LHC long term upgrade plans
and
the CERN accelerator R&D programs

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CERN

Content

- LHC and the nominal performance
- The long term upgrade plans for the LHC
- Accelerator R&D programs for the upgrades

LHC 2010-2011 run

- 2010-2011 run aim:

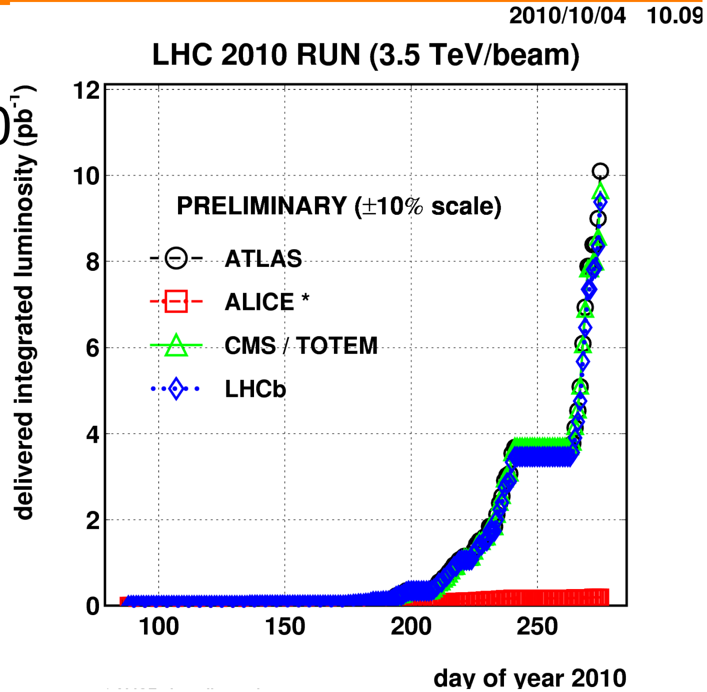
  at 3.5 + 3.5 TeV: get to $L=10^{32}\ cm^{-2}s^{-1}$ in 2010

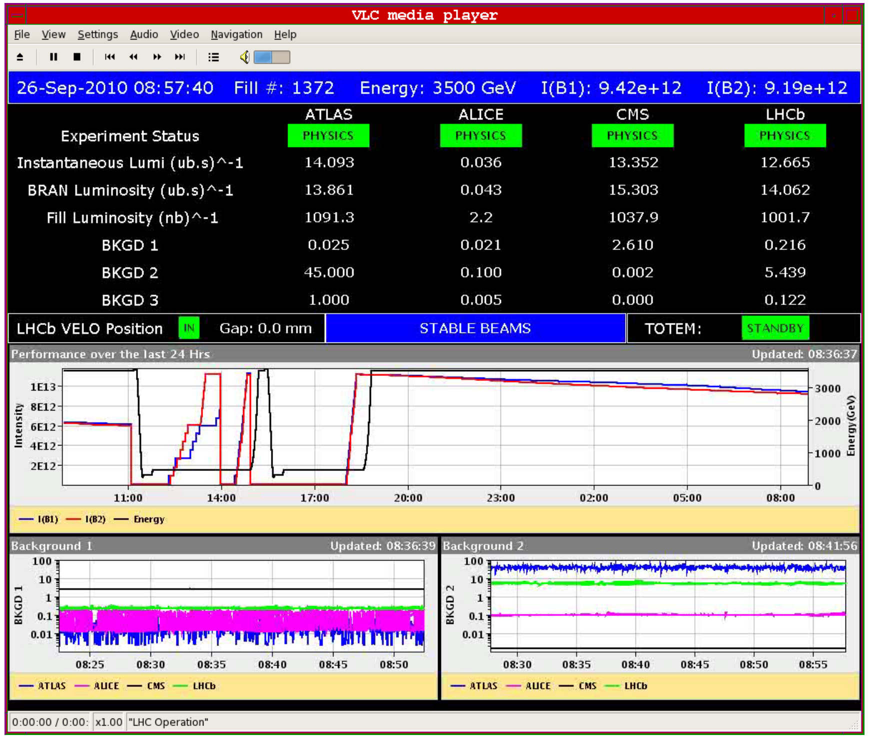
  and make $L_{integral}=1\ fb^{-1}$ in 2011

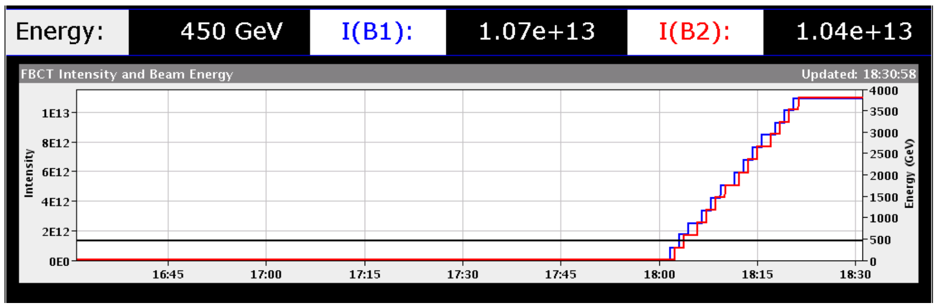
up to today

record $L = 6.8*10^{31} cm^{-2}s^{-1}$

With 200 bunches of $1*10^{11}$ p (trains of 8 b)







For 2010: still 4 weeks to go with p,

then switch to Pb ions

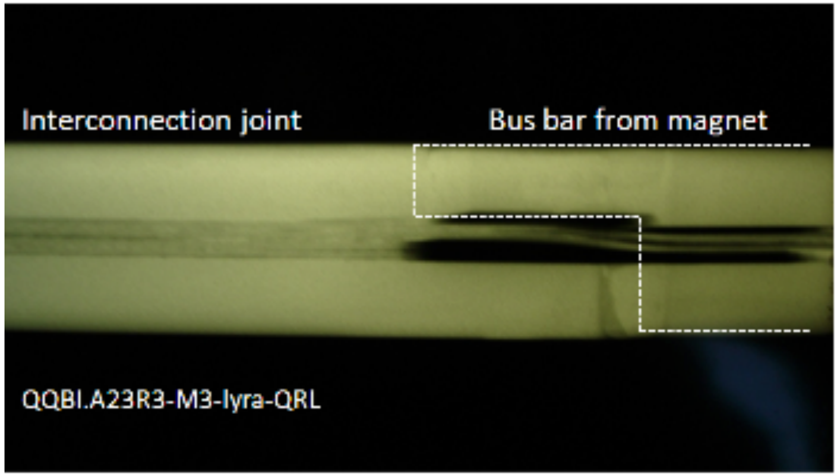
3 reasons why the LHC is not yet at nominal performance

- **Beam energy (1):**

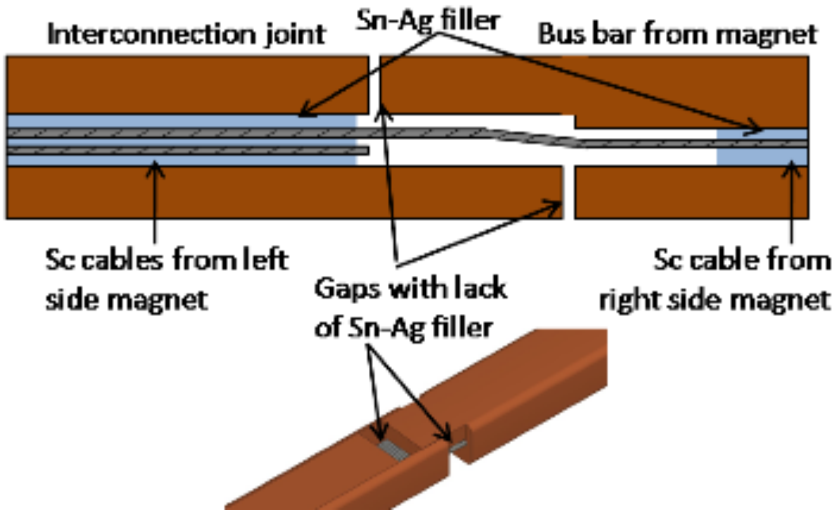
  Design value 7 TeV per beam (I = 12850 A for B = 8.34 T in the dipoles)

  – Running 2010-2011 at 3.5 TeV per beam

  - Limit given by the safe current in the splices in the 13kA busbars between the magnets
  - Bus-bar splices between magnets display voids in the solder which can cause unstabilized lengths of sc cable (known max. of 40 mm in some sectors and 70 mm not excluded in others)



Defective interconnetion-bus bar transition γ-ray picture (left) and scheme (right)



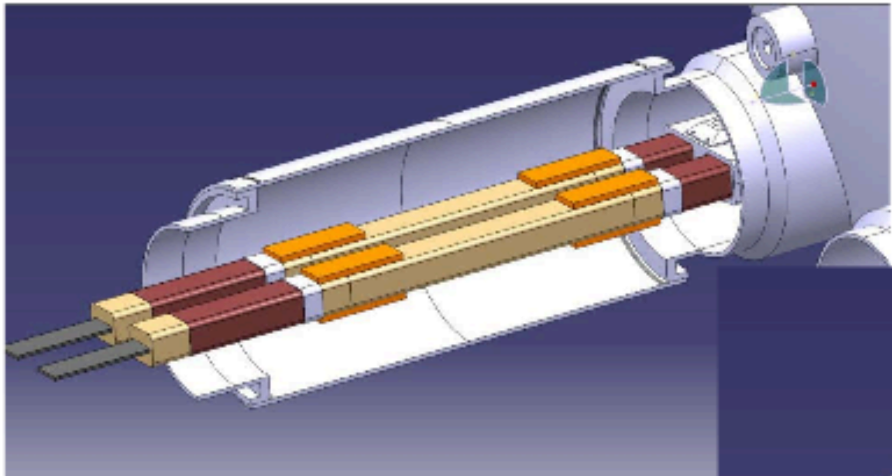
Courtesy: L. Rossi

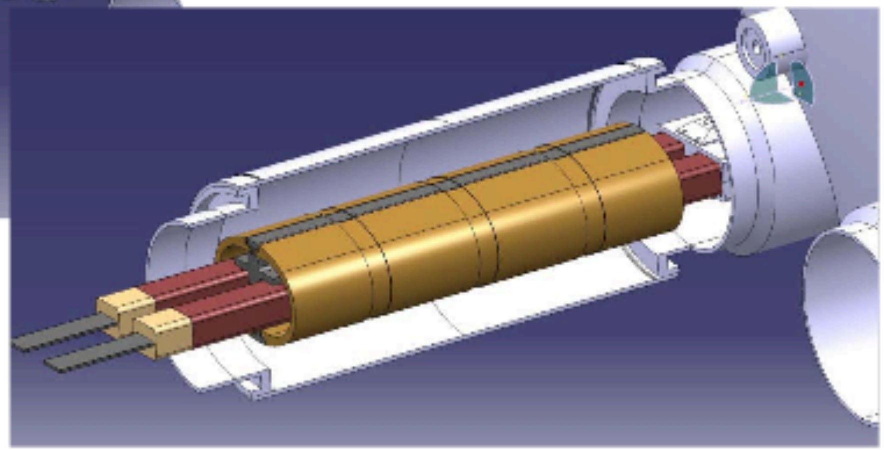
3 reasons why the LHC is not yet at nominal performance

- Splice consolidation in 2012 shutdown.
  - Measure resistance at warm to find the ‘out of tolerance splices’
  - Redo the out of tolerance splices
  - Add redundancy to ALL splices

Making the shunt (reduntant!)

Making a box for lateral restraint and vertical containment)





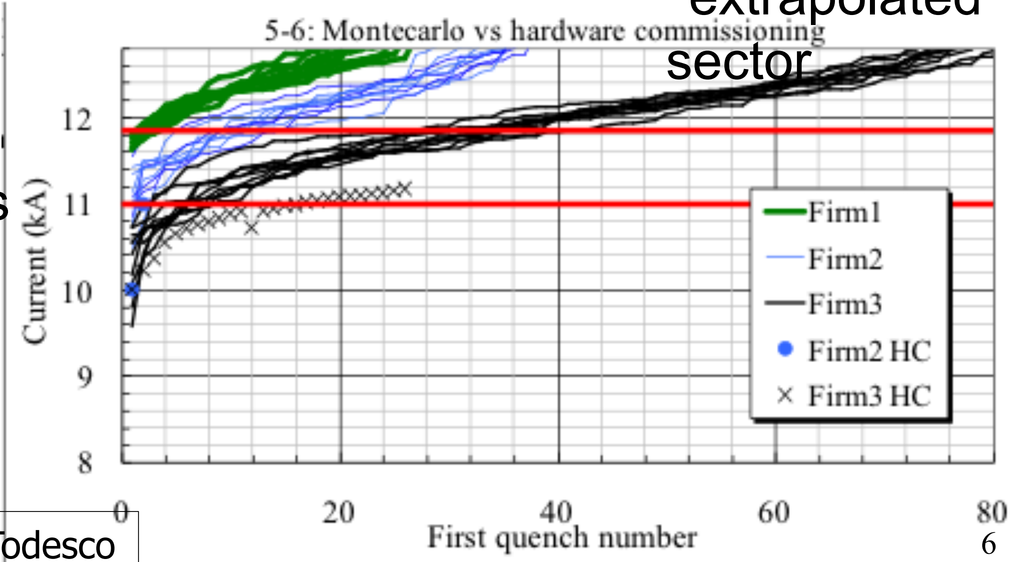
Courtesy: L. Rossi

3 reasons why the LHC is not yet at nominal performance

Beam energy (2) Design value 7 TeV per beam (dipoles: I=12850 A for B=8.34 T)

Dipole training :

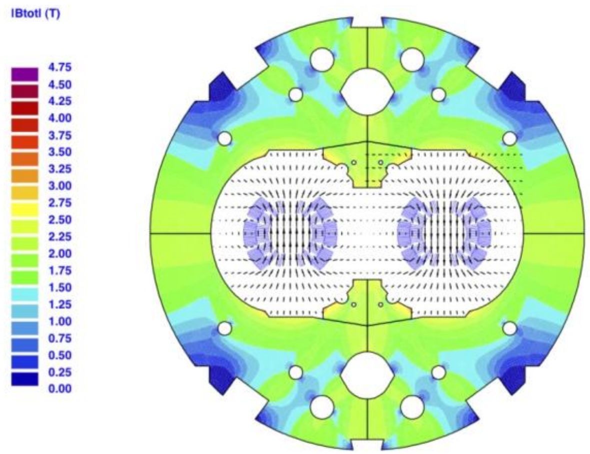
- Expected less than 100 quenches to reach nominal (8.34 T) based on the best prototypes + pre-series dipoles (2000-2002)
- Analysis of data from the tests of series magnets (2005-2007) : ~250 quenches
- Re-analysis (see E. Todesco at Chamonix 2010), of the same test data, points to ~400 quenches
- However HWC data, from one specific extrapolated sector indicates ~800 quenches
- If 4 quenches/day in 2-4 sectors in parallel: 10 quench/day: 40 days of HWC (or 80 ?)
- E=6.5 TeV possible with just a few days of training



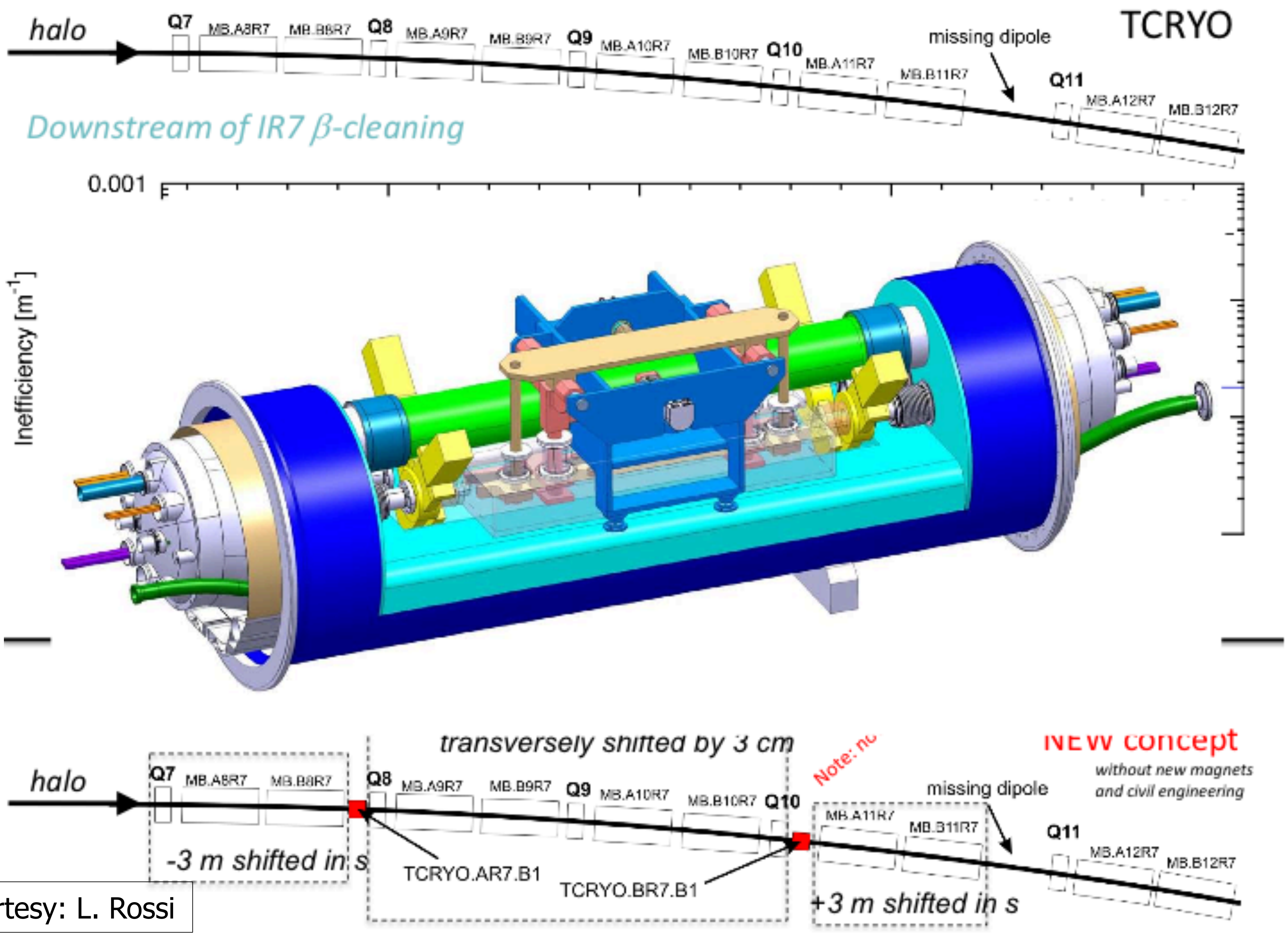
Courtesy: E. Todesco

3 reasons why the LHC is not yet at nominal performance

- **Beam intensity:** nominal 2808 bunches of $1.1*10^{11}$ protons per beam, $L=1*10^{34}$ $cm^{-2}s^{-1}$
  - Collimation limits luminosity to $0.05\text{-}0.2*10^{34}$ $cm^{-2}s^{-1}$
    - Today the so called phase 1 collimation is installed
    - Phase 2 collimation to be installed in 2013 and 2016.
      The scope has changed significantly during the last year: studies also pointed to the need of collimators in the COLD regions (DS).
    - Additional collimators in IP 1, 2, 3, 5, 7
      - 'cold' collimators in IP 3, 7 and 2 (dispersion suppressors)
        in IP7 and 2: make space with 11 m, 11 T dipoles
        (dipoles: CERN-FNAL collaboration)
      - Advanced rotating collimators
        (LARP-SLAC design)
      - IP1 and 5 (collision debris)
      - etc.



3 reasons why the LHC is not yet at nominal performance



Courtesy: L. Rossi

LHC upgrades

2 projects:

10 years time scale: HL-LHC : High Luminosity LHC

Co-ordinator L. Rossi

Aim: deliver by 2030 3000 fb^{-1} of integrated luminosity

aim for L_{max} 2 - $5*10^{34}$ $cm^{-2}s^{-1}$

20+ years time scale: HE-LHC : High Energy LHC

a 17 + 17 TeV collider

exploratory study started in summer 2010 (chairman S. Myers)

EuCARD-AccNet workshop on HE-LHC in Malta 14-16 Oct. 2010

(http://indico.cern.ch/conferenceDisplay.py?confId=97971)

Luminosity...

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

Constants — Beam intensity — Beam focusing

Nominal Luminosity
$1 \cdot 10^{34}$ cm^{-2}s^{-1}

- Beam intensity
  - N_b: number of particle per bunch [1.15 ×10^{11}]
  - n_b: number of bunches [2808]
- Beam focusing
  - β^*: beta function in the IP (transverse size of the beam) [55 cm]
  - F: geometrical loss reduction factor [0.86]

LHC low-β triplet

Position	L* = 23 m
Quad gradient	205 T/m
Coil aperture	70 mm
β*, ℒ	55 cm, 10^{34}cm^{-2}s^{-1}
Dissipated power	180 W @ 1.9 K

The experiments are though only interested in

Integrated Luminosity

Peak luminosity is posing problems when very high (pileup)

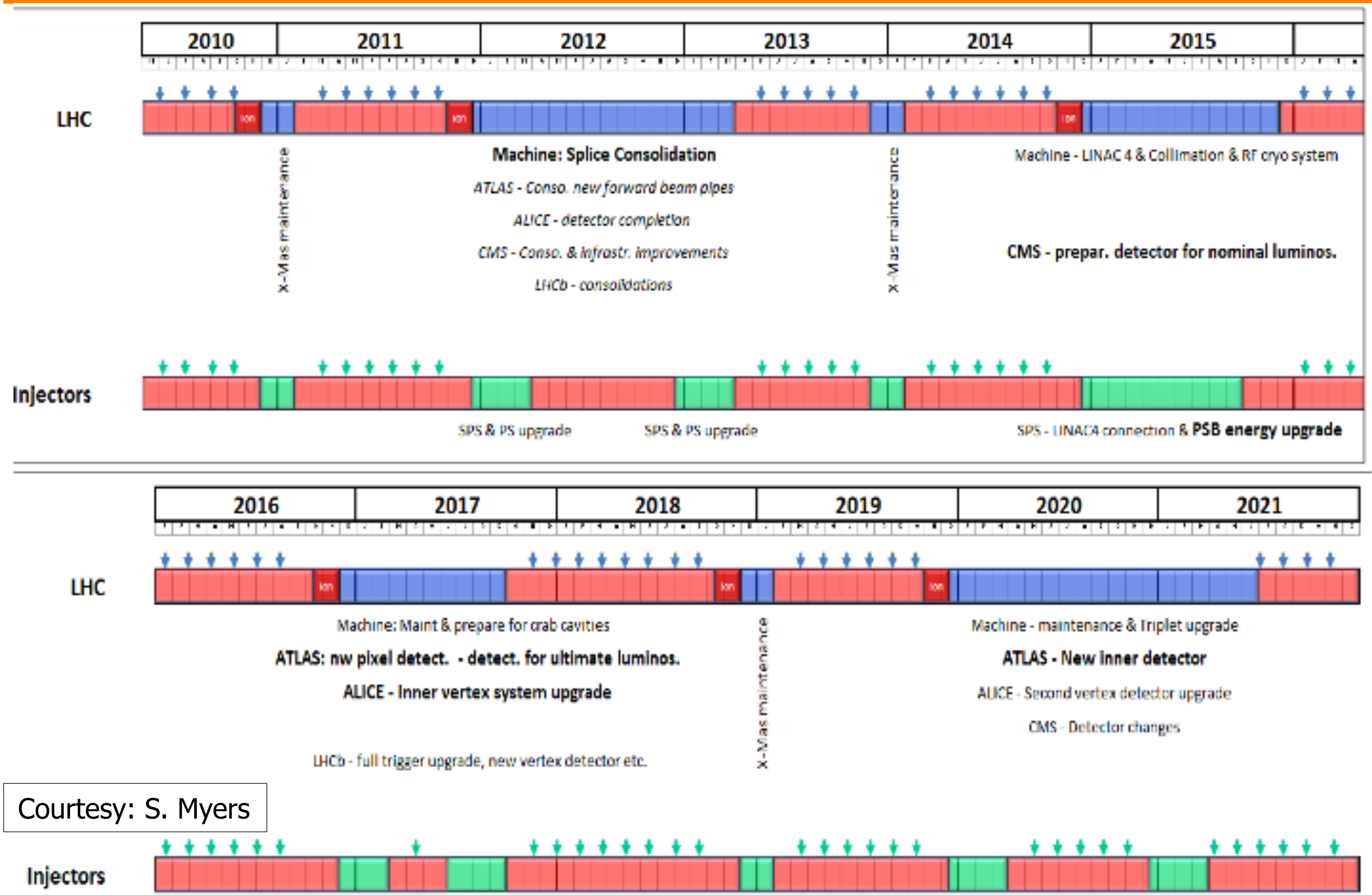
Overall strategy beyond 2016 (dates indicative)

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	etc.
														Increase Beam Energy to 16.5 TeV					
				New interaction region ($\beta^*$to 0.2m, luminosity leveling)															
Increase beam brightness																			
Ultimate				**HL-LHC**										**HE-LHC**					
2.3 10^{34}				**5 10^{34}**										**2 10^{34}**					
≤ 100 fb^{-1}/yr				**≤ 200 fb^{-1}/yr**										**≤ 100 fb^{-1}/yr**					

Courtesy: R. Bailey

(HL-)LHC consolidation and upgrade schedule



Courtesy: S. Myers

What could be needed for L= $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$? (1)

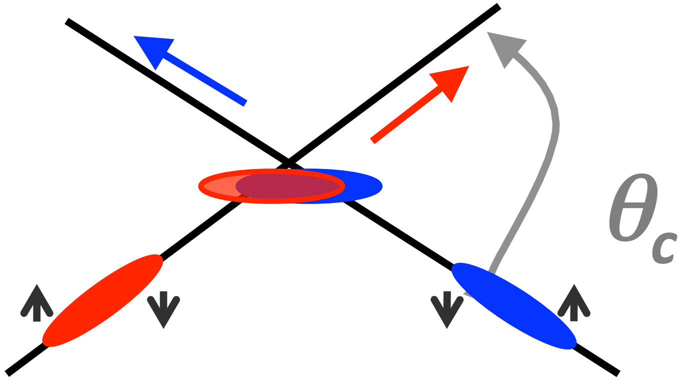
- High Gradient/Large Aperture insertion Quadupole magnets
  - Possibly: l = 8 m, G= 175 T/m, A=120 mm, ($B_{peak-ss}$ =13 T)
  - $\beta^* \leq 22$ cm are possible with a factor ~2.5 in luminosity by itself,
  - Necessarily coupled with a mechanism to compensate the geometrical reduction .

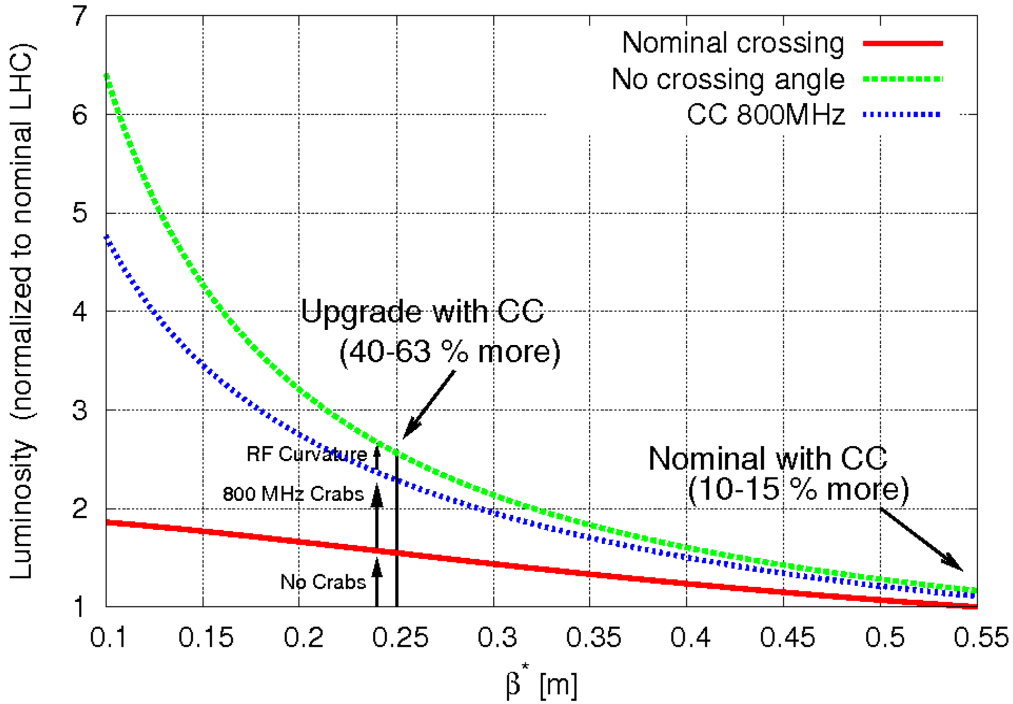
- Crab Cavities:
  - best candidate for exploiting small β^* (for $\beta^*_{nominal}$ only +15%).
  - However today Crab Cavities are not validated for LHC , not even conceptually: the issue of machine protection should be addressed with priority.
  - Global Scheme: 1 cavity in IP4, Proof on LHC, good for 1 X-ing.
  - Local scheme; 1 cavity per IP side. Maybe local doglegs needed.

What could be needed for L= $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$? (2)

- Separation dipole D1: 8 T , 3.5 m long , 150 mm aperture
- SC links to replace at the surface electronic equipment today in the tunnel and exposed to high radiation (Power Converters & DFBs)
- New Cryoplants in IP1 & IP5
- Improve some correctors
- Commissioning the lattice sextupoles @ 600-650 A
- New MQT corrector scheme using existing spare 600 A bus bars
- Review Matching section (MS)
- Change of New Q5/Q4 (today 2x70 mm : larger aperture!), with new stronger corrector orbit, displacements of few magnets
- Larger aperture separation magnet D2
- Cryo-plant for RF in point 4 : 5-7 kW @ 4.5 K
- For extra collimators: l = 11 m, B= 11 T Dispersion Supressor dipoles

Crab Cavities





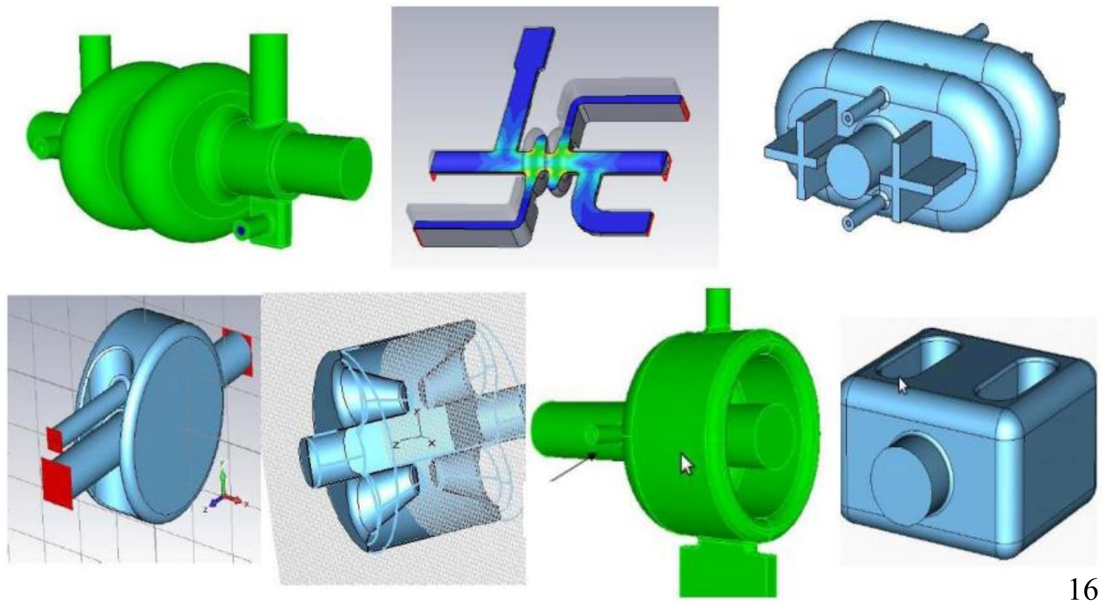
- When colliding under an collision angle, if the beams are not 'head on' there is a geometrical reduction factor in the luminosity.
- Cure: turn the bunches with a transversely accelerating RF field
- First successfully used at KEK B-factory BELLE

Crab Cavities

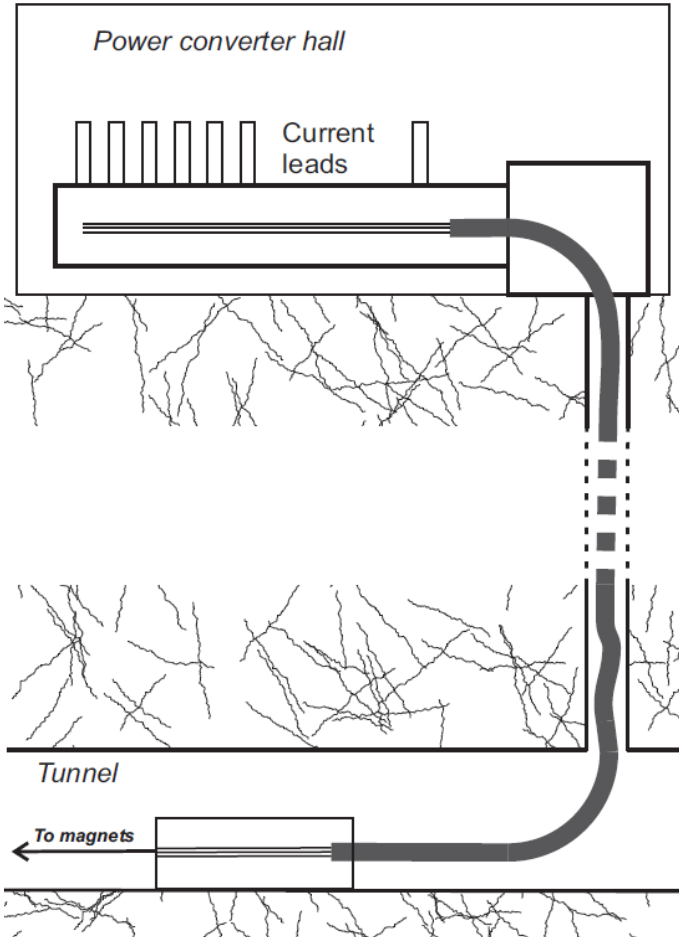
• Elliptical 800 MHz is not far from being designed. Requires a 400 mm beam-beam distance
• 400 MHz small cavity under conceptual study, they can (?) fit in 194 mm beam-beam. Required for final solution

Work done by the LARP collaboration, EuCARD and at CERN

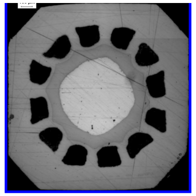
Ref. : F. Zimmermann, Ed Ciapala



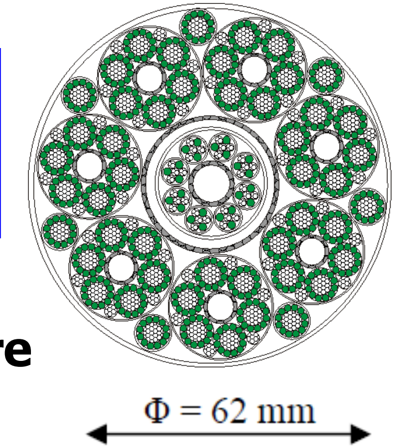
SC link to remove Power Convertors from High Rad zone

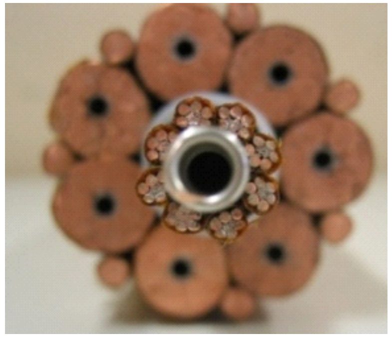


Courtesy: A. Ballerino



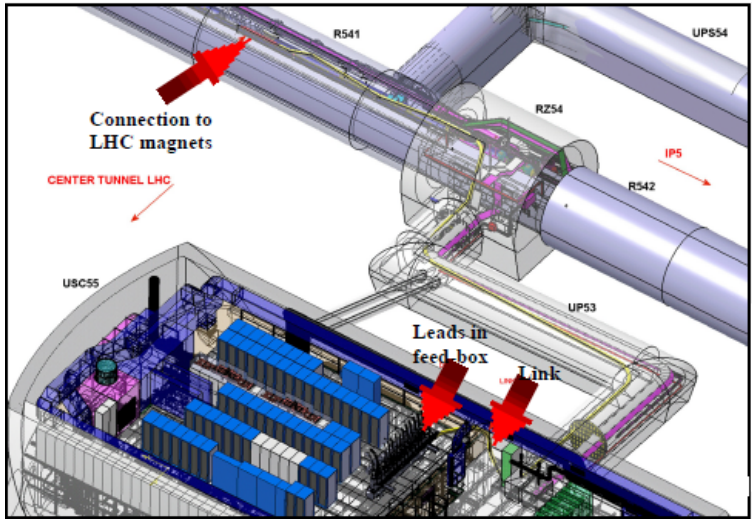
1.1 mm MgB_2 wire





Vertical link H = 100 m

Semi-horizontal link (100-700 m)



HFM options for an LHC luminosity upgrade

An LHC luminosity upgrade envisages in ~ 10 years:

- Inner Triplet quadrupoles
  Aperture ∅ ~ 120 mm, G ~ 175 T/m , L = 8 m

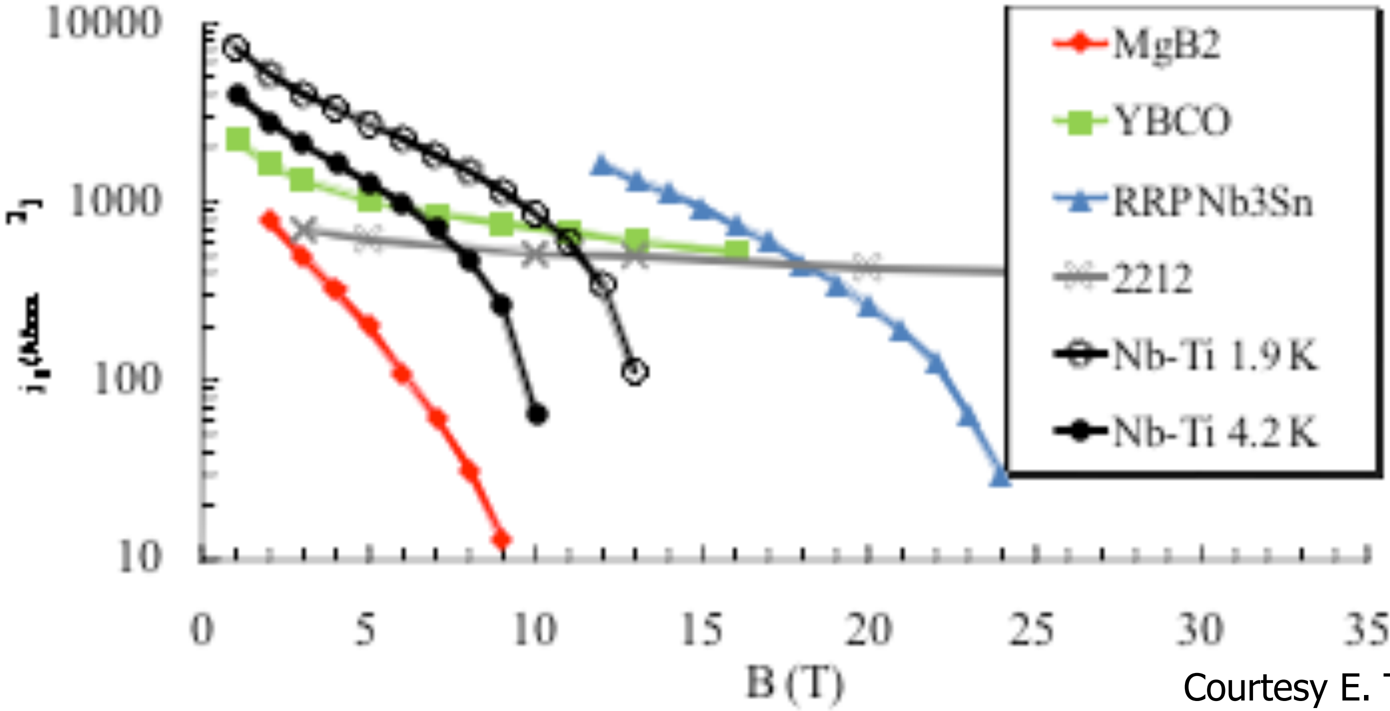
- Dispersion Suppressor twin aperture dipoles
  Aperture ∅ = 60 mm, B = 11 T, L = 11 m

- D1 separation dipole
  Aperture ∅ = 150 mm, B = 8 T, L = 3.5 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 conductors



Courtesy E. Todesco

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)   (~2018)
- Twin aperture Dispersion Suppressor dipole (∅ = 60 mm, B = 11 T, L = 10.8 m) (~2018)
- Separation Dipole D1 (∅ = 180 mm, B = 10 T, L = 5 m) (~2018)

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
  - CERN program: model 2012-2013
- Models for DS dipole: collaboration CERN-FNAL
- Models for D1 dipole: CERN and/or collaboration

Third step (2014 – 2016):

- Inner triplet quadrupole prototype (LARP)
- DS twin aperture dipole prototype (CERN-FNAL)
- 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

Now testing (HQ): Aperture ∅ = 120 mm, G = 190 T/m, L = 1 m

Conductors used:

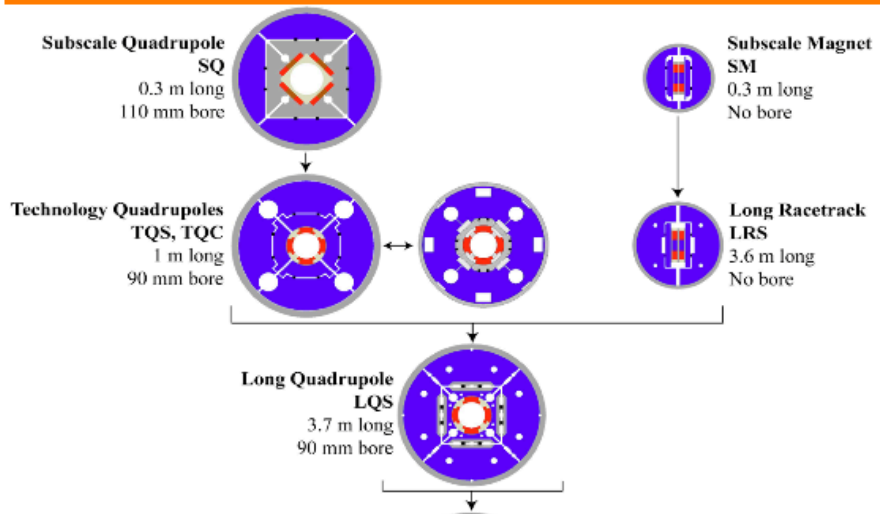
OST-RRP-54/61 and OST-RRP-108/127

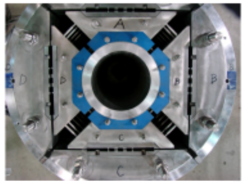
Cable 27 strands, ∅ = 0.7 mm , sub-elements ∅ = 50 μm

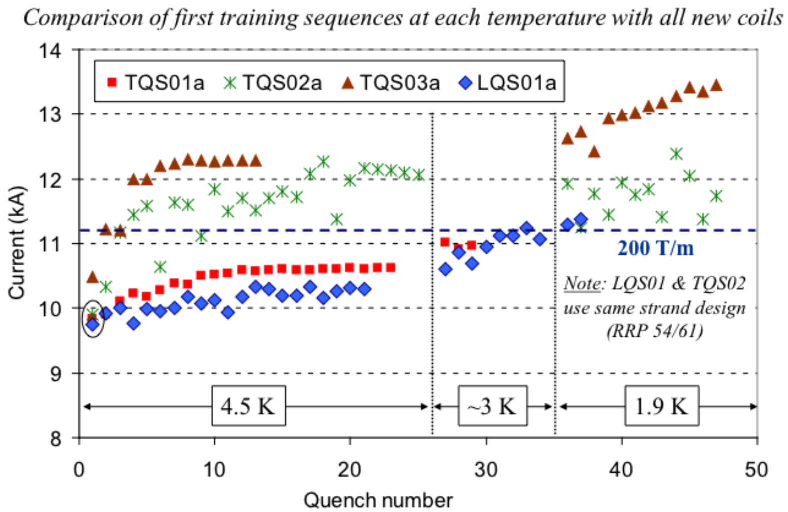
Open issues:

- 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:

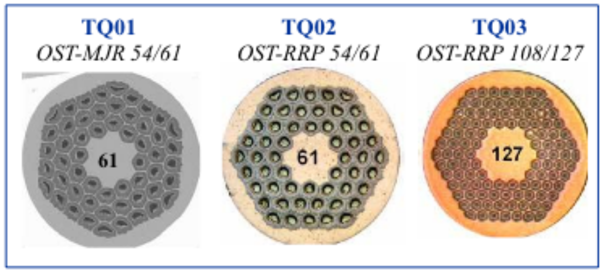
- TQ: 1 m, 220 T/m, 90 mm aperture
- LQ: 3.8 m, 200 T/m, 90 mm aperture

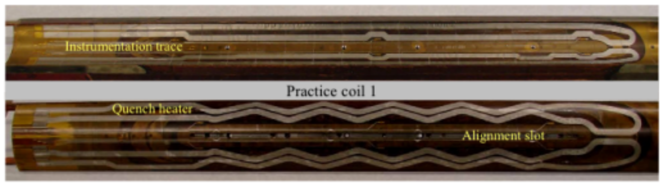
To be tested in May 2010:

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

Plan:

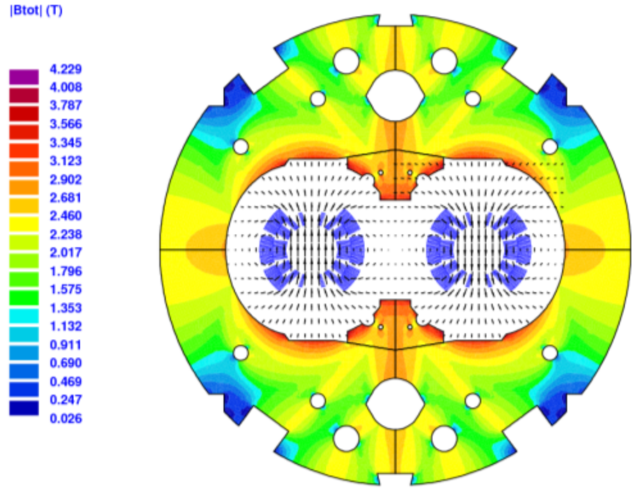
- 4 m prototypes for LHC





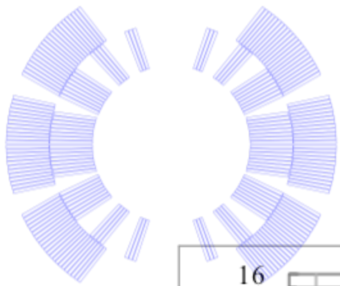
HFM R&D for an LHC luminosity upgrade: DS dipole

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



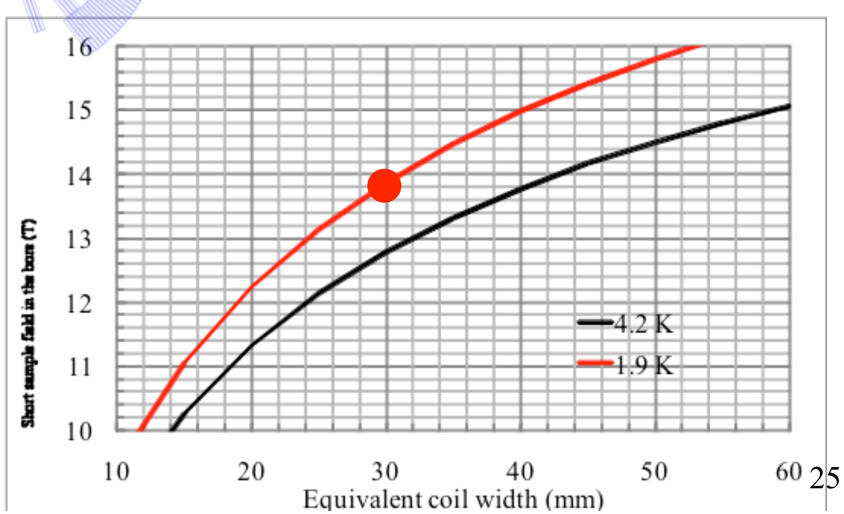
First estimates:

- 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 ?



EuCARD WP7 High Field Magnets

EuCARD WP7 on High Field Magnets,

13 partner collaboration,

CEA, CERN, CNRS-Grenoble, Columbus, BHTS, INFN-LASA, KIT, PWR, SOTON, STFC-D, TUT, UNIGE

5 R&D tasks:

2. Support studies, thermal studies and insulation radiation hardness
3. High field model: 13 T, 100 mm bore (Nb_3Sn)
4. Very high field dipole insert (in HTS, up to ΔB=6 T)
5. High Tc superconducting link (powering links for the LHC
6. Short period helical superconducting undulator (ILC e^+ source)

Duration: April 2009 – April 2013

Budget 6.4 M€ total, 2.0 M€ EC contribution

EuCARD HFMs: Fresca2 dipole

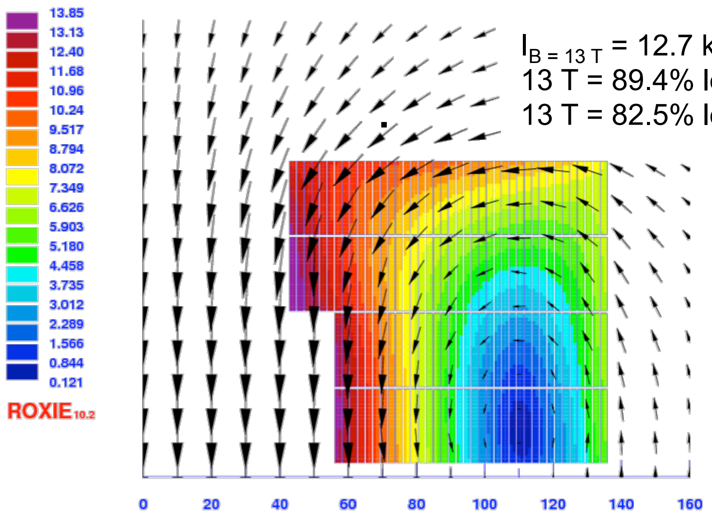
EuCARD WP7 on High Field Magnets, 13 partners, 6 tasks: 13 T dipole, HTS insert, HTS link, helical undulator; April 2009 – April 2013

Dipole for cable test station aperture 100 mm, 13 T

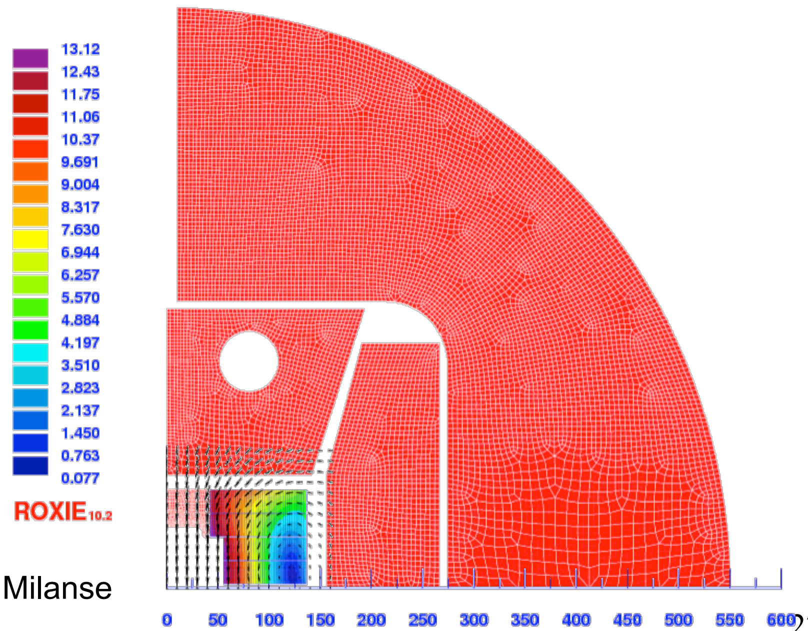
- Nb_3Sn 1 mm strand, 40 strand cable (RRP or PIT)
- Preparation: Short Model Coil: test in August
- Design: 9/2009-12/2010 ; coil winding start 11/2011;

  first assembly begin 2013;

  first cold test March 2013



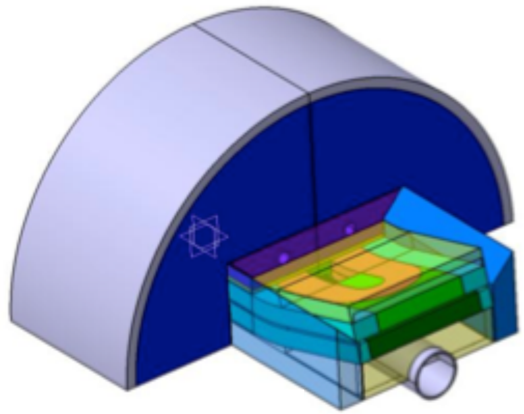
$I_{B = 13\,T}$ = 12.7 kA
13 T = 89.4% load line at 4.2 K
13 T = 82.5% load line at 1.9 K



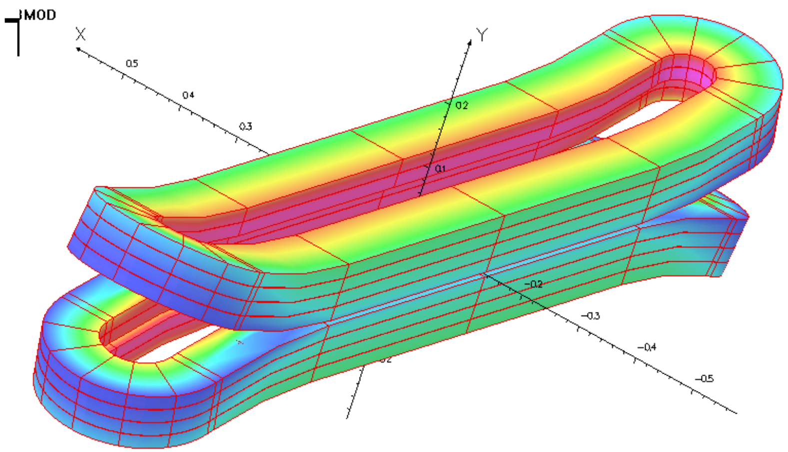
A. Milanse

EuCARD HFMs: Fresca2 dipole

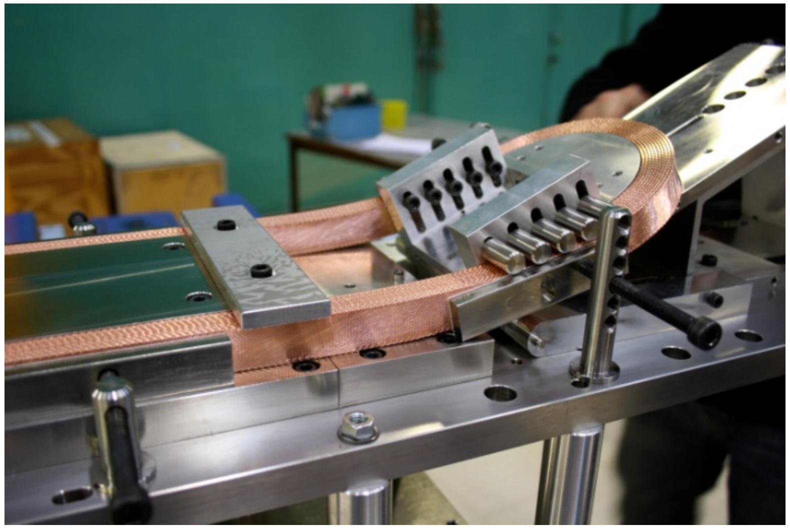
- Magnetic 2D design done, 3D in progress
  - Block coil 156 turns, “flared ends”
  - Conductor 1 mm strand, 40 strands
- Mechanical 2D design nearly done, 3D started
  - “shell-bladder-and–keys” (LBNL style)
- Strand procurement started
- Cable design done, manufacturing tests in progress
- Winding to start end 2011



P. Manil

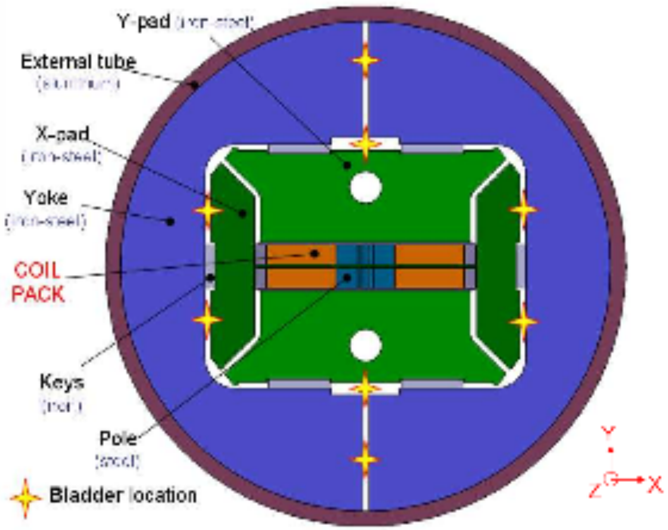


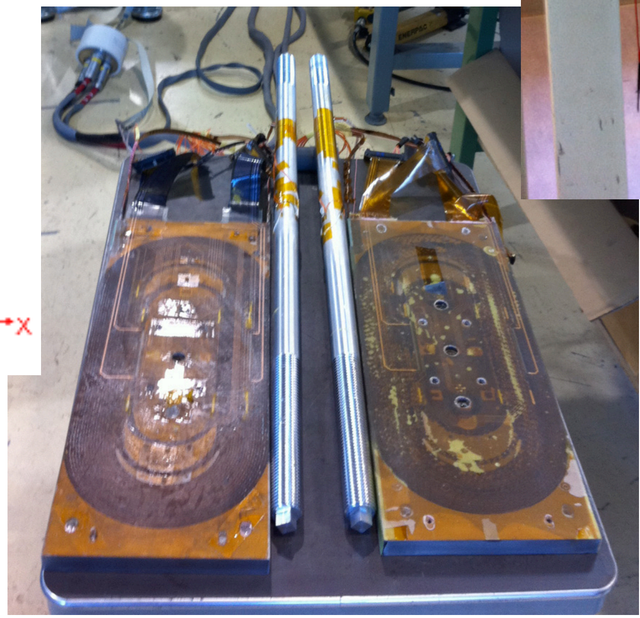
A. Milanse

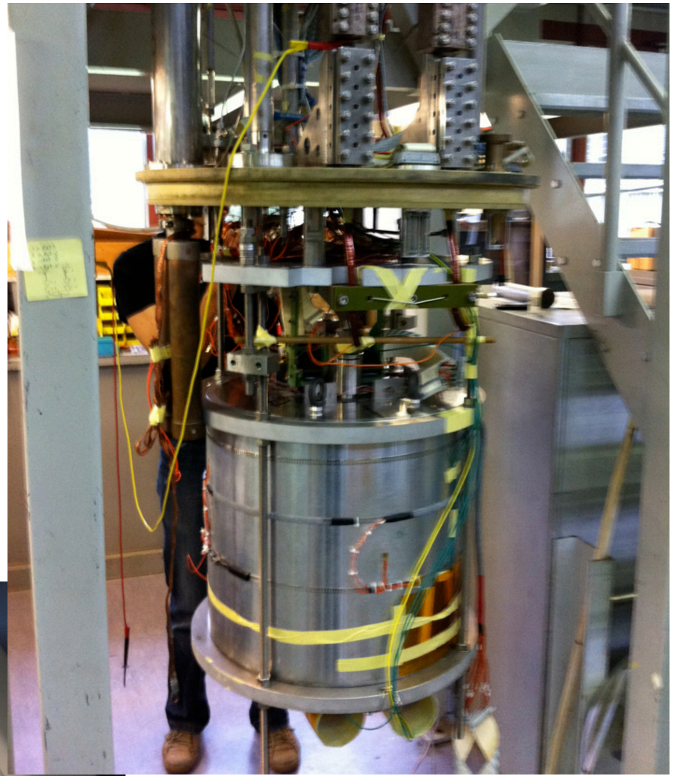


EuCARD HFMs: preparation for Fresca2: SMC

- In preparation: technology test with a "Short Model Coil" (CEA, CERN, RAL, LBNL)
- First test started last week at CERN
- 4 layer flat racetrack coil 21 turns, Nb_3Sn 1.25 mm strand, 14 strand cable.





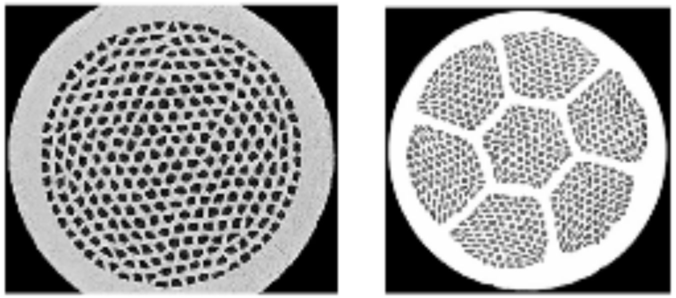


Very high field dipole insert

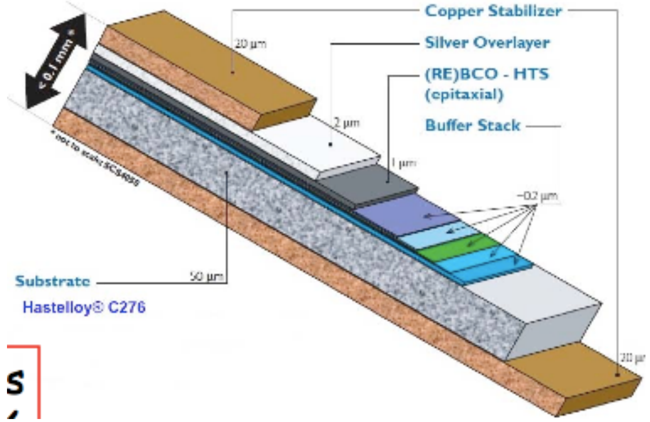
- Try to approach 20 T Using an HTS insert in the 13 T dipole.

- Conductor possibilities:

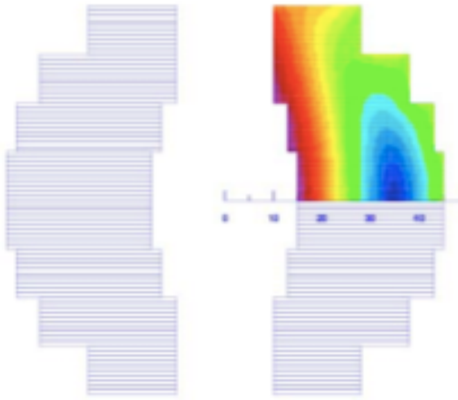
BI 2212 round wire

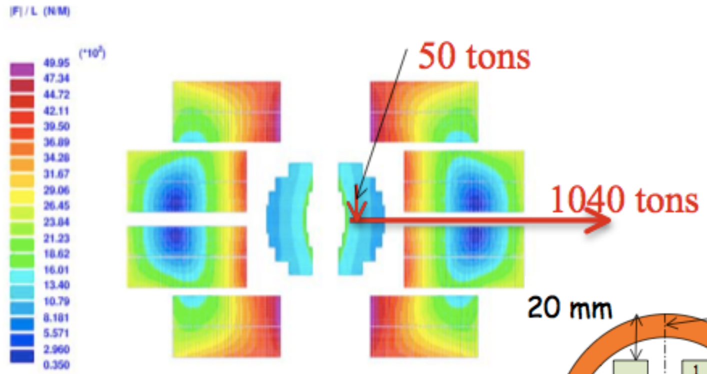


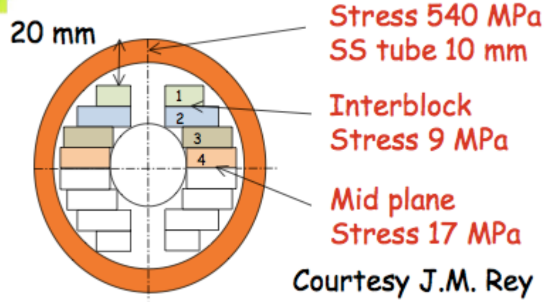
YBaCuO coated conductor (tape)



Very high field dipole insert







Courtesy J.M. Rey

- Challenges:
  - Ic (critical current density) at 20 T :
    - Needed: 300 A/mm^2 average in the coil
    - Need long lengths (few 100 m)
  - Cables of ~15 kA (wire or tape 200 A – 400 A)
  - Force retaining structure, fixing inside dipole
  - Quench protection
  - Interference with the dipole

Short period helical undulator

Short period undulator for the ILC positron source

Period 11.5 mm , field >1 T

Aim :

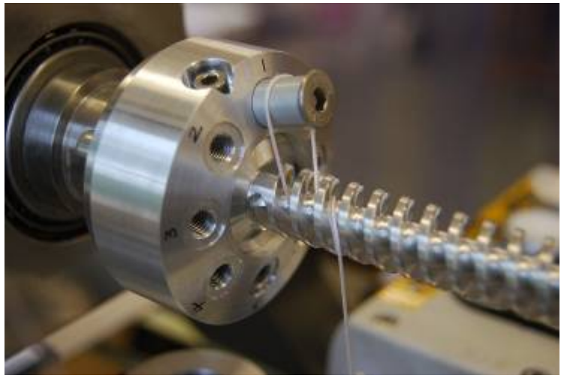
- fabricate and test a short helical undulator prototype using Nb3Sn wire.
- With: 11.5 mm period and winding bore of 6.35 mm.
- Nb_3Sn usage for high current density and large thermal margin to go higher than the 1.15 T achieved for Nb-Ti

Primary challenges:

- Nb_3Sn insulation system (compatibility with heat treatment at 650C)
- Thin insulation (high current density).

Short period helical undulator

- Electromagnetic design done
  - Cu beam pipe
  - Steel helix
  - 27 turns of 0.5 mm strand
  - Field on coil ≅4T
- Conductor selected
- Conductor characterization in progress
- Insulation 0.075 mm braided glass fibre
- Winding tests in progress
- Reaction and impregnation tests soon to follow.



0.5 mm
27 wires at 658 A
855 A (76 %)

Radiation resistance

- The radiation resistance of the Nb_3Sn magnets has to be fully proven
- In the EUCARD program we have a task of the High Field Magnets work package dedicated to these issues
  - Radiation tests on Nb_3Sn conductor carried out in Vienna, Russia [L. Oberli, R. Fluckiger, et al.]
  - Radiation tests on Nb_3Sn insulation carried out in Poland [J. Polinski, R. Fluckiger, et al.]
  - Possible synergy with LARP
- The validation of the radiation resistance of all material used in LARP Nb_3Sn magnet should be assessed as soon as possible to avoid surprises and delays
  - If a material has to be replaced this can have an impact on magnet design and performance
  - This can considerably delay the project
  - Time is a relevant variable … our goal is integrated luminosity
  - For instance: e-glass not acceptable (large remnant radioactivity), s-glass ok

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 (10 % performance increase is not negligible)
- In the sub-element diameter of 50 μm small enough ?

We do not yet know what the present 0.6 – 1.0 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 (LARP) at CERN (ongoing)
  - On HQ (LARP) 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:

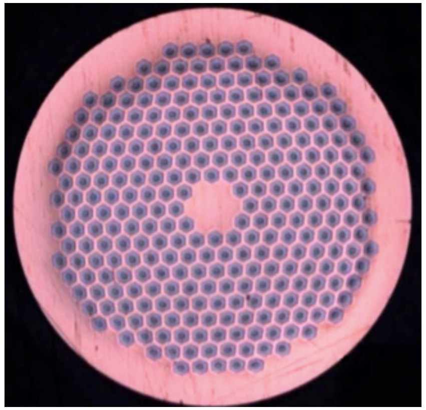
- R&D on cable inter-strand resistance control, 2 options
  - Cored cable
  - Coated strands

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:

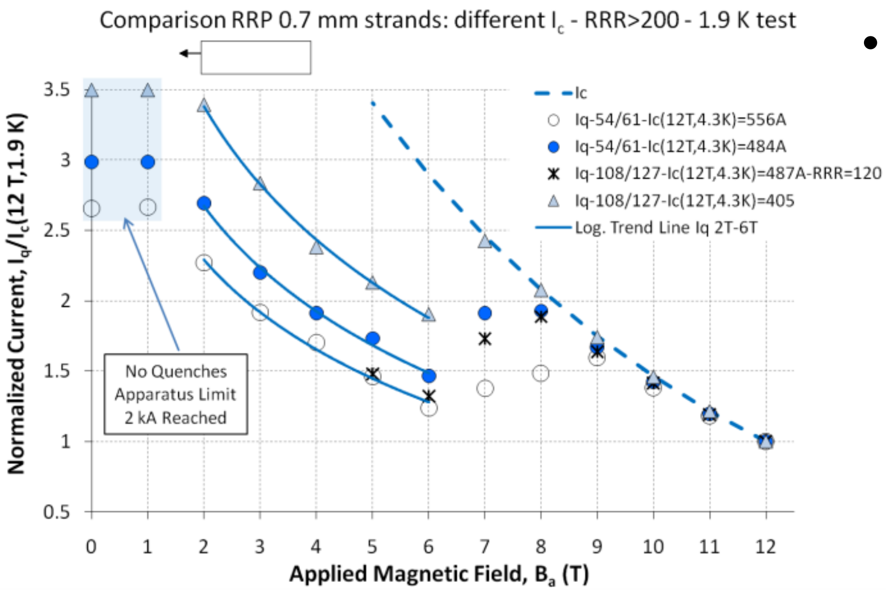
- R&D contracts on strand with smaller sub-elements (towards 20 μm)

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, $(Nb\text{-}Ta)_3Sn$

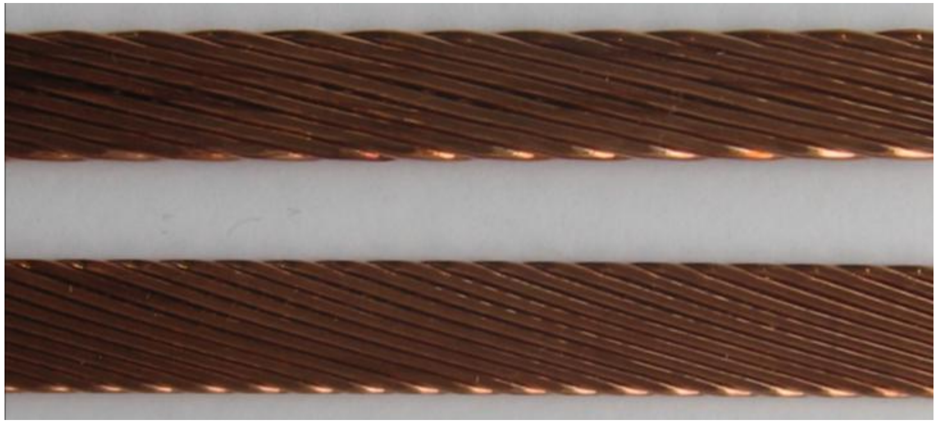


Courtesy L. Bottura, B. Bordini

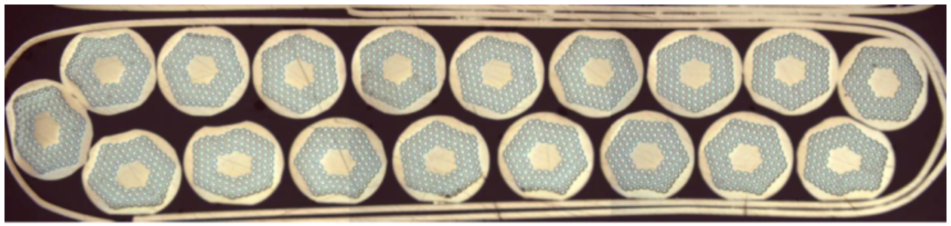
- An improved understanding of the thermo-magnetic stability has led to the decision to:
  - Reduce strand diameter (1 mm)
  - Limit strand critical current density (1250 A/mm^2 at 15 T and 4.2 K)
  - Maintain a strict requirement on RRR and filament diameter

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)



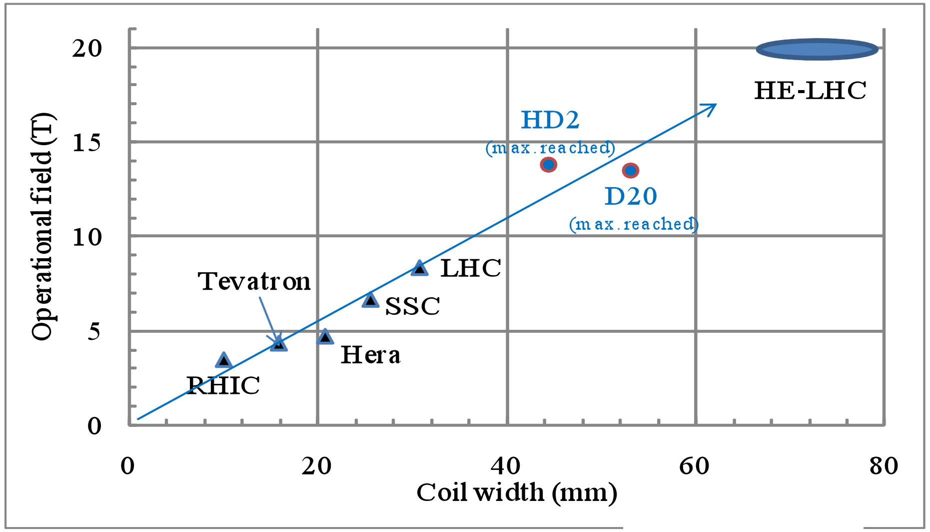
- SMC-class cables
  - Cu dummies
  - 14 strands, 1.25 mm
    - PIT (EAS), IT (Alstom)
  - 18 strands, 1 mm
    - IT (OST-RRP)



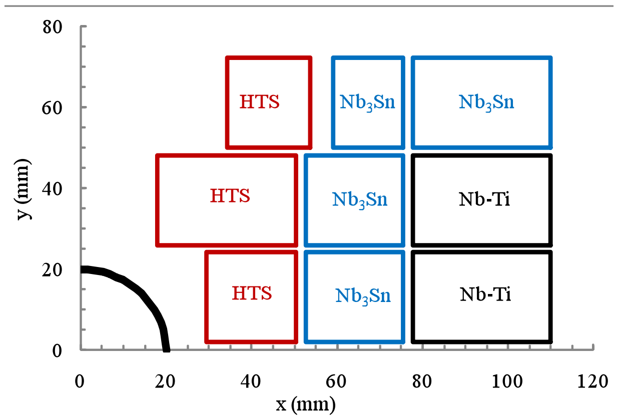
- Fresca2-class cables
  - Cu dummies
  - 40 strands, 1 mm
    - PIT (EAS)

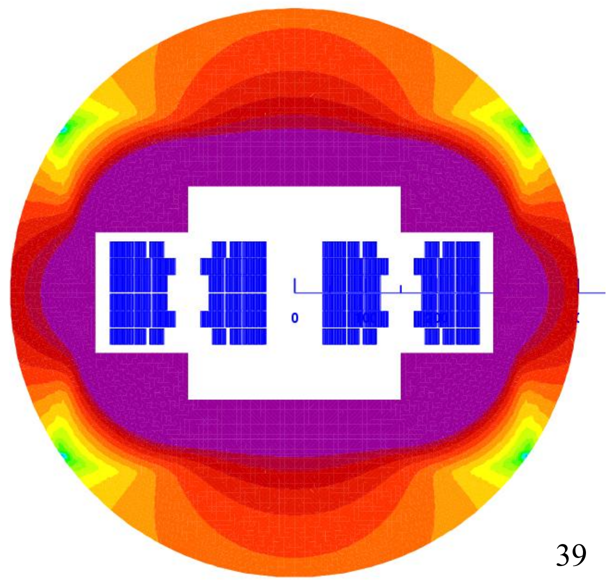
Magnets for HE-LHC

- For a 17 + 17 TeV collider
  - Need 20 T dipoles
- study to start soon
  - HTS-Nb_3Sn-Nb-Ti nested coil
- EuCARD2 HFM proposal being discussed
  - 20 T design study
  - Construct 80% demonstrator
  - 20 T conductor development



E. Todesco





Summary

- CERN has set out an LHC consolidation and upgrade strategy
  - Working groups on HL-LHC (L. Rossi)
  - New initiative on HE-LHC (S. Myers)

- For medium and short term applications CERN has engaged in a HFM development program together in several world wide collaborations
  - HL-LHC large aperture quadrupoles (LARP)
  - HL-LHC 11 T dipoles (FNAL)
  - HE-LHC 20 T dipoles
  - HTS current links
  - ...

- There will be more opportunities in the near future to join into this work