Lecture 2

Live Feed – CERN Control Centre

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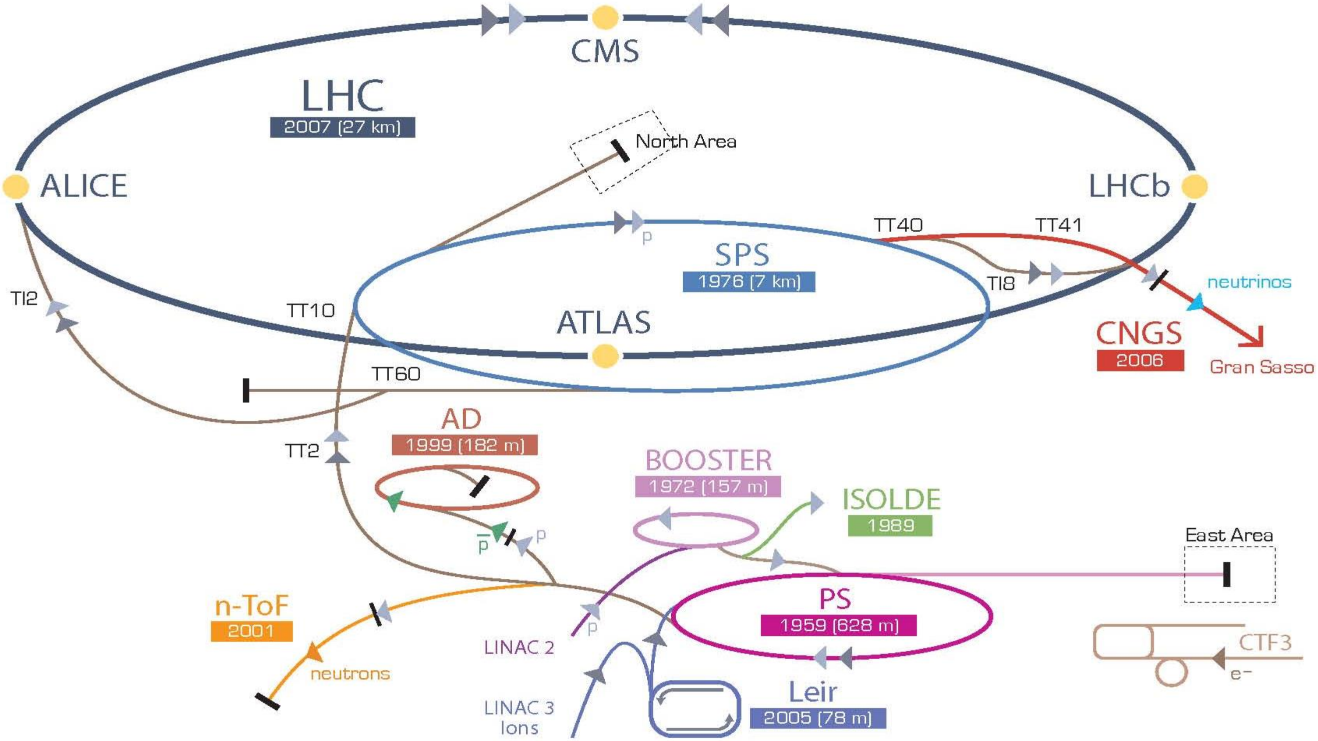
CERN & University of Oxford

Graduate Accelerator Physics Course

John Adams Institute for Accelerator Science

11 October 2017

CERN Accelerator Complex



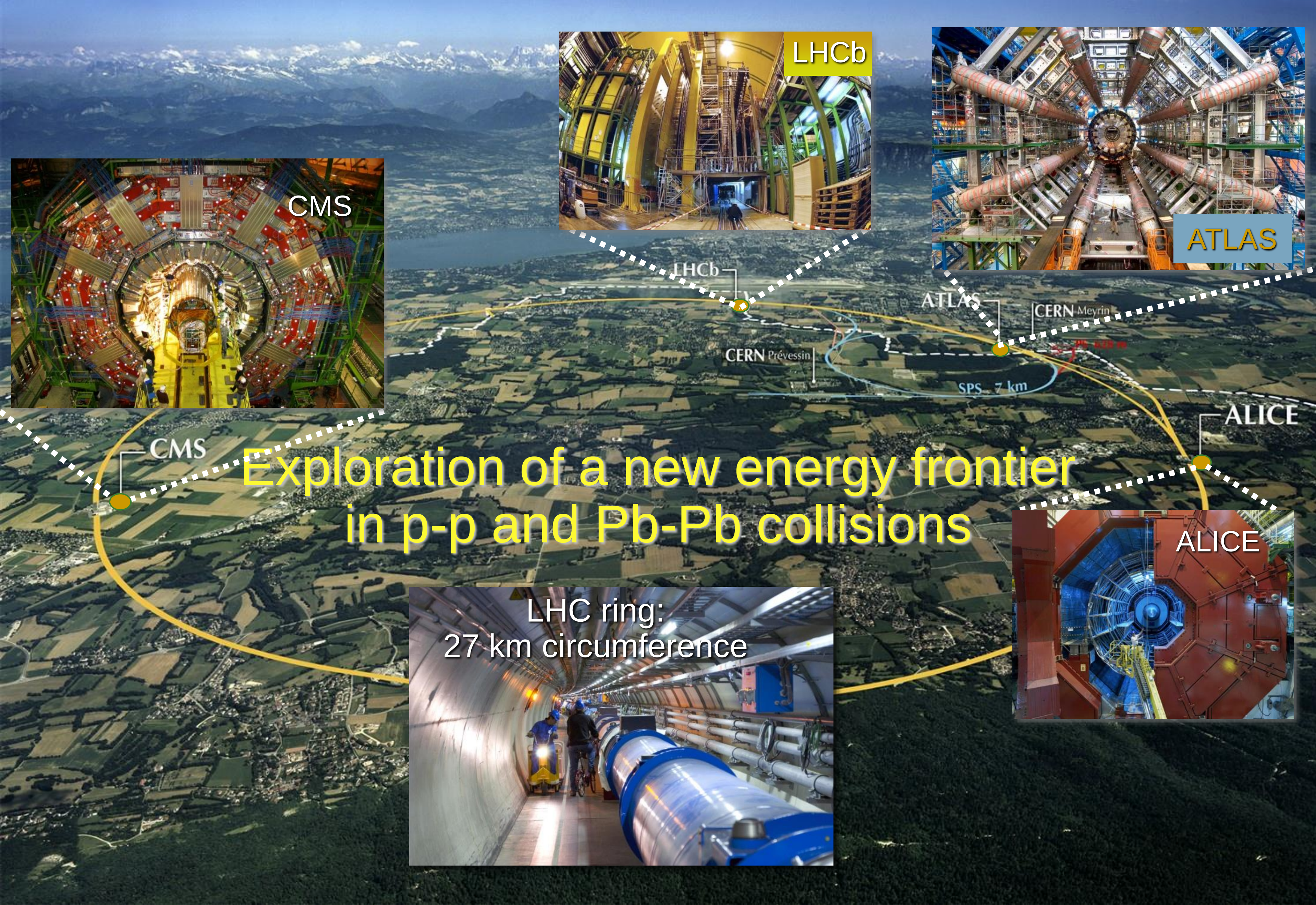
p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

A New Era in Fundamental Science

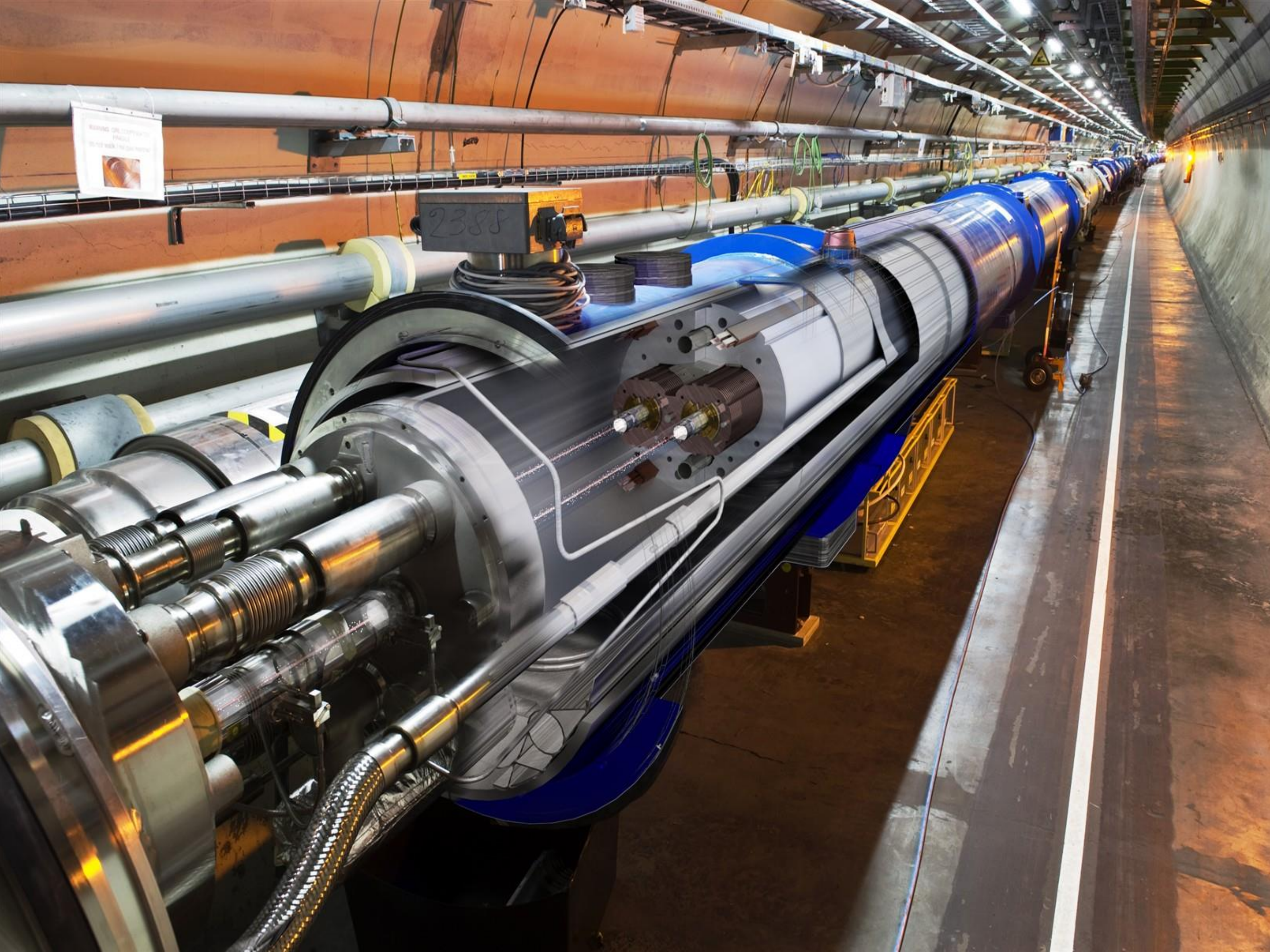


Exploration of a new energy frontier
in p-p and Pb-Pb collisions

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".*

The LHC Arcs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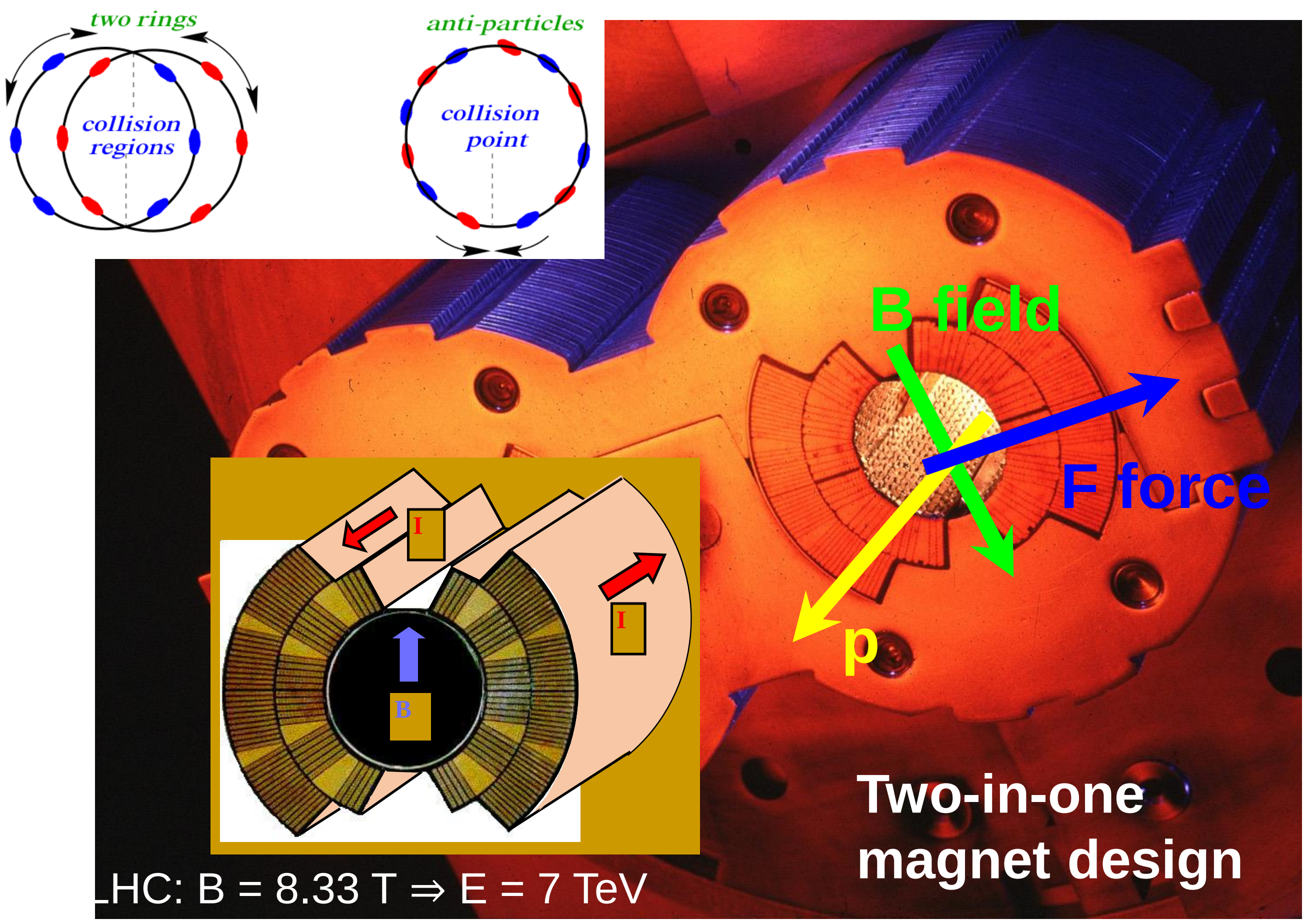
Steering the Particle Beams

- A magnetic field can be used to deflect the particles.
- Lorentz force: $f = q(E + v \times B)$
- The LHC uses very strong magnets to keep its particles in a circular orbit.

LHC Dipole

http://lhc-machine-outreach.web.cern.ch

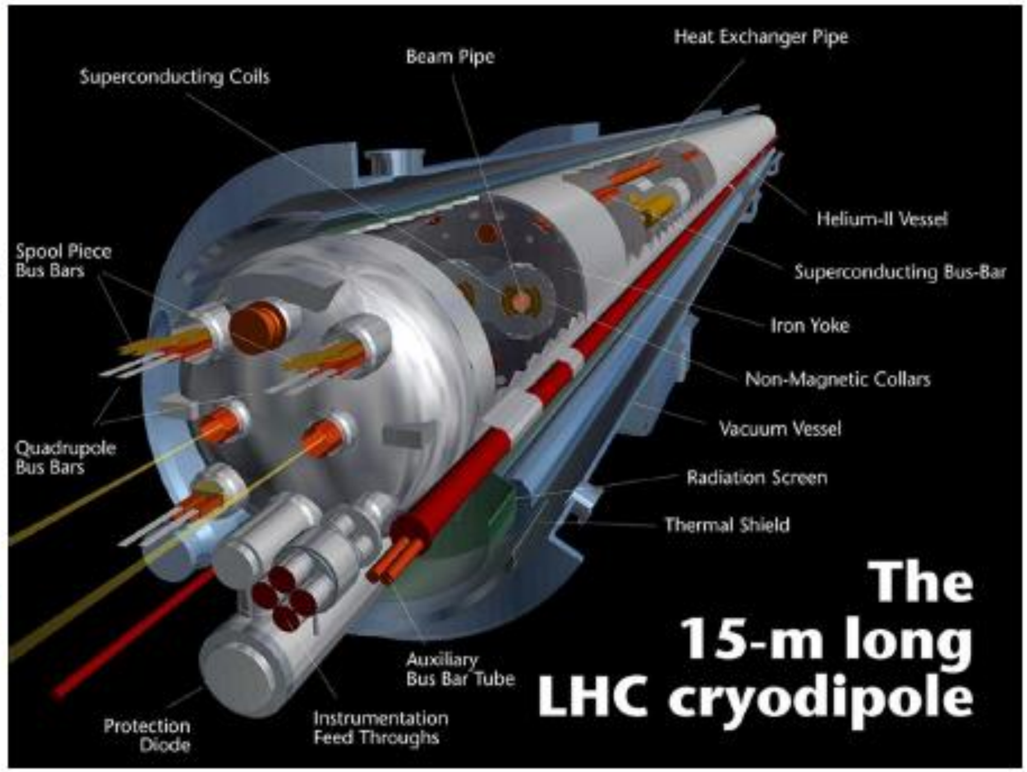
Bending



two rings
collision regions
anti-particles
collision point
B field
F force
p
I
I
B
Two-in-one magnet design
LHC: B = 8.33 T ⇒ E = 7 TeV

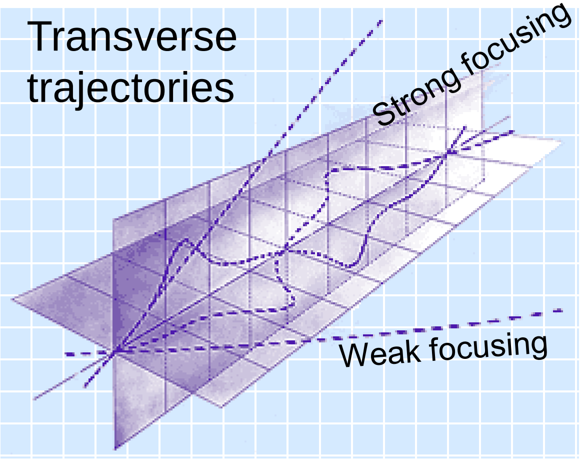
Superconducting Magnets

- The intense magnetic field used by the LHC magnets (dipoles, quadrupoles, etc…) requires a high current to flow in these magnets.
- To avoid dissipating large amount of power in these magnets the LHC uses superconducting technology



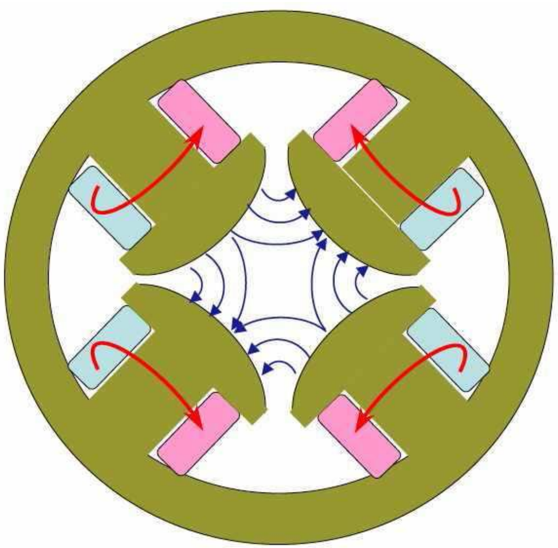
http://cds.cern.ch

- “Strong focusing” alternates focusing-defocusing forces (provided by quadrupoles) to give overall focusing in both X & Y planes.



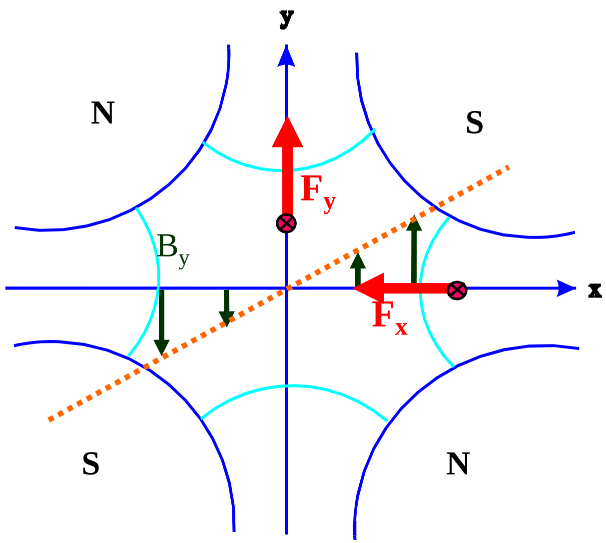
Strong focusing allows use of more compact magnets, thus achieving many times larger energy with the same cost.

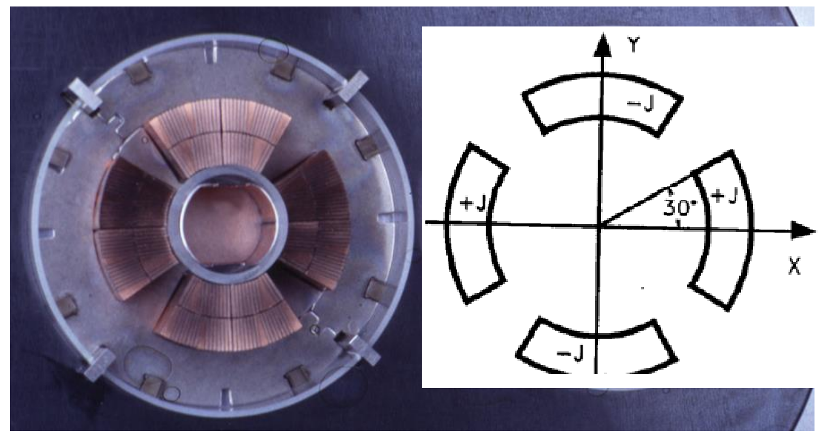
200-m diameter ring, weight of magnets 3,800 tons

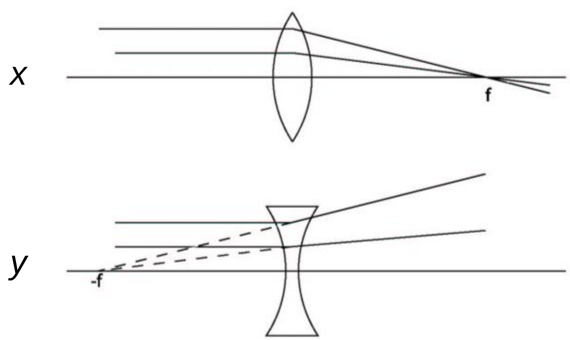


CERN's Proton Synchrotron, was the first operating strong-focusing accelerator.

Strong Focusing







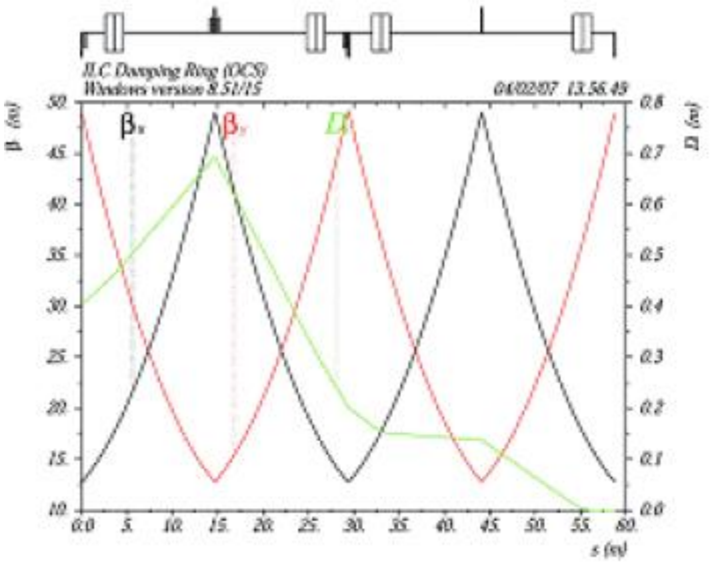
Transverse focusing is achieved with **quadrupole magnets**, which act on the beam like an optical lens.

Linear increase of the magnetic field along the axes (no effect on particles on axis).

Focusing in one plane, **de-focusing** in the other!

F0D0 Lattice

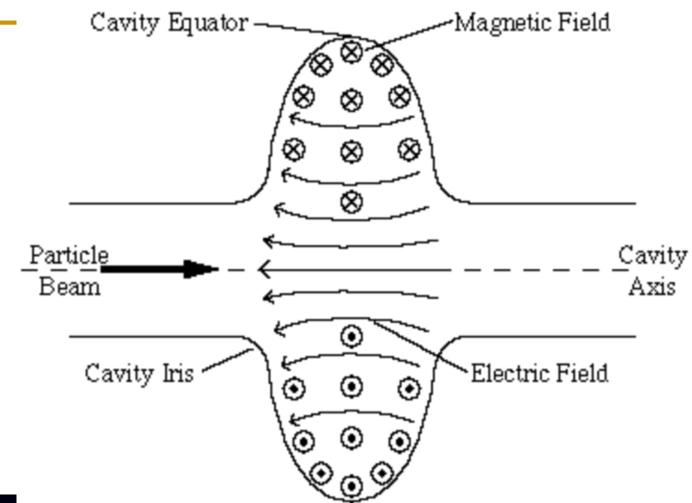
- Quadrupole focuses in one plane and defocuses in the other.
- To keep beam within envelope, quadrupoles arranged to focus alternately in each plane.
- Called `F0D0' (Focusing-Defocusing) lattice.
- At Collider, lattice slightly more complex as space needs to be created for experiments/utilities.

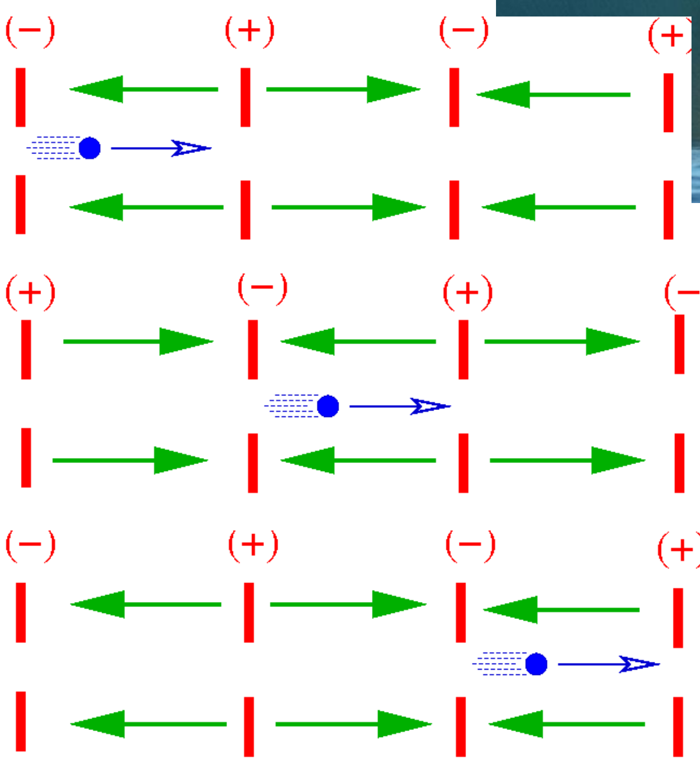


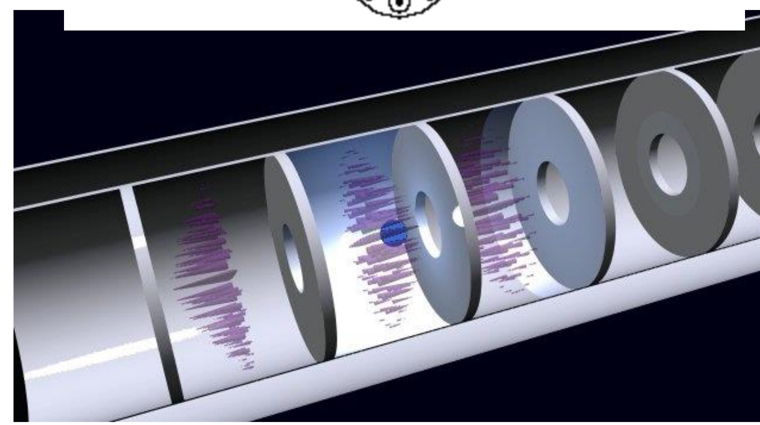
Magnet layout
http://ilc-china.ihep.ac.cn

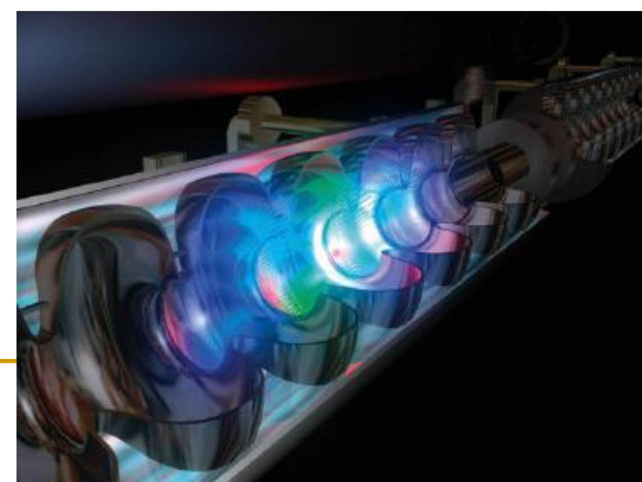
RF Cavities

- ...are used in almost all modern accelerators...
- In an RF cavity the particles “surf” on an electromagnetic wave that travels in the cavity.



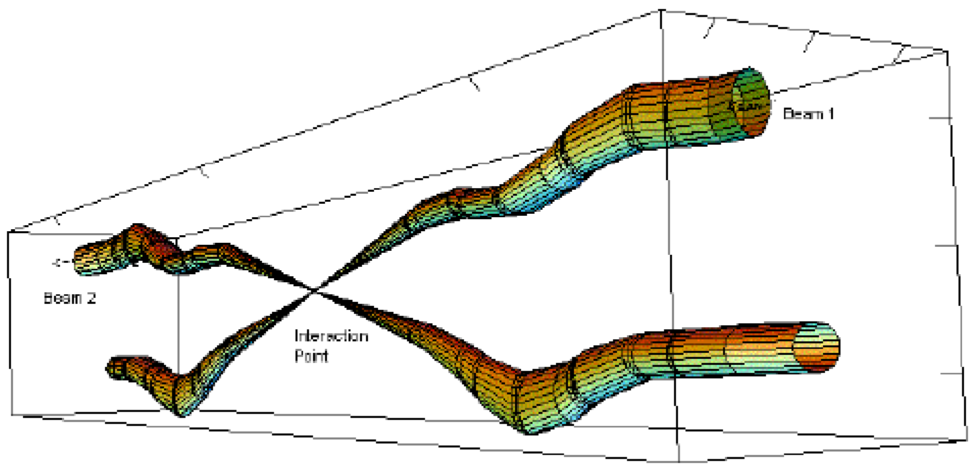






Beam Size

- The beam size varies along the accelerator.
- At ISIS the beam can be as wide as 100mm.
- In Diamond it is only a few hundred micrometers wide.
- In the LHC near the interaction points the beam is only 64 micrometres wide (the size of a human hair).



Relative beam sizes around IP1 (Atlas) in collision

Beam size in the LHC
http://lhc-machine-outreach.web.cern.ch/

Charge and Current

- The charge of one electron (or one proton) is 1.6×10^{-19} Coulombs.
- The LHC can store up to 3×10^{14} protons.
- This corresponds to a total charge of 4.8×10^{-5} C, that is 48 micro-Coulombs.
- As it takes 90 microseconds for the particles to travel around the ring this corresponds to a current of 0.54 Amps!
  Current = Charge/duration

The LHC tunnel
http://cds.cern.ch

Stored Beam Energy

- 1 electron-volt is 1.6×10^{-19} Joules.
- 3.5 TeV= 560 nJ.
- Hence the full beam of 3×10^{14} protons contains 1.7×10^{8} J, that is 170 Megajoule.
- This energy is comparable to that of an Airbus 380 at 100km/h!
- This will double when the beam will reach 7 TeV!
- An energy of 170 MJ over 90 microseconds corresponds to a power of
  2 Petawatt!
  Power=Energy/time

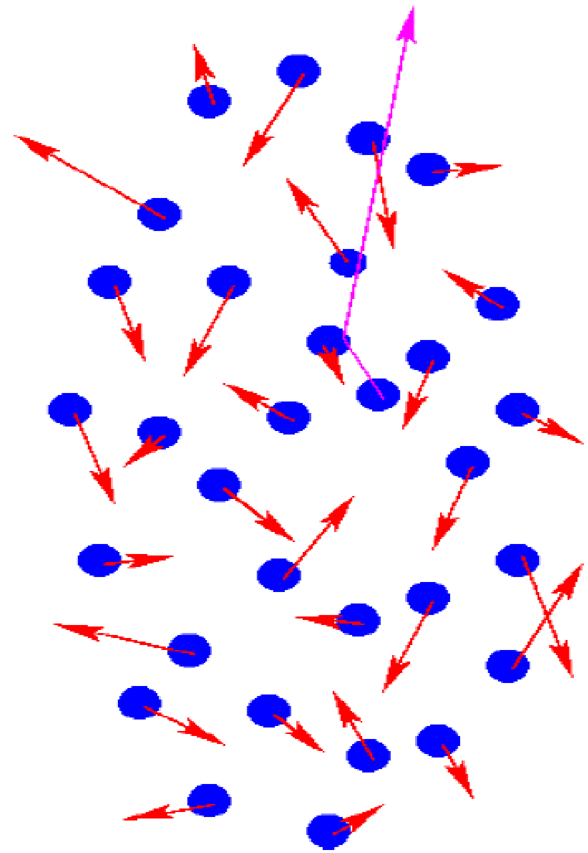
Airbus A380

wikipedia

Beam Lifetime

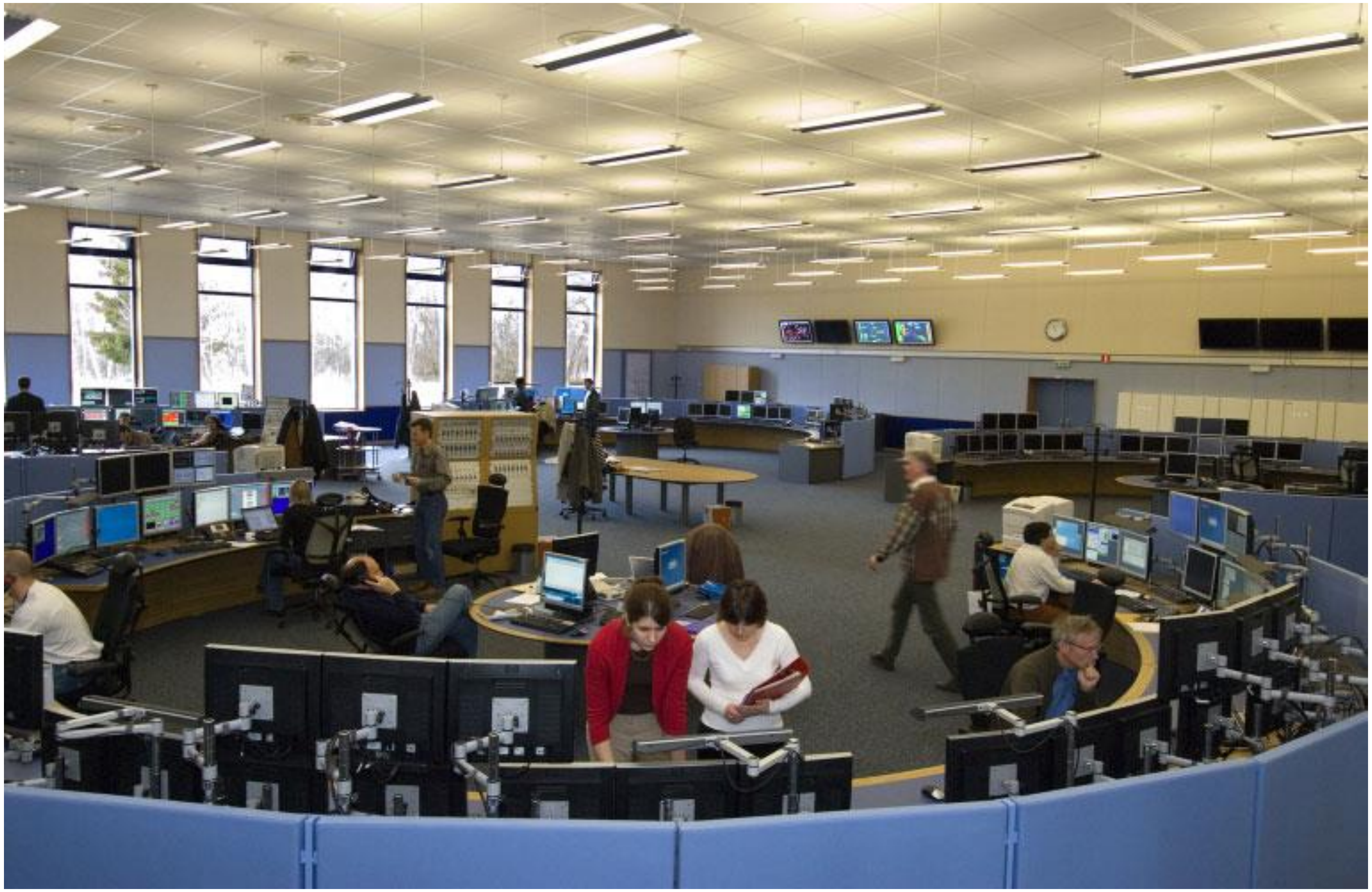
Lifetime

- The beam does not stay for ever in a ring.
- Some particles will scatter on each other and be ejected from the beam.
- Some particles "hit" the walls of the beampipe.
- In some rings the beam lifetime can be only a few minutes.
- In rings where stability is important (such as the LHC or Diamond) the beam lifetime will be several days.



Particle scattering inside a bunch

CERN Control Centre - Layout



What do the Experiments Want?

High energy

B = bending field
ρ = bending radius
p = momentum
e = charge

$$B\rho = \frac{p}{\mathrm{e}}$$

Determined by the maximum field of bending dipoles, B

High luminosity

$$\mathcal{L} = \frac{N^2 n_b f_{\text{rev}}}{4\pi\sigma_x\sigma_y} F$$

N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
F = geometric factor

Depends on machine parameters: charge per bunch (N), num. of bunches (n_b) and transverse beam sizes (σ)

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

Nominal LHC Design Parameters

Nominal LHC parameters	
Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance (μm rad)	3.75
Colliding beam size (μm)	16
Bunch length at 7 TeV (cm)	7.55

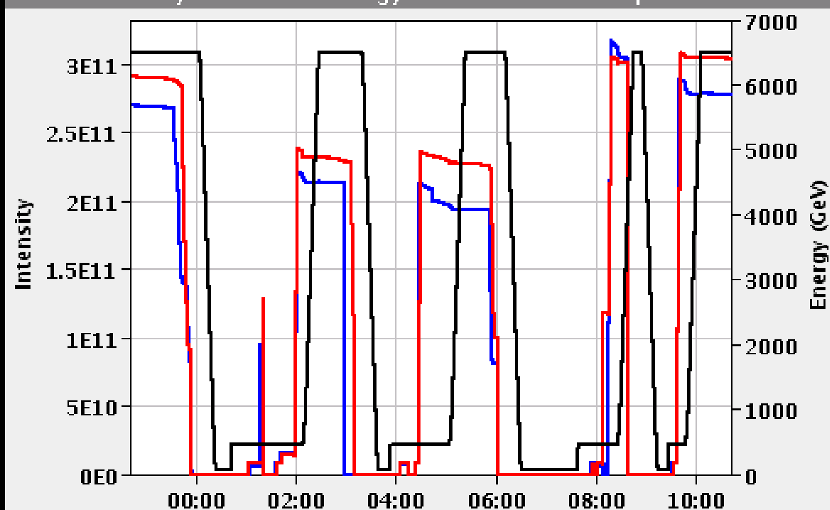
- ...

LHC Page1 | Fill: 3819 | E: 6500 GeV | t(SB): 00:00:19 | 03-06-15 10:40:51

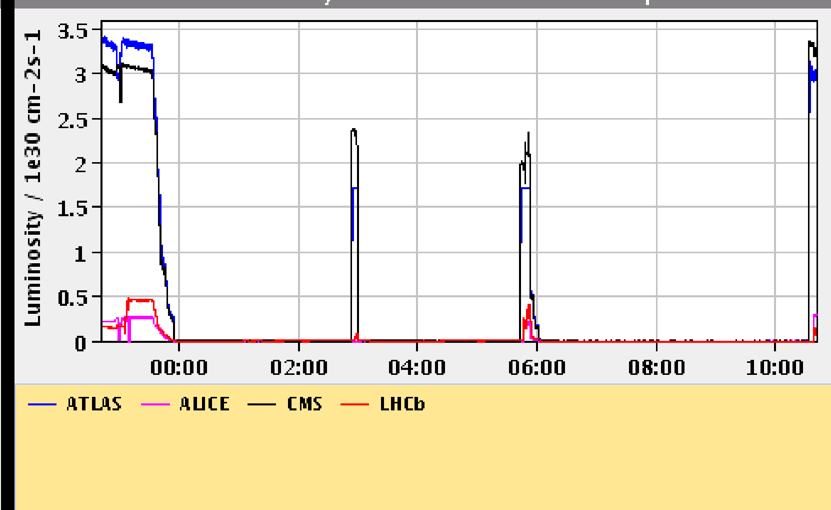
PROTON PHYSICS: STABLE BEAMS

Energy:	6500 GeV	I(B1):	2.93e+11	I(B2):	2.96e+11

FBCT Intensity and Beam Energy Updated: 10:40:51



Instantaneous Luminosity Updated: 10:40:51



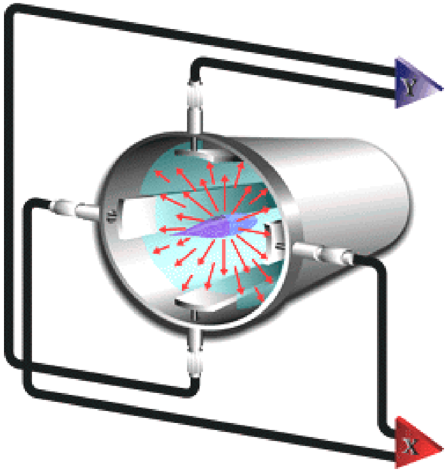
Comments (03-Jun-2015 10:40:01)

collapsed separation bumps in IP1 and 5
collapsed separation bumps in I IP2 and 8
preparing for stable beams

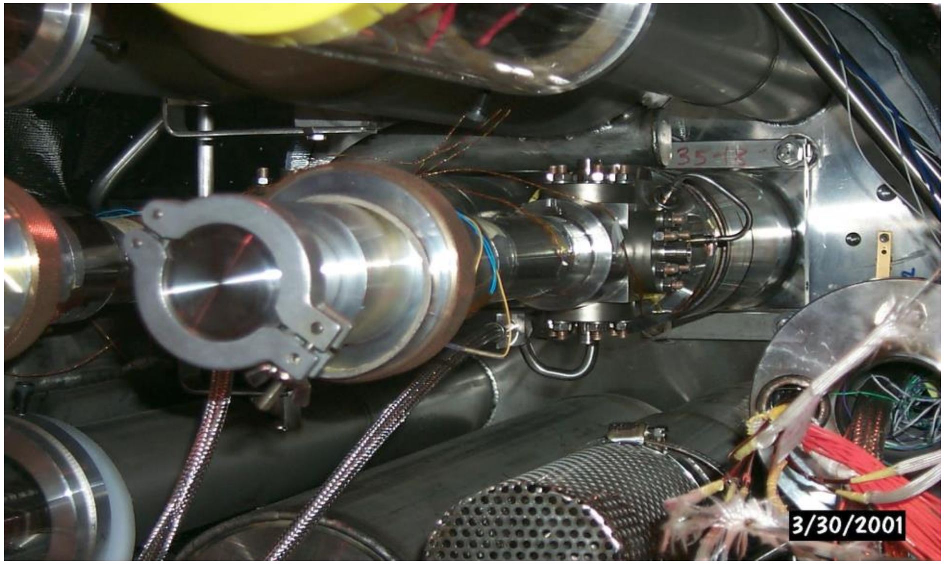
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_3b_2_2_2_with_nc_probes | PM Status B1 ENABLED | PM Status B2 ENABLED

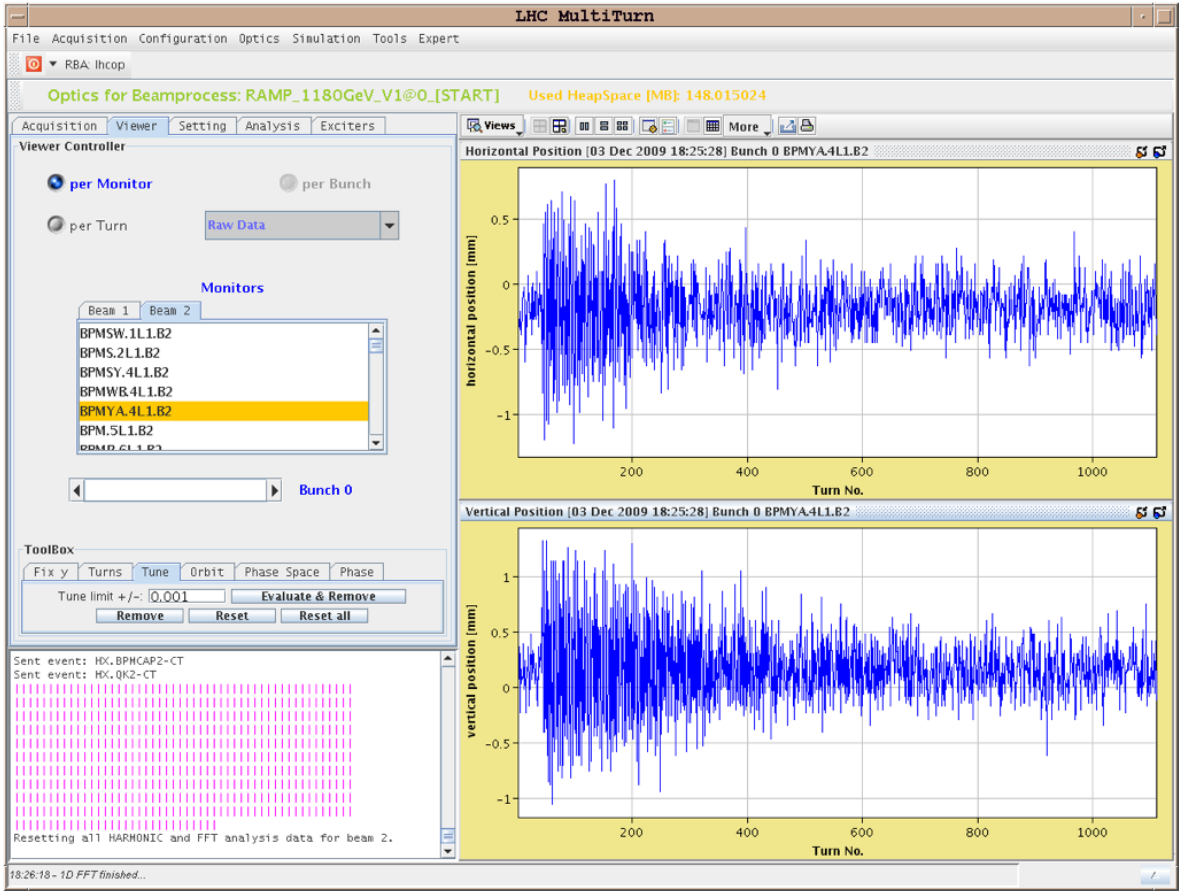
LHC Beam Position Monitors (BPMs)



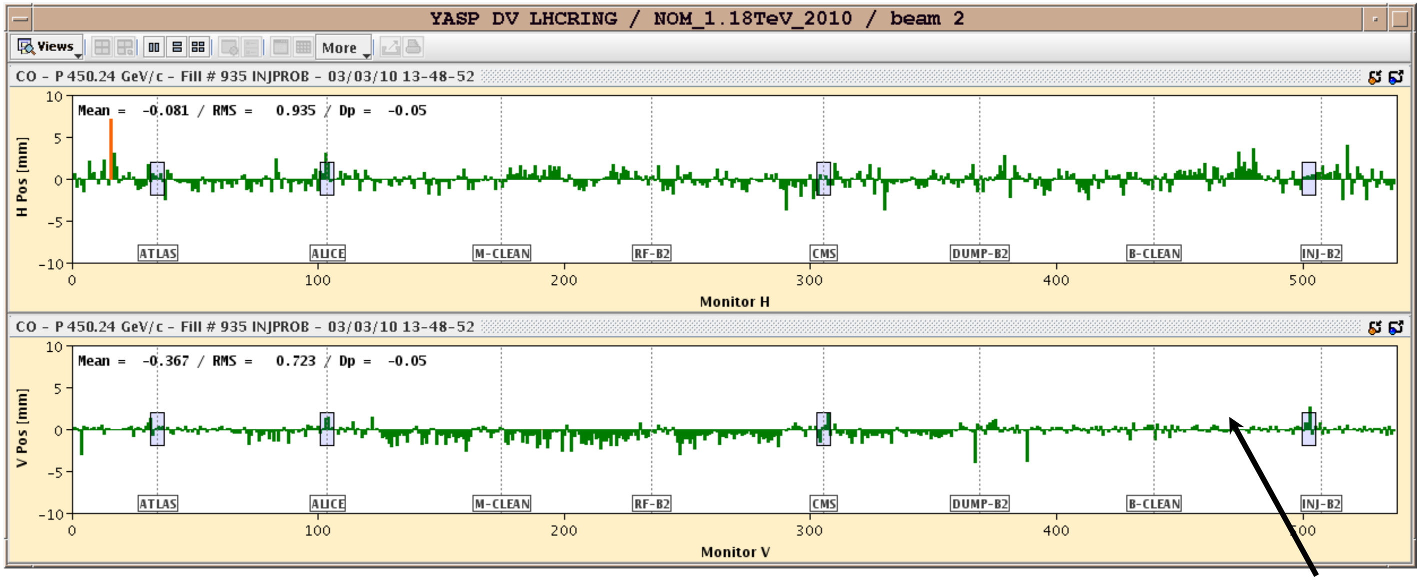
4 buttons pick-up the e.m. signal induced by the beam. One can infer the transverse position in both planes.



Multi-turn Acquisitions of Beam Position



Closed-orbit Measurements



> 500 measurements per beam per plane!

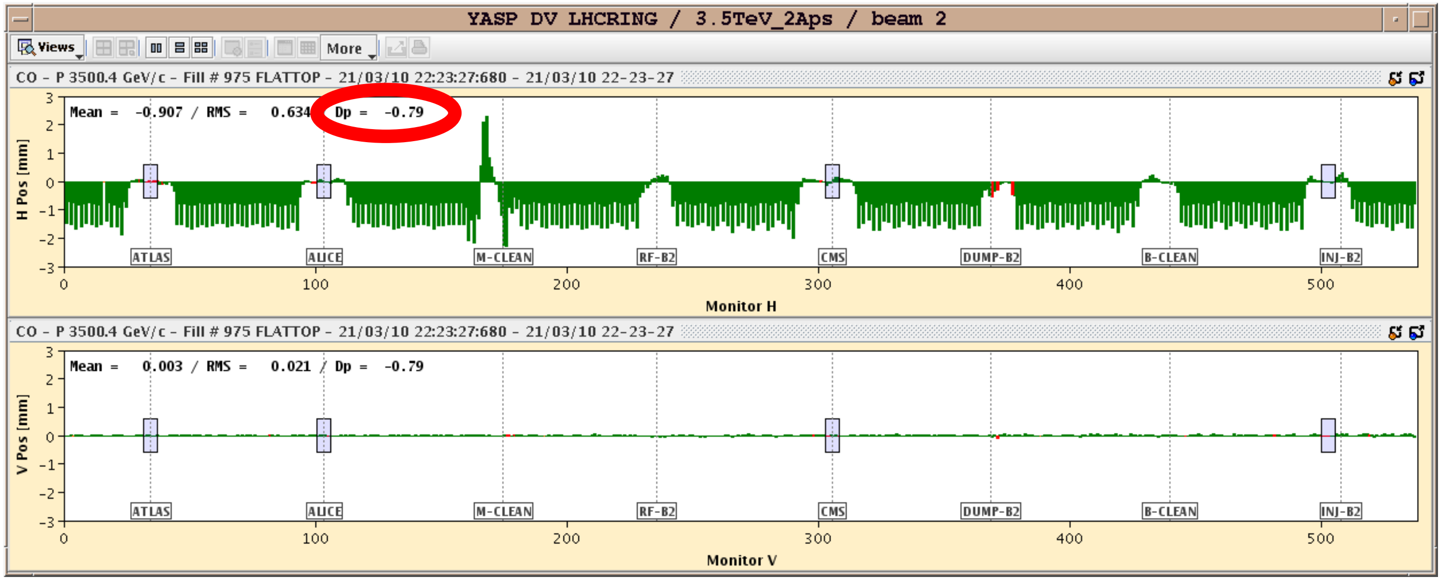
More than 1 per quad!

1 Hz data + turn-by-turn are possible

Dispersion Measurements

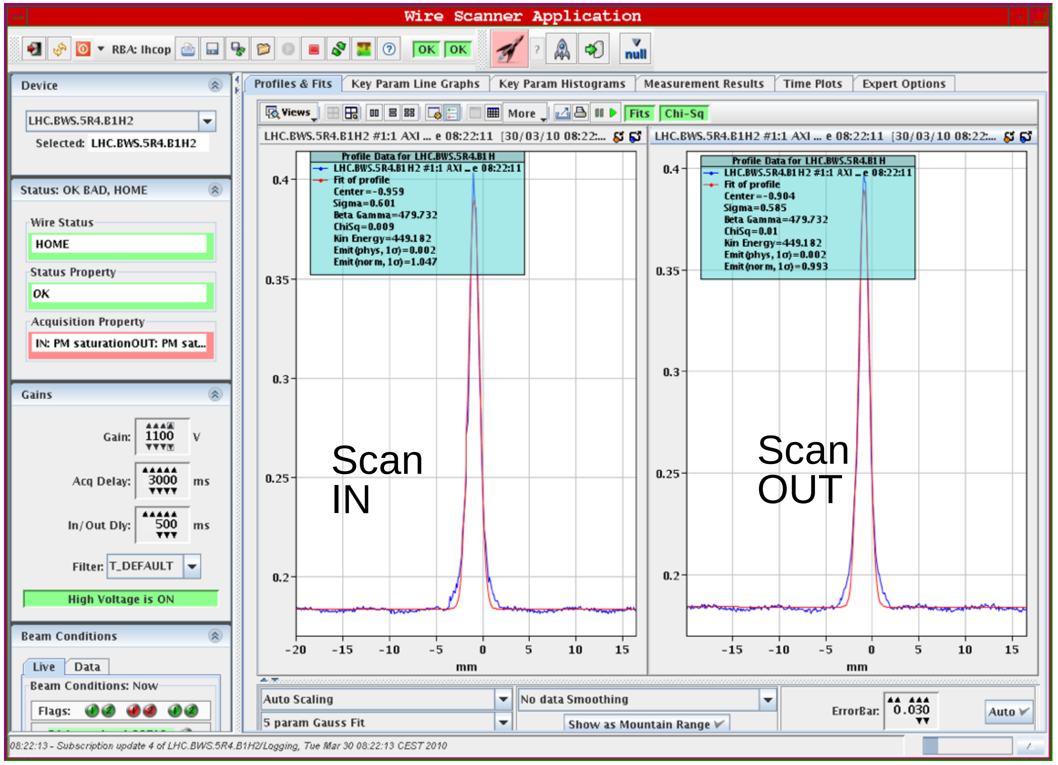
$$\Delta x(s) = D(s) \times \frac{\Delta p}{p}$$

Measure the orbit offset for different beam energies.

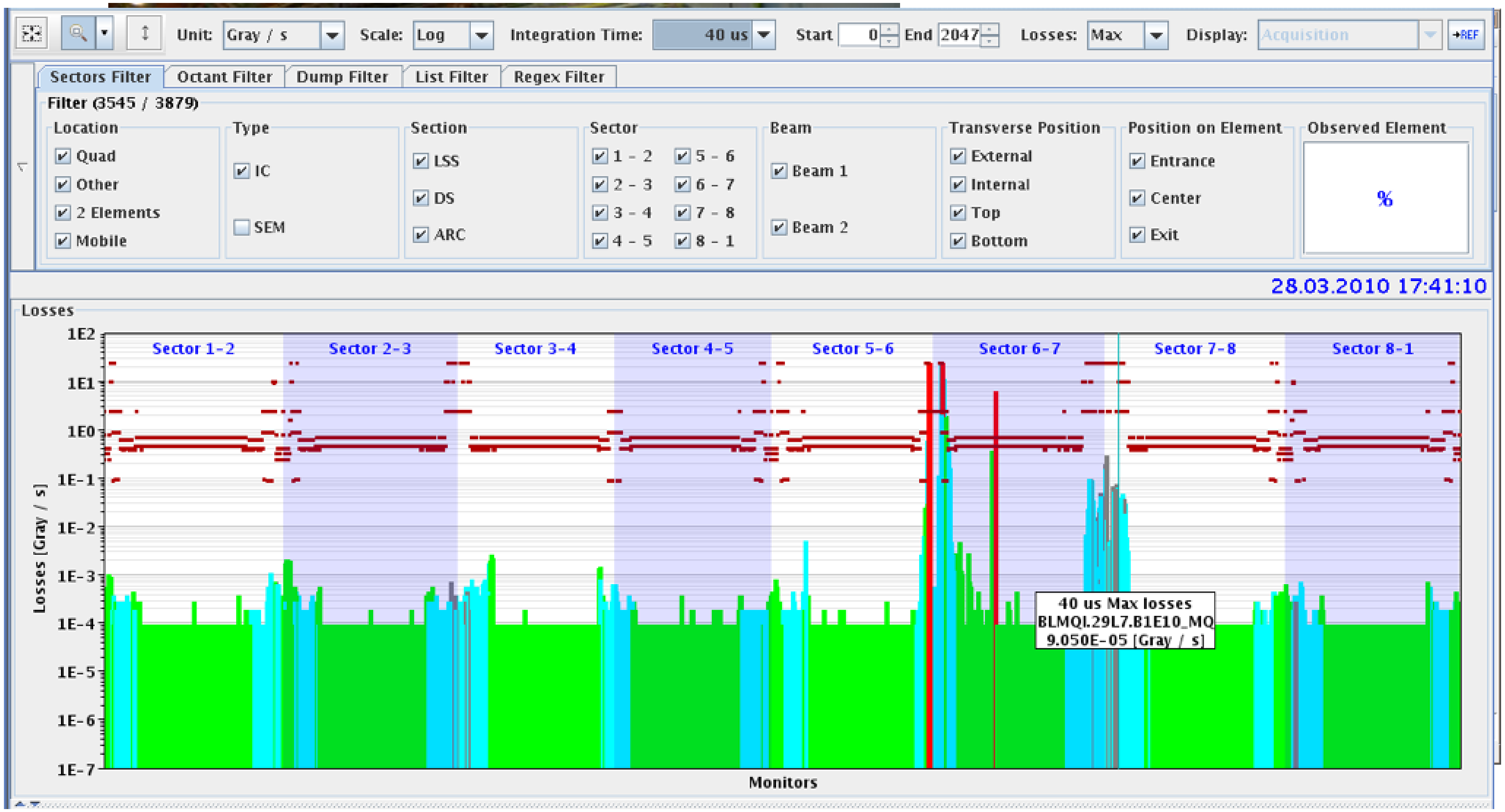


Beam Size Measurements

- Flying wire moved across circulating beam
- Measure secondary particles
- Calibrate wire position to get size in mm



Beam Loss Monitoring



The Predictable Future - *LHC Timeline*

2009

Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to several 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14

LS1 - LHC shut-down to prepare … design energy and n…

… minal (10^{34} cm^{-2} s^{-1}, ~50 to 100 fb^{-1}) and … gy (13 and 14 TeV)

201…

… Injector and LHC upgrades to go to ultimate luminosity

Run 3: Ramp up luminosity to 2.2 x nominal, reaching ~100 fb^{-1} / year accumulate few hundred fb^{-1}

~2023

LS3 – High-luminosity LHC (HL-LHC). New focusing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

>2035

Study of the properties of the Higgs Boson & physics beyond the Standard Model