CERN

AXEL- 2023: Colliders

Rende Steerenberg – BE-OP

Topics

- Why Colliders ?
- Different Types of Colliders
- Luminosity, Cross Section and Events
- Crossing Angle
- Tune Shift as Result of Beam-Beam
- Collimation
- What will change for HL-LHC?

Fixed Target v.s. Colliders

Fixed Target

$$E \propto \sqrt{E_{beam}}$$

Much of the energy is lost in the target and only part is used to produce secondary particles

Collider

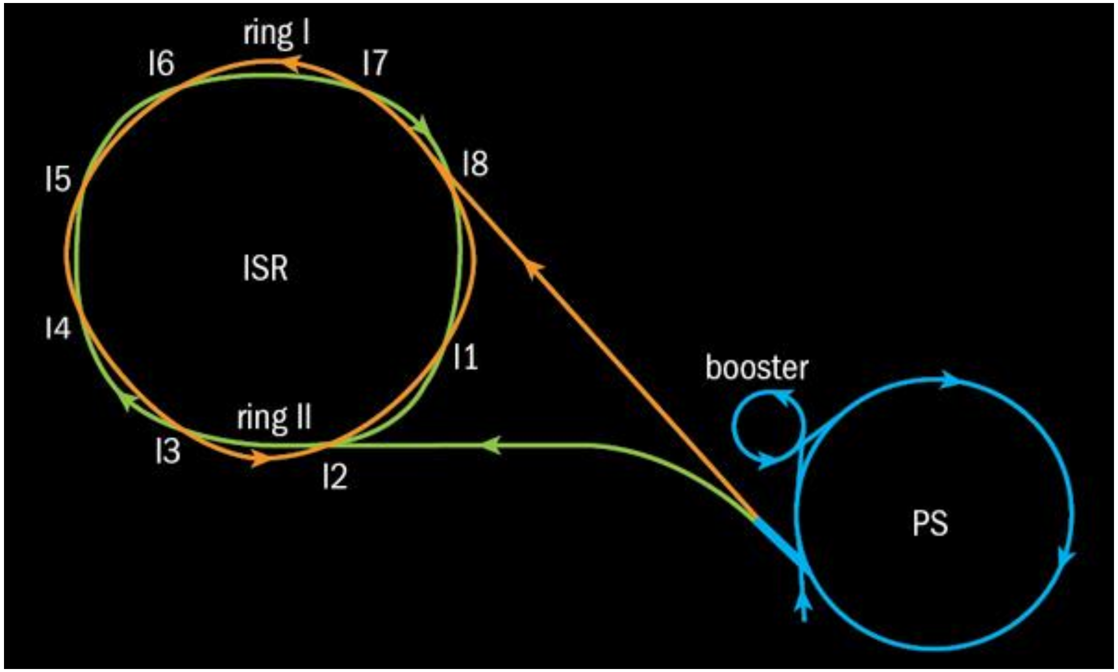
$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

Types of Colliders

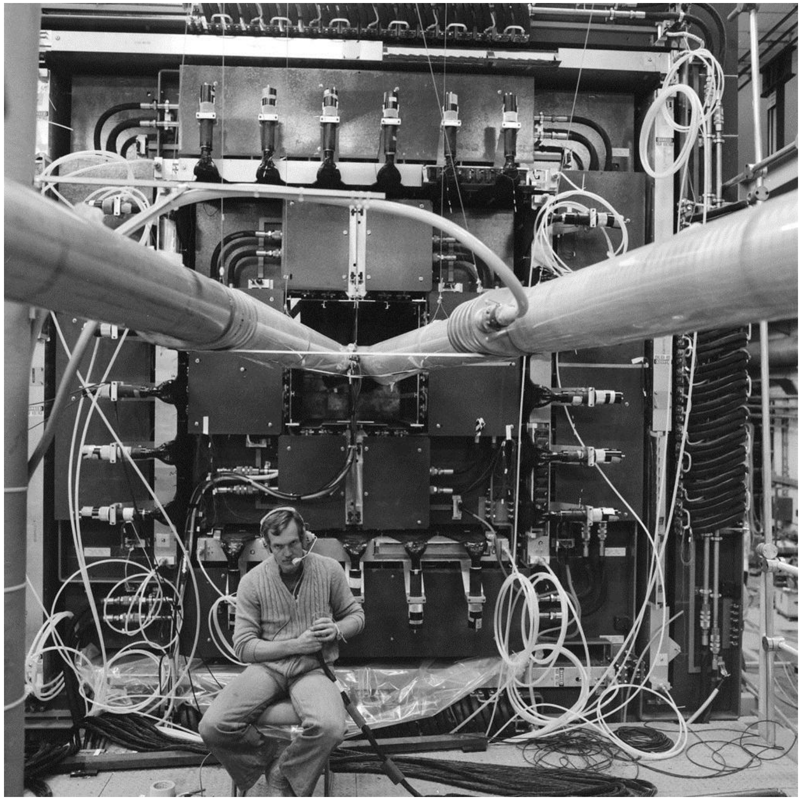
- **Single-ring collider**
  - Uses oppositely charged particle in single vacuum chamber
  - Electrons – Positrons (e^- - e^+)
  - Protons - Antiprotons (p^+ - p^-)
  - Opposite charged particles circulating in opposite directions are bend and focused along the same orbit by the same magnetic fields
  - SPS was CERN's first single-ring collider, followed by LEP (80's and 90's)
- **Twin-ring collider**
  - Two synchrotron rings, clockwise and anticlockwise, meeting at crossing points common to both rings
  - Can work with identical charged particles or even with different particle species
  - Initially with electron machine (Novosibirsk in1965 and Stanford in 1966)
  - CERN build the first hadron collider, the ISR, with 30 GeV per beam (1971)
  - The LHC is also a twin-ring collider
- **Linear Collider**
  - Electron Colliders (e.g. CLIC, ILC)
  - High energy and circular lepton colliders have reached more or less the limit with LEP
  - Although for the Future Circular Collider study a lepton variant is being studied

The CERN Intersection Storage Ring



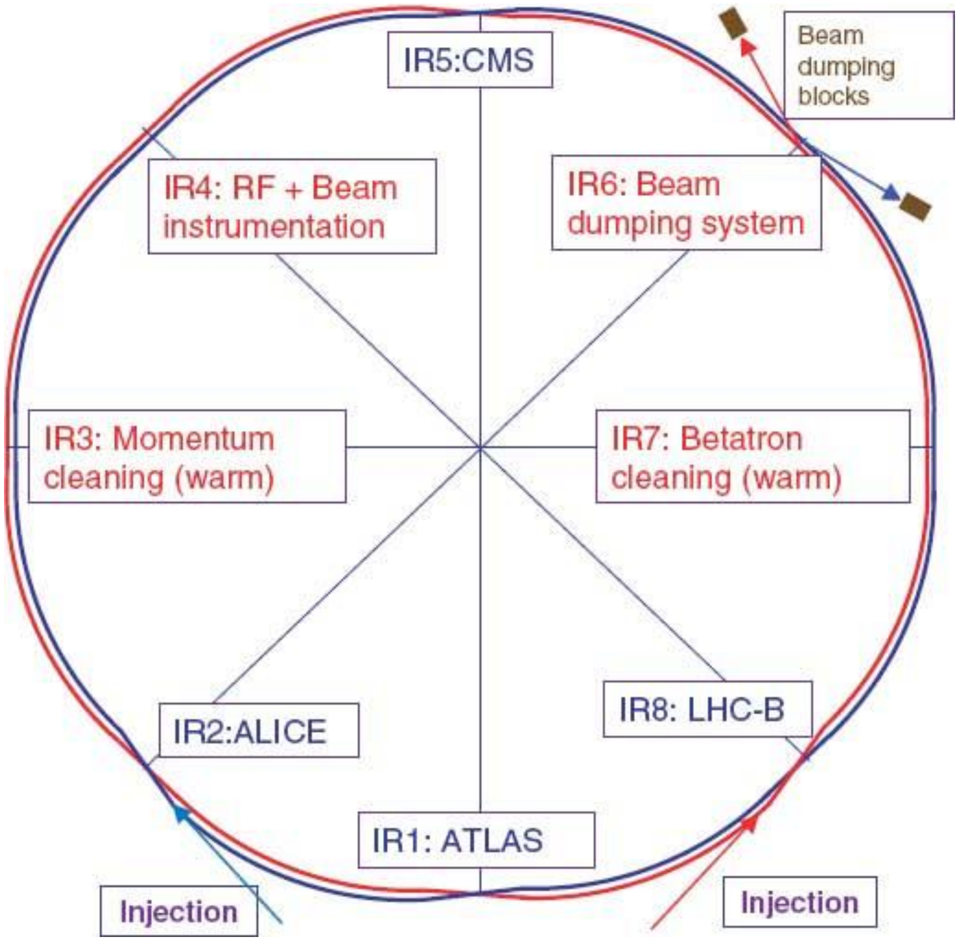
- The ISR collided beam at 30 GeV per beam
- In the ISR many hadron collider challenges were tackled and studied and have now become standard practice

Some Twin-ring ISR images



- 40 Amperes of beam current with de-bunched beam circulating

LHC a Twin-Ring Collider



- 8 sectors / arcs
- 8 long straight section
- 2 separate vacuum chambers
- 4 beam crossing points

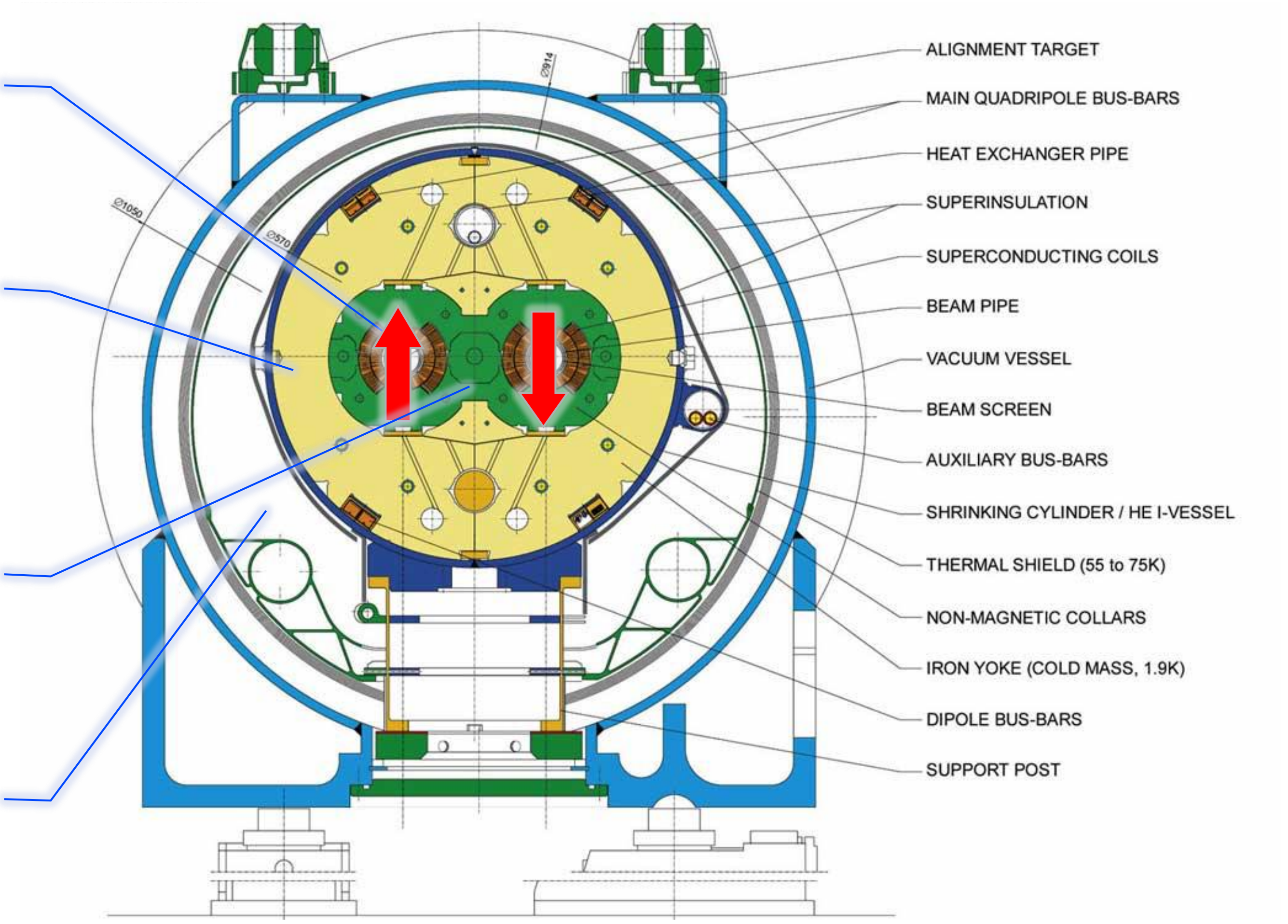
LHC Twin-Aperture Dipole Magnet

Magnetic field in opposite direction

Superconducting magnets, using superfluid helium as coolant

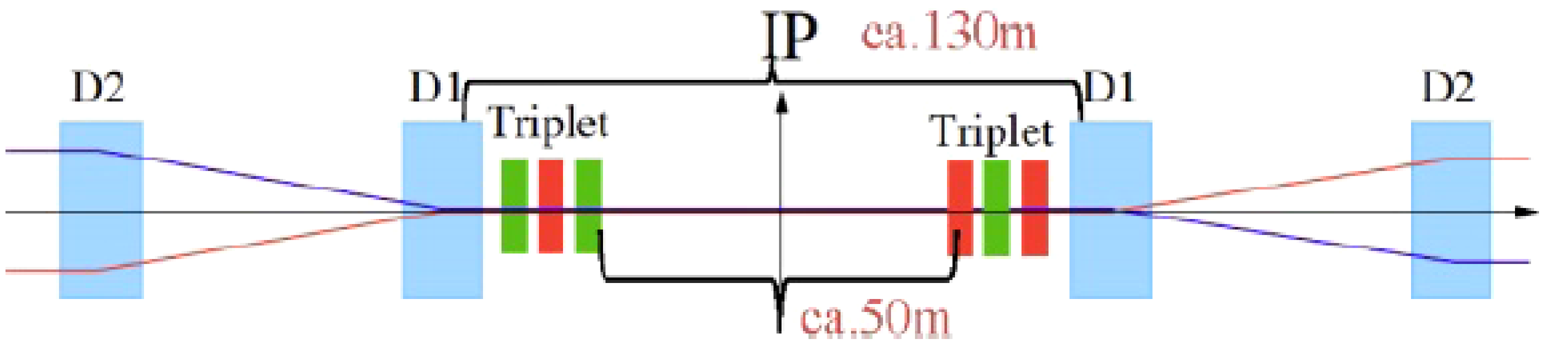
Beam pipe distance is 198 mm

Insulation vacuum



Beam Crossing in Interaction Region

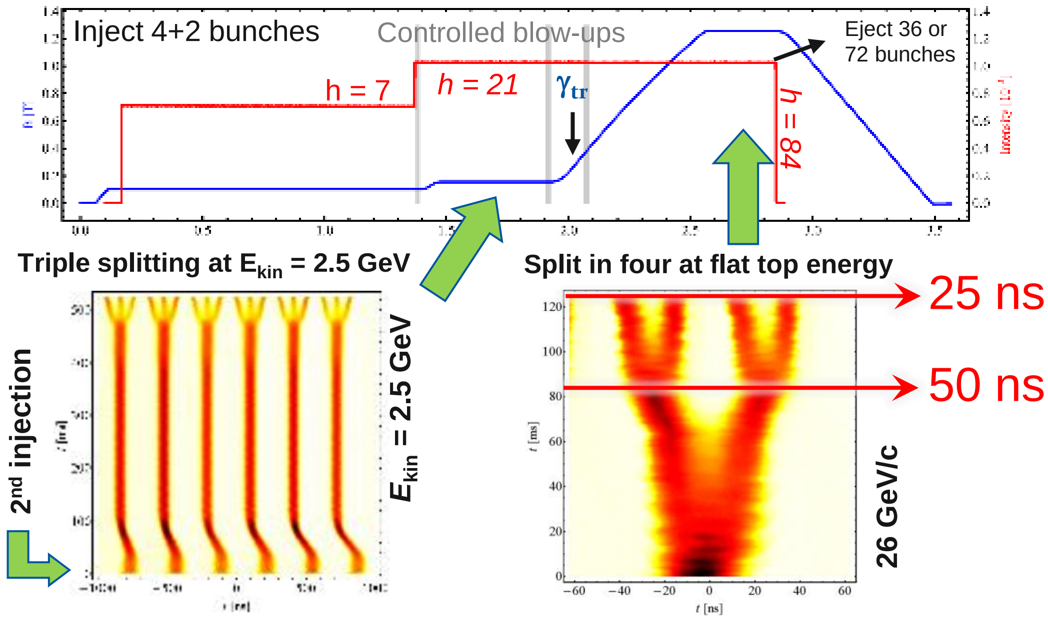
- Both beams Beam 1 and Beam 2 have the same energy and see the same magnetic field strength, but in opposite direction
- Therefore, they need to have an orbit with the same circumference



- Therefore Beam 1 and Beam 2 go from inner to outer ring and vise versa at the interaction points (IP)

A PS LHC Beam Production Scheme

- The LHC cycle in the PS with 1.4 GeV injection plateau, 2.5 GeV intermediate plateau and a flat top at 26 GeV
- Triple splitting at 2.5 GeV
  - Lower space charge, Larger bucket
- Two times a bunch splitting on the 26 GeV/c flat top
- Non-adiabatic bunch rotation before extraction ➔ 4ns bunch length (4σ)
- For 25 ns, the PSB bunch intensity is divided by a factor 12
  - $I_{LHC} = 1.2\text{x}10^{11}$ ppb → $I_{PSB} = 14.4\text{x}10^{11}$ ppb



25 ns: Each PSB bunch divided by: 12 → 6 x 3 x 2 x 2 = **72**
50 ns: Each PSB bunch divided by: 6 → 6 x 3 x 2 = **36**

- The transverse emittance determined by PSB (multi-turn injection)

Luminosity: The Collider Figure of Merit

- The challenge in a collider is to obtain a **high probability of collisions** in order to have many events in the experiments.
- This probability is called **luminosity**
- The actual number of events in the experiments therefore depends on the **Luminosity** and the proton **cross section**
- The total **cross section** of proton-proton interactions increases with **energy**
  - 1 barn = 10^{-24} cm^2 (size of Uranium nucleus)
  - 1 nanobarn (nb) = 10^{-33} cm^2
  - 1 picobarn (pb) = 10^{-36} cm^2
  - 1 femtobarn (fb) = 10^{-39} cm^2

The formula for Luminosity

Number of colliding bunches

Beam 1 intensity

Revolution frequency

Beam 2 intensity

$$L = \frac{f_{rev} \cdot n_b \cdot N_1 \cdot N_2}{2\pi \sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)} \cdot \sqrt{(\sigma_{y,1}^2 + \sigma_{y,2}^2)}} \cdot F \cdot H$$

Horizontal beam size

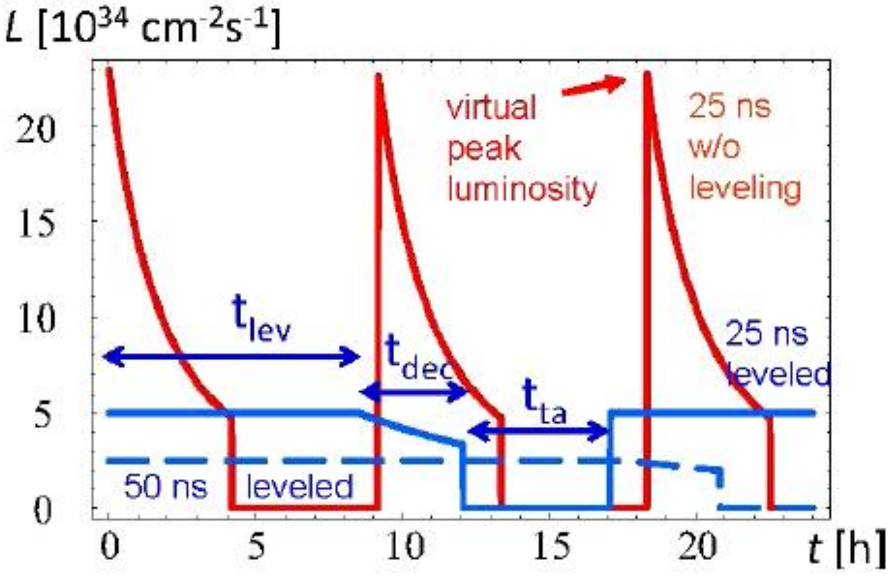
Vertical beam size

Geometrical reduction factors

- L is expressed in $cm^{-2}\ s^{-1}$
- At the LHC design luminosity of $1\text{x}10^{34}\ cm^{-2}\ s^{-1}$ and with a proton-proton cross section of $1\text{x}10^{-33}\ cm^{2}$ and design beam parameter we would produce 10 events per second
- In 2018 we went up to ~$2\text{x}10^{34}\ cm^{-2}\ s^{-1}$
- The experiments can cope with ~ 50 event per bunch crossing.

Luminosity burn-off & levelling

- When the beams just enter in collision the luminosity is the highest.
- Each proton that collides leaves a ‘hole’, which means that the beam brightness decreases, hence the luminosity decreases
- This phenomena is called **Luminosity burn-off**
- The peak luminosity can cause too many events
- This is called **Pile-up**
- In these cases, we can apply luminosity levelling
  - Separate the beams
  - Change crossing angle
  - Modulate the β^*
- Should provide about the same integrated luminosity with less pile-up

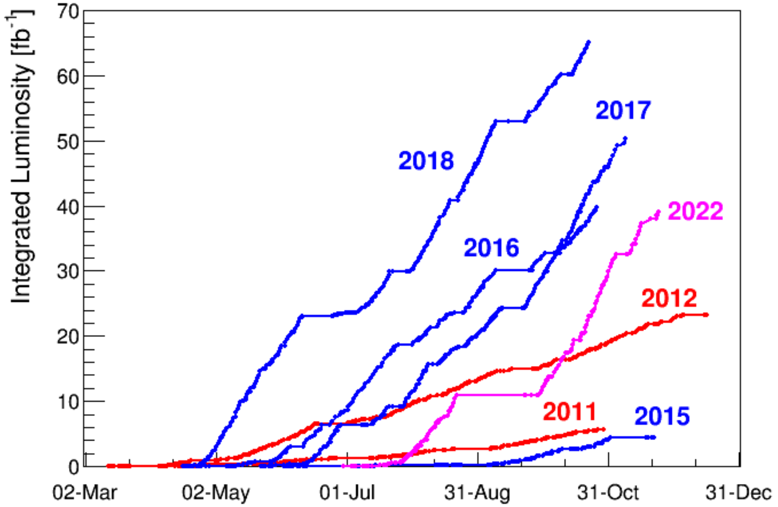


Integrated Luminosity

- The **integrated luminosity** is the peak luminosity multiplied by the time the beams were in collision, corrected by the burn-off and the turn-around

$$L_{\text{int}} \approx H L_{\text{peak}} T_{\text{phys}}$$

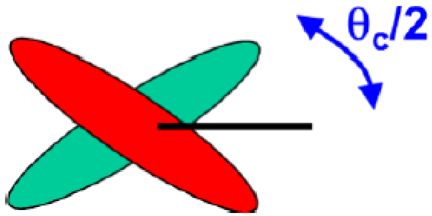
- *H* = Hübner factor which contains the burn-off correction and the turn around time from fill to the next
- Peak or instantaneous luminosity → $1x10^{-34}$ cm^{-2} s^{-1} (design value)
- Integrated luminosity unit is fb^{-1} (inverse femtobarn)
- In 2018 we managed 66 fb^{-1}
- In the short re-commissioning year 2022 we managed 41 fb^{-1}
- In 2023 we plan for 75 fb^{-1}



Crossing angle

- In the interaction regions the beam crosses and collides with an angle.
- This crossing angle will lead to a luminosity loss which is caused by the increase of the effective transverse beam size

$$L = \frac{f_{rev} \cdot n_b \cdot N_1 \cdot N_2}{2\pi\sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)} \cdot \sqrt{(\sigma_{y,1}^2 + \sigma_{y,2}^2)}} F \; H$$

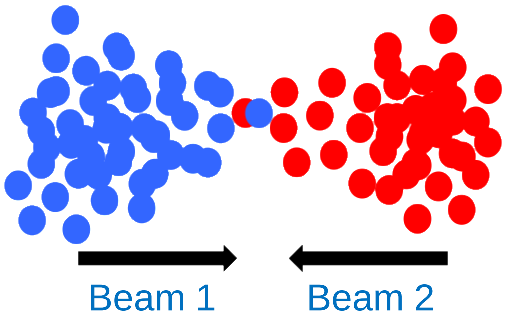


- The Luminosity loss is described by:

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}} \quad \text{where} \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Beam-Beam Effect

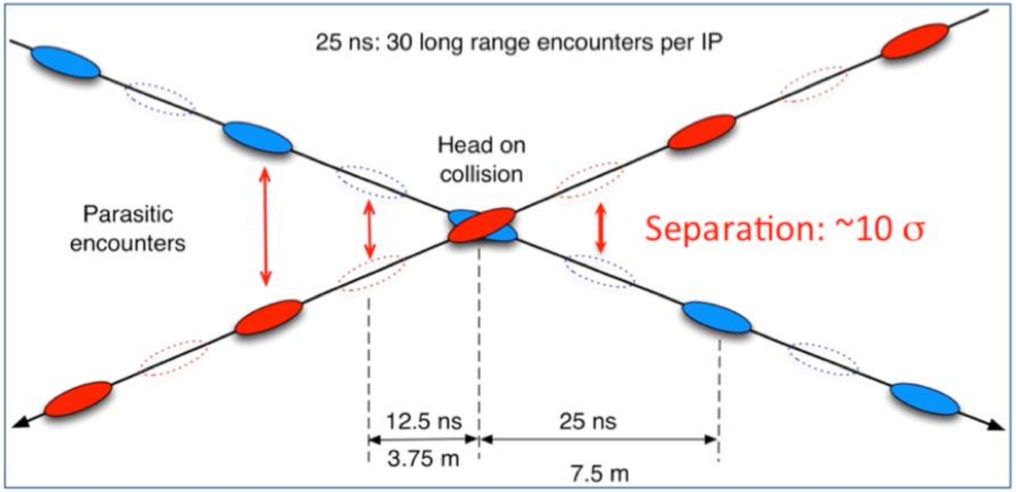
- When two beams collide, they interact
  - Elastic and inelastic collisions between particles → desired
  - Other electromagnetic interactions → undesired



- The particles in one bunch act like an electromagnetic lens on the others in the bunch and can change the beam parameters
  - The forces from one beam on another are non-linear
  - We cannot avoid the beams exerting forces on each other
  - This can have a detrimental effect, and can lower the luminosity

Beam-Beam Effect

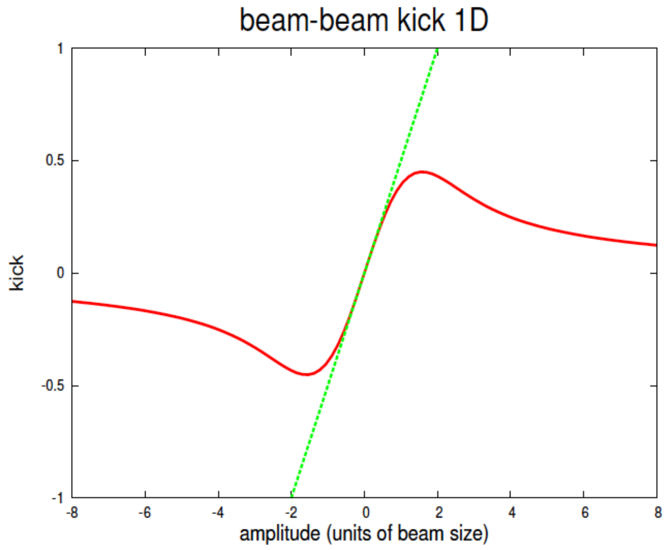
- Particle beam are surrounded by magnetic fields
- If the beams “see” each other in colliders these magnetic fields can act on the both beams and can cause tune shifts
- There are two types of interactions to be considered
  - Long range (parasitic encounters)
  - Short-range (head-on)



Short Range

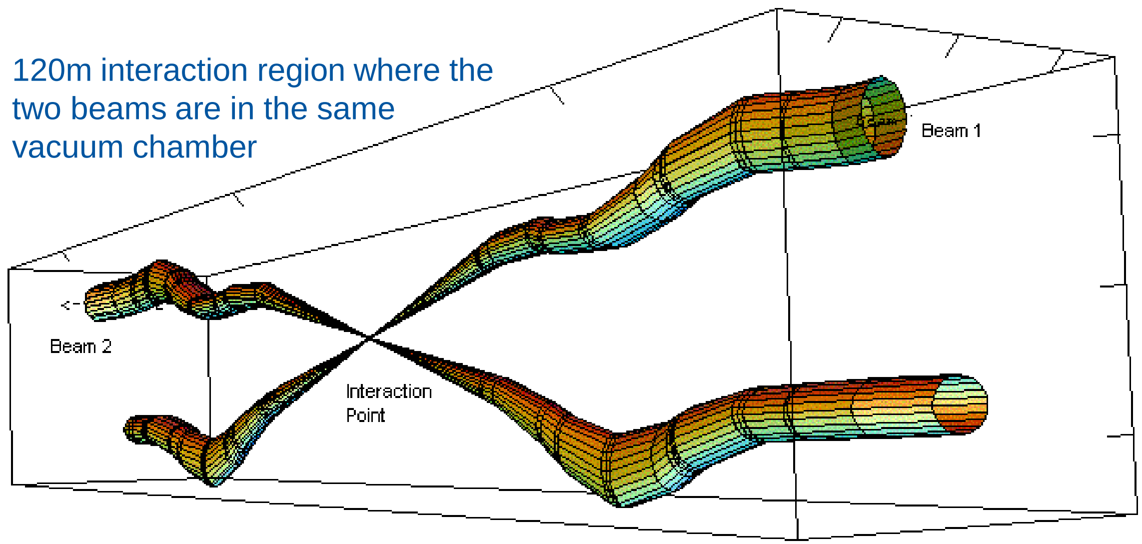
- Beam-beam force or kick:
  - Small amplitudes → linear force → large tune shift (quadrupole-like)
  - Large amplitude → non-linear force –> smaller amplitude dependent tune shift
- These forces can slightly modify the β-function and cause β-beating (modulation of the β-function)
- For round beams we characterise the effect by the beam-beam parameter:

$$\xi = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$



Long Range Beam-Beam Interaction

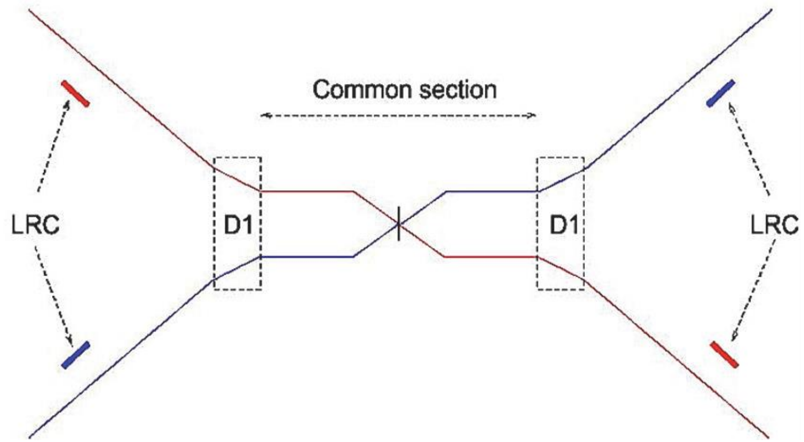
- In the LHC we locally separate the beams in the interaction regions with a crossing angle
- The larger the crossing angle the smaller the long-range beam-beam effect, but also lower luminosity



Relative beam sizes around IP1 (Atlas) in collision

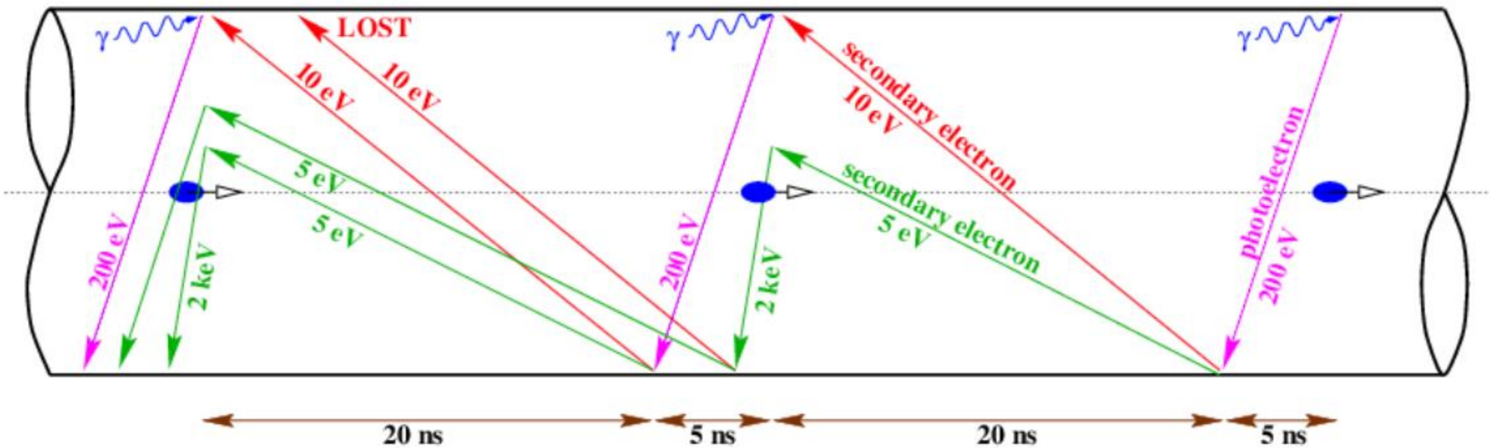
LR Beam-Beam Compensation Wires

- For HL-LHC Beam beam effect takes place in areas where the two beams share the same vacuum chamber → Interaction regions



- By adding wires next to the beam through which a current flows a part of the long-range beam-beam effect can be compensated

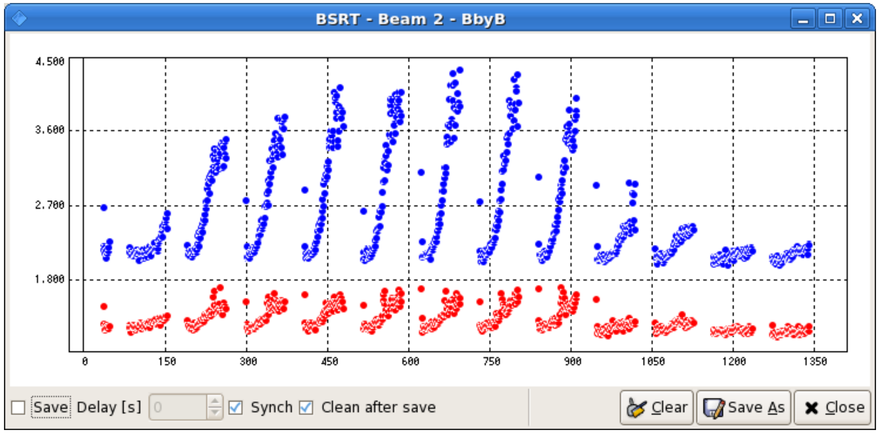
Electron Cloud



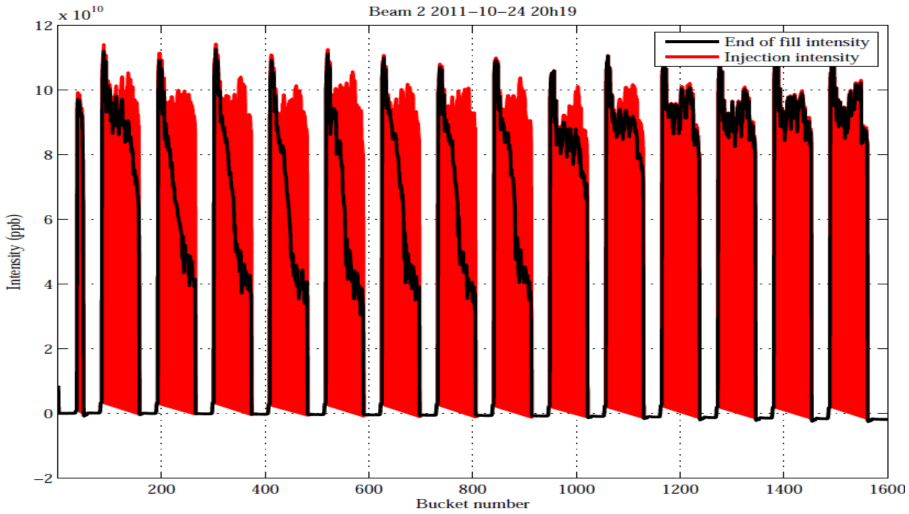
- e-cloud when secondary electron emission yield (SEY) of vacuum chamber is beyond 2, hence it depends on the vacuum chamber surface
- The electron cloud forms an impedance to the beam and can cause
  - Beam instability
  - Beam emittance growth
  - Beam losses
- e-cloud can cause severe dynamic vacuum bumps

Effects of Electron Cloud

- Increasing emittance growth along the batch of 25 ns bunches



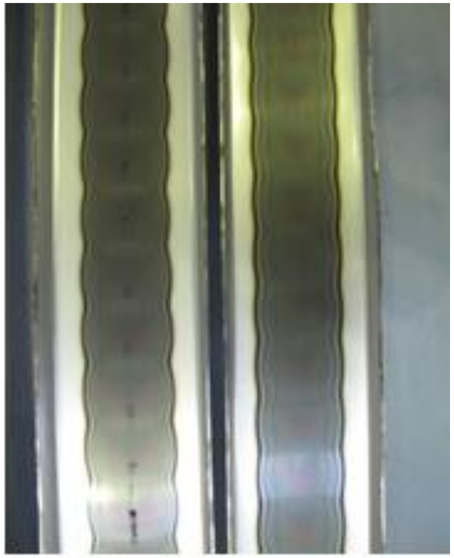
- Sustained loss of intensity along the batch of 25 ns bunches for the whole cycle



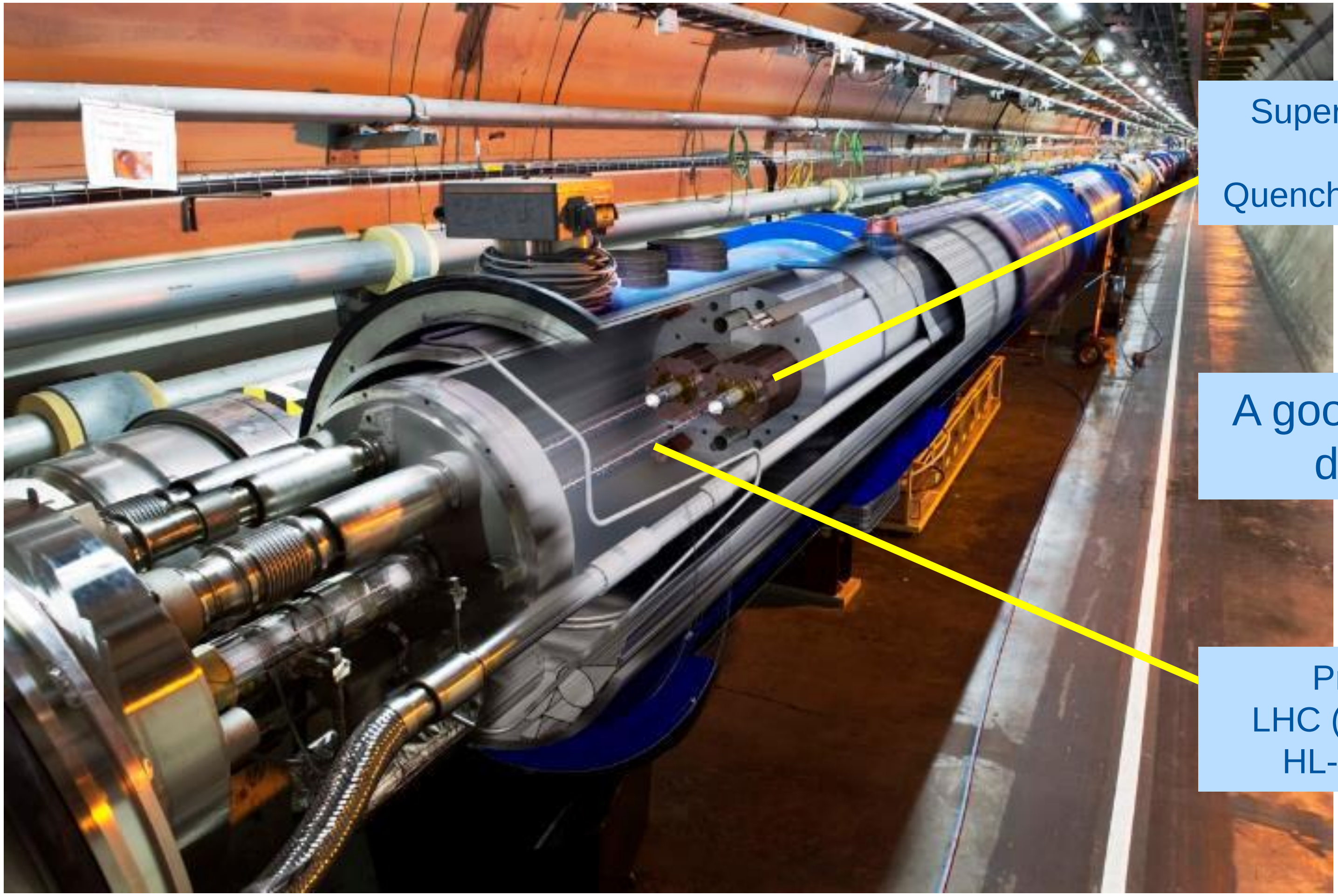
- It also causes an extra heat load to the cryogenic system

Mitigation measures

- In the SPS and the LHC we use the “scrubbing” method to reduce the SEY
- During the long shutdown (LS2) part of the SPS vacuum chambers have been carbon coated to reduce the SEY



Need for Collimation (protection)



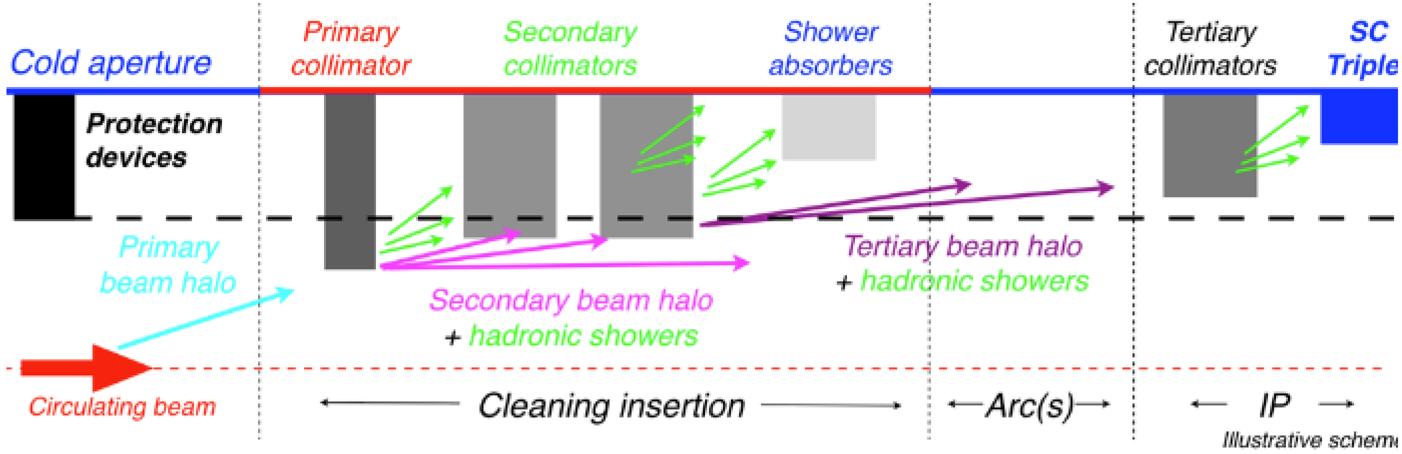
Superconducting coil
T = 1.9 K
Quench limit ~15mJ/cm^3

A good factor 10^{10} difference

Proton beam
LHC (today): 400 MJ
HL-LHC: 600 MJ

Collimation System

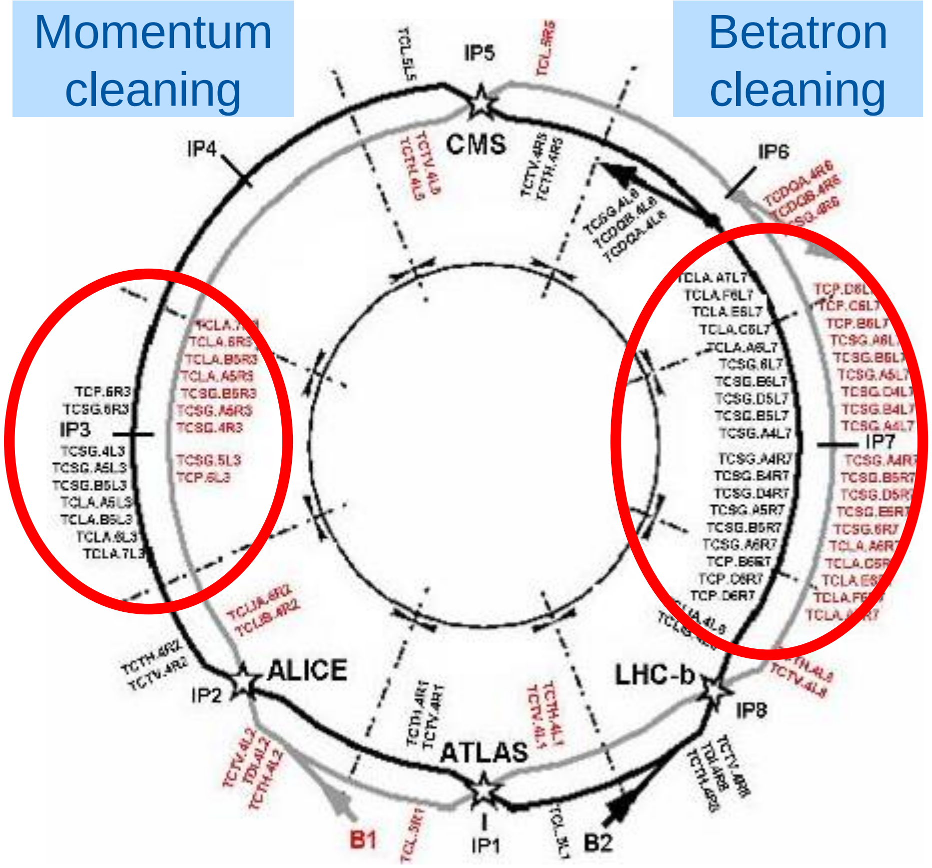
- Collimation is there to remove the halo (large Betatron amplitude) particles from the beam
  - Those halo particle are susceptible to be lost in the superconducting magnets



- The collimator jaws must follow the adiabatic damping of the beam size and remain centered around the beam

Betatron & Synchrotron Collimation

- Betatron cleaning
- Momentum cleaning
- Local cleaning at inner triplets
  - Protect experiments
  - Catch collision debris



Q3: Betatron & Momentum Cleaning

- In order to enhance the efficiency of the cleaning would you want or need to do something special on the machine optics in the area of the collimators?

Q3: Betatron & Momentum Cleaning

- In order to enhance the efficiency of the cleaning would you want or need to do something special on the machine optics in the area of the collimators?

- Put the horizontal betatron cleaning in areas where the β_{h} is large

$$\sigma_x = \sqrt{\beta_x \varepsilon}$$

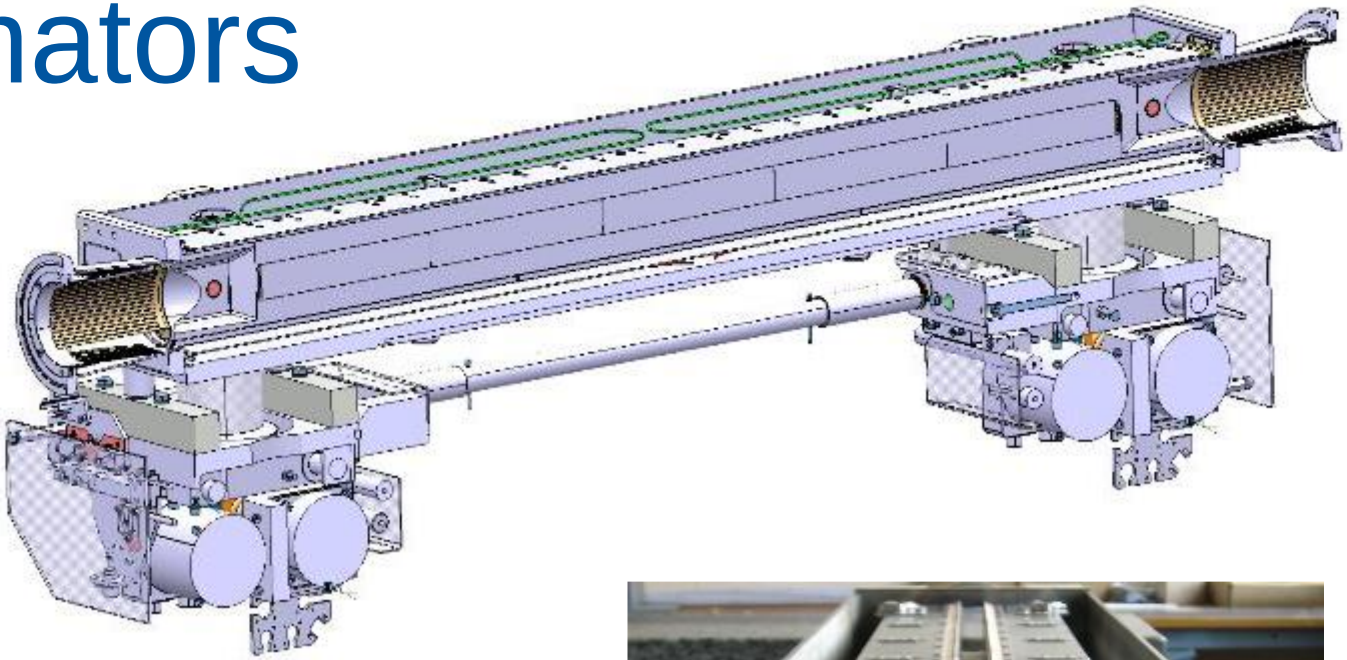
- Put the vertical betatron cleaning in areas where the β_{v} is large

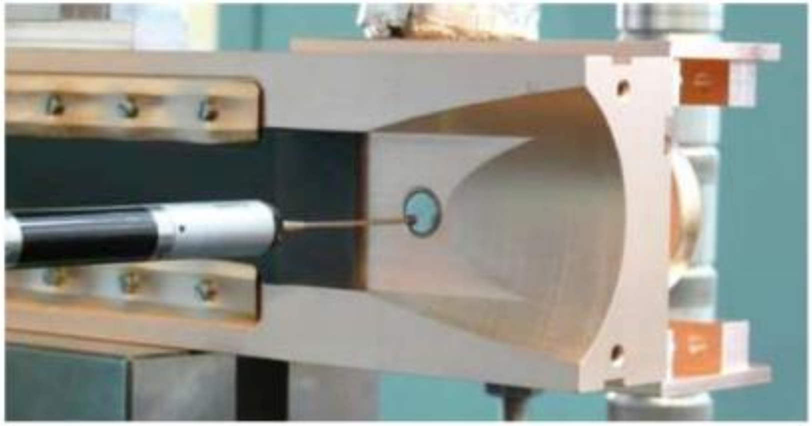
$$\sigma_y = \sqrt{\beta_y \varepsilon}$$

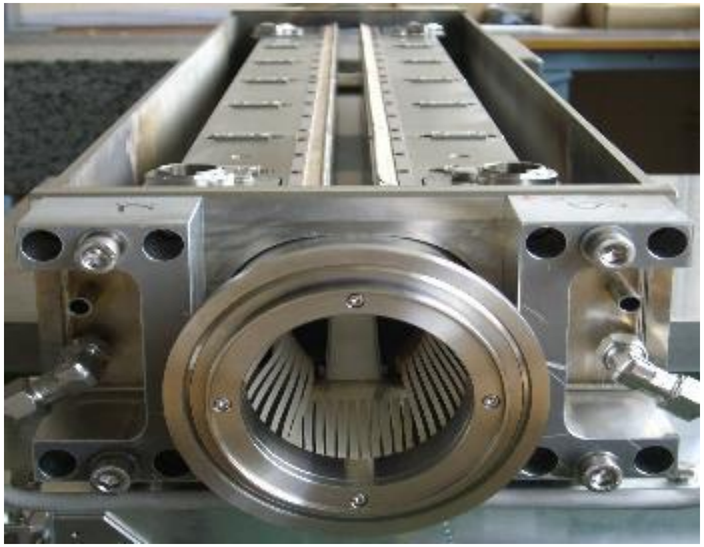
- Put the momentum cleaning there where the dispersion is large

$$\frac{\Delta x}{x} = D(s)\frac{\Delta p}{p}$$

Collimators

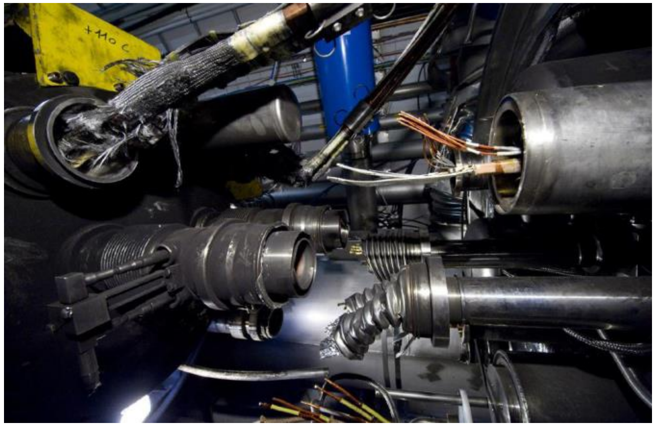
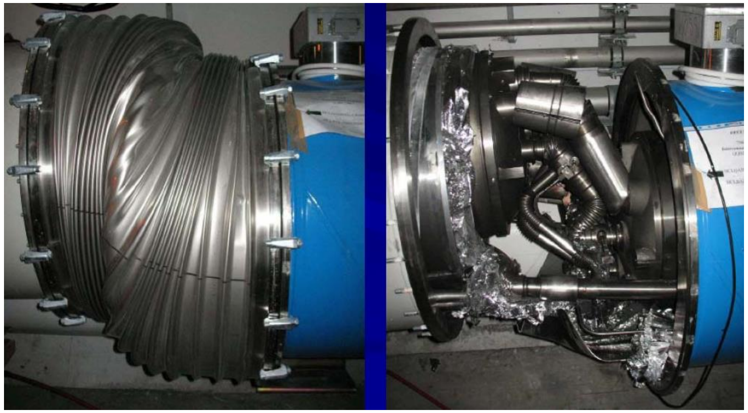






Machine Protection system

- In the 2008 incident an electrical arc released 600 MJ
- There was no beam in the machine !

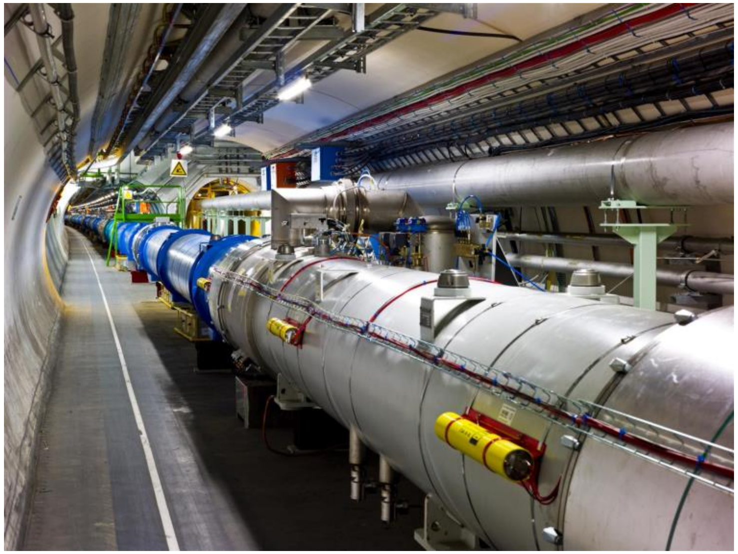

Machine Protection System

- This happened despite the presence of an already sophisticated machine protection systems

- Since then, the system has been further improved.

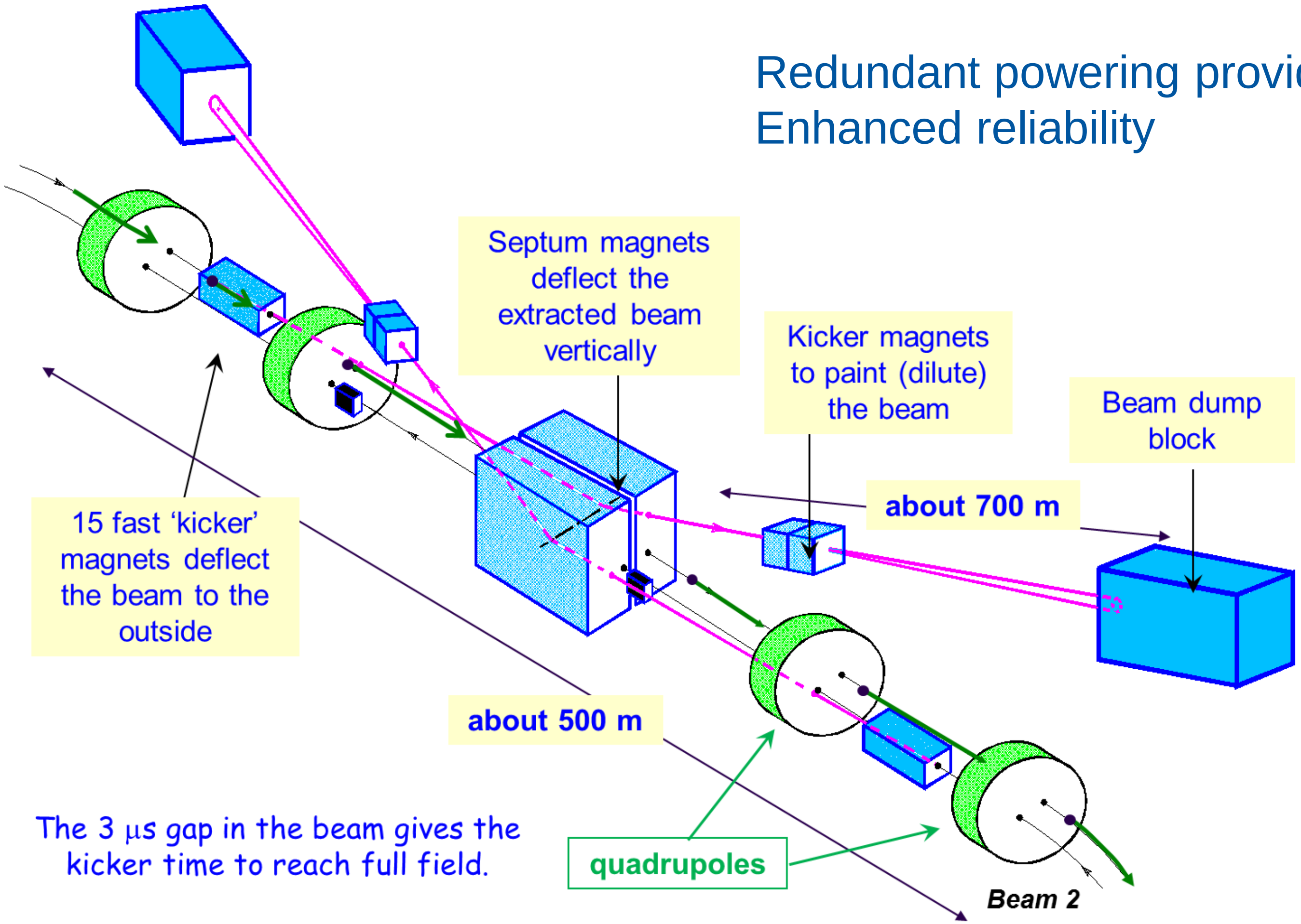
Interlocking & Beam Dumping

- Improved magnet quench protection systems and consolidated interconnections make that this is of the past.
- Nowadays nearly all type of beam instruments are used in interlocks:
  - Beam current transformer (BCT)
  - Beam Loss Monitors (BLM)
  - Beam Position Monitors (BPM)
- But also, power converters etc.
- The interlock system triggers the beam dump system



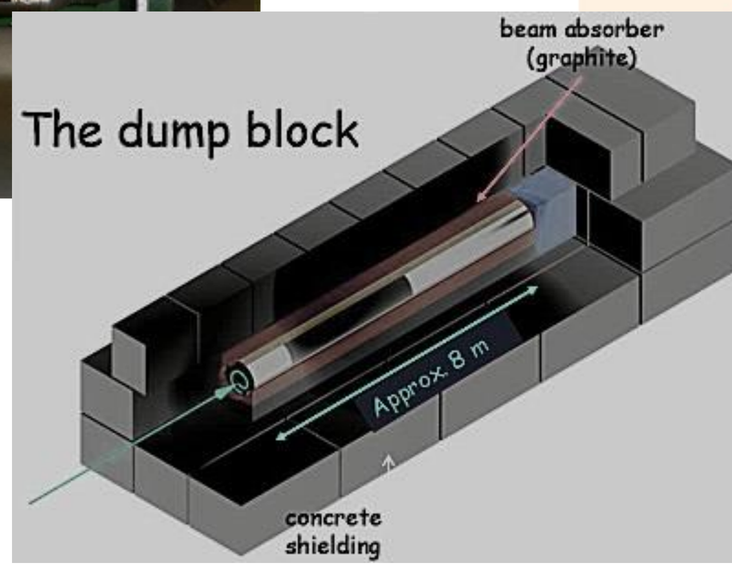
LHC Beam Dump System Layout

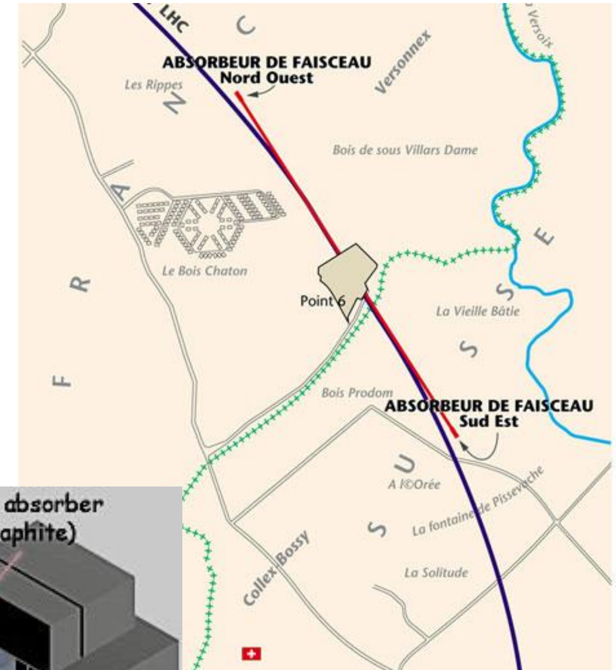
Redundant powering provides
Enhanced reliability



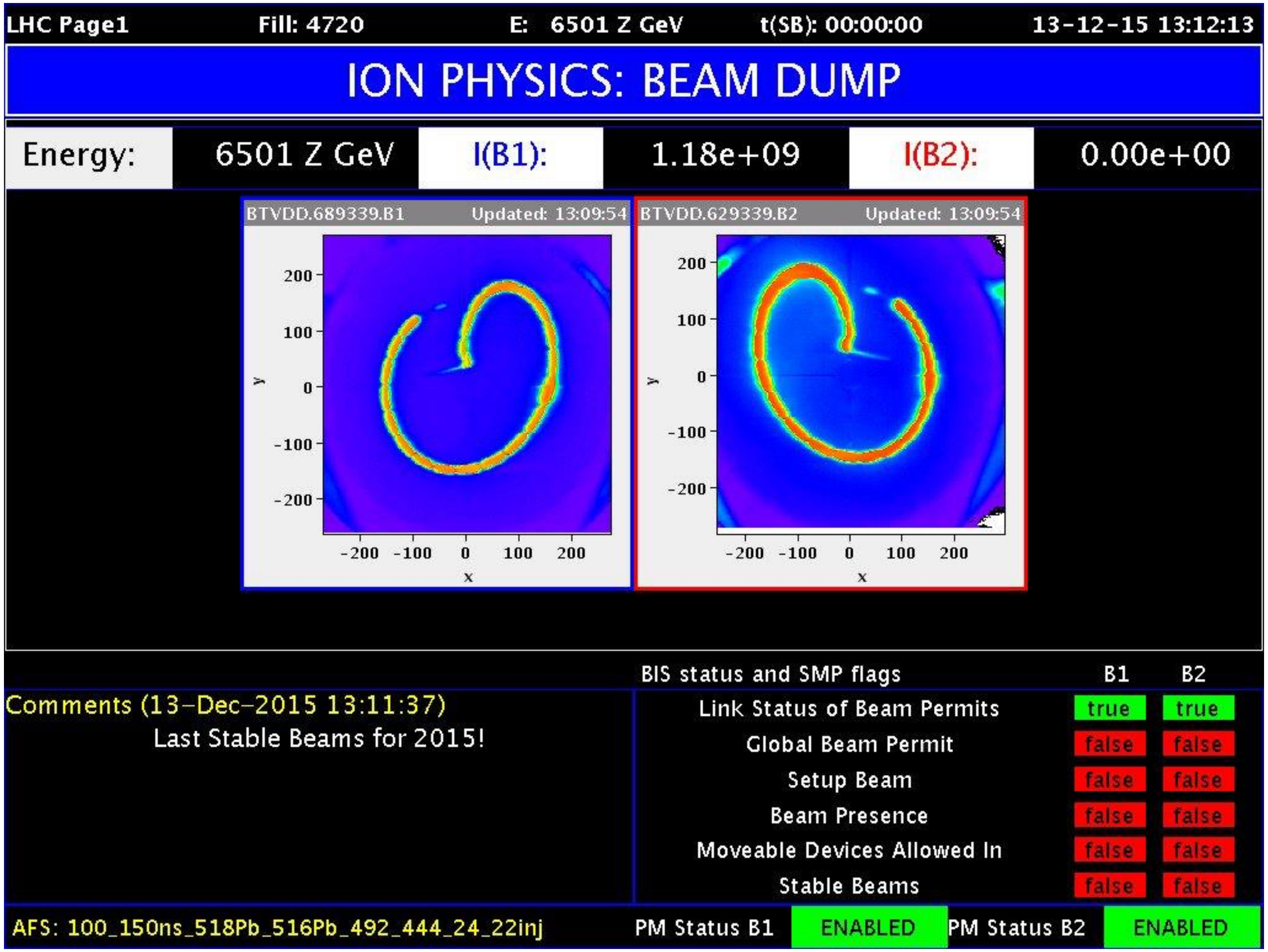
The 3 μs gap in the beam gives the kicker time to reach full field.

LHC Beam Dump





The Beam Dump on "LHC Page 1"



HL-LHC & LIU:
What Has and Still Will Changed

Luminosity, the Figure of Merit

Intensity per bunch

Number of bunches

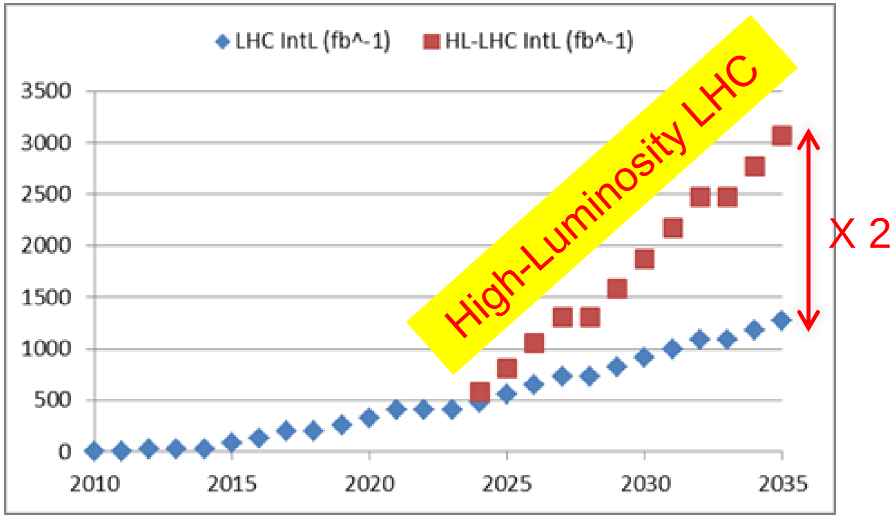
Geometrical Correction factors

Beam dimensions

$$LUMINOSITY = \frac{N_{event/\sec}}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi\sigma_x\sigma_y} F$$

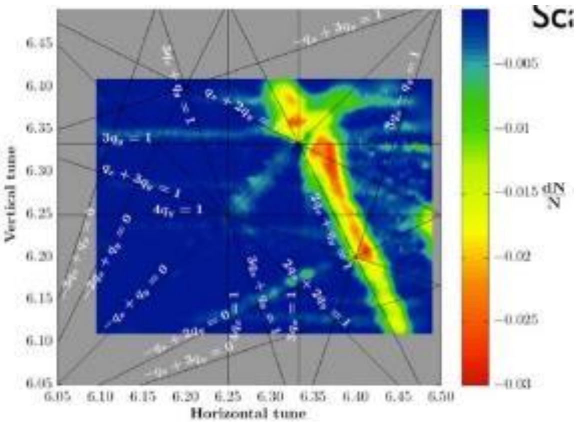
- More or less fixed:
  - Revolution period
  - Number of bunches

- Parameters to optimise:
  - – Number of particles per bunch
  - – Beam dimensions
  - – Geometrical correction factors



LIU: What has changed ?

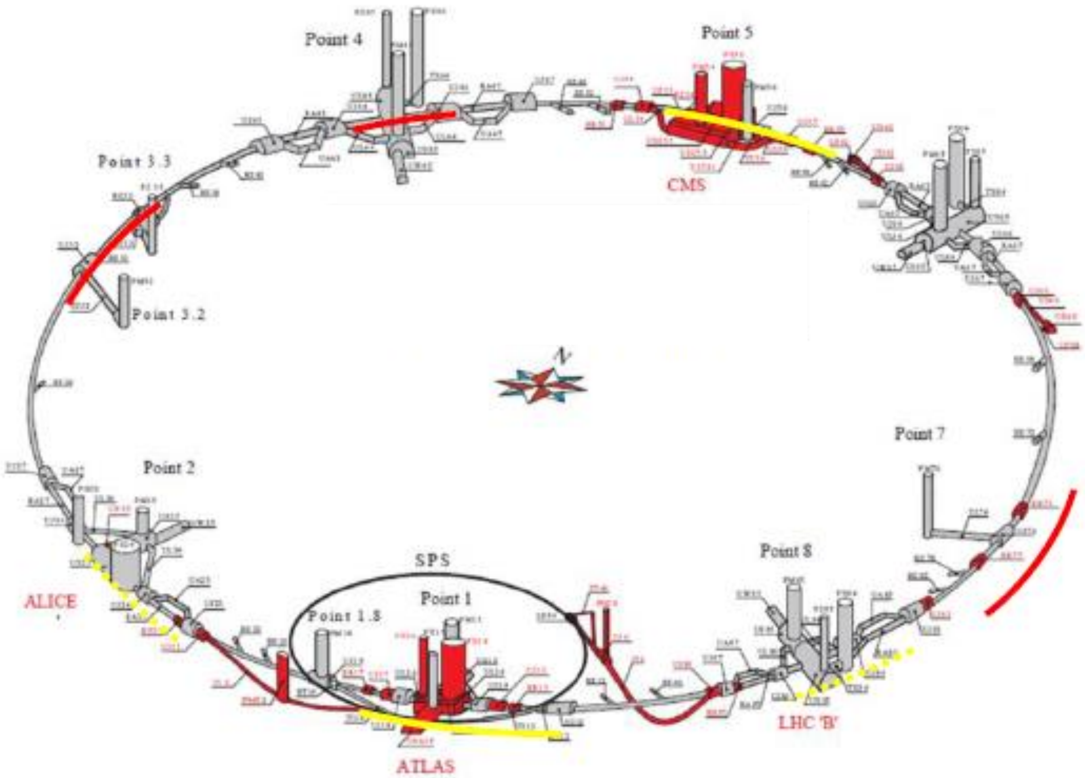
- LINAC4 – PS Booster:
  - New LINAC 4 with H^- injection
  - Higher injection energy
  - New Finemet® RF cavity system
  - Increase of extraction energy
- PS:
  - Injection energy increase from 1.4 GeV to 2 GeV
  - New Finemet® RF Longitudinal feedback system
  - New RF beam manipulation scheme to increase beam brightness
- SPS
  - Machine Impedance reduction (instabilities)
  - New 200 MHZ RF system
  - Vacuum chamber coating against e-cloud



Courtesy of A. Huschauer

These are only the main modifications and this list is not exhaustive

HL-LHC: What will be changed ?

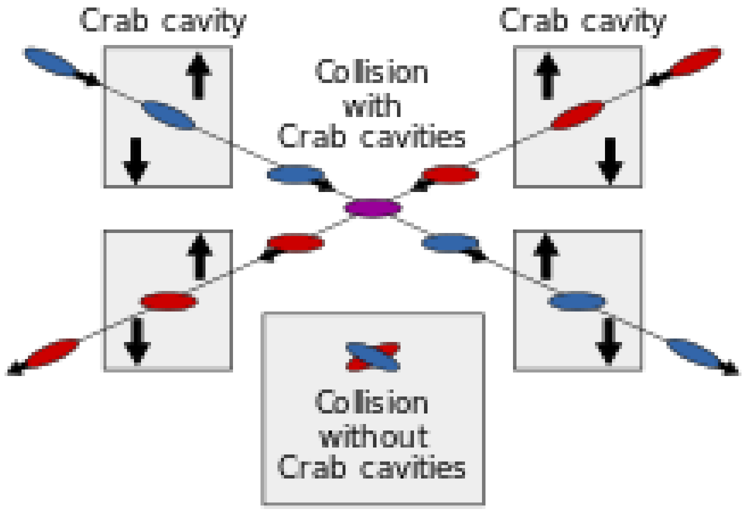


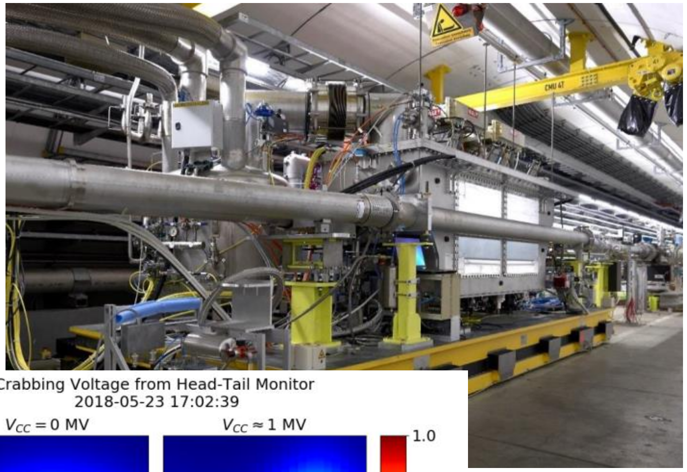
- New IR-quads (inner triplets)
- New 11T short dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

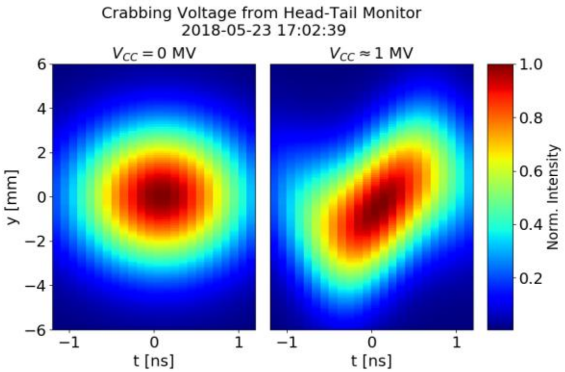
Major intervention on more than 1.2 km of the LHC
These are only the main modifications and this list is not exhaustive

Crabbing to reduce crossing angle effect

- To reduce the effective transverse beam size as a result of the crossing angle we should rotate the bunch before collision and return it in its original position after collision



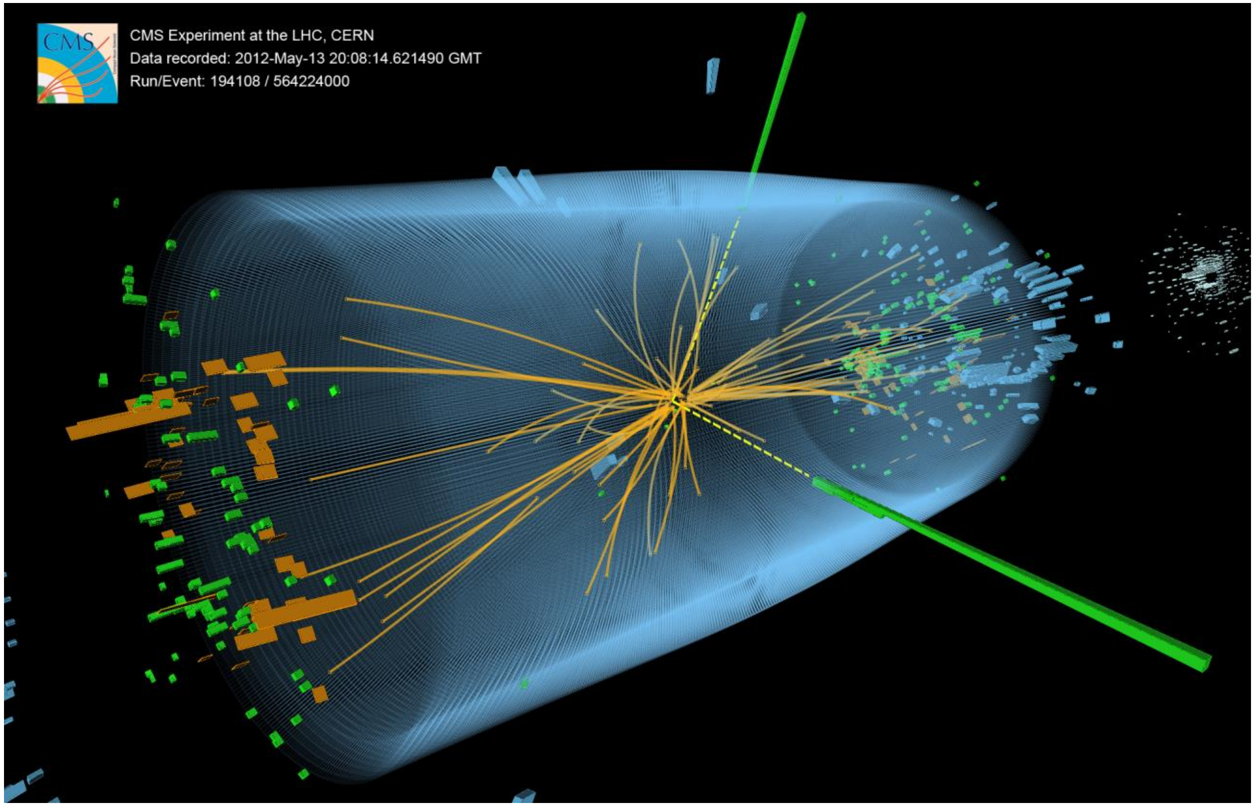




World's first crabbing on a proton beam

(23 May 2018)

Our rewarded: Very Nice and Impressive Physics Results



An event recorded with the CMS detector in 2012 at a proton-proton center-of-mass energy of 8 TeV.
The event shows characteristics expected from the decay of the SM Higgs boson to a pair of photons (dashed yellow lines and green towers). .

Any Questions ?

www.cern.ch