High Field Magnets

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CERN

CAS – Intermediate level Course
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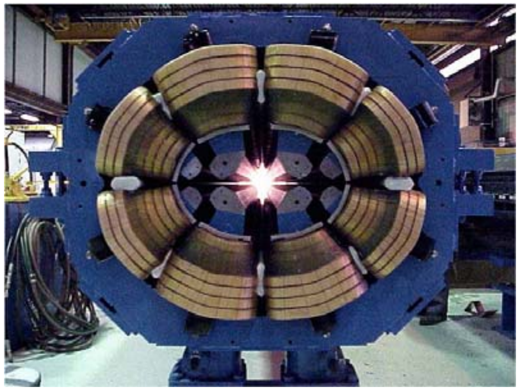
Content

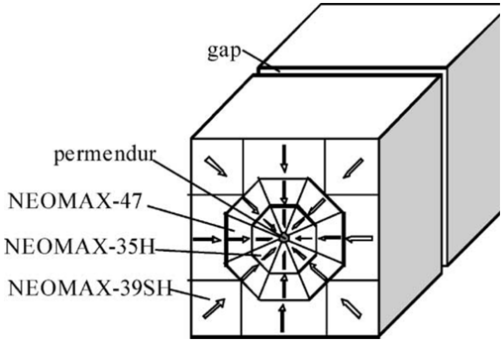
- Definition and historic
- Basic of Sc magnets for accelerator
- Superconductivity and Nb-Ti review
- Reasons to pursue HFM
  - LHC lum up (high grad quads)
  - LHC energy upgrade; upgrade of any
- Current Densities progress
- Issues: brittleness, insulation, radiation
- Structural design
- Fabrication technologies
- The perspectives and the roadmap
- Acknowledgements:
  - **A. Devred & E. Todesco CERN, G. Ambrosio FNAL, G.L. Sabbi LBNL and many others colleague of US-LARP**

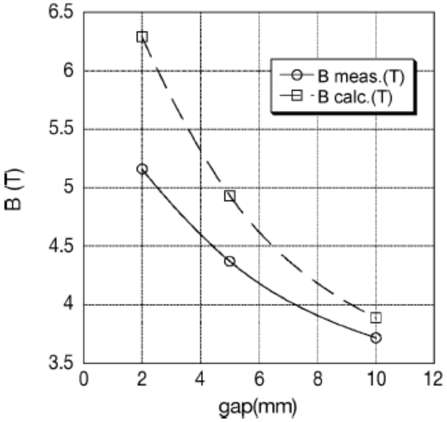
When a magnetic field is high ? - 1

- Iron dominated magnets < 2 T
- The coils are giving a minor contribution, field quality is iron dominated
- PM configuration may reach 4-6 T peak (small bore)
- Stored energy in iron is very small

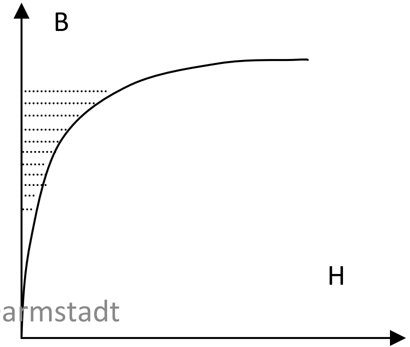
CERN LHC MQW
Twin resistive !





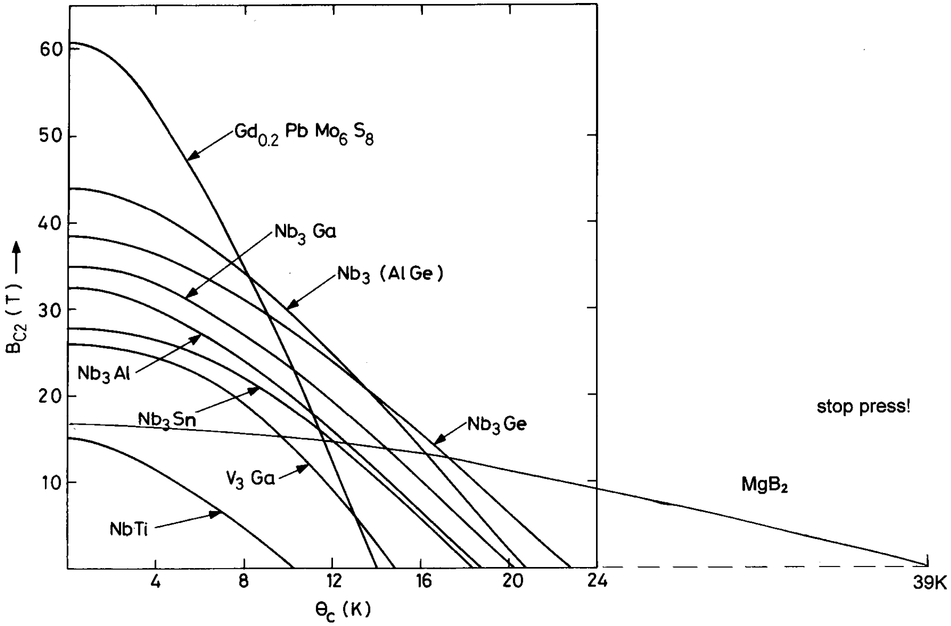


$$E = \int_V \frac{B^2}{2\mu_0} d\tau = \int_V H \cdot dB d\tau$$



When a field is high ? - 2

- Superconductor may reach more
- The field that can be reached depends on the temperature
- Sc not only reach high field but also they do not dissipate!

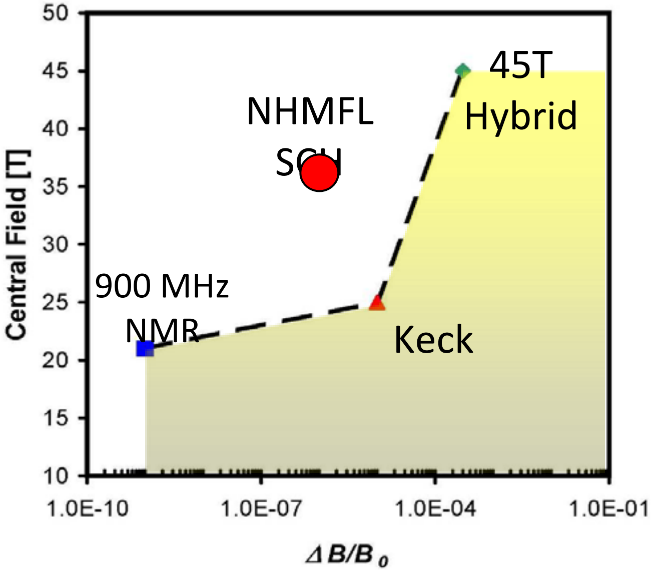


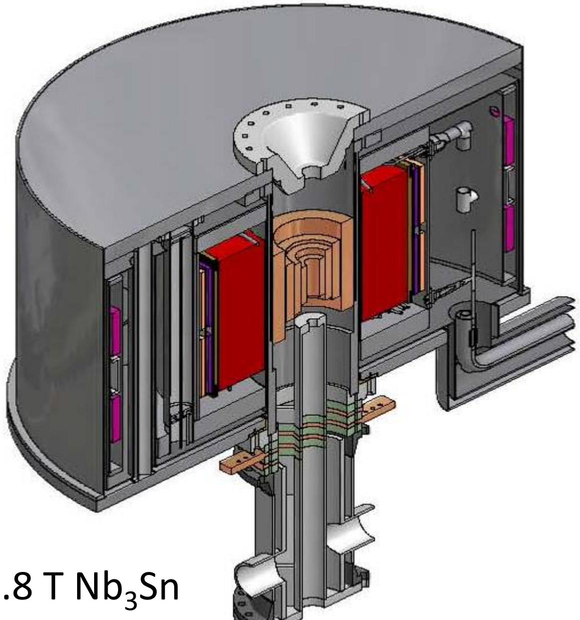
When a field is high ? - 3

- However simple copper coil cryogenically cooled (typically Liquid Nigtrogen @ 77 K) can give more…
- Resistive coils: **40 T** in LN, ∅ 20 mm 77 K bore. It relies on heat capacity of the conductor –reinforced copper reaching 300 K each shot.
- **4 milliseconds of field duration.**
- A little longer (40-100 ms ms), 10 mm bore the 60 T long pulse of NHMFL in Florida

When a field is high ? - 4

- And, surprisingly as it may be, the highest d.c. field are also obtained by copper coils !
- Field in excess of 30 T in steady state! However an enormous cooling power of 10-40 MW is needed for 50-70 mm bore
- Hybrid system (SC outsert with a resistive insert) provide the record 45 T field.



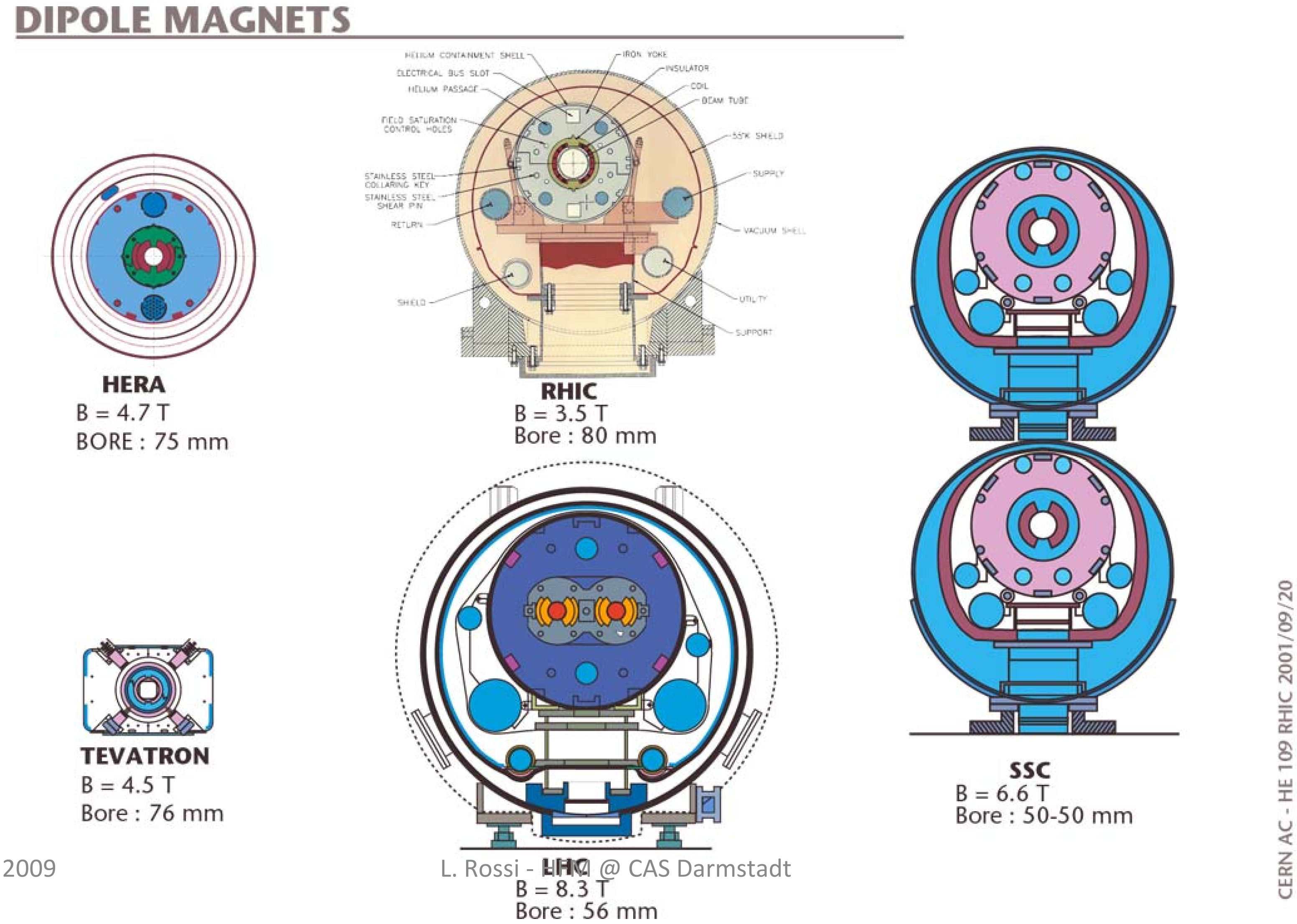


13.8 T Nb_3Sn Superconducting Outsert

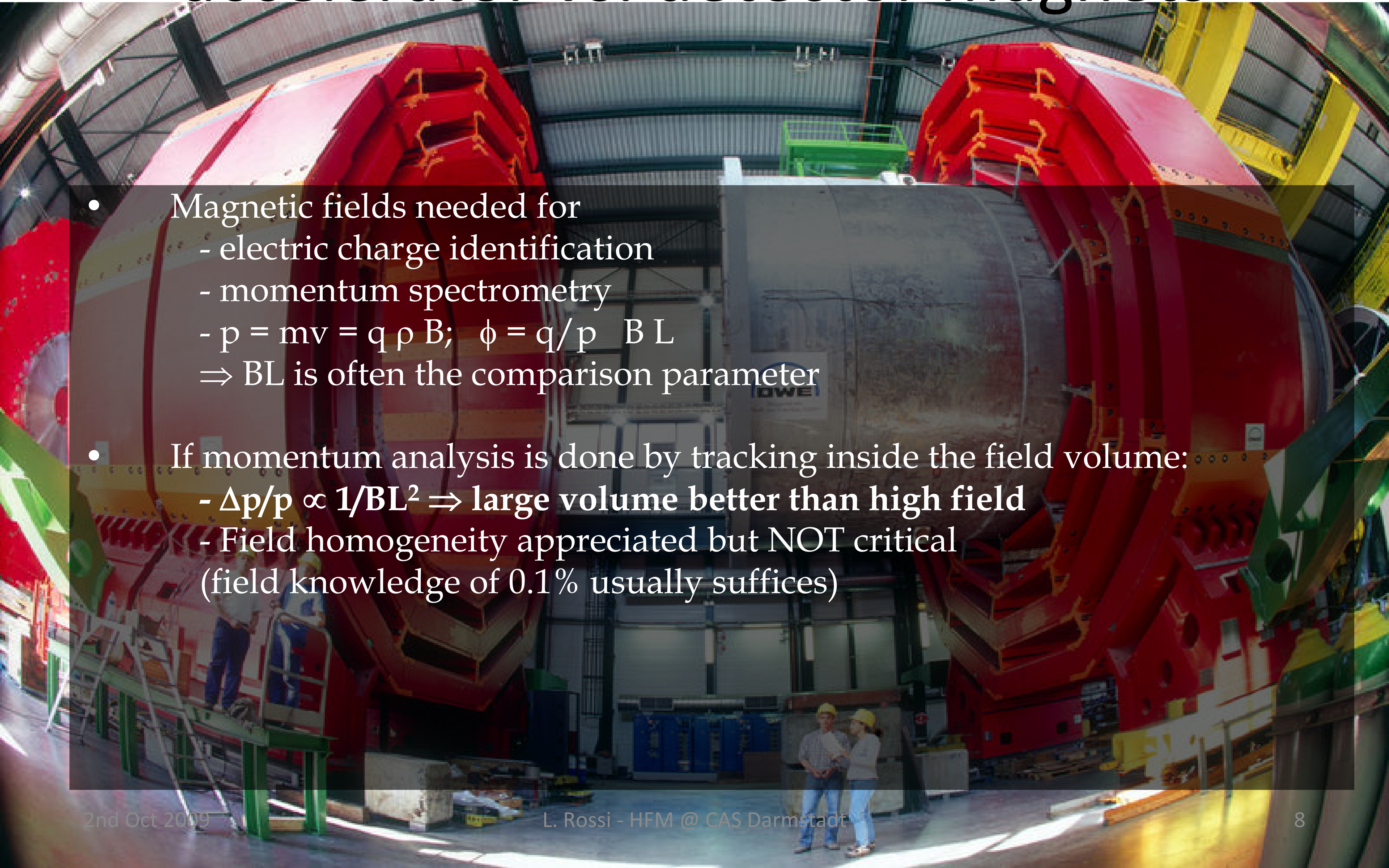
22.3 T Resistive Insert

When a field is high ? – 5

- **In practice : High Field Magnet (HFM) is what is beyond LHC, 10 T !**



High field: accelerator vs. detector magnets

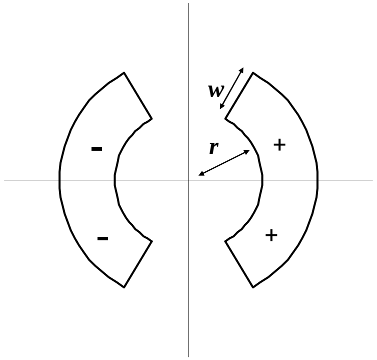


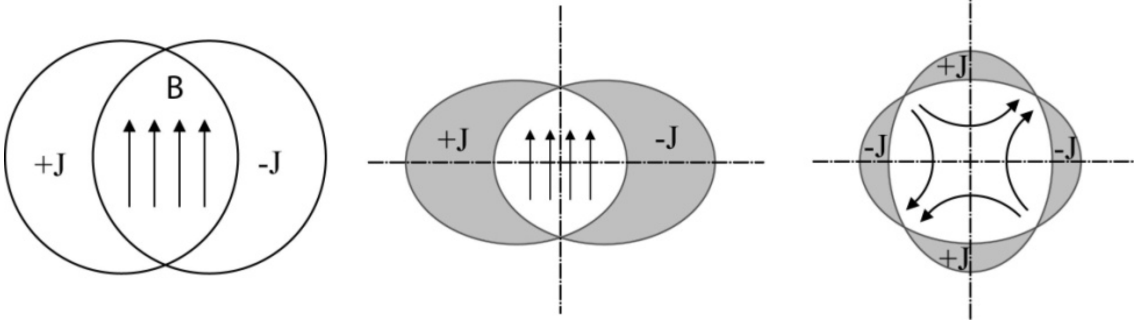
- Magnetic fields needed for
  - electric charge identification
  - momentum spectrometry
  - $p = mv = q \rho B; \quad \phi = q/p \quad B L$
  - $\Rightarrow$ BL is often the comparison parameter

- If momentum analysis is done by tracking inside the field volume:
  - **$\Delta p/p \propto 1/BL^2 \Rightarrow$ large volume better than high field**
  - Field homogeneity appreciated but NOT critical (field knowledge of 0.1% usually suffices)

Accelerator magnets : basic - 1

- Field shape DIPOLE
  - Half the field of a solenoid for same J and coil thickness
  - $J = J_0 \cos\vartheta$
- Field shape QUADRUPOLES
  - $J = J_0 \cos 2\vartheta$





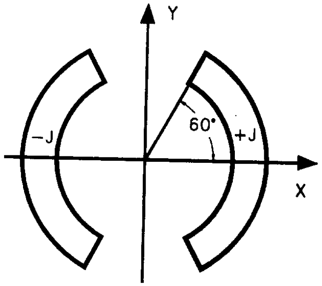
$$B_x = \frac{\mu_0 J(a-b)}{a+b}\, y$$

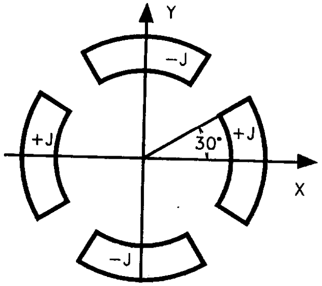
$$B_y = \frac{\mu_0 J(a-b)}{a+b}\, x$$

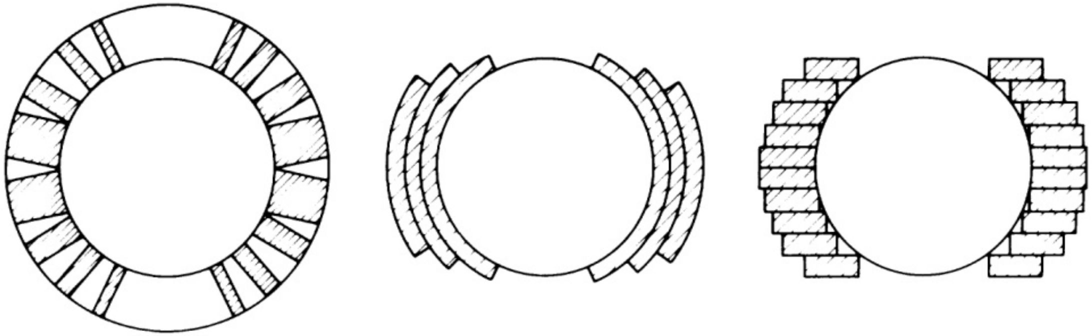
$$\mathbf{B} = \frac{\mu_\mathbf{0} Jd}{2}\mathbf{e_y} \qquad B_y = \frac{\mu_0 Jbd}{a+b}$$

Accelerator magnets : basic - 2

In practice the above current distributions are approximate, so the field contains also higher order harmonics (see later).
It can be shown that if the cos(nθ) is approximate by step function, there is a “magic” angle that makes nil the first higher order harmonics.



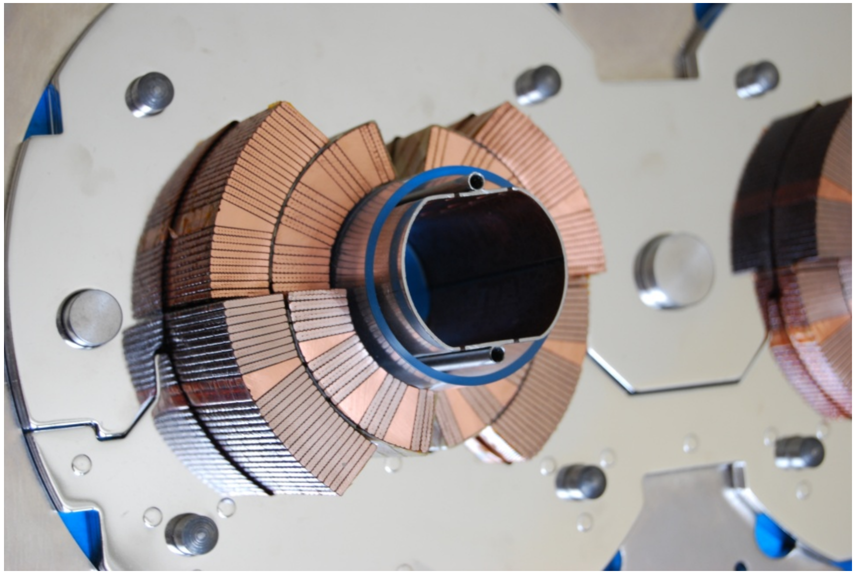




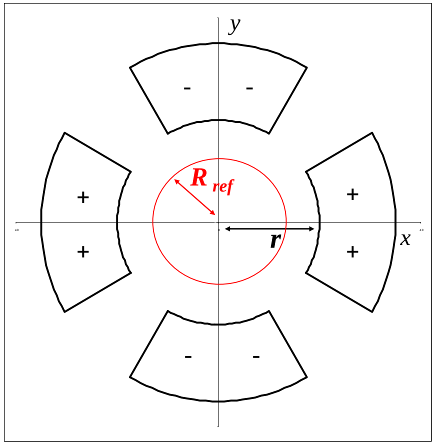
Approximation of cosθ with coil blocks (left) and multiple shells (centre) and of intersecting ellipses (from Wilson book).

Accelerator magnets : basic - 3

- The basic shape : mix between cosϑ and shell
- Shells with const J is a very good approximation
- Field expansion

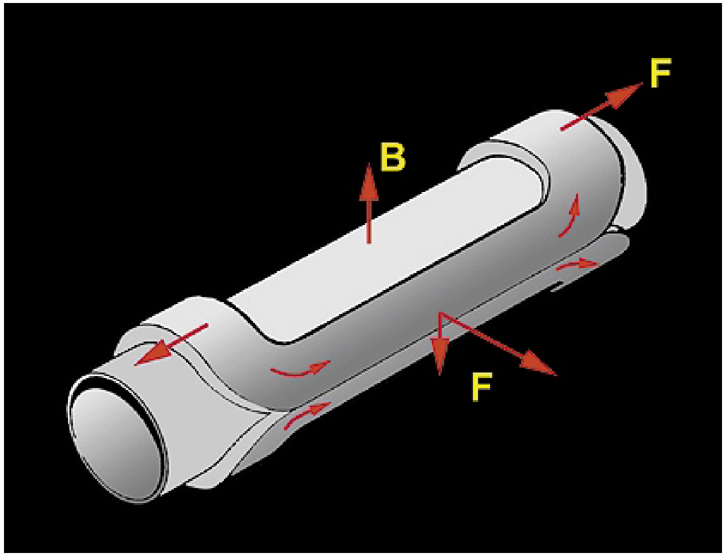


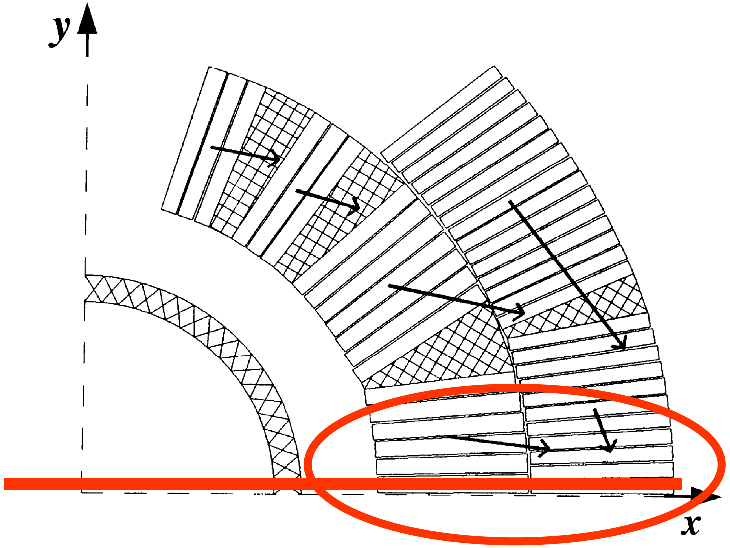
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$



Accelerator magnets : basic - 4

- Transverse field: no self supporting w.r.t. stress
- $J_{overall} \approx 500$ A/mm^2 ! e.m. forces are not kept by conductors but tend to torn apart the winding.



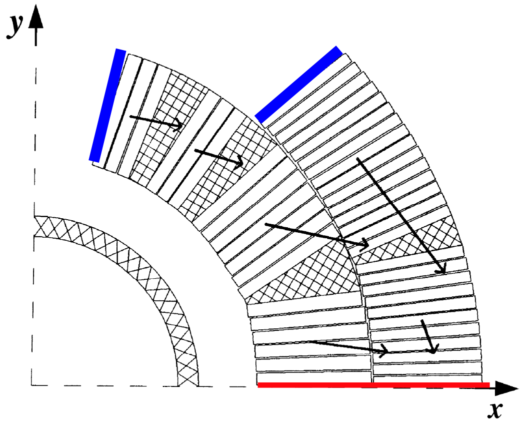


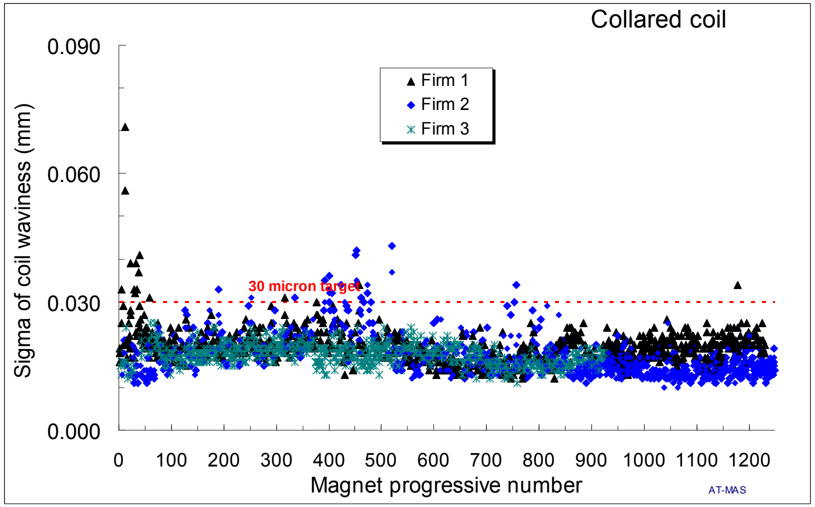
Midplane

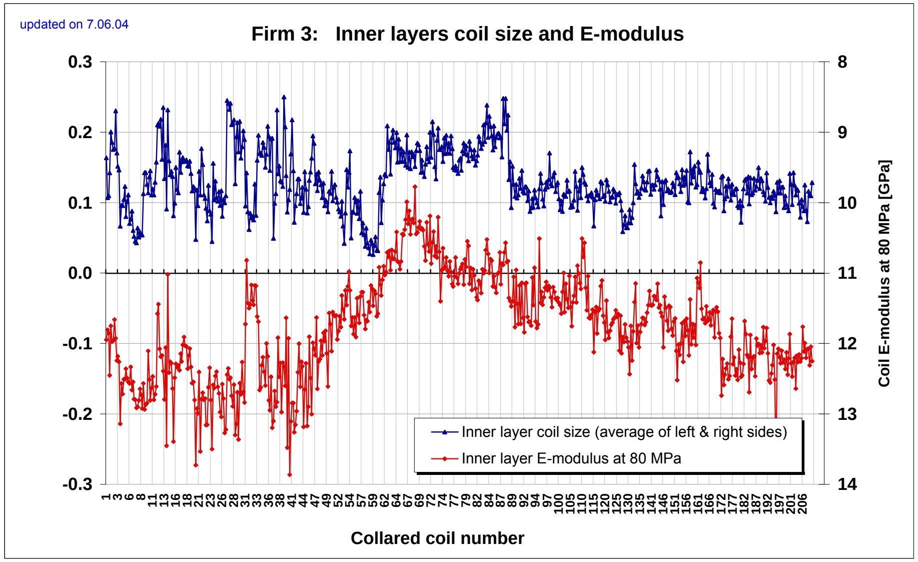
Area of Maximum Displacements

Accelerator magnets : basic - 5

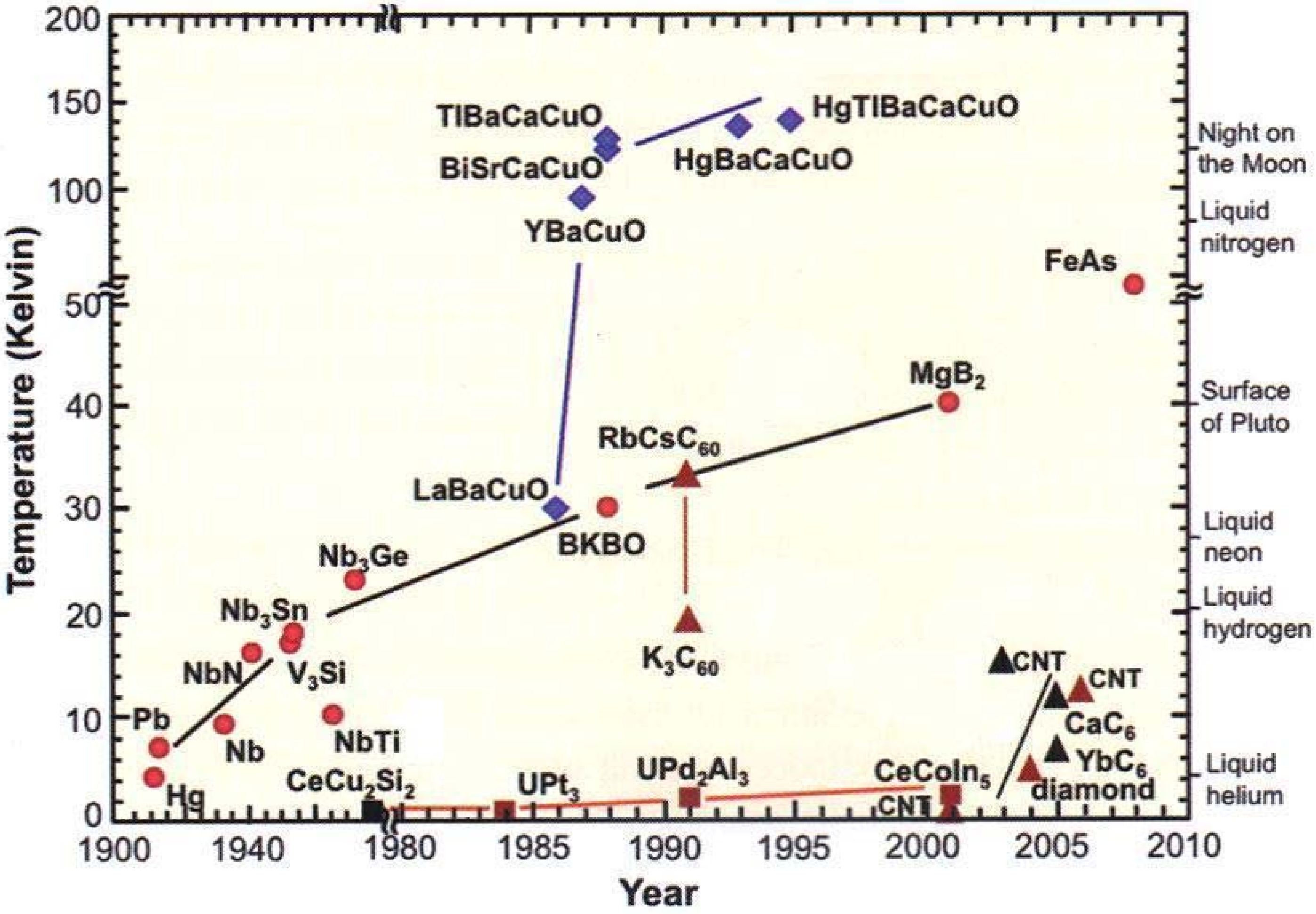
- All in series
  - The worst performing determines the accelerator energy
  - They must be all equal (within few units , 1 u=10^{-4})
- Stand-alone magnets (DS, MS, low beta triplets) they also must ha
- The field quality is typically controlled at a fraction of unit over a wide range.
  - Coil positioning and e.m. forces



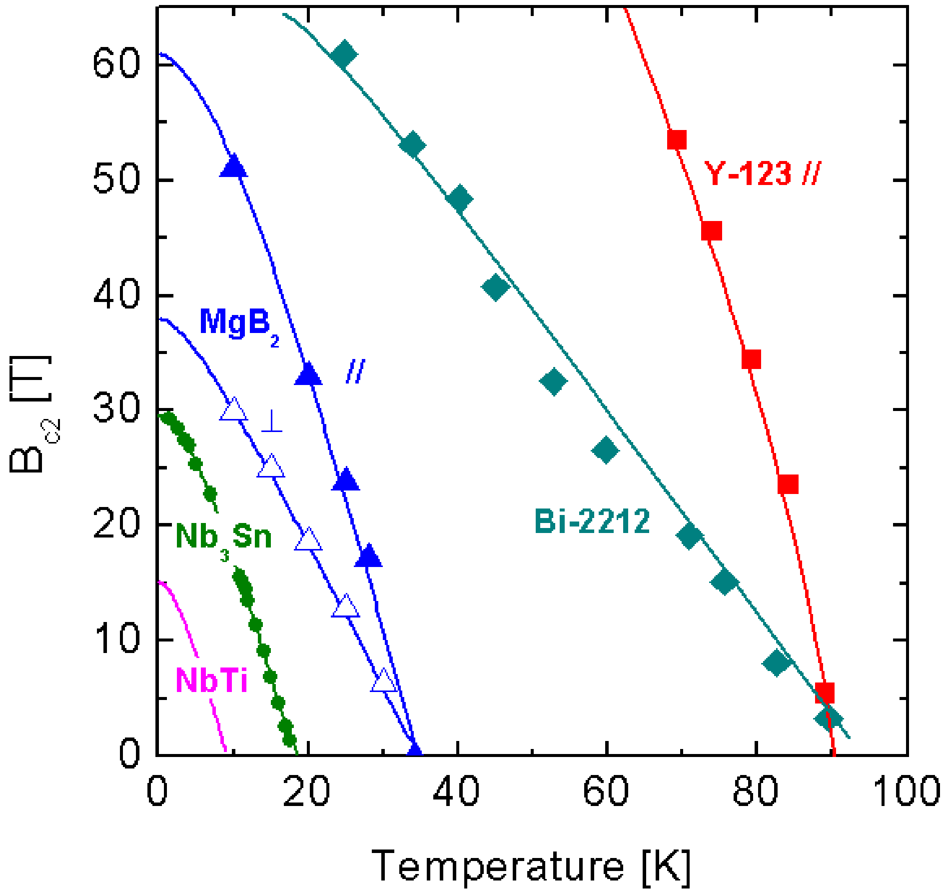




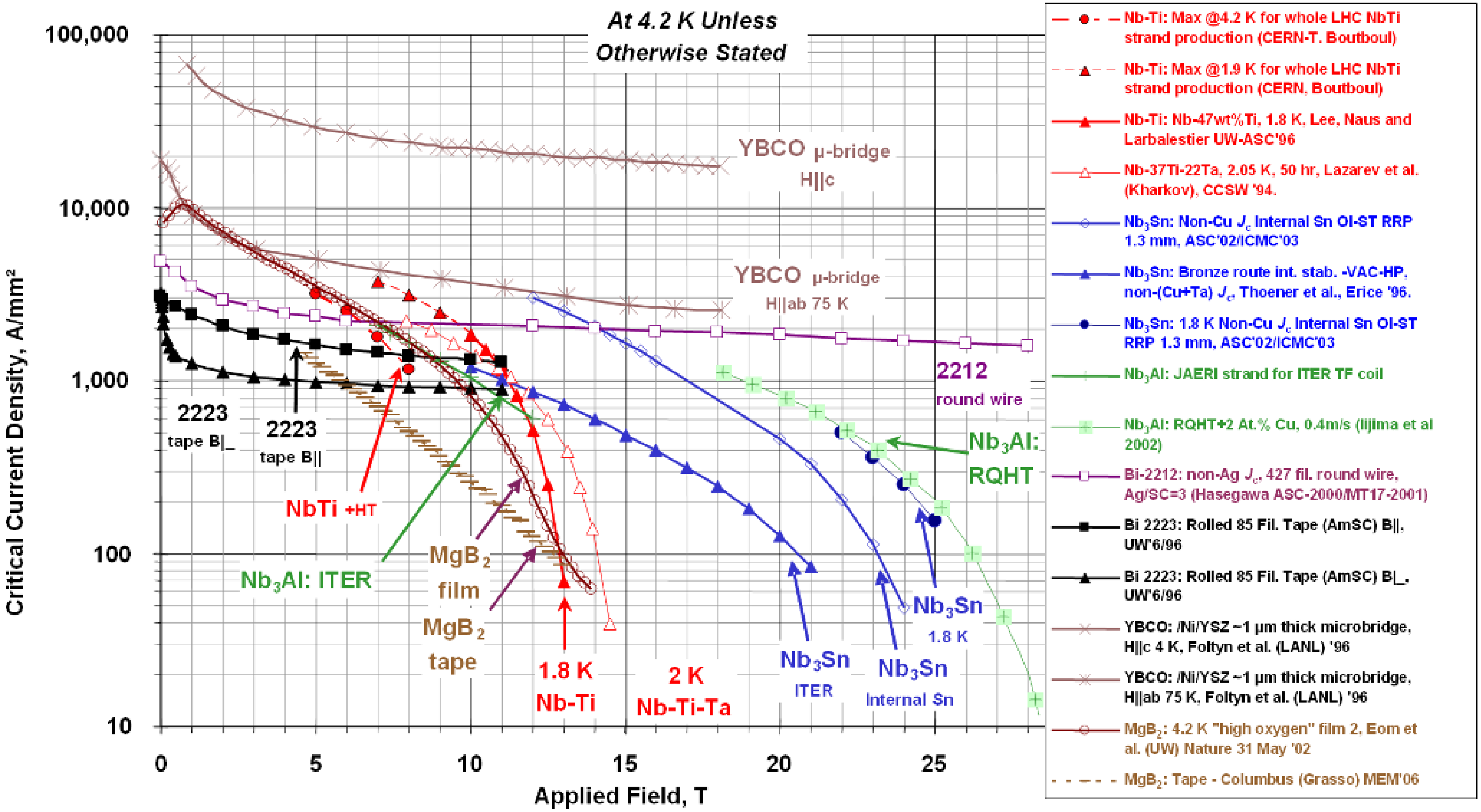
SC and critical parameters: Critical Temperature



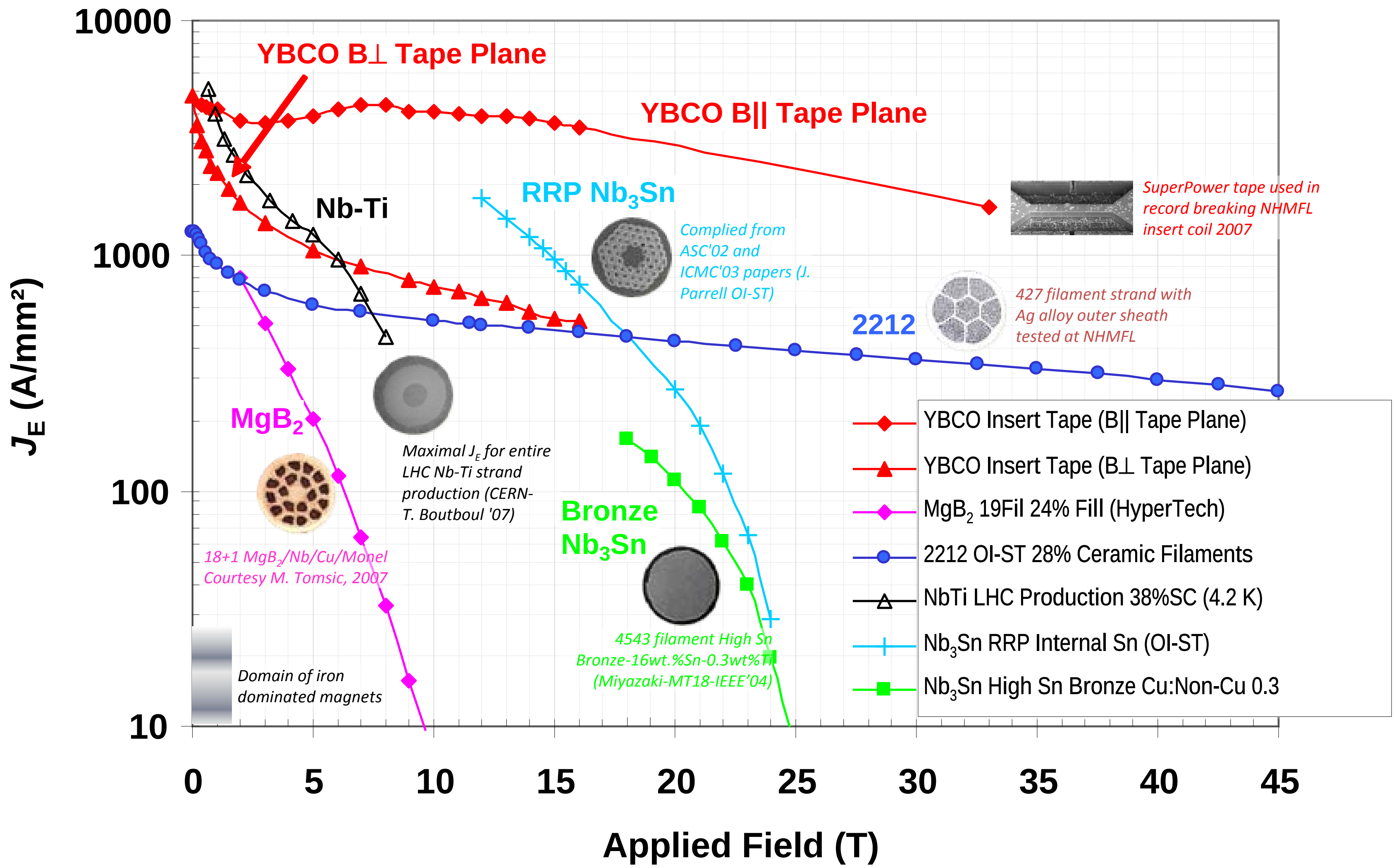
SC and critical parameters: Critical Field



SC and critical parameters: Critical Current Densities



(Overall) Engineering J_e @ 4.2 K



SuperPower tape used in record breaking NHMFL insert coil 2007

Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)

427 filament strand with Ag alloy outer sheath tested at NHMFL

Maximal J_E for entire LHC Nb-Ti strand production (CERN-T. Boutboul '07)

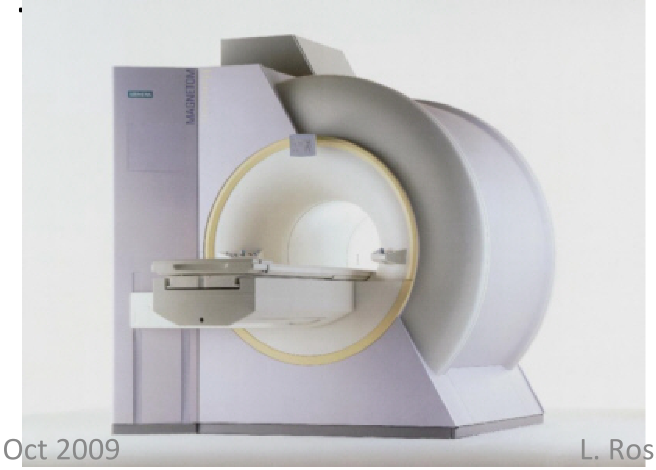
18+1 MgB_2/Nb/Cu/Monel Courtesy M. Tomsic, 2007

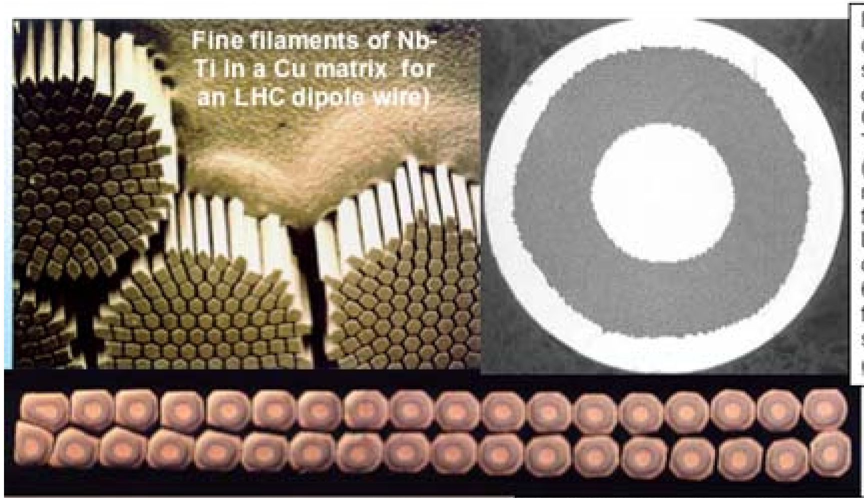
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

Domain of iron dominated magnets

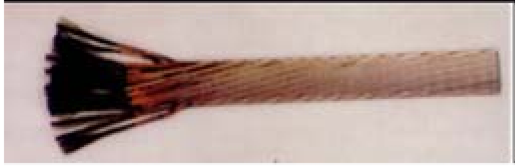
Nb-Ti the almost invariable choice

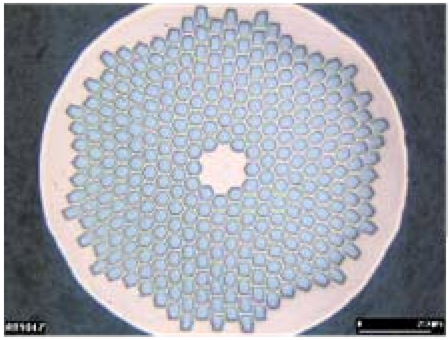
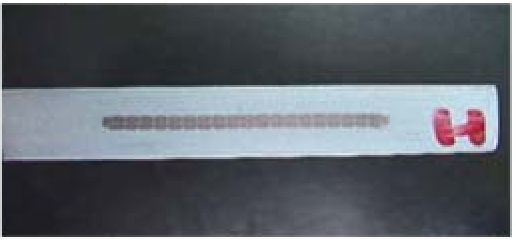
- Used in 95% of the Sc magnets
- Ductile, robust, relatively easy to manufacture, 30 years of large projects
- 300-500 tonnes the yearly production (70%




Fine filaments of Nb-Ti in a Cu matrix for an LHC dipole wire)

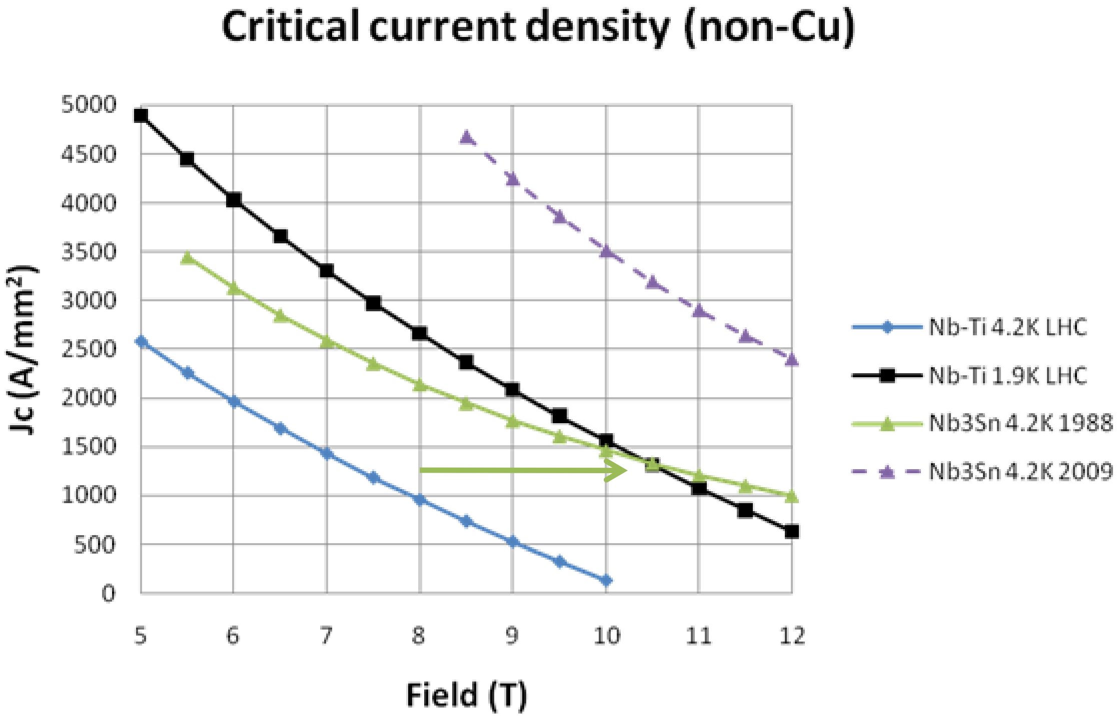
Full cross section of a Cu/Nb-Ti wire (1.06 mm dia.) for an LHC dipole, 6000 filaments of 7 μm dia.


Rurtherford cables, composed by the wire shown above.
View of the flat side (at right), with one end etched to show the Nb-Ti filaments. View of the cross section at the top



1.3 mm dia. wire (at left) composed of 600 Nb-Ti filaments of 35 μm dia. in Cu matrix. 40 of these wires composed the Rutherford cable that is clamped in a pure aluminum sheat for superstabilsation. This conductor has been used for ATLAS BT and ECT

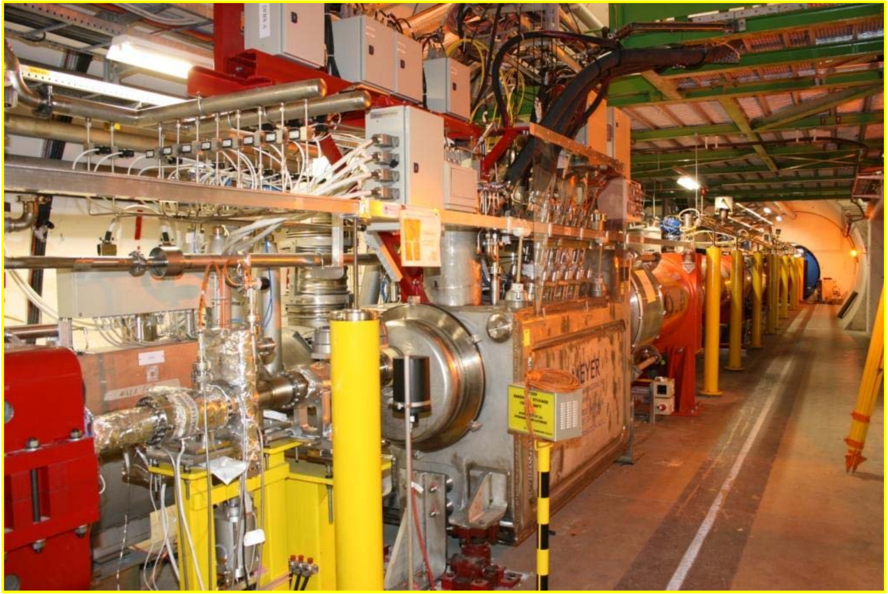
… and boosted by use of HEII

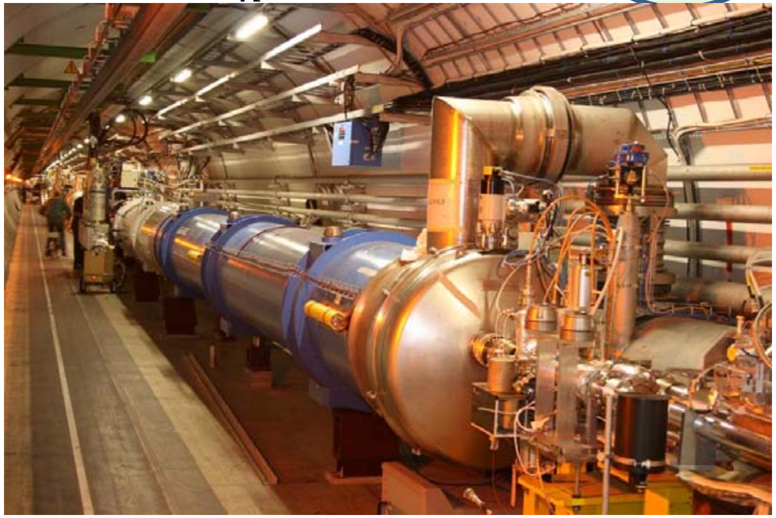
- 1985-1990: LHC conceptual design two routes, one in Nb_3Sn alternative to Nb-Ti. 1 model magnet successful at about 10 T @ 4.2 K but …
- Extra cost of HEII vs. LHe: 15% of the cryomagnet system
- Extra cost of the Nb_3Sn vs. NbTi : at least 50%...



Good reasons to pursue HFM : 1
LHC HigherG-LargerA low-β triplet

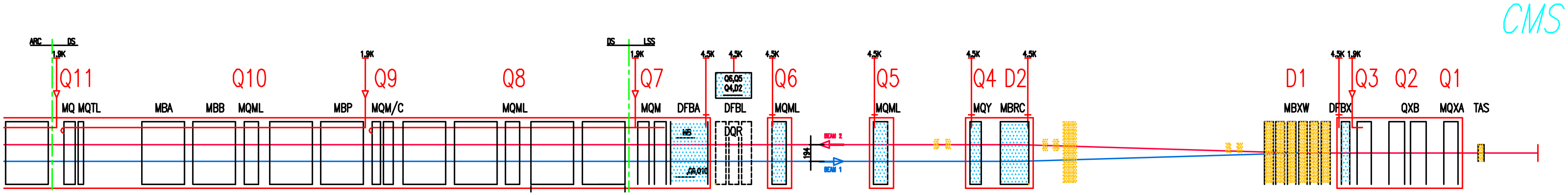
$$L = \frac{f_{rev}\gamma}{4\pi\varepsilon_n}(N_b)^2 n_b \boxed{\frac{F(\beta^*)}{\beta^*}}$$





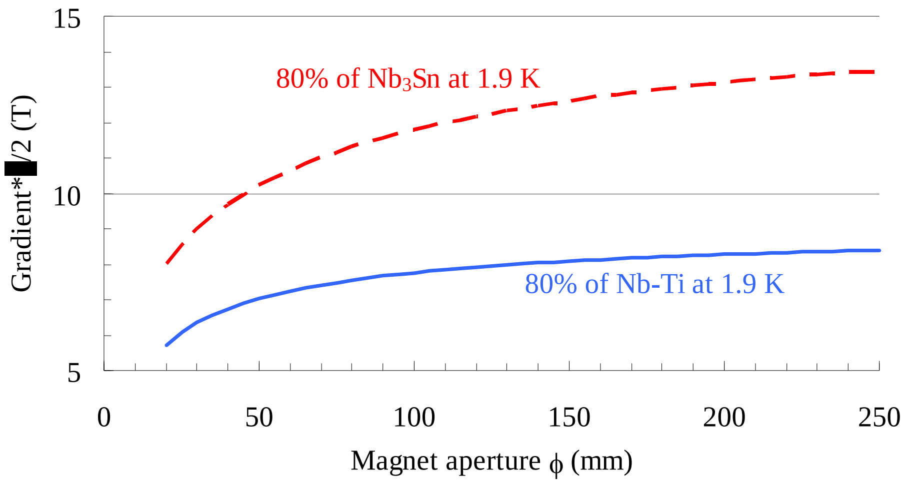
Q1-Q2a-Q2b-Q3 low-β triplet

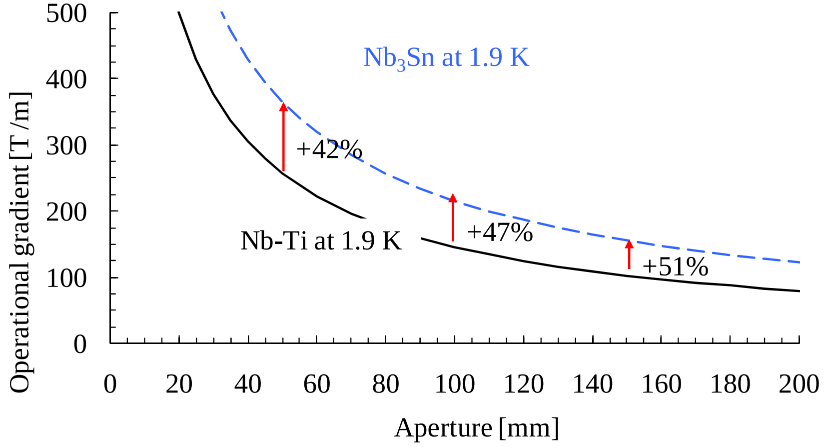
D2 Sc magnet in LHC



What we can get

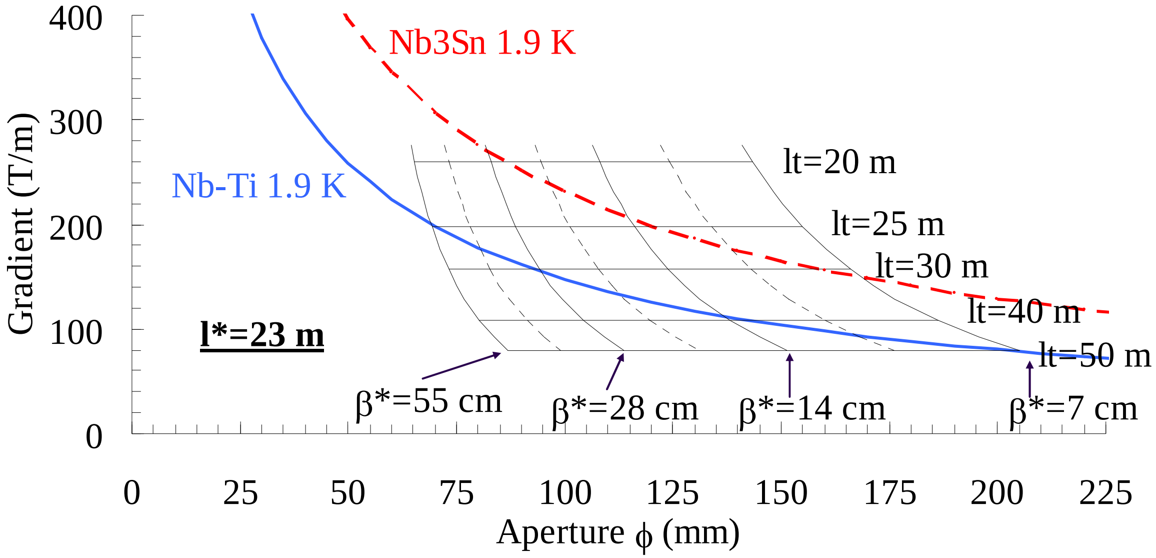
- Order zero: $G\phi/2 \sim$ critical field
  - $\sim$13T for Nb-Ti, $\sim$25T for Nb_3Sn
  - This is a bad approximation !
- Results relative to a sector coil for $\phi \sim 100$ mm
  - Nb-Ti: $G\phi/2 \sim 10$ T
  - Nb_3Sn: $G\phi/2 \sim 15$ T
  - Nb_3Sn: 50% more than Nb-Ti
- Some dependence on aperture
  - Better for large apertures
- A safety margin of 20% is then subtracted on both cases

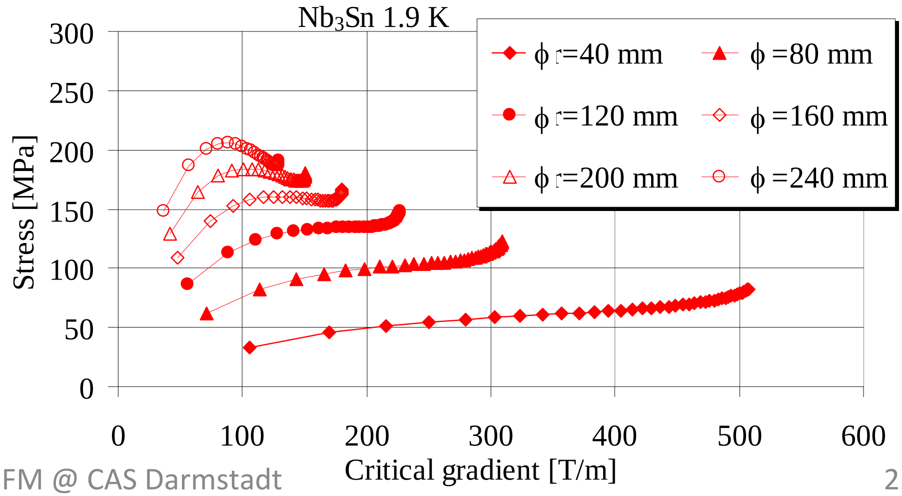




Scaling laws for LHC triplets

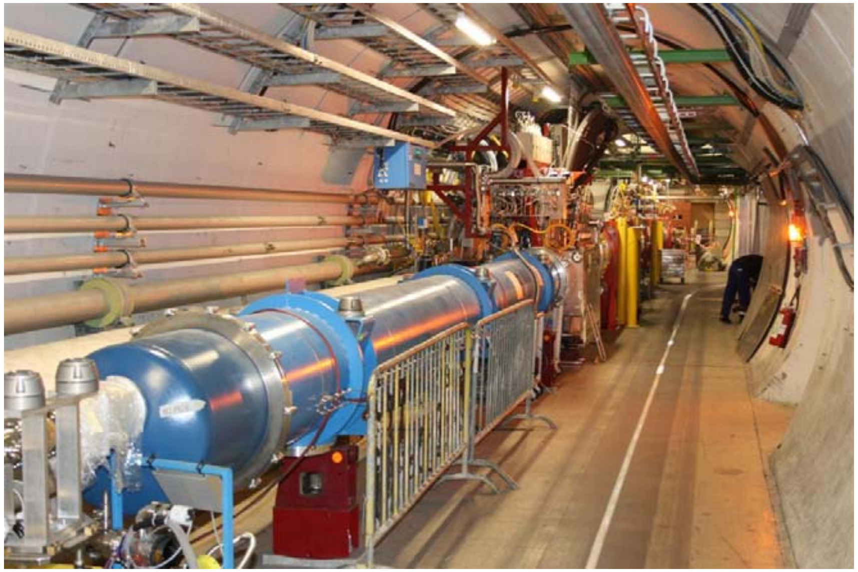
- Solutions can be found for both materials. What we need is a given focusing strength: G×***lt***
- Large apertures: is this possible?
- Increase of ***lt***, triplet length < 50 m (today 20, phase 1 ***lt***=40 m)
- Stresses, difficult beyond ϕ=120 mm. We need 150-160 mm, R&D needed.
- aberrations ?





Luminosity up: more than low-beta quads…

- Separation dipoles
  - Today 1.5 and 3 T
  - In 2014 upgrade 3.5 and 4.5 T
  - In final lum up: may be 7-10 T needed at 4.2 K
  - ⇒ Nb3Sn or HTS (here high temperature may be an invaluable asset
- Matching section: large quads with samse G*L are really an asset (for LHC)
- Dispersion suppression zone to make room for collimators: LHC 8.3 T x 14.2 m.
  ⇒ 12 T x 10 m !!! Possible



Good reasons to pursue HFM : 2
Energy upgrade with same size

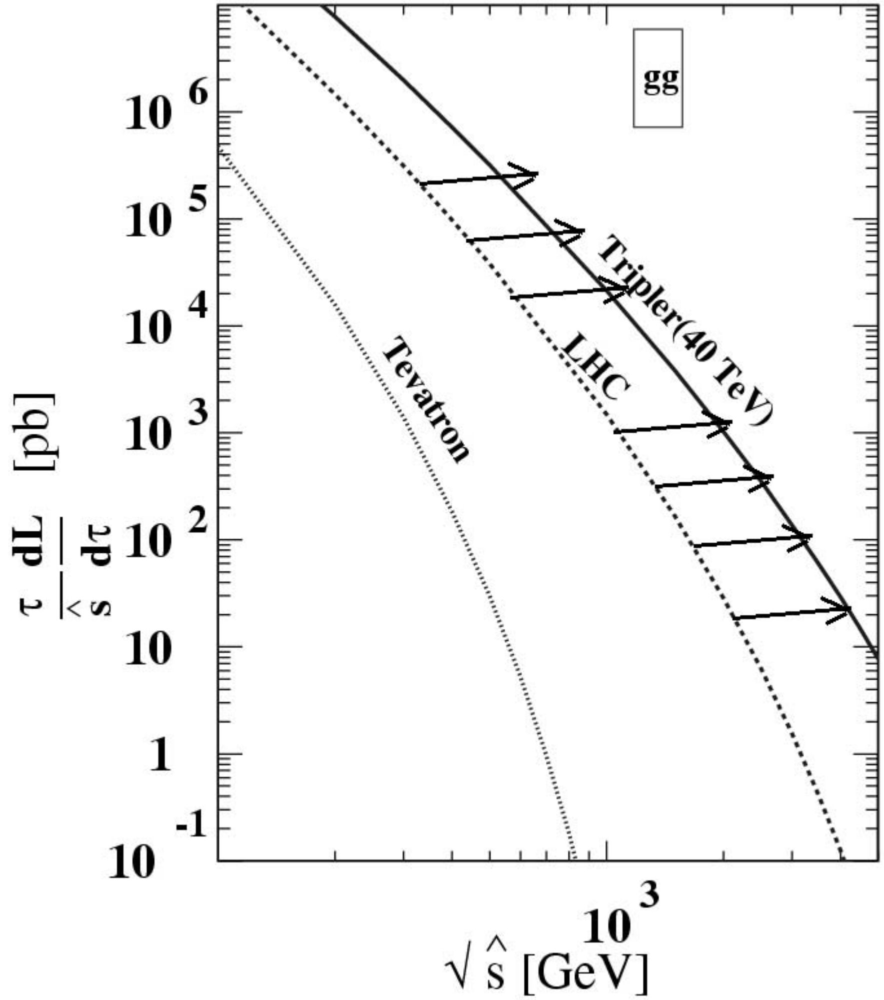
Evolution of the gluon spectrum

Assumptions:

- Luminosity grows x3 with adiabatic damping
- Luminosity needed to produce a given number of particles of mass m (assuming gauge couplings constant) scales with m^2
- So twice the mass scale requires 4/3 the luminosity.

Triple the energy – double the m
reach

P. McIntyre – Texas A&M Acc. center

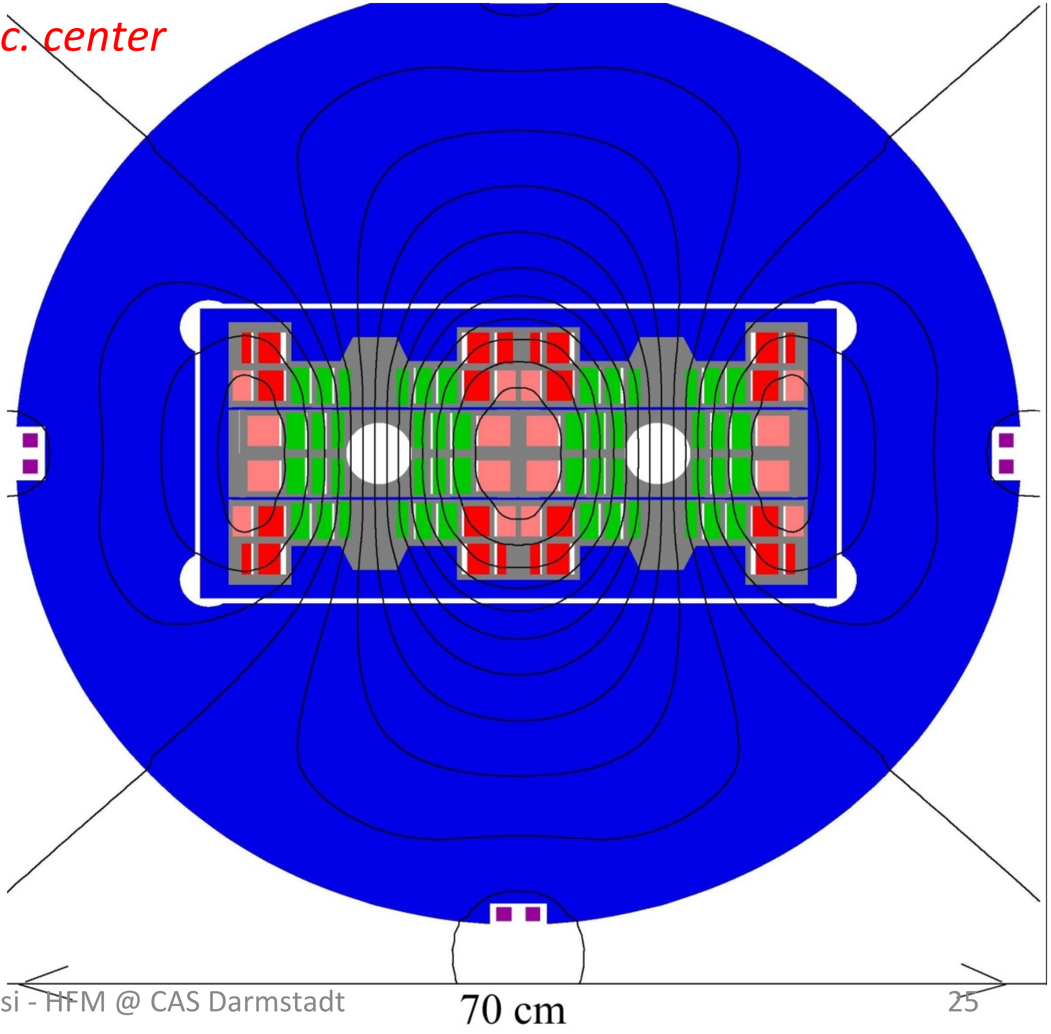


Dutta 2004

Extend to 24 Tesla: Bi-2212 in inner (high field) windings, Nb_3Sn in outer (low field) windings

P. McIntyre – Texas A&M Acc. center

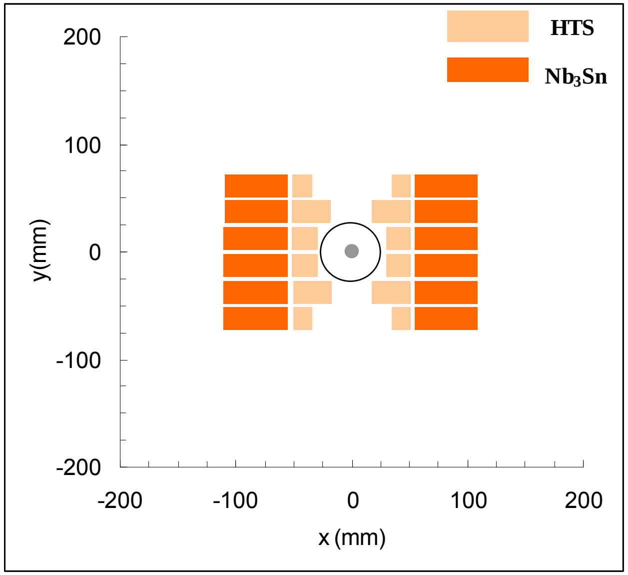
Dual dipole (ala LHC)	
Bore field	**24 Tesla**
Max stress in superconductor	**130 MPa**
Superconductor x-section:	
Nb_3Sn	**$26\ cm^2$**
Bi-2212	**$47\ cm^2$**
Cable current	**25 kA**
Beam tube dia.	**50 mm**
Beam separation	**194 mm**

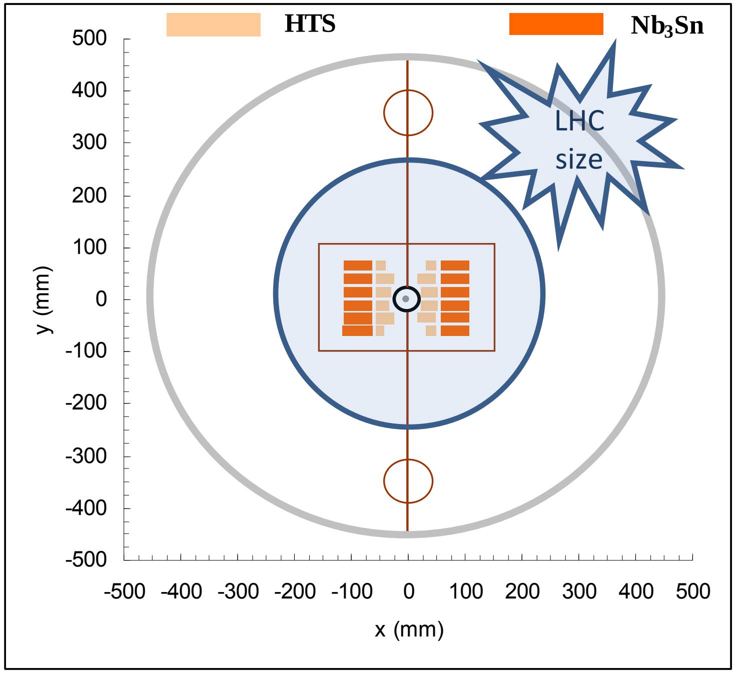


More modestly: 20 T….

- 50 mm aperture
- 20 Tesla operational field
  - Inner layers: High Tc superconductor
  - Outer layers: Nb_3Sn

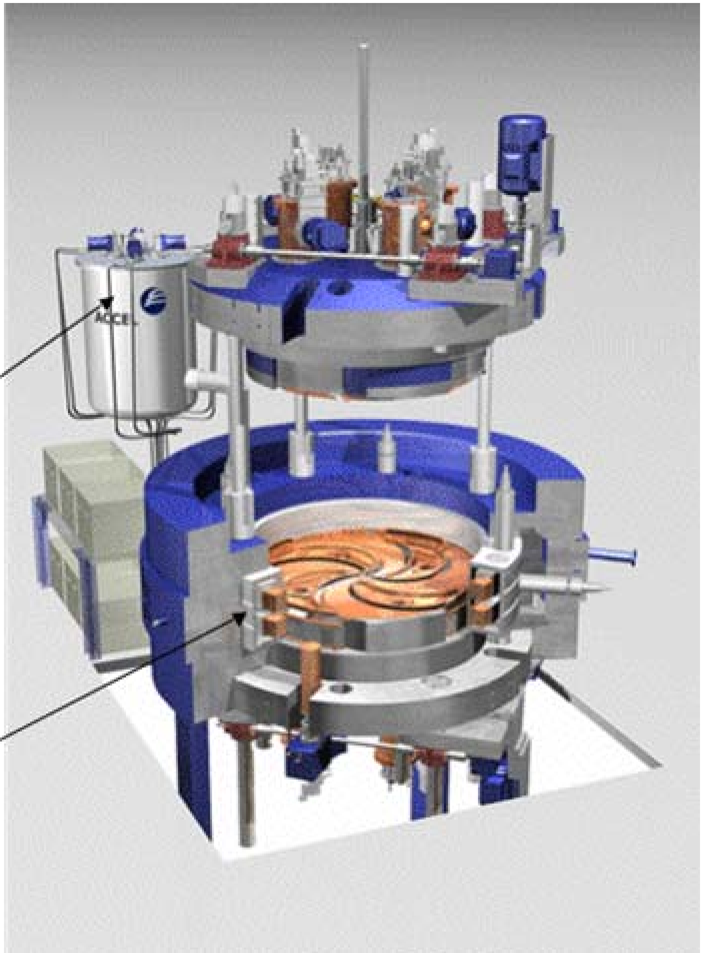
- Operational current: 18 KA
- Operational current density: 400 A/mm^2
- 20% operational margin: Max B = 24 T





Good reasons to pursue HFM : 3
Medical accelerators : hadron teraphy

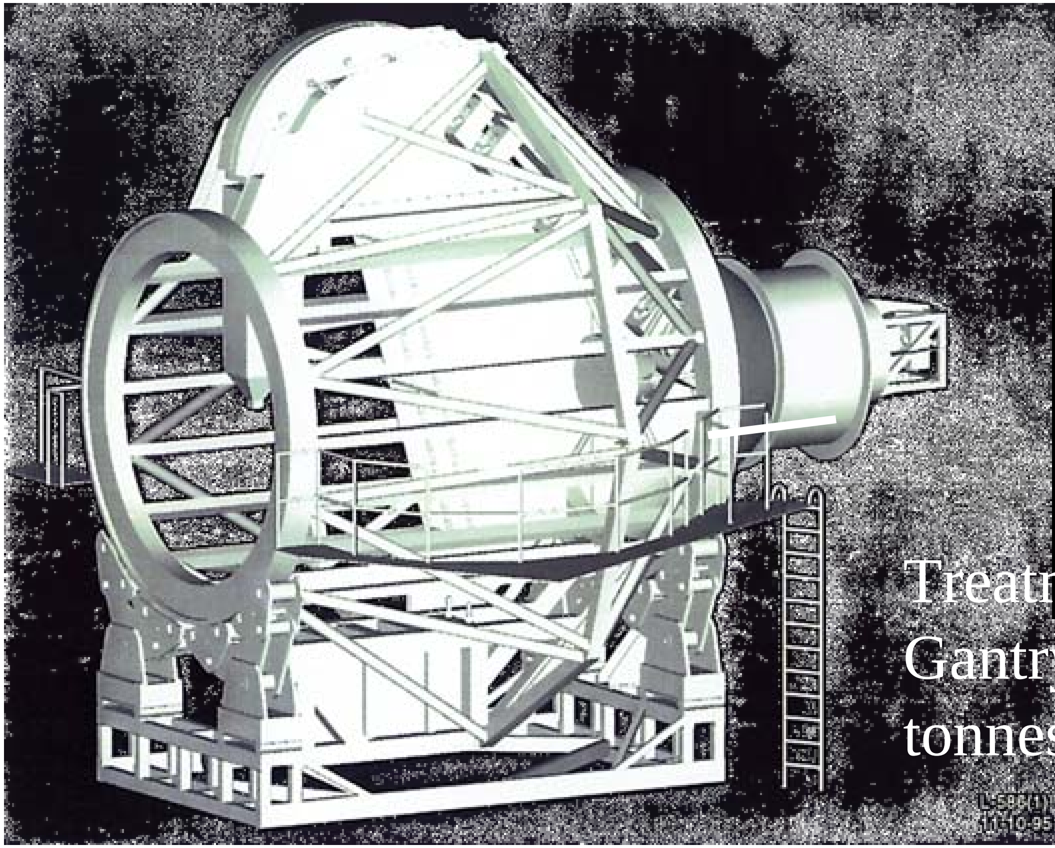
ACCEL
250 MeV
Superconducting
Proton Cyclotron



Closed Loop LHe supply system with 4 Cryocoolers providing 6 W@4.2 K, margin factor ~2

Sealed LHe Cryostat with sc coils, 200 A, Field: 2.8 - 4 T

Protons- Current Beam Delivery System

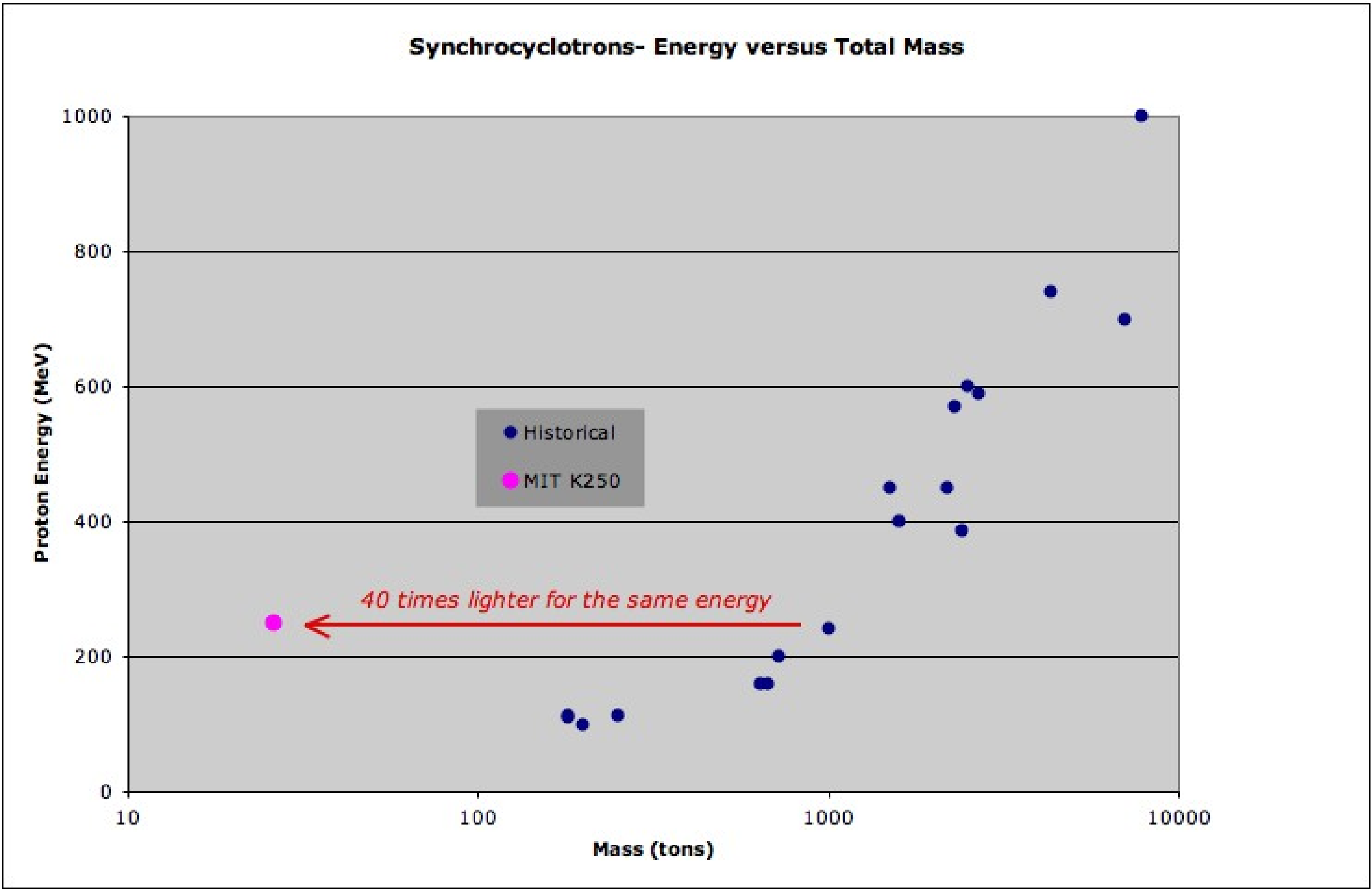


Treatment
Gantr
tonne

Problem

Proton Beam Radiation Therapy costs prohibitively are too high

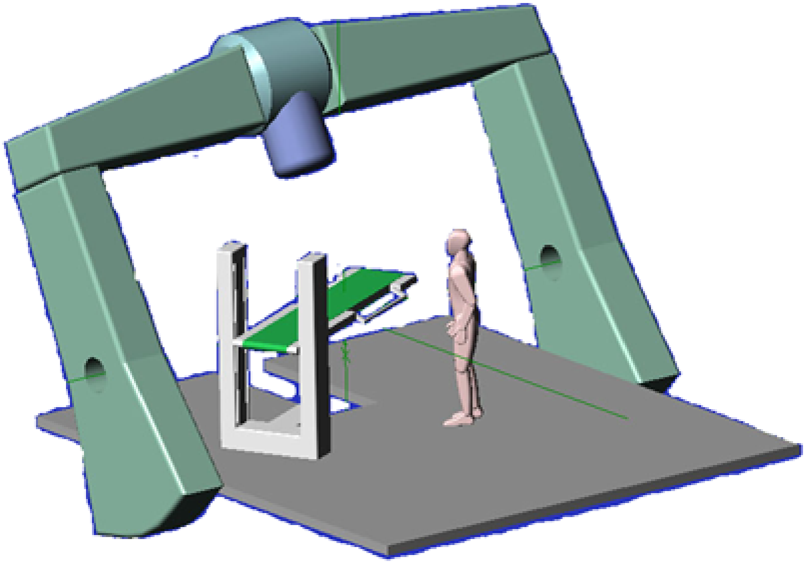
- One room plus equipment: >$50 million
- Four rooms plus equipment: >$100 million
- Big problem to manage project, staff, patients
- **Price: much more than $100 million**



Solution

High Field Weak Focusing Cyclotron

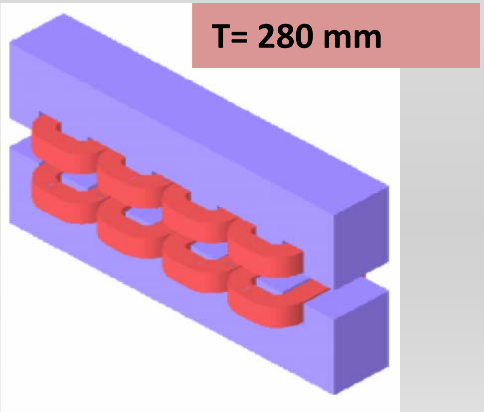
- High Field (8-12 T) Superconducting magnets reduce size of accelerator
- Accelerator on conventional X-ray gantry
- Allows retrofit into existing space

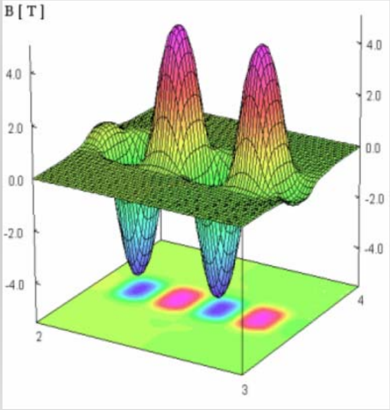


Price: less than $15 million

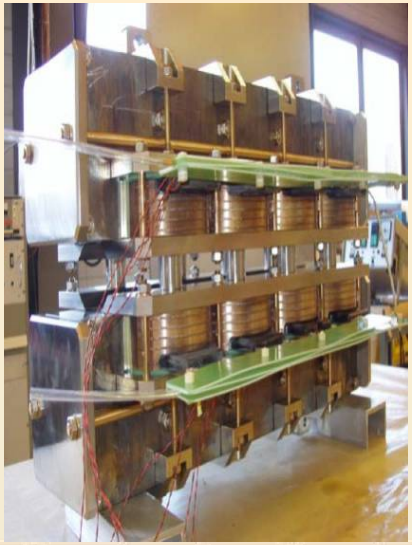
Good reasons to pursue HFM : 4 Undulators and Wigglers

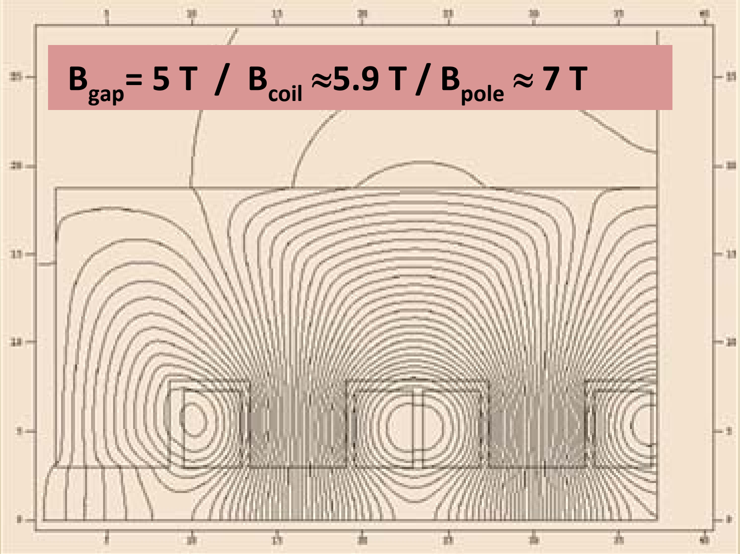
- **SC undulator in LHC**
  - NbTi Undulator for the LHC beam monitor
    - Period = 280 mm
    - 8 NbTi coils placed horizontally
    - Operating at 4.4 K with Current=450 A
    - Design magnetic flux density = 5 T (gap)





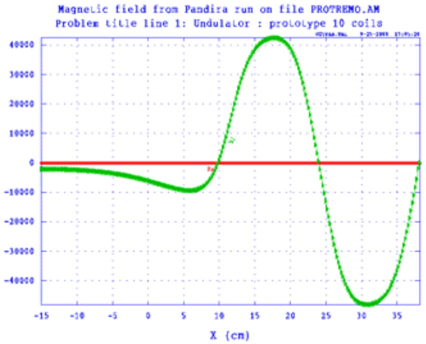
" Manufacture and Test of the Prototype 5 T Superconducting Undulator for the LHC Synchrotron Radiation Profile Monitor"
Maccaferri, R ; Bettoni, S ; Tommasini, D ; Venturini-Delsolaro, W

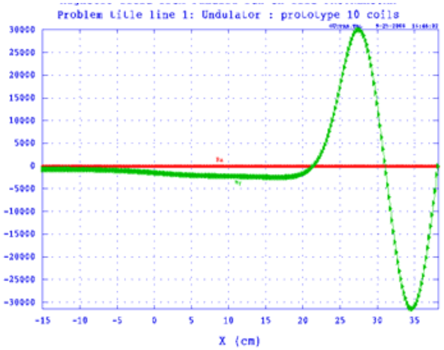


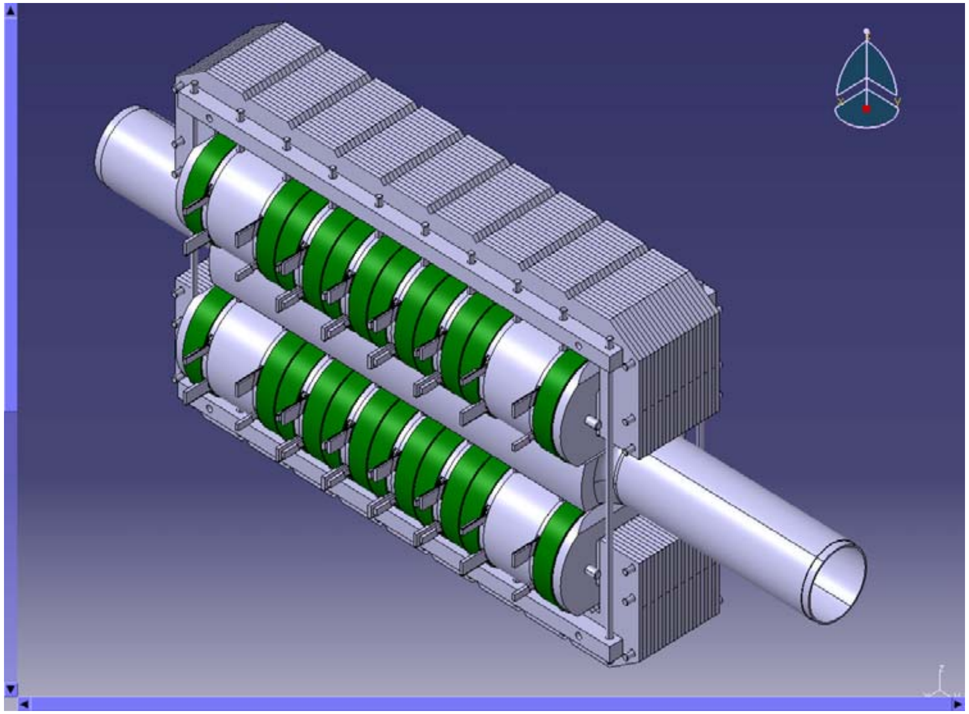


Upgrade of existing LHC undulators for LHC ion beam

- Flexible operation: undulator period 280 mm/140 mm with 60 mm gap
- B_{GAP} = 5 T for 280 mm period which mean B_{COIL}: 8 T(590 A/mm^2) @ 4.2 K
  B_{GAP} =>3 T for 140 mm period which mean B_{COIL}= 9T (550 A/mm^2) @ 4.2 K

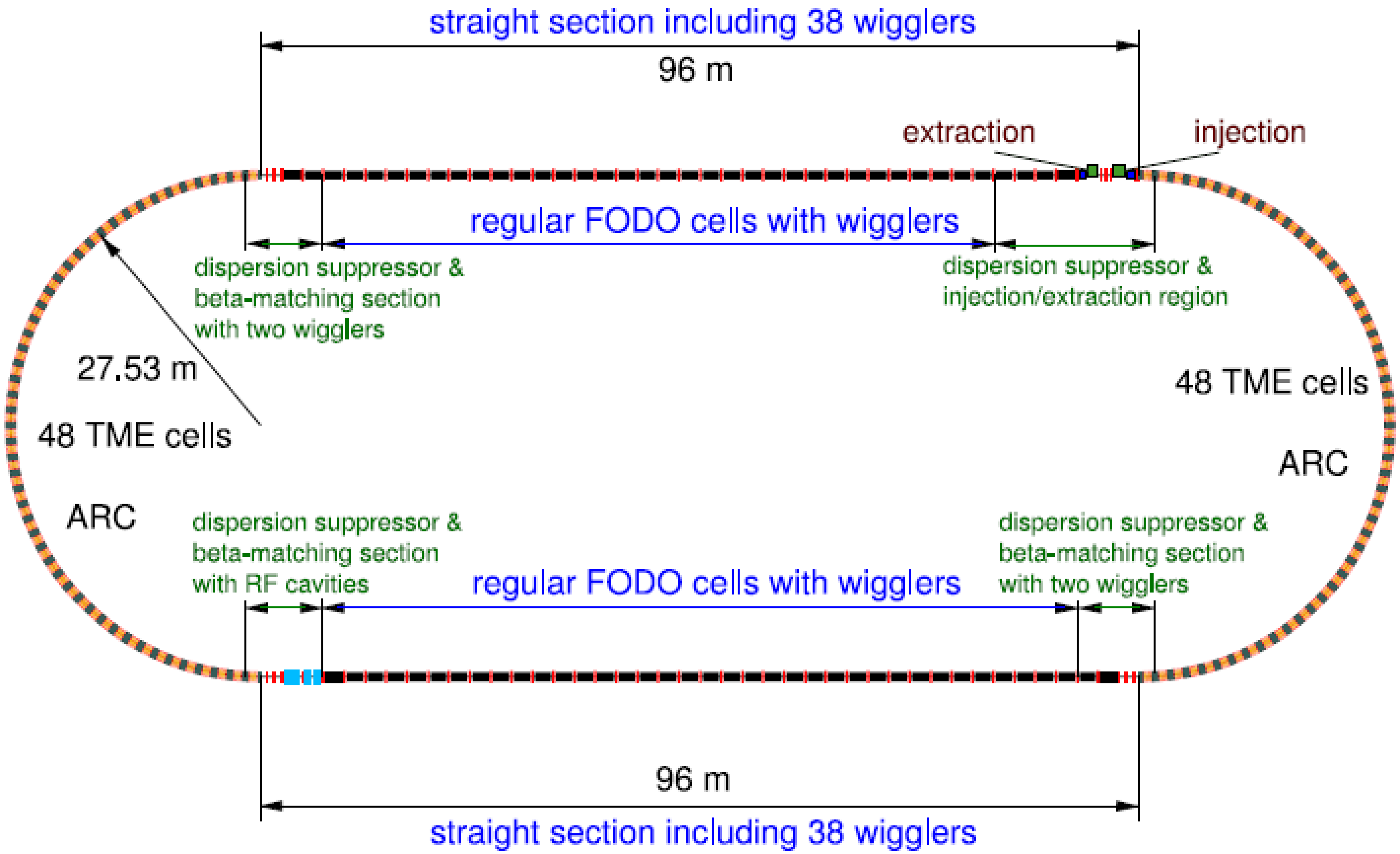






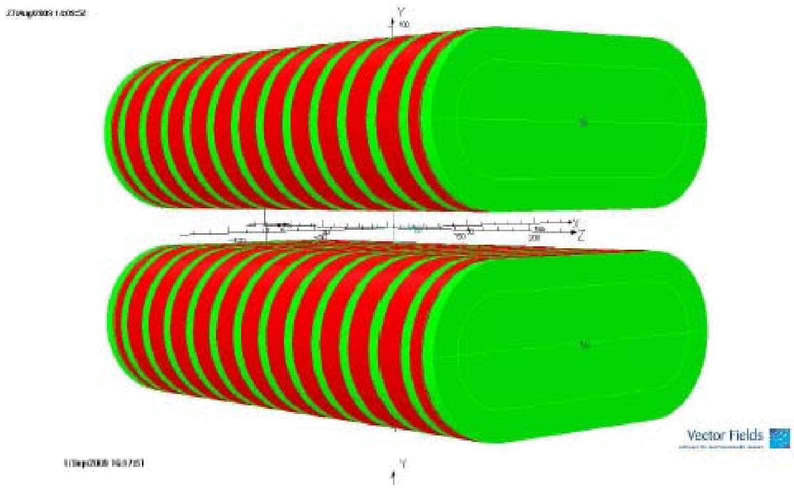
Courtesy R. Maccaferri, N. Duarte - CERN

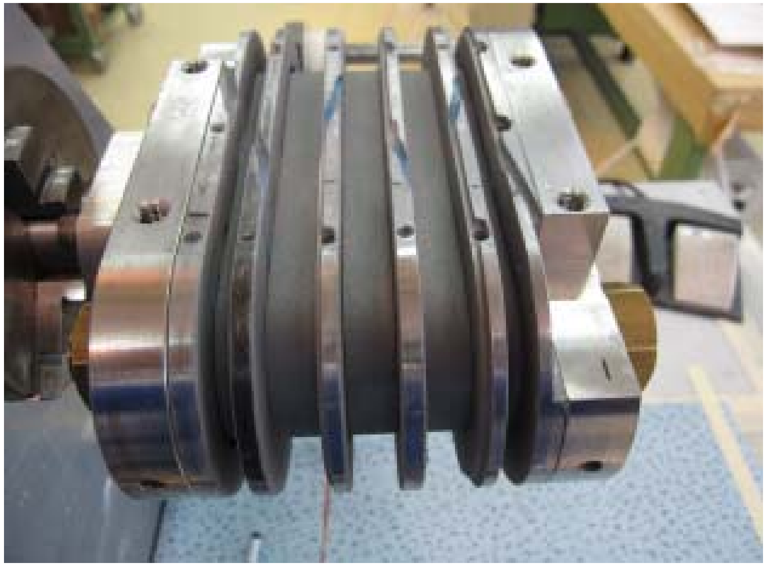
What about CLIC (and ILC) ?



M. Korostelev: *Optics Design and Performance of an Ultar-Low Emittance Damping Ring for the Compact Linear Collider*

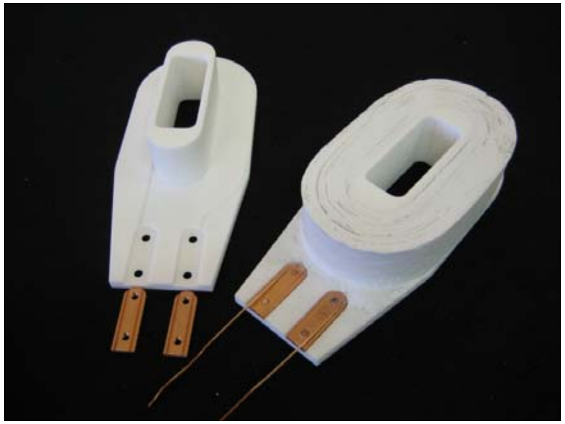
Test at CERN from Nb-Ti to Nb_3Sn





Nb-Ti winding trial

NbSn single coil manufactured and tested: **B > 10 T**

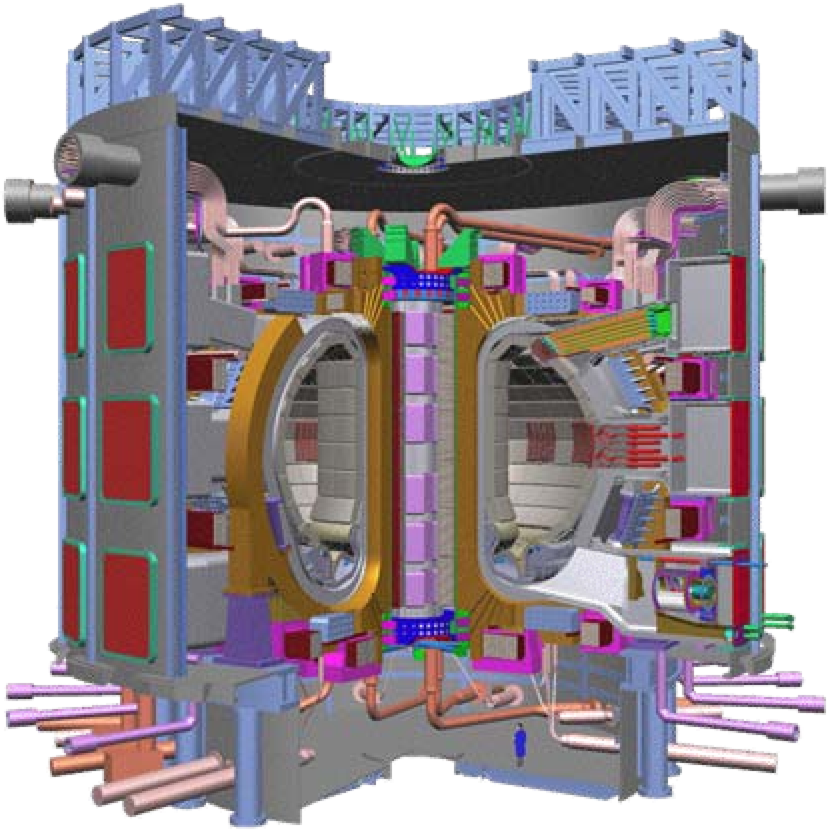


Courtesy R. Maccaferri, D. Schoerling - CERN

Is Nb3Sn used in large scale ? Yes… about 100 HF NMR solenoids per year HF: the next large project ITER

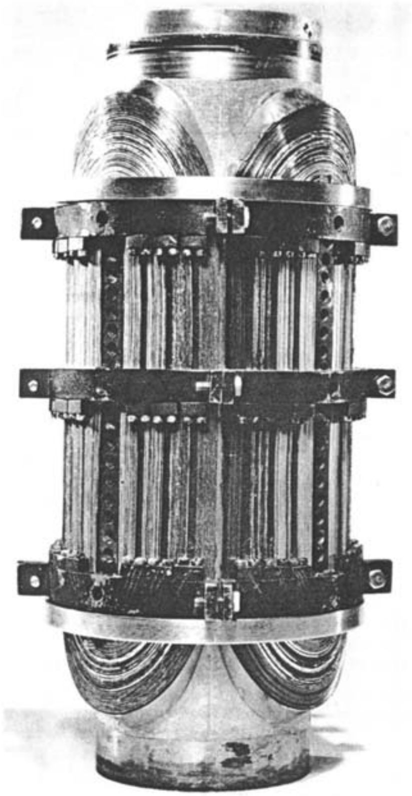
900 MHz (21 T, @ 1.9 K)

ITER: 13 T coils, 400 tons of Nb3Sn

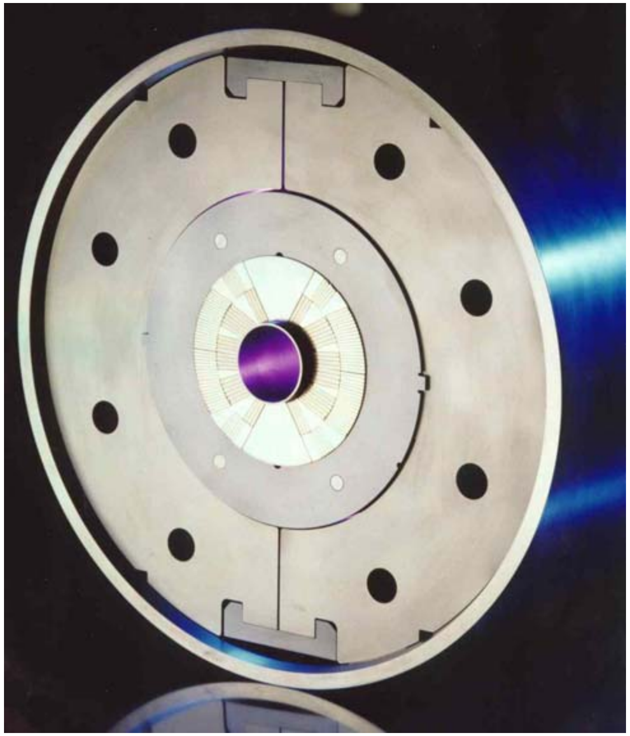


Nb3Sn magnets : a long history

W. Sampson Nb_3Sn 76 mm quad
BNL, 1976

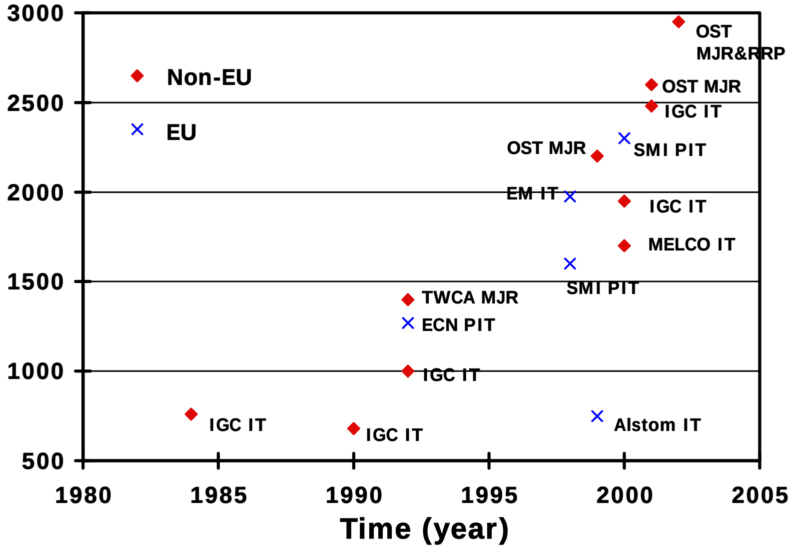


11 T @ 4.4 K in a 50-mm-bore, 1 m long
(Twente University, - CERN, 1995)

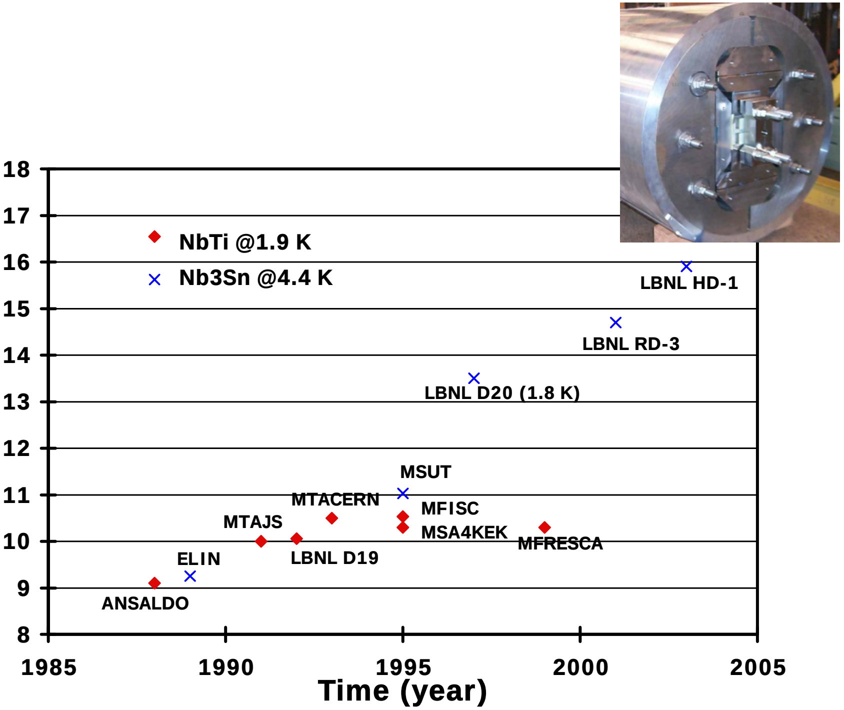


Attained field follow progress in J_c

Progress on non-Cu JC (at 4.2 K and 12 T) of multifilament composite wires



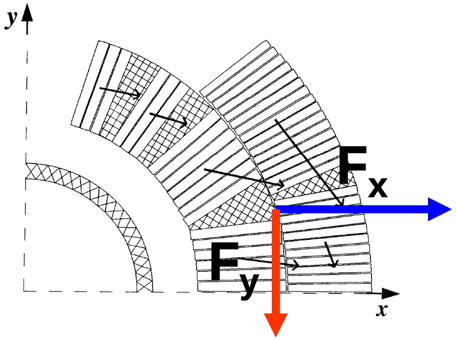
Progress on maximum quench field of dipole magnet models

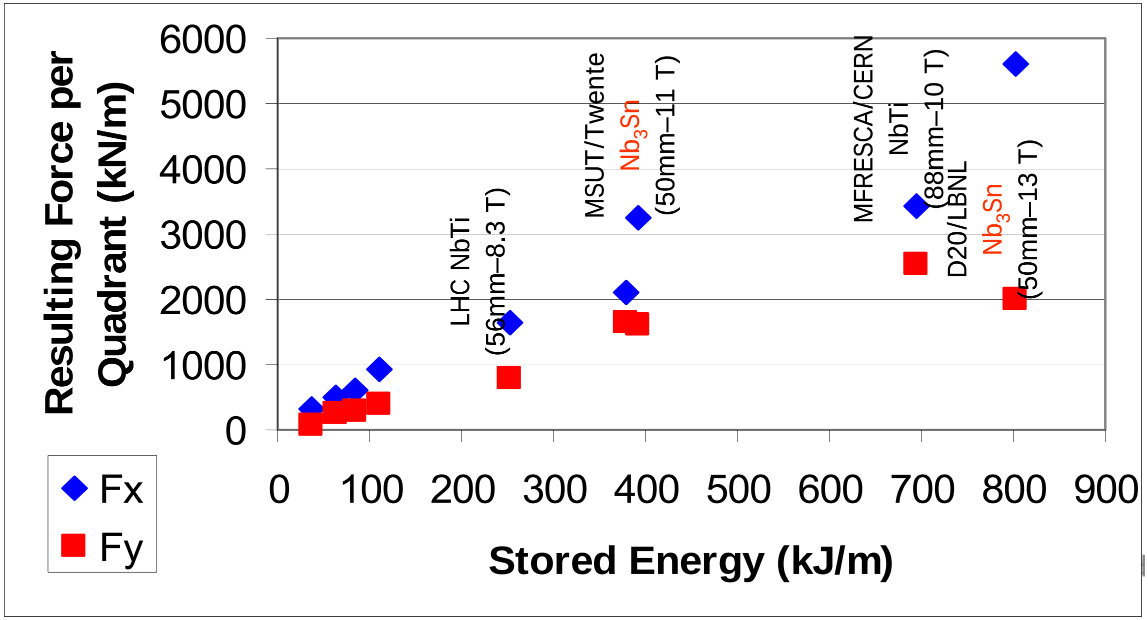


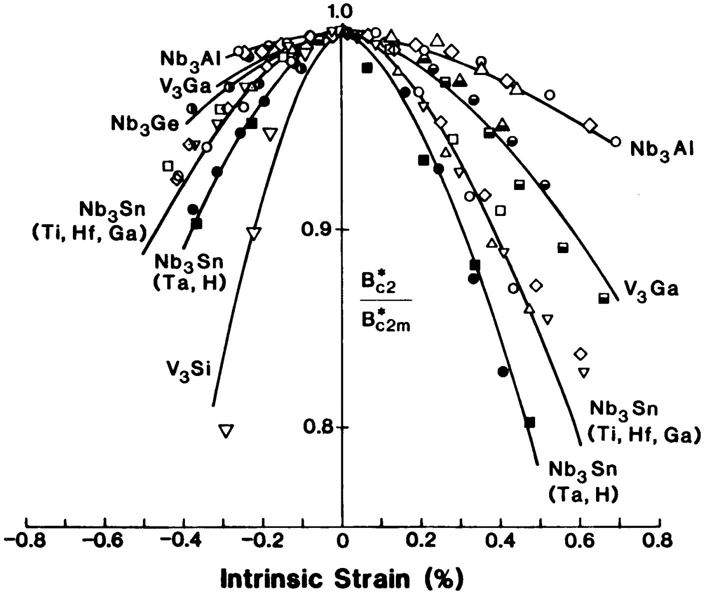
Where is the issue? brittleness

Degradation of critical magnetic field as a function of strain (J.W. Ekin, 1984)

Of course F ∝ B^2

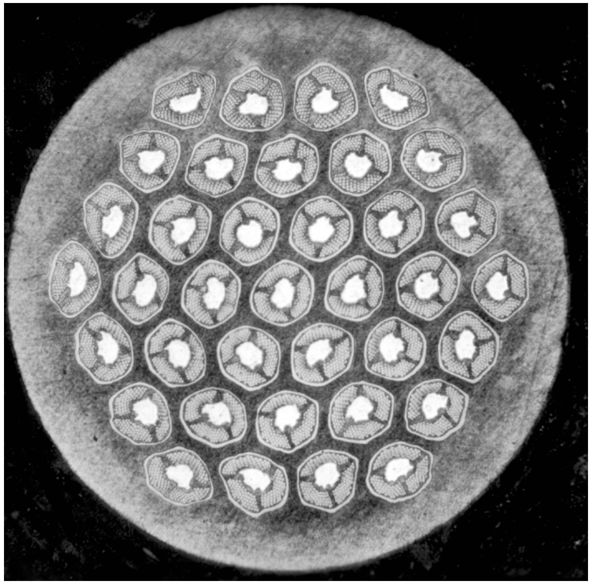




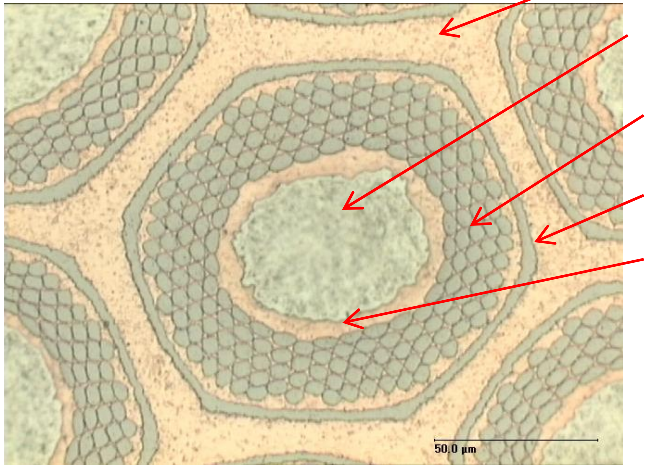


Nb3Sn wires

- Nb3Sn is a compound.
- Formed in solid state reaction in inert atm. at 650-700 °C x 5-20 days
- Internal Tin diffusion is best for J_c but gives large effective filaments size
- This materila has 110 μm eff. Fil. Dia.



Before reaction



copper

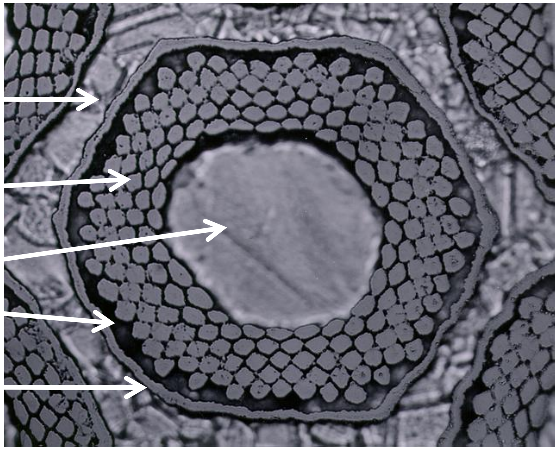
Sn pool

Nb filaments

Nb barrier

copper

After reaction



copper

Nb_3Sn filaments

tin-reach bronze

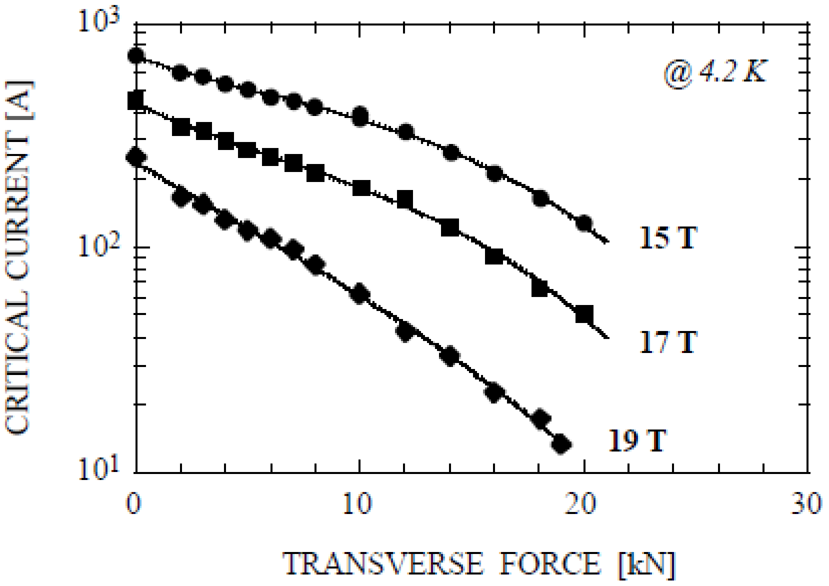
bronze

Nb barrier

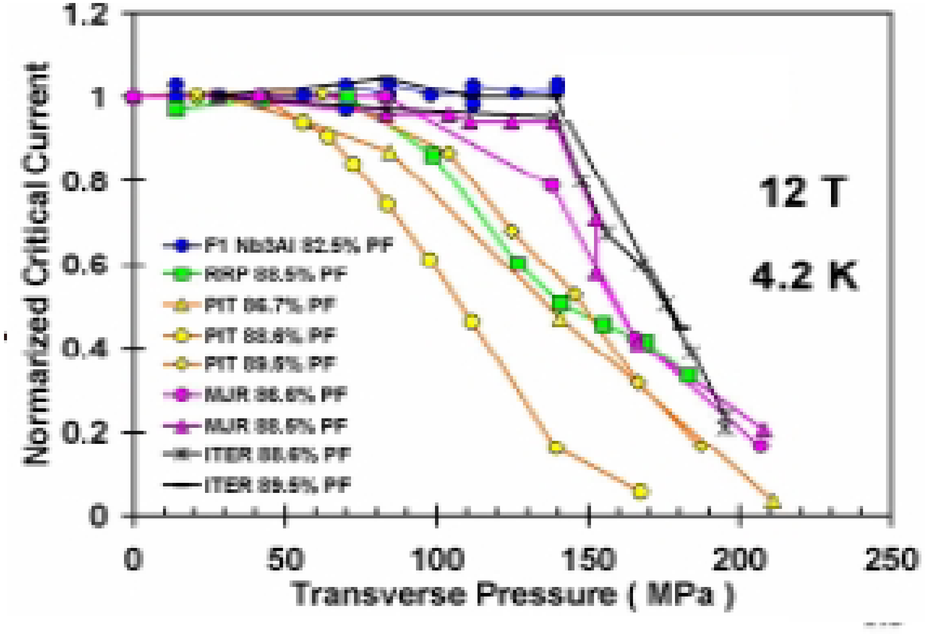
(partially Nb_3Sn)

After reaction Nb3Sn is very brittle

Decrease in Ic upon longitudinal stress in PIT conductor

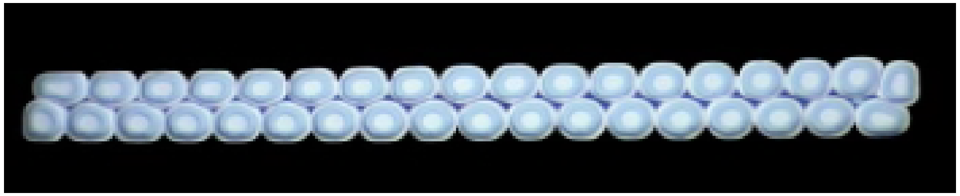


Behaviour of Ic on Rutherford cable vs. transverse stress



E. Barzi

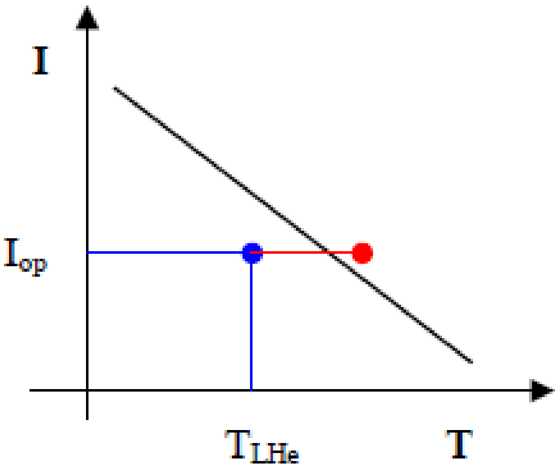
And we need to use 10-20 kA CABLE



2nd issue

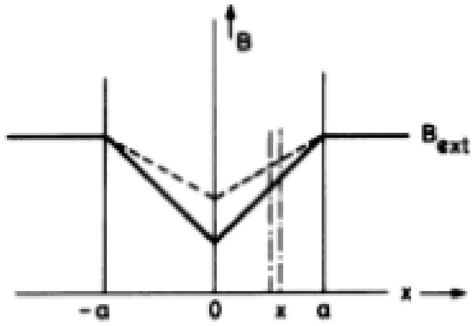
A conductor made of superconducting material only, is NOT stable against small perturbations. ΔE of μJ or even nJ are enough to drive superconductor normal.

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



ΔE is given by :

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

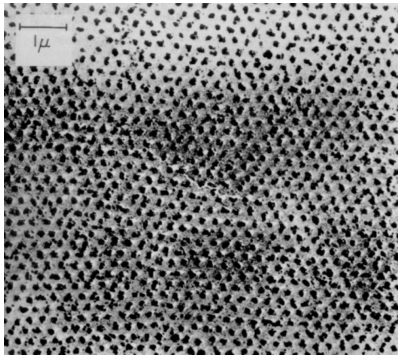


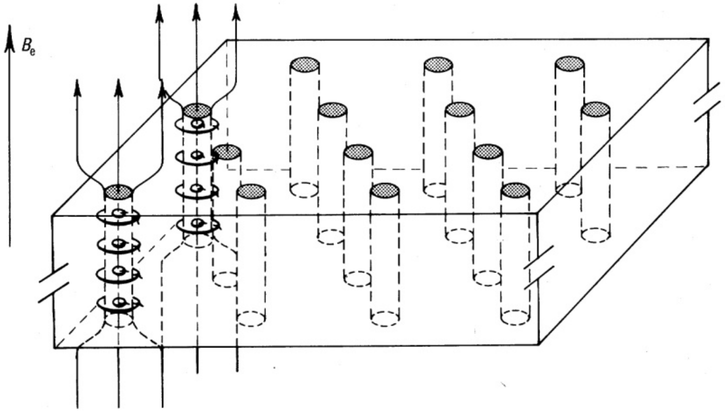
Flux jump: sudden movement of fluxoids

- Fluxoid array interact with current. When f = J x B > $f_{pinning}$ the flux moves and generates heat
- Criteria to avoid this avalanche effect:

$$\frac{\mu_0 J_c^2 a^2}{\gamma C(T_c - T_{op})} < 3$$

First photo of the fluxoid array





In practice this means filament diameter of less than 100 μm

Embedding fine filaments inside a good conductor (copper for LTS) to achieve both goals

MAGNETO-THERMAL INSTABILITIES AND MAGNET PERFORMANCE

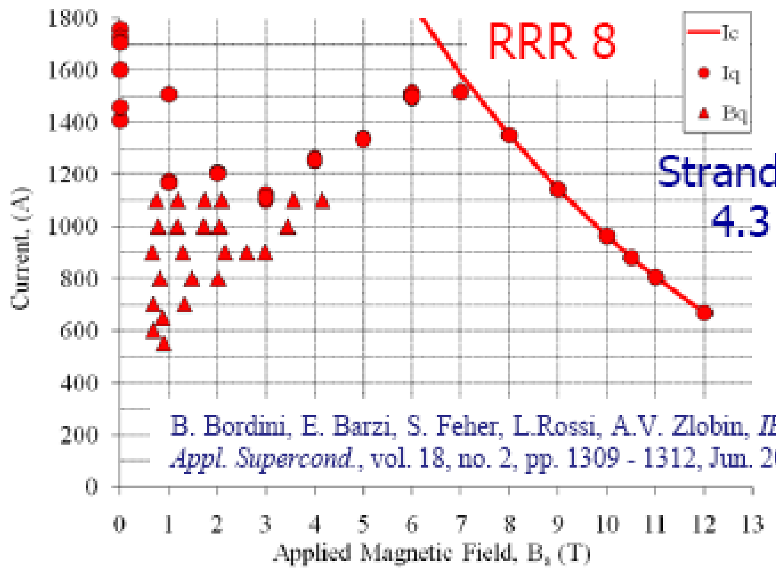
- Magnetization instability has been the primary cause of the limited quench performance (40-70 % of the short sample limit) at 4.4 K of some Nb_3Sn high field magnets built at FNAL [1] and LBNL [2] in the early 2000s

- At present the problem of magnetization instability at 4.4 K is contained through optimized heat treatments and cabling processes that guarantee a high RRR

[1] A. V. Zlobin et al , "R&D of Nb_3Sn Accelerator Magnets at Fermilab", IEEE Trans. Appl. Supercond., vol. 15, no. 2, Jun. 2005

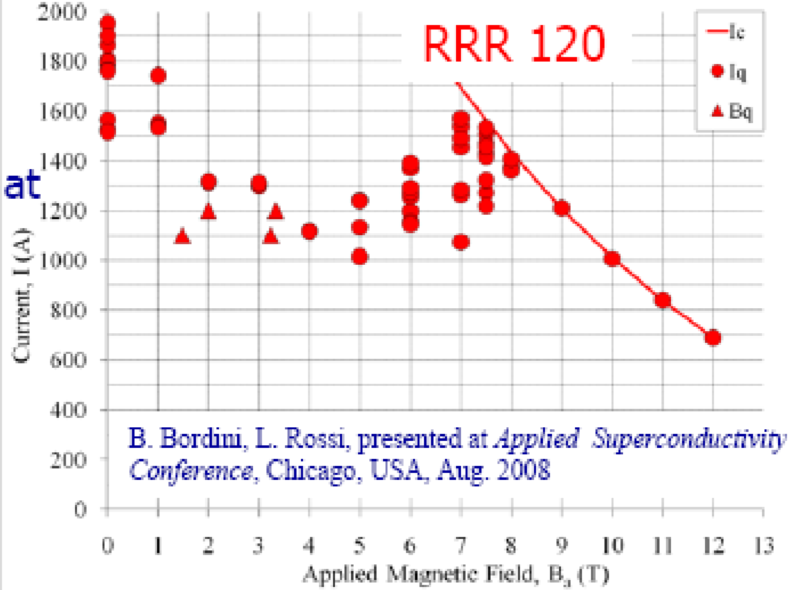
[2] D. R. Dieterich et al , "Correlation between strand stability and magnet performance", *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, Jun. 2005

Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm²]	B_{c2} @ 4.2 K [T]	D_{eff} [μm]	RRR
0.8	RRP®	2602	24.54	80	8
		2645	23.56		120



B. Bordini, E. Barzi, S. Feher, L.Rossi, A.V. Zlobin, *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 1309 - 1312, Jun. 2008

Strand measurements at 4.3 K performed at CERN

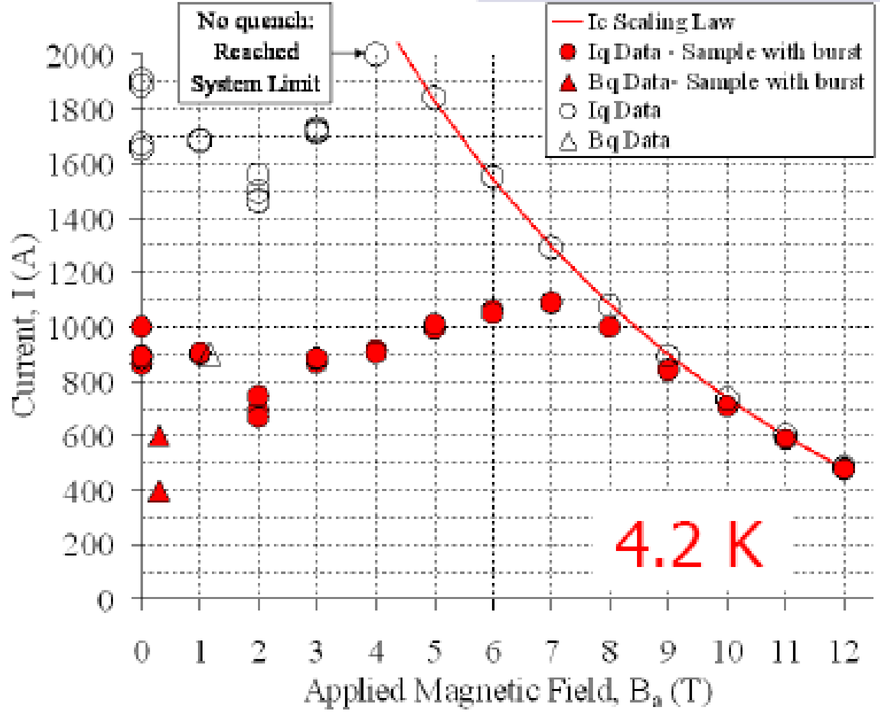


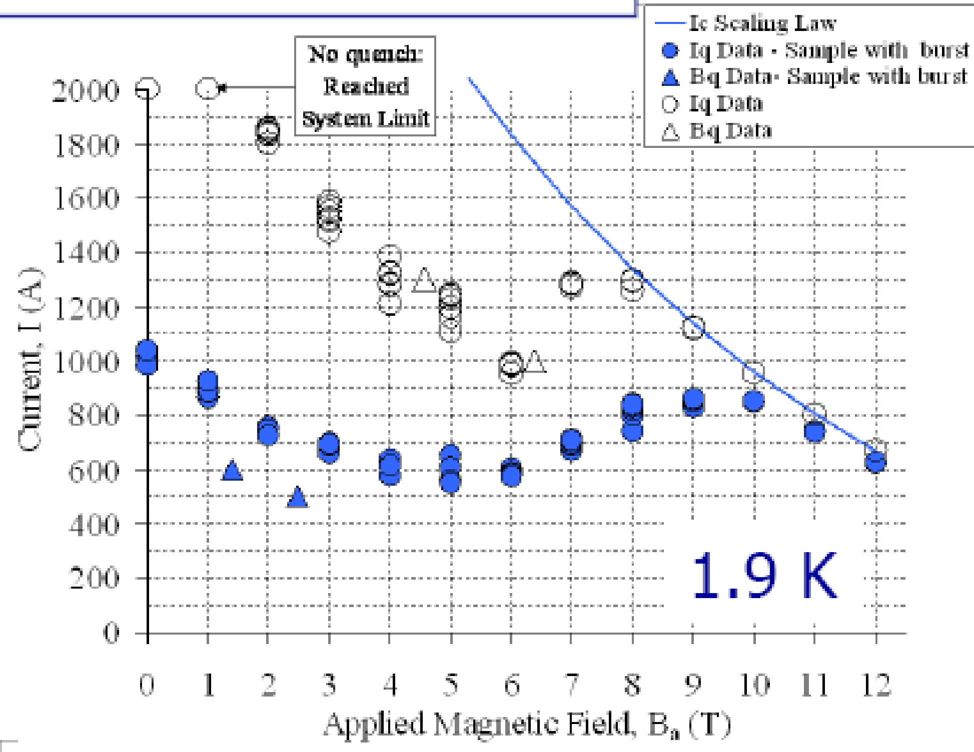
B. Bordini, L. Rossi, presented at *Applied Superconductivity Conference*, Chicago, USA, Aug. 2008

EFFECTS OF LOCAL STRAND'S DAMAGES

- A small local damage of the copper stabilizer can completely jeopardize the dynamic stabilization of a high J_c Nb_3Sn strand

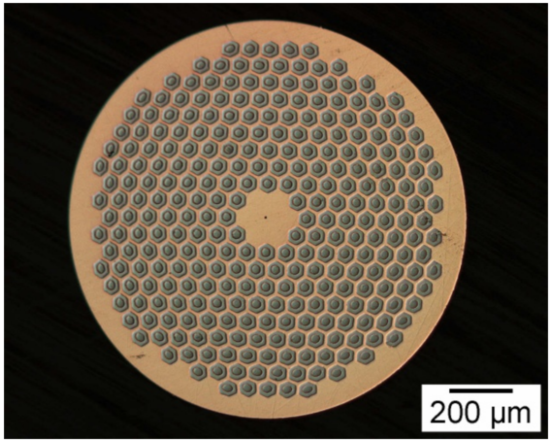
LARP 54 /61 RRP 0.7 mm RRR > 250

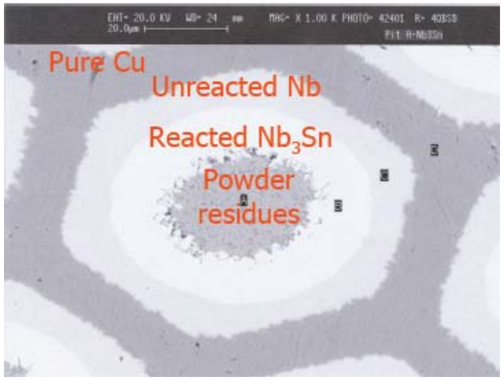




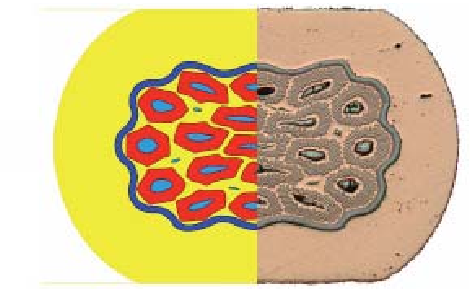
More conductor development

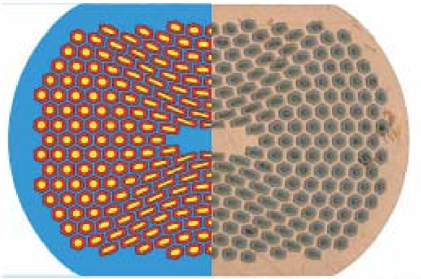
Wire with only 50 μm filam. Dia.
And with more Cu (58%), 1 mm
Powder-intube (Europe under developemnt

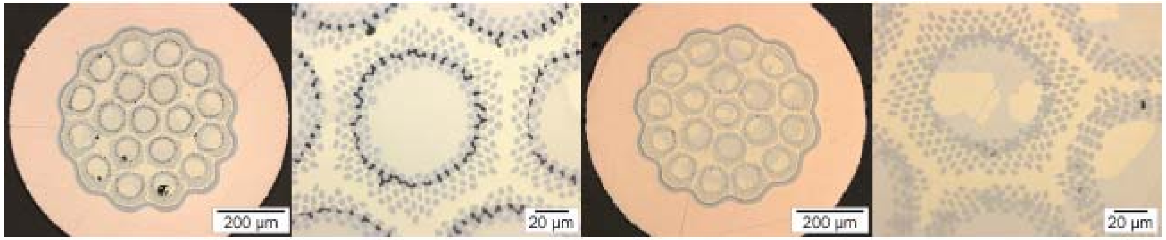




Building comprhensive 3-D model to understand deeformation and its dynamics





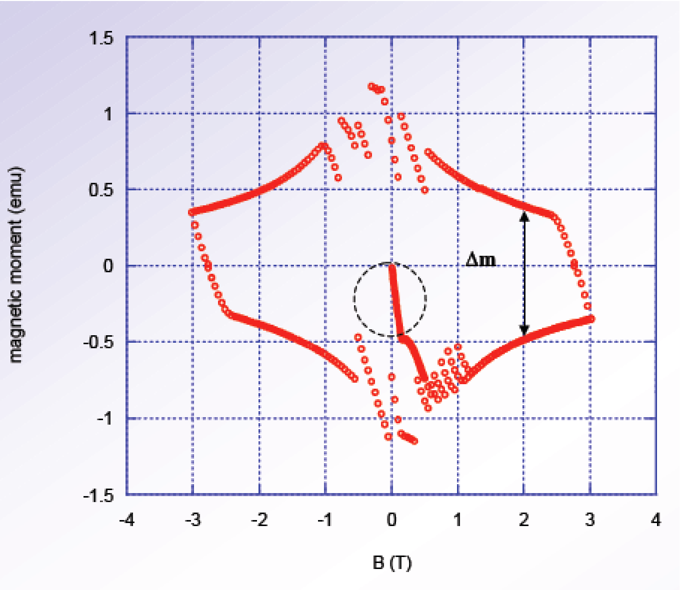


6 °C h^{-1} to 580 °C

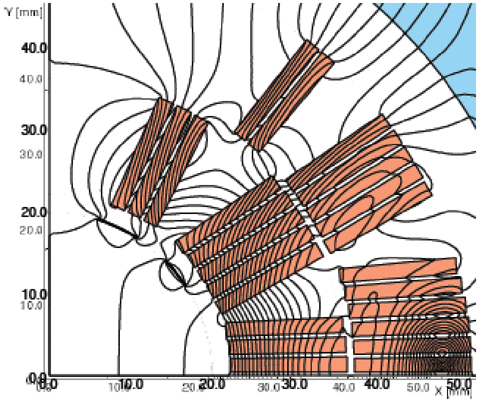
>100 °C h^{-1} to 580 °C

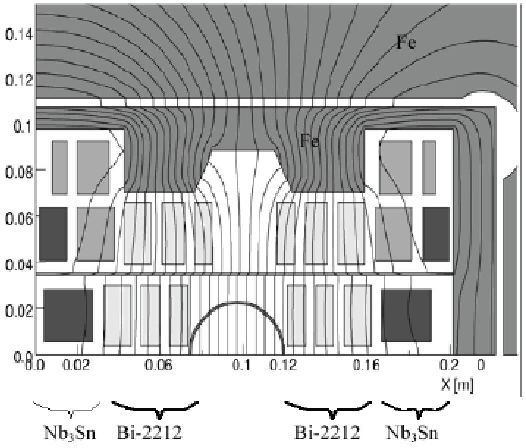
Influence of temperature ramp rate on void formations in internal tin wire

Intrinsic diamagnetism of Sc and magnegtization loop



- Techniques to compensate/correct this problem
  - Iron strips (cos θ coils)
  - Iron plate (block type coils)

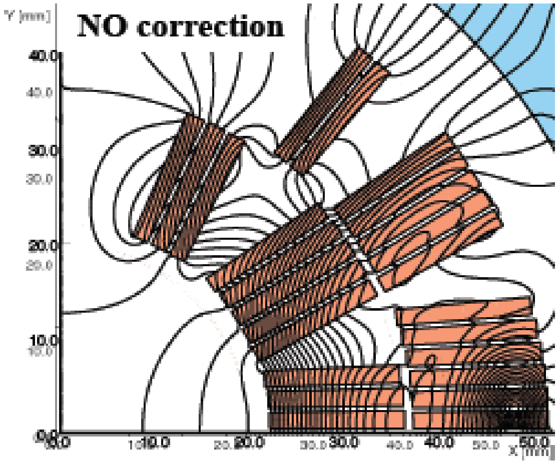


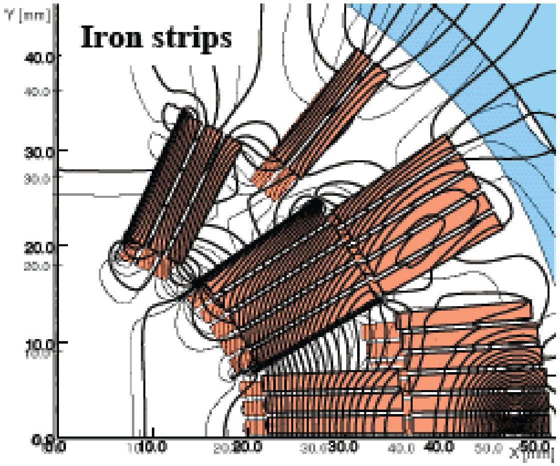


- E. Barzi, et al., *"Passive Correction of the Persistent Current Effect in Nb3Sn Accelerator Magnets"*, IEEE Trans. on Appl. Superc., Vol. 13, No. 2, June 2003, pp.1270-1273.
- P McIntyre, A. Sattarov, *"HYBRID DIPOLES FOR FUTURE HADRON COLLIDERS"* available at care-hhh.web.cern.ch

G. Ambrosio, FNAL,
CERN Ac. Training 2008

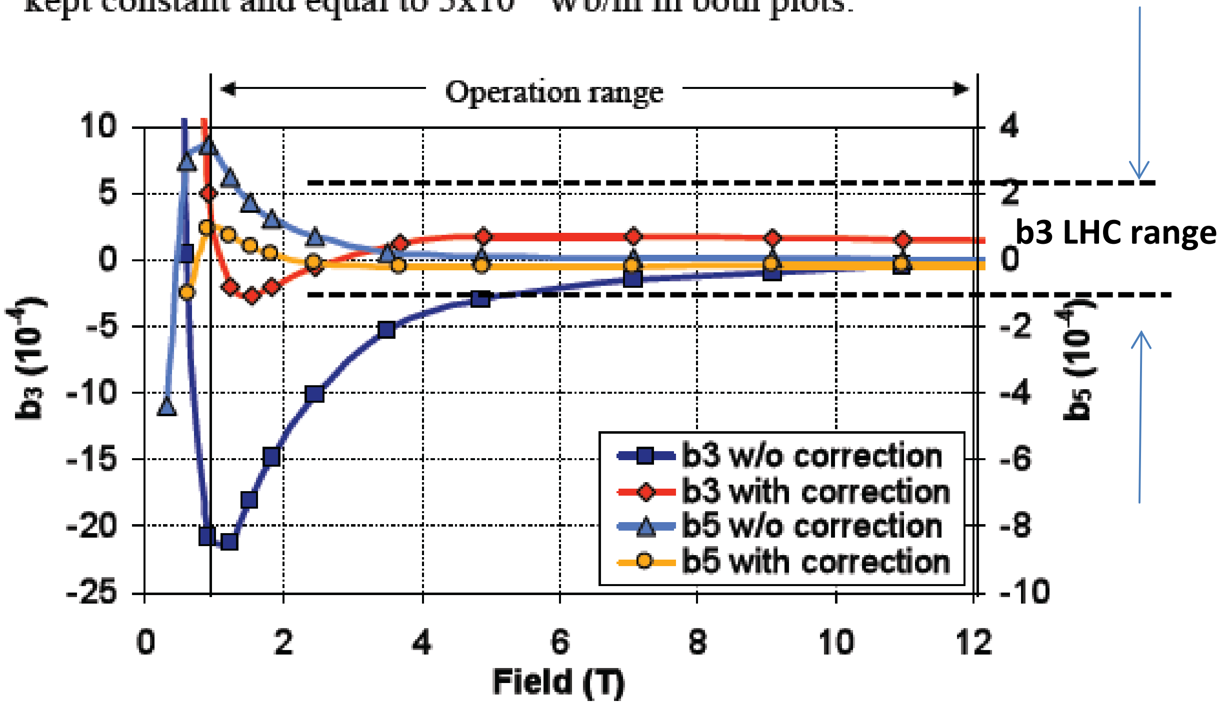
Correction works





Example: correction with iron strips

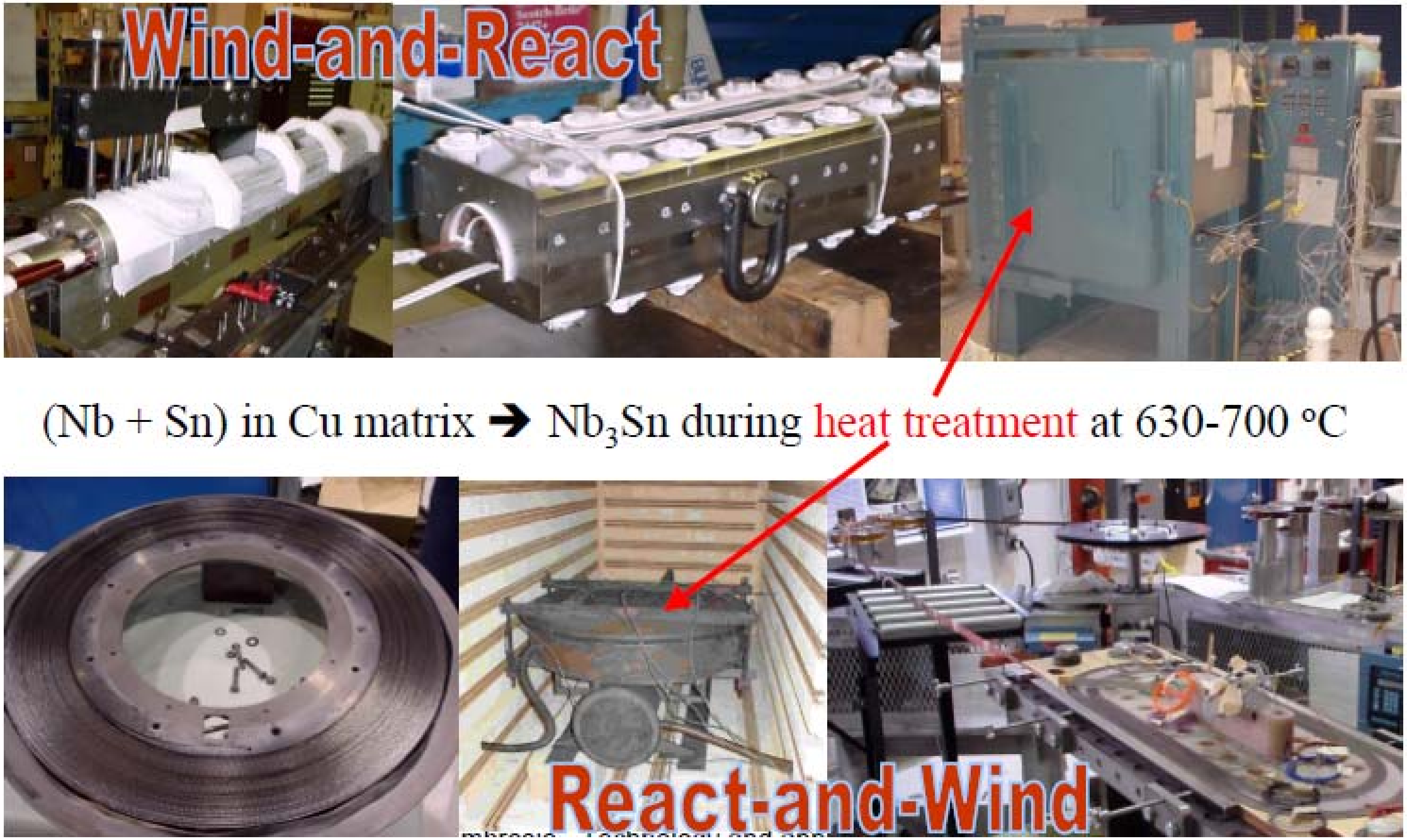
Magnetization flux in dipole magnet (no transport current nor iron yoke magnetization). Flux increment between adjacent lines is kept constant and equal to $5\text{x}10^{-5}$ Wb/m in both plots.



Multipoles in dipole magnet before and after correction

G. Ambrosio, FNAL, CERN Ac. Training 2008

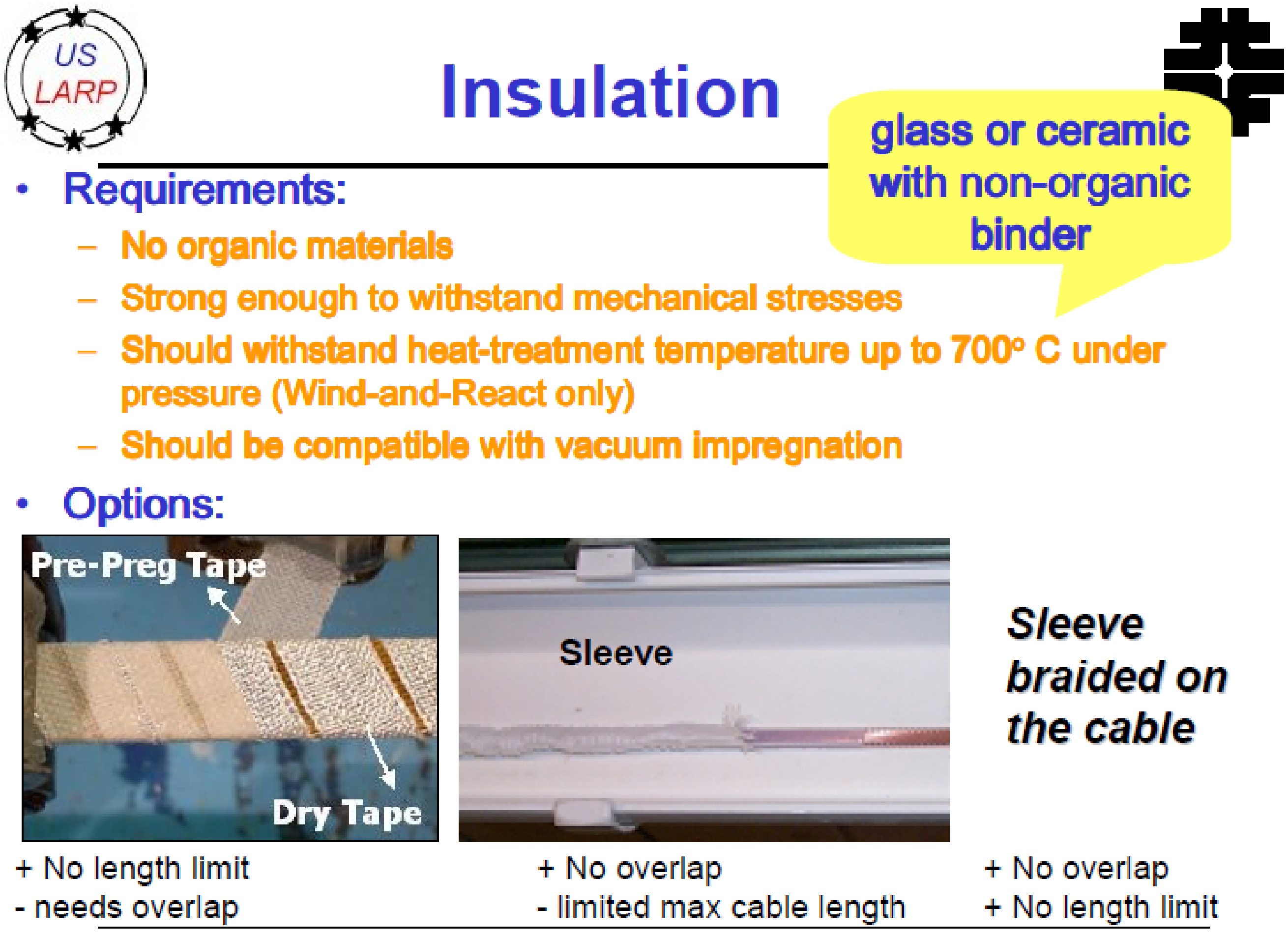
Coil technology issues: W&R vs. R&W



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

Despite few attempt R&W has to be abandoned
(good for large radius - jacketed- coils like ITER

Insulation: a further issue…



Insulation

glass or ceramic with non-organic binder

- Requirements:
  - No organic materials
  - Strong enough to withstand mechanical stresses
  - Should withstand heat-treatment temperature up to 700° C under pressure (Wind-and-React only)
  - Should be compatible with vacuum impregnation
- Options:

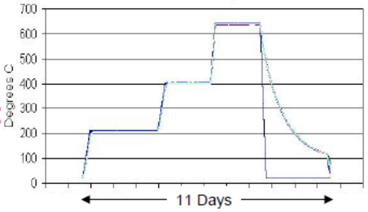
Sleeve braided on the cable

Pre-Preg Tape / Dry Tape	Sleeve	Sleeve braided on the cable
+ No length limit - needs overlap	+ No overlap - limited max cable length	+ No overlap + No length limit

Heat treatment (steps 1-3) Vacuum impegnation (step 4)

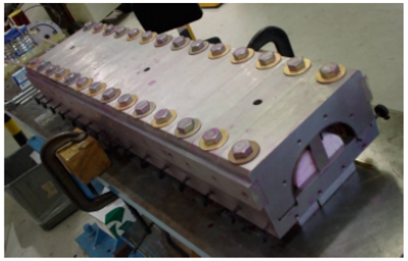
1

- This is a very critical step!
  - Temperature control and uniformity
    - Steps at ~210º C, 400-450º C, and 630-670º C
  - No oxygen (argon or vacuum)
- Reaction fixture should accommodate:
  - Coil volume increase
    - Due to Nb_3Sn formation
  - Different thermal expansions
- Reaction fixt. should provide
  - Nominal coil geometry
  - Easy extraction of reacted coil
    - Most critical handling



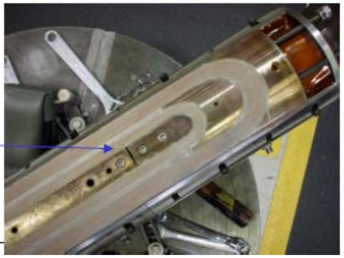
2

- Segmented tooling with base and top plates
  - ➔ Very high accuracy of coil cavity size for any length
- The fixture can be assembled / disassembled around the coil
  - ➔ Minimize coil handling



3

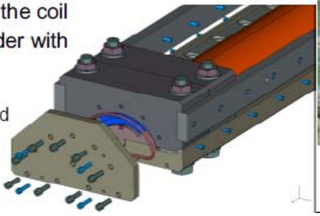
- Coil azimuthal size:
  - Size of curing mold is slightly smaller than nominal dimension
  - Size of reaction fixture is equal to nominal dimensions
  - ➔ coil growths during HT, and fills the reaction cavity with small pressure
- Coil longitudinal behavior:
  - The coil CTE changes during the HT
  - Al-bronze pole matches the coil CTE after HT but leaves gaps at pole tips
  - ➔ gaps between pole parts
  - Ti (Ti-Al-V) has smaller CTE and doesn't leave gaps at pole tips

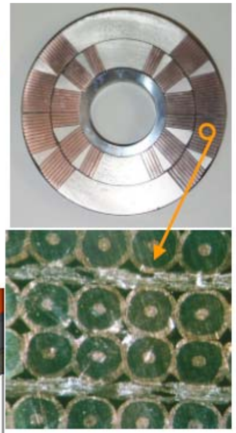


4

- Goals:
  - Fill all voids inside the coil in order to avoid stress concentration on the conductor
  - The coil becomes a solid object for easy and well controlled magnet assembly
- LARP Solution: CTD-101 K:
- long pot life
- very good penetration inside the coil
- Compatible with ceramic binder with good mechanical properties

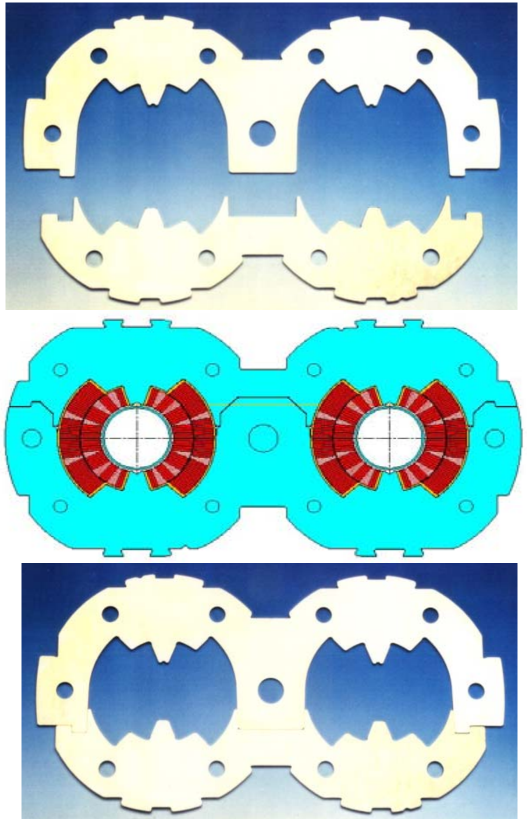
The reaction fixture can be sealed by using a shell and O-rings
➔ Impregnation fixture





Mechanical structure: the classical route

The long tradition from BNL and Fermilab: collaring concept

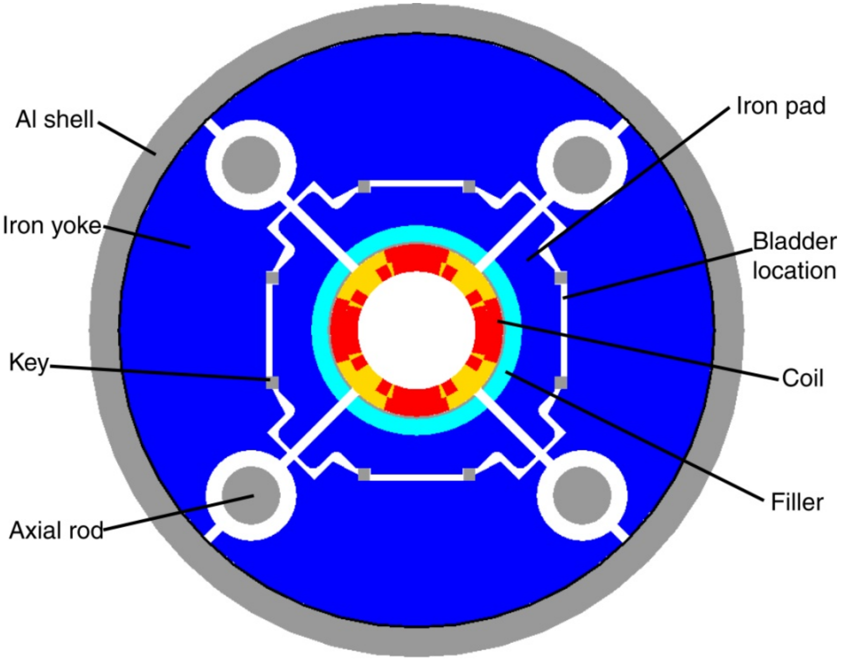


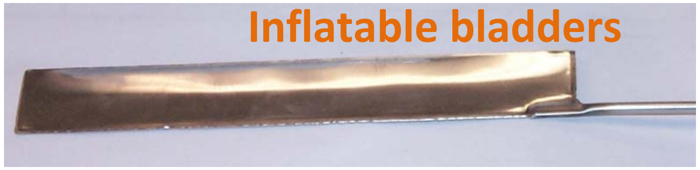
Pros and cons

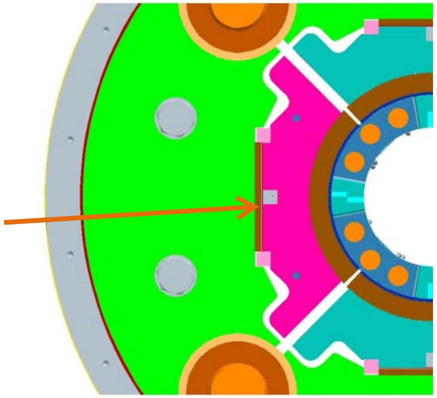
- The coils is well contained in a fixed cavity
- Field quality is in good part determined by collar shape
- If the coils size is not so well controlled, the stress can be too high or too low
- A prestress 2-3 times what is need is applied because of stress losses during cool-down: for very high field tends to be too high
- Since NbSn is stress sensitive…

Mechanical structure
The new route (from LBNL)

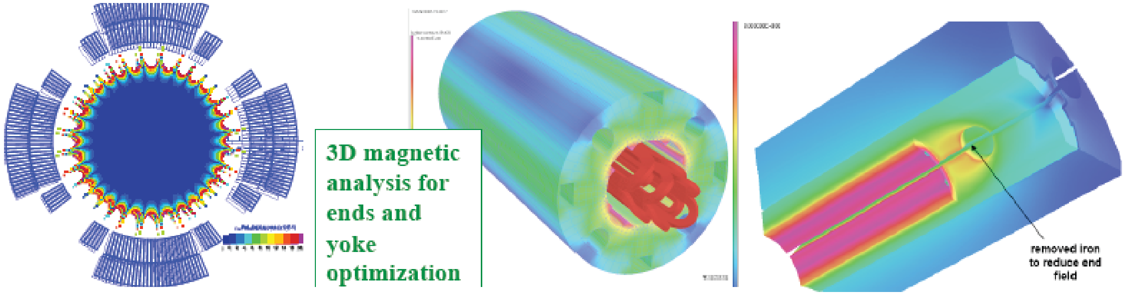
- Suppose the inner blue ring (iron pads) just in contact wit key with yoke. No prestress.
- Then you insert the bladders in the interstice. Then you pump in the bladders.
- Alu shell expands and goes in tension. The keys become loose.
- Remove the keys and put new keys as thick as the new interstice.
- Then depressurize the bladders and remove.
- The Al shell, not anymore pushed by the bladders exerts all its pressure on the coils through yoke-keys-iron pads.



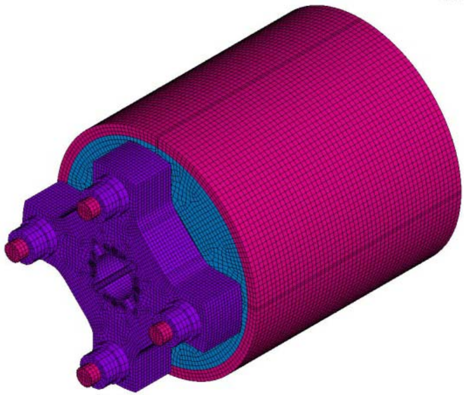


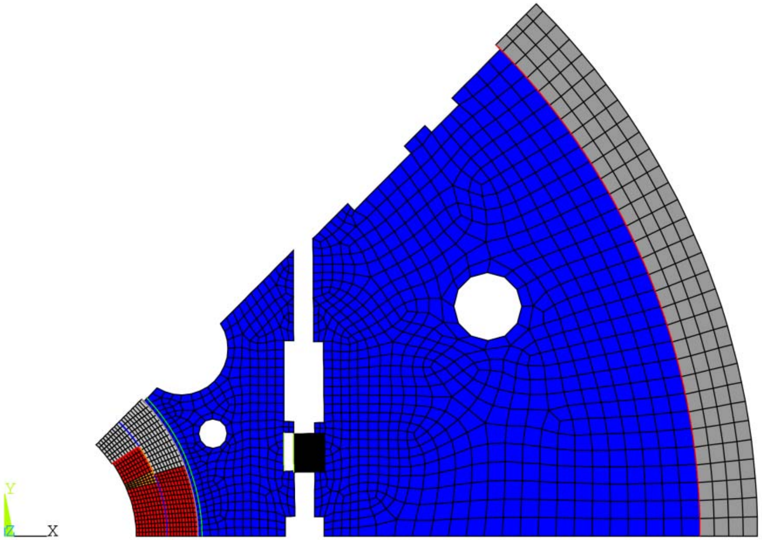


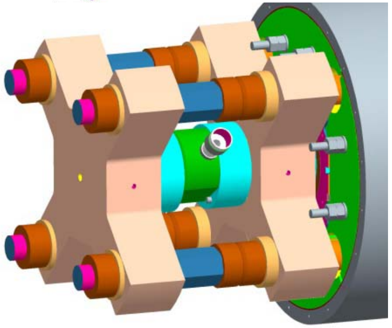
A lof of 3-D FEM



3D magnetic analysis for ends and yoke optimization

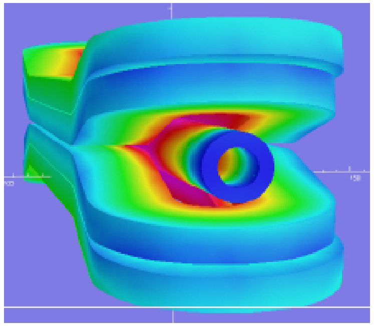


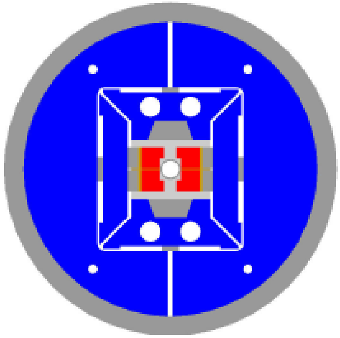


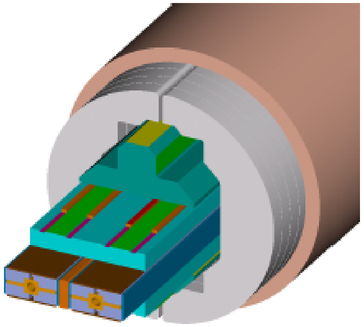


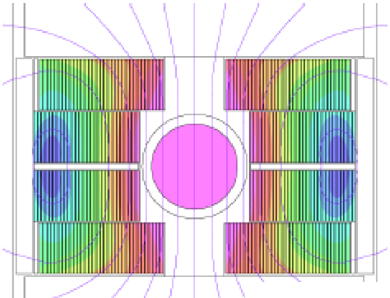
The last “product”
HD2 –a real magnet with bore (LBNL)

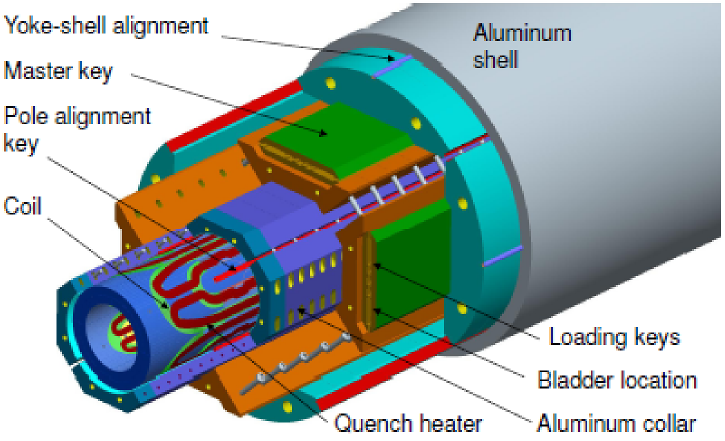
- Target dipole field: 15 T
- Target aperture: 40-43 mm
- Coil design: block-dipole with flared ends
- Designed for accelerator field quality
- Suitable for 2-in-1 layout
- Can be used for high field cable testing



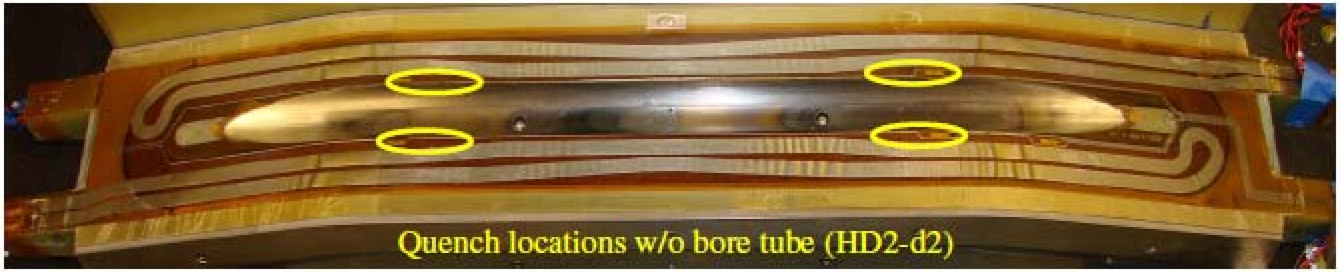


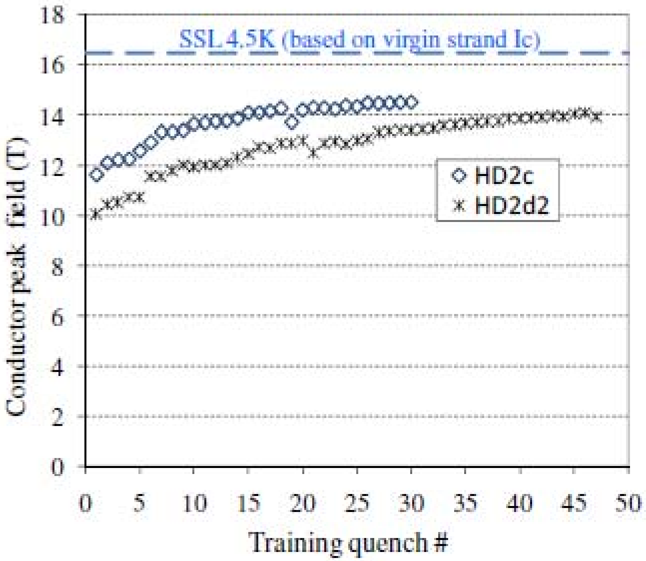


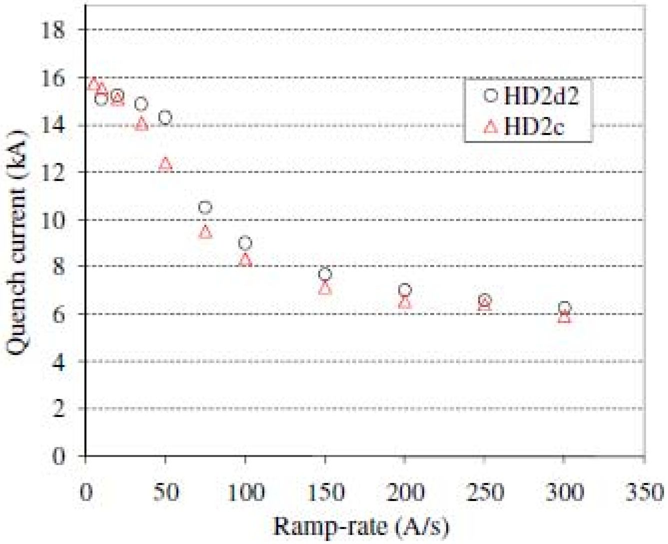




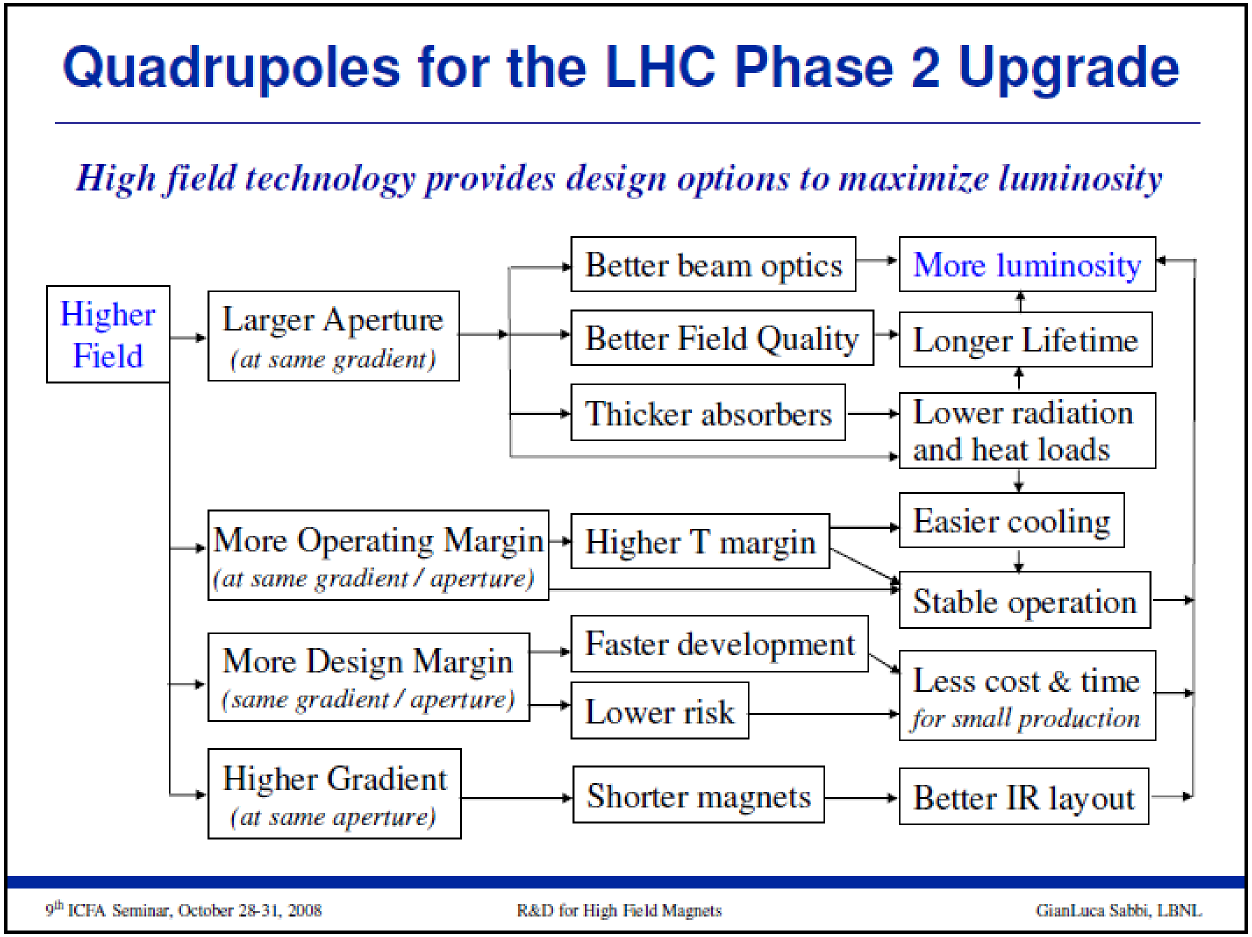
And it works … as first model


Quench locations w/o bore tube (HD2-d2)





Roadmap for HG quadrupole



Quadrupoles for the LHC Phase 2 Upgrade

High field technology provides design options to maximize luminosity

Higher Field

Larger Aperture
(at same gradient)

More Operating Margin
(at same gradient / aperture)

More Design Margin
(same gradient / aperture)

Higher Gradient
(at same aperture)

Better beam optics

Better Field Quality

Thicker absorbers

Higher T margin

Faster development

Lower risk

Shorter magnets

More luminosity

Longer Lifetime

Lower radiation and heat loads

Easier cooling

Stable operation

Less cost & time
for small production

Better IR layout

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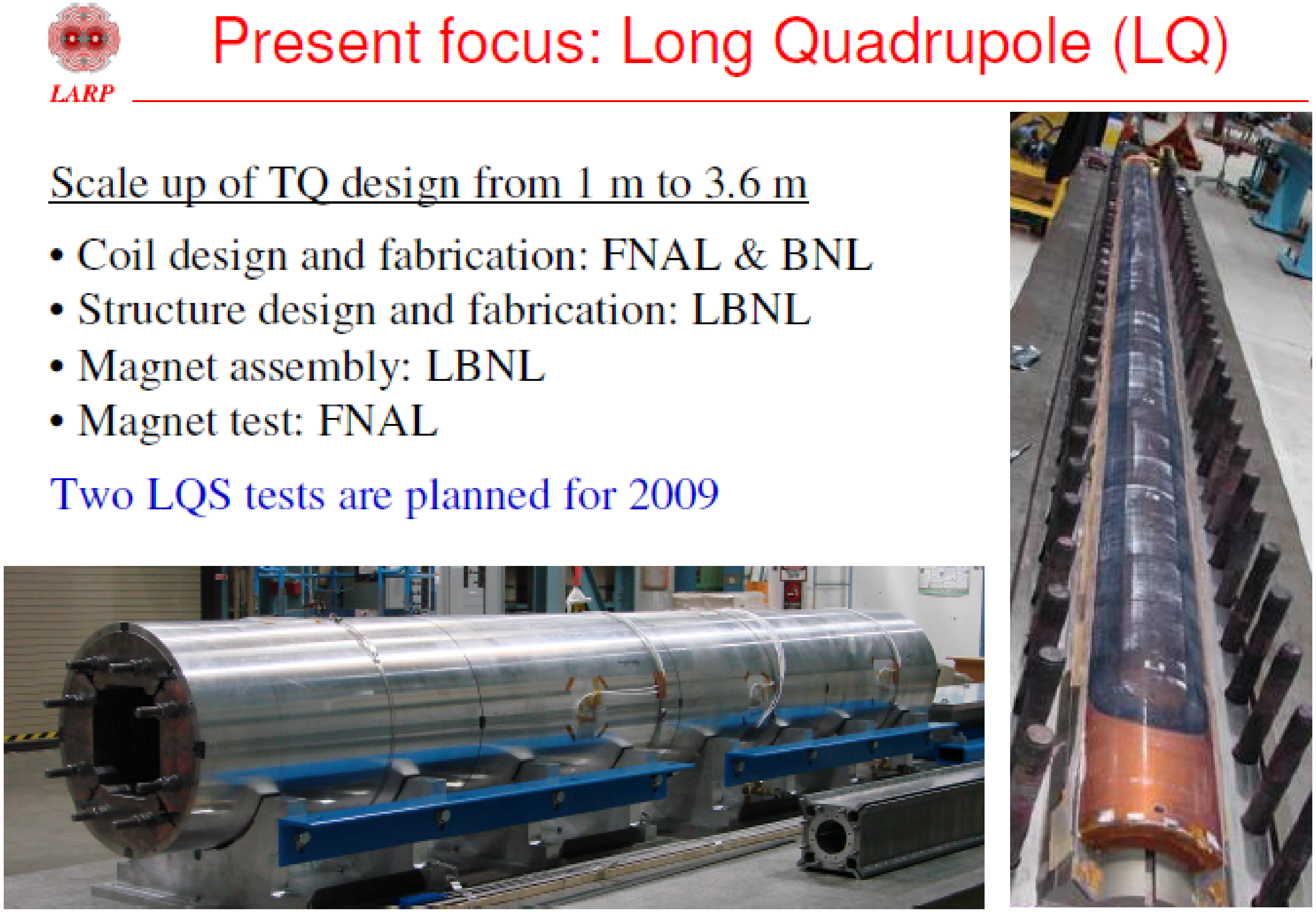
Fist long (4 m) HF magnet test Nov 09: 200 T/m in 90 mm bore



LARP

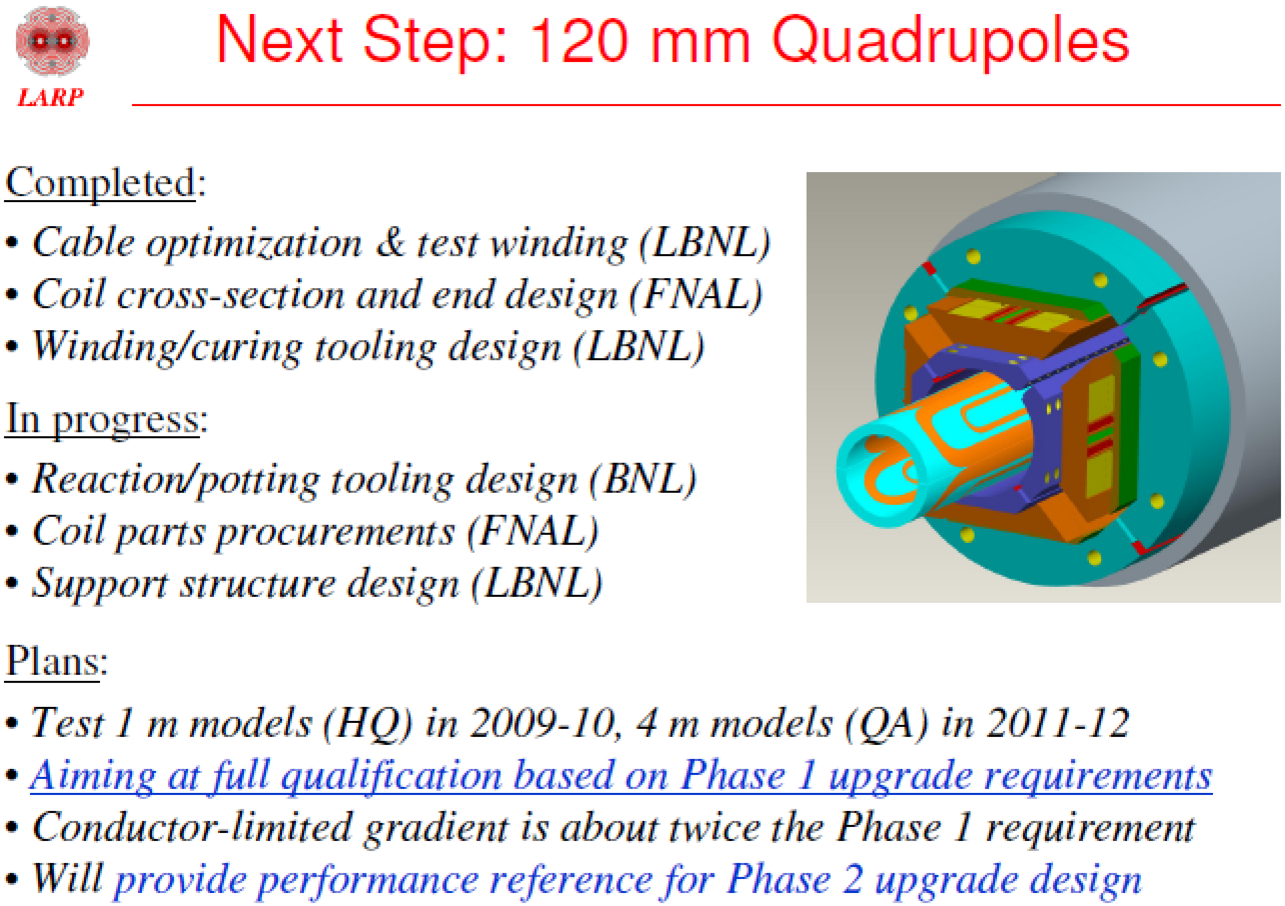
Present focus: Long Quadrupole (LQ)

Scale up of TQ design from 1 m to 3.6 m

- Coil design and fabrication: FNAL & BNL
- Structure design and fabrication: LBNL
- Magnet assembly: LBNL
- Magnet test: FNAL

Two LQS tests are planned for 2009

Next step: near our needs:
G> 200 T/m in 120 mm aperture



Next Step: 120 mm Quadrupoles

Completed:

- *Cable optimization & test winding (LBNL)*
- *Coil cross-section and end design (FNAL)*
- *Winding/curing tooling design (LBNL)*

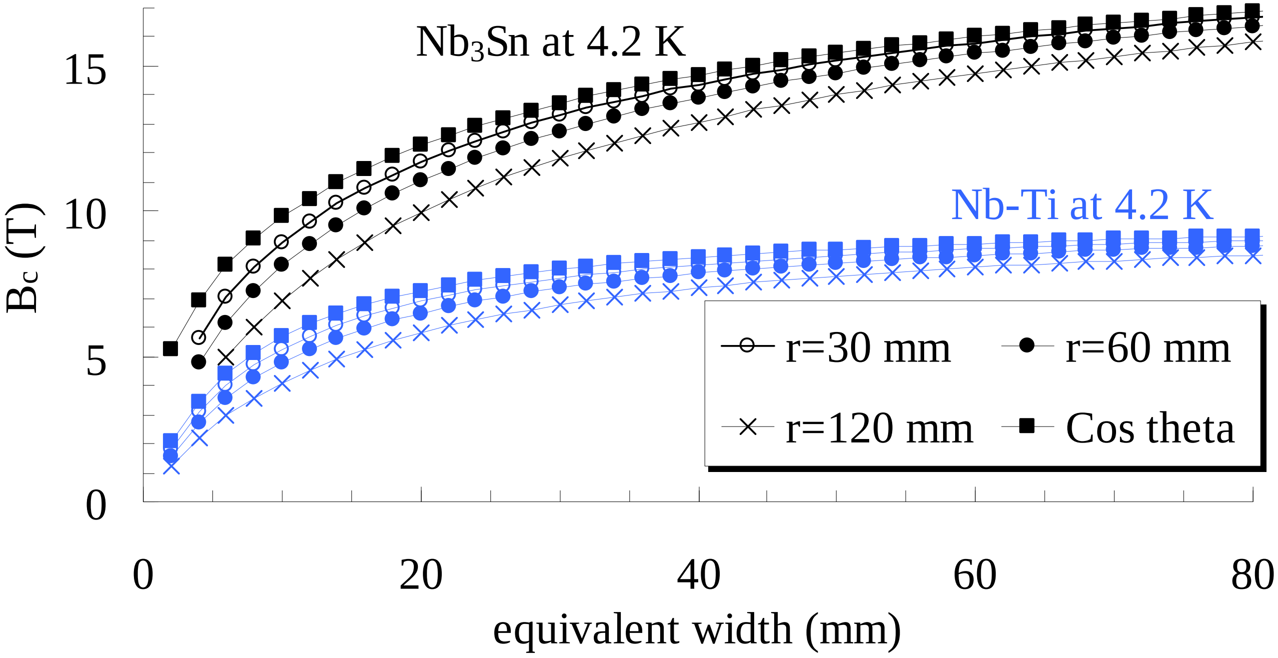
In progress:

- *Reaction/potting tooling design (BNL)*
- *Coil parts procurements (FNAL)*
- *Support structure design (LBNL)*

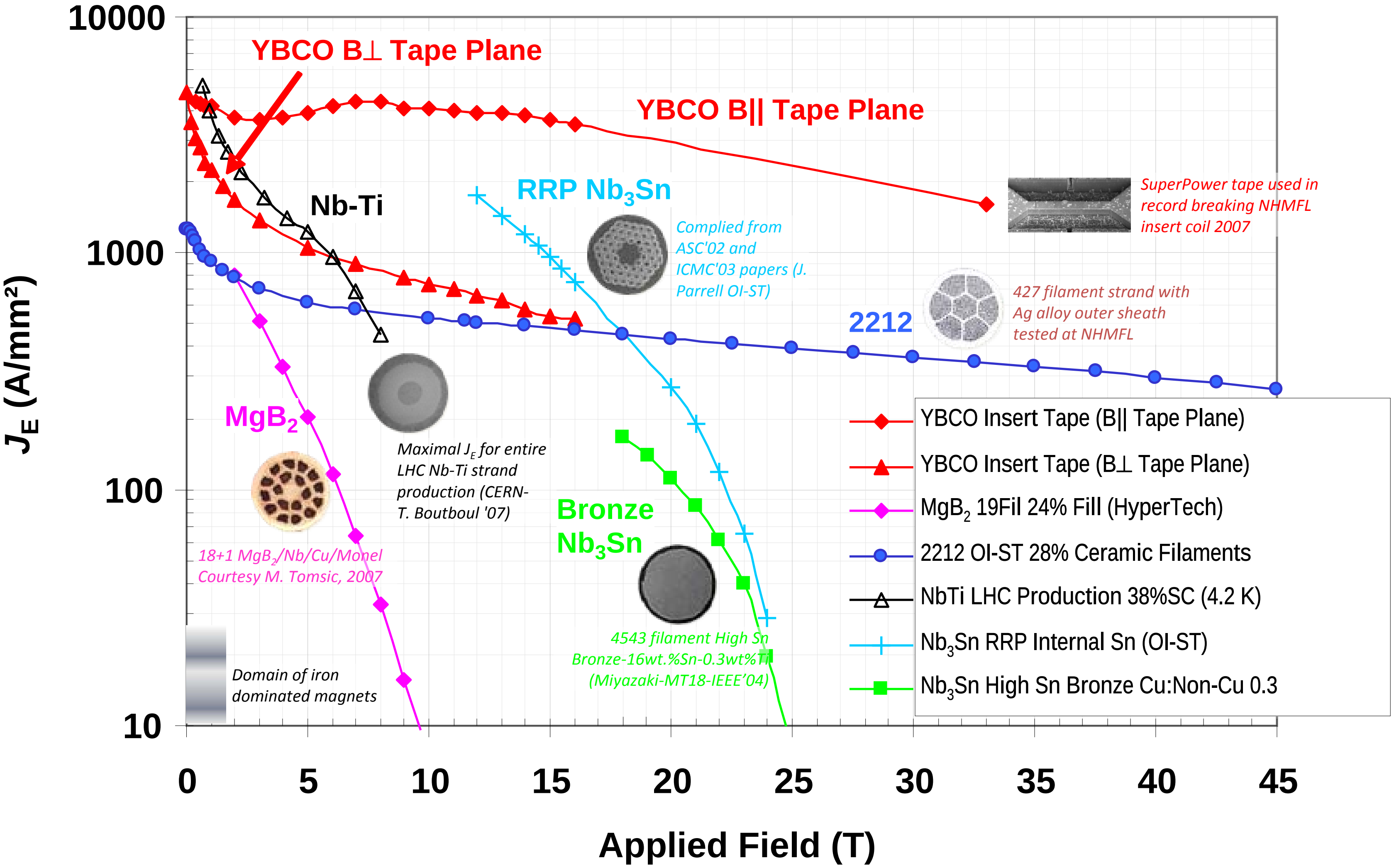
Plans:

- *Test 1 m models (HQ) in 2009-10, 4 m models (QA) in 2011-12*
- *Aiming at full qualification based on Phase 1 upgrade requirements*
- *Conductor-limited gradient is about twice the Phase 1 requirement*
- *Will provide performance reference for Phase 2 upgrade design*

And for dipole ?
NbSn cannot go beyond 15-16 T…



Can HTS made to work for us?



SuperPower tape used in record breaking NHMFL insert coil 2007

Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)

427 filament strand with Ag alloy outer sheath tested at NHMFL

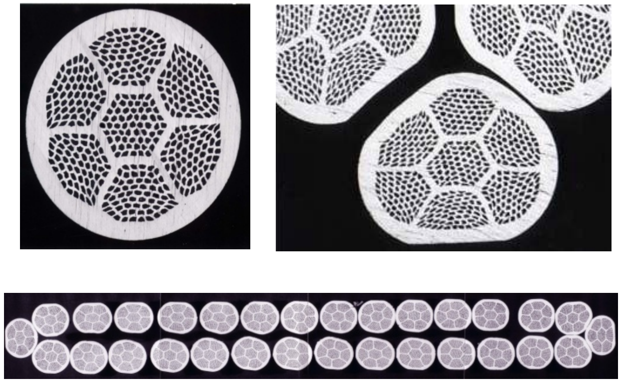
Maximal J_E for entire LHC Nb-Ti strand production (CERN-T. Boutboul '07)

18+1 MgB_2/Nb/Cu/Monel Courtesy M. Tomsic, 2007

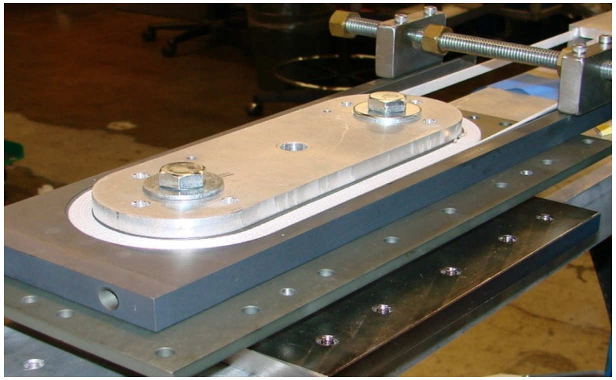
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

Domain of iron dominated magnets

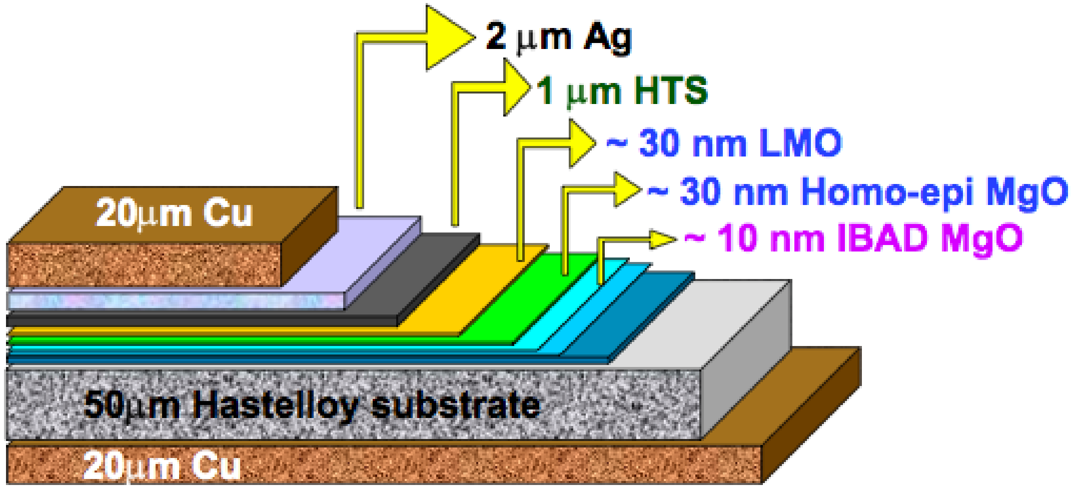
Part of R&D in Magnet Labs

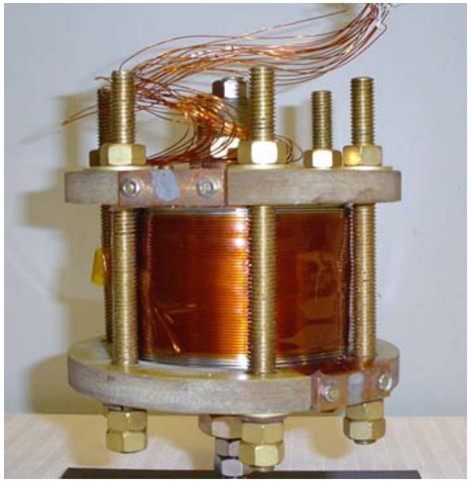


Cable fabrication



Bi-2212 Coil Winding



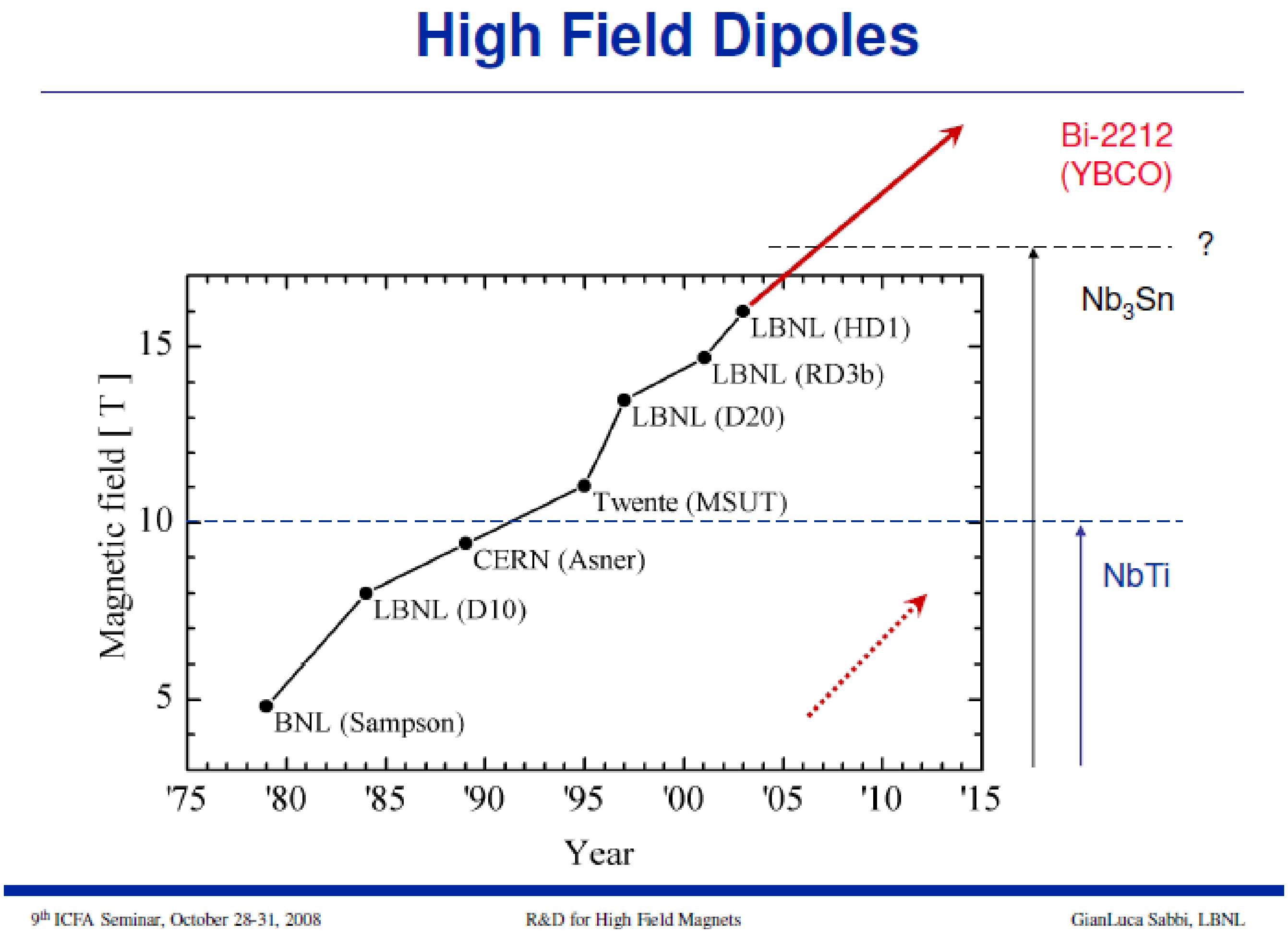


YBCO
SUPERPOWER
Record field (25 T),
adding 3 T
NHMFL - Florida

Their technology is more difficult than Nb$_3$Sn

Nb3Sn	**HTS**
Limit of 16-18 T (acc. mag.)	Can go to 25 T and beyond
Very high Jc	Realtively low Jc
Low Tc (average stability, “easy” to protect)	High Tc (better stability , more difficult to protect)
Available in long wire	Wire uniformity is an issue
Developed 10-20 kA cables	Cabling possible for Biscco, not yet for Ybco
Brittle but we can work out	Very brittle, still to learn
Th. Treatment: difficult	Th. Treatment: much more difficult, with “leakage”

Where can go with HF dipoles?



High Field Dipoles

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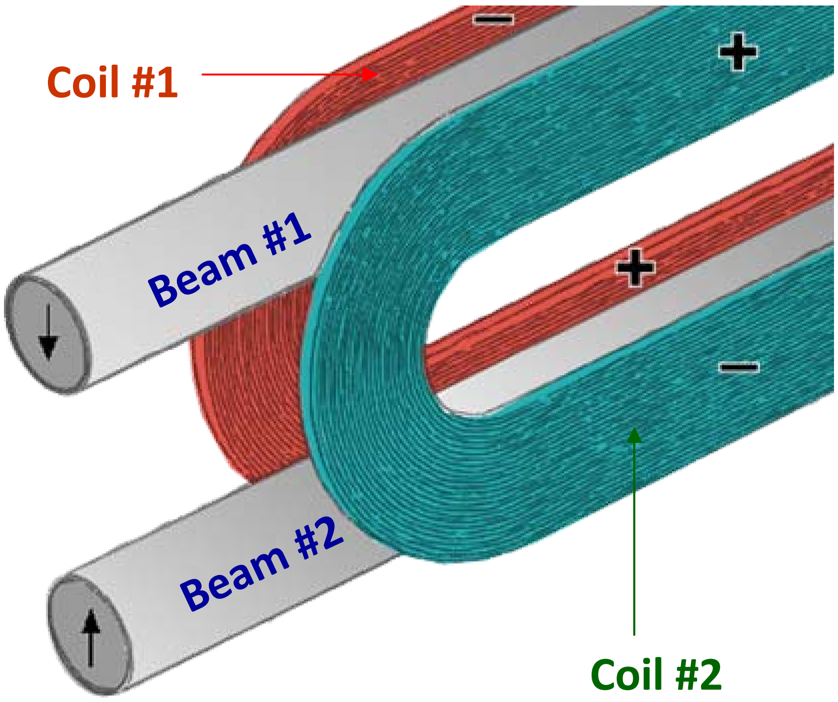
Where we can go? Design to fit HTS ?

To the farthest energy frontier !



Main Coils of the *Common Coil Design*

Courtesy R. Gupta BNL