High Field Magnets

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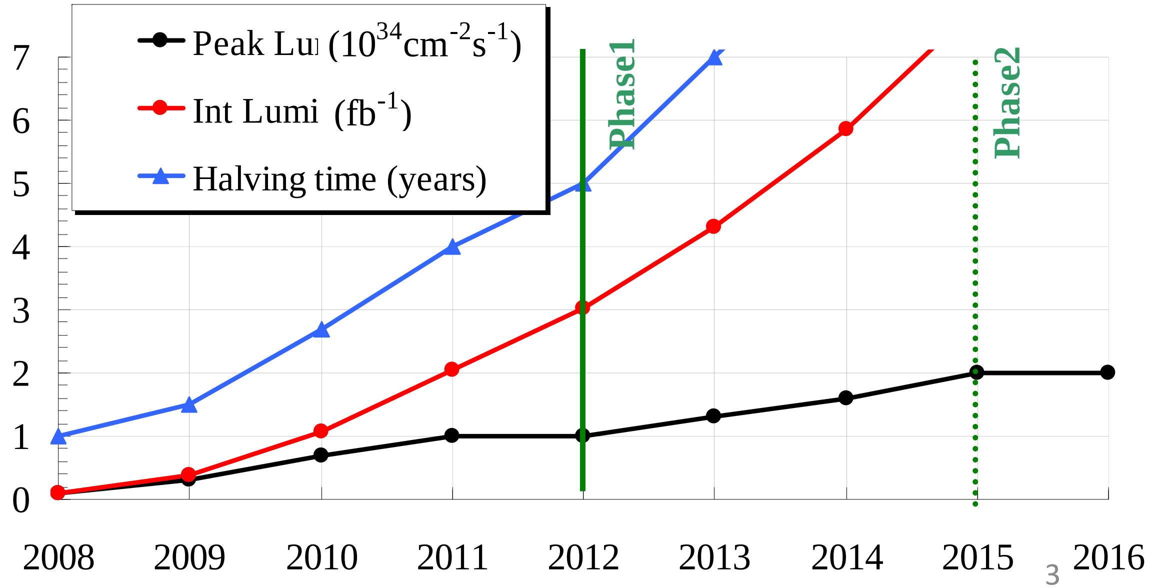
Content

- Reasons for the High Field magnets for LHC
- Comments on materials availabale
- World panorama
- Advances in HFM in EU
- Plans

Reason: LHC Lumi up -1

Aim of phase II (2018)

- After some years (~4) at nominal/ultimate luminosity, a big boost is needed → factor 10/5 is needed
  - Otherwise the time to halve the statistical error becomes huge)
- Go up to $L \sim 10 \times 10^{34}$ [$cm^{-2}\ s^{-1}$]
- This involves detector and injector upgrade
- All solutions that can be envisaged should be adopted
- Challenge: energy deposition



Reason: LHC Lumi up - 2

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

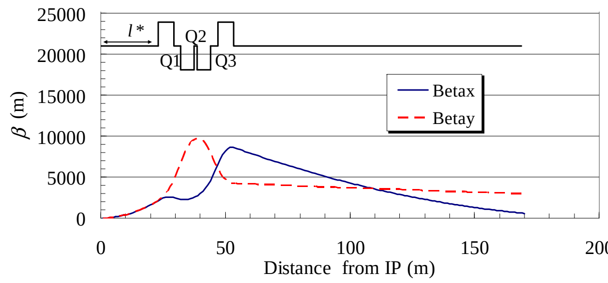
- The focusing is presently limited by the aperture of the quadrupoles Q1-Q3 around the IP (the so-called triplet)
  - The beta function of the beam in the quadrupoles is $\propto 1/\beta^*$
  - The present aperture of 70 mm limits β^*=0.55 cm
  - Changing the triplet, one hits the hard limit of the chromaticity correction at
    - Nb_3Sn triplet β^*=0.14 cm

[E. Todesco et al, CARE LUMI-06 J. P. Koutchouk et al., PAC 07]

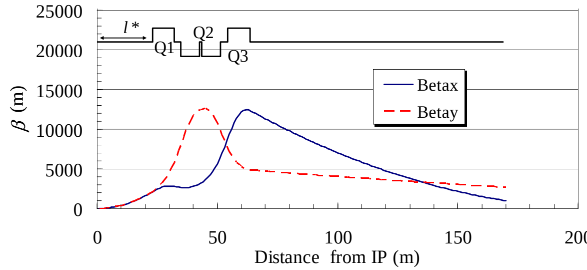
  - If the distance of the triplet from the IP is reduced from 23 m to 13 m (extreme case, not feasible), one can further improve by ~25%
    - Nb_3Sn triplet β^*=0.11 cm

Cont.

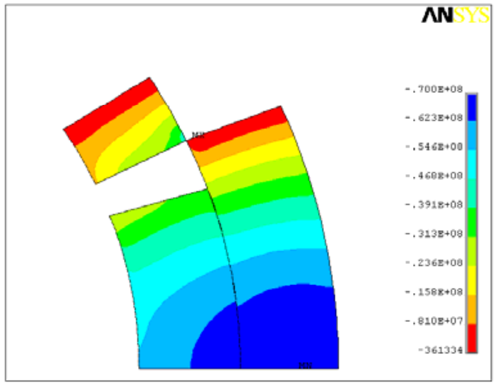
- A larger (longer) triplet
  - Aim: have a larger aperture to be able to go at β^*= 15 cm down to the limit imposed by chromaticity
- Final solutions (could be)
  - Nb_3Sn magnets, around 150 mm, ~ 10 m long, to be used for phase II (with … see next slide)
    - Smaller β^*
    - Better tolerance to energy deposition
- General challenges
  - Large aperture, large stress
  - Energy deposition
  - Good field quality



Today baseline of IP



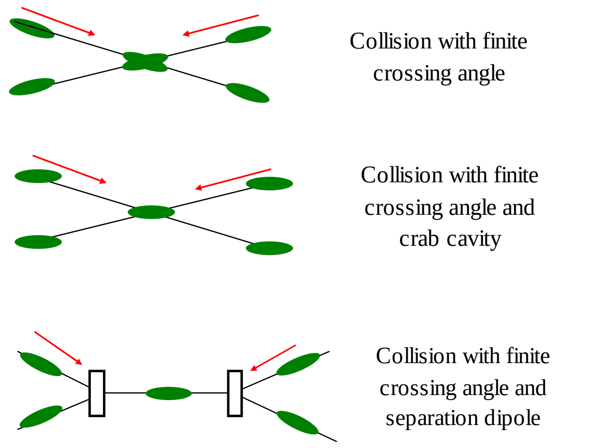
Upgrade with 40m Nb-Ti triplet



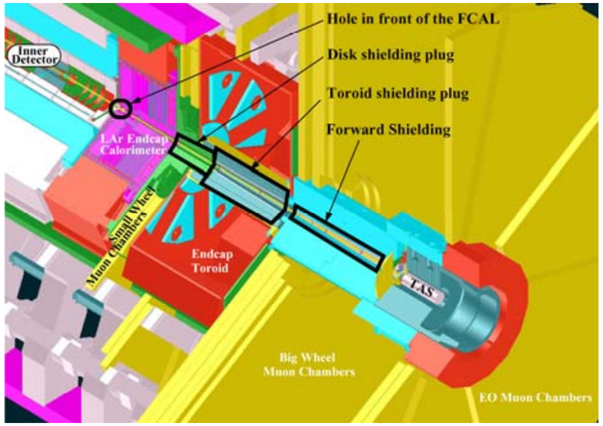
Estimated forces in the coil

… in conjuction with Crab cavity and/or Early separation scheme

- Crab cavity
  - Aim: kill the geometrical reduction factor that reduces luminosity for β^*<25 cm
  - Idea: the bunch is rotated longitudinally to maximize the collision area
  - Status: tested at KEK on electron machine



- Early separation dipole
  - Aim: as crab cavity
  - Idea: Have zero crossing angle but separate the beams as soon as possible to avoid parasitic beam-beam interaction with a dipole (~5 Tm)
  - Challenges: has to be in the detector, in a high radiation environment
  - Status: integration studies ongoing
- Each technologies could not completely set *F*=1 → both could solve it completely



Positions where D0 could be integrated

General consideration

- Touching the insertion is a “local” action, easier than touching the entire machine.
- Very high beam intensity, beyond nominal will not be easy to manage and machine protection might become a real issue

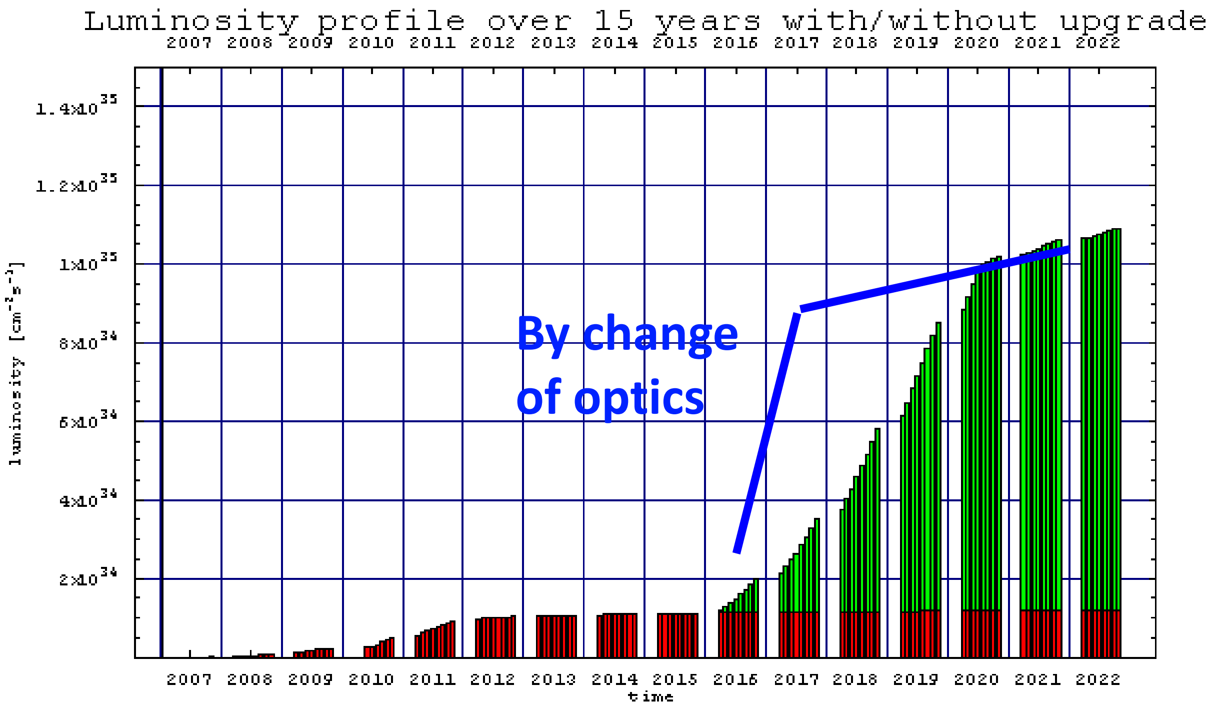
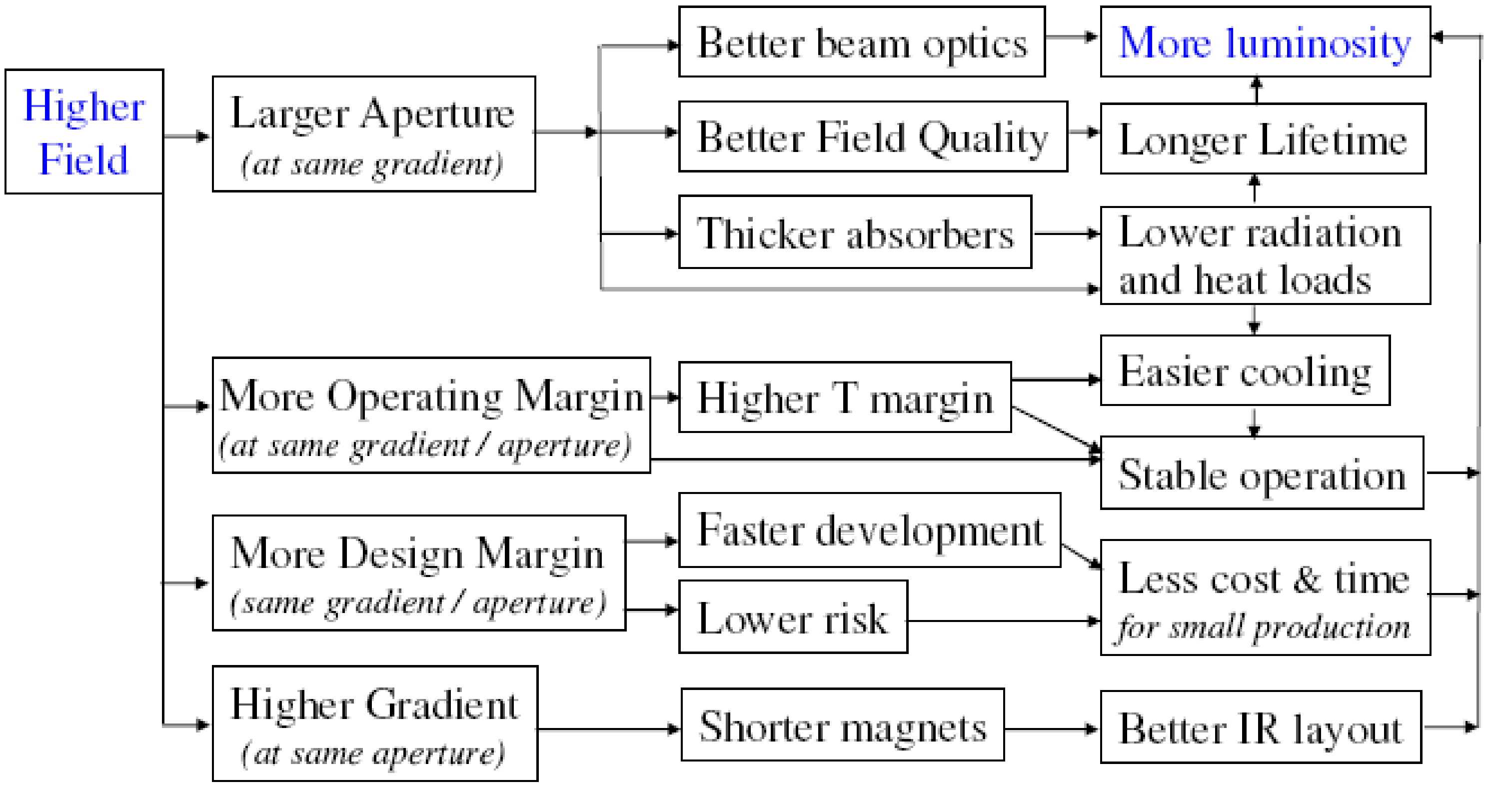


Fig. 1 Evolution of LHC luminosity according to the reference scenario (LHC project report 626 (2002) scaled according to empirical law (V. Shiltev, J. P.Koutchouk)

Space of parameters for a choice

Quadrupoles for the LHC Phase 2 Upgrade

High field technology provides design options to maximize luminosity



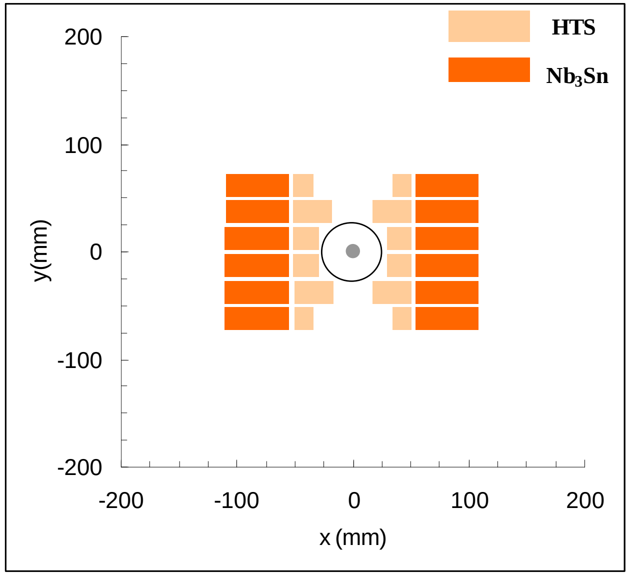
HFM – reasons (not only triplets)

- New magnets are needed for the LHC phase 2 upgrade in about 10 years
  - Quadrupoles for the low-beta insertions
  - Corrector magnets for the low-beta insertions
  - Early separation dipole (D0)

  and possibly
  - Dogleg dipoles for the cleaning insertions
  - Q6 for cleaning insertions
  - 10 m dipoles for the dispersion suppressors (room for collim.)
- New magnet types needed for a neutrino factory
  - Open midplane dipole for a muon decay ring (10-15 T)
  - Open midplane dipole for a beta beam decay ring (6-8 T)
- **LHC-FEF horizon:**
  - **we have a tunnel with the proper infrastructure, the Farthest Energy Frontier (30-40 TeV c.o.m.) will be on the table in 2013-2015.**

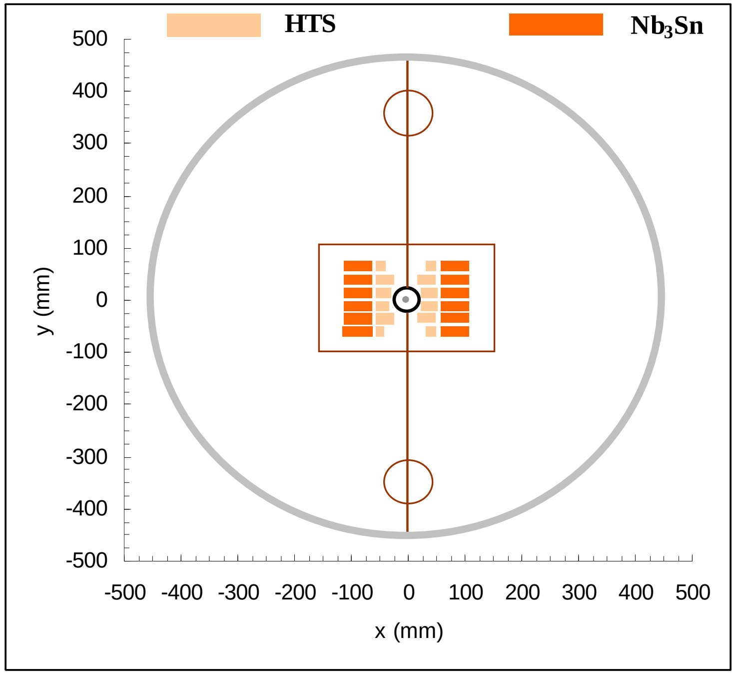
A 20 TESLA DIPOLE

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

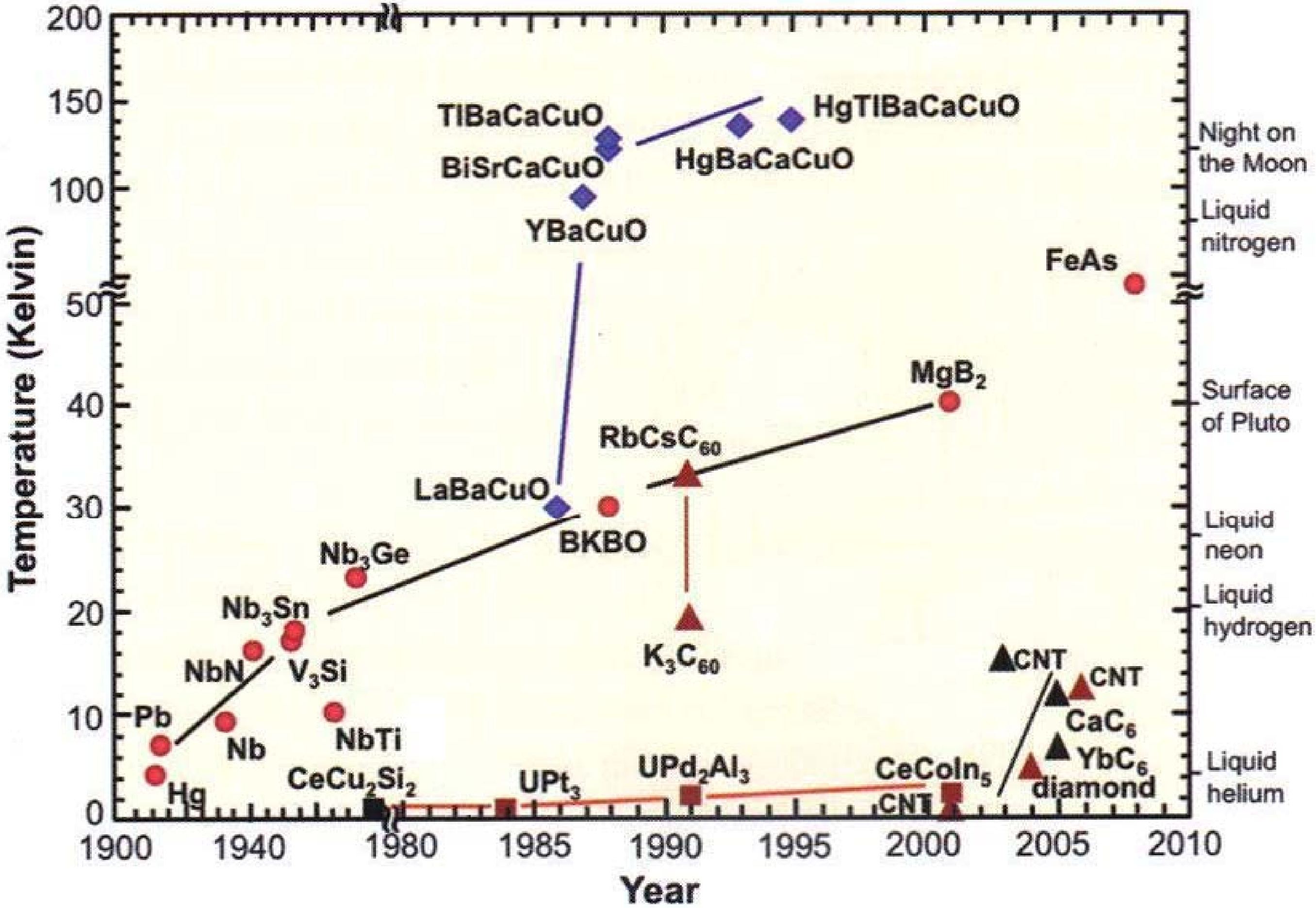


Courtesy E. Todesco

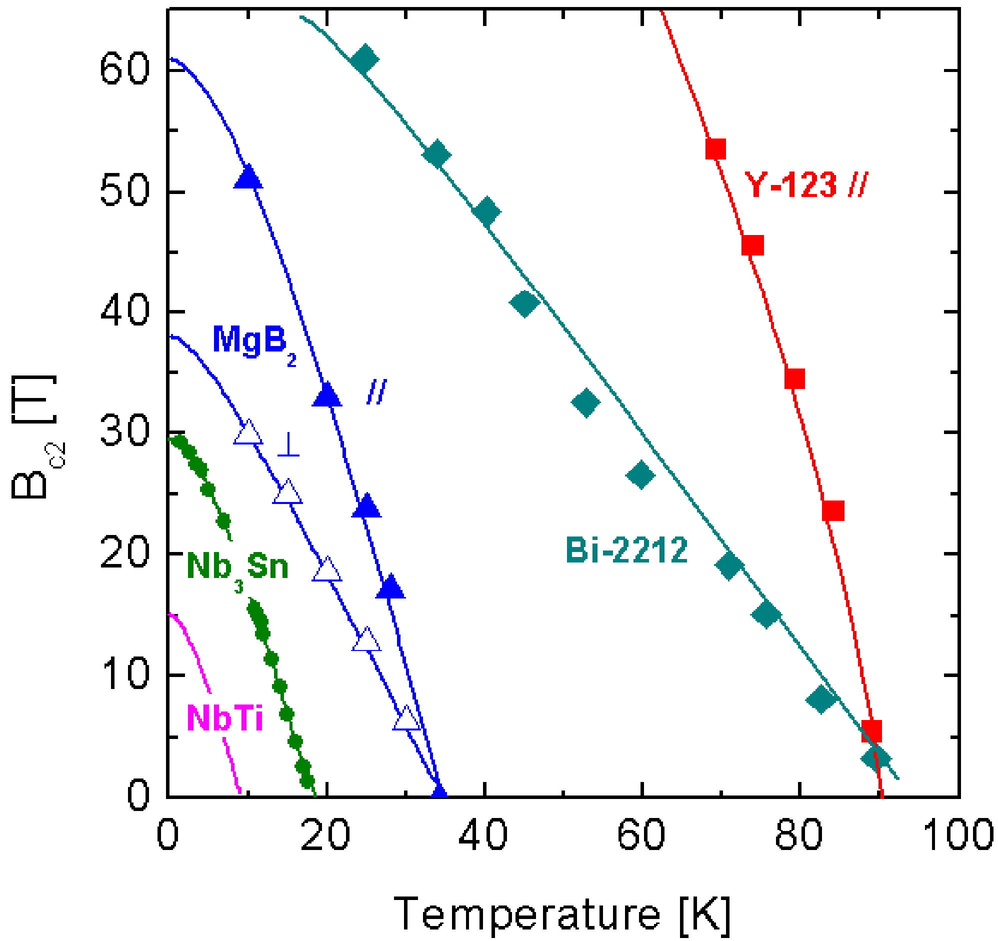
- Operational current: 18 KA
- Operational current density: 400 A/mm^2
- **20% operational margin**



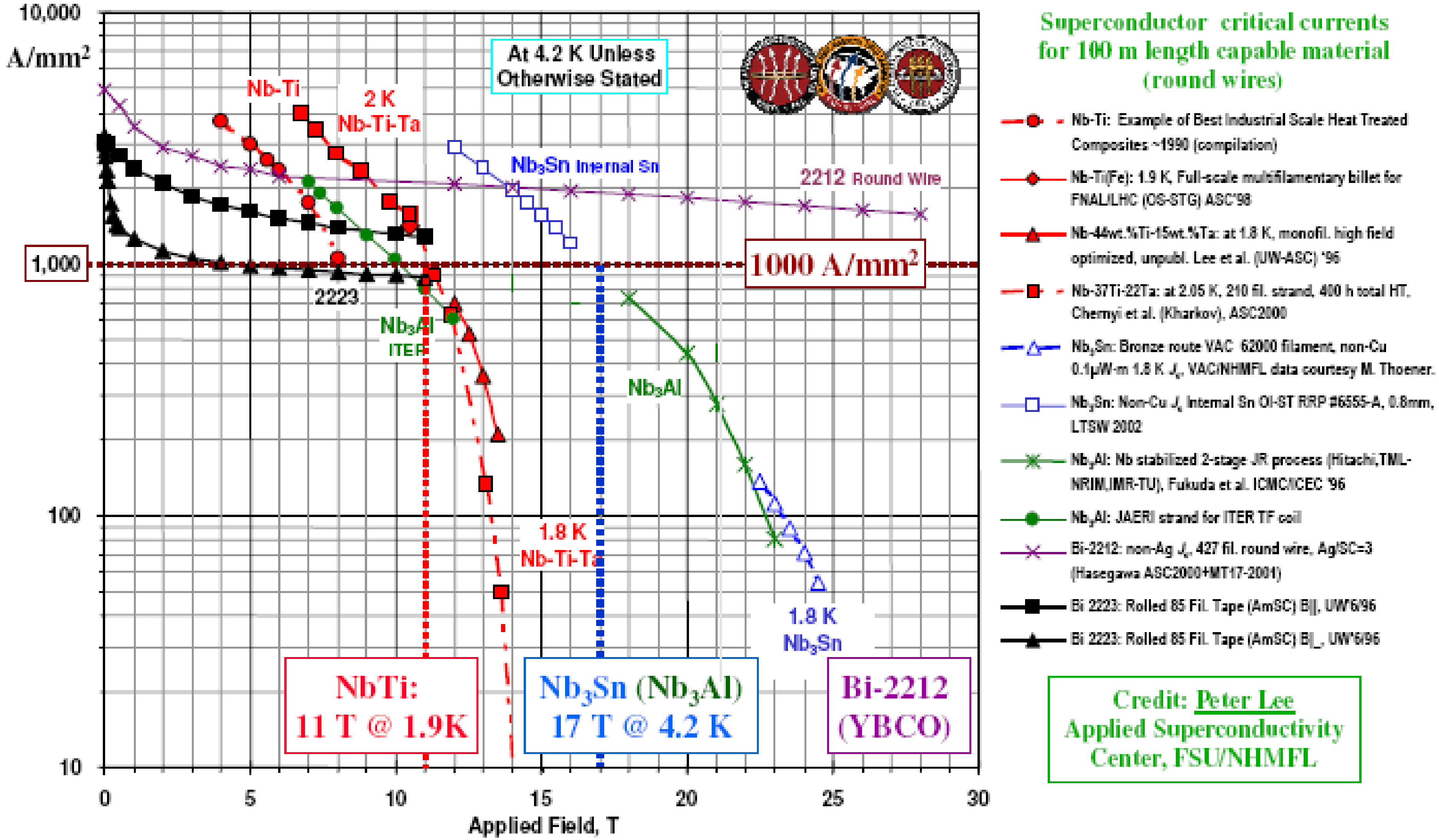
First: critical temperature



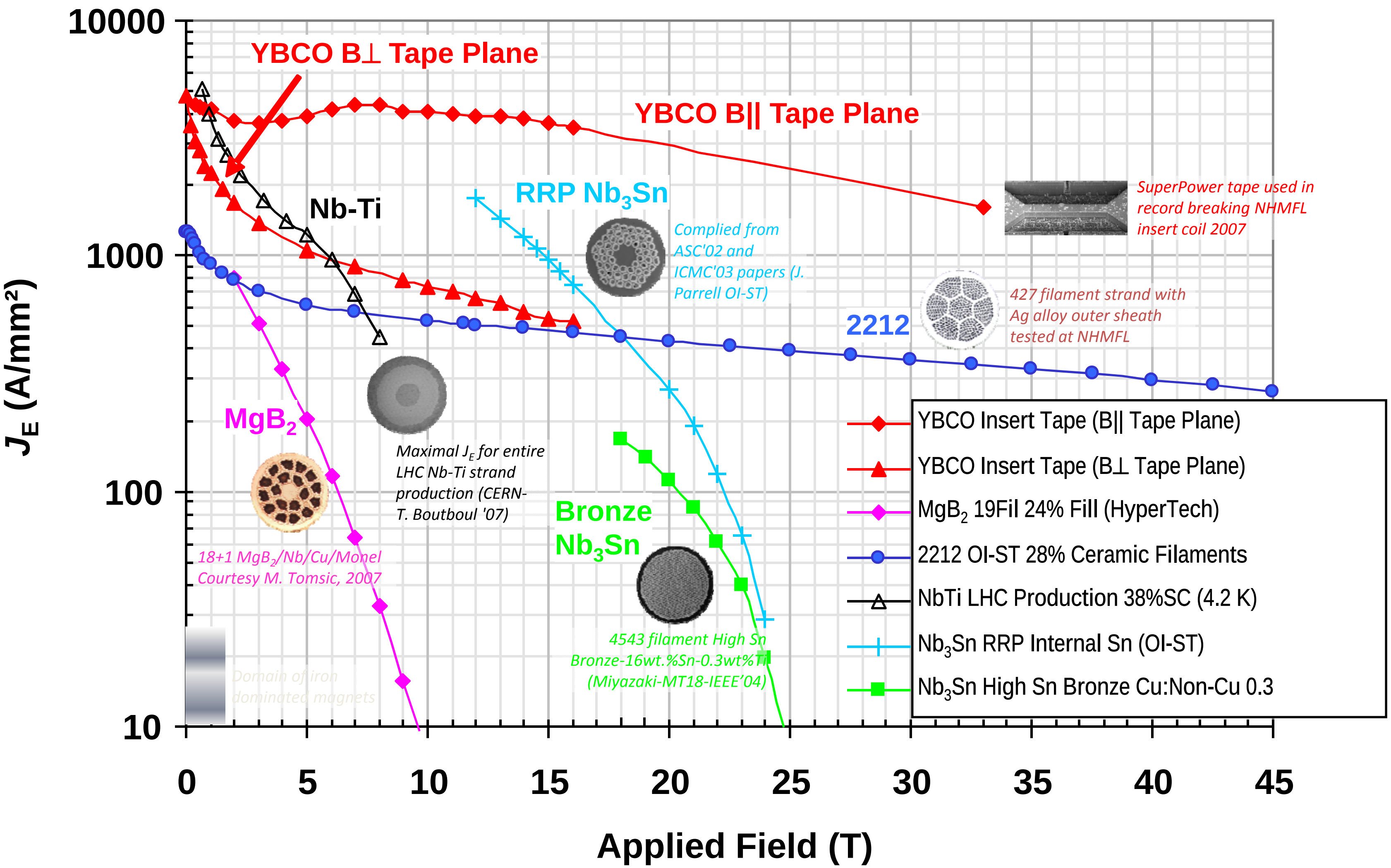
Second (for magnets): Critical field



Third : Critical current



Critical current in actual conductor

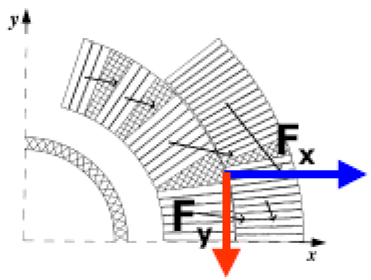


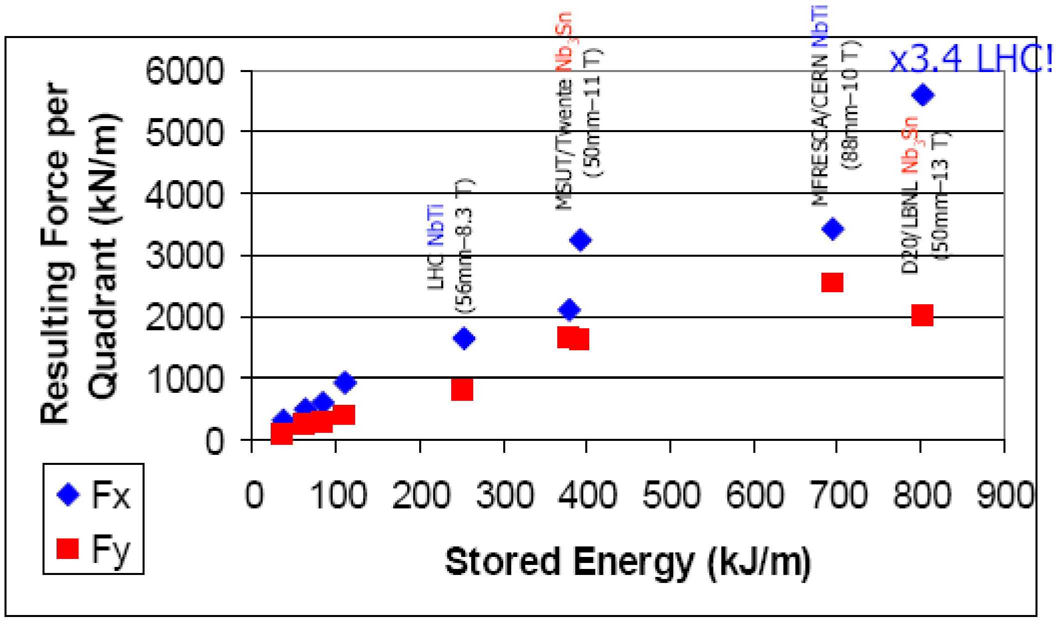
HF SC are there: so why waiting?

- NbTi was an affirmed technology at the end of the ‘70s
- In the ‘80 4 T accelerator magnets were available
- In the ‘90 8 T accelerator magnets proved
- Only in 2001 we started the industrial production of LHC.

HF/large margin SC is an enabling technology but…

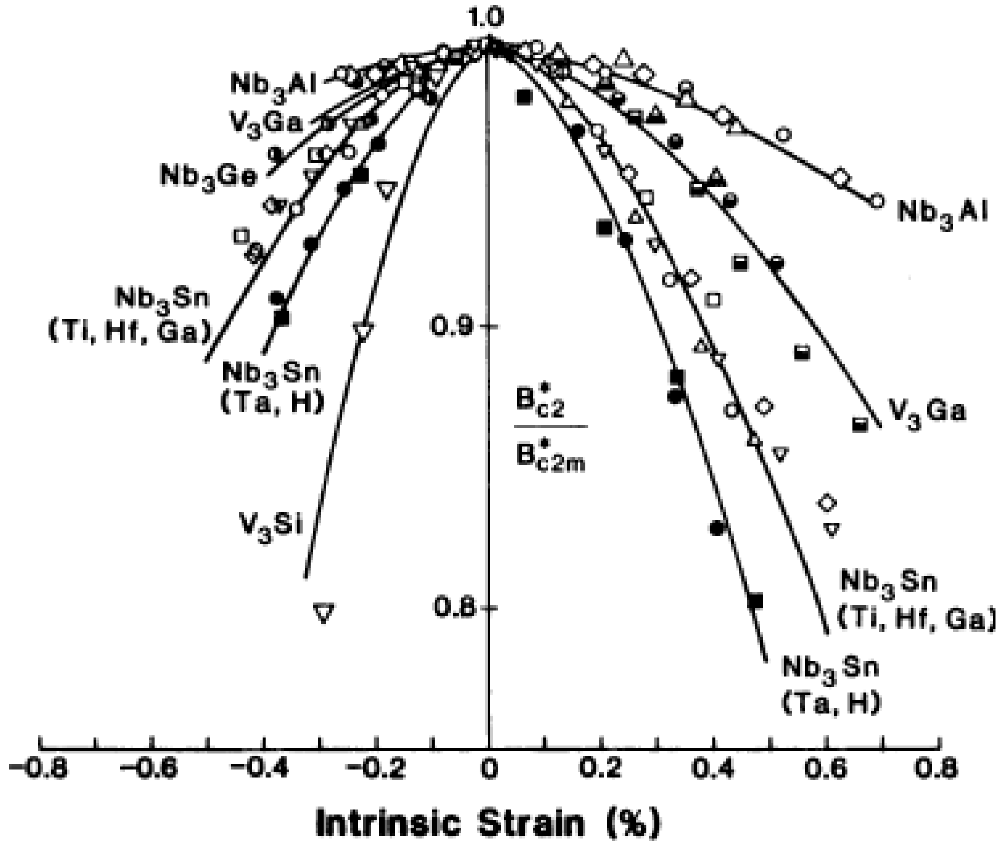
- Control of large forces and large stresses
- Magnet protection becomes more and more severe (due to high temperature margin thermal stability is less an issue)





… continue

- All HF superconductor are brittle and strain sensitive



The route (we are pursuing)

- (super)conductor first:
  - Proper material that can be manufactured in industrial technology
  - Proper choice for cable and “cablability”: what is used is cable with fairly large current: 10-20 kA
  - Development of proper winding and coil manufacturing technology
  - Extending reach of costheta coils but also explore new concepts: mechanical structure and assembly
  - Advancing in modelling capability and diagnostic

The frame

A Worldwide Collaboration Network

LARP (MagSys)	• Participants: BNL, FNAL, LBNL + CERN • Goal: fully qualified quadrupoles for SLHC (Phase 2 upgrade)
CARE (NED)	• Participants: CCLRC, CEA, CERN, CIEMAT, INFN, UT, WTU • Goal: basic R&D on conductor, insulation, design, quench protection
EUCARD (HFM)	• Participants: CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE • Goal: high field Nb_3Sn dipole model & very high field (HTS) insert

Inter-Laboratory collaborations on specific topics:

- CERN, RAL, CEA, LBNL on Short Model Coil development
- KEK & NIMS, FNAL, CERN on Nb_3Al conductor and coils
- LBNL & KEK on Nb_3Sn coil, structure and assembly methods
- KEK & CERN on LHC upgrades
- CERN & CEA, UT, LBNL/LARP on magnet testing
- LBNL & FNAL, CERN, UT, TAMU on cable development

The necessary start: small models to test conductor in real situation

LARP

LARP Sub-scale Quadrupoles (2005-06)

Design features:

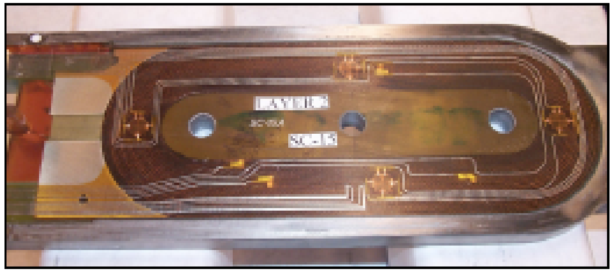
- Based on LBNL "SM" design
- Four racetrack coils, square bore
- Aperture 130 mm, Length 30 cm

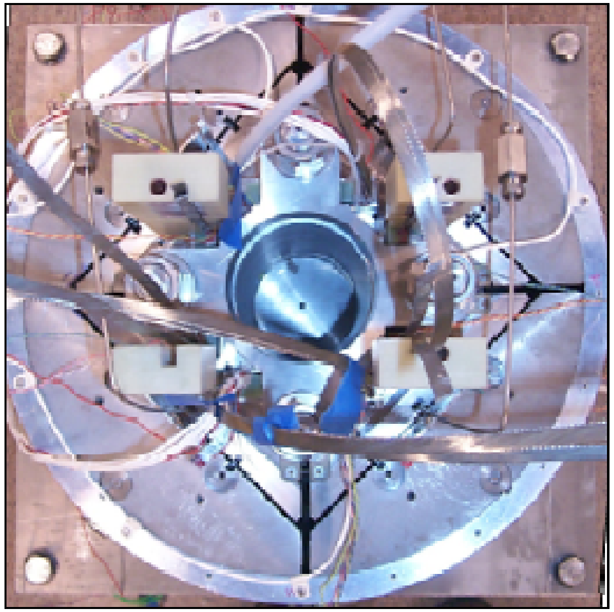
R&D Goals:

- *Conductor performance verification*
- *First shell-based quadrupole structure*
- *FEA models verification*
- *Quench propagation analysis*

Results:

- Two models tested at LBNL & FNAL
- SQ02: **98% of SSL at 4.5K & 1.9K**





Then easy shape (racetrak) to scale up

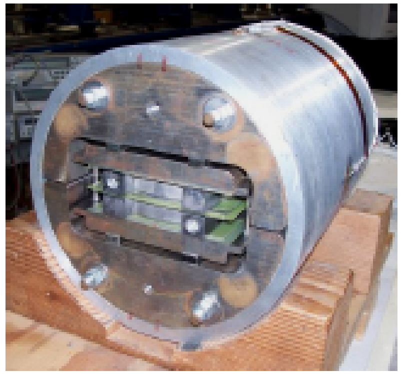
LARP Long Racetrack (2006-08)

LARP

- Scale up LBNL SM coil and structure: 30 cm to 4 m
- Coil R&D: Cable, handling, reaction, impregnation
- Structure R&D: friction effects, magnet assembly

- *BNL: coil fabrication, magnet assembly and test*
- *LBNL: magnet design, structure fabrication/assembly*
- *FNAL: contributions to design and coordination*

- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, **96% of short sample limit**



Series of models &long dipoles at FERMI

Less striking as quench performance but extremly useful for:
Assessing and stabilizing coil winding technology; Instability issue pointed out
Assess of field quality in NbSn winding : a CERN analysis showed only a factor 2 worst than mature NbTi technology in random hamonics.

Fermilab Mirror Dipole (2006-08)

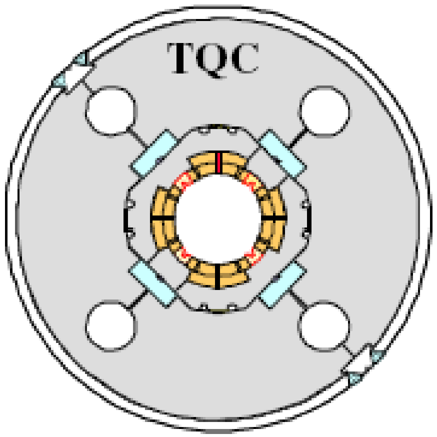
- Three steps were performed: 1m, 2m and 4m models
- First length scale-up of Nb_3Sn $\cos\theta$ coil technology
- Experience applied toward LARP models

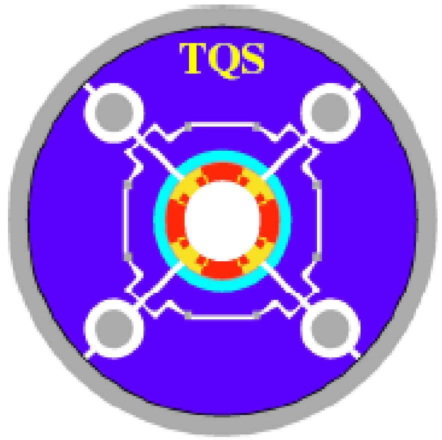
Gradients higher than LHC triplet are already there (in 1 m long)

LARP Technology Quadrupoles (2005-08)

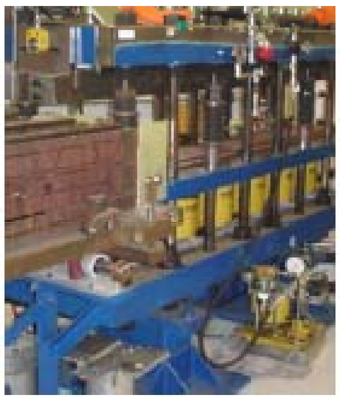
LARP

- Double-layer, shell-type coil
- 90 mm aperture, 1 m length
- Two support structures:
  - *TQS (shell based)*
  - *TQC (collar based)*
- Target gradient **200 T/m**





Winding & curing (FNAL - all coils)



Reaction & potting (LBNL - all coils)

… continue on 1 m long quads

LARP

TQ Results Summary

Model	First Training at 4.4K			First Training at 1.9K			Highest Quench*	
	G_{Start} (T/m)	G_{Max} (T/m)	G_{max}/G_{ss} (%)	G_{Start} (T/m)	G_{Max} (T/m)	G_{max}/G_{ss} (%)	G_{Max} (T/m)	G_{Max} quench conditions
TQC01a	131	154	72	151	196	87	200	1.9K, *100A/s*
TQC01b	142	178	86	179	200	90	200	1.9K
TQC02E	177	201	87	198	199	79	201	4.4K
TQC02a	124	157	68	145	164	65	169	1.9K, *50 A/s*
TQC02b	141	173	85	158	173	78	175	*3.6K, 50A/s*
TQS01a	180	193	89	n/a	n/a	n/a	200	*3.2K*
TQS01b	168	182	84	n/a	n/a	n/a	182	4.4K
TQS01c	159	176	81	176	191	82	191	1.9K
TQS02a	182	219	92	214	221	85	222	*2.2K*
TQS02b	190	200	84	196	205	79	205	1.9K
TQS02c	216	222	93	205	209	80	231	2.7K

Optimized models surpassed the 200 T/m target gradient with good margin

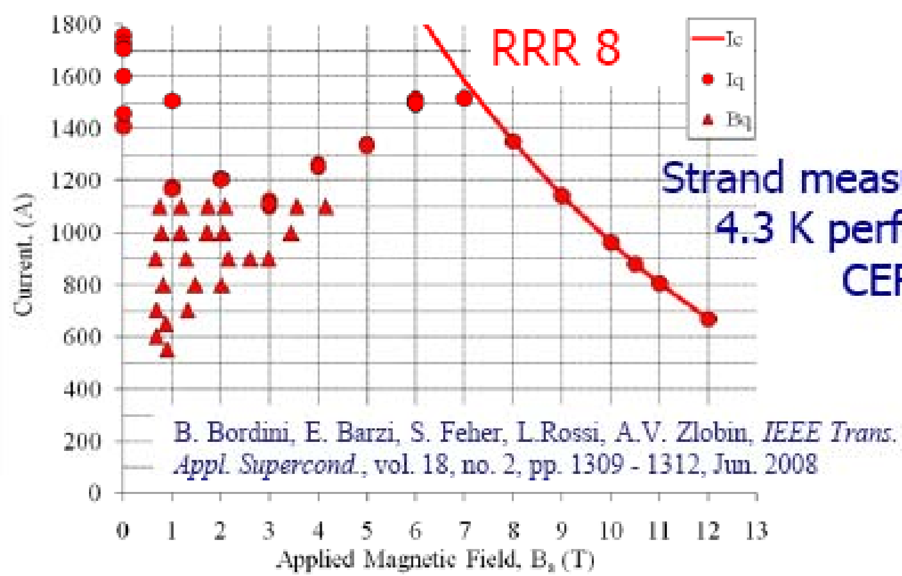
MAGNETO-THERMAL INSTABILITIES AND MAGNET PERFORMANCE

- 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

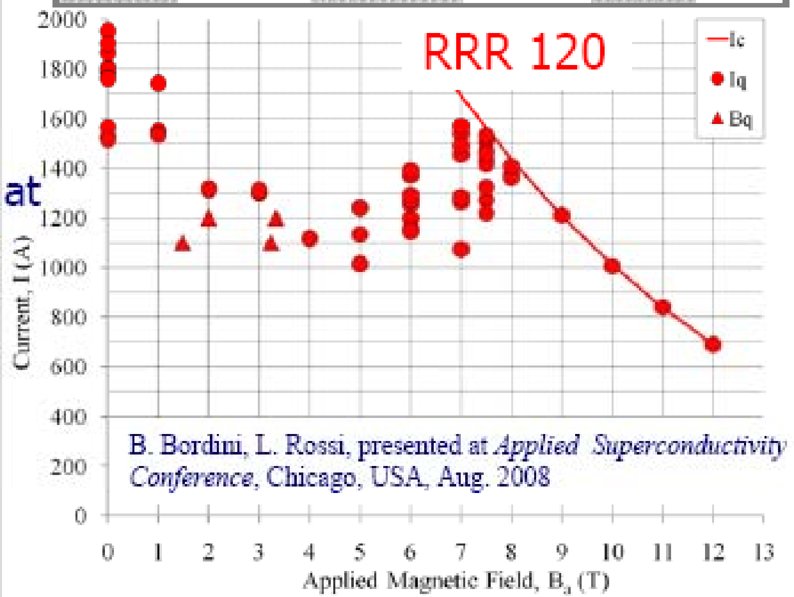
[1] A. V. Zlobin et al , "R&D of Nb_3Sn Accelerator Magnets at Fermilab", IEEE Trans. Appl. Supercond., vol. 15, no. 2, Jun. 2005

[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



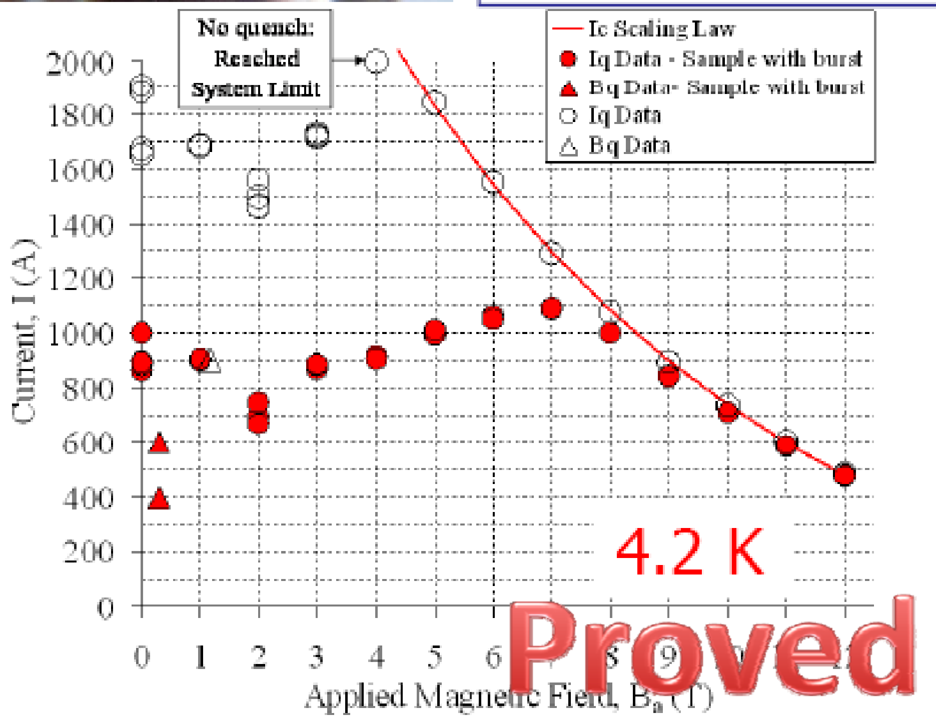
Strand measurements at 4.3 K performed at CERN

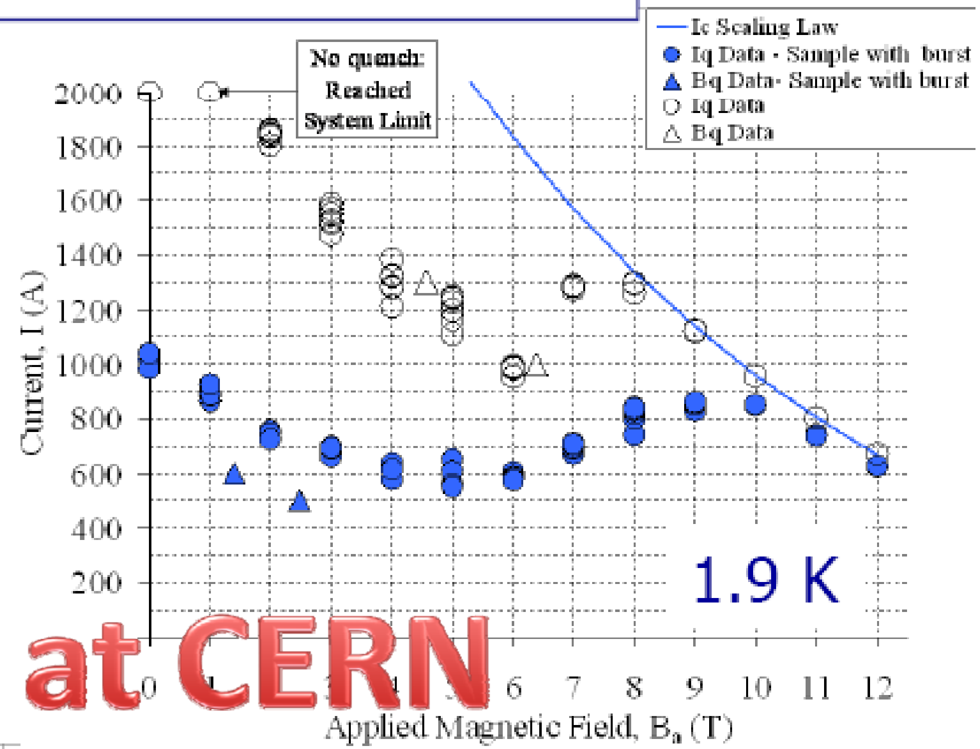


EFFECTS OF LOCAL STRAND'S DAMAGES

- 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





Proved at CERN

Will good news continue to come from beyond the US ?

LARP

Present focus: Long Quadrupole (LQ)

<u>Scale up of TQ design from 1 m to 3.6 m</u>

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

Two LQS tests are planned for 2009

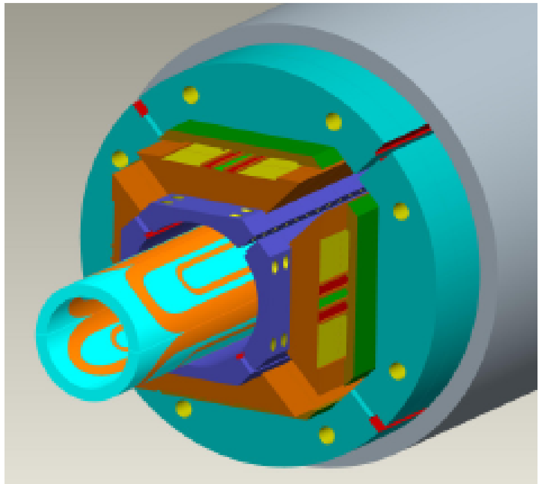
Test bench for Nb3Sn : the CERN phase 1 NbTi quads

LARP

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)*

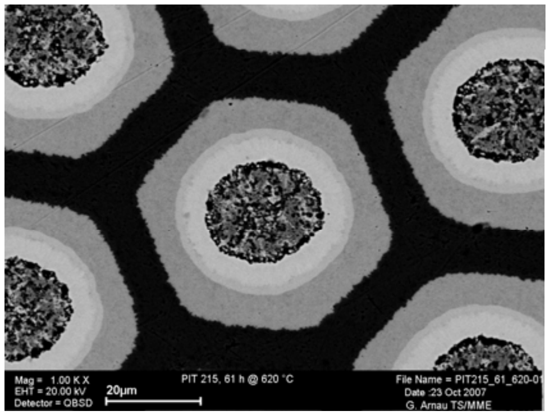
Plans:

- *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*

The results of NED conductor

Before NED in EU

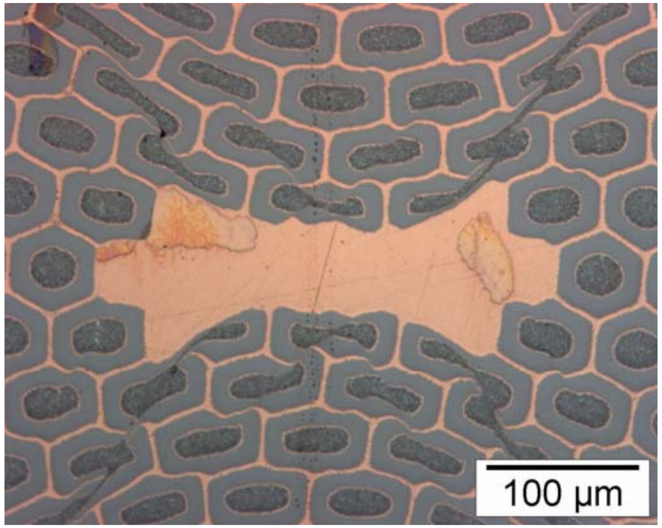
- Jc = 1000 A/mm2
- Filament diameter of 70 μm
- Wire size of 0.9 mm
- RRR only occasionally good
- Small size billet
- No industrialization scale up

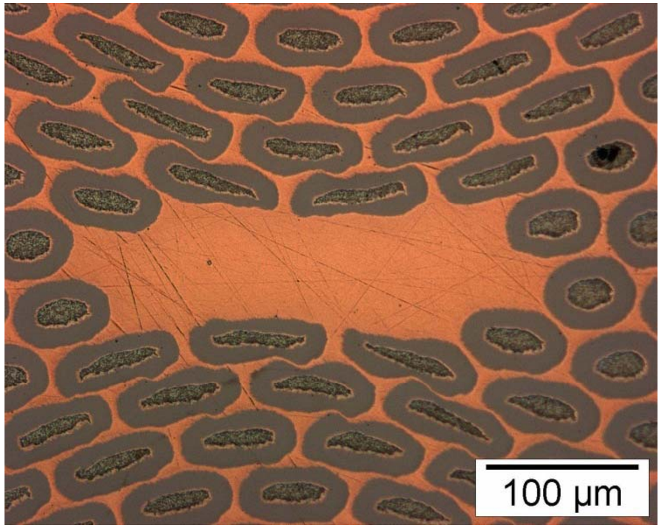


Today state-of-the-art in EU

- Jc = 1500 A/mm2
- Filament diameter 50 μm
- Wire size of 1.25 mm
- RRR = 200
- Factor 10 size billets
- Process taken up by large industry
- Long length in production: strands for 250 m of cable (done b CERN/LBNL) in 2008

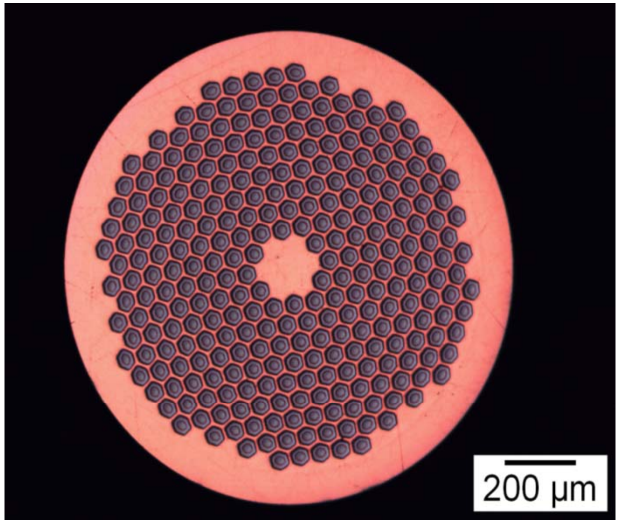
Technological advancement needed to make this Material a CONDUCTOR





25 % def.

Optimization of heat treatment B215



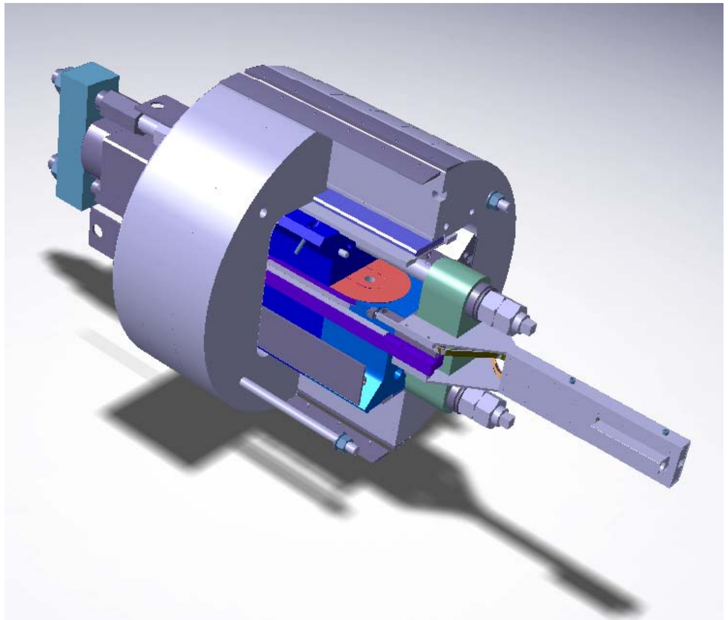
- After two trials at 625 ^{o}C (200 and 260 hours), 2 samples were treated 320 h @ 625 ^{o}C at CERN, 2 additional samples reacted at Twente.
- I_c data consistently measured at CERN and Nijmegen in the range: **I_c = 1494-1539 A** @ 12 T 4.22 K, corresponding to ***J_c ~ 2700 A/mm²***, **+ 10 %** as compared to standard HT.
- 15 T, 4.222 K: **I_c > 818 A** (NED spec.), ***J_c ~ 1500 A/mm²***
- ***New record!!*** B215 strand completely fulfilling NED specification.
- RRR data impressive as well since ***RRR ~ 220*** for virgin strands!! Better for stability.

Next step : NED1.5 phase
Short model coil (SMC)

- Participant funding only (formally outside FP6-CARE-NED)

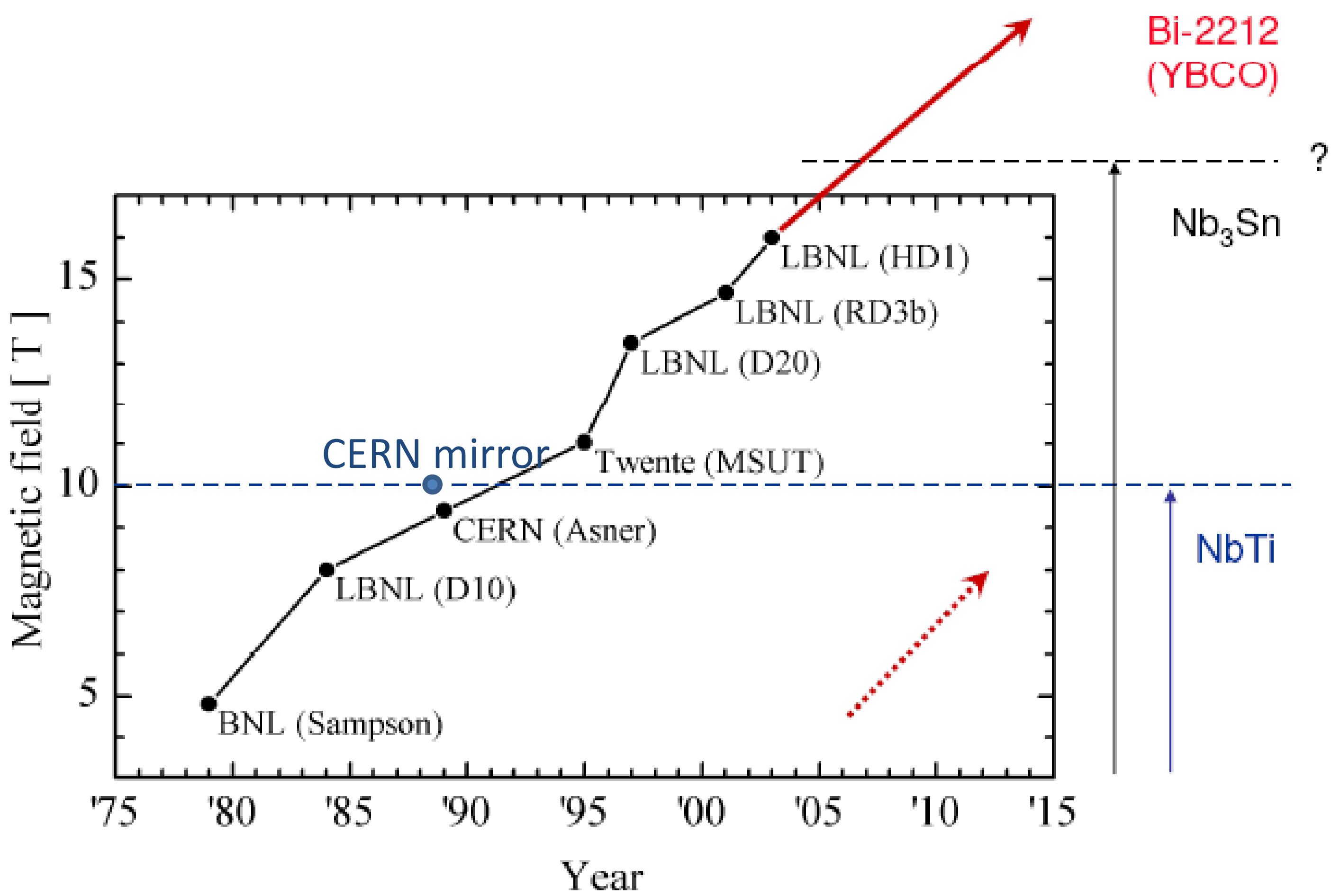
- CCLRC/RAL, CEA and CERN have agreed to manufacture and test a series of LBNL-type Short Model Coils wound from NED-sub-cables so as to investigate
  - cable and insulation performances in real coil environment,
  - design limits for transverse and longitudinal loads.

- Coil and cold mass design finished,
  winding tests with dummy Cu+Nb_3Sn
  in progress by RAL-CERN team (with LBNL)
  Nb_3Sn cable done (120 m ready: 3 poles).
  Tender for structure components called.
  First magnet foreseen to be tested
  in Spring/Summer2009 at CERN



The scope in the next five year

High Field Dipoles



2 scopes of the HF dipole

upgrade of CERN MFRESCA cable test facility
(presently limited to 10 T, ϕ = 88 mm) to:
• 13-15 T
• ϕ = 88-100 mm
• Imax = 30 kA with Power converter
• Imax . 50 kA with transformer
to offer unique services to the entire applied superconductivity community.

Getting ready when we will need HFM in LHC or for the upgrade: around y >2015
The experience of LHC has shown that 10 years are needed to develop a tecniology and make it usable in real conditions.
CARE, and HHH in particular has provided a unique background to unify the magnet community of accelerator in Europe. EUCARD and alllprogress are based on the succes of HHH network and of the NED program