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LHC & Future High-Energy Circular Colliders

Frédérick Bordry
JUAS 2018– European Scientific Institute – Archamps
17th January 2018

juas Joint Universities Accelerator School

esi European Scientific Institute

Outline

- **LHC accelerator: recall in few slides**

- **Run 2 (from LS1 to LS2)** ⇒ ***13 TeV;*** **150 fb^{-1}**
- **Run 3** ⇒ ***14 TeV;*** **300 fb^{-1}**

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

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

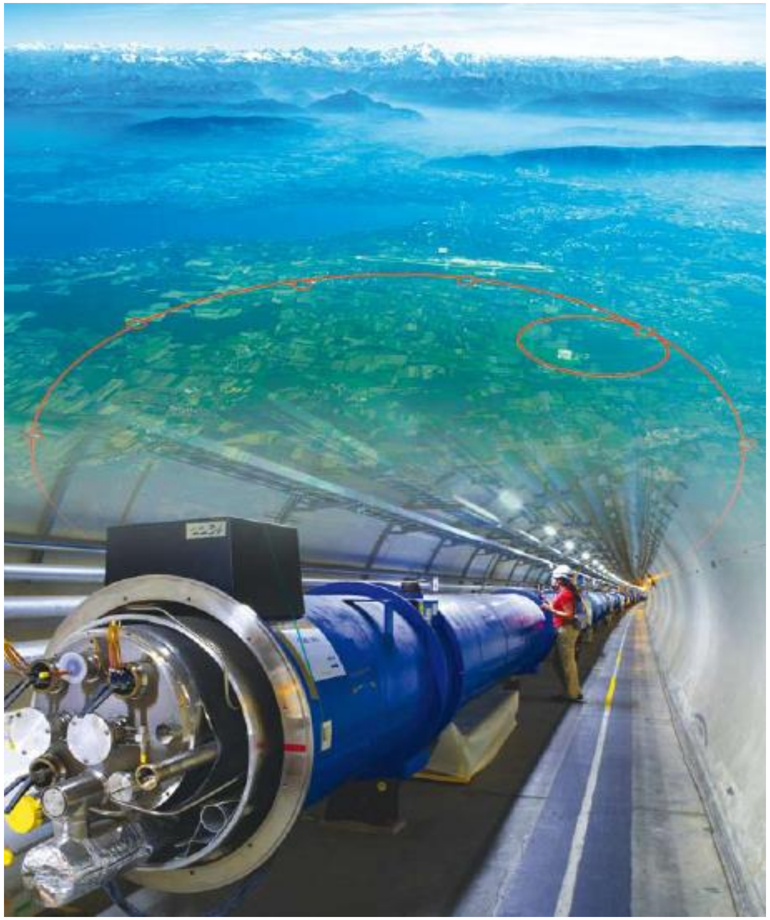
- **Conclusion**

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



2010-2037: 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 – 2037… : HL-LHC operation

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

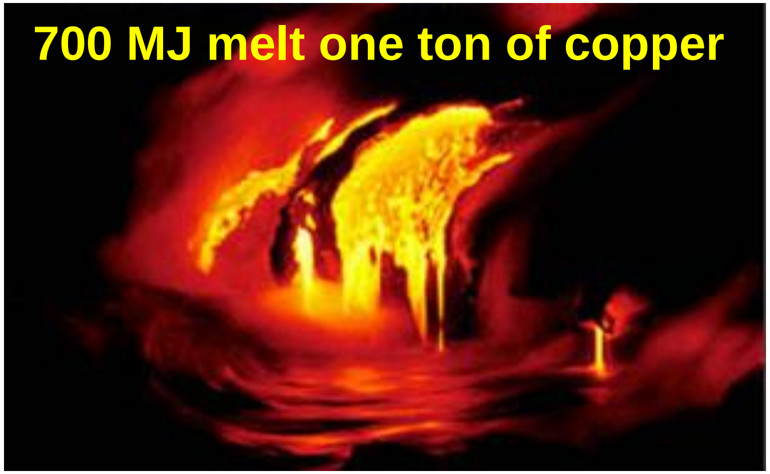
10 GJoule ≅ flying 700 km/h

560 tons

10 GJoule ≅ 55 km/h

88’000 tons

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



700 MJ melt one ton of copper

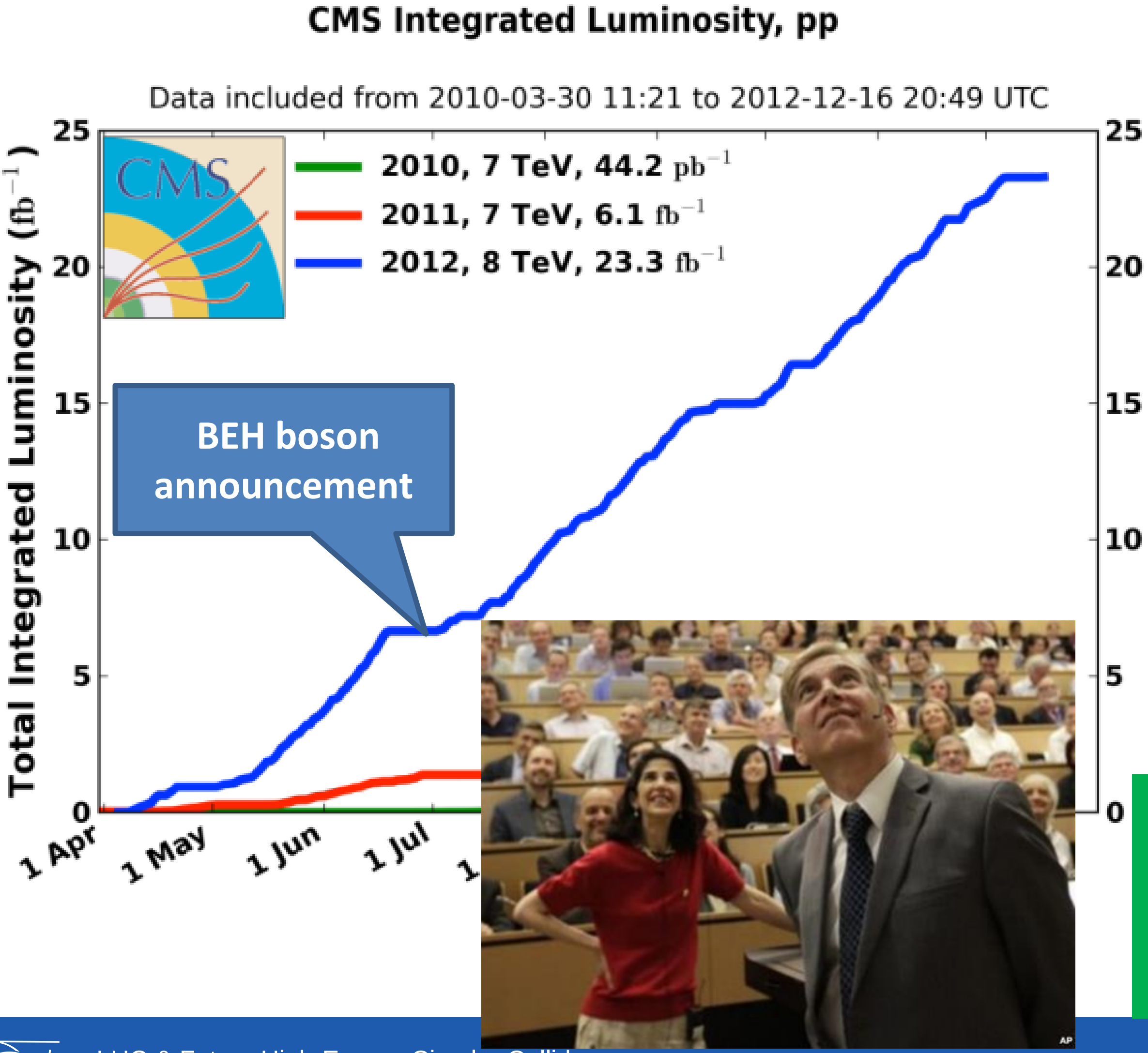
700 MJoule dissipated in 88 µs

700.106 / 88.106 ≅ 8 TW

World Electrical Installed Capacity ≅ 3.8 TW

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

LHC 2010-2012: Run 1



BEH boson announcement

Σ ~30 fb^{-1}

~ 2 10^{15} collisions

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

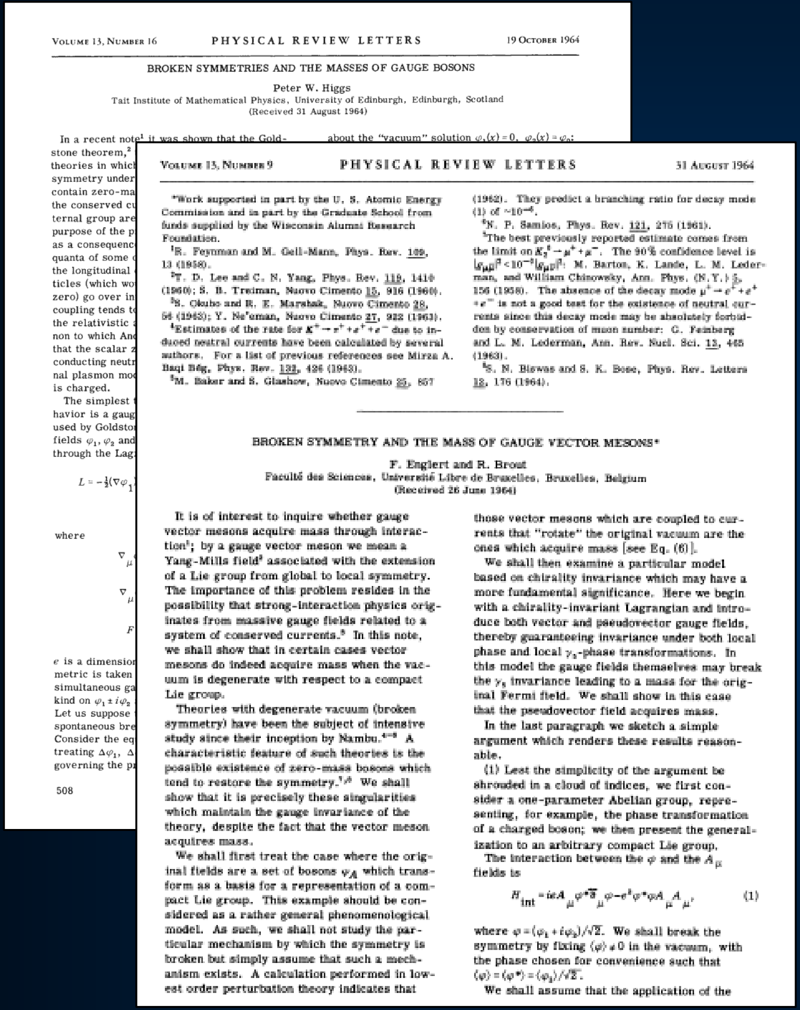
2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits

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

7 TeV cm in 2010 and 2011
8 TeV cm in 2012
Up to 1380 bunches with1.5 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 whic
symmetry under
contain zero-ma
the conserved cu
ternal group are
purpose of the p
as a consequenc
quanta of some
the longitudinal
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non to which An
that the scalar
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is charged.
The simplest
havior is a gaug
used by Goldsto
fields φ_1, φ_2 and
through the Lag

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

where

∇_μ

∇_μ

F

e is a dimensio
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 $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

508

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 ~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 $|g_{\mu\mu}|^2 < 10^{-2}|g_{\mu p}|^2$: 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.

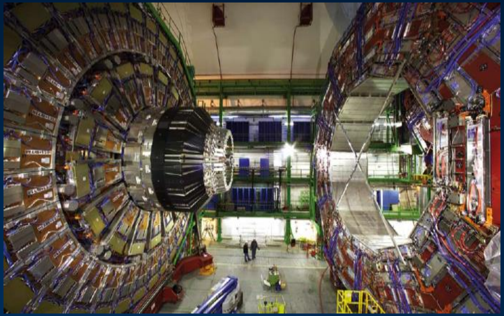
The interaction between the φ and the A_μ fields is

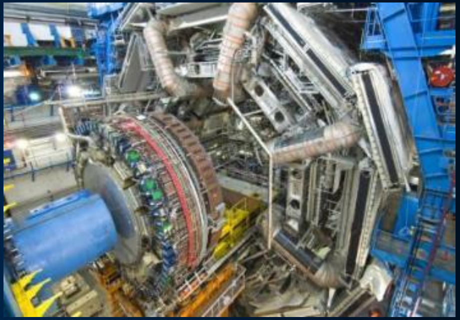
$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \qquad (1)$$

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

April '13 to Sep. '14

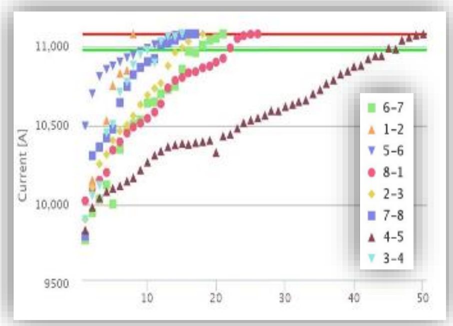
The main 2013-14 LHC consolidations

5th April

3rd June
First Stable Beams

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

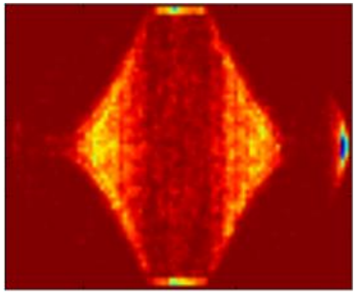
13-14 | Aug 14-Apr | 2015



Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



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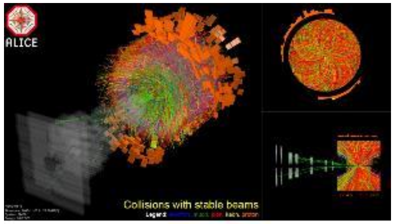


Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

LHC 2017 : Integrated Performance

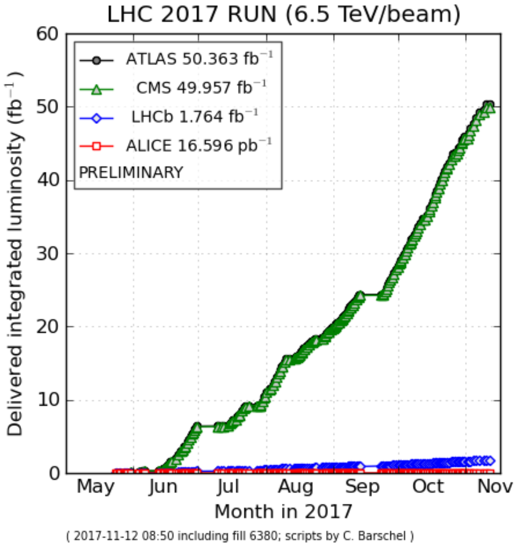
Achieved : 50 fb^{-1}

2017 goal:
45 fb^{-1}

Peak luminosity
2.0 10^{34} cm^{-2} s^{-1}

With luminosity levelling at
1.5 10^{34} cm^{-2} s^{-1}

Availability: 81%



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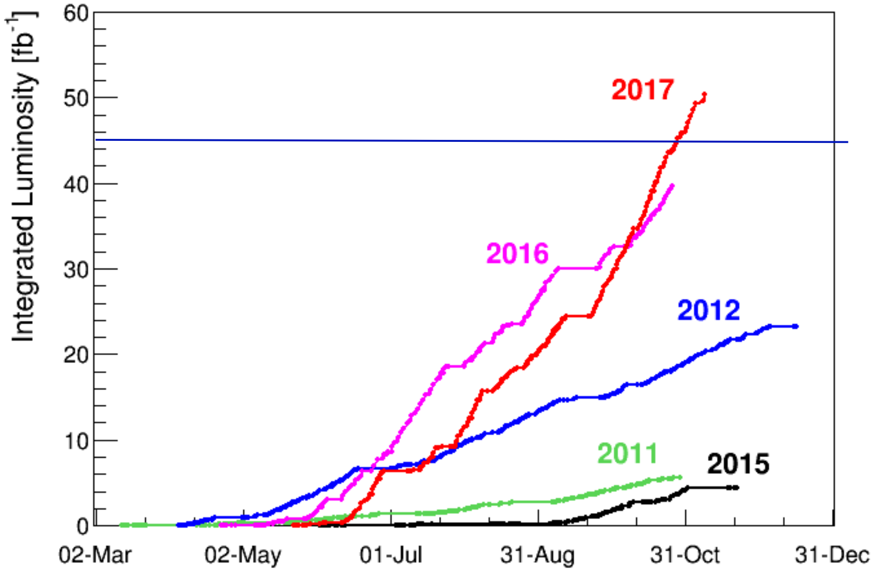
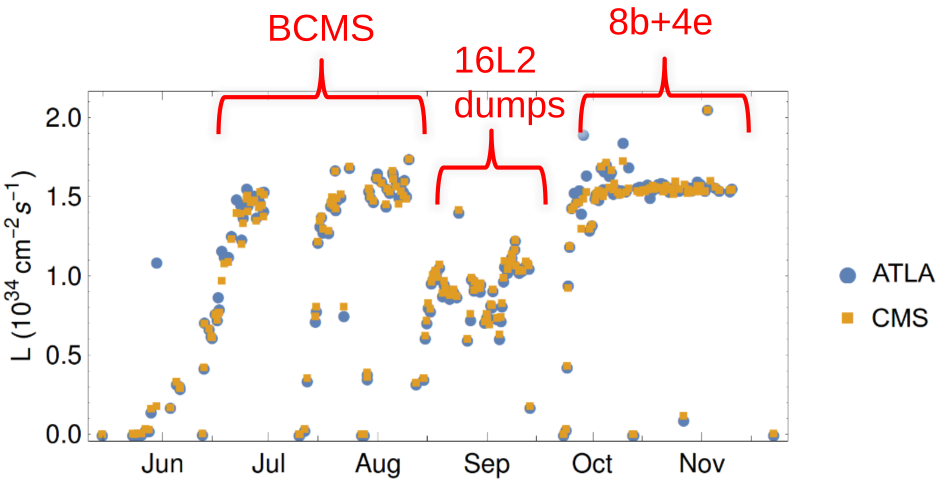
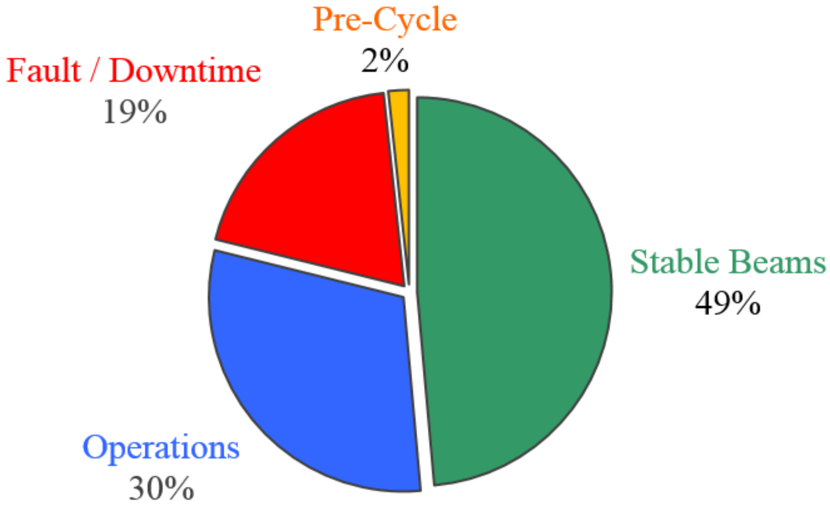
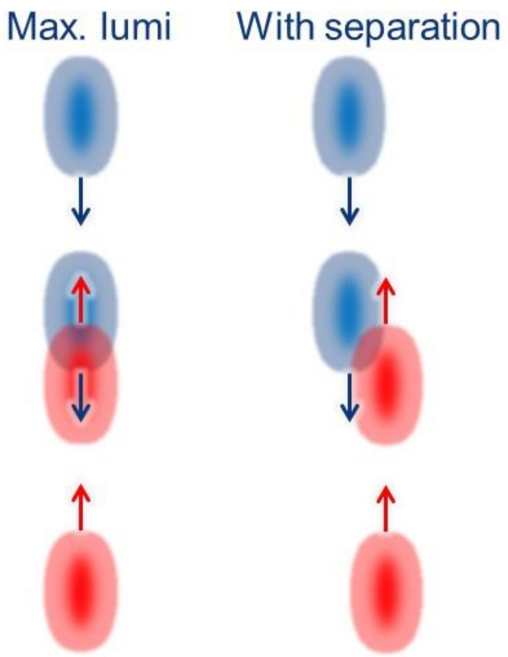


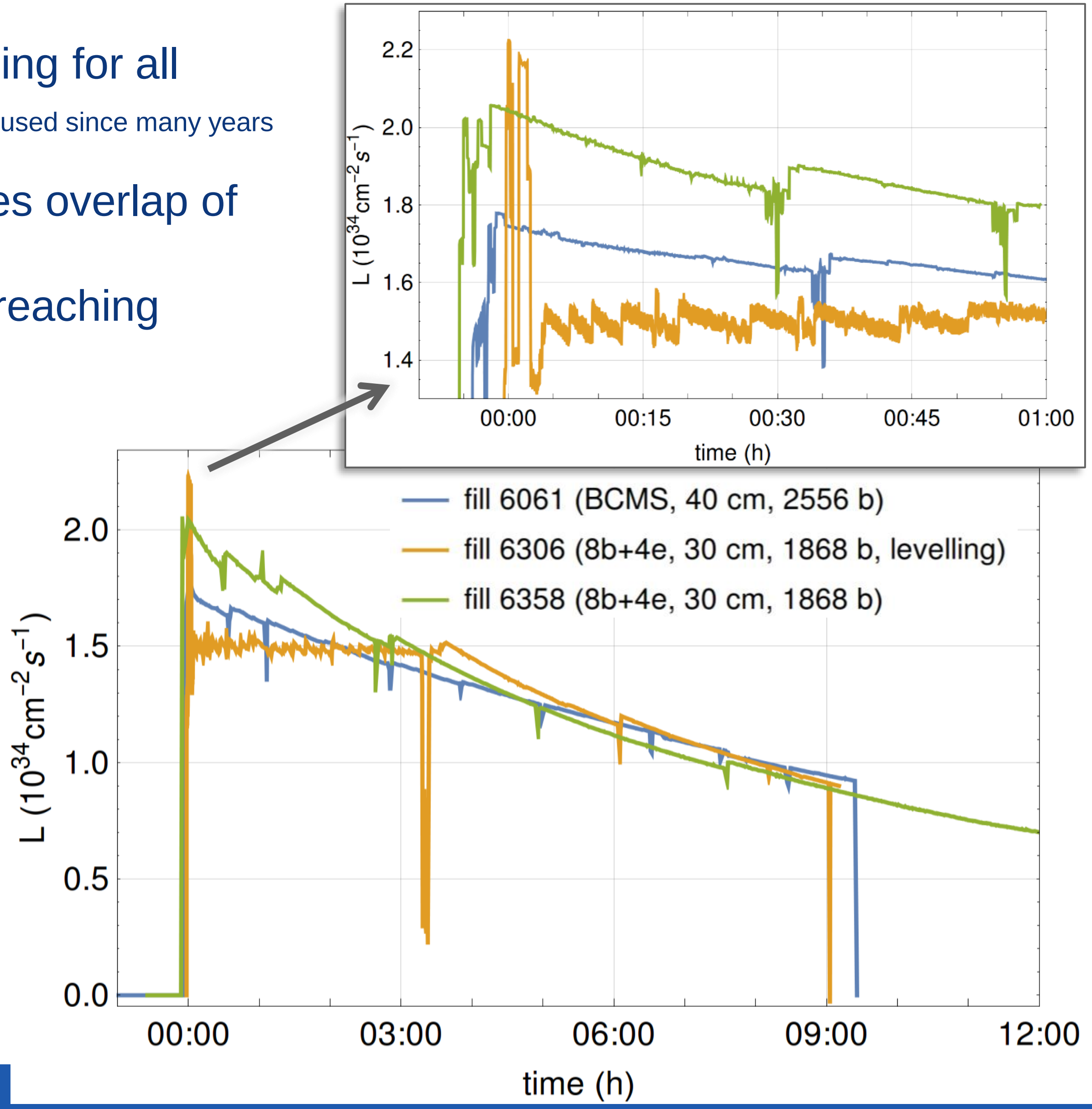




LHC 2017 : separation levelling

- Introduced separation levelling for all experiments (Separation levelling is used since many years for ALICE and LHCb)
- Dynamic orbit bump changes overlap of colliding bunches
- Initial spike before leveling reaching $2.2\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$

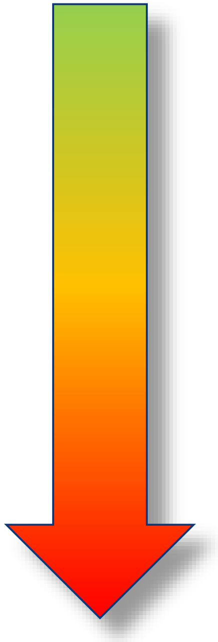




Courtesy of Roderik Bruce

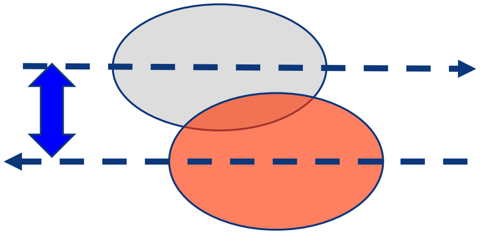
Luminosity Levelling

- In certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **levelling**
- Each levelling technique has its advantages and drawbacks

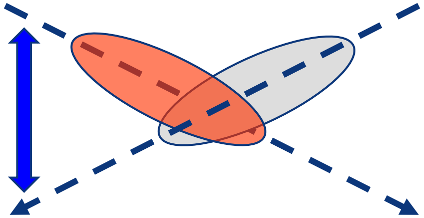


Complexity

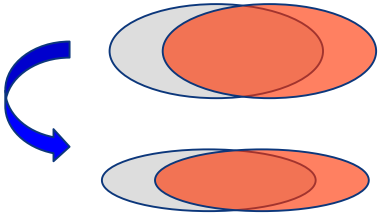
Levelling by beam offset / separation



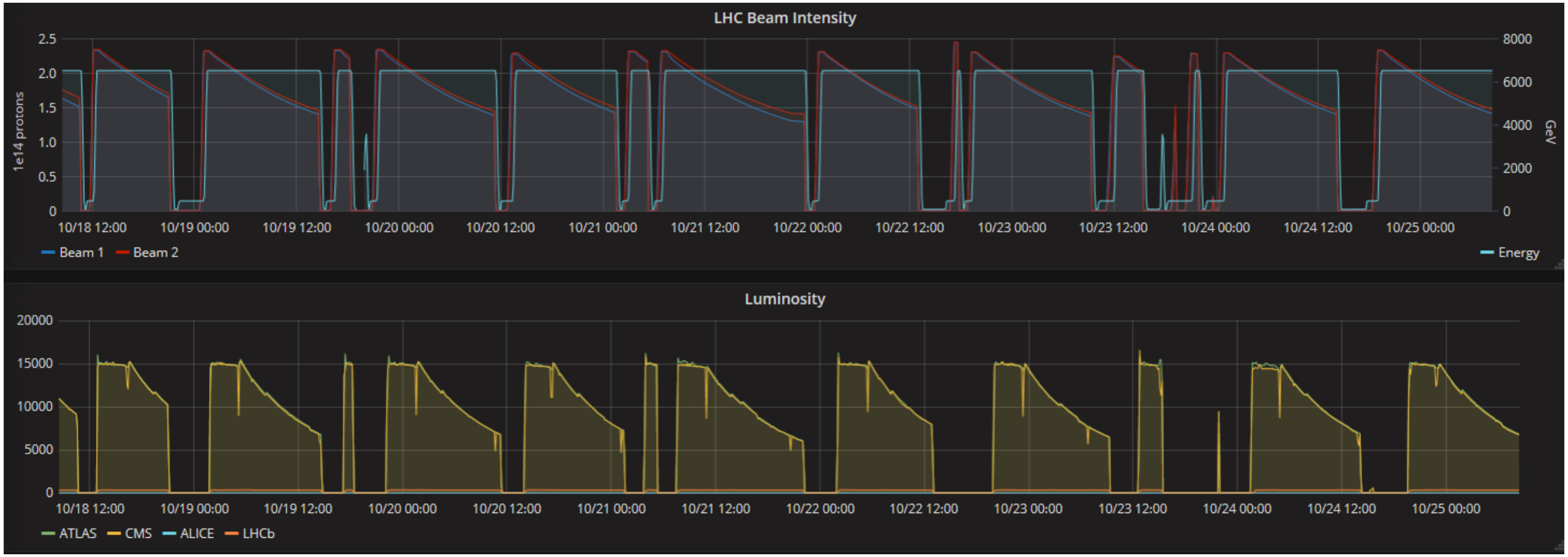
Levelling by crossing angle



Levelling by β* (= beam size at IP)



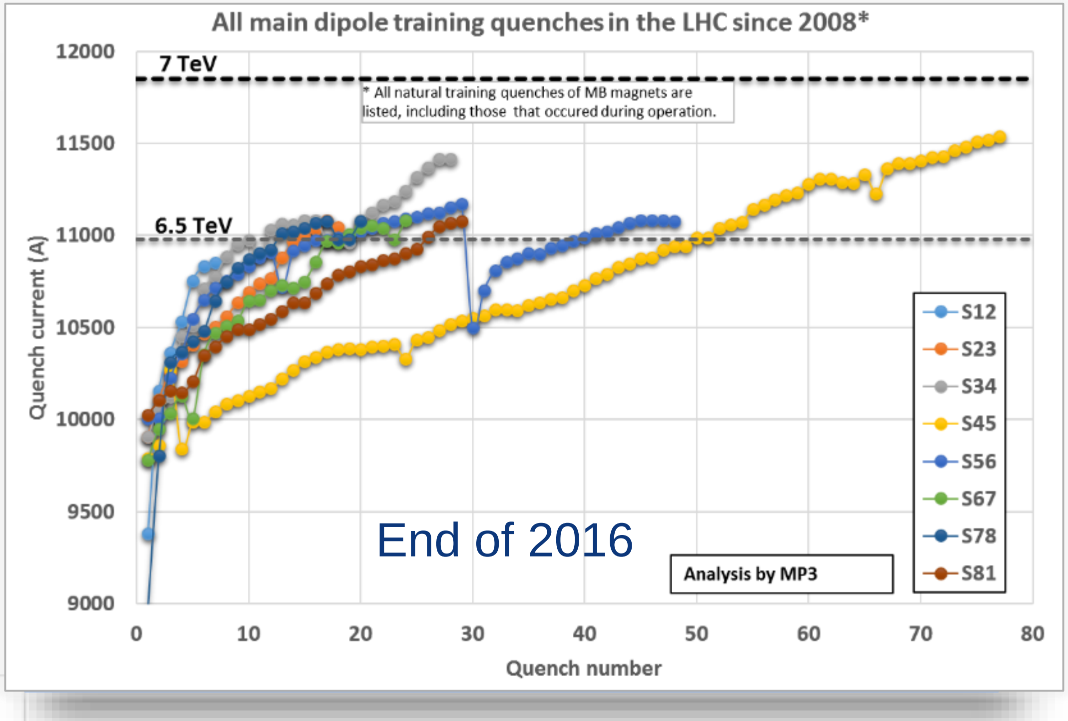
Luminosity Levelling (separation) & Anti-Levelling (crossing angle)



- Initially ATLAS & CMS luminosity levelled at 1.5x10^{34} cm^{-2}s^{-1}, using beam separation
- Later anti-levelling by reducing the crossing angle and increase the instantaneous luminosity

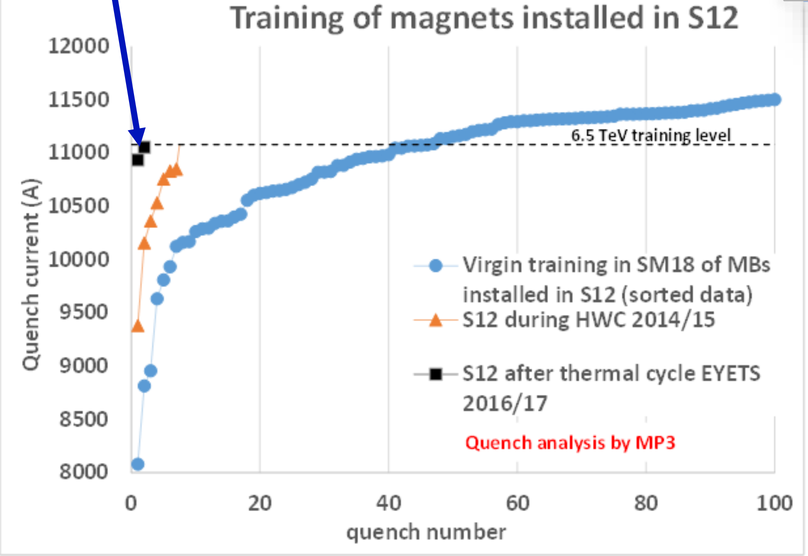
LHC Training Dipoles

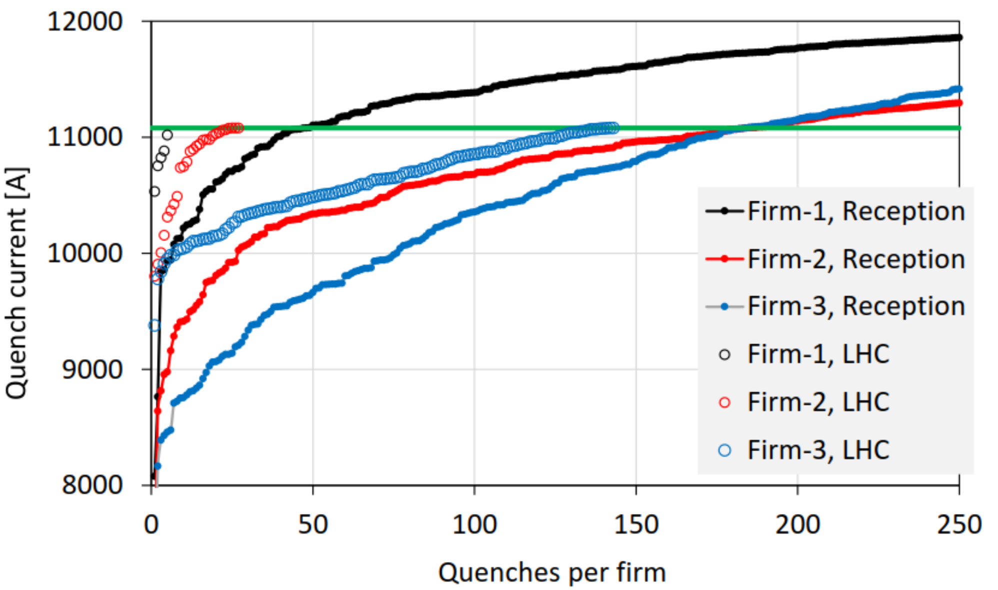
Each Sector Trained to 6.55TeV (11080A)
(100 A above the operational field)
≈ 7.82 T



End of 2016

2017

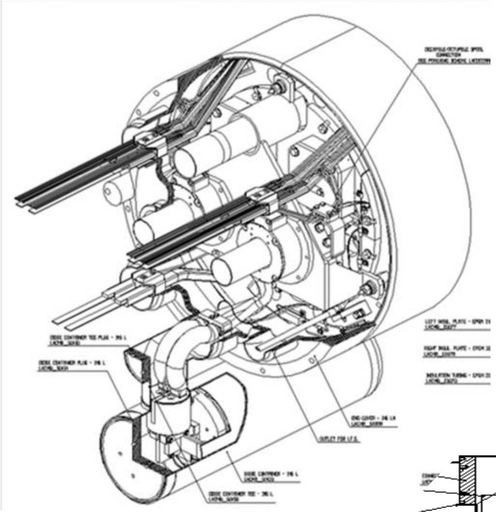




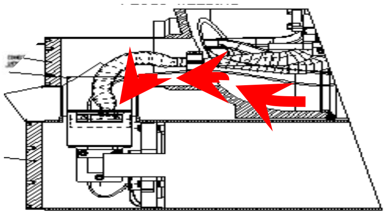
Beam energy : **Run 2 @ 13 TeV c.m.**

NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.



Study how to reinforce the insulation (and to clean) during LS2 the electrical part connecting the dipole bypass diode.
Powering tests before and during LS2 should be defined



Working group was set up:
How ?, How long ?, How much ?

Work will be done during LS2

Full Energy Exploitation of the LHC

Working group – Chair: Oliver Bruning

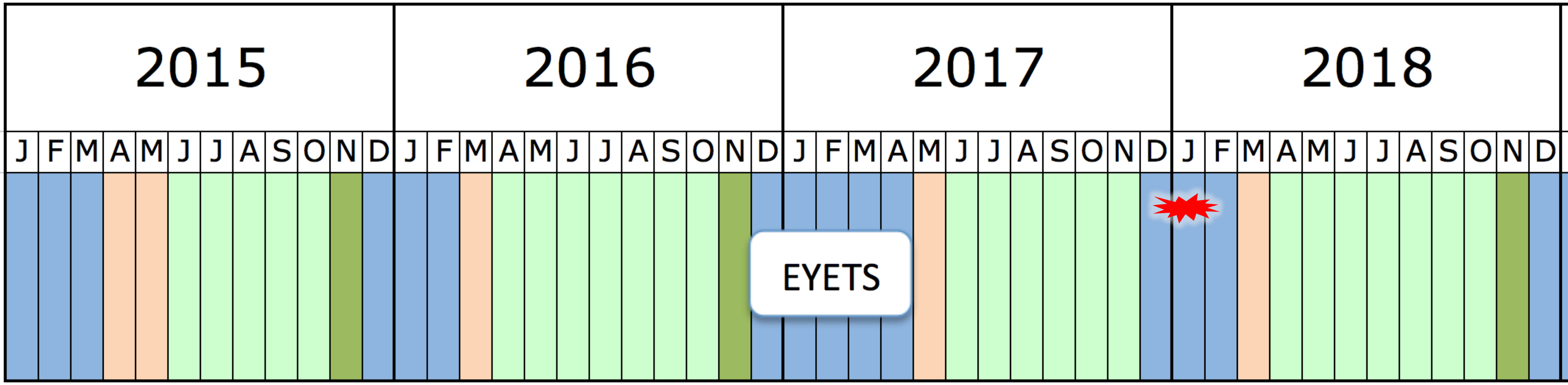
Main scope and goals :

Study divided into 3 parts:

1. Implications for pushing the LHC to 7 TeV (nominal energy) ***(report by March 2017 – Done)***
2. Implications for pushing the LHC to 7.7 TeV (ultimate energy) ***(report by June 2018 but better knowledge after LS2)***
3. Implications and feasibility for pushing the LHC beam energy beyond ultimate by replacing some of the LHC magnets with 11T magnets ***(report by end 2018 on feasibility)***

Run 2

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



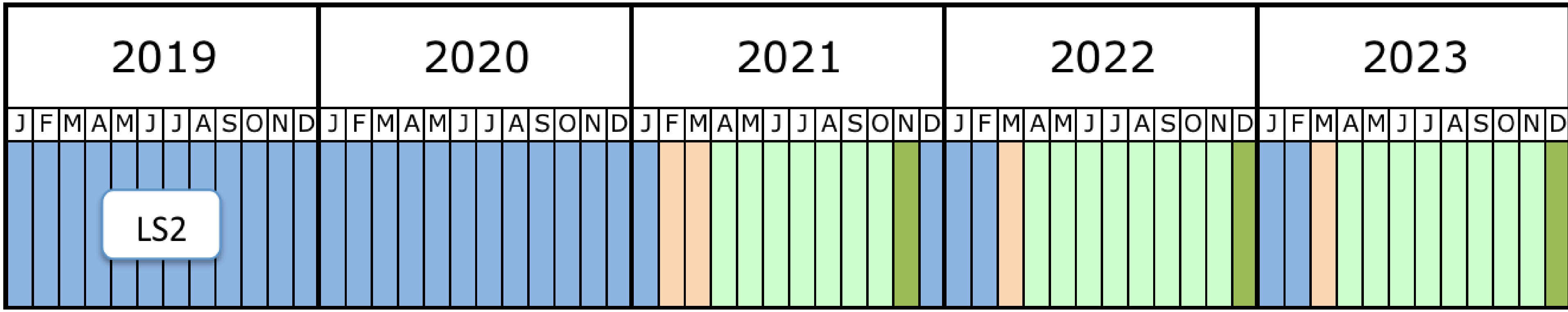
EYETS

	J	F	M	A	M	J	J	A	S	O	N	D
2015	🟦	🟦	🟦	🟧	🟧	🟩	🟩	🟩	🟩	🟩	▨	🟦
2016	🟦	🟦	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟦
2017	🟦	🟦	🟦	🟦	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟦
2018	🟦	🟦	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟦

🟦 Shutdown/Technical stop
🟩 Protons physics
🟧 Commissioning
▨ Ions

$\sum$(Run1 + Run2) >150 fb^{-1}

$\sum$(Run1 + Run2 + Run 3) > 300 fb^{-1}

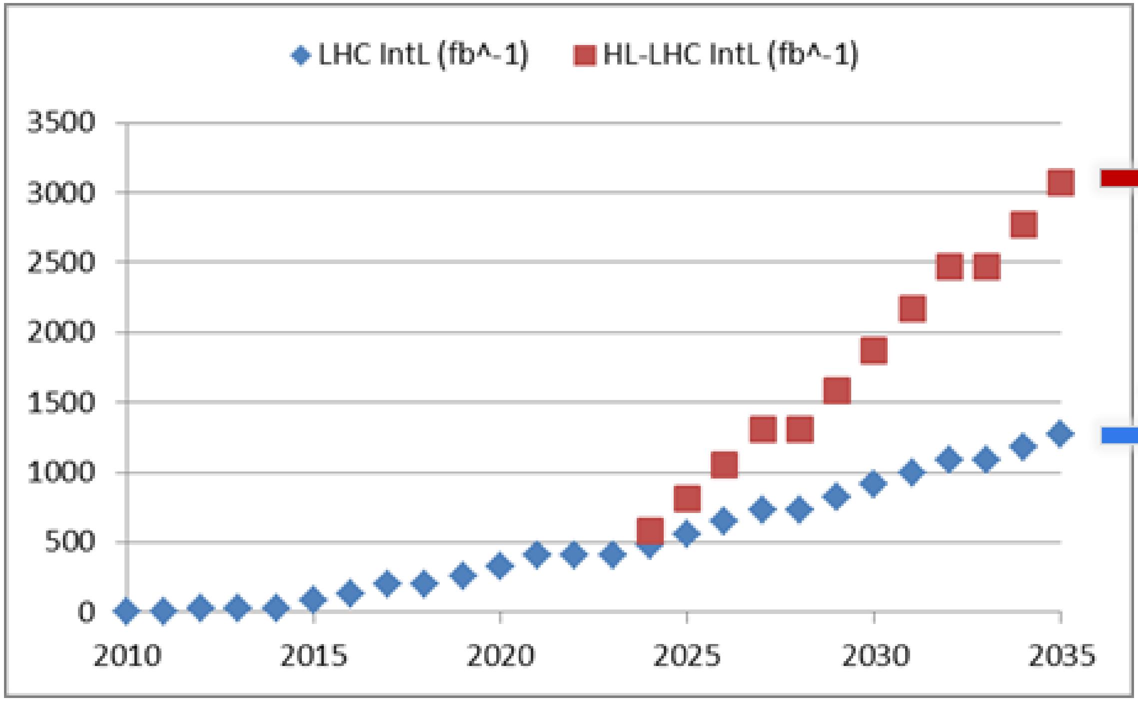


LS2

	J	F	M	A	M	J	J	A	S	O	N	D
2019	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2020	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2021	🟦	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟦
2022	🟦	🟦	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨
2023	🟦	🟦	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Why High-Luminosity LHC ? (LS3)

High
Luminosity
LHC



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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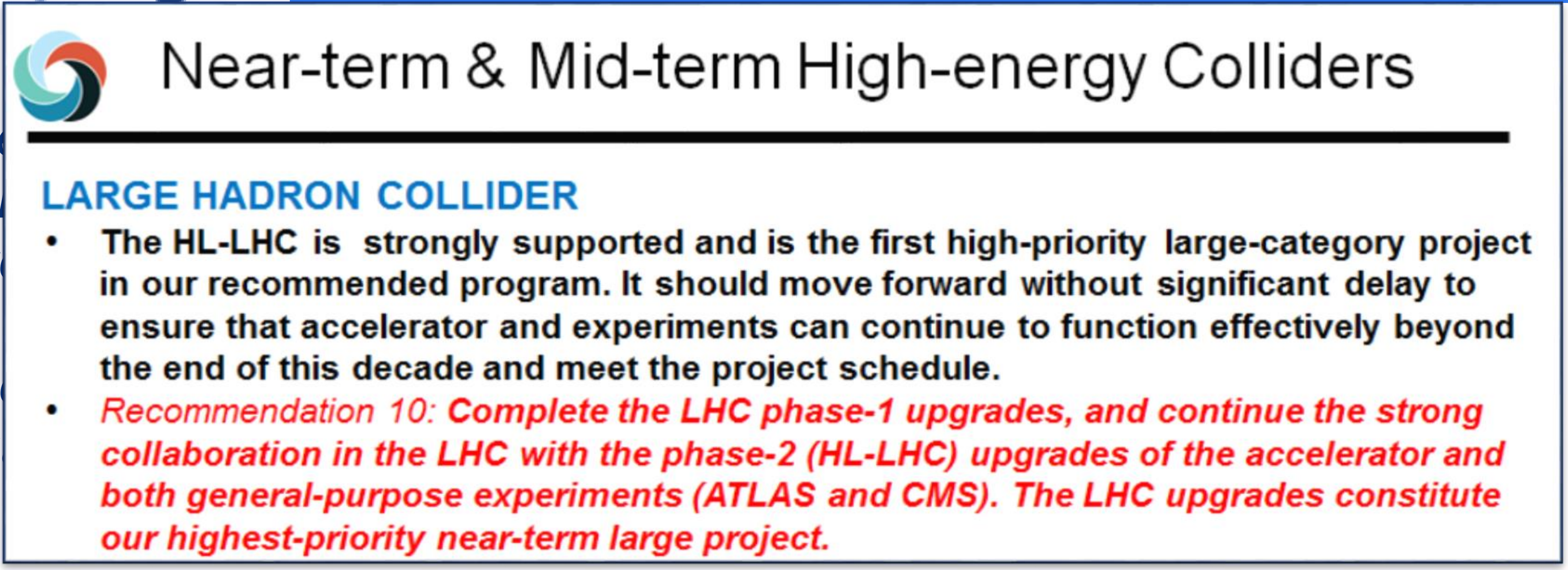


Near-term & Mid-term High-energy Colliders

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.***

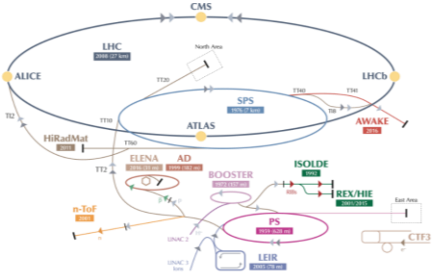
HL-LHC from a study to a PROJECT

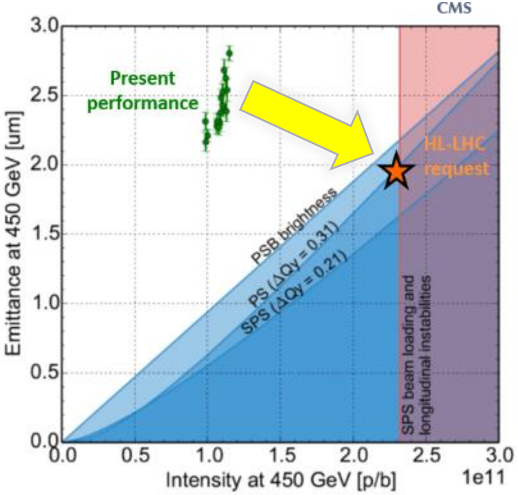
300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU**

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

Goals and means of the LHC Injectors Upgrade: LIU project





	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU Baseline	2.3	2.2
HL-LHC	2.3	2.1

Increase injector reliability and lifetime to cover HL-LHC run (until ~2040) 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

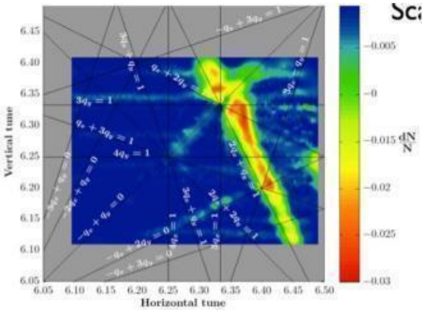
LS2 : (2019-2020), LHC Injector Upgrades (LIU)

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:

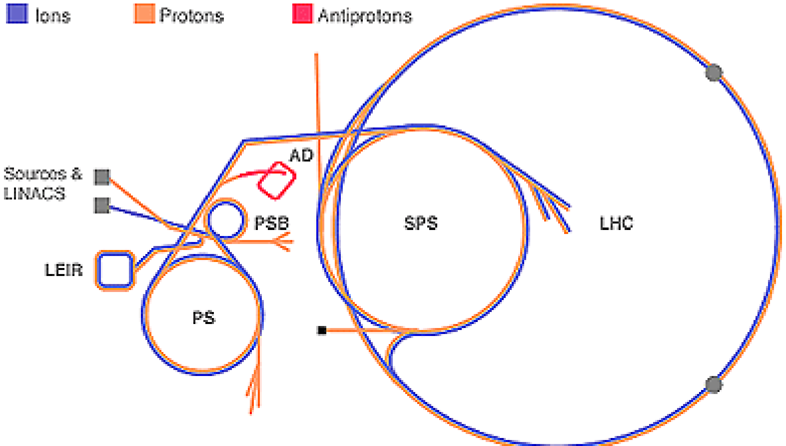
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness



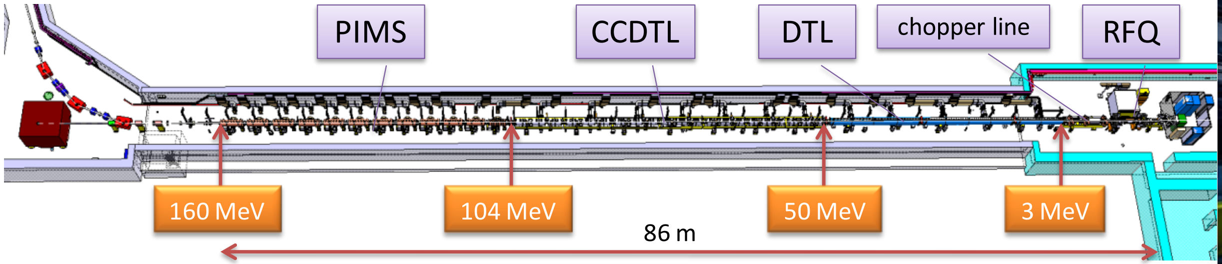
SPS

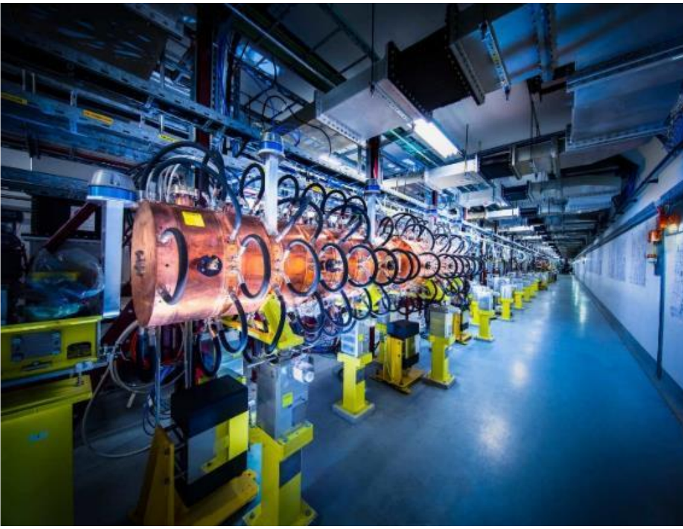
- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

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



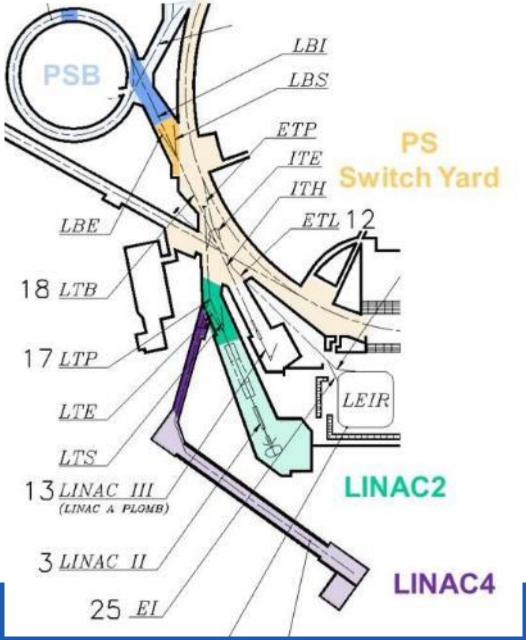
LINAC 4: Reliability Run from June 2017





- Linac4 operation fully integrated in CERN Control Center: run since 30th October by PSB operations team
- Accelerator Fault Tracker deployed to assess availability (faults mainly from power converters, RF and pre-chopper)
- Source exchanged in September 2017 to increase current, other options being investigated to further improve performance
- Linac4 Working towards post-LS2 operational beam conditions

Average availability for weeks 44-47: ~87%



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 :

$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

➔1) maximize bunch intensities ➔ Injector complex

➔2) minimize the beam emittance LIU ⇔ IBS

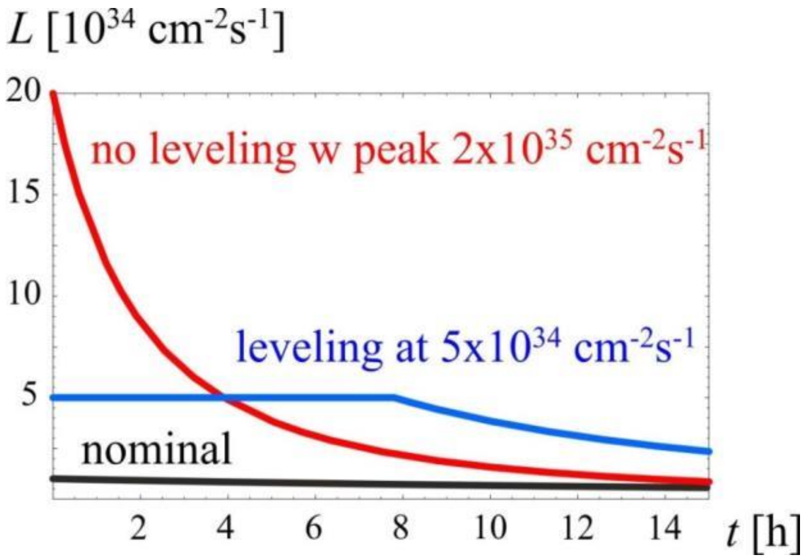
➔3) minimize beam size (constant beam power); ➔ triplet aperture

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

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

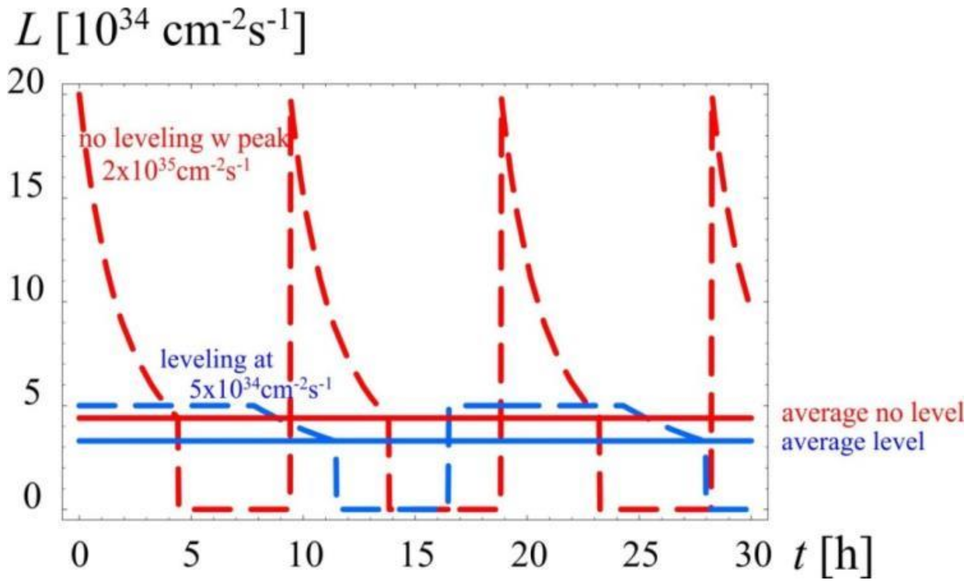
➔6) Improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

Luminosity Levelling, a key to success



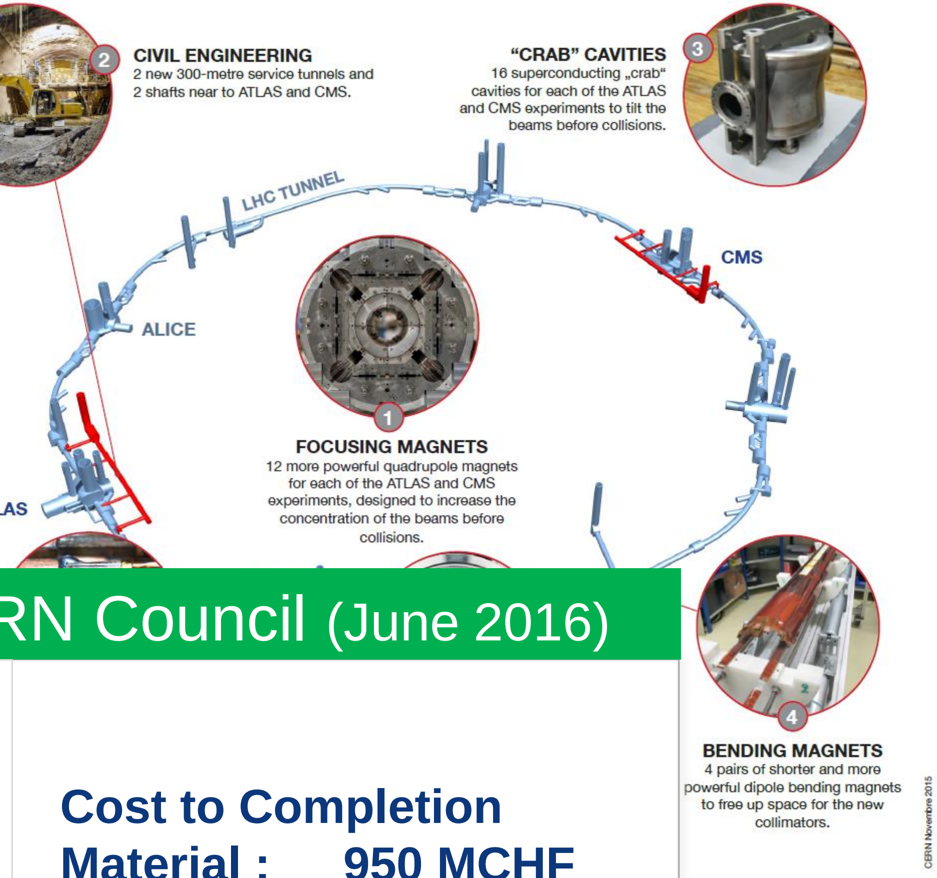
- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

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

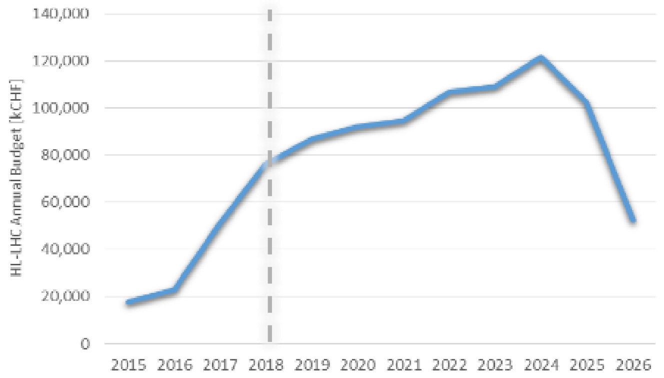


The HL-LHC Project: 300 fb^{-1} → 3000 fb^{-1}

- **New IR-quads Nb$_3$Sn (inner triplets)**
- **New 11 T Nb$_3$Sn (5.5 m dipoles)**
- **Crab Cavities**
- Collimation upgrade
- Cryogenics upgrade
- C
- M
- …



Formal approval by CERN Council (June 2016)



Cost to Completion
Material : 950 MCHF

Ma

LHC

Squeezing the beams: High Field SC Magnets

Quads for the inner triplet

Decision 2012 for low-β quads

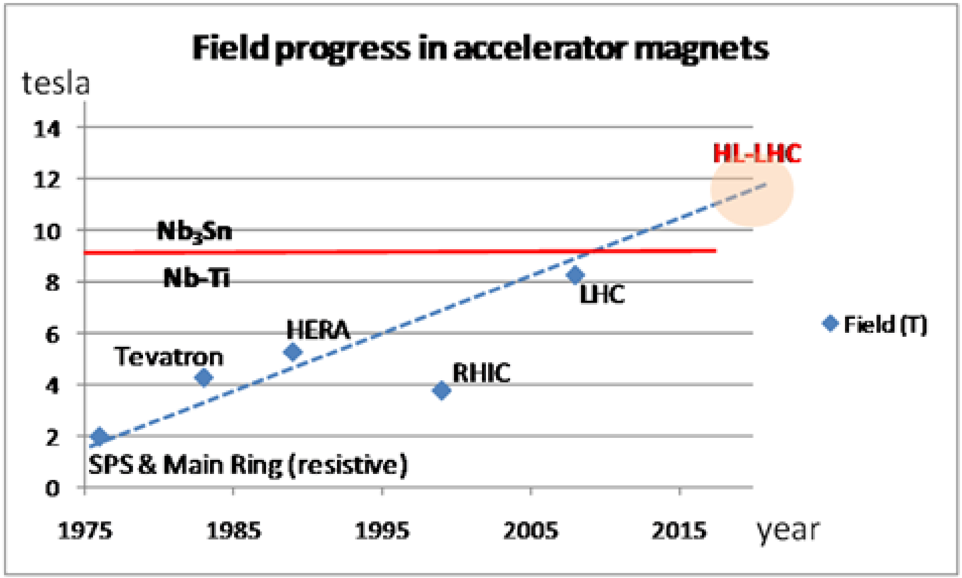
Aperture ∅ 150 mm – 140 T/m

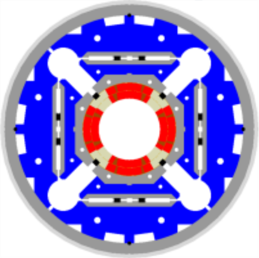
(B_{peak} ≈12.3 T)

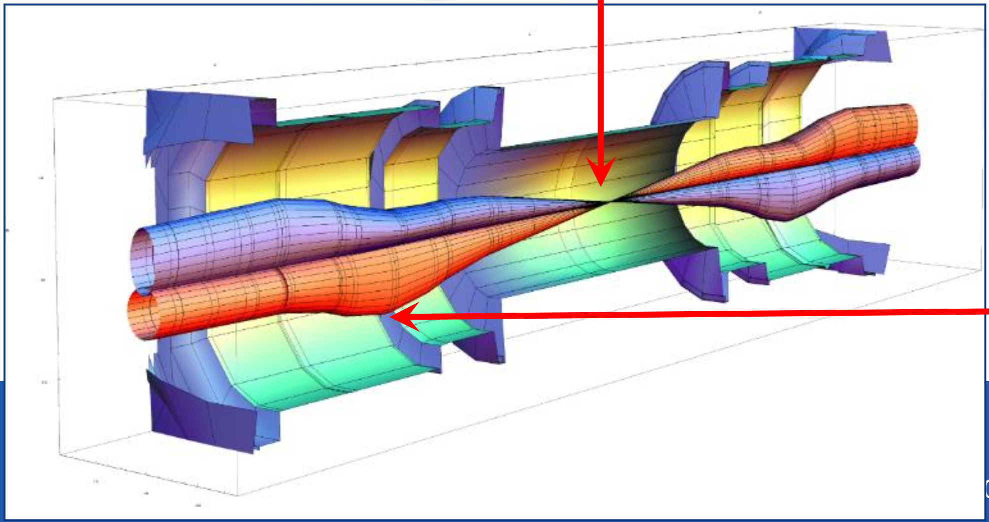
operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)





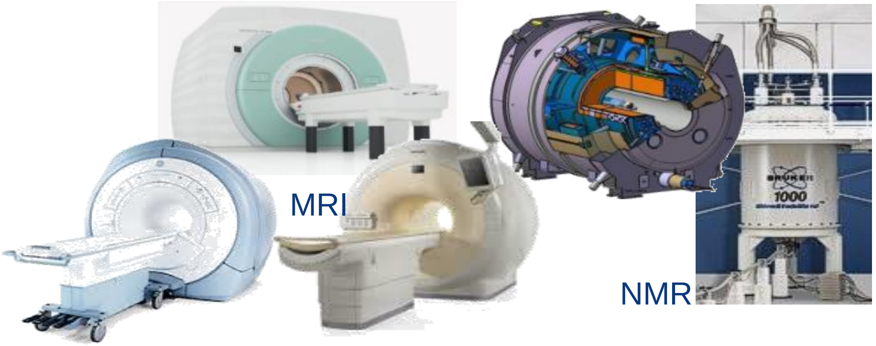


	$β_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

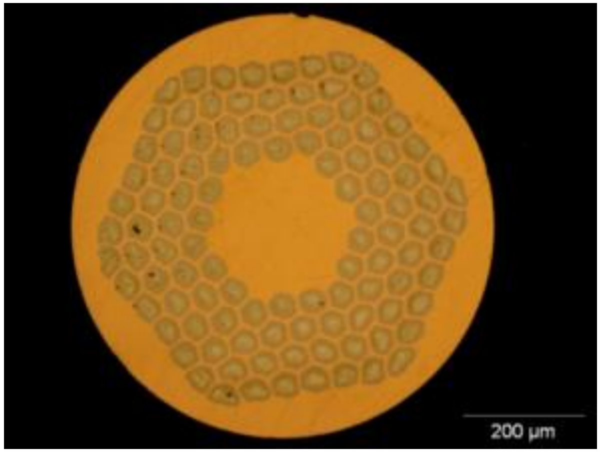
The « new » material : Nb_3Sn

- 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)*

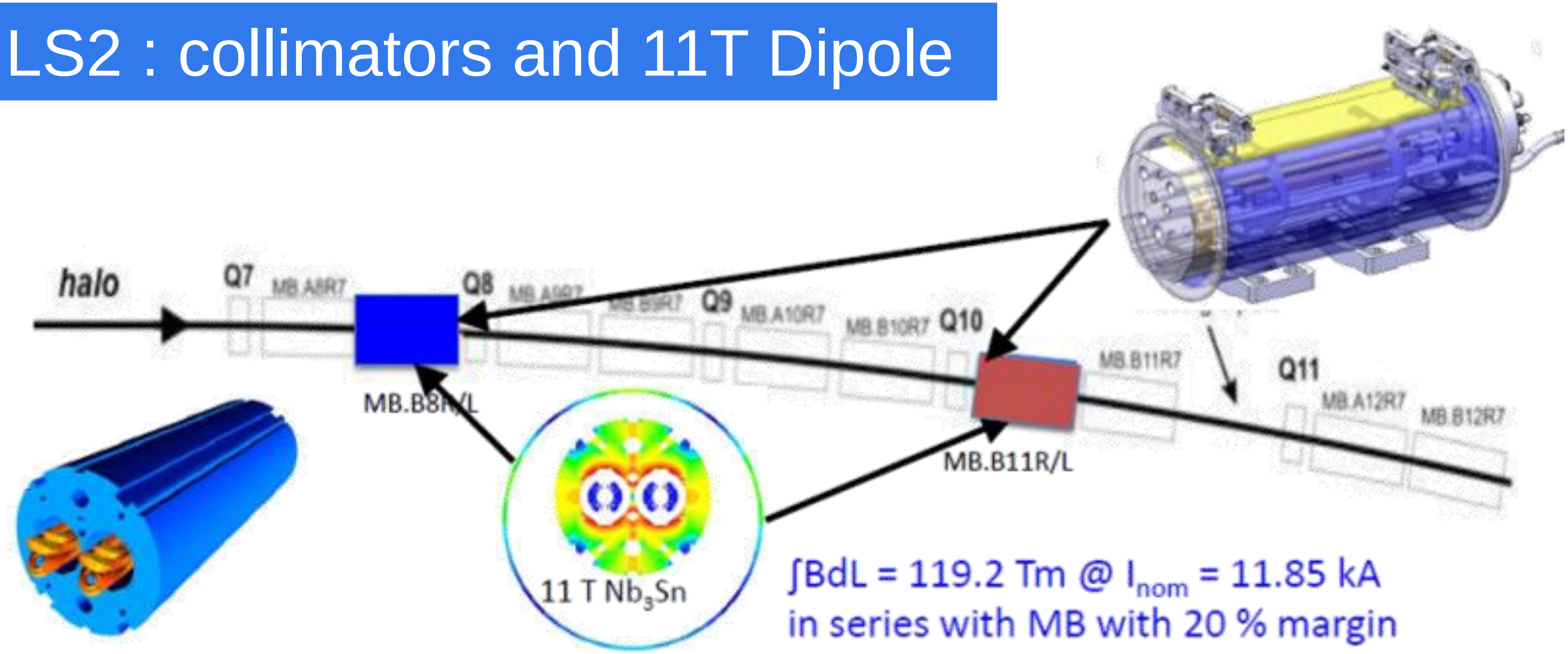


- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is 5 times LHC Nb-Ti



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

LS2 : collimators and 11T Dipole



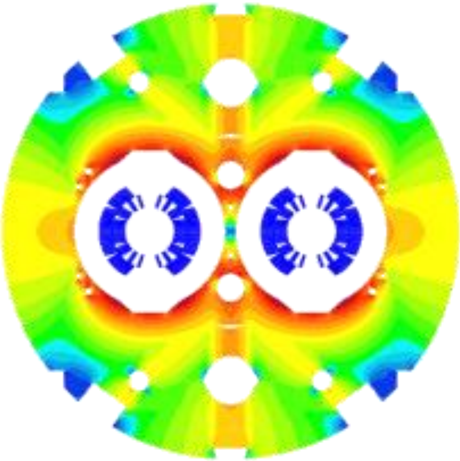
$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB with 20 % margin

11 m Nb_3Sn | **3 m Collim**

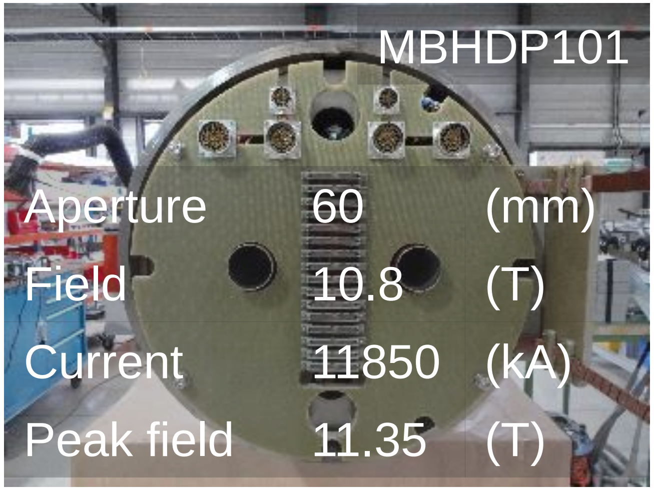
5.5 m Nb_3Sn | 5.5 m Nb_3Sn | **3 m Collim**

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

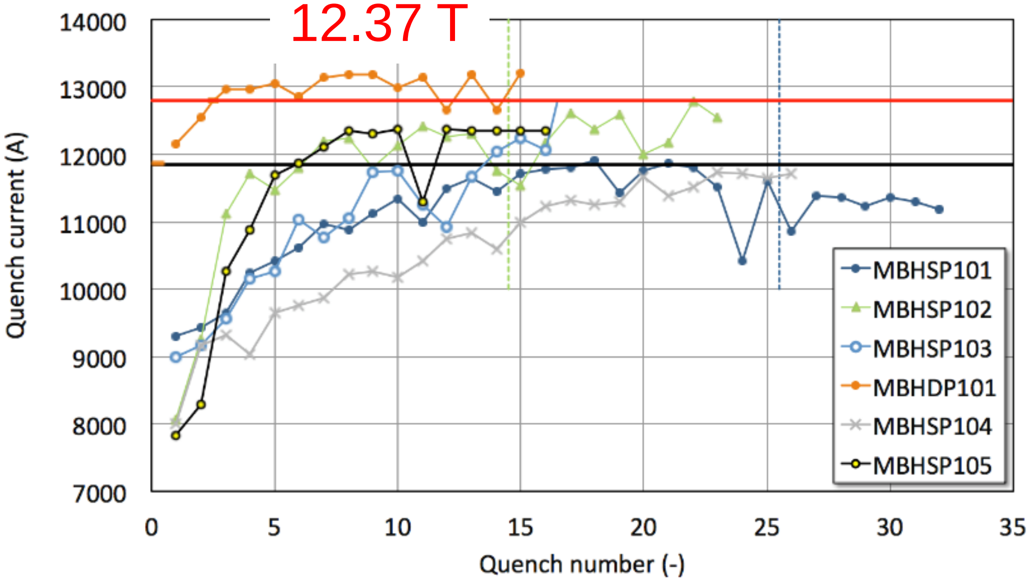
HL-LHC 11T dipole (MBH) R&D

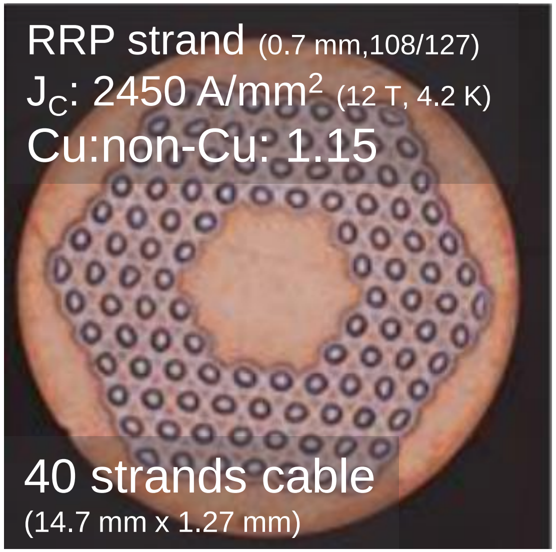



MBHSP101


MBHDP101

Aperture	60	(mm)
Field	10.8	(T)
Current	11850	(kA)
Peak field	11.35	(T)


12.37 T


RRP strand (0.7 mm,108/127)

J_C: 2450 A/mm^2 (12 T, 4.2 K)

Cu:non-Cu: 1.15

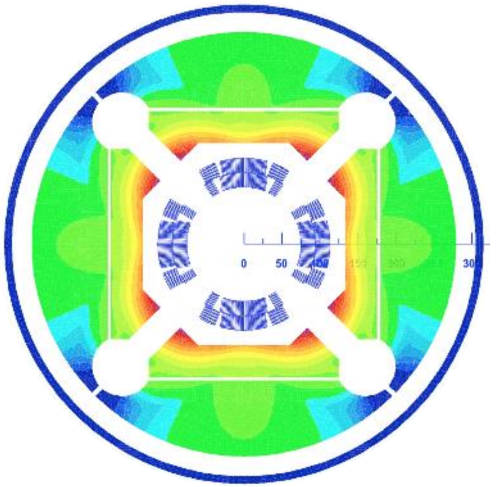
40 strands cable

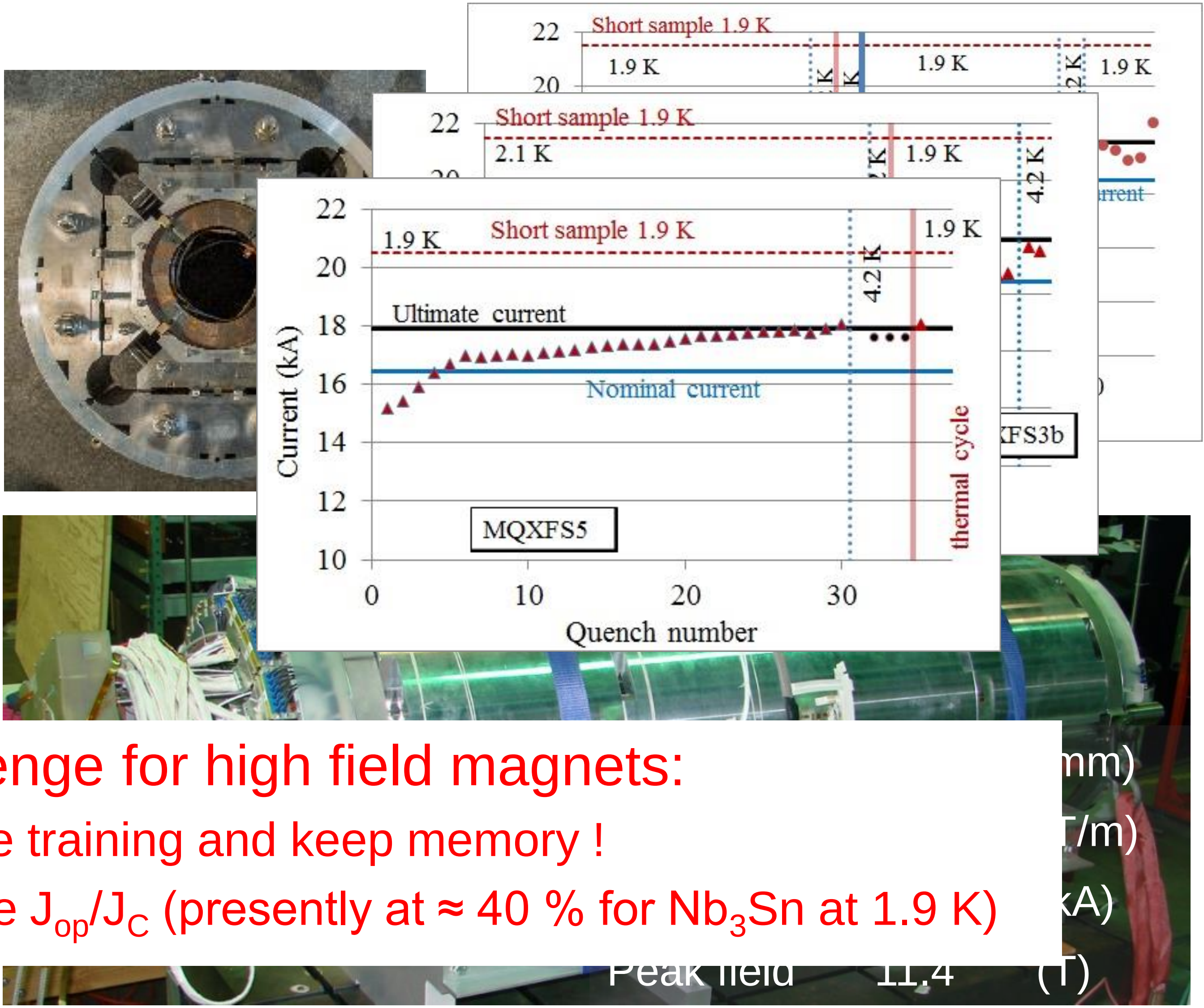
(14.7 mm x 1.27 mm)

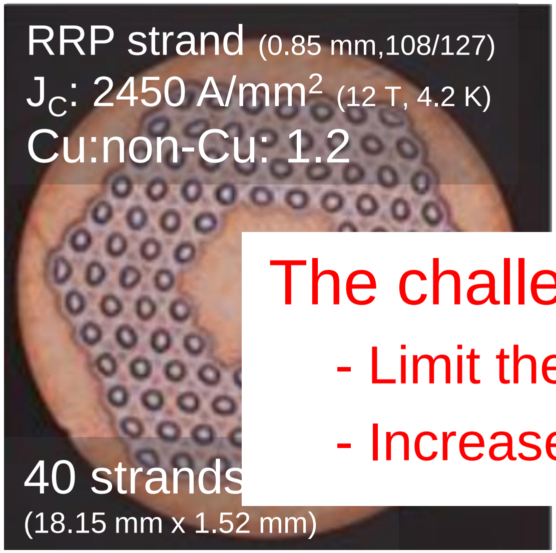
Courtesy of F. Savary, J. C. Perez, G. Willering, CERN

11T dipole (Nb_3Sn): long prototype under assembly at CERN (Bldg 180 Facility)

HL-LHC quadrupole R&D







RRP strand (0.85 mm,108/127)

J_C: 2450 A/mm^2 (12 T, 4.2 K)

Cu:non-Cu: 1.2

40 strands

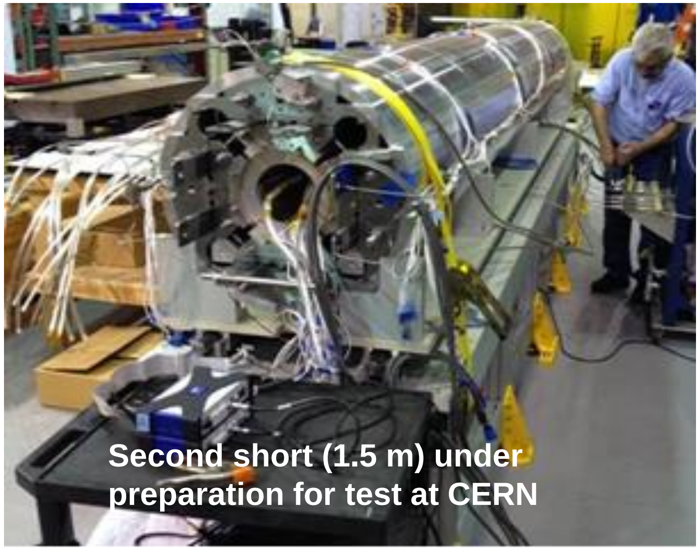
(18.15 mm x 1.52 mm)

The challenge for high field magnets:

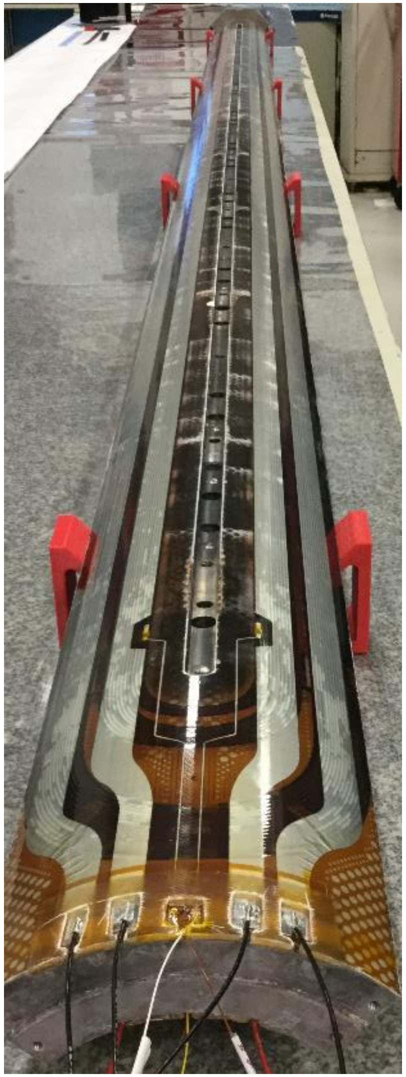
- Limit the training and keep memory !
- Increase J_{op}/J_C (presently at ≈ 40 % for Nb_3Sn at 1.9 K)

Courtesy of G. Ambrosio, G. Chlachidze, US-LAUP and CERN

Nb_3Sn quadrupole: 1st long prototype under construction



Second short (1.5 m) under preparation for test at CERN



Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

HL-LHC Upgrade Ingredients: Crab Cavities

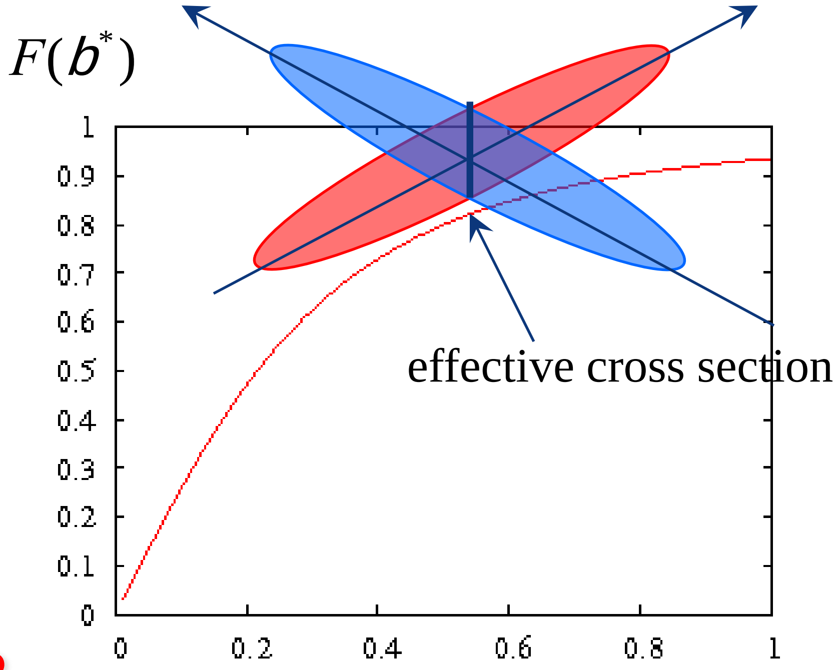
Geometric Luminosity Reduction Factor:

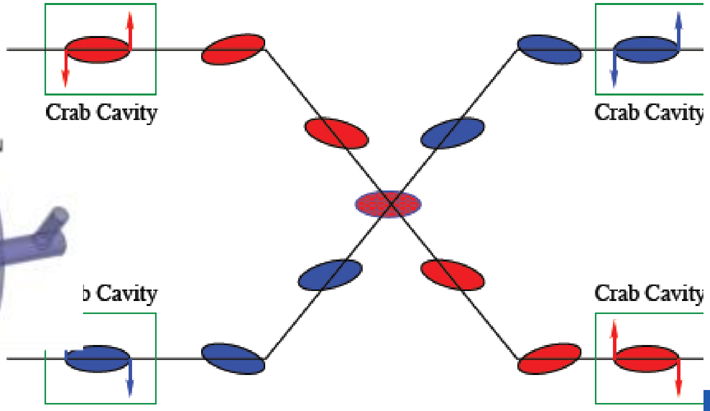
Crab Cavities:

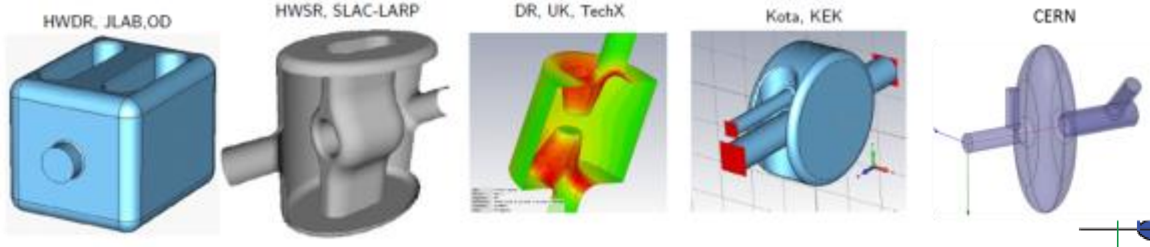
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

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



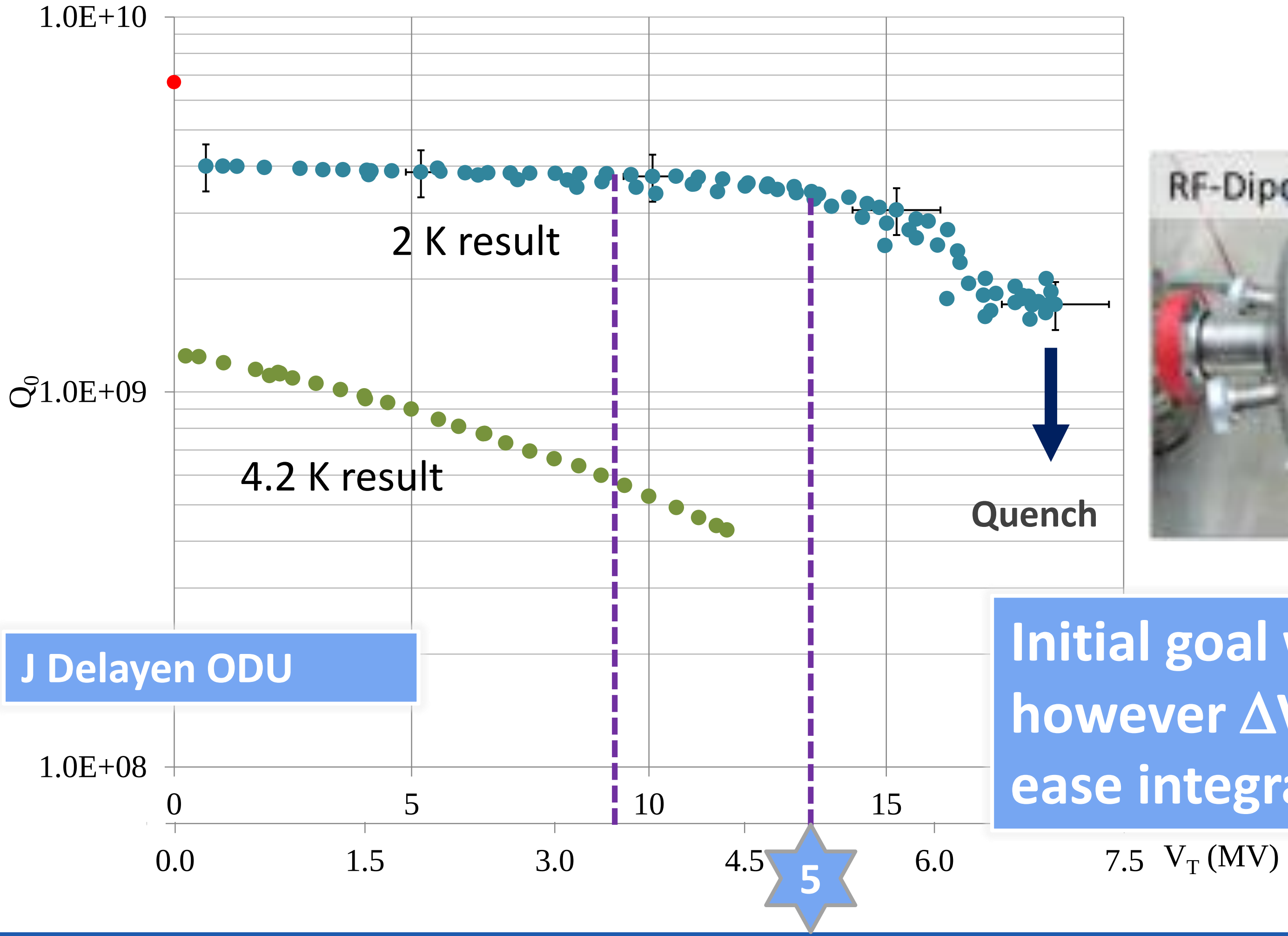




Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

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

¼ w and 4-rods also tested (1.5 MV)



J Delayen ODU

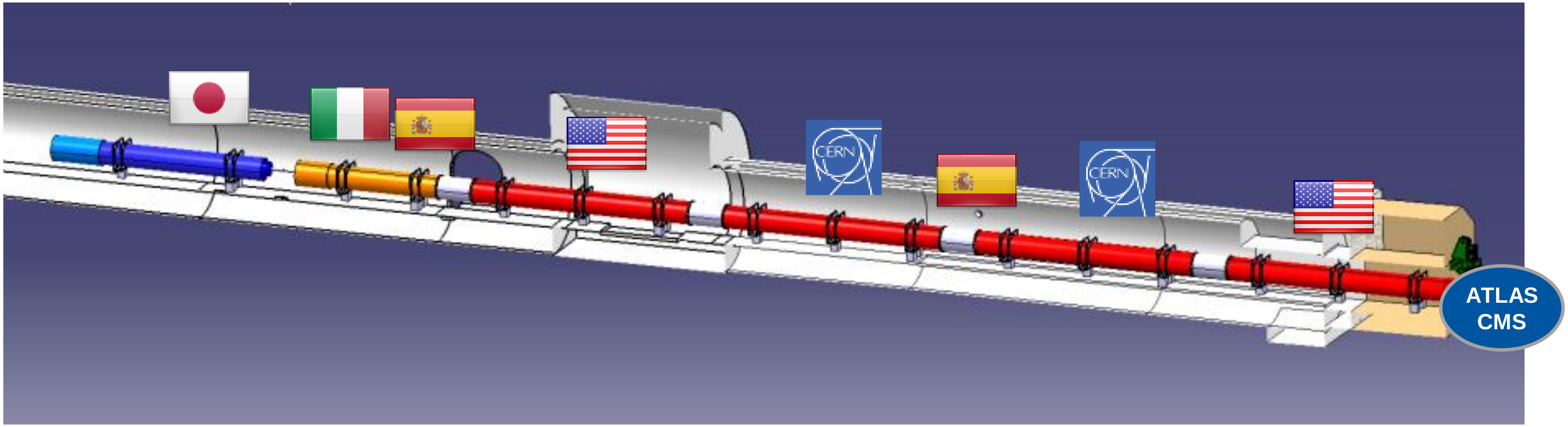

RF-Dipole Nb prototype

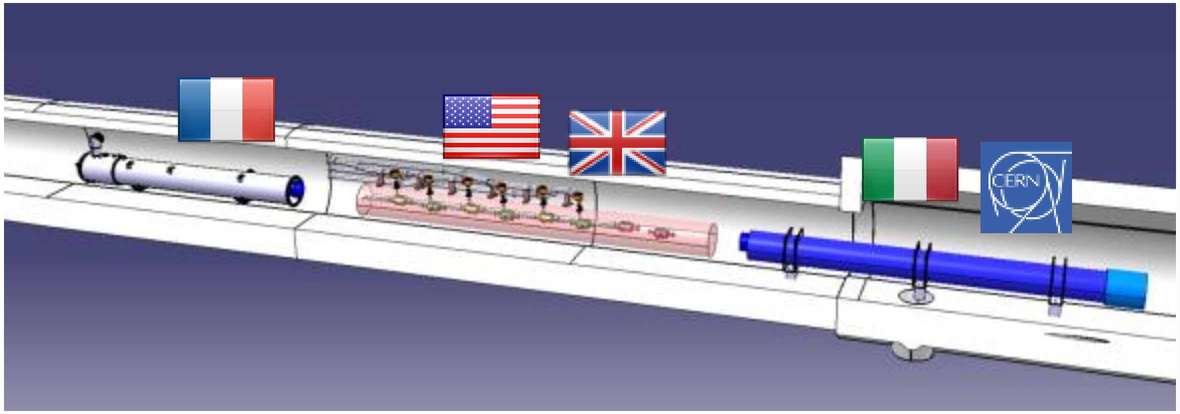
Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

Crab cavity cryo-module ready to be installed in SPS

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

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



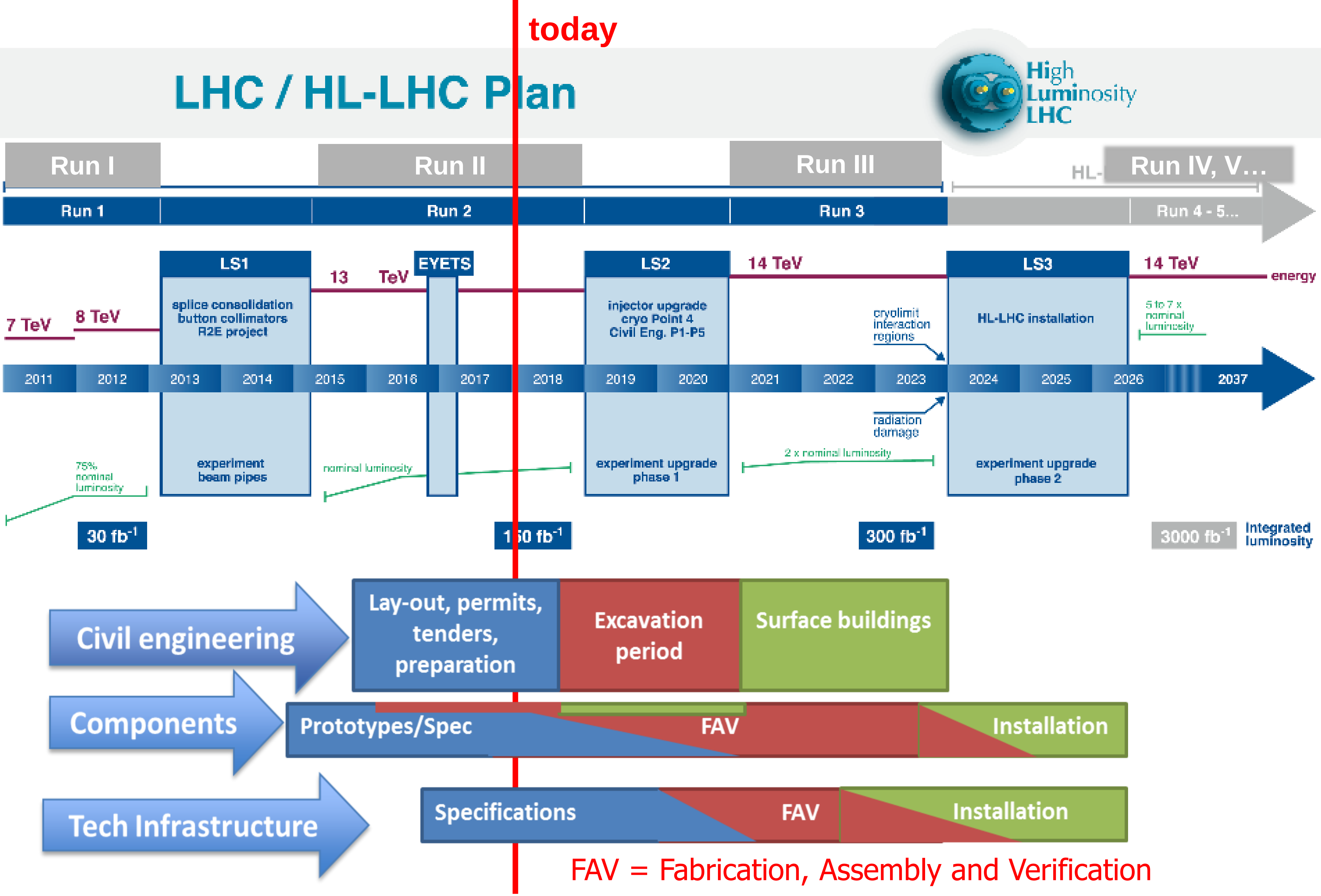


Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

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

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

LHC / HL-LHC Plan



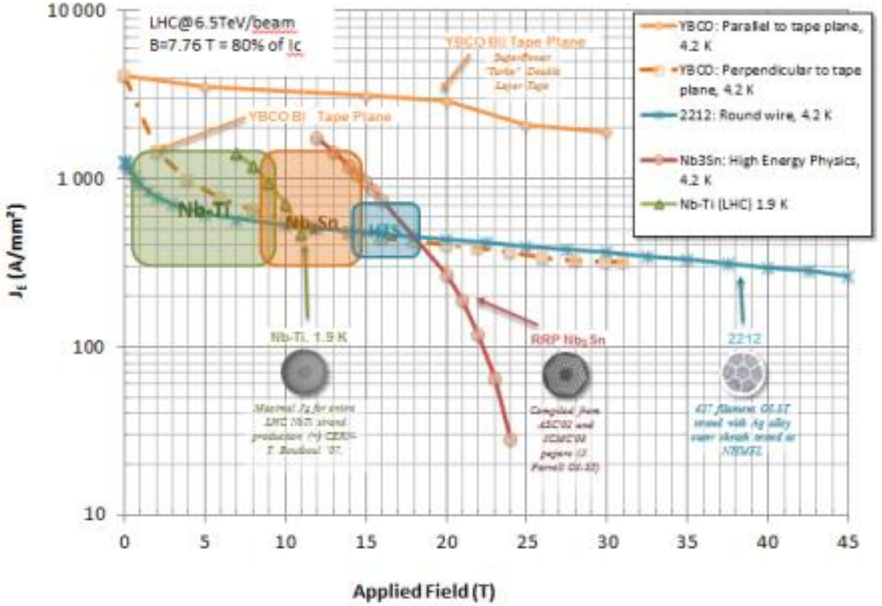
FAV = Fabrication, Assembly and Verification

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

CERN should undertake design studies for accelerator projects in a global context,

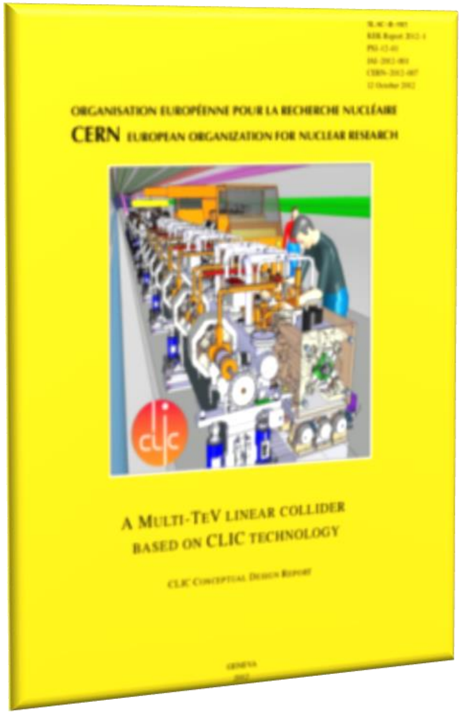
*with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets** **and** **high-gradient accelerating** **structures**, **in collaboration with national institutes,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

HFM - FCC



HGA - CLIC

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



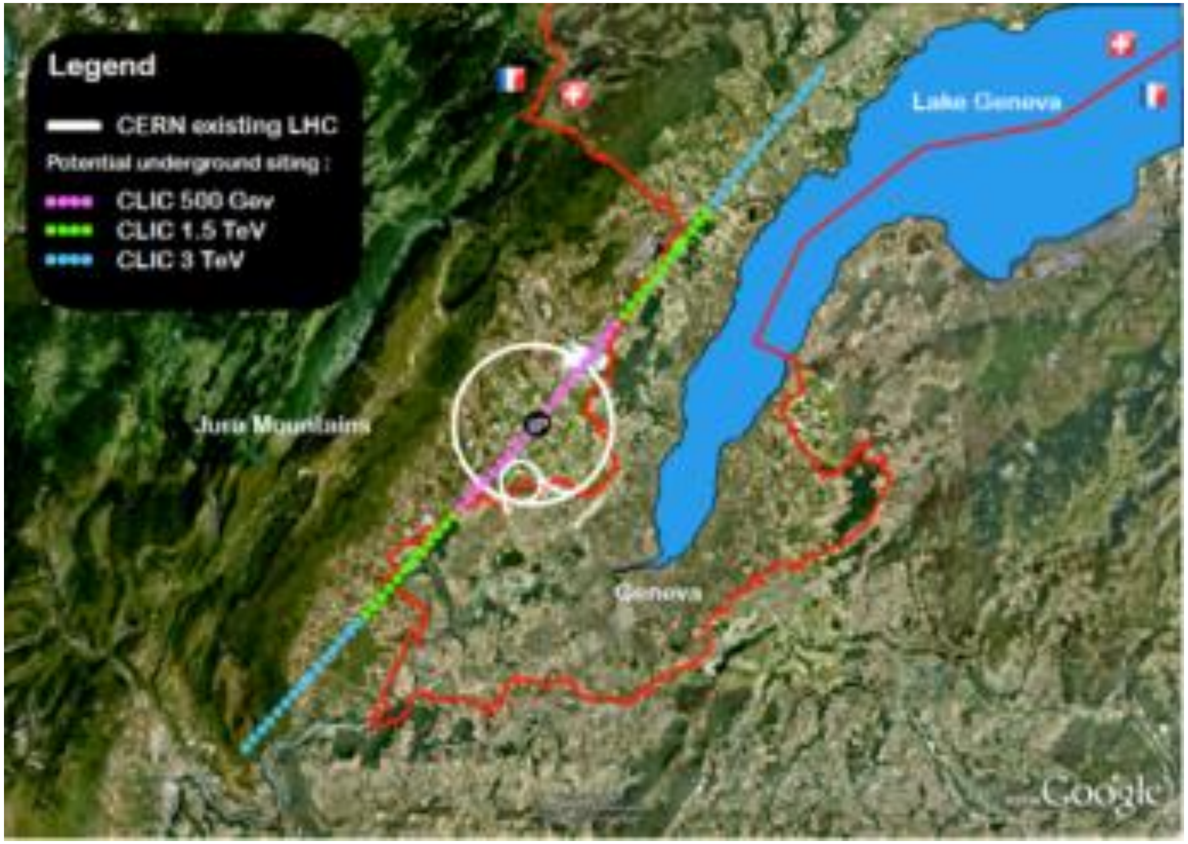
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA



Highest possible energy e$^+$e$^-$

with CLIC (CDR 2012)

Multi-lateral collaboration

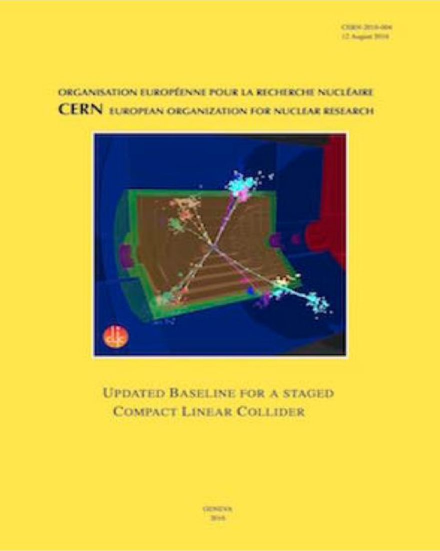
The CLIC project

Main goal for the European Strategy update :

- Cost and power optimised 380 GeV machine (~11 km) (drivebeam and klystrons), upgradeable to 3 TeV

Key technical activities in the CLIC collaboration:

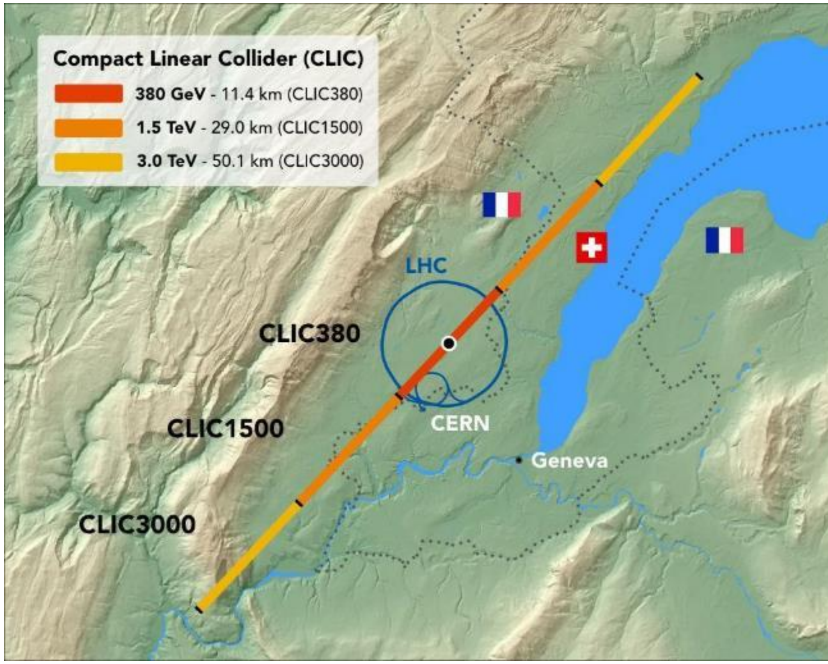
- X-band statistics and optimization for cost
- Work with FEL labs using technology in smaller machine
- Perman
- High Effi nd cost)
- Stability rformance)
- Tests CT ttance rings
- Physics a

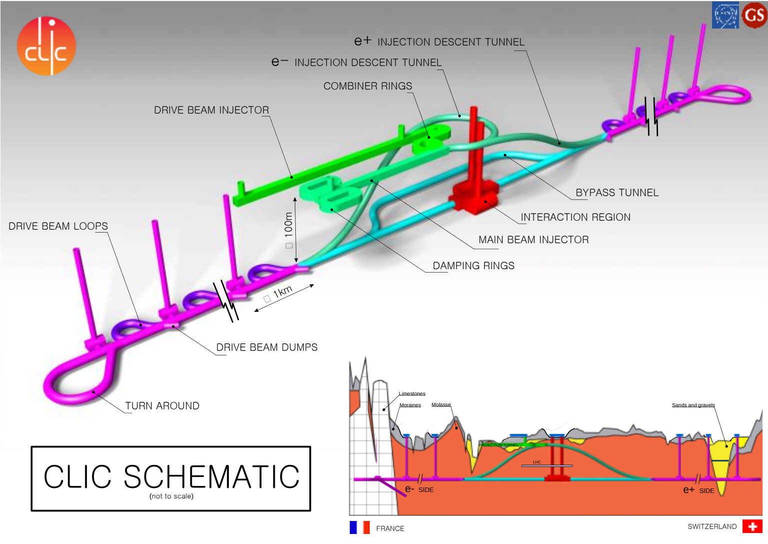


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

Param		380 GeV	3 TeV
Centre		0.38	3
Total lu	s^{-1}	1.5	5.9
Lumino	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
Site length	km	11	50

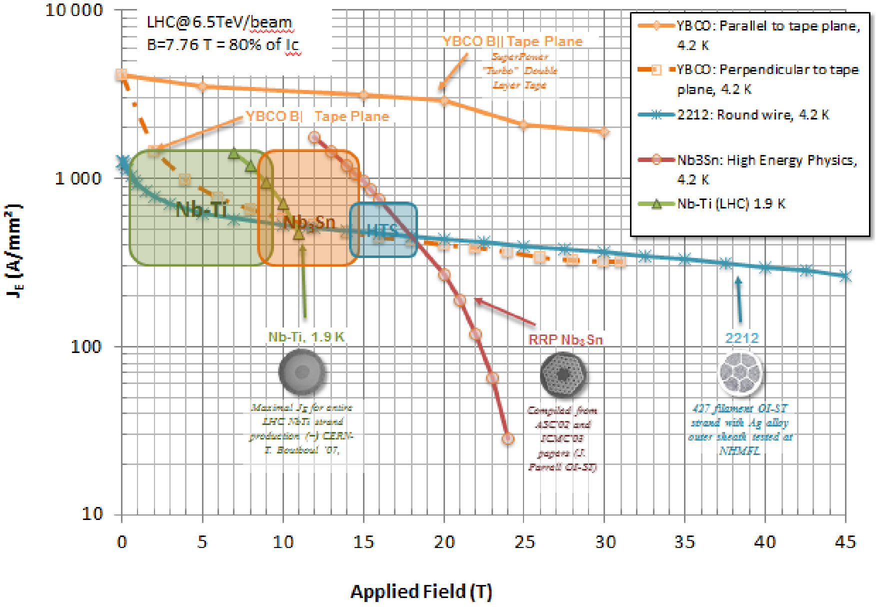




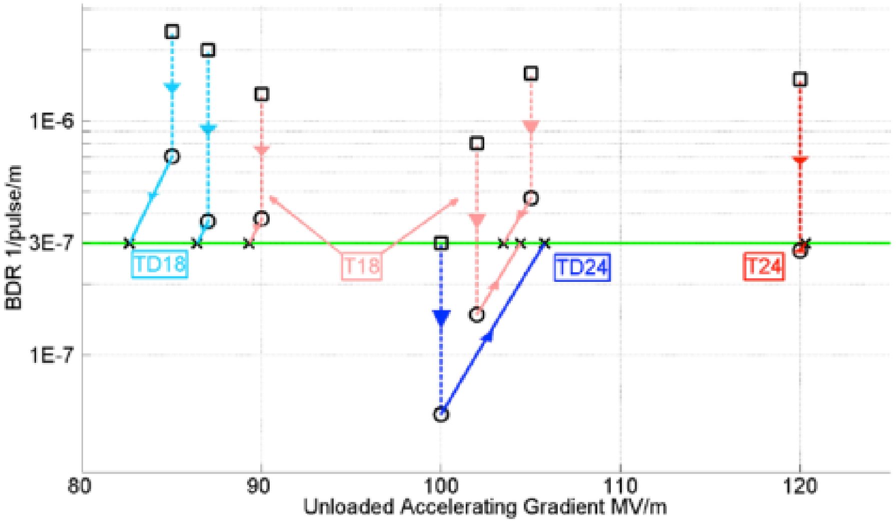
“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”

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

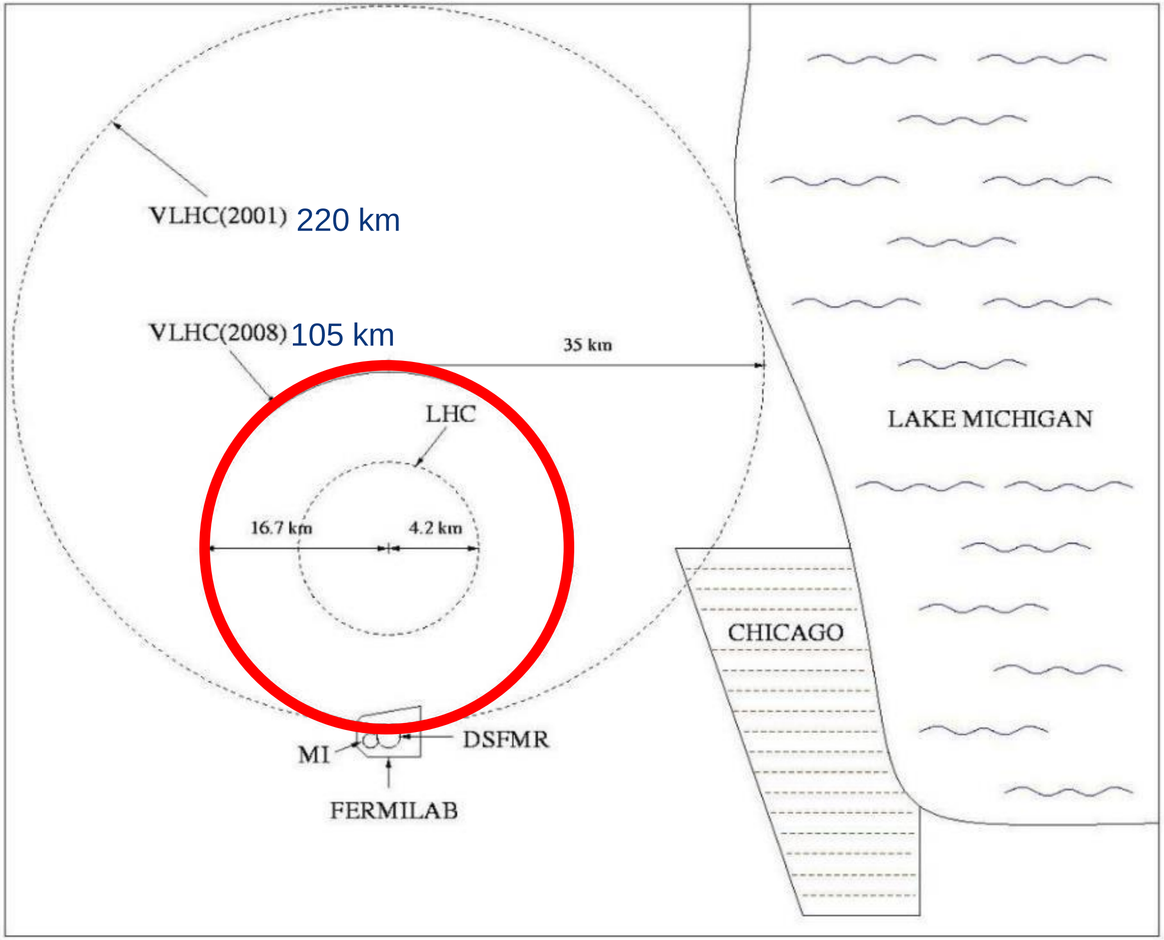


HGA



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

105 km tunnel near FNAL



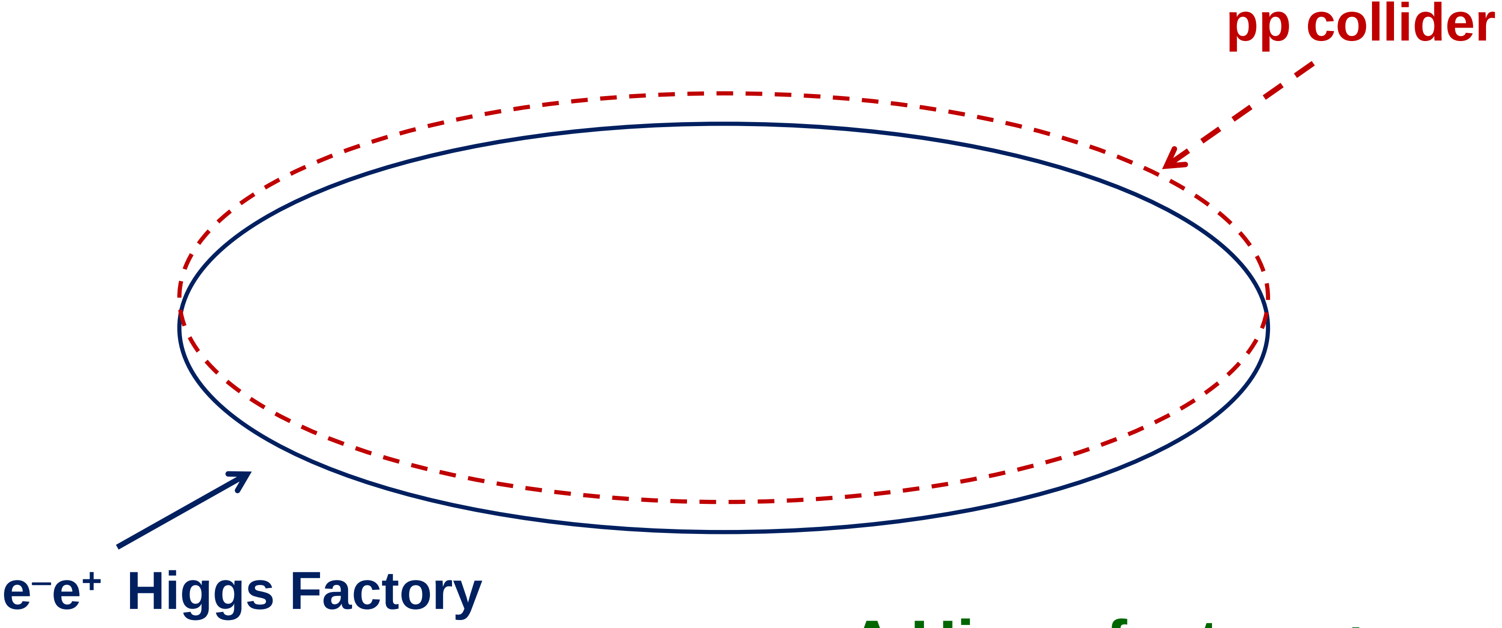
H. Piekarz, "… and … path to the future of high energy particle physics," JINST 4, P08007 (2009)

80 km ring in KEK area

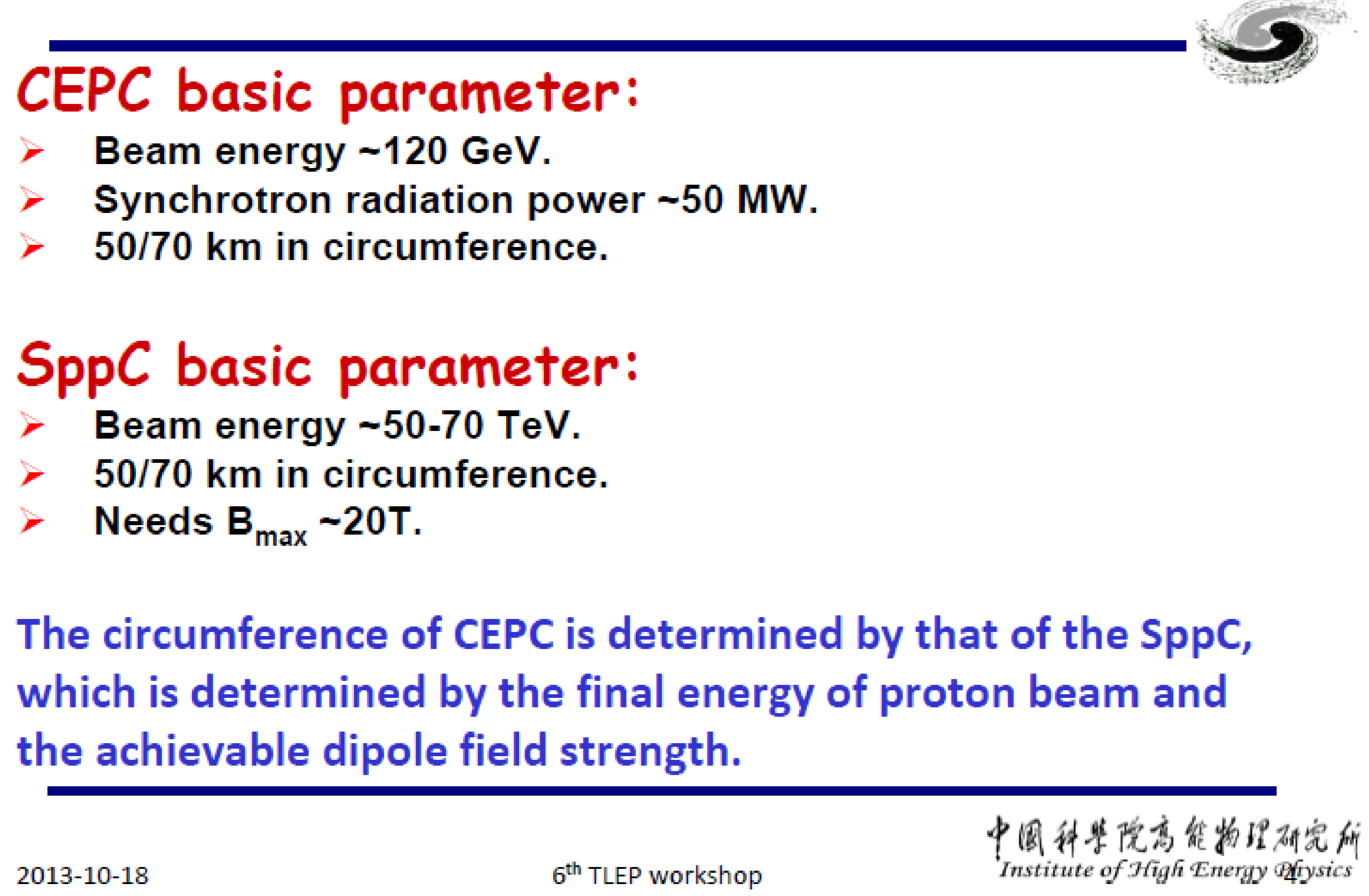
Map data ©2012 Google, ZENRIN -

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 4

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

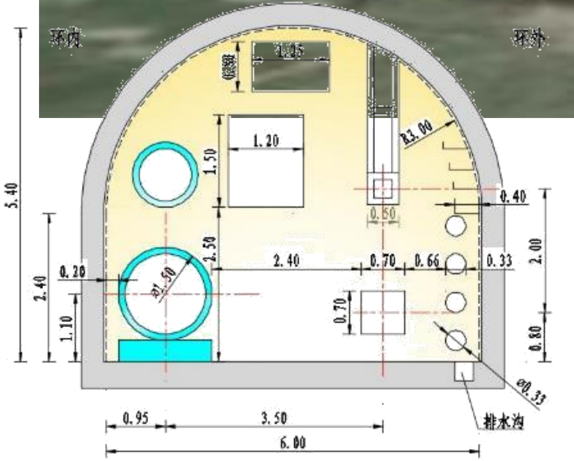
When(**dream**):

- 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)

Super proton-proton Collider (SppC)

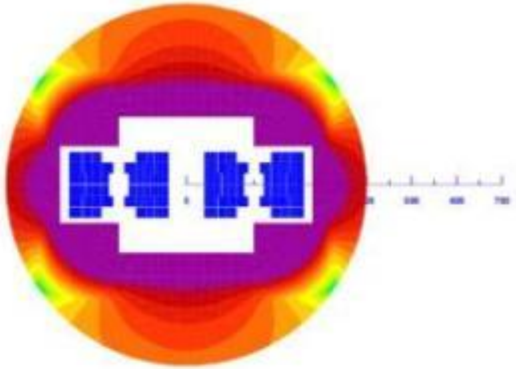


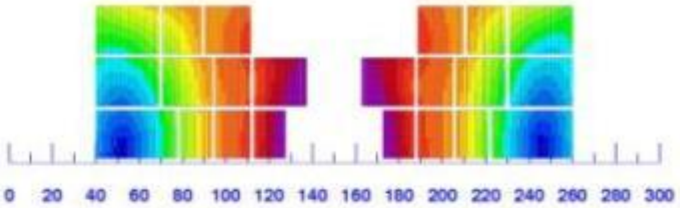
	LHC	FCC	SppC
Circumference (km)	26.7	97.5	100
Dipole field (T)	8.33	16	12…24
C.o.M. energy (TeV)	14	100	70…125

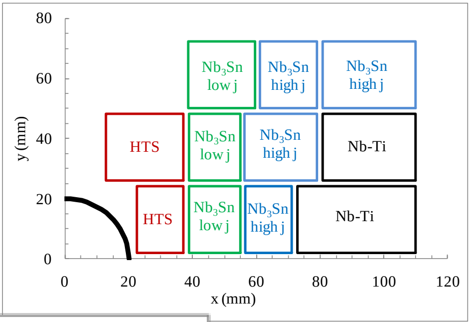
Courtesy of Q. Xu, IHEP

Malta Workshop: **HE-LHC @ 33 TeV c.o.m.**

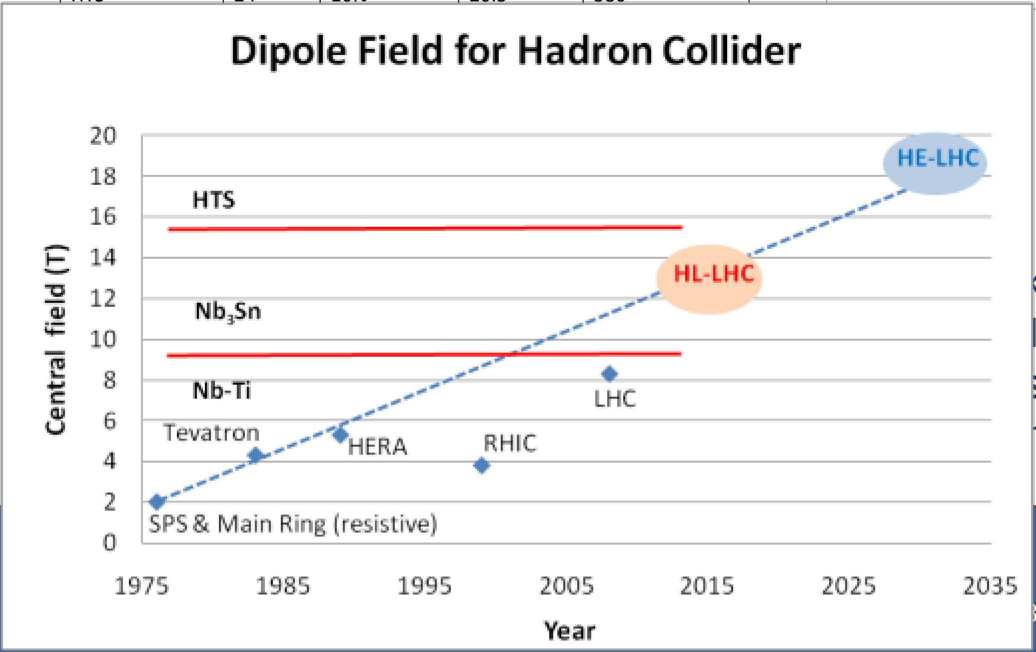
14-16 October 2010







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:

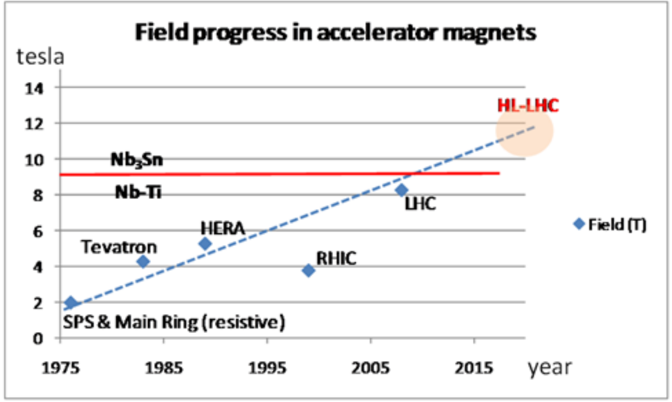
nake twice more room for LHC kickers.

HE-LHC main parameters

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

O. Dominguez, L. Rossi, F. Zimmermann

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 accelerator magnets were never built nor operated in accelerators.

Manufacturing, strain tolerance, protection, quench, training, ***field quality*** *are the focus today to make this new technology a reality*

Solid and aggressive R&D in Nb_3Sn High Field Magnet for **accelerators** must be intensified to increase further critical current Jc (up to 16 T)

HTS

Can HTS displace LTS (NbTi, Nb_3Sn) ?

Not today (performance and cost)

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

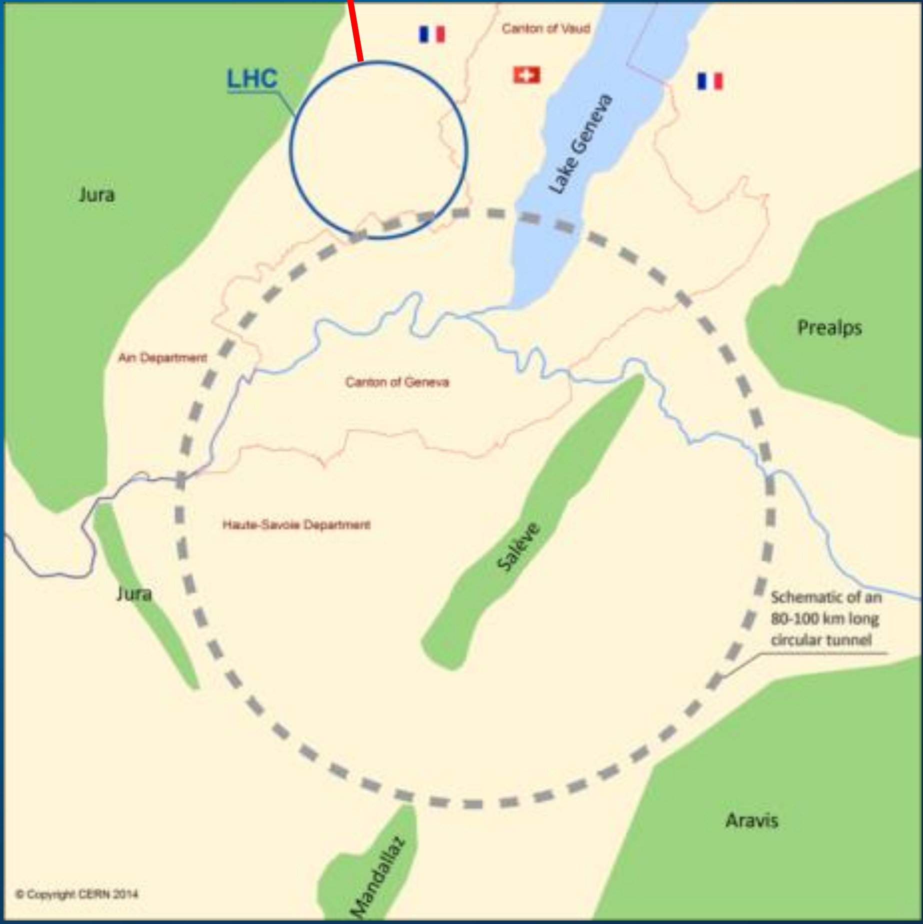
Step-up application demands, from self-field (SC-link is an ideal test-bed) to high-field accelerator magnets (feasibility)

Future Circular Collider

High Energy-LHC :33 TeV with 20T magnets

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

- **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**



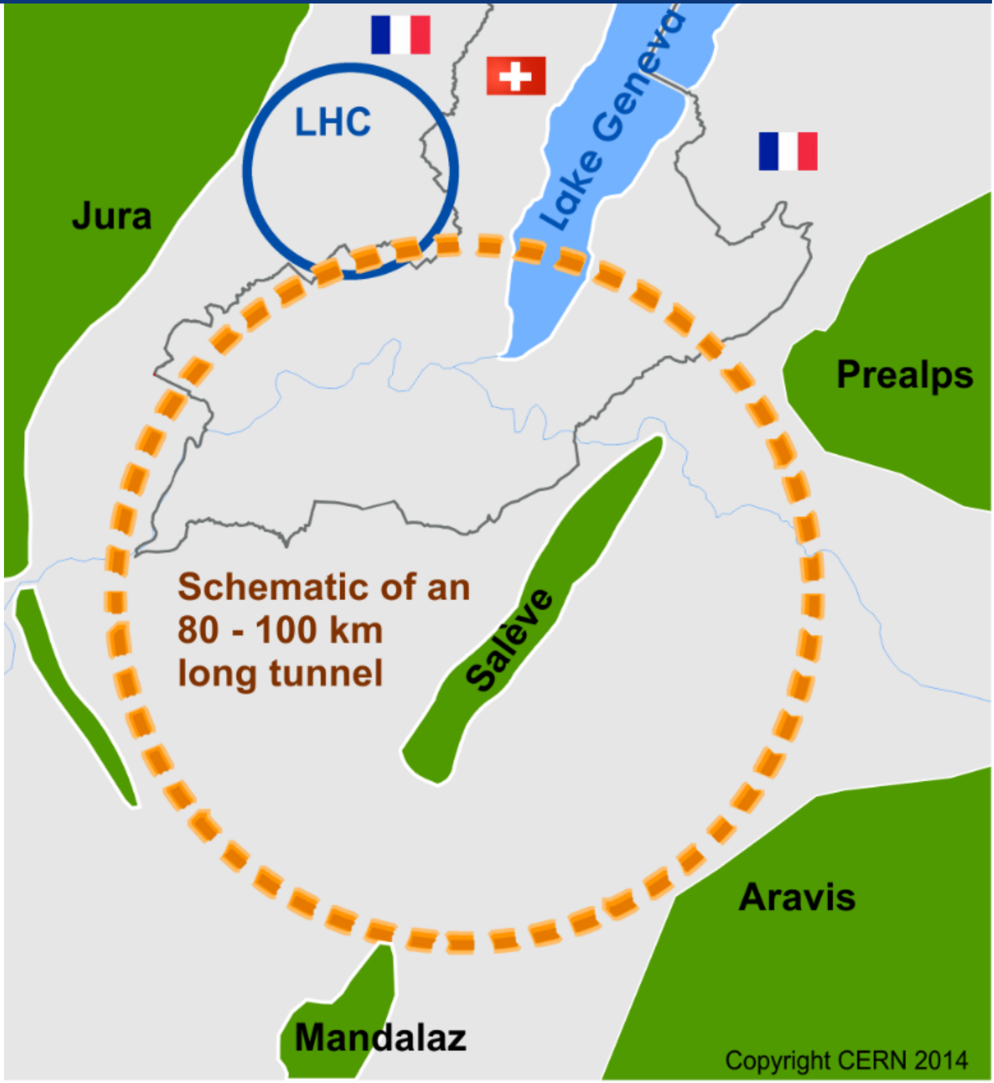
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



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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 ⇒ 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

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 μs $\Rightarrow$ 24 TW
- Tunnel Geology

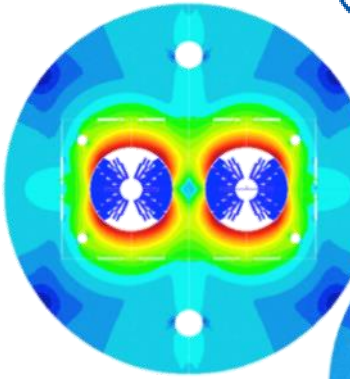
High Field Magnet challenges

- To increase the critical current Jc
- To sustain larger forces
- To protect those magnets (large numbers in series)
- To train those magnets faster
- To keep the memory after installation and thermal cycles

- Global optimization: magnet and powering
  current leads, superconducting links, energy extraction, power converters

16 T dipole design activities and options

Cos-theta



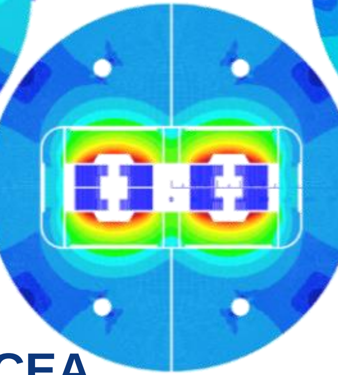
INFN

H2020

EuroCirCol

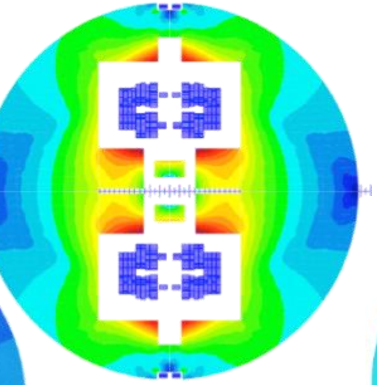
A key to New Physics

Blocks



CEA

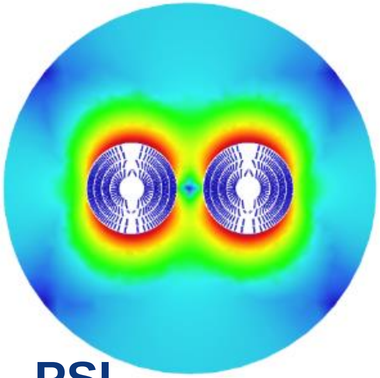
Common coils



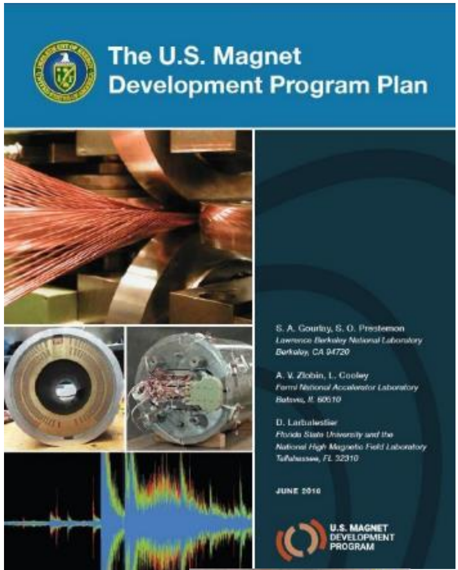
CIEMAT

Swiss contribution

Canted Cos-theta



PSI



The U.S. Magnet Development Program Plan

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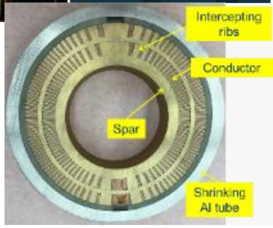
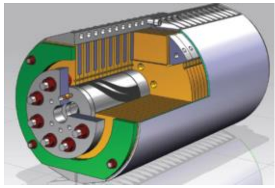
JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

LBNL



FNAL

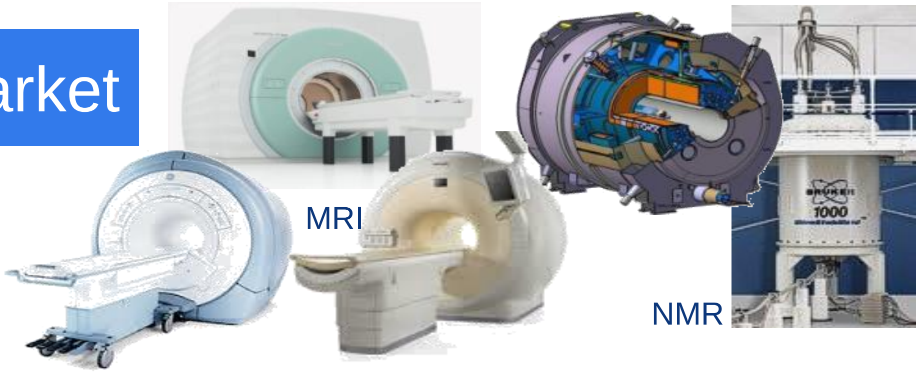


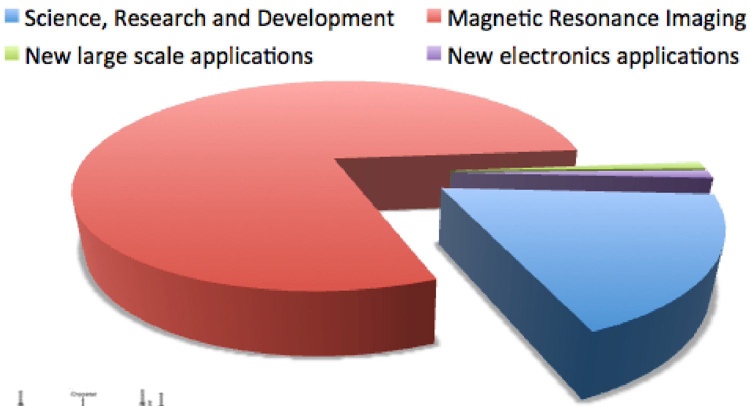
Short model magnets (1.5 m lengths) will be built from 2017 - 2021

Superconducting magnet market

At present, the vast majority of the use of superconductors is for magnet applications:

- **MRI (*NbTi*): 5.5 BUSD/year[1];**
  7.0 BUSD/year in 2017
- **NMR, science and research: *(Nb3Sn)***
  ~ 1 BUSD/year[1]

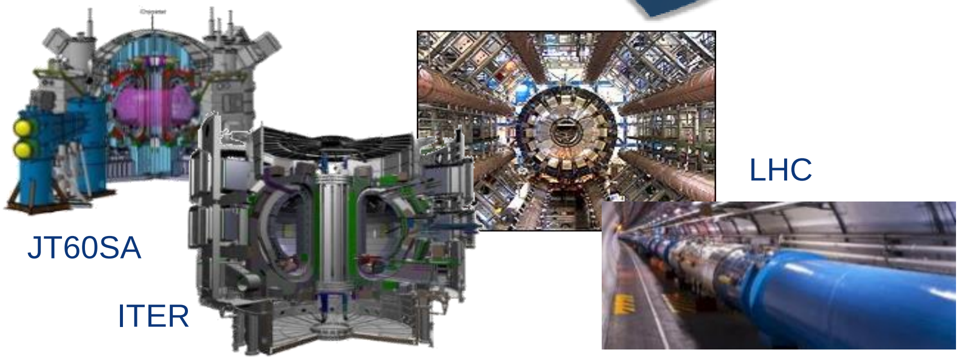




Large scale projects (HEP, Fusion) represent only a fraction of the total market and discontinuities:

Evaluated cost of LHC magnet system (material): 2 BUSD[2]

Quoted cost of ITER magnet system (material): 1.4 BUSD[3]



Sources: [1] from market report at Conectus.org, converted from repored 5.3 BEUR in 2013
[2] Report to the CERN Finance Committee, 2008, reported 1.7 BCHF(2008) escalated to 2013
[3] DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013

Superconducting conductor production

NbTi in the world : **~ 600 tons/year**, driven by MRI production

Nb3Sn : ~ 10 tons/year, driven by NMR magnets and laboratory solenoids

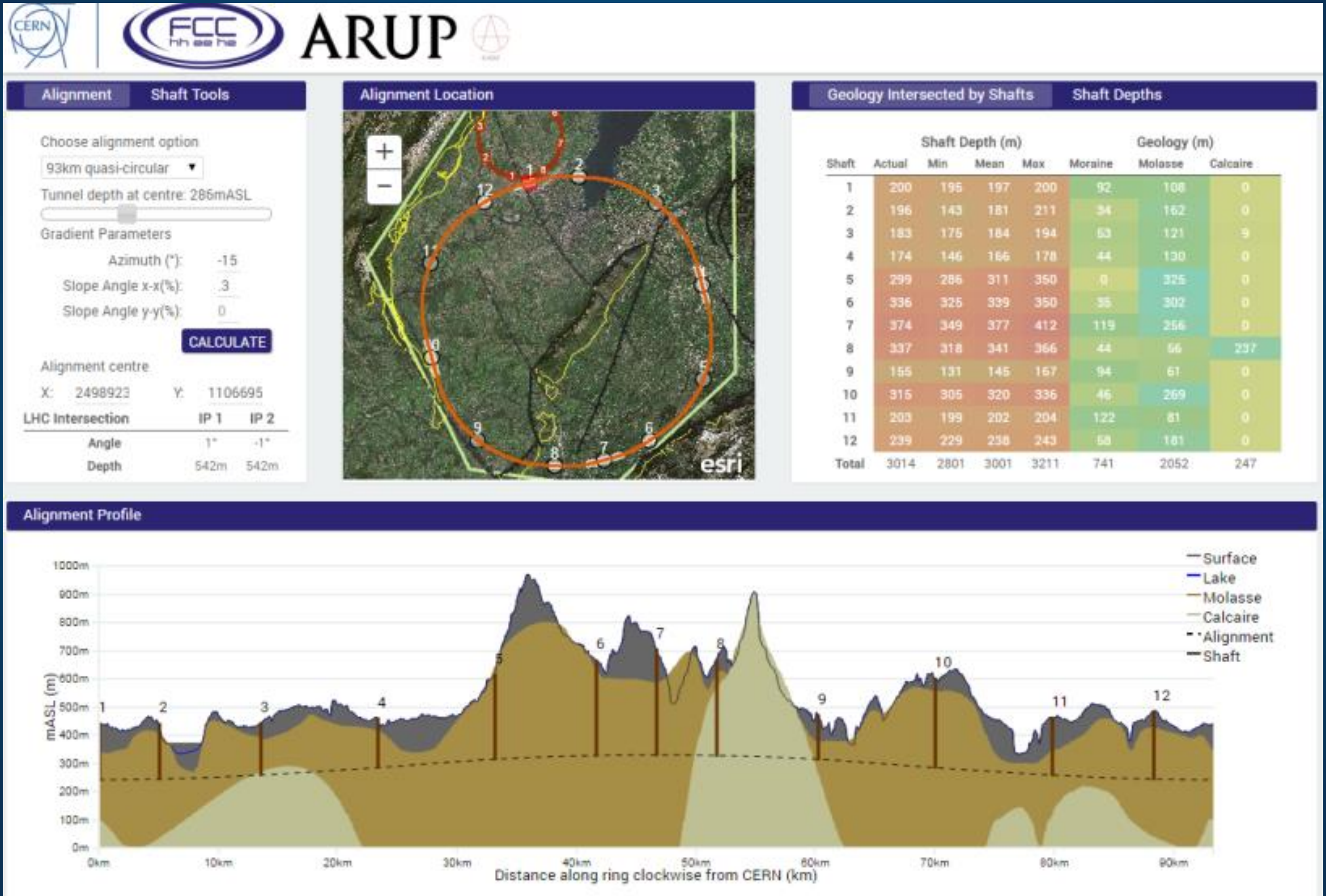
All of **HTS** (BSCCO, YBCO,…) and MgB2: around 100...200 km of 4-10 mm wide tape per year, presently driven by R&D applications and delivered by around 10 worldwide producers,
In total below **1 ton/year**

LHC required 1300 tons of Nb-Ti (300 t/year peak production) (~30% cost of the magnet)
ITER required 300 tons of Nb-Ti and 600 tons of Nb3Sn (250 t/year peak production)

HL-LHC requires: 30 tons Nb3Sn and about the same for NbTi

HE-LHC will require : ~ 3’000 tons Nb3Sn
FCC-hh will require : ~ 9’000 tons Nb3Sn (between 50% to 60% cost of the magnet)

Layout Studies



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

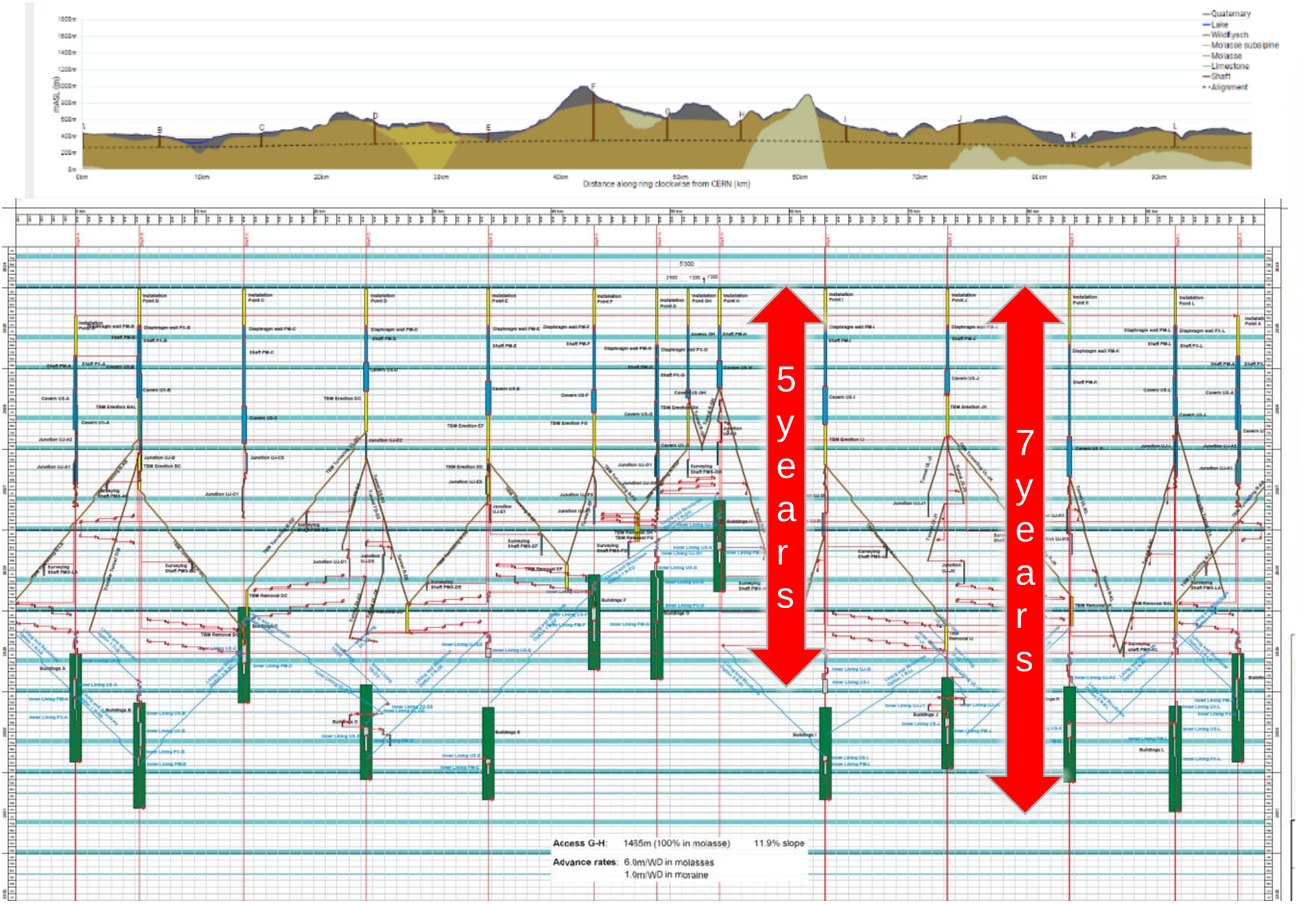
Alignment centre

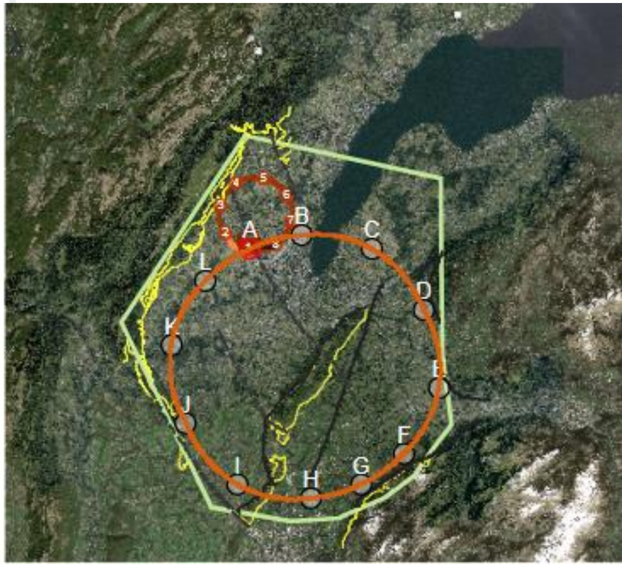
X: 2498923 Y: 1106695

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

	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

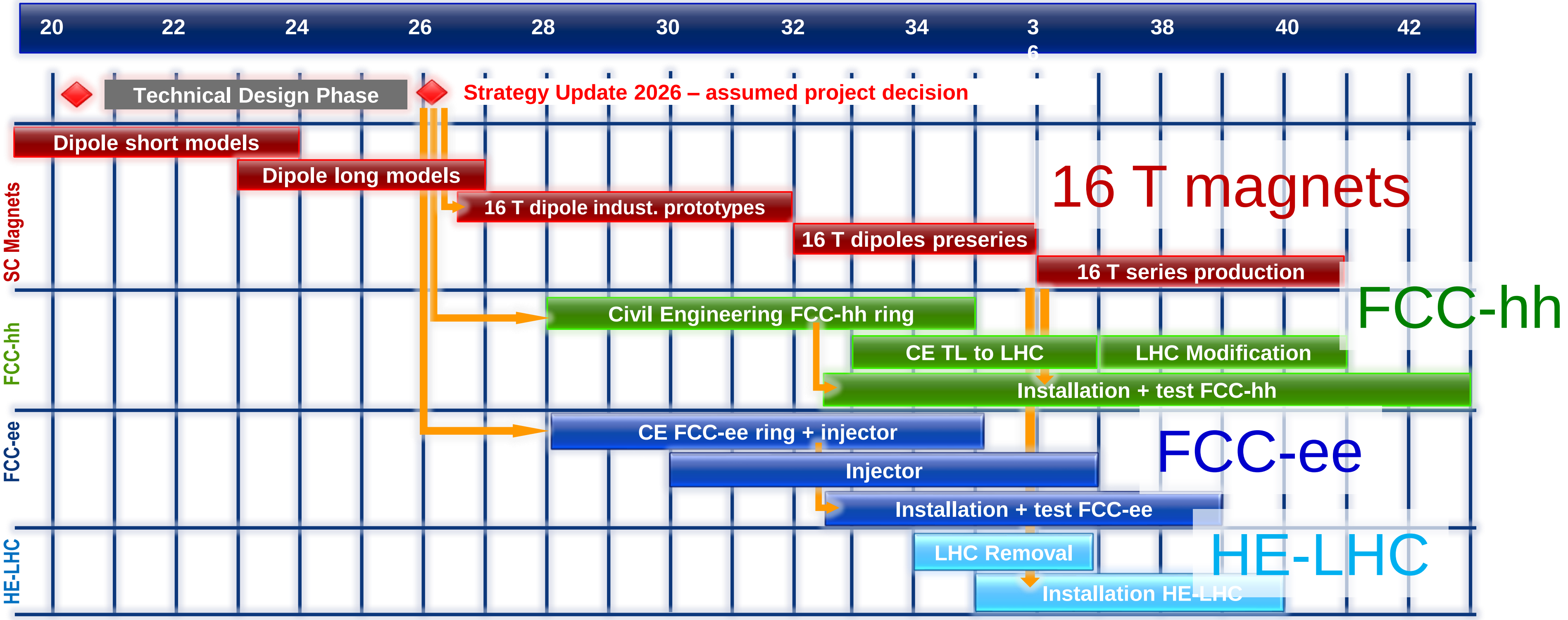
Civil Engineering schedule studies





- **CE & schedule studies with consultants**
- **first sectors available after 4.5 to 5 years for Technical Infrastructure installation**
- **total CE duration ~7 years**

Technical Schedule for the 3 Options



20 22 24 26 28 30 32 34 36 38 40 42

Technical Design Phase

Strategy Update 2026 – assumed project decision

SC Magnets

- Dipole short models
- Dipole long models
- 16 T dipole indust. prototypes
- 16 T dipoles preseries
- 16 T series production

16 T magnets

FCC-hh

- Civil Engineering FCC-hh ring
- CE TL to LHC
- LHC Modification
- Installation + test FCC-hh

FCC-hh

FCC-ee

- CE FCC-ee ring + injector
- Injector
- Installation + test FCC-ee

FCC-ee

HE-LHC

- LHC Removal
- Installation HE-LHC

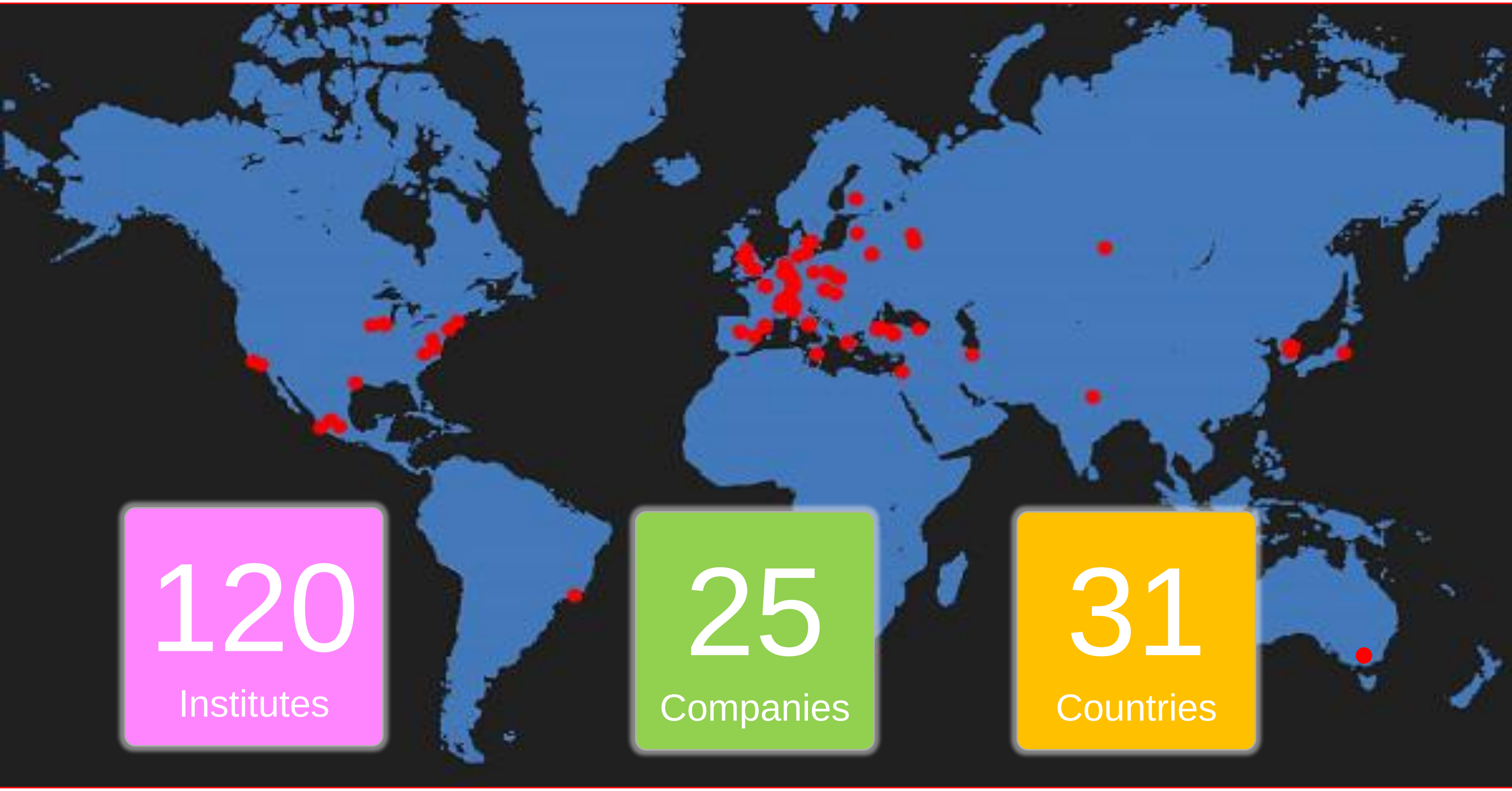
HE-LHC

schedule constrained by 16 T magnets & Civil Engineering

→ earliest possible physics starting dates

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

collaboration & industry relations



120
Institutes

25
Companies

31
Countries

High Energy Physics Roadmap:
3 pillars: based on the 2013 European Strategy for Particle Physics

Full exploitation of the LHC:

- successful operation of the nominal LHC until end 2023: Run3 at 14 TeV **=> Goal $\sum$300 fb^{-1}**
- construction & installation of LHC upgrades: LIU (LHC Injectors Upgrade) and **HL-LHC**

Scientific diversity programme serving a broad community:

- ongoing experiments and facilities at Booster, PS, SPS and their upgrades (HIE-ISOLDE, ELENA)
- participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

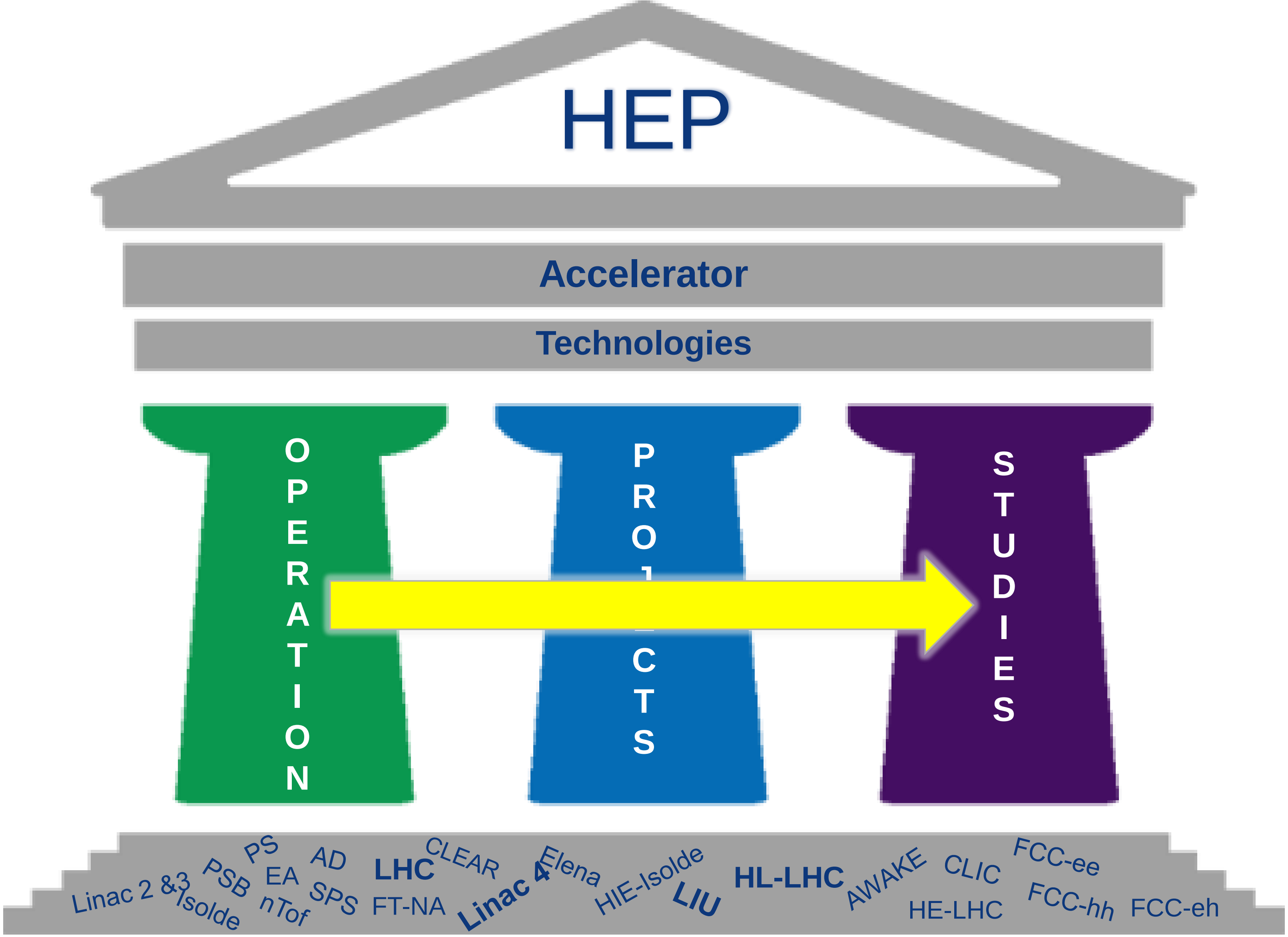
Preparation of CERN's future:

- vibrant accelerator R&D programme exploiting CERN's strengths and uniqueness (including superconducting high-field magnets, plasma wakefield acceleration, etc.)
- design studies for future high-energy accelerators: **CLIC, FCC (includes HE-LHC)**
- future opportunities of diversity programme: Physics Beyond Colliders Study Group

Important milestone:

next update of the European Strategy for Particle Physics (ESPP) to be completed in May 2020

Conclusion: HEP Roadmap



HEP

Accelerator

Technologies

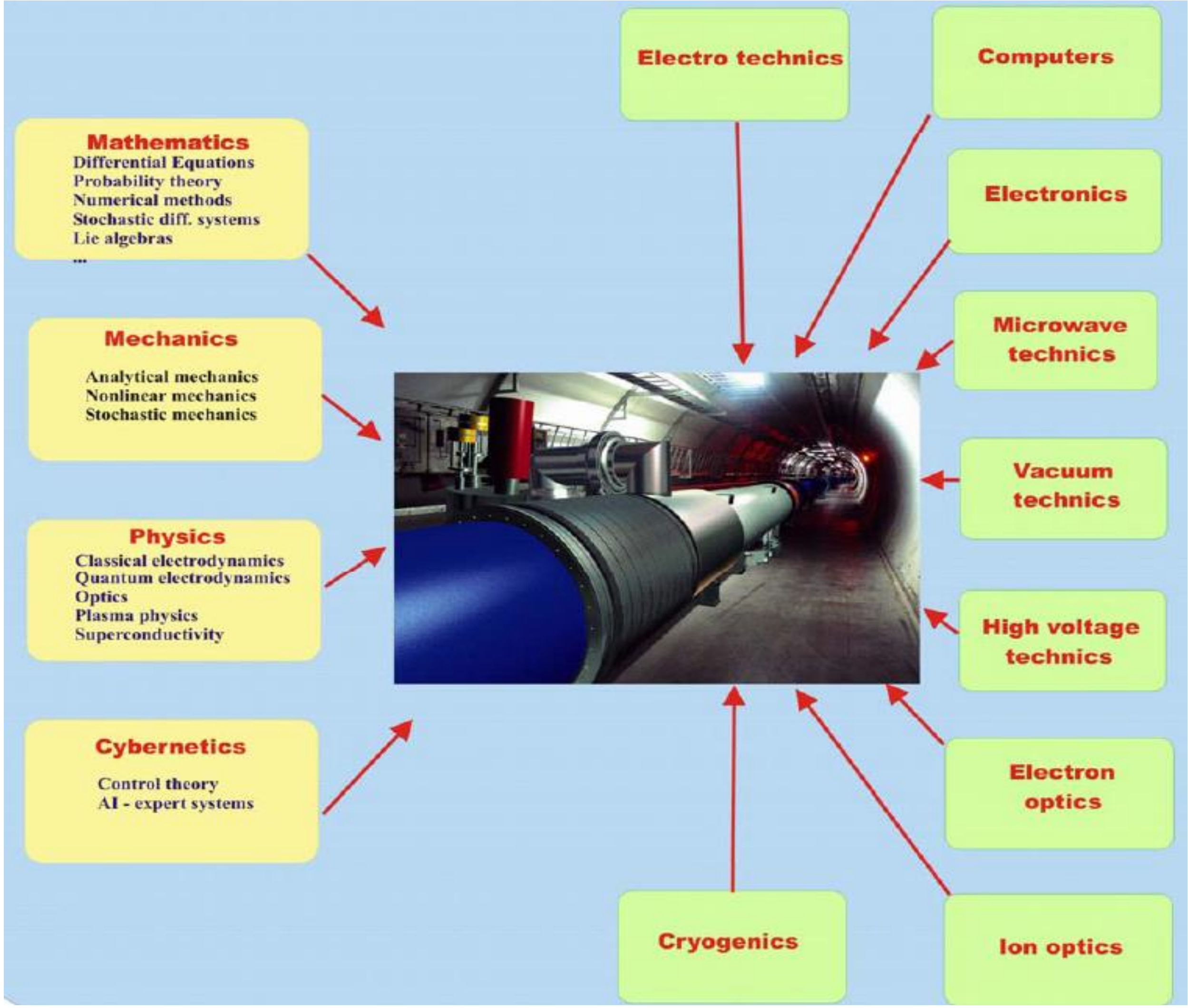
OPERATION

PROJECTS

STUDIES

Linac 2 &3
Isolde
PSB
PS
EA
nTof
AD
SPS
LHC
FT-NA
CLEAR
Linac 4
Elena
HIE-Isolde
LIU
HL-LHC
AWAKE
HE-LHC
CLIC
FCC-ee
FCC-hh
FCC-eh

List of Technologies needed for building and exploiting Accelerators



Mathematics
Differential Equations
Probability theory
Numerical methods
Stochastic diff. systems
Lie algebras
...

Mechanics
Analytical mechanics
Nonlinear mechanics
Stochastic mechanics

Physics
Classical electrodynamics
Quantum electrodynamics
Optics
Plasma physics
Superconductivity

Cybernetics
Control theory
AI - expert systems

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 and physicists

Thanks for your attention

"The task of the mind is to produce future"
Paul Valéry

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