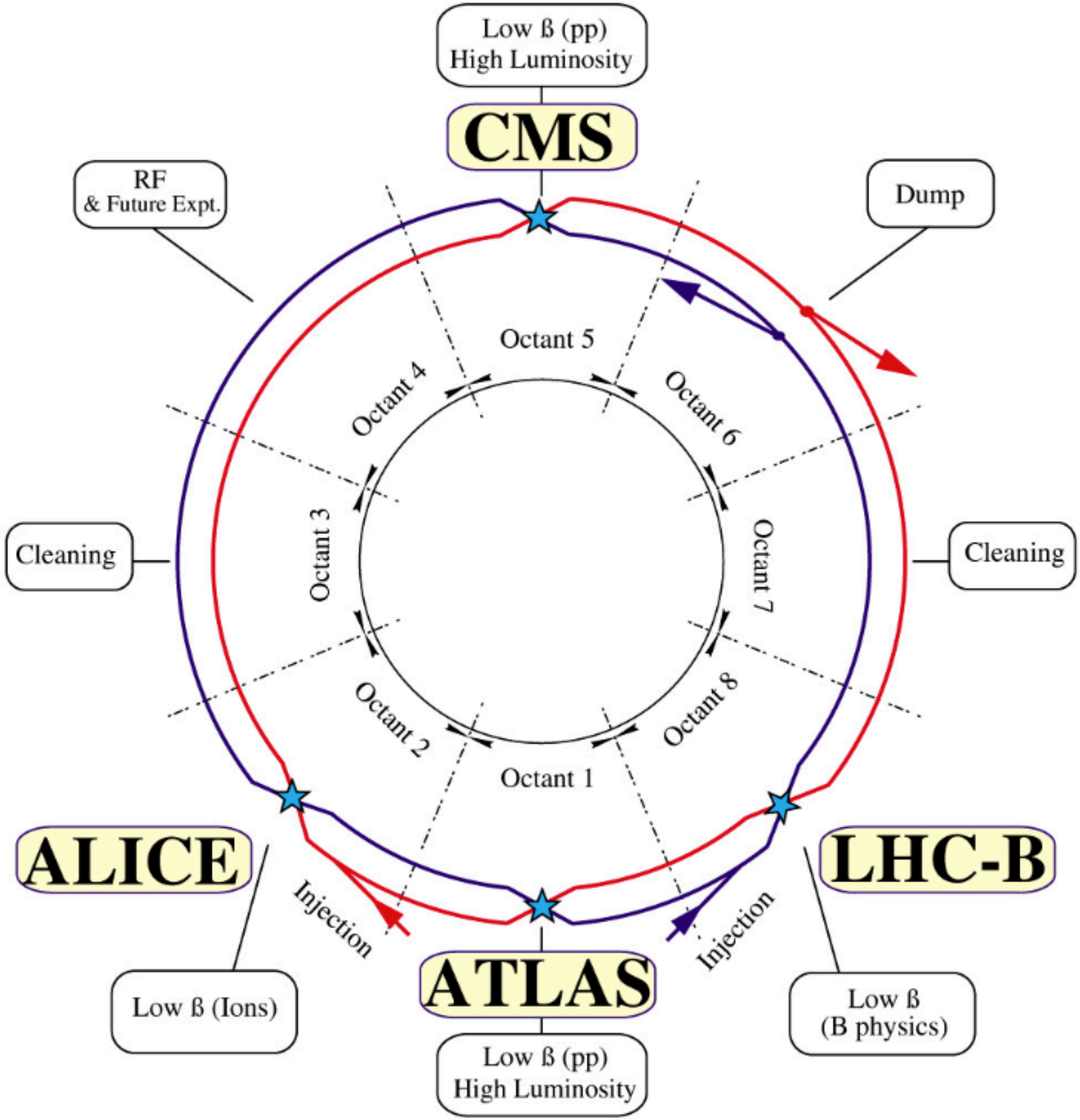
HL-LHC Accelerator Physics and Technology Challenges

Alexander Valishev

Fermilab, HL/HE LHC Meeting
April 4, 2018

Content

- Collider accelerator physics primer (with focus on LHC)
- LHC vs. HL-LHC bird's eye view
- HL-LHC novel technology and challenges



$E = 7$ TeV

$B = 8.3$ T

$C = 27$ km

$$R = \frac{pc}{eB}$$

$$\frac{2\pi\ pc}{C\ \ eB} = 0.66$$

packing factor

Luminosity of a Collider

$$\dot{N}_{event} = \sigma_{event} \times L$$ – instantaneous luminosity

$$N_{event} = \sigma_{event} \times \int L \cdot dt$$ – luminosity integral

Initial luminosity

$$L = \frac{n_b N_p^2 f_0}{4\pi\, \sigma^2} R(\sigma_z, \theta)$$

n_b – Number of bunches
N_p – Number of protons/bunch
f_0 – Revolution frequency
σ – Beam size at IP
σ_z – Bunch length
θ – Crossing angle

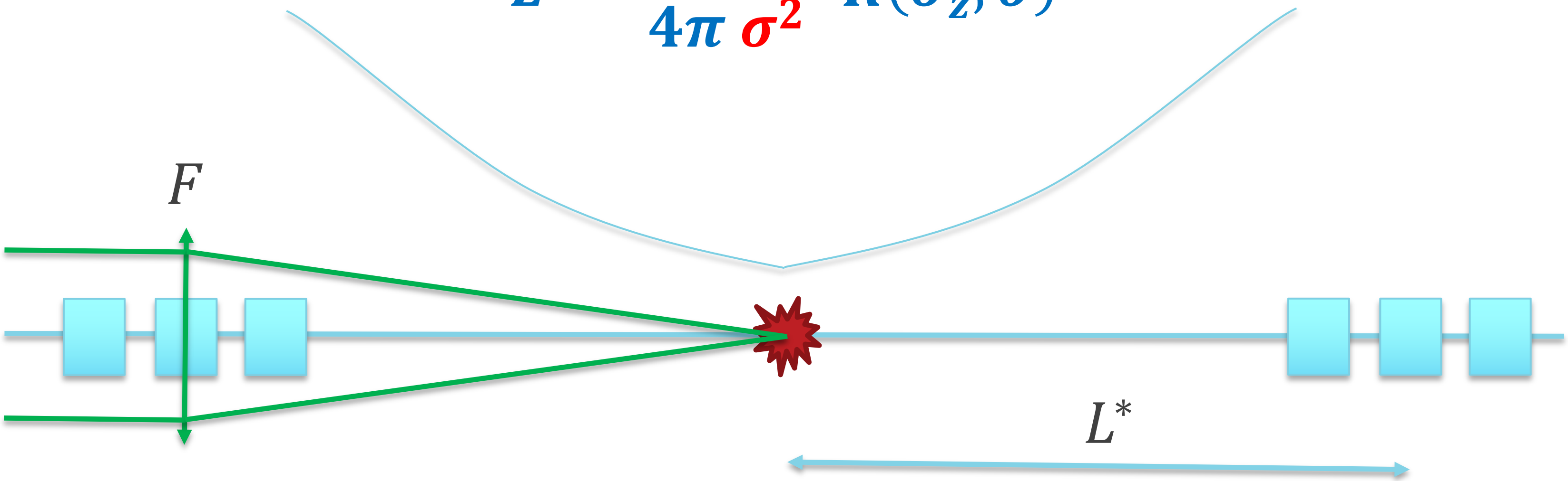
Luminosity lifetime

- Particle burn-off
- Coulomb intra-beam scattering
- Synchrotron radiation
- Noise/diffusion

Machine availability

Luminosity – Final Focus

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_z, \theta)$$



$$F \approx L^* \rightarrow G \approx \frac{pc}{L^* l}$$

$$\sigma^* = \sqrt{\varepsilon\beta^*} \approx 17\mu m$$

$$\sigma_L = \sigma^* \sqrt{1 + L^{*2}/\beta^{*2}} \approx 2\ mm$$

pc – Beam momentum

G – Quadrupole gradient

l – Quadrupole length

ε – Beam emittance

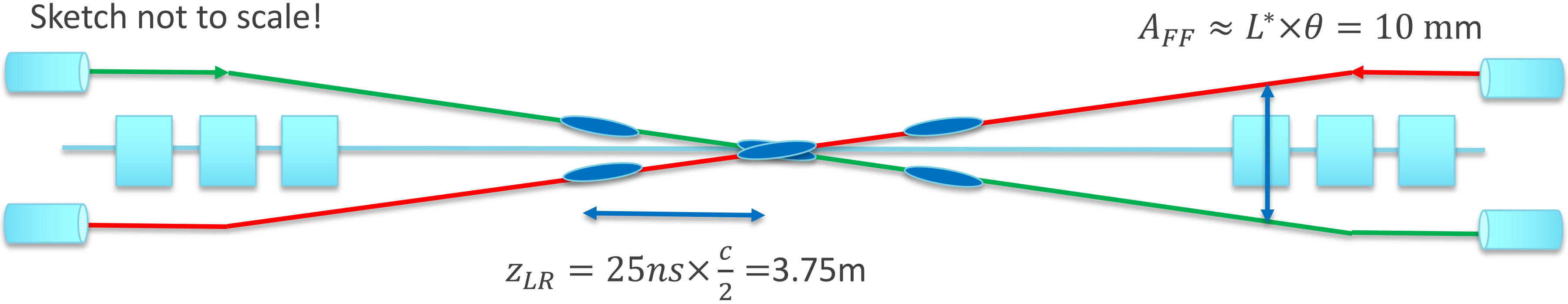
β – Optical beta-function

L^* – Final focus length

Luminosity – Crossing Scheme

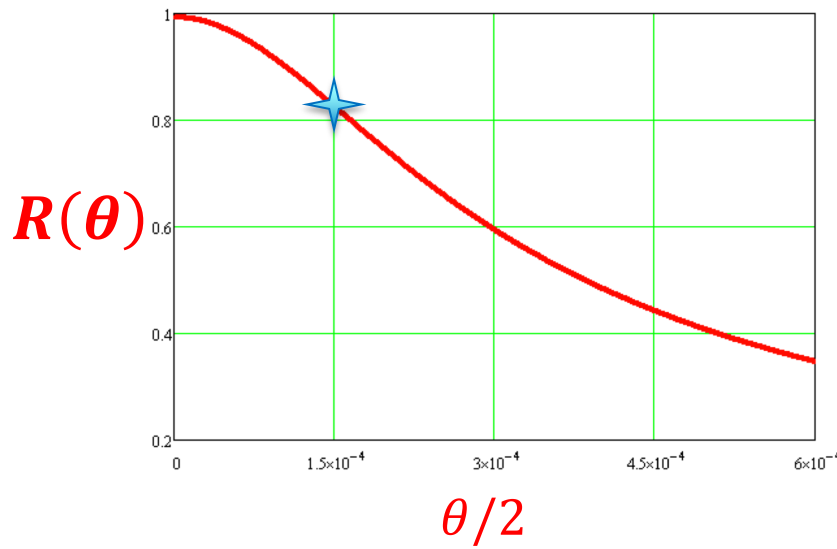
$$L = \frac{n_b N_p^2 f_0}{4\pi\, \sigma^2} R(\sigma_z, \theta)$$

Sketch not to scale!



Beams must be separated in parasitic crossings

- Too small angle → disruptive electromagnetic interaction (*beam-beam*)
- Too large angle →
    - Geometric luminosity loss R
    - Aperture limitation in triplet A_{FF}
- LHC optimal crossing angle θ =300 μrad

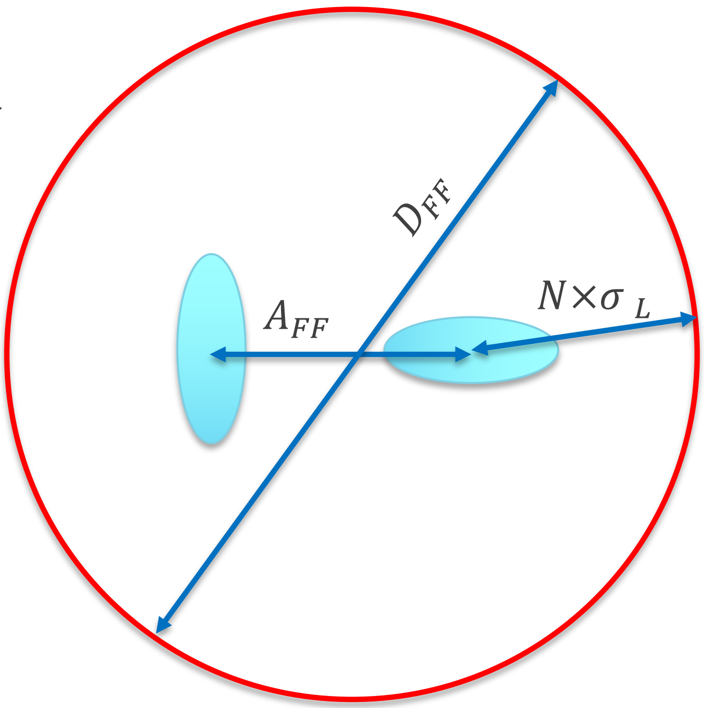


Final Focus (Low-Beta Triplet) Quadrupoles

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_z, \theta)$$

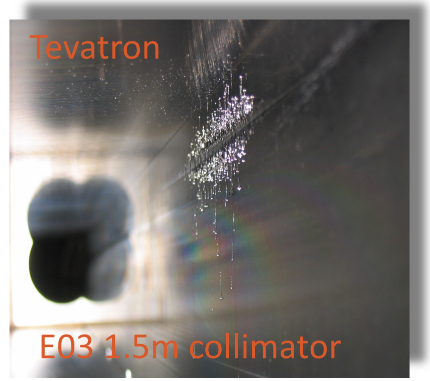
Final Focus Quadrupole Magnet Challenges

- Bore is determined by beam size and crossing angle/separation $D_{FF} = L^{*}\times\theta + 2\times10\times\sigma_L = 63\ mm$
- Gradient is determined by beam energy, magnet length, beta-function, magnet technology
  - NbTi conductor, 70 mm coil bore
  - Gradient $G = 215\ T/m$
  - Peak field in coil 7.7 T
- Must possess high field uniformity
- Must withstand high levels of radiation / heat load near IP



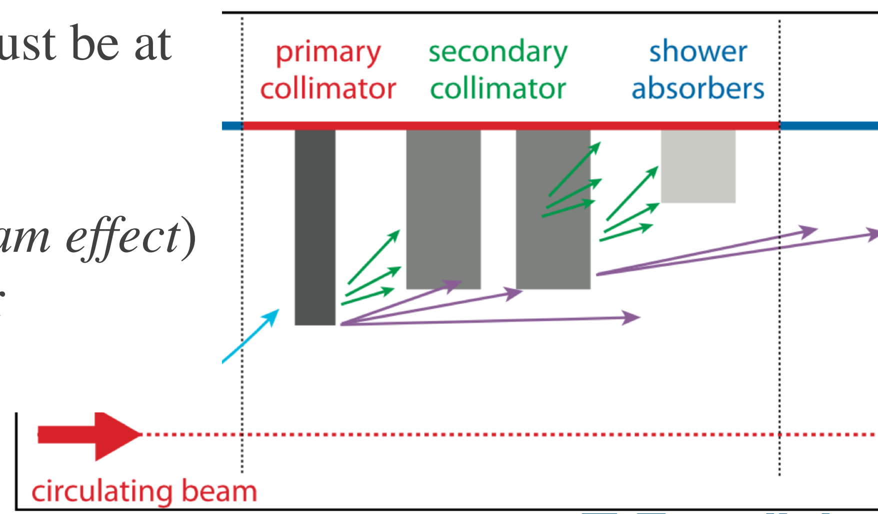
High-Current Issues

$$L = \frac{n_b N_p^2 f_0}{4\pi\, \sigma^2} R(\sigma_z, \theta)$$



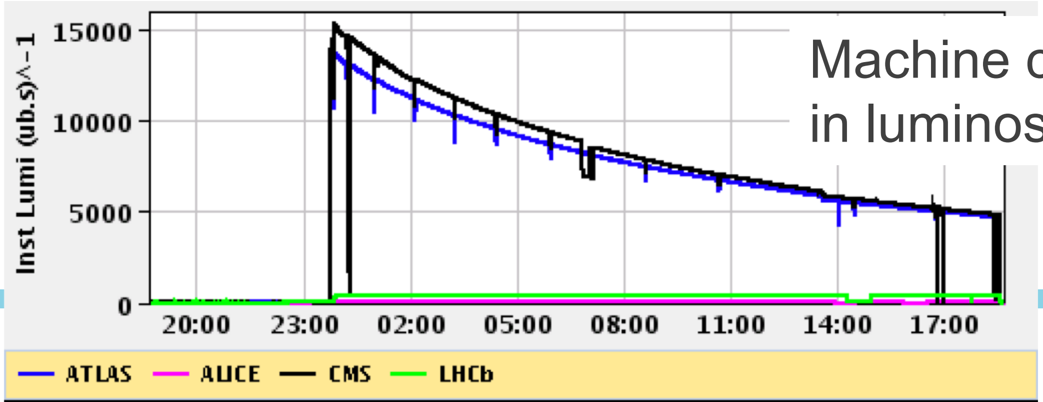
Energy stored in the beam is significant $\sim 400MJ$.
Even %-scale beam loss can damage components

- Collimation system to safely remove/absorb beam halo and protect the machine
- Beam dynamics understanding/control must be at the highest level
  - Interaction of colliding bunches via electromagnetic fields (aka *beam-beam effect*)
  - Interaction of beams with accelerator environment



LHC Design Parameters

	LHC nominal
Beam energy	7 TeV
Number of bunches	2808 (25 ns separation)
protons / bunch [10^{11}]	1.15 (0.58A)
Energy in one beam [MJ]	360
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75
β^* [m] at IP1-5	0.55
X-angle [μrad], separation	285, 9.3 σ
Geometrical Luminosity loss factor	0.83
Quadrupole bore [mm], gradient [T/m]	70, 215
Peak luminosity [10^{34}]	1.0
Pile up	27



Machine configuration is ***mostly* static** in luminosity run!

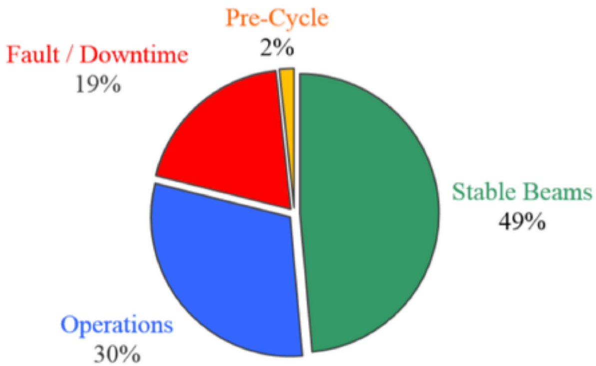
Main achievements 2017

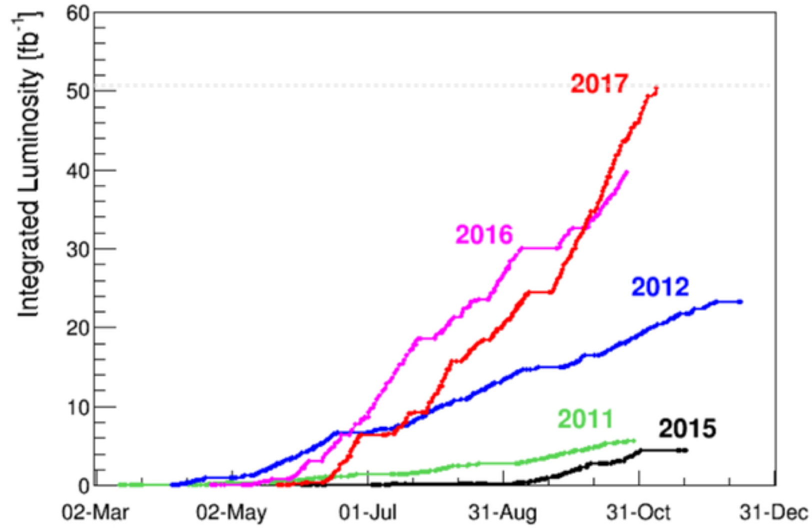
Total integrated luminosity

- **ATLAS/CMS** > 50 fb^{-1}
- **LHCb** = 1.98 fb^{-1}
- **ALICE** = 19.1 pb^{-1}

2017: Best production year
(~0.5 fb^{-1} /day on average after TS2)

Excellent Machine Availability
(~50% in Stable Beams)

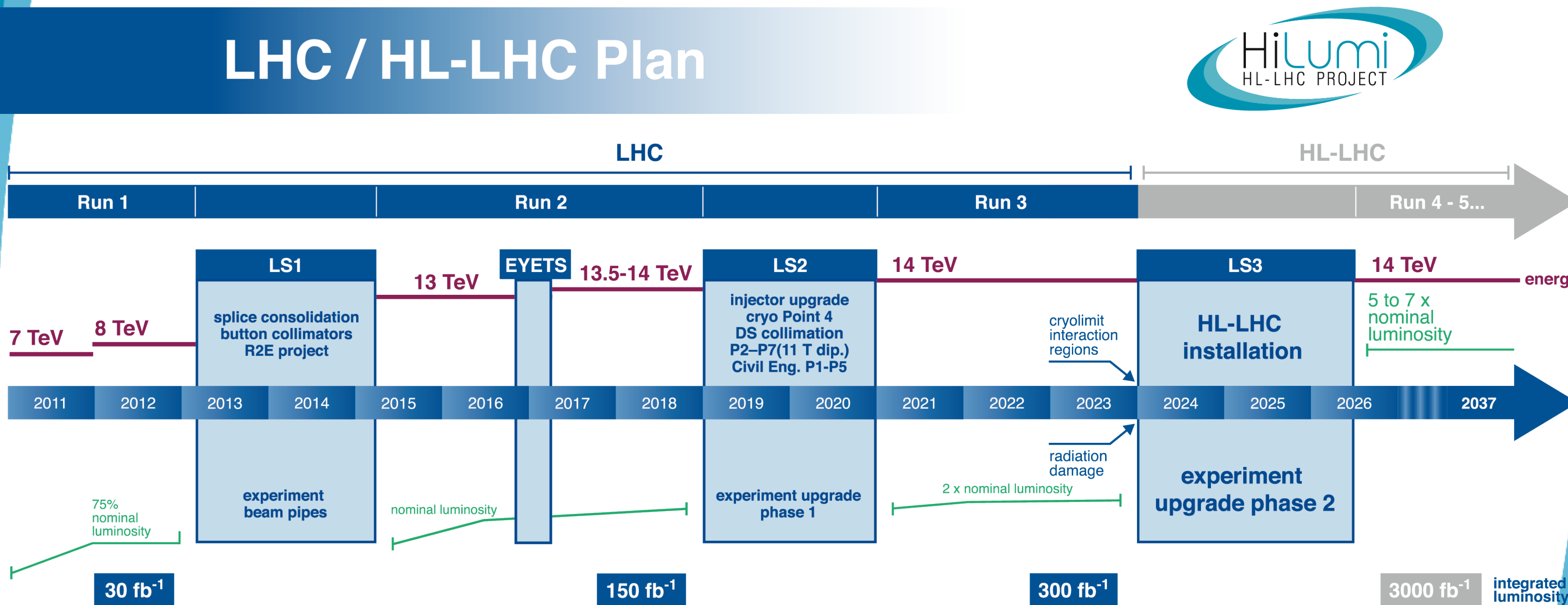




World's record **Peak Luminosity:**
2.2x10^{34} $cm^{-2}s^{-1}$

This was achieved by optimising the cycle, better orbit control, smaller beta-star, etc. and by exploring new beam with higher brightness

Timeline & Goal:
Commissioning 2026; 3 ab^{-1} by 2037 (250 fb^{-1}/y)



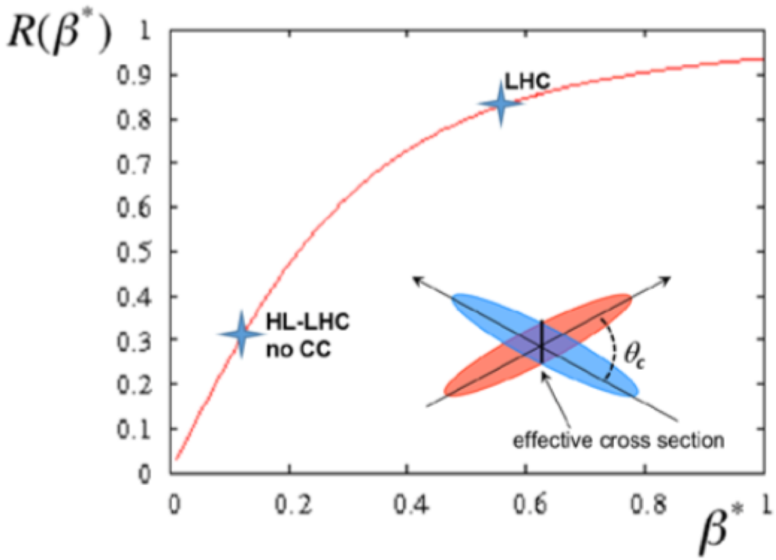
Levelled Luminosity $L = 5 \times 10^{34} cm^{-2} s^{-1}$

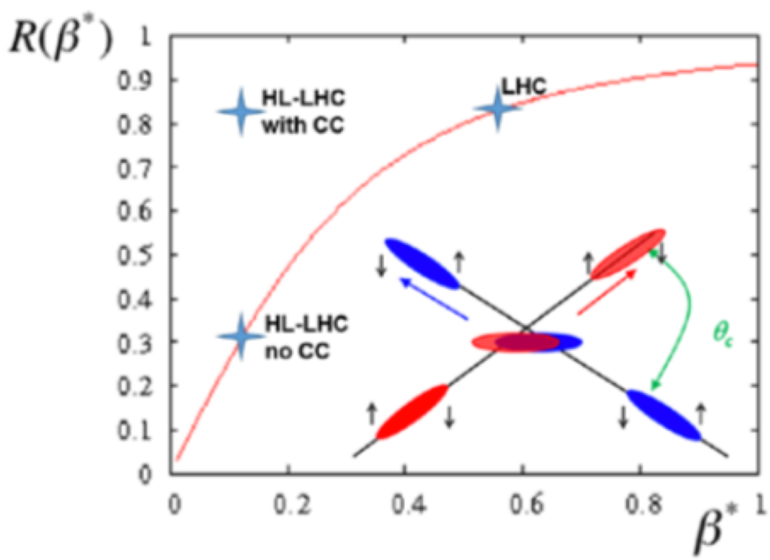
HL-LHC Luminosity Ingredients

1. 1.9× number of particles N_p
2. 0.4× beam size at IP σ
3. 2× crossing angle θ → 0.3× luminosity reduction R

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_z, \theta)$$

- The result is L=7×10^{34} BUT pile-up density > 3mm^{-1}
- Crab Cavities for luminous area control!
  - RF transversely deflecting cavity where deflection depends on longitudinal position in bunch





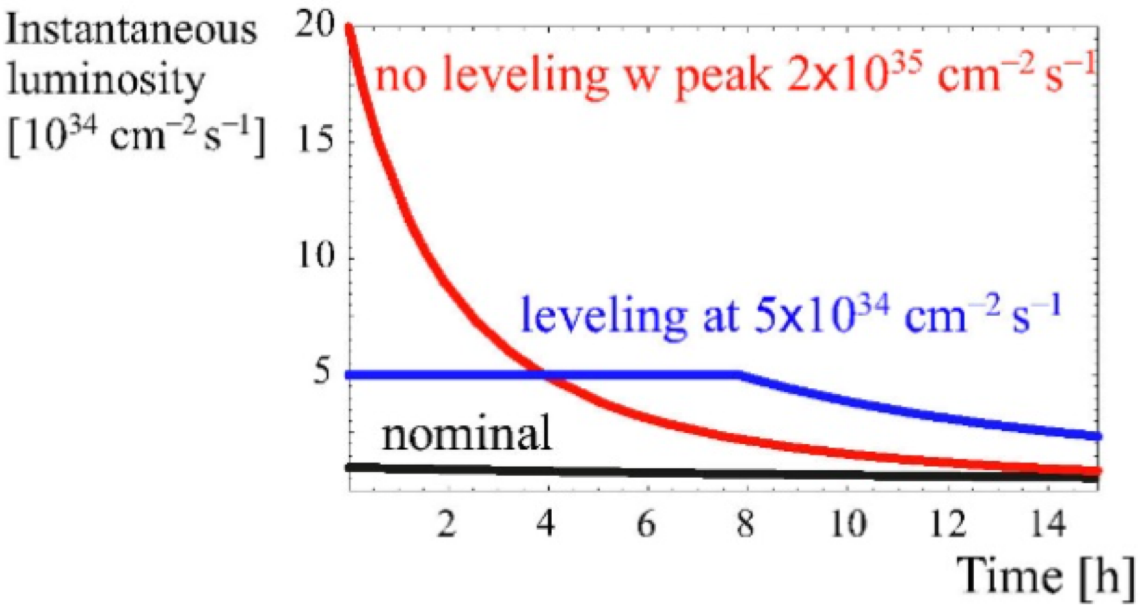
HL-LHC Luminosity Ingredients (2)

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_z, \theta)$$

1. 1.9× number of particles N_p
2. 0.4× beam size at IP σ
3. 2× crossing angle θ AND Crab Cavities 1× luminosity reduction R

- The result is L=19×10^{34} – too high!

4. Luminosity levelling by dynamically changing focusing (β^* =0.7→0.15m) in store

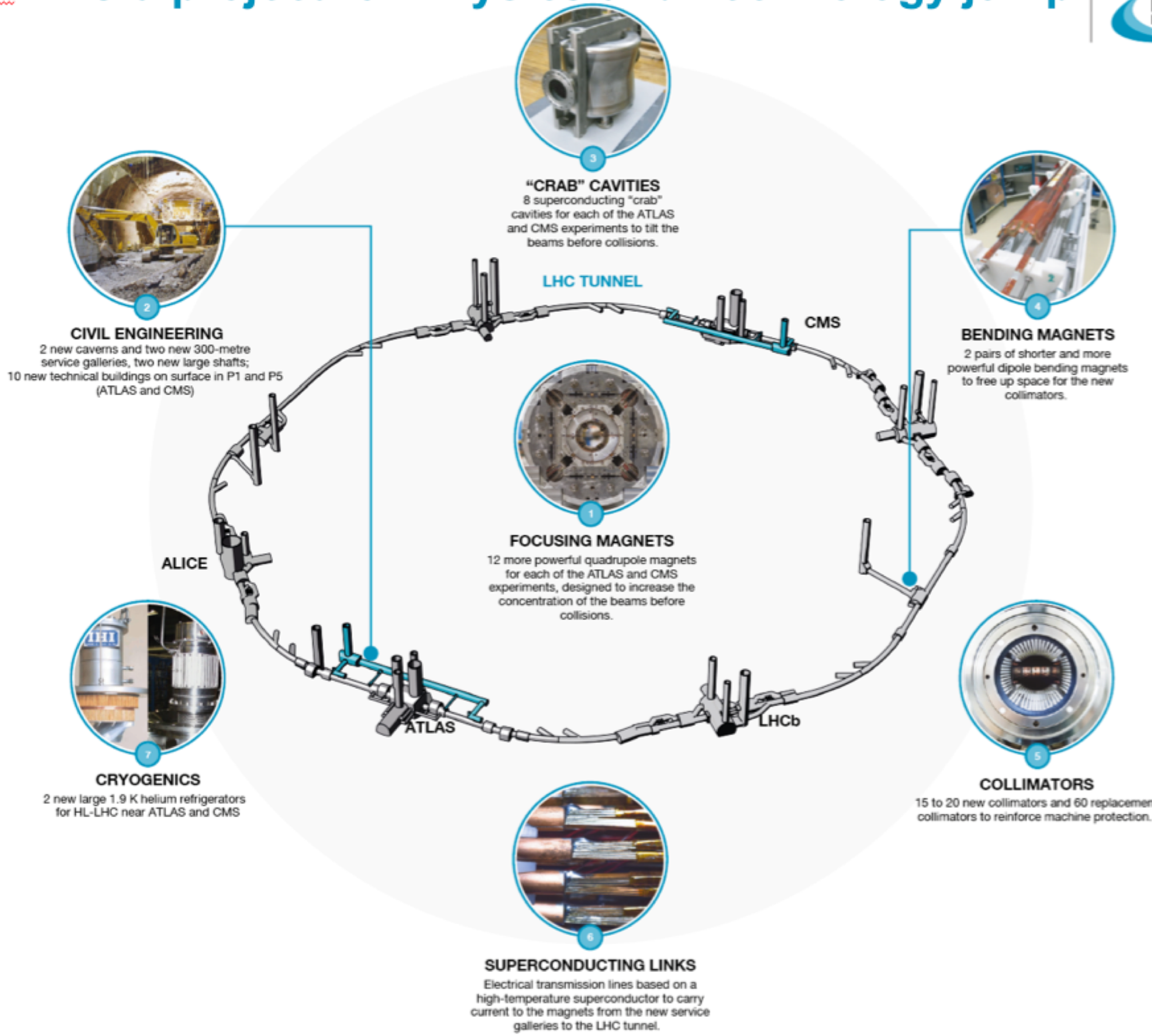


Fermilab

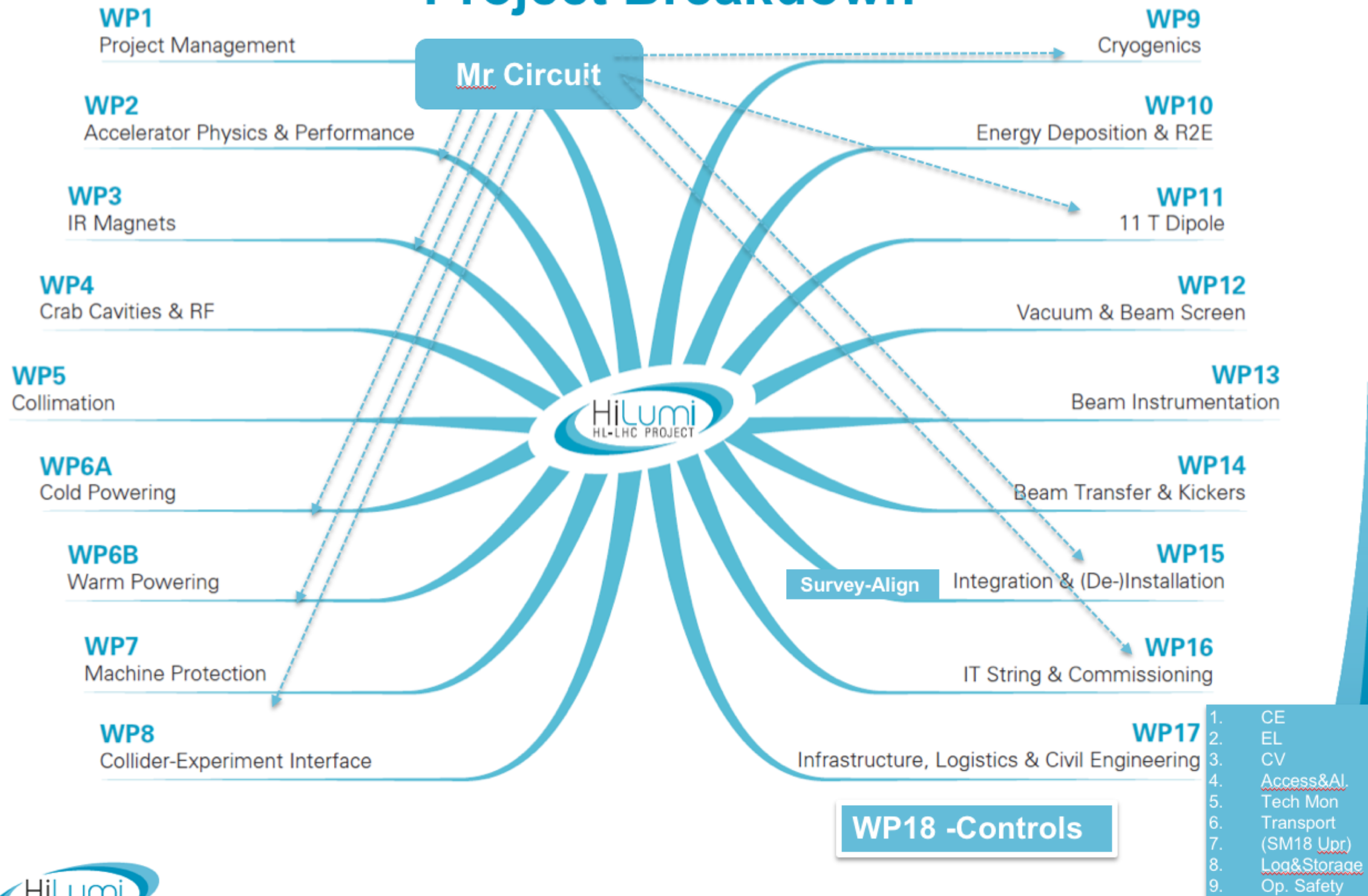
LHC vs. HL-LHC

	LHC nominal	HL-LHC
Beam energy	7 TeV	
Number of bunches	2808 (25 ns)	2748
protons / bunch [10^{11}]	1.15 (0.58A)	2.2 (1.09A)
Energy in one beam [MJ]	360	680
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75	2.5
β^* [m] at IP1-5	0.55	0.15
X-angle [μrad], separation	285, 9.3σ	590, 12.5σ
Geometrical Luminosity loss factor	0.83	0.3 **Crab Cavities**→0.83
Quadrupole bore [mm], gradient [T/m]	70, 215	150, 132.6
Peak luminosity [10^{34}]	1.0	5.0
Pile up	25	138
Line pile up density [mm^{-1}]	0.1	1.25
Machine state during HEP store	static	dynamically changing focusing – β^* levelling

HiLumi LHC landmarks
Hilumi LHC a project for Physics and Technology jump



Project Breakdown



U.S. LARP – US HL-LHC AUP

LHC Accelerator Research Program – National Program started in 2003

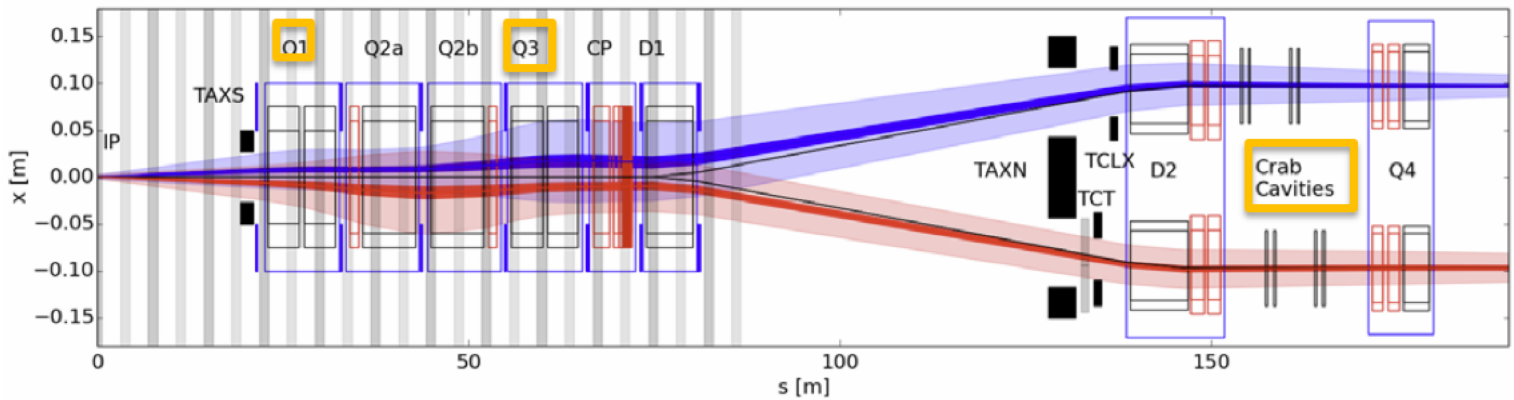
- Coordinates and funds work by accelerator experts from FNAL, BNL, LBNL, SLAC, JLAB and several U.S. universities
- Leverages the U.S. experience in collider/accelerator physics and technology, provides continuity of knowledge
- Numerous contributions to the success of the LHC
  - Magnets, Crab Cavities, Rotating Collimators, Luminosity Monitors, Beam Instrumentation, E-Lens, Wide Band Feedback System, Accelerator Physics, Irradiation assessment, etc.
- Very successful personnel program
  - Toohig Fellowship, Long-term visitor program

HL-LHC AUP – Formal DOE Construction Project to deliver

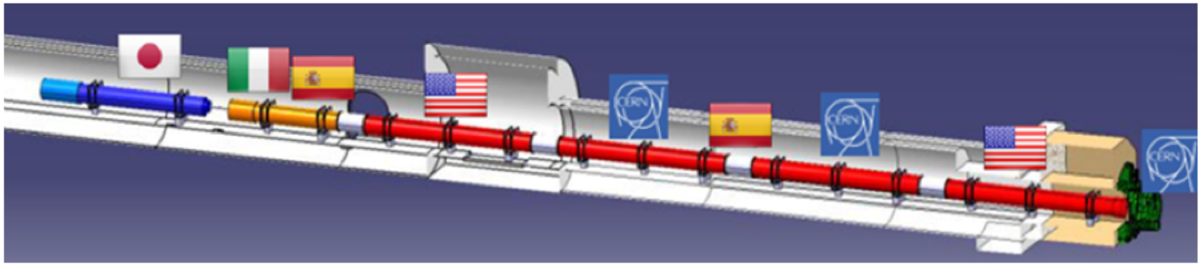
- Q1/Q3 Cryoassemblies
- Dressed RFD Cavities

Preliminary U.S. contributions to HL-LHC (in pictures)

Insertion Region layout from the IP to Q4



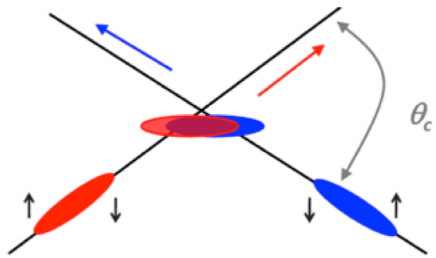
Large Aperture IR Quadrupoles:

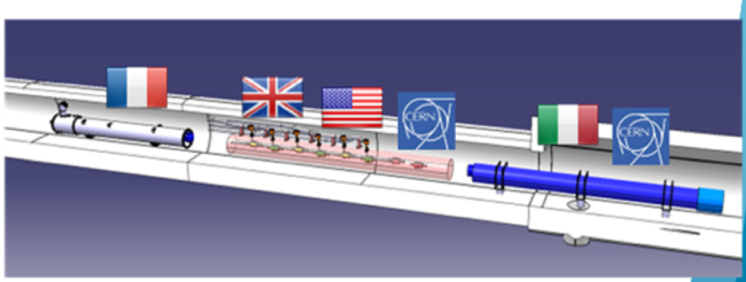


- *From 70 mm MQXA/B to 150 mm MQXF*
- *From NbTi to Nb_3Sn for higher field/gradient*
- *Minimum β^* from 0.55 m to 0.15 m*
- *Compatible with 10x integrated luminosity*

Crab cavities:

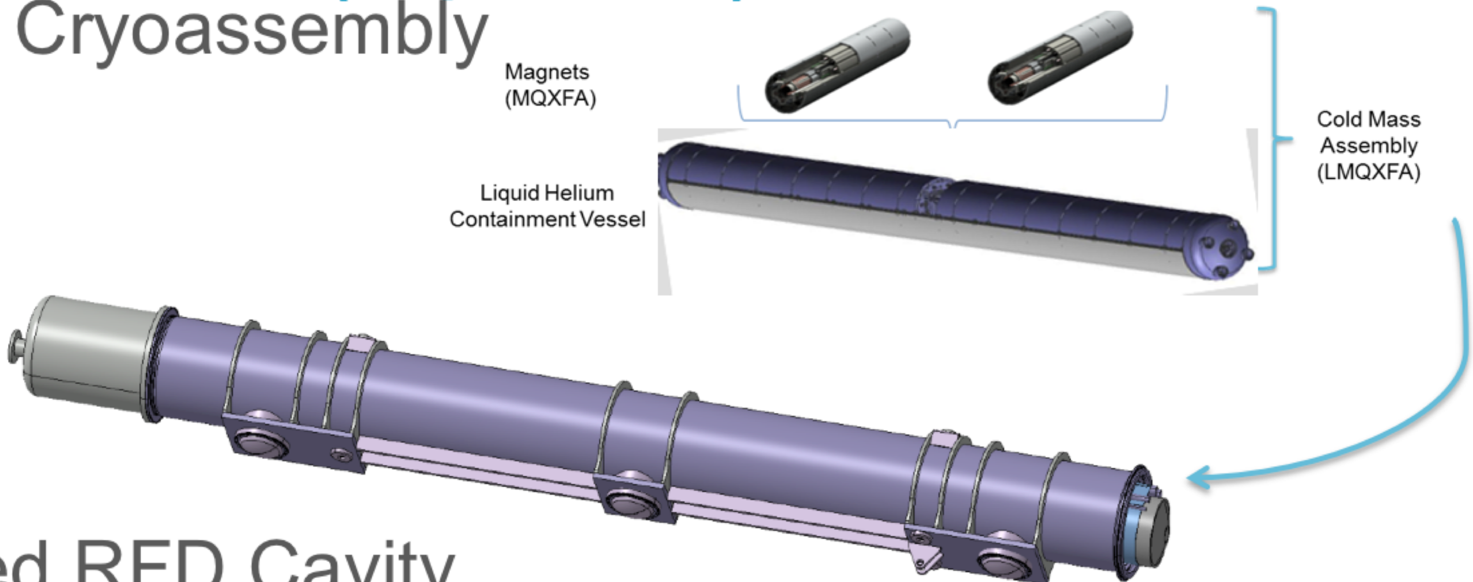
- *Deflect bunch at IP to collide head-on*
- *Restore luminosity loss due to crossing angle*
- *Requires compact superconducting cavities*



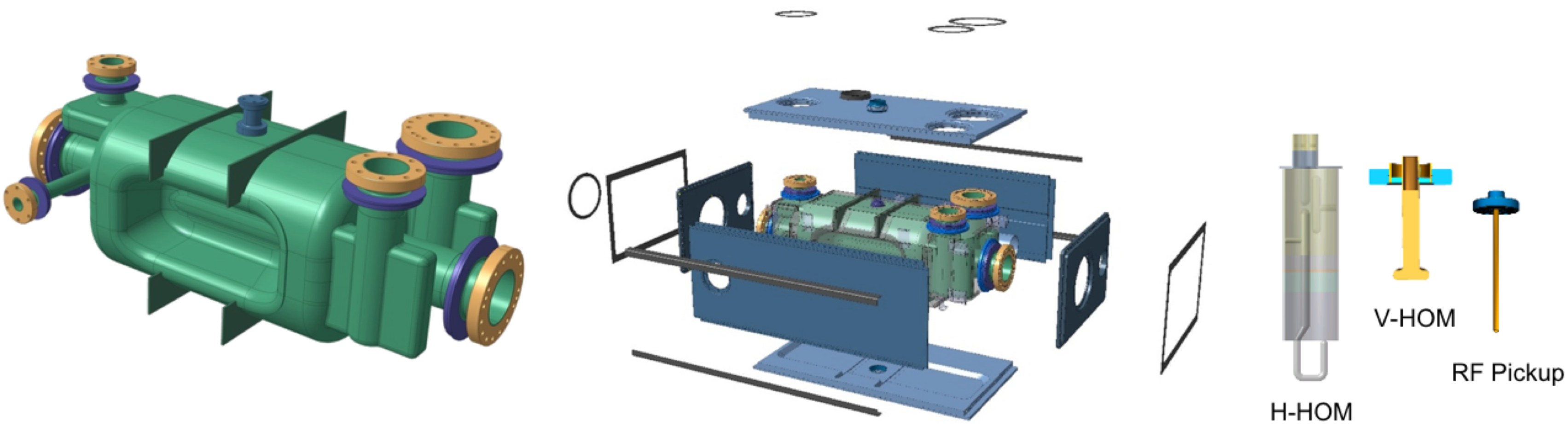


Preliminary U.S. contributions to HL-LHC (in pictures)

- Q1/Q3 Cryoassembly



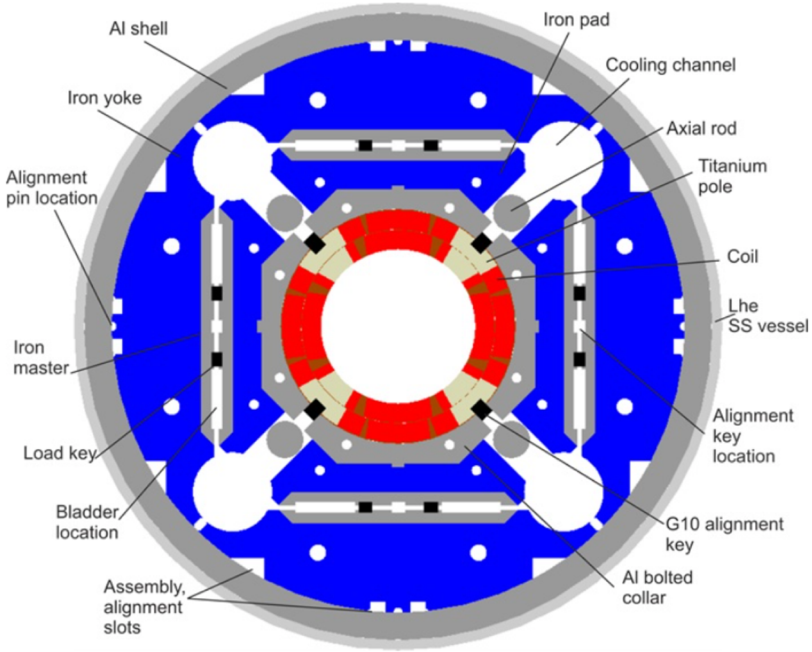
- Dressed RFD Cavity



HL-LHC Insertion Magnets

Basic Parameters

- Bore – 150 mm
- Gradient – 140 T/m (coil field 9T)
- Conductor – Nb_3Sn
- Length – two 4-m coils



Selected HL-LHC AP Topics

- ATS (Achromatic Telescopic Squeeze) Optics
- Hollow e- Beam Collimation
- Long-range Beam-Beam Effect Compensation

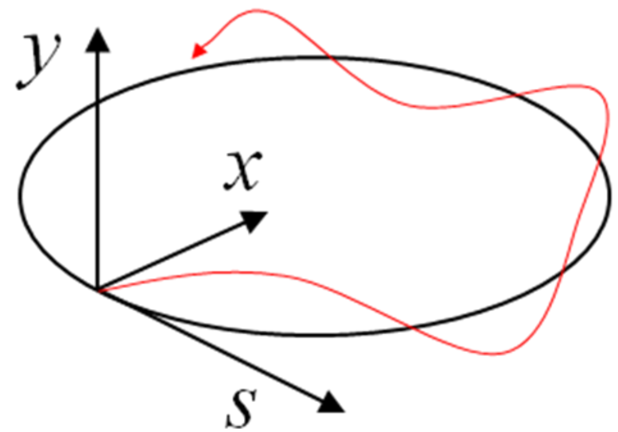
Particle Confinement in Rings

Charged particles are kept moving around a circular orbit with the use of static transverse magnetic fields.

$$\vec{F} = e\vec{v}\times\vec{B}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

$$K_{x,y}(s + C) = K_{x,y}(s)$$



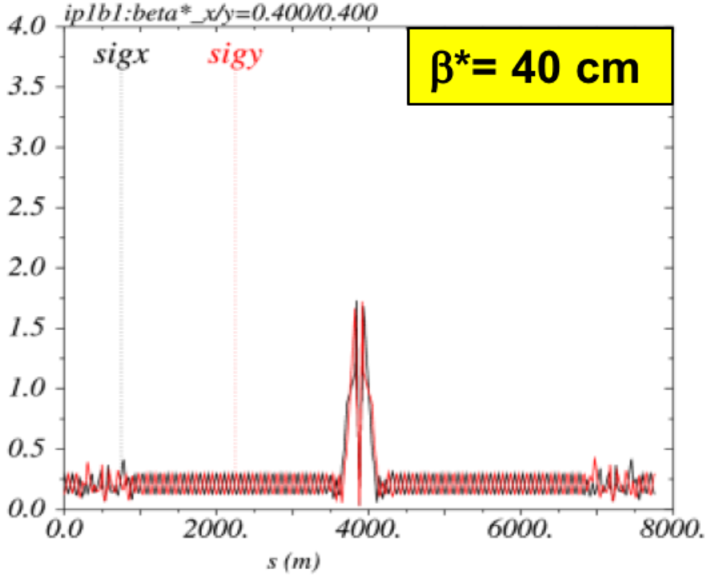
Linear focusing – dipole and quadrupole magnets

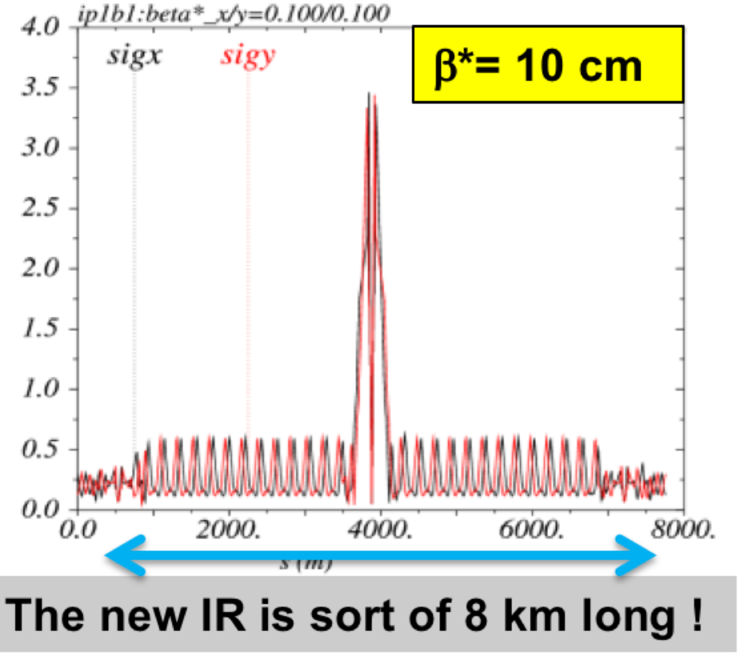
x,y motion – *betatron oscillations*

Longitudinally the beam is kept bunched with time-varying electrical field. s-motion is usually weekly coupled to x-y

ATS Optics

- Arc quadrupoles are powered in series
- Small number of “matching” quadrupoles in IR1/IR5 perform the function of “squeezing” beams in to the final focus
- Via clever use of IR2/IR8 matching quadrupoles, one can further decrease beam size in IR1/IR5

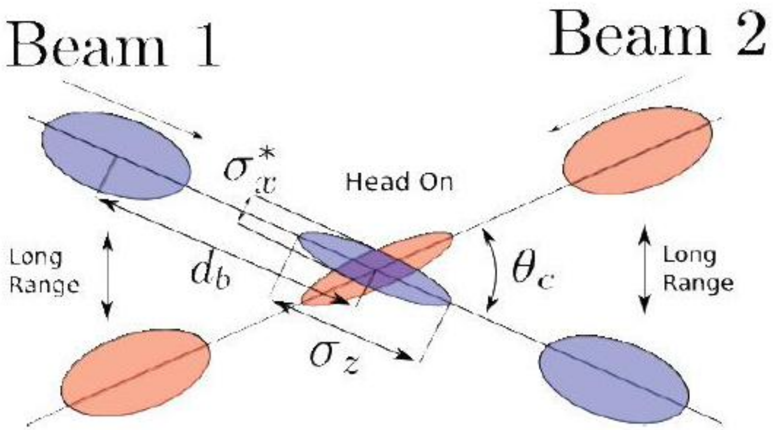




S.Fartoukh, PRSTAB 18-111002, 2013

Beam-Beam Interactions

In colliders in addition to the focusing magnets, particles experience interactions with electromagnetic field of counter-rotating beam.



$$F_{BB} \propto \Delta\nu_{BB}\frac{1}{r}(1-e^{-\frac{r^2}{2\sigma^2}})$$

$\Delta\nu_{BB} = \xi = \frac{Nr_0\beta}{4\pi\gamma\sigma^2}$	**b-b tuneshift**

$$x'' + K_x(s)x = F_{BB}(x,y,s)$$

Even though beam-beam adds relatively little to focusing (typical tune shift for LHC is 0.02 at lattice tune of 60), the beam-beam force is strongly nonlinear and localized in time → **unstable motion and losses**

HL-LHC represents a leap into uncharted territory in terms of beam-beam for hadron colliders

- Large beam-beam tune shift ξ=0.03
- Two-fold increase of beam current, hence 2× Long-Range Beam-Beam
- Crab-cavities strongly couple longitudinal and transverse dynamics

Long-Range Beam-Beam Compensation

The 2× HL-LHC beam current would lead to tremendous enhancement of Long-Range Beam-Beam (LRBB) for the same separation of beams in IR1,5.

Because of this, HL-LHC relies on

a) Large crossing angle (590 μrad) in IR1,5 to increase separation.

b) Crab Cavities (CC) to recover luminosity performance.

Are there ways to achieve the same luminosity performance with less (or no at all) CC voltage *or* smaller crossing angle?

– A *risk reduction* strategy for CC project

Possibly – with the use of Wire LRBB Compensators !

Concept of LRBB Compensation

- Beam-beam (LR) kick (round beams)

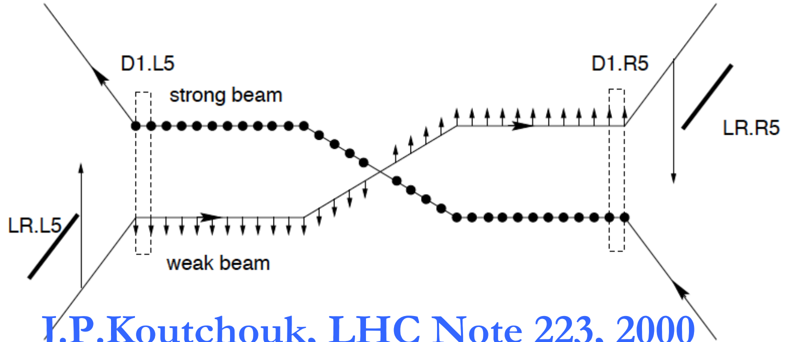
$$\Delta\{x',y'\} = -\frac{2N_b r_p}{\gamma}\frac{\{X,Y\}}{X^2+Y^2}(1-e^{-\frac{X^2+Y^2}{2\sigma^2}})$$

with $X = x + x_c,\quad Y = y + y_c$ beam separation

- Neglecting form factor (sufficiently large separation), can be approximated by an "infinite" wire

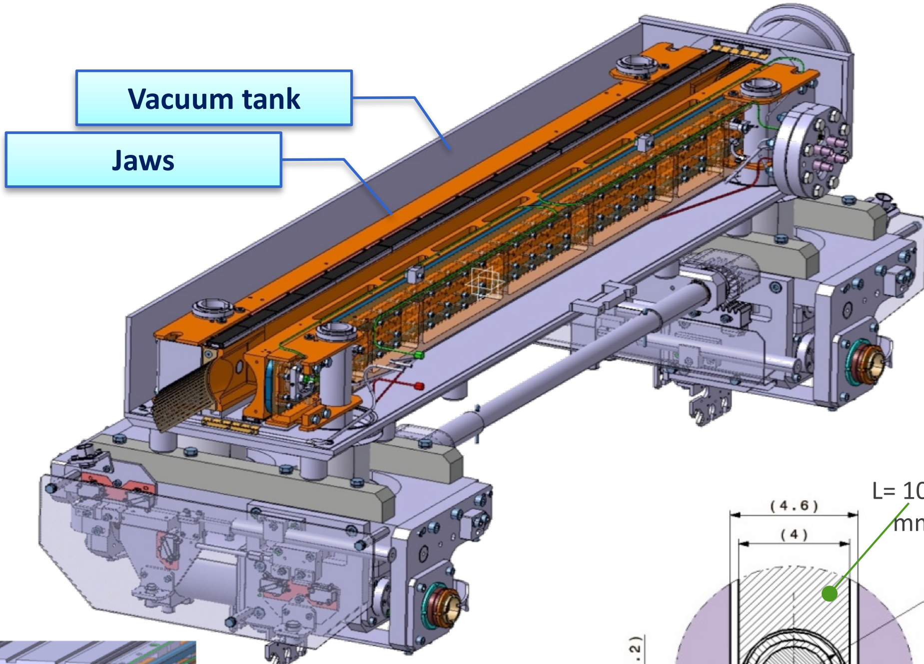
$$\Delta\{x',y'\}_W = \frac{\mu_0}{2\pi}\frac{I_W L_W}{B\rho}\frac{\{X_W,Y_W\}}{X_W^2+Y_W^2}$$

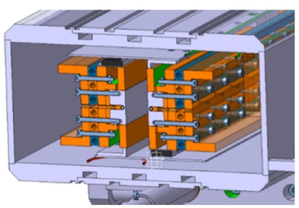
with $X_W = x + x_W\,,\quad Y_W = y + y_W$ wire separation

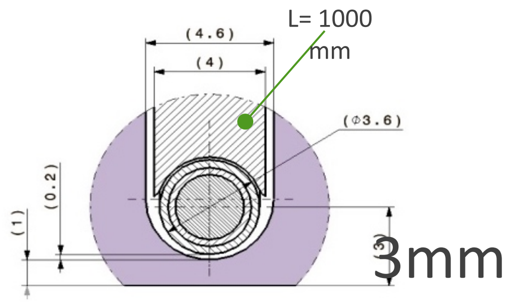


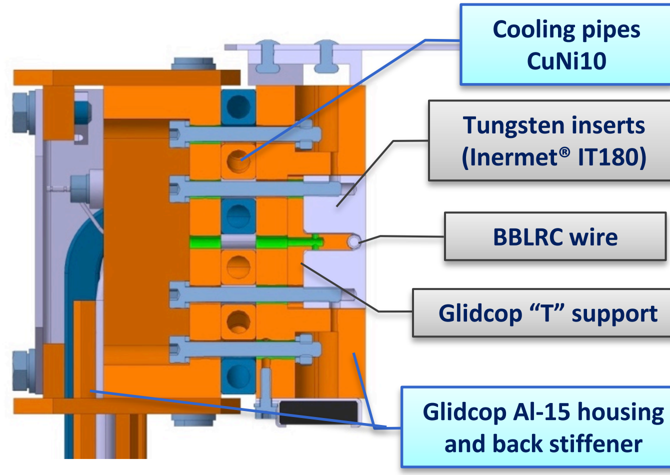
J.P.Koutchouk, LHC Note 223, 2000

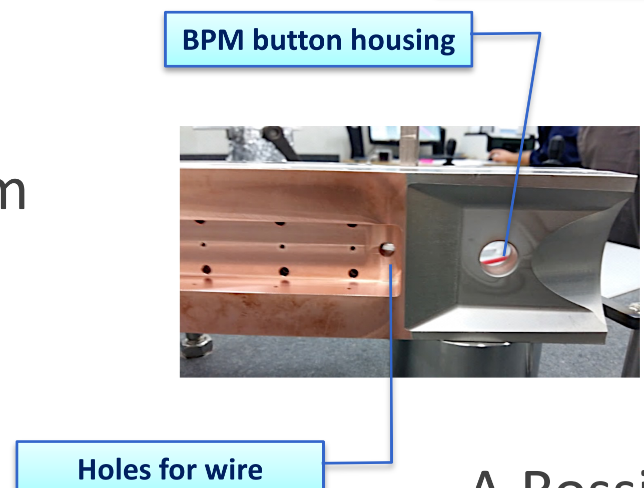
Collimator with Embedded Wire









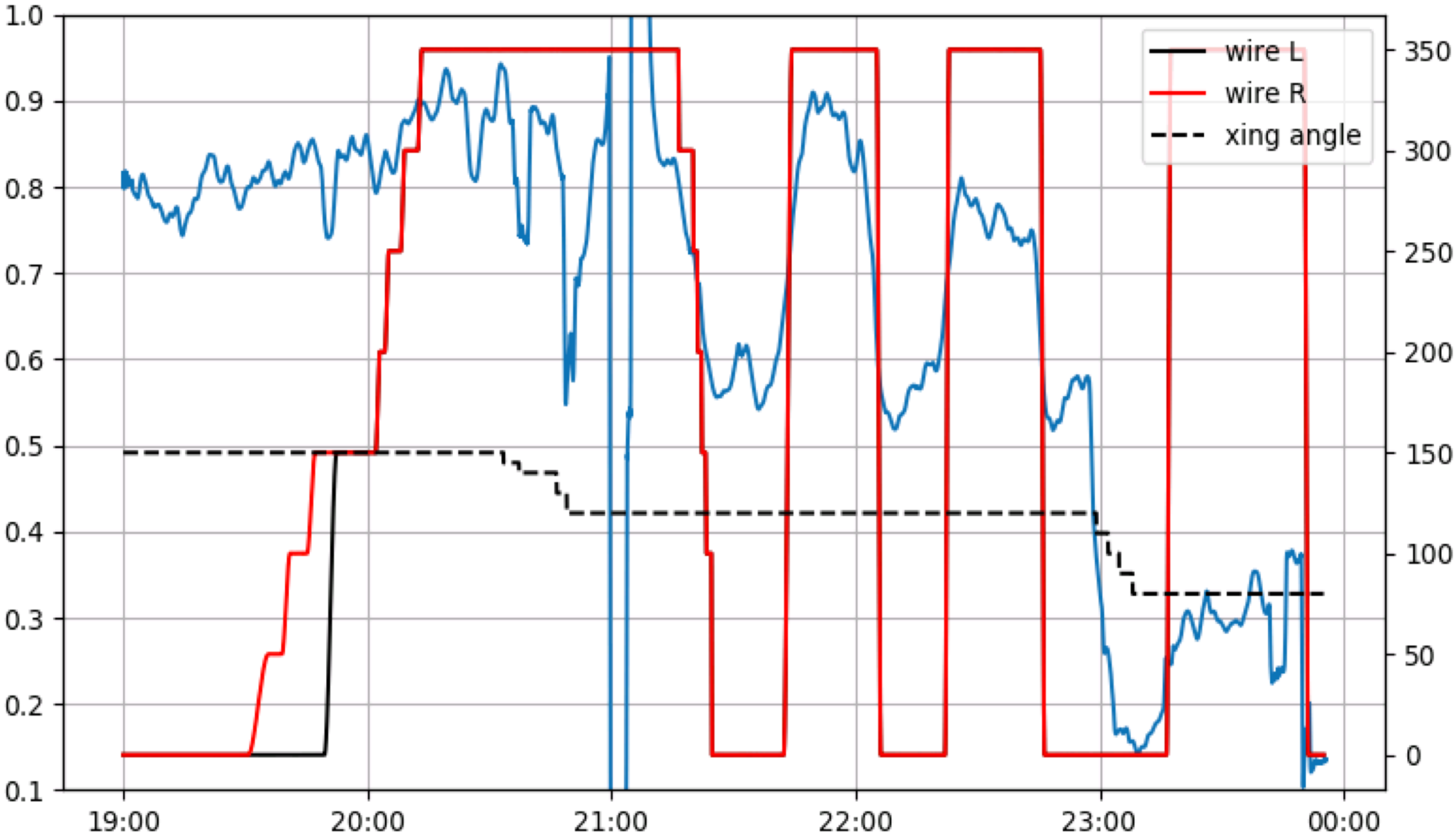


A.Rossi

Design:

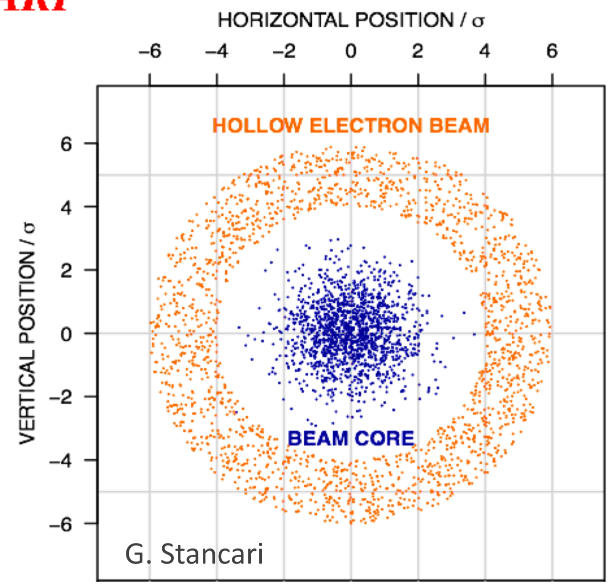
- High DC current (up to 350 A)
- Thin wire ($Ø_{CU} \leq 2.5$ mm)
- In-jaw wire (depth ≤ 3 mm)

Demonstration of Compensation 7/2017

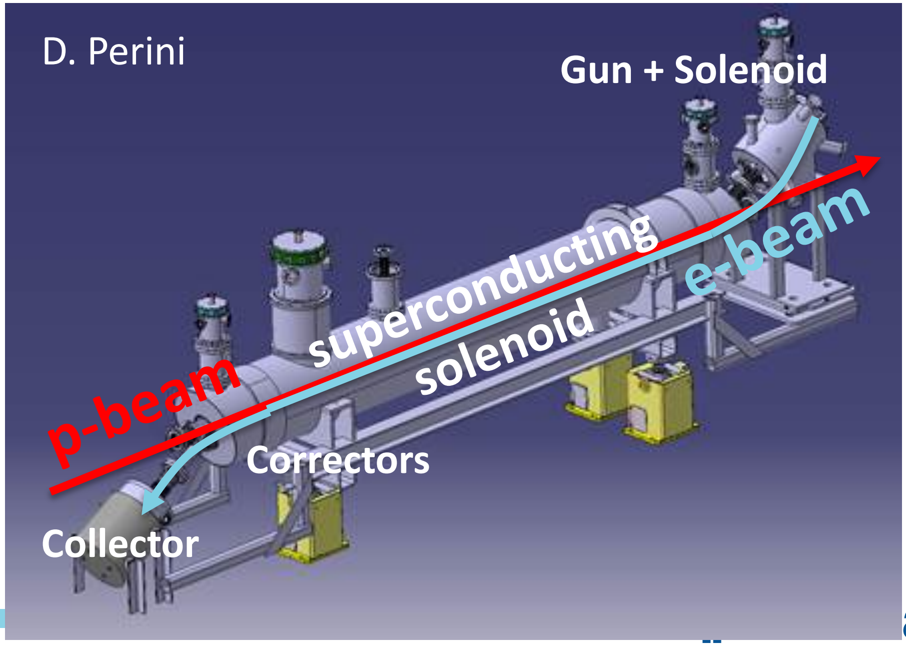


Blue trace – ratio of losses from control bunch/compensated bunch

Hollow e- Beam Collimation



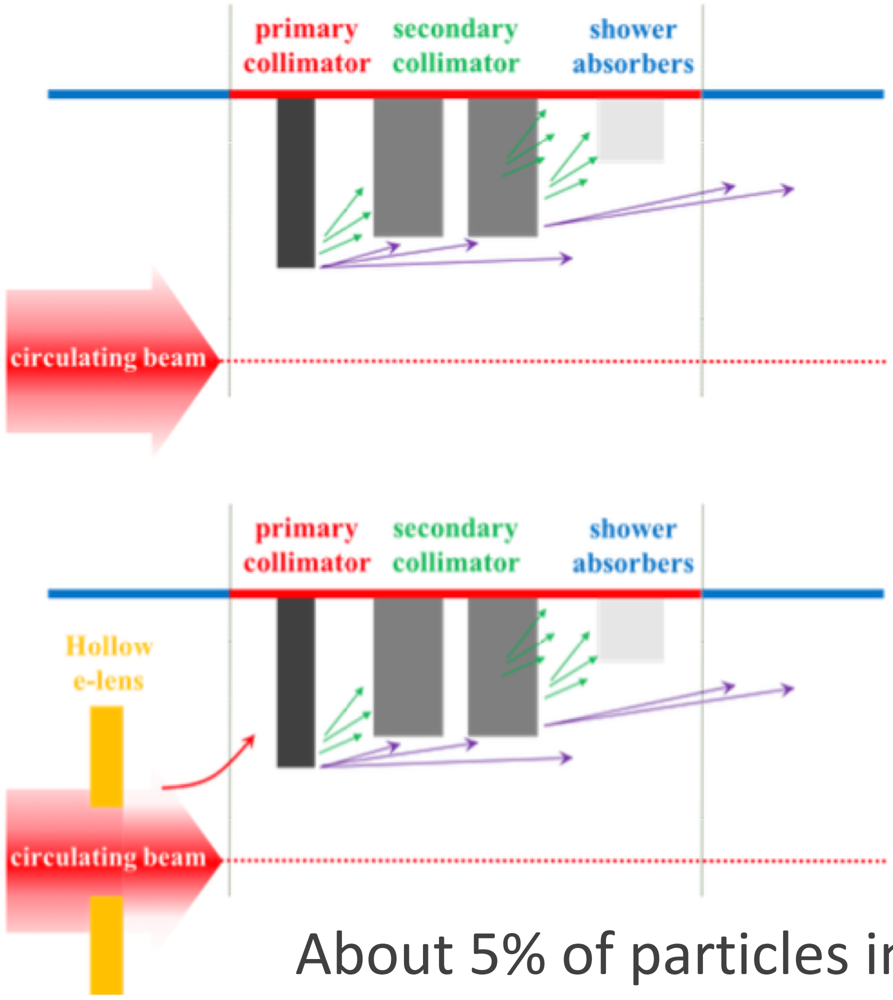
- proton beam (p-beam) traveling inside a hollow electron beam (e-beam)
- hollow profile of e-beam => p-beam core (ideally) not affected
- halo particles kicked to higher amplitudes by electromagnetic field of e-beam => cleaning of halo particles

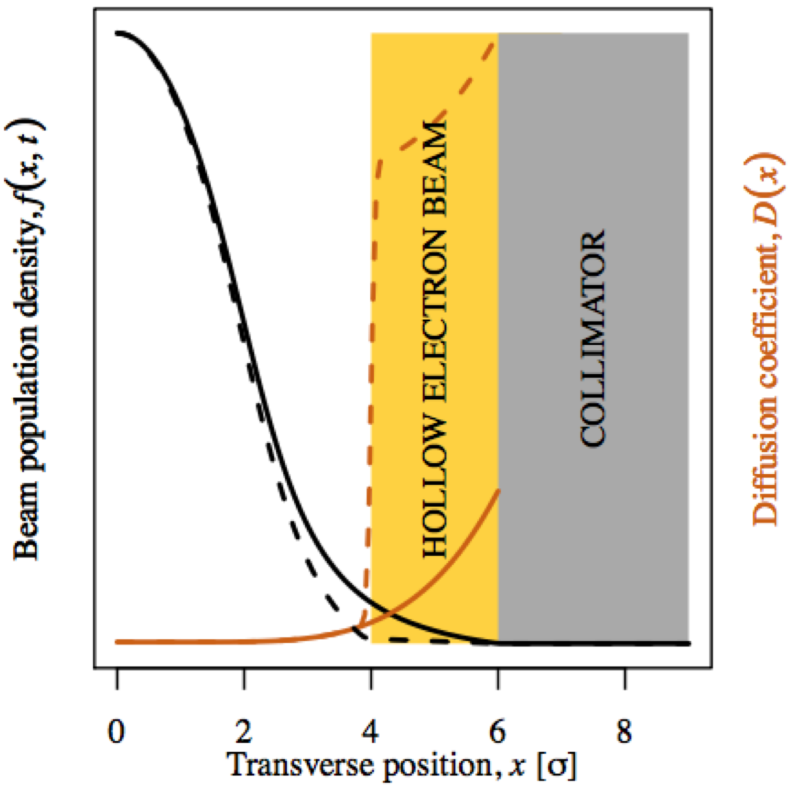


- magnetically confined, low-energy e-beam
- tunable transverse kicks of approx. 0.3 μrad

Tevatron demonstration:
G.Stancari et al,
Phys. Rev. Lett. 107, 084802 (2011).

Hollow e- Beam Collimation





About 5% of particles in the tails –
Stored energy 34MJ !

Conclusion

- HL-LHC is an exciting project from the accelerator physics/technology perspective with many novel and challenging problems to solve

HL-LHC Documentation

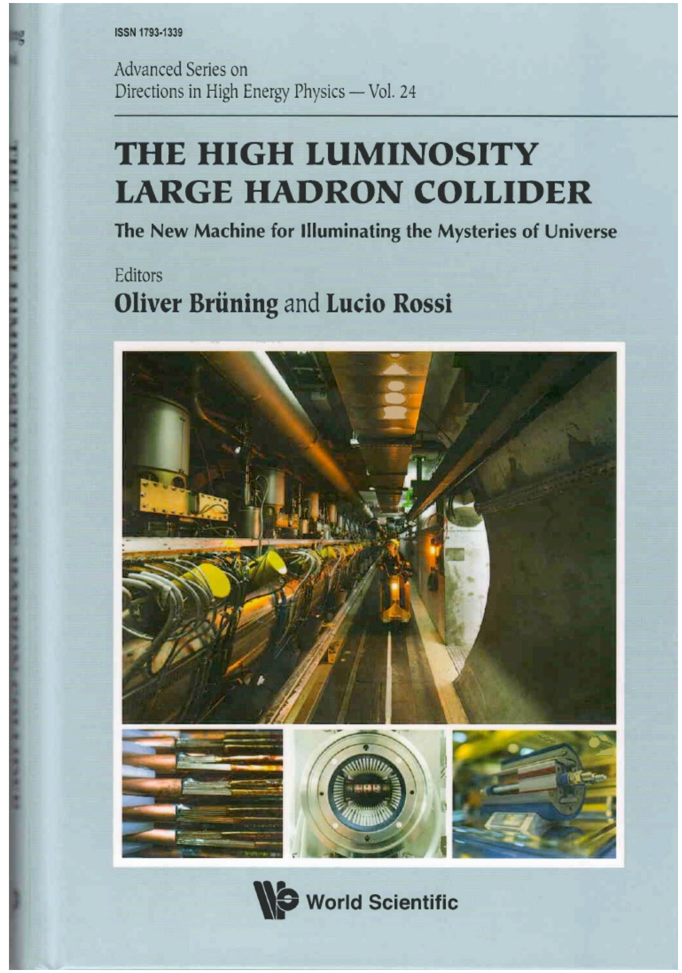
CERN-2015-005
17 December 2015

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

High-Luminosity Large Hadron Collider (HL-LHC)
Preliminary Design Report

Editors: Apollinari G.
Béjar Alonso I. (Executive Editor)
Brüning O.
Lamont M.
Rossi L.

GENEVA
2015



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