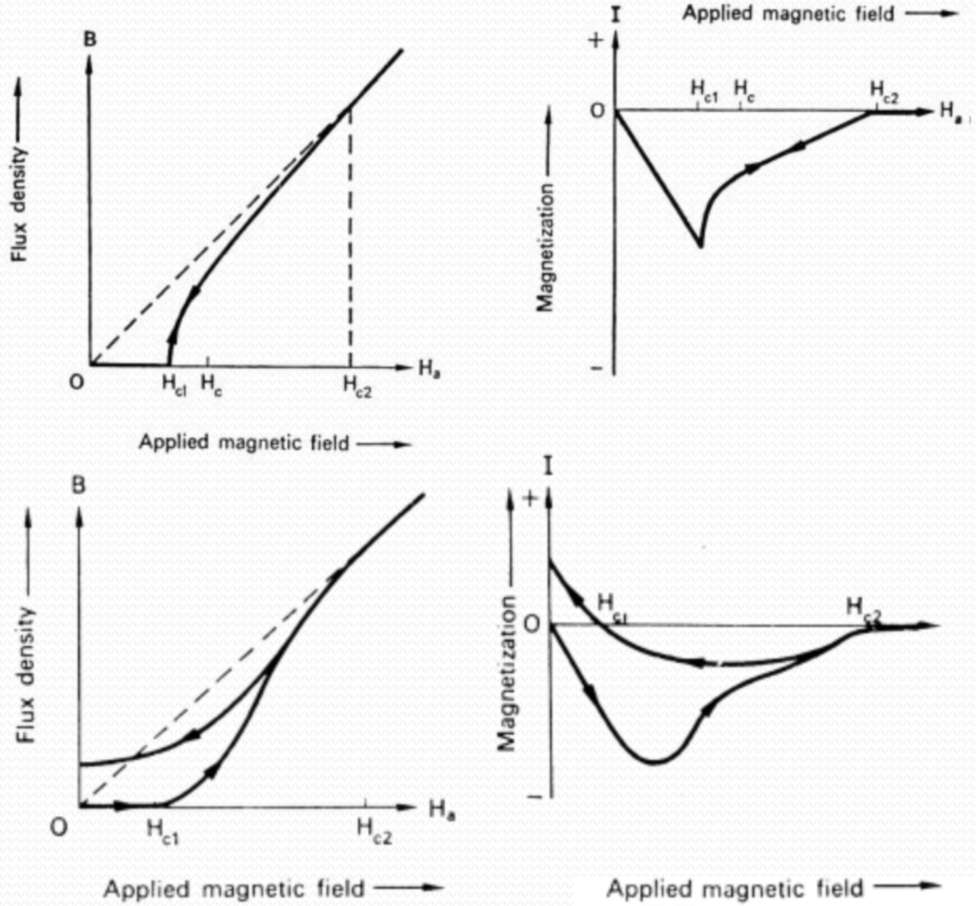
Magnetic flux density $B = \mu_0 \left(H + M \right)$ Magnetization

- Magnetization curves
  - Reversible effect
    - No pinning
  - Irreversible effect
    - Some vortices are pinned
    - Explained by Bean's critical state model which introduces a critical current density J_c



Charles Bean

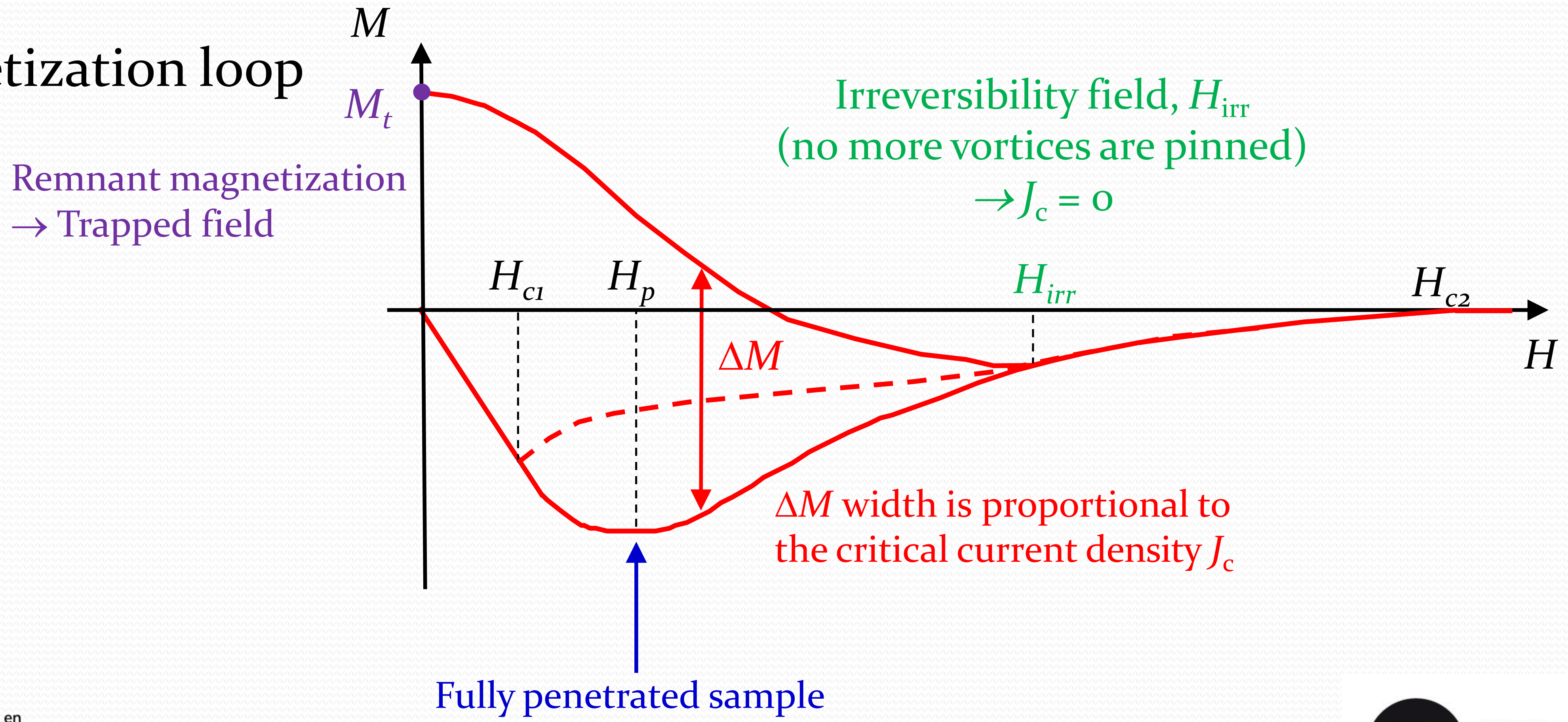
{Ref.} Bean, C. P. (1962). Magnetization of hard superconductors. *Physical review letters*, 8(6), 250.



Pictures from « Introduction Superconductivity », Rose-Innes, 1969

Superconductivity basics

- Magnetization loop

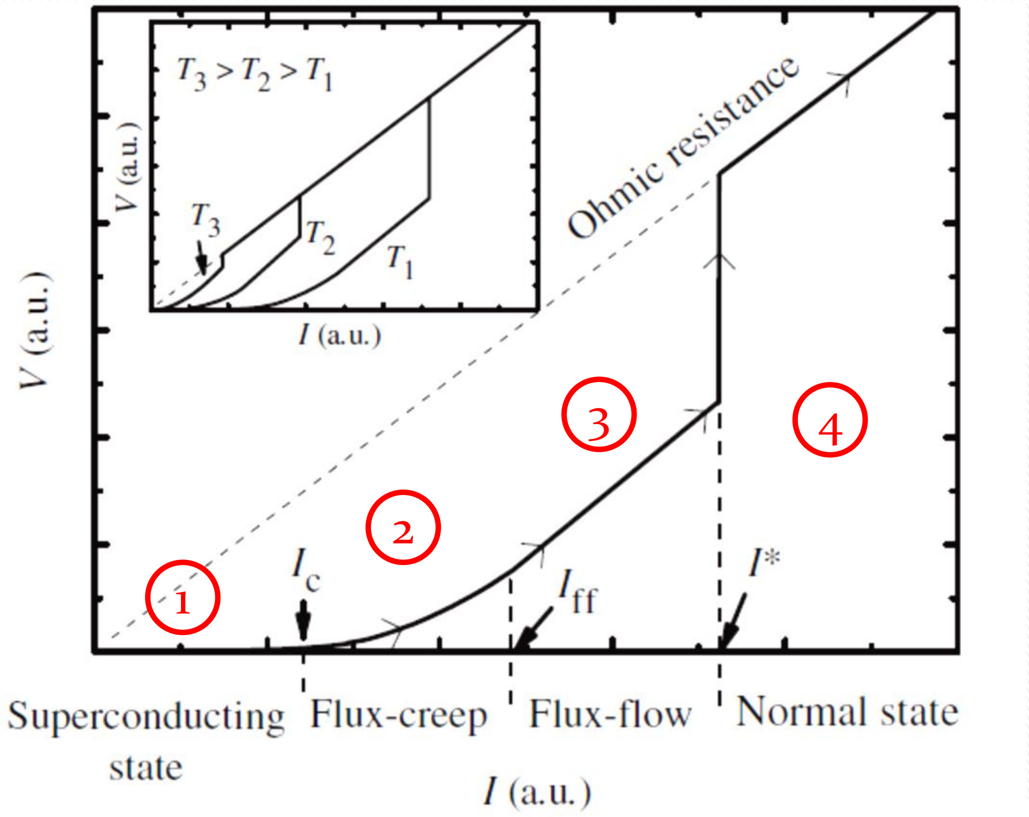


Superconductivity basics

[{Ref.} Osorio, M. R., Morales, A. P., Rodrigo, J. G., Suderow, H., & Vieira, S. (2012). Demonstration experiments for solid-state physics using a table-top mechanical Stirling refrigerator. European journal of physics, 33(4), 757.]

- Influence of vortex motion
  - (1) Zero resistance
  - (2) $V \propto I^n$
  - (3) $V \propto (I - I_{ff})$
  - (4) $V \propto I$

  - Only true for isothermal experiment



Superconductivity basics

- $E(J)$ models vs Experiments
  - Percolation model

$$E(J)=\begin{cases}0, & \text{if } J \le J_{c,\min} \\ E_c\left(\dfrac{J-J_{c,\min}}{J_c-J_{c,\min}}\right)^n, & \text{if } J > J_{c,\min}\end{cases}$$

  - Power law

$$E(J)=E_c\left(\frac{J}{J_c}\right)^n \quad \text{with } E_c = 1\ \mu\text{V/cm}$$

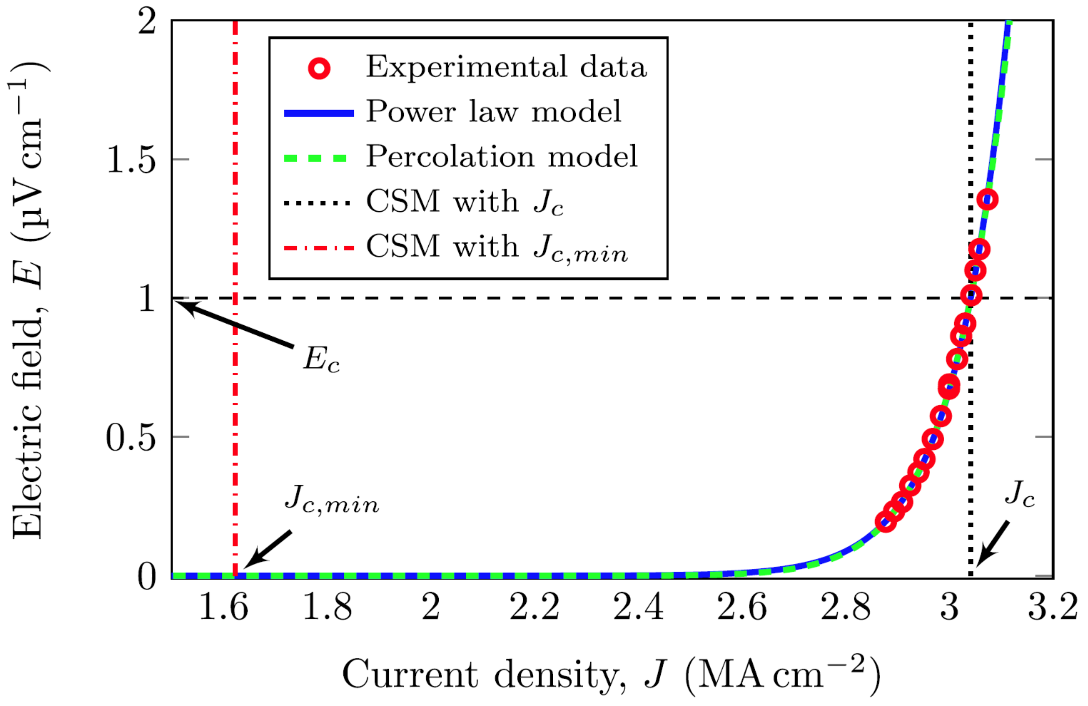


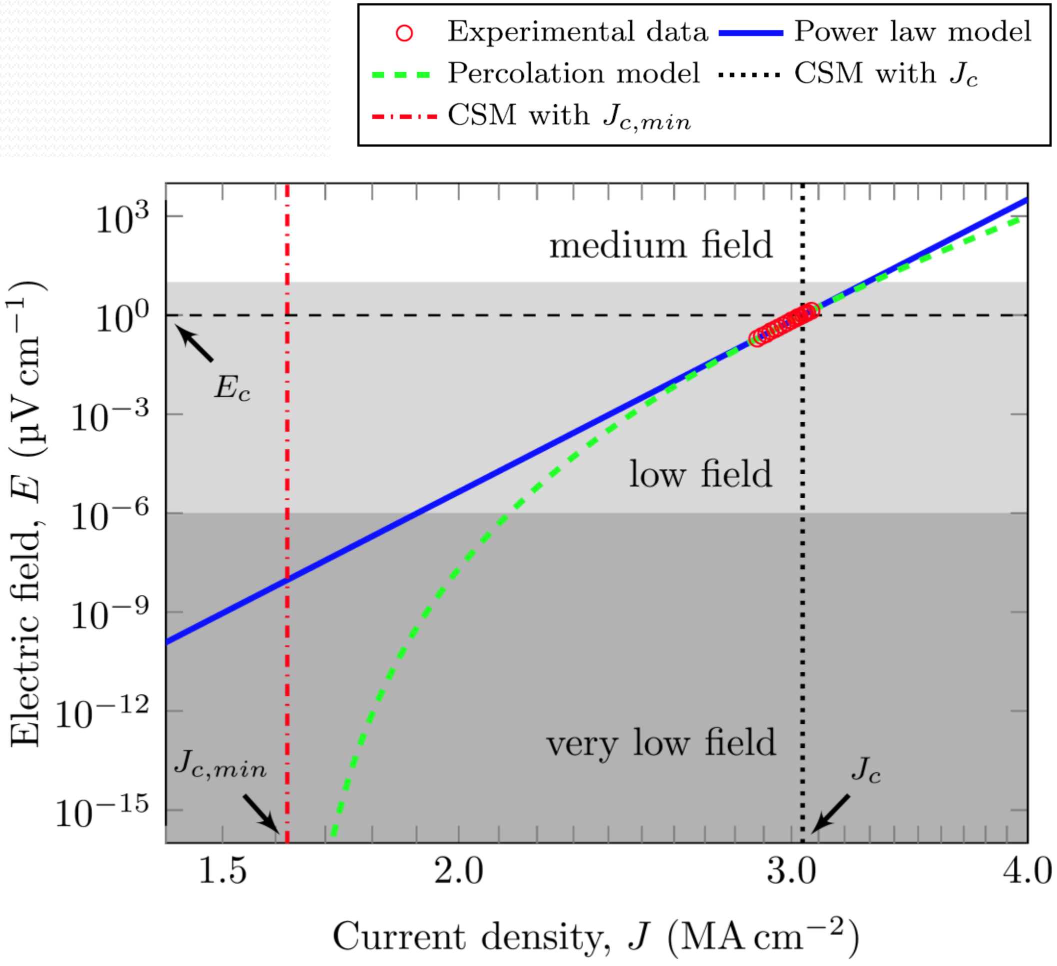
Fig. 1. Experimental data points measured on a 4 mm wide SuperPower tape, as well as $E-J$ curves for the four different models defined in Section III-A. On this scale, the power law and the percolation models are undistinguishable.

Superconductivity basics

- Both models agree on a common area
- The differences are significant
  - in the low electric field zone

- What can change the current's relaxation

{Ref.} Sirois, F., Grilli, F., & Morandi, A. (2018). Comparison of constitutive laws for modeling high-temperature superconductors. *IEEE Transactions on Applied Superconductivity, 29*(1), 1-10.



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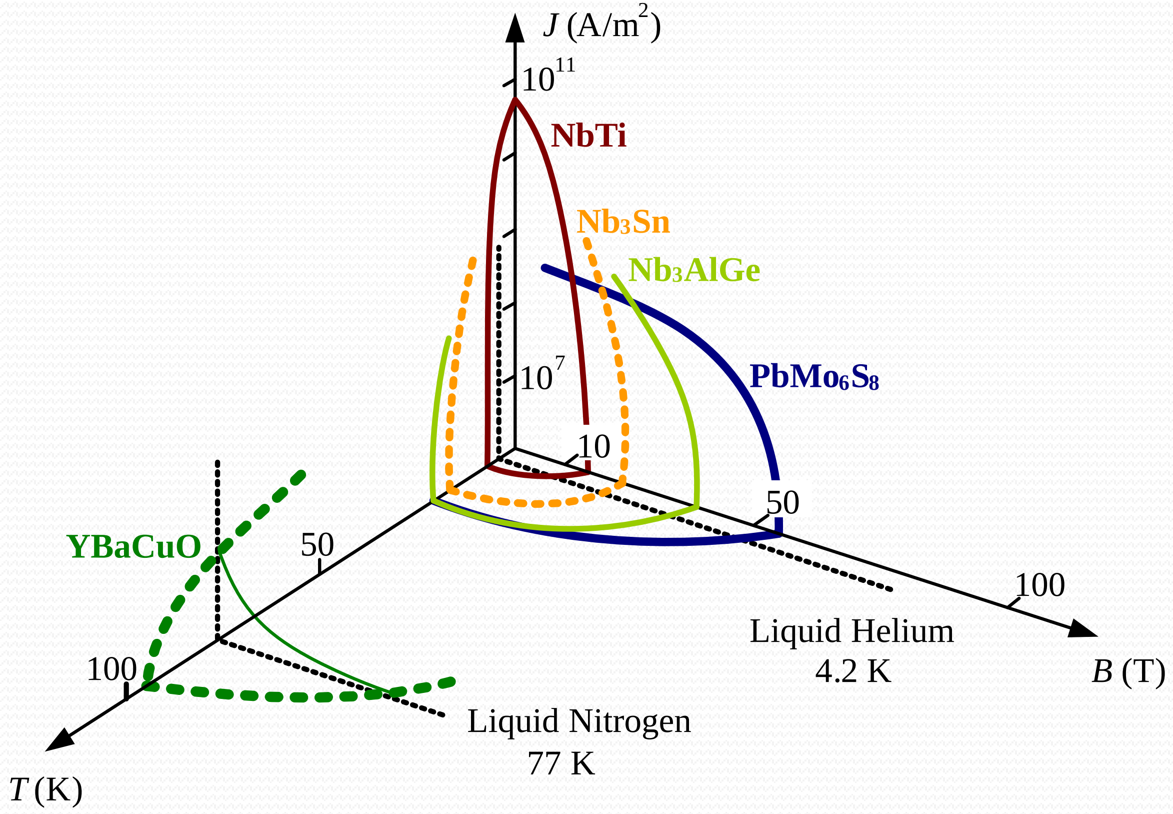
Superconductivity basics

- 3 critical quantities
  - Critical temperature T_c
  - Critical field H_c (or B_c)
  - Critical current density J_c (or I_c)
    - Related to pinning forces!
    - There are several definitions…
      - Electrical voltage criterion $E_c = 1\ \mu V/cm$
      - Magnetization loop width
- It defines a critical surface



Bulk High-Temperature Superconductors (HTS)

- The most famous are probably the (RE)BaCuO
  - (RE) = Rear Earth elements

    Y, Gd, Nd, Eu, Dy...
- Trapped magnetic field is achieved by pinning penetrated magnetic field (quantized flux lines)
- By means of induced macroscopic electric currents

A large, single grain YBaCuO bulk superconductor from ATZ GmbH (top side machined)

Bulk High-Temperature Superconductors (HTS)

- Trapped field and magnetization increase with sample volume
  - t = thickness, a = radius, and z is the height above the top surface

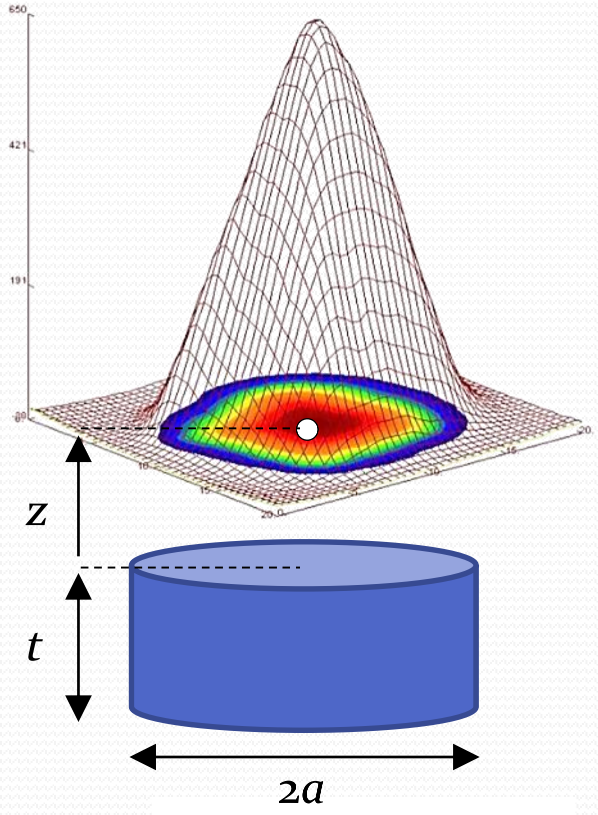
$$B_{\text{trap}} = \frac{\mu_0 K_s}{2}\left(\frac{z+t}{\sqrt{a^2+(z+t)^2}} - \frac{z}{\sqrt{a^2+z^2}}\right)$$

K_s = surface current density (A/m)

J_v = volume current density (A/m²)

Only valid for fully penetrated samples and constant J_v

$$+\frac{\mu_0 J_v}{2}\left((z+t)\ln\left(\frac{a+\sqrt{a^2+(z+t)^2}}{z+t}\right) - z\ln\left(\frac{a+\sqrt{a^2+z^2}}{z}\right)\right)$$



{Ref.} Chen, I. G., Liu, J., Weinstein, R., & Lau, K. (1992). Characterization of YBa2Cu3O7, including critical current density J c, by trapped magnetic field. Journal of applied physics, 72(3), 1013-1020.

Bulk High-Temperature Superconductors (HTS)

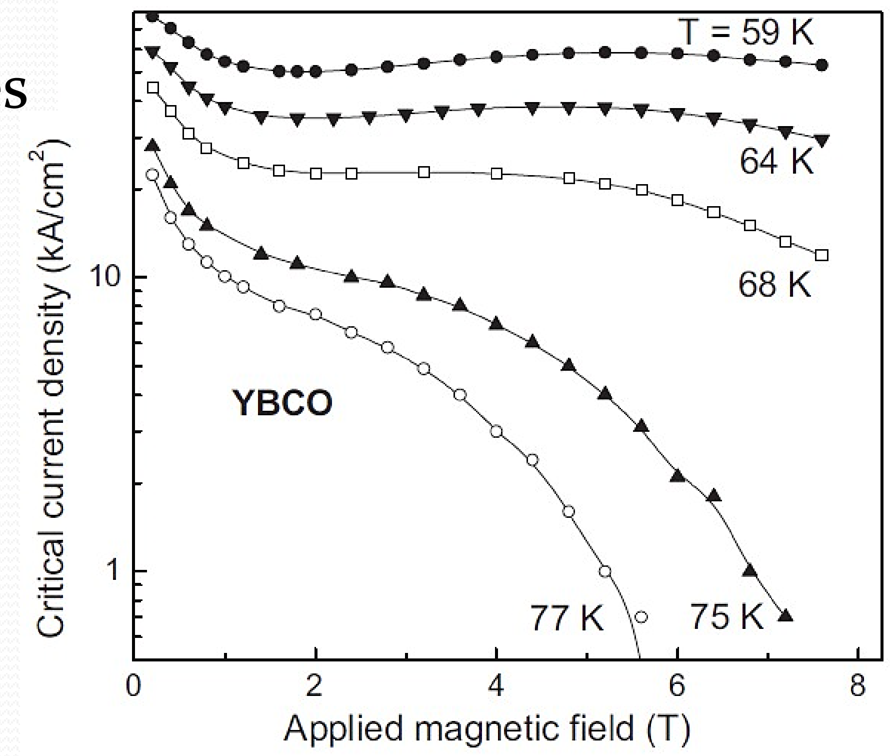
- Trapped field analytical models
  - Easier to deal with & faster
  - Based on Bean's model and Biot-Savart law
  - Simplified geometries
  - Constant and uniform J_v is assumed
  - Magnetostatic approximation
    - Current's paths are assumed to be known

- In other cases, numerical simulations are required!
  - This is still a quite complicated task to do
  - Very difficult to precisely predict the whole HTS behavior

Bulk High-Temperature Superconductors (HTS)

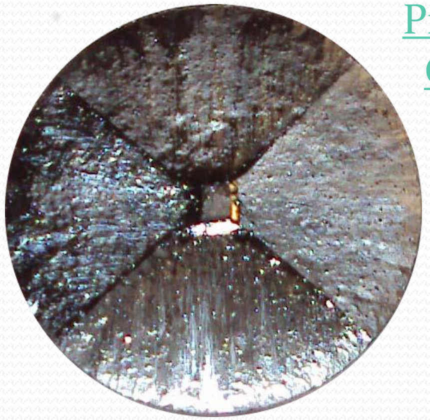
- Candidate materials of possible interest should
  - Carry large current density over large length scales
  - Be "insensitive" to application of large magnetic fields
    - Field dependence of critical current density $J_c(B)$
  - Have high critical temperature
    - to reduce cooling system constraints

Example of magnetic field dependence of the critical current density of a YBCO

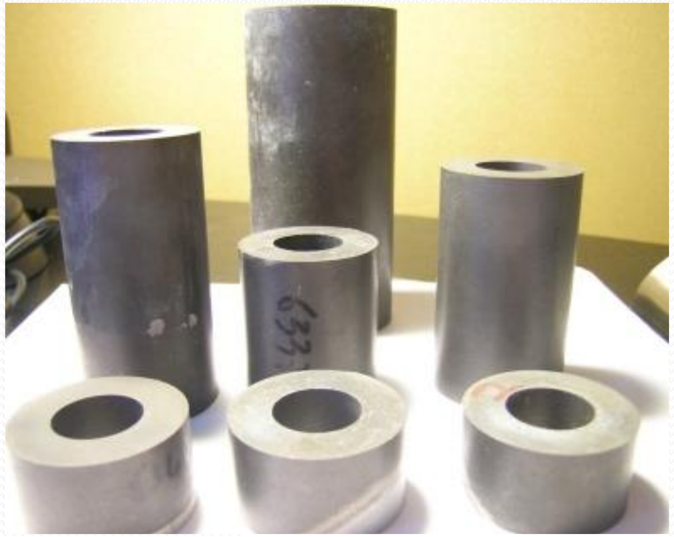


Bulk High-Temperature Superconductors (HTS)

- Currently, there are 2 main candidates for bulk HTS magnets
  - (RE)BaCuO
    - $T_c \approx 90 - 96$ K
    - Manufacturing is complicated / slow
    - Homogeneity difficult to achieve
  - MgB2
    - Discovered in 2001, $T_c = 39$ K
    - Easy to manufacture
    - Cheap and light-weight

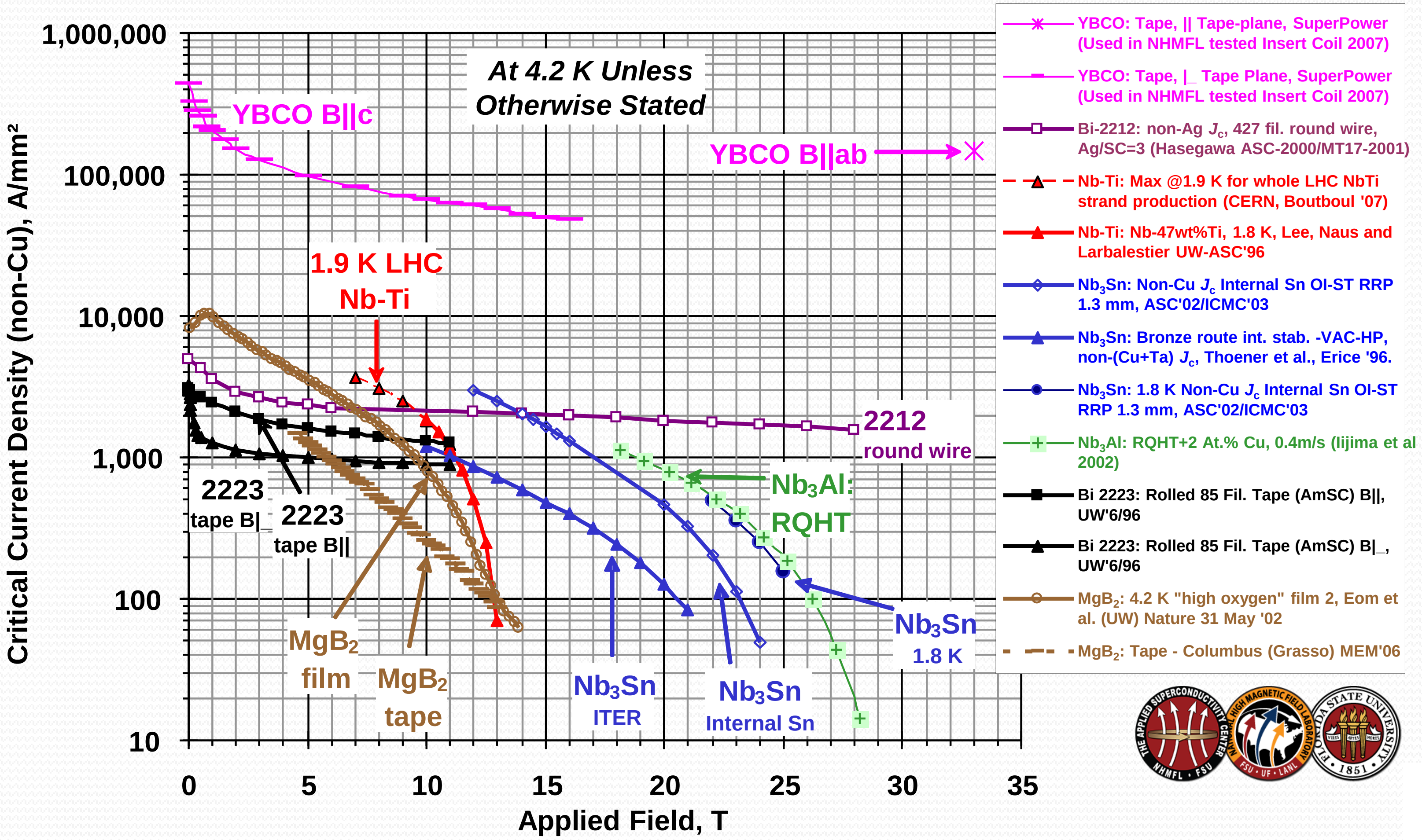


Picture from BSG, Cambridge, UK



MgB2 cylinders by Mg-RLI process (Edison SpA)

Bulk High-Temperature Superconductors (HTS)



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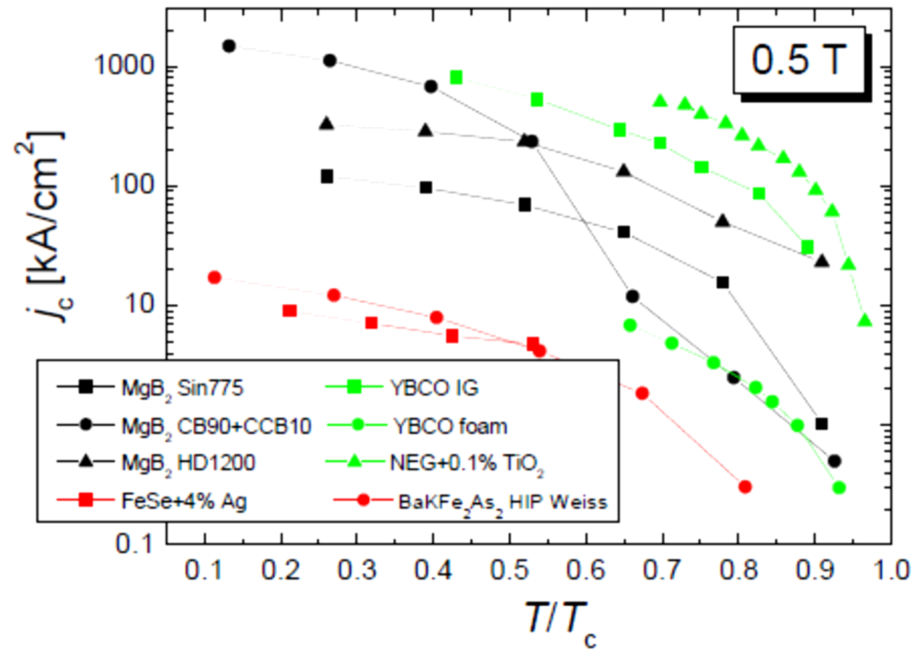
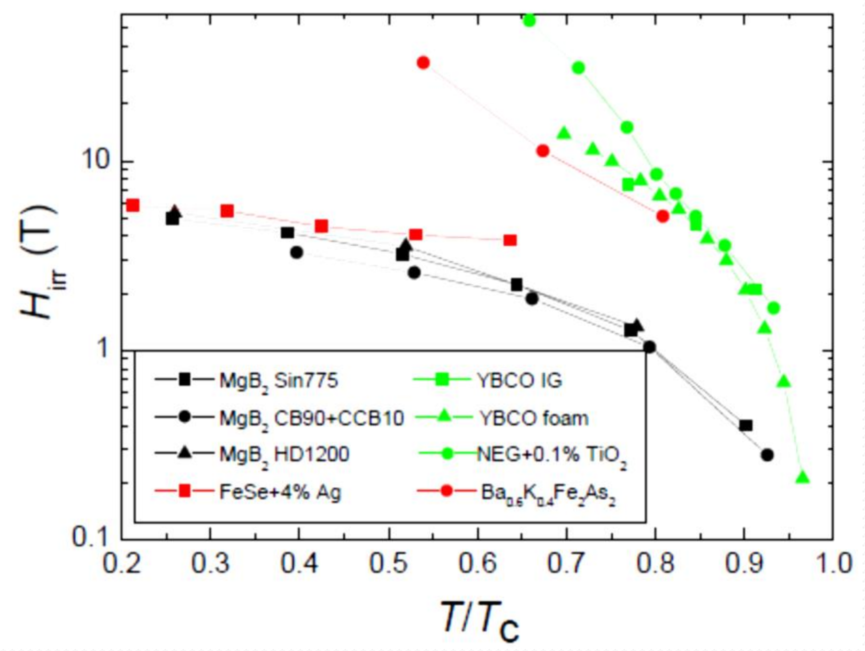
Bulk High-Temperature Superconductors (HTS)

- Applications are determined by high J_c and H_{irr} rather than by high T_c





{Ref.} Koblischka-Veneva, *et al.* (2019). Comparison of Temperature and Field Dependencies of the Critical Current Densities of Bulk YBCO, MgB2, and Iron-Based Superconductors. *IEEE Transactions on Applied Superconductivity*, 29(5), 1-5.

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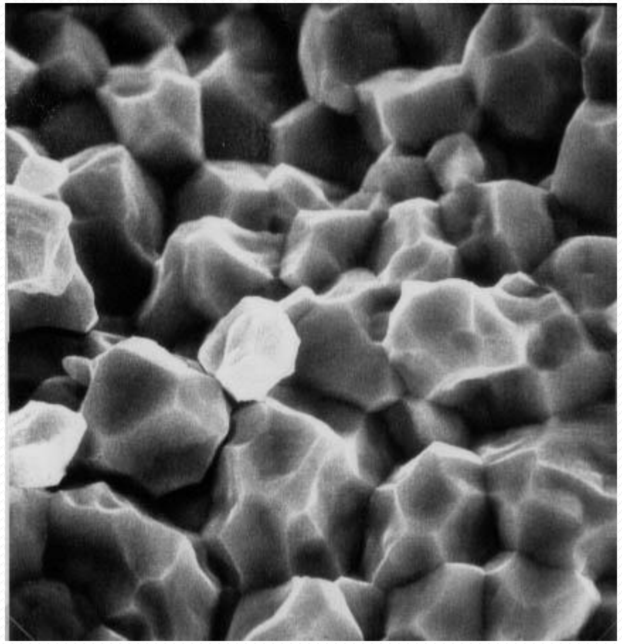
Processing Bulk HTS (courtesy of BSG, Cambridge, UK)



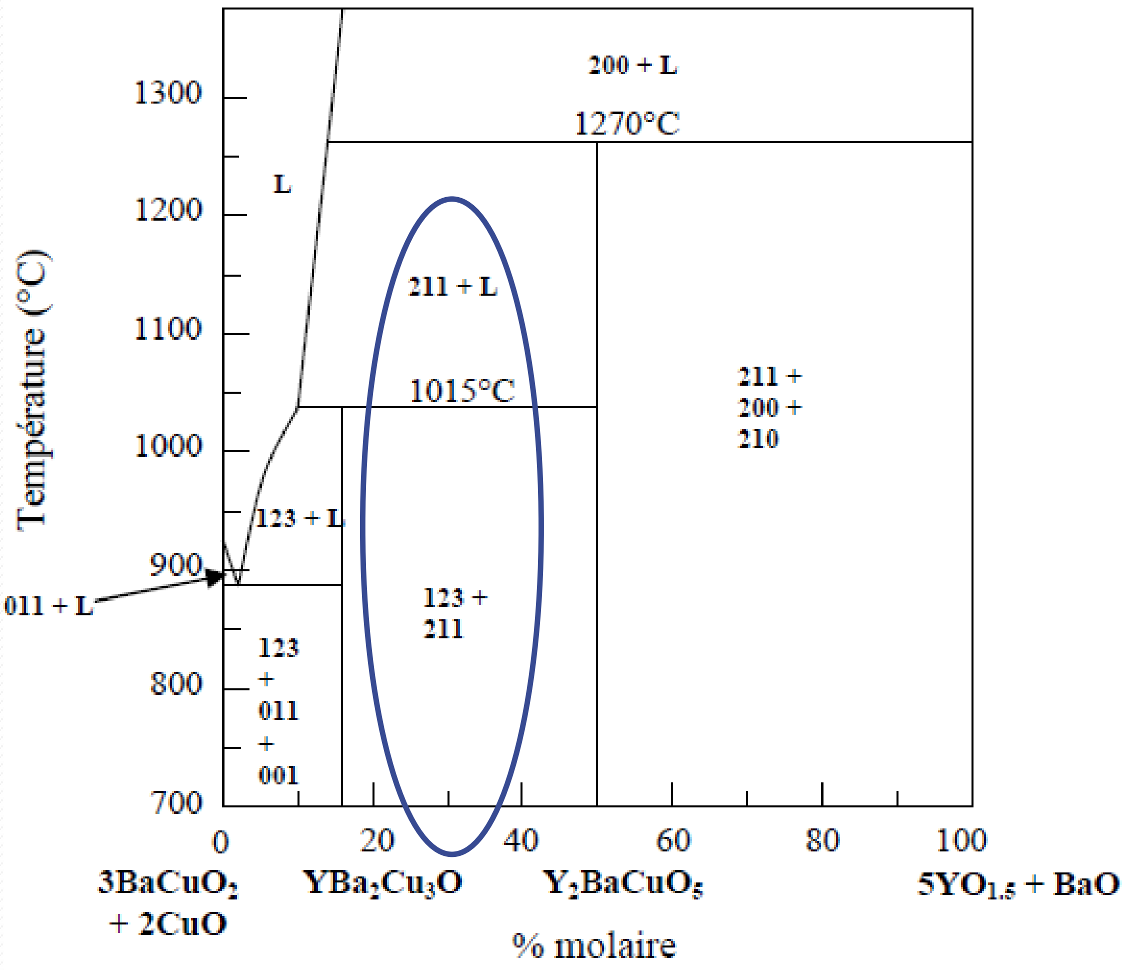
Sintered YBCO 2 μm

- Simple sintering of (RE)BCO powder in bulks does not result in the best possible material
- Early attempts at sintered bulk materials were disappointing
  - Low J_c
  - Granularity is a problem & grain boundaries = 'weak-links'
  - Microcracking

Processing Bulk HTS

- Grain boundaries can be avoided using a seeded peritectic growth process
- All (RE)BCO melt processes are based on the following peritectic reaction that occurs around 1015°C:

$$\underset{(123)}{2(RE)Ba_2Cu_3O_{7-\delta}} \leftarrow \underset{(211)}{(RE)_2BaCuO_5} + \underset{\text{Liquid}}{(Ba_3Cu_5O_8)}$$



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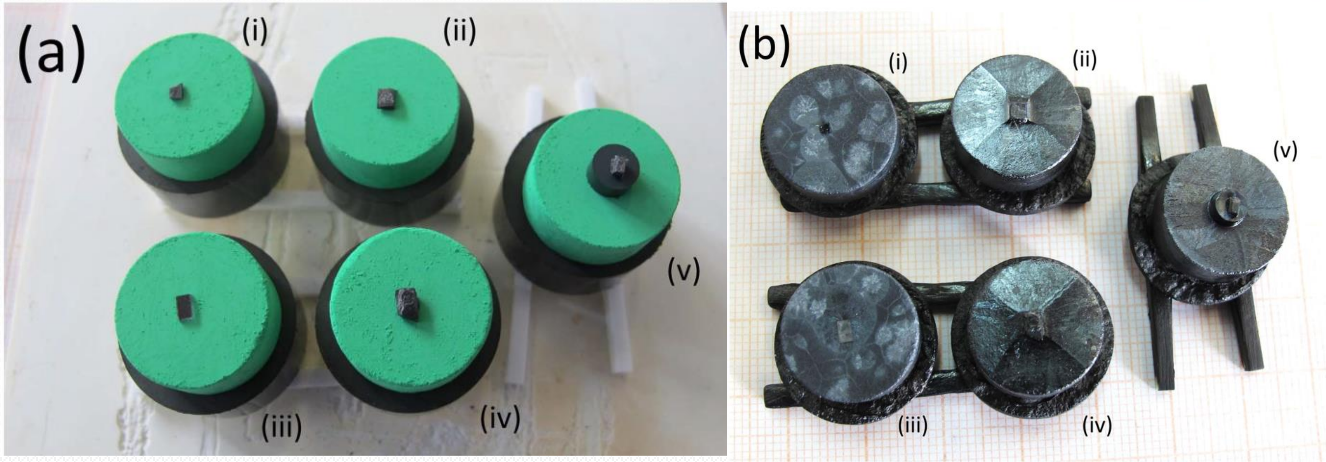
Processing Bulk HTS

- Top Seeded Melt Growth (TSMG):
  - Seed with the same lattice structure
  - Phase stability with the BaCuO melt
  - Higher melting temperature → initializes growth & controls orientation
  - T_p(Sm-123) ~ 1054 °C or T_p(Nd-123) ~ 1068 °C > T_p(Y-123) ~ 1015 °C



Namburi, D. K., *et al.* (2018). A robust seeding technique for the growth of single grain (RE)BCO and (RE)BCO–Ag bulk superconductors. *Superconductor Science and Technology, 31*(4), 044003.

Processing Bulk HTS – TSMG

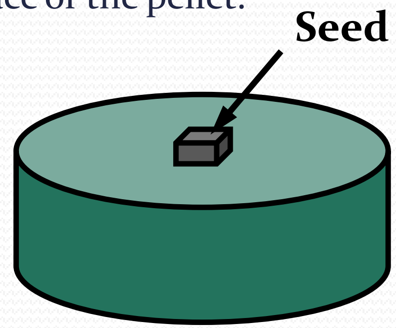
1. Mixing

Precursor powders of desired composition are mixed together using a mortar and a pestle.
2 hours are used for a mix of 200g.

Typical composition:
70wt% Y-123 + 30wt% Y-211
+ 0.1wt %Pt (grain-refining agent)

2. Pressing + Seeding

The mixed precursor is weighed and poured into a die of desired dimensions. The powder inside the die is pressed using a press. A seed is then placed on top of the surface of the pellet.

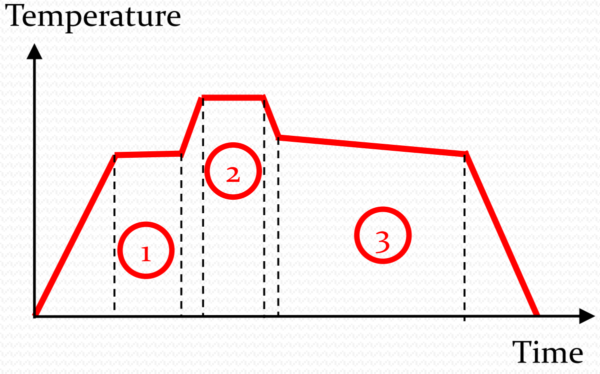


Pressed pellet

Pressure applied: 20 kN-50 kN
for a pellet 20-40 mm in diameter

3. Melt-processing

The pressed pellet with seed is then put into a furnace. The heating profile is as follows:



(1) Sintering ~ 940°C 15 min - 24h
(2) Decomposition ~1040°C 1h
(3) Nucleation from 1000°C to 960°C
~ 2h with respect to the crystal growth of that is about 0.1 mm/h (a slower rate of temperature decrease is better)

4. Oxygenation

Necessary in order to obtain the orthorhombic structure (superconducting phase)

Heat treatment under oxygen for approx. 150h - 300h at 450°C

Processing Bulk HTS (Infiltration Growth and Top Seed Textured)

{Ref.} Chaud, X., Bourgault, D., Chateigner, D., Diko, P., Porcar, L., Villaume, A., ... & Tournier, R. (2006). Fabrication and characterization of thin-wall YBCO single-domain samples. *Superconductor Science and Technology*, *19*(7), S590.

https://iopscience.iop.org/0953-2048/19/7/S33/media/video1.mpg

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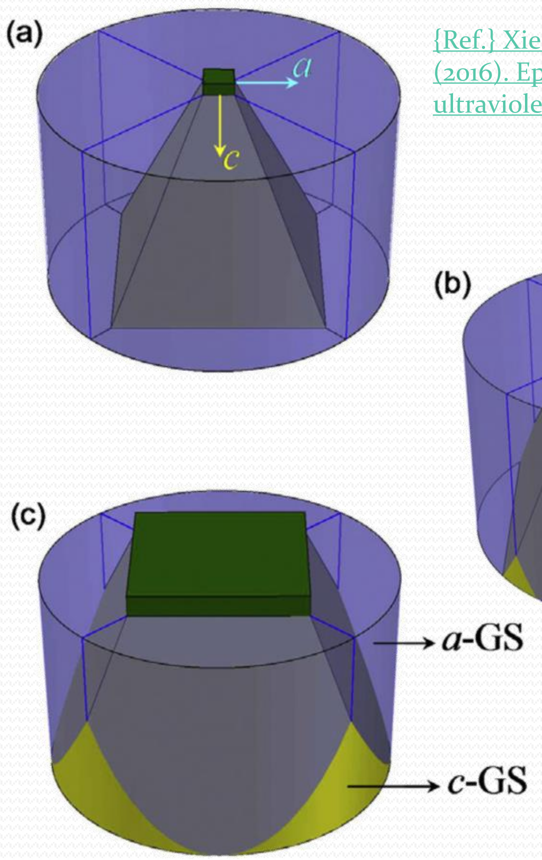
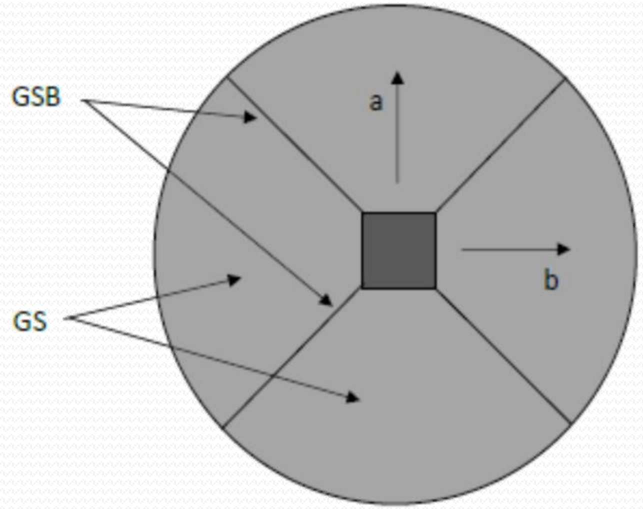
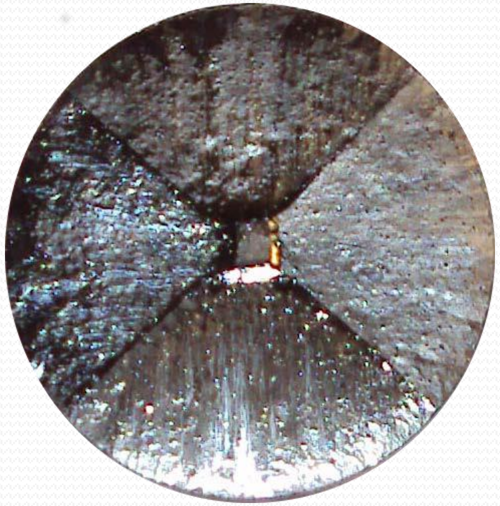
Processing Bulk HTS – Growth Sector



[{Ref.} Xie, Y., Wei, L., Li, Q., Chen, Y., Yan, S., Jiao, J., ... & Mei, L. (2016). Epitaxial rutile TiO2 film based on MgF2 substrate for ultraviolet detector. *Journal of Alloys and Compounds, 683*, 439-443].



Picture from BSG, Cambridge, UK



GSB: Growth Sector Boundary
GS: Growth Sector
a-GS: a-Growth Sector
c-GS: c-Growth Sector

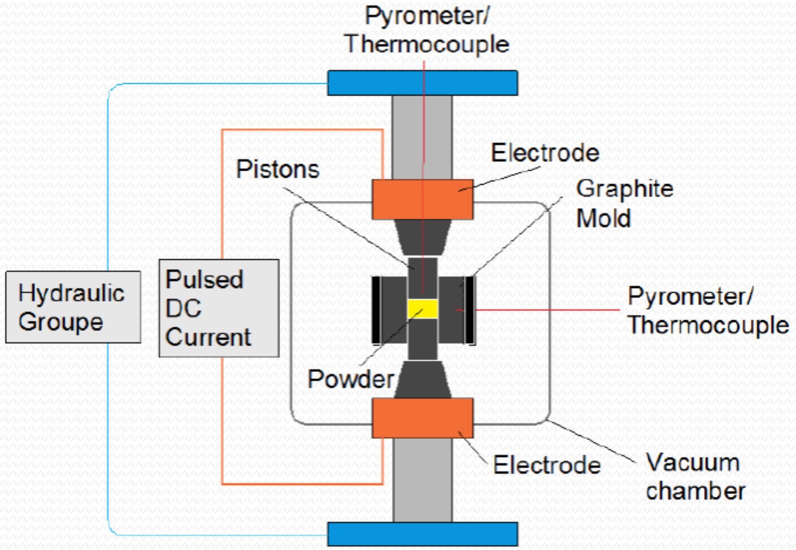
Processing Bulk MgB_2

- Manufacturing process
  - Unconventional Sintering with SPS

  = Spark Plasma Sintering

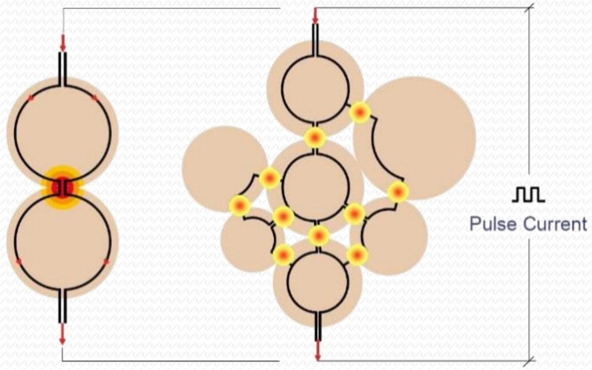
  = Field Assisted Sintering Technology

  = Pulsed Electric Current Sintering



  - Temperature: RT-2200 °C
  - Speed: 0-700 °C/min
  - Force: 0.5-250 kN
  - Atmosphere: Air / N2 / Ar
  - Size (mm): 8 / 15 / 20 / 30 / 36 / 40 / 50 / 80

only 2h of sintering!!!



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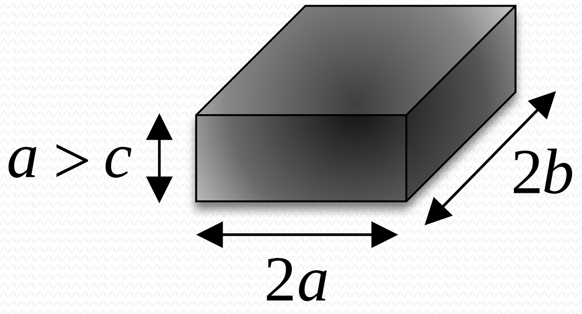
Characterization of Bulk HTS

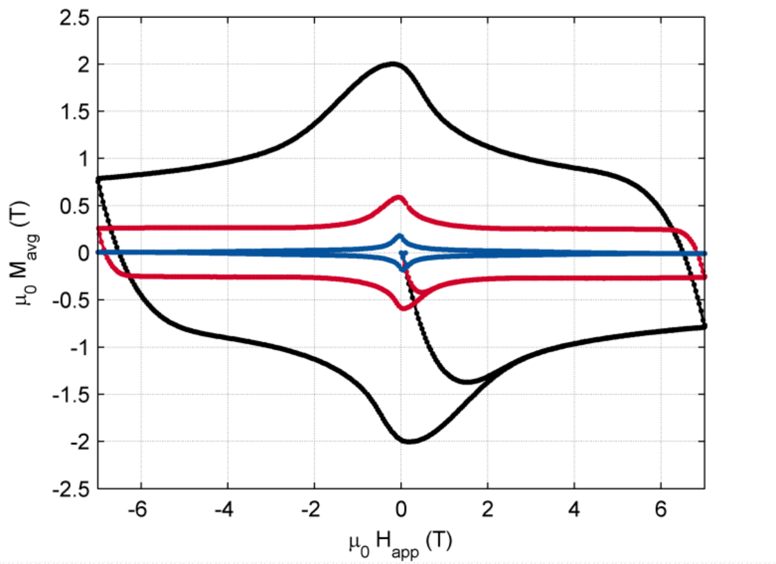
- Strong inhomogeneities for some materials
- Difficult to characterize the whole pellet
- Sample has to be cut in an orthorhombic shape
  - Typical size: 2 mm x 2 mm x 0.5 mm

{Ref.} Chen, D. X., & Goldfarb, R. B. (1989). Kim model for magnetization of type-II superconductors. *Journal of Applied Physics, 66*(6), 2489-2500.

{Ref.} Sanchez, A., & Navau, C. (2001). Critical-current density from magnetization loops of finite high-Tc superconductors. *Superconductor science and technology, 14*(7), 444.

{Ref.} Philippe, M. M. (2015). *Magnetic properties of structures combining bulk high temperature superconductors and soft ferromagnetic alloys* (Doctoral dissertation, Université de Liège, Liège, Belgique).

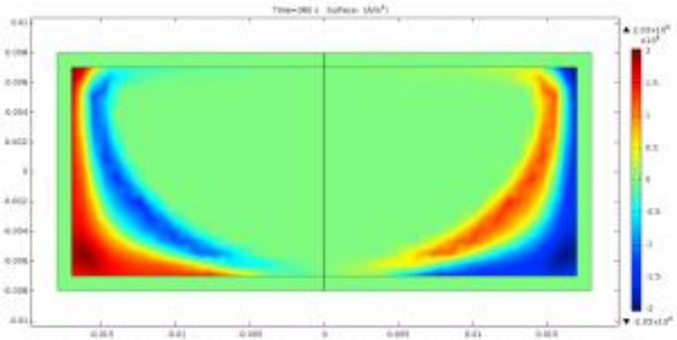


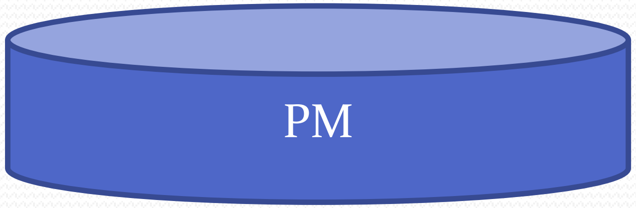


$$J_c(H)\left[\text{A/m}^2\right] = \frac{\Delta M(H)\left[\text{A/m}\right]}{a[\text{m}]\left(1-\frac{a}{3b}\right)}$$

for $H_p < H < H_{max} - H_p$

Characterization of Bulk HTS



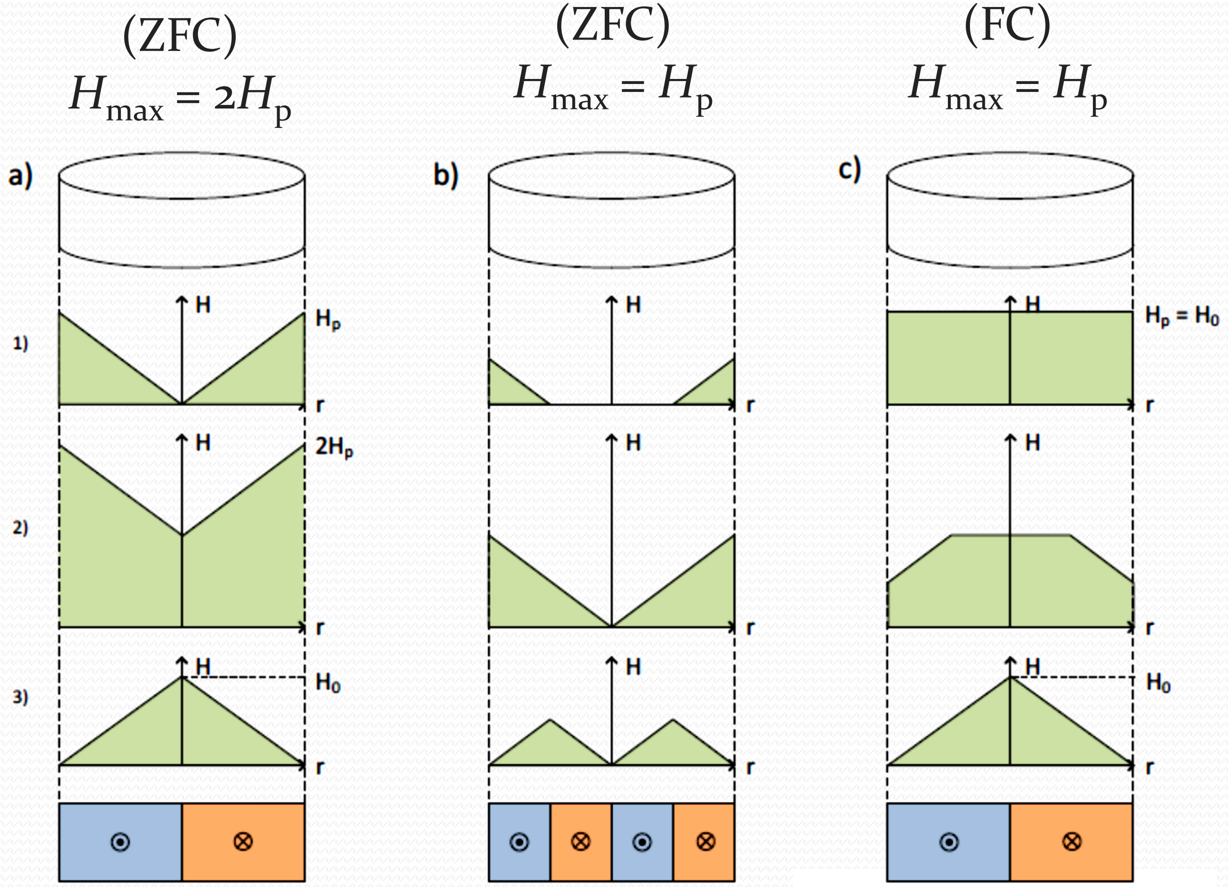


- Assessing the average performance of the entire sample
  - Force measurements with PM in front of a bulk
    - HTS is only magnetized on the surface
  - Determination of the critical current density from magnetic field measurements at the center of the top surface
    - Practical way to measure without cutting
    - Need to reach the full penetration field
    - Influences of the Hall probe location and sweep rate are taken into account

{Ref.} Douine, B., Berger, K., *et al.* (2018). Determination of the complete penetration magnetic field of a HTS pellet from the measurements of the magnetic field at its top-center surface. IEEE Transactions on Applied Superconductivity, 28(4), 1-4.

Magnetization of Bulk HTS

- 3 magnetization processes
  - Zero Field Cooling (ZFC)
  - Field Cooling (FC)
  - Pulsed Field Magnetization (PFM)
- To trap 5 T, need at least 5 T or higher
  - FC and ZFC require large coils and long magnetizing times
  - PFM is the only practical process for applications / devices



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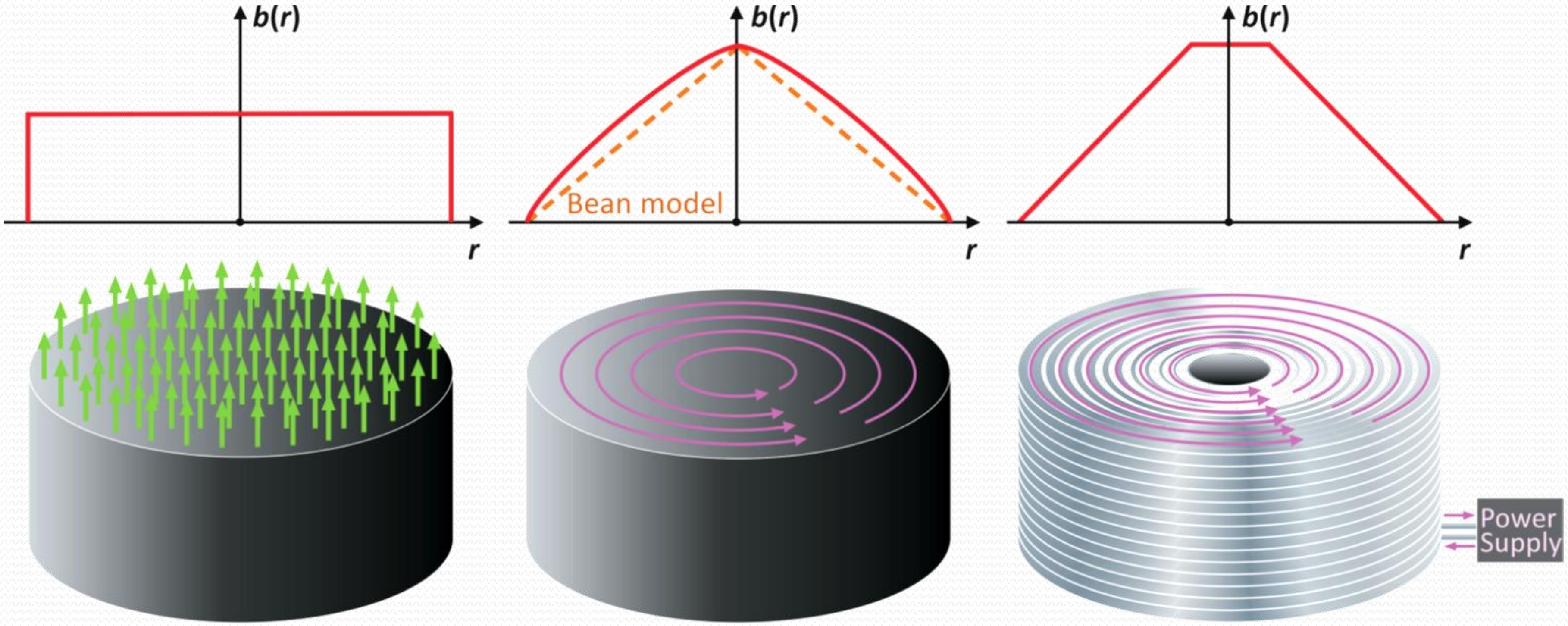
Magnetization of Bulk HTS

Courtesy of
A. Yamamoto, Tokyo



Permanent ferromagnet	**SC bulk magnet**	**Electromagnet**
Spin	Induced loop SC current	Supplied loop current
Nd-Fe-B (~1.6 T)	MgB_2 (3-5 T), YBCO (17 T)	Cu (~2 T), HTS (>30 T)

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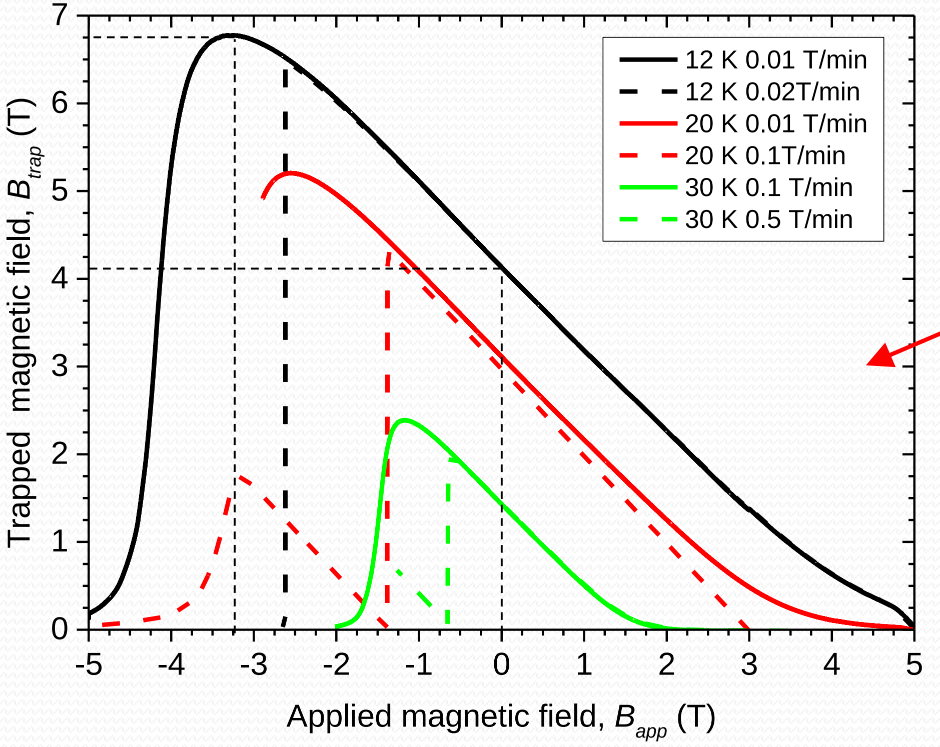
Magnetization of Bulk HTS by FC

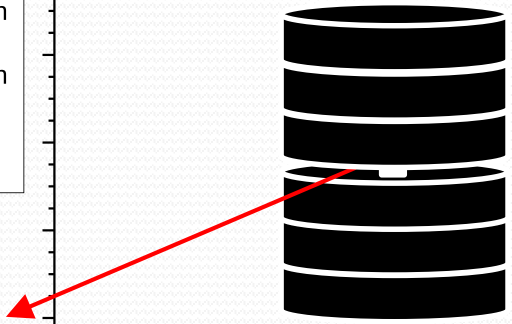
- Trapped field records with FC process (between a stack of 2 disks)
  - 17.2 T @ 29 K, YBaCuO, two 26.5 mm Φ x 15 mm (M. Tomita *et al.*, 2003)
  - 17.6 T @ 26 K, GdBaCuO, two 25 mm Φ x 15 mm (J. Durrell *et al.*, 2014)
  - 3.05 T @ 77 K, GdBaCuO, single 65 mm Φ x 19 mm (S. Nariki *et al.*, 2005)
  - 5.4 T @ 12 K, MgB2, single 20 mm Φ x 8 mm (G. Fuchs *et al.*, 2013)
  - 5.6 T @ 10 K, MgB2, two 28 mm Φ x 10 mm (T. Naito *et al.*, 2020)
    - 6.6 T expected @ 4.2 K without flux jumps
  - 6.78 T @ 12 K (4.1 T rem.), MgB2, six 20 mm Φ x 4 mm (B. Badica *et al.*, 2020)

Magnetization of Bulk HTS by FC

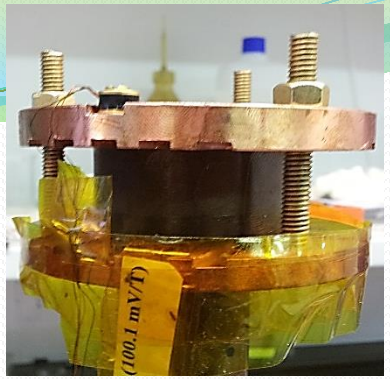
- MgB_2 samples with $Ge_2C_6H_{10}O_7$ (Repagermanium)
  6x MgB_2 Ø 20 mm, h = 6x4 mm

{Ref.} Badica, P., Aldica, G., Grigoroscuta, M. A., Burdusel, M., Pasuk, I., Batalu, D., ... & Koblischka, M. R. (2020). Reproducibility of small Ge2C6H10O7-added MgB2 bulks fabricated by ex situ Spark Plasma Sintering used in compound bulk magnets with a trapped magnetic field above 5 T. *Scientific Reports*, *10*(1), 1-11.

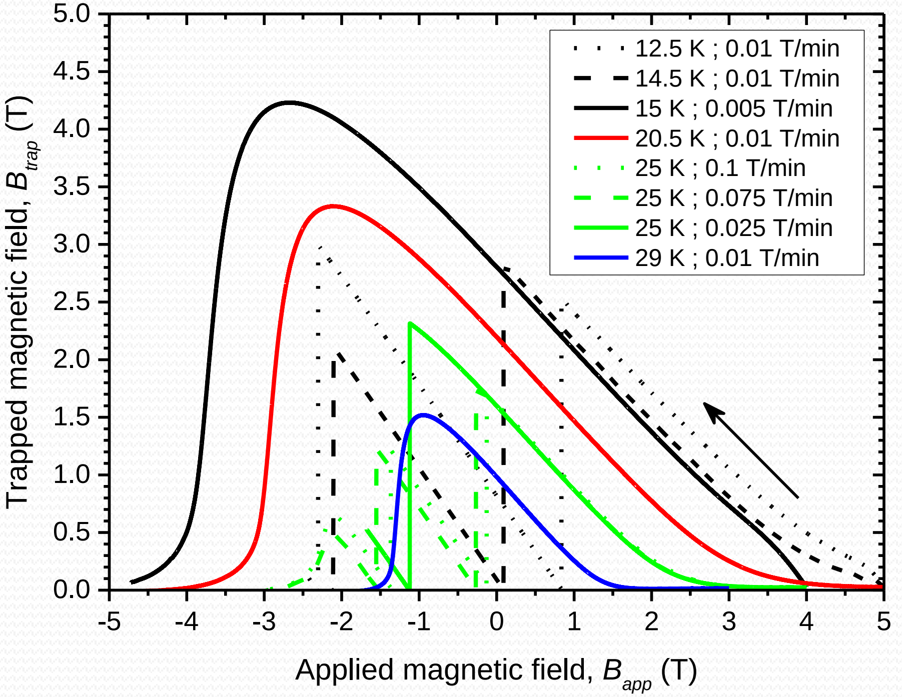


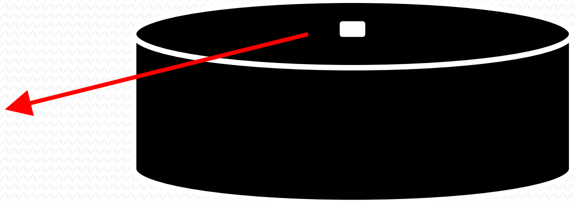


What are flux jumps?



- Magneto-thermal instabilities
  - Due to the low thermal diffusivity and heat capacity of some superconductors…
    - MgB2
    - But not only…
  - It's worse with
    - low temperatures
    - using large samples
    - high sweep rates





MgB2 pellet (Mg-RLI) of 50 mm Φ x 20 mm

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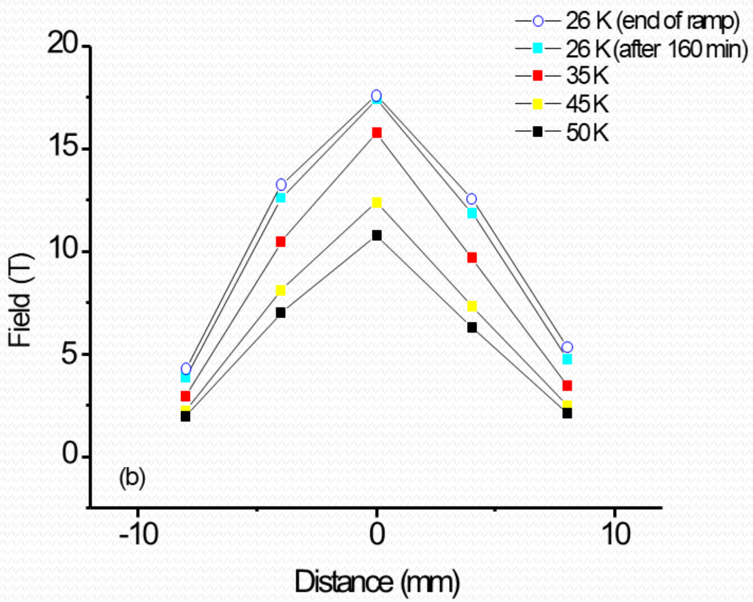
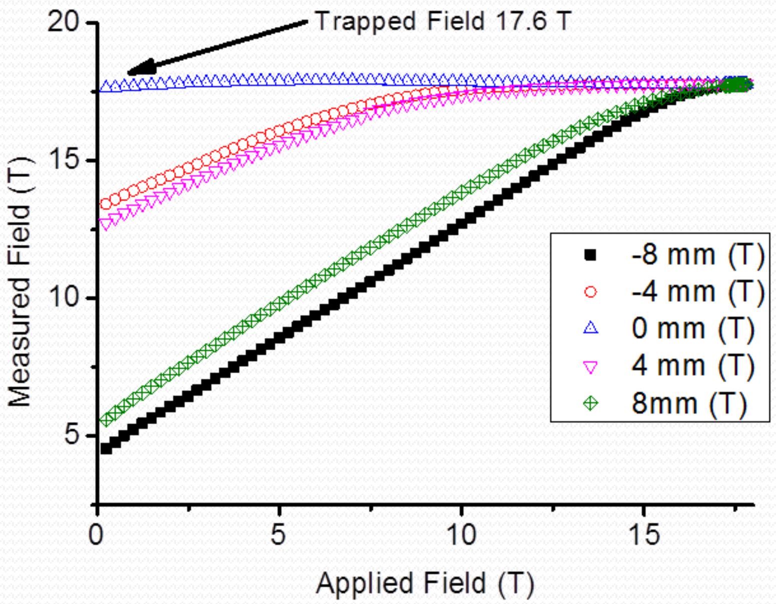
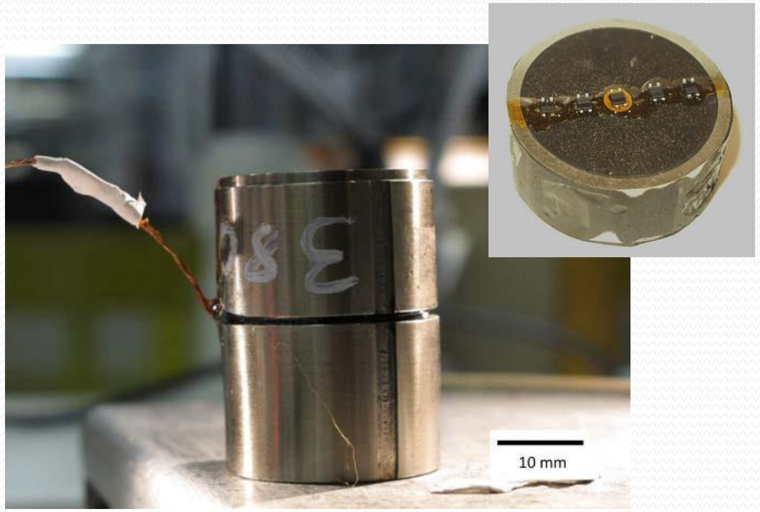
Magnetization of Bulk HTS by FC

- Trapped field records with FC process (between a stack of 2 disks)
  - 17.6 T @ 26 K, GdBaCuO, two 25 mm Φ x 15 mm (J. Durrell *et al.*, 2014)







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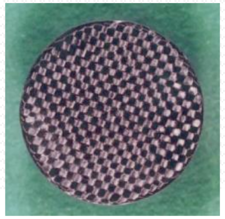
Magnetization of Bulk HTS by FC

- What limits performance?
  - At 17 T, internal stresses are ~ 90 Mpa
    - Stress scales as ~ 0.282 B^2
  - Leads to practical maximum trapped field of 7-9T in unreinforced samples as tensile strength can be < 10 MPa
  - Common failure mode seems to be a simple crack across sample

- How to overcome this?
  - Add 15 wt% AgO – converted to Ag during processing, filling voids/cracks
    - Can improve fracture strength by an order of magnitude (a few MPa → 10 MPa)
  - Shrink-fit Stainless Steel onto sample, achieves ~250 MPa interface pressure
  - Tomita *et al.* used Carbon Fiber/Epoxy – Nature 421, 517-520 (2003)



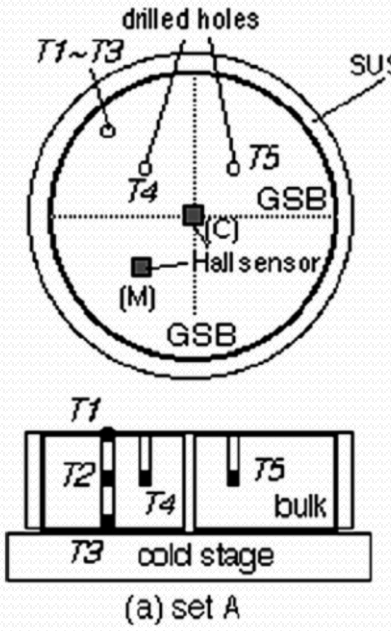
Magnetization of Bulk HTS by PFM

- Trapped field records with PFM process (top surface)
  - 5.2 T @ 28-50 K, GBaCuO, single 45 mm Φ x 15 mm (H. Fujishiro *et al.*, 2006)
  - 3.2 T @ 40-65 K, GBaCuO, single 30 mm Φ x 15 mm (M. Ainslie *et al.*, 2016)
  - 1.1 T @ 20 K, MgB2, single 22 mm Φ x 15 mm (H. Fujishiro *et al.*, 2016)
  - 1.61 T @ 20 K, MgB2, single 30 mm Φ x 19 mm (T. Hirano *et al.*, 2020)

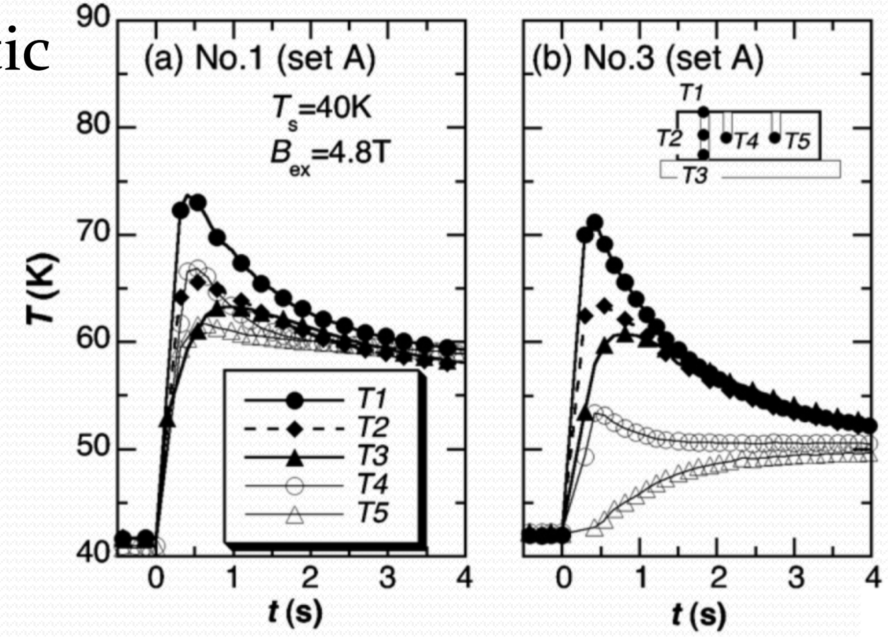
Magnetization of Bulk HTS by PFM

- What limits performance vs FC?
  - Heat induced during PFM!

[{Ref.} Fujishiro, H., Naito, T., Furuta, D., & Kakehata, K. (2010). Temperature measurements in small holes drilled in superconducting bulk during pulsed field magnetization. *Physica C: Superconductivity and its applications*, *470*(20), 1181-1184.]



- Who to optimize dynamics of magnetic flux during PFM process
  - Pulse magnitude/ pulse duration,
  - Number of pulses,
  - Operating temperature(s),
  - Type of magnetizing coil(s),
  - Use of ferromagnetic materials…



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Magnetization of Bulk HTS by PFM

- PFM is the only practical process for applications using bulk magnets
  - We have to deal with strong magnetic field variations
  - And induced currents in all conducting parts

- A coupled electro-thermal modeling is mandatory

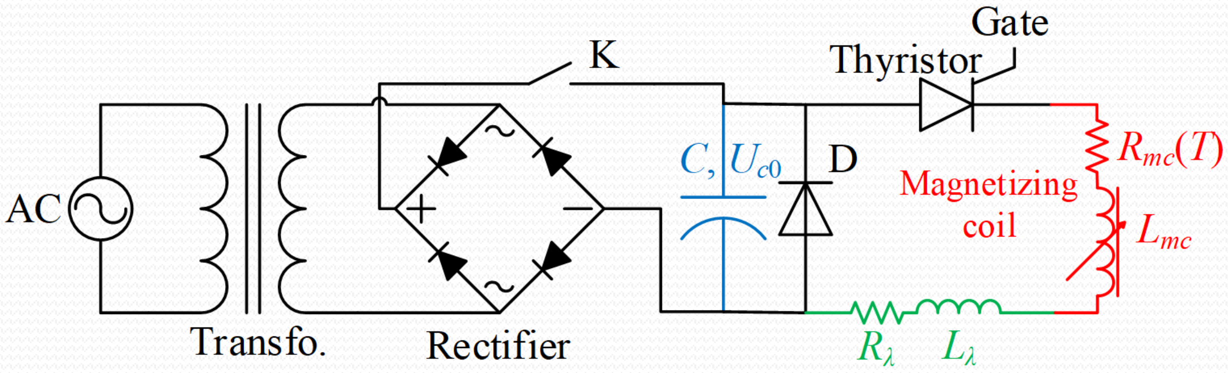
- But how does PFM process work?

How does PFM process work?

- Pulsed Field Magnetization
  - What do we usually need
  - How it works
  - Equation of current/applied field
  - Main characteristics
  - Examples of operational setups
  - Summary
- In real applications?

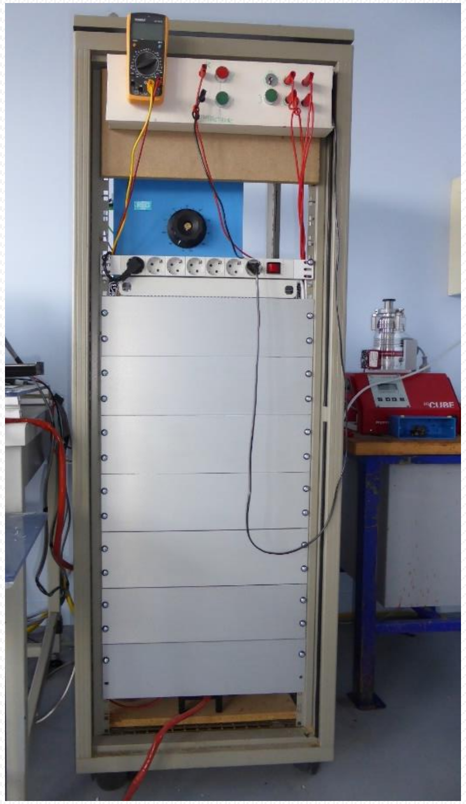
Pulsed Field Magnetization?

- Usually, charge of capacitors and then short circuit



- It can also be a short-circuited coil made on a
  - Transformer
  - Electric machine

Capacitors bank…



5.1 kJ– 15 kA
115 mF, 300 V

10 kJ – 25 kA
5 mF – 2000 V

60 kJ – 10 kA
40 mF to 120 mF – 1000 V

About the current waveform

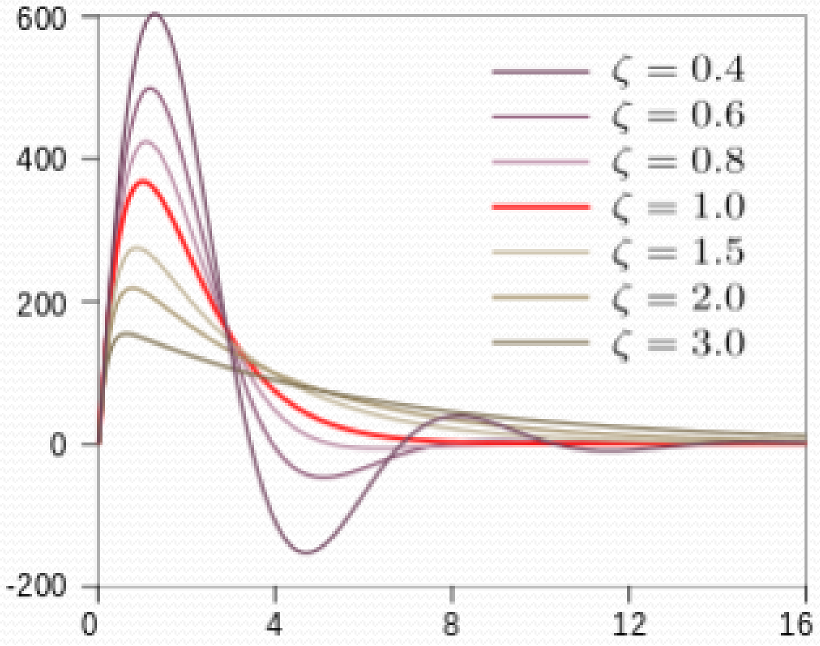
- General equation (same eq. with *i* or *u*)

$$U_c + Ri + \frac{d\phi}{dt} = 0 \Rightarrow \frac{d^2q}{dt^2} + \frac{R}{L}\frac{dq}{dt} + \frac{q}{LC} = 0 \text{ with } q_0 = CU_{c0}$$

- Damping factor

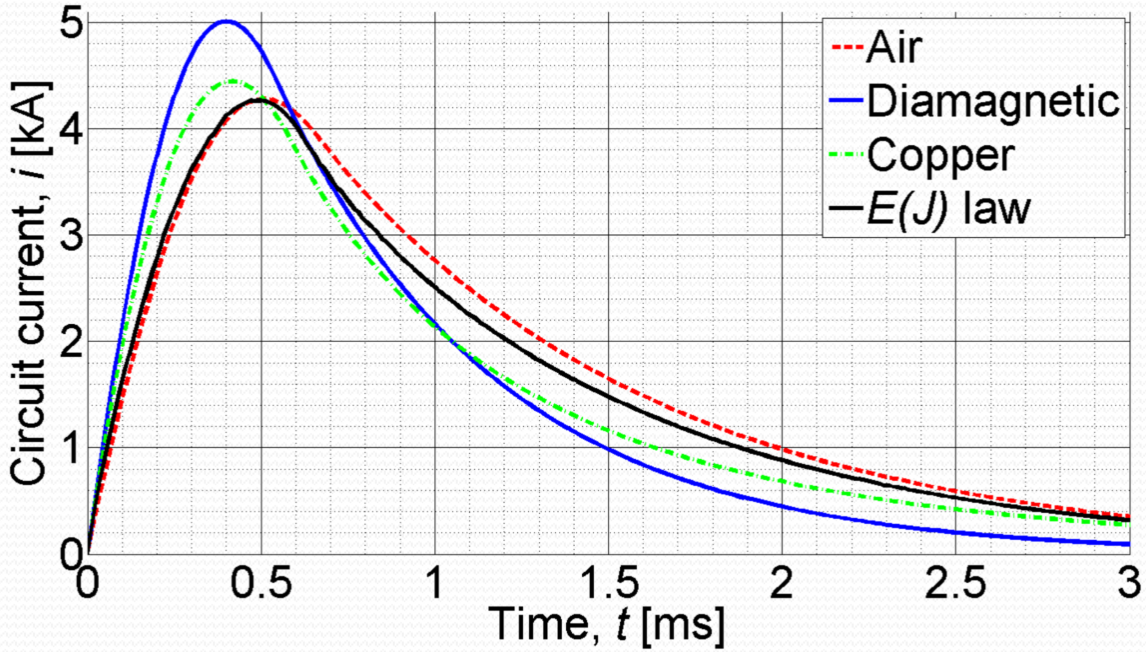
$$\zeta = \frac{\alpha}{\omega_0} = \frac{R}{2}\sqrt{\frac{C}{L}}$$

$$\text{with } \alpha = \frac{R}{2L} \text{ and } \omega_0 = \frac{1}{\sqrt{LC}}$$



Influence of bulk HTS on inductance

Bulk pellet surrounded by a circular coil (circuit coupled problem)



{Ref.} Kapek, J., Berger, K., Koblischka, M. R., Trillaud, F., & Lévêque, J. (2019). 2-D numerical modeling of a bulk HTS magnetization based on H formulation coupled with electrical circuit. *IEEE Transactions on Applied Superconductivity*, 29(5), 1-5.

- From the point of view of the coil
  - A bulk HTS during PFM is almost equivalent to air

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Different regimes

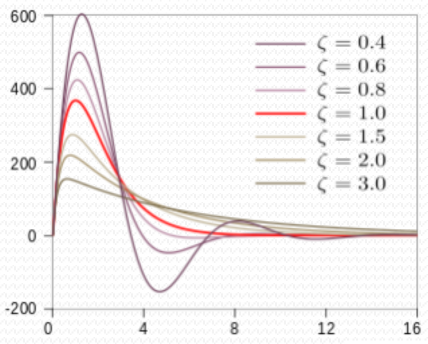
$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}},\ \alpha = \frac{R}{2L},\ \omega_0 = \frac{1}{\sqrt{LC}}$$

- Overdamped response $\zeta > 1$

$$i(t) = A_1 \exp\left(-\omega_0\left(\zeta + \sqrt{\zeta^2 - 1}\right)t\right) + A_2 \exp\left(-\omega_0\left(\zeta - \sqrt{\zeta^2 - 1}\right)t\right)$$

- Underdamped response $\zeta < 1$

$$i(t) = \frac{U_{c0}}{L\omega}\exp(-\alpha t)\sin(\omega t) \text{ with } \omega = \sqrt{\omega_0{}^2 - \alpha^2}$$

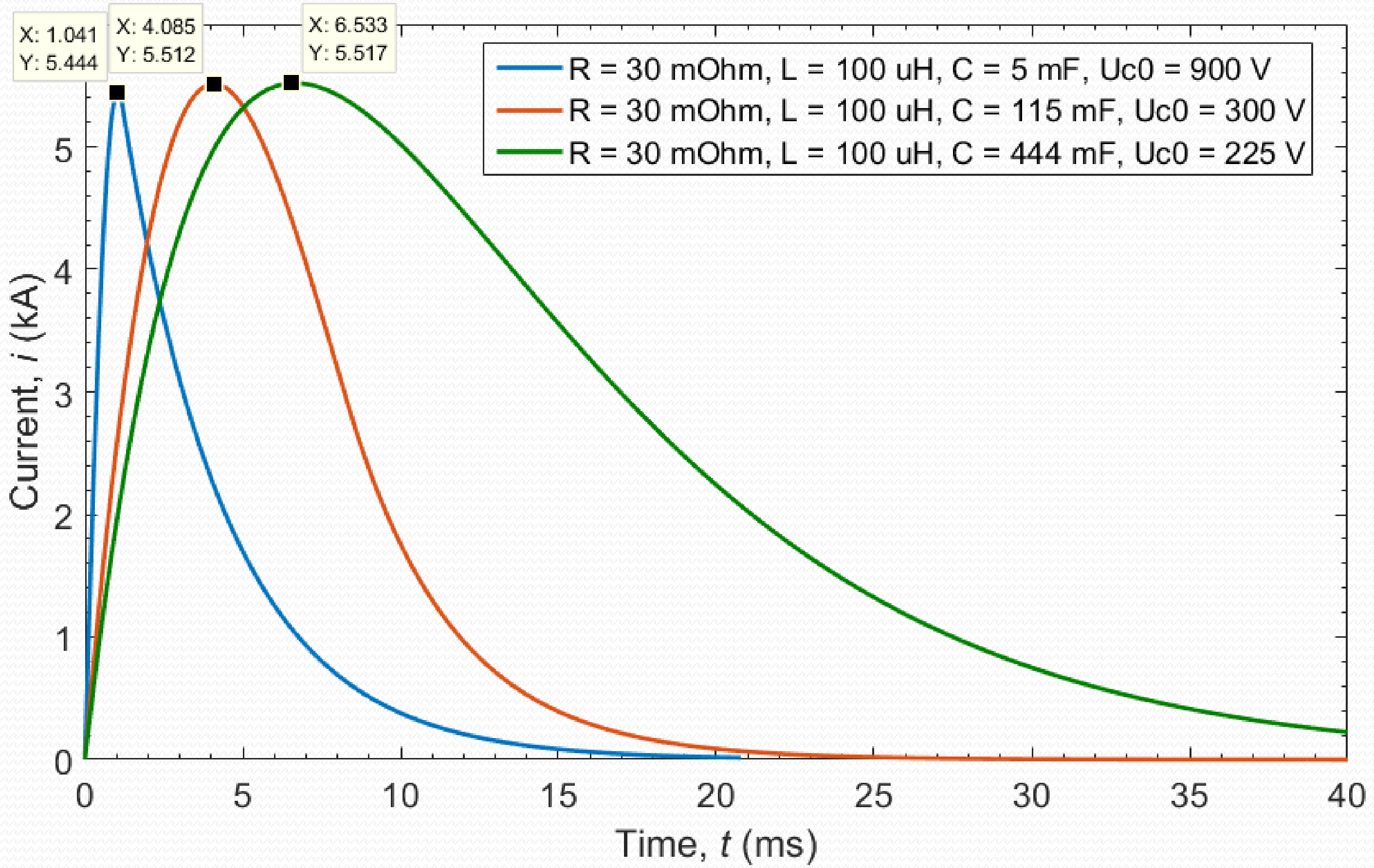


- Critical $\zeta = 1$

$$i(t) = \frac{U_{c0}}{L} t \exp\left(-\alpha t\right) = i_{max}\frac{t}{\tau}\exp\left(1 - \frac{t}{\tau}\right)$$

Examples

Capacitors bank influence



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Underdamped regime

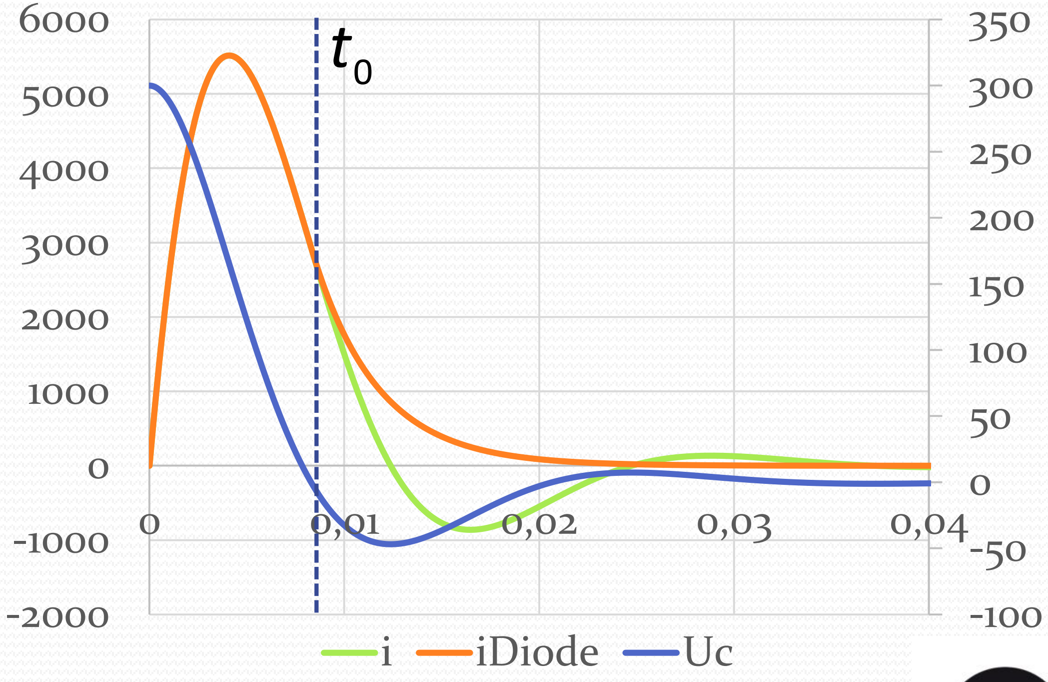
- Maximal current at $t_{max} = \omega^{-1}\left(\arctan(\omega / \alpha)\right)$
- $U_c = 0$ at $t_0 = \omega^{-1}\pi - t_{max}$
  - Before t_0

$$i(t) = \frac{U_{c0}}{L\omega}\exp(-\alpha t)\sin(\omega t)$$

$$\text{with } \omega = \sqrt{\omega_0^{\ 2} - \alpha^2}$$

  - After t_0

$$i(t) = i(t_0)\exp\left(-(t - t_0)/\tau\right)$$



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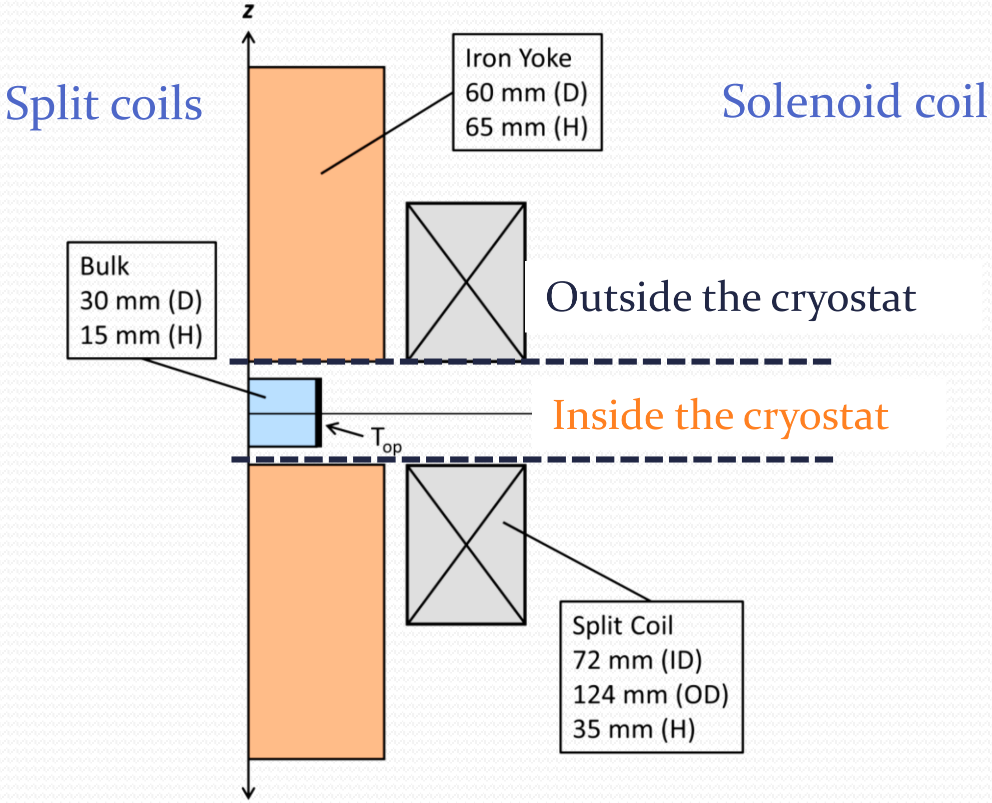
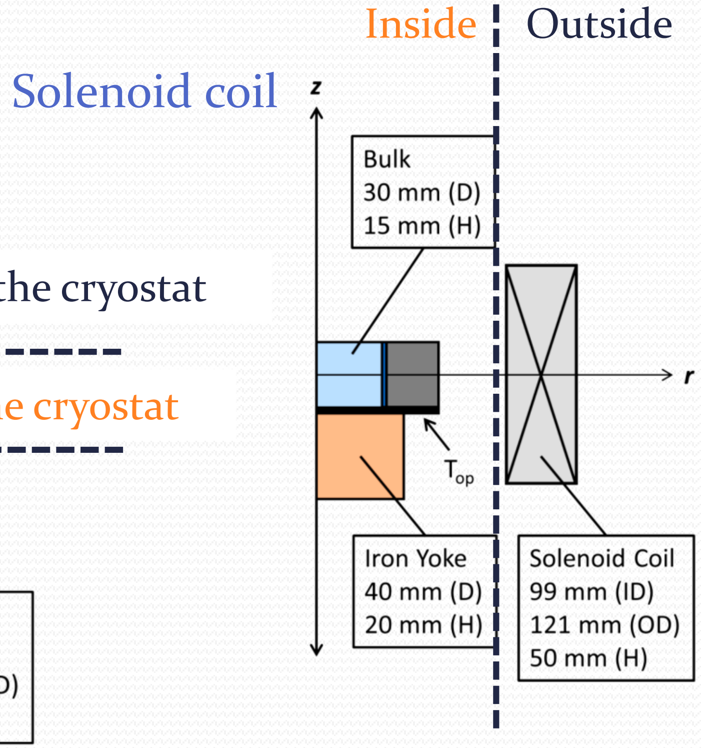
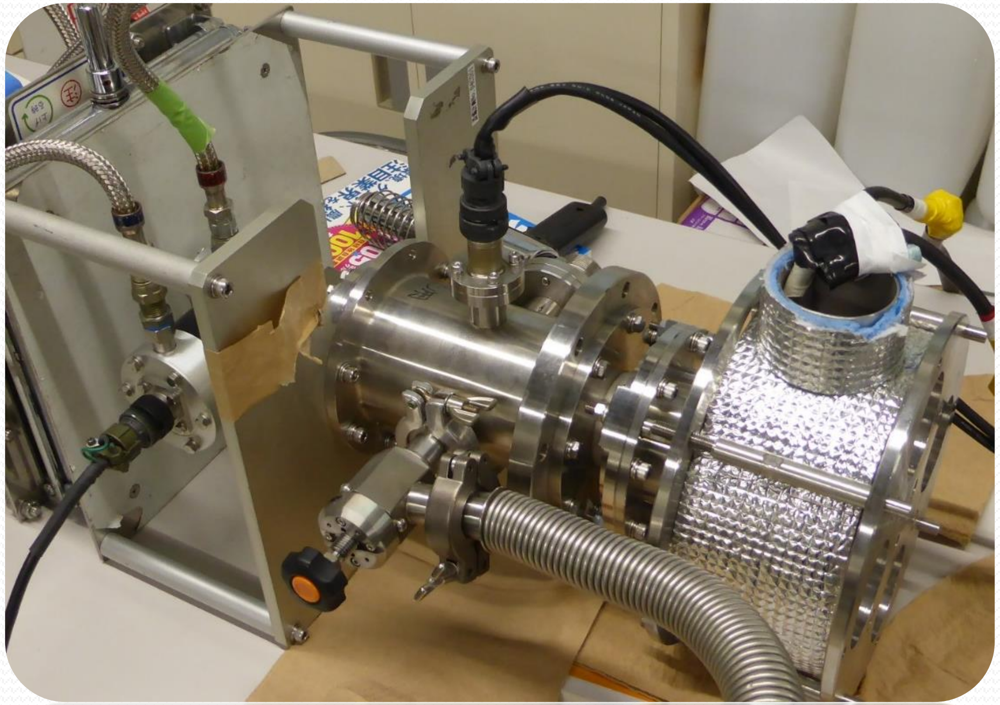
Examples of operational setups

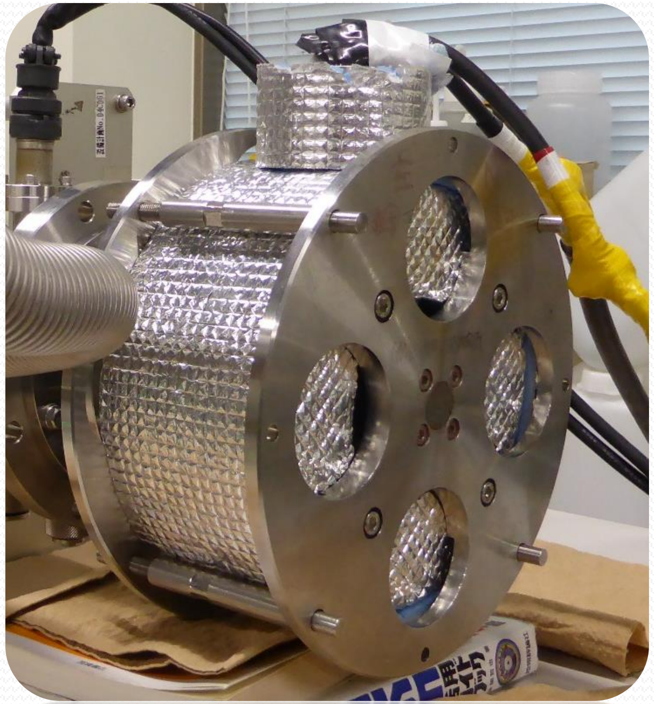




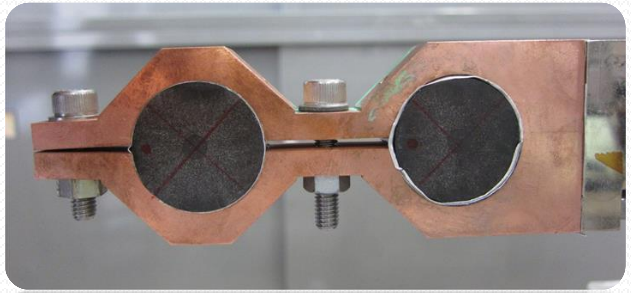
{Ref.} Ainslie, M. D., Fujishiro, H., Mochizuki, H., Takahashi, K., Shi, Y. H., Namburi, D. K., ... & Cardwell, D. A. (2016). Enhanced trapped field performance of bulk high-temperature superconductors using split coil, pulsed field magnetization with an iron yoke. *Superconductor science and technology*, *29*(7), 074003.

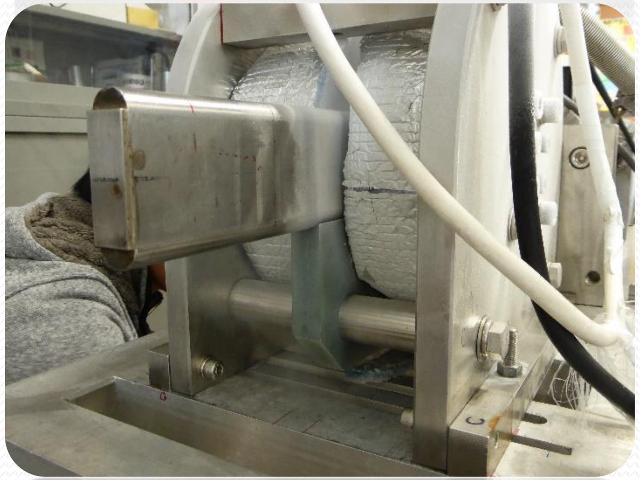
Niigata University (T. Oka and J. Ogawa)

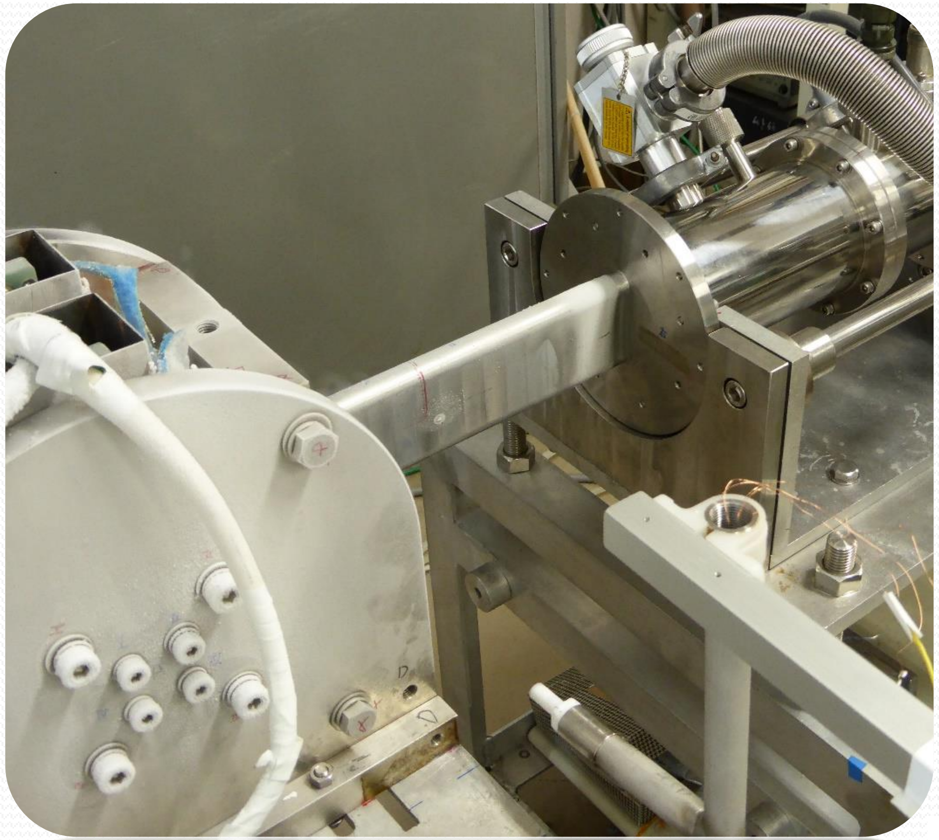




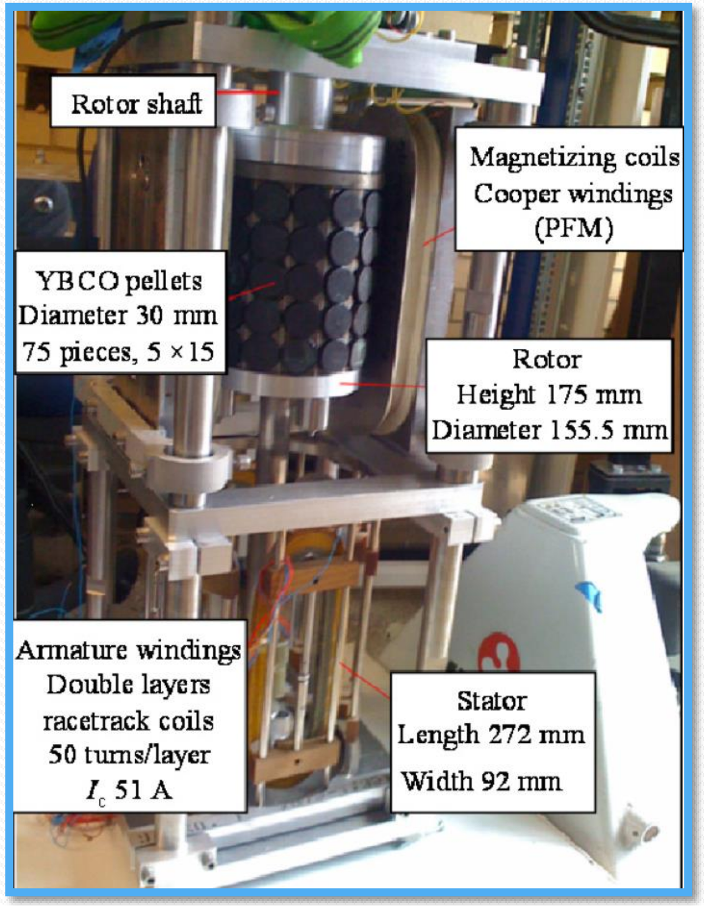
Morioka University (H. Fujishiro)

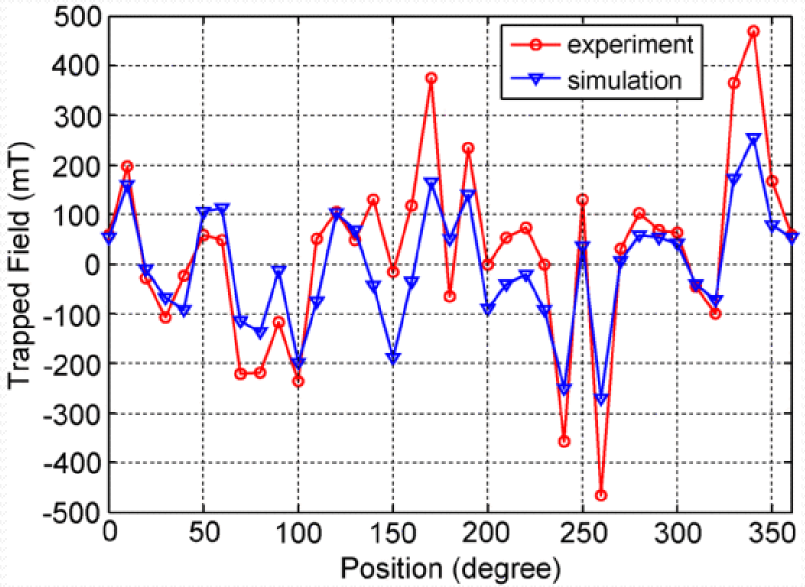






Magnetization by stator windings (4 poles)



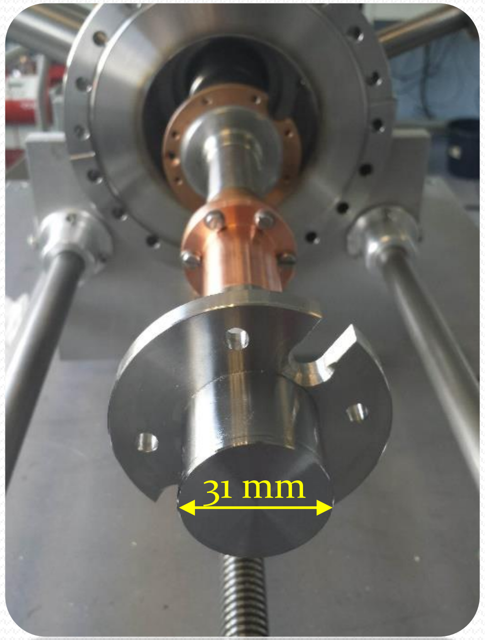


Xian, W., Yan, Y., Yuan, W., Pei, R., & Coombs, T. A. (2010). Pulsed field magnetization of a high temperature superconducting motor. *IEEE transactions on applied superconductivity, 21*(3), 1171-1174.

Operational test rig @ GREEN

in situ magnetization

VACODUR® 50
49% Co, 1.9% V, rest Fe
from VACUUMSCHMELZE GmbH



Bsat > 2.3 T
Hc < 200 A/m
$\rho = 4.10^{-7}\ \Omega.m$
density 8120 kg/m³
$\alpha = 10.10^{-6}\ K^{-1}$

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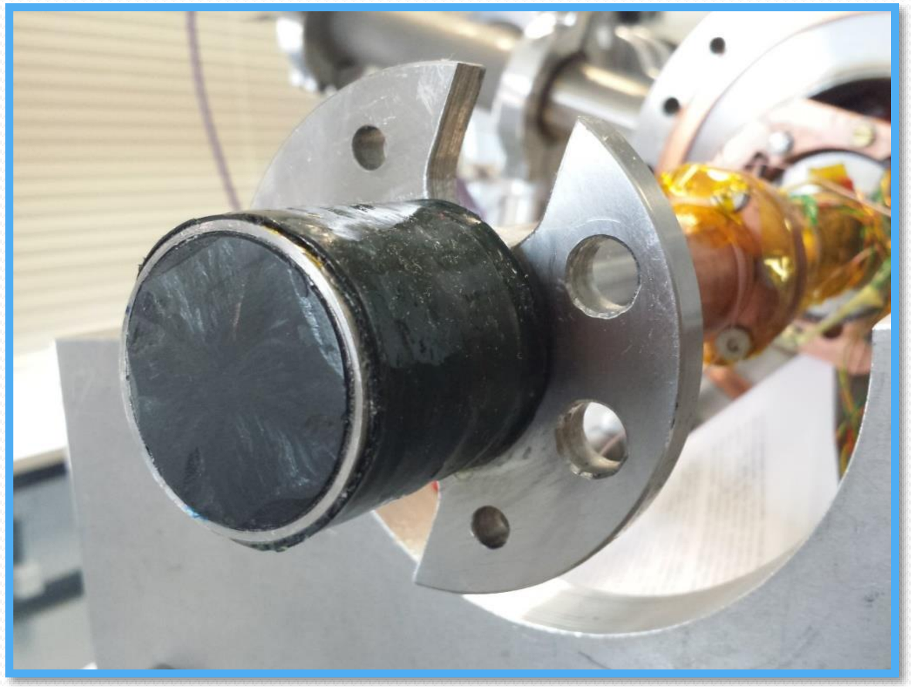
YBaCuO samples with SS Ring

- Sample and SS ring are glued together with Stycast 2850 FT

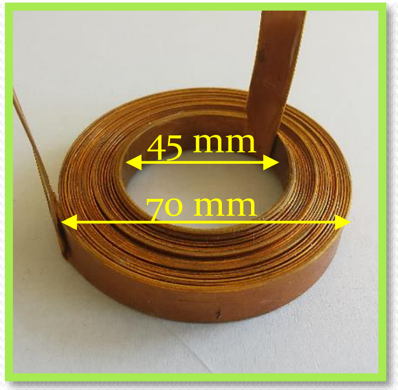
35 mm diameter - 12 mm high
from CAN SUPERCONDUCTORS s.r.o.



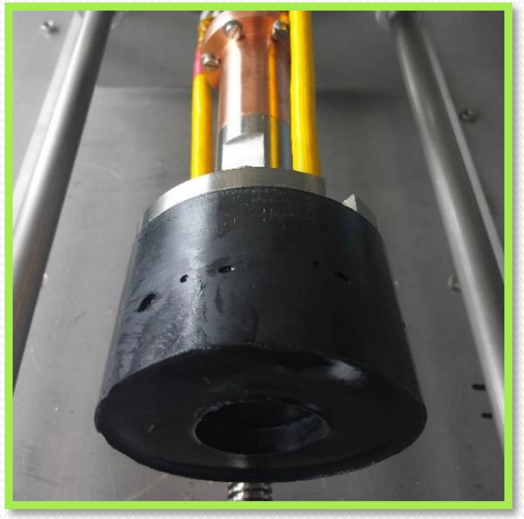
31 mm diam. - 17 mm high
from ATZ GmbH

Coil design and realization

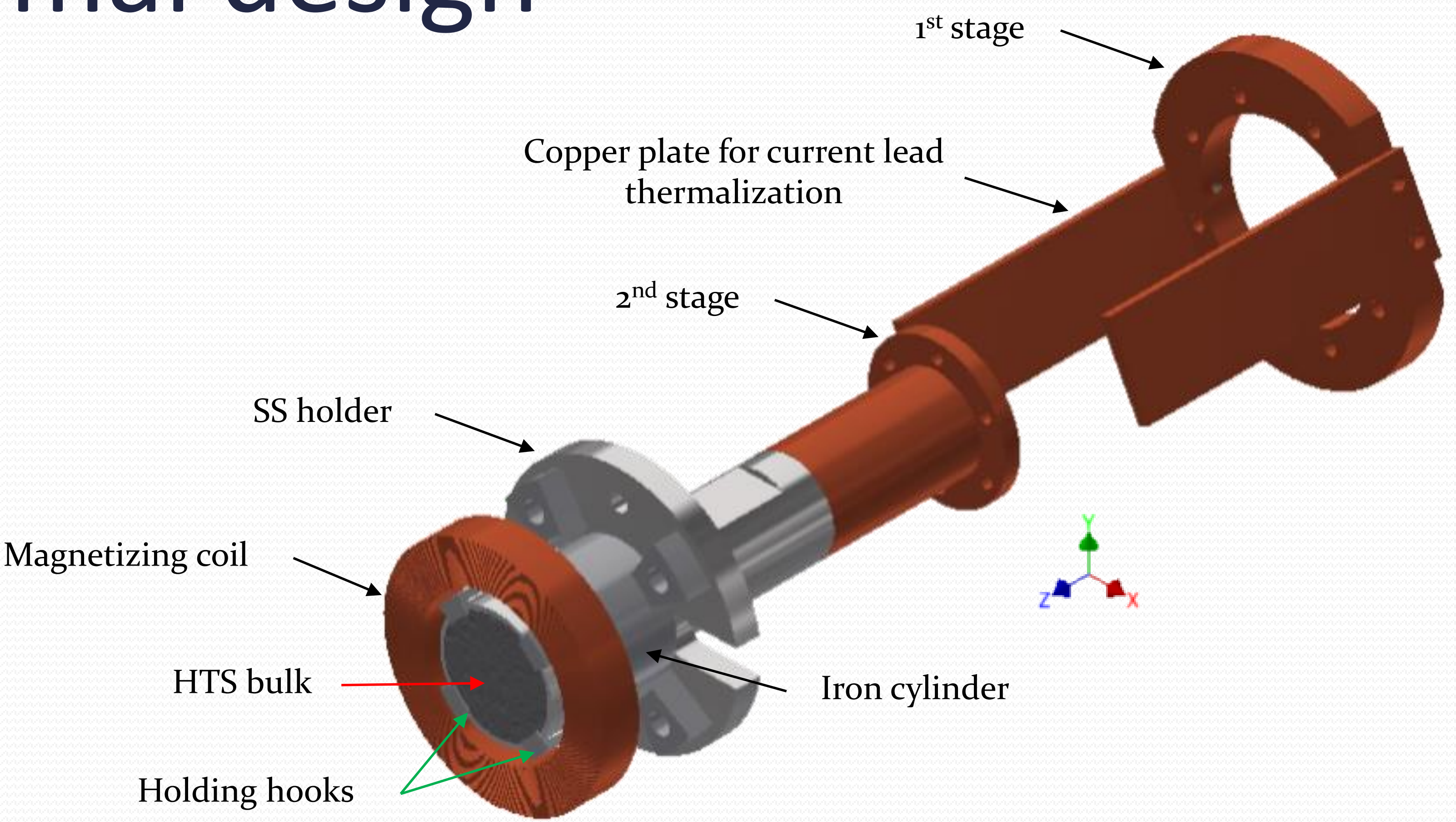
- Coil should be as close as possible to the sample
  - Better magnetic coupling and optimized size
  - Copper foils of 0.2 mm thick
  - Kapton tape for turn-to-turn insulation



- Our first aim was to thermalize the coil with the 2nd stage of the crycooler using Stycast molding
  - Easy to manufacture and mount

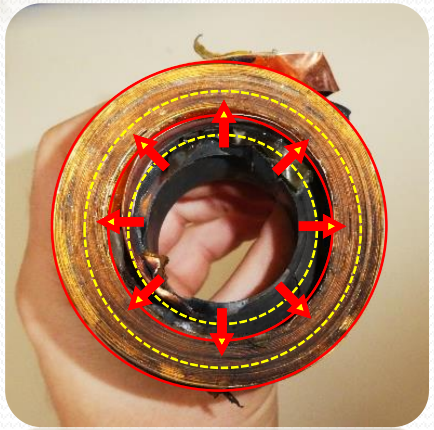


Thermal design



Coil design and realization

- Some problems occurred during the experiences
  - Stycast can not handle the Lorentz force during the pulsed magnetization (~ 2.5 GPa @ 10 kA)
  - Heat is not well extracted (it's still epoxy resin…)
- Fiber Glass + Araldite impregnation
- Cooling using the 1st stage of the cryocooler



Other issues

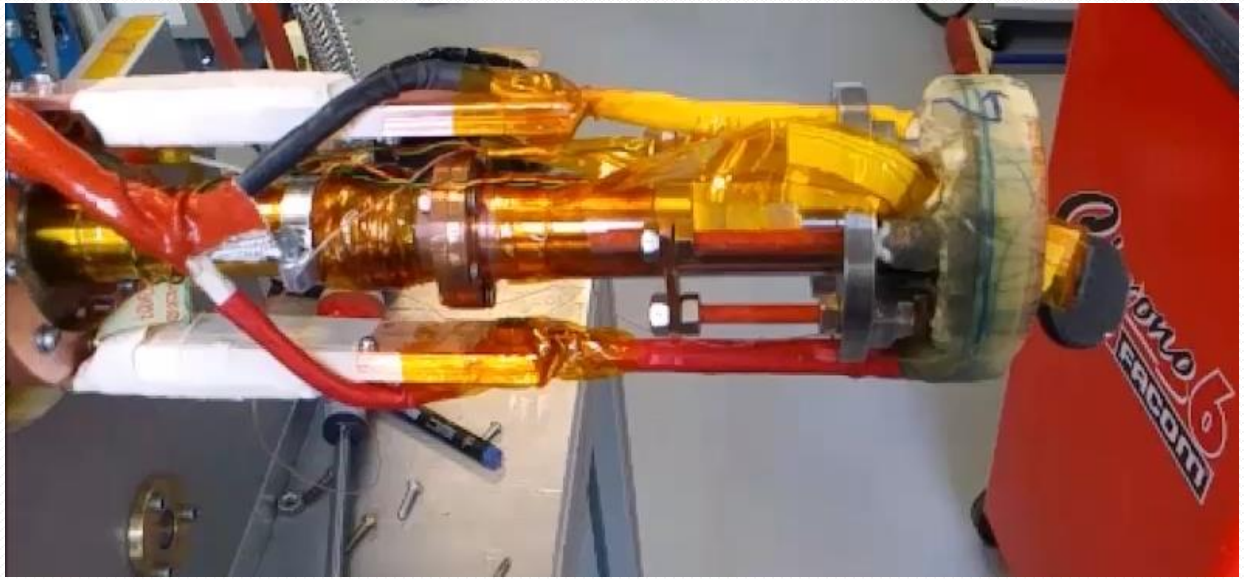
- High voltage up to 2 kV and high current densities > 1 kA/mm²
  - Working with HV in small environment that requires good thermal connections and compactness is not easy...

- Thermalization of the coil leads through the 1st stage of the cryocooler was made with Aluminium Nitride
  - (Cu / AlN / Cu) sandwich with copper plates of 20 mm x 80 mm
  - AlN properties: $k > 150$ W/(m.K), $\rho > 1010$ Ω.m, $E_d = 15$ kV/mm, density of 3300 kg/m³, $\alpha = 4.6\text{x}10^{-6}$ K⁻¹

Other issues

- During PFM, the coil attempts to place at the center of the iron cylinder
  - The resulting force on the coil holder @ 10 kA reaches 13 kN

    ~ the weight of my Peugeot 5008



Other homemade coils

Short summary

- PFM usually needs capacitors
- Current waveform/magnetization strongly depends on
  - The inductance and so of the environment
- HTS bulk needs to be tightly coupled with the coil
- About the use of iron
  - Increases the applied field for a given current
  - Increases the homogeneity of the applied field
  - Increases L, so $t_{\text{max}} \uparrow$ and $i_{\text{max}} \downarrow$
- Design of the coil is essential in HTS bulks applications

Thank you for your attention!

Dr. Kévin Berger

Group of Research in Electrical Engineering of Nancy – GREEN (France)
https://www.researchgate.net/profile/Kevin_Berger