Magnets for the next generation accelerators at CERN

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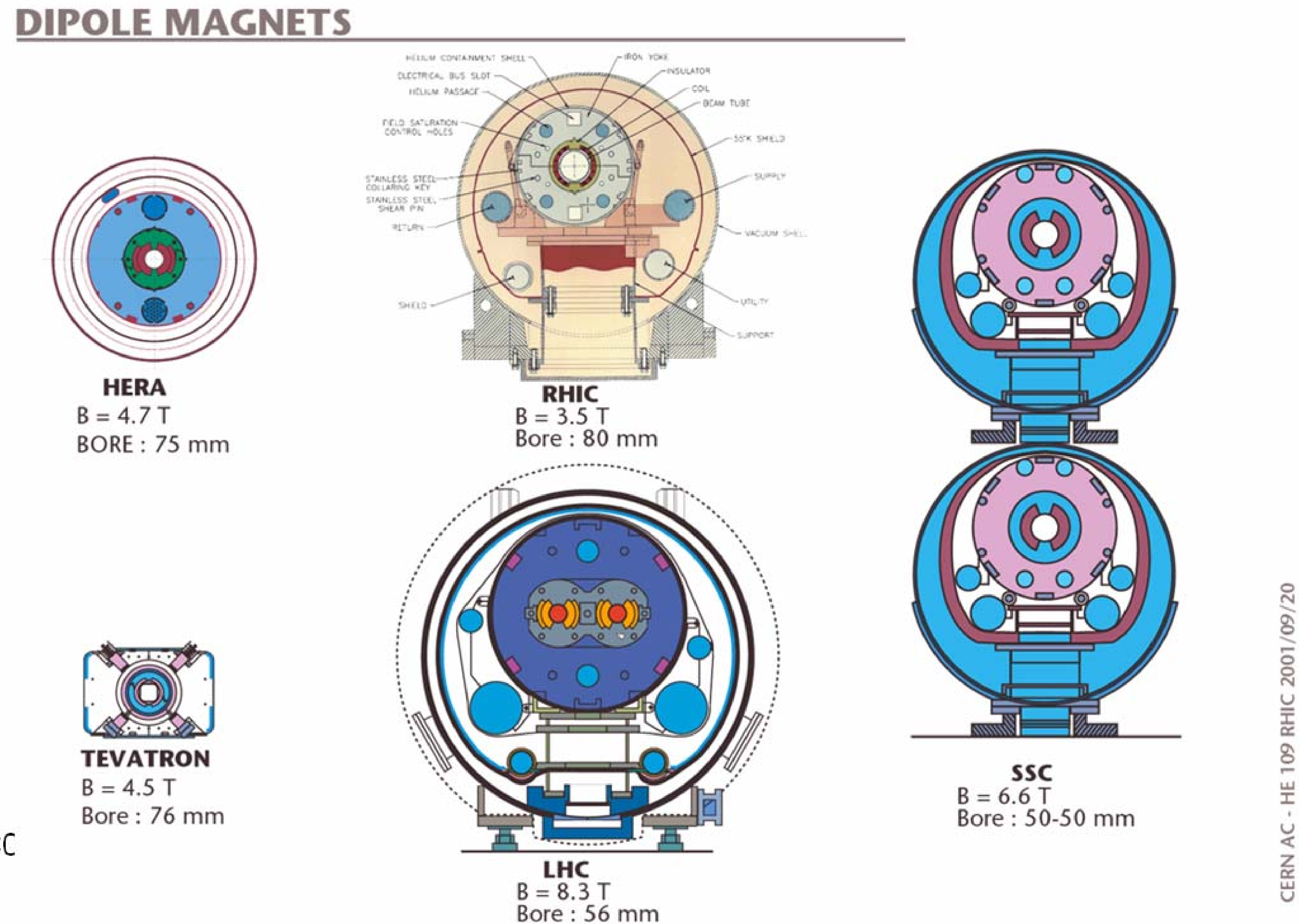
Contents

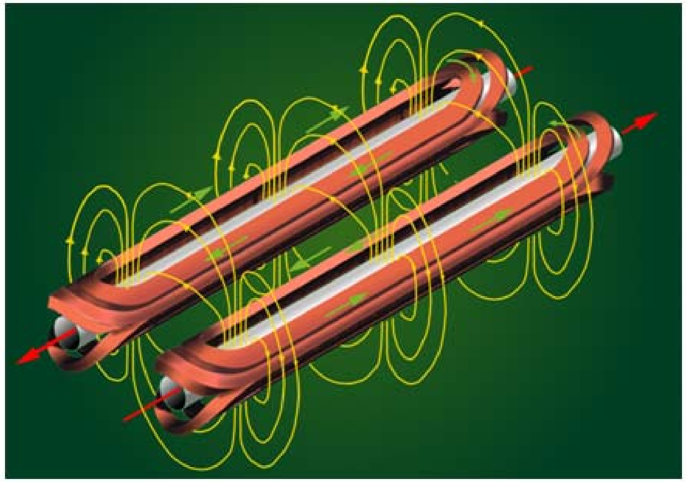
- LHC and magnet technology today
- Upgrade of the LHC ring
  - Luminosity upgrade
  - R&D toward higher fields
- Upgrade of the injector chain
  - PS2 vs PS2+
  - SPS
- *(Study for beta beam ring & NbSn Undulator)*
- Thanks to E. Todesco, A. Devred, L. Bottura, G. Kirby

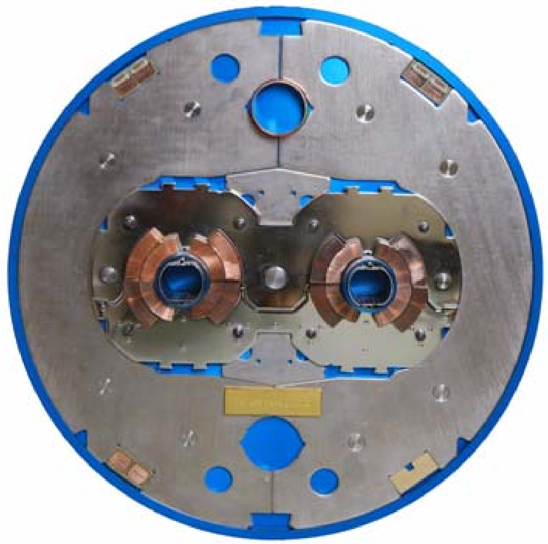
30 years of SC Accelerator Magnets



LHC Main dipoles

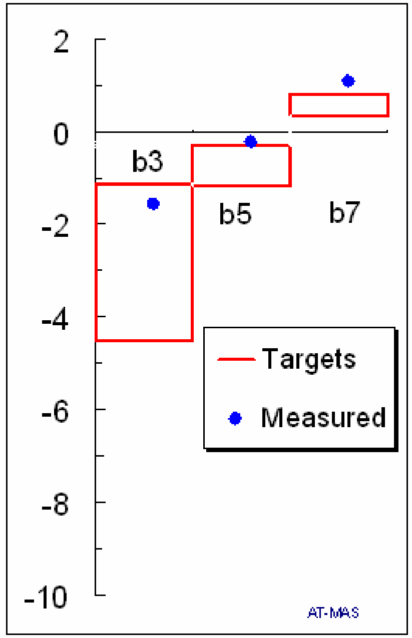
- Nb-Ti Sc
- Field 8.3-9 T (9.65)
- Kapton tape as insulation
- Superfluid helium
- F_x = 180 MN/m per quadrant
- F_y= 0.81 MN/m (70 MPa)
- Stress 150 MPa at collaring
- Energy : 6.93 MJ
- T_{max}= 375 K (adiabatic)
- T_{op}= 1.9 K
- Heat removal: 10 W/m
- T_{margin}=1.5 K
- Margin for beam losses: 10 mW/cm^3

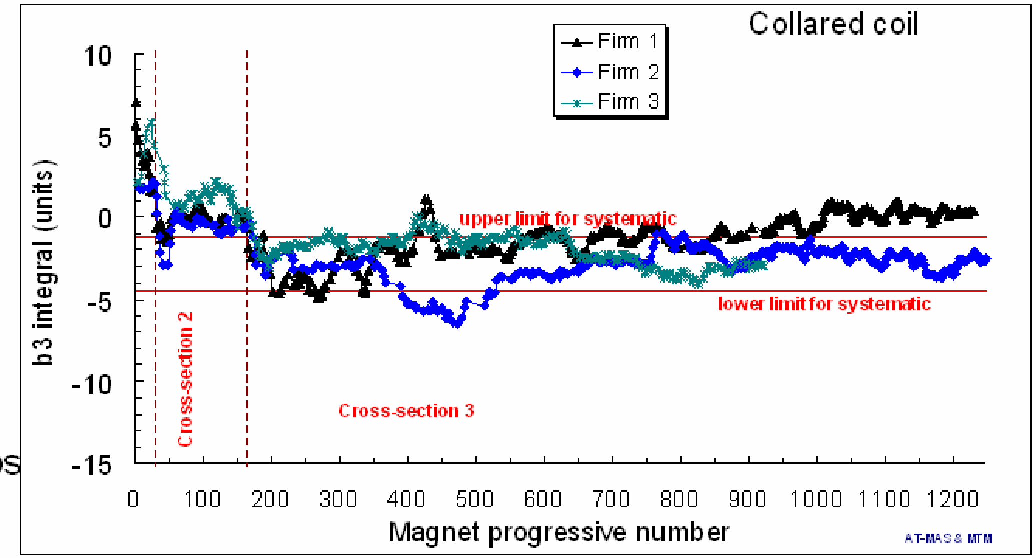




Collider magnets

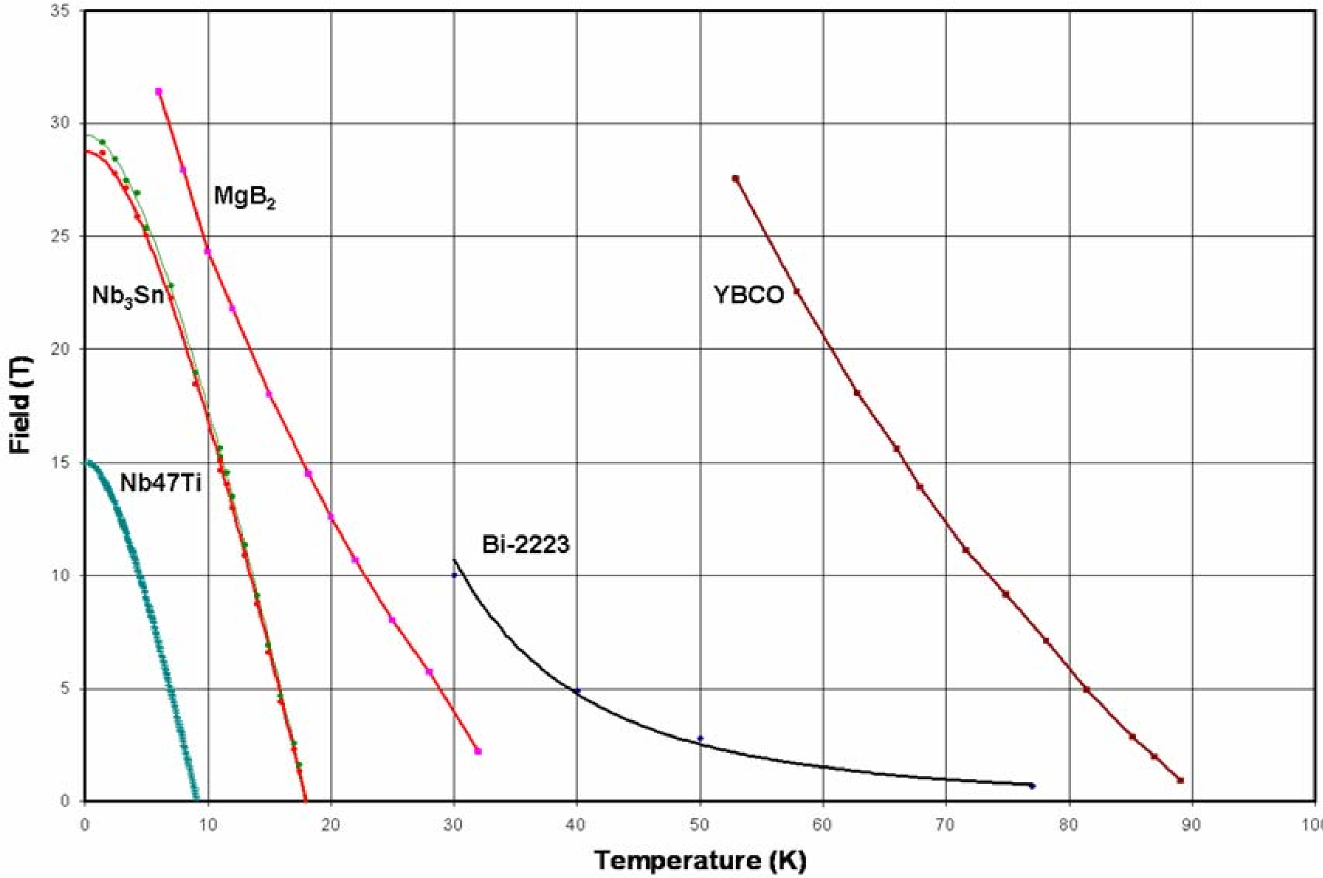
- Field accuracy (and knowledge!) must be very high (10-100 ppm)
  - At collision (500 millions turns)
  - At injection: large emittance « soft »beam field distorsion by persistent current





Specific problems of SC in accelerator magnets - 1

Cryogenic operation with LHe or HeII is still necessary to exploit the higher field and the zero-dissipation regime



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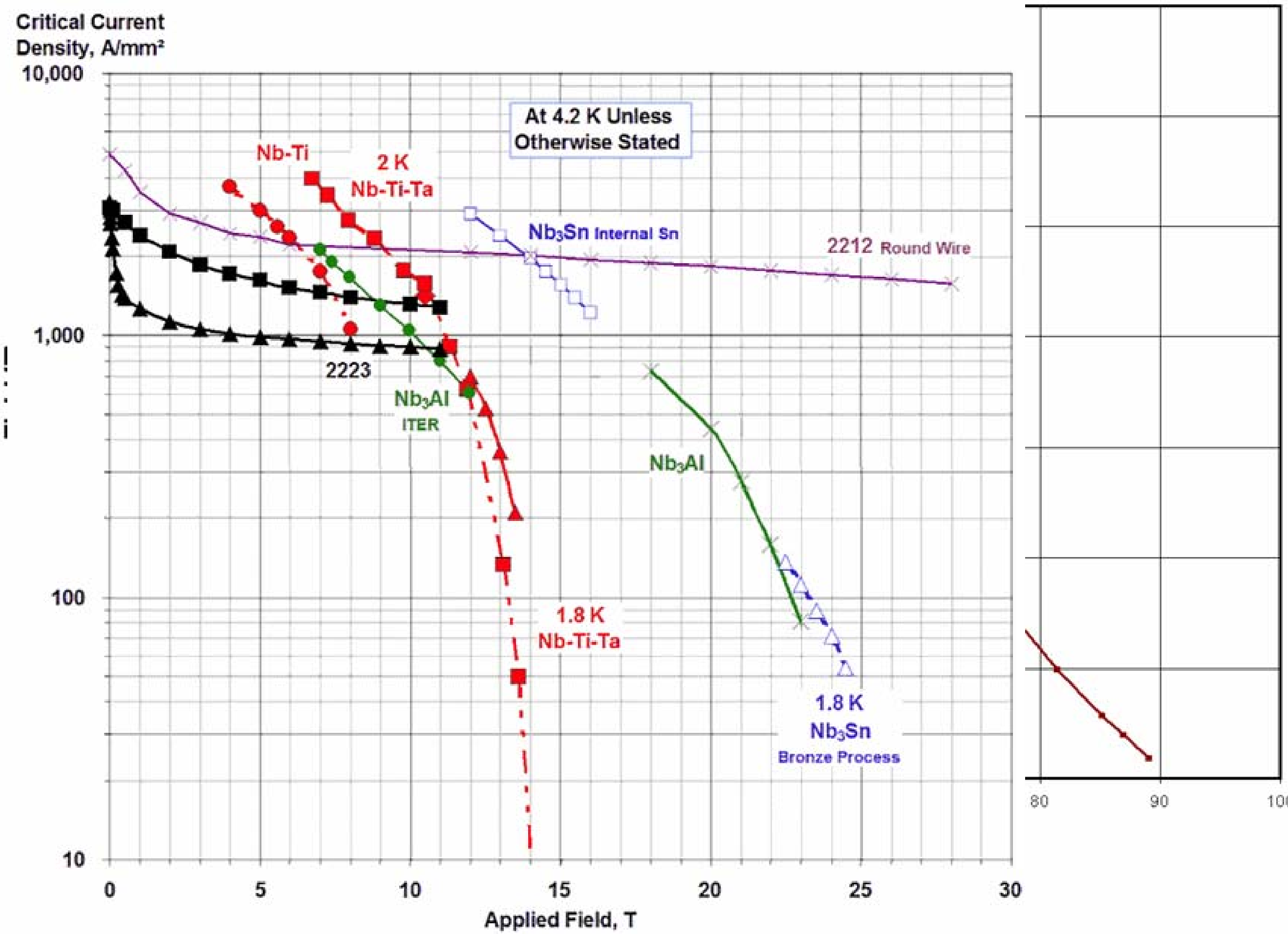
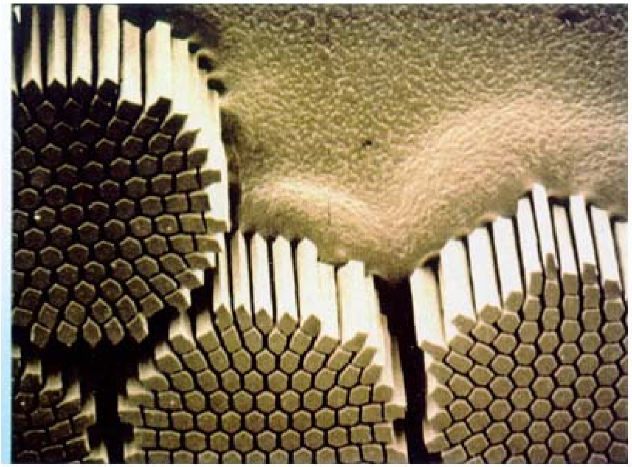
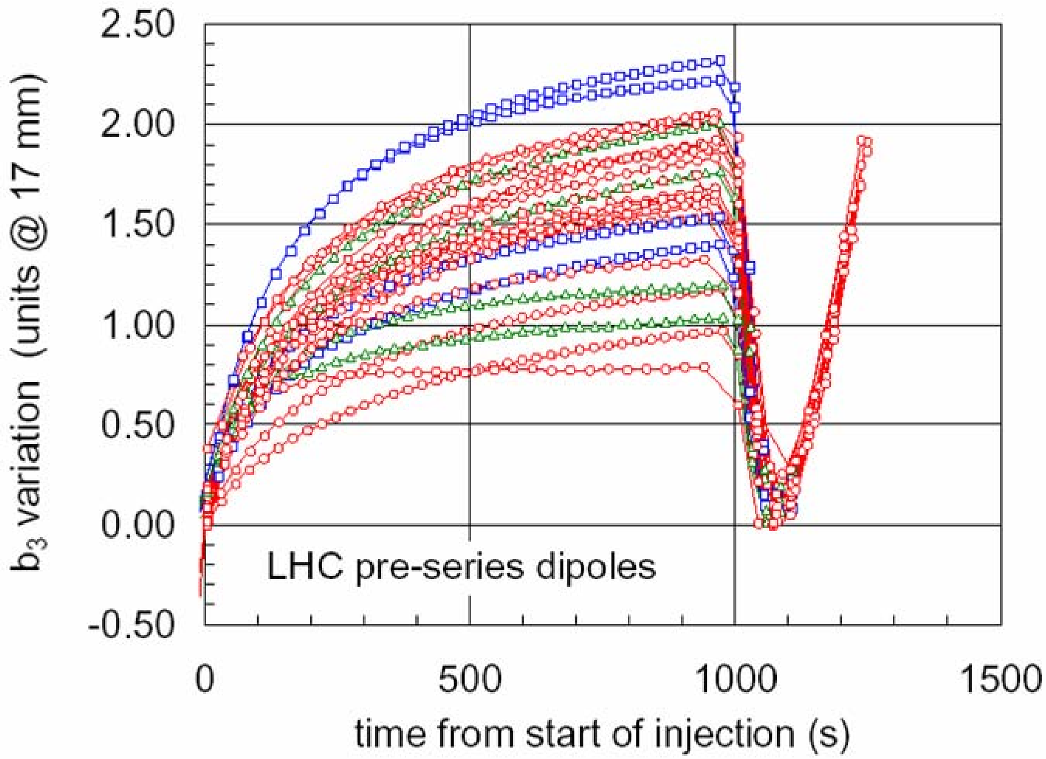


Specific problem of using SC in accelerator magnets - 2

- Magnetization as results of persistent currents.
- Fine filaments (1-10 μm range). This implies 3-10,000 filaments in a single wire)





LHC Magnets are all tested

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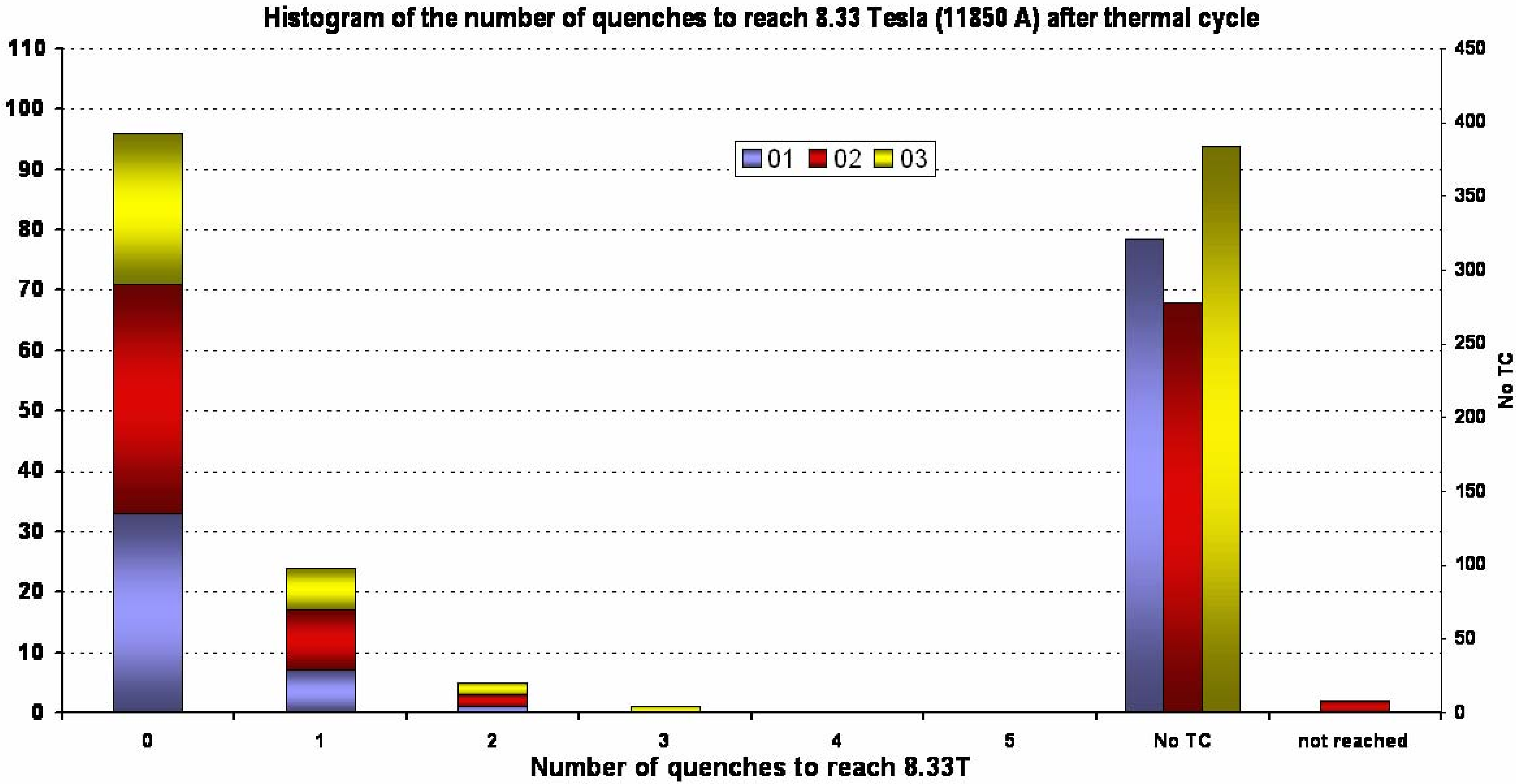


Large tooling repatriation: MAR (Magnet Rescue Facility)

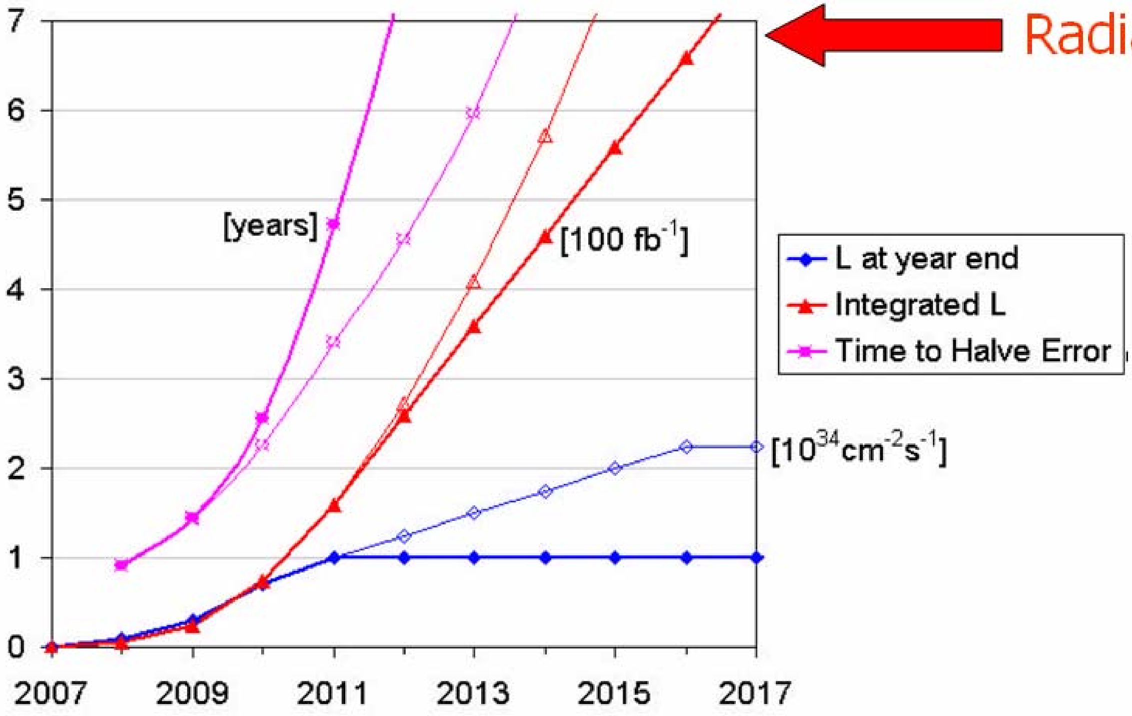
- At CERN from Sept 07 we will start install and use the LHC tooling used in Industry

Reconstitution of short model labo and constitution of a complete MAR

What's next?

- Upgrade of the LHC ring
  - Luminosity upgrade Phase I
  - Luminosity upgrade Phase II
  - R&D toward higher fields

LHC (peak) luminosity upgrade



Radiation damage limit ~700 fb^{-1}

Improving the peak luminosity should be soon or later a necessity:

- For statistics
- If we reach the luminosity goal we need to replace –too- irradiated magnets
- If we don't reach it for reason related to difficulty in handling the beam current, optics may in part compensate this shortfall.

High quadrupole strength is always a gain (but not at any price).

- ***The technology of the luminosity upgrade is fully relevant for an eventual energy upgrade.***

Gradient versus aperture for Nb-Ti and Nb_3Sn

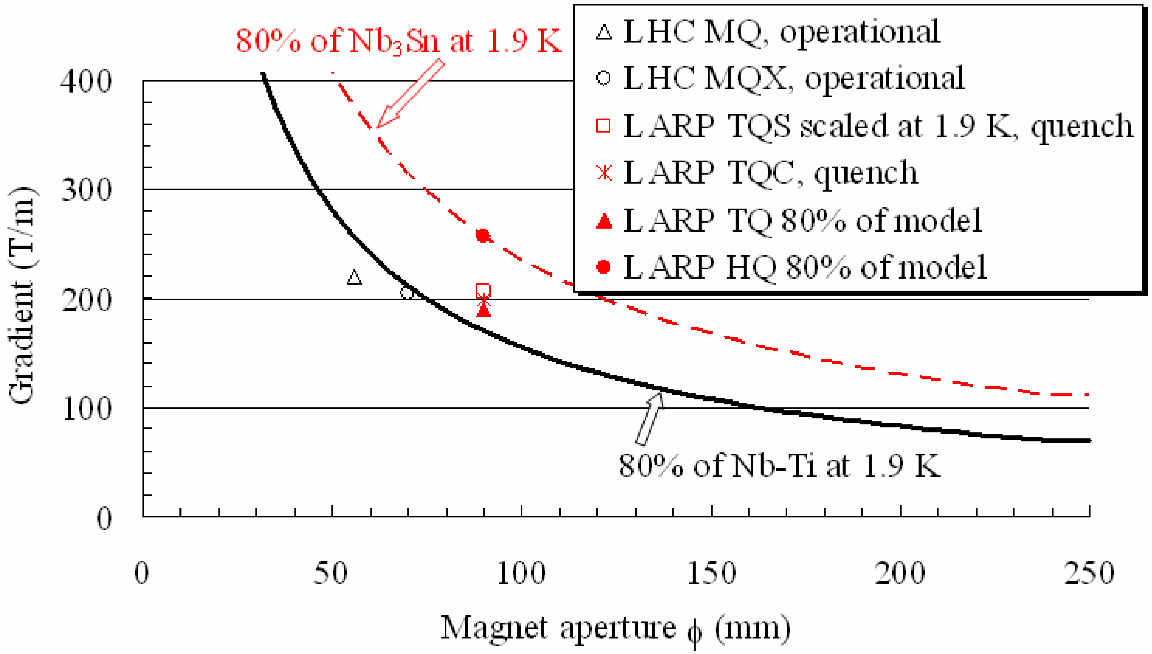
- Bc~13T for Nb-Ti,
- Bc ~25T for Nb_3Sn

However for quadrupoles does not work like this.

Results relative to a sector coil for $\phi \sim 100$ mm

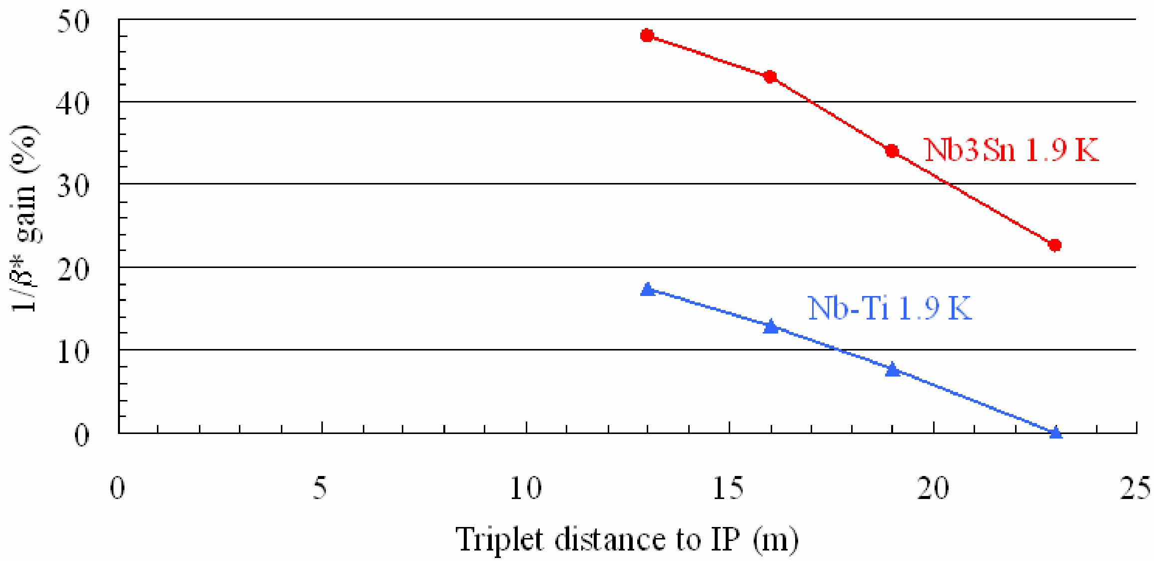
- Nb-Ti: $G\phi/2 \sim$ 10 T
- Nb_3Sn: $G\phi/2 \sim$ 15 T
- Nb_3Sn: 50% more than Nb-Ti

[L. Rossi, E. Todesco, Phys. Rev. STAB, October 2006, and IEEE Trans. Appl. Supercond., ASC06]



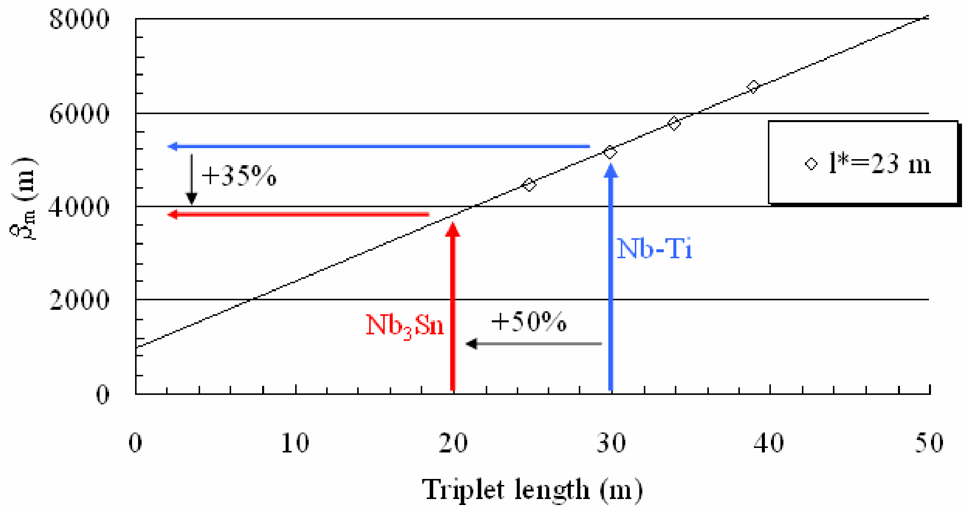
Gain in β^* versus technology and l^* (distance to IP)

- Comparison of lay-outs giving the same chromaticity
  - For each technology, apertures and triplet length optimized
  - Both technologies used at the limit
  - Aperture set at the minimum requirement (energy deposition ?)
  - For the same chromaticity,
  - Nb_3Sn gives 30% more



Understanding the gain in Nb_3Sn

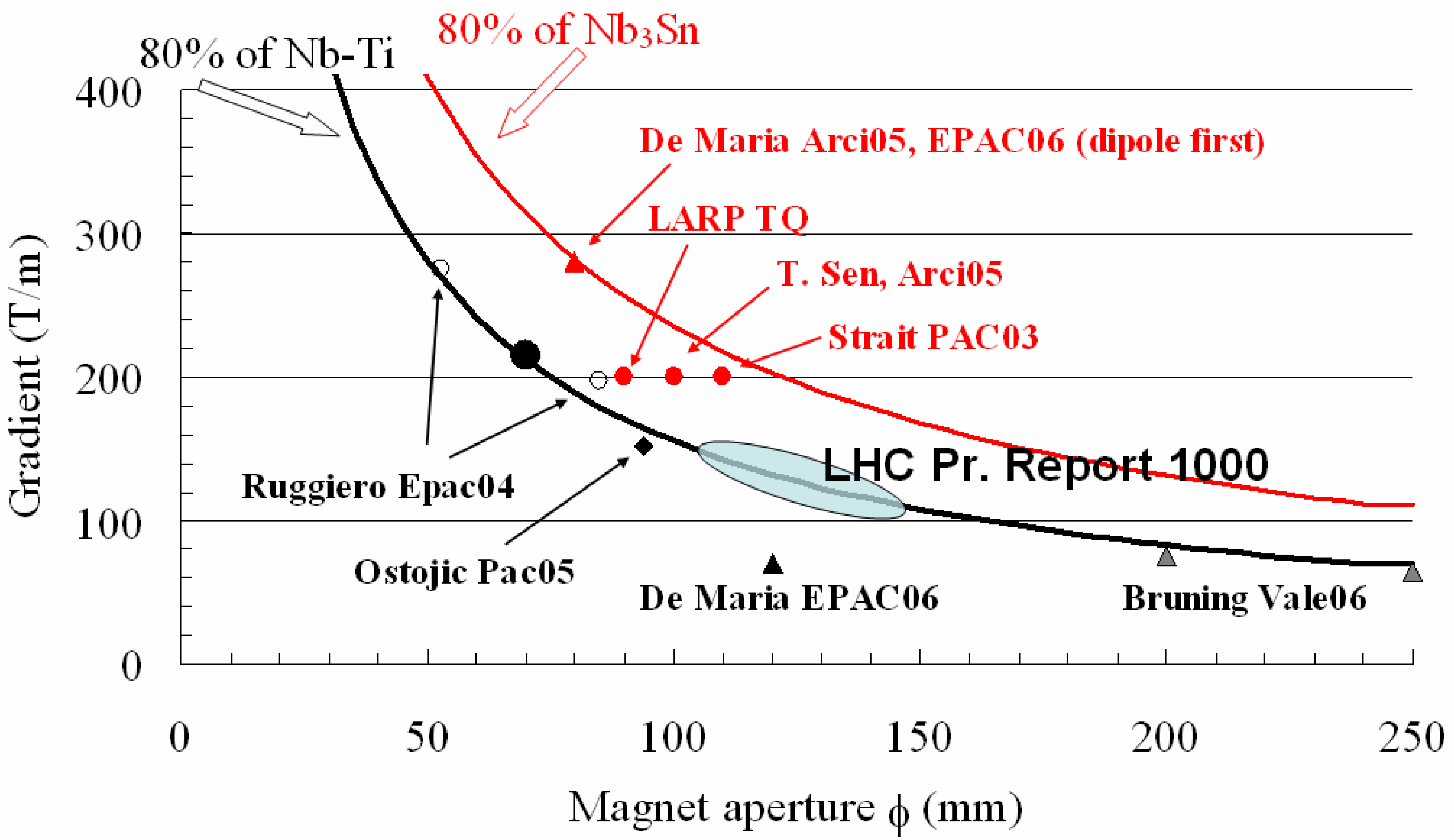
- Nb_3Sn gives improvement in *G* of a factor α=1.5 $\hat{G} = \alpha G$
- Constant integrated gradient: triplet length decreases with α $\hat{l}_t = \frac{l_t}{\alpha}$
- Chromaticity proportional to β_m $Q' = \int G\beta ds \propto \beta_m \int G ds$
- Equal chromaticity, constant int. G $\Rightarrow$ equal β_m
- Using the empirical fit for β_m $\beta_m = \frac{l^{*2} + a l_t}{\beta^*}$
- We obtain the gain in $1/\beta^*$
- For +50% in *G*, +35% in $1/\beta^*$



Scope of phase 1

- The LHC will have difficulty to reach nominal luminosity 10^{34} , not to mention ultimate (in the baseline configuration) 2.3 10^{34}
- A change of the triplet (just it!) it is certainly one way to recover and also to improve: for example a big advantage from an aperture increase of the triplet
- The luminosity may saturate quickly $\Rightarrow$ the change must be fast and be feasible for 2012.
- The scope is to be able to reach 2 and pass 10^{34} with a $\beta^{*} \sim 20$ cm.

Phase 1 : exploring the range 130 mm aperture ?

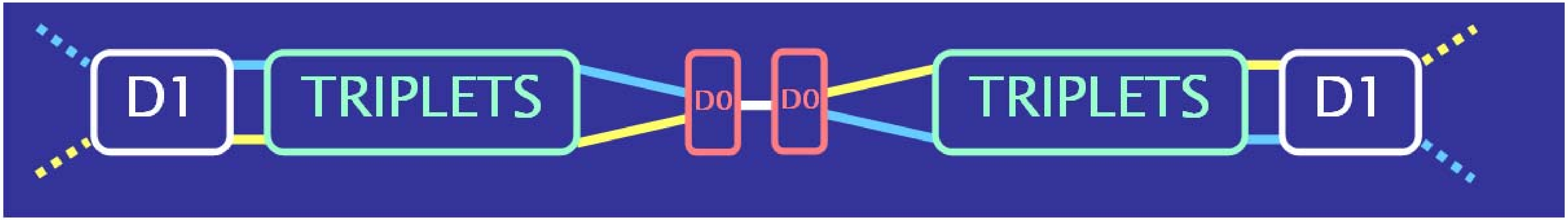


EU-FP7 SLHC proposal

- Model and prototype for a 130 mm wide NbTi quadrupole.
- **Based on existing Sc cable left over from LHC main dipole production**
- **Some other material like iron and collar steel is left over from LHC production**
- **Main tooling adapted from existing LHC tooling.**
- Time scale June 2008-june 2010
- From 2010 till 2012 production of 16 magnets (8 and 9 m long, same Xsect).
- New shielding scheme (Mokhoff) and new more porous insulation scheme (Tommasini) might be implemented.
- Substitution vs. modifications of D1 and cryogenics must be addressed in a more detailed study
- The Program is NOT in the CERN plan today but we are confident it will next year.

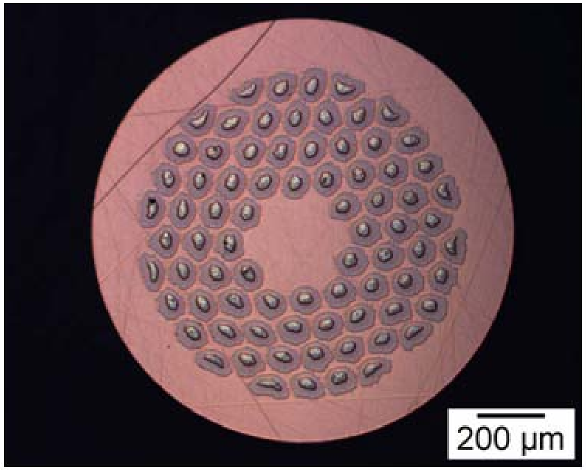
Upgrade Phase II

- The scope is going from 2 to 10 × 10^{34}
- Based on Nb_3Sn superconductor magnets, **and on many other new equipments in the whole machine and experiments**
- Because of the luminosity gain, a 6 months shutdown will be acceptable (or even 1 year if required by experiments)
- Carefully prepared it will probably require to revisit the machine-detector interface and the whole Interaction Region.
- It will probably (possibly) contain a new scheme like the Early Separation Scheme with "moderate'crab cavities. This will make best use of the larger reach in β^*, up to 11 cm
- Time frame: 2016/17.

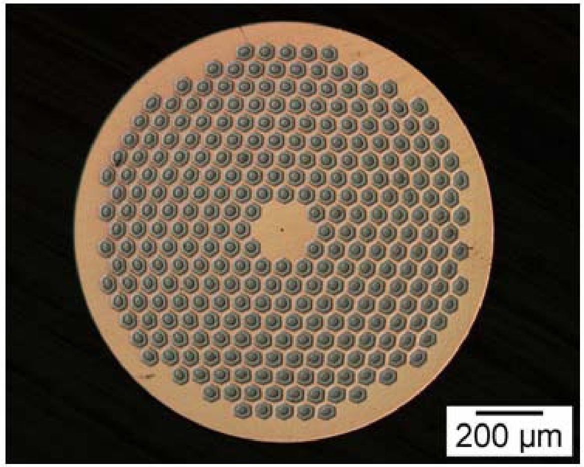


R&D - 3 NED conductor

- We achieved significant milestones but porgress are slow. Task should be completed by 2007-08. SMI first conductor is being cabled and has sold the businness to EAS (former VAC). Alstom has still to show the capability to attain 2500 A/mm2



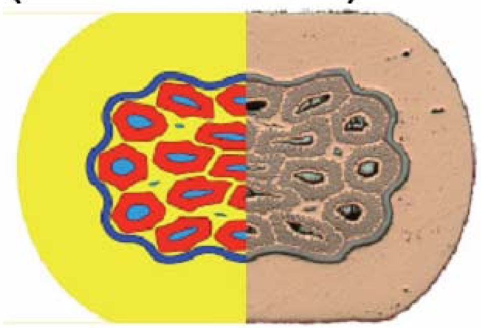
Alstom/NED
(workability program milestone)
1.25 mm ; 78x85 μm sub-element
740 A (~1500 A/mm^2)@4.2 K & 12T

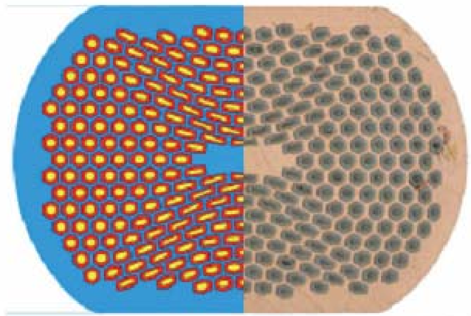


SMI/NED
1.26 mm ; 288 x 50 μm tube
1400 A (~2500 A/mm^2)
@4.2 K & 12T

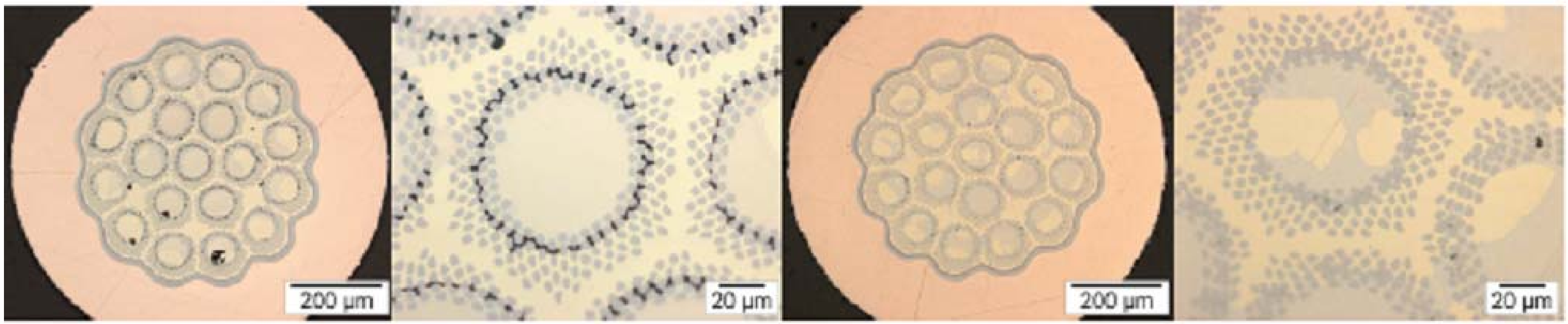
Conductor study

- Building a comprehensive model to understand the deformation (INFN-GE).





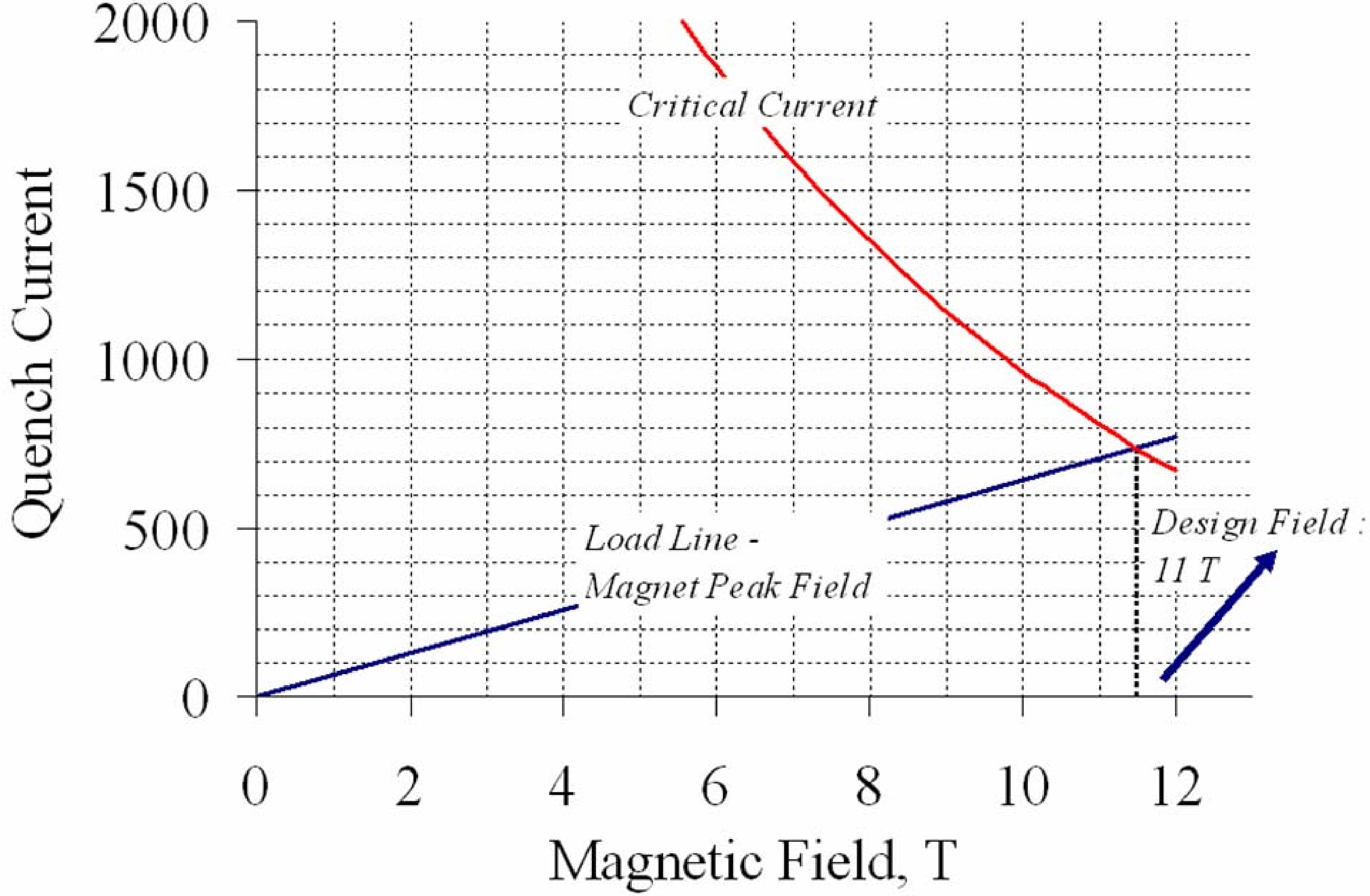
- Understand Reaction parameter



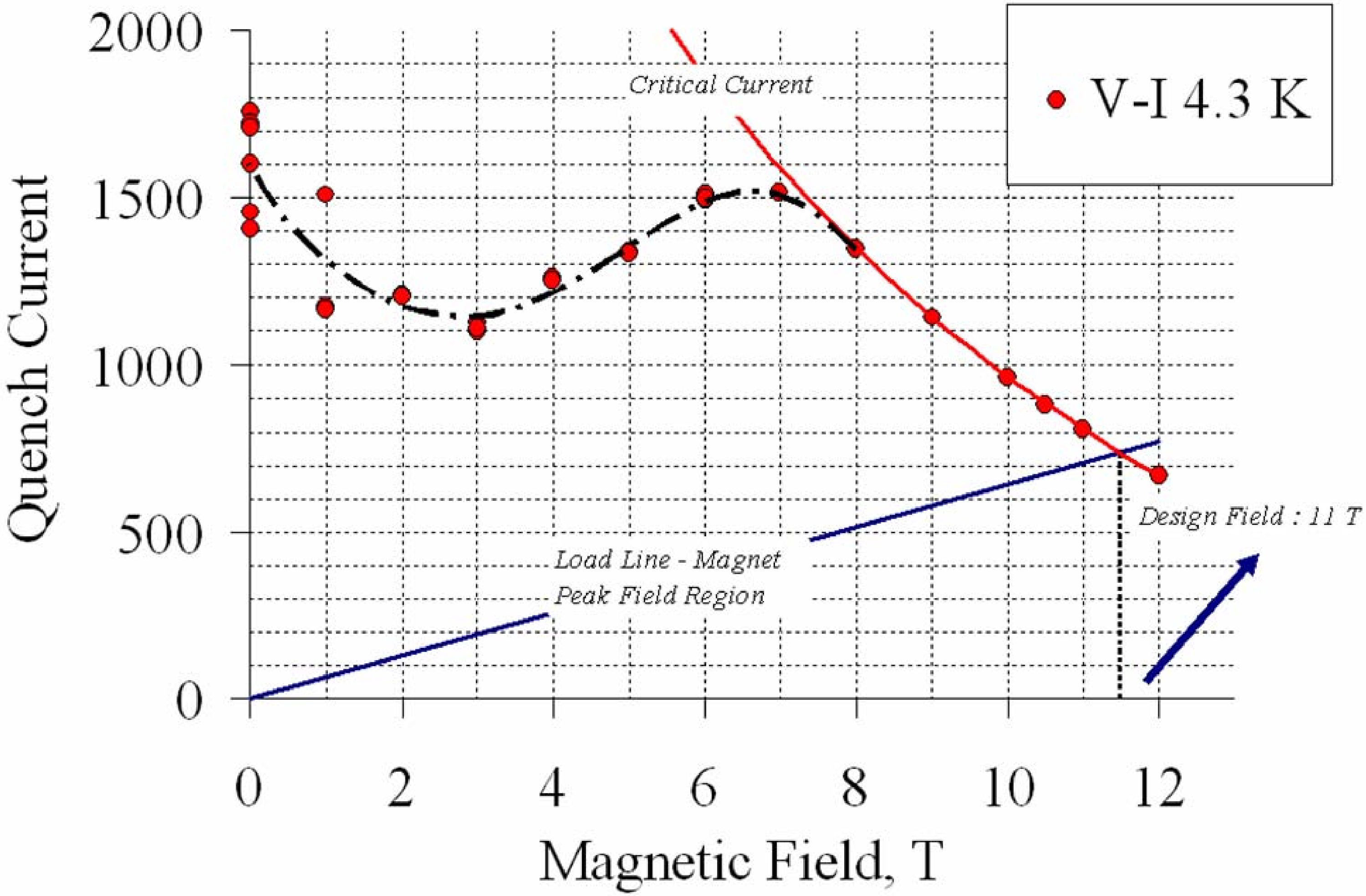
6 °C h^{-1} to 580 °C

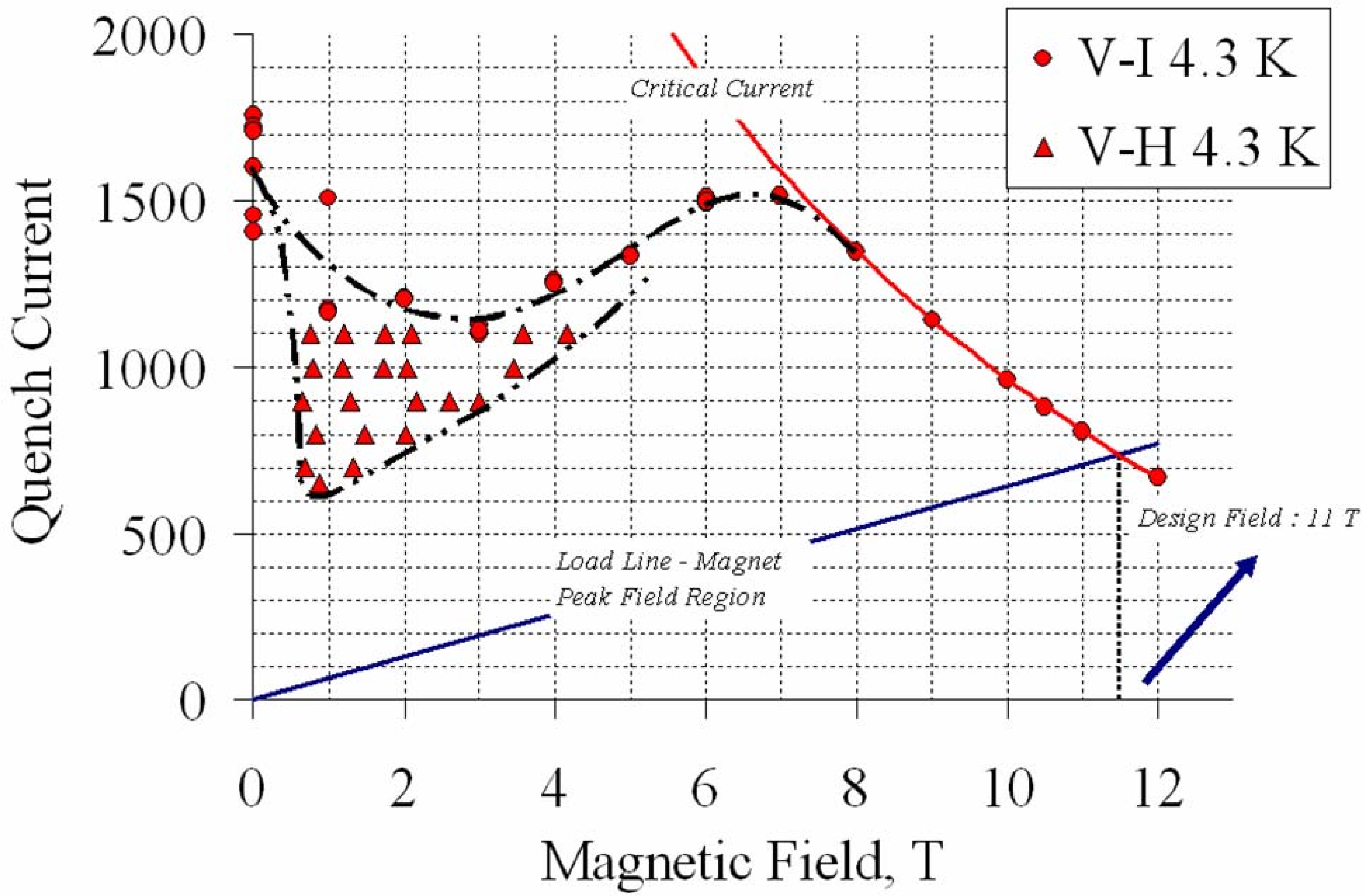
>100 °C h^{-1} to 580 °C

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

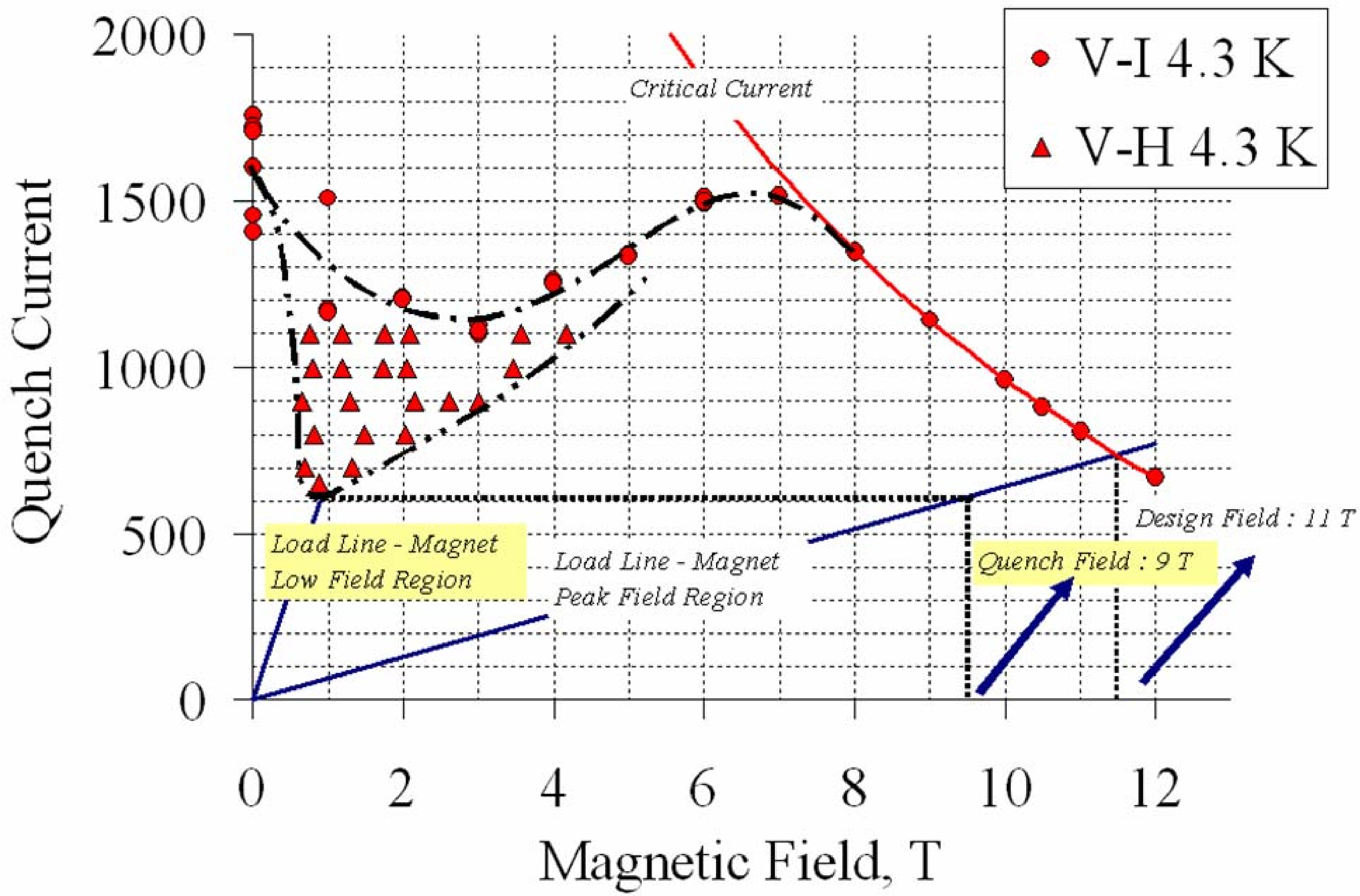


Quench Current
2000
1500
1000
500
0
0
2
4
6
8
10
12
Magnetic Field, T
Critical Current
Load Line -
Magnet Peak Field
Design Field :
11 T

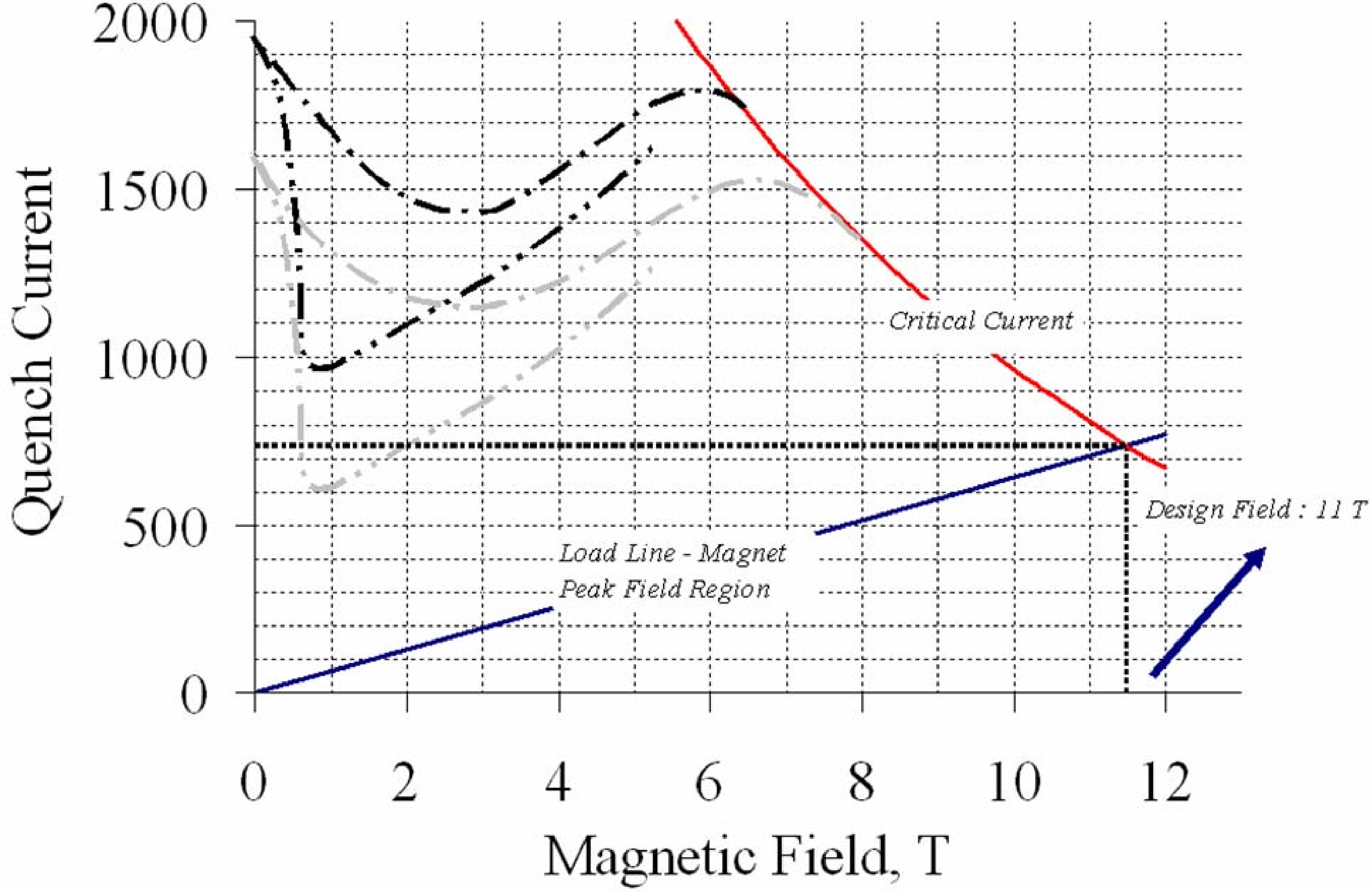

V-I 4.3 K
Critical Current
Design Field : 11 T
Load Line - Magnet
Peak Field Region
Quench Current
Magnetic Field, T
2000
1500
1000
500
0
0
2
4
6
8
10
12



V-I 4.3 K
V-H 4.3 K
Critical Current
Load Line - Magnet
Peak Field Region
Design Field : 11 T
Quench Current
Magnetic Field, T
0
500
1000
1500
2000
0
2
4
6
8
10
12



V-I 4.3 K
V-H 4.3 K
Critical Current
Design Field : 11 T
Quench Field : 9 T
Load Line - Magnet
Low Field Region
Load Line - Magnet
Peak Field Region
Quench Current
Magnetic Field, T
2000
1500
1000
500
0
0
2
4
6
8
10
12


Quench Current
2000
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2
4
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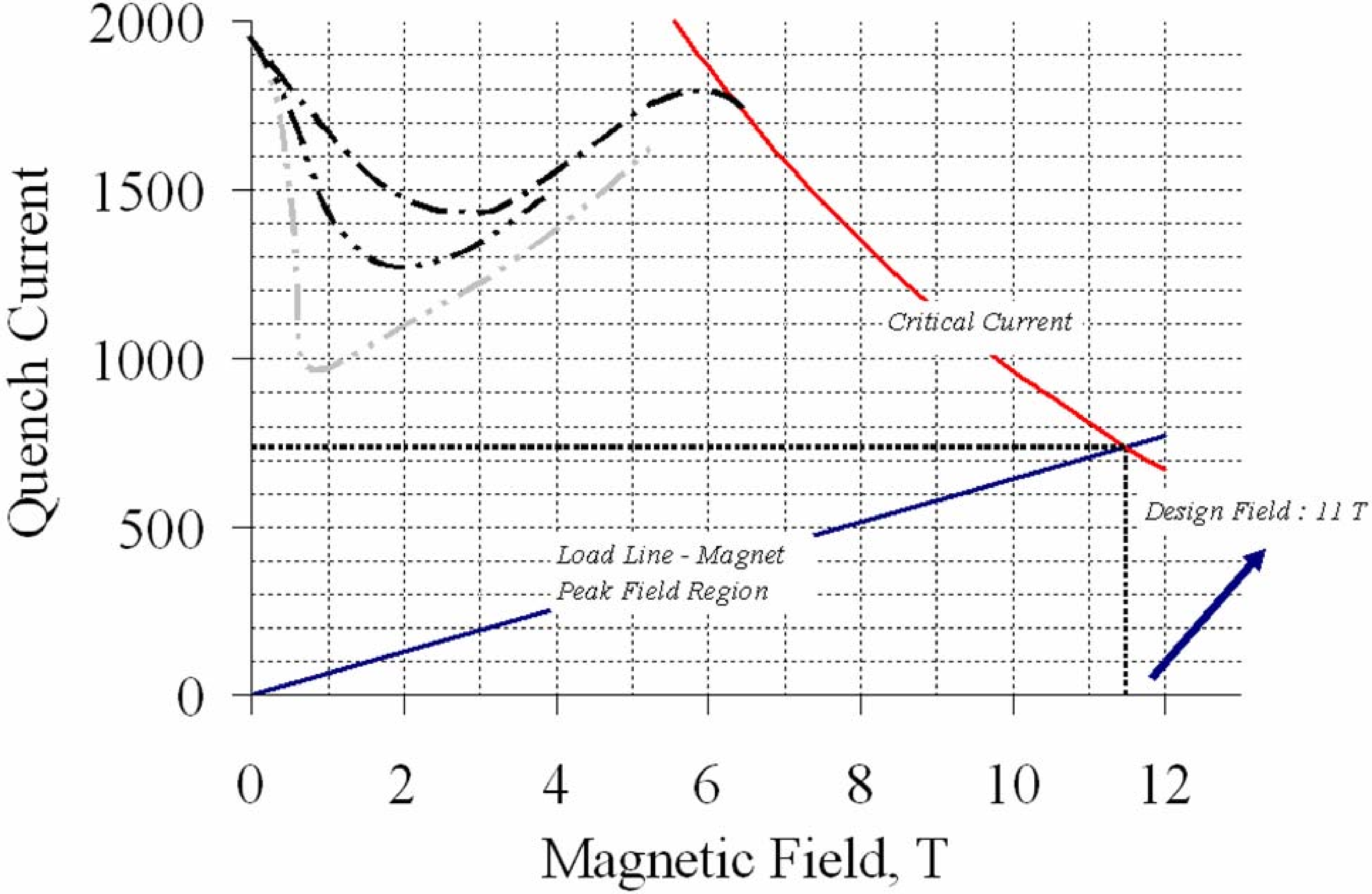
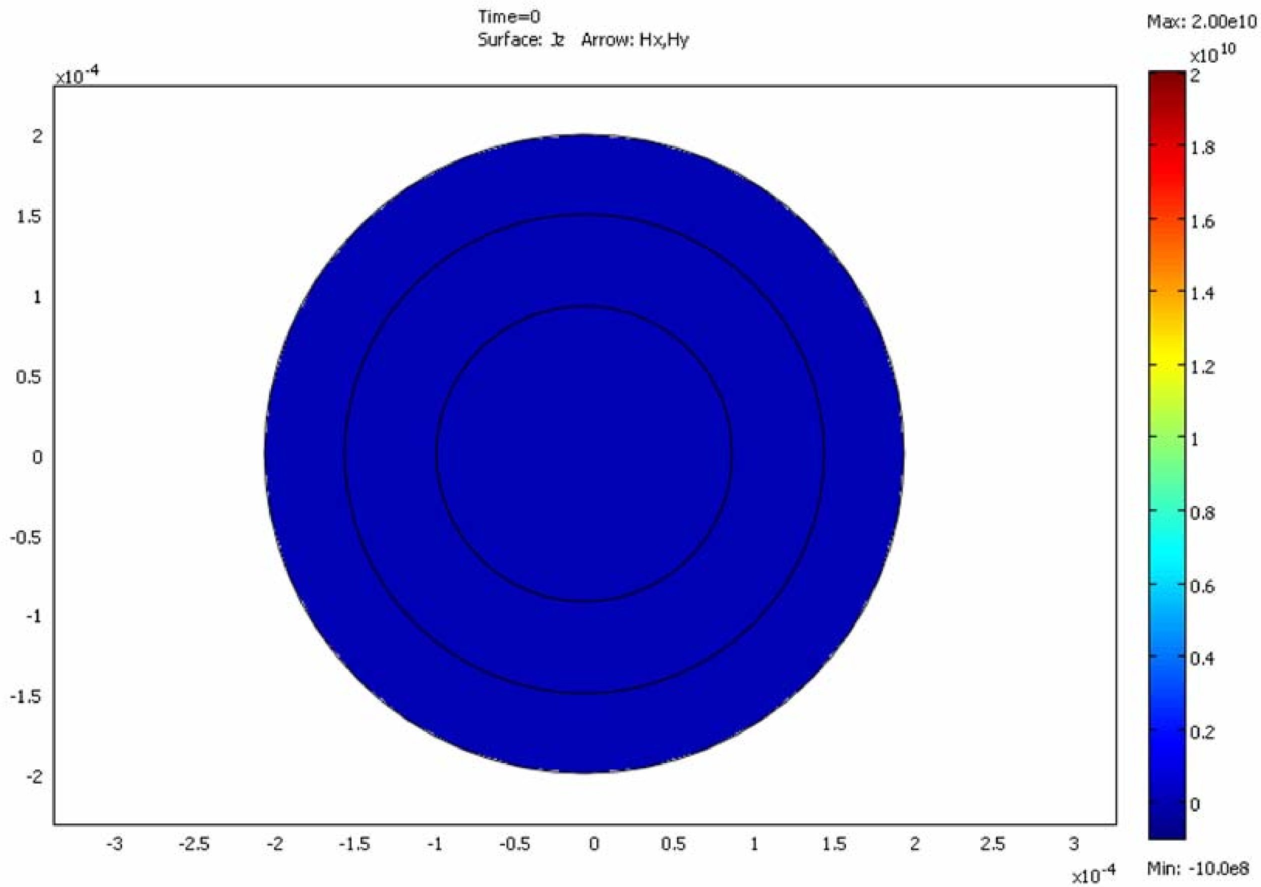
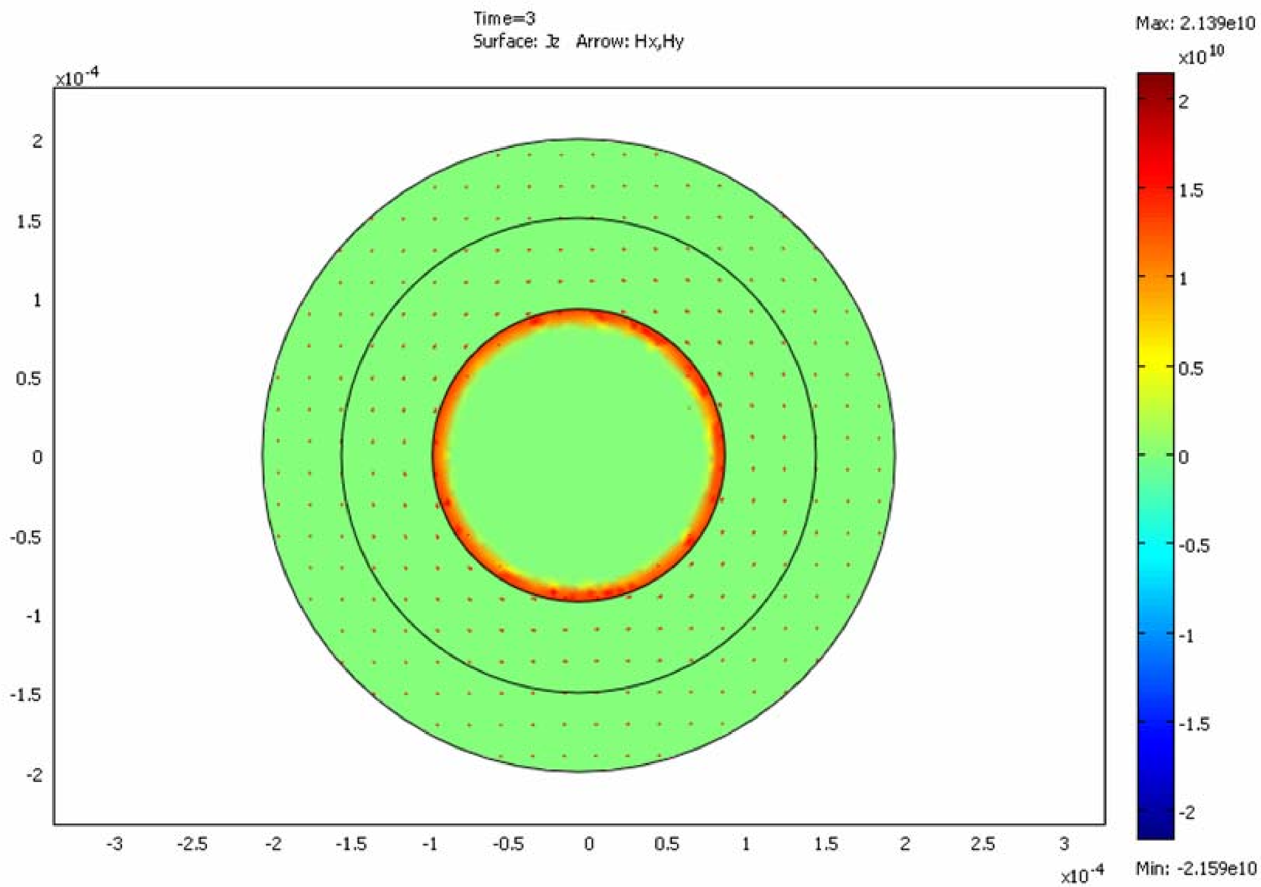
8
10
12
Magnetic Field, T
Critical Current
Design Field : 11 T
Load Line - Magnet
Peak Field Region


Quench Current
2000
1500
1000
500
0
0
2
4
6
8
10
12
Magnetic Field, T
Critical Current
Design Field : 11 T
Load Line - Magnet
Peak Field Region

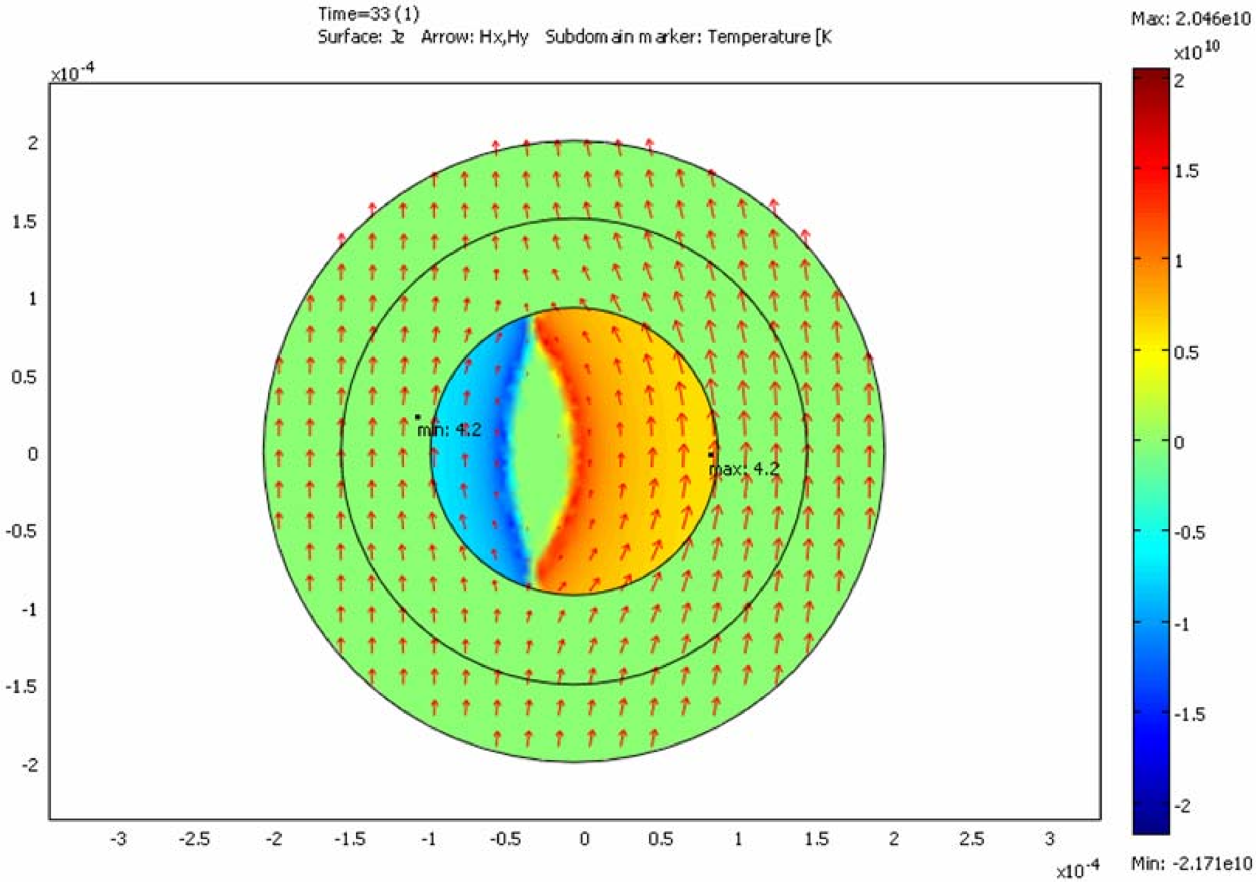
Current distribution (V-H test)



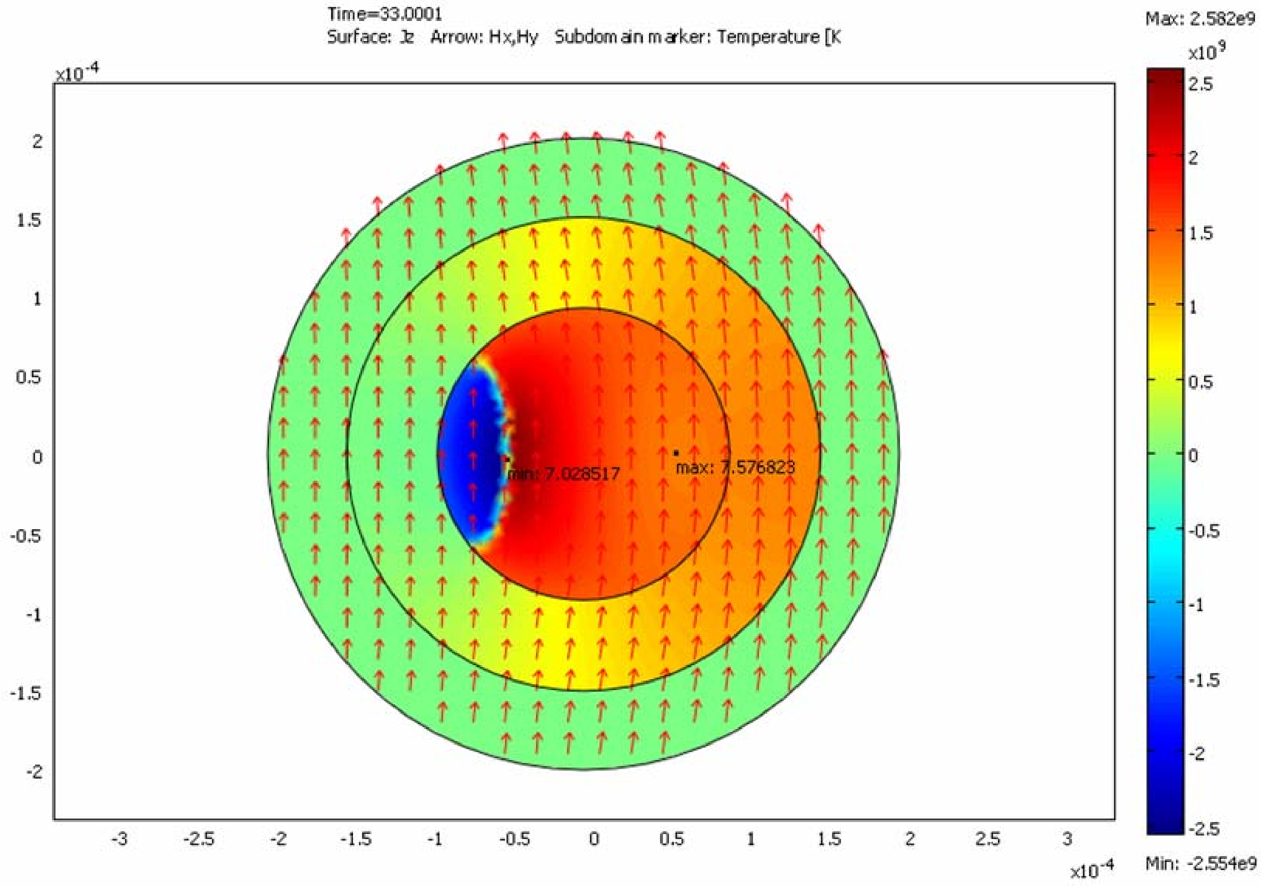
Current distribution
(V-H test)



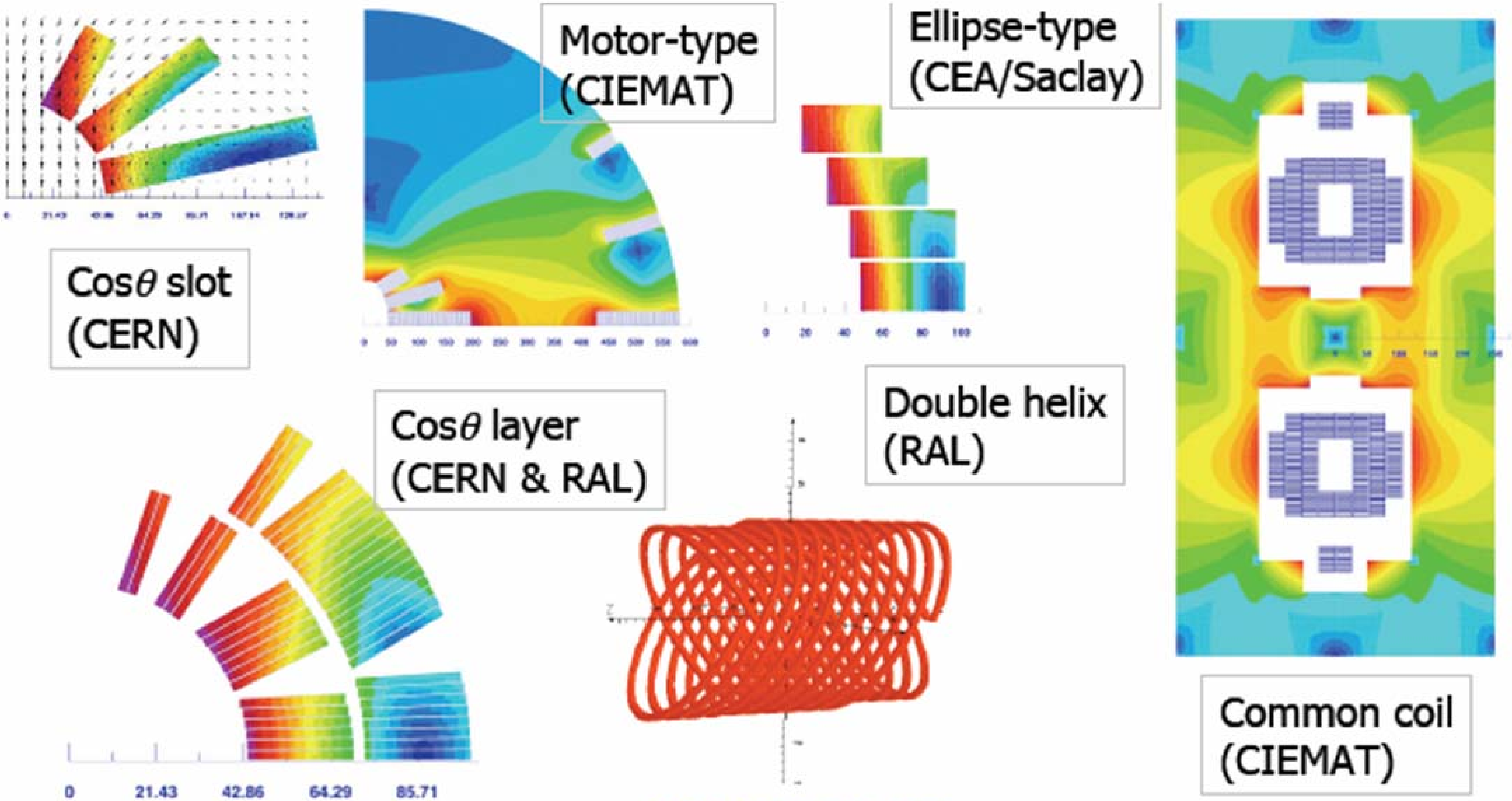
Quench due to a Flux Jump (V-H test)



Quench due to a Flux Jump (V-H test)



Design issue for the NED dipole



NED Magnet Zoo
(Courtesy F. Toral, CIEMAT)

NED is dipole for 15 (12) T in 88 mm bore

HF Program next 4 years

- **White Paper approved**
- **Some 18 MCHF (material) for HFM in 2008-2011**
- Technology R&D and associated study (heat deposition, heat removal, etc.)
- Quadrupole development for LHC up
  - 1 m long model by 2010
  - 6 m long magnet by 2011 (2012)
  - Schedule based on LARP success
- Dipole development: NED and beyond

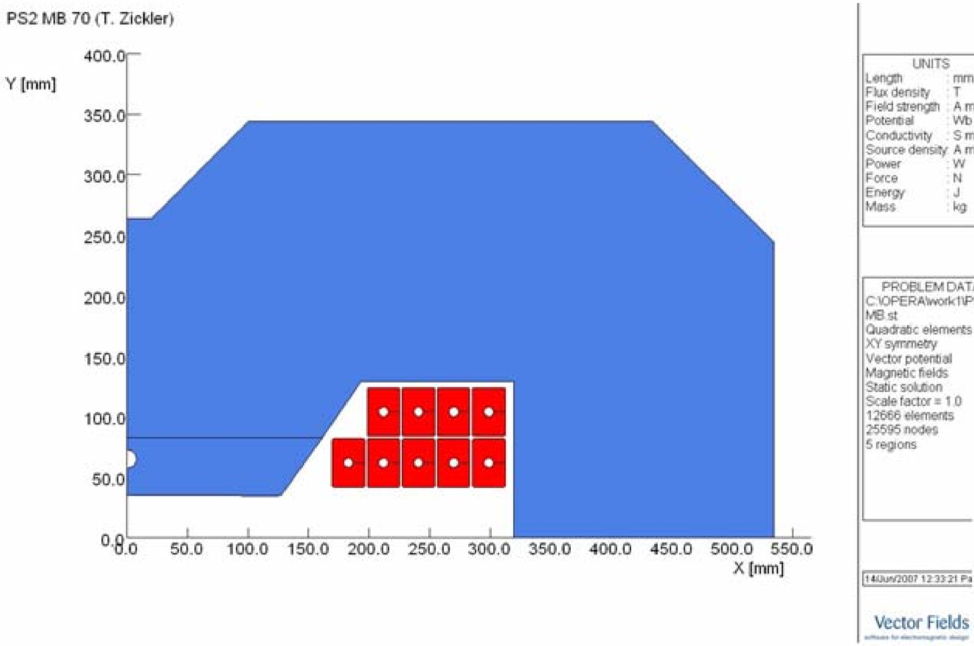
Area where Nb_3Sn can play a role in the LHC up (or consolidation)

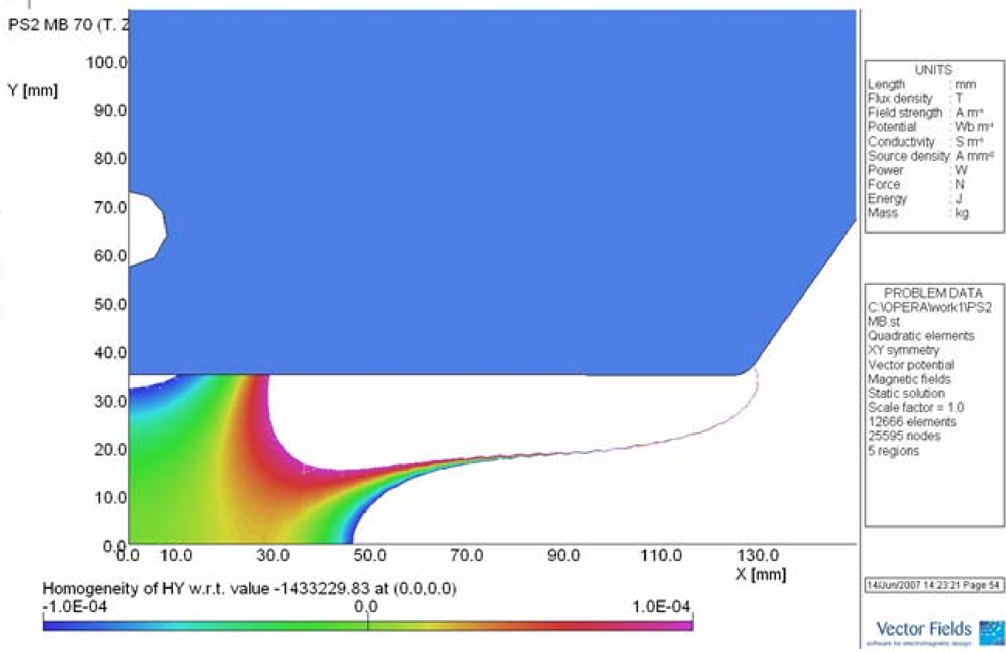
	Field	Aperture (mm)	Radiation load	e.m. Forces	Peak field	Radiation Hardness	Heat removal	Temperature margin
Low-beta insertion quadrupoles	>140 T/m	>130	high	large	>9 T	increased	very good	large
slim dipole in front of Q1	8 T	70	high	large	>9 T	increased	very good	large
corrector in front of Q1	4 T -6 T	>130	high	as lhc	9 T	increased	very good	large
dogleg dipole	5 T	>56	high	as lhc	9 T	increased	very good	large
dispersion suppressor dipole	12 T	>56	high	large	>12 T	increased	very good	large
Muon decay ring	4-6 T	large	high	?	9 T	increased	very good	large

Cycling (or pulsed) Magnets

- SPS upgrade will require 1.8 T $\rightarrow$ 4.5 T, with dB/dt about 2 T/s
- 2/3 of the 6 km long tunnel
- The 6 km long inj.lines needs same field
- However the upgrade of SPS has been postponed in favor of the PS renewal:PS2
- At present the baseline magnet for PS2 is 70 mm gap, 1.8 T $\Rightarrow$ normal conducting

First draft of NC dipole

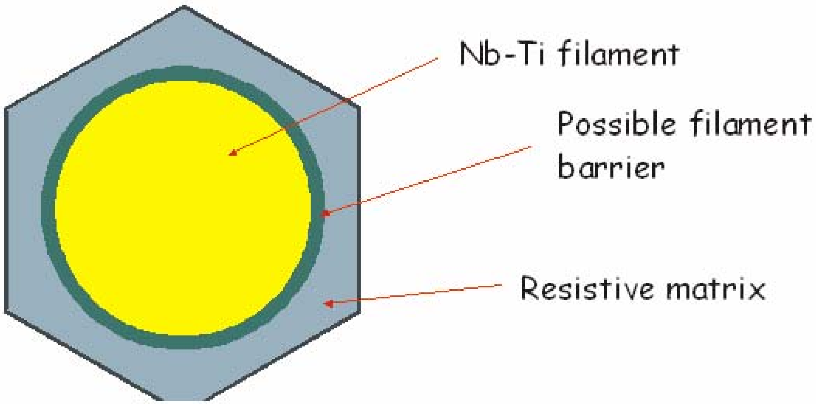




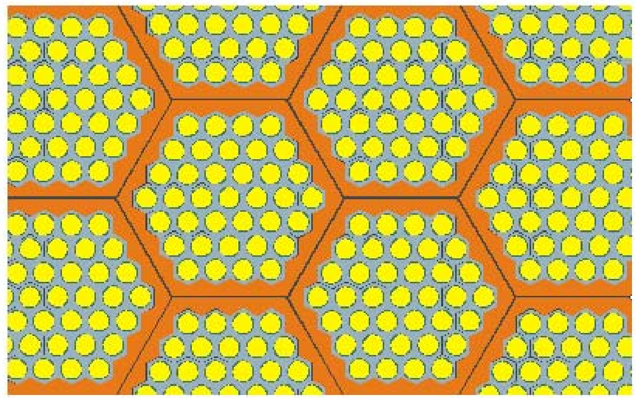
However the weight is 15 tonnes

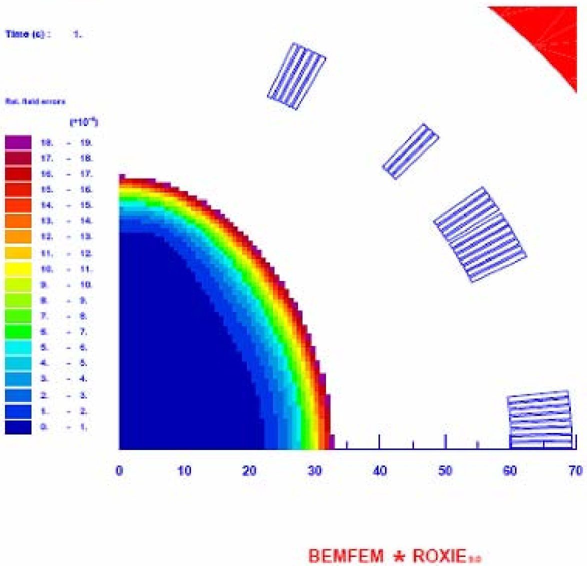
A Sc solution may be 2.5 tonnes with saving in construction cost. However operation cost seems higher for Sc option.

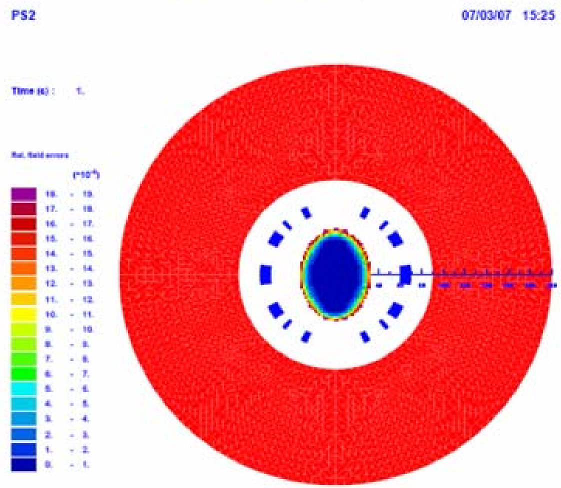
Conductor development (1-3 μm) & simple magnet design (2-3 T)



Filamentbundles with interbundle Cu

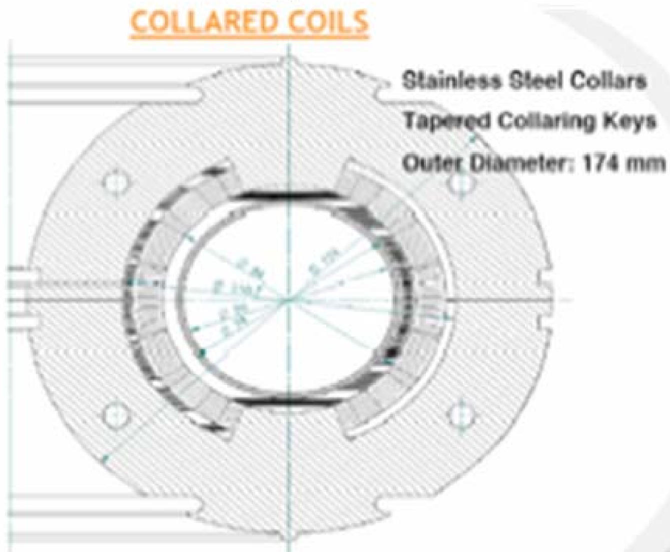






Similar R&D in Europe (very relevant for the SPS up)

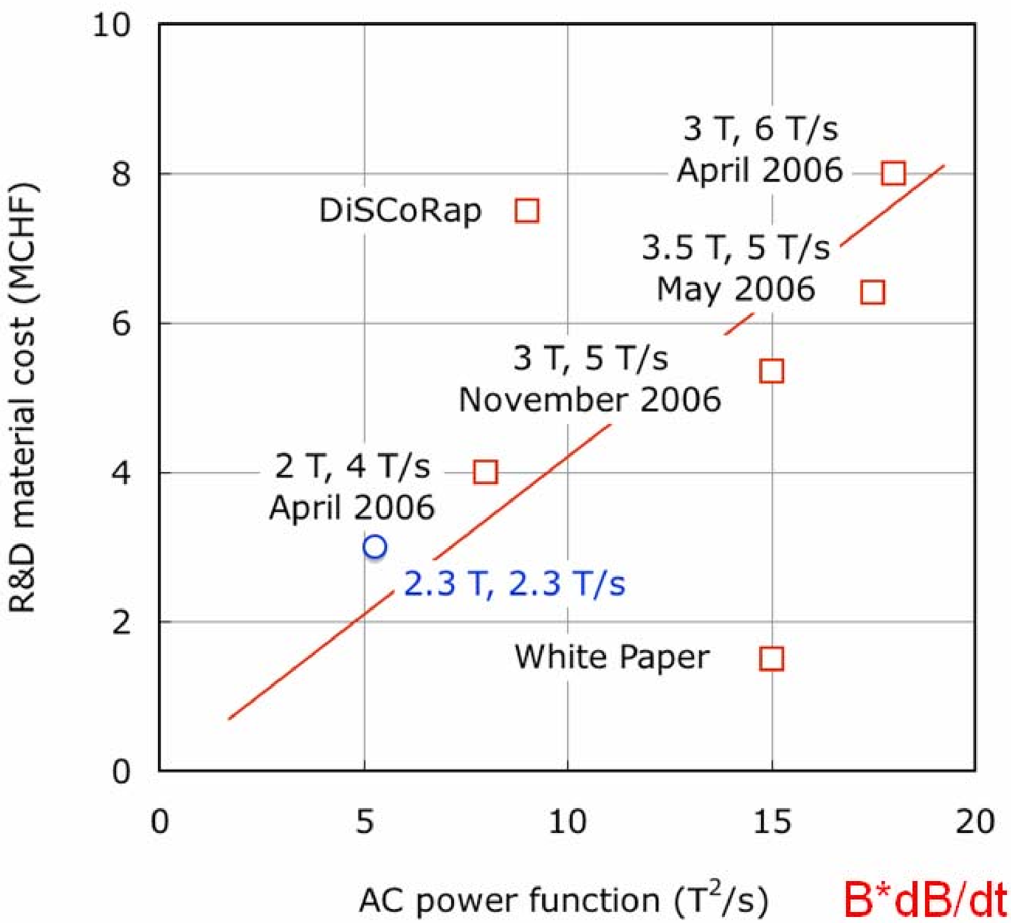
- FAIR at GSI (Darmstadt, D)
  - SIS-100 (2 T, 4 T/s, Superferric, Nuclotron magnets)
  - SIS-300 (4.5 T, 1 T/s, cos-theta magnets)
    - DiSCoRap at INFN (Milano, Genova, Frascati,I) R&D on a 5…6 T, 1…1.5 T/s dipole for SIS-300



R&D target

- Target: produce and test a representative model of a PS2+ dipole B_{max} = (1.8) 2.3 T
  - dB/dt_{max} = (1.5) 2.3 T/s (B_{max} in 1 s)
  - Q_{AC} < (10) 5 W/m (average over 2.4 s cycle), room for beam losses
  - Good field region (10^{-4} homogeneity):
    - Injection (3.5 GeV): ±42 mm x ±30 mm
    - Extraction (50 GeV): ±42 mm x ±14 mm
  - Address fatigue issues at > 100 MCycles lifetime
  - Address magnet protection issues
  - Address radiation damage issues
- With this choice:
  - The R&D complements the on-going work for FAIR at GSI and INFN
  - *R&D is scalable "also possibly for an SPS2+ in the future"*

The cost estimate in perspective

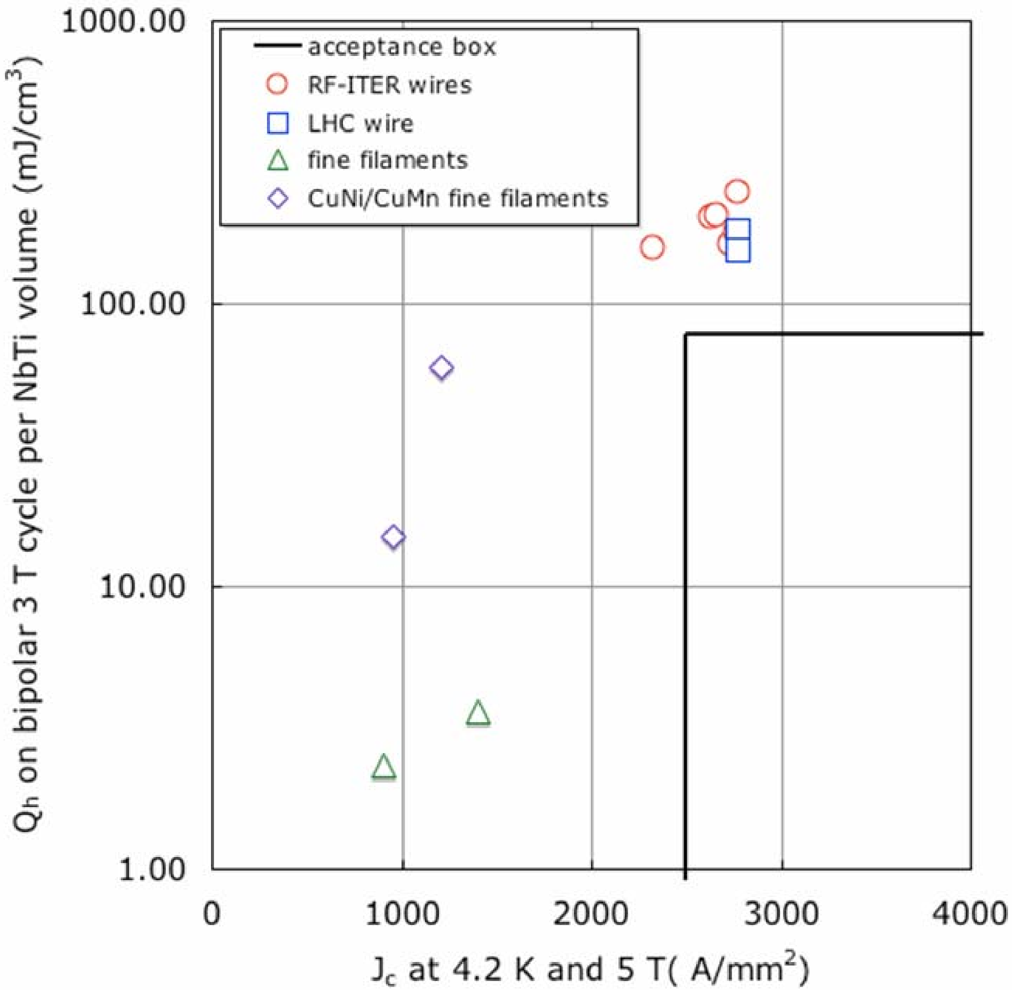


- In the plot are the various CERN options. Our target of today (blue) will requires some increase wrt allocation(+ 1.5 MCHF)
- Resources will be likely taken from HFM program. However a plan must be worked next months also in agreement with PS2 strategy.

R&D work breakdown themes

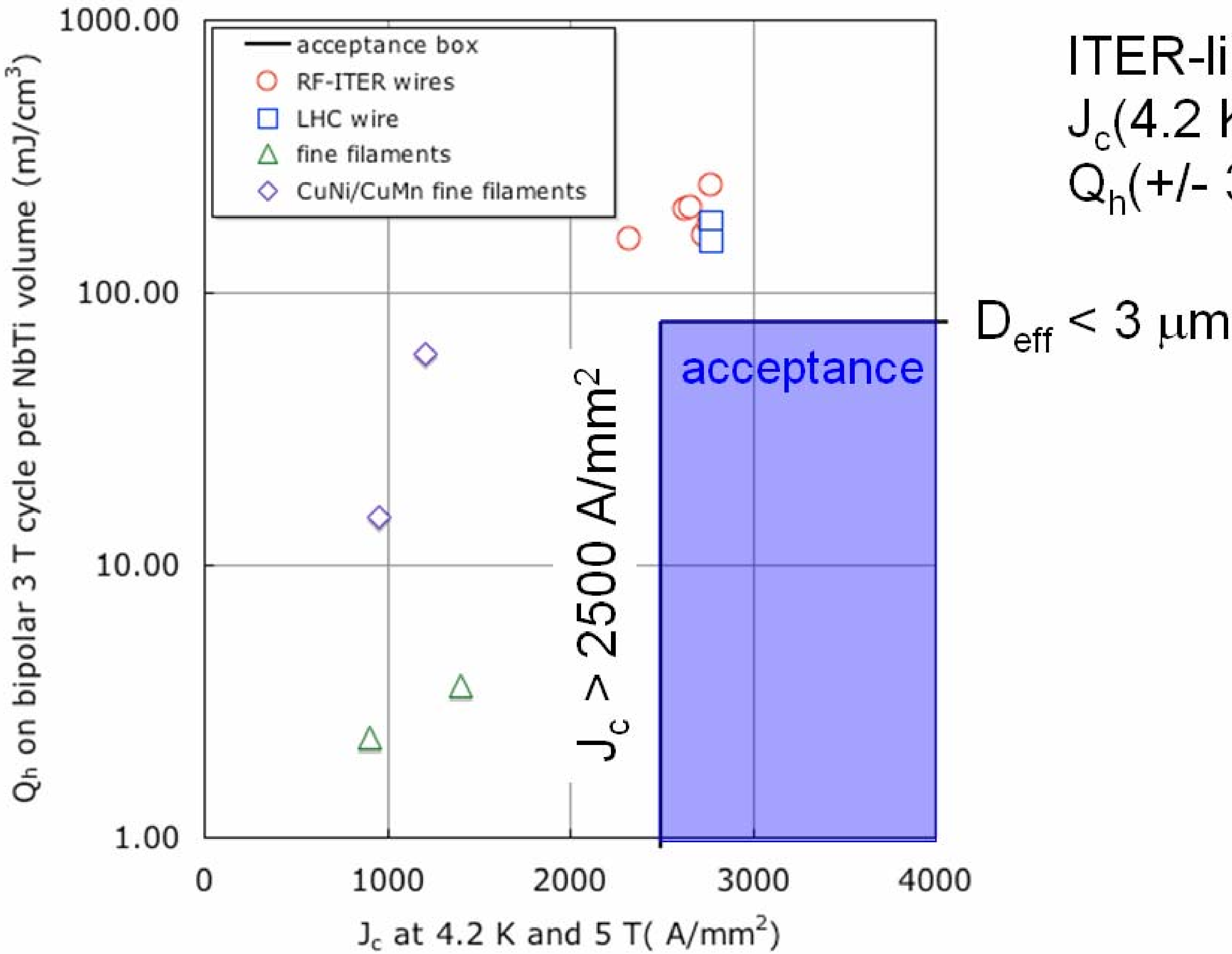
- **Design and procure NbTi wire with**
  - **$J_c > 2500$ A/mm^2**
  - **$D_{eff} < 3$ μm (Q_h for a 3 T bi-polar cycle < 80 mJ/cm^3 of NbTi)**
  - **$\tau < 1$ ms**
- Design and produce a cable for pulsed operation
  - Define targets for R_c and R_a TBD (100 μΩ or larger) to have negligible AC loss and stable pulsed operation. Surface coating options vs. central core for cable production
  - Choose a cable insulation scheme for heat removal and test
  - Develop the joint technology for pulsed operation (AC loss and current distribution)
- **Design and produce a 1-m long magnet model (re-usable for coil test purpose)**
  - Low-loss iron and coil components (spacers, collars)
  - Verify heat transfer from coil (and heat removal from magnet ?)
  - Demonstrate quench detection and magnet protection scheme
  - Simulate fatigue at large number of cycles
- Test and instrumentation R&D (both for cable and magnet losses and AC field)

NbTi wire procurement



ITER-like specification box:
J_c(4.2 K, 5 T) > 2500 A/mm^2
Q_h(+/- 3) < 80 mJ/cm^3 NbTi

NbTi wire procurement

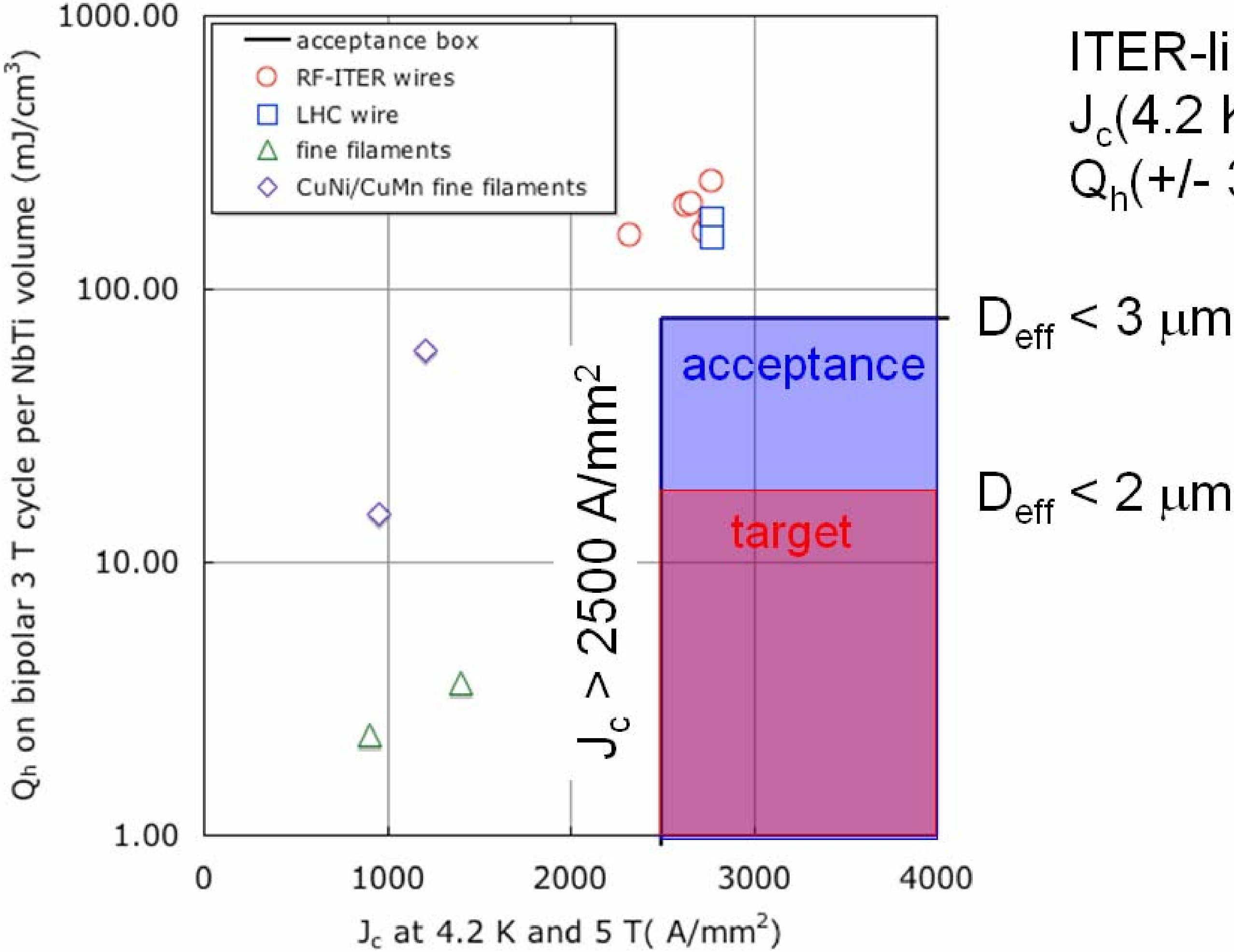


ITER-like specification box:

J_c(4.2 K, 5 T) > 2500 A/mm^2

Q_h(+/- 3) < 80 mJ/cm^3 NbTi

NbTi wire procurement



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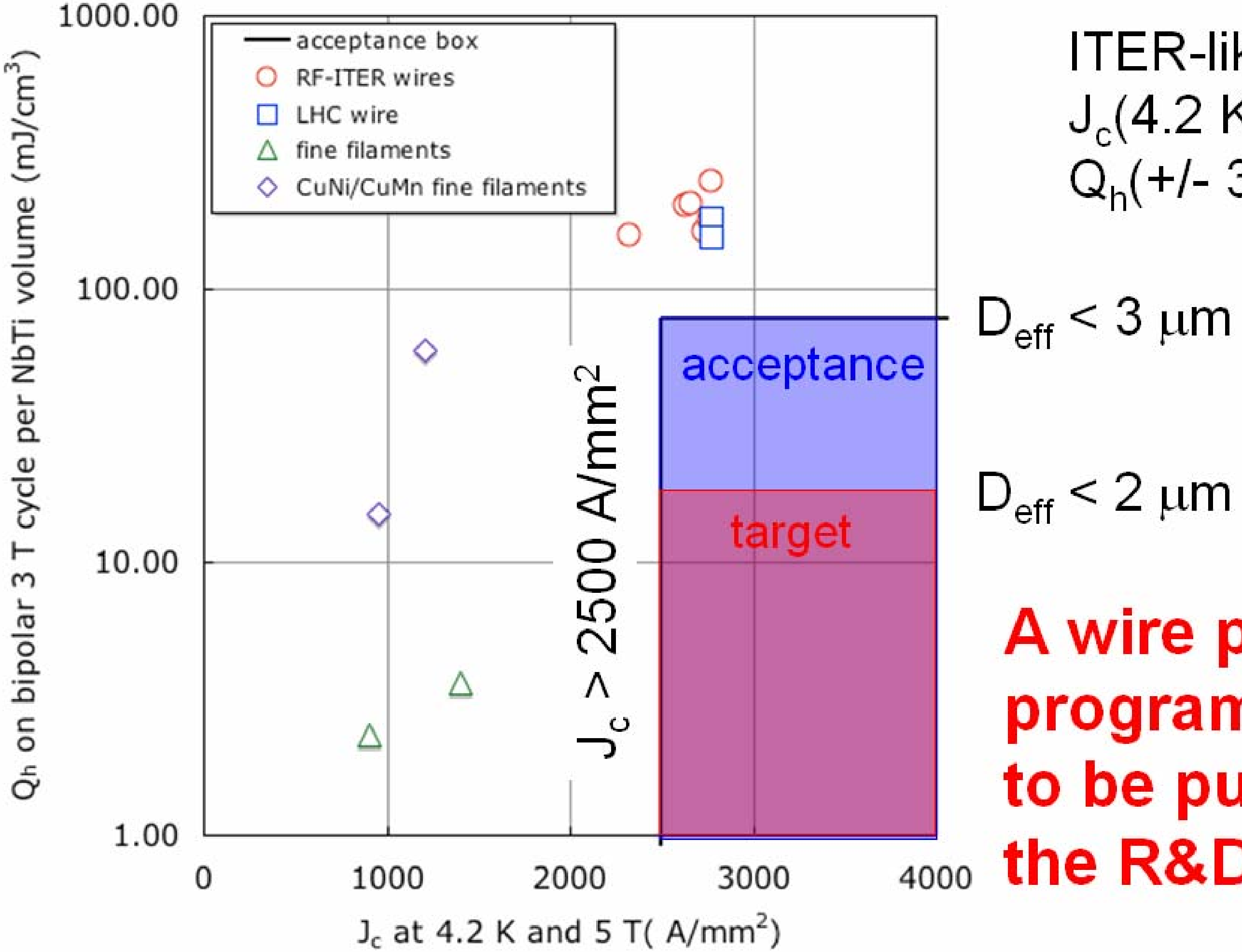


ITER-like specification box:
J_c(4.2 K, 5 T) > 2500 A/mm^2
Q_h(+/- 3) < 80 mJ/cm^3 NbTi

A wire procurement program is the first action to be pursued as soon as the R&D is approved

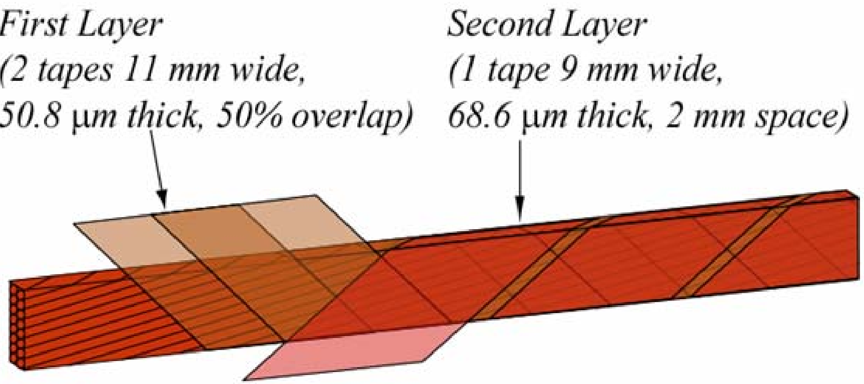
Thermally Enhanced insulation

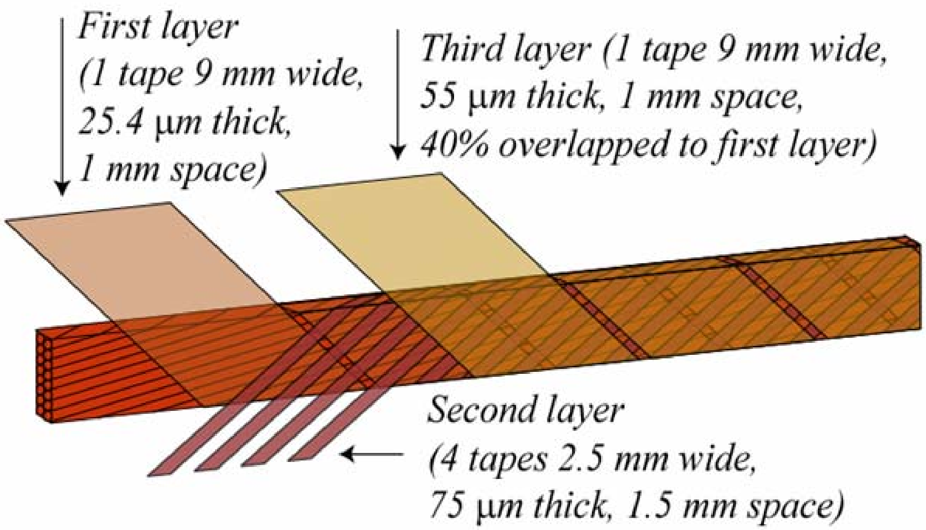
State-of-the-art

•Overlap is present between tapes of first layer, nominally no channels.

Enhanced

•Overlap is present between first and third layer: finite dimension channels determined by thickness of second layer tapes

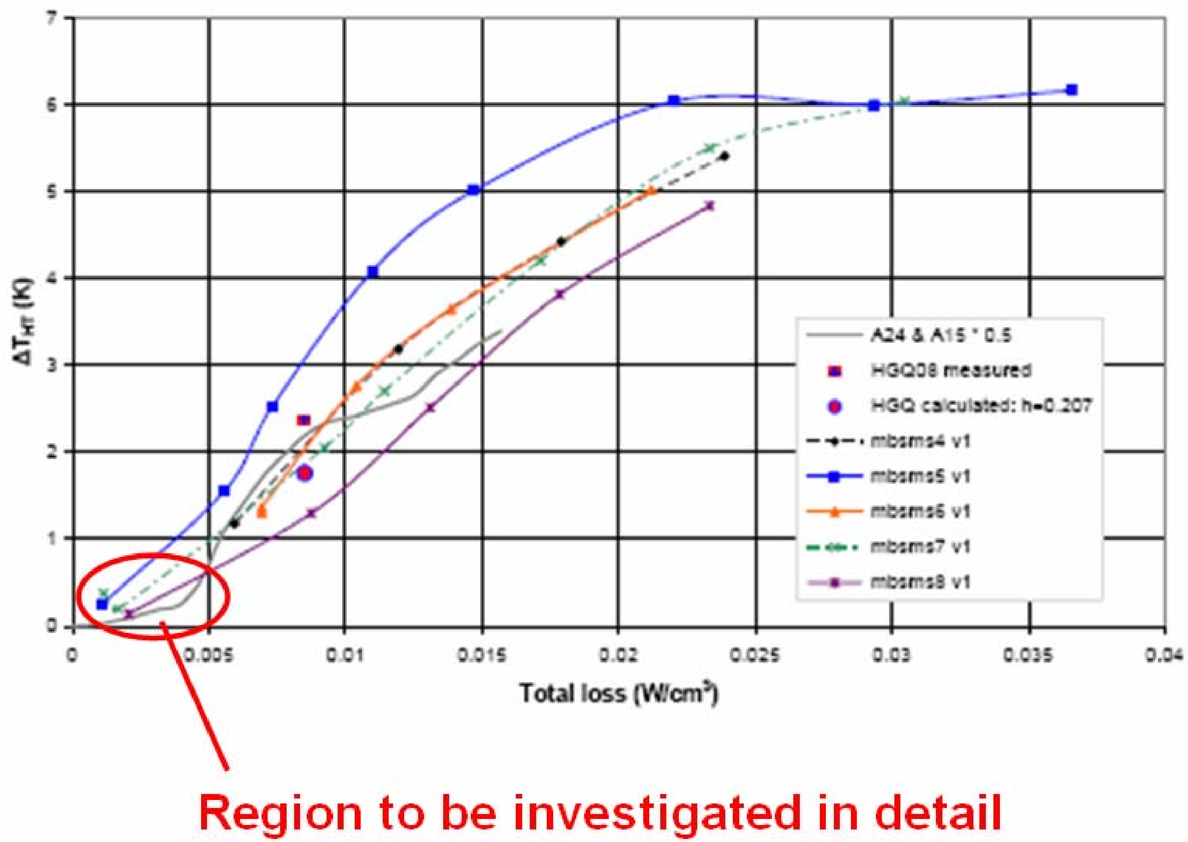




M. La China, D. Tommasini

Enhanced Heat Tr of 3 to 5

Heat transfer study (for LHC first)



D. Ritcher

Possible roadmap

- The horizon for magnet R&D related the the LHC is changing, **objectives should be adapted accordingly**