LHC & Future High-Energy Circular Colliders

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www.cern.ch

Outline

- **LHC recall in few slides**

- **Run 2 (from LS1 to LS2)** ⇒ ***13 TeV***
- **Run 2 and Run 3** ⇒ **300 fb^{-1}**

- **High Luminosity LHC project** ⇒ **3'000 fb^{-1}**

- **Post-LHC machines:**
  World studies
  Future Circular Colliders ⇒ ***towards 100 TeV***

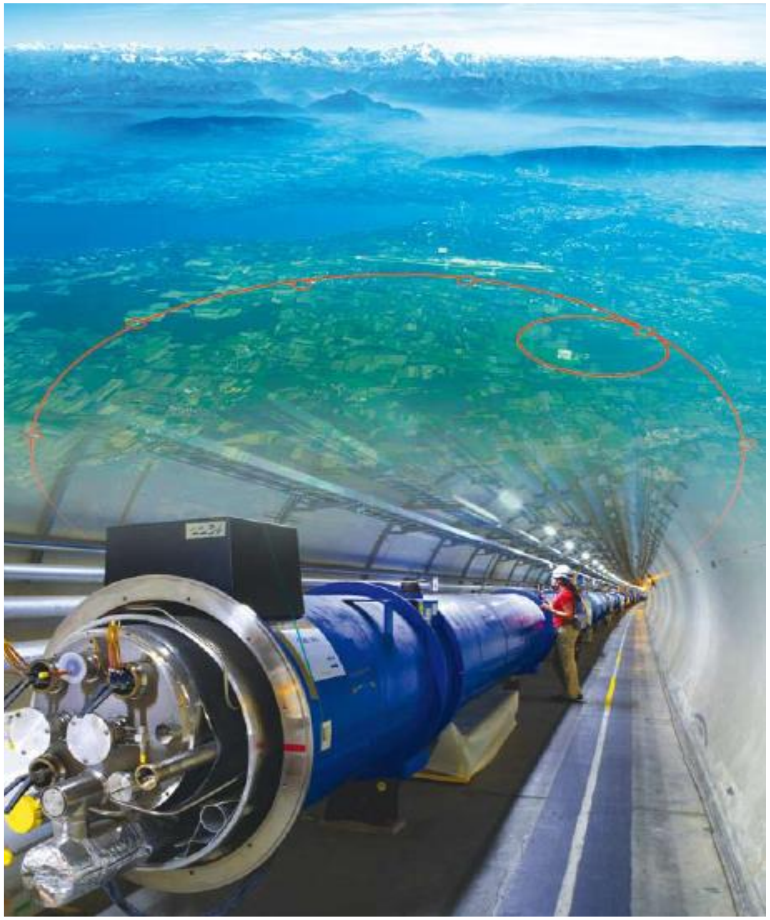
- **Conclusion**

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



2010-2035: Physics exploitation

2010 – 2012 : Run 1 ;7 and 8 TeV

2015 – 2018 : Run 2 ; 13 TeV

2021 – 2023 : Run 3 (13 TeV – 14 TeV)

2024 – 2025 : HL-LHC installation

2026 – 2035… : HL-LHC operation

HiLumi HL-LHC PROJECT

A 27 km circumference collider…

LHC: technological challenges

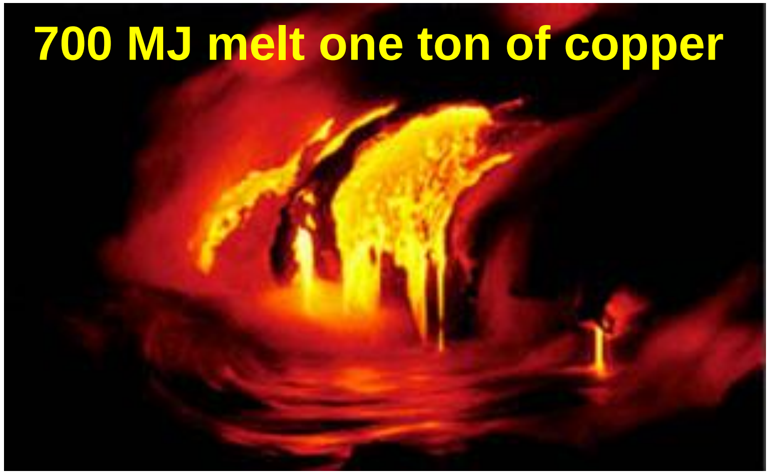
The specifications of many systems were over the state of the art.
Long R&D programs with many institutes and industries worldwide.

- **The highest field accelerator magnets: 8.3 T** (1232 dipole magnets of 15 m)
- **The largest superconducting magnet system** (~10'000 magnets)
- **The largest 1.9 K cryogenics installation** (superfluid helium, 150 tons of LHe to cool down 37'000 tons)
- **Ultra-high cryogenic vacuum for the particle beams** (10^{-13} atm, ten times lower than on the Moon)
- **The highest currents controlled with high precision** (up to 13 kA)
- **The highest precision ever demanded from the power converters** (ppm level)
- **A sophisticated and ultra-reliable magnet quench protection system**
  (Energy stored in the magnet system: ~10 Gjoule, in the beams > 700 MJ)

Energy management challenges

Energy stored in the magnet system: ~10 GJoule

Energy stored in the two beams: 720 MJ *[6 10^{14} protons (1 ng of H+) at 7 TeV]*



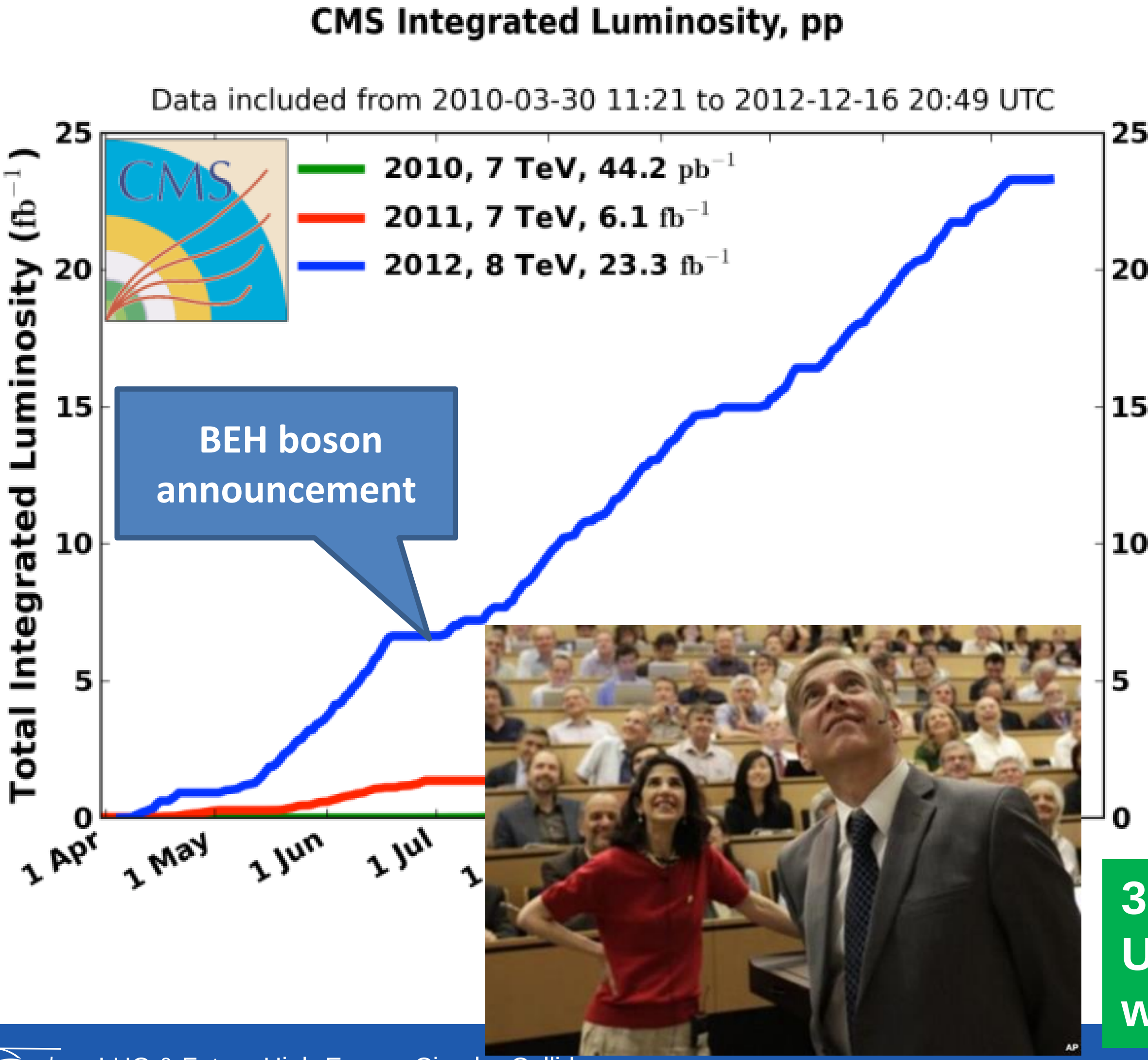
700 MJoule dissipated in 88 μs

700.106 / 88.106 ≅ 8 TW

World Electrical Installed Capacity ≅ 3.8 TW

1 electron volt = 1,602× 10^{-19} joule

LHC 2010-2012: a rich harvest of collisions



Σ ~30 fb^{-1}

~ 2 10^{15} collisions

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
with 1.5 10^{11} protons

From **individual** theoretical physicist **idea**….

…to **collective innovation** !

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Gold- stone theorem,[2] theories in which symmetry under contain zero-ma the conserved cu ternal group are purpose of the p as a consequence quanta of some the longitudinal ticles (which wo zero) go over in coupling tends to the relativistic non to which An that the scalar conducting neutr nal plasmon mo is charged.

The simplest havior is a gaug used by Goldstor fields φ_1, φ_2 and through the Lag

$L = -\frac{1}{2}(\nabla\varphi_1$

where

∇_μ

∇_μ

F

e is a dimension metric is taken simultaneous ga kind on $\varphi_1 \pm i\varphi_2$ Let us suppose spontaneous bre Consider the eq treating $\Delta\varphi_1$, Δ governing the p

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

*Work supported in part by the U. S. Atomic Energy Commission and in part by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

[1]R. Feynman and M. Gell-Mann, Phys. Rev. 109, 13 (1958).

[2]T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960); S. B. Treiman, Nuovo Cimento 15, 916 (1960).

[3]S. Okubo and R. E. Marshak, Nuovo Cimento 28, 56 (1963); Y. Ne'eman, Nuovo Cimento 27, 922 (1963).

[4]Estimates of the rate for $K^+ \to \pi^+ + e^+ + e^-$ due to induced neutral currents have been calculated by several authors. For a list of previous references see Mirza A. Baqi Bég, Phys. Rev. 132, 426 (1963).

[5]M. Baker and S. Glashow, Nuovo Cimento 25, 857 (1962). They predict a branching ratio for decay mode (1) of $\sim 10^{-6}$.

[6]N. P. Samios, Phys. Rev. 121, 275 (1961).

[7]The best previously reported estimate comes from the limit on $K_2^0 \to \mu^+ + \mu^-$. The 90 % confidence level is $|g_{\mu\mu}|^2 < 10^{-2}|g_{\mu\mu}|^2$: M. Barton, K. Lande, L. M. Lederman, and William Chinowsky, Ann. Phys. (N.Y.) 5, 156 (1958). The absence of the decay mode $\mu^+ \to e^+ + e^+ + e^-$ is not a good test for the existence of neutral currents since this decay mode may be absolutely forbidden by conservation of muon number: G. Feinberg and L. M. Lederman, Ann. Rev. Nucl. Sci. 13, 465 (1963).

[8]S. N. Biswas and S. K. Bose, Phys. Rev. Letters 12, 176 (1964).

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.[7,8] We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

We shall first treat the case where the original fields are a set of bosons φ_A which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reasonable.

(1) Lest the simplicity of the argument be shrouded in a cloud of indices, we first consider a one-parameter Abelian group, representing, for example, the phase transformation of a charged boson; we then present the generalization to an arbitrary compact Lie group.

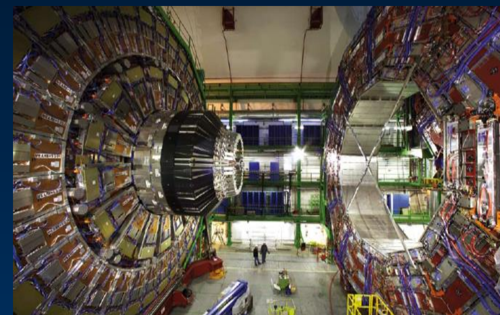
The interaction between the φ and the A_μ fields is

$$H_{\mathrm{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \quad (1)$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that $\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$.

We shall assume that the application of the

1964



1964-2012

Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

2013 - 2015

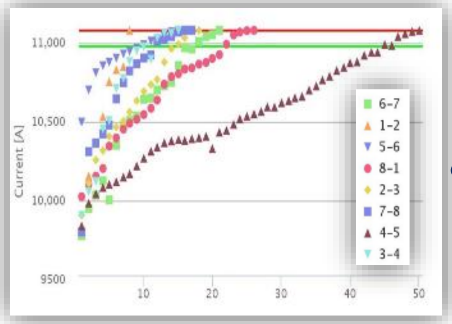
28th October
Physics with record number of bunches
Peak luminosity 5 x 10^{33} $cm^{-2}s^{-1}$

April ‘13 to Sep. ‘14

3rd June
First Stable Beams

5th April

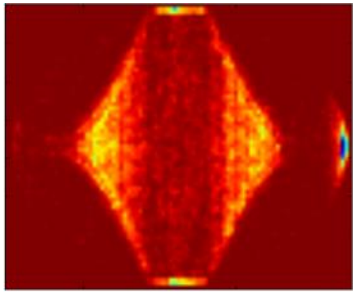
13-14 | Aug 14-Apr | 2015



Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



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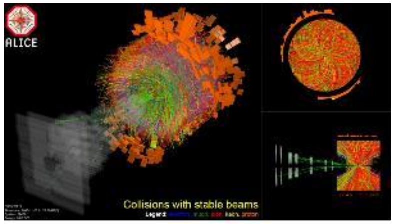
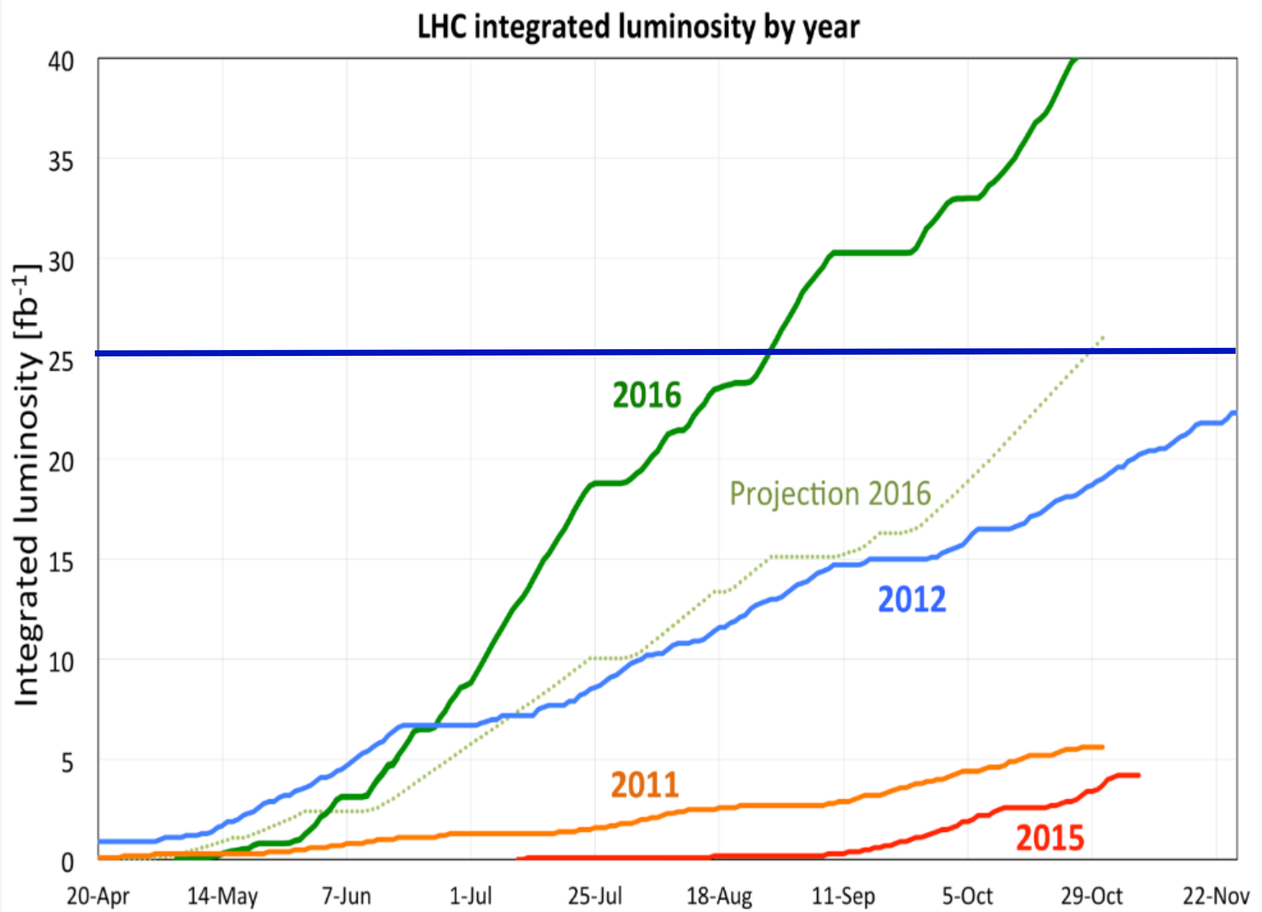


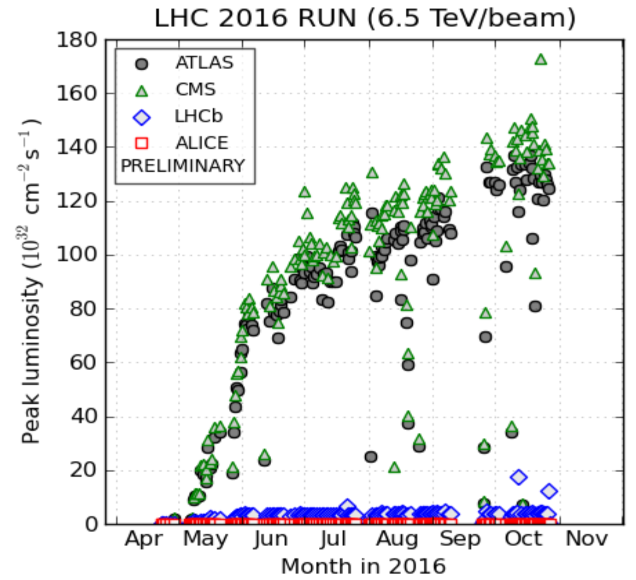
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

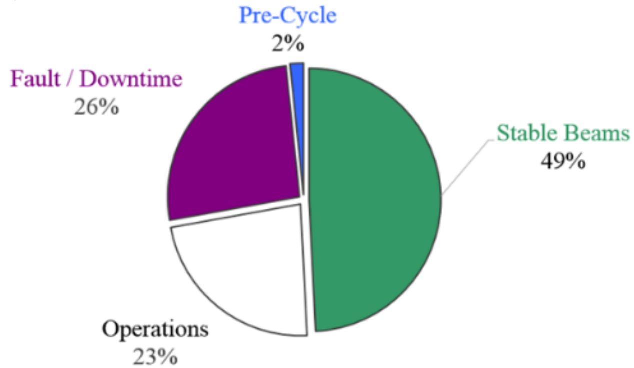
2016 LHC

Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

OVER 25 fb^{-1} in both ATLAS and CMS ☺







≈153 days physics ≈3738.7 hours

	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

TS1 - TS2 : stable beams 58 %
TS2 - TS3 : stable beams 54 %

LHC Limitations

SPS beam-dump

Nb of bunches per injection limited to 96

Total number of bunches: 2200

LHC Injection kickers

Outgassing from ceramic

Bunch population limited to around 1.1 x 10^{11}

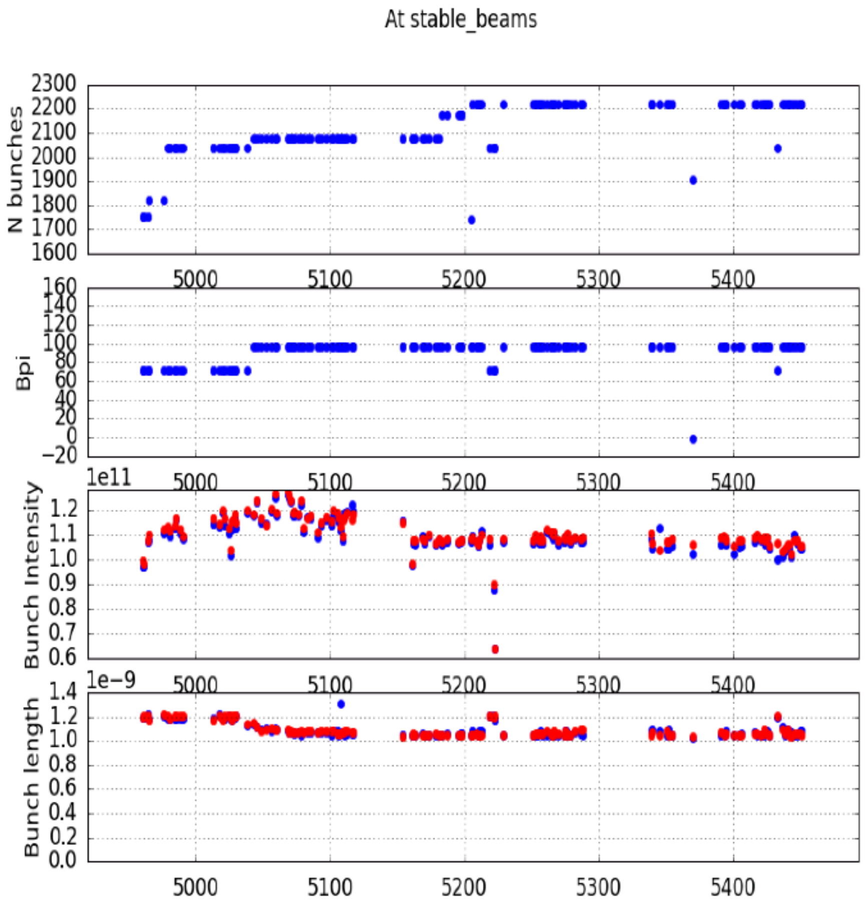
Electron cloud

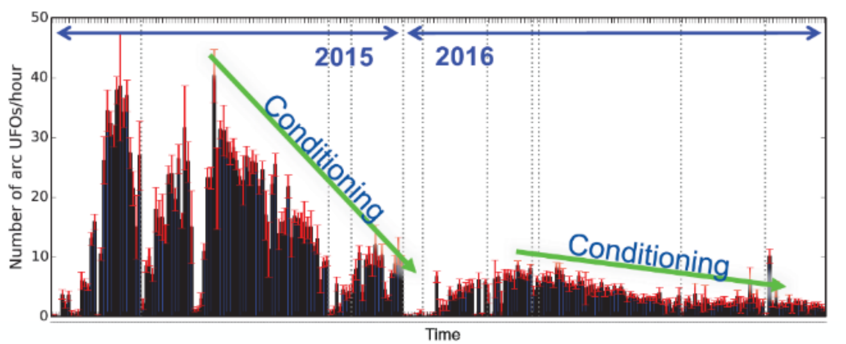
Still significant heat-load within cryogenic limits

Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

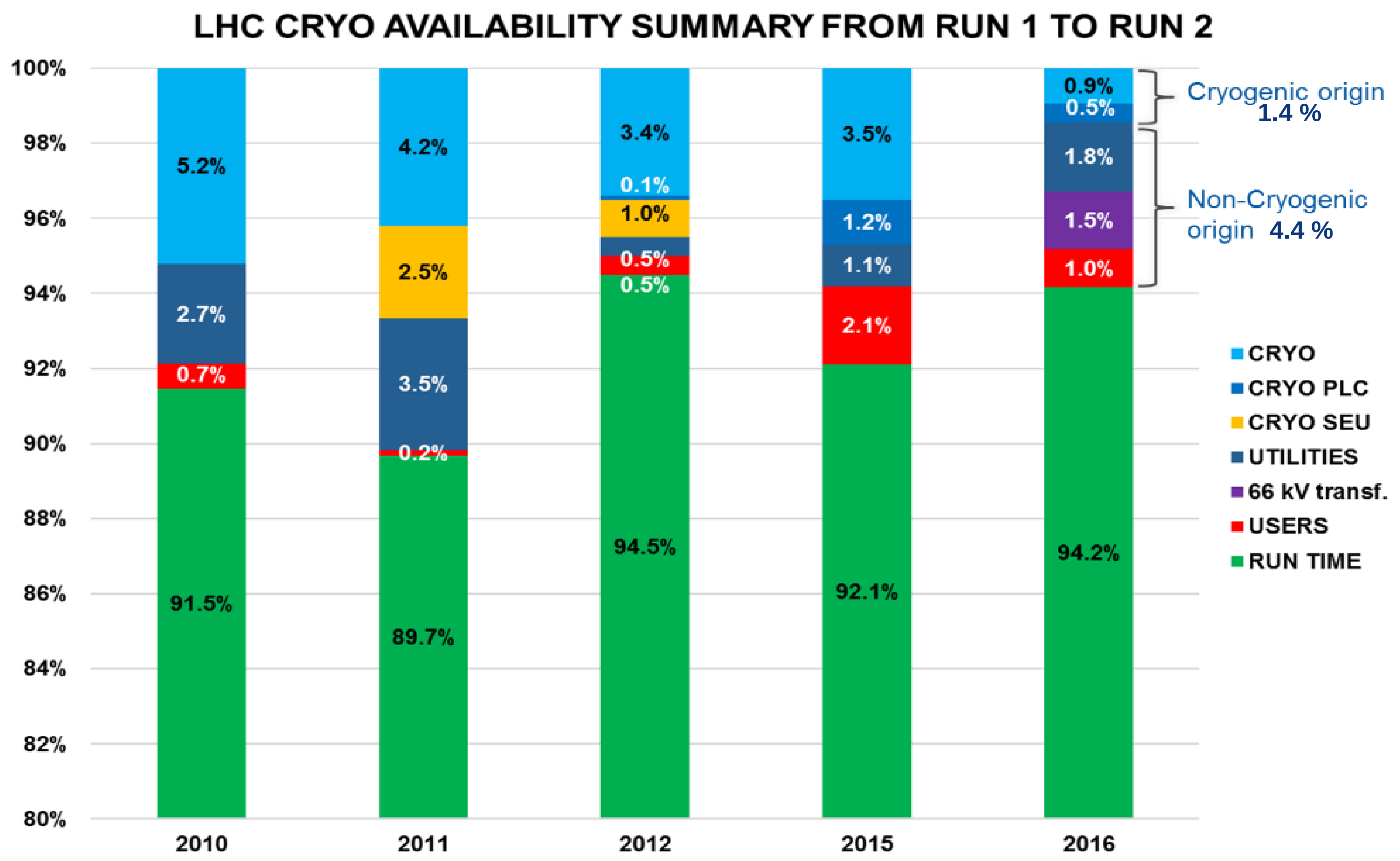
UFOs

Frequency has happily conditioned down



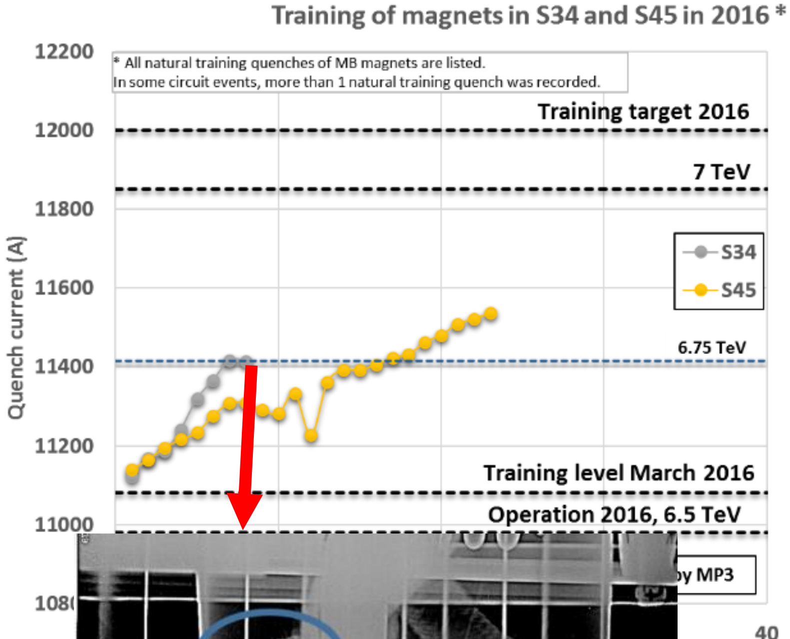


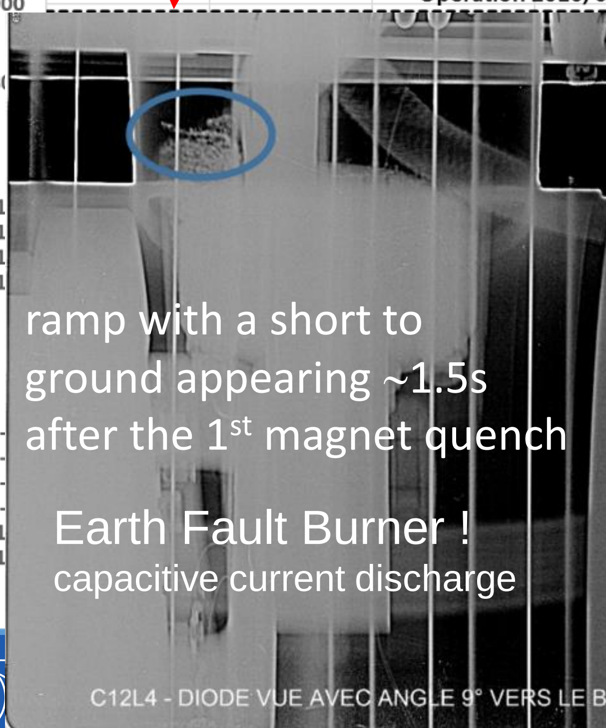
LHC Cryogenics availability (2016): 98.6% (**94.2%**)

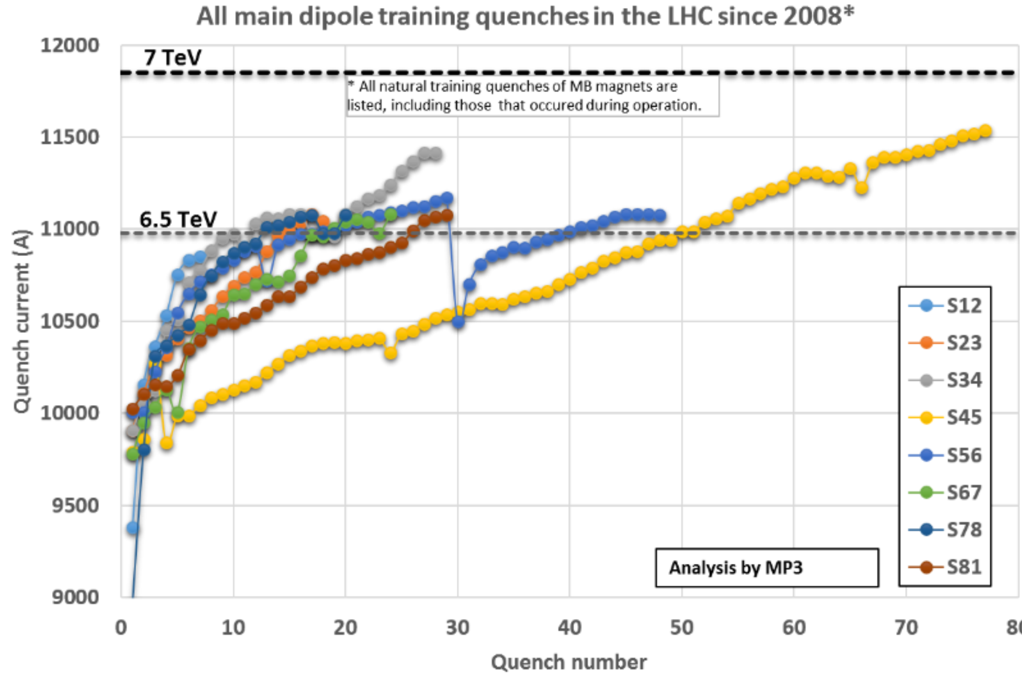


Courtesy Dimitri Delikaris

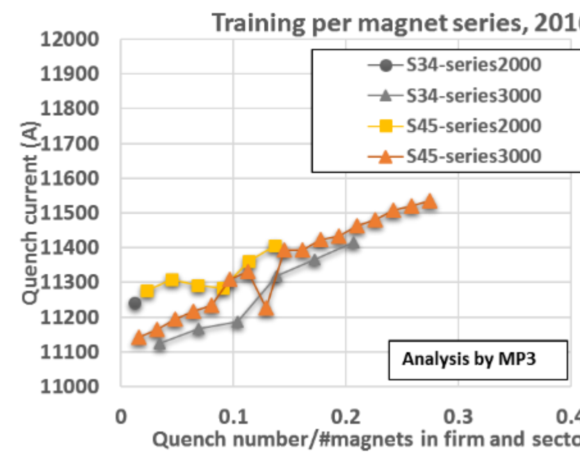
MB Training campaign 2016, December 5 - 14







	Training quenches December 2016		
	Series 1000	Series 2000	Series 3000
RB.A34	1	1	6
RB.A45	0	6	17
total	1	7	23

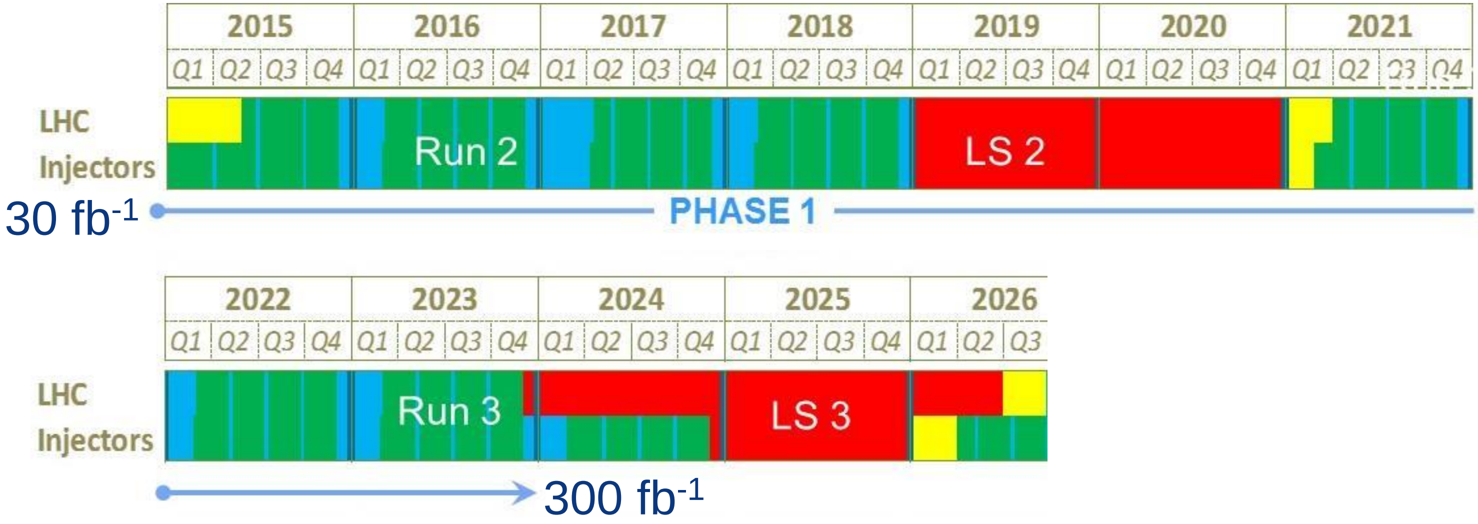


LHC goal for Run 2 and 3

Integrated luminosity goal:

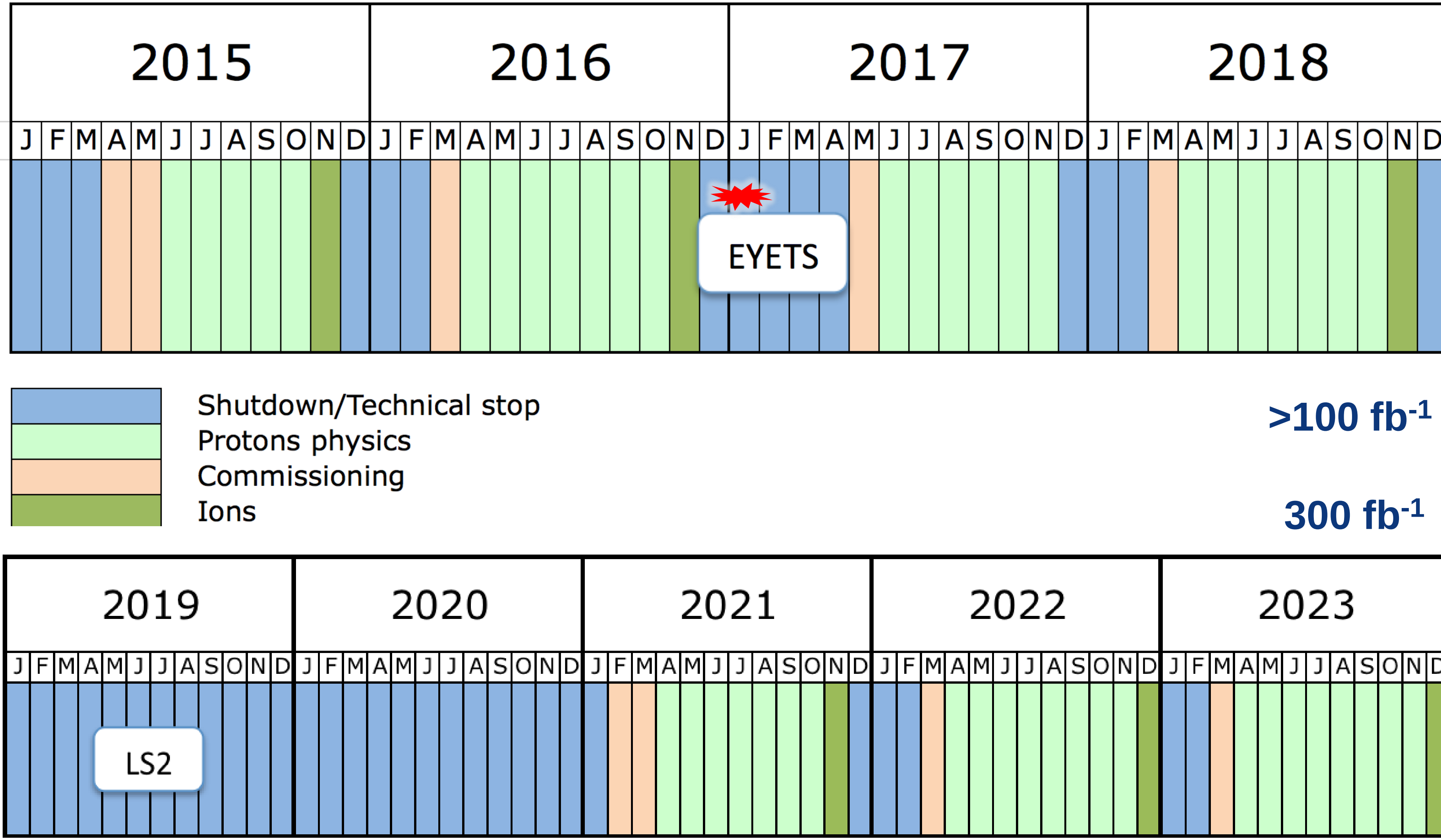
Run2: ~100-120 fb^{-1}

~ 300 fb^{-1} before LS3

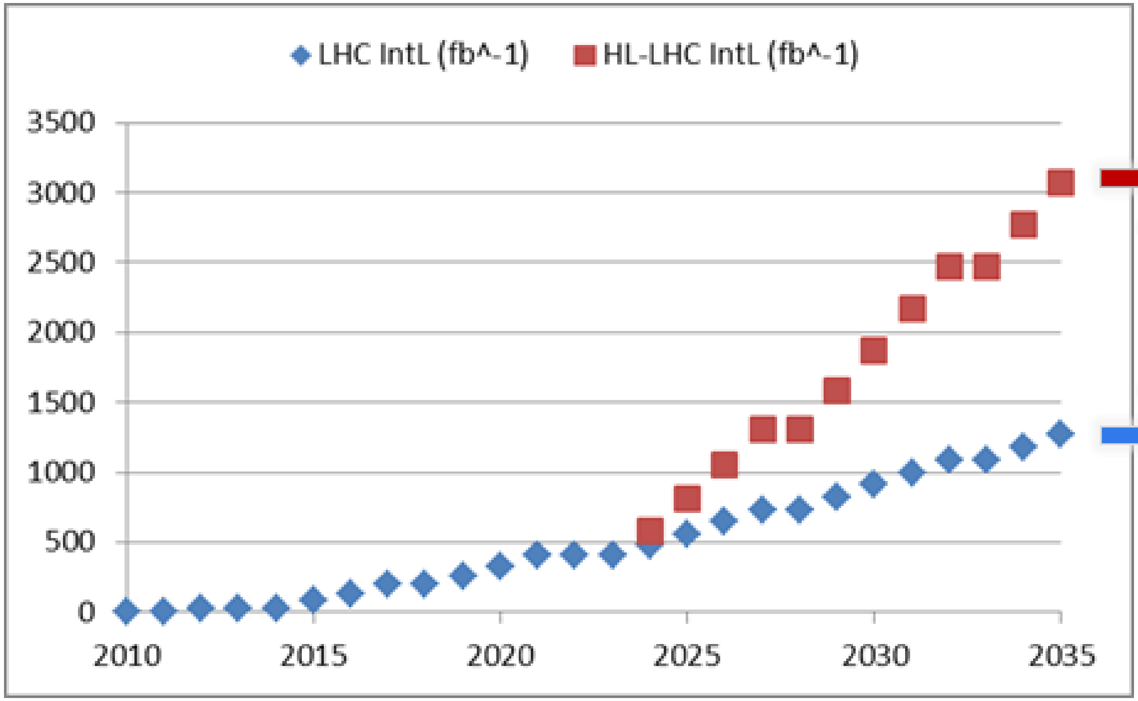


Run 2

Ion runs in 2016 (p-Pb) and 2018 (Pb-Pb)



Why High-Luminosity LHC ? (LS3)



By implementing HL-LHC

Almost a factor 3

By continuous performance improvement and consolidation

Around 300 fb^{-1} the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.

Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- **3000 fb^{-1} in about 10 years**

The European Strategy for Particle Physics
Update 2013

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Near-term & Mid-term High-energy Colliders

LARGE HADRON COLLIDER

- **The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.**
- *Recommendation 10:* ***Complete the LHC phase-1 upgrades, and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.***

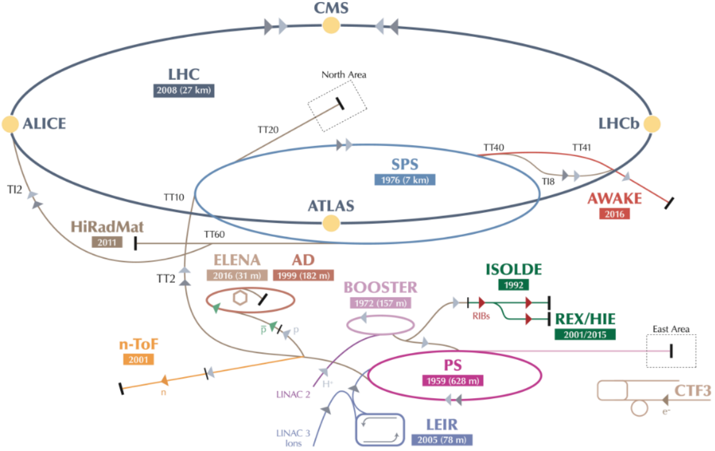
HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU**

(Linac 4, Booster 2GeV, PS and SPS upgrade)

Goals and means of the LHC Injectors Upgrade: LIU project



Increase injector reliability and lifetime to cover HL-LHC run (until ~2035) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)

⇒ Improve radioprotection measures (shielding, ventilation…)

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)

⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

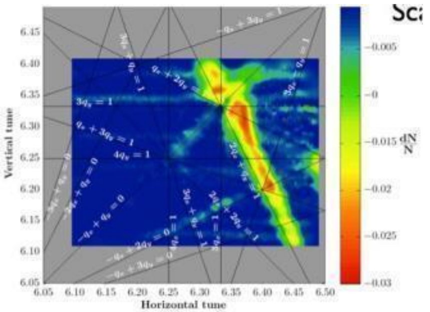
LS2 : (2019-2020), LHC Injector Upgrades (LIU)

LINAC4 – PS Booster:

- H^- injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

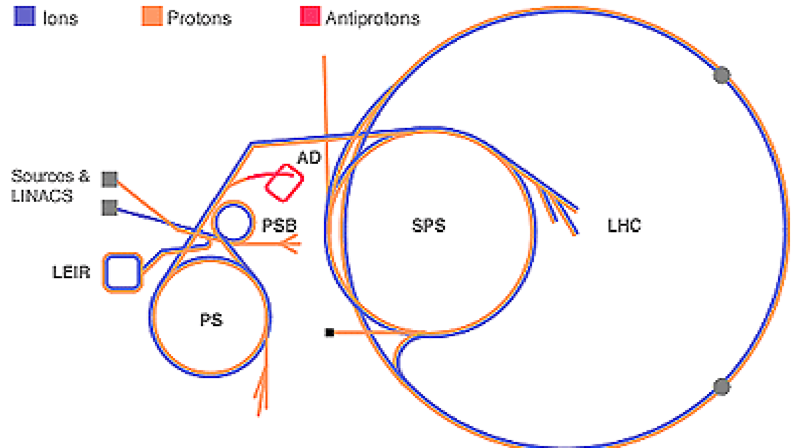
PS:

- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness



SPS

- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system



These are only the main modifications and this list is far from exhaustive

Linac4 reached its energy goal – October 2016

The PIMS section

September-November 2016: Commissioning with beam of 12 PIMS accelerating structures (built in collaboration CERN-NCBJ-FZJ).

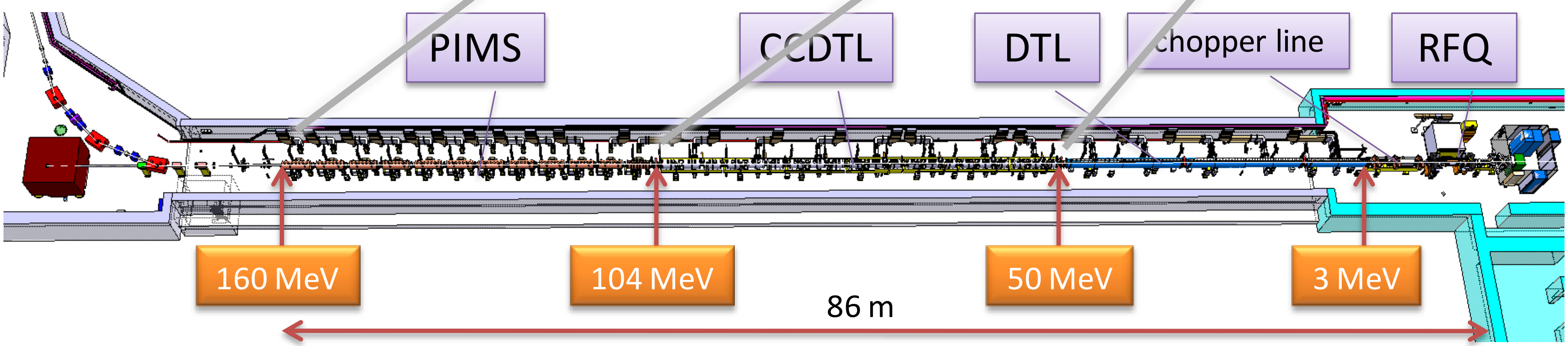
160 MeV design energy reached on 25.10. 2016

Installation of the last beam line element, August 2016

October 2016
160 MeV

June 2016
107 MeV

November 2015
50 MeV



Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

- enabling a total integrated luminosity of **3000 fb^{-1}**
- implying an integrated luminosity of **250-300 fb^{-1} per year**,
- design for $\mu \sim$ **140 (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
- design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

LHC Upgrade Goals: Performance optimization

Luminosity recipe :

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

➔1) maximize bunch intensities ➔ Injector complex

➔2) minimize the beam emittance LIU ⇔ IBS

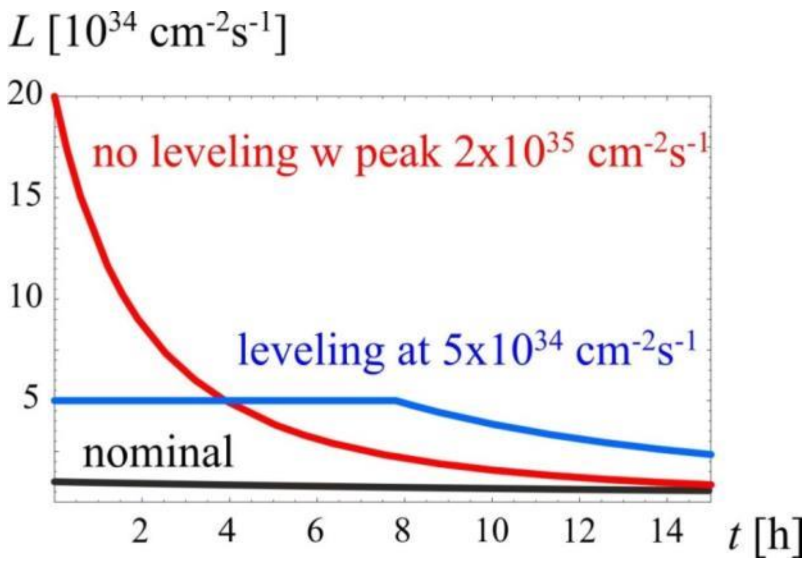
➔3) minimize beam size (constant beam power); ➔ triplet aperture

➔4) maximize number of bunches (beam power); ➔ 25ns

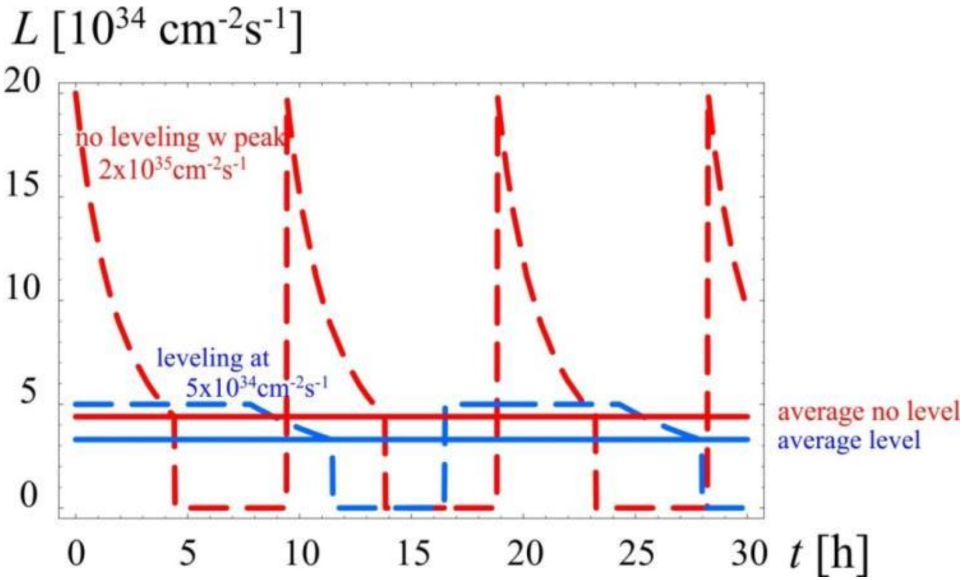
➔5) compensate for 'F'; ➔ Crab Cavities

➔6) Improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

Luminosity Levelling, a key to success

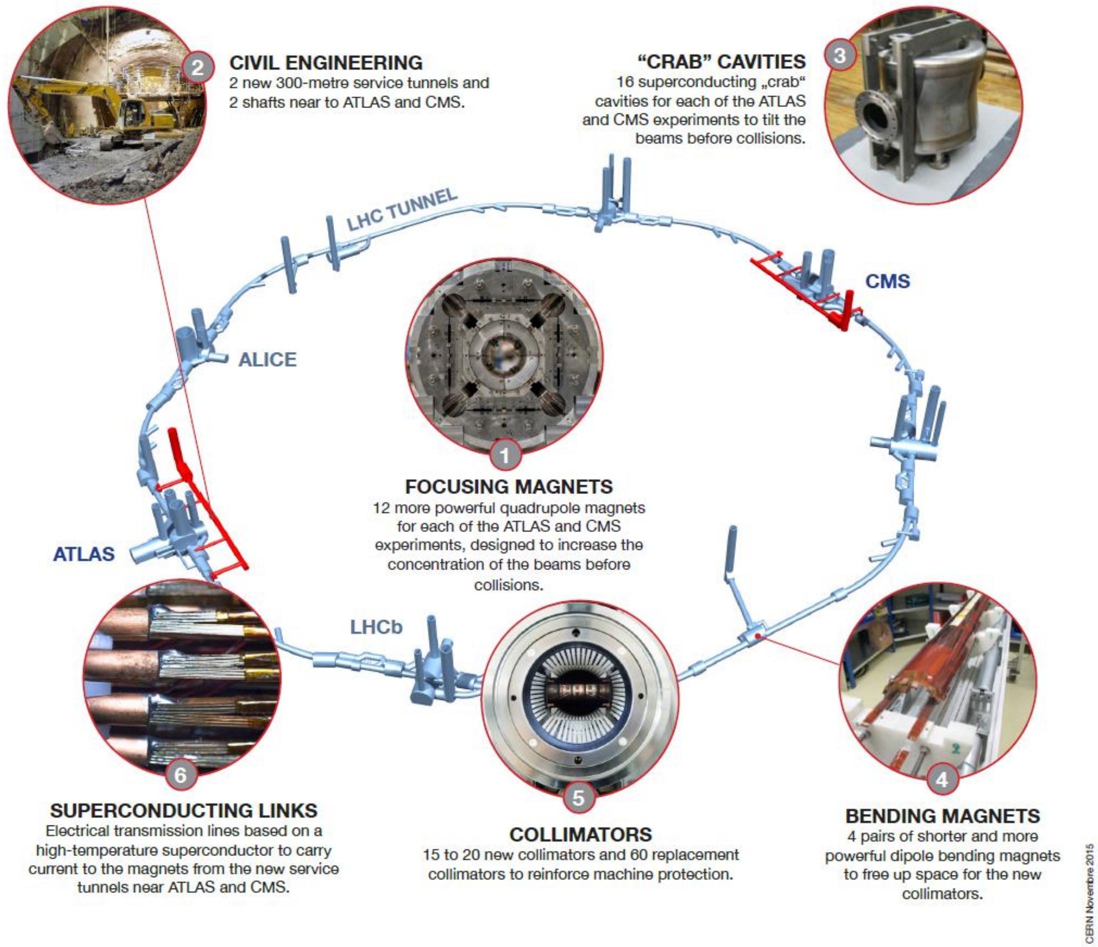


- High peak luminosity
- Minimize pile-up in experiments and provide "constant" luminosity



- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/year

The HL-LHC Project



- **New IR-quads Nb_3Sn (inner triplets)**
- **New 11 T Nb_3Sn (short) dipoles**
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Squeezing the beams: High Field SC Magnets

Quads for the inner triplet

Decision 2012 for low-β quads

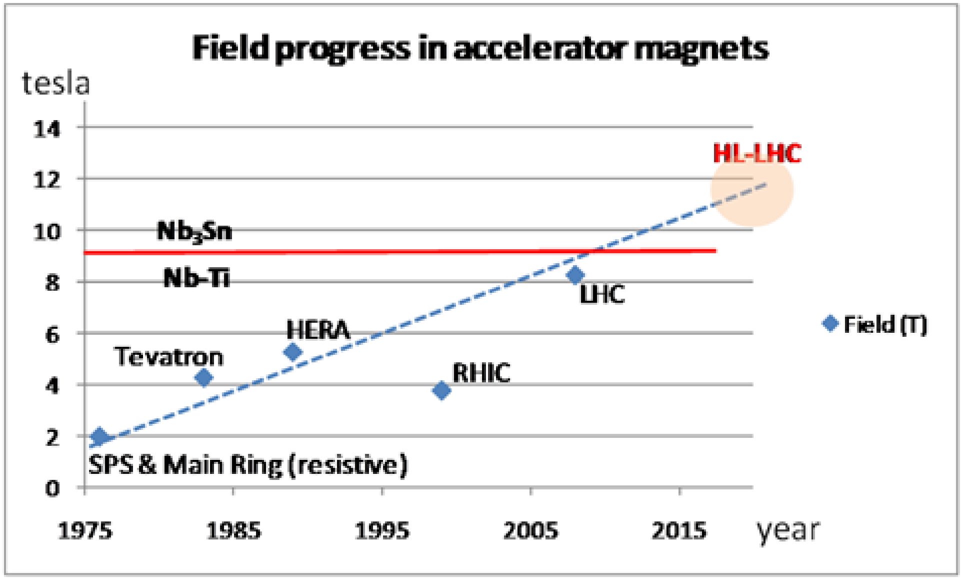
Aperture ∅ 150 mm – 140 T/m

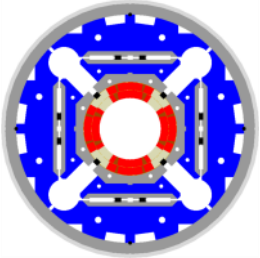
(B_{peak} ≈12.3 T)

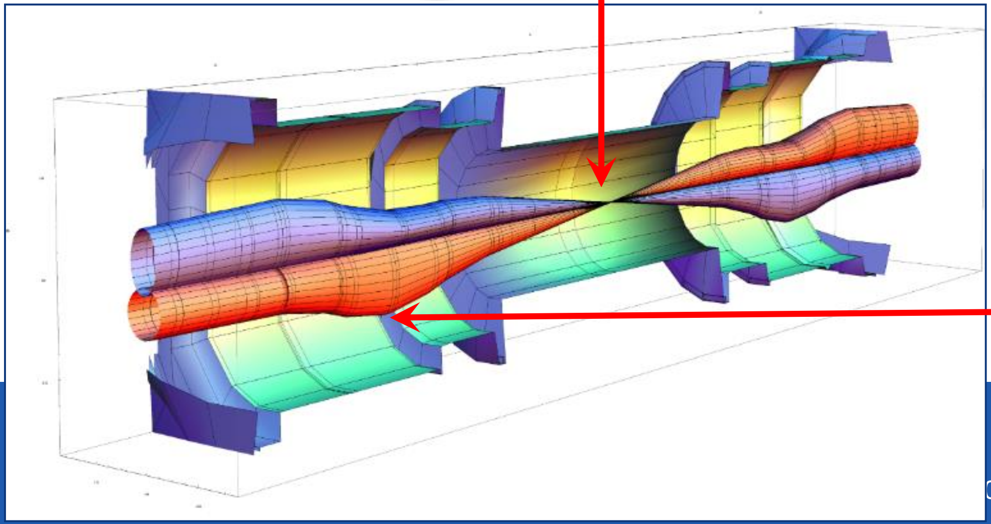
operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)



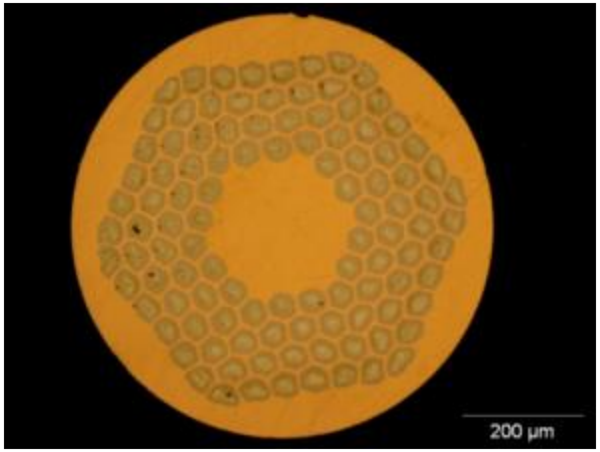




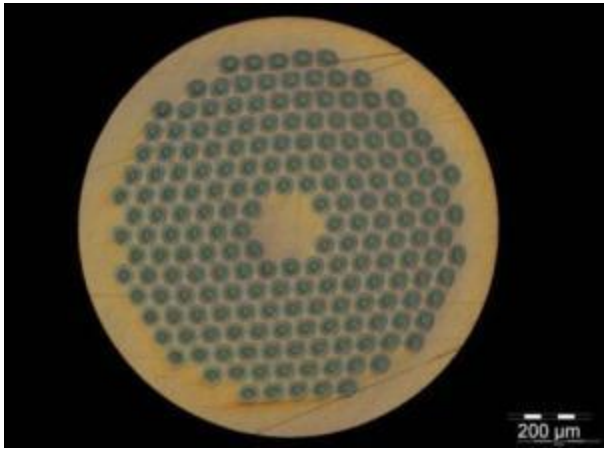
	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

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 2010-2016!
  It is comparable to LHC *(1200 tons of Nb-Ti but HL-LHC will require only 20 tons of Nb_3Sn)*
- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is 5 times LHC Nb-Ti

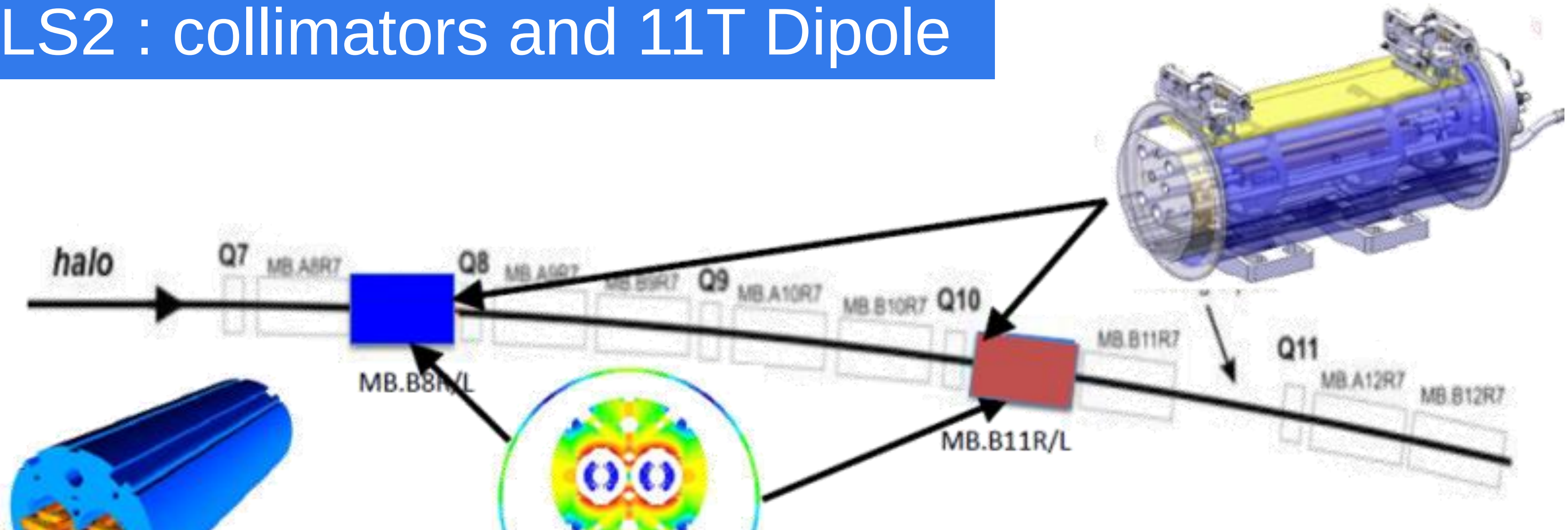


0.7 mm, 108/127 stack RRP from **Oxford OST**



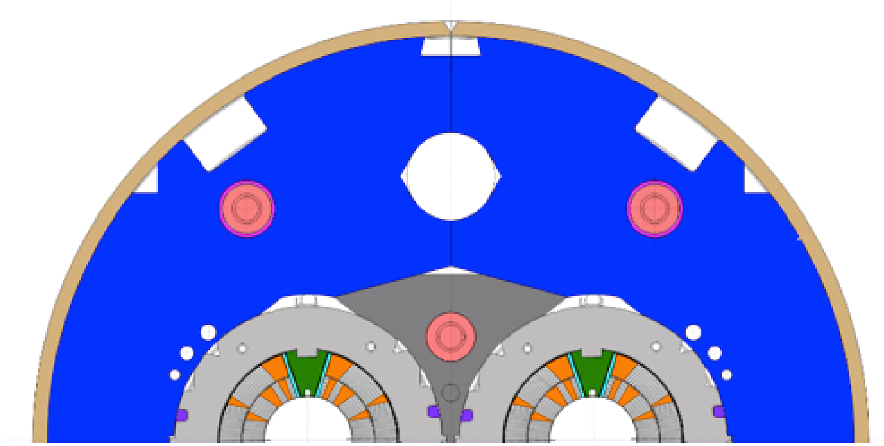
1 mm, 192 tubes PIT from **Bruker EAS**

LS2 : collimators and 11T Dipole

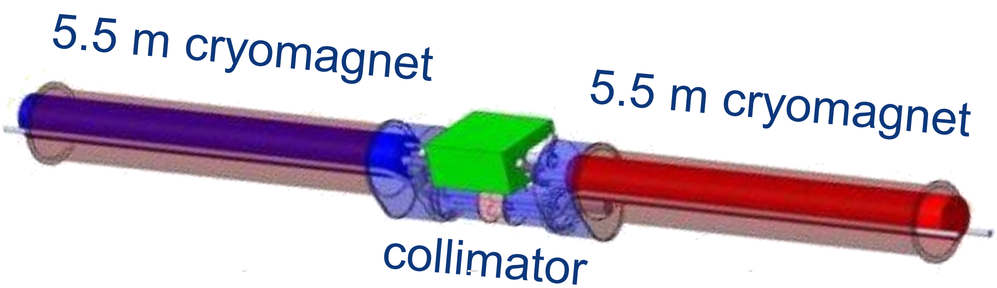


$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB with 20 % margin

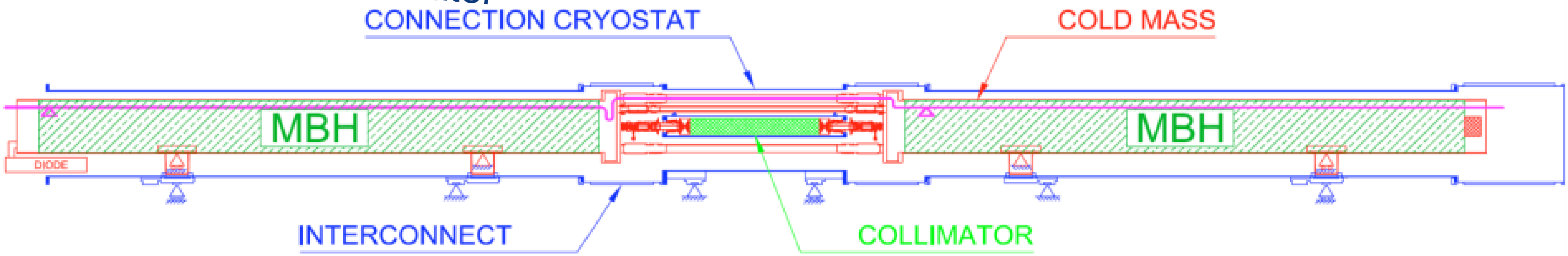
11 T dipole program (Nb_3Sn)



Aperture	(mm)	60
Field	(T)	10.8
Current	(A)	11850
Temperature	(K)	1.9
Peak field	(T)	11.35



Cryo-unit design with integrated collimator



HL-LHC Upgrade Ingredients: Crab Cavities

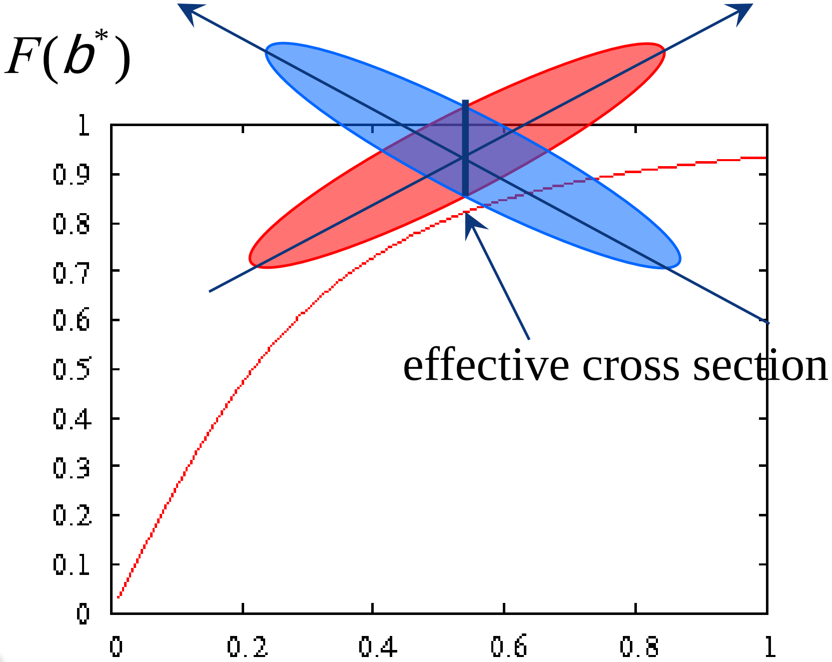
Geometric Luminosity Reduction Factor:

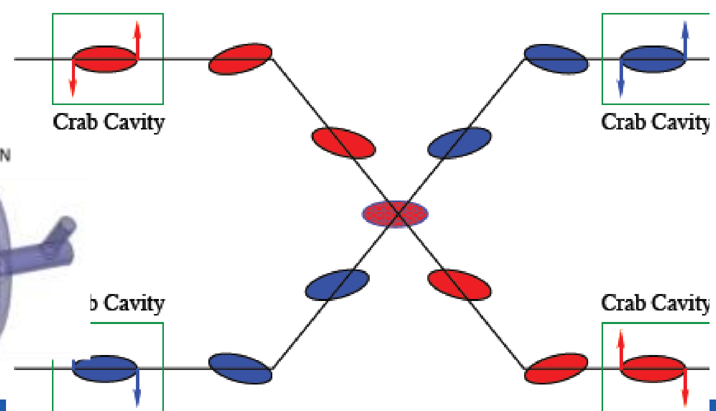
Crab Cavities:

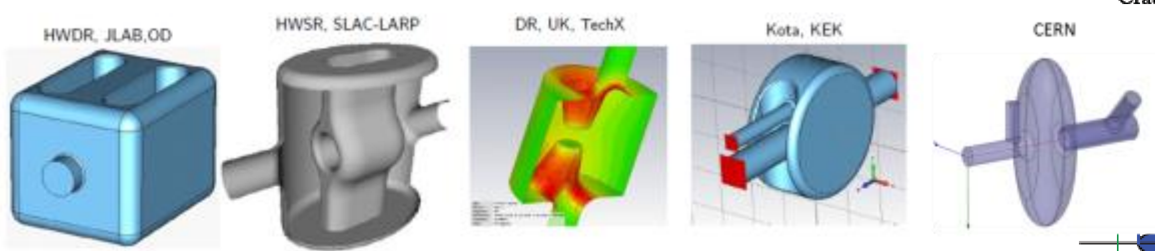
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+\Phi^2}}; \quad \Phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

- Noise from cavities to beam?!?
- Challenging space constraints



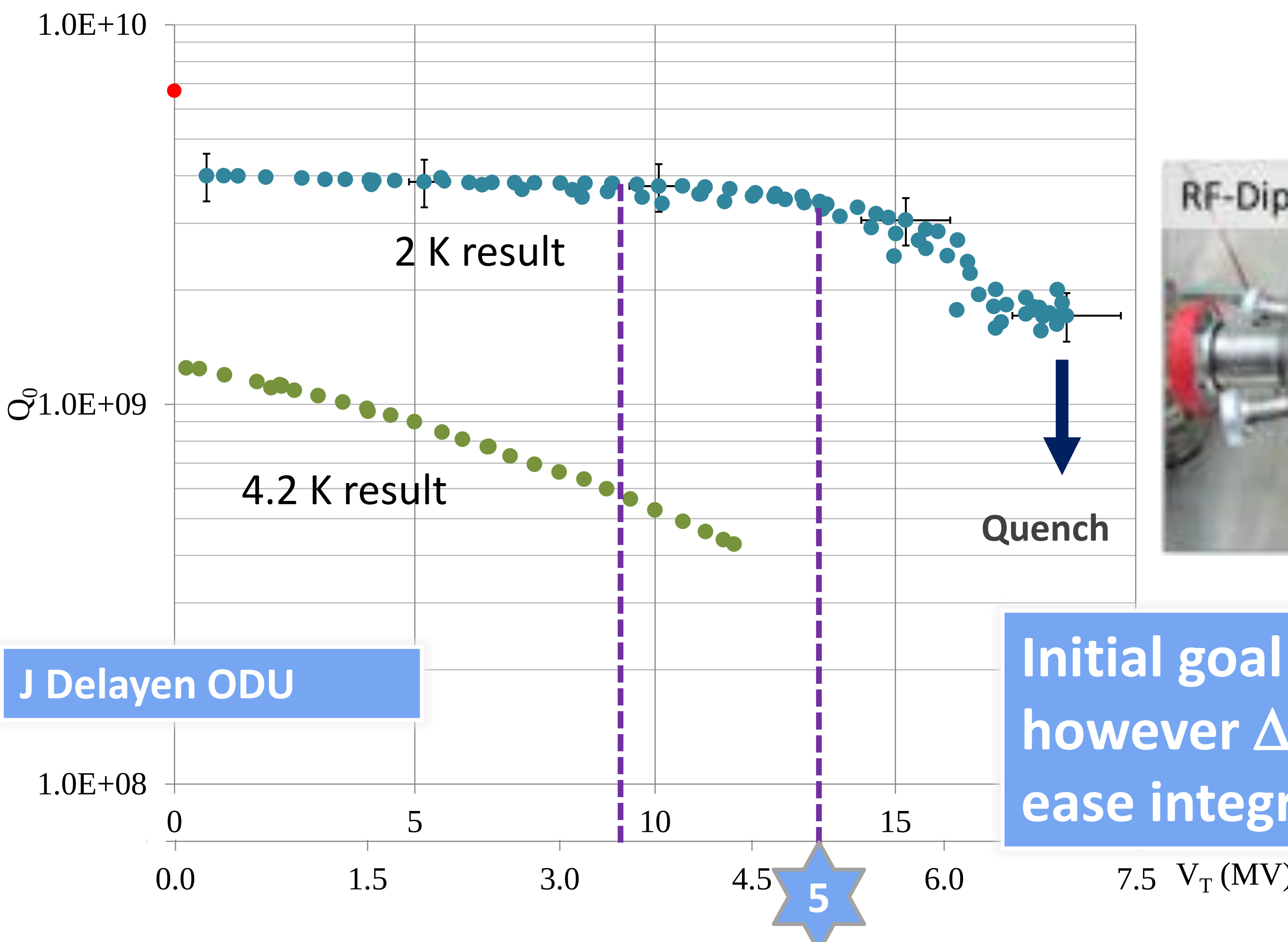




Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

Excellent first results: e.g. RF dipole > 5 MV

¼ w and 4-rods also tested (1.5 MV)



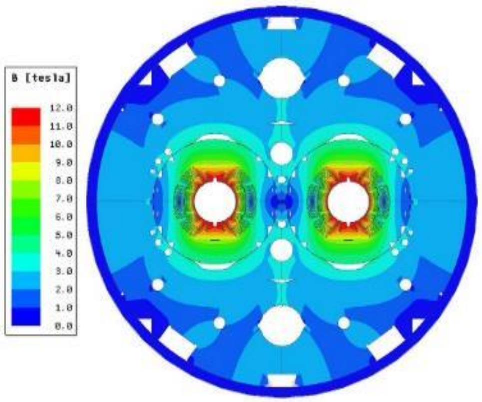
OLD DOMINION UNIVERSITY

LARP

Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

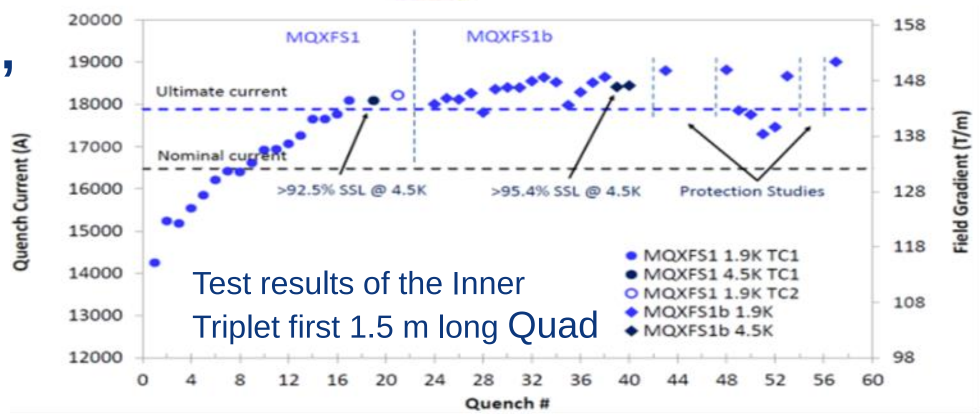
HL-LHC Main achievement 2016

The 11 T dipole 2 m long model reached a B_{max} of 12.5 T



Cross section of the 11 T dipole

Test of the first full cross-section (150 mm aperture) Triplet Quadrupole, 1.5 m long, half CERN, half USA: it went beyond ultimate ($B_{max\ eq.}$ of 12.5 T)



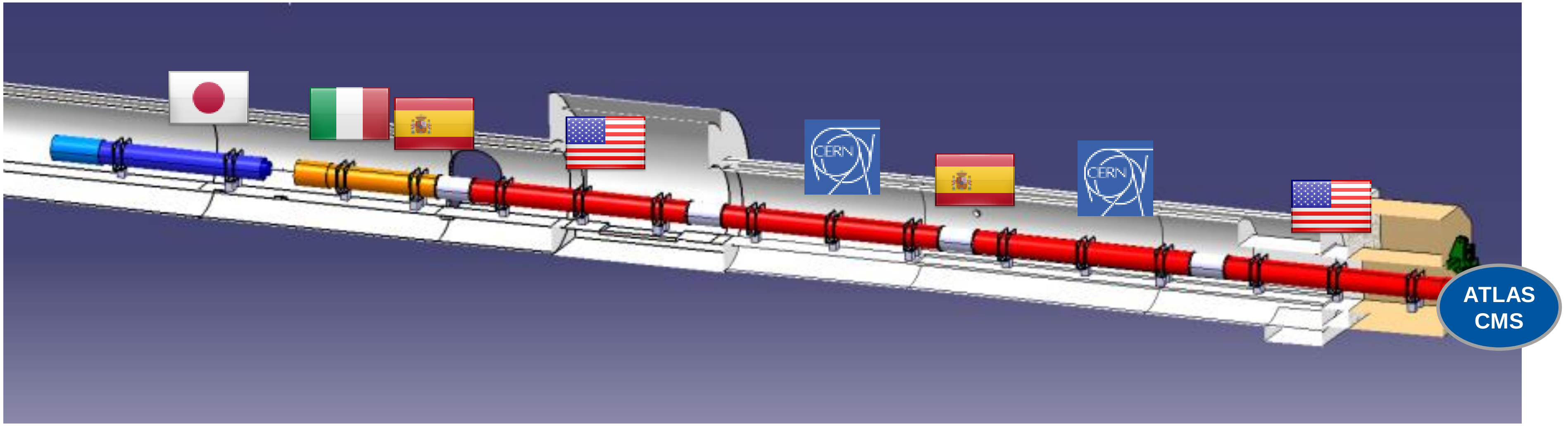
Test results of the Inner Triplet first 1.5 m long Quad

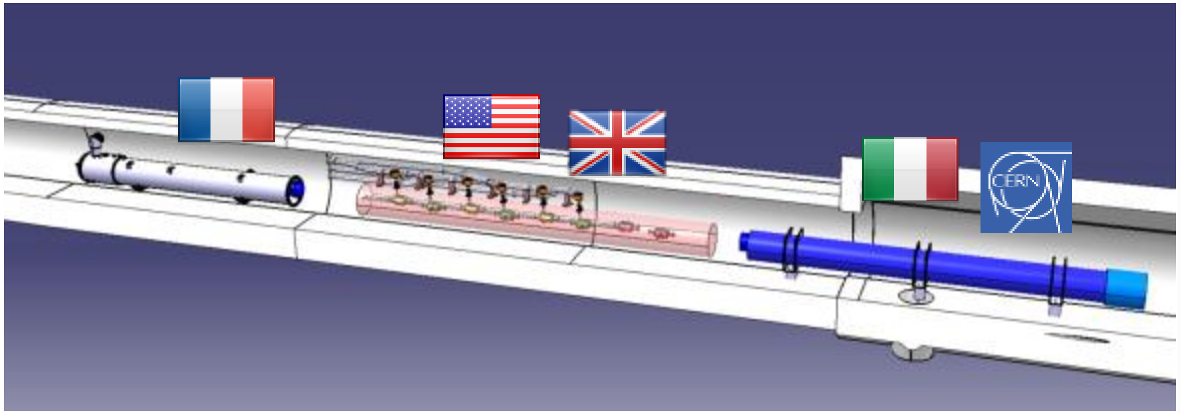
Completion of the first Crab Cavity, type Double Quarter Wave at CERN just before Christmas!

First Crab Cavity produced at CERN

In-kind contributions and collaborations for design, prototypes, production and tests

Discussions are ongoing with other countries, e.g Canada, China, Korea…



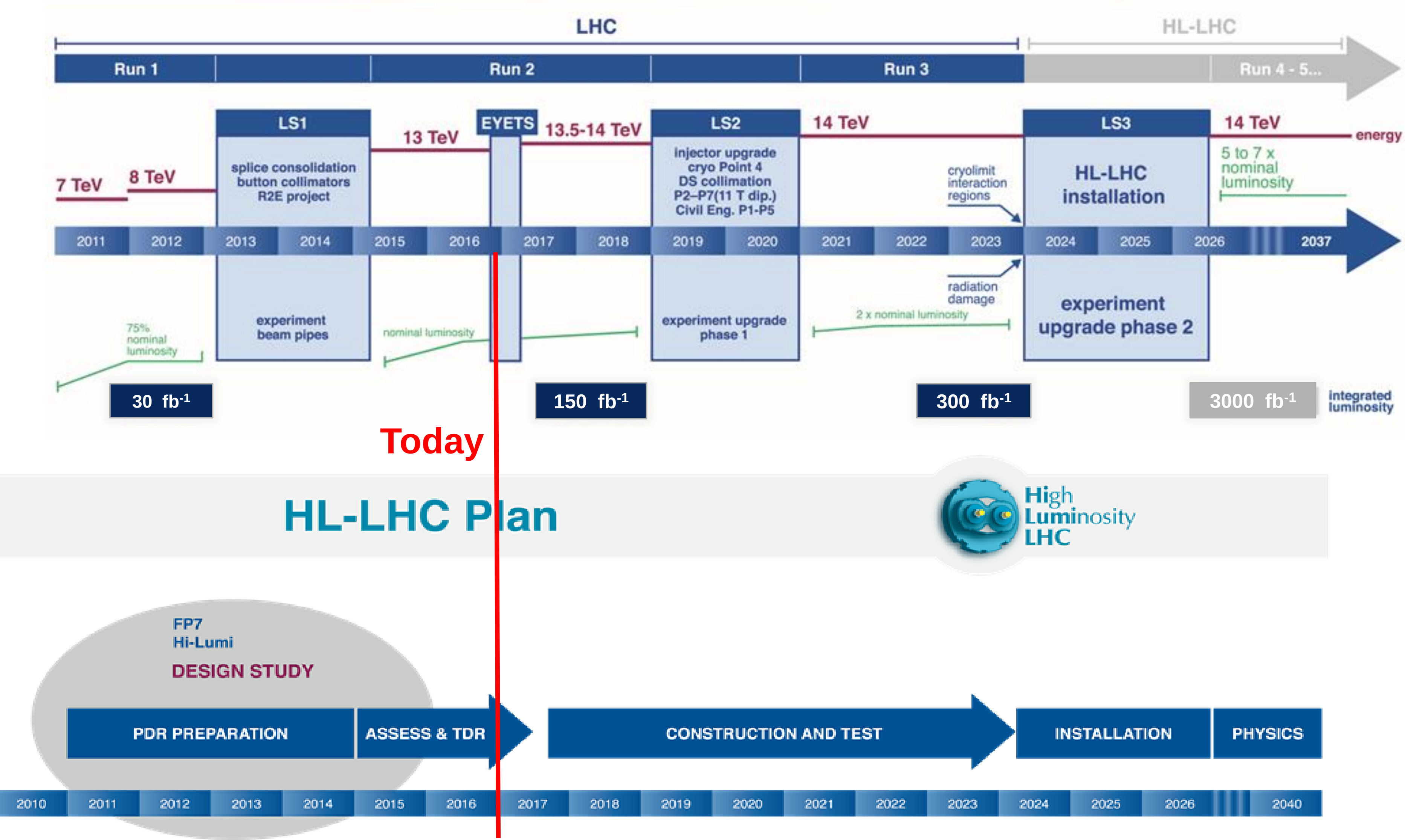


Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

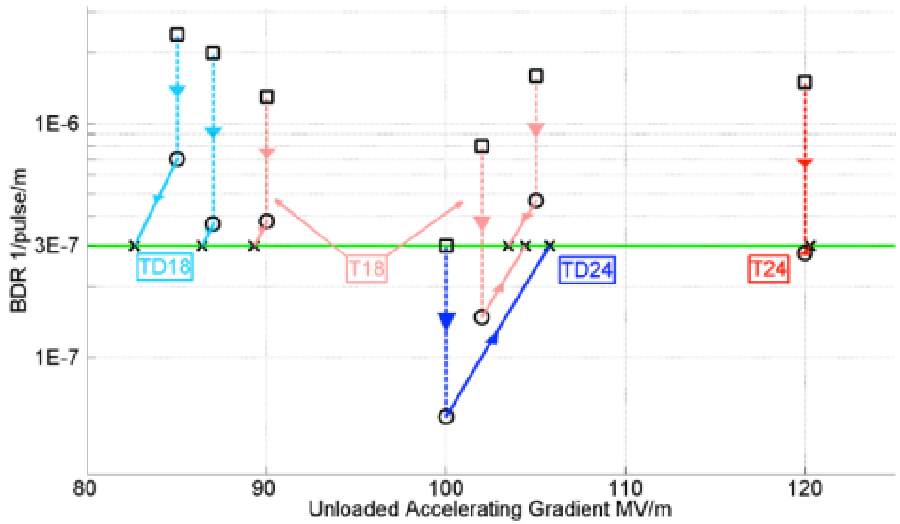
LHC / HL-LHC Plan



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

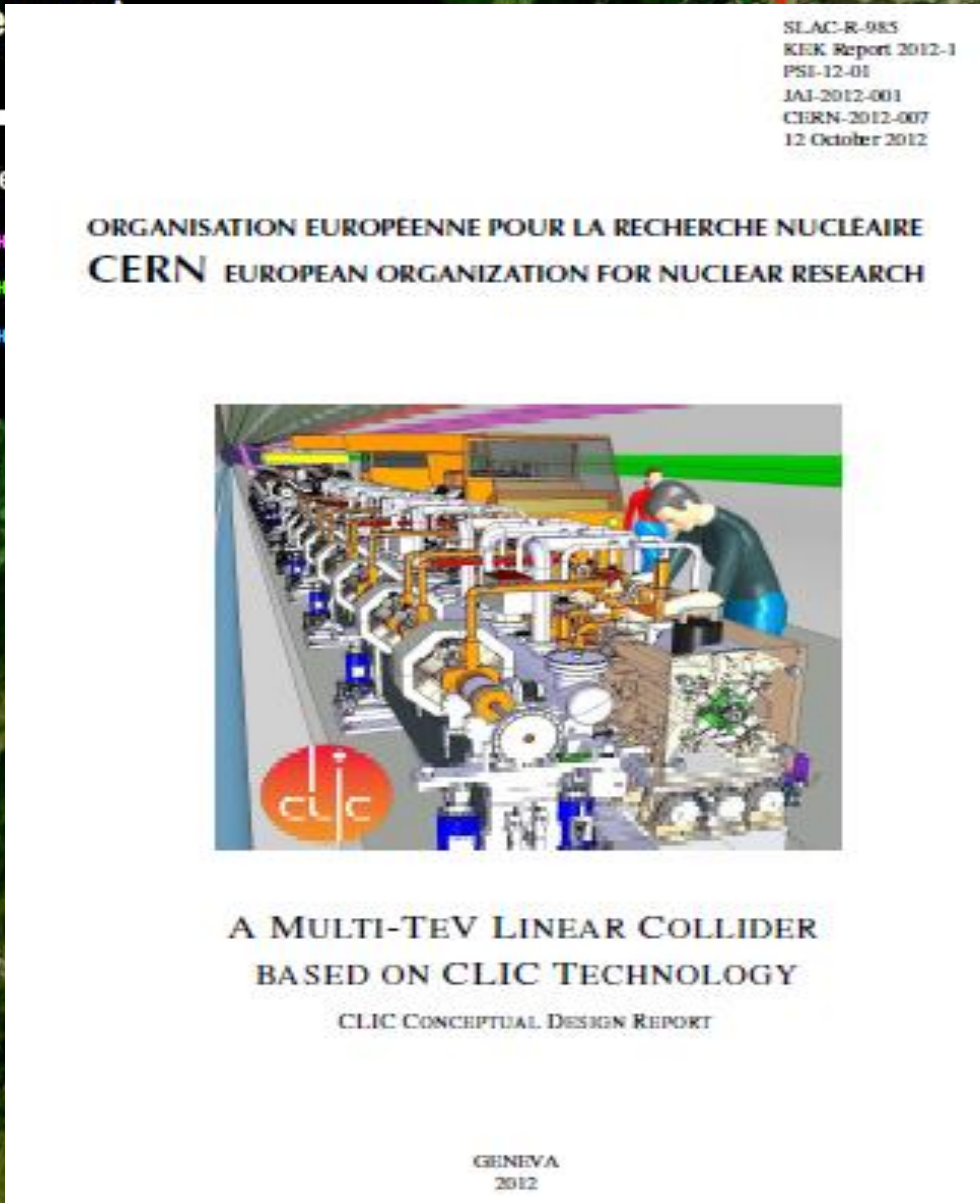
d) *CERN should undertake design studies for accelerator projects in a global context,* *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****. These design studies should be coupled to a vigorous accelerator* ***R&D programme****, including* ***high-field magnets***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

HGA



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

CLIC Multi-TeV Linear Collider



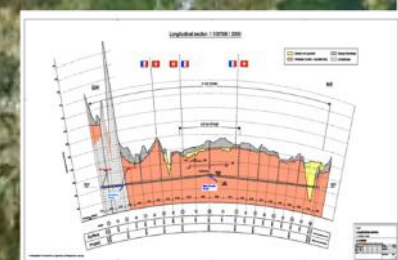
SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

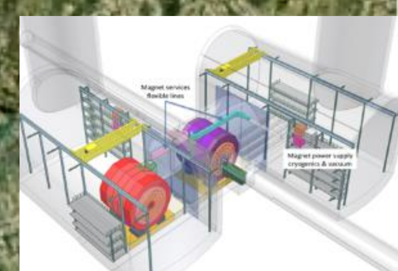
A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012



Tunnel implementations (laser straight)



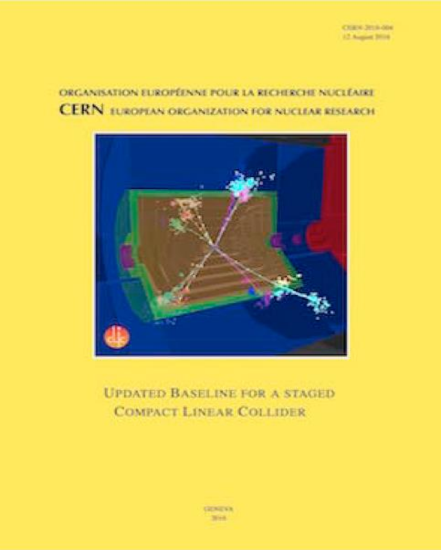
Central MDI & Interaction Region

Compact Linear Collider (CLIC)

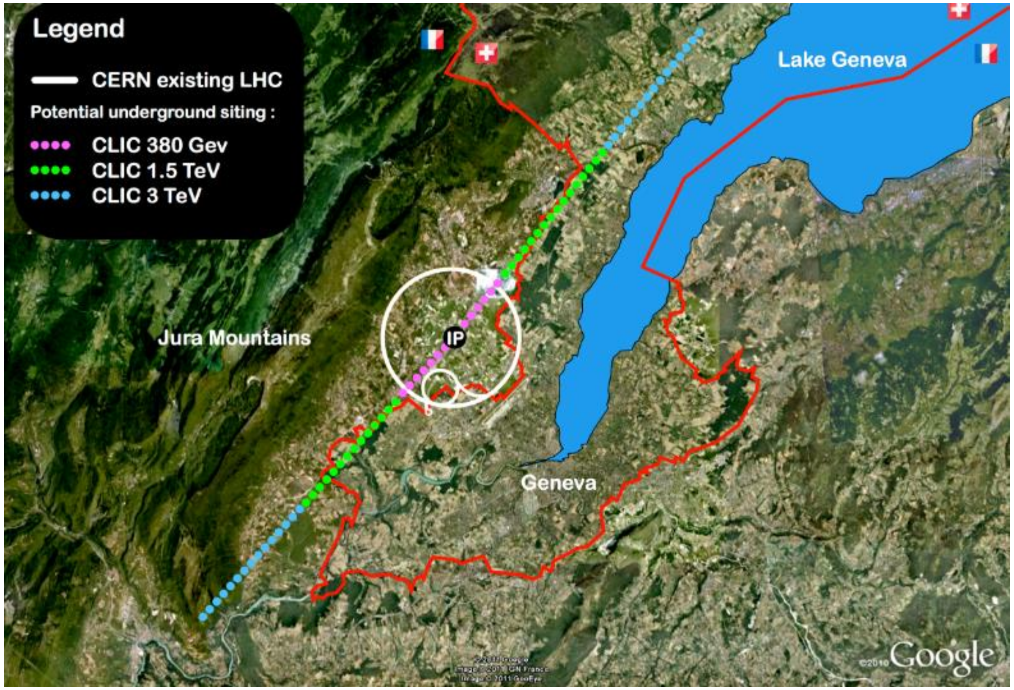
Linear e^+e^- collider $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine
→ based on normal-conducting accelerating structures and a two-beam acceleration scheme

- Direct d… precis… w particl… to m~
- Indirect … Λ ~ O(…
- Measur… gs couplin… 10%



Most recent operating scenario: start at $\sqrt{s}$=380 GeV for H and top physics

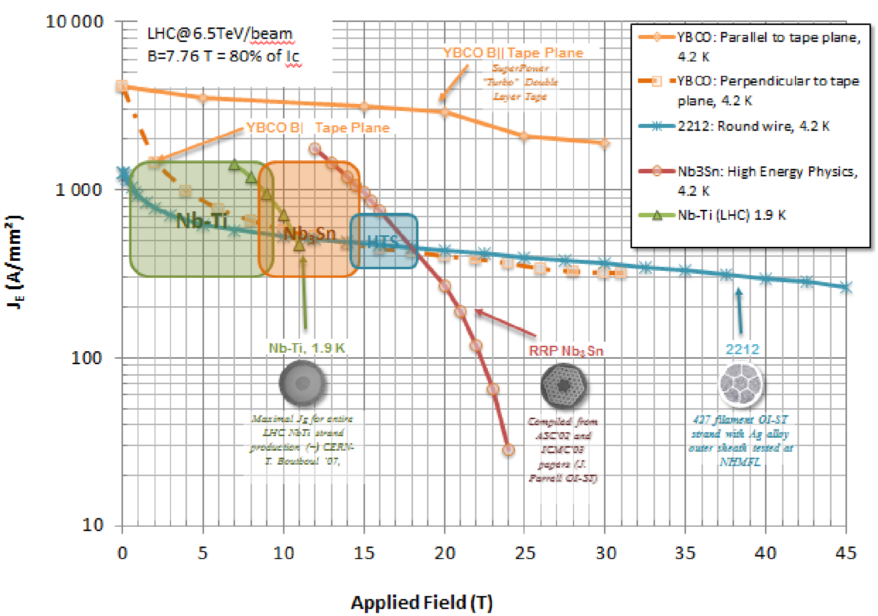


Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of $\sqrt{s}$	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

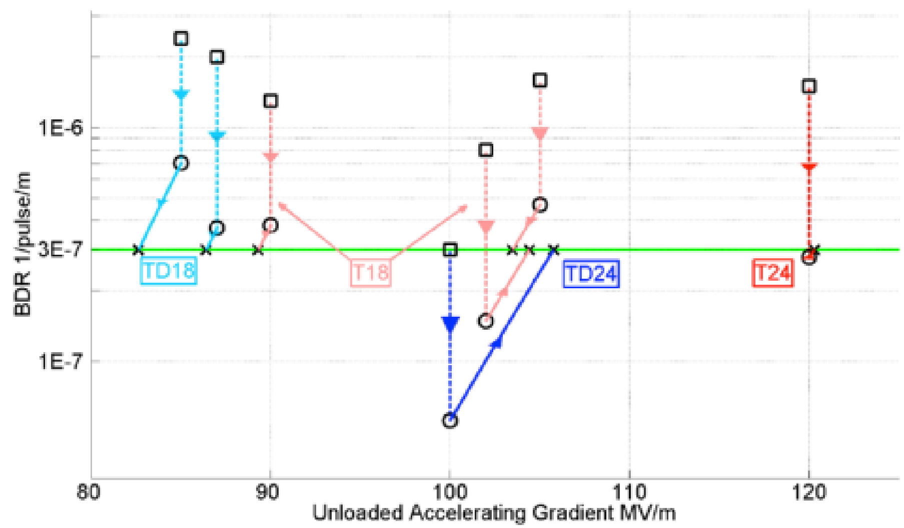
“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”

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

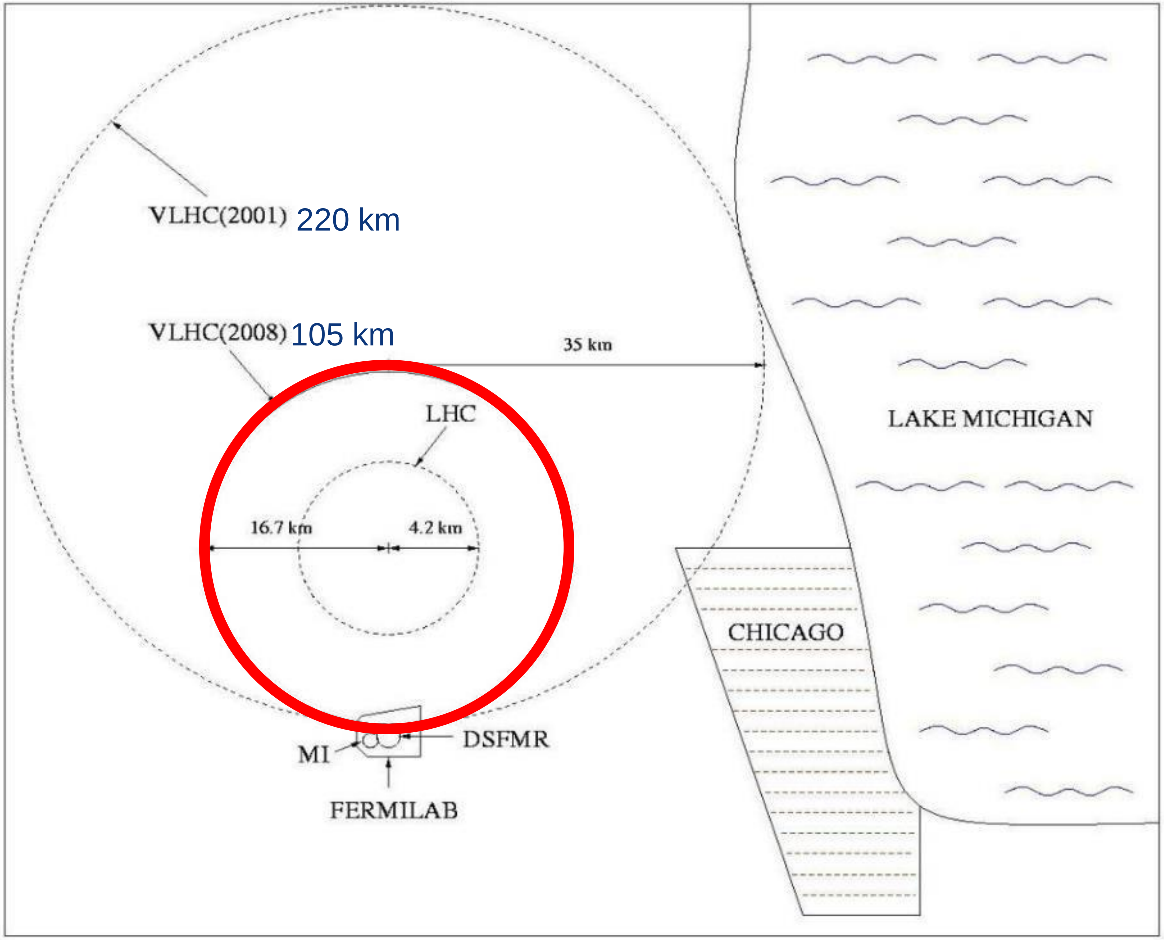


HGA



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

105 km tunnel near FNAL

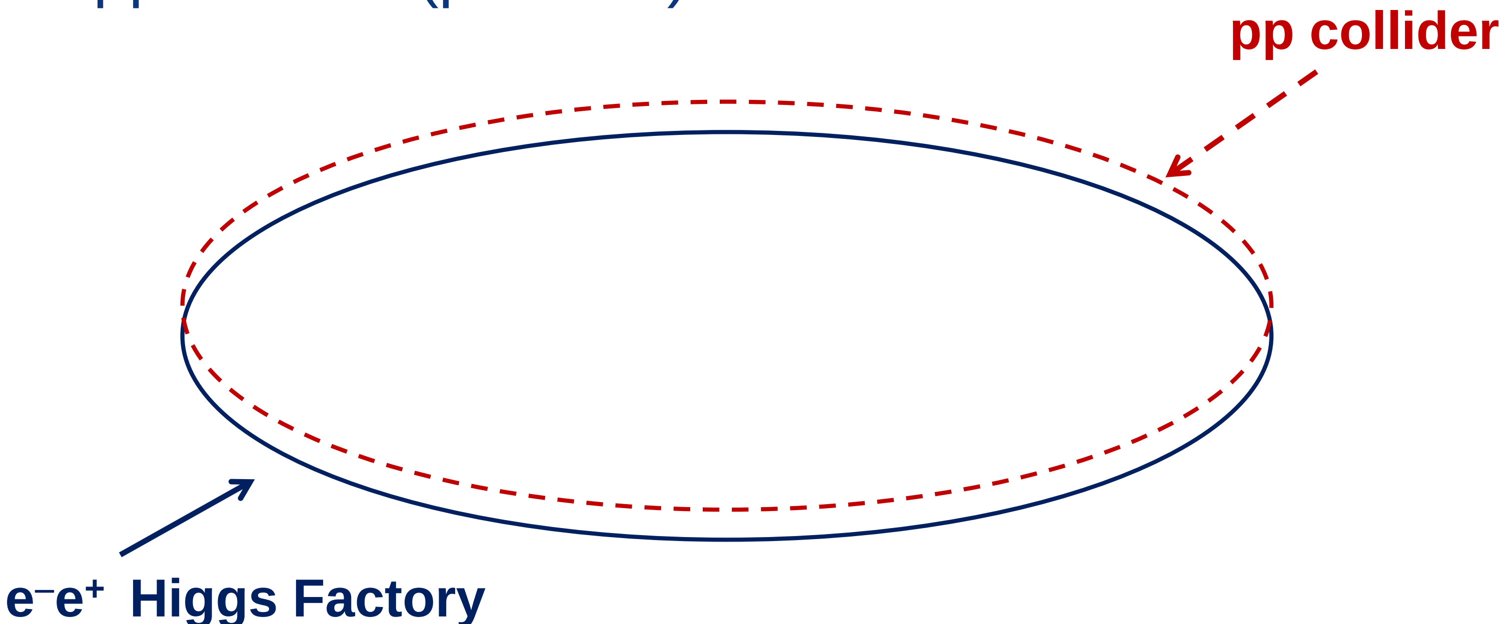


H. Piekarz, "… and … path to the future of high energy particle physics," JINST 4, P08007 (2009)

80 km ring in KEK area

Introduction — What is a (CEPC + SppC) ?
Chinese project

- Circular Electron Positron Collider (phase I) + Super pp Collider (phase II) in the same tunnel



A Higgs factory +
A machine of discovery

CEPC basic parameter:

- Beam energy ~120 GeV.
- Synchrotron radiation power ~50 MW.
- 50/70 km in circumference.

SppC basic parameter:

- Beam energy ~50-70 TeV.
- 50/70 km in circumference.
- Needs B_{max} ~20T.

The circumference of CEPC is determined by that of the SppC, which is determined by the final energy of proton beam and the achievable dipole field strength.

2013-10-18 6th TLEP workshop

中國科學院高能物理研究所
Institute of High Energy Physics

CEPC+SppC

Where(if in China):
For example, Qin-Huang-Dao

CEPC+SppC

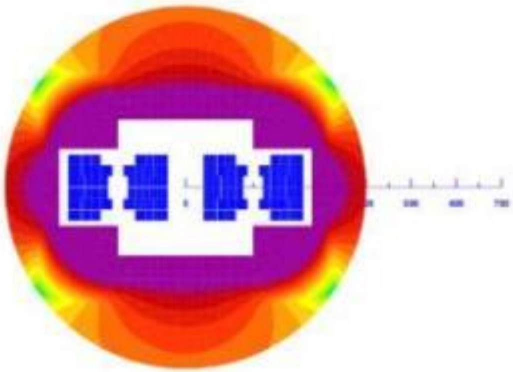
When(**dream**):

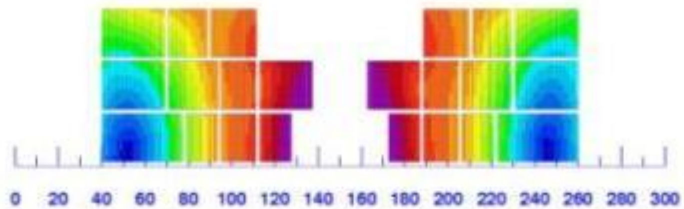
- CPEC
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
    - R&D: 2015-2020
    - Engineering Design: 2015-2020
  - **Construction: 2021-2027**
  - **Data taking: 2028-2035**
- SppC
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - **Construction: 2035-2042**
  - **Data taking: 2042 -**

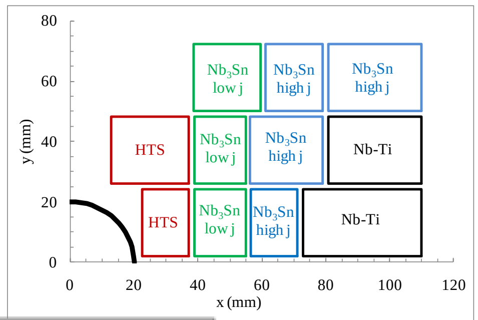
International Workshop on Future High Energy Circular Colliders (December 2013) (IHEP, Beijing)

Courtesy of Prof. Yifang Wang (IHEP)

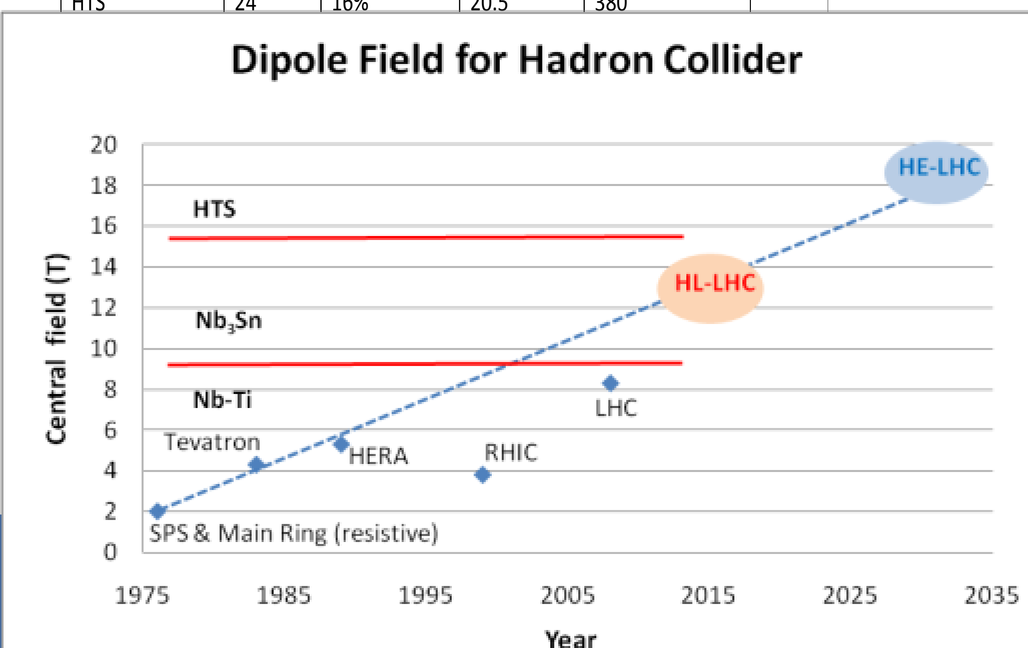
Malta Workshop: **HE-LHC @ 33 TeV c.o.m.**
14-16 October 2010







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.

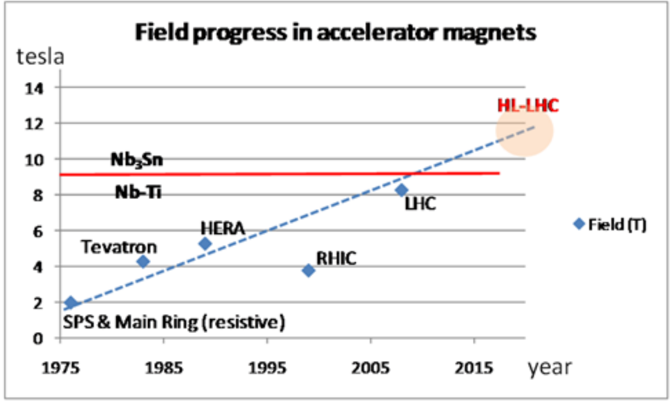
s beam handling for INJ & beam dump:

nake twice more room for LHC kickers.

HE-LHC main parameters

<table>
<tr><th>parameter</th><th>LHC</th><th>HL-LHC</th><th>HE-LHC</th></tr>
<tr><td>c.m. energy [TeV]</td><td colspan="2">14</td><td>33</td></tr>
<tr><td>circumference C [km]</td><td colspan="2">26.7</td><td>26.7</td></tr>
<tr><td>dipole field [T]</td><td colspan="2">8.33</td><td>20</td></tr>
<tr><td>dipole coil aperture [mm]</td><td colspan="2">56</td><td>40</td></tr>
<tr><td>beam half aperture [cm]</td><td colspan="2">~2</td><td>1.3</td></tr>
<tr><td>injection energy [TeV]</td><td colspan="2">0.45</td><td>>1.0</td></tr>
<tr><td>no. of bunches</td><td colspan="2">2808</td><td>2808</td></tr>
<tr><td>bunch population N_b [10^{11}]</td><td>1.15</td><td>2.2</td><td>0.94</td></tr>
<tr><td>init. tr. norm. emittance [μm]</td><td>3.75</td><td>2.5</td><td>1.38</td></tr>
<tr><td>init. longit. emittance [eVs]</td><td colspan="2">2.5</td><td>3.8</td></tr>
<tr><td>no. IPs contributing to ΔQ</td><td>3</td><td>2</td><td>2</td></tr>
<tr><td>max. total b-b tune shift ΔQ</td><td>0.01</td><td>0.015</td><td>0.01</td></tr>
<tr><td>beam current [A]</td><td>0.584</td><td>1.12</td><td>0.478</td></tr>
<tr><td>rms bunch length [cm]</td><td colspan="2">7.55</td><td>7.55</td></tr>
<tr><td>IP beta function [m]</td><td>0.55</td><td>0.15</td><td>0.35</td></tr>
<tr><td>rms IP spot size [μm]</td><td>16.7</td><td>7.1 (min.)</td><td>5.2</td></tr>
</table>

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

From Luca Bottura

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)

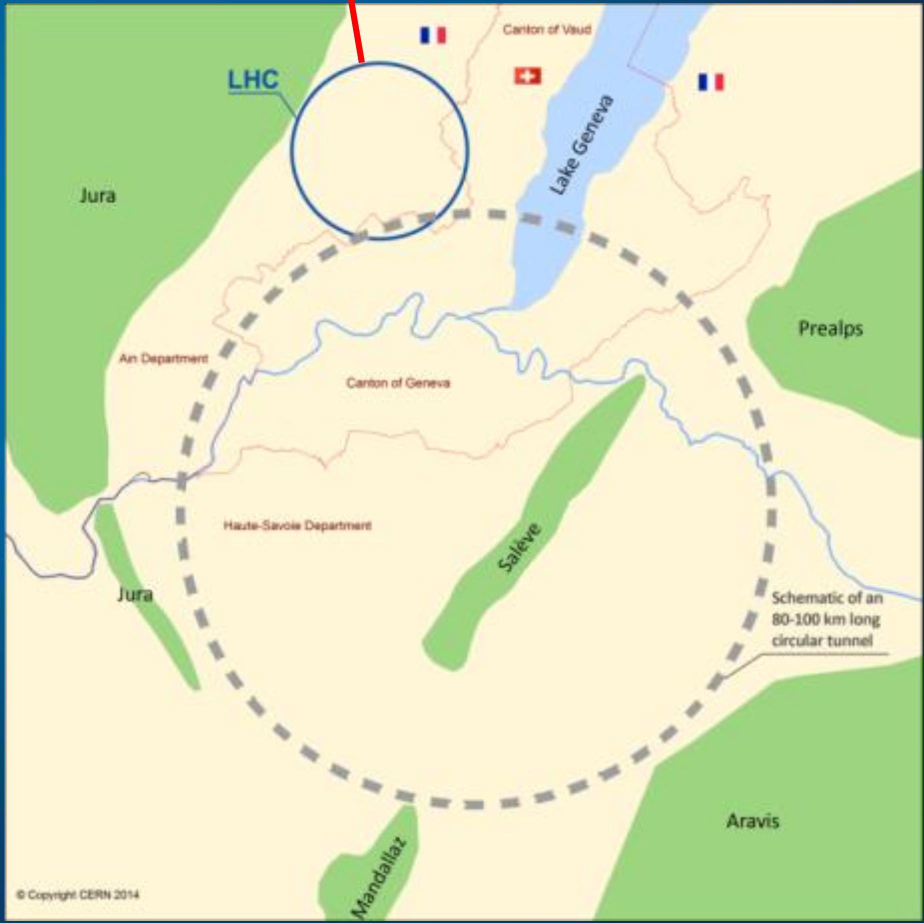
From Luca Bottura

Future Circular Collider

First studies on a new 80 km tunnel in the Geneva area

High Energy-LHC :33 TeV with 20T magnets

- **42 TeV with 8.3 T using present LHC dipoles**
- **80 TeV with 16 T based on Nb_3Sn dipoles**
- **100 TeV with 20 T based on HTS dipoles**



Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

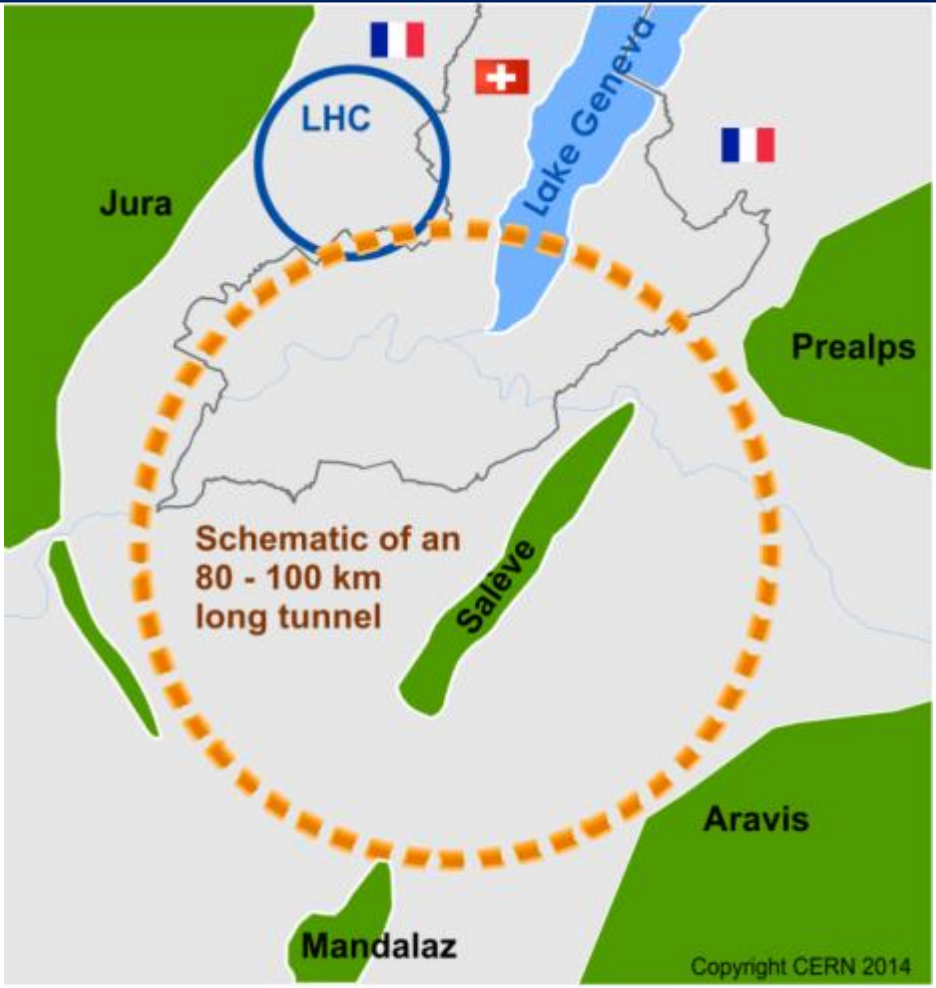
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**

→ defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**



FCC: 80-100 km infrastructure in Geneva area

FCC-hh Key Parameters

Parameter	FCC-hh	LHC
Energy [TeV]	**100 c.m.**	**14 c.m.**
Dipole field [T]	**16**	**8.33**
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5-10 x 10^{34}	1 x 10^{34}
Energy/beam [GJ]	**8.4**	**0.39**
Synchr. rad. [W/m/apert.]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Preliminary, subject to evolution

discharge 330 μs $\Rightarrow$ 24 TW

FCC-ee Key Parameters

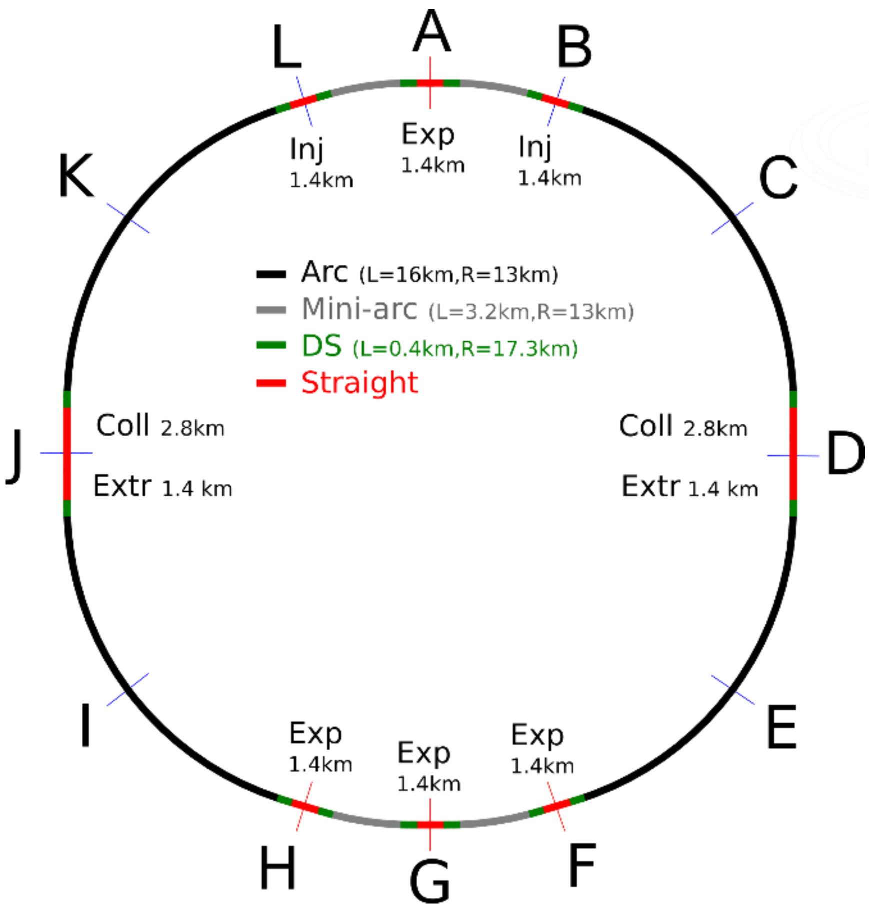
Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	16700	1360	98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	28	6	1.8	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchr. Power [MW]	**100**			**22**
RF Voltage [GV]	2.5	5.5	11	3.5

Preliminary, subject to evolution

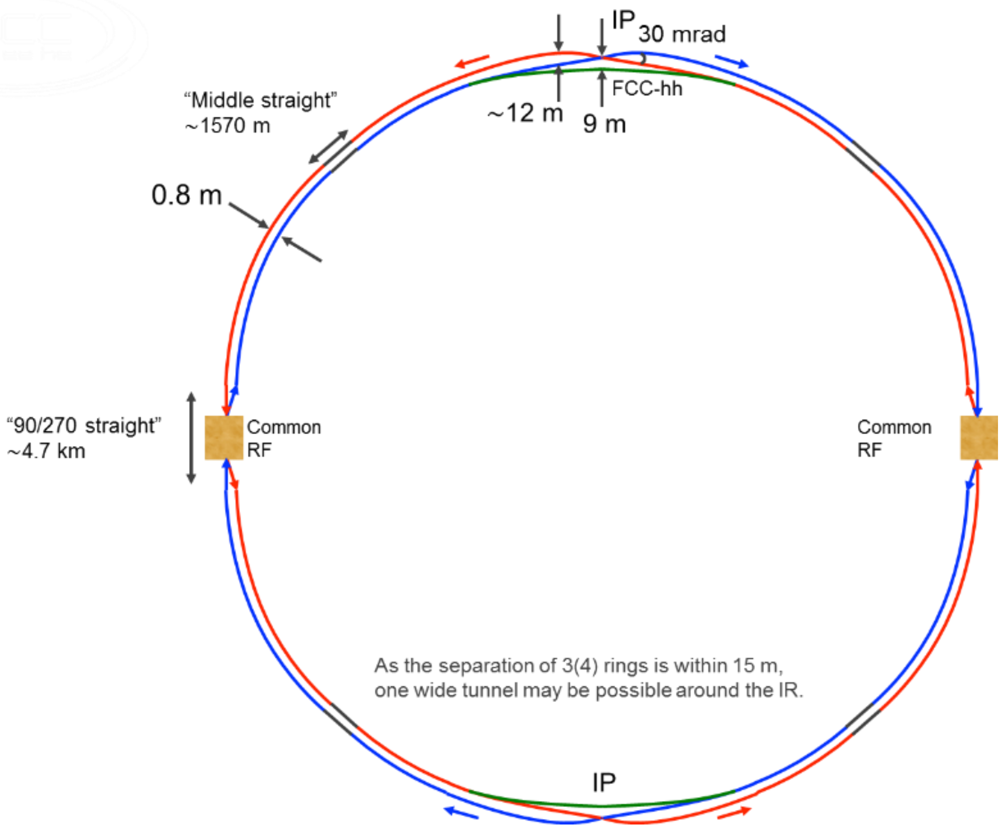
22 MW at LEP2

consistent layouts for hh & ee

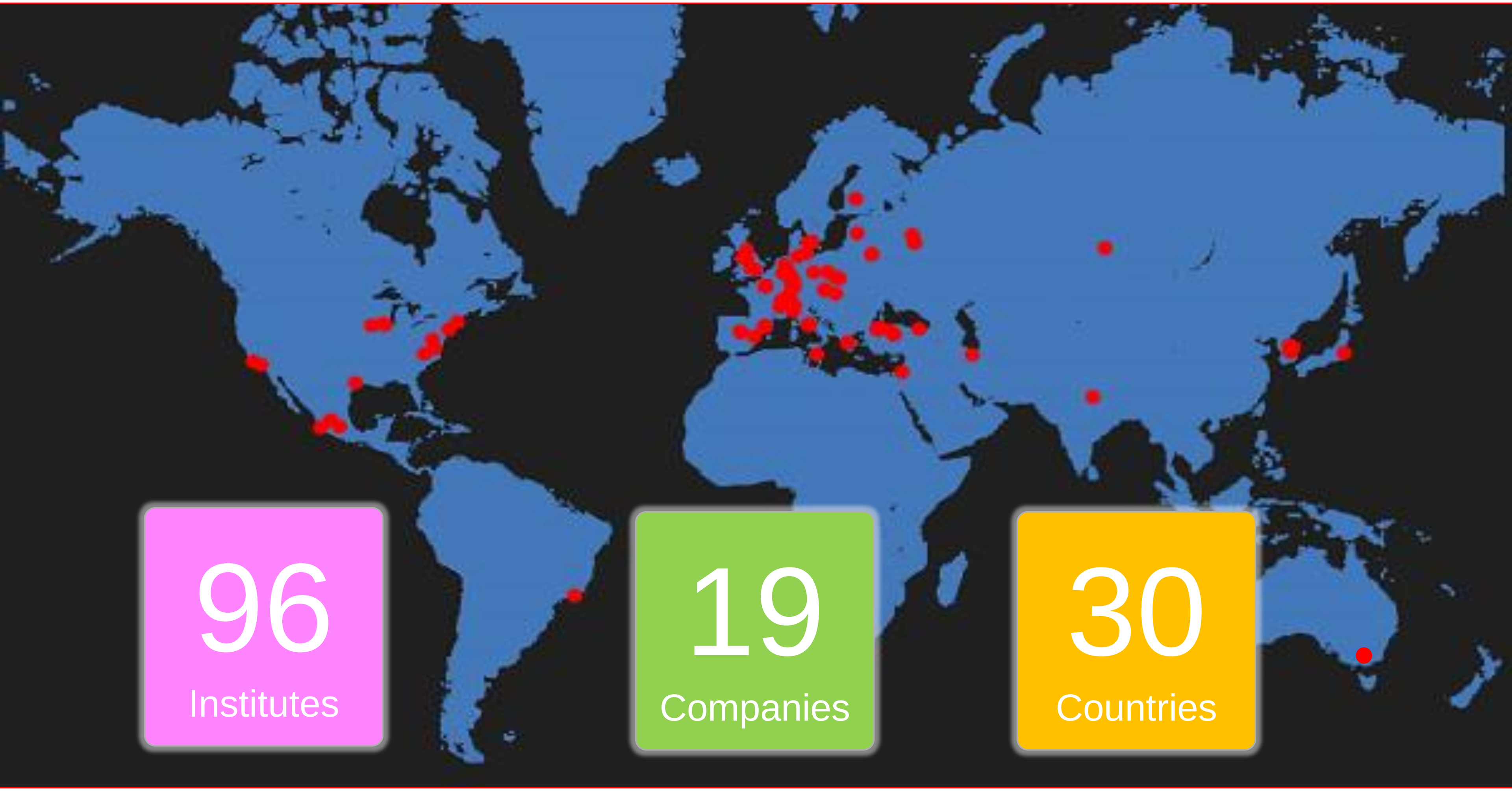
FCC-hh



FCC-ee 1, FCC-ee 2, FCC-hh and FCC-ee booster



collaboration & industry relations




FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch
IEEE CSC
DPG
DESY

Key Technologies and Challenges

- 16T superconducting magnets
- Superconducting RF cavities
- RF power sources
- Affordable & reliable cryogenics

- Reliability & availability concepts
- Stored Energy in the beams

  8.4 GJ / beam ; discharge 330 $\mu s \Rightarrow$ 24 TW
- Tunnel Geology

Layout Studies

ARUP

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2498923 Y: 1106695

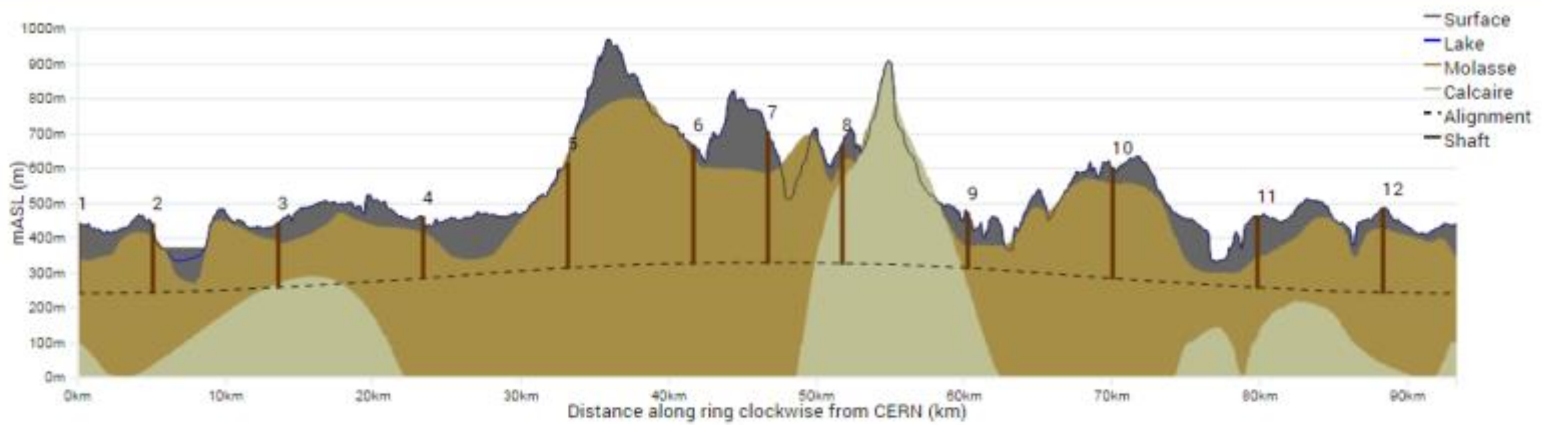
LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

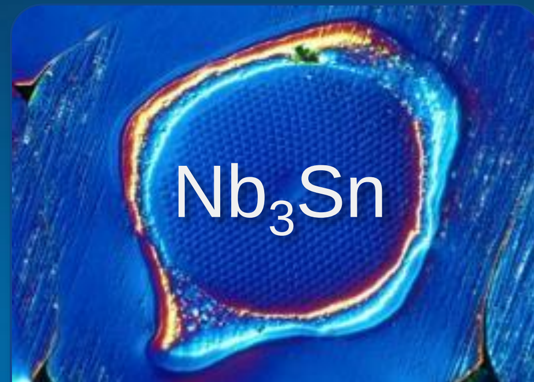
	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile



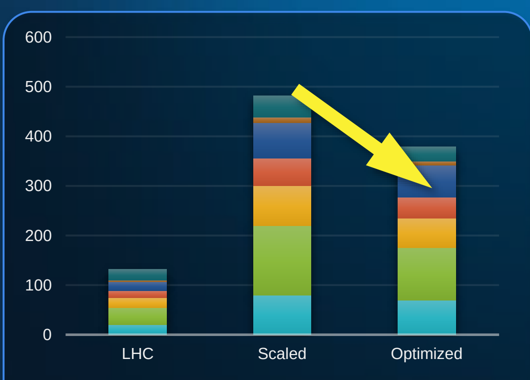
Push Technologies

High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics

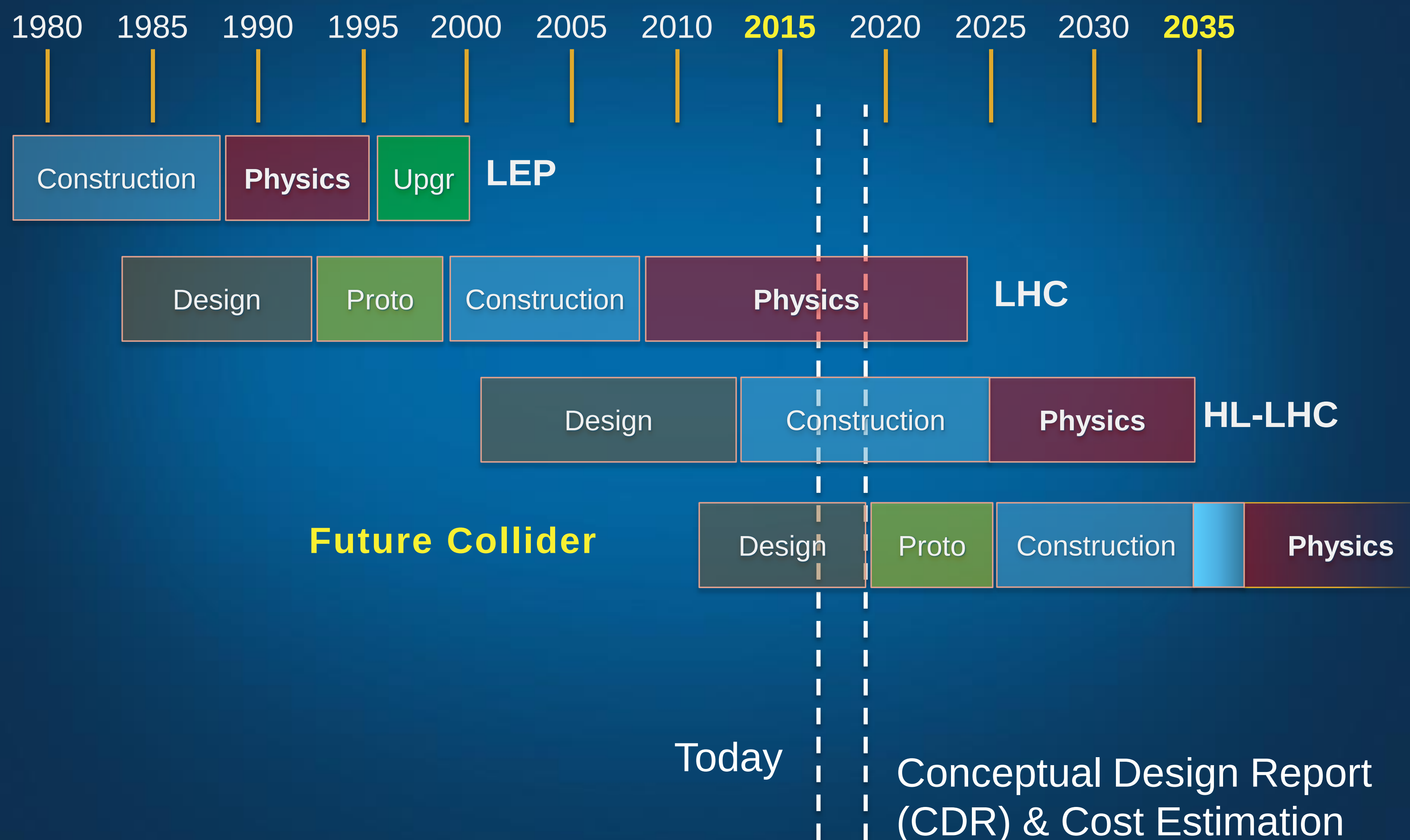


Power Efficiency

Reliability & Availability

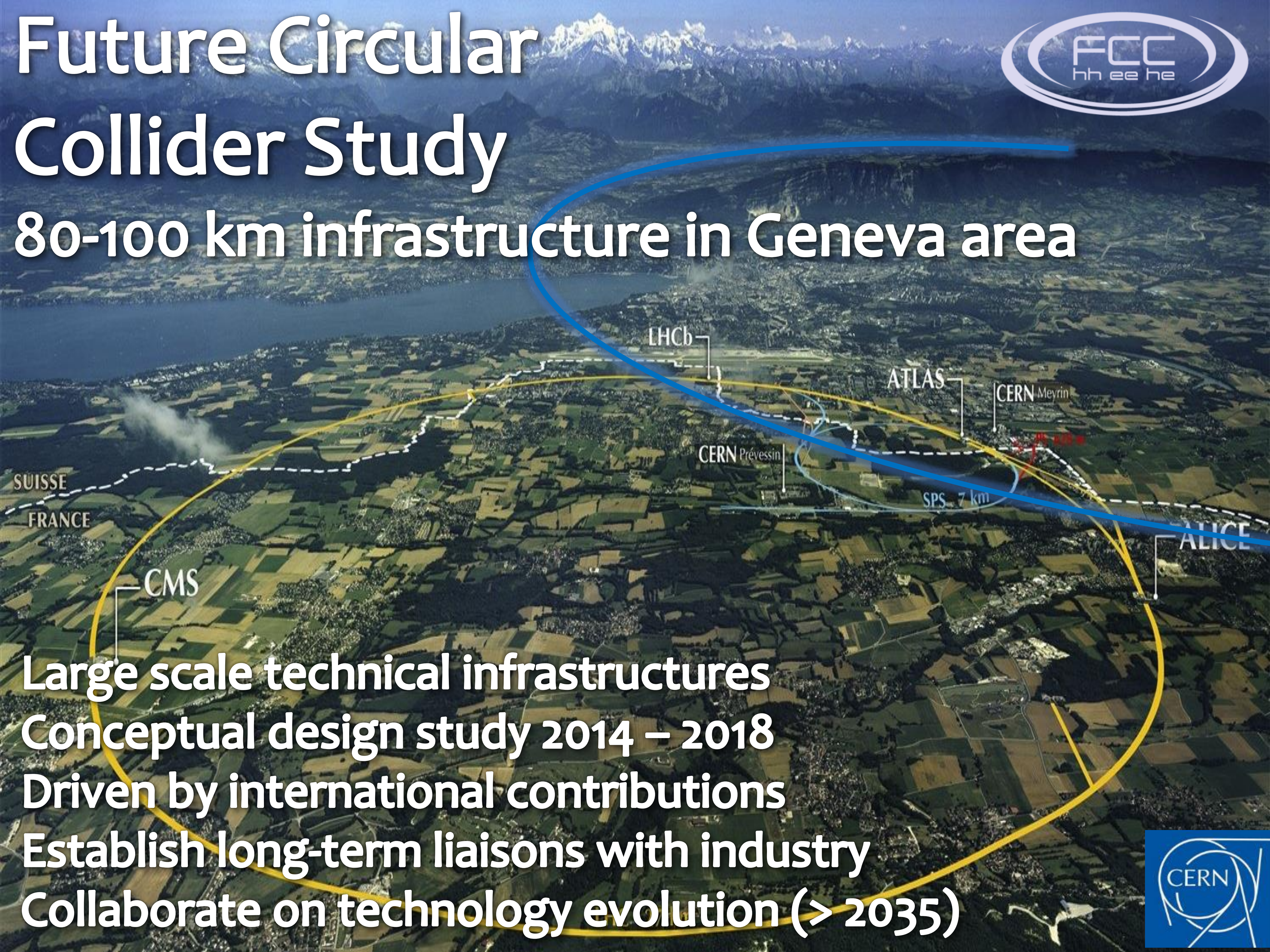
Global Scale Computing

CERN Circular Collider Timescale



Future Circular Collider Study

80-100 km infrastructure in Geneva area

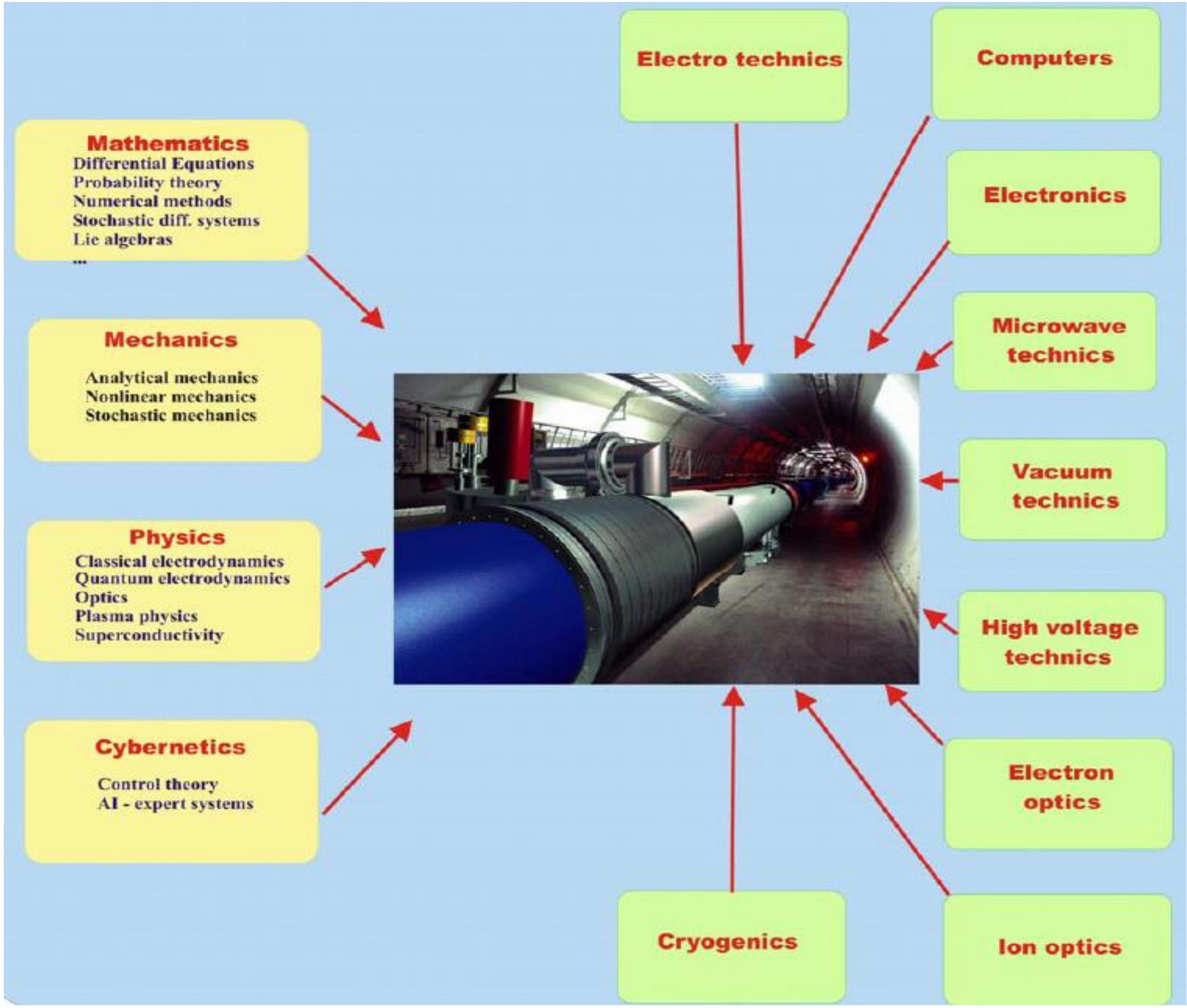


Large scale technical infrastructures
Conceptual design study 2014 – 2018
Driven by international contributions
Establish long-term liaisons with industry
Collaborate on technology evolution (> 2035)

Conclusion

- **CERN is presently exploiting the physics potential of the LHC**
- **After LS1 the LHC operates at 13 TeV (2016 “production year”)**
  Study when to increase towards 14 TeV (after LS2).
  => Goal 300 fb^{-1}
- **The high luminosity project HL-LHC (construction phase) will allow to collect ten times more data (2026 - mid 2030ies)**
  => Goal of 3’000 fb-1
- **Depending on the physics findings of the LHC “precision” e+e- linear colliders might be built in Japan (ILC) or at CERN (CLIC)**
- **CERN is hosting a study performed in international collaboration for a Future Circular Colliders in the Geneva area with a circumference of 80 – 100km:**
  - **pp-collider (FCC-pp) defining the infrastructure requirements**
  - ***e+e- collider (FCC-ee) as potential intermediate step***
  - ***p-e (FCC-ep) option***
  - **HE-LHC is also a possible option: High Field Magnets in the present LHC tunnel**

List of Technologies needed for building and exploiting Accelerators



Electrical engineering
Electronics
Mechanical engineering
Beam-materials science
Computer engineering
Civil Engineering
Large scale simulations
……

A multidisciplinary domain !

High Energy Physics can offer interesting and challenging careers for skilled engineers

Thanks for your attention

"The task of the mind is to produce future"

Paul Valéry

www.cern.ch