High Field magnets for LHC upgrades

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HFM options for an LHC luminosity upgrade

An LHC luminosity upgrade envisages in ~ 10 years:

- Inner Triplet quadrupoles
  Aperture ∅ ~ 120 mm, G ~ 190 T/m, L = 6 m - 10 m

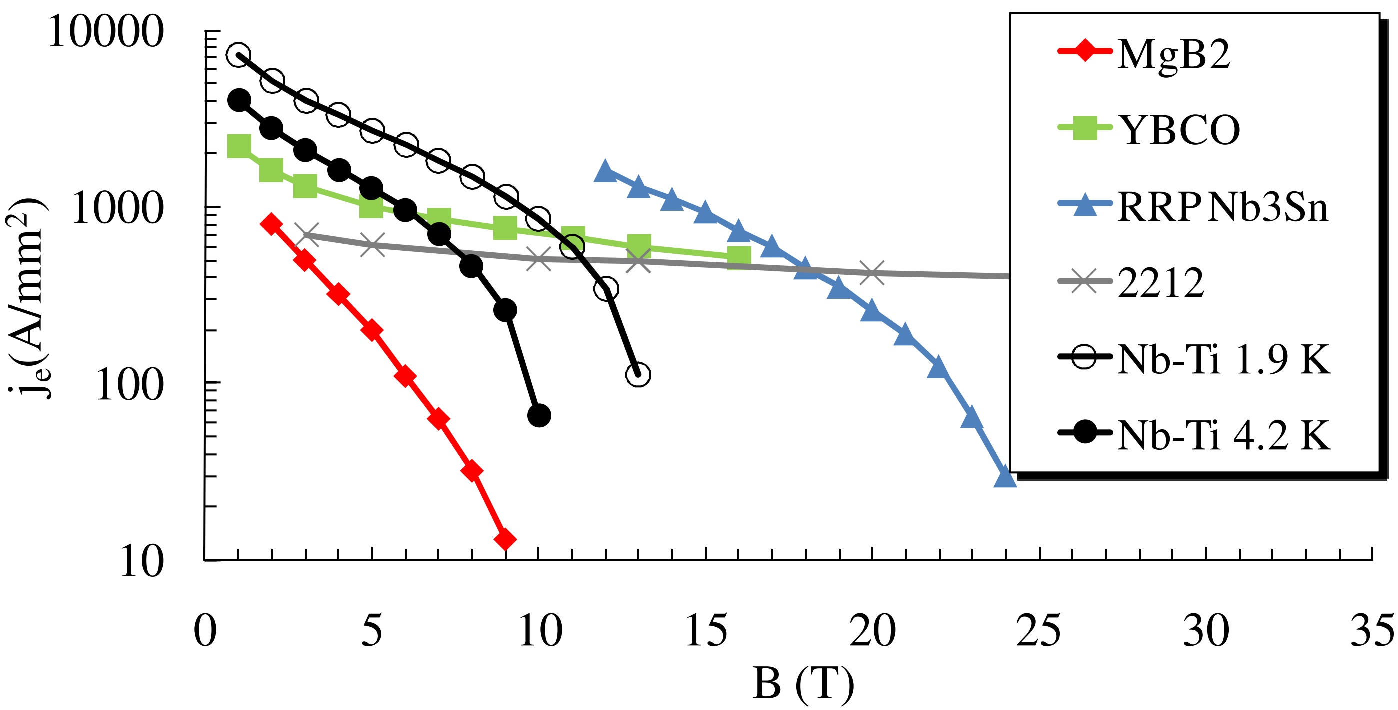
- Dispersion Suppressor twin aperture dipoles
  Aperture ∅ = 60 mm, B = 11 T, L = 11 m

- D1 separation dipole
  Aperture ∅ = 180 mm, B = 10 T, L = 5 m

Note all fields and gradient are operational values (20% margin usually taken)

Conductors for HFMs

To meet these requirements one has to switch from Nb-Ti to Nb_3Sn (or Nb_3Al) superconductors



Engineering current density in practical superconductors

CERN program on High Field Magnets

HFM program aim: High field magnets technology (dipoles and quads) for LHC upgrades and future accelerators

Priorities:
- Conductor is the heart of the magnet
- Magnet design and tests

First step (2004 – 2012):

- Conductor technology development
- Magnet technology development
- Personnel training on existing technologies

Second step (2009 – 2014):

- Conductor test facilities upgrade to 15 T
- Magnet models (IR quad and DS dipole models)
- Magnet concepts from 15 T to 20 T

Third step (2014 – 2016):

- LHC Inner triplet quadrupole prototype
- LHC Dispersion Suppressor dipole prototype

CERN program on High Field Magnets: implementation

HFM program medium term aim:

Technology readiness by 2016 for:

- Large aperture high gradient quadrupole magnets for the LHC inner triplets upgrade (∅ ~ 120 mm, G ~ 190 T/m) (~2020)

- Twin aperture Dispersion Suppressor dipole (∅ = 60 mm, B = 11 T, L = 10.8 m) (~2020)

- Separation Dipole D1 (∅ = 180 mm, B = 10 T, L = 5 m) (~2020)

First step (2004 – 2012):

- Conductor development base program (CERN + Fr in-kind contr.)
- Short Model Coil (collaboration CEA, RAL, CERN, LBNL)
- test of TQS & HQ at CERN (Collaboration CERN- LARP-LBNL)

CERN program on High Field Magnets: implementation

Second step (2009 – 2014):

- EuCARD WP7-HFM project (collaboration with 13 partners)
  - High field model to upgrade the cable test facility Fresca (∅ 100 mm, B=13-15 T)
  - Very high field HTS insert to approach 20 T domain
- Models for IR quadrupole: LARP program in US
- Models for DS dipole: CERN program
- Models for D1 dipole: CERN or collaboration

Third step (2014 – 2016):

- Inner triplet quadrupole prototype
- DS twin aperture dipole prototype
- D1 prototype

HFM R&D for an LHC luminosity upgrade: IT Quad

R&D in the US (LARP):

Up to now achieved (LQ): Aperture ∅ = 90 mm, G = 200 T/m, L = 3.4 m

Soon to come (HQ): Aperture ∅ = 120 mm, G = 190 T/m, L = 1 m

Conductors used:

OST-RRP-54/61 and OST-RRP-108/127

Cable 27 strands, ∅ = 0.7 mm , sub-elements ∅ = 50 μm

Open issues:

- Inter-strand resistance in the cable is low and variable : field quality
- Stability of the strand at 1.9 K to be confirmed
- In the sub-element diameter of 50 μm small enough ?
- Length limit at 3.4 m, should be 8-10 m
- Radiation hard insulation
- Heat removal from the coil

LARP IT quad development program

Achieved with Nb_3Sn:

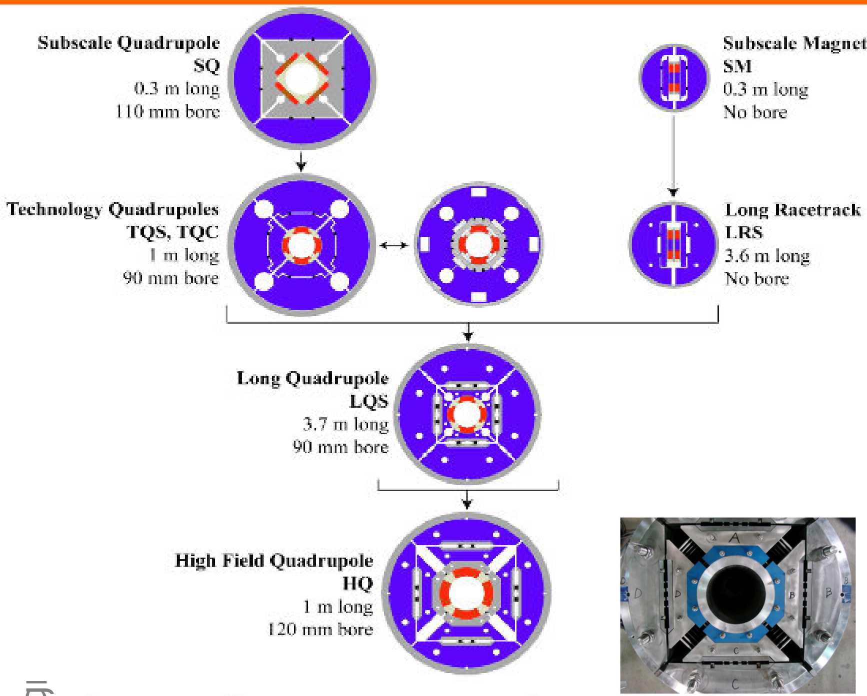
- TQ: 1 m, 220 T/m, 90 mm aperture
- LQ: 3.8 m, 200 T/m, 90 mm aperture

To be tested in May 2010:

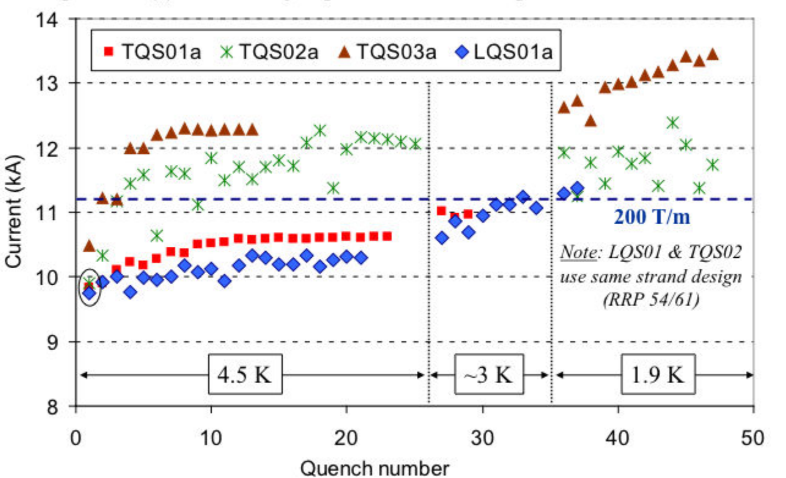
- HQ: 1 m, 190 T/m, 120 mm aperture with alignment features

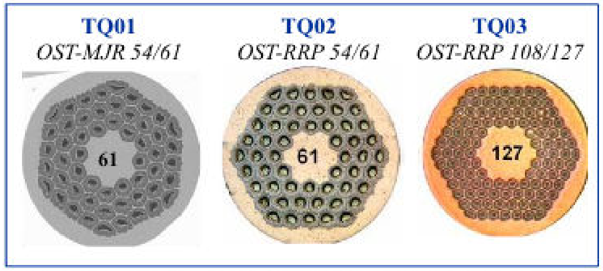
Plan:

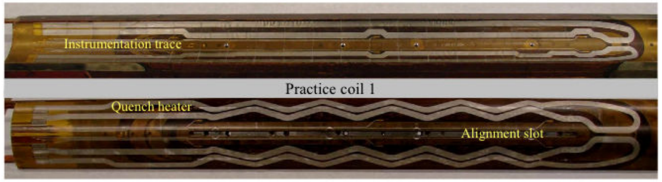
- 4 m prototypes for LHC



Comparison of first training sequences at each temperature with all new coils





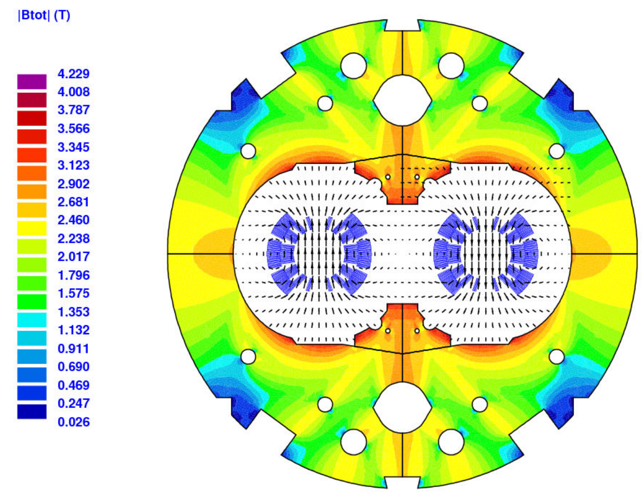


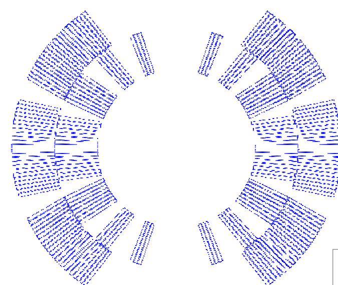
HFM R&D for an LHC luminosity upgrade: DS dipole

Feasibility study recently started for a twin aperture ∅ = 60 mm, B = 11 T, L = 10.8 m dipole magnet.

First estimates:

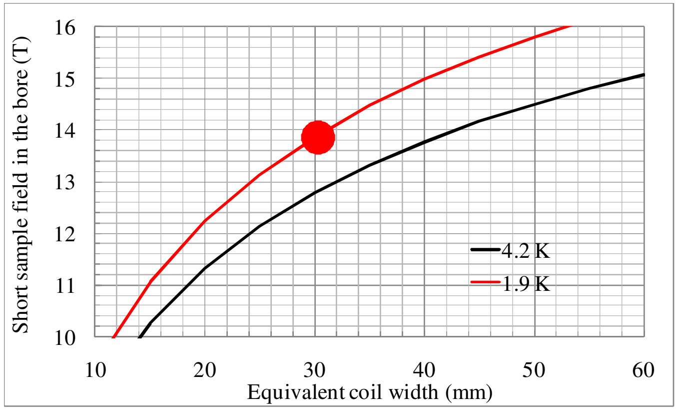
- 47 strands of 0.65 mm
- 2 layers 17.5 mm width cable
- B=11.0 T at 80% I_{ss}, T=1.9 K, I=11850 A





Open issues:

- Coil length 10.8 m
- Stability of the strand at 1.9 K
- LHC dipole like collar structure
- Radiation hard insulation
- Heat removal from the coil
- Inter-strand resistance in the cable : field quality
- Is sub-element diameter 50 μm small enough ?

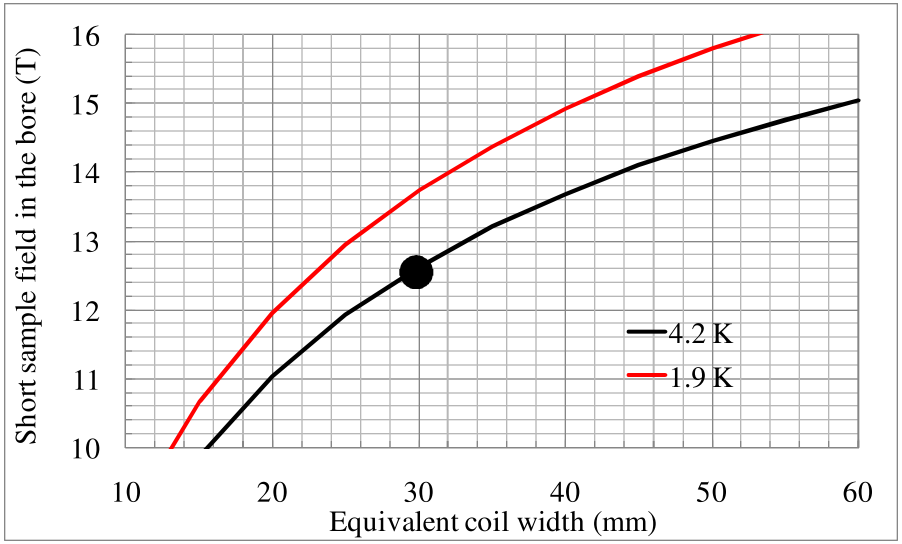


HFM R&D for an LHC luminosity upgrade: D1 dipole

Feasibility study recently started for ∅ = 180 mm, B = 10 T, L = 5 m dipole magnet.

First estimates:

- ~30 mm coil width
- 4.2 K operational temperature
- 20% operational margin



Open issues:

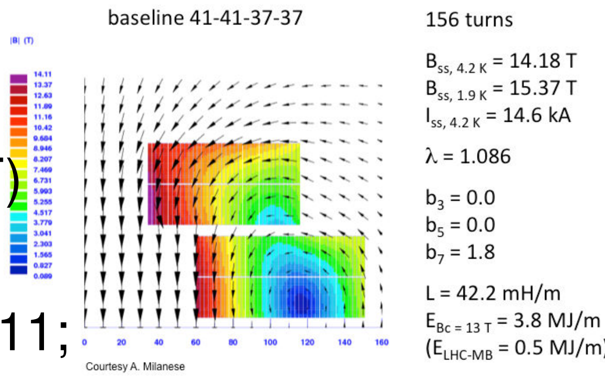
- Coil length 5 m
- Stability of the strand at 1.9 K
- Inter-strand resistance in the cable : field quality
- Is sub-element diameter 50 μm small enough ?
- LHC dipole like collar structure
- Radiation hard insulation
- Heat removal from the coil

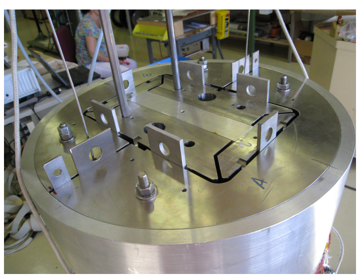
EuCARD HFMs: Fresca2 dipole

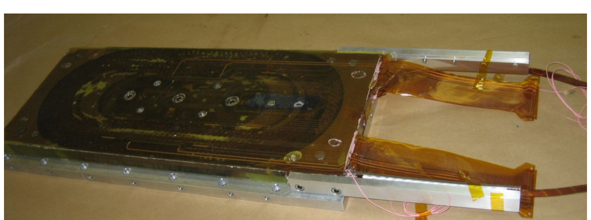
EuCARD WP7 on High Field Magnets, 13 partners, 6 tasks: 13 T dipole, HTS insert, HTS link, helical undulator; April 2009 – April 2013

Dipole for cable test station aperture 100 mm, 13 T

- Nb_3Sn 1 mm strand, 40 strand cable (RRP or PIT)
- Preparation: Short Model Coil: test in June
- Design: 9/2009-12/2010 ; coil winding start 05/2011;
  first assembly 05/2012;
  first cold test 2nd half 2012







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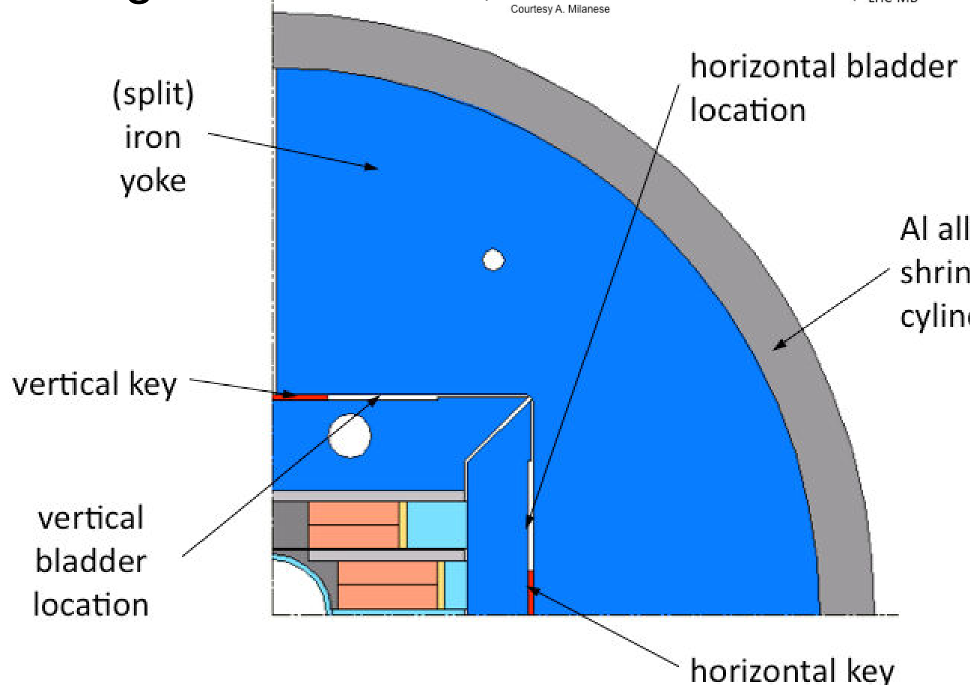
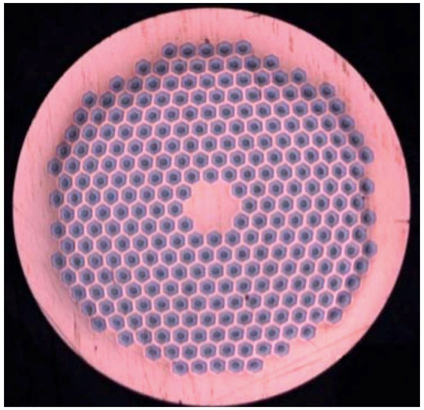
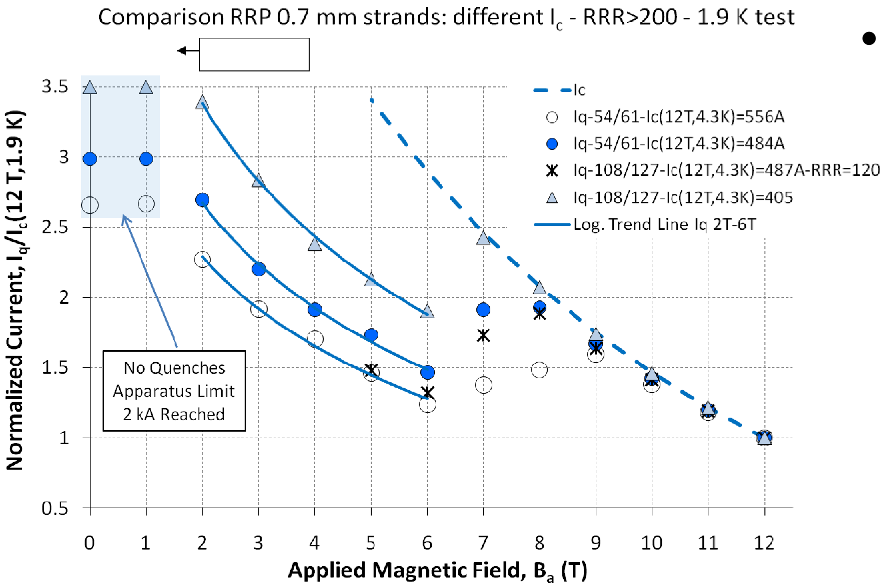


Conductor R&D - NED and post-NED strands

- The NED program achieved Nb3Sn 1.25 mm strands with J_C of 1500 A/mm^2 at 15 T and 4.2 K, filament diameter of 50 μm, and RRR regularly in excess of 150
- The HFM program has since focussed on issues of cable production and degradation, and thermo-magnetic stability



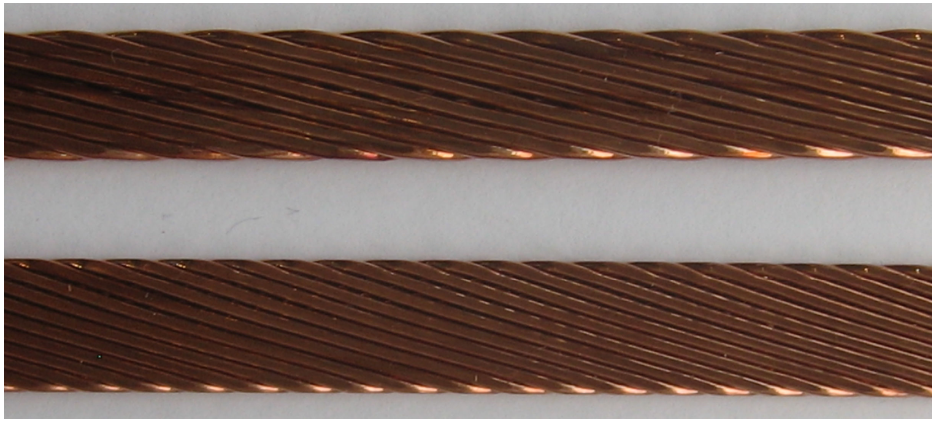
Bruker-EAS PIT, 288 subelements, $(Nb\text{-}Ta)_3Sn$

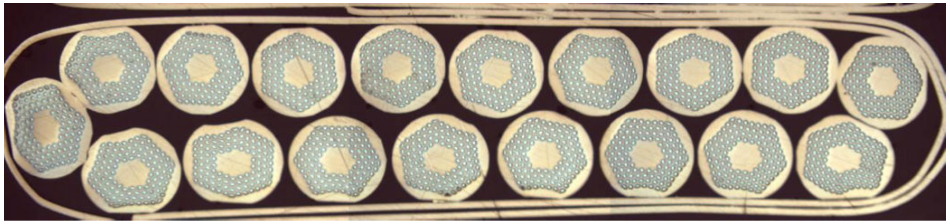


- An improved understanding of the thermo-magnetic stability has led to the decision to:
  - Reduce strand diameter (1 mm)
  - Limit strand critical current density (1250 A/mm^2 at 15 T and 4.2 K)
  - Maintain a strict requirement on RRR and filament diameter

Conductor R&D - Cable variants

- Cabling tests were performed on several variants of strands/cable sizes to explore the space of parameters, and among others: dimensions, compaction, twist pitch, cabling angle and cabling force, …
- Cabling degradation was reduced from 45 % (worst case) to *negligible* (within the scatter of measurements of extracted strands)



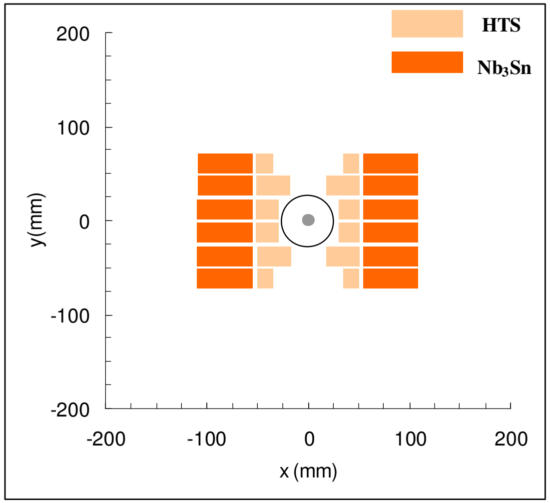


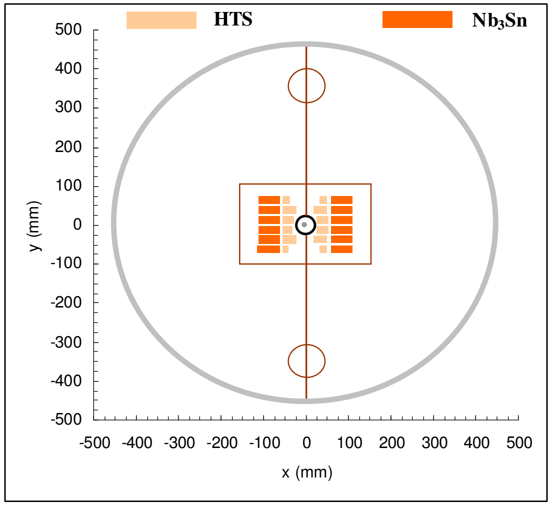
- SMC-class cables
  - Cu dummies
  - 14 strands, 1.25 mm
    - PIT (EAS), IT (Alstom)
  - 18 strands, 1 mm
    - IT (OST-RRP)
- Fresca2-class cables
  - Cu dummies
  - 40 strands, 1.25 mm
    - PIT (EAS)

A glimpse on the future: HFM for a ~17.5 TeV LHC?

Is it possible to increase the LHC energy? DLHC in ~ 15-25 years

- To have at least a factor two increase, one needs HTS conductors
  - With Nb_3Sn one only gets a maximum 1.5 increase
- Example: twin aperture dipole ∅ = ~50 mm, B ~ 20 T (17.5+17.5 TeV), designed at 24 T (short sample)
  LHC main dipoles are designed for fields of 9.7 T





End of presentation

A few more slides for detail discussion…

HFM R&D items: Dynamic effects in conductors (1)

For both the IR quad and the dipole, there are questions on the conductor performance :

- Inter-strand resistance in the cable
- Stability of the strand at 1.9 K to be confirmed
- In the sub-element diameter of 50 μm small enough ?

We do not yet know what the present 0.6 - 0.7 mm conductors will do.

3 options to measure these effects:

- On the Strand: characterization: stability and magnetization
  - Program at the test stations at CERN up to 15 T (ongoing)
- On the cable: stability and loss measurements
  - Program at CERN in Fresca up to 10 T (ongoing)
- On magnets: loss measurements and fast magnetic measurements
  - On TQS at CERN (ongoing)
  - On HQ at CERN (summer 2010)

HFM R&D items: Dynamic effects in conductors (2)

Based on measured losses and field decay effects in 2010 on the strand, cable and magnet level by the second half of 2010 we should be able to launch:

- R&D on cable inter-strand resistance control, 2 options
  - Cored cable
  - Coated strands

Based on the fast magnetic measurements to see persistent current effects on the magnets by the second half of 2010 we should be able to launch:

- R&D contracts on strand with smaller sub-elements (towards 20 μm)

HFM Nb_3Sn strand

Strand diameter	1.000 ± 0.004 mm
Filament diameter (geometric)	< 50.0 μm
Copper to non-copper volume ratio	1.25 ± 0.10
Strand twist pitch	24 ± 3 mm
Strand twist direction	right-handed screw
Critical current at 4.222 K	> 873 A at 12 T > 437 A at 15 T
Critical current density at 4.222 K	≈ 2500 A/mm² at 12 T ≈ 1250 A/mm² at 15 T
n-value at 15 T and 4.222 K	> 30
RRR (after heat treatment)	> 150 (200)

Conductor R&D - Proposed procurement strategy

- HFM program and Fresca2
  - Qualify producers (worldwide) for the revised strand specifications with a sizeable production (approx. 100 kg, 14 km) of HFM strand
  - Pilot HFM production for Fresca2 at two qualified producers (approx. 100 kg, 14 km)
  - Fresca2 production at the best-performing producer (approx. 400 kg, 40 km)
  - Follow-up with procurement of conductor for prototype magnets (TBD)
- Other applications (e.g. DS dipole, undulators, wigglers)
  - Procure test material (approx 100 kg. 30 km) to develop cables suitable for winding LHC-like dipoles, at moderate to small diameter (0.7 mm) and high Jc (3000 A/mm^2)

HFM Nb_3Sn cables

	SMC	Fresca2
Cable width	10 mm	21.4 mm
Cable mid-thickness at 50 MPa	1.81 mm	1.82 mm
Keystone angle	0 degree	0 degree
Cable transposition pitch	~ 75 mm	~ 160 mm
Cable transposition direction	left-handed screw	left-handed screw
Number of superconducting strands	18	40
Critical current at 4.222 K, field normal to broad face	7080 A at 15 T 14140 A at 12 T	15730 A at 15 T 31430 A at 12 T
Minimum critical current at 4.222 K of extracted strand (cabling degradation 10 %)	393 A at 15 T 786 A at 12 T	393 A at 15 T 786 A at 12 T
n-value @ 15 T and 4.222 K	> 20	> 20
Residual resistance ratio before reaction after reaction	≥ 70 ≥ 120	≥ 70 ≥ 120
Minimum unit length	100 m	350 m
Interstrand resistance	-	50 ± 15 μΩ