Lecture 3

Live Feed – CERN Control Centre

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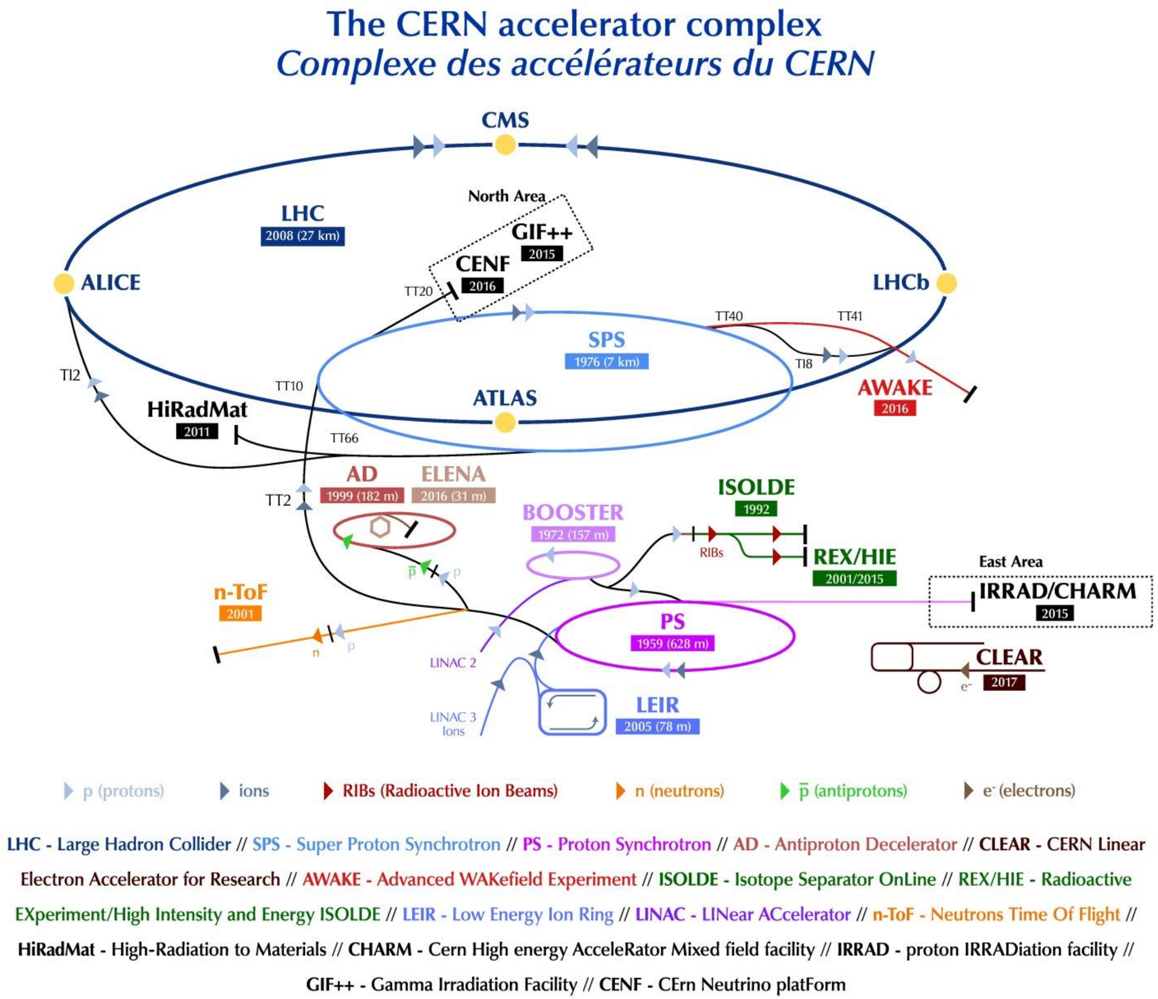
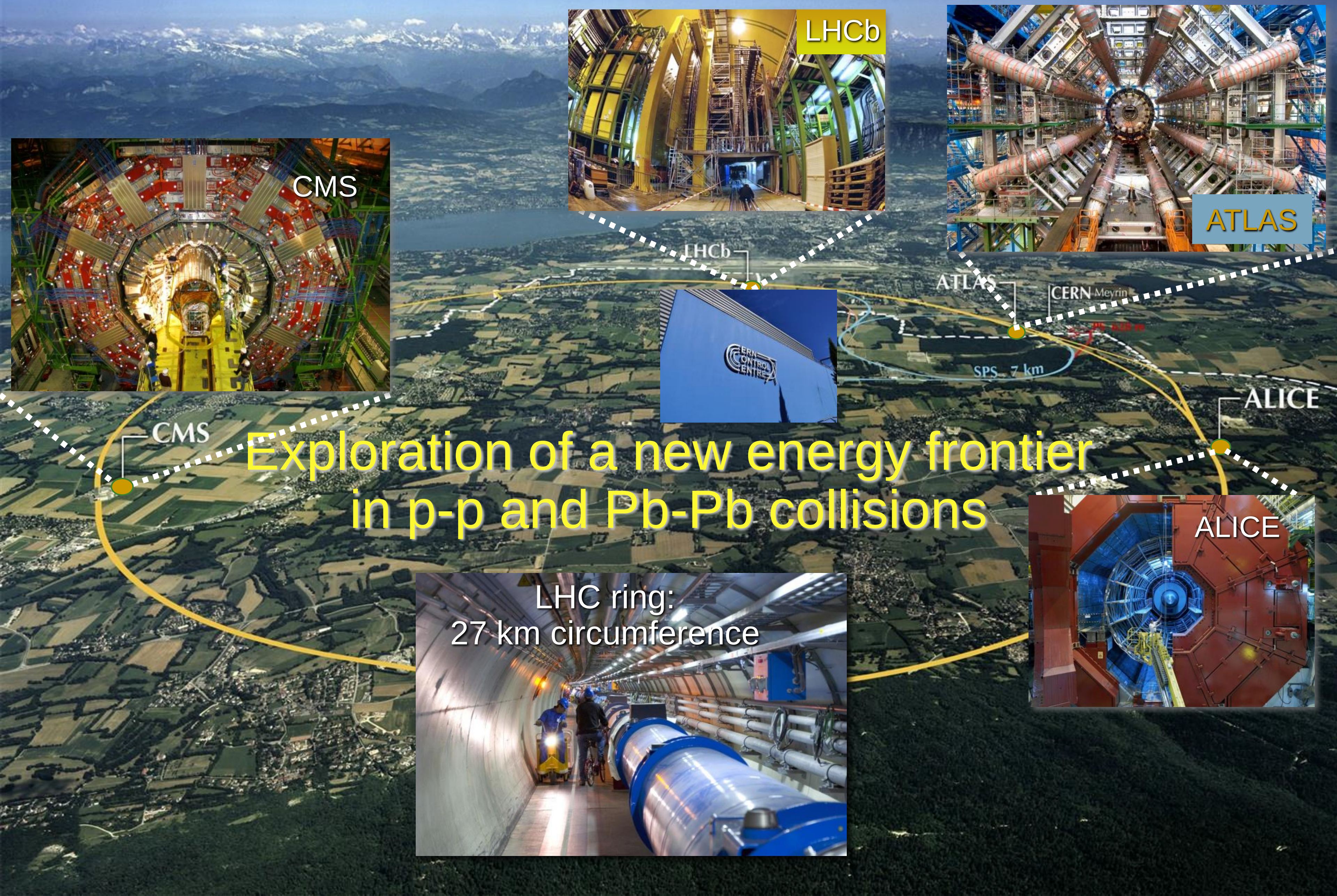
Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
11 October 2023

CERN Accelerator Complex



LHC - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n-ToF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials // **CHARM** - Cern High energy AcceleRator Mixed field facility // **IRRAD** - proton IRRADiation facility // **GIF++** - Gamma Irradiation Facility // **CENF** - CErn Neutrino platForm

A New Era in Fundamental Science



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

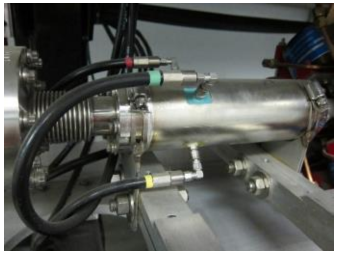
LHC ring:
27 km circumference

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”*.

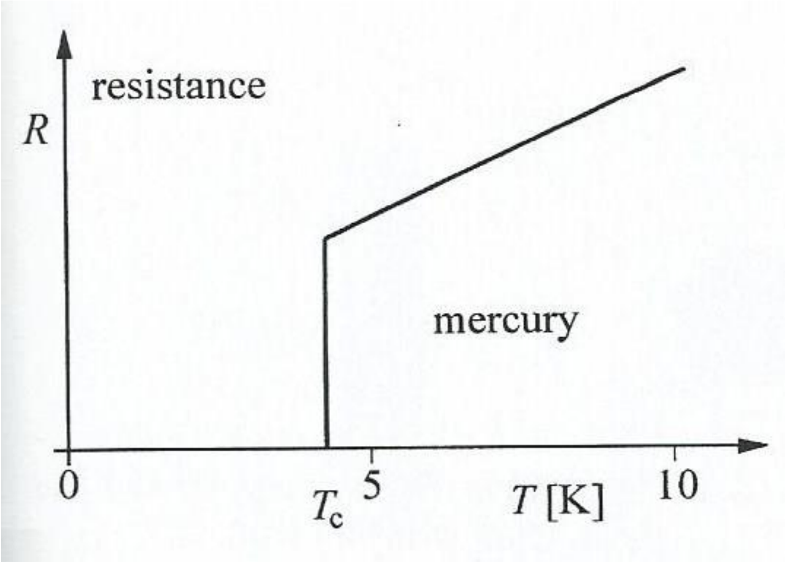
What is in the LHC?

- Thousands of magnets: dipoles, quadrupoles, sextupoles, octupoles, and decapoles.
- 16 Superconducting Radio Frequency (SCRF) Cavities housed in 4 cryomodules.
- Diagnostic equipment, such as beam position monitors, wire scanners, and beam loss monitors.
- Other equipment, such as vacuum pumps, radiation shielding, safety equipment, etc…



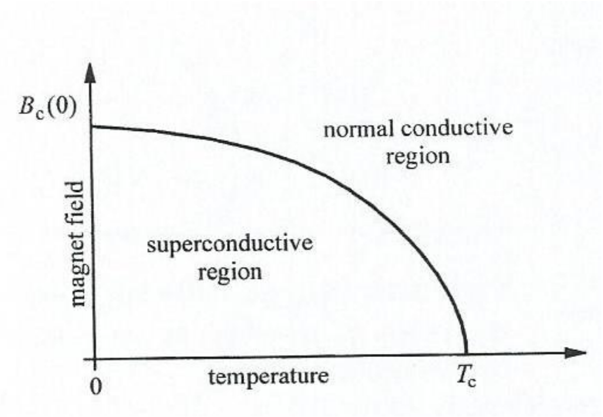
Superconductivity – Enabling Technology

- Disappearance of ohmic resistance in Hg at very low T.



- Dependence of superconductivity on the T and surrounding *B*-field.

$$B_c(T) = B_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

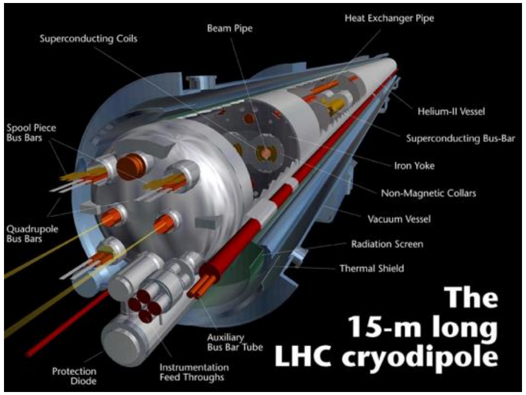


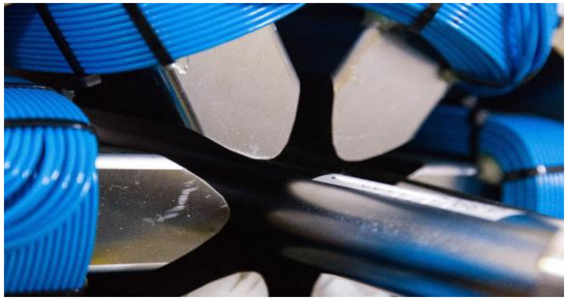
Magnet Systems

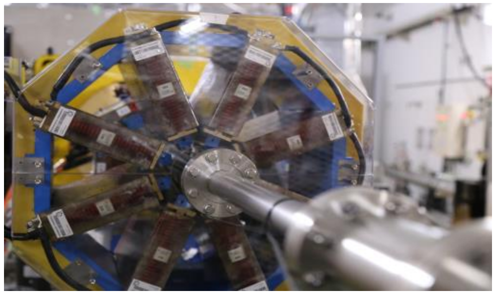
- Beam is made of moving, charged particles that follow Lorentz Force

$$\vec{F} = q(\vec{E} + \vec{v}\times\vec{B})$$

- Dipole Magnets: Bend the beam trajectory.
- Quadrupole Magnets: Focus / de-focus beam.
- Sextupole Magnets: Correct chromaticity.
- Octupole Magnets: Change tune vs. amplitude or interaction-region optics.

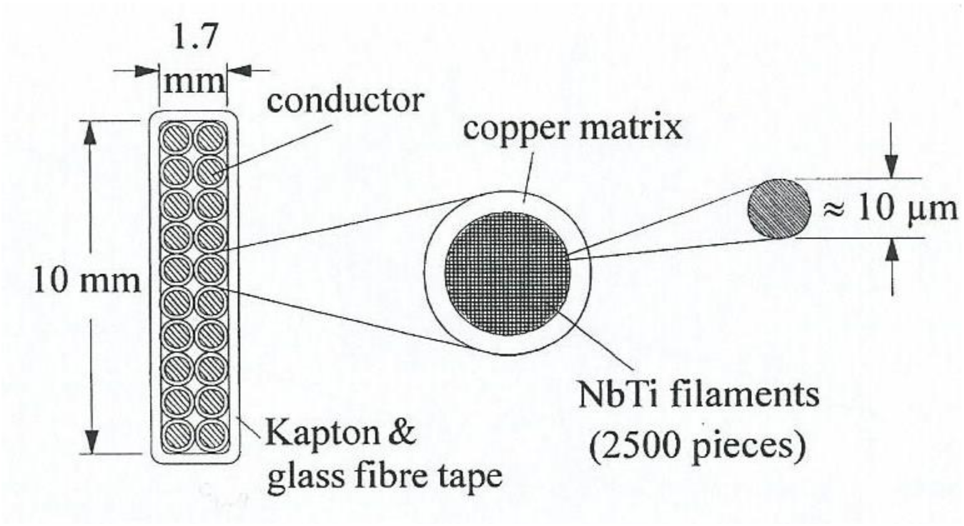


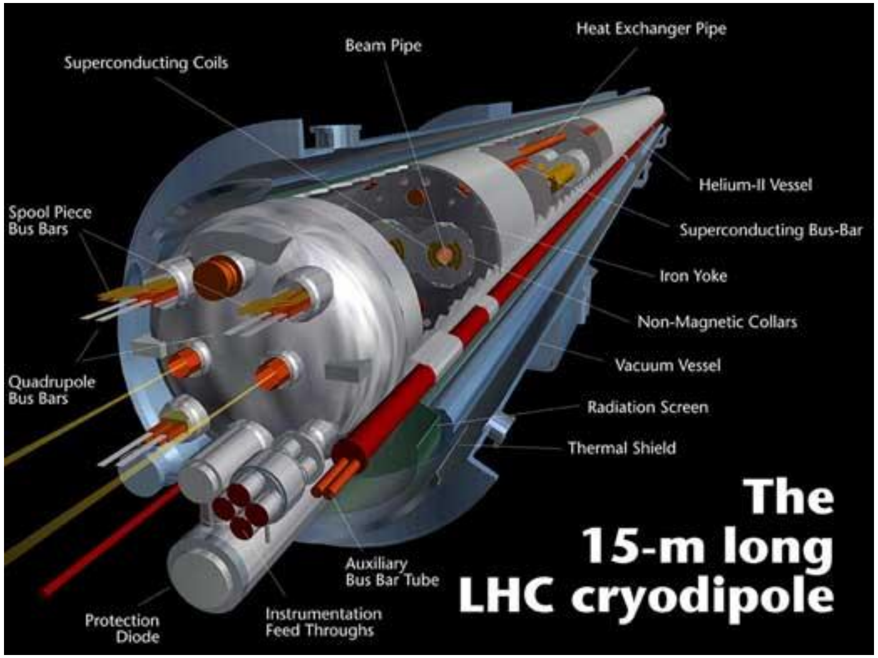




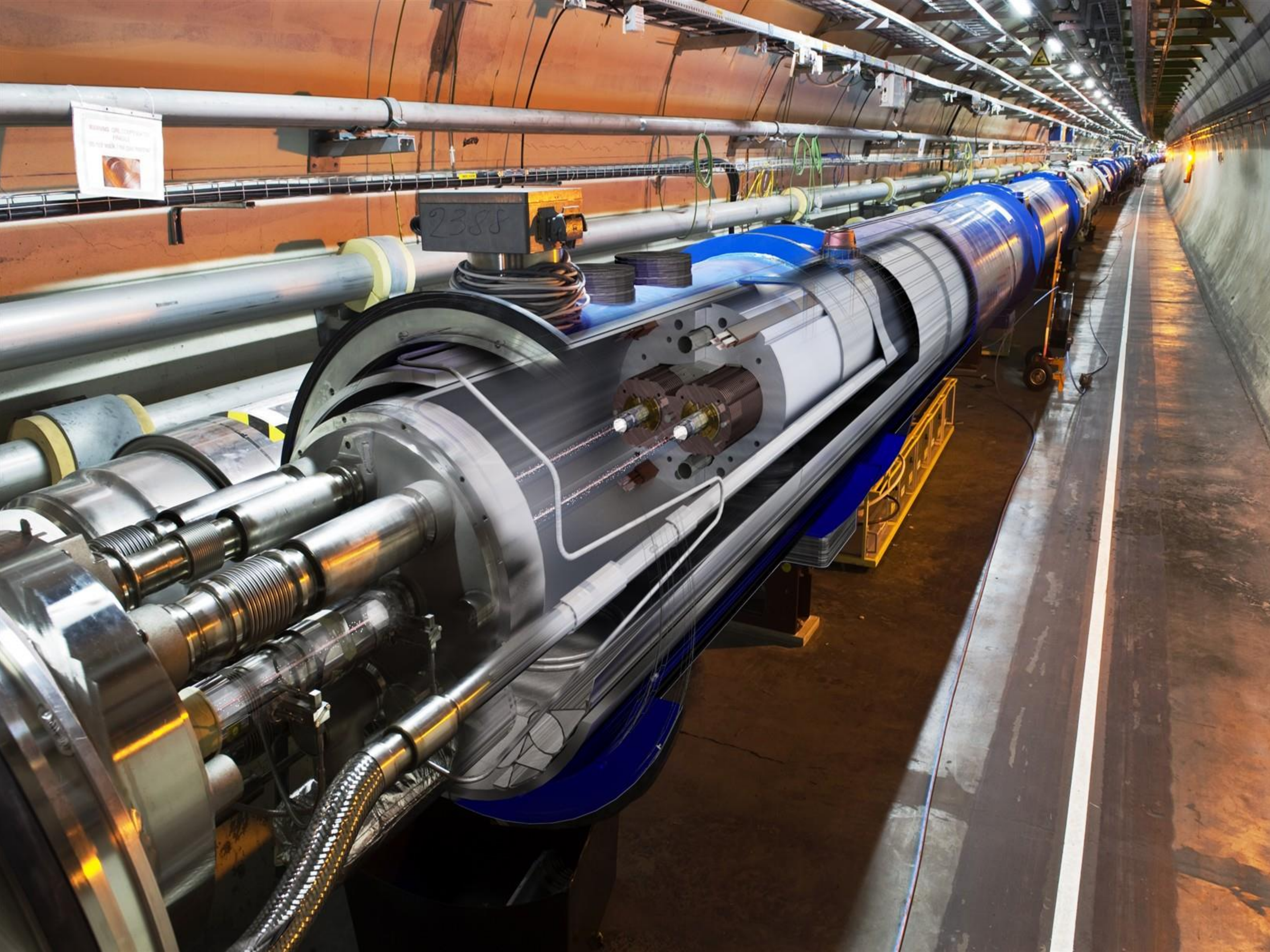
Superconducting Magnets

- Construction of superconductor from niobium-titanium (NbTi)



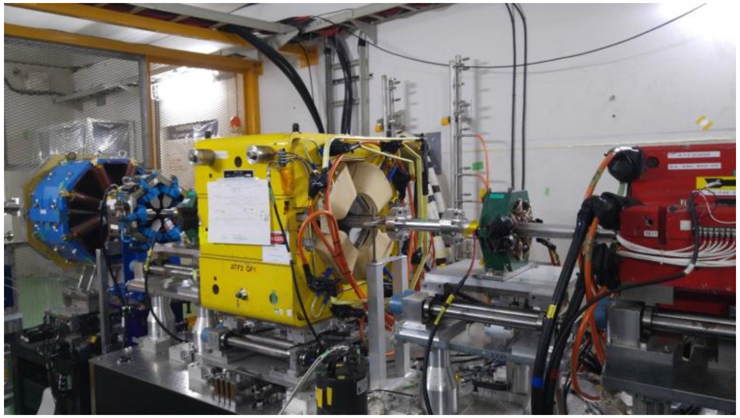


The LHC Arcs

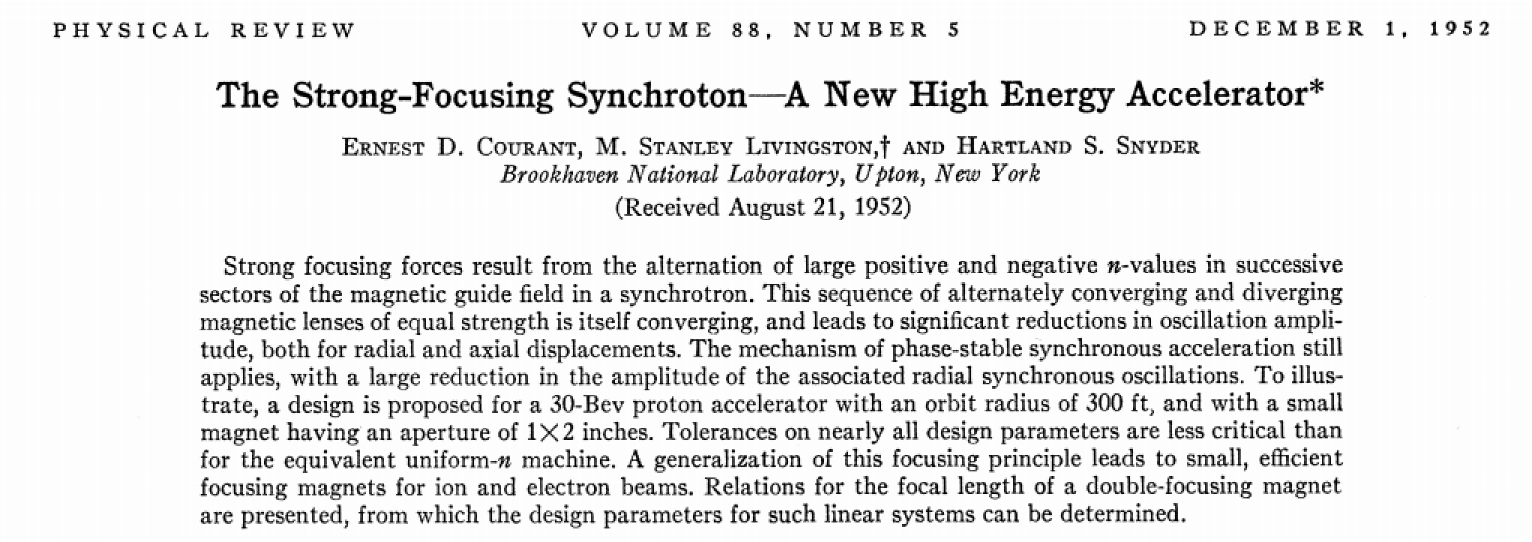

2388

The Lattice

- Magnets are arranged onto a lattice to control the beam.
- The most fundamental lattice is the F0D0 or FODO lattice
  - F = focusing (in one plane)
  - D = defocusing (in same plane)
  - 0/O = drift



F0D0 Lattice from Strong Focusing



PHYSICAL REVIEW VOLUME 88, NUMBER 5 DECEMBER 1, 1952

The Strong-Focusing Synchroton—A New High Energy Accelerator*

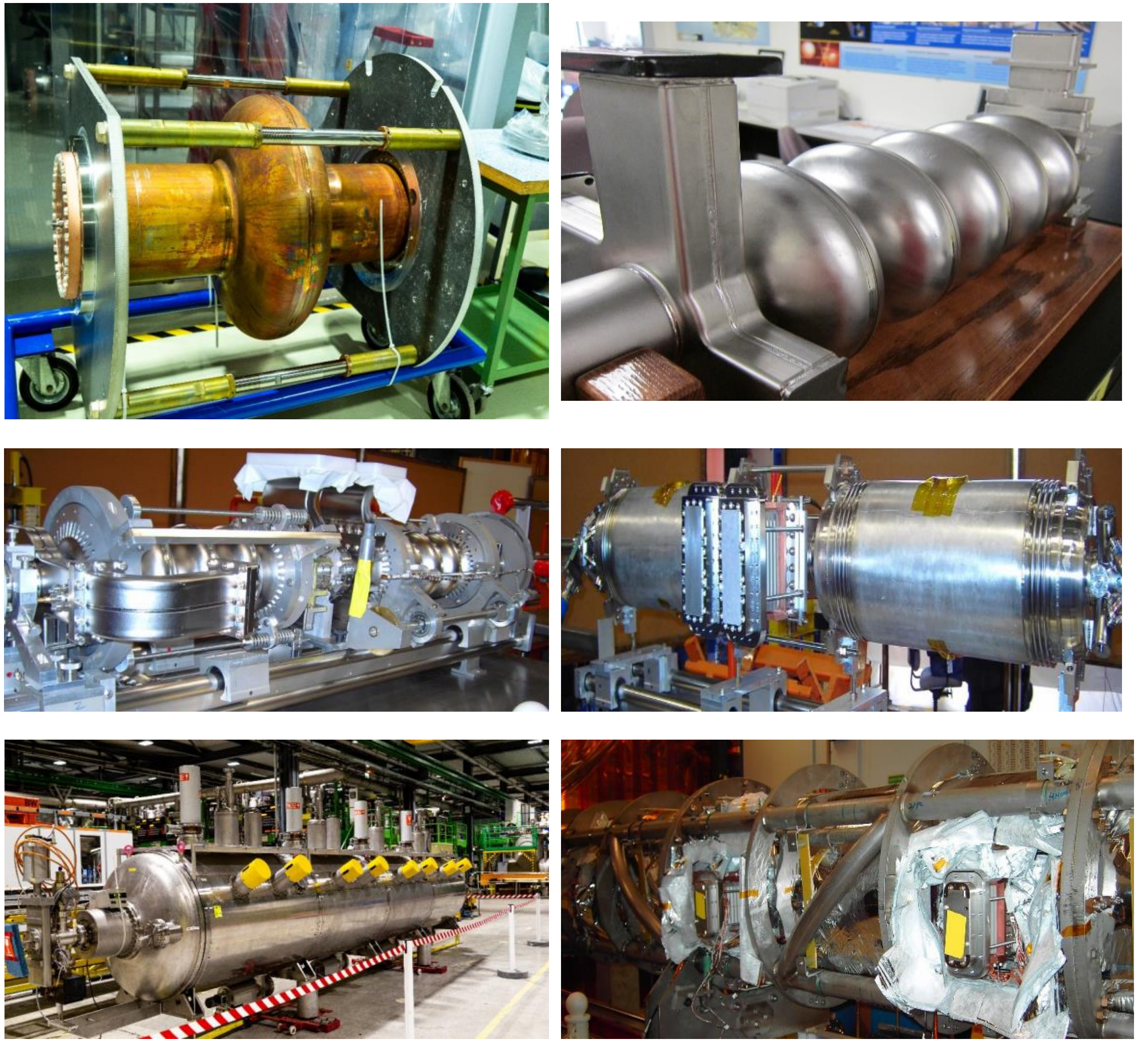
ERNEST D. COURANT, M. STANLEY LIVINGSTON,† AND HARTLAND S. SNYDER
Brookhaven National Laboratory, Upton, New York

(Received August 21, 1952)

Strong focusing forces result from the alternation of large positive and negative *n*-values in successive sectors of the magnetic guide field in a synchrotron. This sequence of alternately converging and diverging magnetic lenses of equal strength is itself converging, and leads to significant reductions in oscillation amplitude, both for radial and axial displacements. The mechanism of phase-stable synchronous acceleration still applies, with a large reduction in the amplitude of the associated radial synchronous oscillations. To illustrate, a design is proposed for a 30-Bev proton accelerator with an orbit radius of 300 ft, and with a small magnet having an aperture of 1×2 inches. Tolerances on nearly all design parameters are less critical than for the equivalent uniform-*n* machine. A generalization of this focusing principle leads to small, efficient focusing magnets for ion and electron beams. Relations for the focal length of a double-focusing magnet are presented, from which the design parameters for such linear systems can be determined.

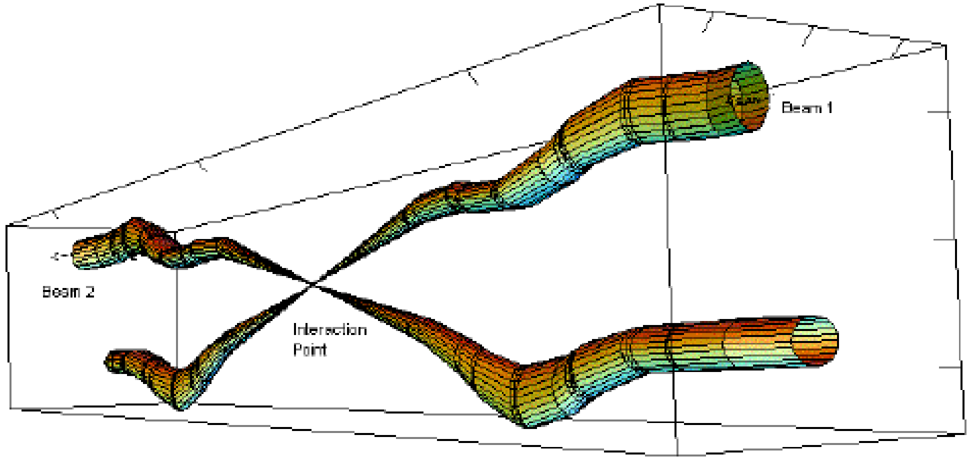
RF Cavities

- Both superconducting & normal-conducting radio frequency cavities.
- Used in most modern accelerators.
- Particles "surf" along RF waves that travel in cavity.
- SLAC – normal-conducting, copper.
- JLAB – first SRF accelerator.
- LHC – superconducting.



Beam Size

- At the interaction points of the LHC, the beam size is compressed to 64 micrometres wide (~human hair)
- The ISIS beam gets up to 100 mm.
- At Diamond, the beam is a few hundred micrometers.
- The possible future linear colliders (ILC and CLIC) will have flat beams on the order of a nanometer high by tens of nanometers wide.



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

Power and Stored Energy

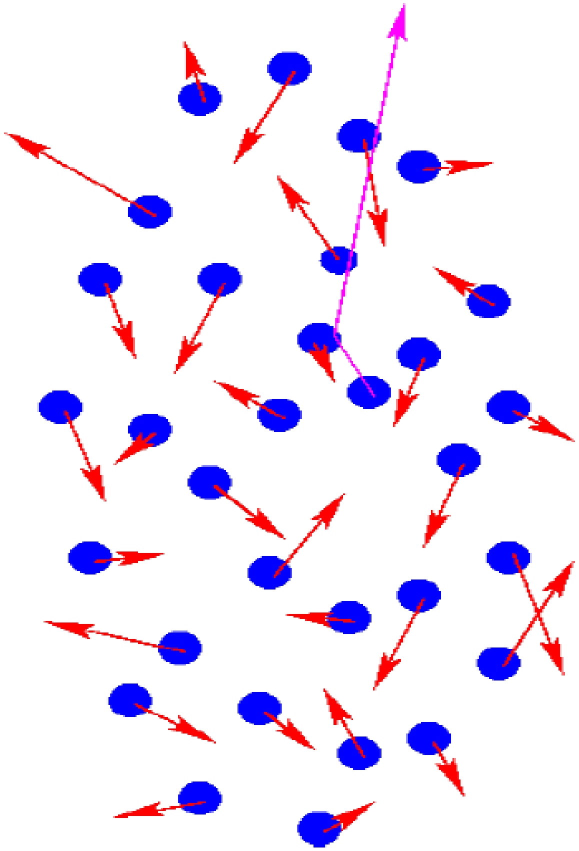
- 1 eV = 1.6E-19 J, therefore 7 TeV = 1120 nJ
- Since 3E14 protons, get 340 MJ
  - Similar to Airbus 380 flying at 100kph

- Power = Energy / Time
  - 340 MJ / 90 microseconds = 4 Petawatts

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

LHC Experiment Needs

- High Energy
  - Limited by max field of dipoles

$$B\rho = {}^{p}/_{e}$$

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

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

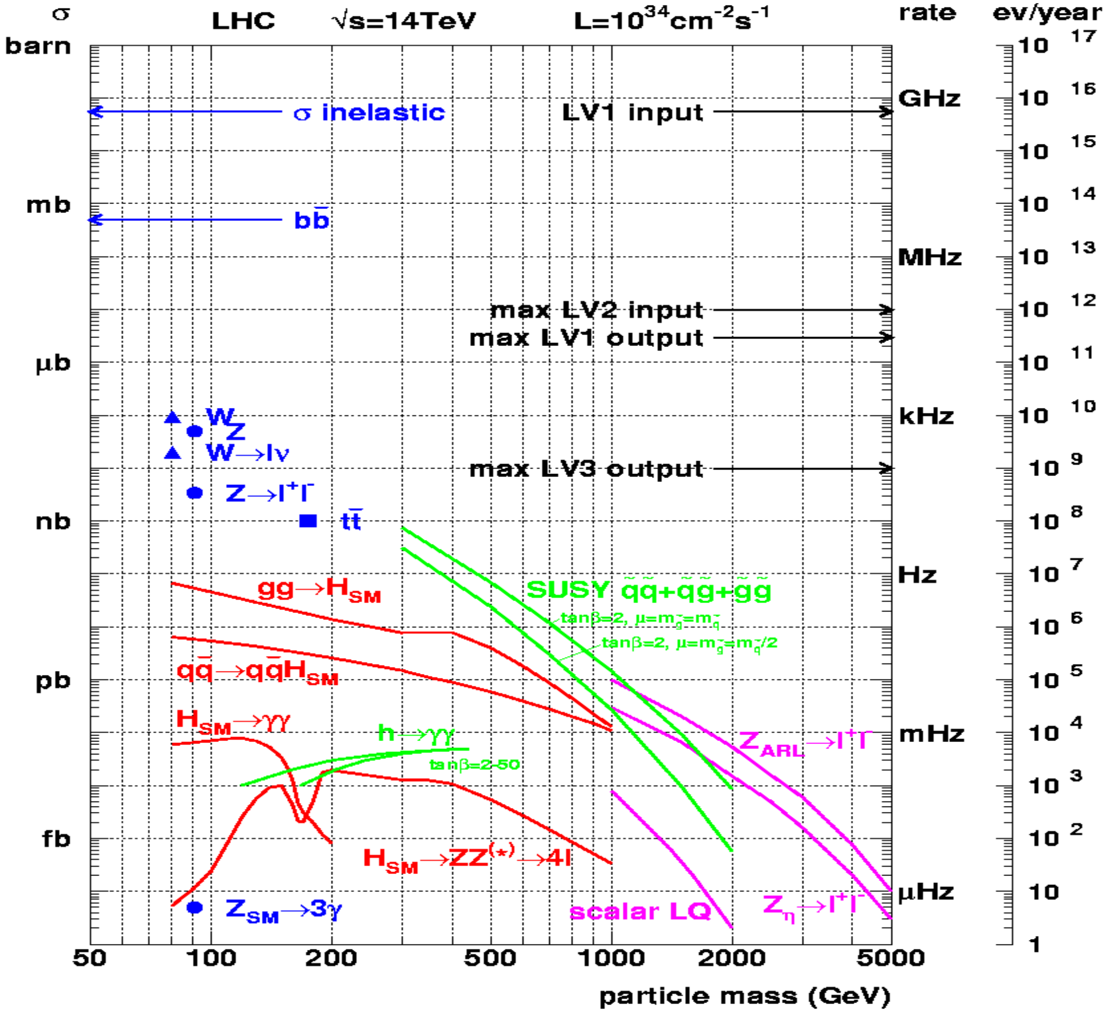
- High Luminosity

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

N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
σ = beam size
F = geometric factor

- Minimize IP beam size, maximize number of particles

Cross-sections at the LHC



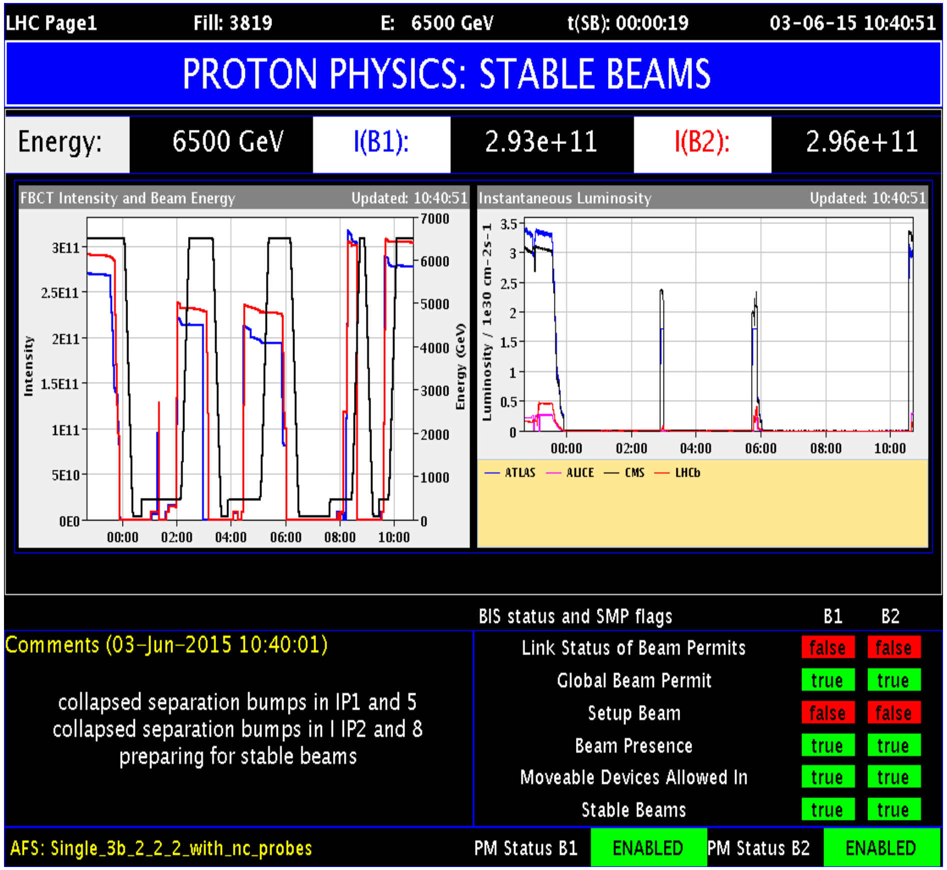
“Well known” processes. Don’t need to keep all of them …

New Physics!!

We want to keep!!

Keeping Track of Accelerator Performance

- Operations in the CCC track the various aspects of the beam to make sure that the needs of the experiments are being met.
- Here, tracking beam intensity, energy, and luminosity.



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

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

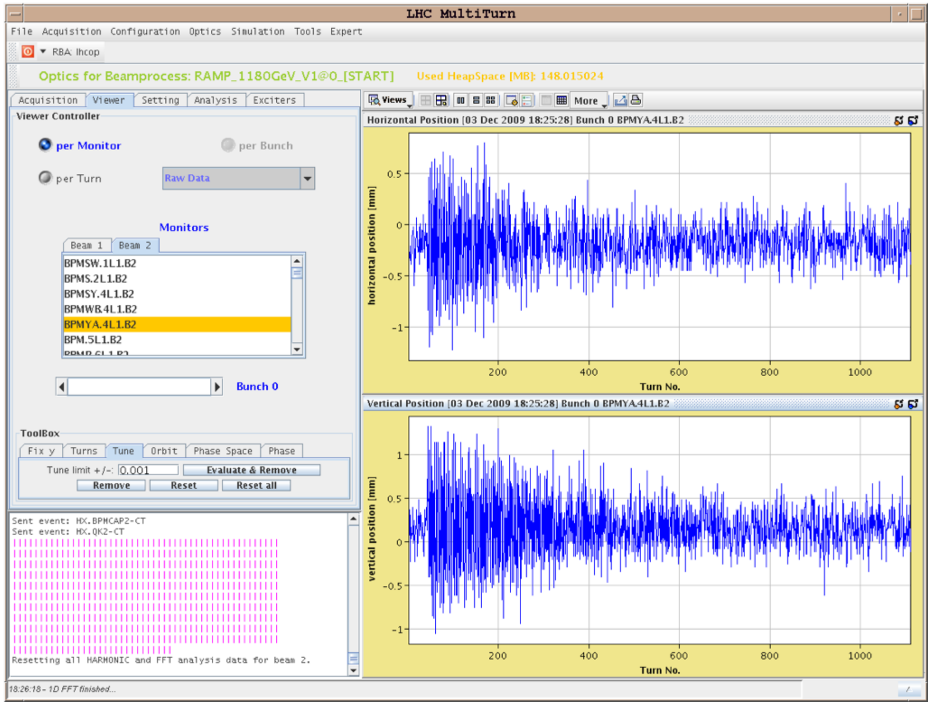
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_3b_2_2_2_with_nc_probes

PM Status B1 ENABLED PM Status B2 ENABLED

Keeping Track of Performance

- Operations in the CCC track the various aspects of the beam to make sure that the needs of the experiments are being met.
- Here, beam positions are monitored in each plane by using Beam Position Monitors.



LHC MultiTurn

Optics for Beamprocess: RAMP_1180GeV_V1@0_[START]

Used HeapSpace [MB]: 148.015024

Viewer Controller

● per Monitor

○ per Bunch

○ per Turn

Raw Data

Monitors

Beam 2:

- BPMSW.1L1.B2
- BPMS.2L1.B2
- BPMSY.4L1.B2
- BPMWB.4L1.B2
- BPMYA.4L1.B2
- BPM.5L1.B2

Bunch 0

ToolBox

Tune limit +/-: 0.001

Horizontal Position [03 Dec 2009 18:25:28] Bunch 0 BPMYA.4L1.B2

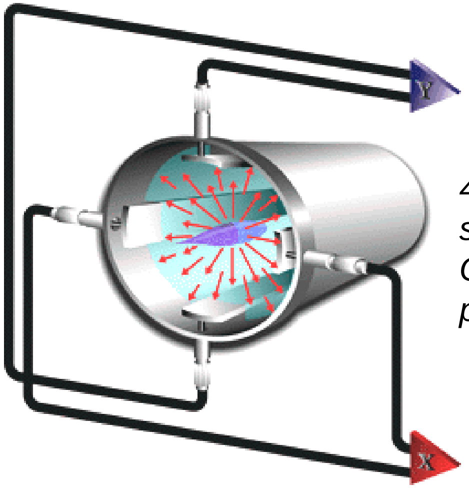
Vertical Position [03 Dec 2009 18:25:28] Bunch 0 BPMYA.4L1.B2

```
Sent event: HX.BPMCAP2-CT
Sent event: HX.QK2-CT
Resetting all HARMONIC and FFT analysis data for beam 2.
```

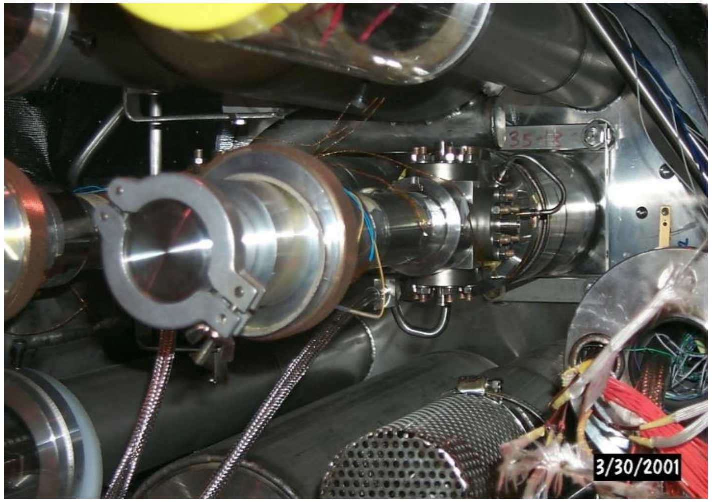
18:26:18 - 1D FFT finished...

Beam Position Monitor (BPM)

- The electric field from the beam induces a charge on the antennas
- The charges on each antenna are measured, and one can then calculate the position of the beam inside the beamline



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

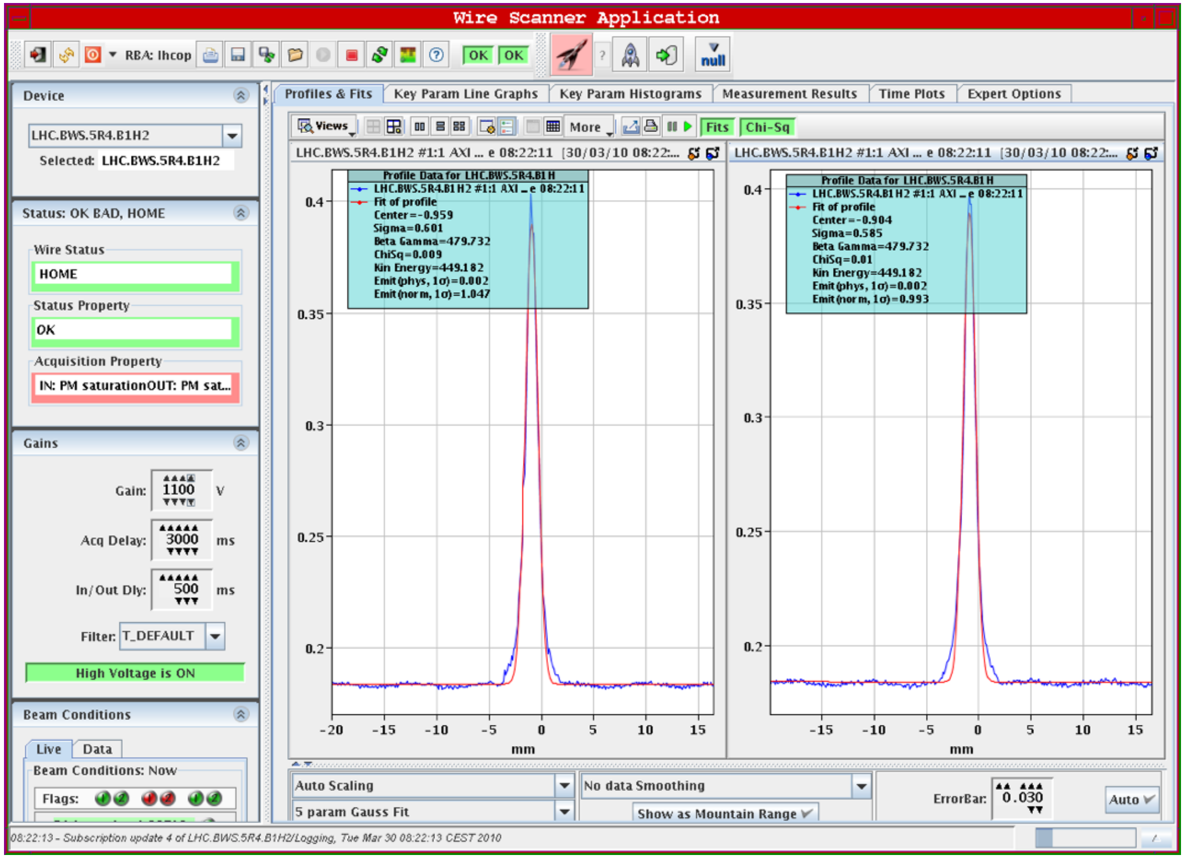


Beam Position Monitor (BPM)

- Different sizes & styles, but most behave in similar manner.
- Sizes and lengths carefully designed.
- Here, we have two views of one of the BPM types used at Jefferson Lab (notice the antennas along the inside.)

Beam Profile

- To find beam size and distribution, measure profile.



Wire Scanner Application

Device: LHC.BWS.5R4.B1H2
Selected: LHC.BWS.5R4.B1H2

Status: OK BAD, HOME
Wire Status: HOME
Status Property: OK
Acquisition Property: IN: PM saturationOUT: PM sat...

Gains
Gain: 1100 V
Acq Delay: 3000 ms
In/Out Dly: 500 ms
Filter: T_DEFAULT
High Voltage is ON

Beam Conditions
Beam Conditions: Now

LHC.BWS.5R4.B1H2 #1:1 AXI ... e 08:22:11 [30/03/10 08:22:...

```
Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H2 #1:1 AXI _ e 08:22:11
Fit of profile
Center=-0.959
Sigma=0.601
Beta Gamma=479.732
ChiSq=0.009
Kin Energy=449.182
Emit(phys, 1σ)=0.002
Emit(norm, 1σ)=1.047
```

LHC.BWS.5R4.B1H2 #1:1 AXI ... e 08:22:11 [30/03/10 08:22:...

```
Profile Data for LHC.BWS.5R4.B1H
LHC.BWS.5R4.B1H2 #1:1 AXI _ e 08:22:11
Fit of profile
Center=-0.904
Sigma=0.585
Beta Gamma=479.732
ChiSq=0.01
Kin Energy=449.182
Emit(phys, 1σ)=0.002
Emit(norm, 1σ)=0.993
```

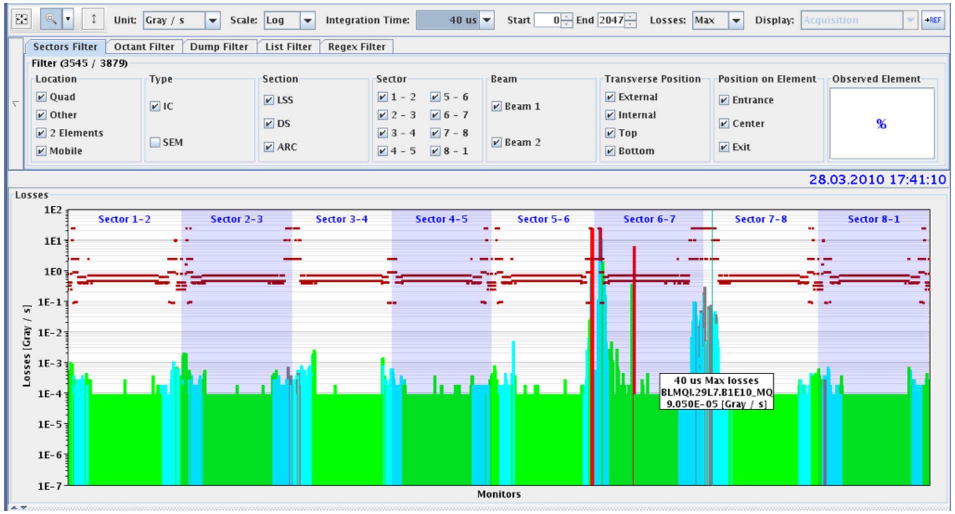
Auto Scaling
5 param Gauss Fit
No data Smoothing
Show as Mountain Range ✓
ErrorBar: 0.030
Auto ✓

```
08:22:13 - Subscription update 4 of LHC.BWS.5R4.B1H2/Logging, Tue Mar 30 08:22:13 CEST 2010
```

Beam Profile

- This is commonly done using a wire scanner.
- The wire will move through the beam twice (in and out), giving information about the size and distribution of particles.

Keeping Track of Performance



Unit: Gray / s Scale: Log Integration Time: 40 us Start 0 End 2047 Losses: Max Display: Acquisition

Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter

Filter (3545 / 3879)

Location: ☑ Quad ☑ Other ☑ 2 Elements ☑ Mobile

Type: ☑ IC ☐ SEM

Section: ☑ LSS ☑ DS ☑ ARC

Sector: ☑ 1 - 2 ☑ 2 - 3 ☑ 3 - 4 ☑ 4 - 5 ☑ 5 - 6 ☑ 6 - 7 ☑ 7 - 8 ☑ 8 - 1

Beam: ☑ Beam 1 ☑ Beam 2

Transverse Position: ☑ External ☑ Internal ☑ Top ☑ Bottom

Position on Element: ☑ Entrance ☑ Center ☑ Exit

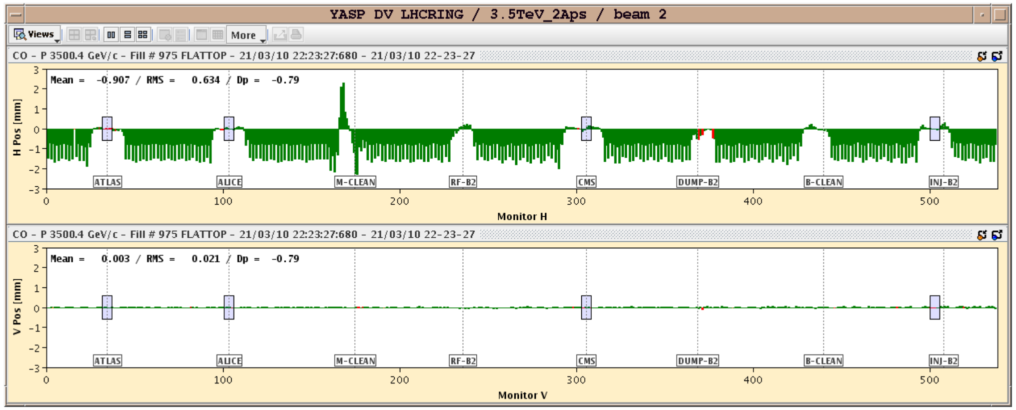
Observed Element: %

28.03.2010 17:41:10

40 us Max losses
BLMQI.29L7.B1E10_MQ
9.050E-05 [Gray / s]

Beam loss monitoring

Dispersion measurements



YASP DV LHCRING / 3.5TeV_2Aps / beam 2

CO - P 3500.4 GeV/c - Fill # 975 FLATTOP - 21/03/10 22:23:27:680 - 21/03/10 22-23-27

Mean = -0.907 / RMS = 0.634 / Dp = -0.79

CO - P 3500.4 GeV/c - Fill # 975 FLATTOP - 21/03/10 22:23:27:680 - 21/03/10 22-23-27

Mean = 0.003 / RMS = 0.021 / Dp = -0.79

CERN Control Centre - Layout