ACADEMIC TRAINING

Technology and applications of high field accelerator magnets

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Lesson 1:

- Introduction
- Superconductors

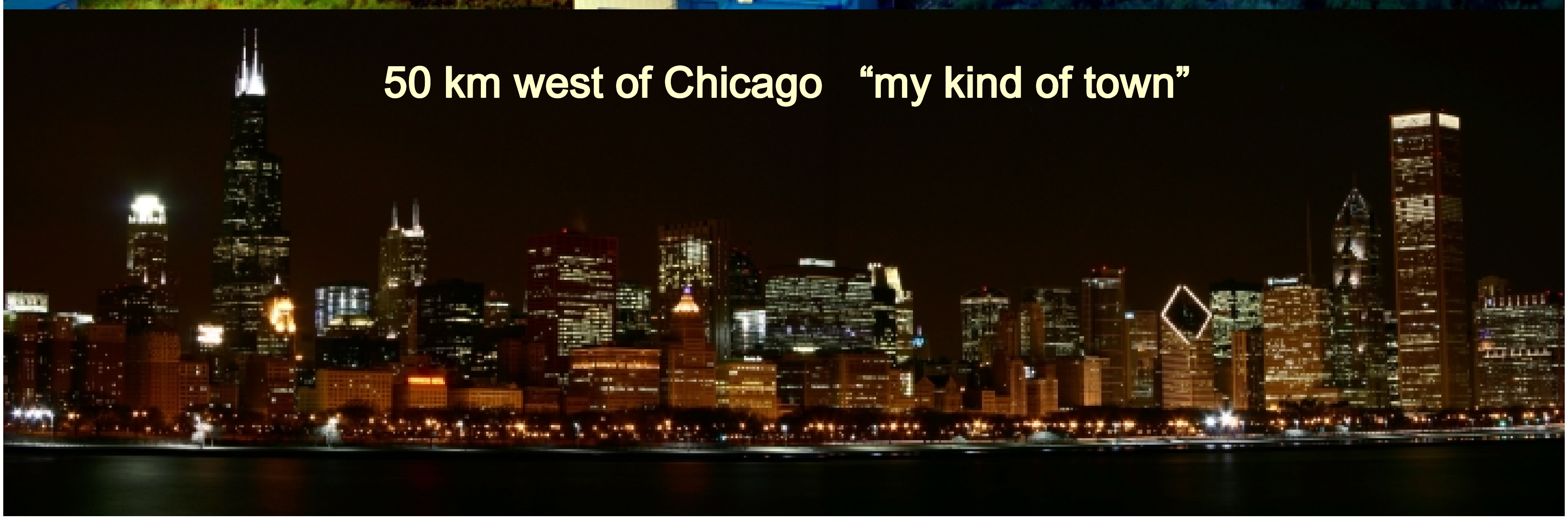
CERN June 2-6, 2008

Outline

- Intro
  - Particle accelerators
    - A few words about Fermilab & Tevatron
  - Magnets for particle accelerators
- Superconductors
  - Available materials
  - Options for accelerator magnets
  - Nb_3Sn conductors
  - Case study: stability in Nb_3Sn conductors

  - Plan for next lessons
  - References


Fermi National Accelerator Laboratory


50 km west of Chicago “my kind of town”

Tevatron

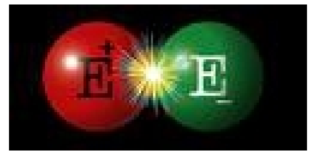
- **Fermilab is the US lab dedicated to High Energy Physics.**
- **It's home to the Tevatron**
  - **Still the world's highest-energy particle accelerator**
- **Energy: ~ 1 TeV (980 GeV)**
  - **99.9999 % of the speed of light in a vacuum**
  - **Energy ÷ B x radius**
- **Circumference: 6.4 Km**
- **Main dipoles: 4.2 T**
- **Peak luminosity: 3.2 10^{32}**
  - **Proton – Antiproton**

Why particle accelerators?

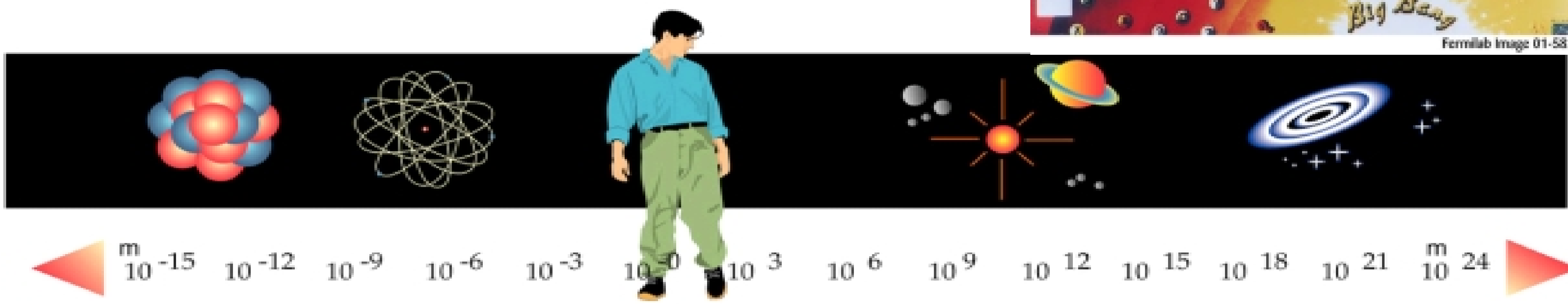
Why magnets in particle accelerators?

Particle accelerators

- Discover new particles
  - E=mc²

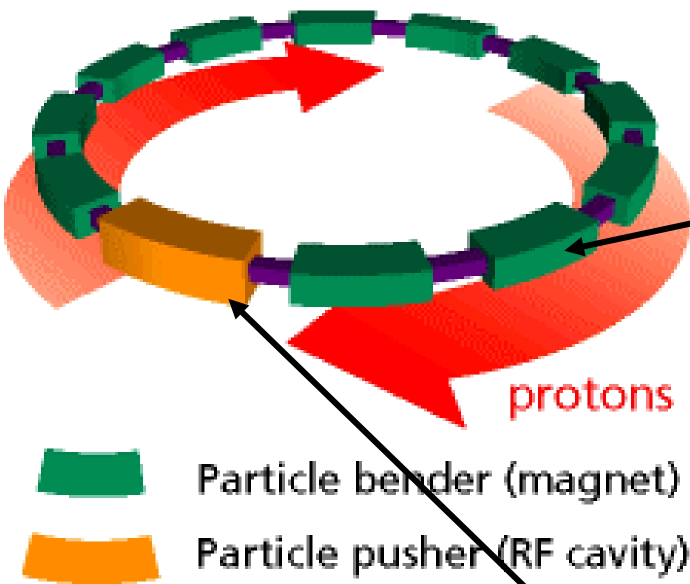


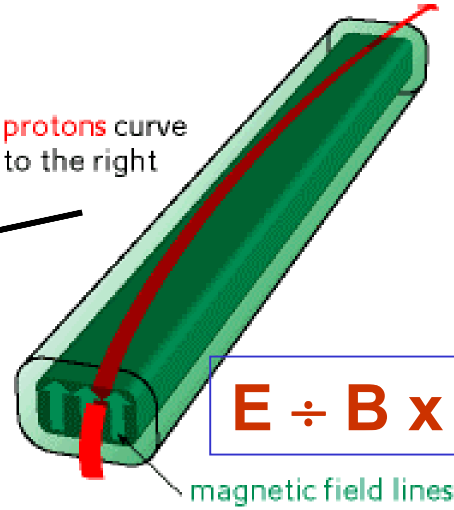
- Reproduce early Universe
  - TeV ➔ 1 ps = 10^{-12} s
- Explore the smallest distances
  - 1 Tev ➔ 10^{-18} m



Accelerators	Microscopes	Binoculars	Optical and radio telescopes

Hadron Collider Concept

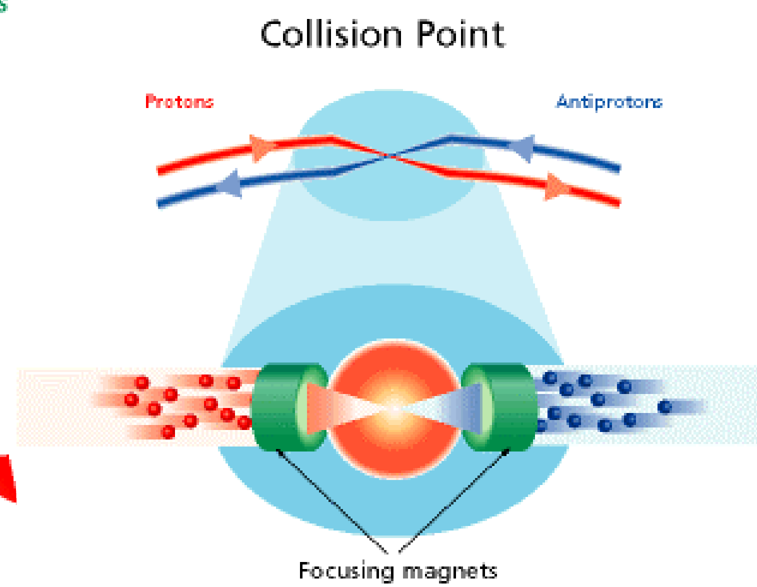




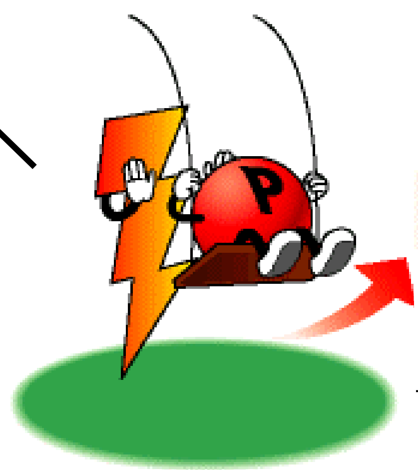
$E \div B \times R$

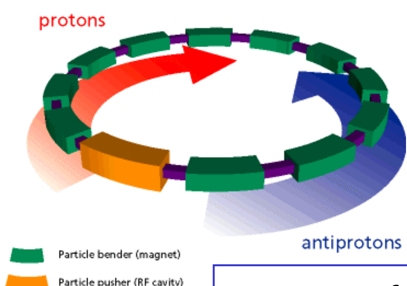
Quadrupole magnets
to keep the particles in the beam
➔ ***Lattice Quadrupoles***

Special quadrupole magnets
To focus the beams in the
Interaction Regions
➔ ***IR Quadrupoles***



With the right timing, the electric field pushes the proton.





In case of PP machine
➔ *2 rings of magnets*

Magnets in colliders

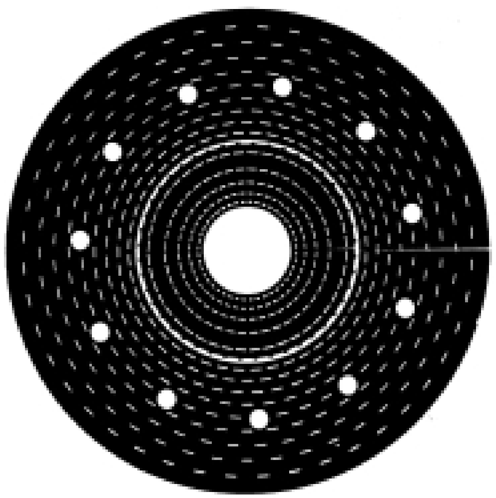
- *Main dipoles* to bend the beam
  - Higher field ➔ higher energy
- *Main quadrupoles* to keep the beam together
- *Corrector magnets* to preserve beam quality
- *Interaction Region quadrupoles* to focus the beam at interaction points
  - Higher gradients and aperture ➔ higher luminosity

Why superconducting magnets?

We need SC magnets

- Iron dominated magnets limited by iron saturation at 2 T
- Permanent magnets practically limited in the range 1-2 T
- Copper (or Al) dominated magnets 50-100 T but for ms !

With excessive power consumption



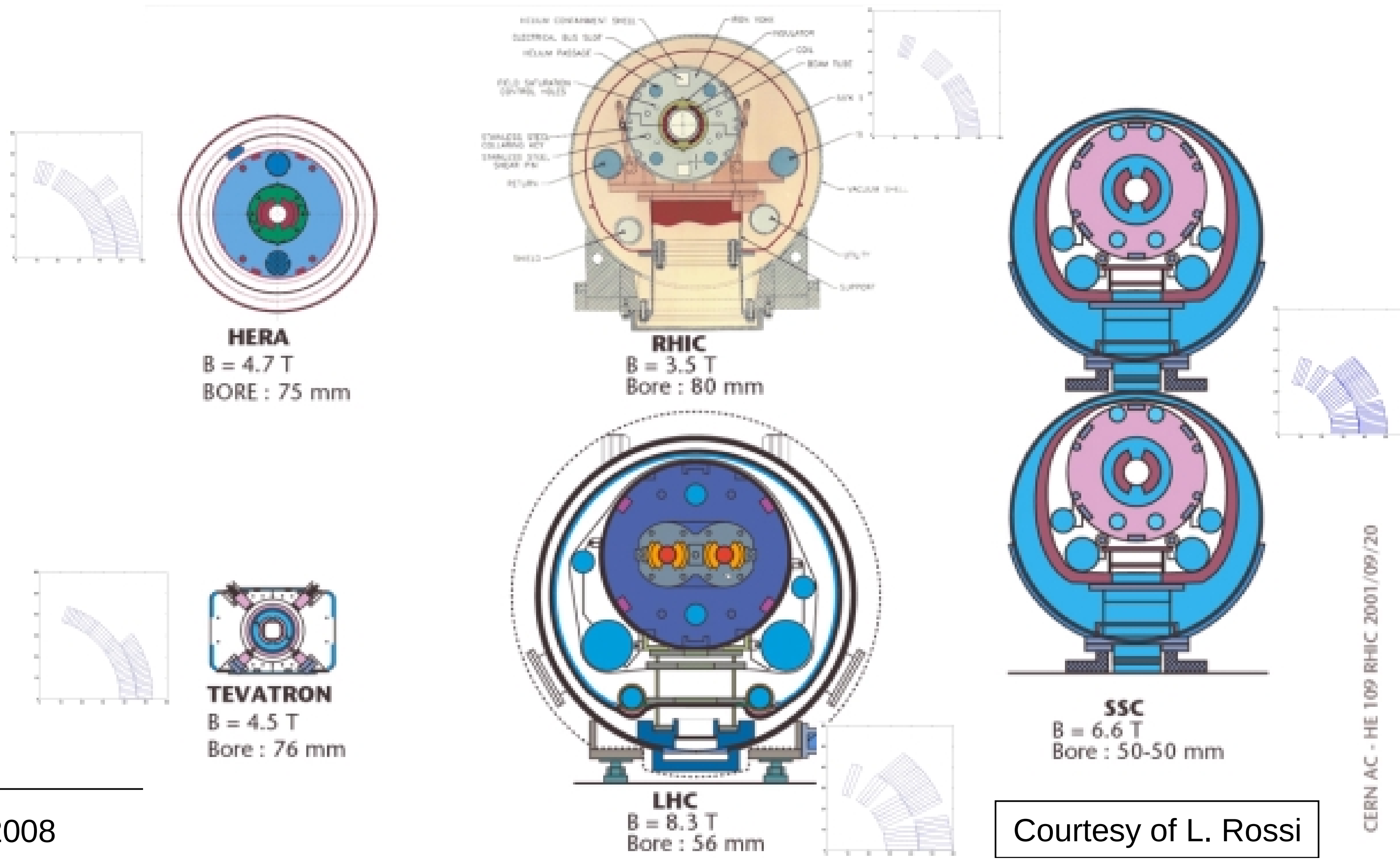
Disk of Bitter magnets (up);

pulsed cryogenic magnet for 40 T - 5 ms

Courtesy of L. Rossi

SC Magnets for Particle Acc.

- Superconducting magnets are an enabling technology for high energy hadron colliders



Courtesy of L. Rossi

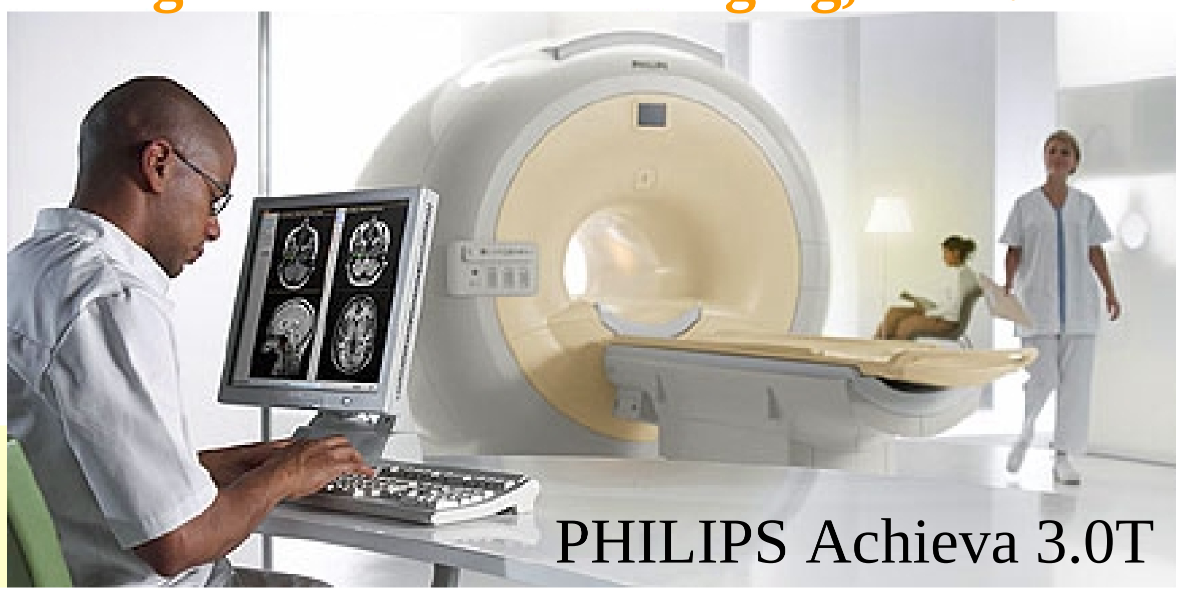
The beginning … with a footnote

- At the project's start in 1974, the worldwide annual production of niobium-titanium (NbTi) was very few hundred Kg.
- The manufacture of the Tevatron magnets required more than 62000 Kg of NbTi

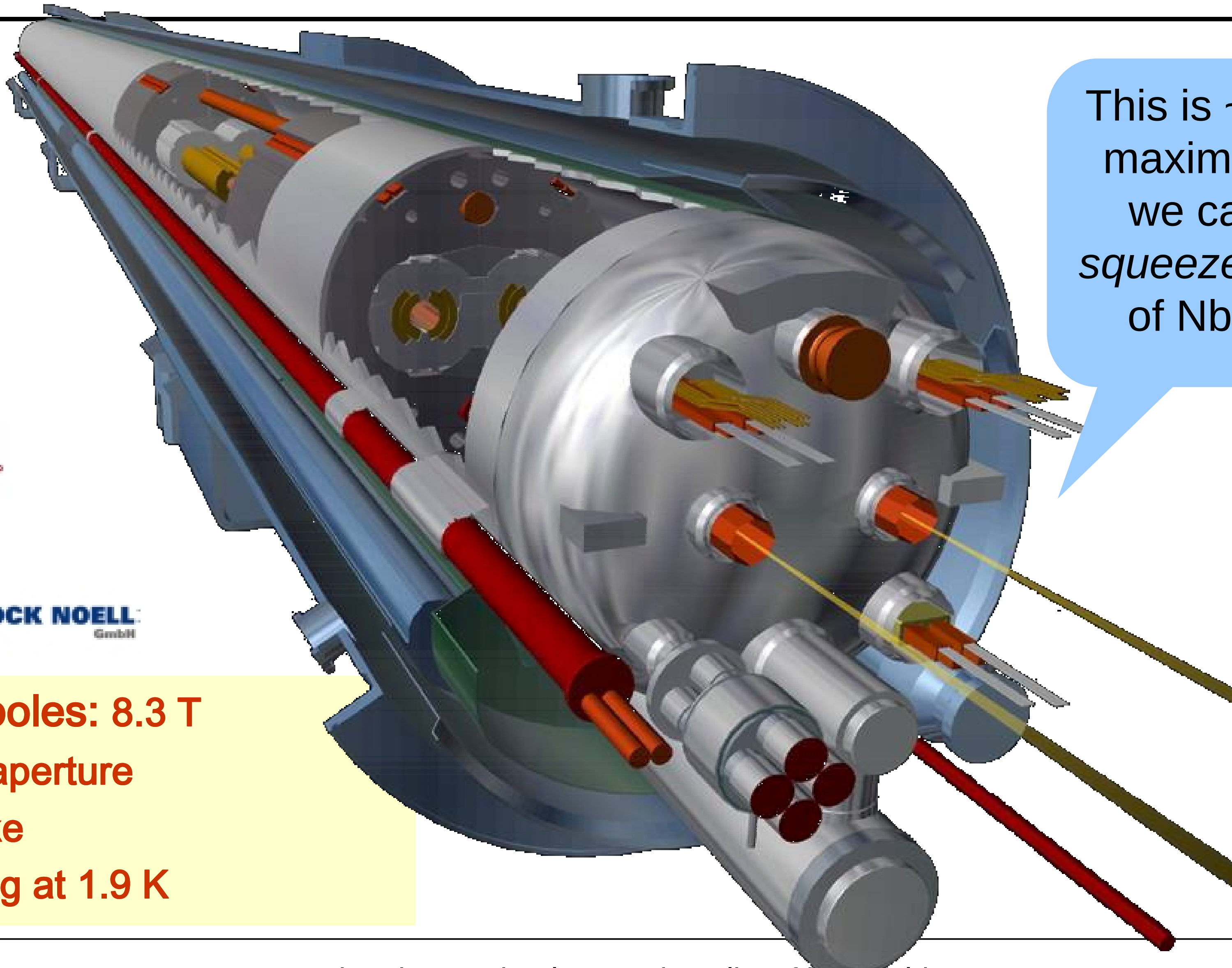
Tevatron dipoles: 4.2 T
single aperture, warm yoke

" The manufacturing technology and capacity developed in response to this demand made possible a new medical diagnostic method "

magnetic resonance imaging, MRI.



State of the art



This is ~the maximum we can *squeeze* out of NbTi

LHC dipoles: 8.3 T
- double aperture
- cold yoke
- operating at 1.9 K

How can we go beyond NbTi?

➔ High Field superconducting magnets

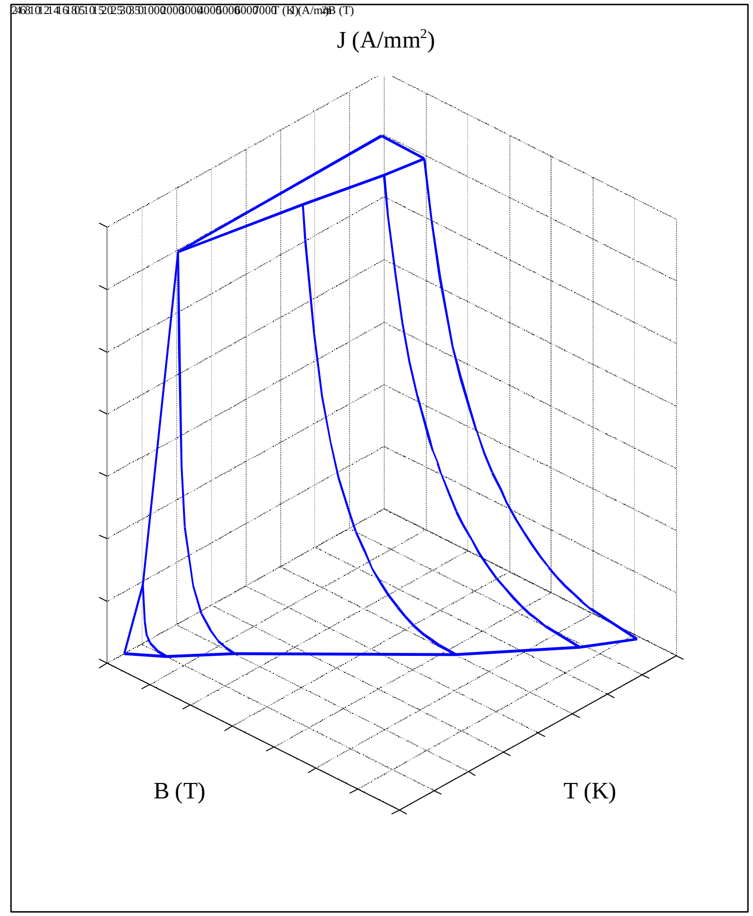
Usable Materials

It's a long journey from material discovery to magnet application…

Iwasa table on the long route

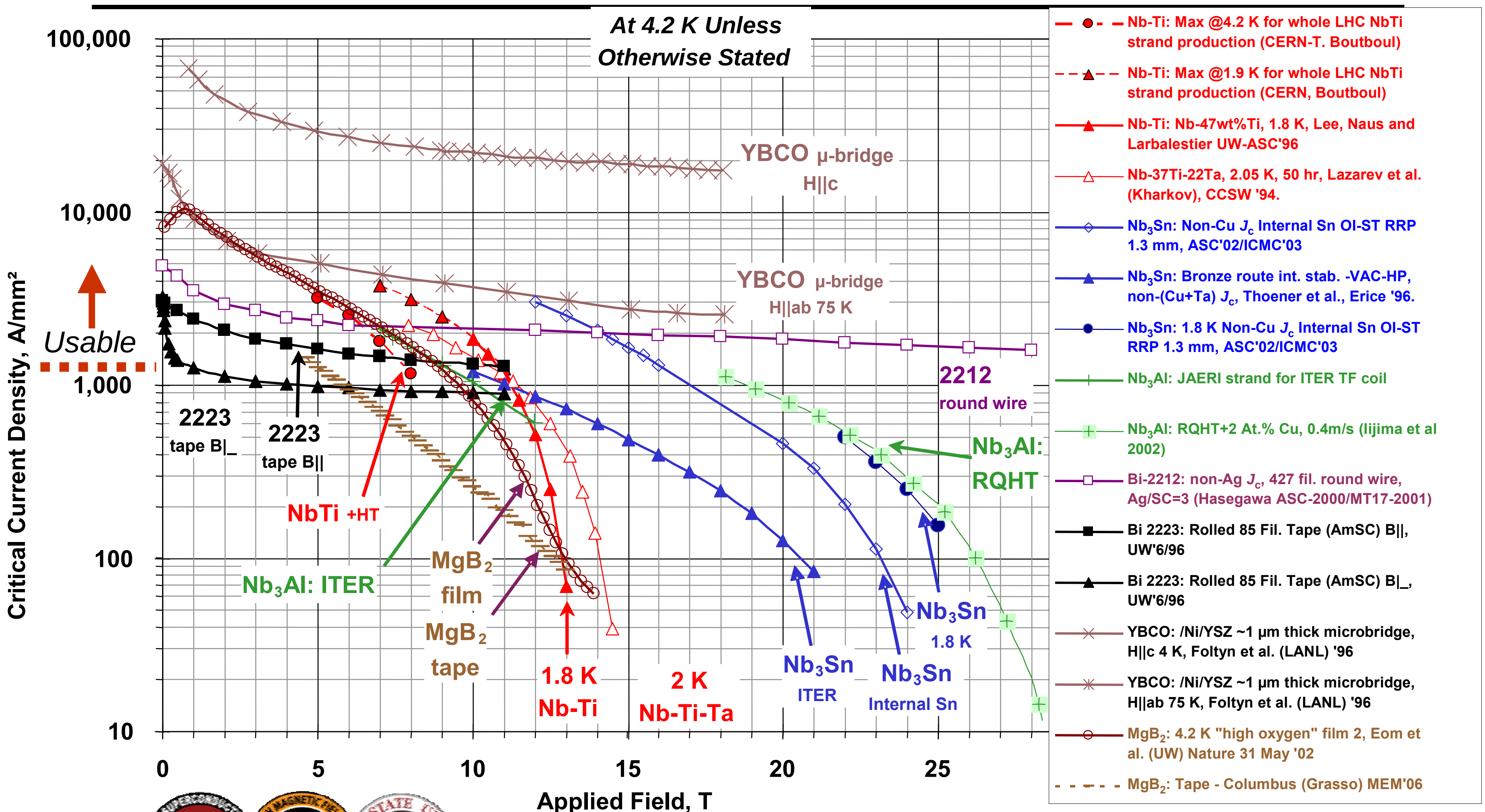
Criterion	*Number*
Superconducting	~ 10,000
$T_c \cong 10$ K and $B_{c2} \cong 10$ T	~ 100
$J_c \cong 1$ KA/mm^2 @ B > 5 T	~ 10
Magnet-grade superconductor	~ 1

Now there may be a few more…



Critical surface for Nb_3Sn
INFN-LASA, 1999

“Available” Superconductors

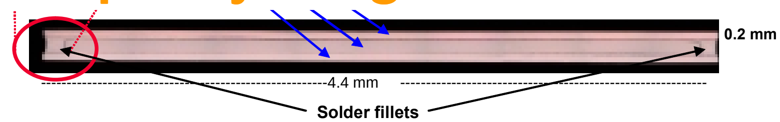


http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html

Options for Acc. Magnets

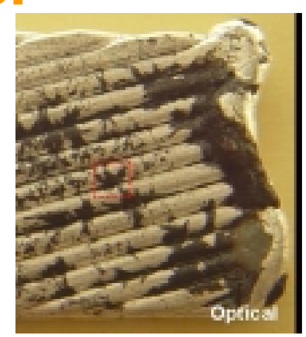
- YBCO and Bi-2223 are made in tapes:
  - Not possible or very difficult to have the twist and transposition needed for accelerator quality magnets

Perpendicular cross section of a 4.4 x 0.2 mm “344” wire
Cu stabilizer on both sides



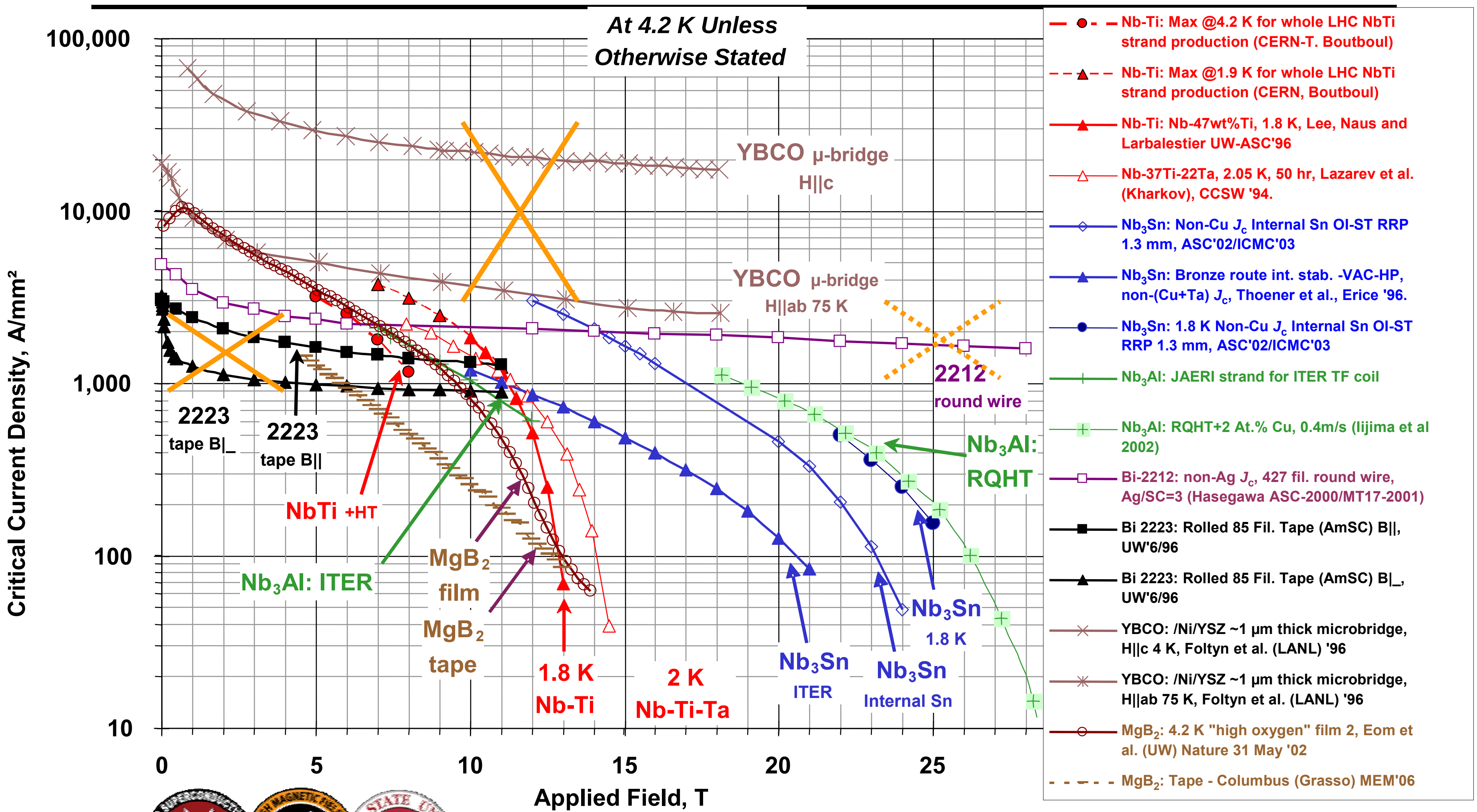
Courtesy: E. Barzi

- Bi-2212 can be made in round strands and Rutherford cables:
  - Needs heat treatment at high temperature in controlled oxygen atmosphere with very tight specs.
  - Large degradation in cables due to contamination and leakage of HTS from silver matrix



For more info about conductors see references at the end

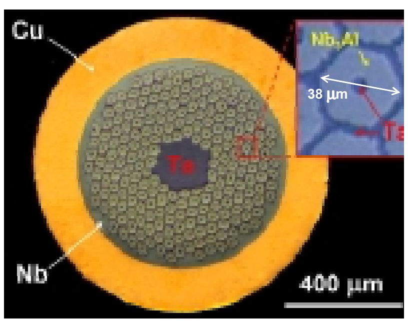
A few left…



http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html

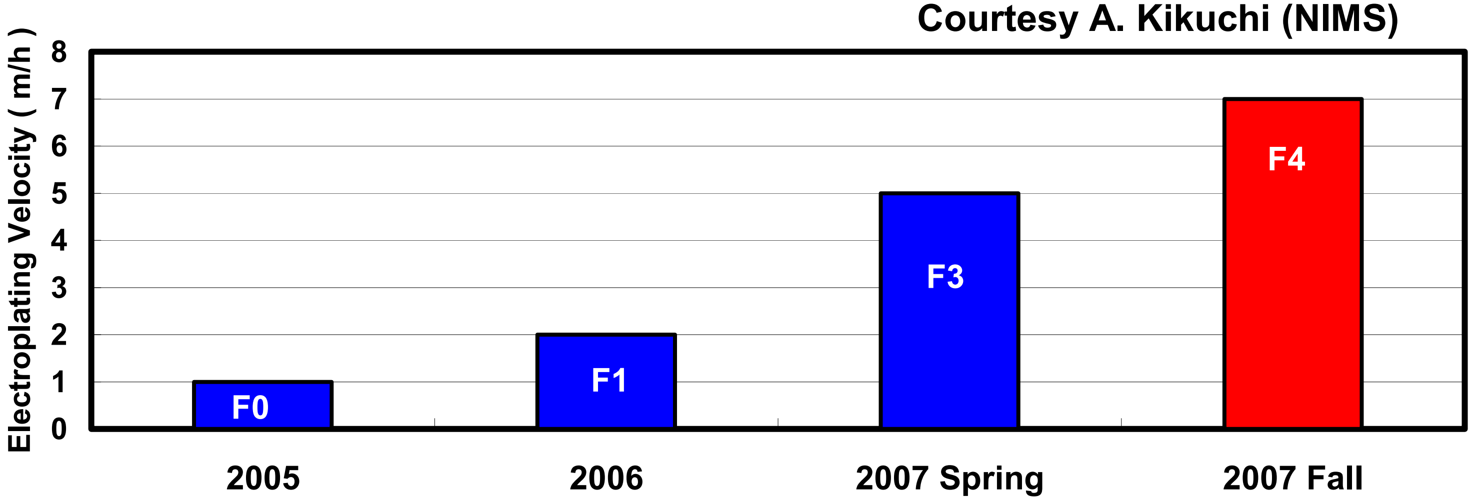
Options for Acc. Magnets II

- Nb_3Al and Nb_3Sn belong to the same family of LTS
  - they are both strain sensitive
  - Nb_3Al is much less strain sensitive than Nb_3Sn
- The problem with Nb_3Al is to add a stabilizer
  - Good progress through NIMS-FNAL collaboration, but it's still a long way…



Courtesy: E. Barzi

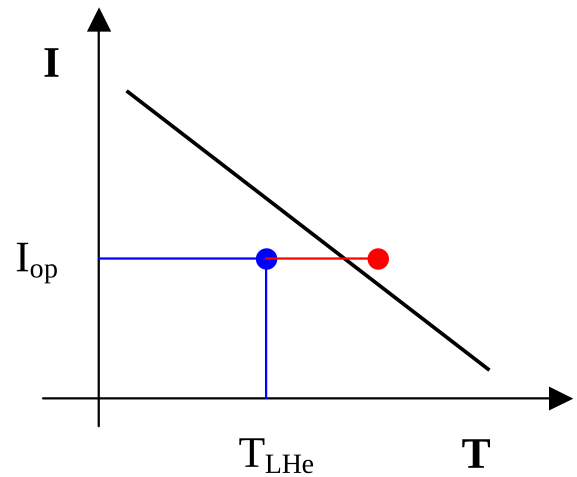
Courtesy A. Kikuchi (NIMS)



Supercond. are not stable

A conductor made of superconducting material only, is NOT stable against small perturbations. ΔE of μJ or even nJ are enough to drive superconductor normal.

Heat capacity drops at low temperature:
$C \propto T^3 \Rightarrow \Delta T = \Delta E/\gamma C$. So even small ΔE generates sensible Δ T
⇒ operating point of the magnet beyond critical surface ⇒
QUENCH

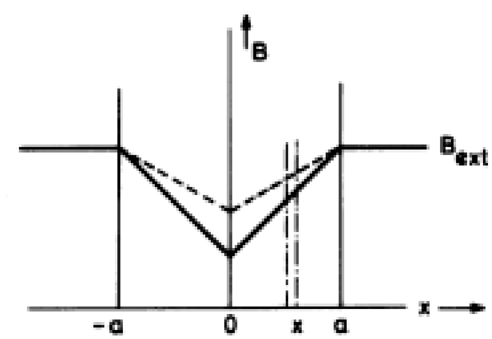


ΔE is given by :

❑**Movements** of the order of 1 μm ! $\Delta E/Vol = J\ B\ \delta \approx 10^9\ 10\ 10^{-6} = 10\ kJ/m^3$
$\gamma\, C \approx$ 1-5 kJ/m^3 for NbTi and NbSn ⇒ $\Delta T \approx$ 2-10 K !

❑**Cracking of the resins** (used to impregnate coils)

❑**Flux Jumping :** sudden rearrangement of the magnetic flux inside the material, due to temperature dependence of the J_c on the temperature.



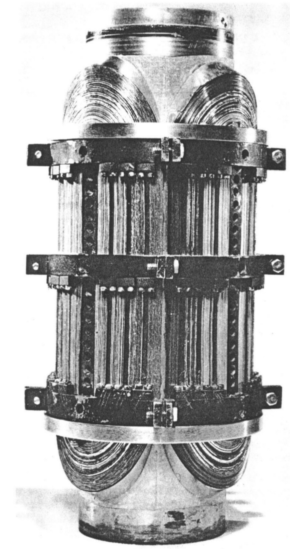
Courtesy of L. Rossi

Closer look at Nb_3Sn

- Better performance (~50%) at 4.2 K than NbTi at 1.8 K
- Larger temperature margin
- Development of Nb_3Sn magnets started in the 60's†

BNL 76 mm aperture Quad from Nb_3Sn Tape

W. B. Sampson, MT-2 1967



†Nb_3Sn accelerator magnet development around the world
M. J. Lamm; *Applied Superconductivity, IEEE Transactions on* Volume 13, Issue 2, Part 2, June 2003 Page(s):1278 - 1283

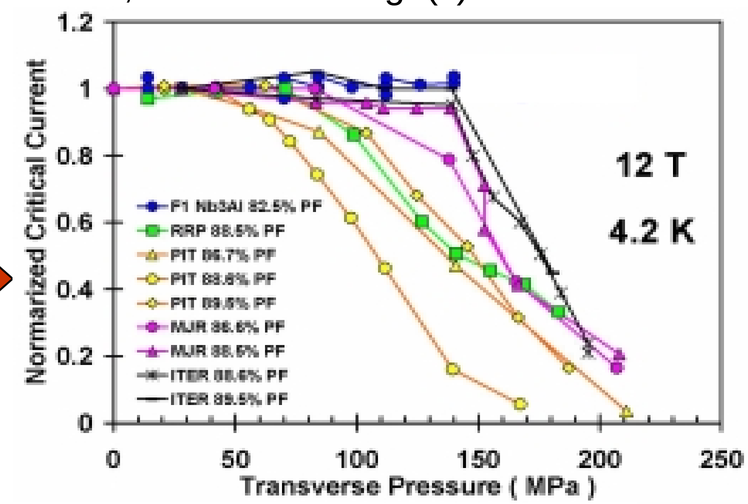
Why not yet?

"Why there are no Nb_3Sn magnets in any HE accelerator?"

Because Nb_3Sn is a brittle material

➔ Large degradation at longit. strain > 0.4%

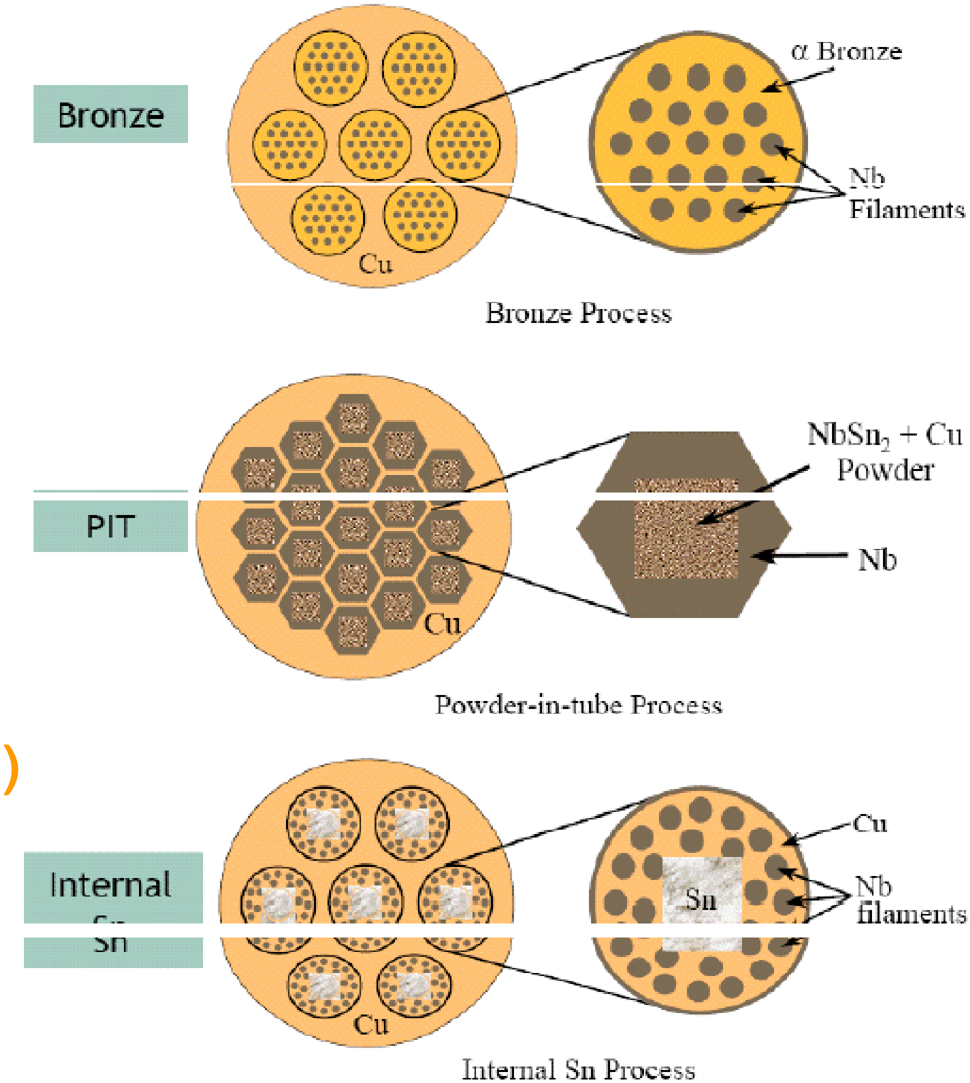
➔ Degradation at transv. pressure > 150 MPa



E. Barzi

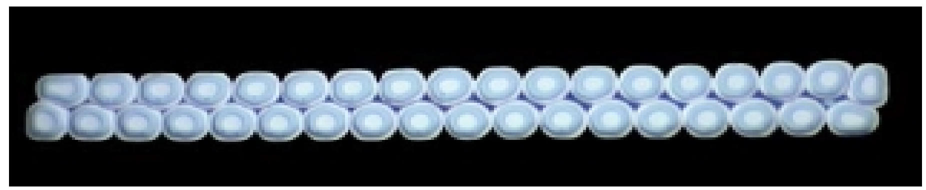
Nb_3Sn strand fabrication

- Bronze method
  - Jc is limited by Sn % (-)
  - Very thin filaments (++)
- Powder in Tube
  - Thin filaments (+)
  - Expensive (-)
  - Cabling properties of high-Jc strands?
- Internal tin
  - Has many variants
  - Presently best performance: (+)
    - RRP: 3000 A/mm^2 at 12T 4.2K
  - Large effective filaments (-)



Rutherford Cable

- **Needs:**
  - High packing factor
  - A simple system to keep the strands together
  - 10-20 kA cable for magnet protection



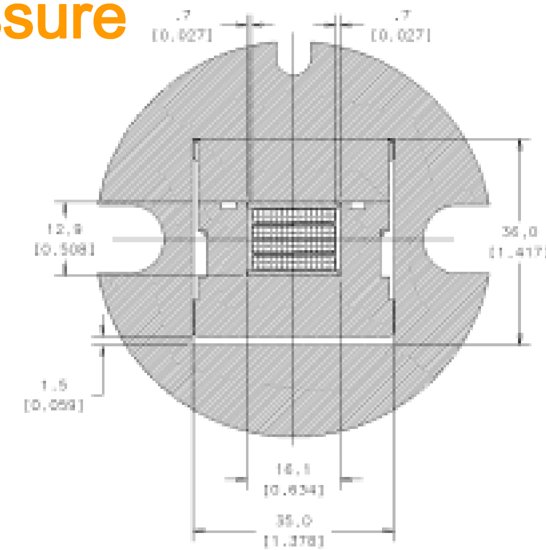
Nb_3Sn conductor characterization

Strand characterization

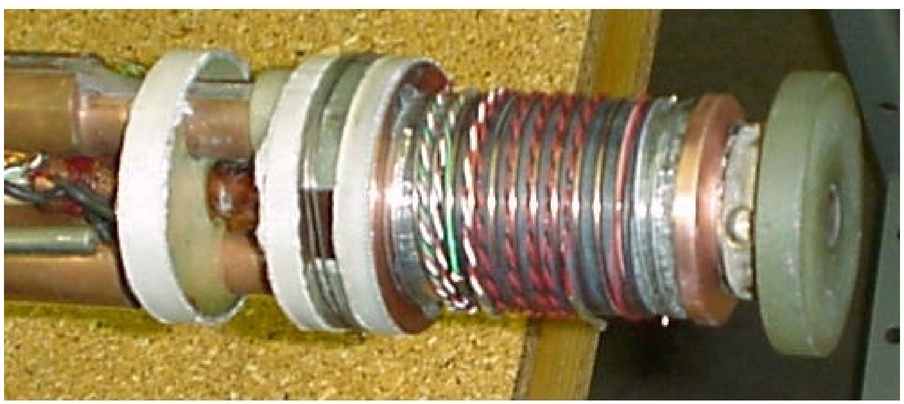
- Ic vs B and T
- Ic vs strain
- Magnetization
- Stability

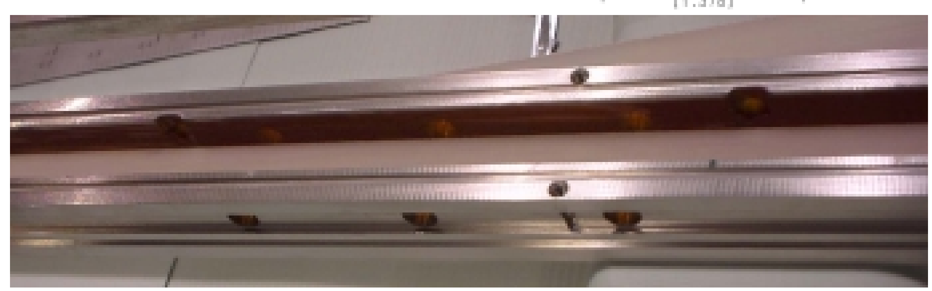
Cable characterization

- Ic vs B and T
- Ic vs pressure
- Stability



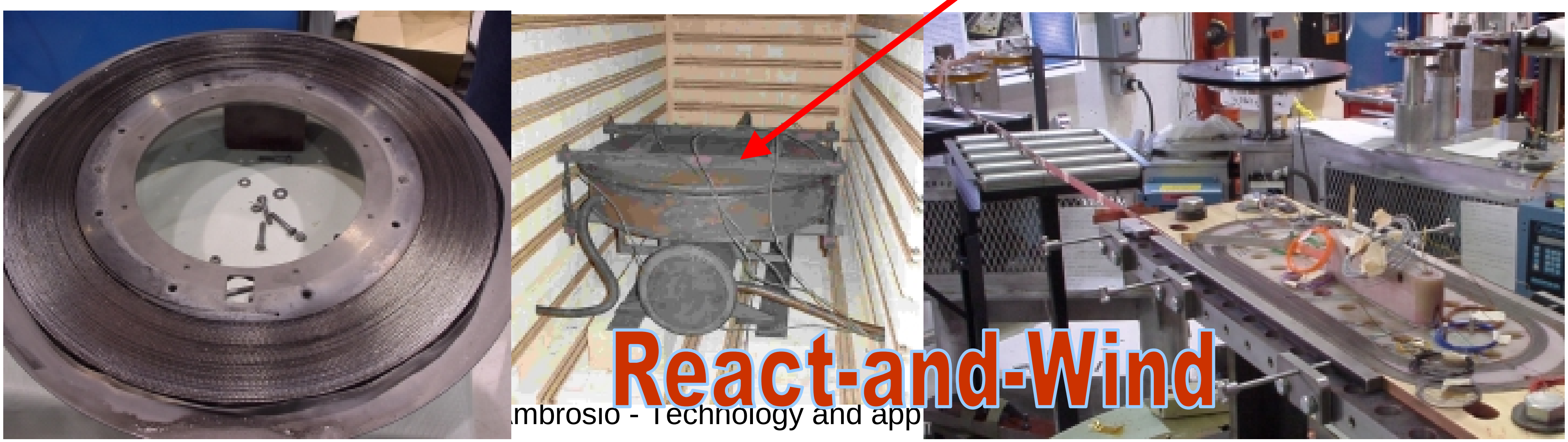
Short Sample Limit





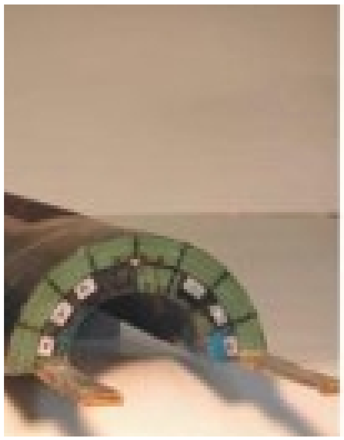
Fabrication Technologies

(Nb + Sn) in Cu matrix ➔ Nb_3Sn during heat treatment at 630-700 ^oC



Past Nb_3Sn Magnet R&D

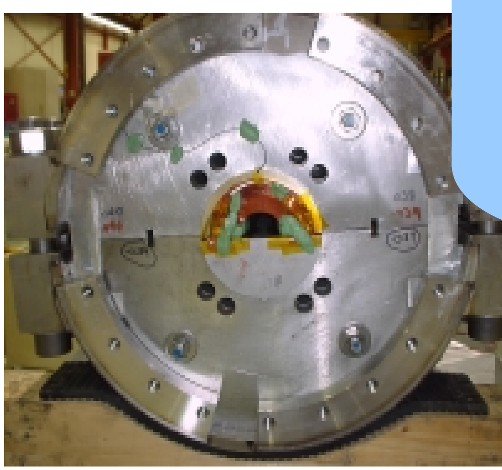
- A few of many successful Nb_3Sn short models



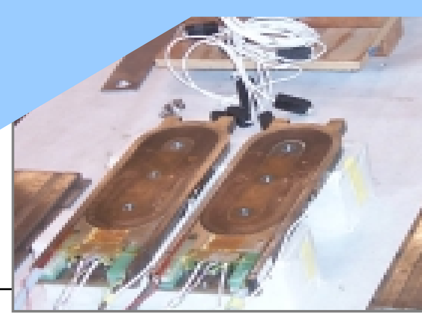
Twente University

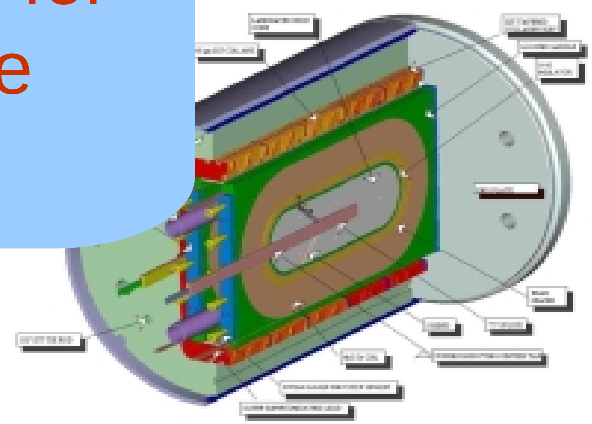
LBNL HD1

Is Nb_3Sn magnet technology ready for use in a particle accelerator?



FNAL HFM Mirror





BNL 12 T Nb3Sn R&W Magnet

LARP

"The US LHC Accelerator Research Program enables U.S. accelerator specialists to take an active and important role in the LHC accelerator during its commissioning and operations, (…) and to be a major collaborator in LHC performance upgrades"
(mission statement)

Magnet R&D (FNAL, BNL, LBNL) goal:

"Demonstrate that Nb_3Sn magnets are a viable choice for an LHC IR upgrade"

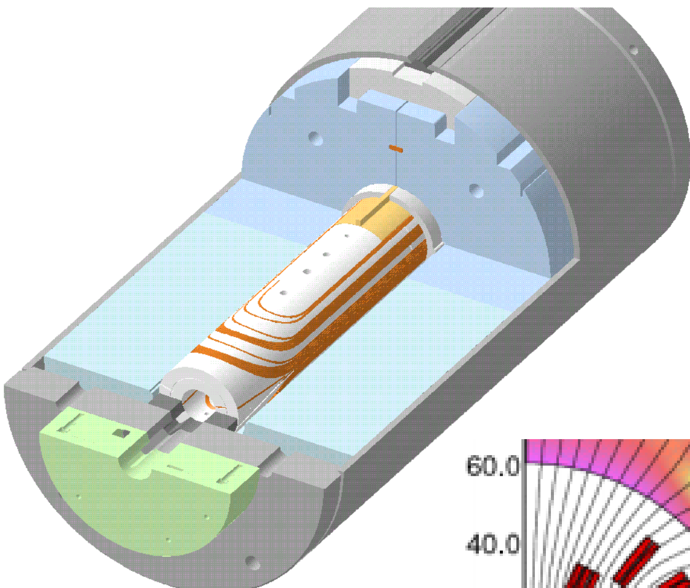
Including the development of the first Long Nb_3Sn Quadrupoles

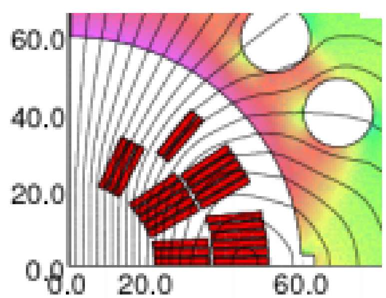
4 m long, 90 mm aperture, G_{nom} > 200 T/m, B_{coil} > 12 T

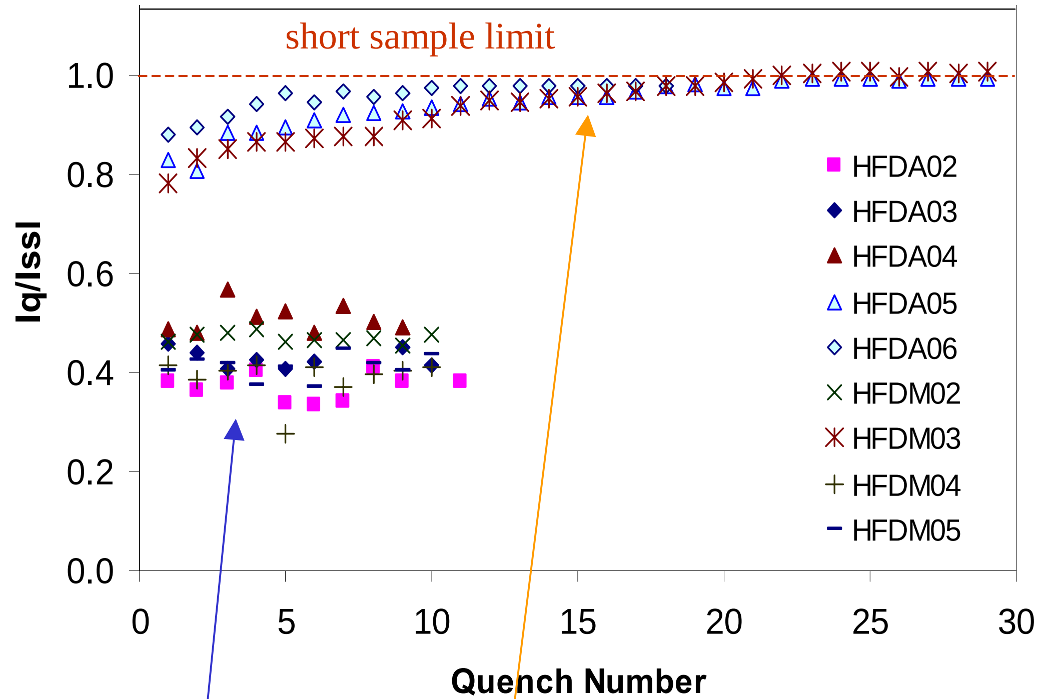
Case Study:
Instability in Nb_3Sn wires

The problem

- FNAL HFDA dipole main features:
  - B_{max} =12 T
  - I_{max} = 21.2 kA
    - Jc = 2000 A/mm² (12T 4.2K)
  - 1 mm diam strands





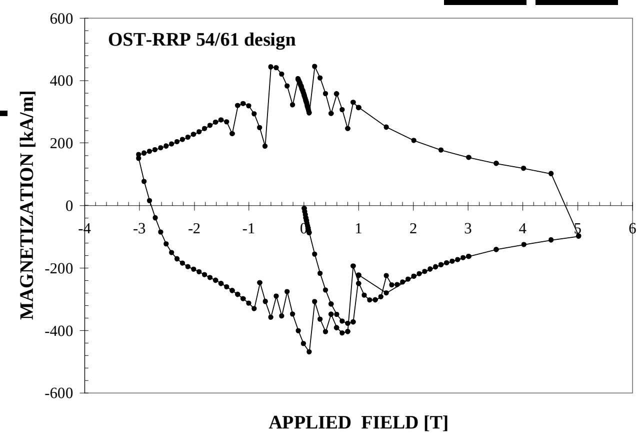


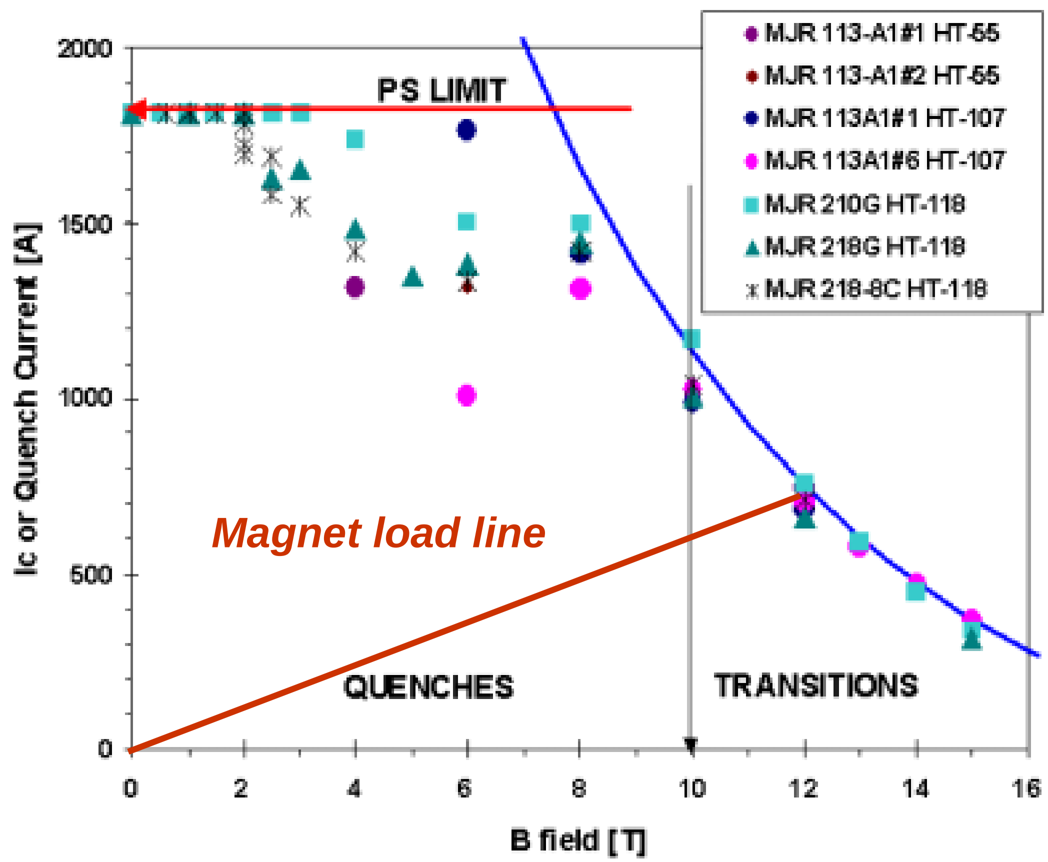
- Limited performance in 2001-2002
- Close to SSL in following years
  - ➔ with different conductor

First studies

Possible causes:

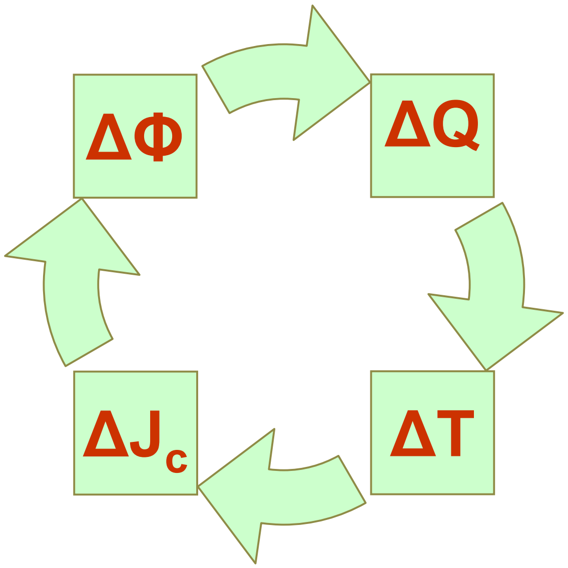
- Filament size is too big
  - 110 μm
- RRR is too low
  - $R_{Cu300K}/R_{cu4.2K}$
  - RRR=10
- Conductor is fine
  - Other Nb_3Sn magnets with same wire had no problems
- Copper amount is too small
  - Cu/nonCu<1

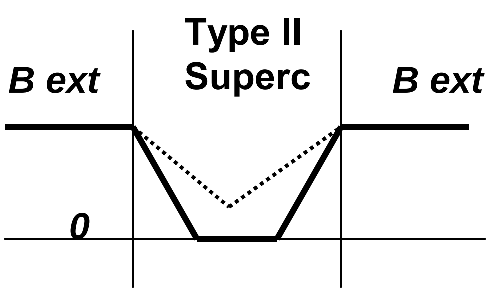


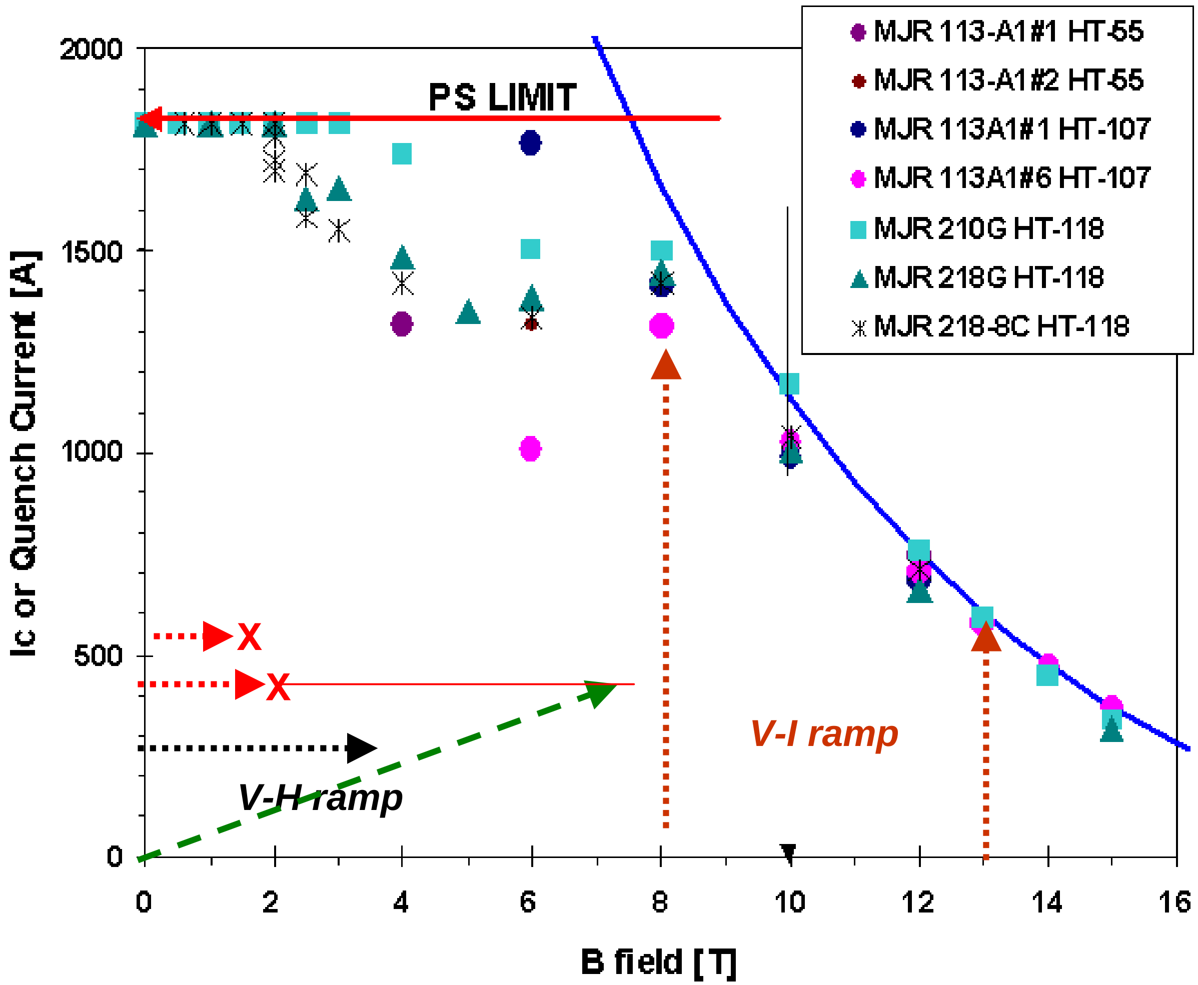


The breakthrough

- **V-H ramps** are right measurement technique for thermo-magnetic instability:

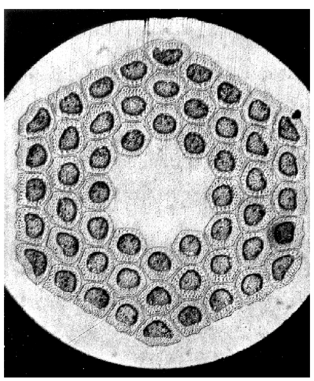






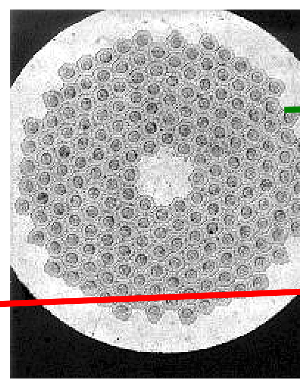
The solutions

- Short term solution:
  - High RRR (slows down flux jumps and improves heat dissipation) by reducing heat-treatment
    - Lower Jc
- Long term solution:
  - Smaller filaments (reduce or avoids flux jumps)



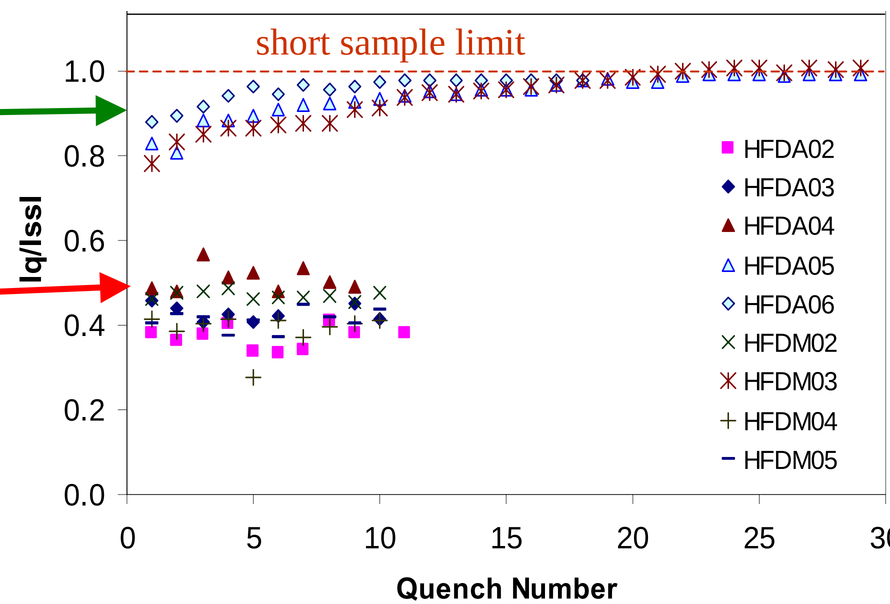
D_{eff}: 110 μm

RRR ~ 10



D_{eff}: 54 μm

RRR ~ 100



... and at 1.9K?

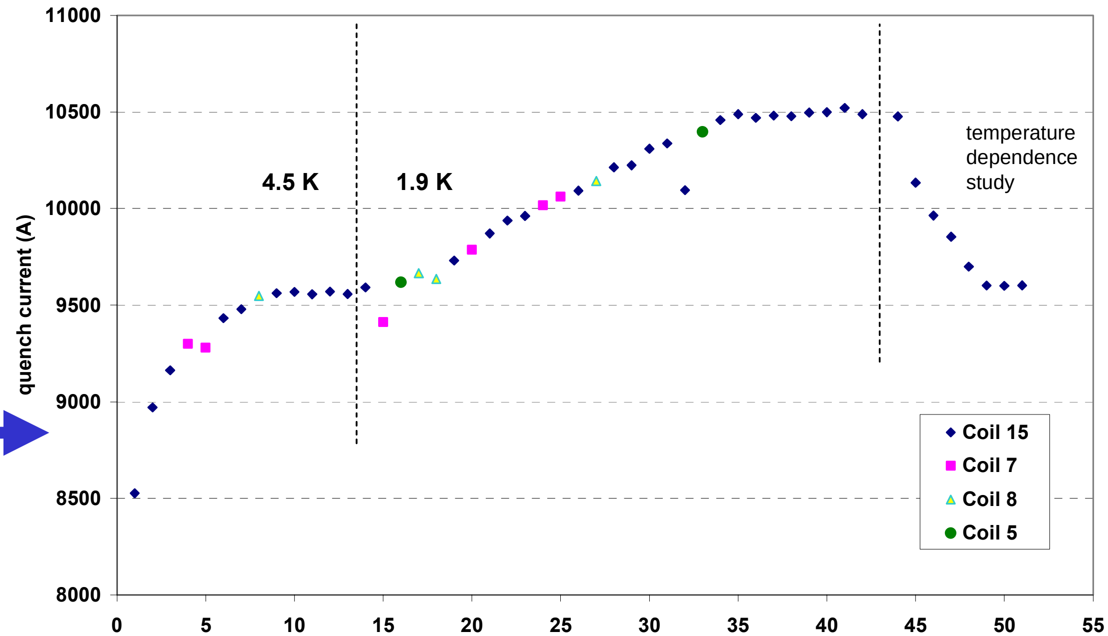
ΔI (4.5 K ➔ 1.9 K)

MJR (IT) coils:

TQS01c: ~1 kA

lower temperature

➔ higher current



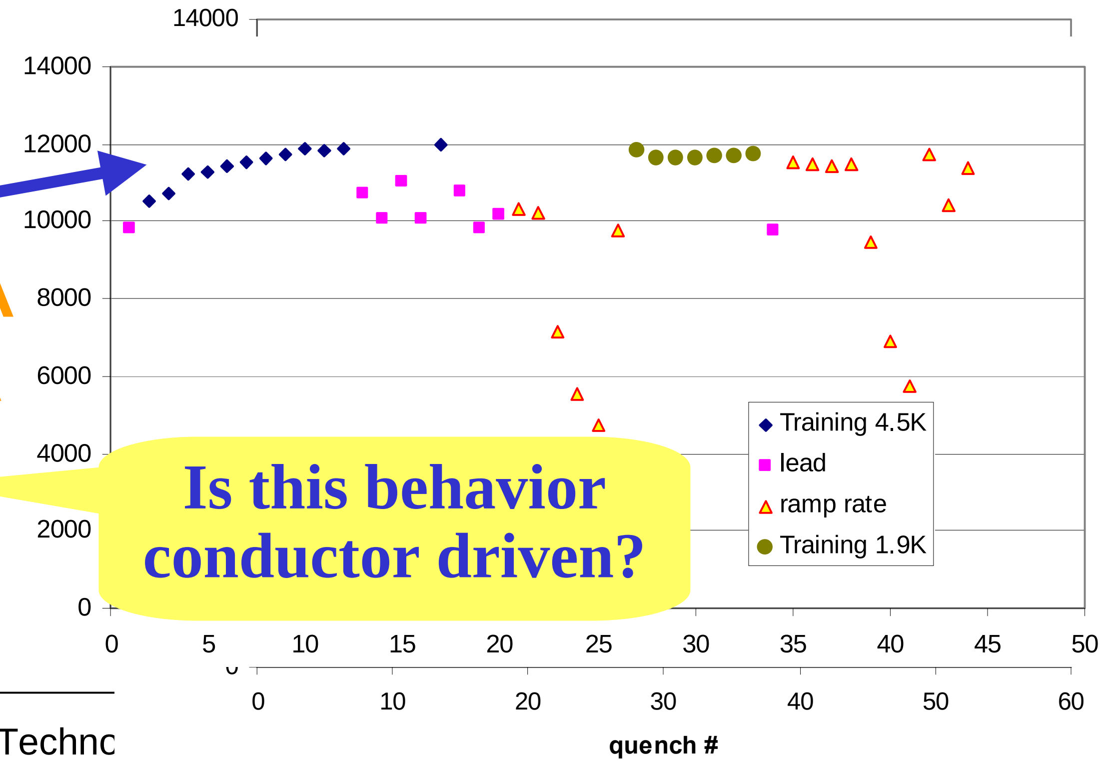
RRP 54/61 (IT) coils:

TQS02a: -750 A +400 A

TQC02e: -370 A -180 A

Lower temperature

➔ ~ same current ???



Is this behavior conductor driven?

Outline of the lessons

D1
- Introduction
- Conductors

D2
- Magnetic design
- Mechanical design

D3
- Coil fabrication technology

D4
- Magnet assembly
  - Long magnets

D5
- Quench protection design
- Cryogenic design
- Magnet test and analysis
- Lifetime issues
- Next steps

A few references (books)

Basic Superconductivity:

- M. Tinkham, *Superconductivity*, Gordon & Breach Publisher
- A.C. Rose-Innes, E.H. Rhoderick, *Introduction to Superconductivity*, Pergamon Press
- W. Buckel, *Superconductivity, Fundamental and Applications*, VCH Publisher
- J. Evetts (editor), *Coincise Encyclopedia of Magnetic and Superconducting Materials*, Pergamon Press
- H.W. Weber *High Tc Superconductivity*, Plenum Press
- G. Vidali, *Superconductivity: the next revolution* , Cambridge University Press

Applied Superconductivity

- **M.N. Wilson, *Superconducting Magnets*, Clarendon Press Oxford**
- H.A. Brechna, *Superconducting Magnet Systems*, Springer Verlag
- K.-H. Mess, P. Schmüser, S. Wolff, *Superconducting Accelerator Magnets*, World Scientific
- E.W. Collings, *Applied Superconductivity*, Plenum Press
- B. Seeber (editor), *Handbook of Applied Superconductivity*, IoP Publishing
- L. Dresner, *Stability of Superconductors*, Plenum Publ. Corp.
- Y. Iwasa, *Case Studies in Superconducting Magnets*, Plenum Publ. Corp.

Other references

- **Superconductors:**

  See the CERN Academic Training lectures:

  D.C. Larbalestier, "*Superconducting materials suitable for magnets*", 2002

  V. Palmieri, "*Applied Superconductivity: theory, superconducting materials and applications*", 2007

- **Superconducting Magnets:**

  See the CERN Summer Student lecture:

  L. Rossi, "Super-conducting magnet technology for particle accelerators and detectors", 2005

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