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High-field superconducting magnets (LHC) and prospects for higher-energy hadron colliders (post LHC machine)

EPS HEP 2013

Frédérick BORDRY

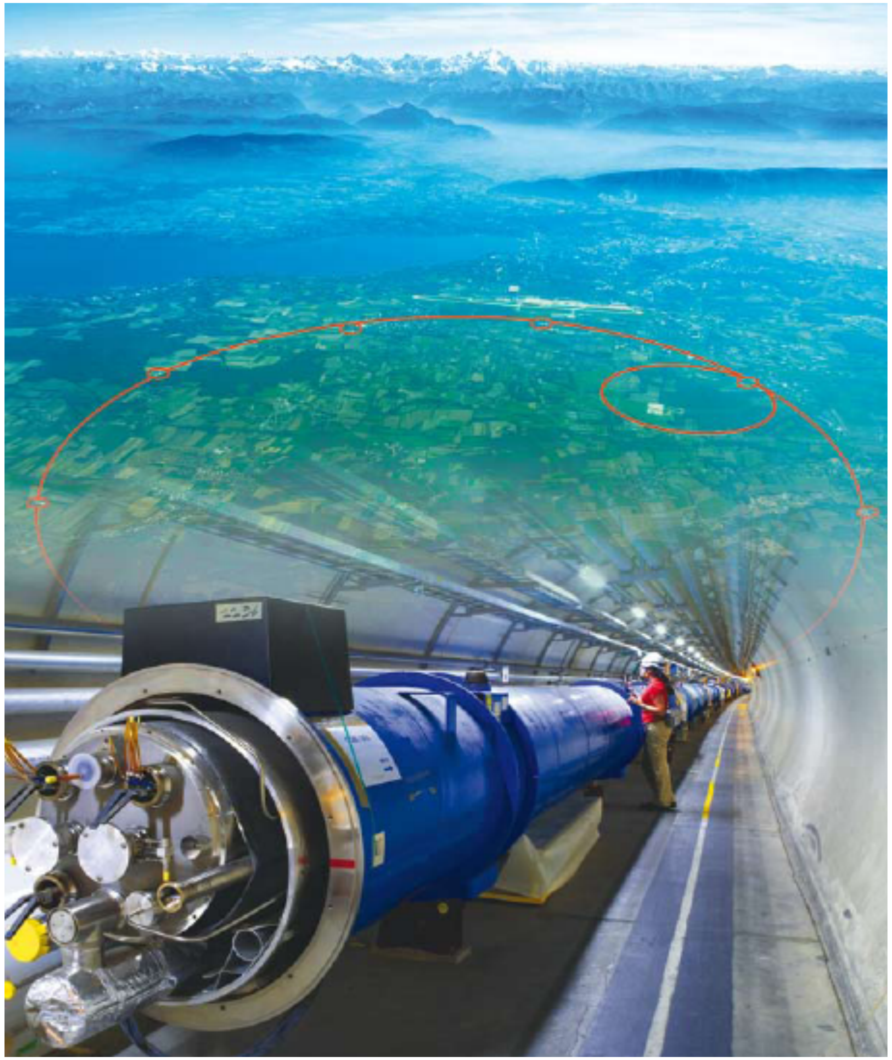
20^{th} July 2013

LHC (Large Hadron Collider)

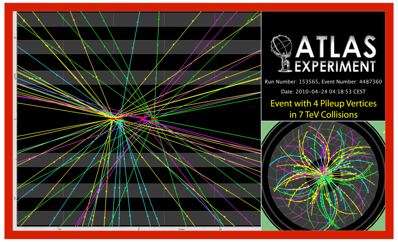
14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

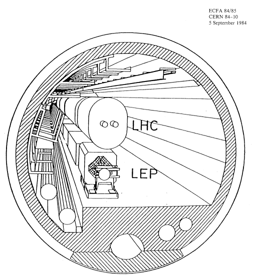
1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair
2009-2030 : Physics exploitation



LHC, the construction timeline: Nb-Ti magnet maturation

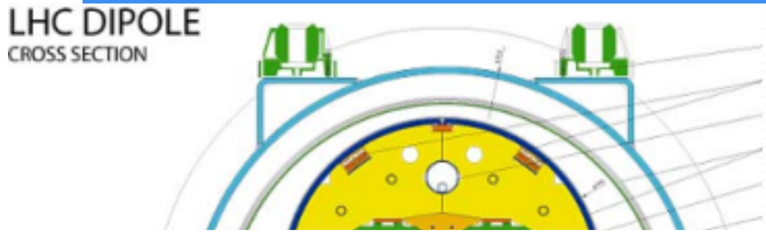


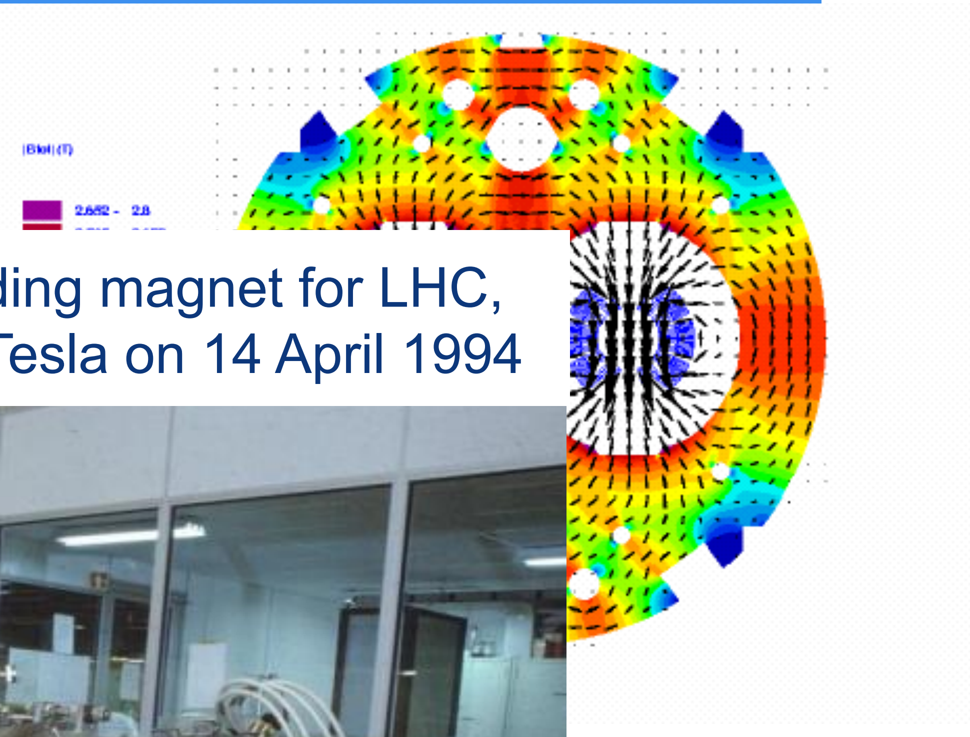
- 1985 — LHC study
- 1987 — 9 T - 1 m single bore
- 1990 — 10 T-1m Nb3Sn dipole
- 1990 — Decision for Nb-Ti
- 1994 — 9 T -10 m long protoype
- 2000 — 9 T-15 m final protoype
- 2000 — Industry contracts Nb-Ti
- 2006 — Last LHC dipole
- 2010 — LHC start-up



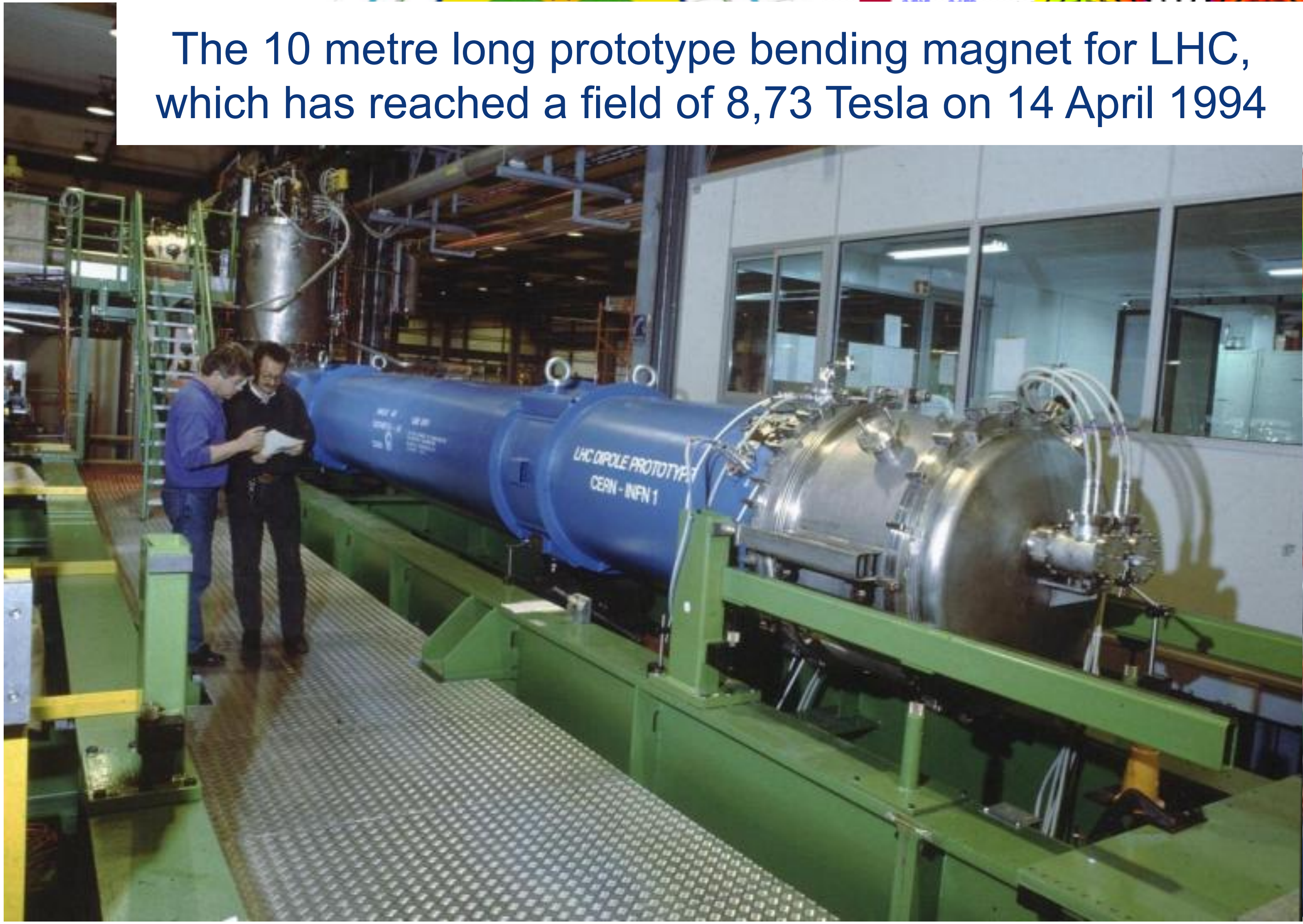
LARGE HADRON COLLIDER IN THE LEP TUNNEL

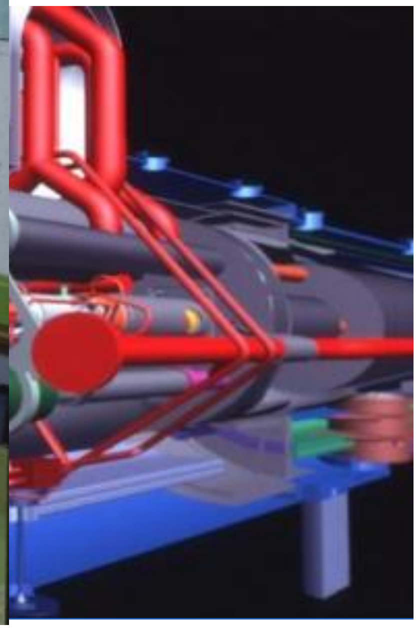
Prototype and industrialisation





The 10 metre long prototype bending magnet for LHC, which has reached a field of 8,73 Tesla on 14 April 1994

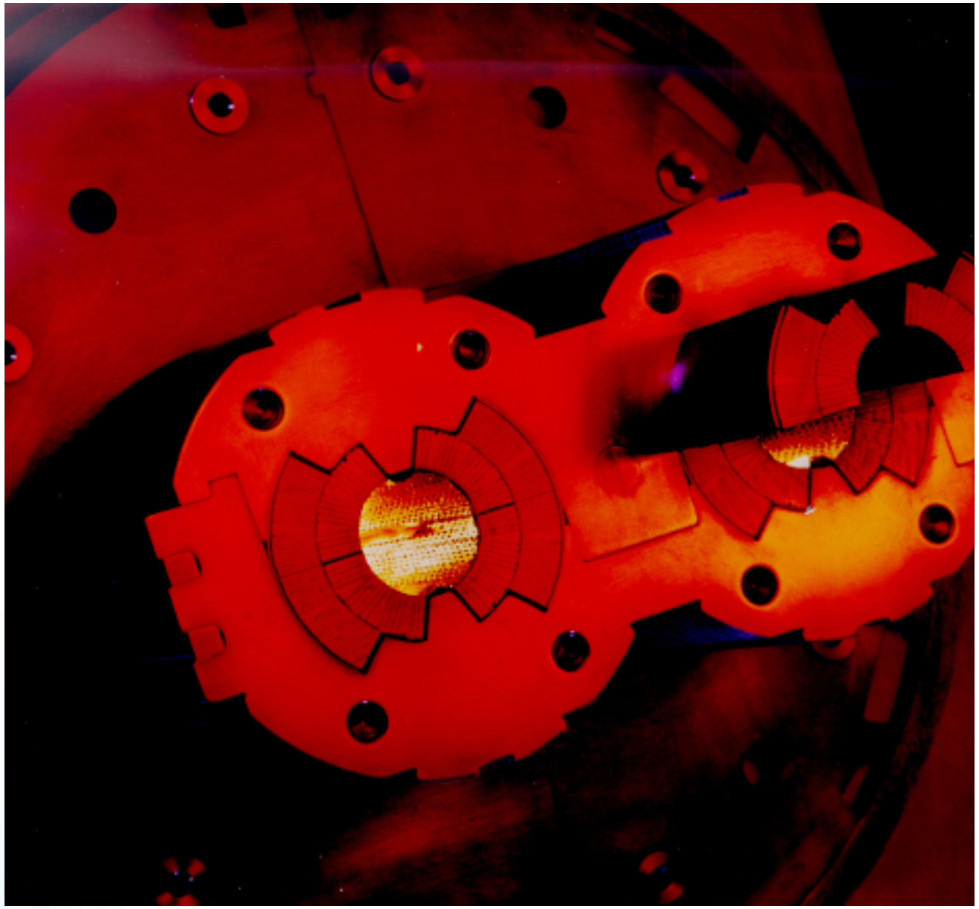


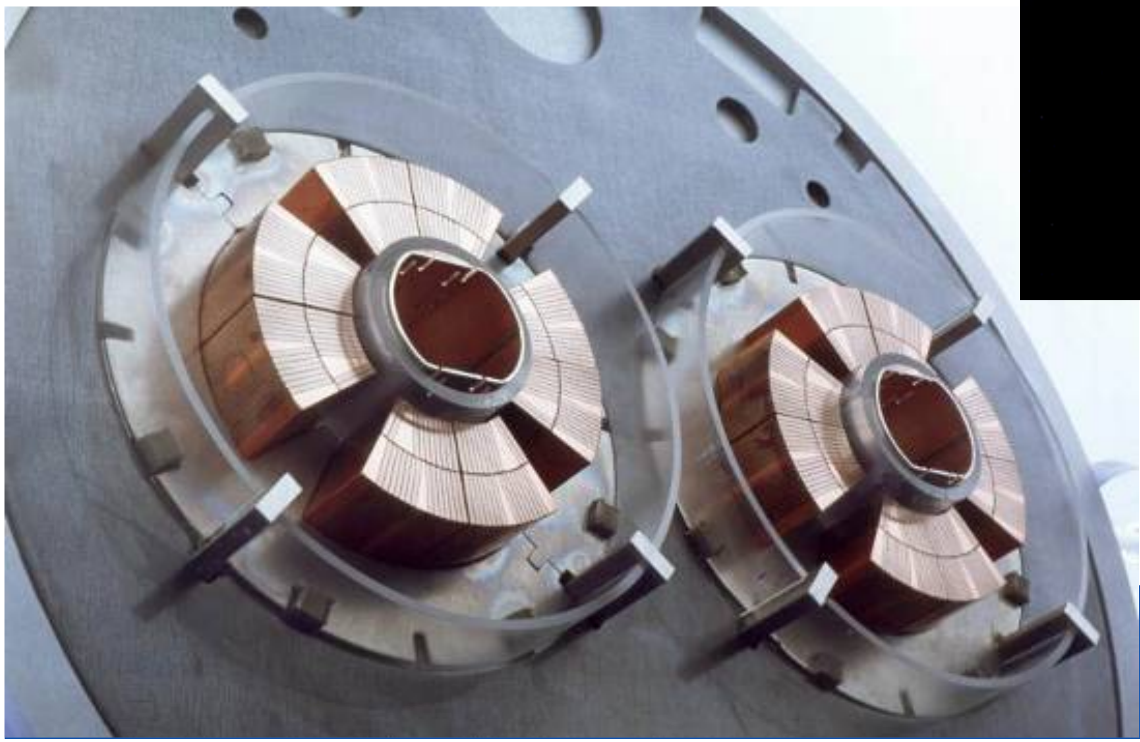


Twin-aperture dipole and quadrupole

Field reproducibility/precision ~ 10^{-3}

Field homogeneity ~ 10^{-4}



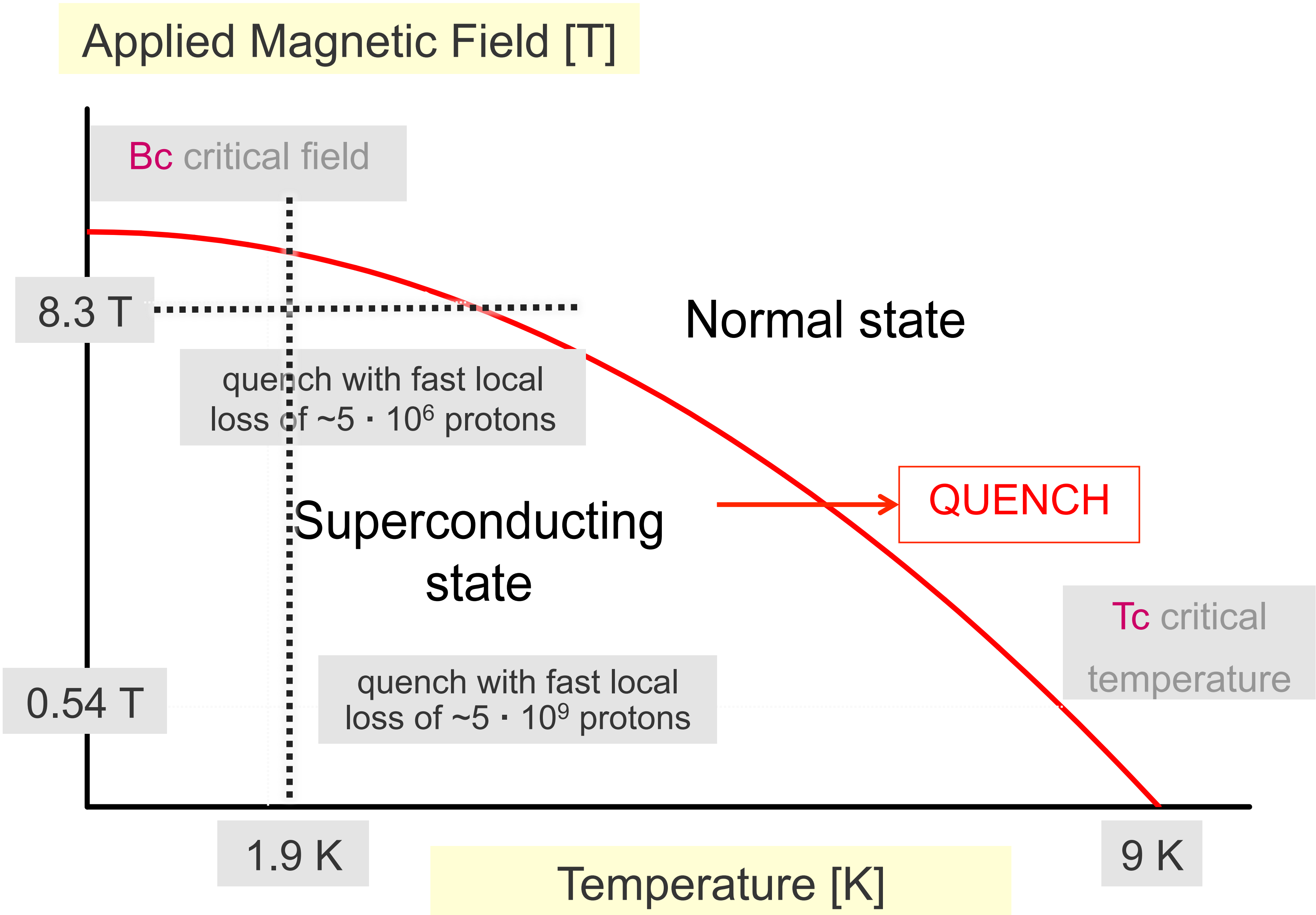


100% cold tests at CERN (up to ultimate field)

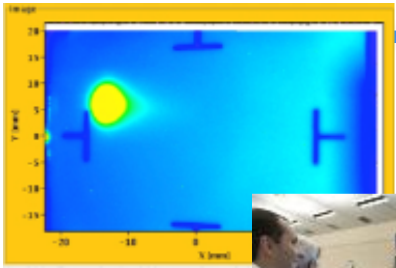
1232 main dipoles and 400 main quadrupoles

Cold magnetic performance measured on 20% of the magnets (correlation between warm and cold measurements)

Operational margin of the 8.3 T superconducting magnet

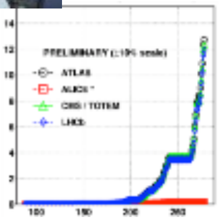


August 2008
First injection test



3.5 TeV

November 29, 2009
Beam back



fb^{-1}
1380 bunches

September 10, 2008
First beams around

June 28 2011
1380 bunches

1380

4 July, 2012
Higgs discovery

October 14 2010
1e32
248 bunches

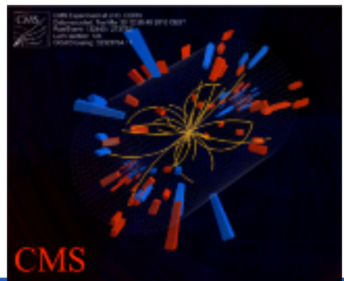
April 2010
Squeeze to 3.5 m

6 June, 2012
6.8e33

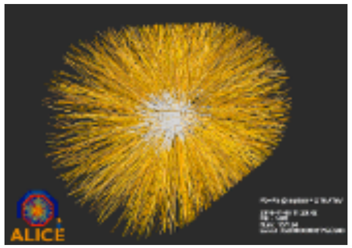
2008 | 2009 | 2010 | 2011 | 2012

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at



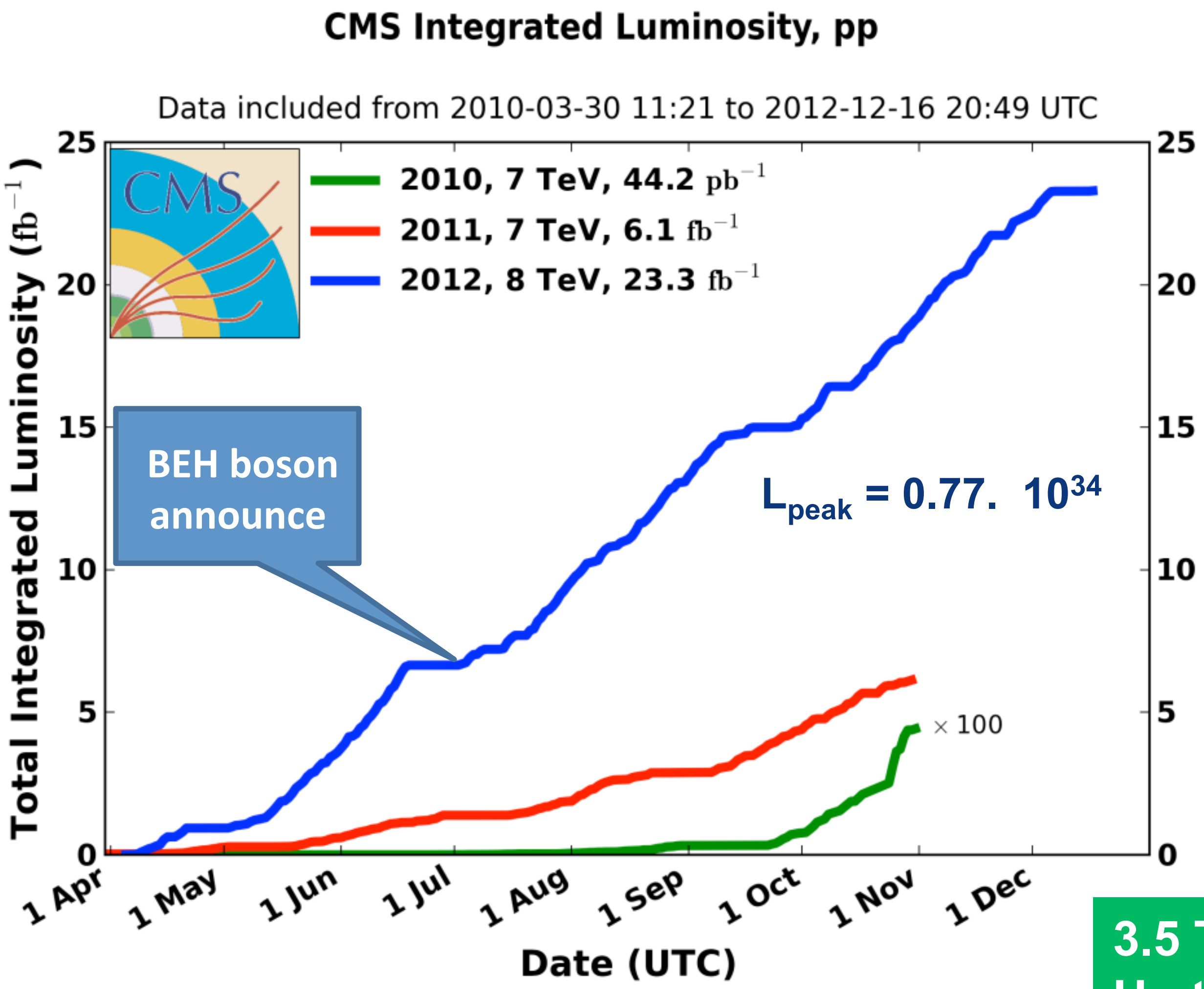
November 2010
Ions



18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

LHC Timeline

2010-2012: LHC integrated luminosity



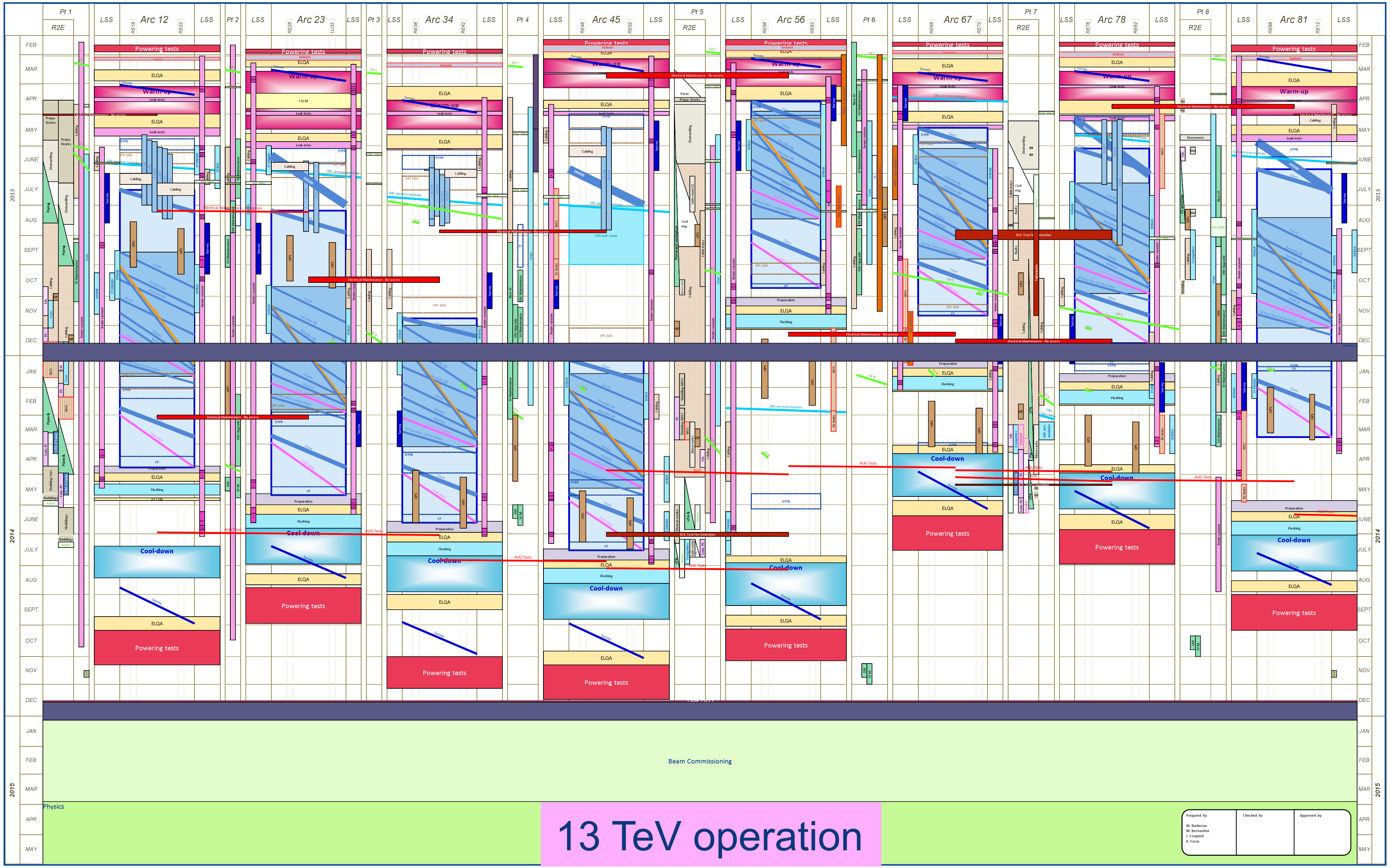
2010: **0.04 fb^{-1}**
7 TeV CoM
Commissioning

2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits

2012: **23.3 fb^{-1}**
8 TeV CoM
… production

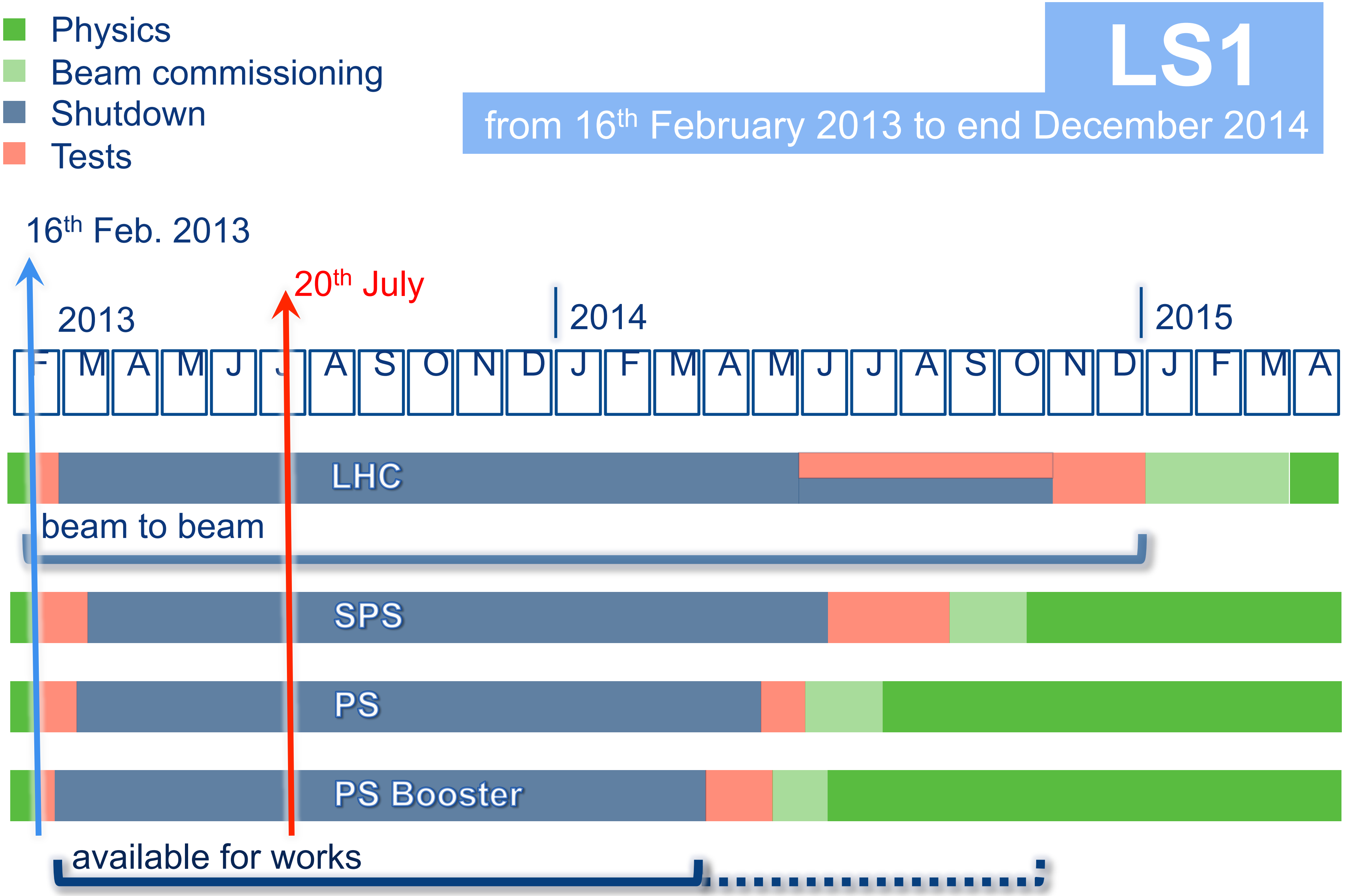
3.5 TeV and 4 TeV in 2012
Up to 1380 bunches
with1.5 10^{11} protons

LS1: LHC schedule



LS1

from 16th February 2013 to end December 2014



The European Strategy for Particle Physics Update 2013

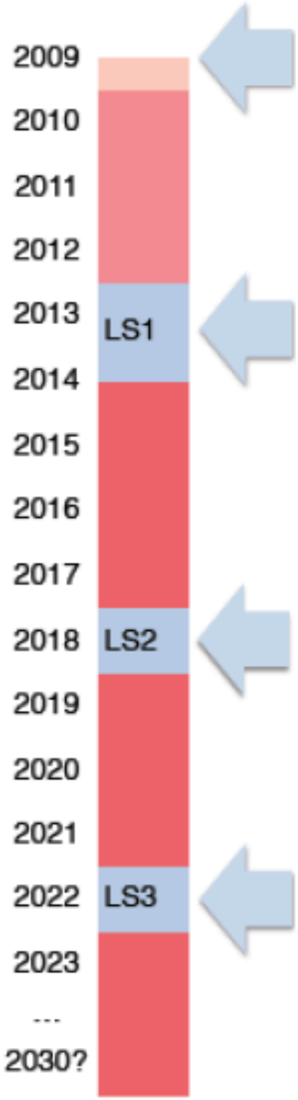
c) *Europe's top priority should be the* ***exploitation of the full potential of the LHC****, including the high-luminosity upgrade of the machine and detectors with a view to collecting* ***ten times more data than in the initial design, by around 2030****. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU** (Linac 4, Booster 2GeV, PS and SPS upgrade)

“Exploitation of the full potential of the LHC"



✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity

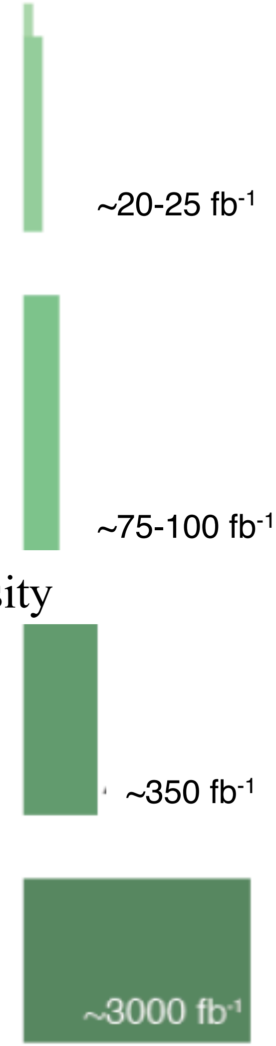
$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-1 upgrade to ultimate design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-2 upgrade, IR, crab cavities?

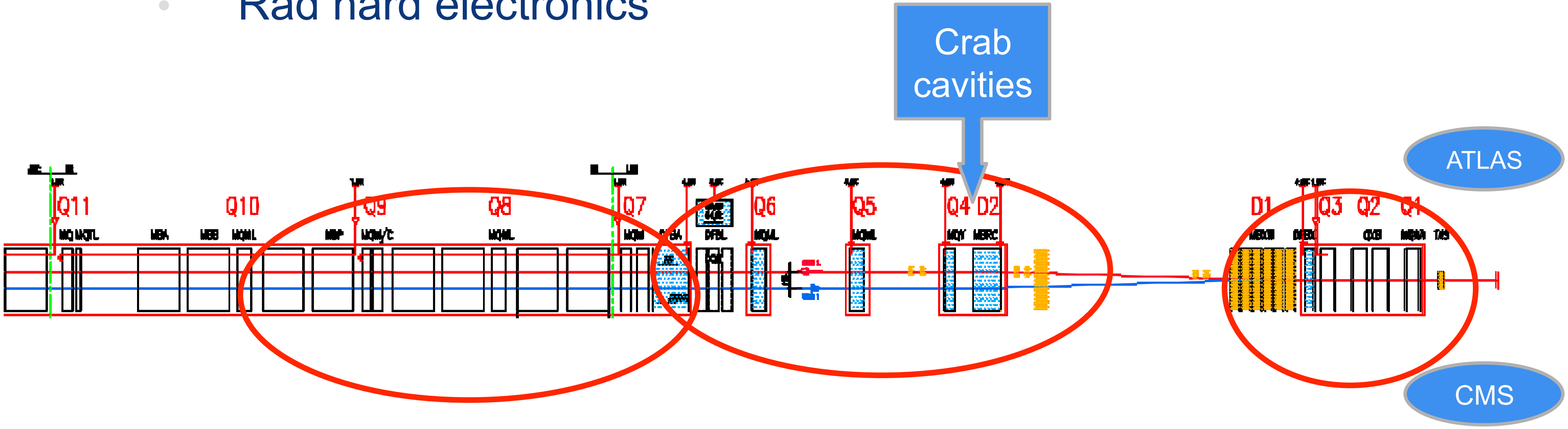
$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling



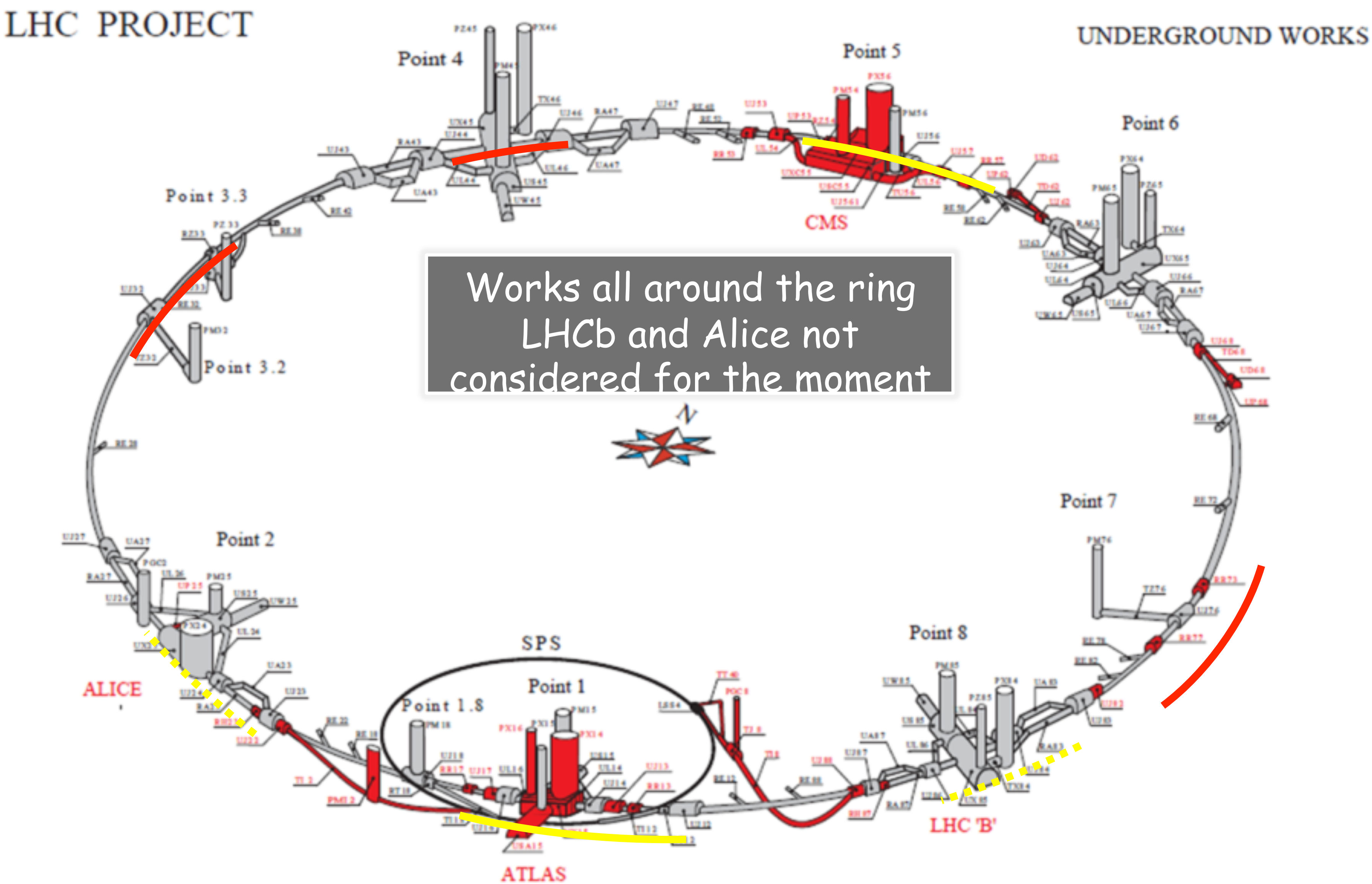
“Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. “

Hardware for the Upgrade

- New high field insertion quadrupoles
- Upgraded cryogenic system for IP1 and IP5
- Upgrade of the intensity in the Injector Chain
- Crab Cavities to take advantage of the small beta*
- Single Event Upsets
  - SC links to allow power converters to be moved to surface
  - Rad hard electronics



Where to intervene: > 1.2 km of LHC

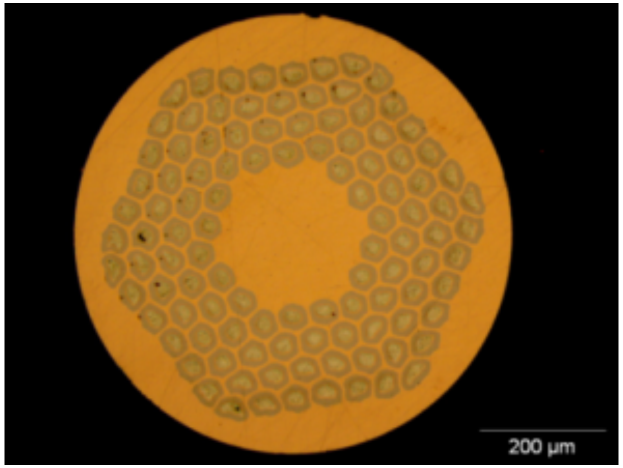


Works all around the ring
LHCb and Alice not
considered for the moment

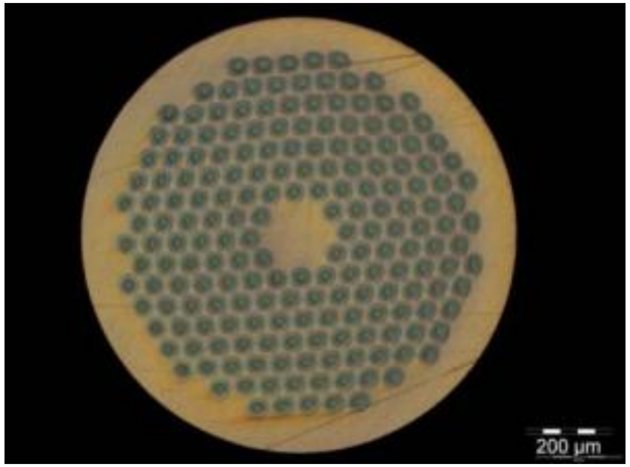
The « new » material : Nb_3Sn

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb_3Sn (and Nb-Ti).
- 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 tons in 2010-2015! It is comparable to LHC!

- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 μm), large coupling current...
  - Cost is 5 times LHC Nb-Ti



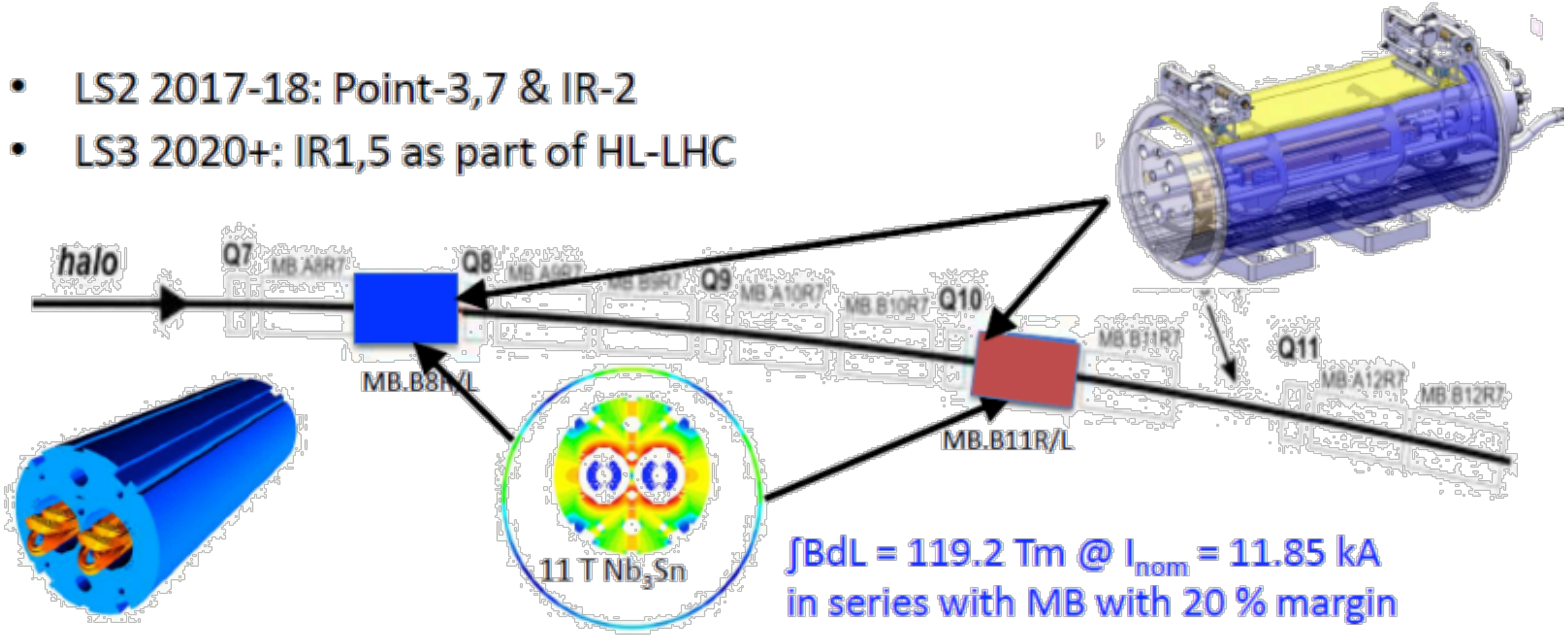
0.7 mm, 108/127 stack RRP from **Oxford OST**



1 mm, 192 tubes PIT from **Bruker EAS**

LS2 : 2018, collimators and 11T Dipole

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



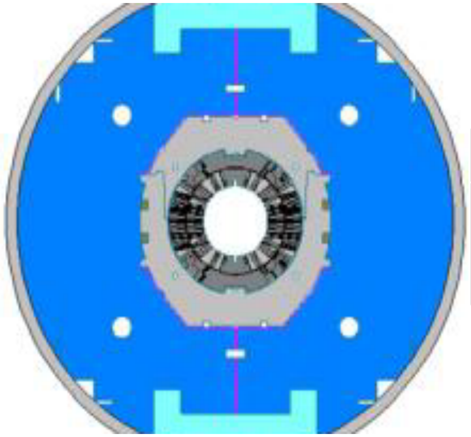
$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB with 20 % margin

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

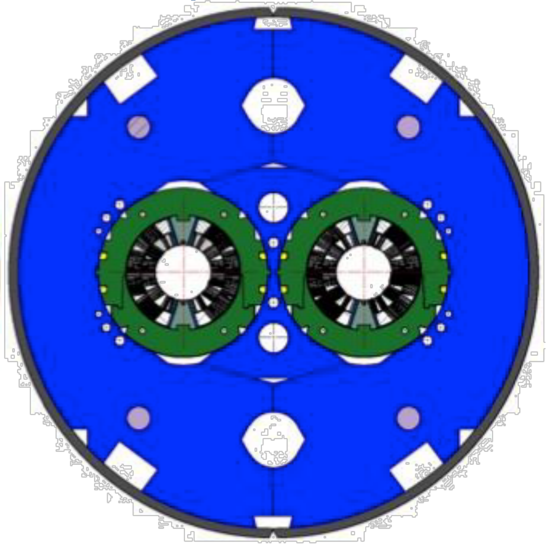
LS2: 24 coldmass + 4 spares = 28 CM
LS3: 16 coldmass + 4 spares = 20 CM
Total 48 CM

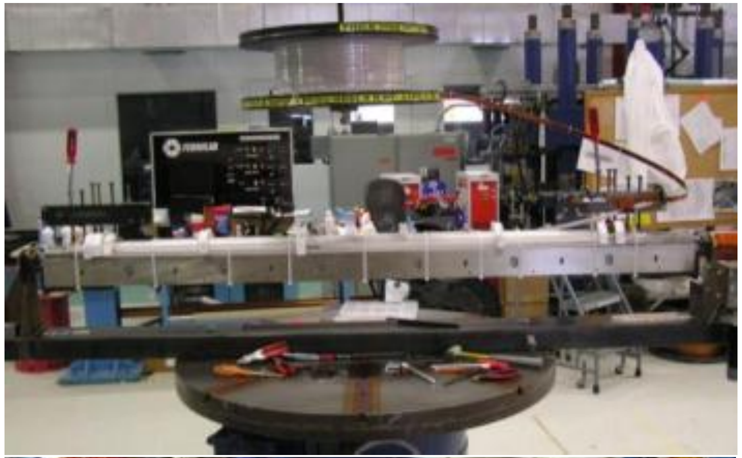
Nb_3Sn 11T Dipole R&D

Single aperture model



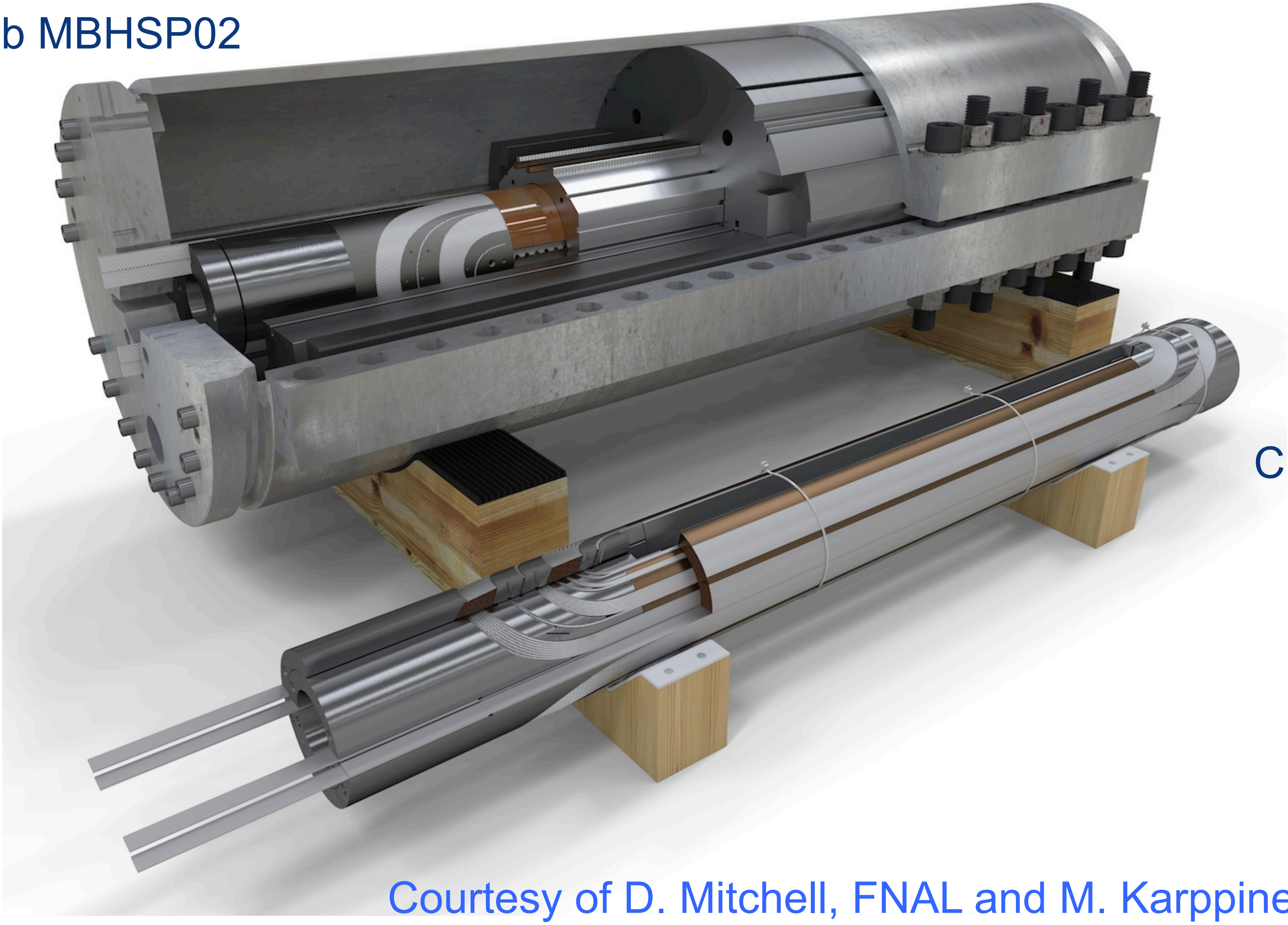
Twin aperture model





Fermilab

DS (Dispersion Suppressor) 11T MB models



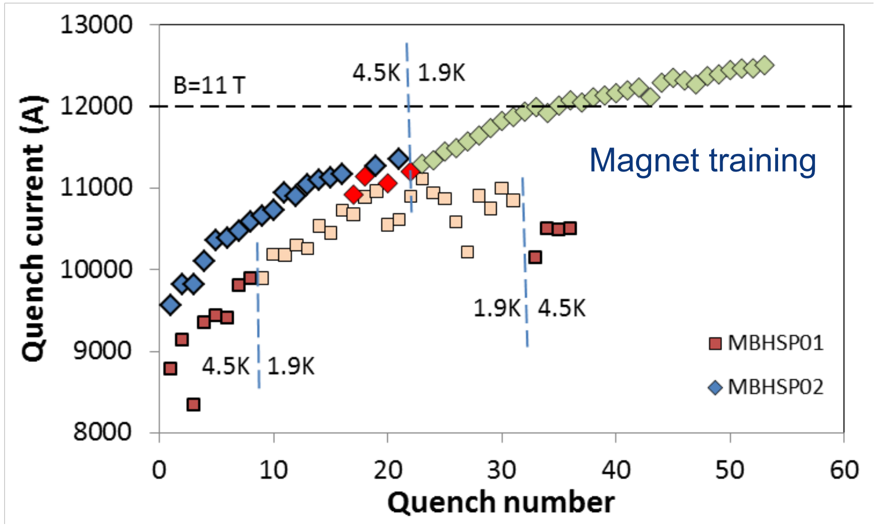
Courtesy of D. Mitchell, FNAL and M. Karppinen, CERN

MBHSP02 Performance

Test completed in April 2013

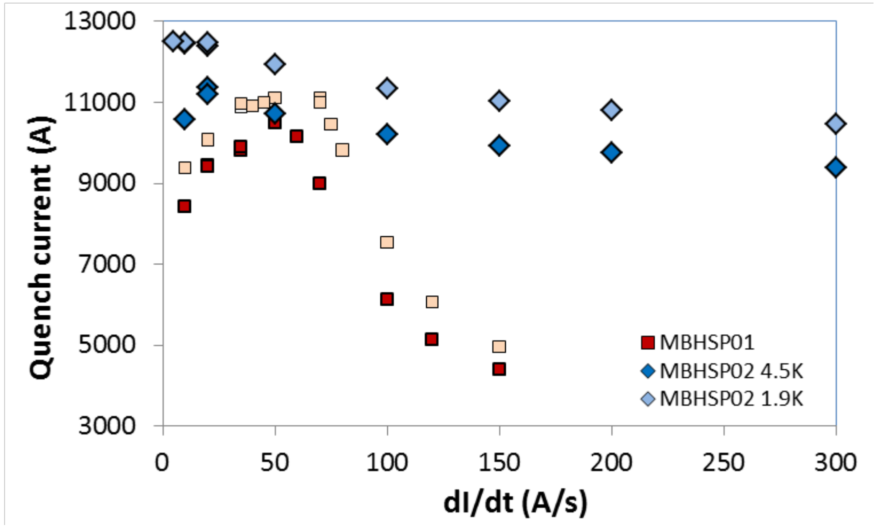
Bmax= 11.7 T – 97.5% of design field

B=12T (78% of SSL at 1.9 K)



Issues to be addressed

- Long training
- Conductor degradation
- Negative ramp rate dependence at dI/dt<20 A/s and 4.5 K



Ramp rate dependence

Tests at Fermilab, reported by courtesy of M. Karppinen, CERN

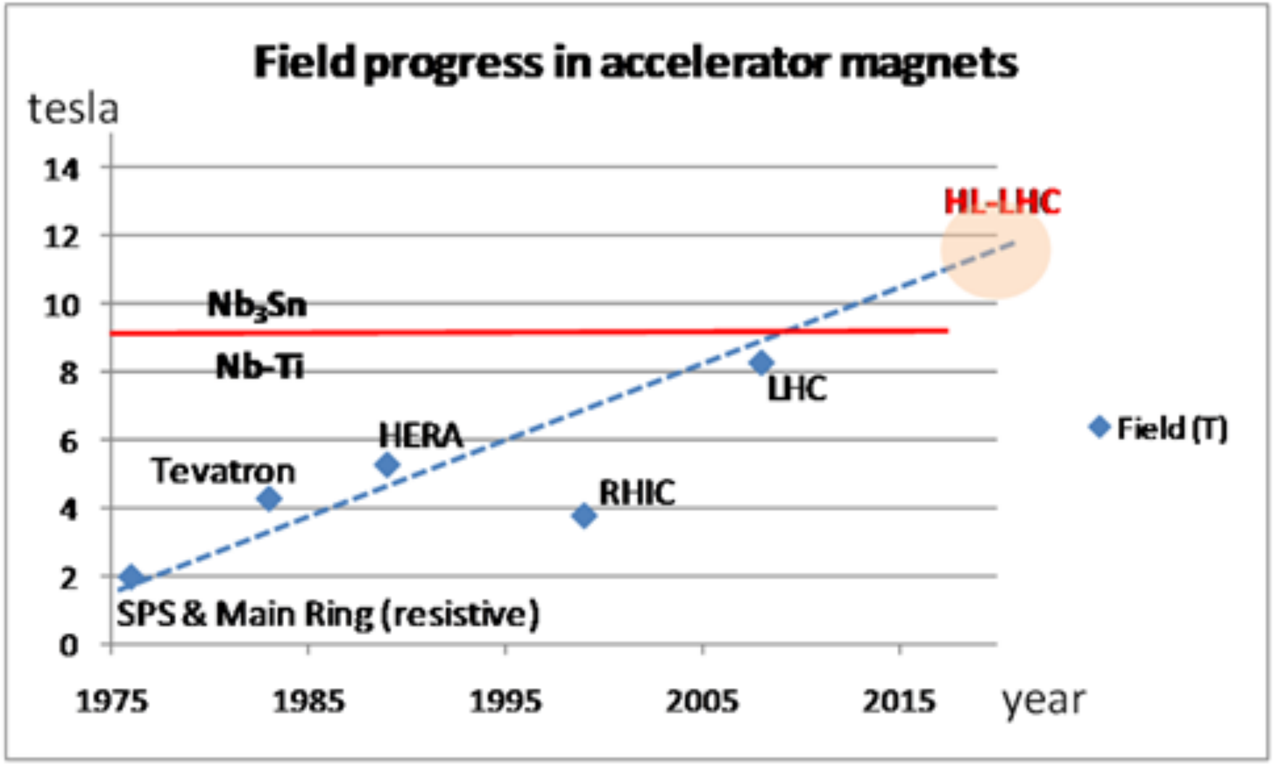
Squeezing the beams: High Field SC Magnets

13 T, 140 mm aperture Quads for the inner triplet

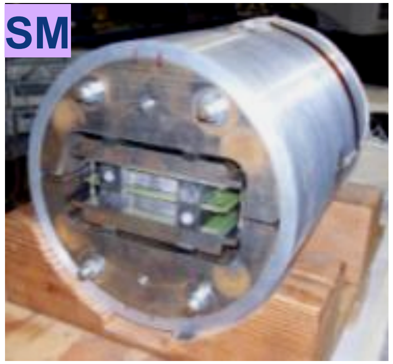
LHC: 8 T, 70 mm.

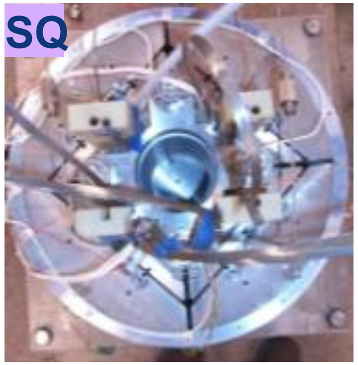
More focus strength, β* as low as 15 cm (55 cm in LHC).
In some scheme even β* down to 7.5 cm are considered

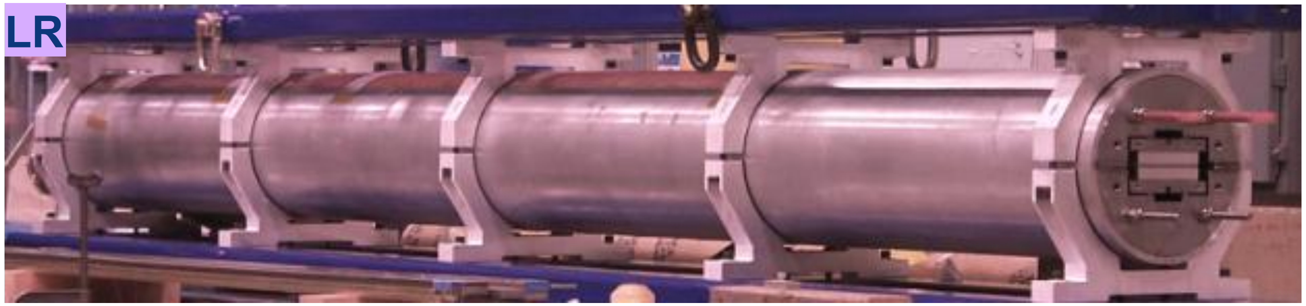
Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture
(LHC: 1.8 T, 70 mm)

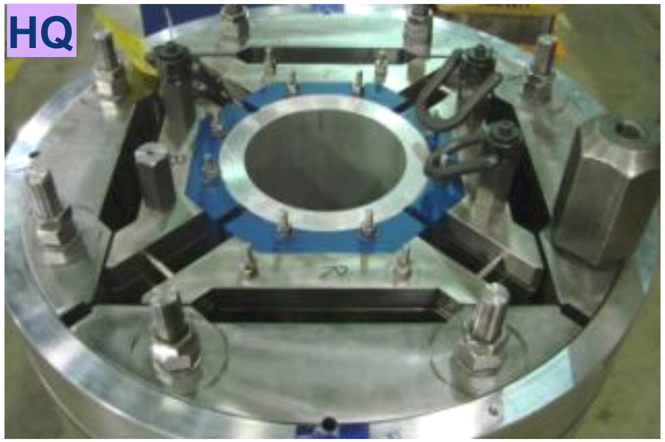


LARP (US LHC program) Magnets

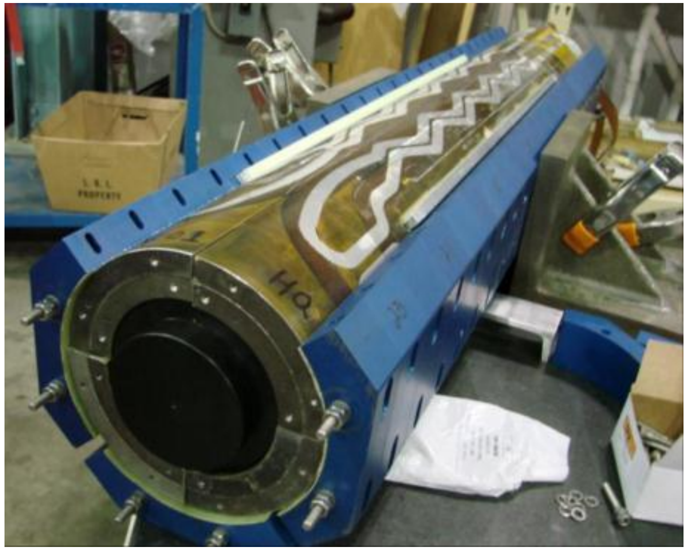


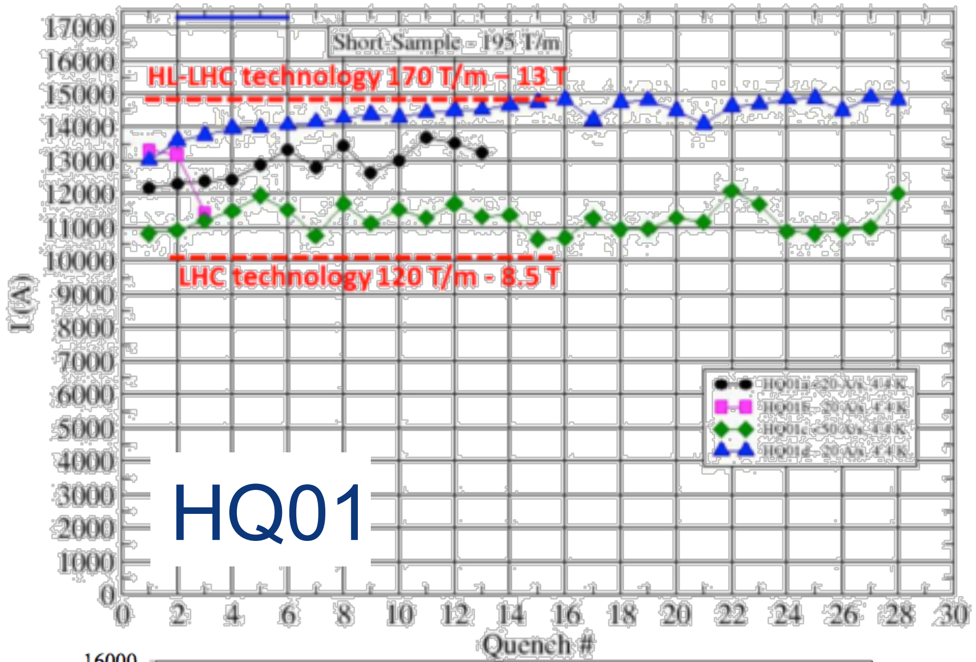


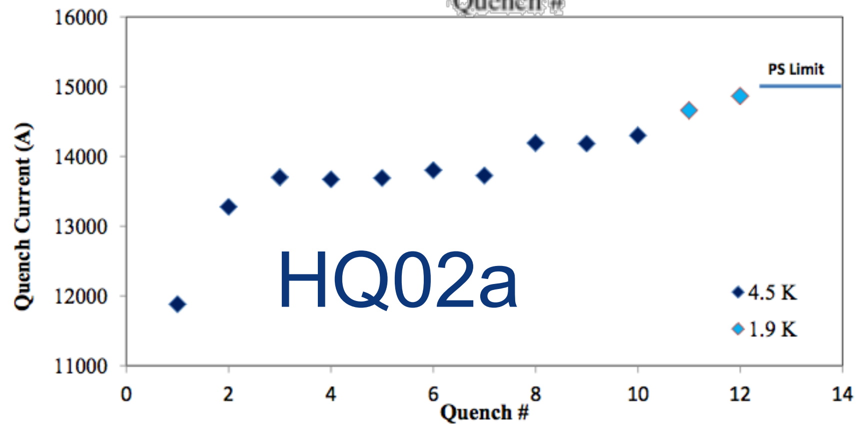




LARP HQ performance



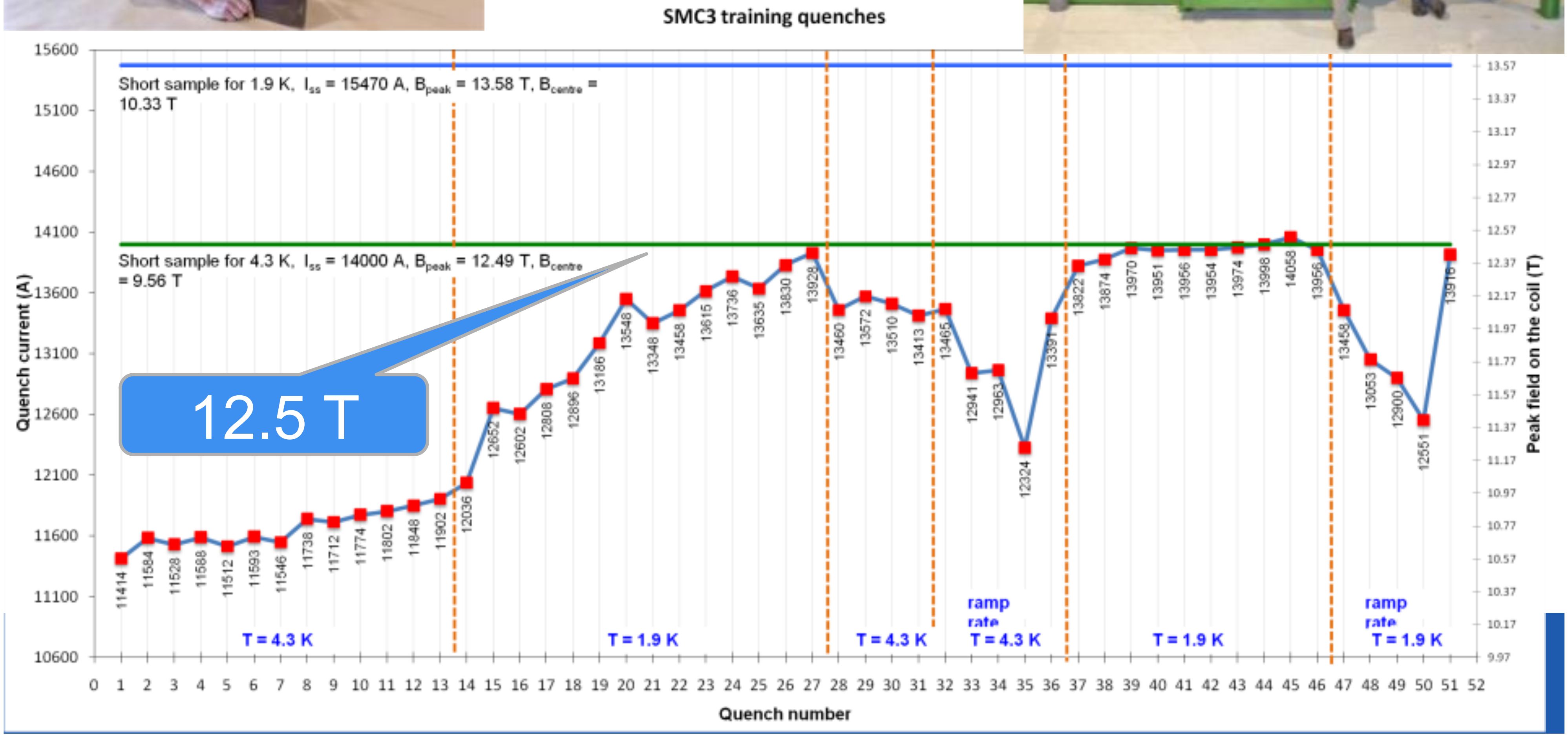




- The test of HQ02 is on-going, but we see very promising results !

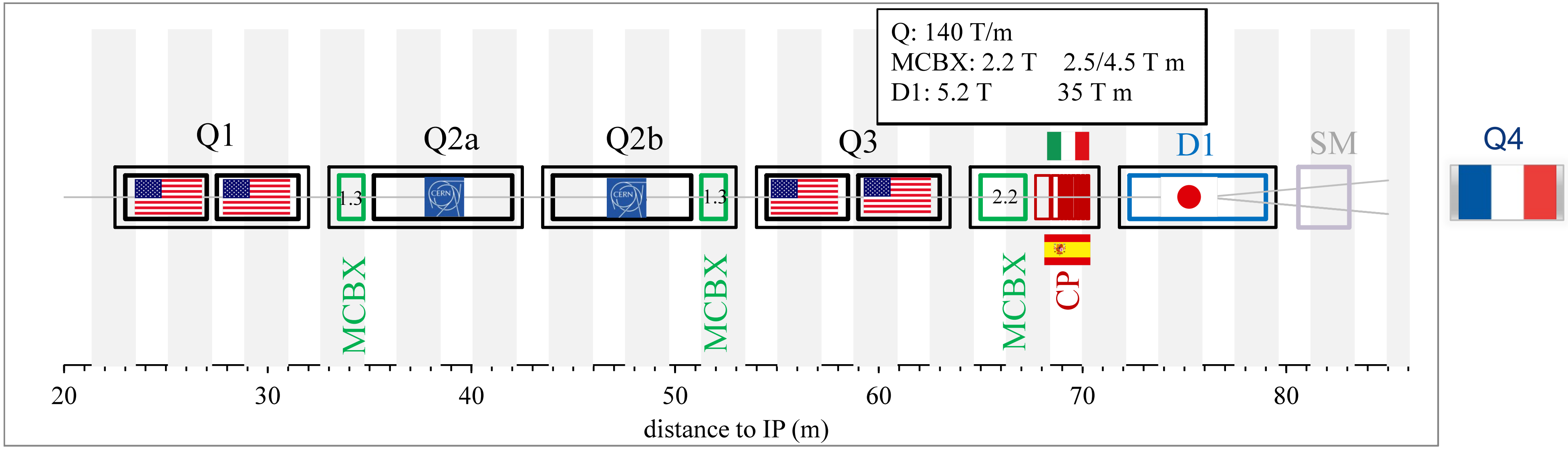
Courtesy of G. Chlachidze, FNAL

CERN: achievement of **12.5 T** at 4.2 K in a (first) 400 mm Nb_3Sn coil!



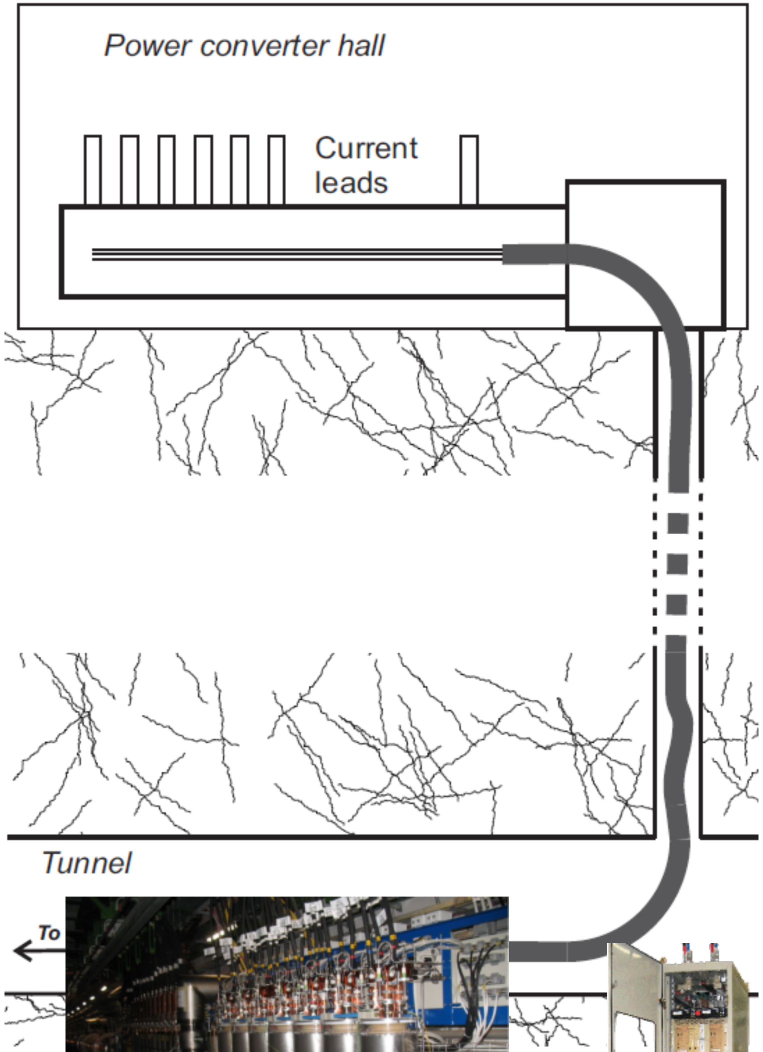
Setting up International collaboration

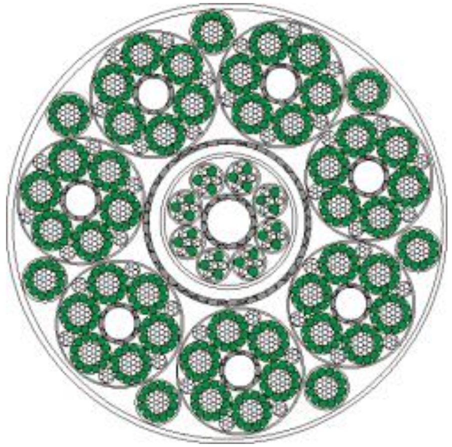
with national laboratories but also involving industrial firms



Baseline layout of HL-LHC IR region

R2E: Removal of Power Converter (200kA-5 kV SC cable, 100 m height)





Φ = 62 mm

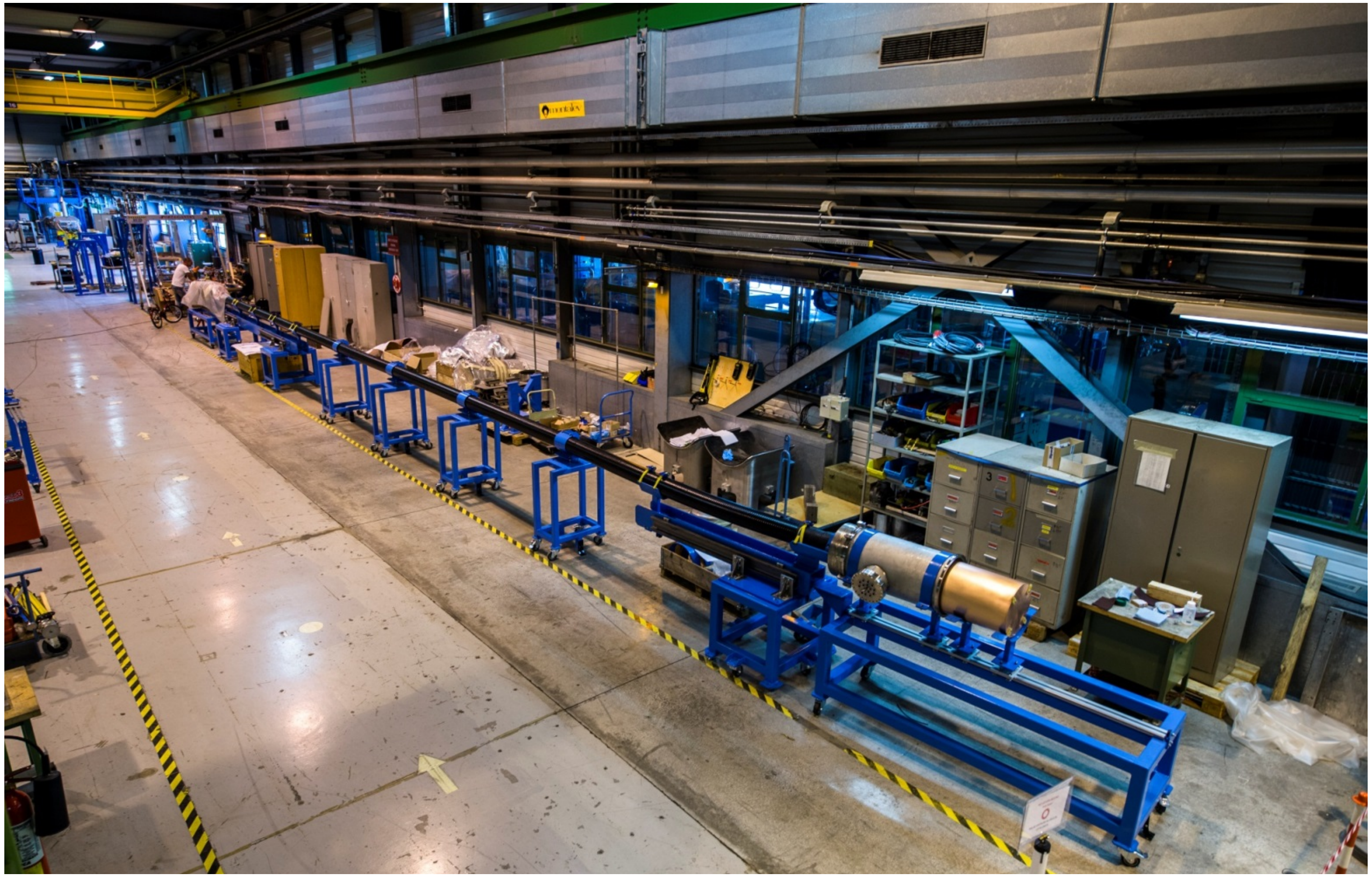
MgB_2
(or other HTS)

7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables – Itot~120 kA @ 30 K

Also DFBs (current lead boxes) removed to surface
Final solution to R2E problem – in some points
Make room for shielding un-movable electronics
Make the maintenance and application of ALARA principle much easier

SC Link prototype test

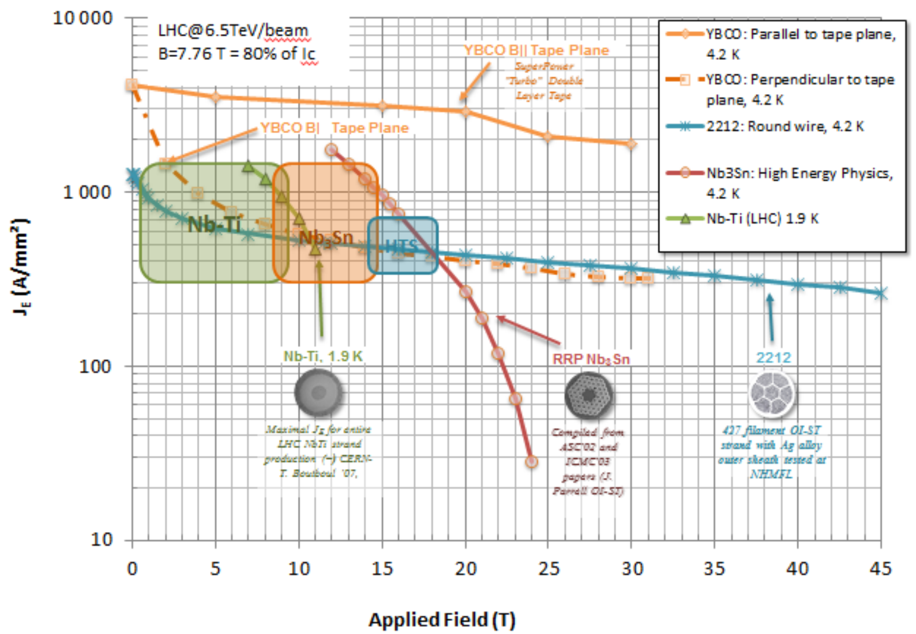
New feed-box for supercritical helium (10 g/s) variable temperature (5 K … > 77K) and high current (13 kA)
Flexible cryostat to host various cable types and materials, up to 20 m length



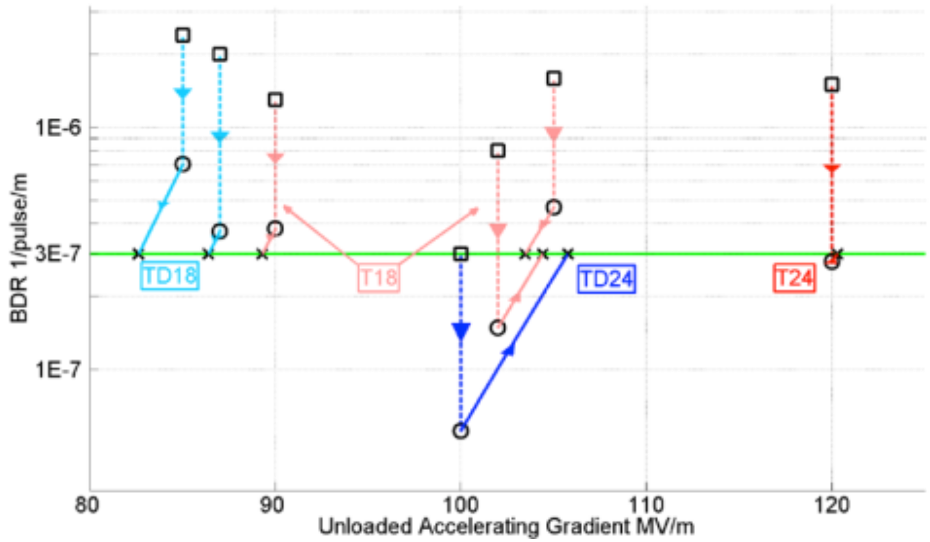
“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”

d) *CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets** and **high-gradient accelerating structures**, **in collaboration with national institutes, laboratories and universities worldwide.***

HFM

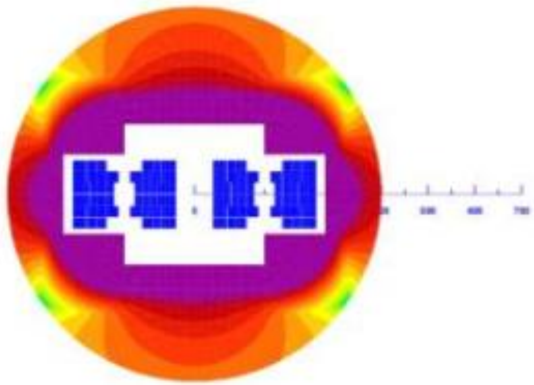


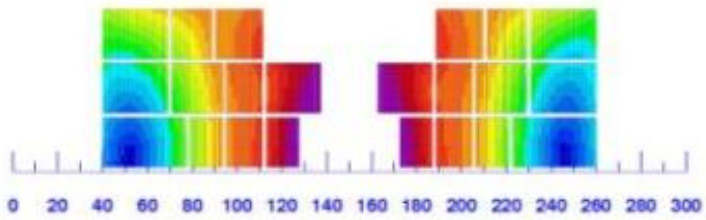
HGA

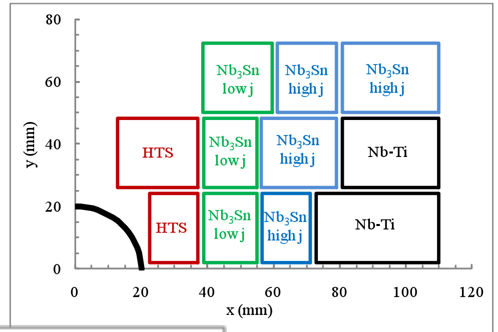


And also R&D on Proton-Driven Plasma Wakefield Acceleration (AWAKE Expt at CERN)

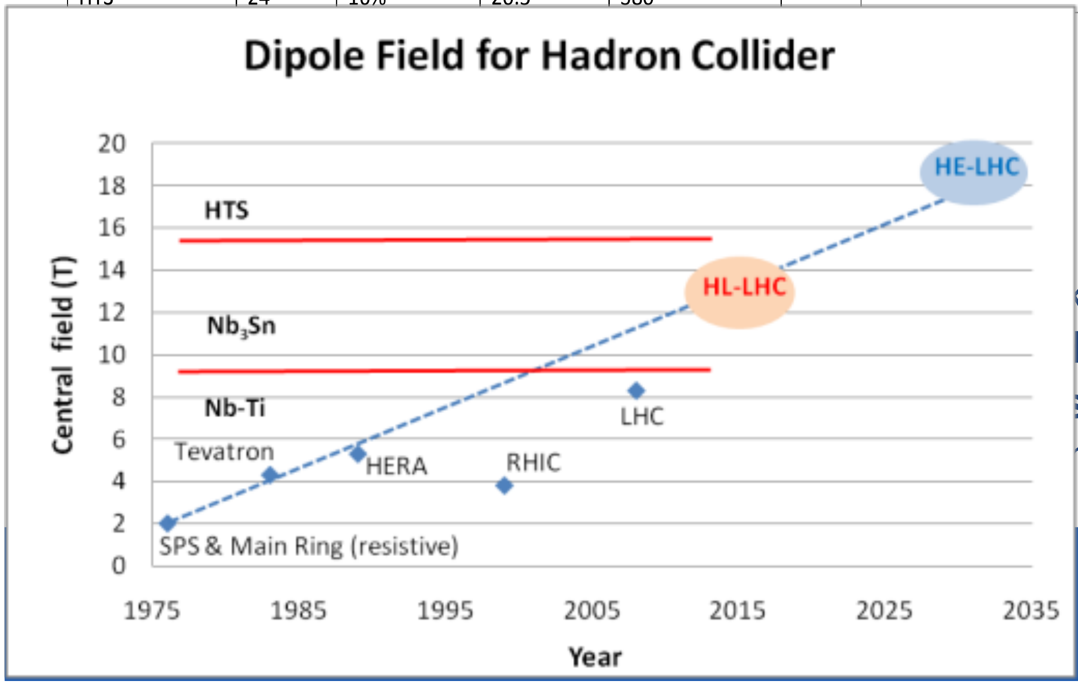
Malta Workshop: **HE-LHC @ 33 TeV c.o.m.**
14-16 October 2010







Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380



Magnet design (20 T): very challenging but not impossible.

300 mm inter-beam

Multiple powering in the same magnet (and more sectioning for energy)

Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam .

Otherwise limit field to 15.5 T for 2x13 TeV

Higher INJ energy is desirable (2xSPS)

ng the beam screen at 60 K.

ks to dumping time.

IC. Reaching $2x10^{34}$ appears reasonable.

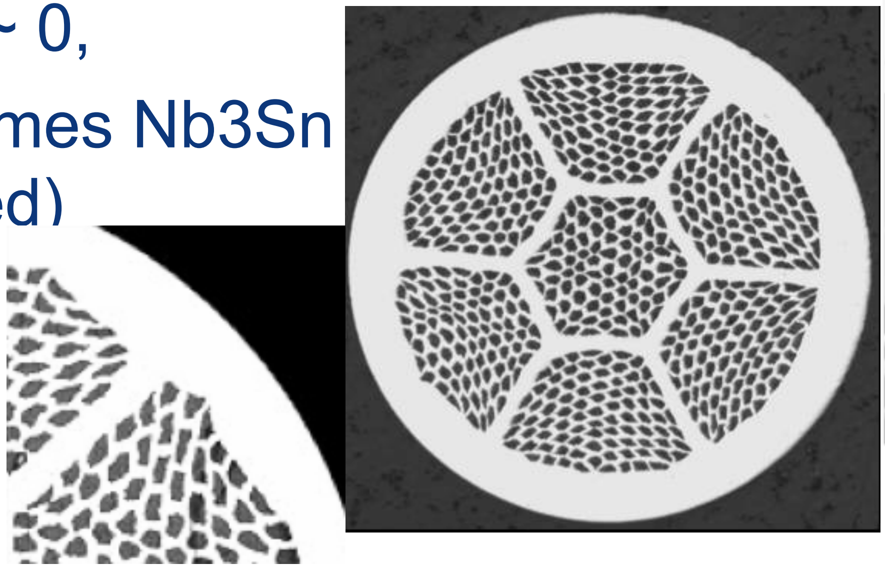
s beam handling for INJ & beam dump:

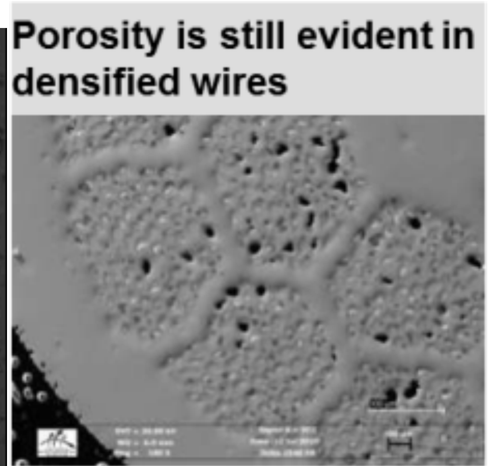
nake twice more room for LHC kickers.

The « new » materials -2 : HTS Bi-2212

- Round wire, isotropous and **suitable to cabling**!
- HEP only users (good < 20K and for compact cable)
- Big issue: very low strain resistance, brittle
- Production ~ 0,
- cost ~ 2-5 times Nb_3Sn (Ag stabilized)

- DOE program 2009-11 in USA let to a factor 2 gain. We need another 50% and more uniformity, eliminating porosity and leakage

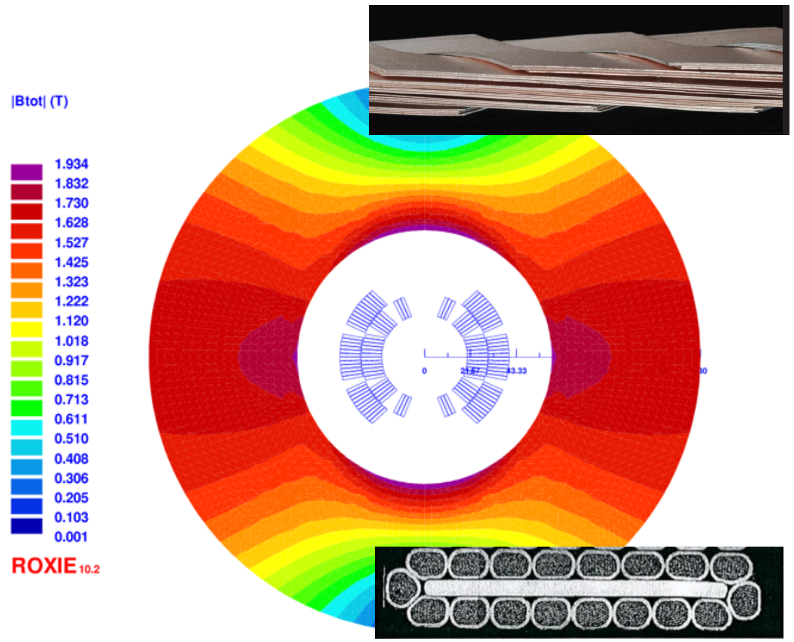




J. Jiang et al 2011

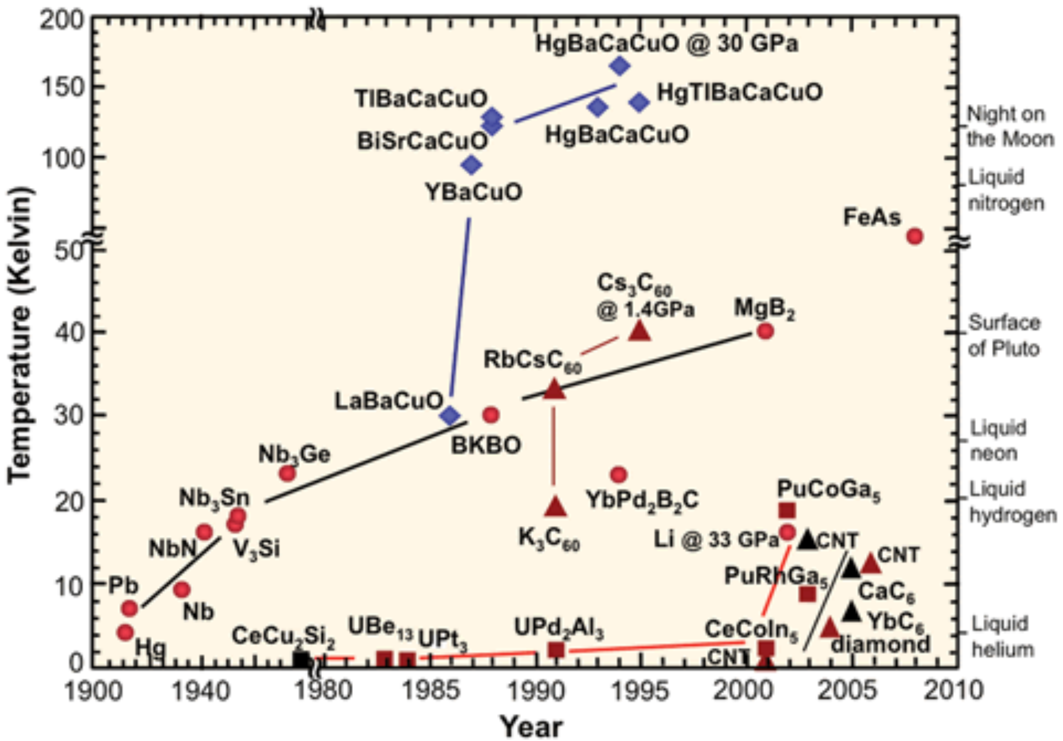
Program Eucard2 on HTS

EuCARD2: Develop 10 kA class HTS accelerator cable using Bi-2212 and YBCO. Test stability, magnetization, and strain tolerance



WP10: a 5 T, 40 mm bore HTS dipole

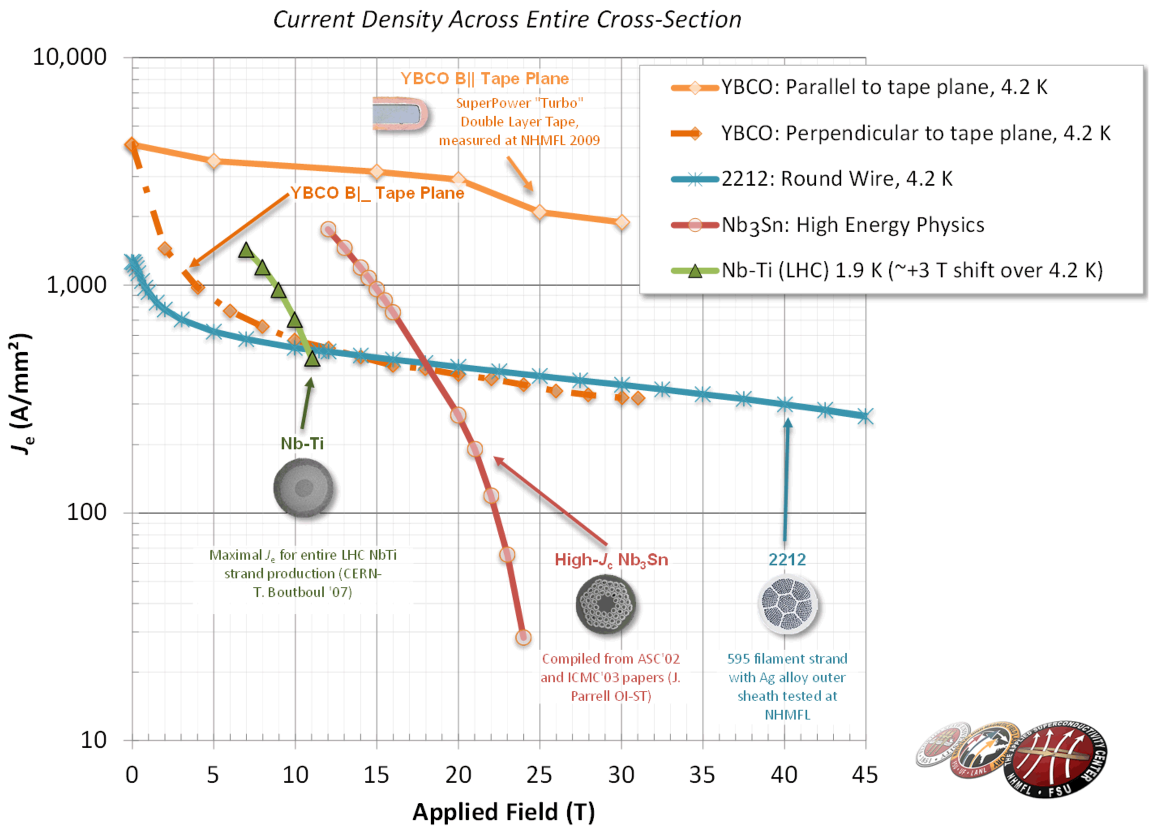
From materials to applications



Superconductors as seen by the eye of a physicist

The grand challenge of today is to find the **room temperature superconductors**

From materials to applications



Superconductors as seen by the eye of an engineer

The grand challenge of today is to develop the technology of **high-field superconductors**

Summary – LTS (NbTi ; Nb_3Sn)

NbTi mature but limited to 9T

Is Nb_3Sn mature ? Yes, and no

performance of Nb_3Sn wires has seen a great boost in the past decade (factor 3 in J_C w/r to ITER)

However, Nb_3Sn magnets were never built nor operated in accelerators. Manufacturing, quench, training, protection, strain tolerance, field quality are the focus today to make this new technology a reality

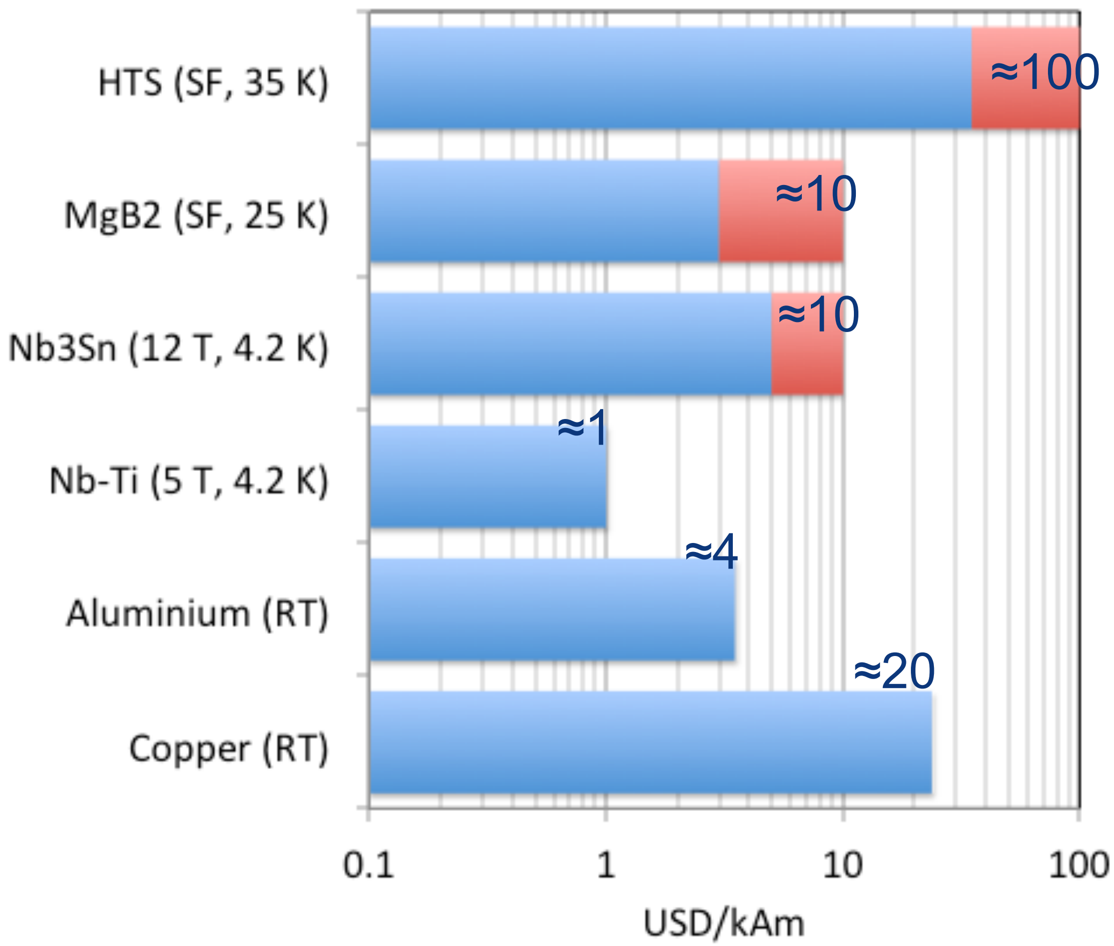
Solid and aggressive R&D in HFM (High Field Magnet) for accelerators must be intensified

Summary - HTS

Can HTS displace LTS ? Not today

- Much needs to be done to bring this technology to a point where it can be sold as “mature”
  - Materials have potential that can be exploited
    - OPHT for BSCCO-2212
    - Thicker layer for YBCO tapes
    - The Holy Grail of a round YBCO wire
- Production quantities, homogeneity and cost need to evolve
- Step-up application demands, from self-field (SC-link is an ideal test-bed) to high-field accelerator magnets (feasibility)

From materials to applications



Superconductors as seen by the eye of a manager

The grand challenge of today is availability of **long lengths of reasonably priced commercial materials**

"…exploitation of the full po
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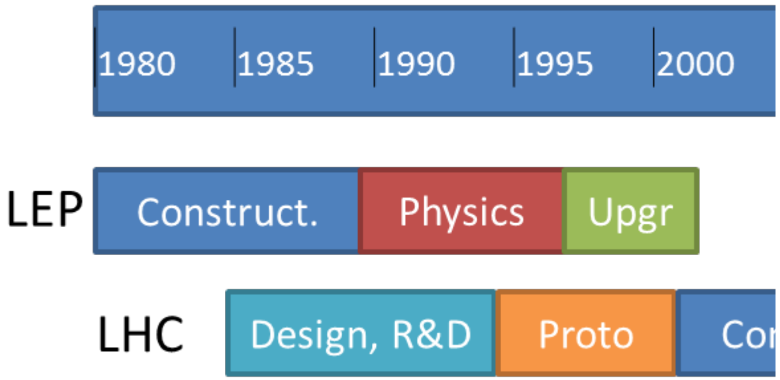
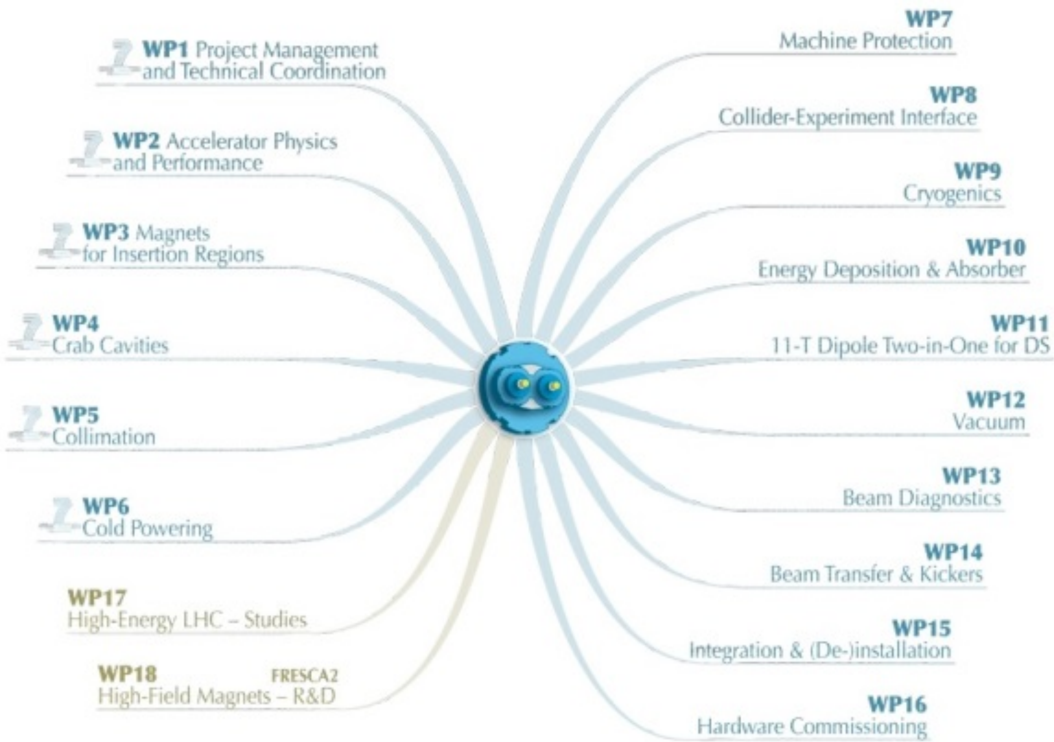
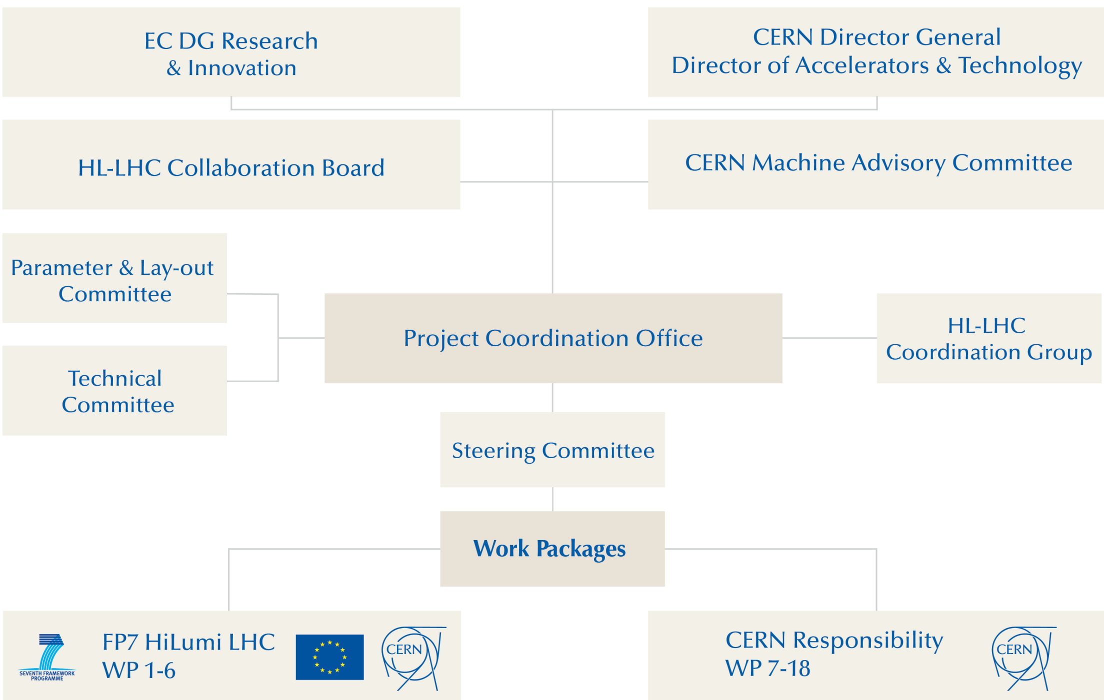
=> High L



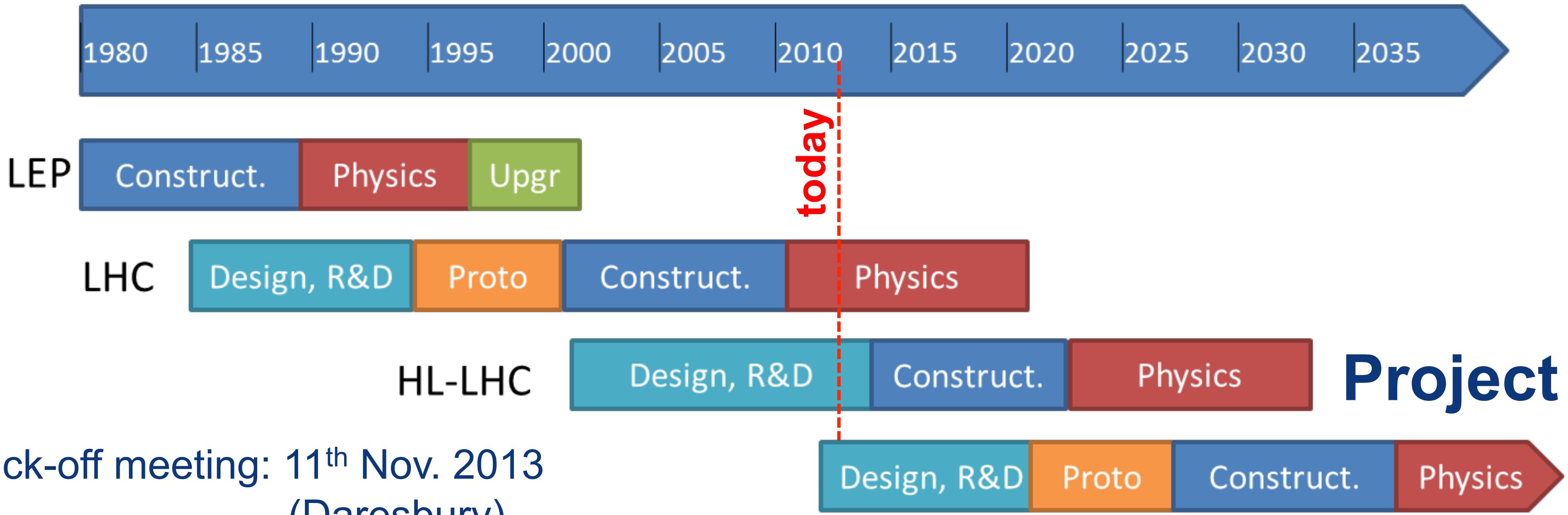
High Luminosity LHC Projec



Project



"CERN should undertake design studies for accelerator projects in a global context, with emphasis on ***proton-proton*** *and electron- positron* ***high-energy frontier machines.****"*



Kick-off meeting: 11th Nov. 2013 (Daresbury)

Study : VHE-LHC with TLEP

Kick-off meeting: February 2014 (CERN)

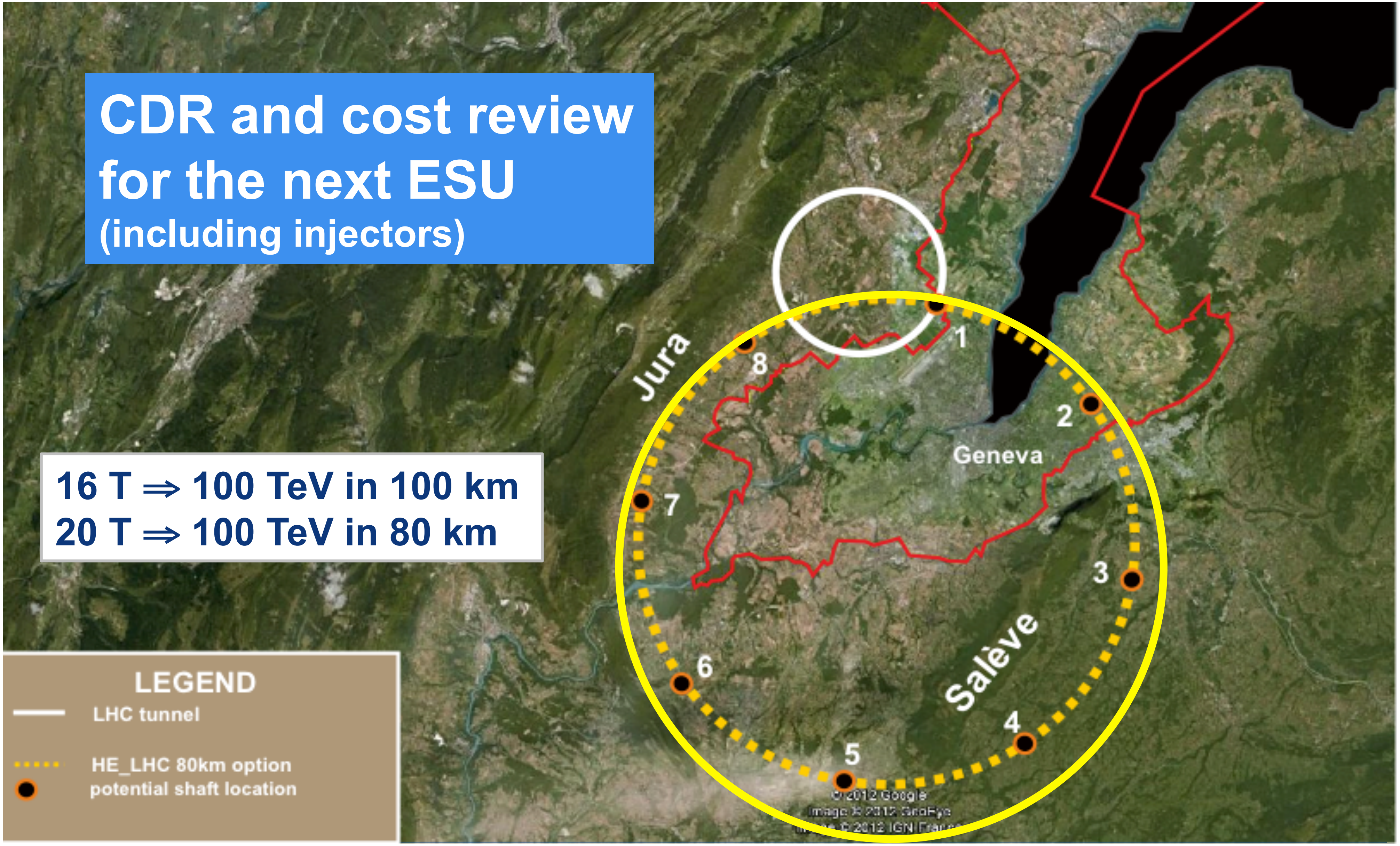
80-100 km tunnel in Geneva area – VHE-LHC

with possibility of e+-e- (TLEP) and p-e (VLHeC)

CDR and cost review for the next ESU

(including injectors)

16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km

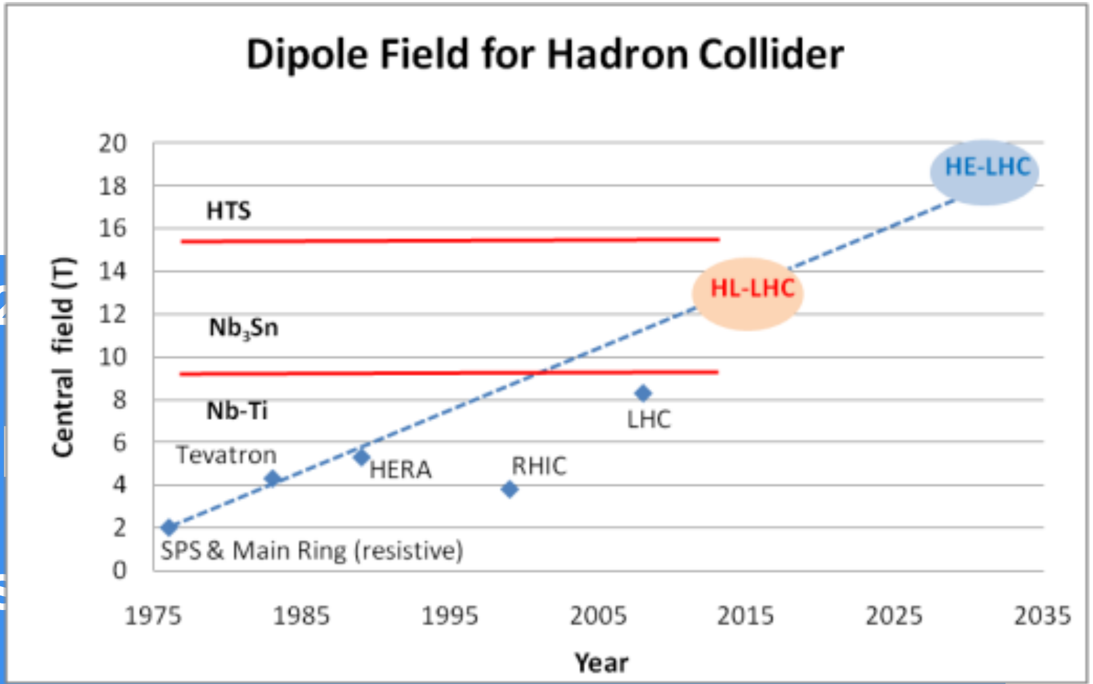


Conclusion

- LS1 (13-14 TeV) [2013-2

- LS2 (higher intensity)

- HL-LHC : R&D => cons



- **Vigorous R&D and preparation for post-LHC machine** (CDR and Cost-Schedule)

  Higher energy hadrons (VHE LHC) **15 to 20 T**

  to be ready for the next European Strategy Update

  (multi-lateral collaboration approach)

Thanks for your attention

www.cern.ch

HE-LHC and VHE-LHC main parameters

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	< 40
beam half aperture [cm]	~ 2	~ 2	1.3	≤ 1.3
injection energy [TeV]	0.45	0.45	>1.0	>3.0
no. of bunches n_b	2808	2808	2808	8420
bunch population N_b [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5	2.5	3.8	13.5
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
rms bunch length [cm]	7.55	7.55	7.55	7.55
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	185	72
stored beam energy [MJ]	362	694	701	6610

2nd Workshop

Energy for Sustainable Science

at Research Infrastructures

CERN, GENEVA, SWITZERLAND 23-25 OCTOBER 2013

ENERGY.SUSTAINABLESCIENCE2013@CERN.CH
HTTP://CERN.CH/ENERGY.SUSTAINABLESCIENCE2013

MAIN THEMES

- **Energy Management at Research Infrastructures**
- **Procurement and Financing of Energy**
- **Energy Efficiency at Research Infrastructures**
- **Energy Efficiency in Computing Centres**
- **Sustainable Campus Development and Management**
- **Energy Quality and Operation**
- **Green Technologies developed at Research Infrastructures**

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