Accelerator Magnet R&D in the Perspective of a LHeC and a HE-LHC

Synergy or Competition ?

Circles in a circle
V. Kandinsky, 1923
Philadelphia Museum of Art

Presented by L. Bottura

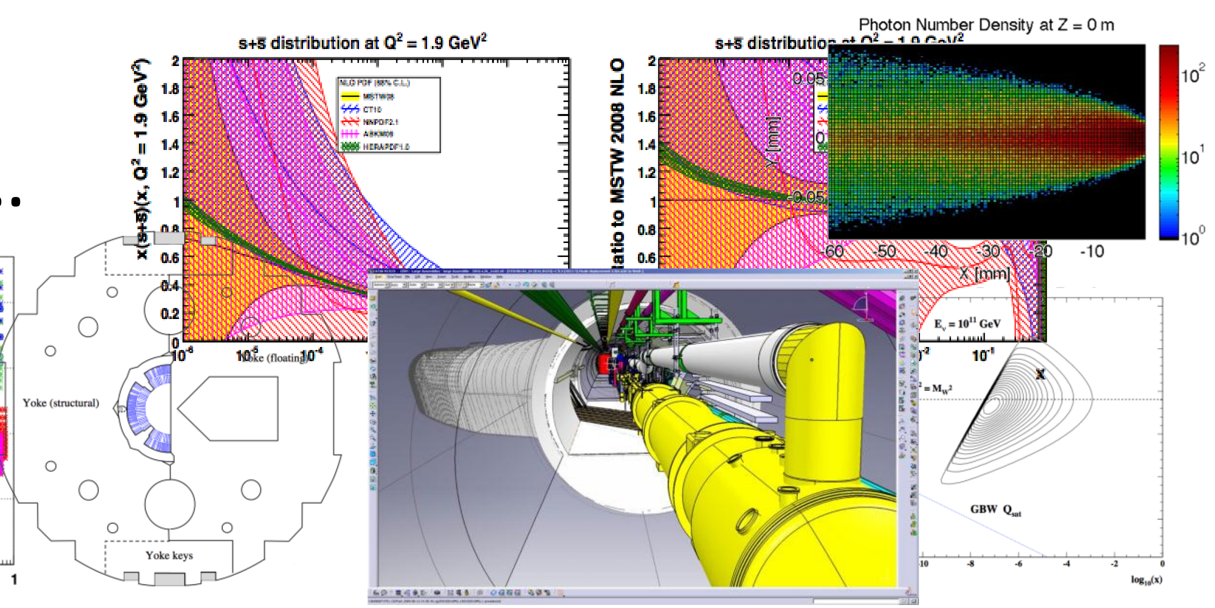
LHC Performance Workshop
Chamonix 2012
10 February, 2012

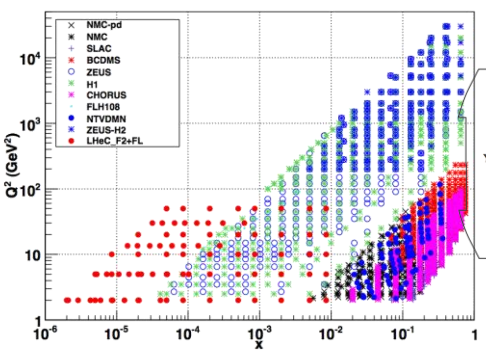
Outline

- A magnet view of LHeC and HE-LHC
  - Scope
  - Challenges
- The CERN magnet R&D programs
- Summary and perspective

LHeC scope

- *“[…] a new electron-hadron collider, the LHeC, in which electrons […] collide with LHC protons”*. (A Large Hadron Electron Collider at CERN, DRAFT 1.0, LHeC-Note-2011-001 GEN)
- e-beam injected at 10 GeV, accelerated to 60 GeV (approximately ½ of LEP), up to possibly 140 GeV
- A piece of art…

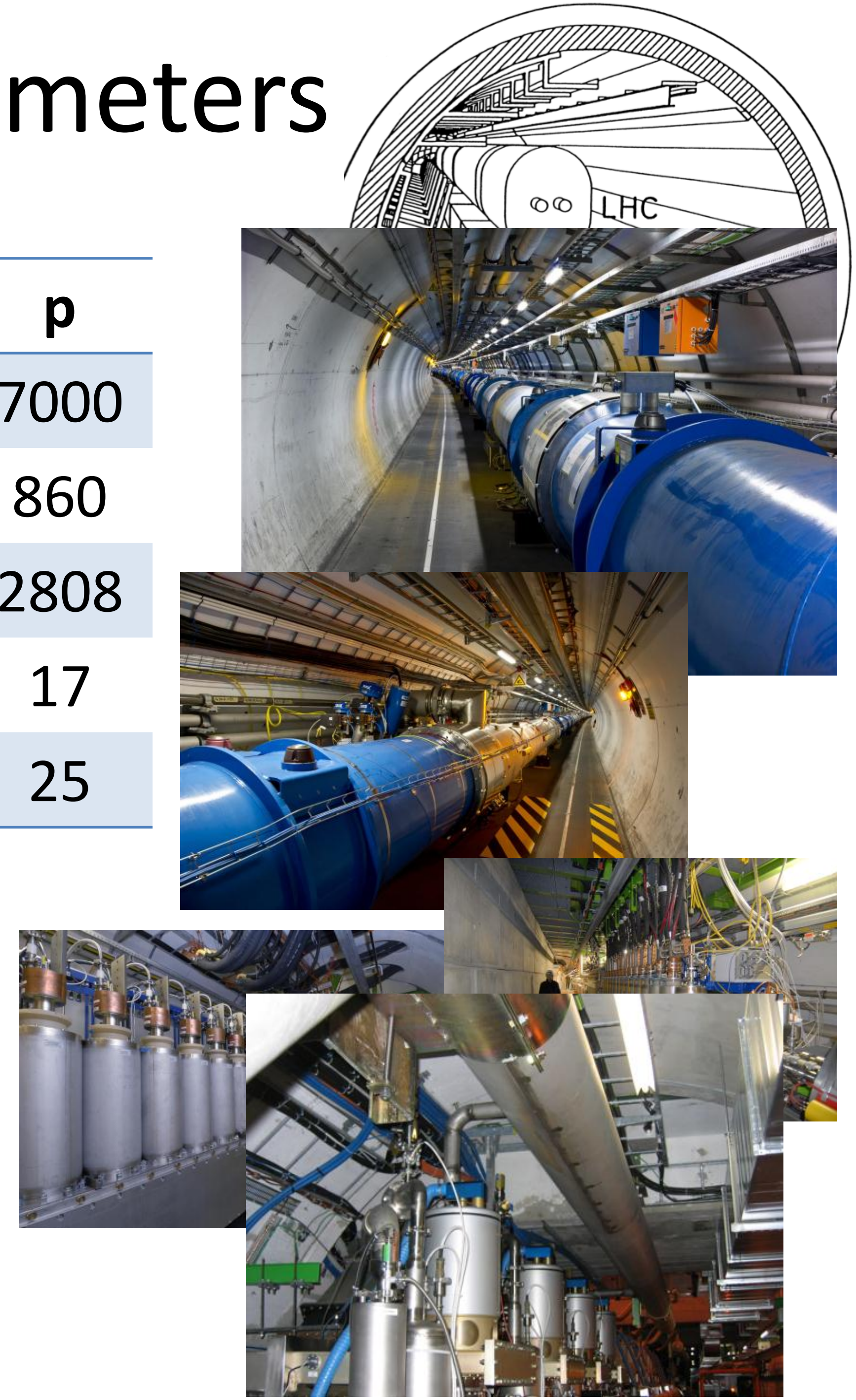




Main parameters

		e	p
Beam energy	GeV	60	7000
Total beam current	mA	100	860
Number of bunches		2808	2808
Particles/bunch	10^{10}	2.0	17
Bunch spacing	ns	25	25

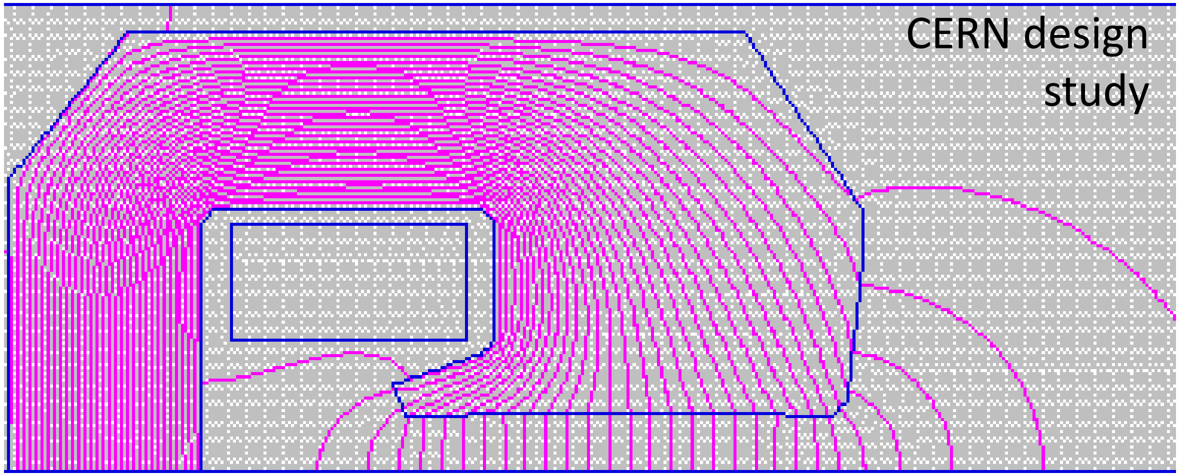
- A couple of hiccups:
  - 2 orders of magnitude difference in p/q – optics !
  - LHC is already in the tunnel, and takes lots of space – integration !

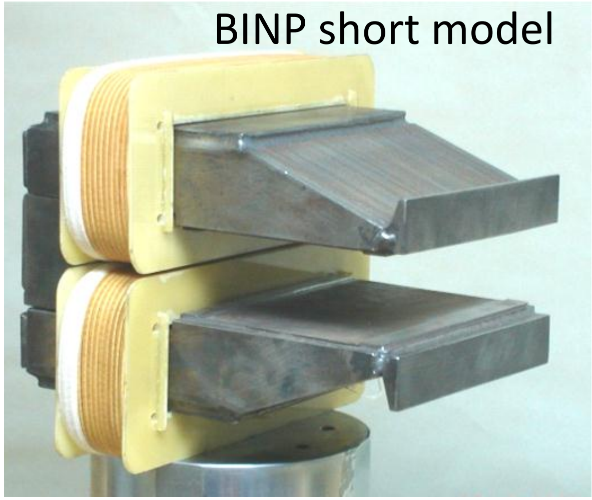


LHeC magnet challenges

- A large number (4000 (RR) to 5000 (LR)) of precise, *low-field, low-mass, low-cost* magnets for the e^- accelerator
- Drive-thru and nested IR's, with space for traversing beams and appreciable synchrotron radiation heat loads
- No major challenges for injection and dump (technical solutions available). Note, however, the dump power in the LR option (50 MW)
- *Integration in the existing complex*
- *Co-activity of installation with a running accelerator and its upgrade plans*

Low field dipoles





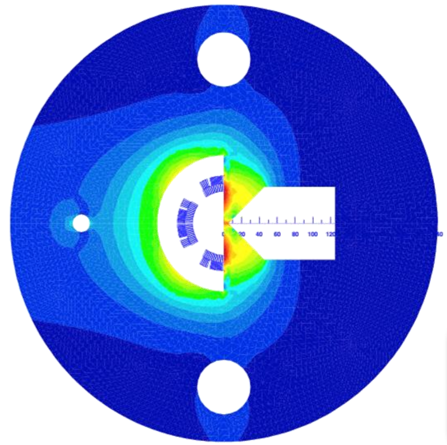
Number of magnets	(-)	3080
Free aperture	(mm x mm)	90(H)x40(V)
Magnetic length	(mm)	5350
Injection field	(Gauss)	**127**
Flat-top field	(Gauss)	763
Good field region	(mm x mm)	±10(H)x6(V)
Field quality	(-)	$\pm 2 \cdot 10^{-4}$
Injection field reproducibility	(Gauss)	**±0.1**

Compact and lightweight to fit in the existing tunnel, yet mechanically stable

Field homogeneity in the whole range of operation ?
Field reproducibility at injection ?

IR magnets

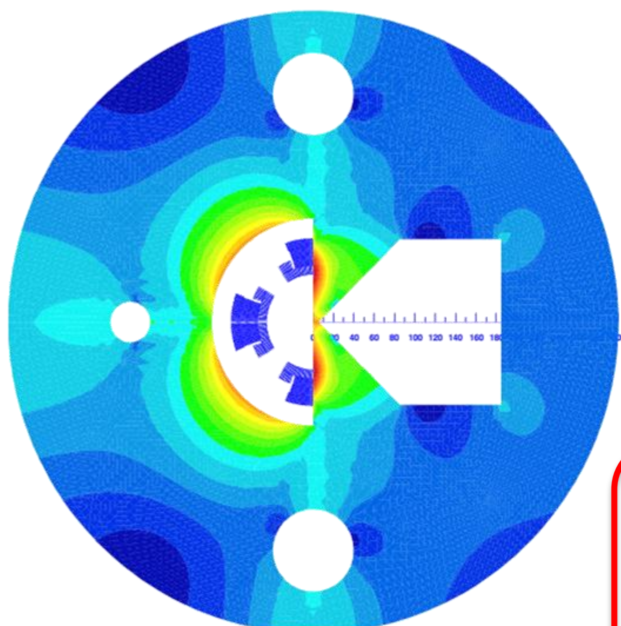
- Ring-ring
  - G=140 T/m
  - A=70 mm
  - **B_{fringe} = 30 mT**
  - **O(15) kW SR power in the proton aperture**

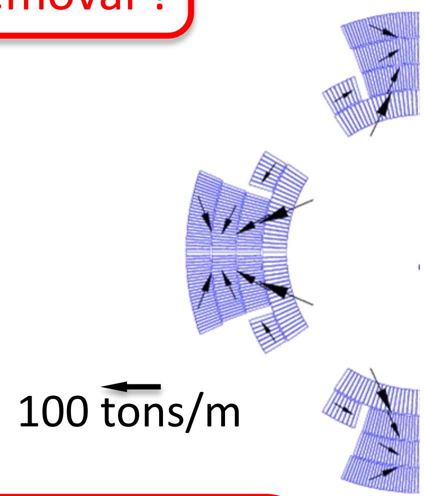


NbTi suitable for this *medium gradient* option

Mechanics ?
Heat removal ?

- Linac-Ring
  - **G=250-300 T/m**
  - **A=90 mm**
  - B_{fringe} = 500 mT
  - **O(2) kW SR power in the proton aperture**





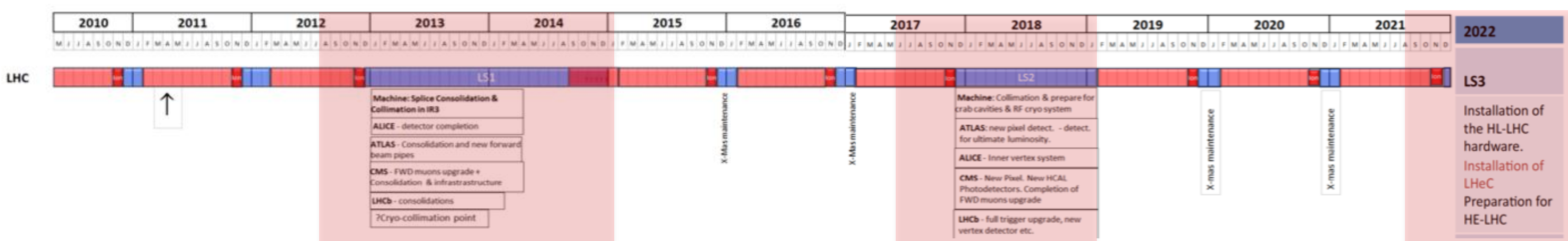
NbTi or Nb3Sn ?
Large aperture ?
Mechanics ?
Heat removal ?

By courtesy of S. Russenschuck

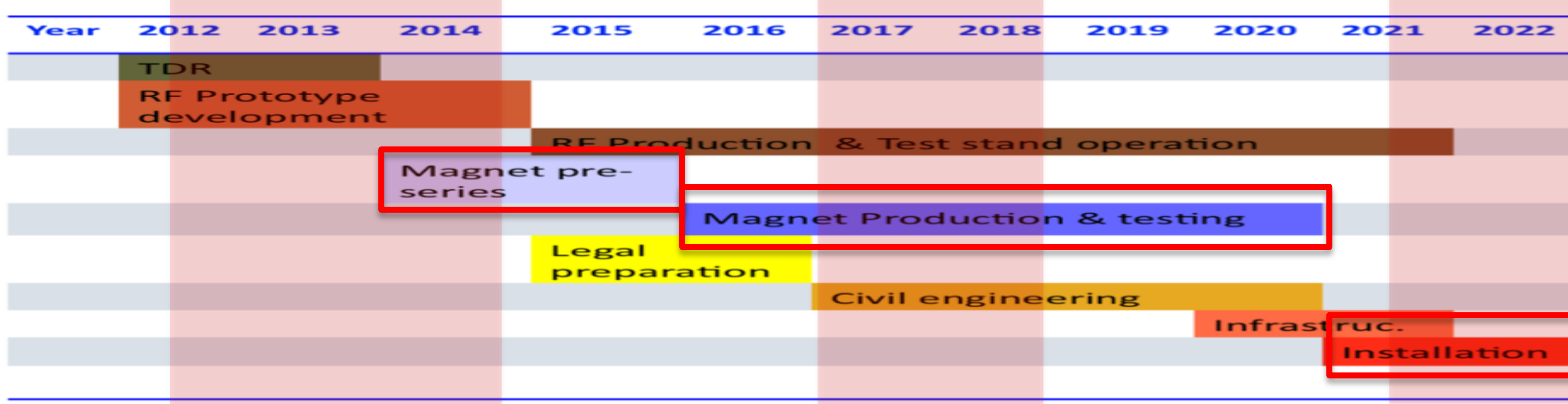
Other *magnet* challenges

- Limit cost, both capital and operating
  - Super-ferric quadrupoles for the SC Linac ?
- The recirculating Linac has the size of the SPS
- Schedule and co-activity

LHC activities



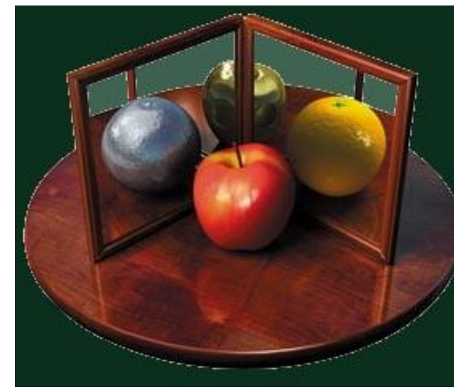
LHeC plan

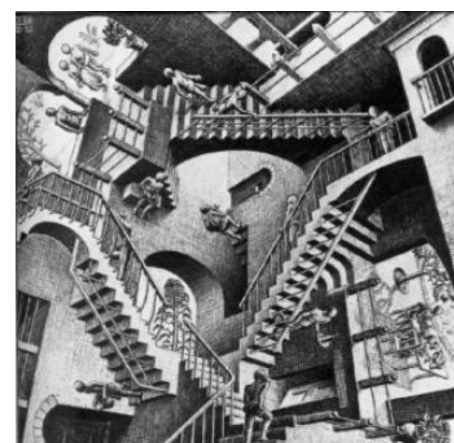


HE-LHC Scope

- *"[…] a 33 TeV centre-of-mass energy proton–proton accelerator in the LHC tunnel […] and the need for new injectors, possibly with 1 TeV energy"*. (The High-Energy Large Hadron Collider, CERN–2011–003, also EuCARD–Conf–2011–001)
- Technicolor, Supersymmetry, Extra dimensions: *"[…] the need to explore the high energy frontier will remain. We will always be able to make that case, today and tomorrow"*. (Elements of a Physics Case for a High-Energy LHC, J.D. Wells, pp. 1-5, CERN–2011–003, 2011)
- *"A project on the scale and innovation level of the HE-LHC has a long preparation lead time"*. (CERN Accelerator Strategy, S. Myers, pp. 6, CERN–2011–003, 2011)

technicolor





HE-LHC magnet challenges

- 27 km of very high field, accelerator grade magnets
  - 40 mm bore, 20 T dipoles
  - 40 mm bore, 500 T/m arc quadrupoles
  - 50 mm bore, 400 T/m IR quadrupoles
- 7 km of pulsed accelerator magnets with low loss
  - 100 mm bore, 5 T dipoles
- 5.6 km of transfer lines, from a SPS+ to HE-LHC
- Field swing and field quality
- Mechanics, protection, powering and stray field in the constrained LHC tunnel space
- Increased heat loads (e.g. a factor 20 on $q_{Synchrotron}$)
- Cost and material availability
- **Dismantle the LHC to make space for the new ring**

HE-LHC injection and dump

EuCARD HE-LHC'10 Accnet Workshop

LHC beam dump, injection system and other kickers

B.Goddard, with input from L.Ducimetière, W.Bartmann, V.Mertens, J.Borburgh, M.Barnes, C.Bracco, V.Senaj, M.Meddahi, V.Kain, J.Uythoven

Summary

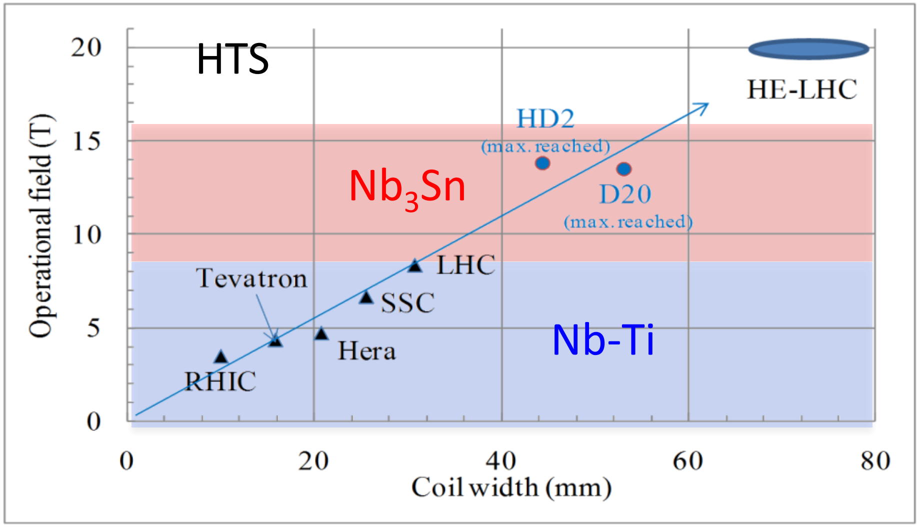
- 16.5 TeV dump system: does not look impossible in similar layout to present system
  - 5 μs kicker rise time feasible, x2.6 kicker length →optics issues
  - Increase septa ∫B.dl (x1.9 septa length, maybe gain by using more of MSDC type), seems feasible (integration?)
  - Increase dilution sweep length: higher f_0, needs more kickers OR SC dilution quadrupole plus kickers; integration issues
  - Upgrade dump block (longer, lower density), seems feasible
  - Upgrade protection devices for higher energy (longer, sacrificial elements), difficult
- 1-1.3 TeV injection system will need new layout
  - Longer kicker rise time 1.9 – 2.2 μs with longer pulse feasible, OR 1 μs with 8 – 9 magnets and 40 m quad spacing: optics?
  - Double number of septa but 60 m between quads: optics?
  - Injection protection devices need more space
  - Cohabitation with experiments in injection regions??

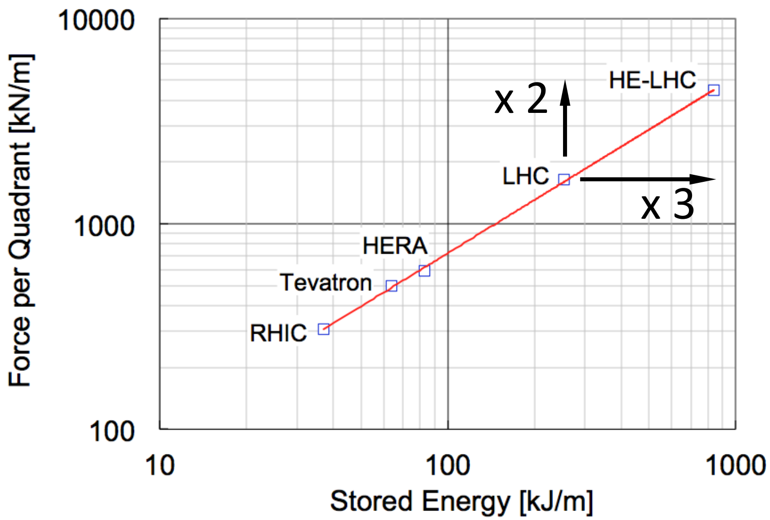
Difficult, but not impossible

A number of R&D items have been identified but no activity at present

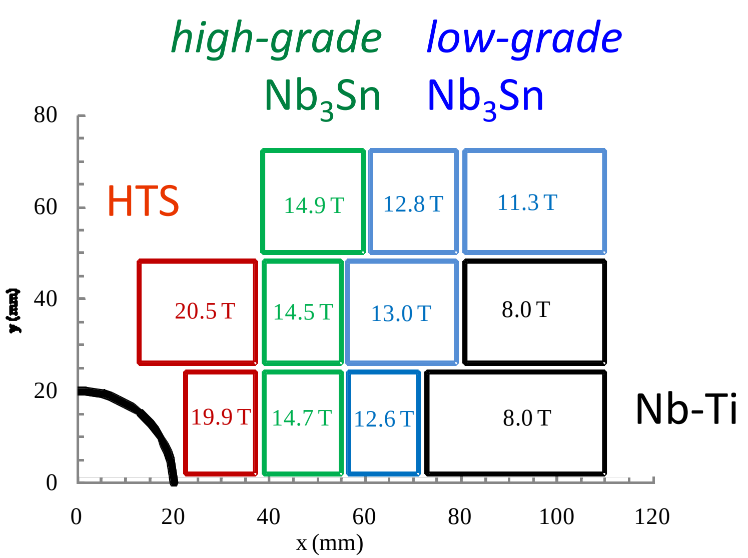
By courtesy of B. Goddard and V. Mertens

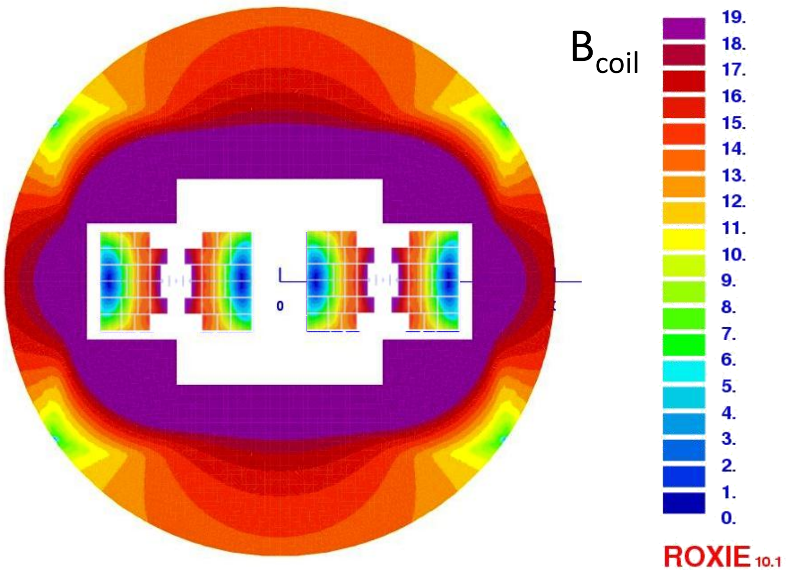
A *really high field* dipole





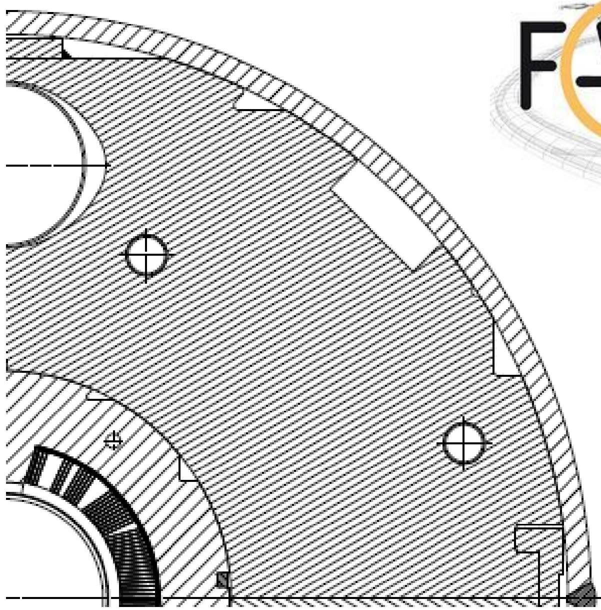
HTS/Nb_3Sn/Nb-Ti nested coil magnet



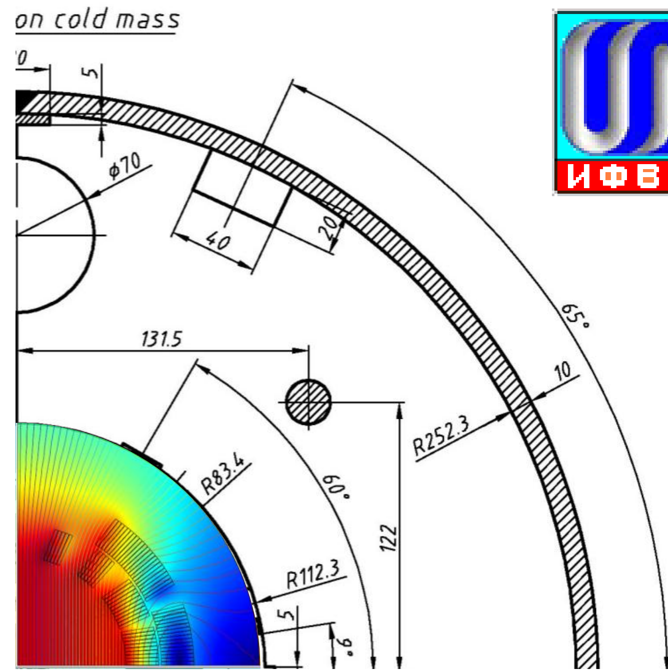


By courtesy of E. Todesco

Low-loss pulsed magnets



4.5 T, Nb-Ti single layer design



6 T, Nb-Ti double layer design

Quench performance and operating margin (recall that the booster was a major stumble for SSC)

AC loss in the SC coil: 10 W/m over 7 km of magnets are 70 kW of required cryogenic power, or 20 MW socket power

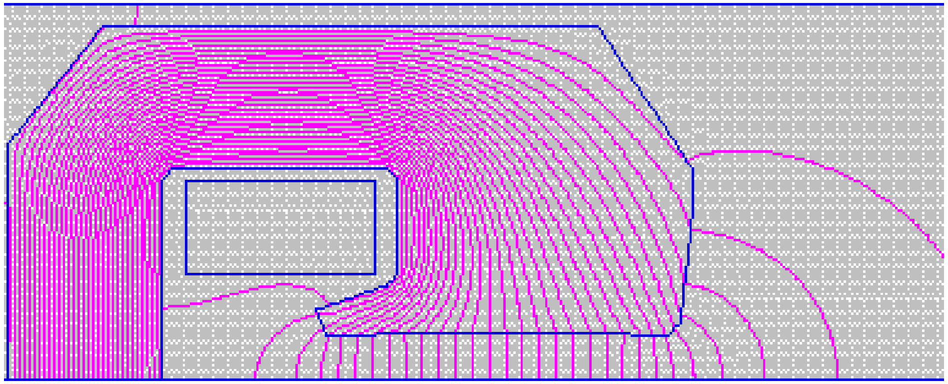
By courtesy of P. Fabbricatore (INFN)

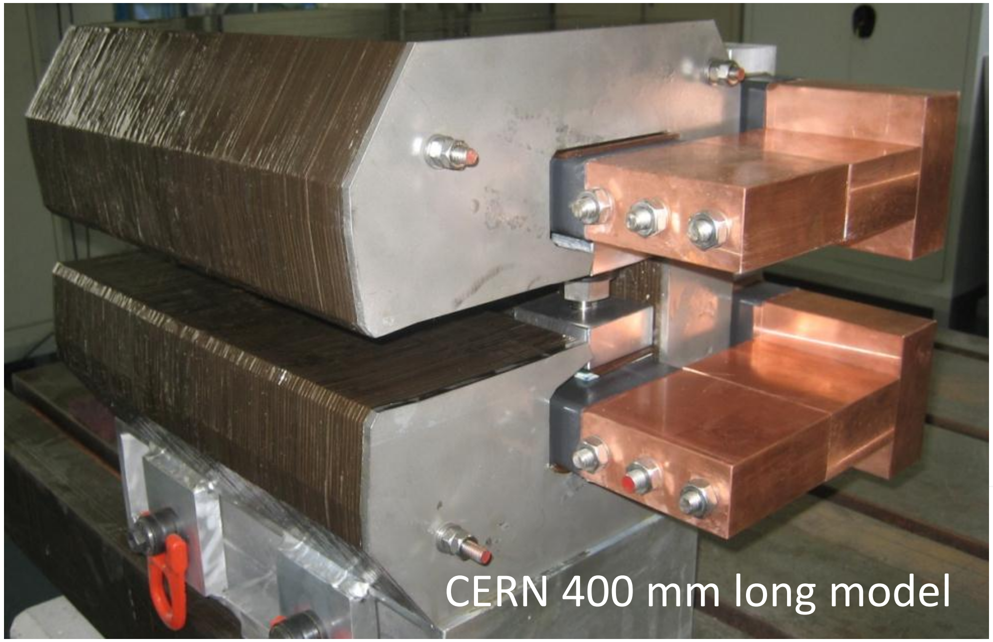
So, what are we doing about it ?

There are no problems, only solutions – John Lennon, 1980

Low Field Magnets

Interleaved ferromagnetic (1 mm) and plastic (2 mm) laminations
Wide pole to spread-out magnetic flux and reduce the effect of magnetic property variation in the yoke
Two turns only, air cooled bolted bars





REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

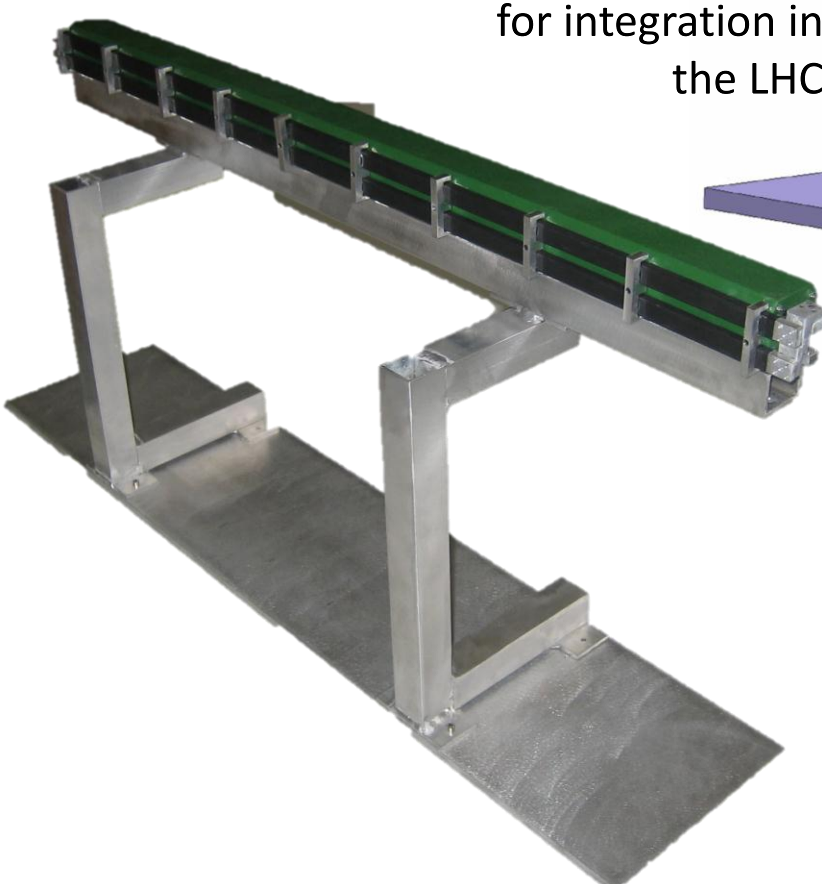
Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5\cdot10^{-5}$	$4\cdot10^{-5}$
Model 2 (Low carbon steel)	$6\cdot10^{-5}$	$6\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4\cdot10^{-5}$	$6\cdot10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3\cdot10^{-5}$	$3\cdot10^{-5}$
Model 2 (Low carbon steel)	$4\cdot10^{-5}$	$5\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2\cdot10^{-5}$	$4\cdot10^{-5}$

Excellent reproducibility achieved

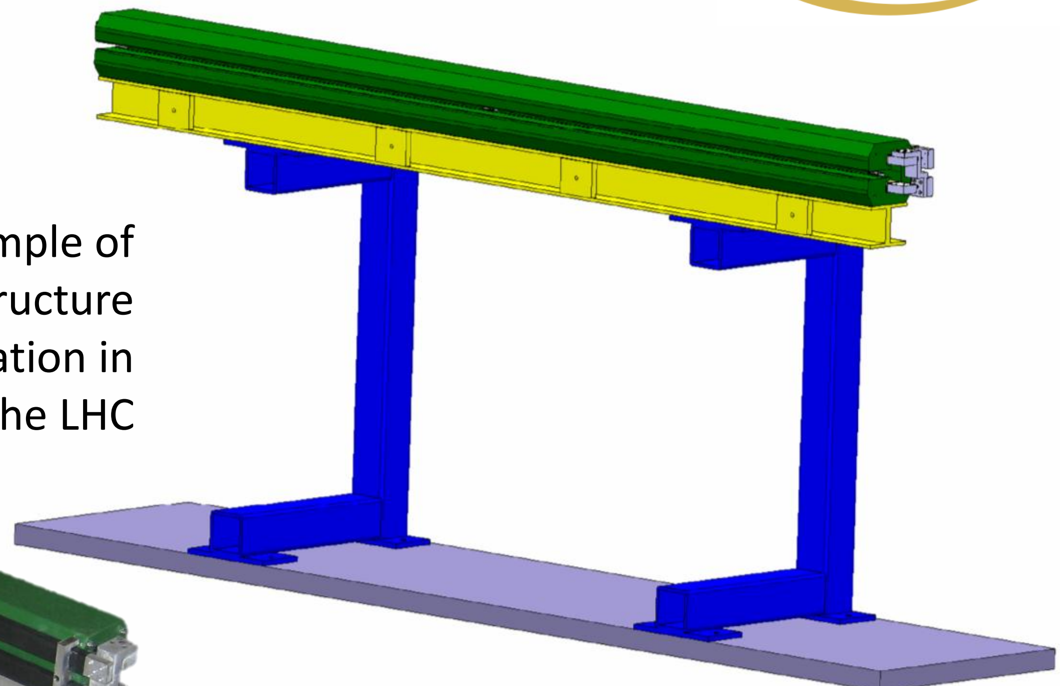
By courtesy of D. Tommasini

RR integration

1:8 mock-up



Example of support structure for integration in the LHC

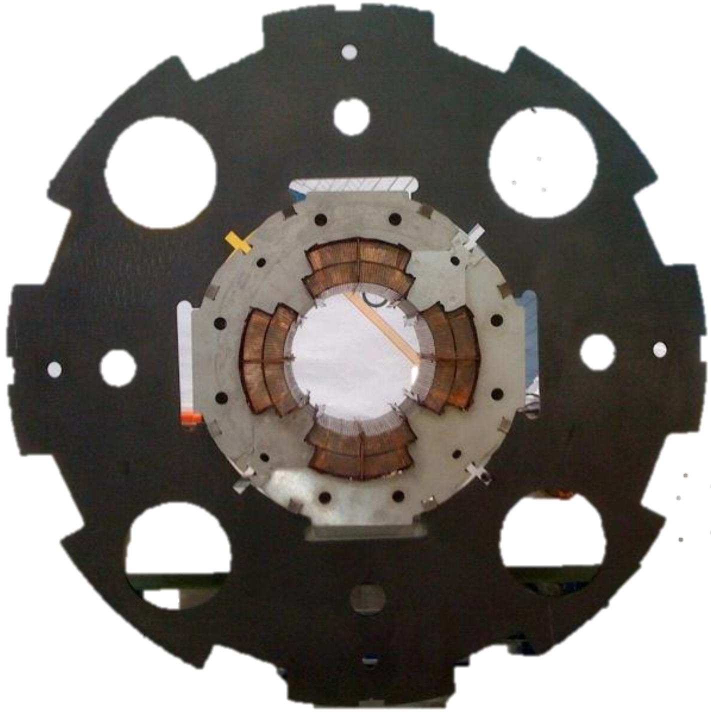


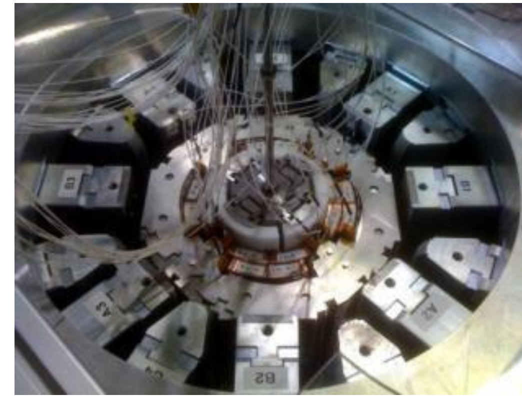
Develop further the integration concept and prototype (BINP ?)

By courtesy of D. Tommasini

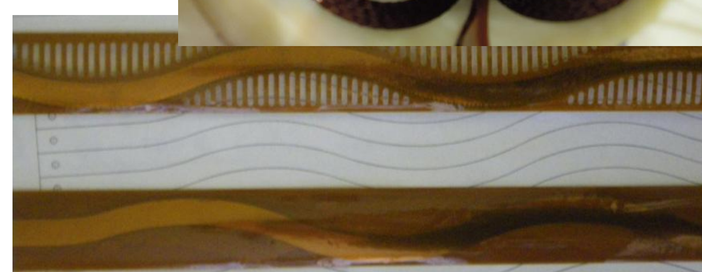
Large Aperture MQXC

Main Magnet Parameters	
Gradient	120 T/m
Aperture	120 mm
Working point	<80% SS
Current	13’052 A

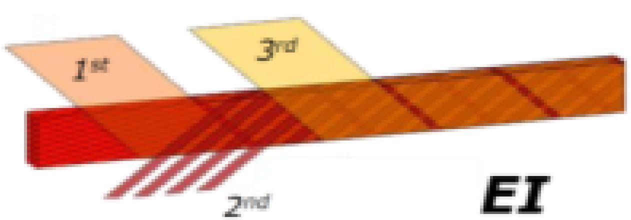




Open collaring shoe



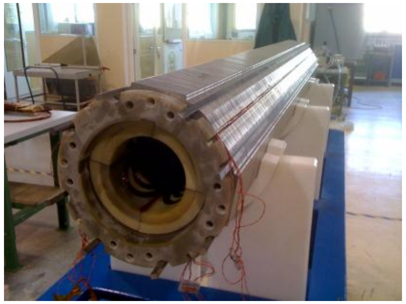
Transparent quench heaters



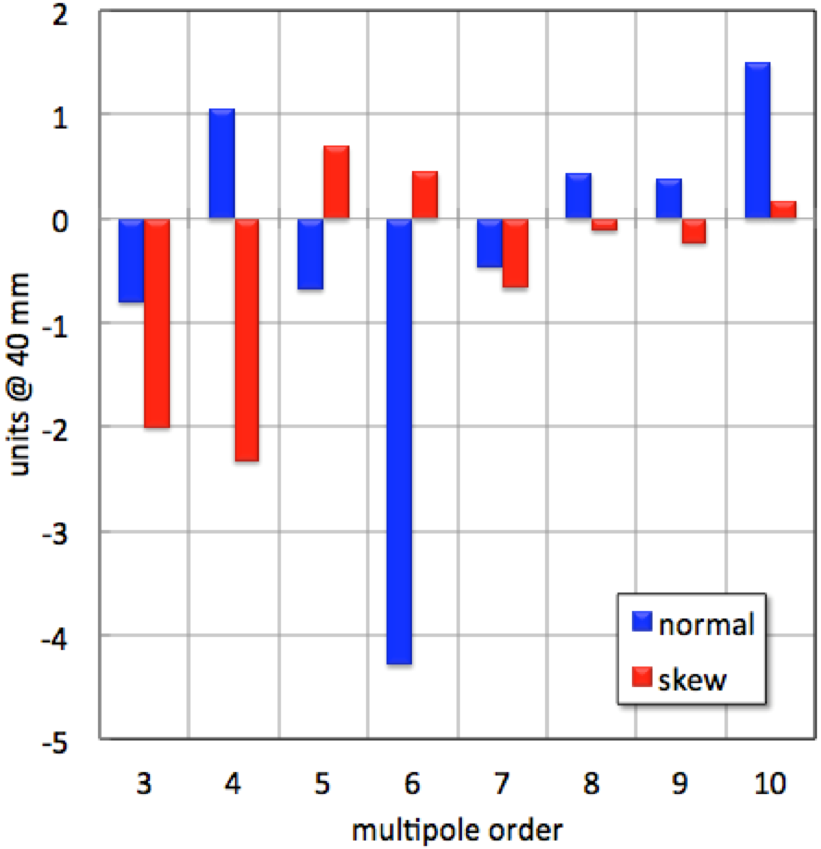
Enhanced insulation

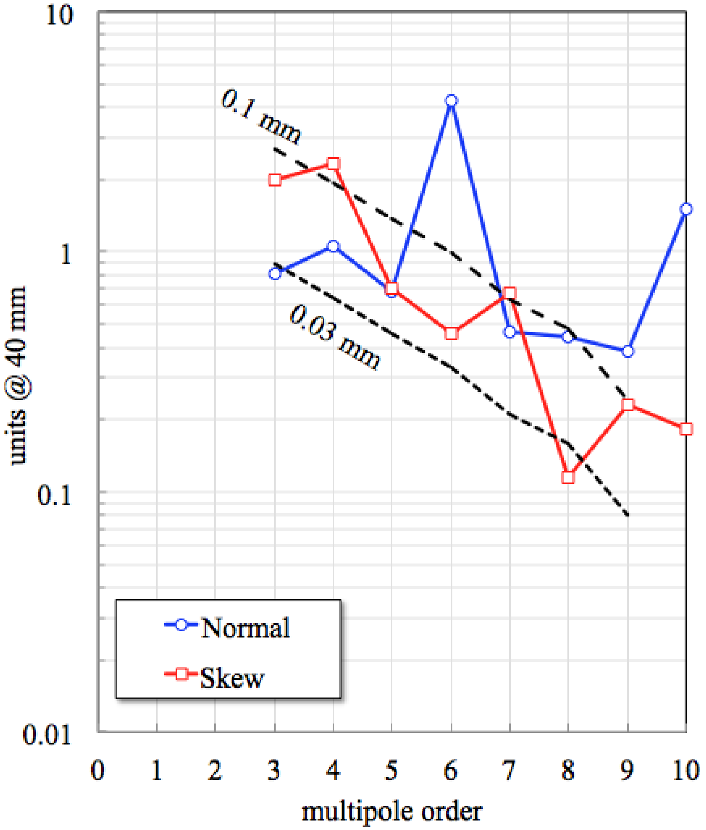
By courtesy of G. Kirby

Excellent first shot !



Harmonics of collared coils at warm





Coils larger than nominal in radius and at the poles by less than 0.1 mm

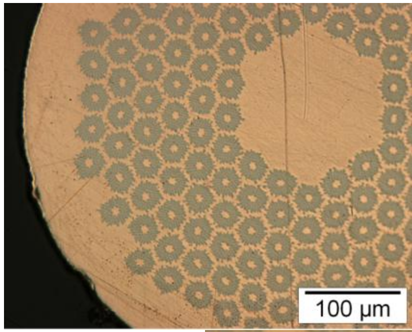
Random multipoles consistent with local errors in the range of 30…100 μm

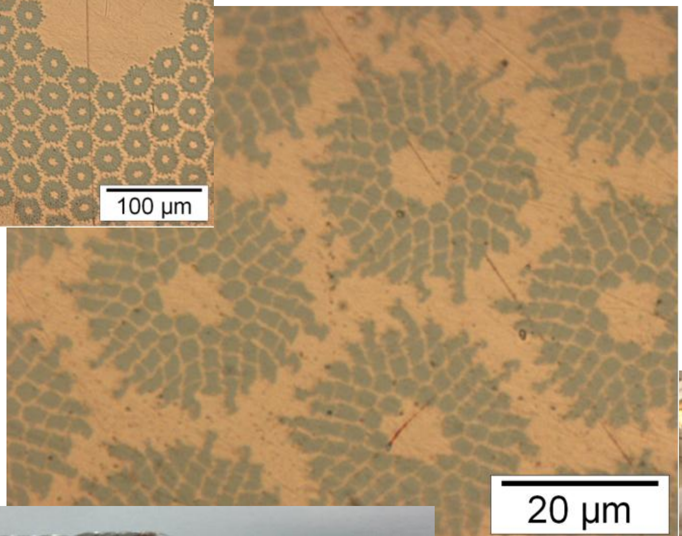
By courtesy of G. Kirby, J.G. Perez, P. Galbraith, S. Russenschuck, E. Todesco

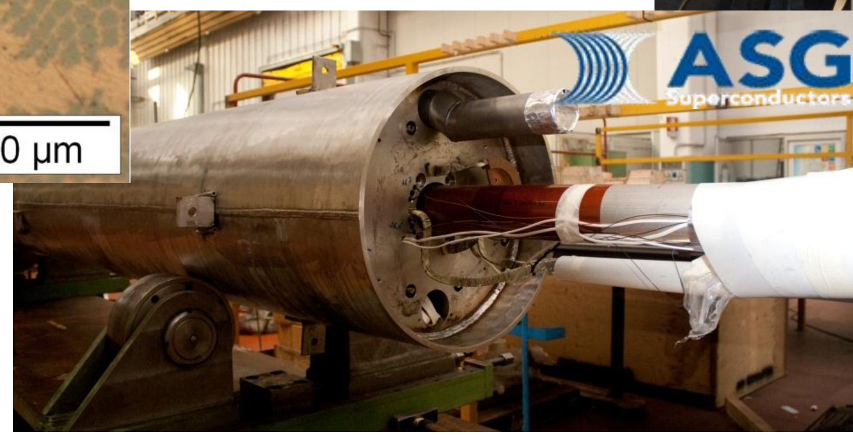
FAIR
Facility for Antiproton and Ion Research in Europe GmbH

Cycled SC magnets

CRISP
The Cluster of Research Infrastructures for Synergies in Physics







CERN
INFN

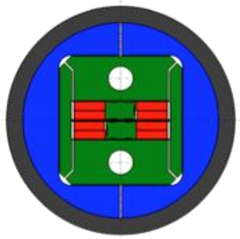
- Joint R&D (GSI/INFN/CERN) for the production of a collared coil of a 4.5 T, Nb-Ti, low-loss pulsed dipole

By courtesy of L. Oberli, P. Fabbricatore (INFN)

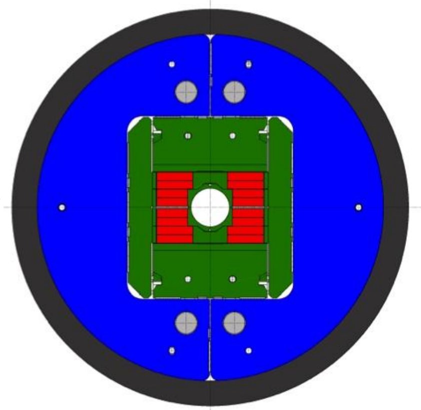
High Field Magnet R&D

Short Model Coil

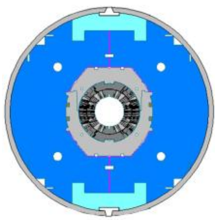
Race-track Model Coil



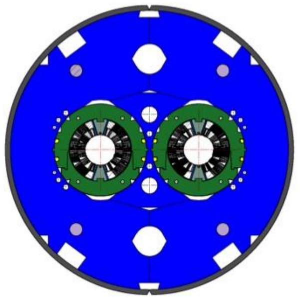
FReSCa2 Nb_3Sn Dipole



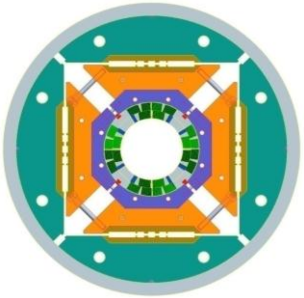
11 T DS 1-in-1 model



11 T DS Nb_3Sn Dipole



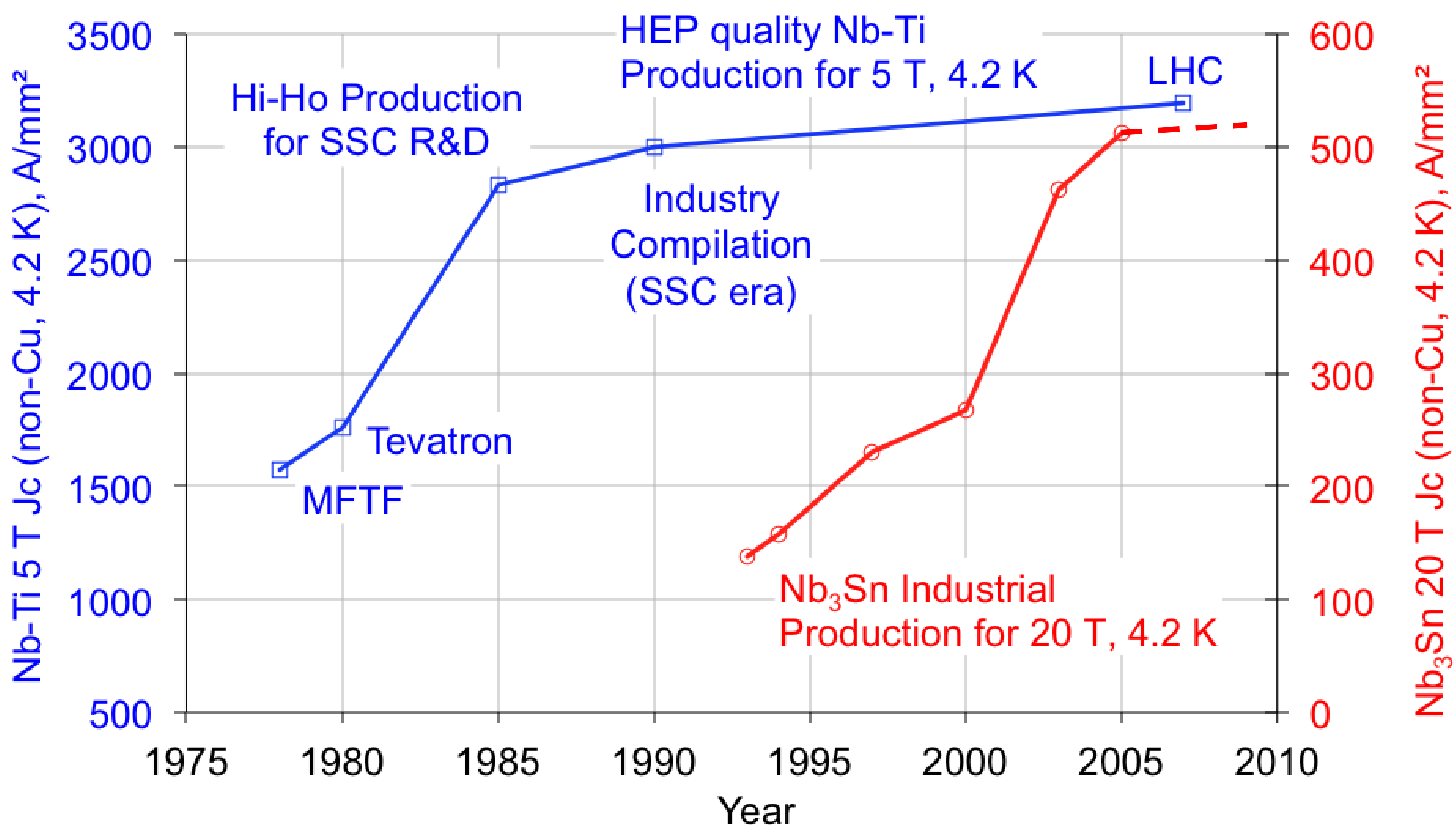
HQ/LHQ Nb_3Sn Quadrupole



US-LARP program

2012 2013 2014 2015 2016 2017 2018 2019 2020

Nb_3Sn knocks at the door

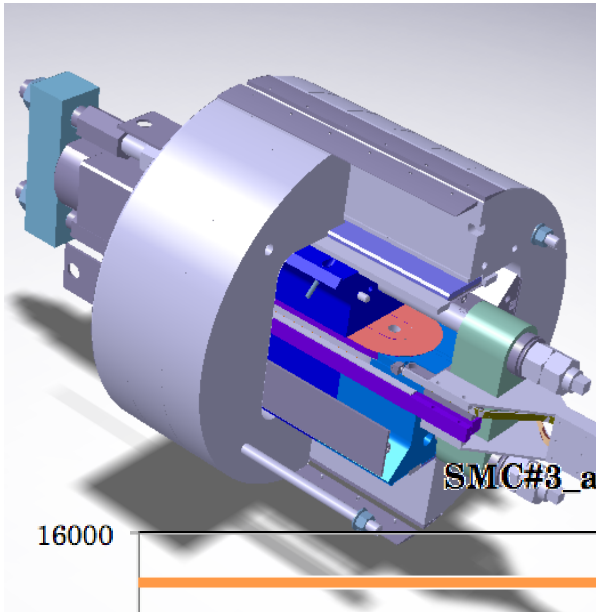


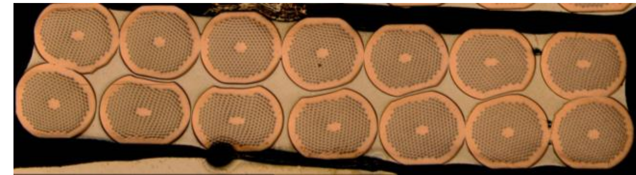
By courtesy of J. Parrell (OST)

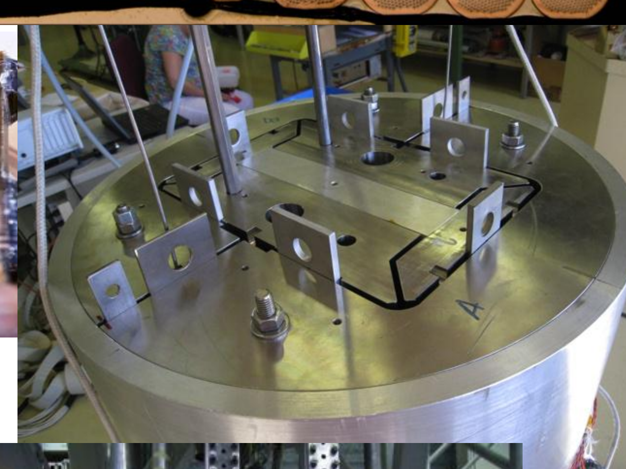
A Nb_3Sn cable for high field

14 strands, 1.25 mm Powder-in-Tube (PIT) SMC cable

SMC-3a



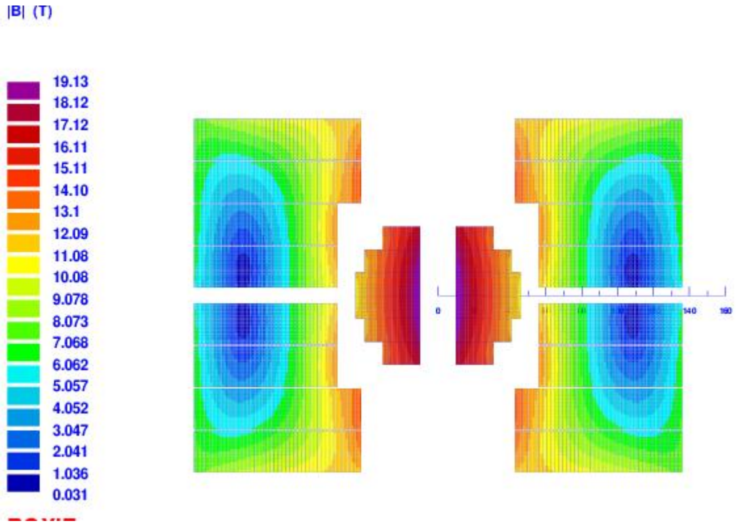




By courtesy of J. Perez and M. Bajko

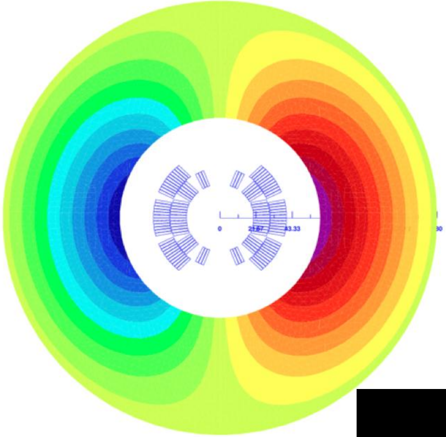
HTS inserts

- EuCARD
  - 6 T insert built with YBCO tapes
  - Current density of 250 A/mm^2
  - Race-track, 20 mm aperture (no bore)
    self-supported for test in FReSCa-2

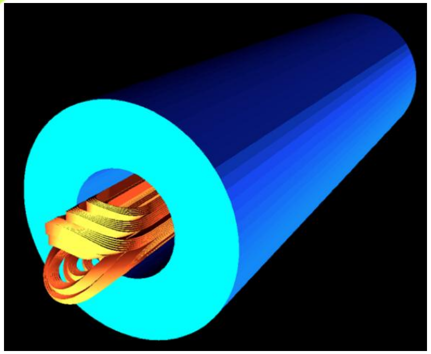


By courtesy of G. de Rijk

- EuCARD2 (proposed)
  - 5 T, 40 mm bore, accelerator quality HTS magnet
  - *10 kA-class* HTS cable at 20 T



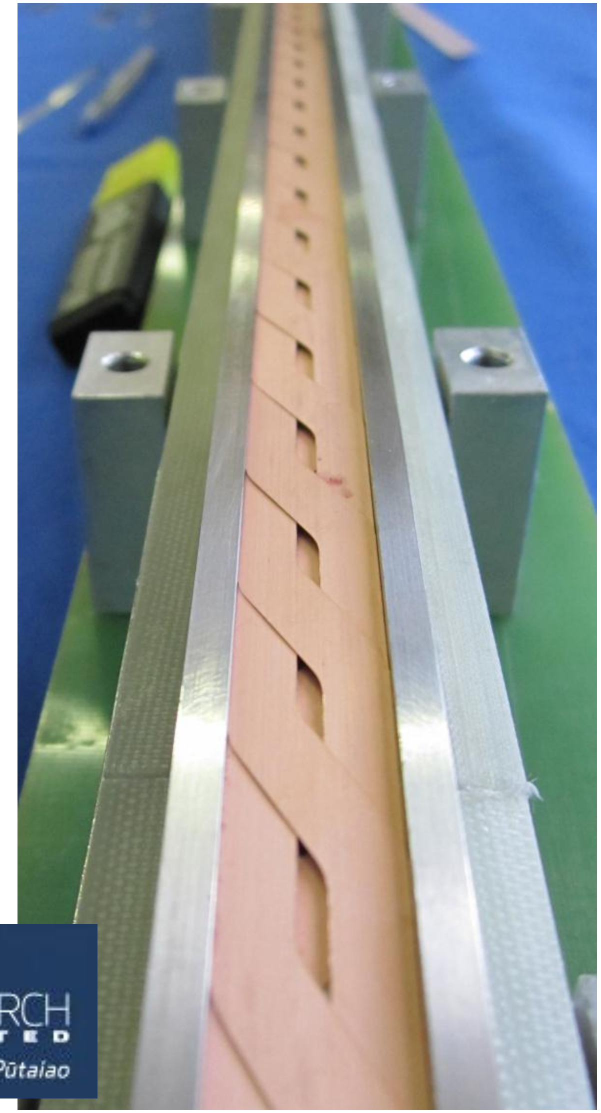
5 T cos-θ magnet design based on flat cable geometry



By courtesy of B. Auchmann

A (maybe) 20 T cable

- Roebel cables of punched HTS tapes after an idea of W. Goldacker (KIT)
- Manufacturing by IRL Ltd.
- First test at liquid helium (4.3 K) and in high field (10 T) show a current carrying capacity of **4 to 10 kA**



IRL INDUSTRIALRESEARCH LIMITED
Te Tauihu Pūtaiao

By courtesy of J. Fleiter, Ph. Denis, G. Peiro, A. Ballarino

Summary table

			LHeC RR dipole prototype	CRISP and fast cycled SC magnets	MQXC R&D	EuCARD FReSCa-II	DS 11 T MB program	US-LARP IR quadrupole program	EuCARD HTS insert	EuCARD2 HTS model	activated SC magnets handling for	Comments
LHeC	Low field resistive magnets	field quality and reproducibility	X									demonstrated
LHeC	Low field resistive magnets	operating cost		x								tests planned in 2012
LHeC	Low field resistive magnets	integration in the LHC tunnel									x	study launched in 2012 (LS1)
LHeC	IR magnets	large aperture			X			X				results in 2012…2014
LHeC	IR magnets	large gradient						X				
LHeC	IR magnets	heat removal		x	X							results in 2012
LHeC	co-activities and tunnel works										x	integration study and models (BINP); schedule revision

			LHeC RR dipole prototype	CRISP and fast cycled SC magnets	MQXC R&D	EuCARD FReSCa-II	DS 11 T MB program	US-LARP IR quadrupole program	EuCARD HTS insert	EuCARD2 HTS model	activated SC magnets handling for	Comments
HE-LHC	Very high field magnets	15 T dipole outsert				X						deliverable Q1 2014
HE-LHC	Very high field magnets	5 T dipole insert							X	X		EuCARD2 proposal
HE-LHC	Very high field magnets	high gradient quadrupoles						X				US-LARP technology demonstration by 2014
HE-LHC	Very high field magnets	magnet protection				X	X	X				
HE-LHC	Very high field magnets	heat loads and removal			x	X						dedicated model tests
HE-LHC	Very high field magnets	field quality					X	X		X		
HE-LHC	Pulsed SC magnets	quench performance and margin		X								
HE-LHC	Pulsed SC magnets	low-loss cables		X								
HE-LHC	Transfer lines											options reviewed at HE-LHC workshop in Malta, 2010
HE-LHC	Material availability and cost					X	X	X	x	x		
HE-LHC	Installation in 2030										X	study launched in 2012 (LS1)

Conclusions

- Many of the critical issues in the long-term programs LHeC and HE-LHC are addressed by synergic medium term activities for which we have commitments, major milestones and proposals (SLHC-PP, EuCARD, US-LARP, HL-LHC, EuCARD2)…
- … however, given the present landscape (LS1 and beyond), there is not much more that we can realistically do on magnets

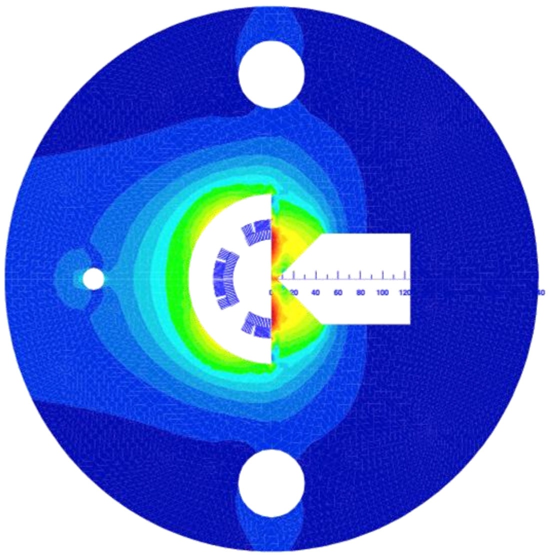
Never mind, the glass is half full !

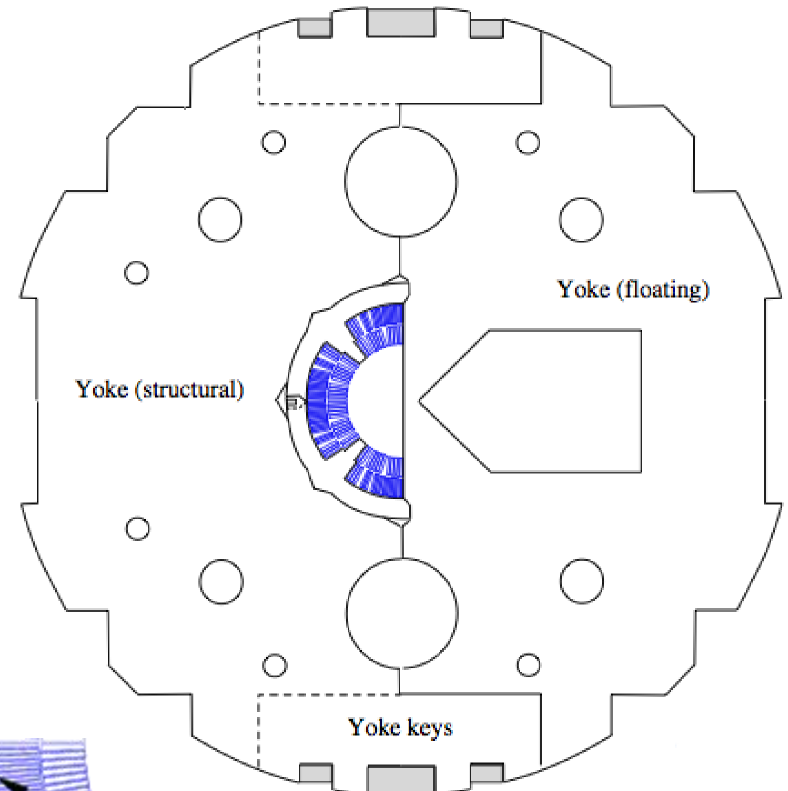
Acknowledgements

- Obviously, the whole Magnet Group (TE-MSC)
- EuCARD partners
- US-LARP partners
- And among the other collaborators
  - Insitutions: INFN, GSI, University of Geneva
  - Industries: Bruker EAS and HTS, OST, IRL

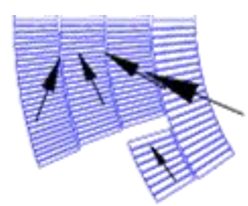
Additional material

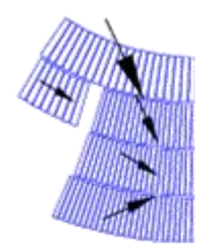
LHeC IR quad R&D work ?





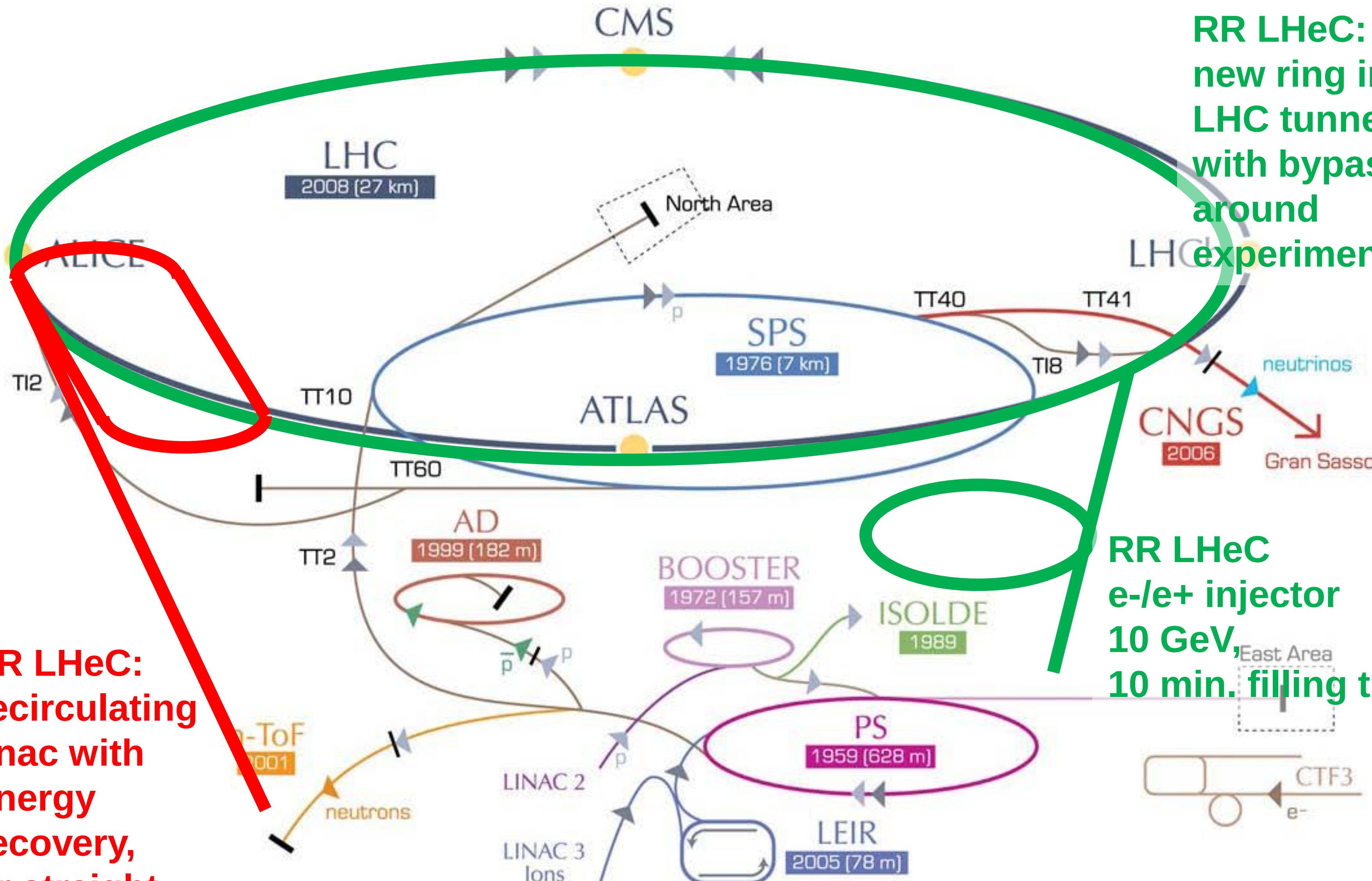
- Half-quad with field-free region, assembled using MQXC coils
  - 2.5 FTE
  - 500 kCHF
  - approx. 2 years till test





Large resultants on the magnetic wedge (> 50 tons/m)

LHeC options: RR and LR



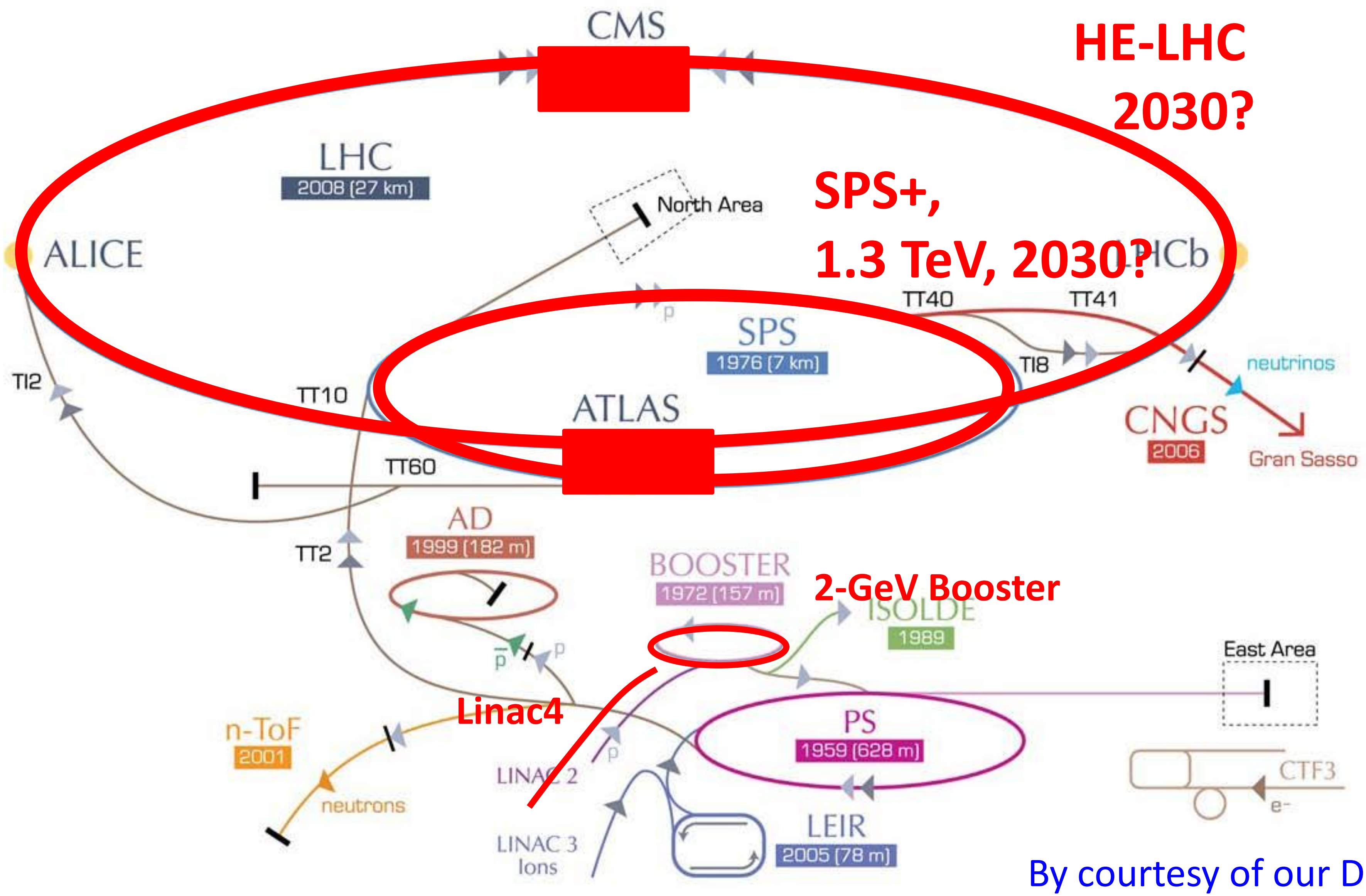
RR LHeC: new ring in LHC tunnel, with bypasses around experiments

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

LR LHeC: recirculating linac with energy recovery, or straight linac

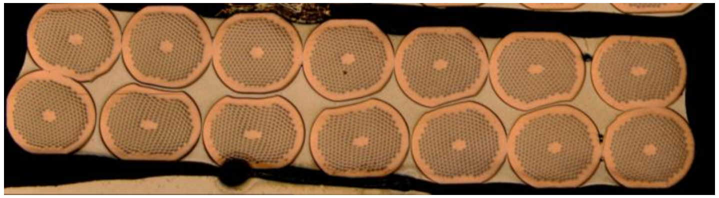
By courtesy of our DG

HE-LHC – (33 TeV cms)



By courtesy of our DG

Cables for HFM Program



SMC Dipole cable – 14 strands (1.25 mm) and 18 Strands (1 mm)
Width = 10 mm, Twist Pitch = 60 mm
Average I_C degradation 0 … 4 %

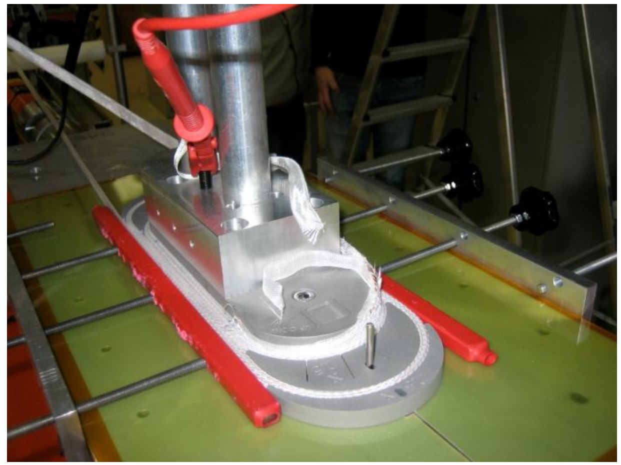
Fresca 2 Dipole cable – 40 Strands (1 mm)
Width = 20.9 mm, Twist Pitch = 120 … 140 mm
Average I_C degradation < 15 %

DS Dipole cable – 40 Strands (0.7 mm)
Width = 14.7 … 15.1 mm, Twist Pitch = 100 mm, 0.8° keystone
Average I_C degradation < 3 %

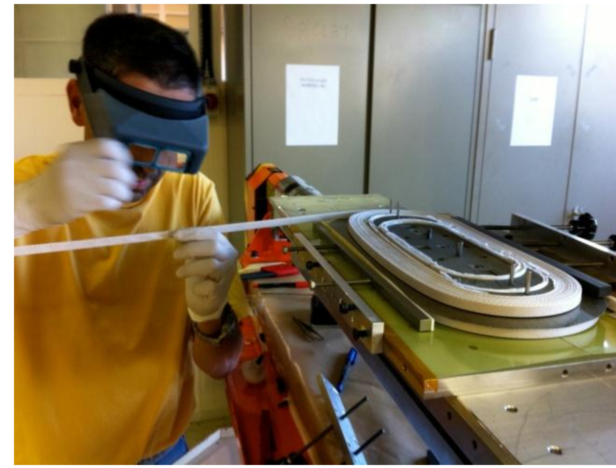
Nb_3Sn Small Model Coil: SMC-3

14 strands, 1.25 mm PIT

Winding



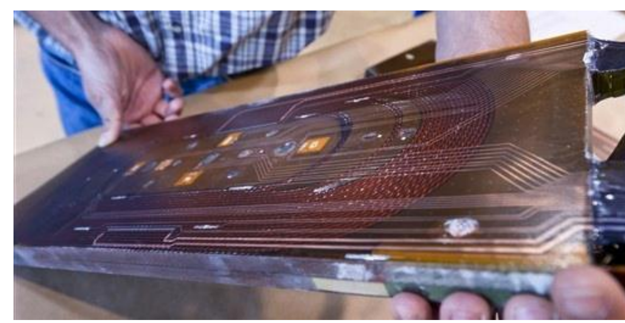
Instrumentation



Reacted

Instrumented

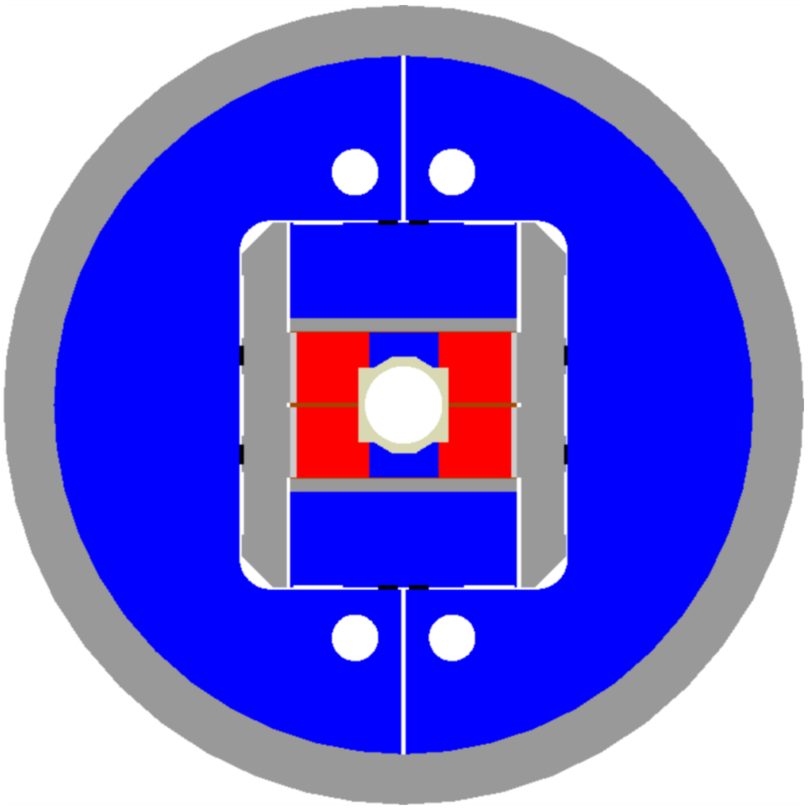
Impregnation



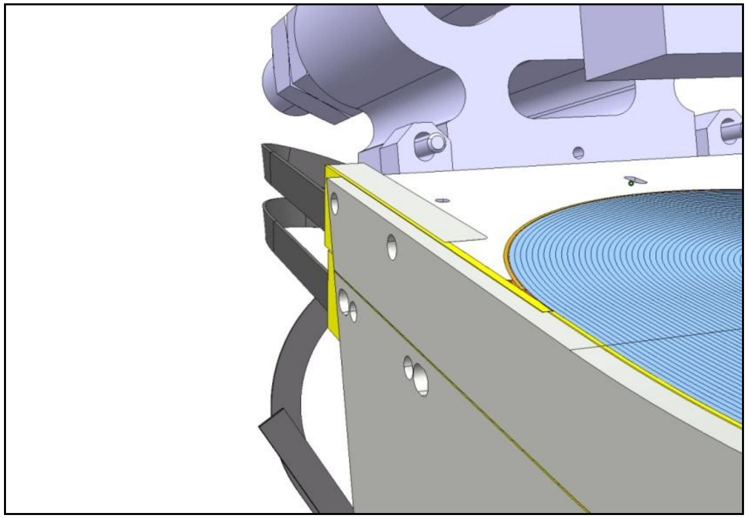
Ready for assembly

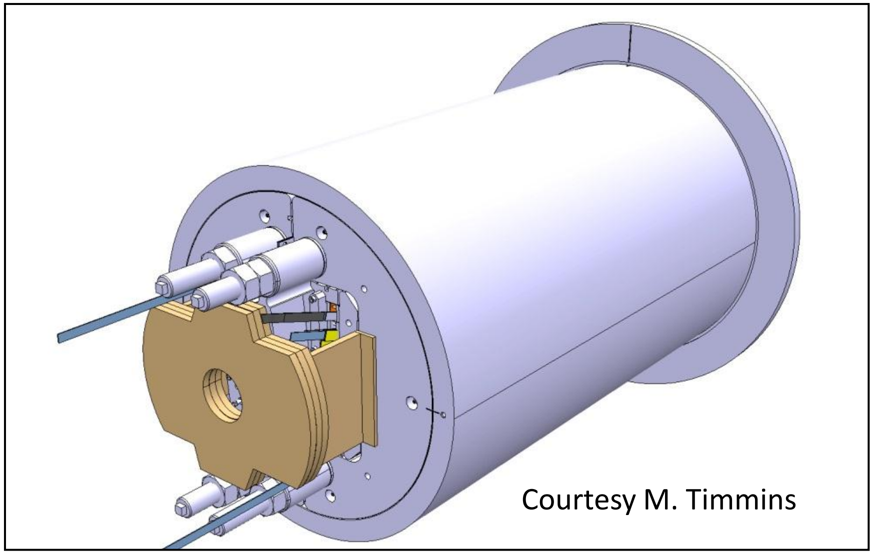
FRESCA2

- Goal
  - 13 T in 100 mm bore for cable test facility
- Status
  - Mechanical and magnetic analysis completed
  - Order for the support structure placed
    - Delivery expected by May 2012
  - Assembly with dummy al coils in June-July
  - Procurement of winding tooling on-going
  - First coil to be fabricated by the end of 2012
  - Conceptual design of the cryostat finished

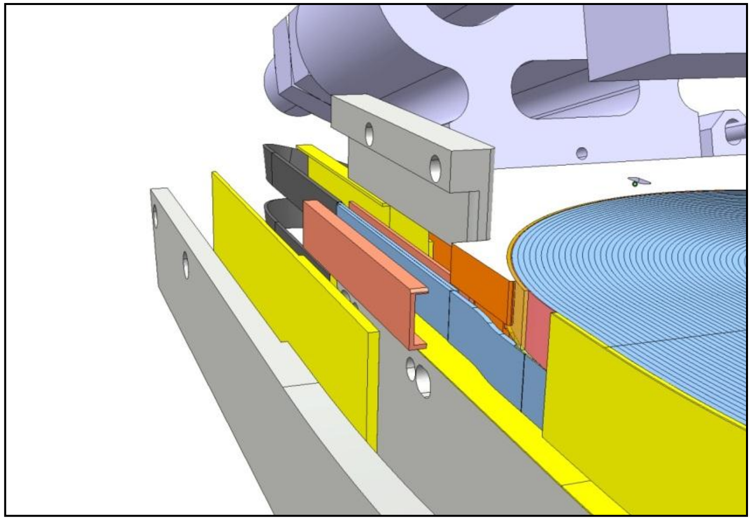


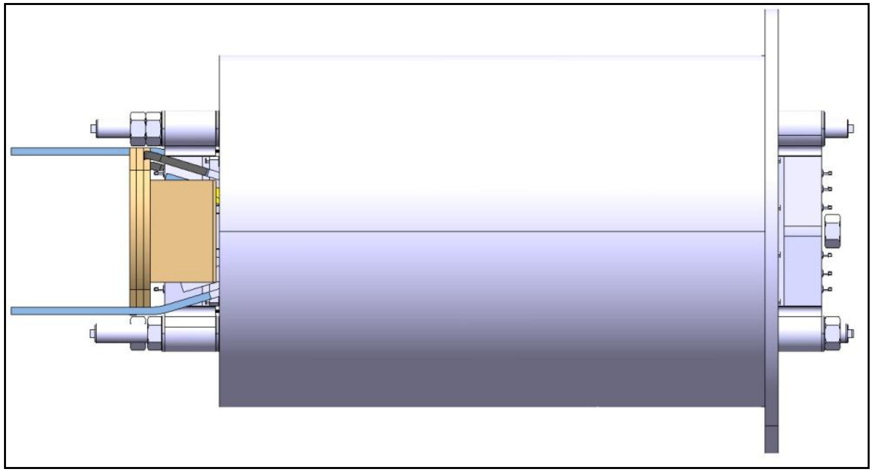
FRESCA2





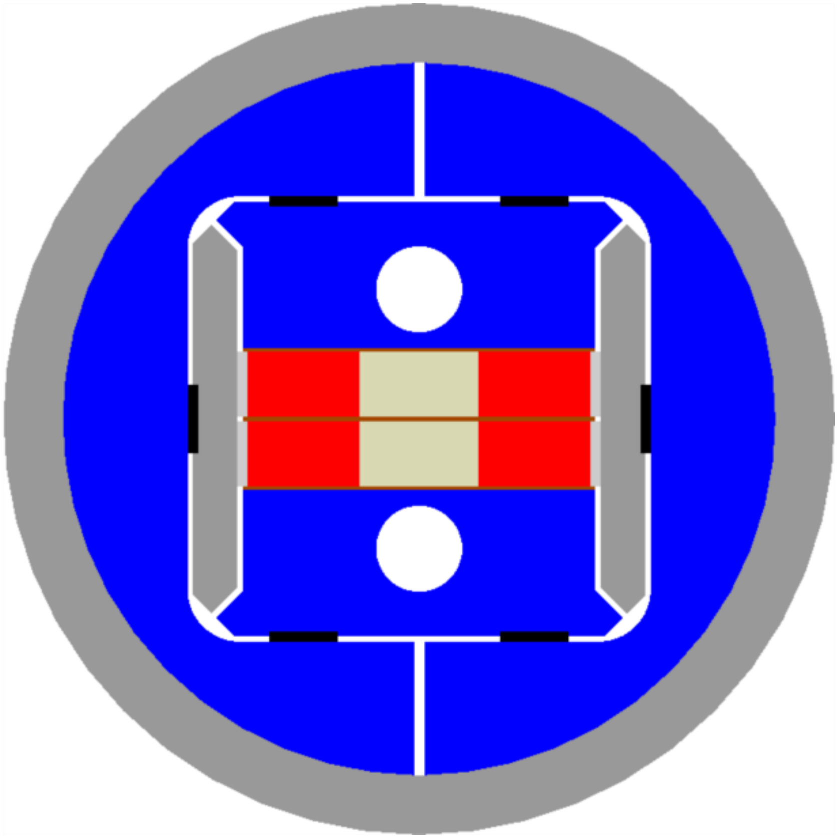
Courtesy M. Timmins



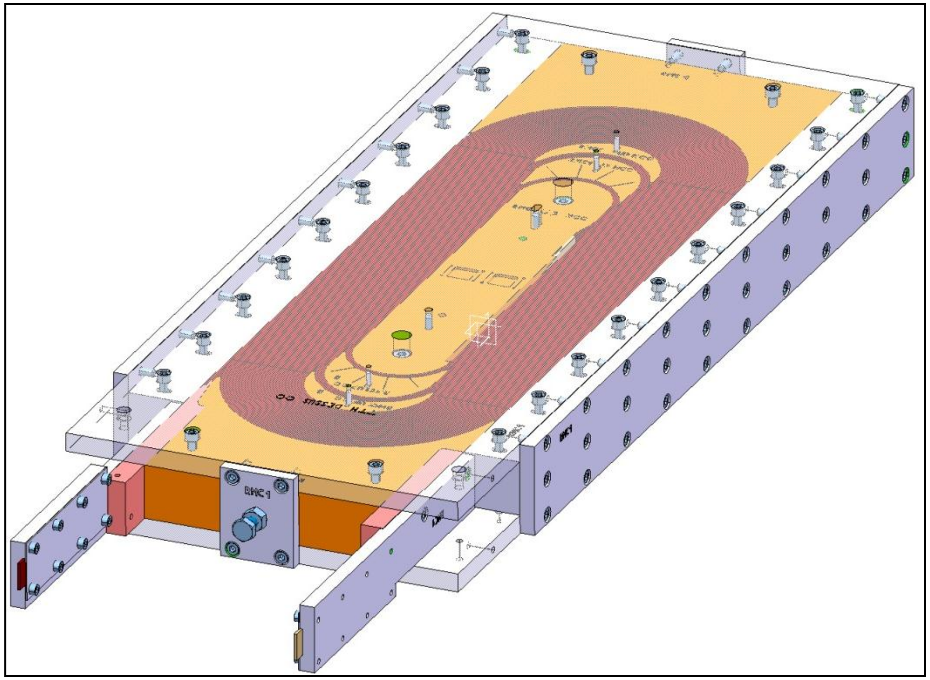


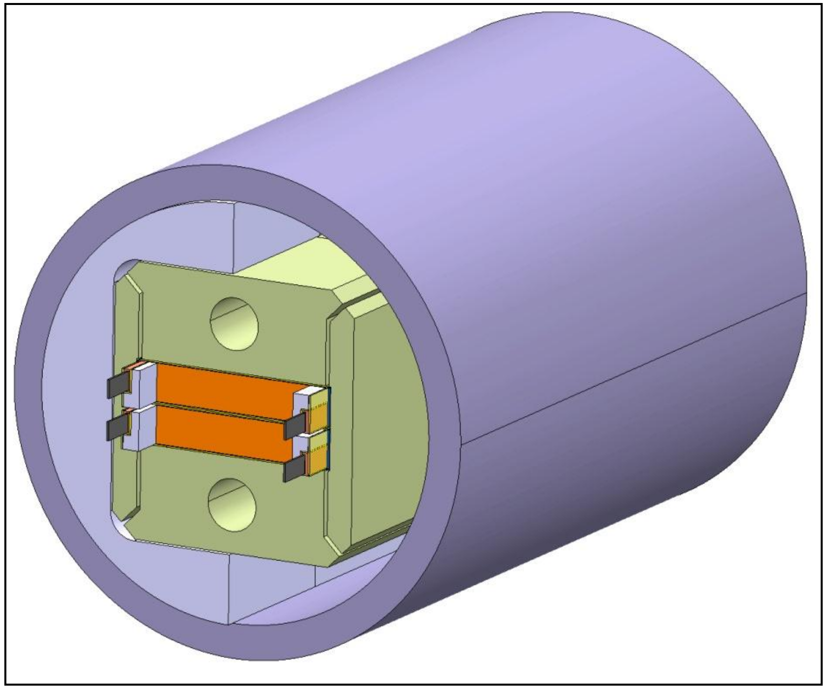
RMC
Racetrack Model Coil

- Goal
  - Test FRESCA2 cable and coil fabrication process in subscale model
- Status
  - Preliminary 2D/3D magnetic and mechanical analysis completed
  - Design of coil components and tooling close to completion
  - Design of structure component underway
  - Start of coil fabrication and structure assembly in summer 20120



RMC
Racetrack Model Coil

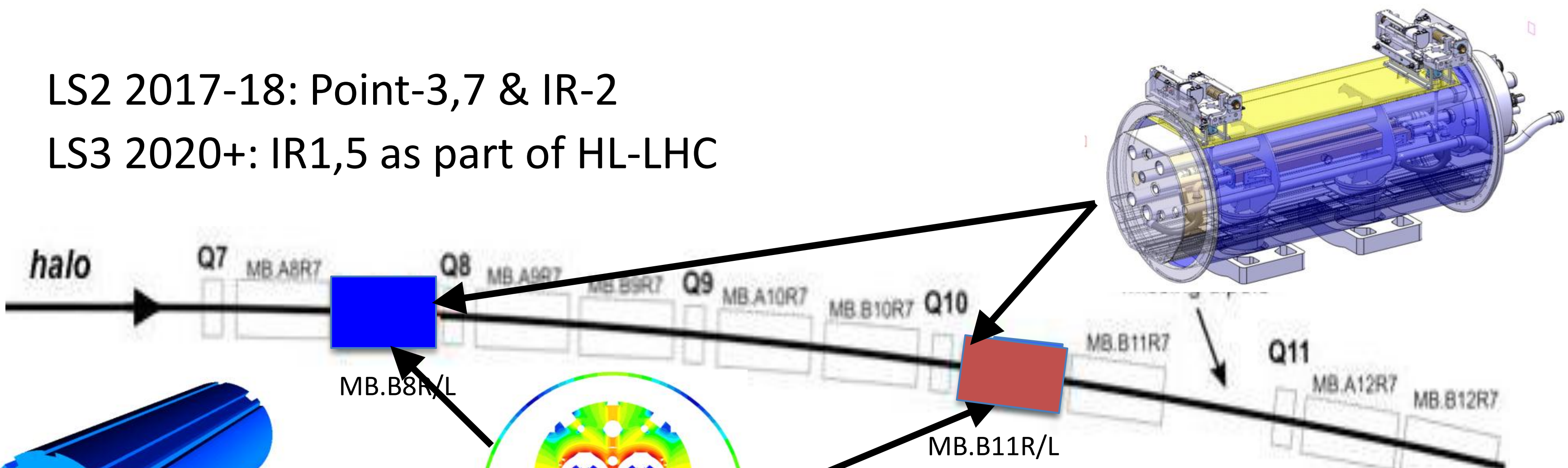


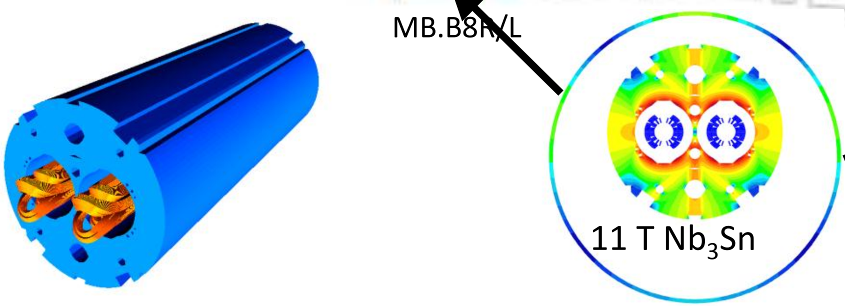


Courtesy M. Timmins
and J. Humbert

DS Upgrade: collimators & 11 T dipoles

- LS2 2017-18: Point-3,7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC





$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB with 20 % margin

11 m Nb_3Sn | **3 m Collim**

LS2: 12 coldmass + 2 spares = 14 CM
LS3: 8 coldmass + 2 spares = 10 CM
Total 24 CM

5.5 m Nb_3Sn | 5.5 m Nb_3Sn | **3 m Collim**

5.5 m Nb_3Sn | **3 m Collim.** | 5.5 m Nb_3Sn

LS2: 24 coldmass + 4 spares = 28 CM
LS3: 16 coldmass + 4 spares = 20 CM
Total 48 CM

Abstract

- Beyond HL-LHC, CERN has a number of physics options that offer potential and challenges. This contribution dwells on the long-term projects LHeC and HE-LHC to put the magnet R&D at CERN (resistive and superconducting, slow and fast) in a long term perspective. In particular synergies and parallel roadmaps will be highlighted. We will show how the on-going development (2012-2015) on low-field, high-field, and low-loss magnets can be used towards longer term objective.