Progress on the High Luminosity LHC

Lucio Rossi – CERN
HL-LHC Project Leader
Oliver Brüning – CERN
deputy Project Leader

Plenary Talk # MOYPLM3

IPAC'19 - Melbourne, 20 May 2019

CONTENT

- LHC present performance and next Run
- HL-LHC
  - Why, scope and challenges
  - Beam Physics
  - LIU (LHC Injector Upgrade project)
- HL-LHC Status
  - Magnets
  - CCs
  - Collimators & other systems
  - Civil engineering
- Budget, time plan

30 papers related to High Luminosity LHC @IPAC'19

Wednesday orals:

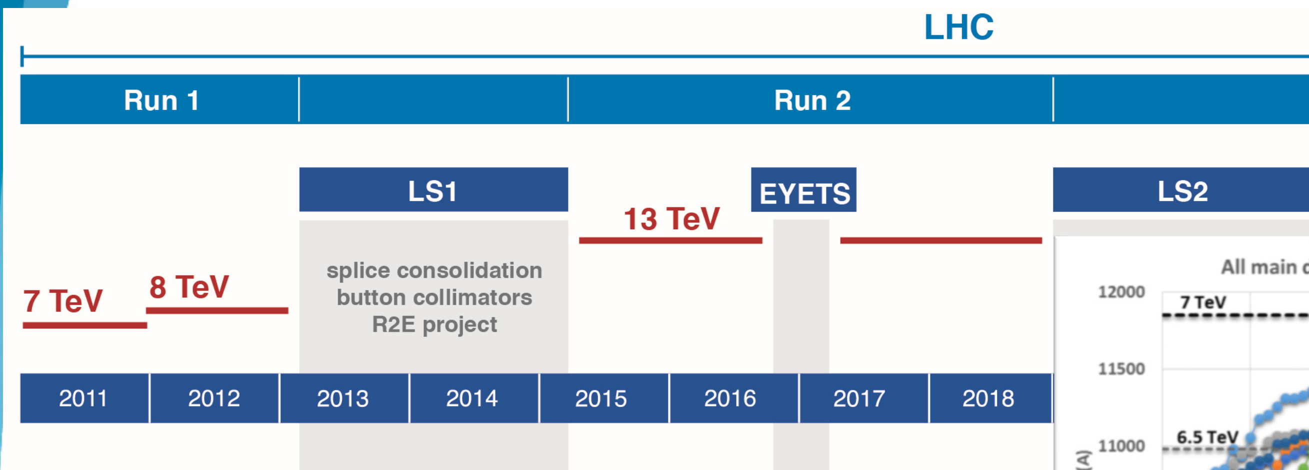
- *B. Salvant et al. (impedance model)-invited*
- *J . Jowett et a. (heavy ion run)*
- *G. Sterbini et al. (Long Range beam-beam compensating wires test)*

Thursday invited oral:

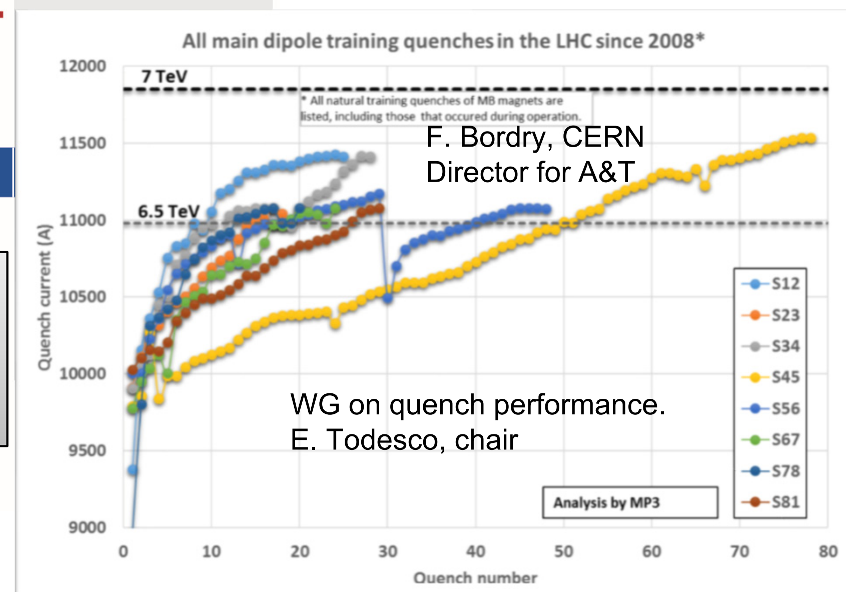
- *M. Meddahi et al. (LHC Injector Upgrade)*

HiLumi HL-LHC PROJECT

LHC performance at a glance: Energy



Energy depends on dipole field:
Design 7 TeV → 8.33 tesla, 86% of the max Ic
We will push LHC @ 2x7 TeV later on in Run3



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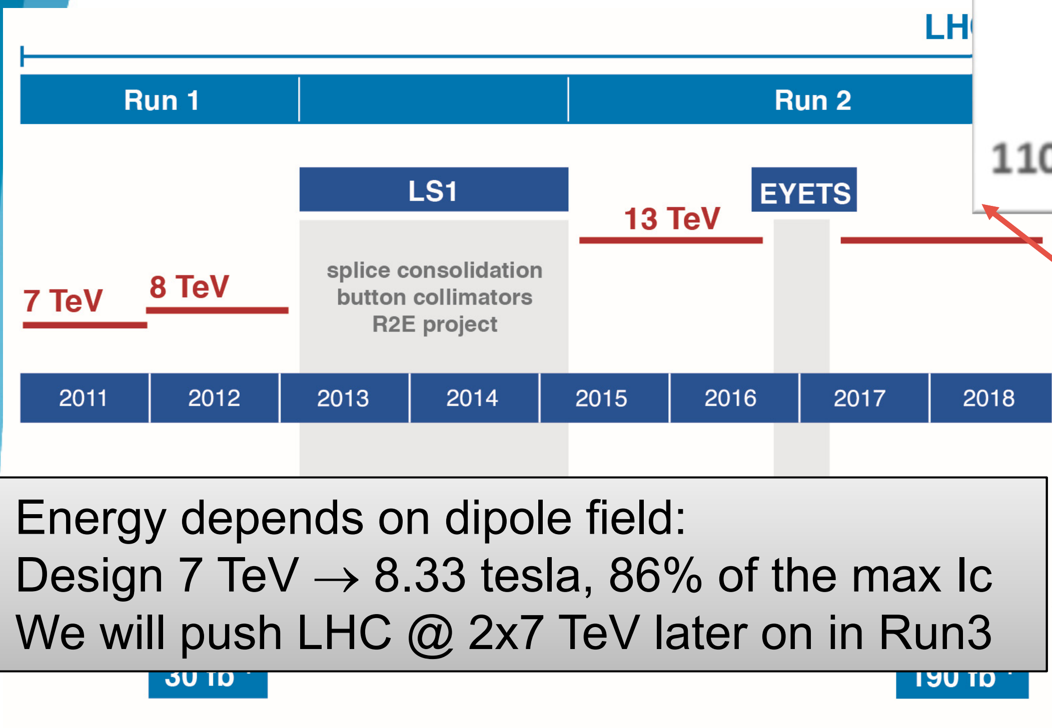

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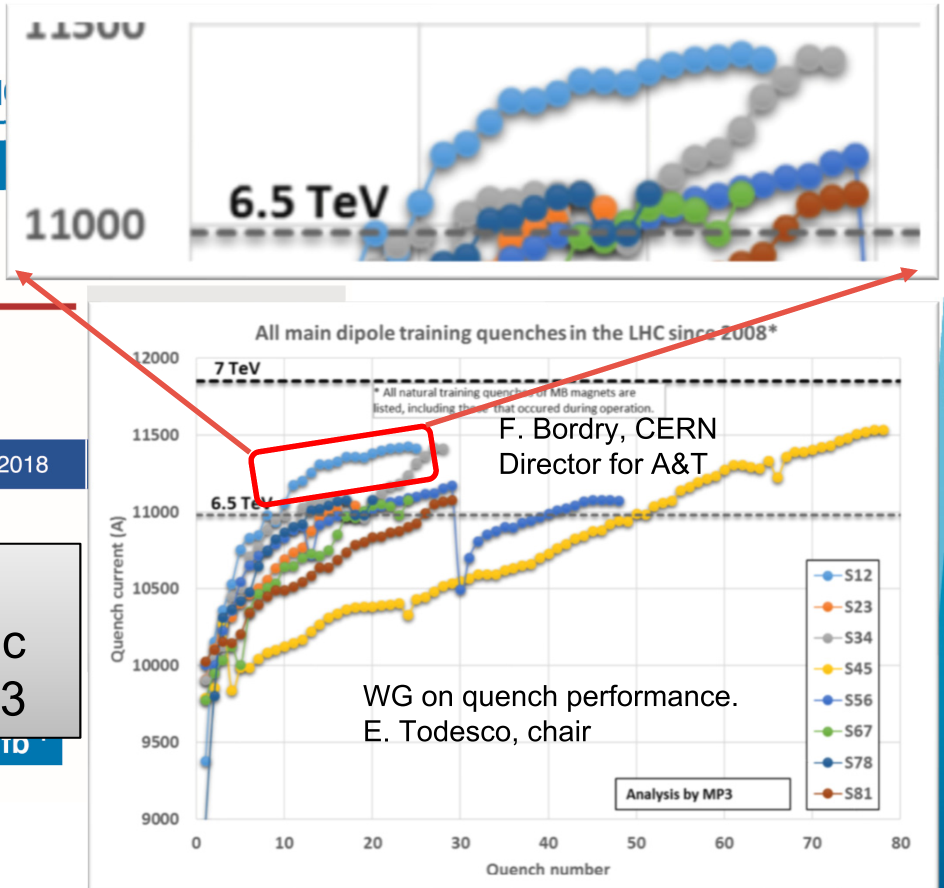
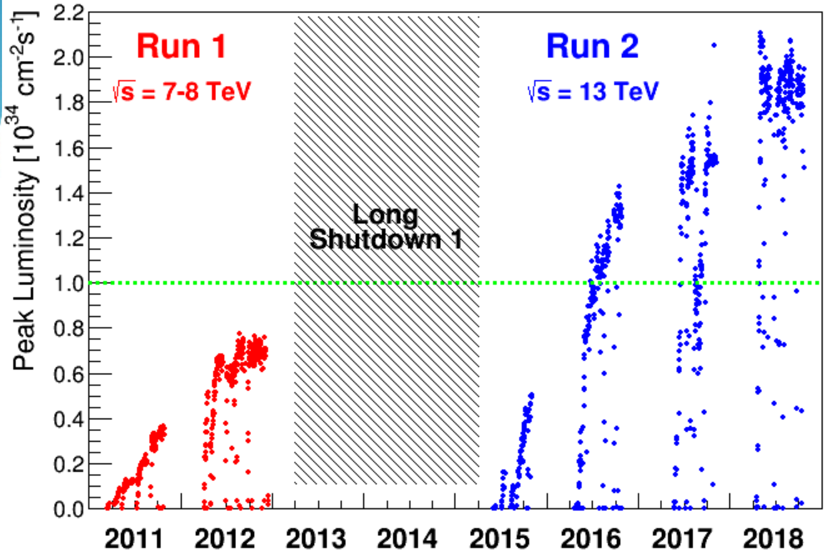
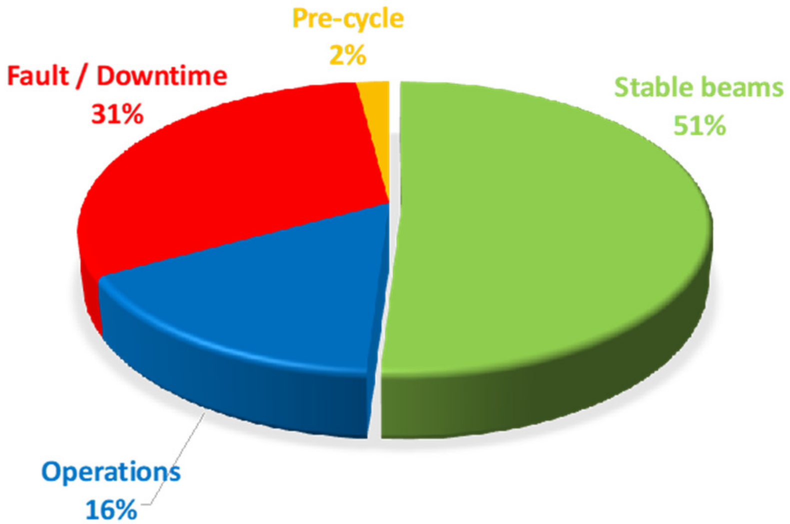


F. Bordry, CERN
Director for A&T

WG on quench performance.
E. Todesco, chair

LHC Performance: Luminosity

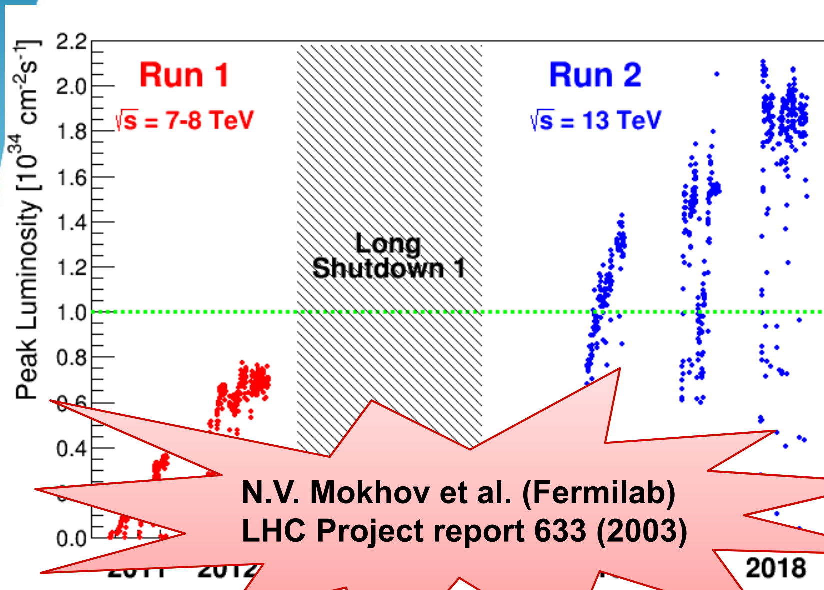




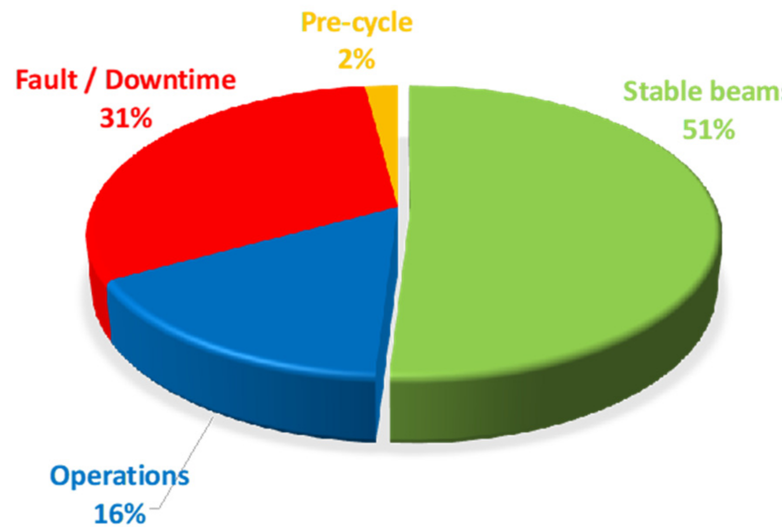
Limited by the heat deposition in the IT Quadrupole in Nb-Ti: forecast 1.7- 2 L_0
($L_0 = 10^{34}$ cm^{-2}s^{-1}, LHC nominal design lumi)

Typical figure for Run 2. this means 70% machine (including injectors) availability and about 60% efficiency!

LHC Performance: Luminosity



N.V. Mokhov et al. (Fermilab)
LHC Project report 633 (2003)



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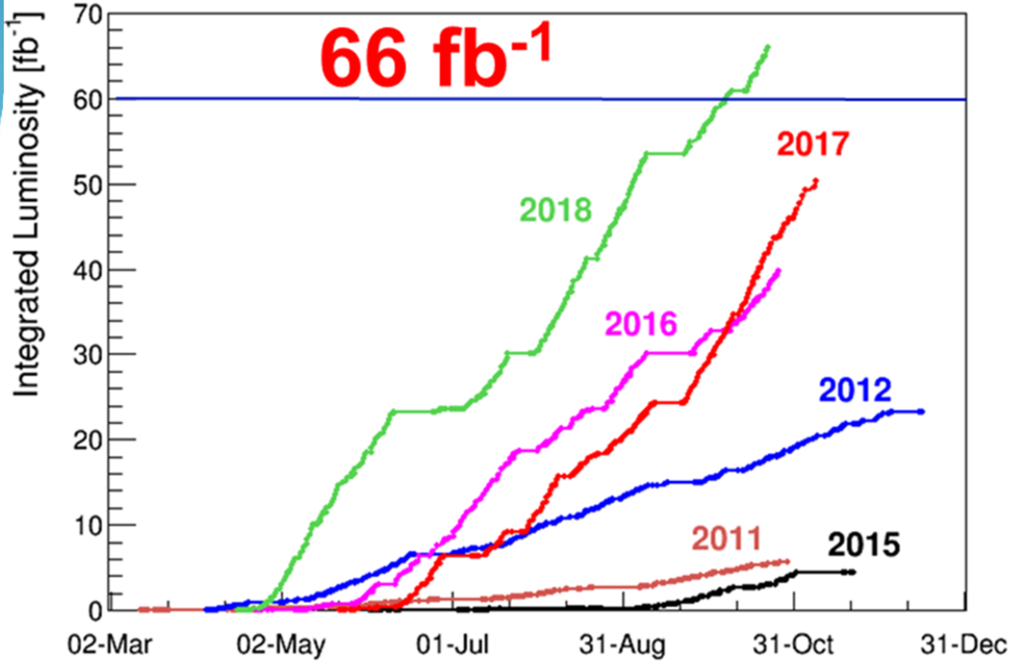
Performance: Integrated Luminosity



F. Bordry, Director of Accelerators & Technology, CERN

Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66.0
Total Run1 + Run 2	189.3

Original goal of Run1+Run2 = 150 fb^{-1}:
Δ = + 20%

Outlook to LHC Run 3 (2021-2023)

Run3 WG ,
S. Fartoukh, chair
N. Karastathis

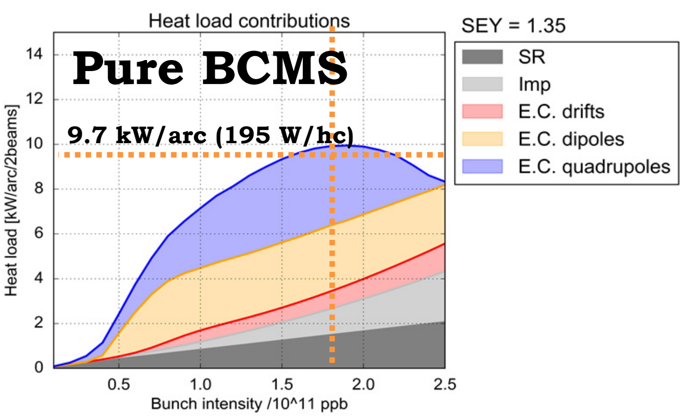
LHC Injectors Upgrade

LIU beam intensity ramp up for HL-LHC: can be used in LHC Run3 ?

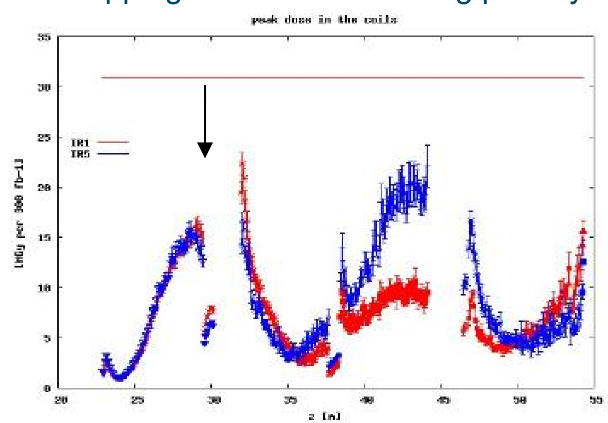
	2021	2022	2023*	Comment
# bunches	Up to 2748 (BCMS)			
$\epsilon_n\ [\mu m]$	1.3	1.3	1.3 → 1.55	Intensity Ramp Up
$N_b\ [10^{11}\mathrm{p}]$	0 →1.4	1.4 →1.8	1.8 → 2.1	Max bunch population at the end of each year

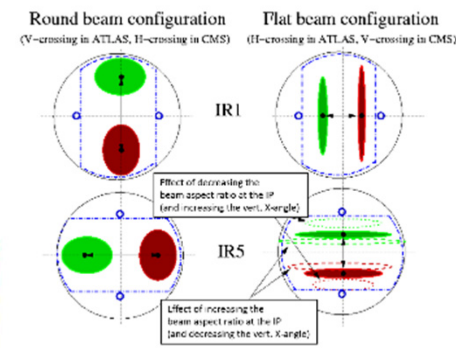
Pushing present LHC at the limits (using HL-LHC studies and early installation of HiLumi equipment in LS2…: Levelling, collimator low-Z and DS, TDIS…)

Approaching cryogenic limitations different heat load emerged in Run2 is to be understood



Swapping the vertical crossing polarity





r=30% decrease → 40% increase in integrated luminosity

Goal Rune 3: L_{int} 160 fb^{-1} with margins
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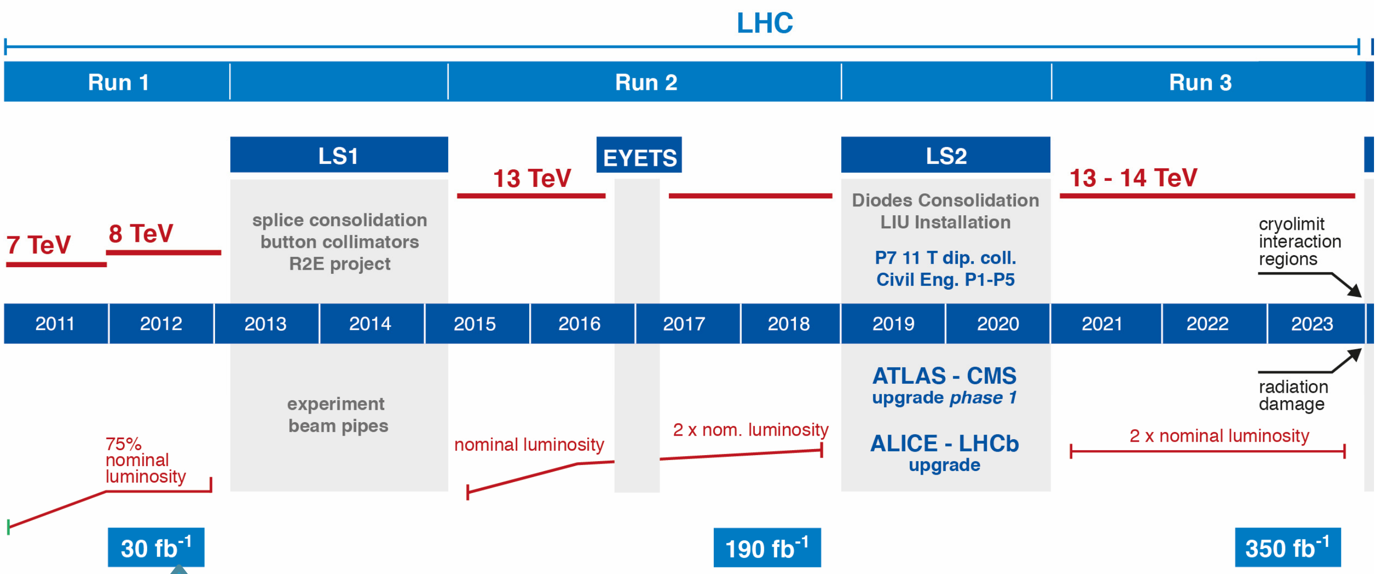
HiLumi HL-LHC PROJECT

LHC / HL-LHC Plan



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50 ns bunch
high pile up ~40

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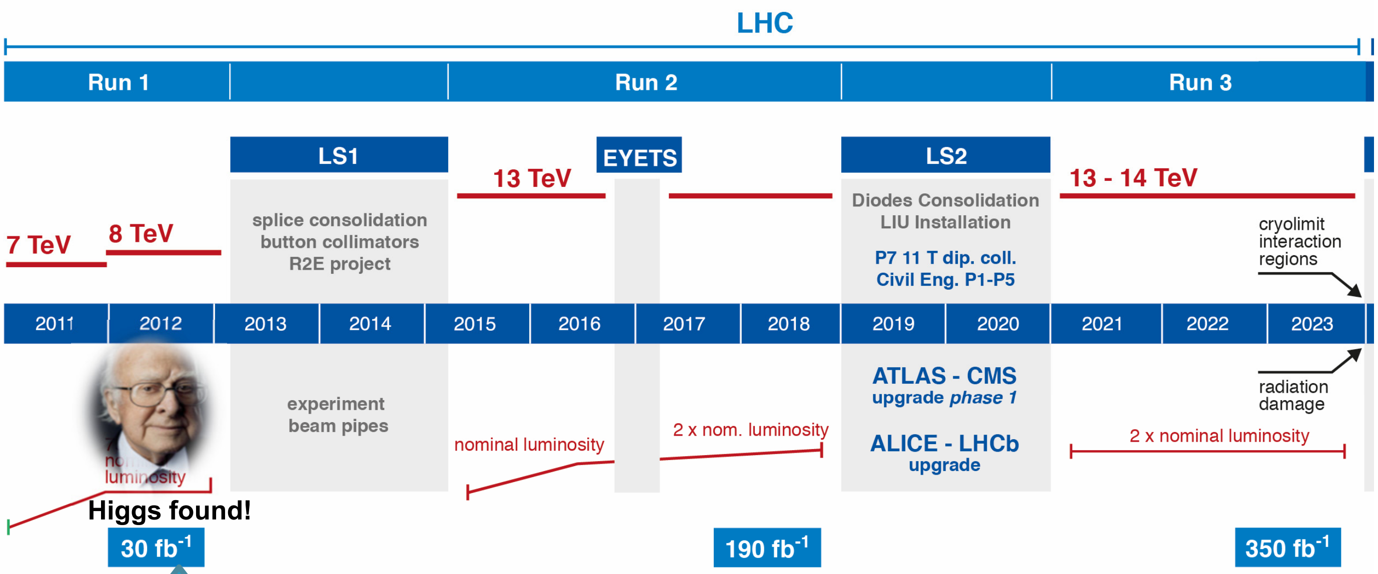

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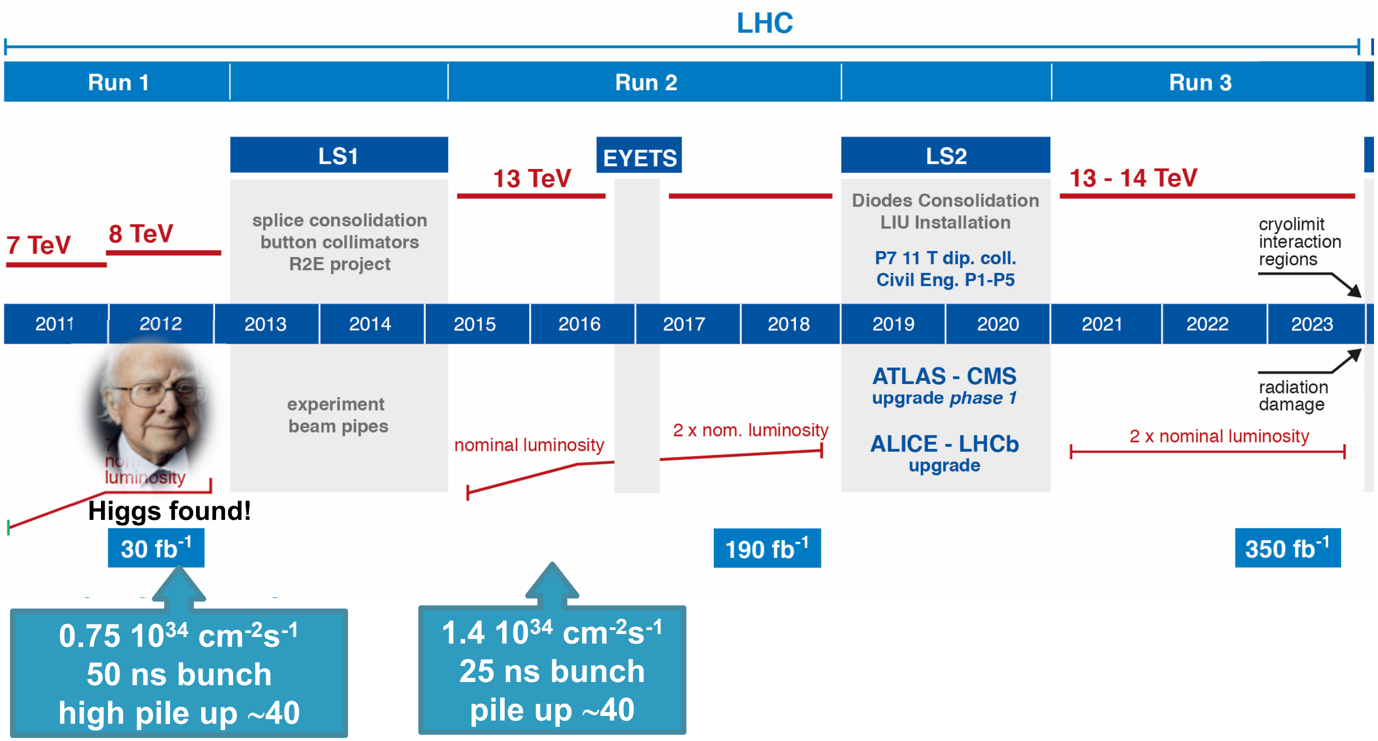

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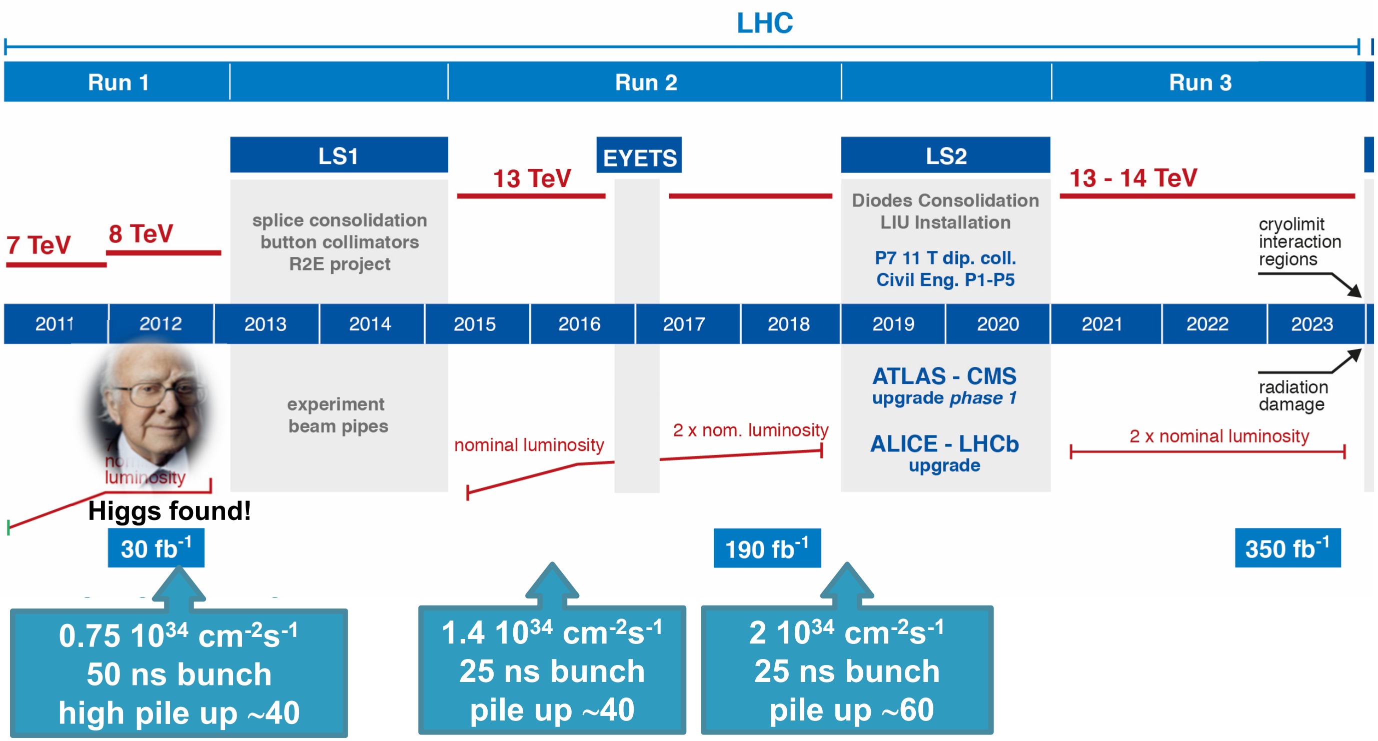

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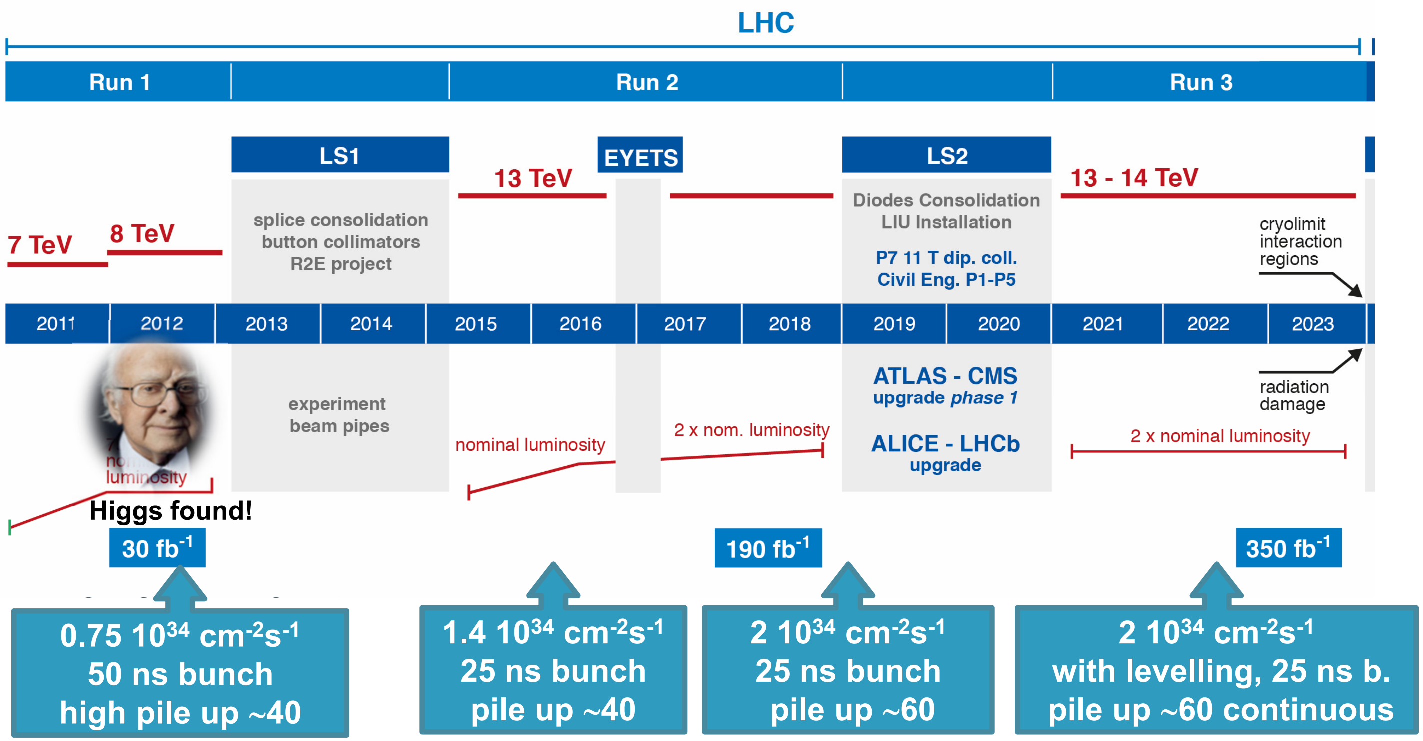

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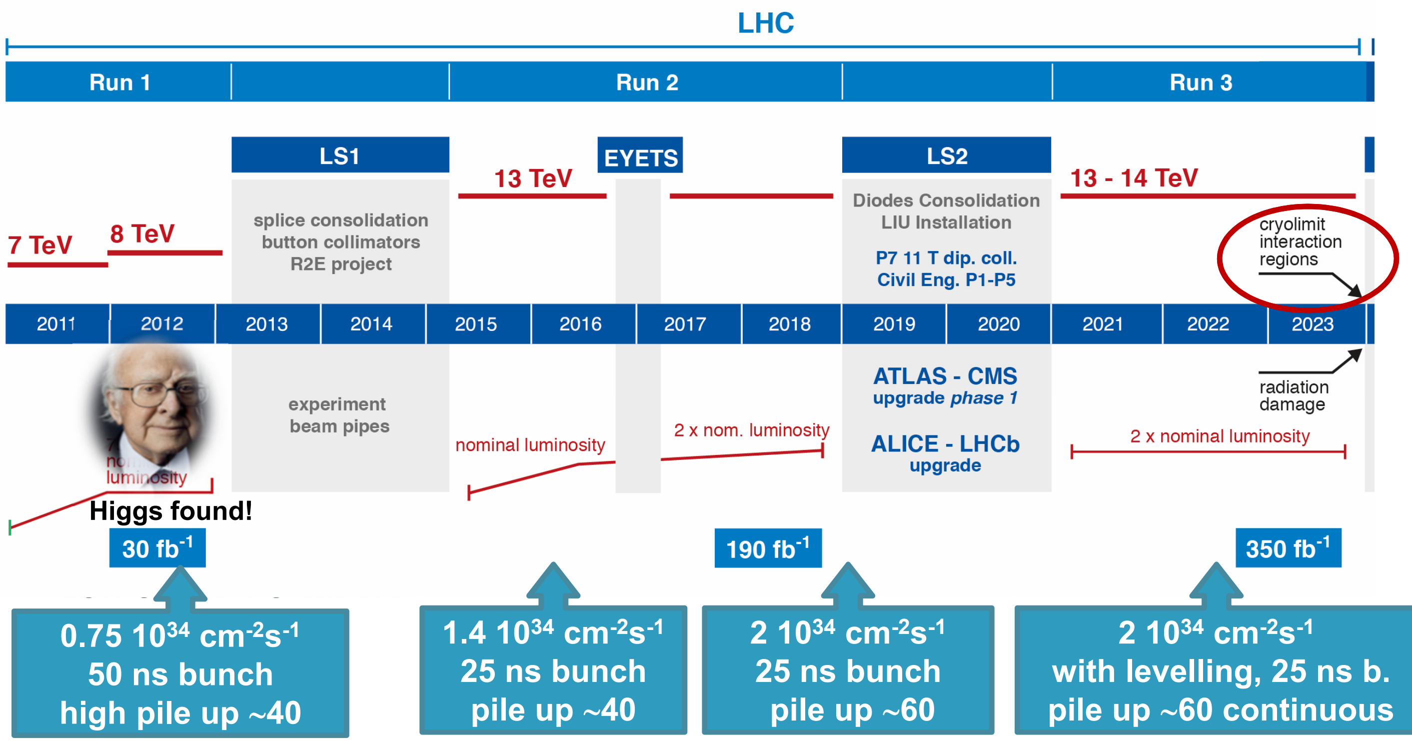

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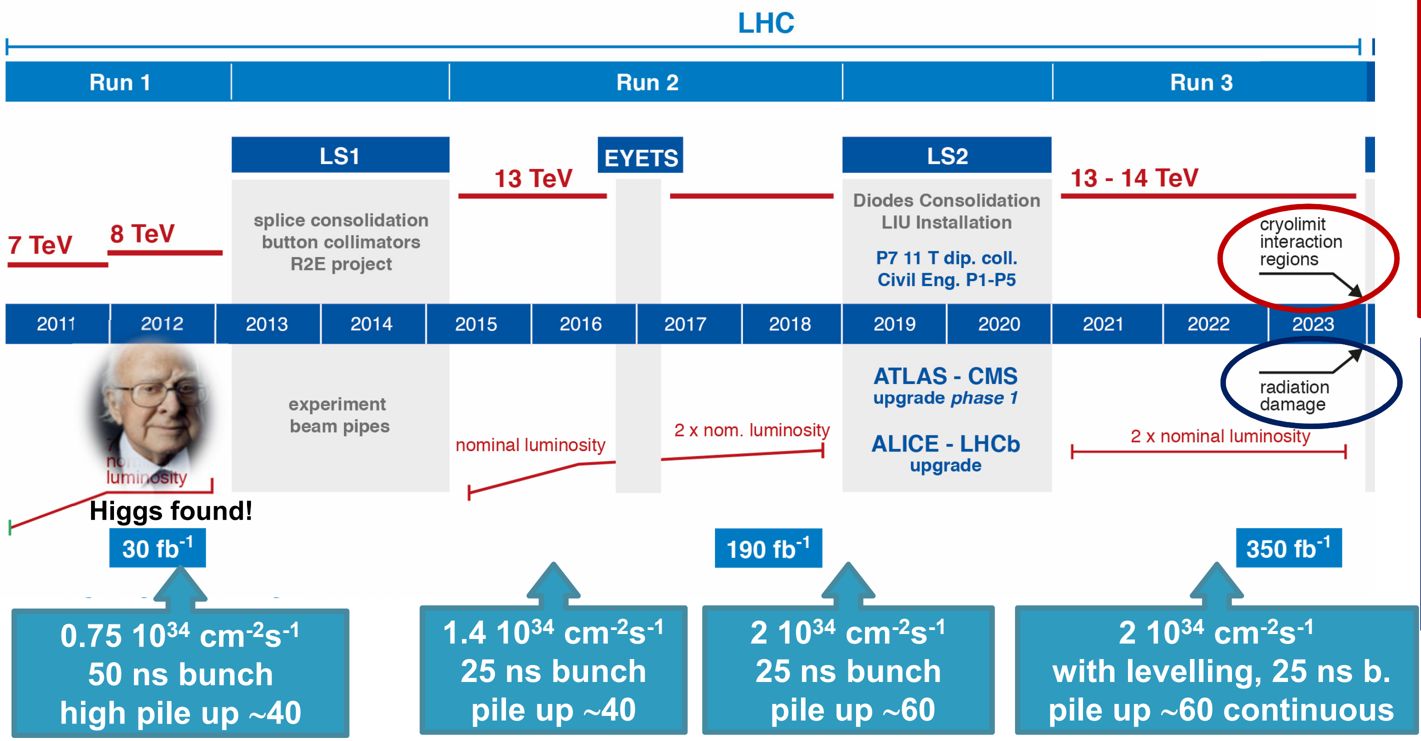

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Technical limitation on integrated lumi:

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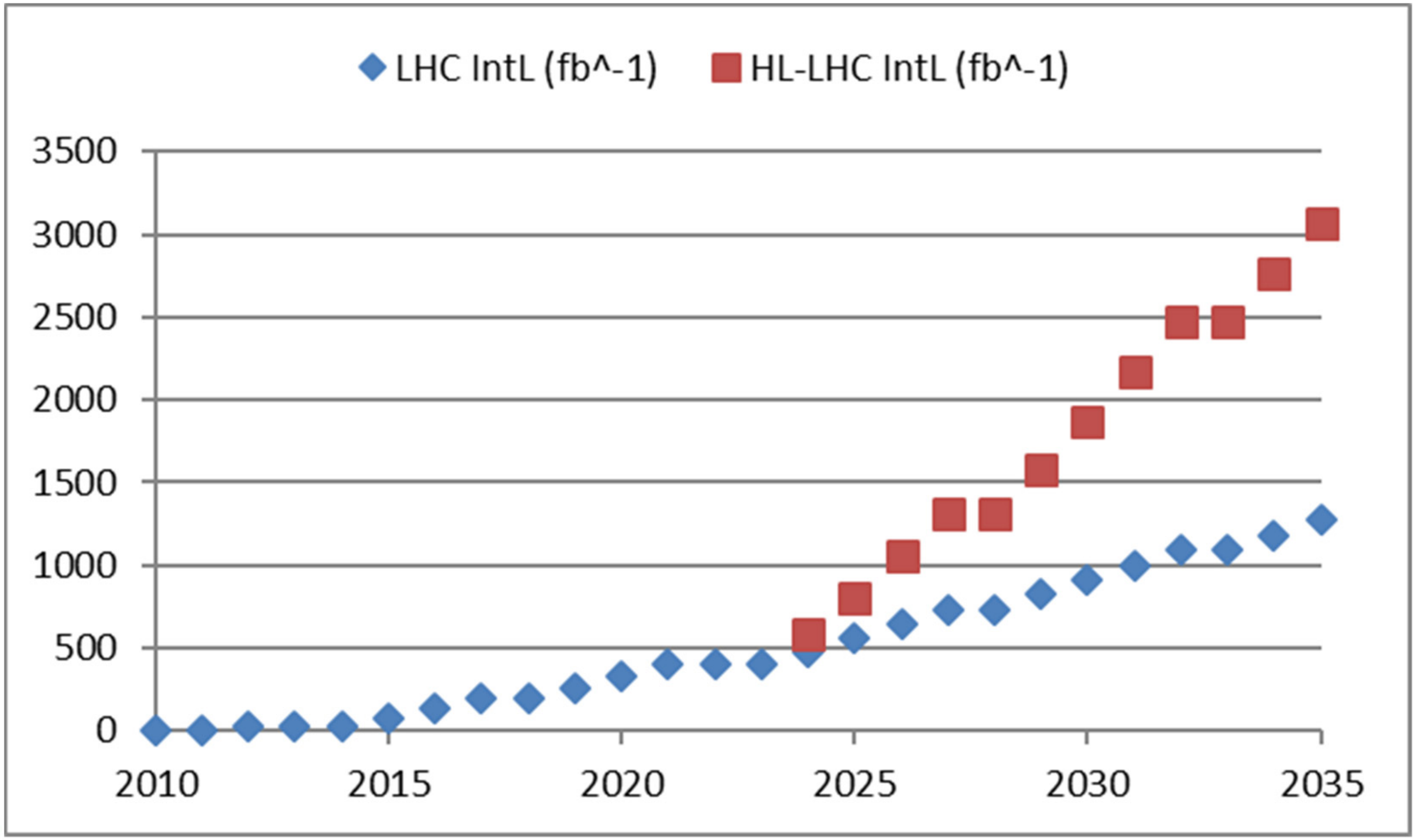

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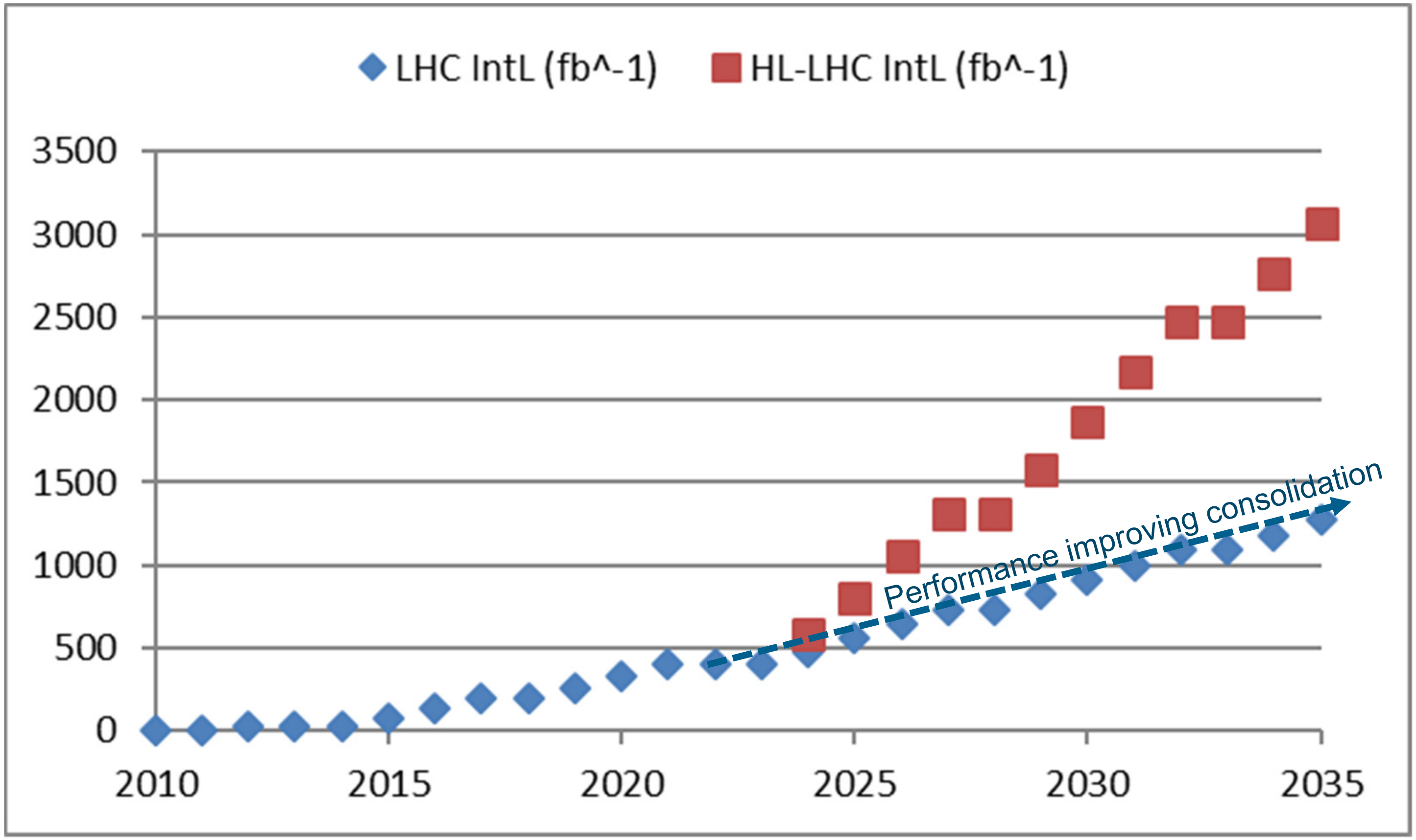

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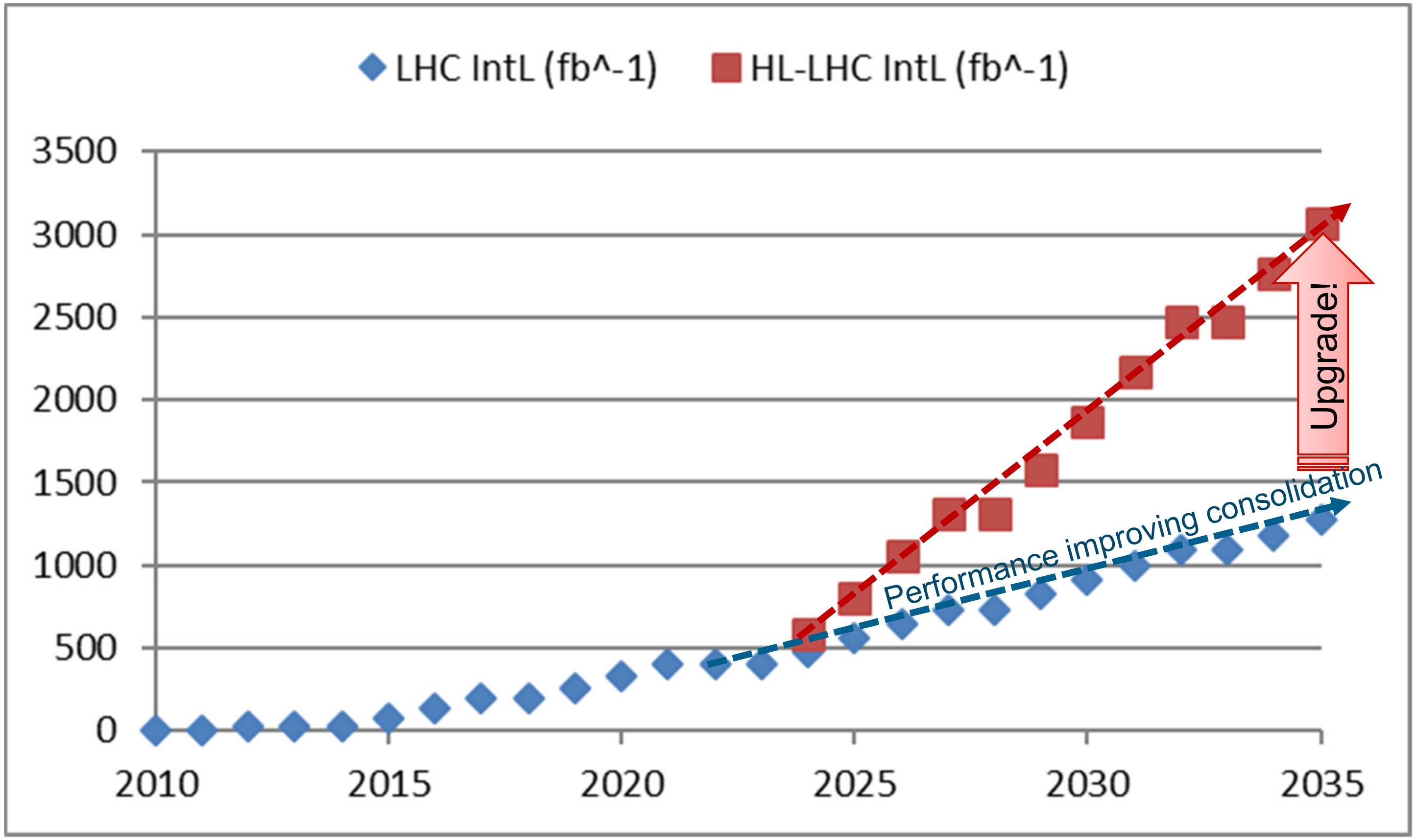

Goal of HL-LHC

From EC-FP7 HiLumi LHC Design Study application of 2010

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:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

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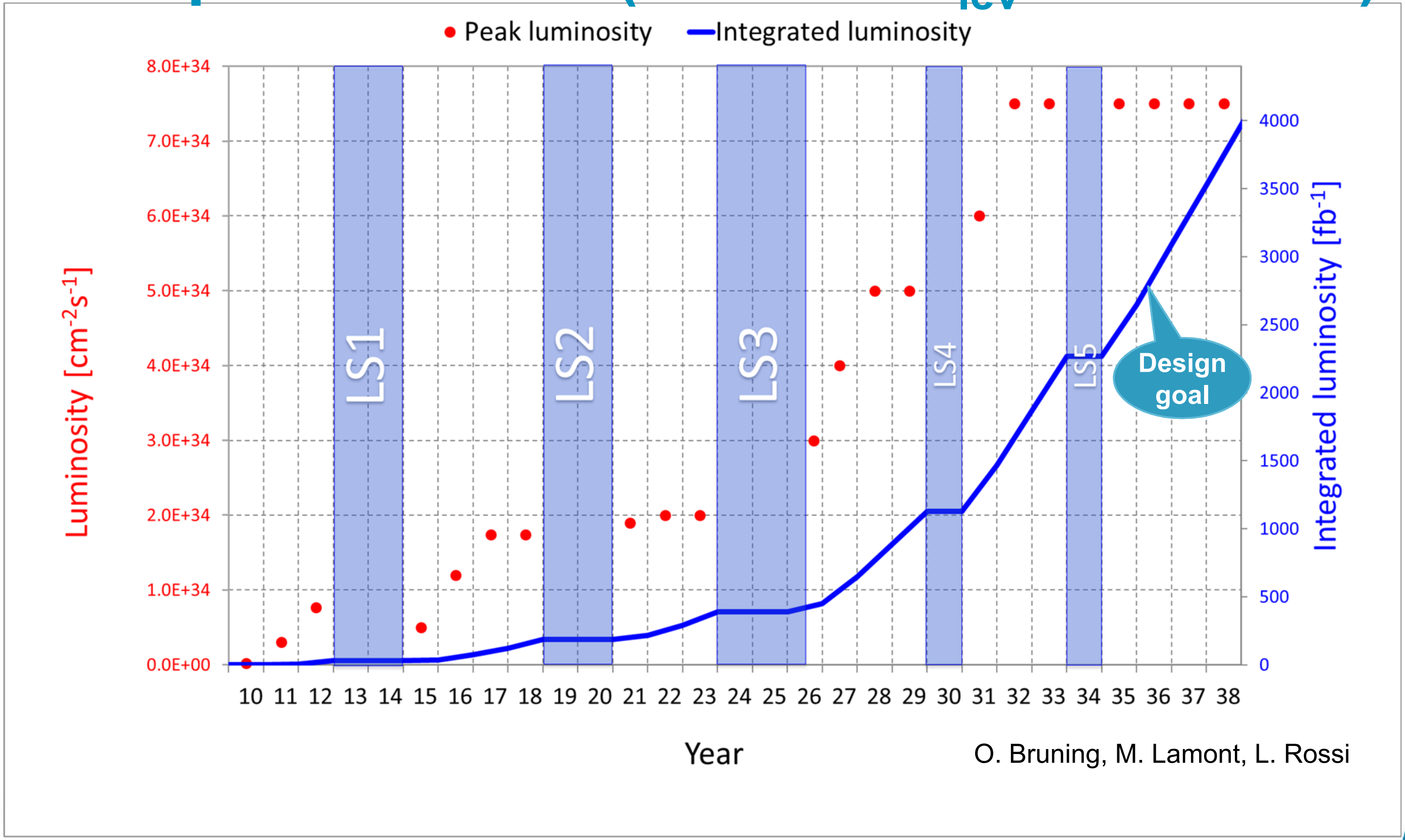
Experiment are designing for this goal.
We need to be compatible with it!

HL-LHC performance (ultimate L_{lev} from 2032)



Luminosity: collision rate per unit cross section which parameters count for LHC?

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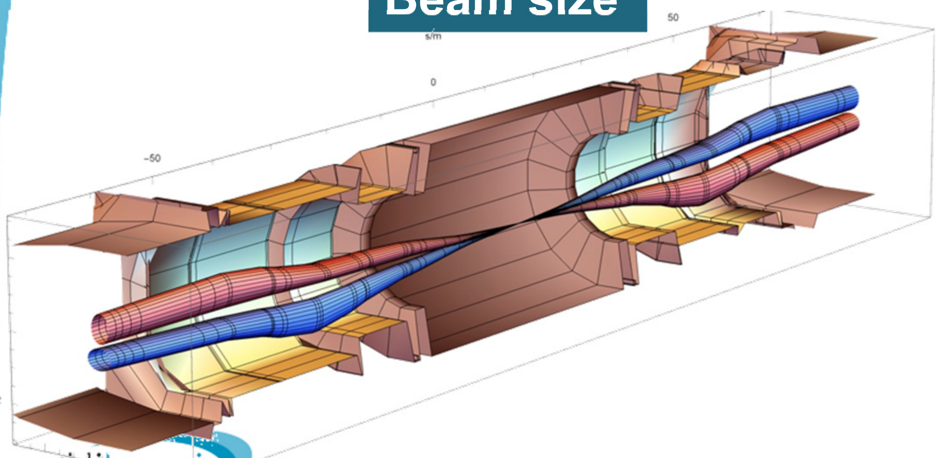

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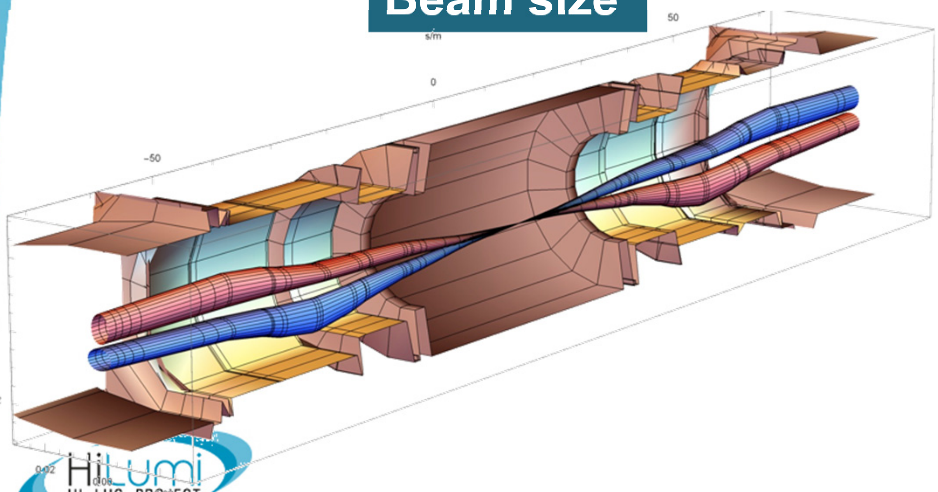

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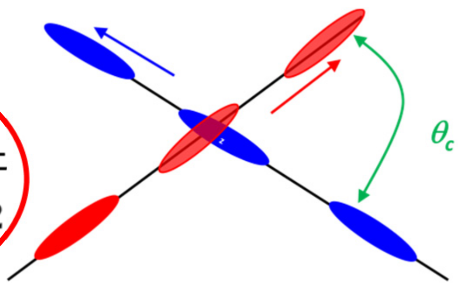

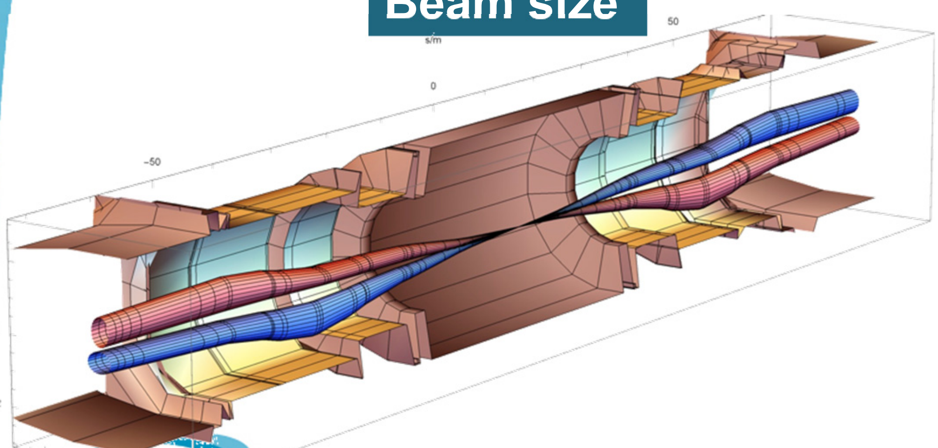

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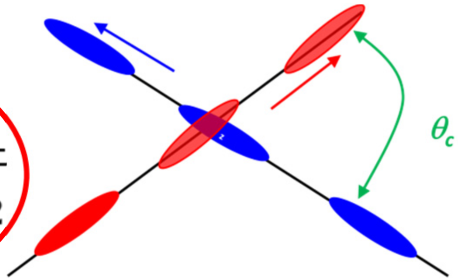

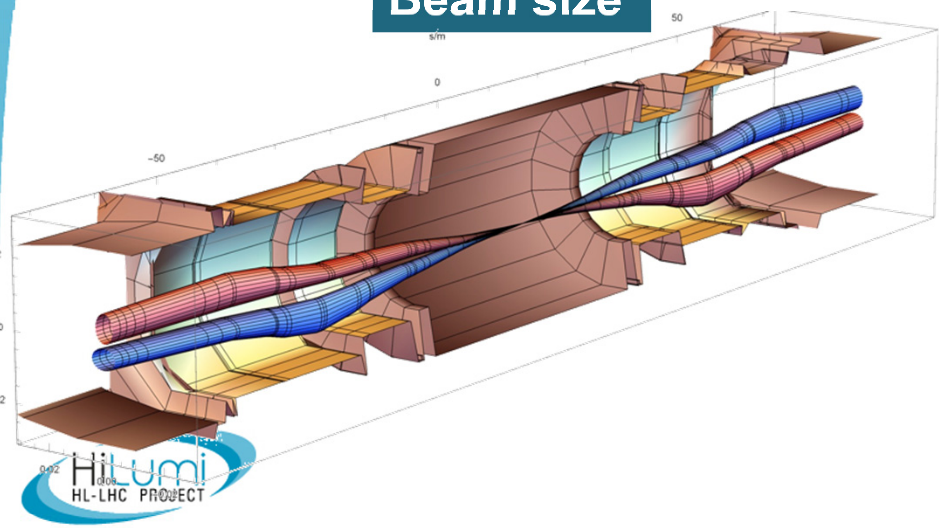

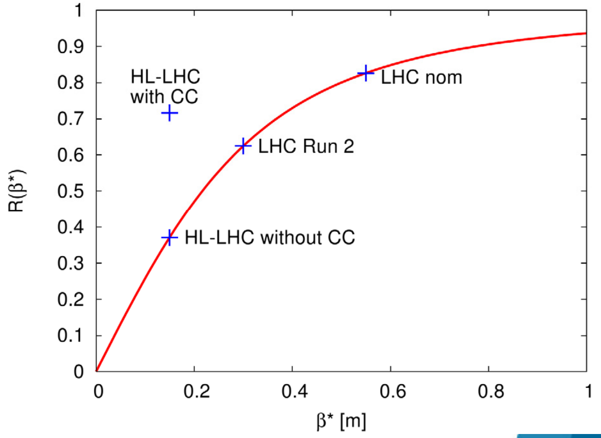

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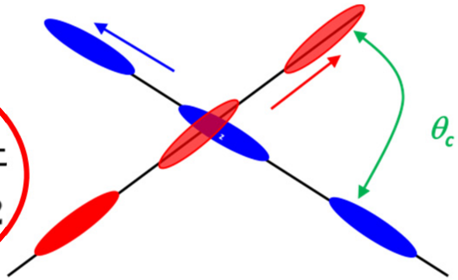

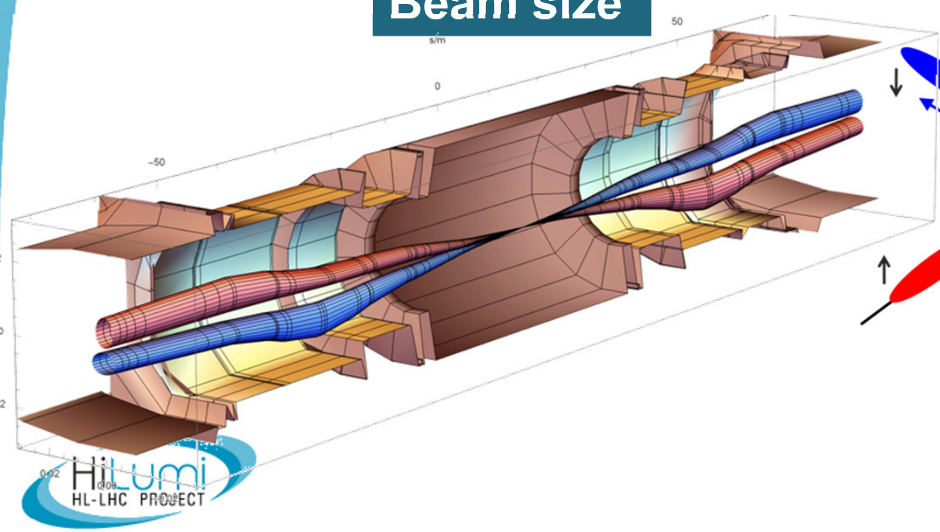

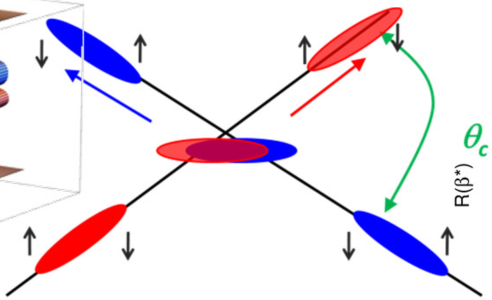

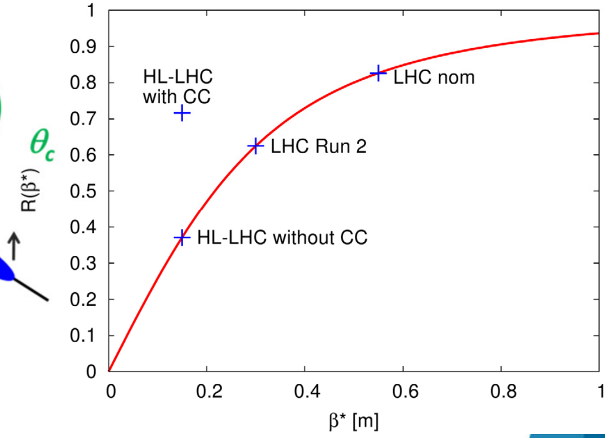

HL-LHC parameters

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1.15E+11	2.2E+11
n_b [12]	2808	2760
Beam current [A]	0.58	1.1
Half Crossing angle [μrad]	142.5	250
Minimum β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
Total loss factor R0 without crab-cavity	0.836	0.342
Total loss factor R1 with crab-cavity	-	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	-	1.70E+35
Levelled Luminosity [cm^{-2} s^{-1}]	-	5.0E+34 [4]
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.28
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Levelled Luminosity [cm^{-2} s^{-1}]	-	5.0E+34 [4]
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.28
Leveling time [h] (assuming no emittance growth) [7]	-	7.3

HL-LHC parameters

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1.15E+11	2.2E+11
n_b [12]	2808	2760
Beam current [A]	0.58	1.1
Half Crossing angle [μrad]	142.5	250
Minimum β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
Total loss factor R0 without crab-cavity	0.836	0.342
Total loss factor R1 with crab-cavity	-	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	-	1.70E+35
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HiLumi HL-LHC PROJECT

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HiLumi HL-LHC PROJECT

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Leveling time [h] (assuming no emittance growth) [7]	-	7.3

HL-LHC parameters

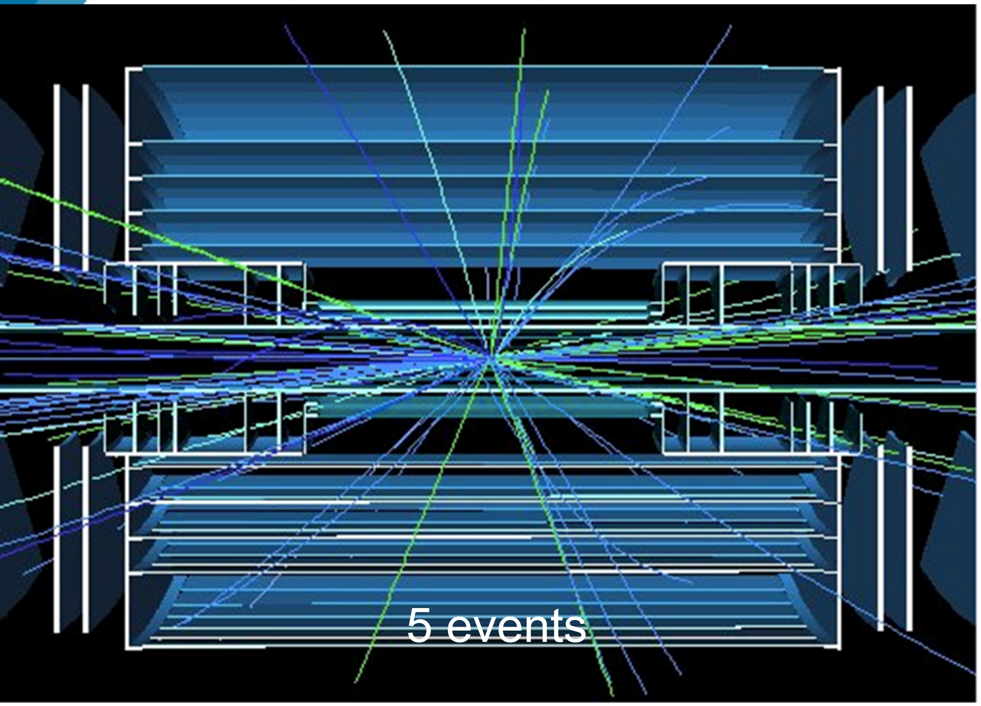
Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 8b+4e[10]
Beam energy in collision [TeV]	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11
n_b [12]	2808	2760	1972
Beam current [A]	0.58	1.1	0.79
Half Crossing angle [μrad]	142.5	250	235 [9]
Minimum β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	2.50	2.20
Total loss factor R0 without crab-cavity	0.836	0.342	0.342
Total loss factor R1 with crab-cavity	-	0.716	0.749
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}\ s^{-1}$]	-	1.70E+35	1.44E+35
Levelled Luminosity [$cm^{-2}\ s^{-1}$]	-	5.0E+34 [4]	3.82E+34
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131	140
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.28	1.3
Leveling time [h] (assuming no emittance growth) [7]	-	7.3	7.1

Back-up for e-cloud

Pile up

Pushing at the maximum the parameters of HL-LHC we would start the fill at L = **17×10^{34} with 400 events/crossing.**

Pile up



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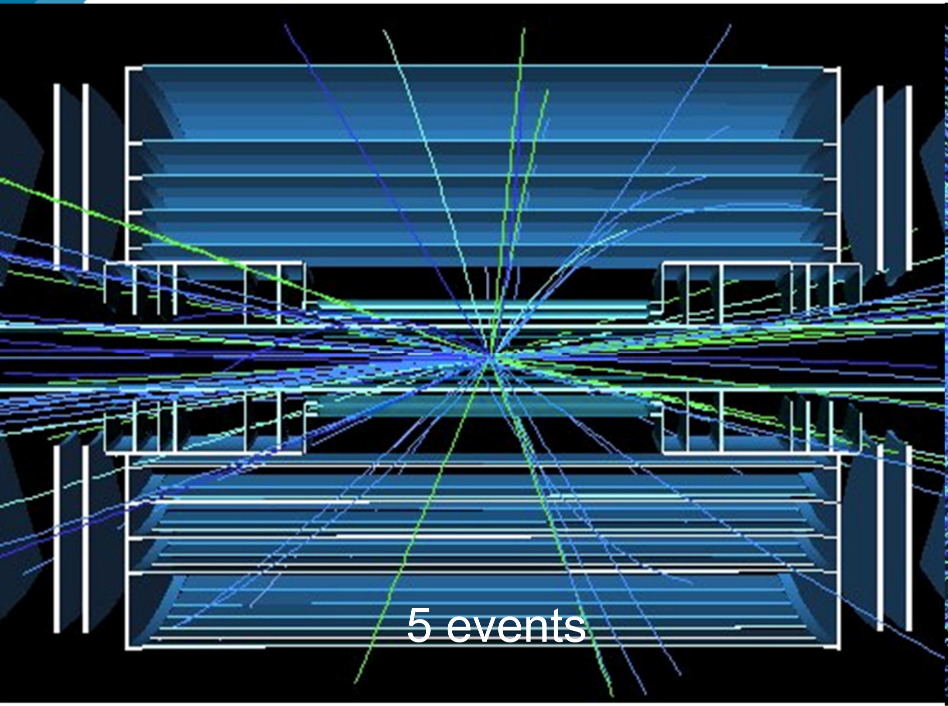
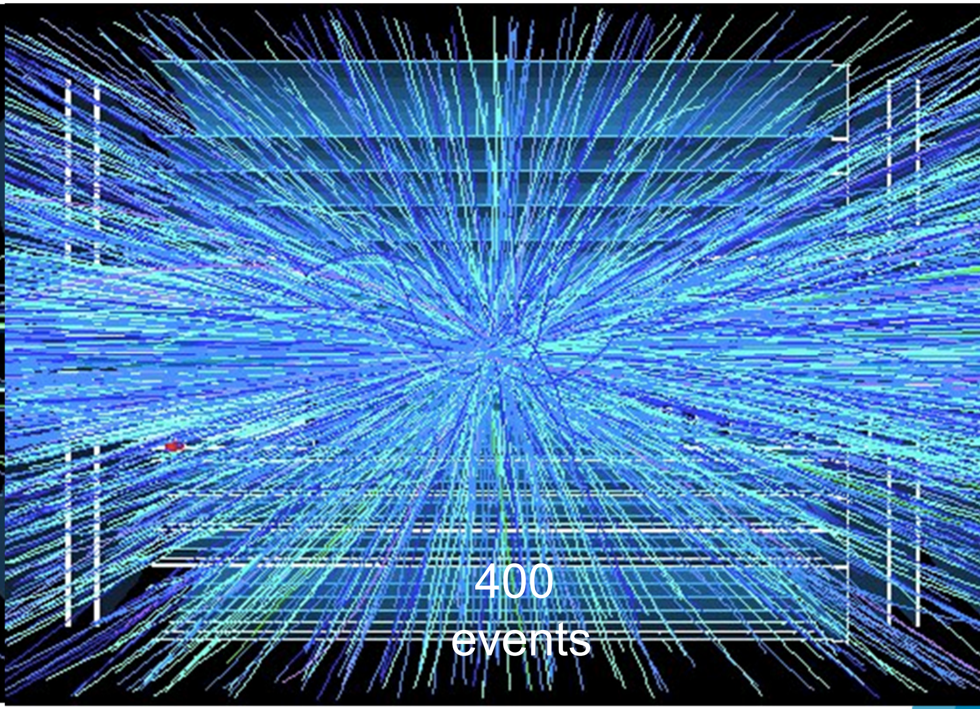
Pile up





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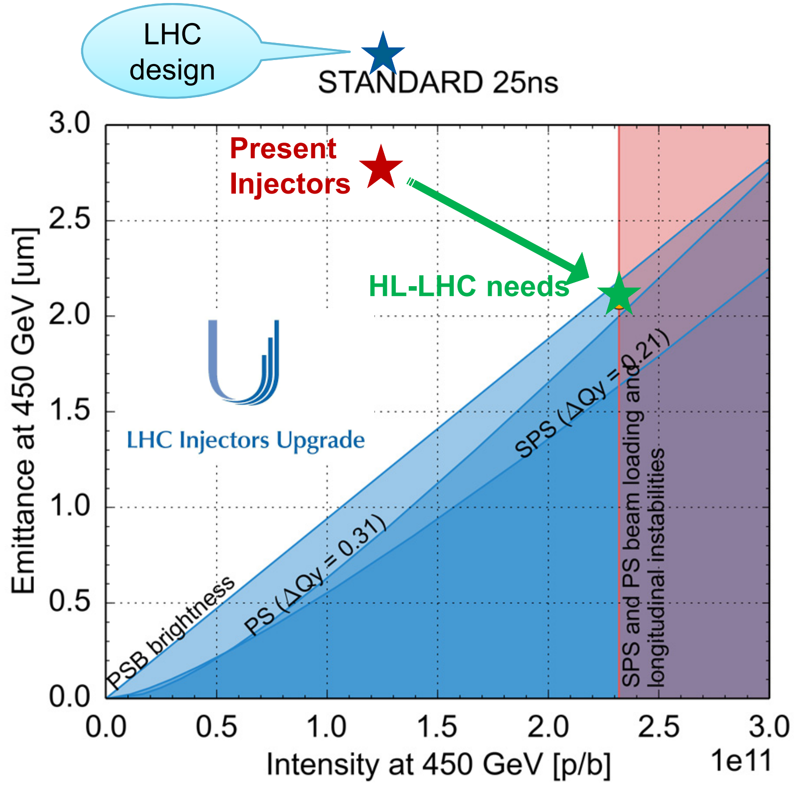
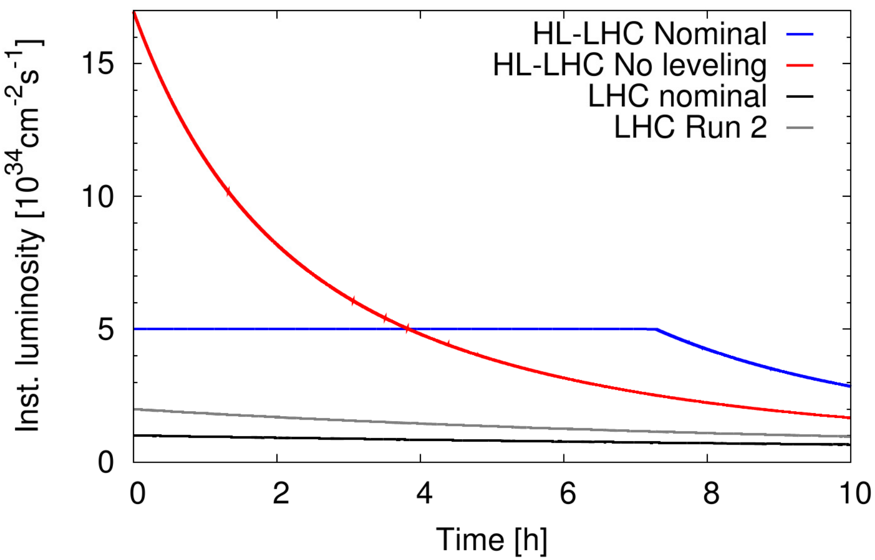
LIU (Intensity) and Levelling mode



Reducing heat load on the IT triplet (quench and cooling limits)
Limiting pile up in the detectors



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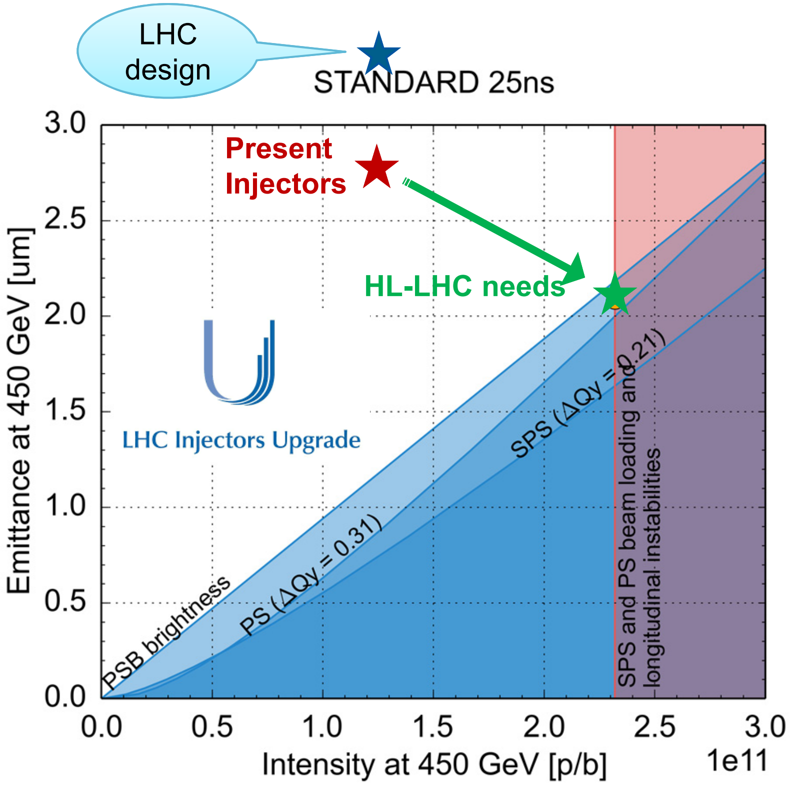

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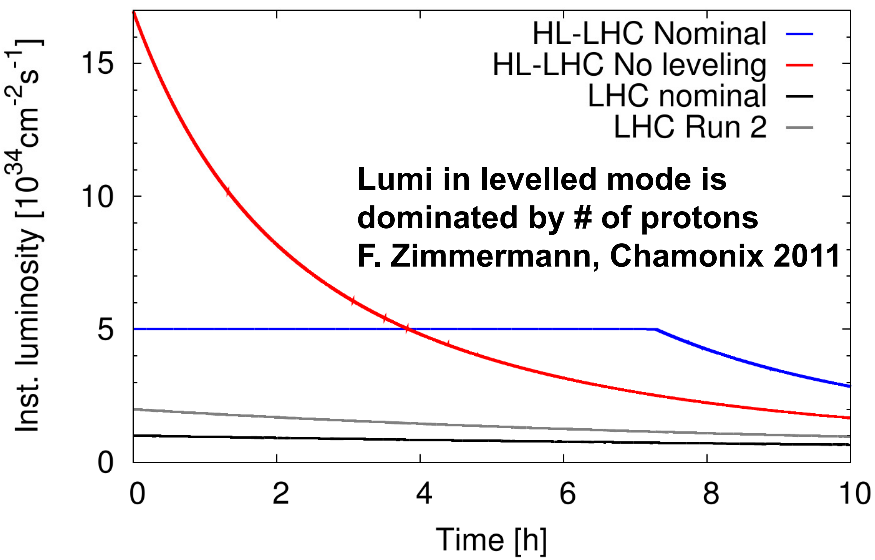
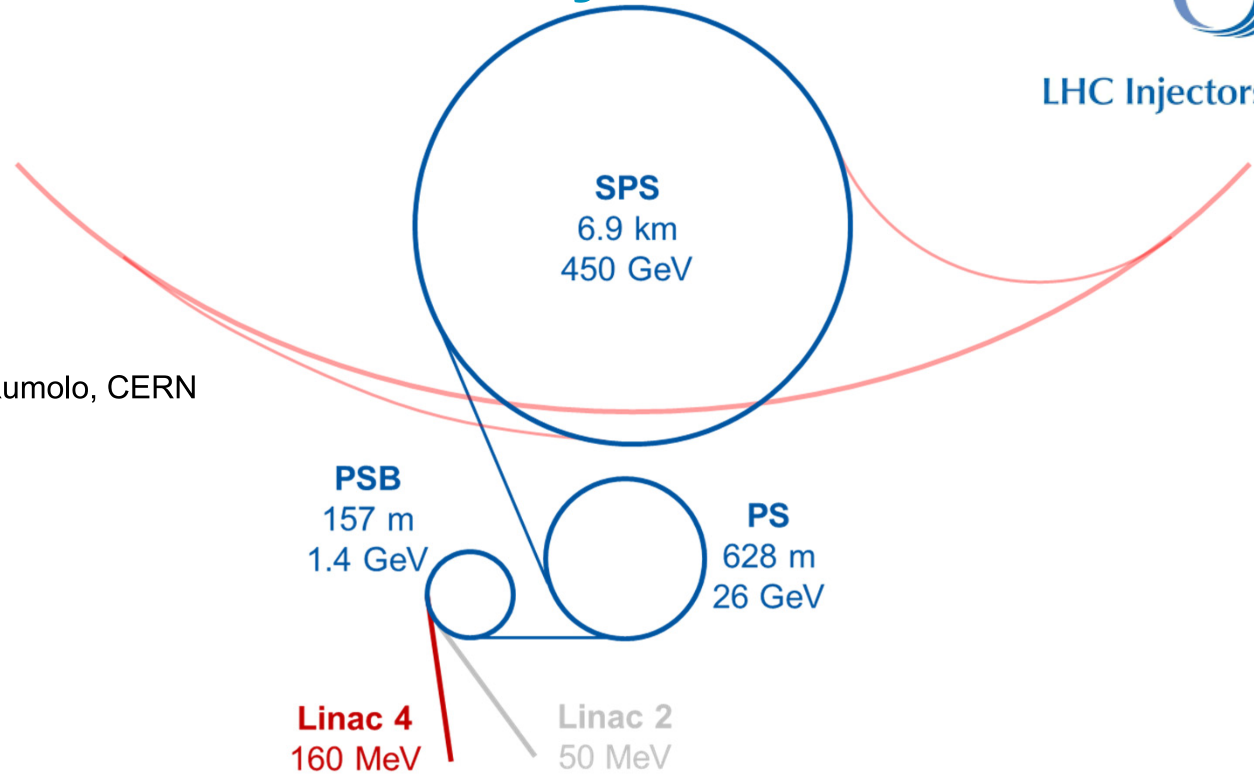


LIU installation under way:2019-2020

LHC Injectors Upgrade

Courtesy M. Meddahi and G. Rumolo, CERN



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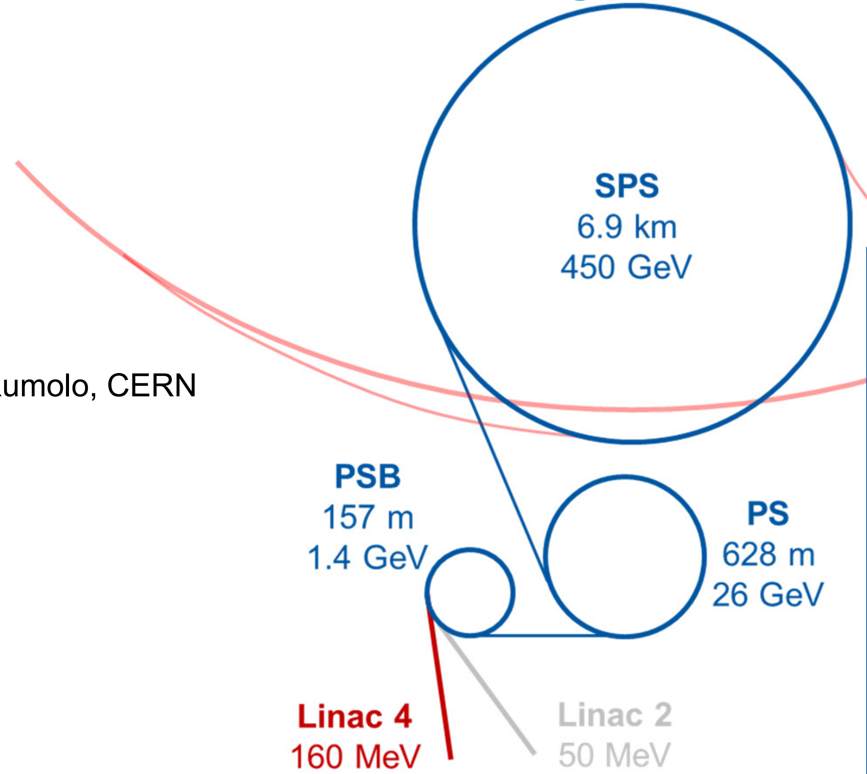


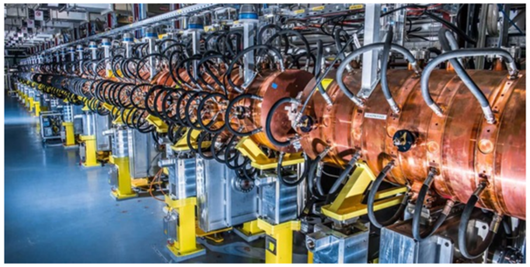
LHC Injectors Upgrade

Linac 4, has been built to take over.

- Higher energy **160 MeV**
- Acceleration of **H^- ions** (charge exchange $H^- \rightarrow p^+$ in the PSB)

Construction **completed in 2017**

- Extensively tested in 2017-2018
- Ongoing **work in LS2 to connect it to the rest of the chain**

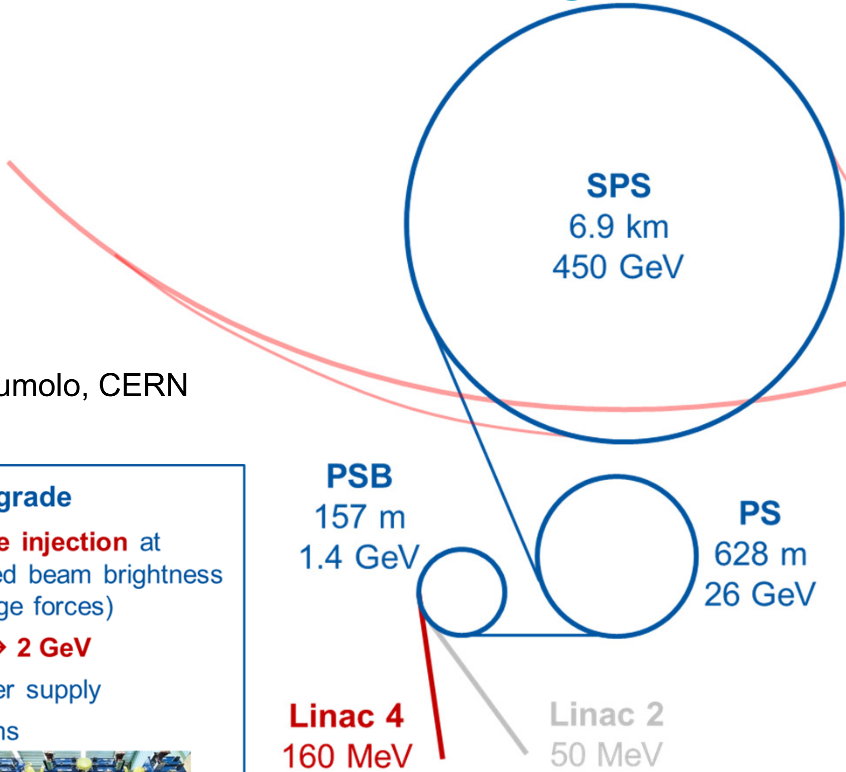


HiLumi HL-LHC PROJECT

LIU installation under way:2019-2020

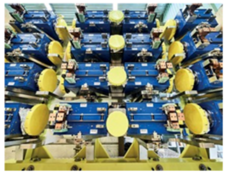
LHC Injectors Upgrade

Courtesy M. Meddahi and G. Rumolo, CERN



PSB upgrade

- **H^- charge exchange injection** at 160 MeV → improved beam brightness (weaker space charge forces)
- **Energy : 1.4 GeV → 2 GeV**
  - New main power supply
  - New RF systems



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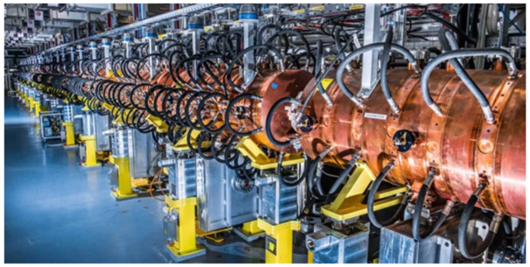


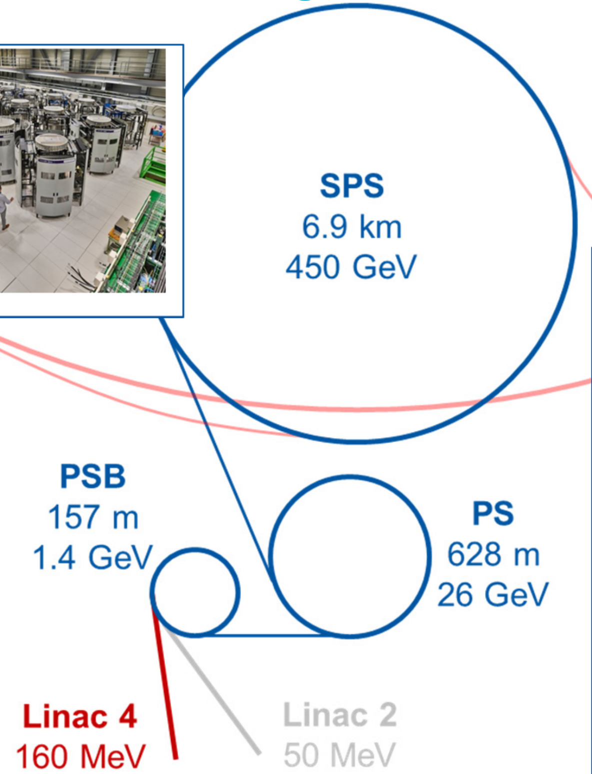
LIU installation under way:2019-2020

LHC Injectors Upgrade

SPS upgrade

- **Main RF system upgrade** (new solid state power plants – 2 x 1.6 MW)
- **Impedance mitigation** to improve beam stability
- More robust **beam dump and protection devices**

Courtesy M. Meddahi and G. Rumolo, CERN



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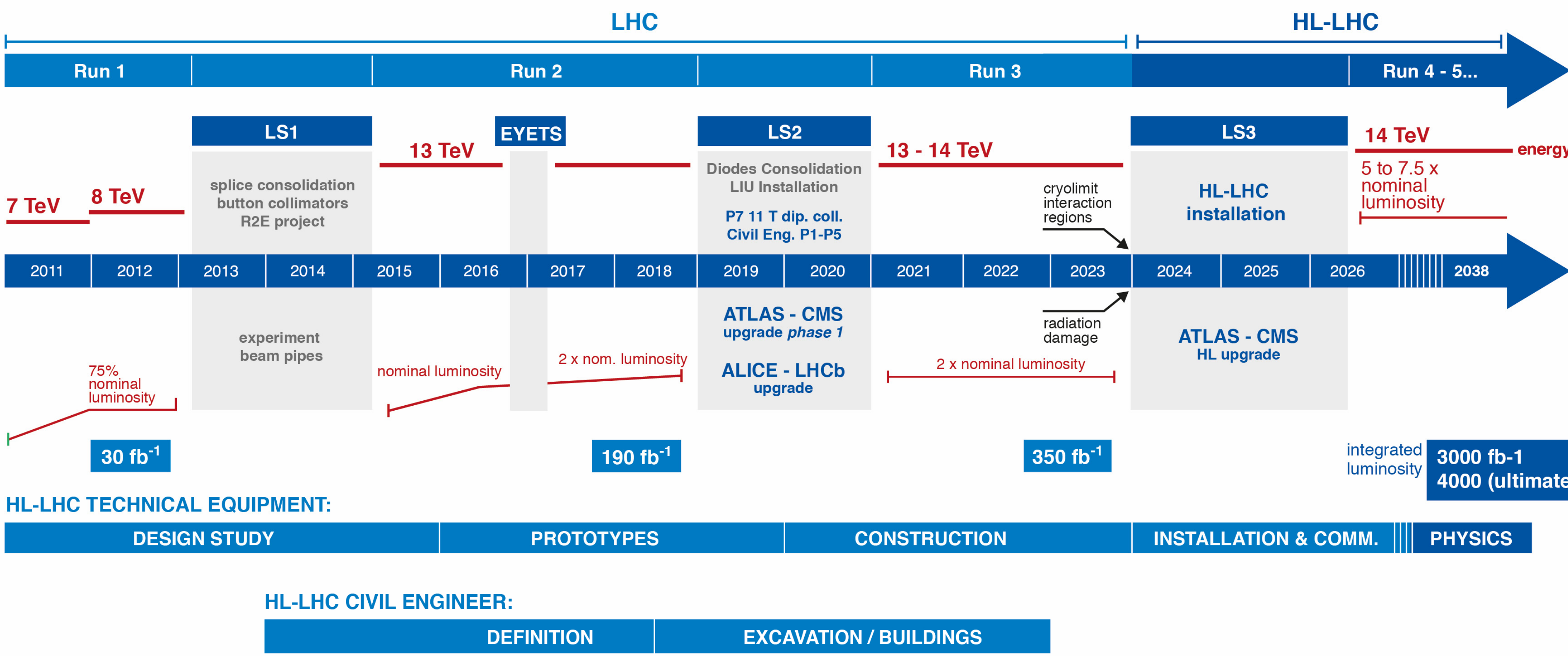
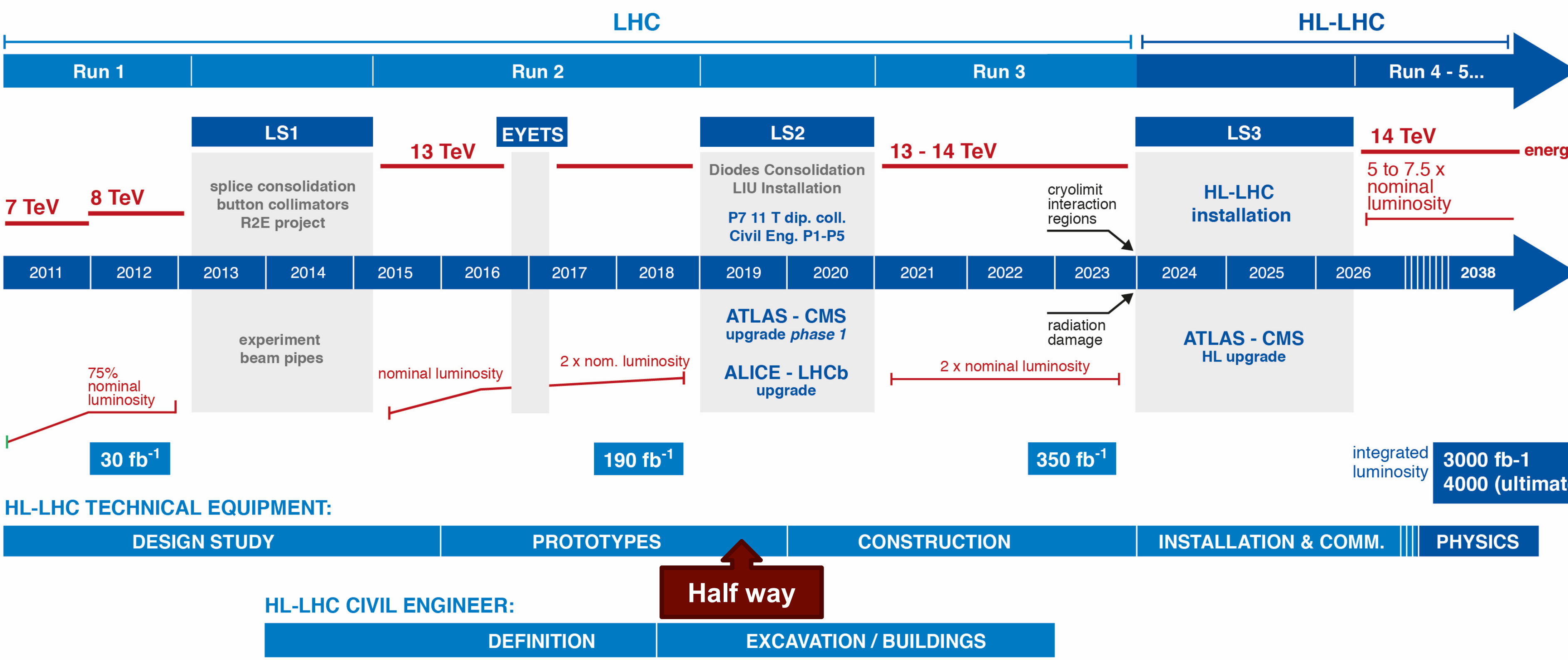
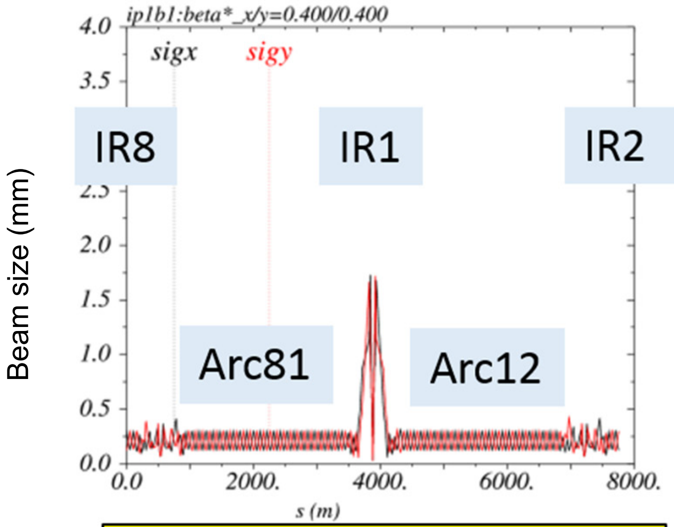
LHC / HL-LHC Plan



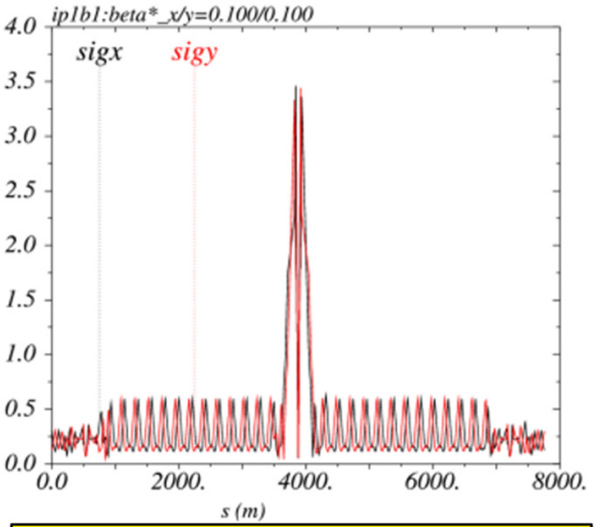
LHC / HL-LHC Plan



ATS: new operation mode for hadron colliders
Extending matching section to 13 km of arcs!



Pre-squeeze to β*= 40 cm



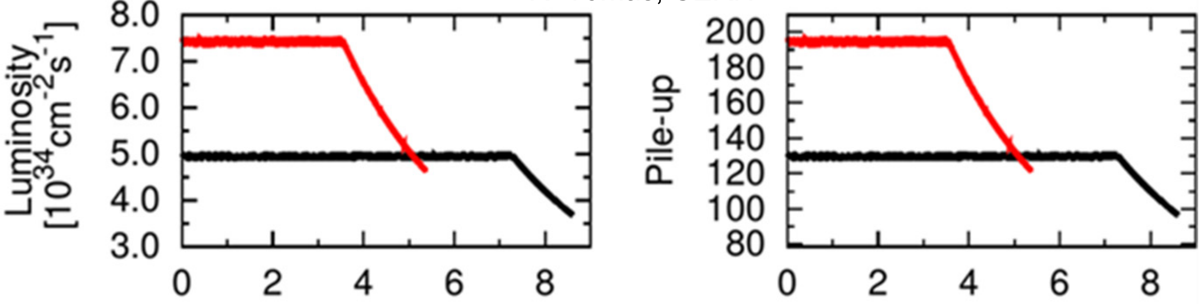
Tele-squeeze to β*= 10 cm

S. Fartoukh, et al. CERN

Overcoming LHC chromatic and matching limitations of β* = 25-30 cm.
Around each P1 and P5 6.5 km machine become a giant matching section and beam size can be made as small as 5 µm.

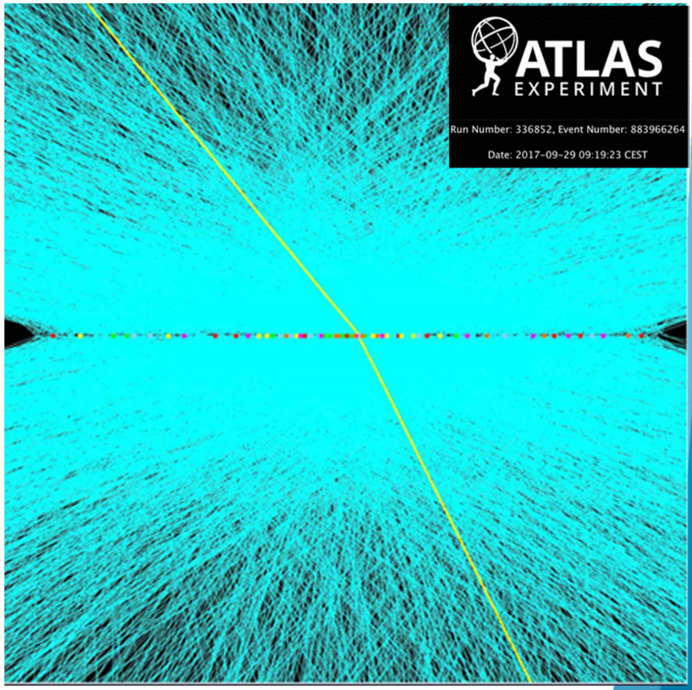
Improving the data quality

R. Tomas, CERN



Levelling helps to limit total pile up:
μ_{ave}= 140 (ultimate: μ_{ave}= 200). Experiments ask to reduce the pile up linear density (number of events/lenght) and need to introduce time stamping
$\Rightarrow$ carefully control and variation of:

- β^* (beam size at collision), main levelling knob
- Bunch tilt (Crab cavities)
- Crossing angle
- Longitudinal bunch length



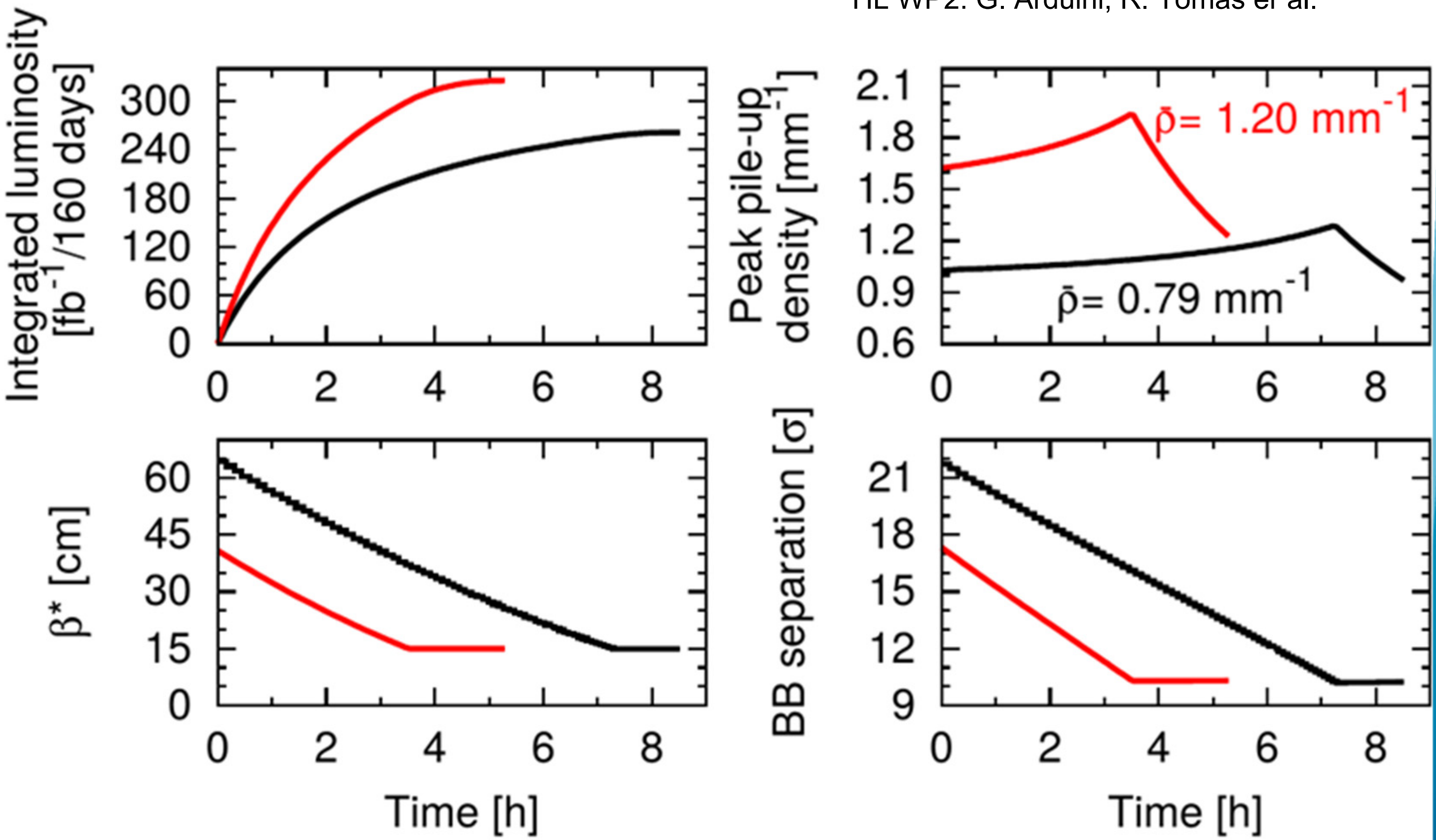
Collision with μ = 65

Performance

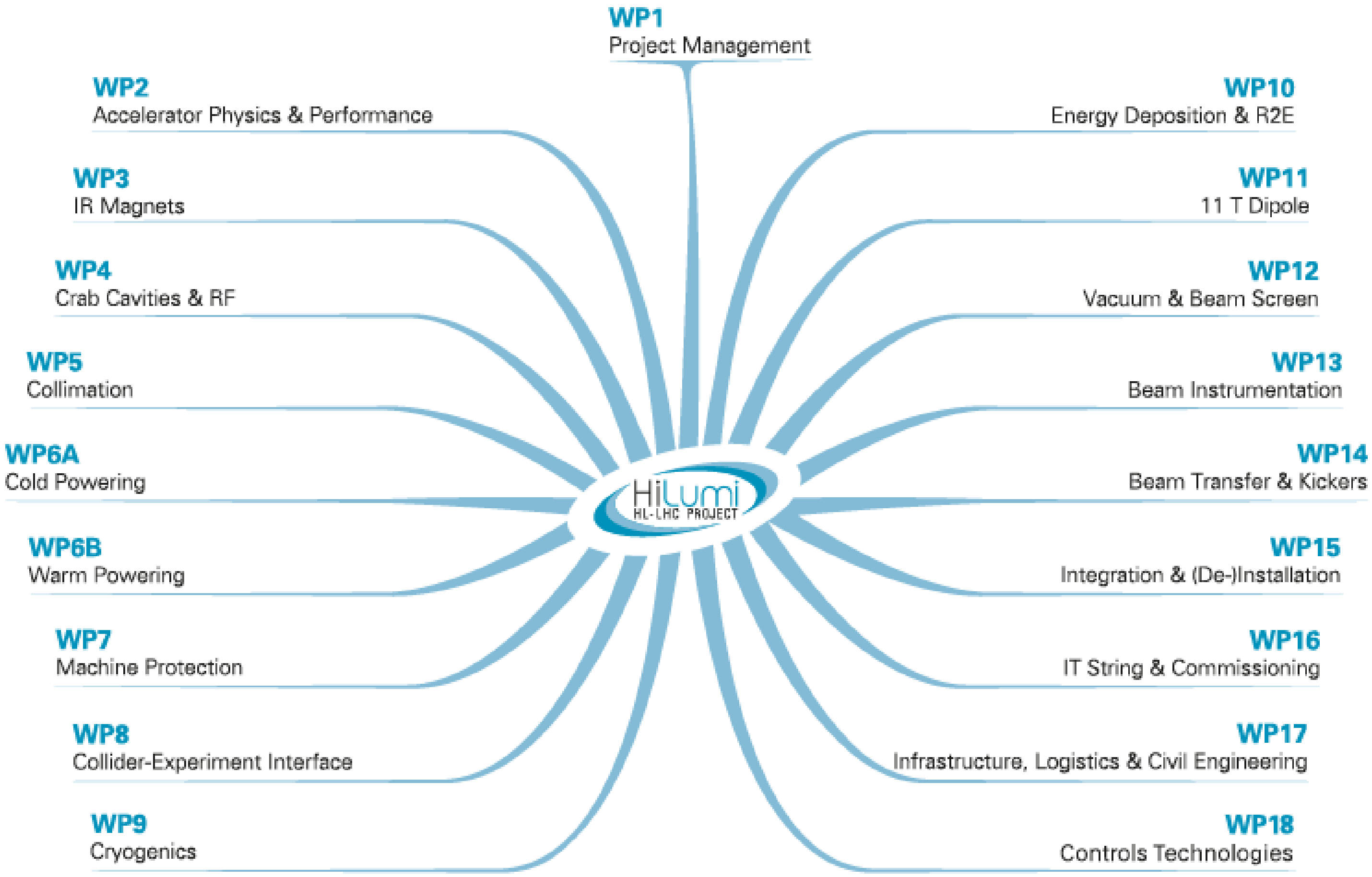
HL WP2: G. Arduini, R. Tomas er al.

Due to many advances in beam bynamics understanding:

- ATS and beam optics controls
- Beam dynamics aperture
- Beam-beam (LR)
- Impedance model
- Noise model
- RF low level



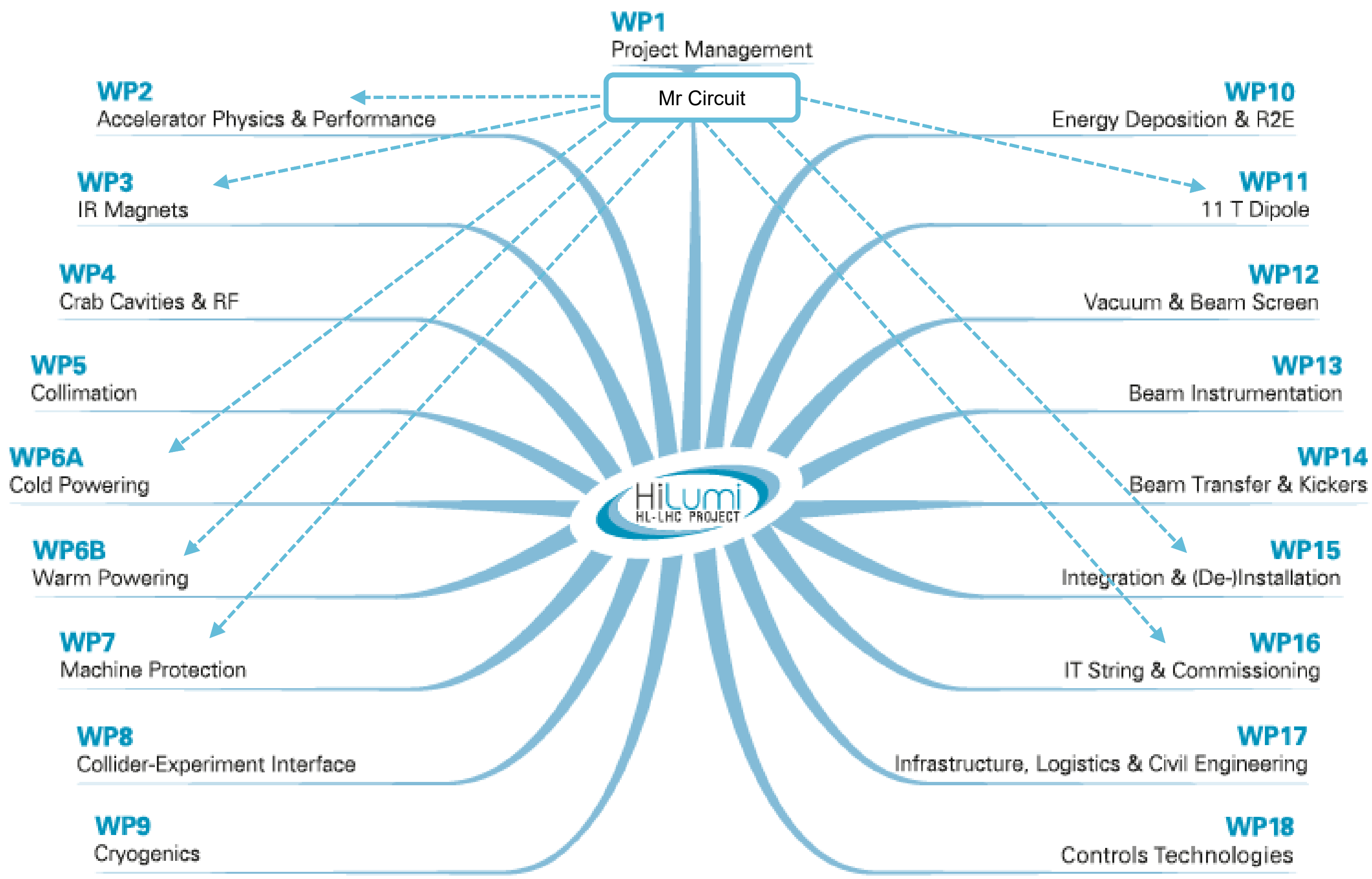
LR2


WP1
Project Management
WP2
Accelerator Physics & Performance
WP3
IR Magnets
WP4
Crab Cavities & RF
WP5
Collimation
WP6A
Cold Powering
WP6B
Warm Powering
WP7
Machine Protection
WP8
Collider-Experiment Interface
WP9
Cryogenics
WP10
Energy Deposition & R2E
WP11
11 T Dipole
WP12
Vacuum & Beam Screen
WP13
Beam Instrumentation
WP14
Beam Transfer & Kickers
WP15
Integration & (De-)Installation
WP16
IT String & Commissioning
WP17
Infrastructure, Logistics & Civil Engineering
WP18
Controls Technologies
HiLumi
HL-LHC PROJECT

Slide 56

LR2 Cecile can you add a New banner with the red circle of WP18?

Lucio Rossi, 22/03/2018



WP1
Project Management
Mr Circuit
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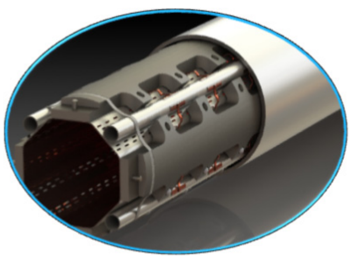
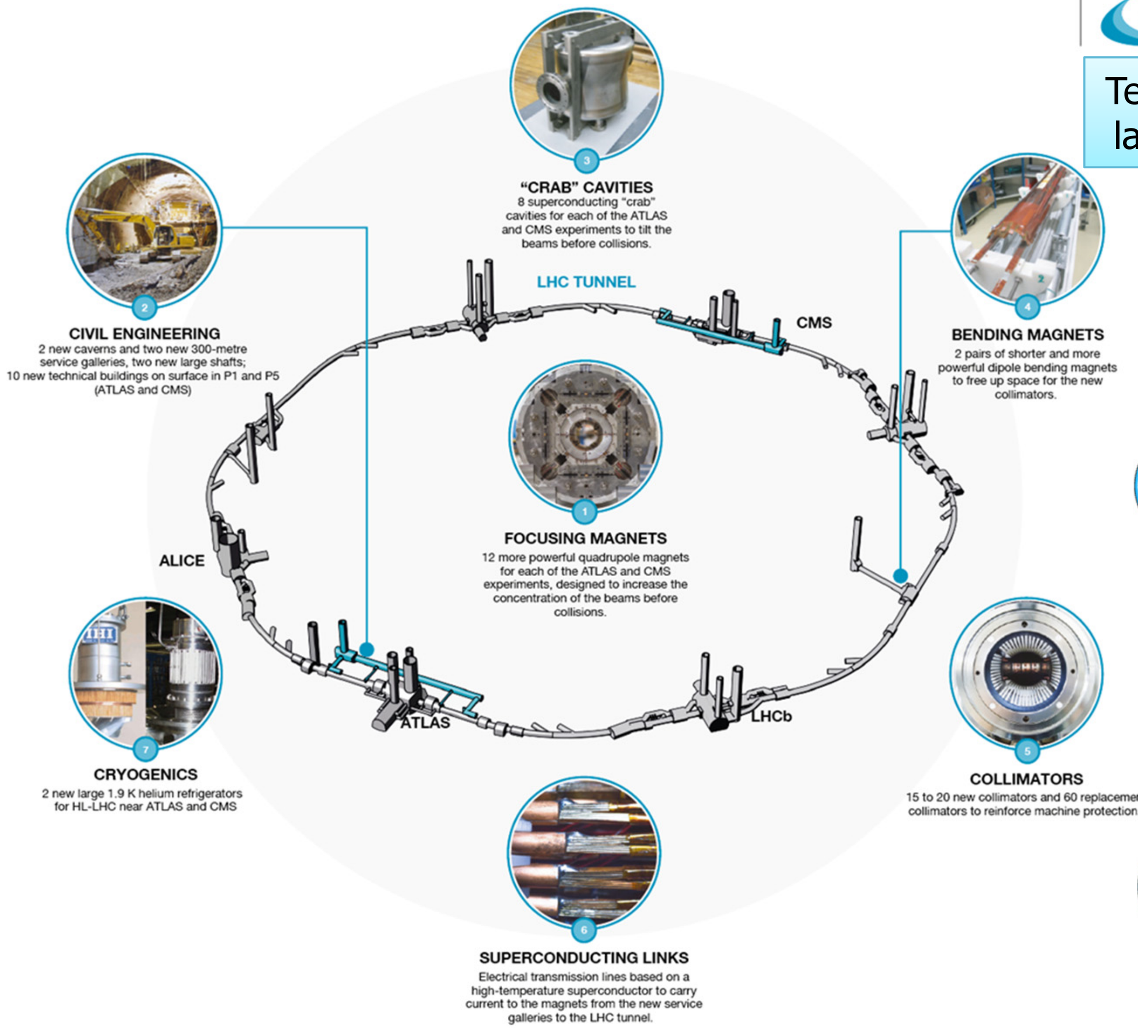
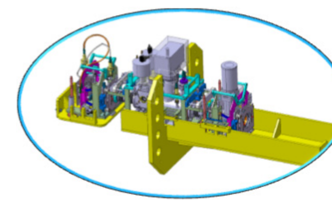
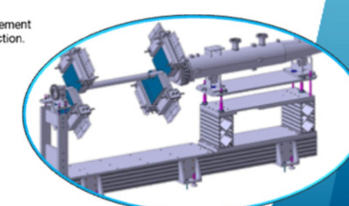
HiLumi
HL-LHC PROJECT

Technology landmarks



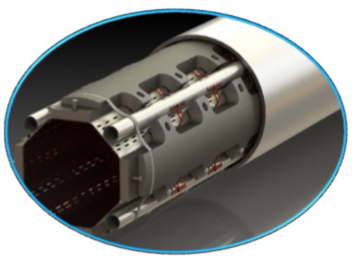


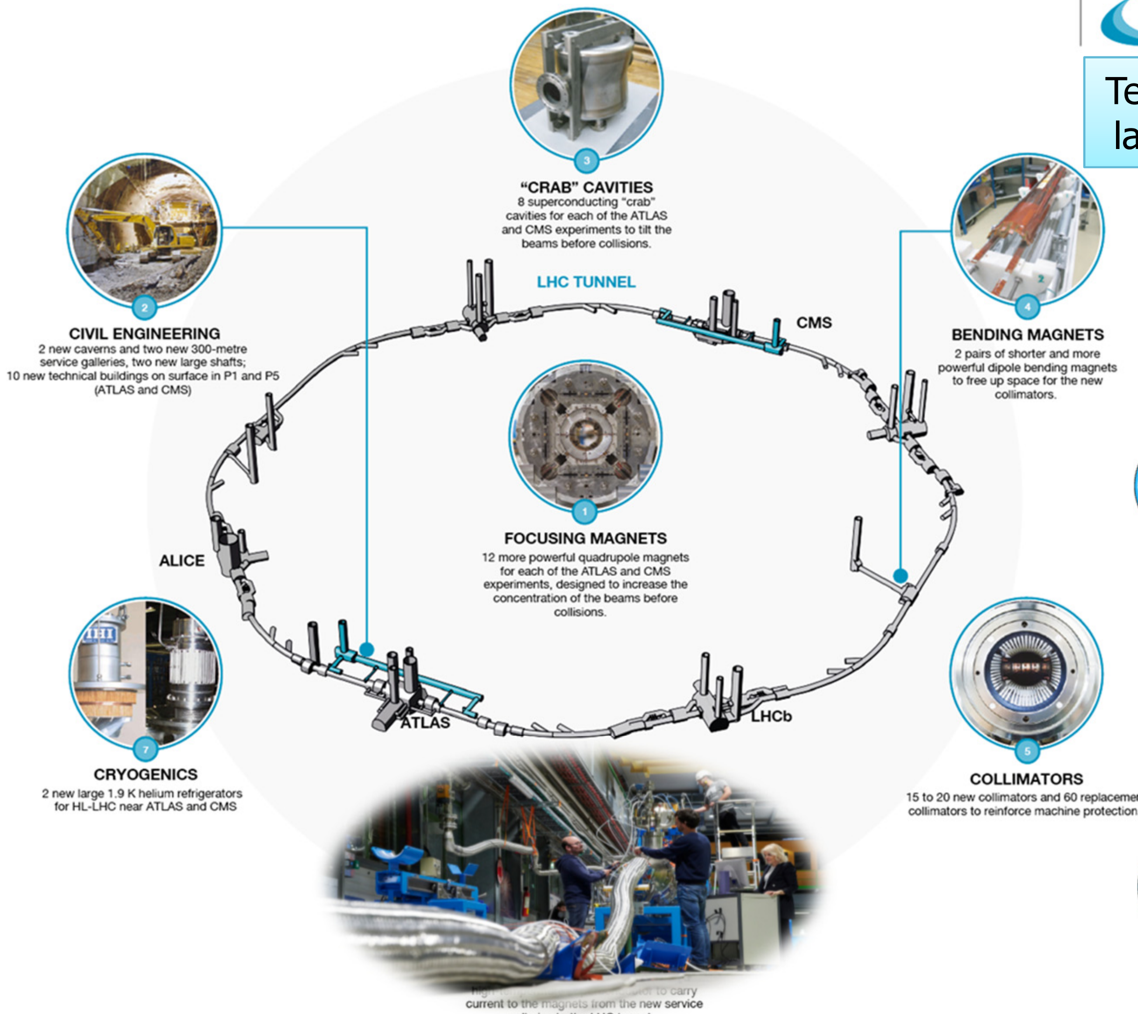


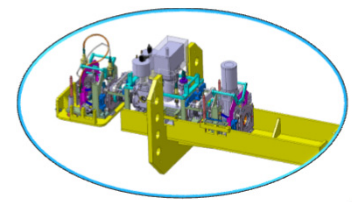


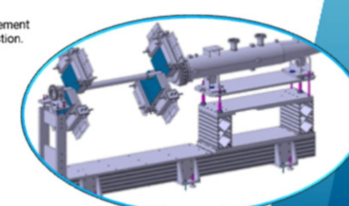
CERN May 2016

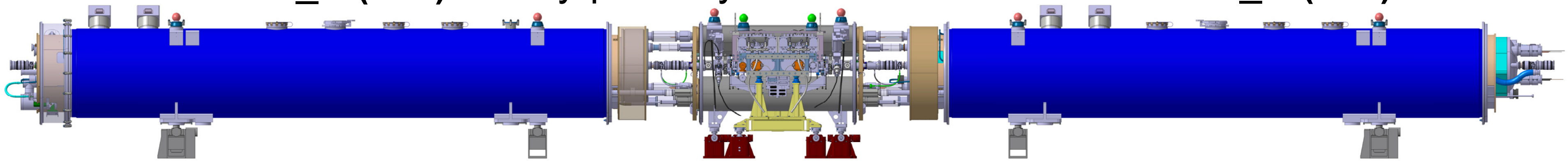
Technology landmarks



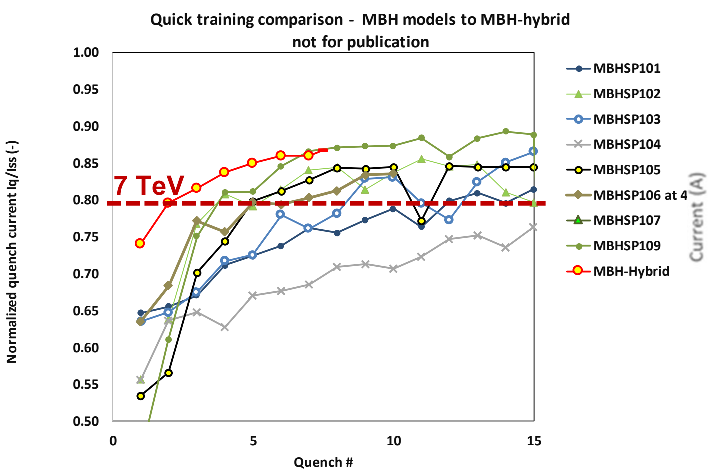


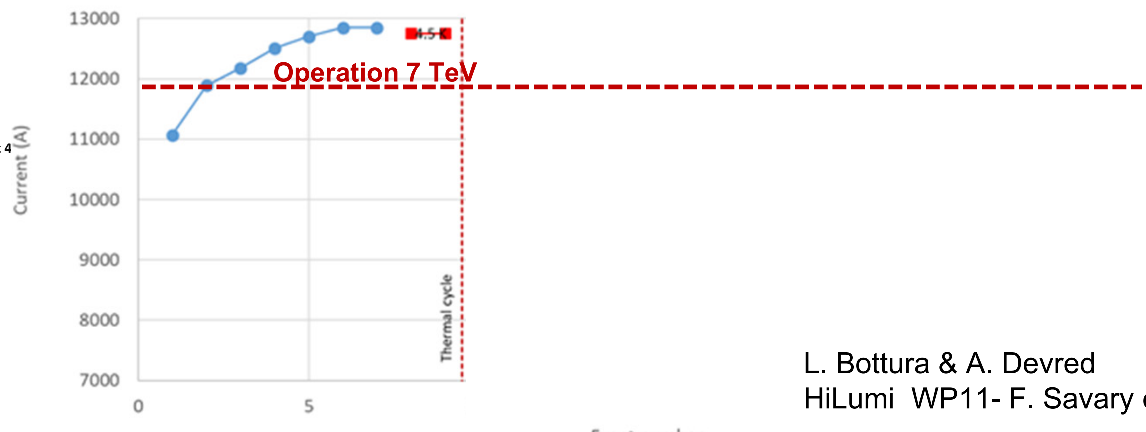






Complete **11.2 T cryo-assembly** replacing a 15 m 8.3 T LHC dipole in 2020

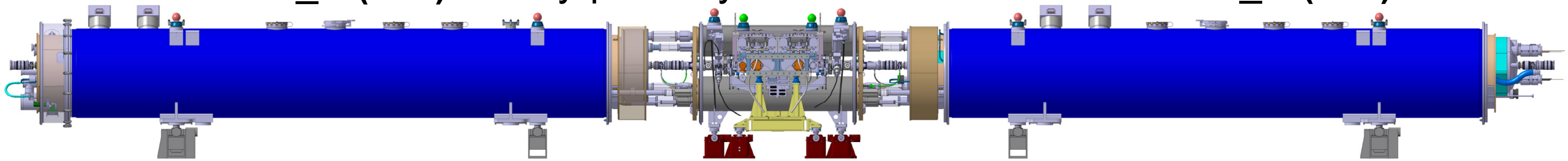




L. Bottura & A. Devred
HiLumi WP11- F. Savary et al.

Hybrid (long proto): Excellent! But strong permanent degradation **after thermal cycle.** Absence of thermal gradient control in the procedure.

LBH_**A (11T)** By-pass cryostat with collimator LBH_**B (11T)**



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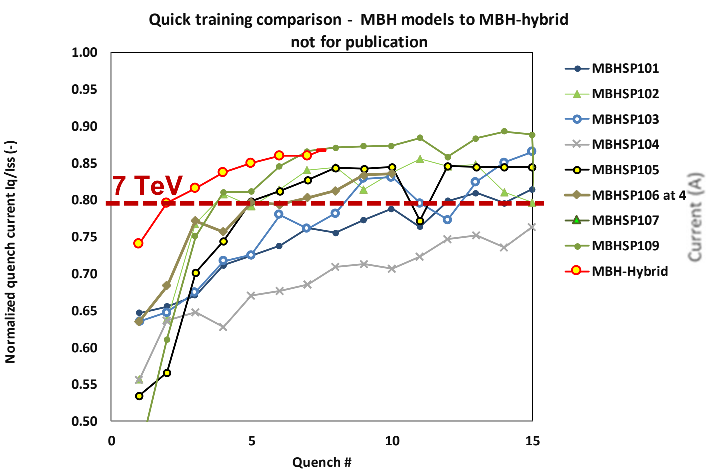

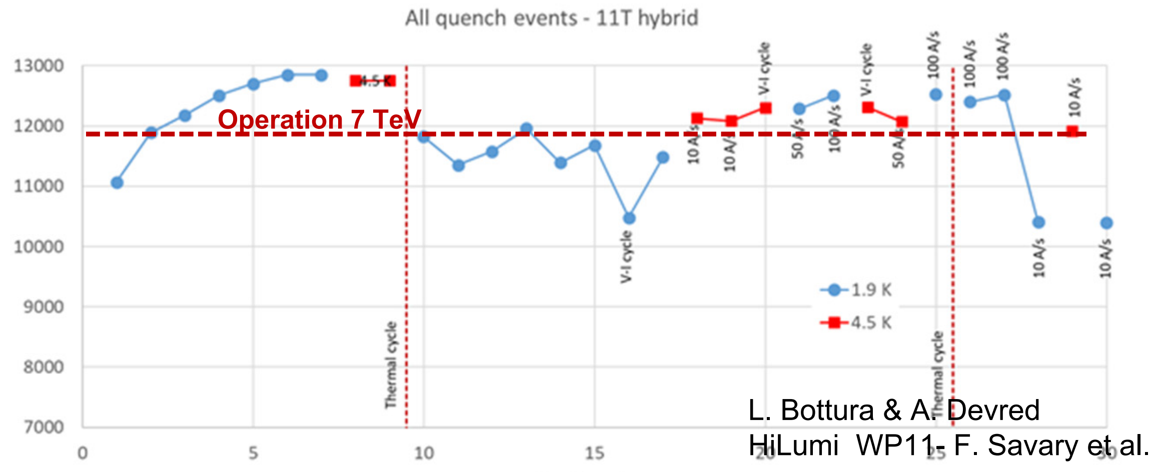

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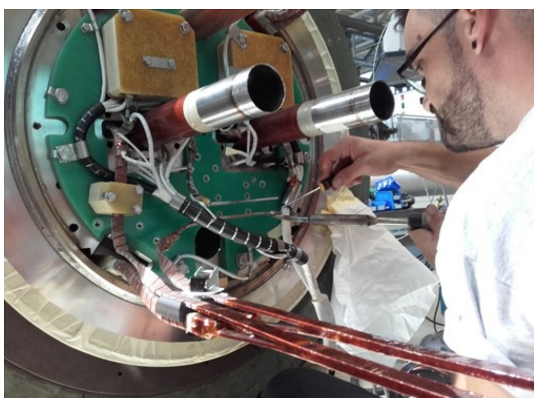
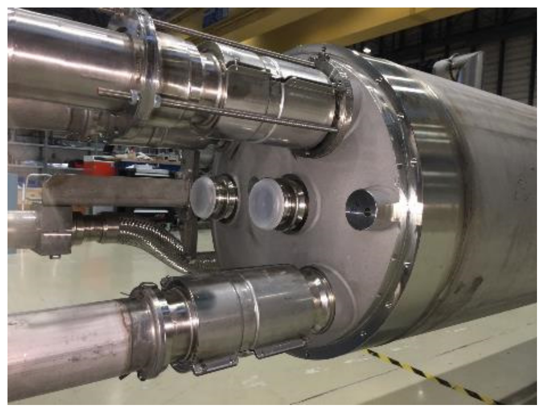
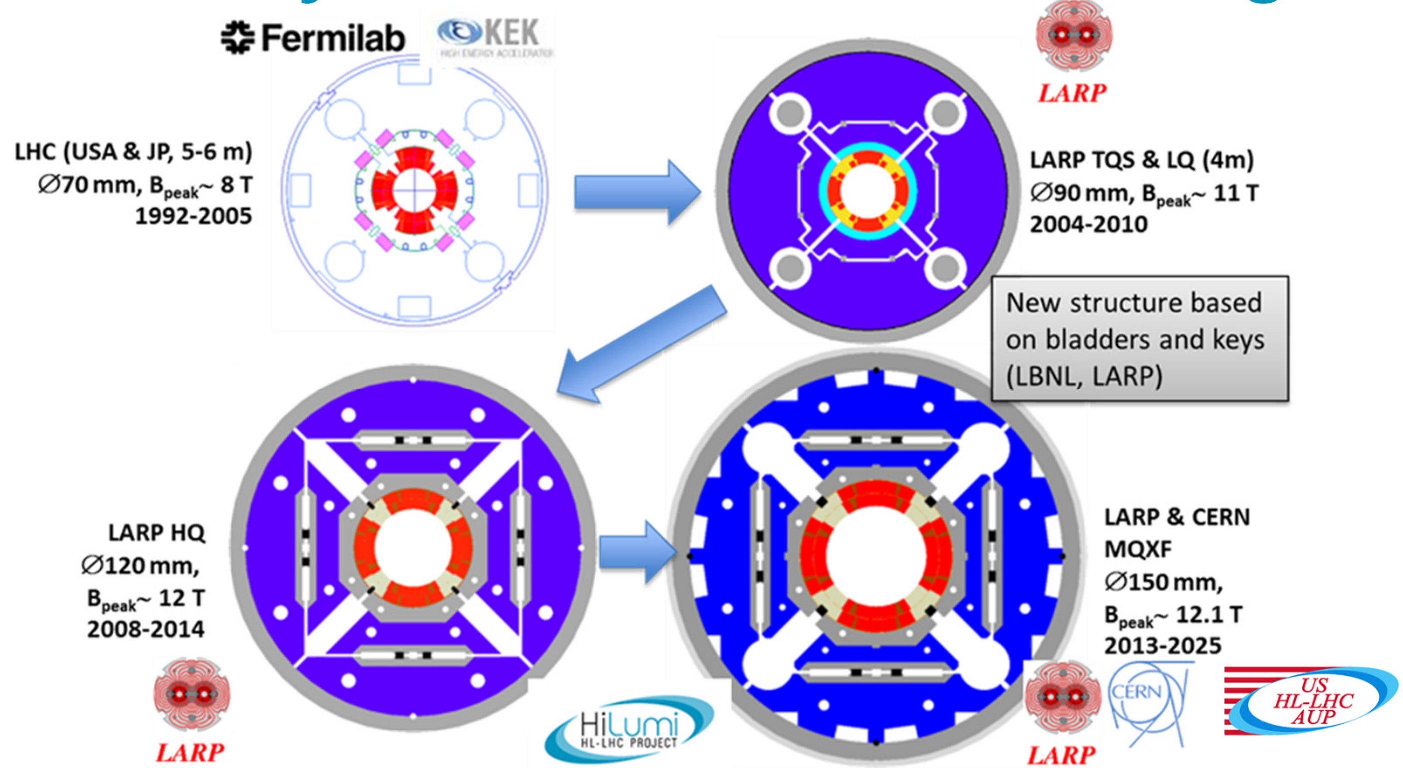
11 T in full swing production: LS2 installation in 2020! great care given the stress sensitivity of Nb_3Sn



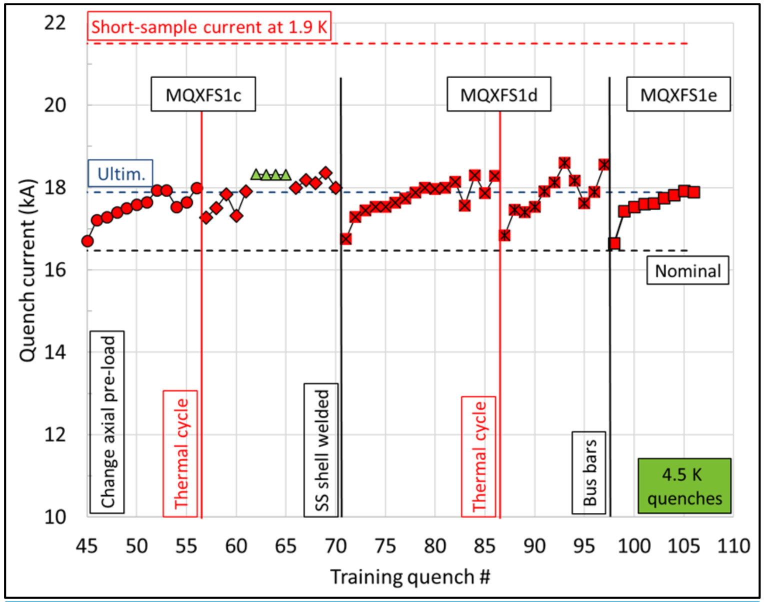


IT quadrupole. Increase in field but also in size wrt LHC. Very relevant also for FCC magnets

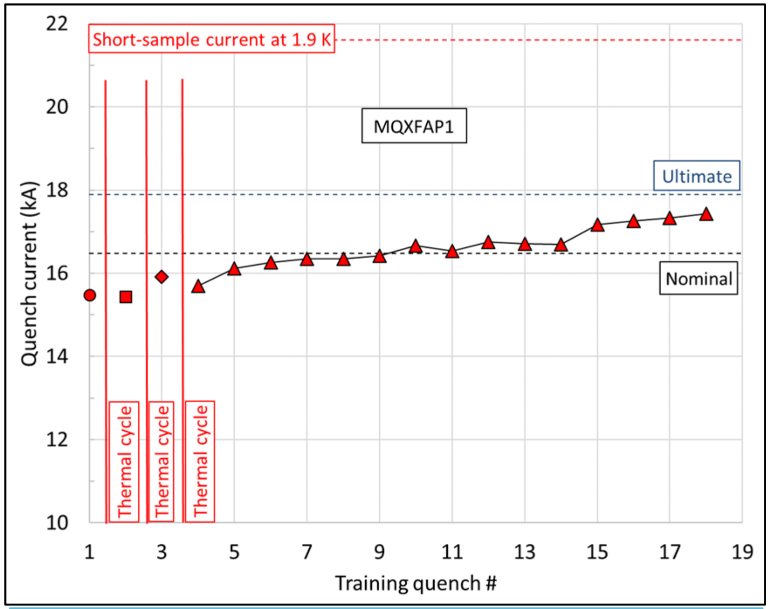


Test results IT QUAD

HiLumi WP3: G. Ambrosio (FNAL), P. Ferracin , E. Todesco (CERN) et al.



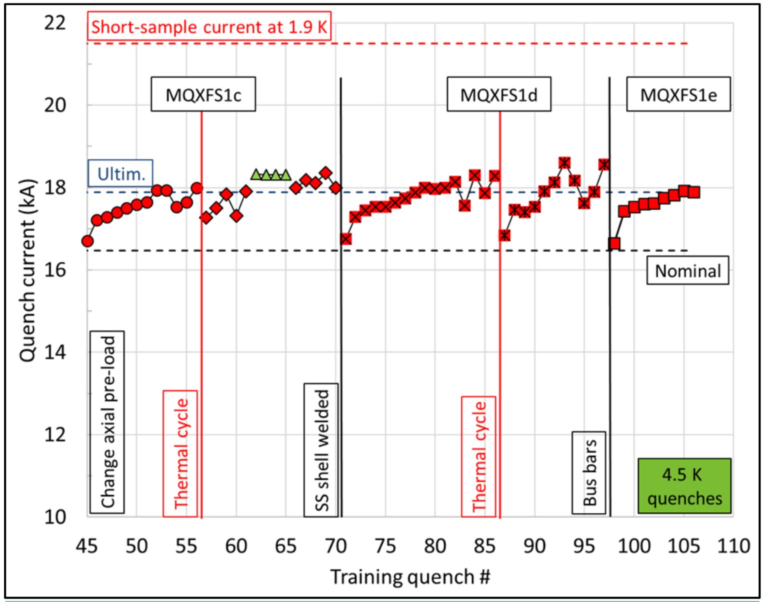
1st short (1 m long) model magnet: 2 coils CERN - 2 Coil US-LARP; test in Fermilab, excellent results and memory



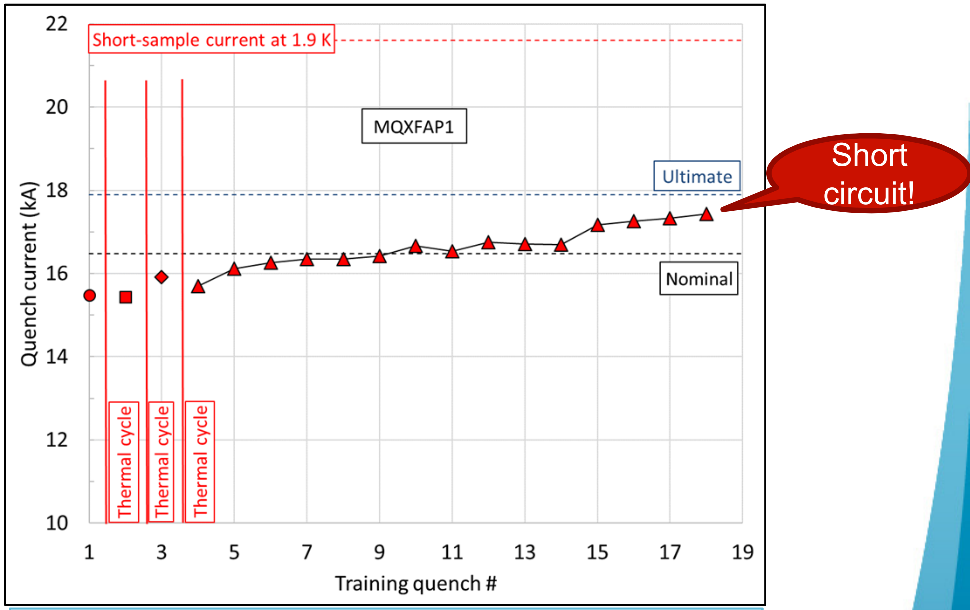
1st long (4 m long) prototype magnet by US-LARP-AUP; test in Fermilab, very good start but short circuit developed. Now repaired and under **re-test next week.**

Test results IT QUAD

HiLumi WP3: G. Ambrosio (FNAL), P. Ferracin , E. Todesco (CERN) et al.

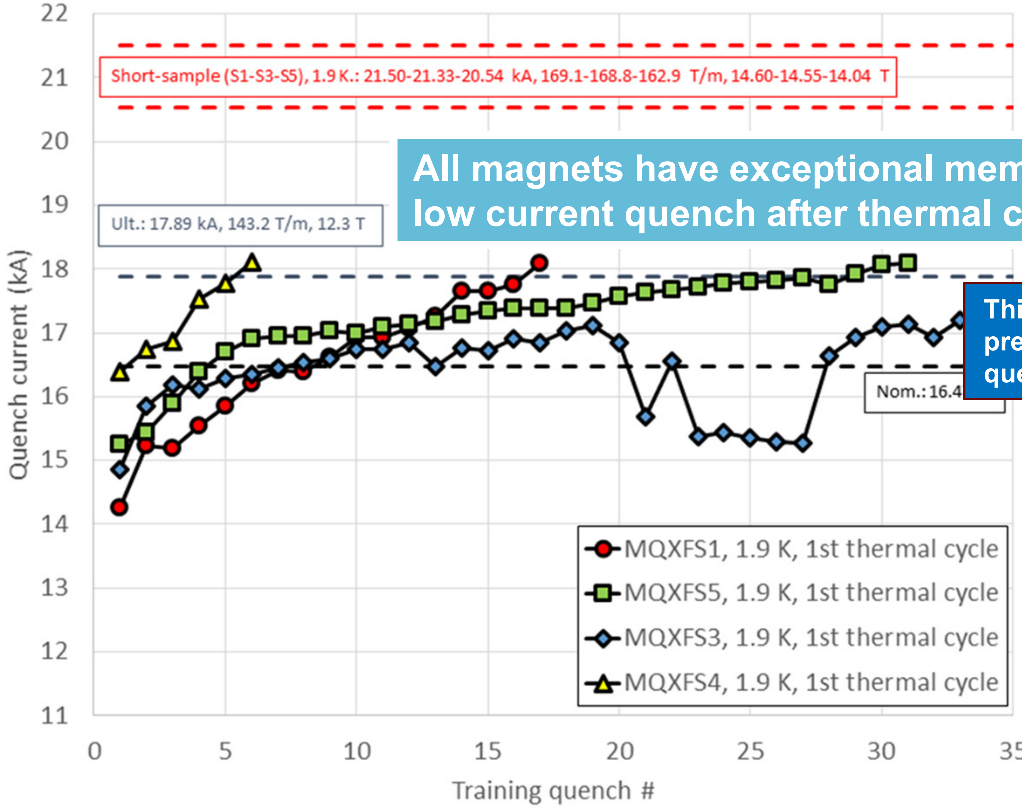


1st short (1 m long) model magnet: 2 coils CERN - 2 Coil US-LARP; test in Fermilab, excellent results and memory



1st long (4 m long) prototype magnet by US-LARP-AUP; test in Fermilab, very good start but short circuit developed. Now repaired and under **re-test next week.**

Further results IT quadrupoles on short models



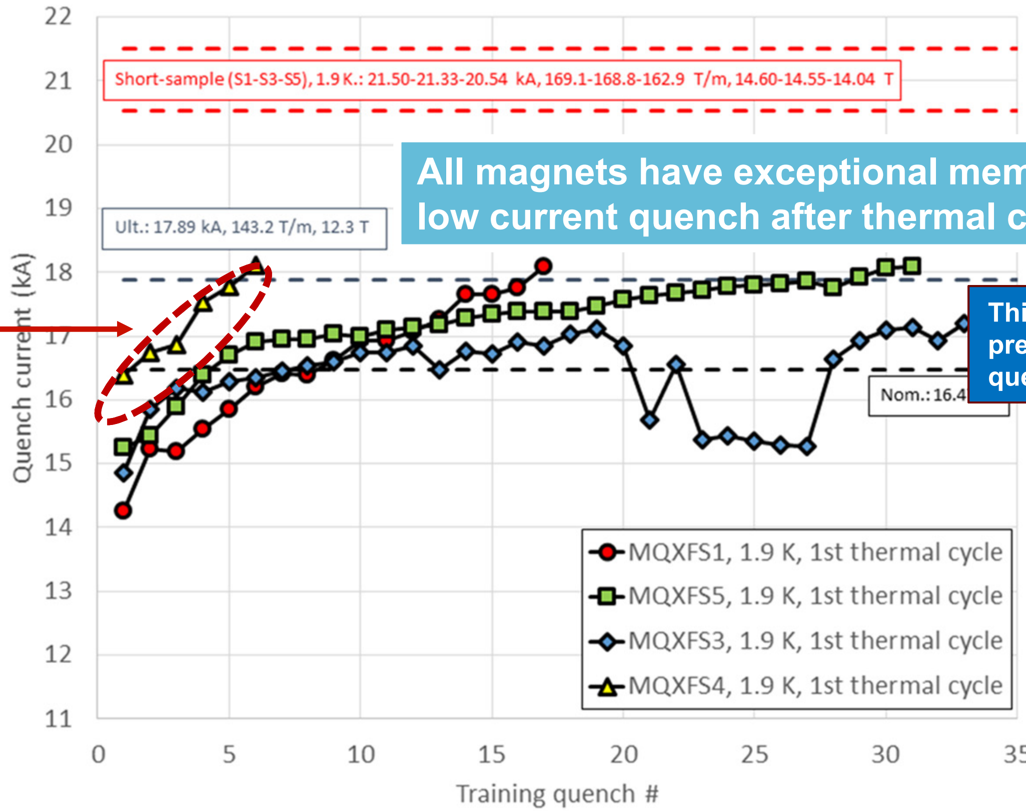
All magnets have exceptional memory (no low current quench after thermal cycle)

This magnet had a too high prestress The last higher quench have fast ramp rate

HiLumi WP3:
E. Todesco et al.

Further results IT quadrupoles on short models

Best HF magnet ever tested in terms of behaviour (not max field) Final conductor, final prestress procedure



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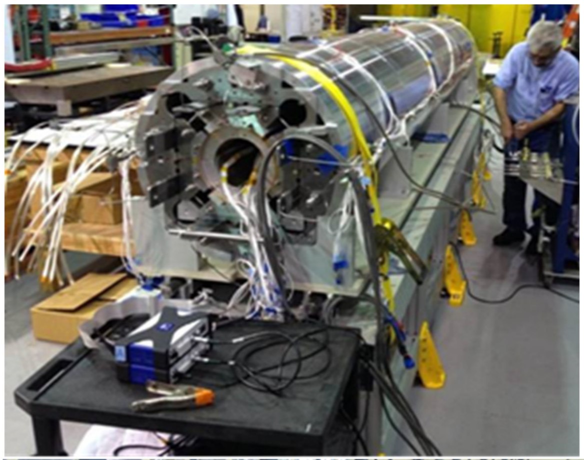
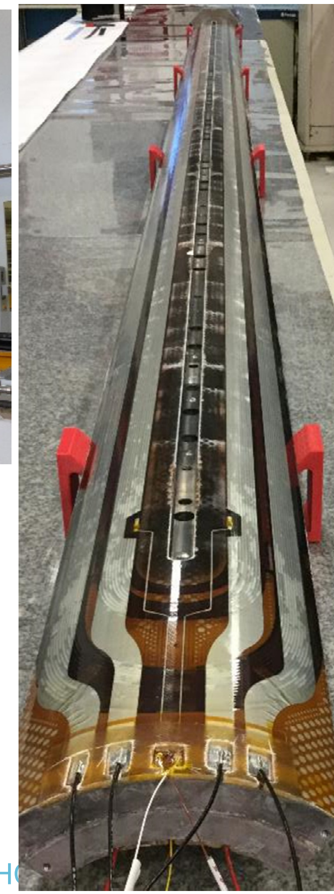
HiLumi WP3:
E. Todesco et al.

Nb3Sn High Field Collider Magnets

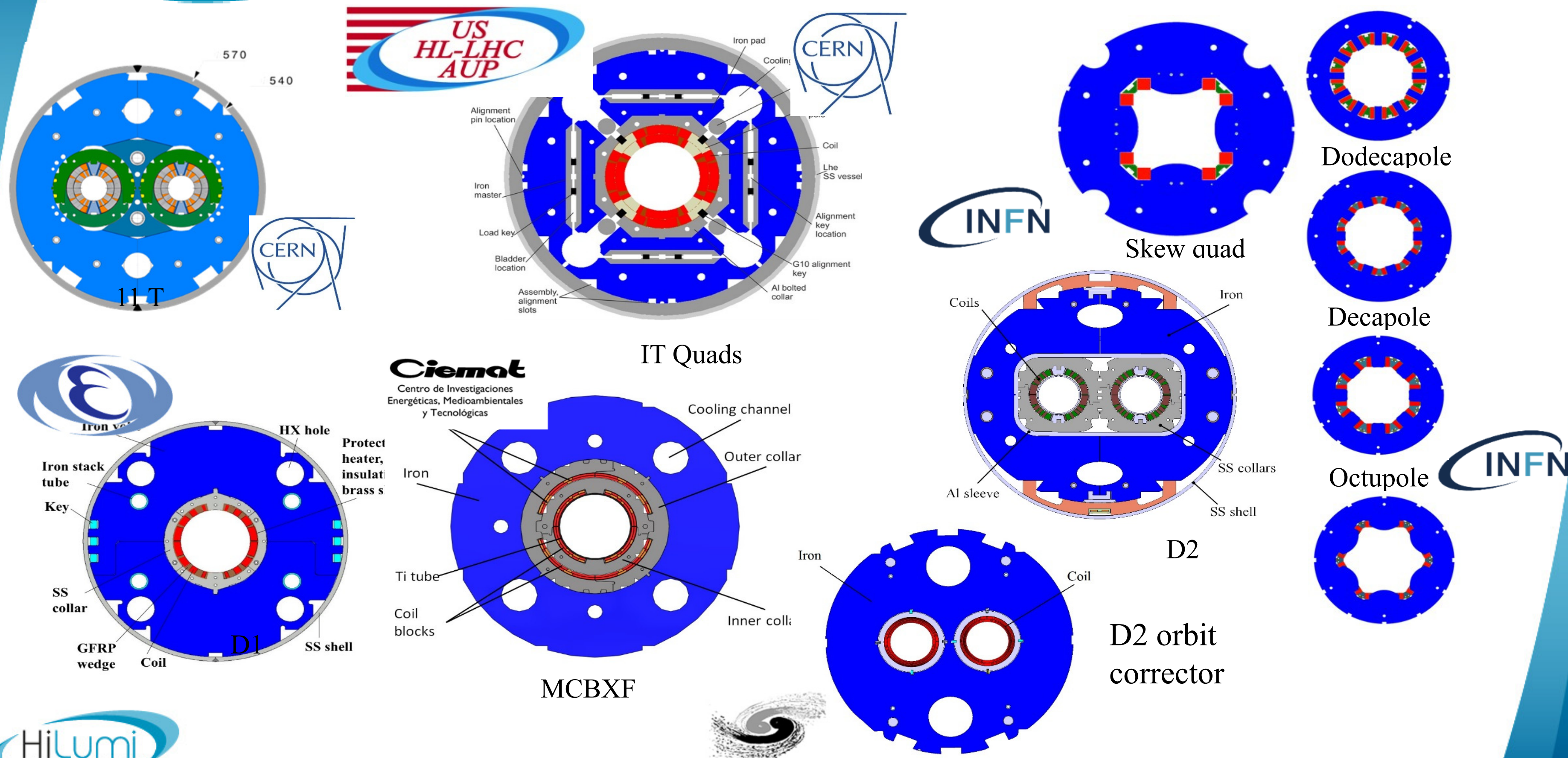
- HiLumi needs by 2024 about 40 Nb_3Sn large magnets:
  - **4+2** 11 T dipoles L=5.5m
  - **8+2** (7.2 m long) and **16+4** (4.2m long) IT quadrupole of 11.5 T
- We have learnt how to deal wiht this difficult technology (700 °C heat treatment, vac.impregnation, performance sensible to stress)
- However we found recently electrical and structural problems **on the first two long prototypes (partly seen also on 11 T).**
  - Structural problems on IT Quads understood and solved: traced to too small margin (in shells) that could led to failure for fatigue effect.
  - Electrical problem (QH insulation): 2 solutions identified, one under test on the 11 T dipole.
- Industrialization of long magnets is being more difficult than anticipated! Difference from LHC NbTi.

Construction of the 1st and 2nd long (7.5 m!) IT Quad in CERN; in USA winding 4th long magnet

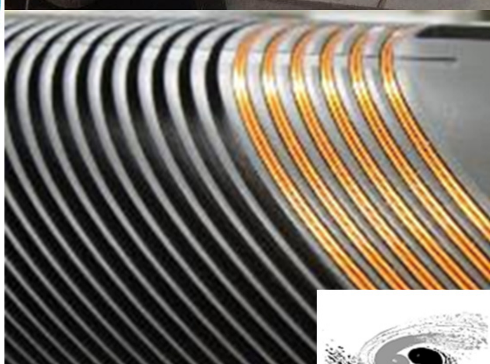


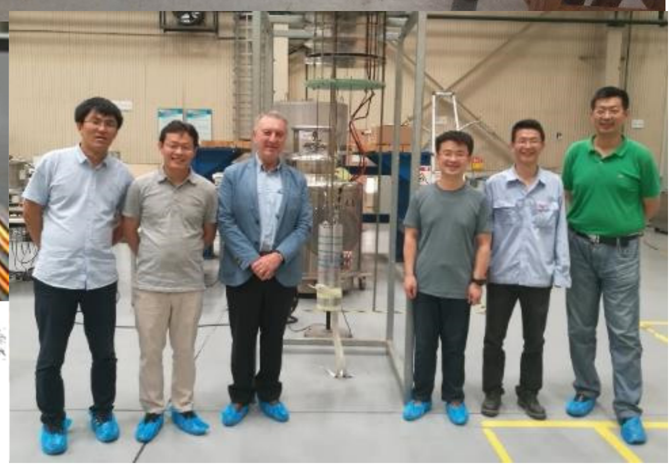


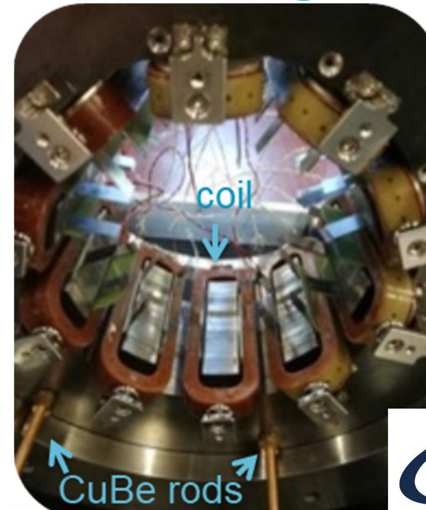
The HiLumi Magnets (~130)



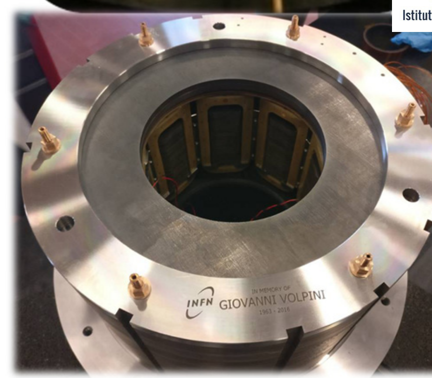
Nb-Ti new technologies: CCT and SF magnets







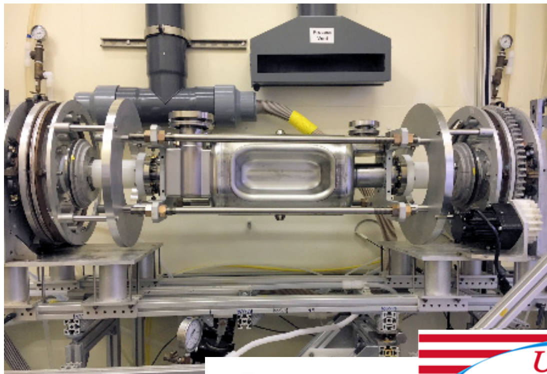
INFN
Istituto Nazionale di Fisica Nucleare



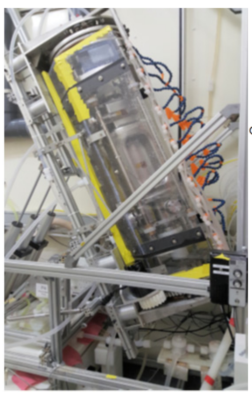
IHEP

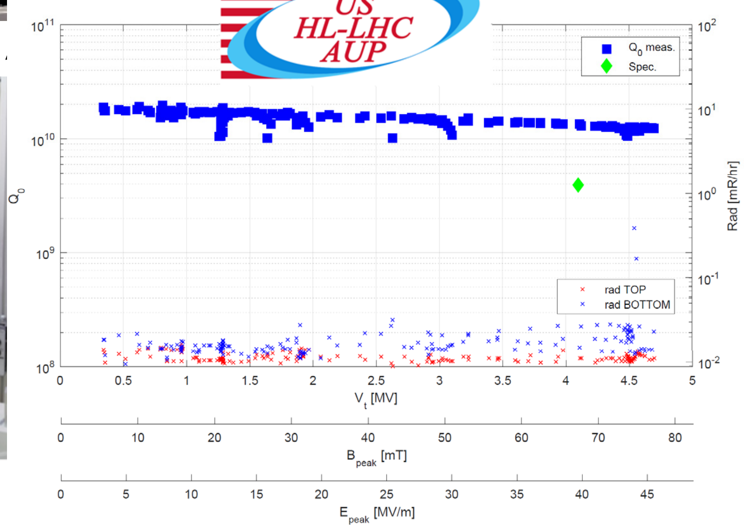
HiLumi
HL-LHC PROJECT

Crab Cavity

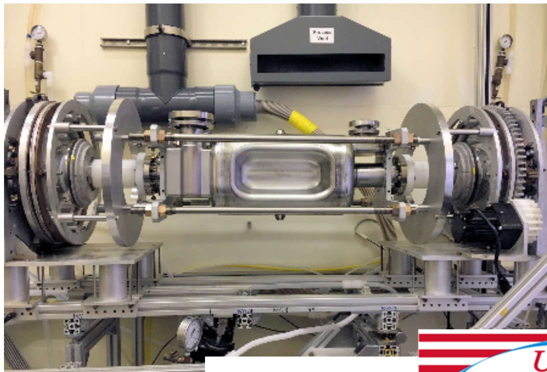


Rotational chemistry at





Crab Cavity



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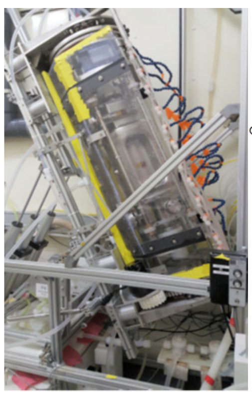
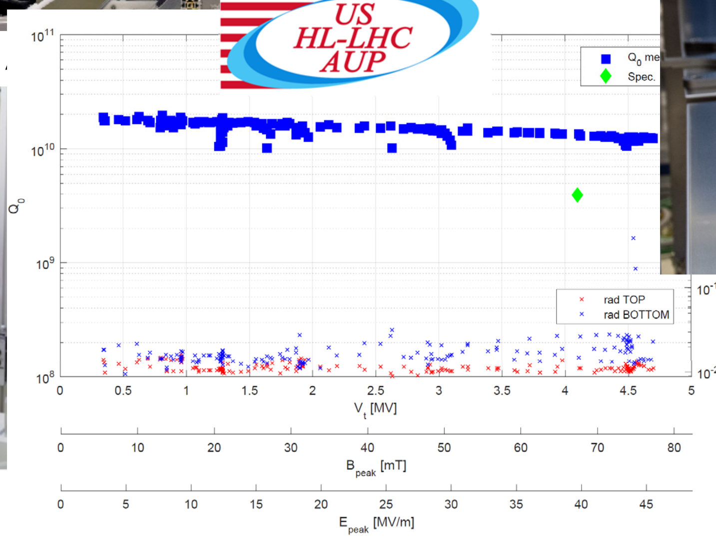
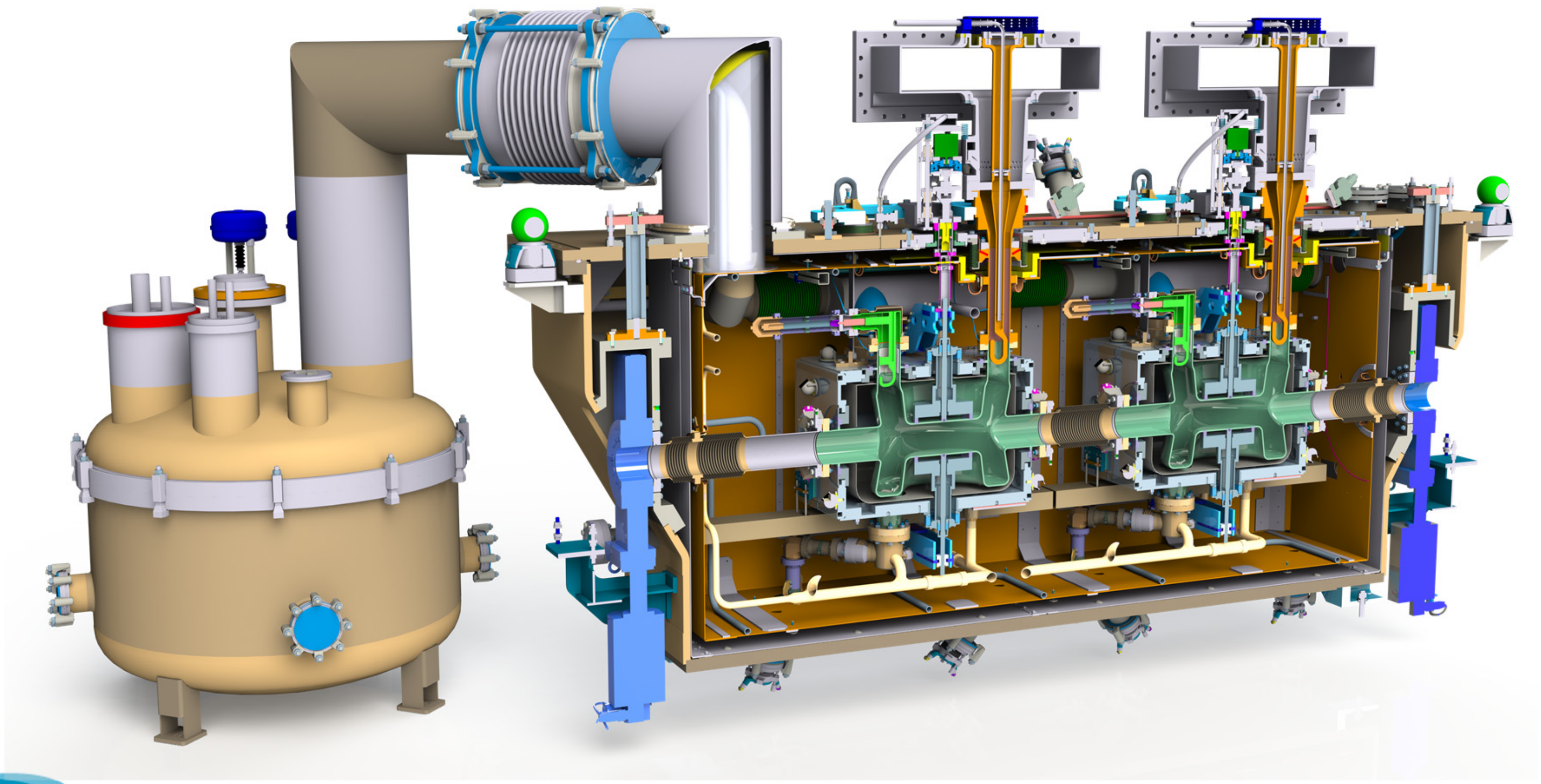


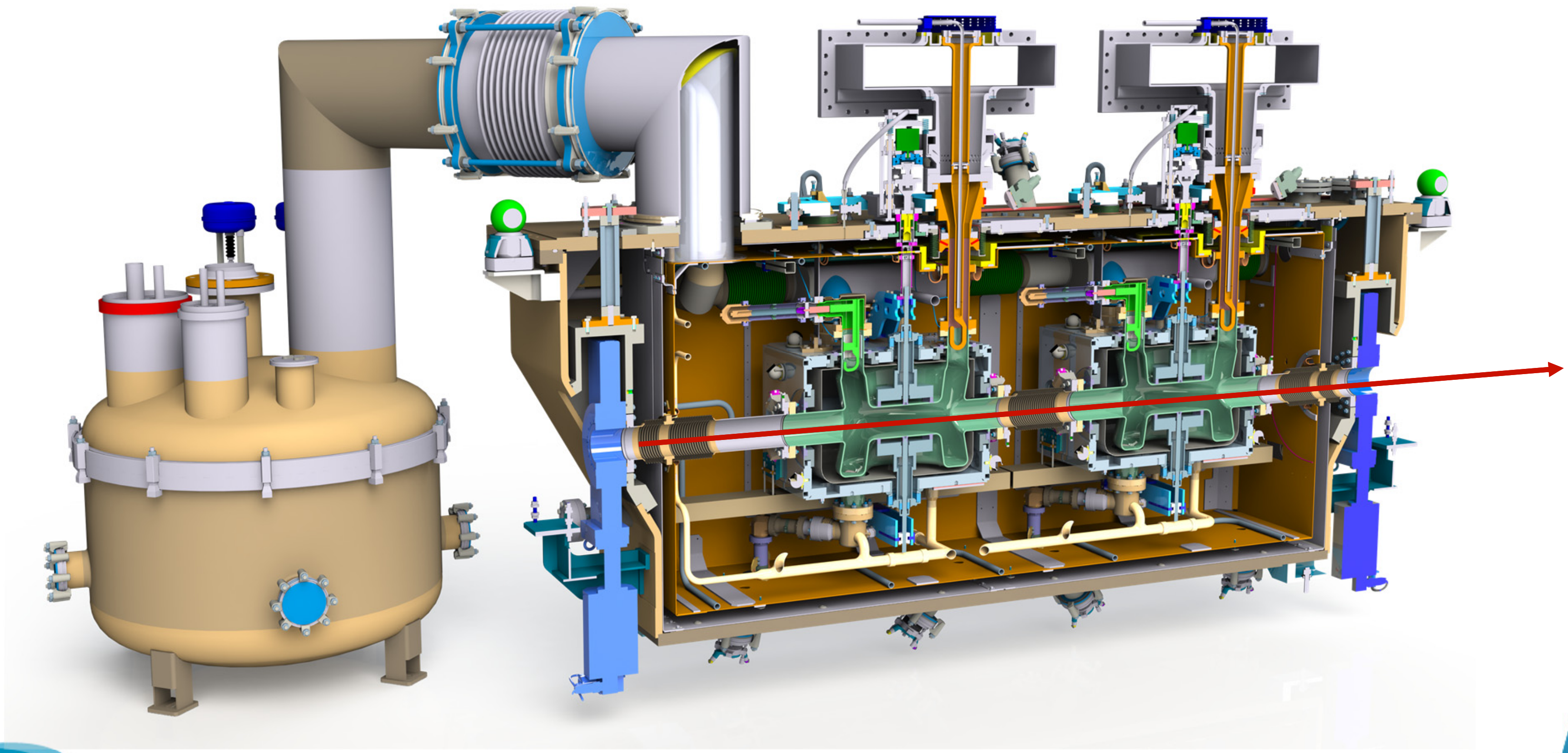


CERN DQW prototype for SPS test
Collaboration with UNILANC & STFC - C.I. Daresbury (UK)

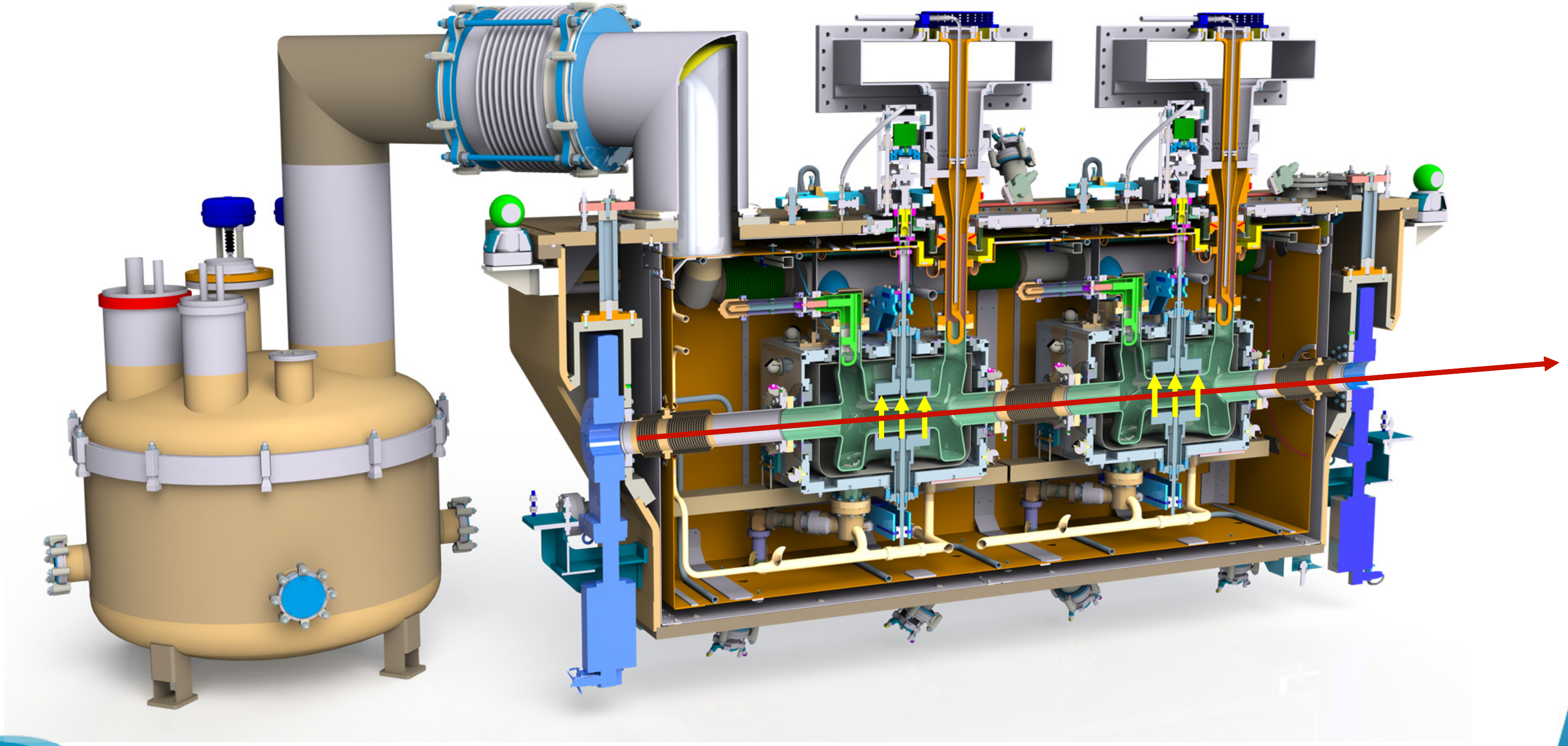
The DQW CC in cryomodule for the SPS test



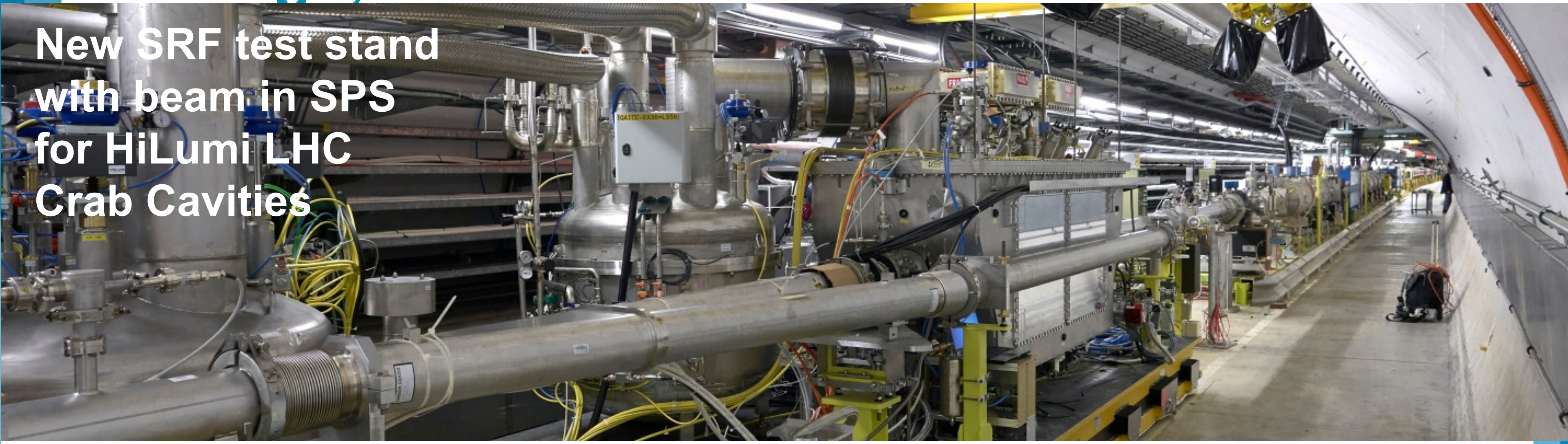
The DQW CC in cryomodule for the SPS test

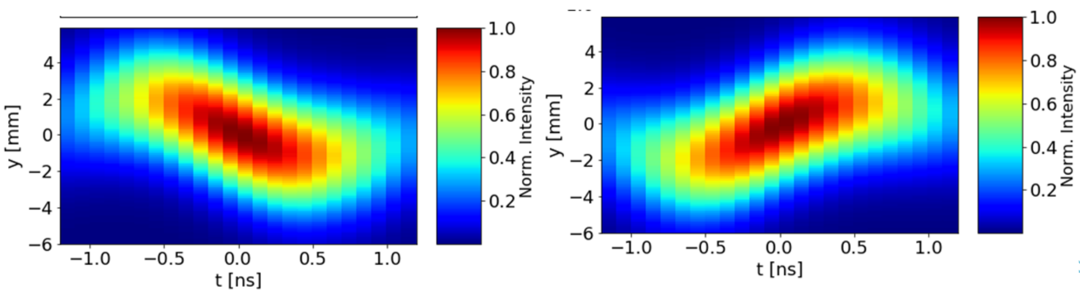


The DQW CC in cryomodule for the SPS test



Crab Cavities: progress in design, construction and test infrastructure



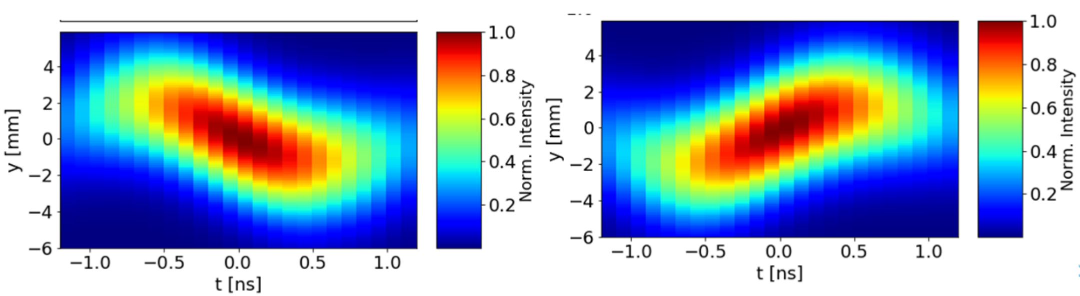


RF phase scan w.r.t the beam phase with cavity 1: principle validated! Transparency of CC to beam demonstrated! MDs very successful (with voltage limitation).

Crab Cavities: progress in design, construction and test infrastructure

New SRF test stand with beam in SPS for HiLumi LHC Crab Cavities

Industrial contracts : launched both from CERN and US-HL-AUP



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New SRF test stand with beam in SPS for HiLumi LHC Crab Cavities

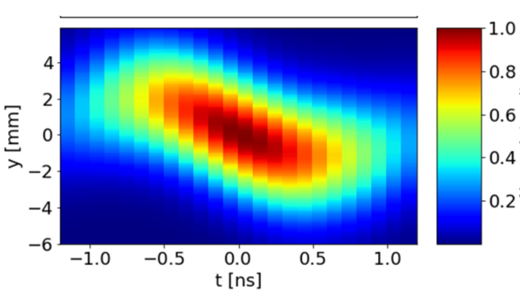
Industrial contracts : launched both from CERN and US-HL-AUP

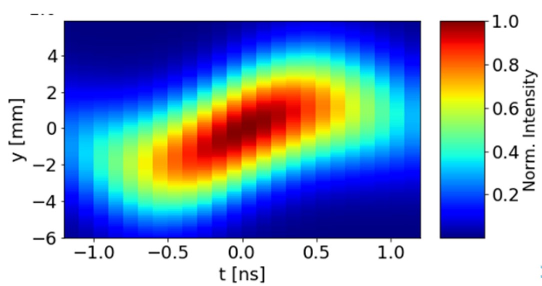
New CC collaborations

ИЯФ СО РАН

Science & Technology Facilities Council

TRIUMF





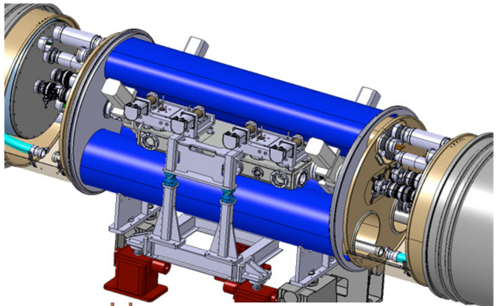
Transparency of CC to beam demonstrated! MDs very successful (with voltage limitation).

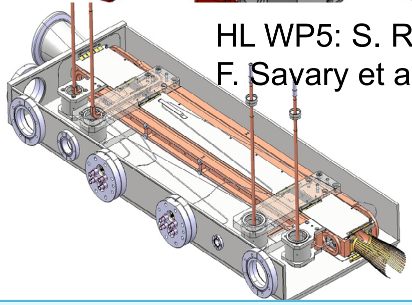
Collimators low-Z : special MoGR Mo-coated upgrade partly in 2020 and then in 2025

Samples of MoGr (Molybdenum-Graphite) from producer (CERN EN/MME/STI)

HL WP5: S. Redaelli, R. Bruce, S. Gilardoni, M. Calviani, A. Bertrelli, R. Carra et al.

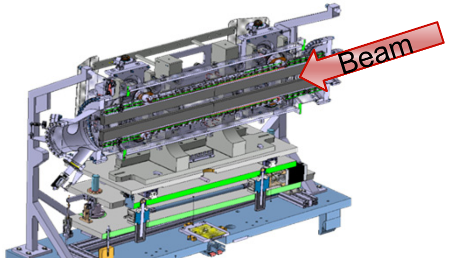
Cold-Warm-Cold bypass to host Collimators in the DS region



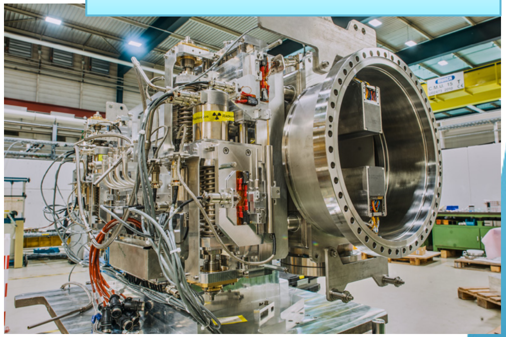


HL WP5: S. Redaelli, F. Savary et al.

New injection protection absorber



HL WP14: C. Bracco et al.

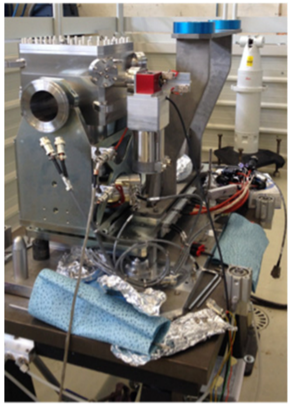


In total some 40 new absorber and collimators devices in LS2 (2020) and LS3 (2025)

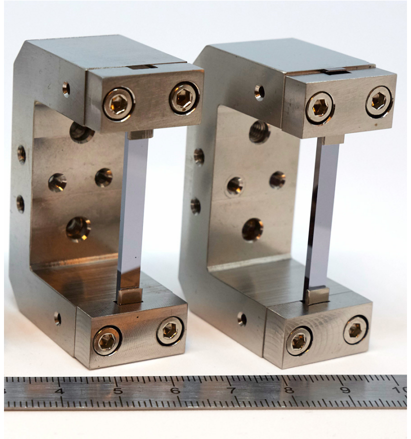
Test on crystal collimation (for baseline)

Scope: further improvement of ion cleaning after 2016 re-baselining.
***Studying if, for ions**, this can be an "adiabatic" upgrade of the IR7 system.*
*2017: **improved by up to x60 collimation cleaning** of Xe beams!*

Courtesy EN/SMM

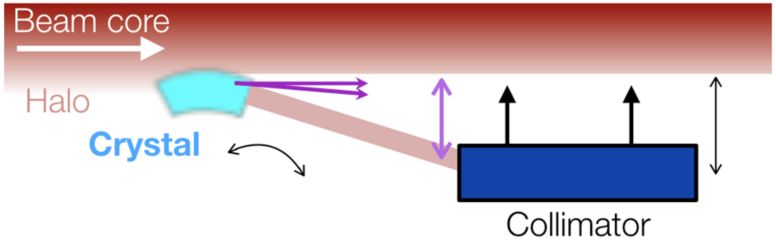


Courtesy UA9 collaboration/PNPI



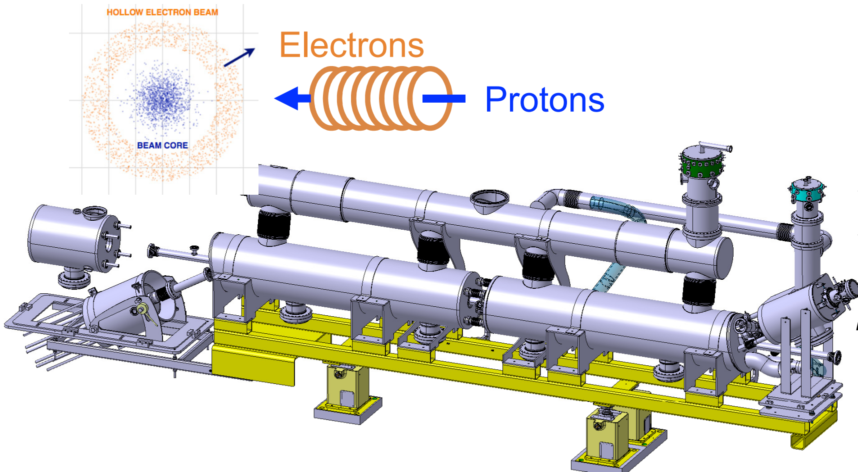
4 mm = 50 µrad,
or 10 x 15m long LHC dipoles
or 300 T at 7 TeV

Two goniometers installed on B1 in LS2; two more on B2 in 2017, upgraded in 2018.
4 operational crystals for collimation.



HL WP5: S. Redaelli, S. Gilardoni, M. Calviani al.

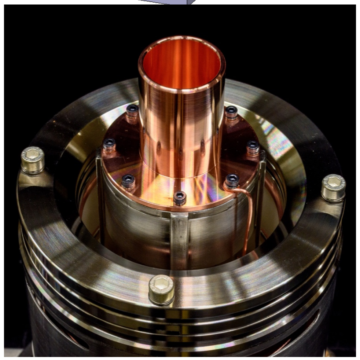
E-lens in HL-LHC for halo control - 30 MJ in the halo



It would allow controlling *actively* *the halo, through a hollow electron beam (overlapped over three meters to the proton/ion beams) that selectively excites halo particles.*

HL WP5: S. Redaelli, D. Perini, A. Rossi et al.

Cathode

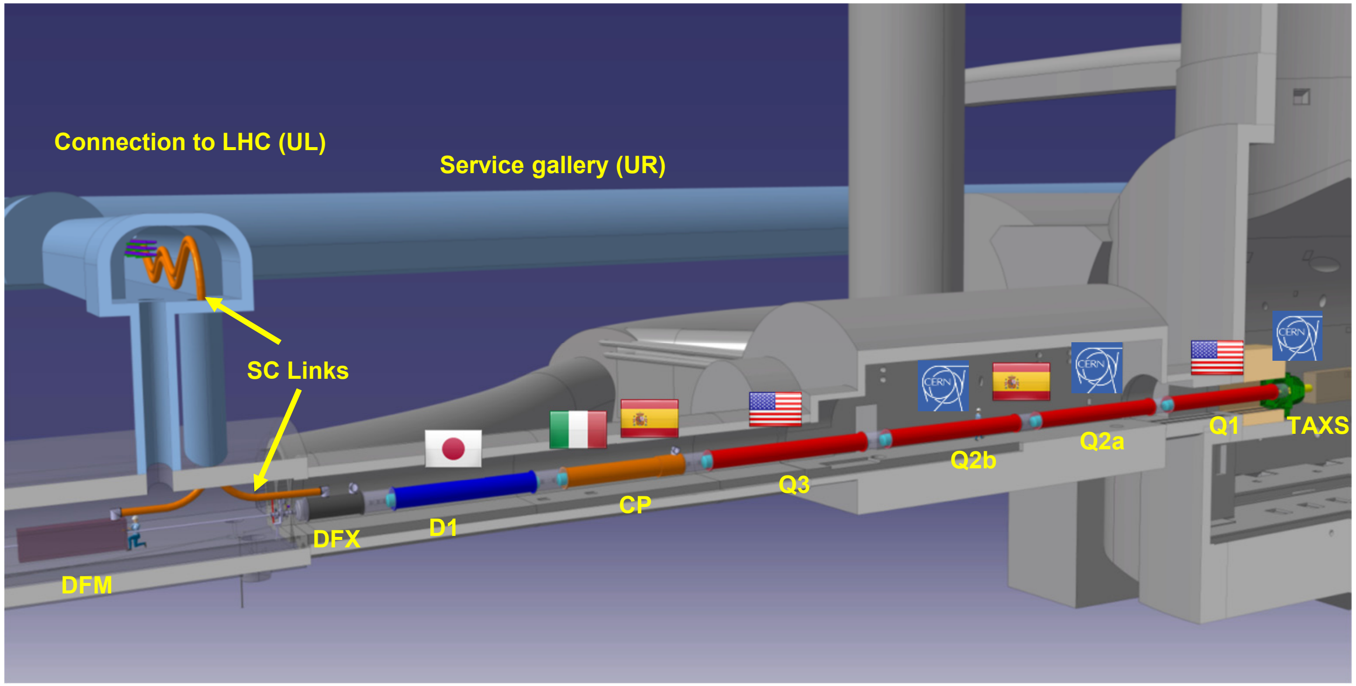


Electron gun

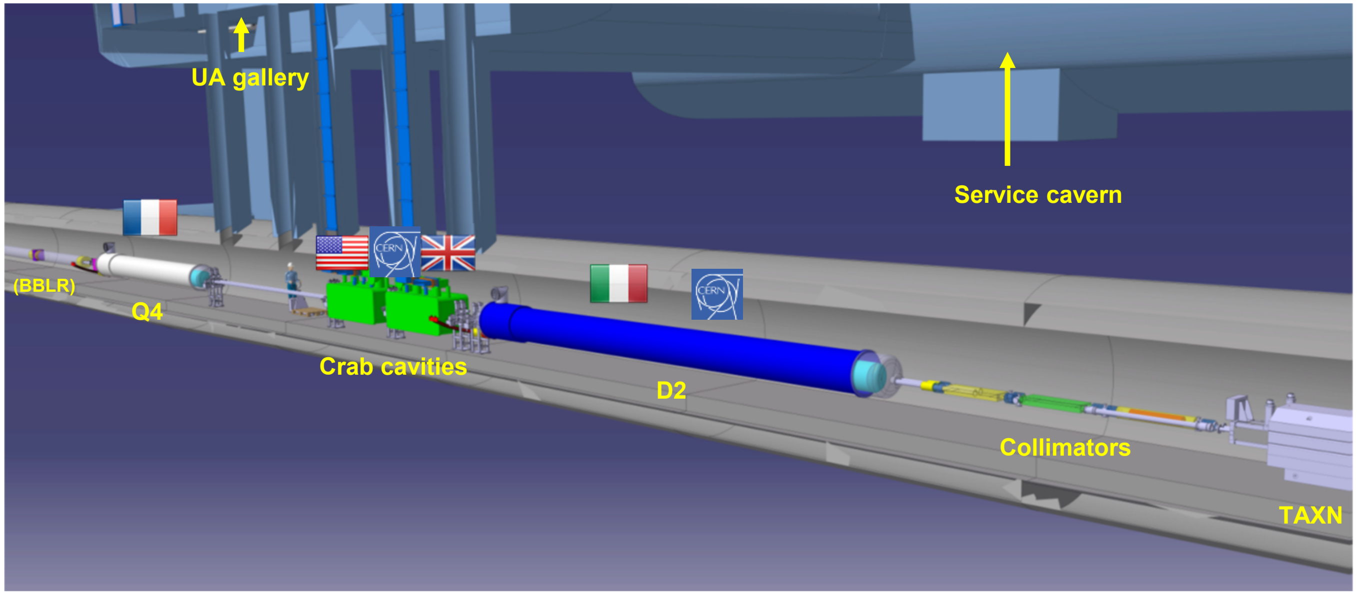
Design nearly complete.
Surpassed target e-beam current of 5A, now final cathode design (smaller) under test at FNAL.

Ready to built it, heading to integrated into the baseline.

High Luminosity LHC IT region



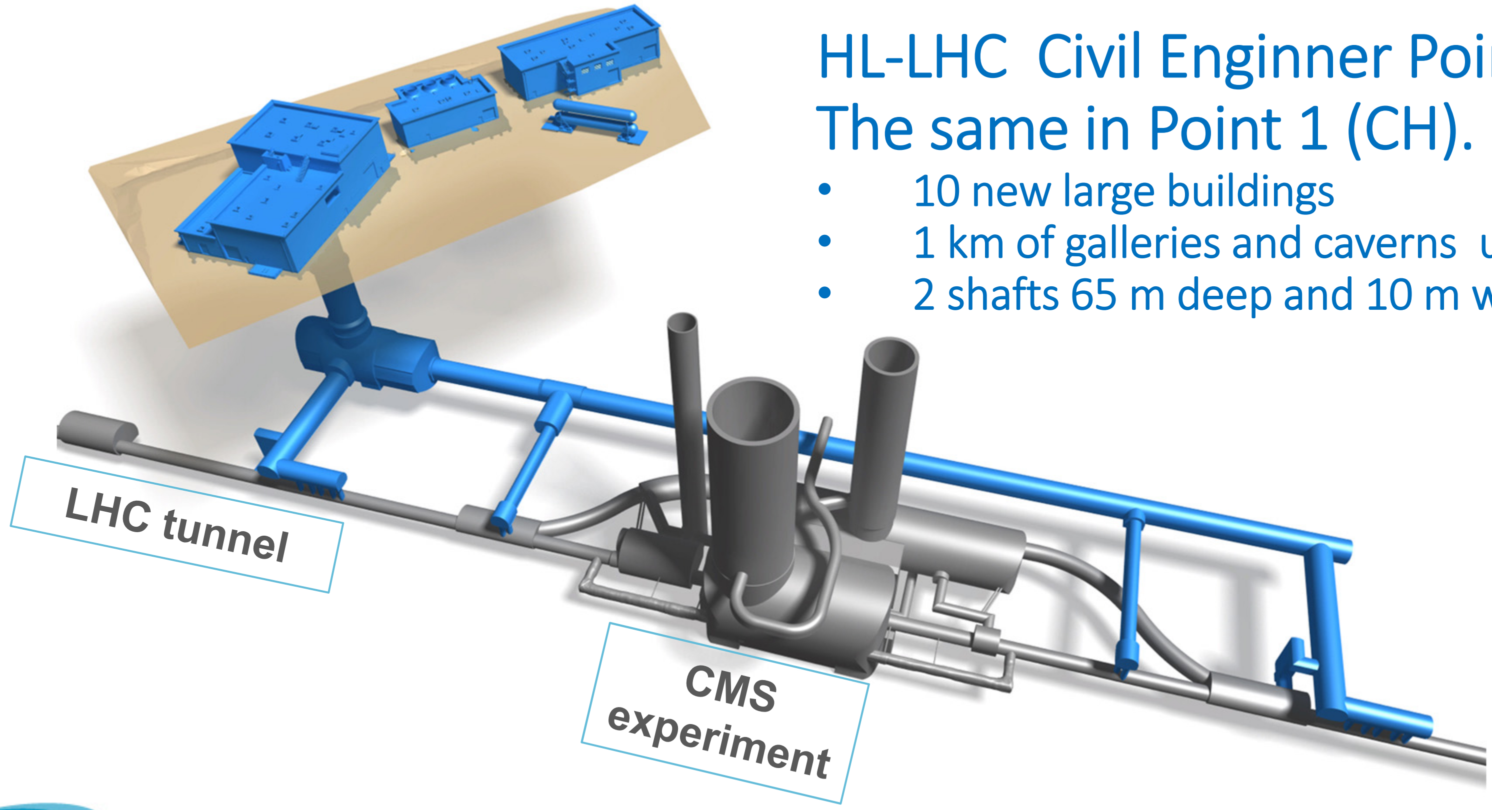
High Luminosity LHC – Matching section



Important upgrade of Technical infrastructure

HL-LHC Civil Enginner Point 5 (FR)
The same in Point 1 (CH). In total:

- 10 new large buildings
- 1 km of galleries and caverns underground
- 2 shafts 65 m deep and 10 m wide




Hilumi Civil Engineer: 2 large shafts; 1 km of new underground; 20 new buildings;

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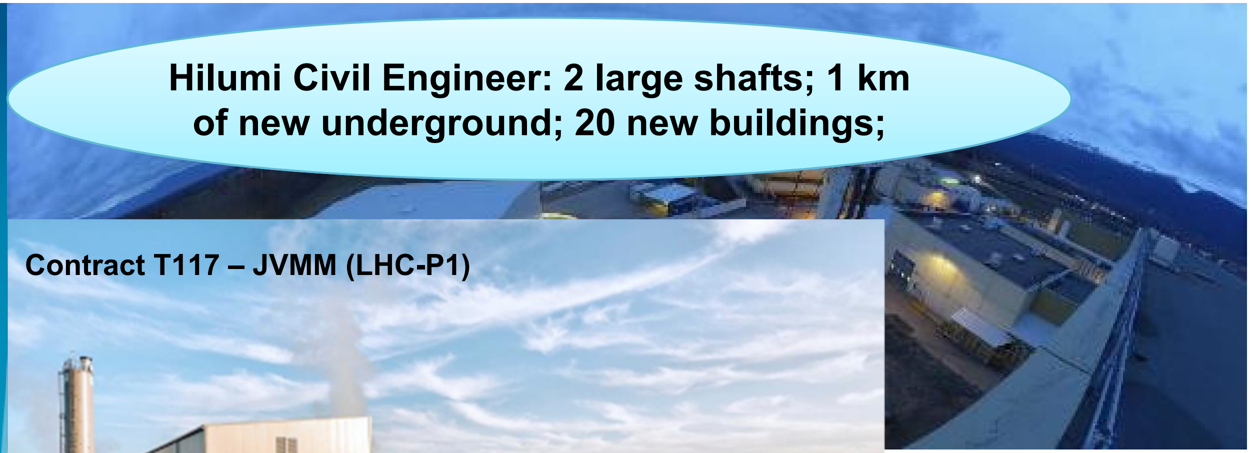

Contract T117 – JVMM (LHC-P1)

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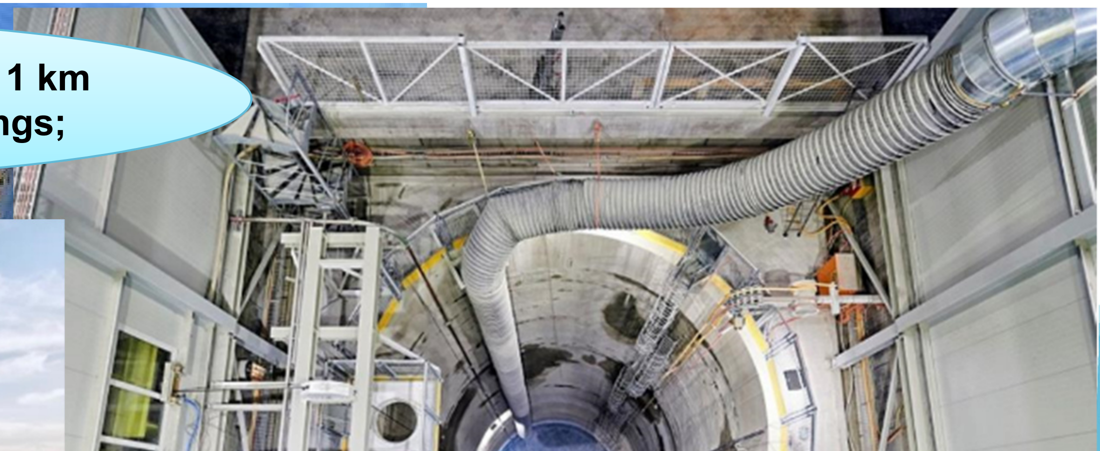
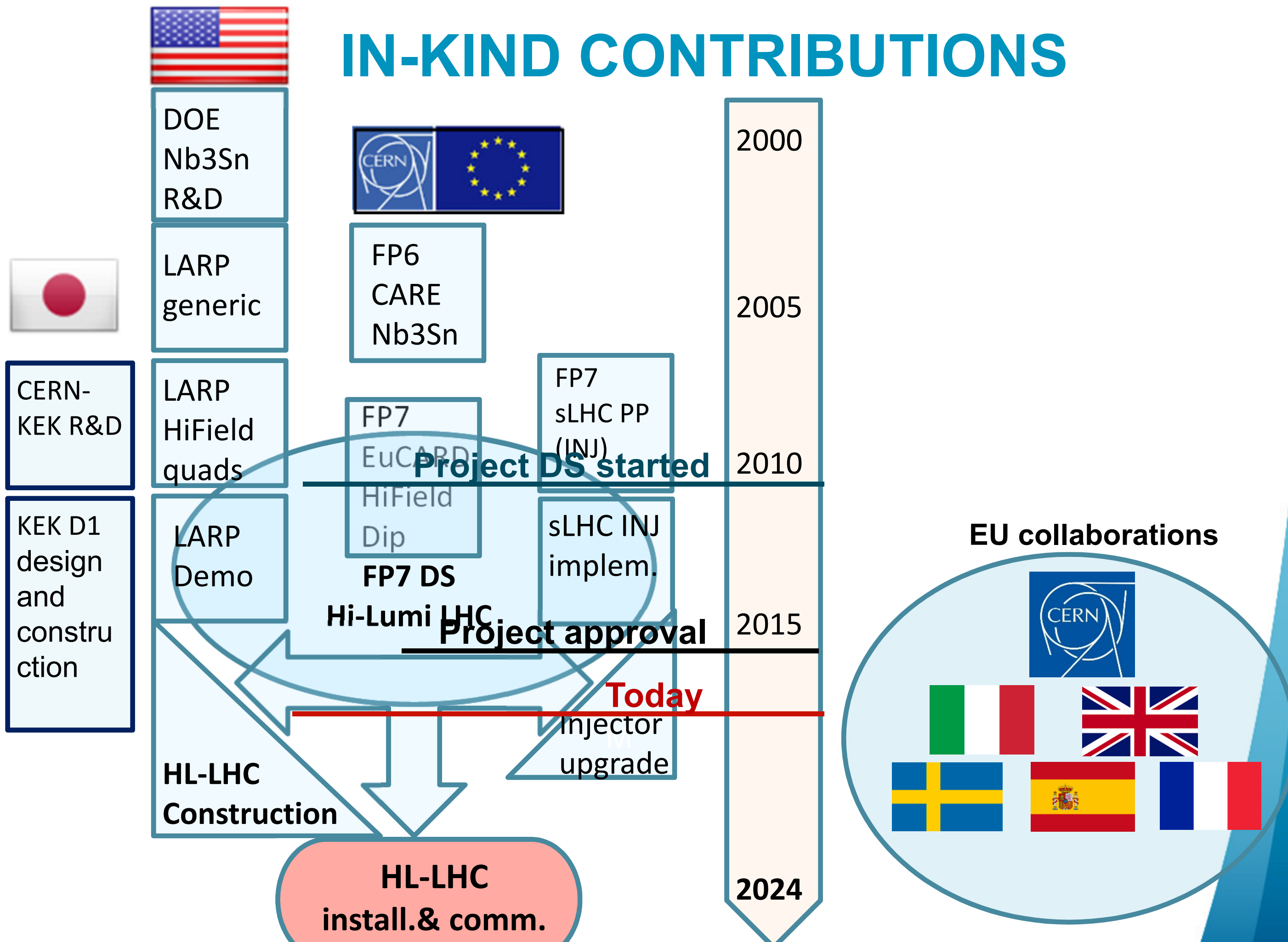


Contract T118 – CIB (LHC-P5)

IN-KIND CONTRIBUTIONS



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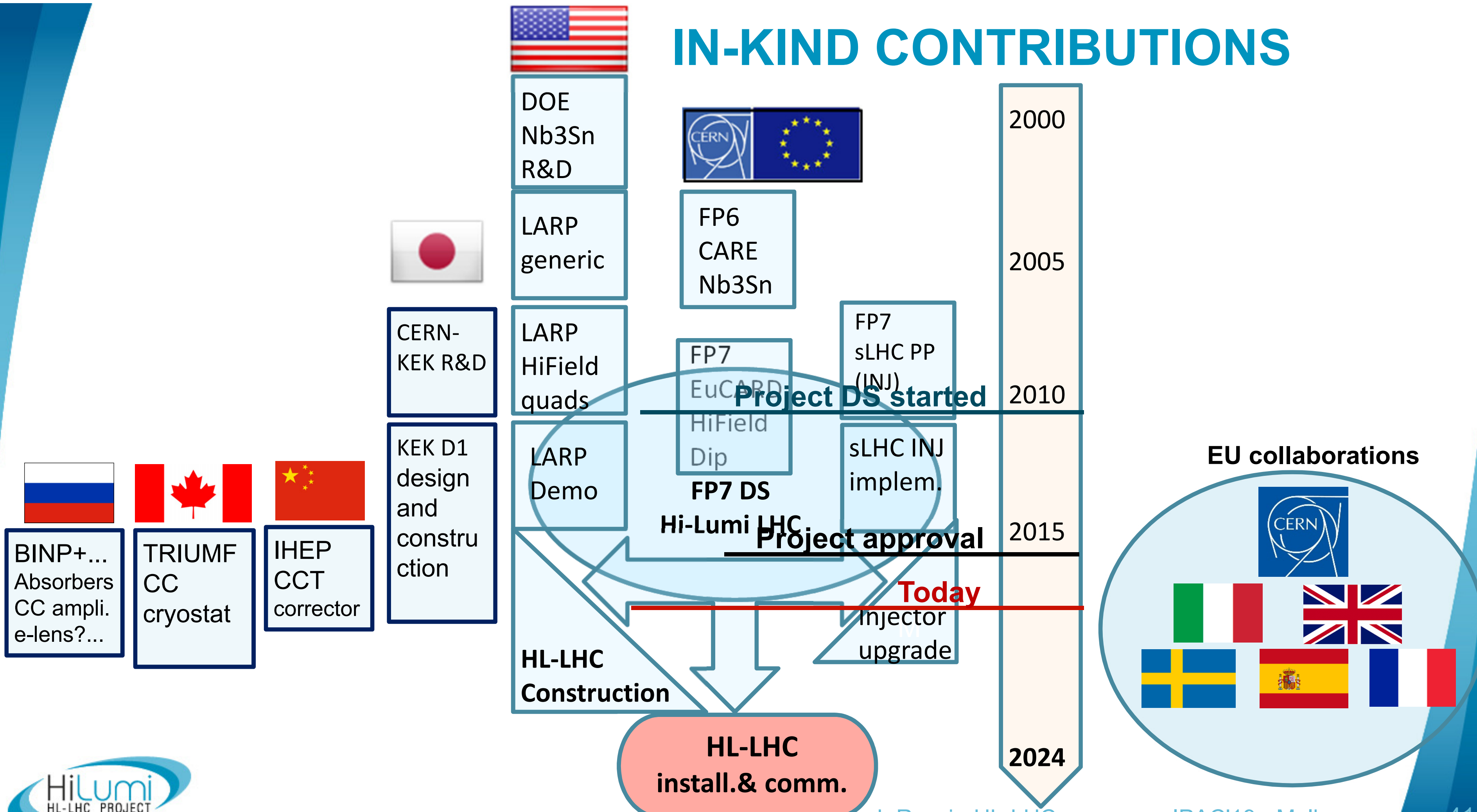

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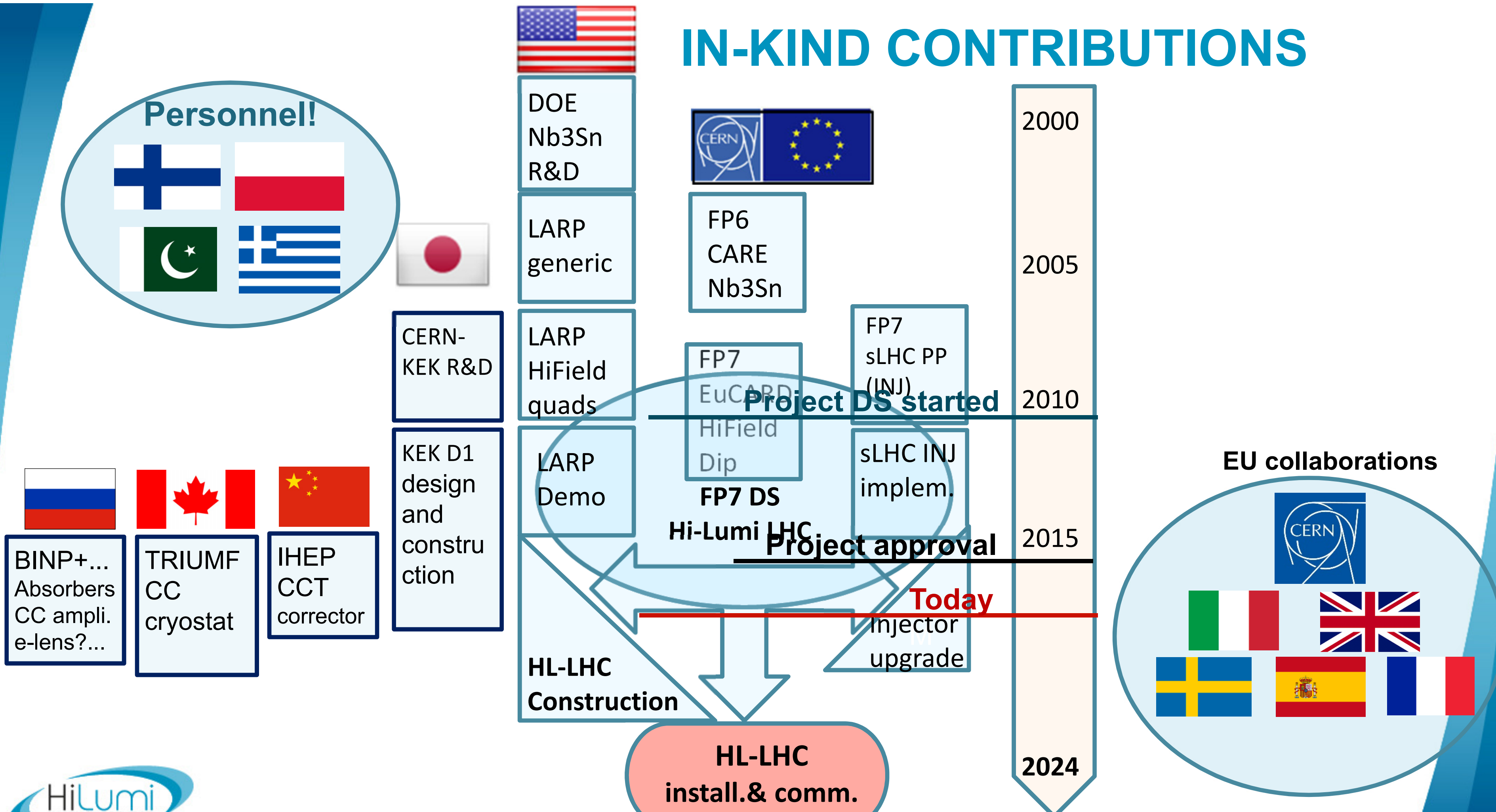
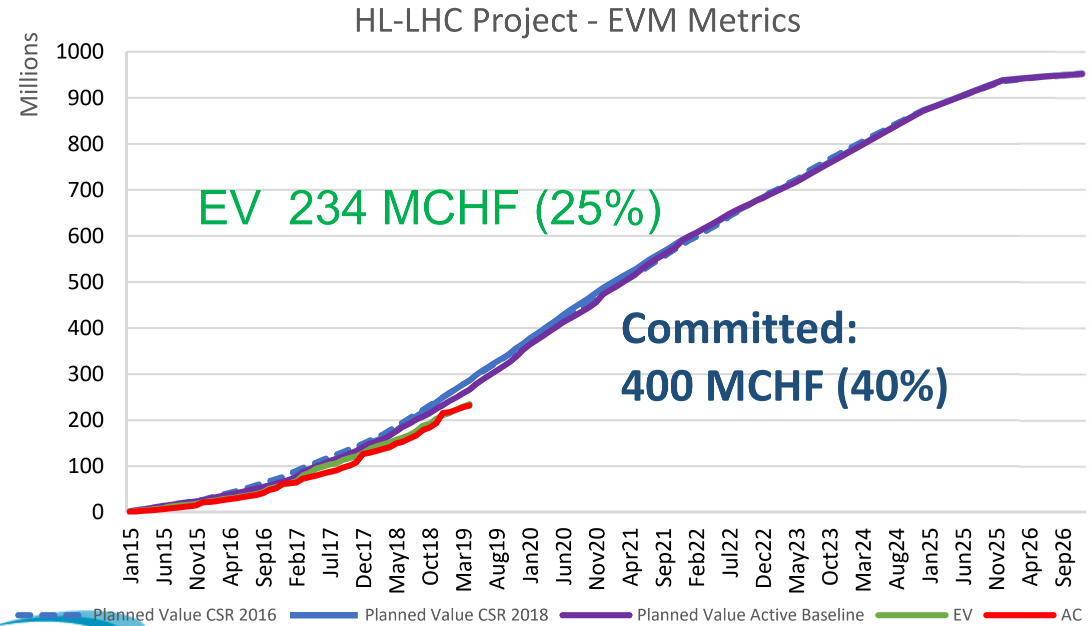
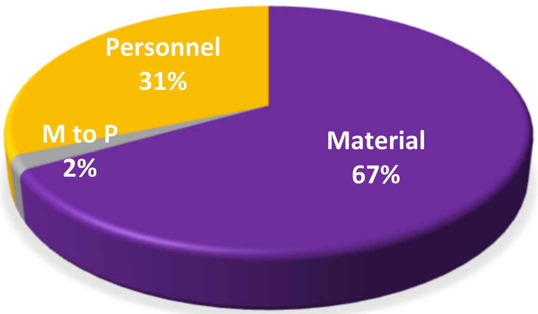
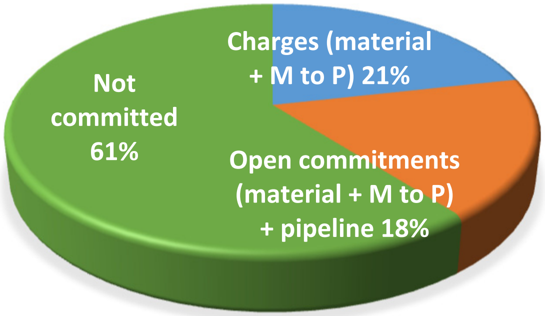


Budget, expenditures & Time Plan

Total Completion	In kCHF
Material	925,345
M to P	25,697
Personnel	435,101
	1,386,143







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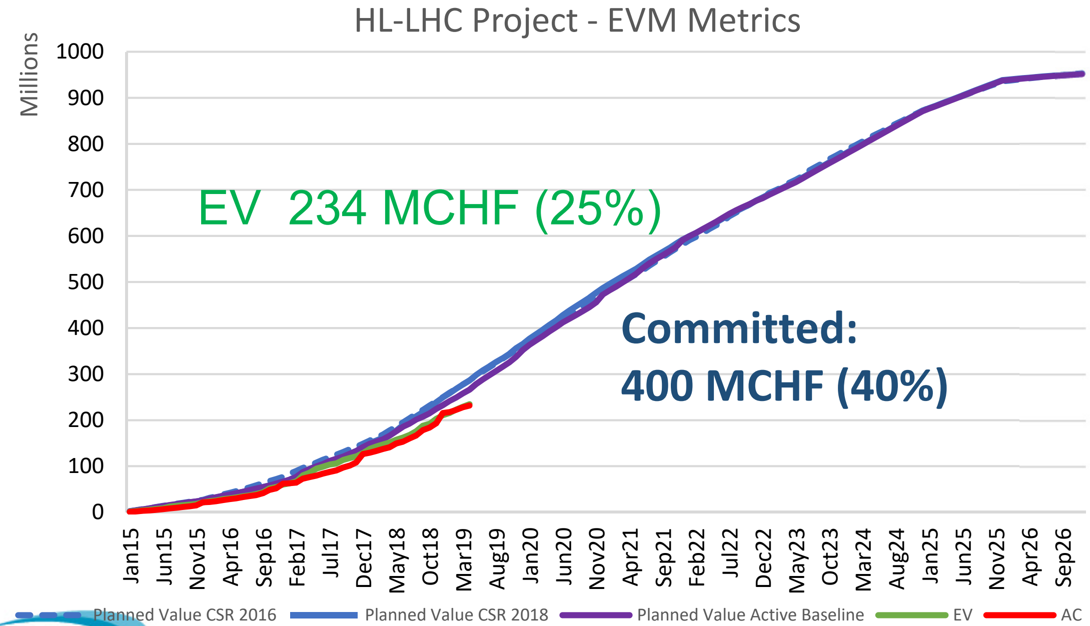
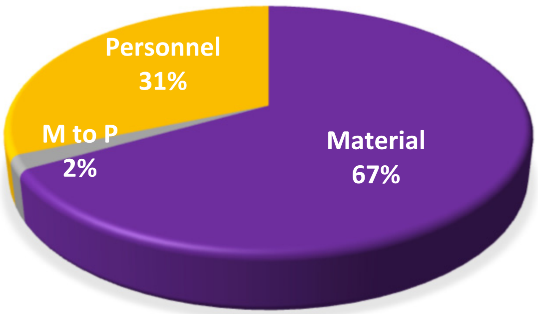
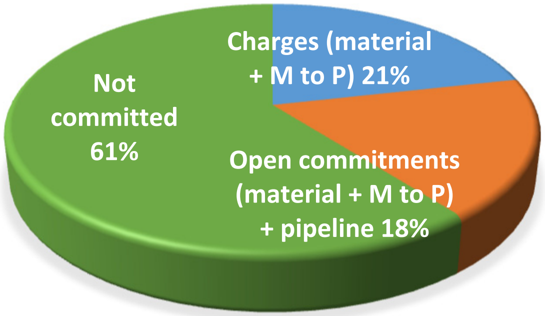
951 MCHF construction budget: no contingency (incl. 130 MCHF in-kind)

~ 2000 FTE-y (+collab.)

~ 80 MCHF of consolidation not incl.







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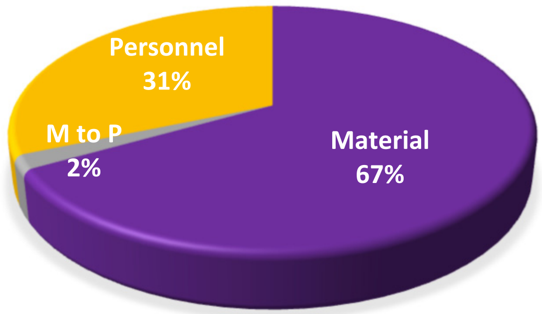

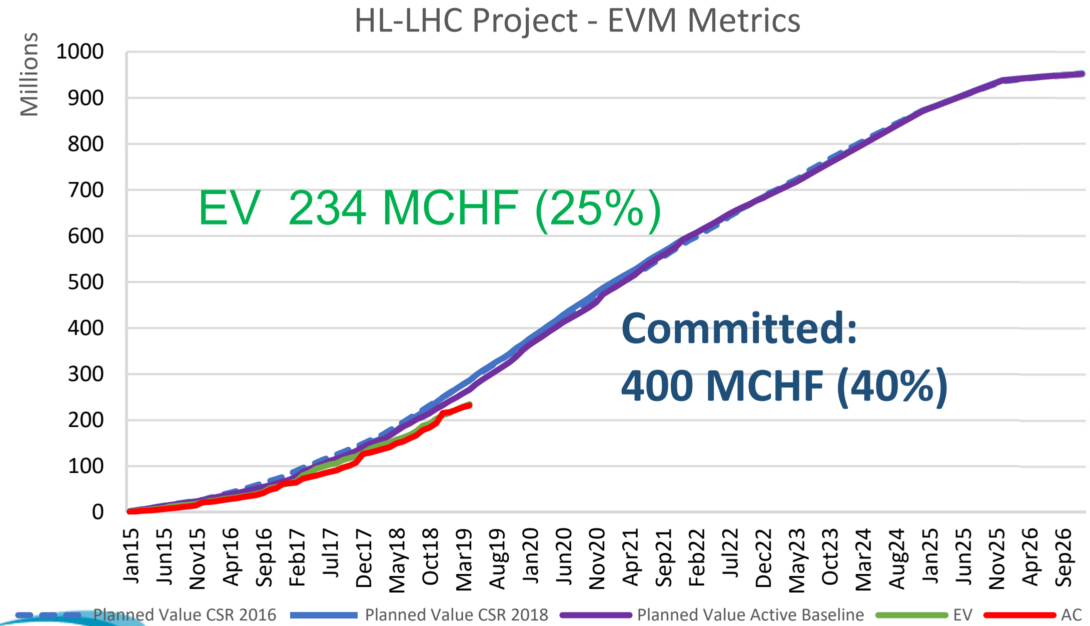

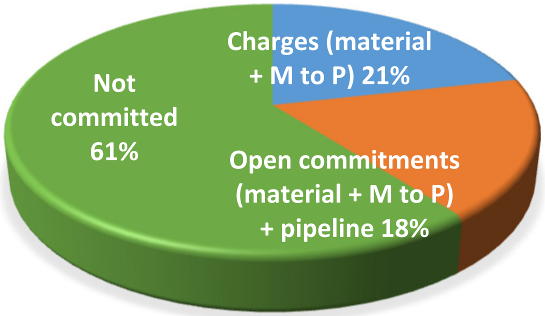

W.r.t. schedule at project approval in 2016: **5 months of non-critical delays**
Extra cost? 3% now, projected → 5%?


Thanks
High
Luminosity
LHC

LHC energy exploitation (input from O. Bruning and task force)

- **14 TeV** operation (nominal design)
  - Tests before YETS 2016/2017 revealed problem with diode box that prevented termination of the proposed tests ➔ LS2 consolidation of diode boxes.
  - The test in sector 1-2 for validating magnet performance **at 7TeV** prior to LS2 showed that we may need 1 quench/magnet: ≥ 1000 quenches, 2-3 months of intense quench campaign. Only question of time: foreseen in Run 3 (or Run 4)
- **15 TeV** (ultimate energy, dipoles at 93% of intrinsic limit):
  - Not impossible but very unlikely due to large time overhead (long quench campaign; and ~400 magnets never trained to ultimate): trade-off between energy gain and luminosity
- Beyond ultimate energy sunstuting 1/3 of main dipole with a 11 T dipole
  - **~16 TeV**
  - Very unlikely: big change, big overheads of de and re-instlalation (2-3 y?) and very difficult operation. The cost is in the 2-3 BCHF range.
  - The 11 T HiLumi dipole not optimized for cost and in series with LHC dipoles: big constraints