

How to “see” the protons in the LHC? (or the electrons in SuperB and the ILC)

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Lectures overview

I. How to produce protons for the LHC?

II. How to get protons in the LHC?

III. How to “see” protons in the LHC?

- Beam-matter interaction
- Radiation emitted by the beam
- Example of accelerator: The LHC

IV. What can you do with a particle accelerator (apart from hunting the Higgs)?

Where are we?

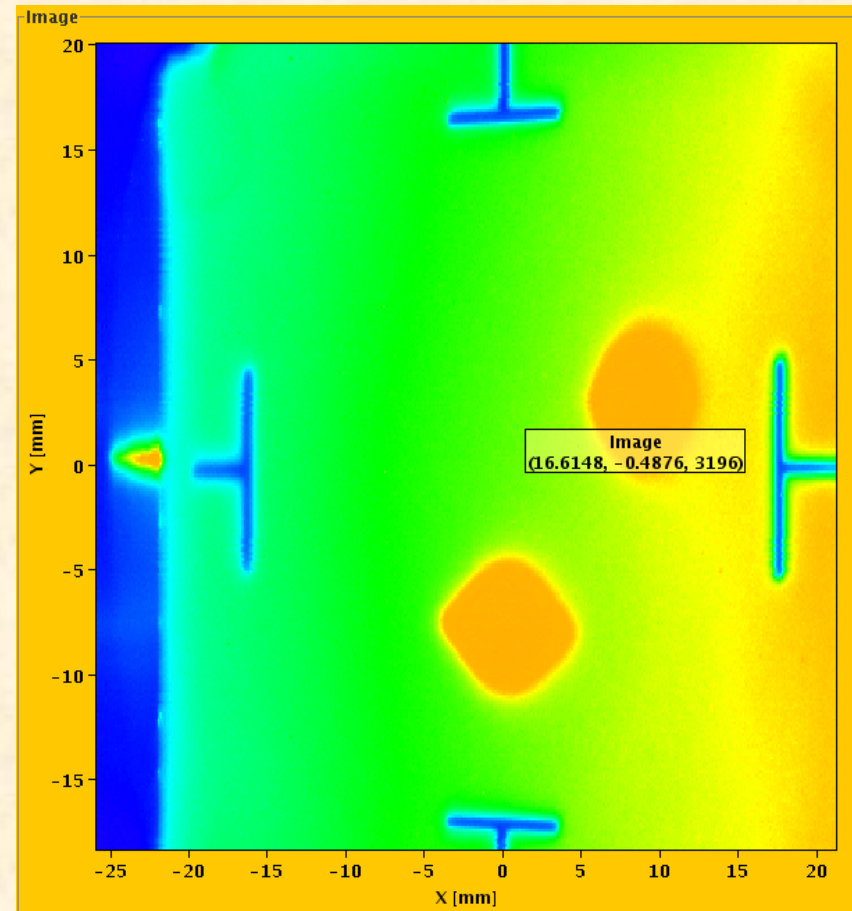
- We have seen how to produce particles
- We also learnt how to accelerate them and how to control them.
- We are aware that some effects such as wakefield, electron cloud, scattering can limit the beam lifetime or performances...
- Today we will learn how to “look” at the beam in the accelerators.
- But to help you wake, up let’s work together first...

What do we want to know
about the beam?

?

What do you want to know about the beam?

- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses

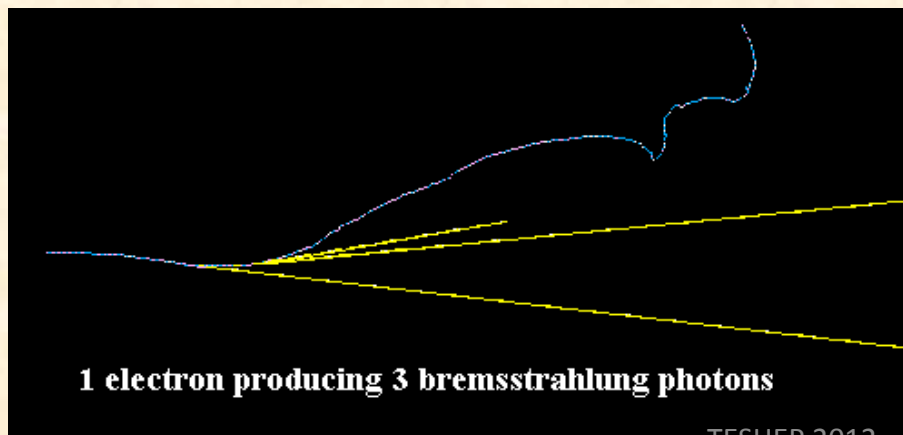
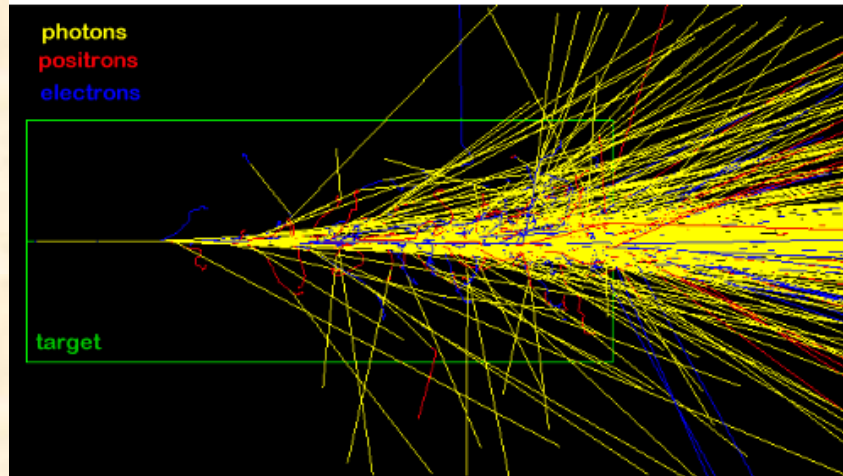


Beam properties measurements

- Almost all accelerators accelerate **charged particles**
- There are mainly 2 types of beam diagnostics:
 - Diagnostics that use the interaction of the beam with matter (see Serguei's lecture)
 - Diagnostics that use radiations emitted by the beam to measure its properties.
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

Particles interactions with matter

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

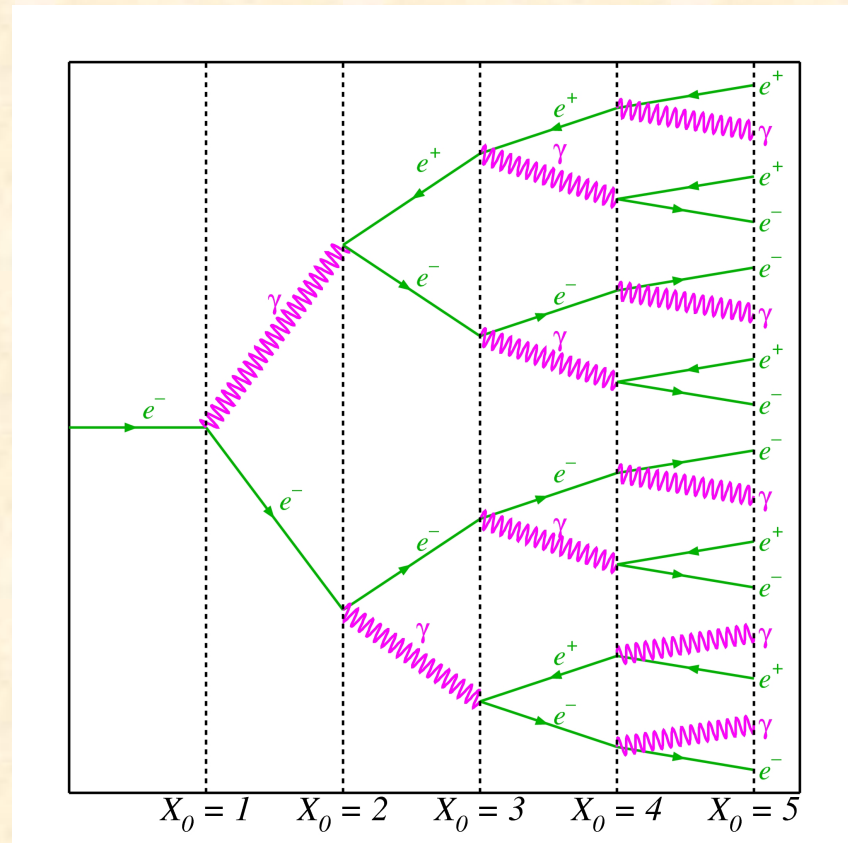


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- High energy particles interact with matter in several ways.
- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produced when such scattering occur will carry a significant energy and scatter themselves.

Example: Electron shower

- The distance after which an electron or a photon interacts is called the “radiation length”
- Radiation length vary from material to material and can be found in tables.
- $X_0(\text{Pb})= 0.56\text{cm}$
 $X_0(\text{Ta})= 0.41\text{cm}$
 $X_0(\text{Cu})= 1.44\text{cm}$
 $X_0(\text{Fe})= 1.76\text{cm}$
 $X_0(\text{C graphite})= 19.32\text{cm}$



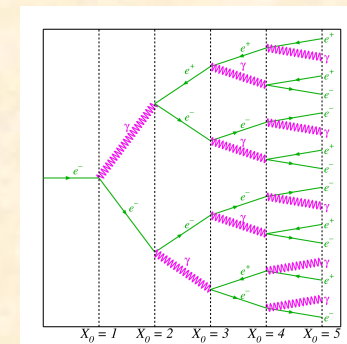
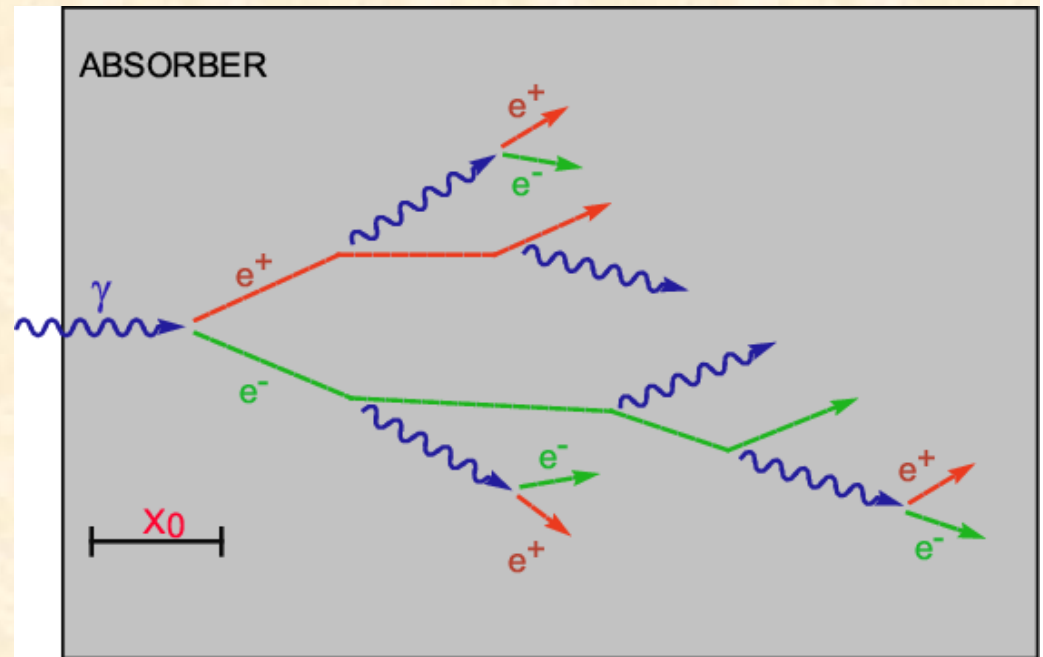
Particle absorption

- Particles loose 1/e of their energy after each radiation length.
- The reality is a bit more complex but statistically this picture is true...
- Heavy particles such as protons will loose some energy as they travel in matter and suddenly stop when their energy slow enough.
- More details in the

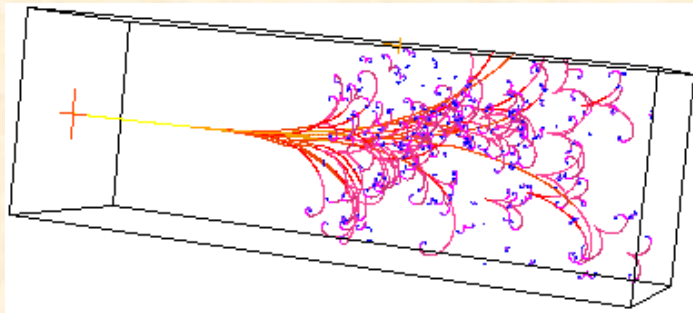
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instrumentation lectures

TESHEP 2012 - Particle accelerators
Diagnostics



Faraday cup (1)



- Let's send the beam on a piece of copper.
- What information can be measured after the beam has hit the copper?

Faraday cup (2)

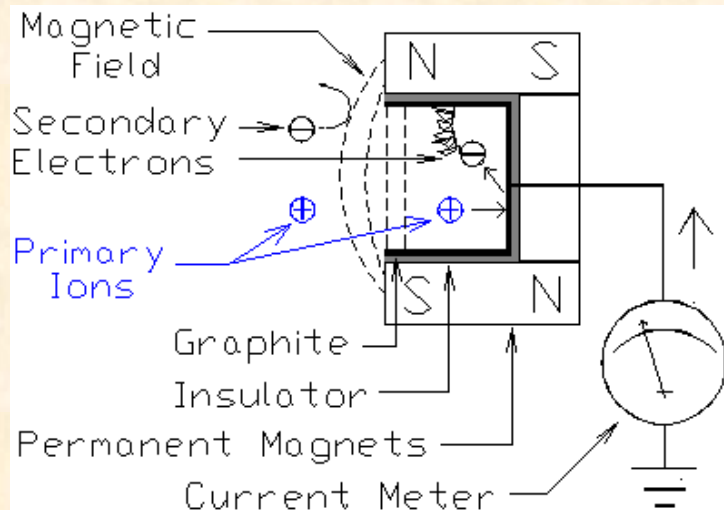


Image source: Pelletron.com

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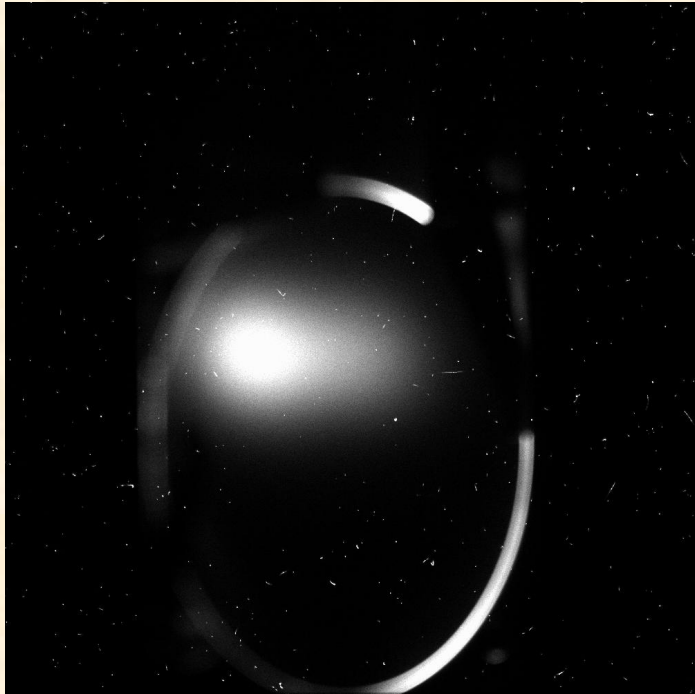
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- The total energy of the beam could also be measured by using the cup as a calorimeter, but usually knowing the charge is enough as most beam are almost monochromatic.
- At high energy Faraday cups can be large:
More than 1m at SOLEIL for a 3 GeV electron beam.

Screen (1)

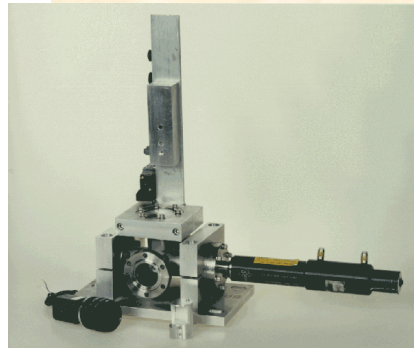
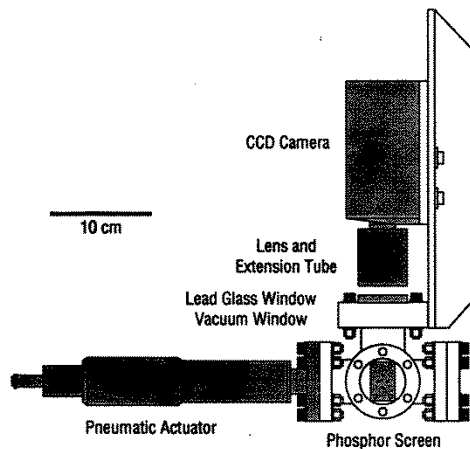


- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

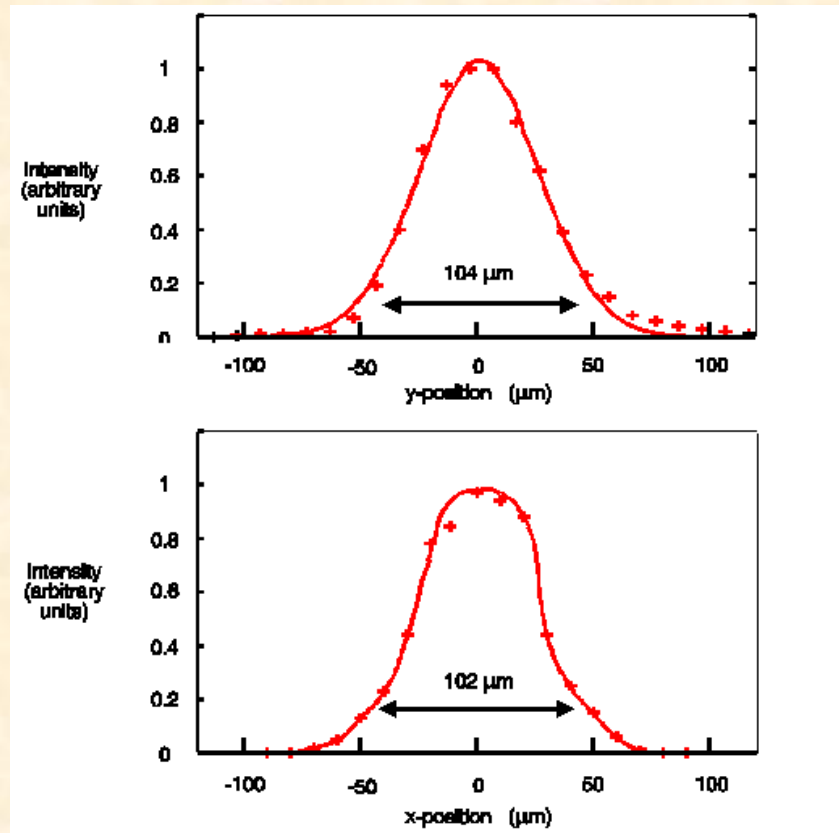
Screen (2)



- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at 45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

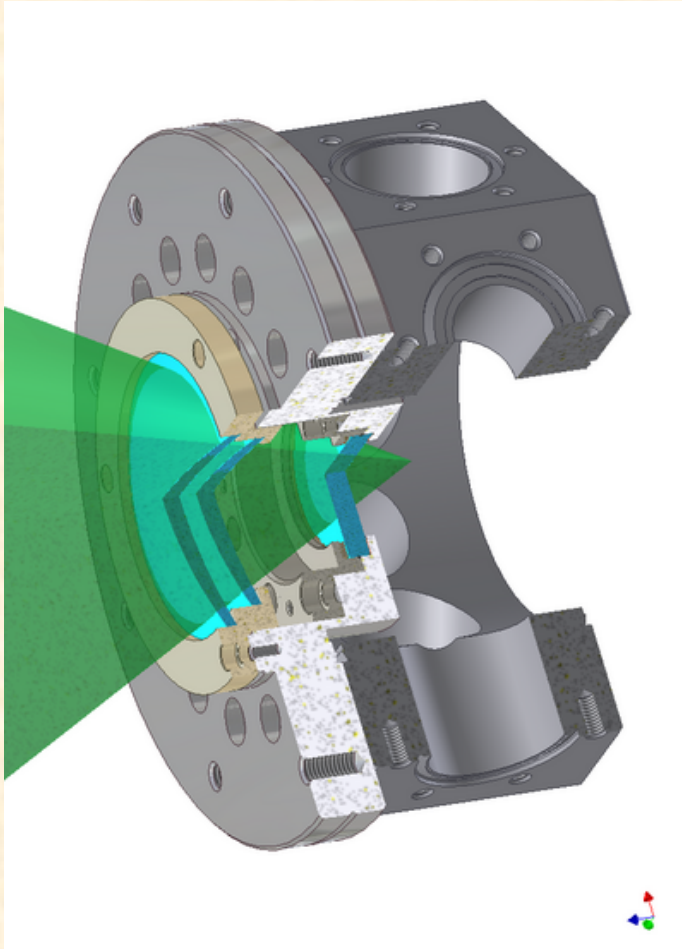


Wire-scanner



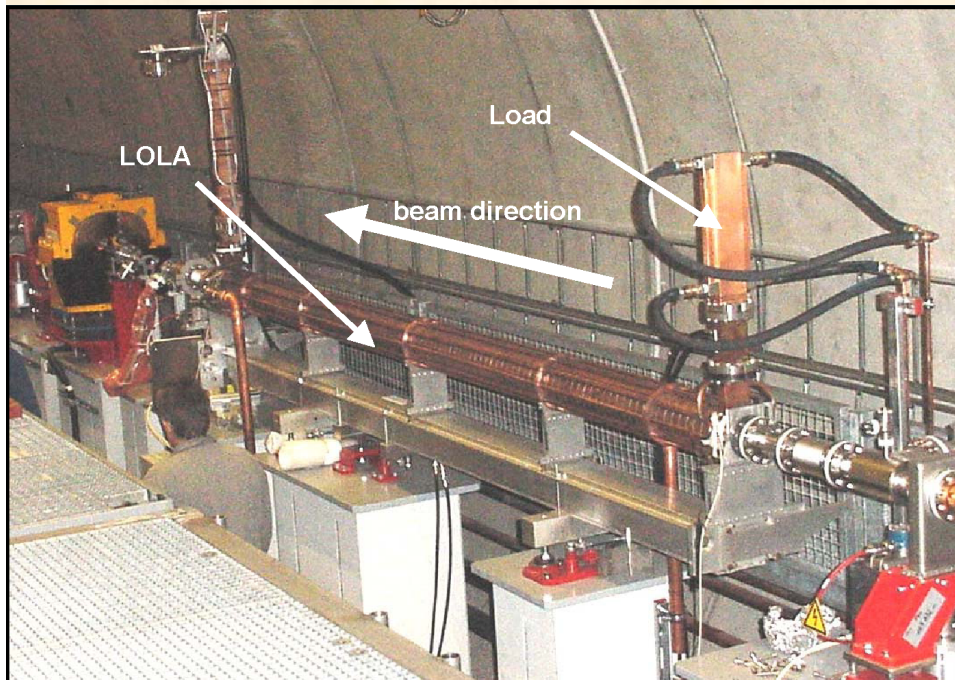
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
=> better resolution than with screens & less disruptive
- However, a too strong beam current can lead to damages to the wire (requiring replacement of the wire).

Laser-wire

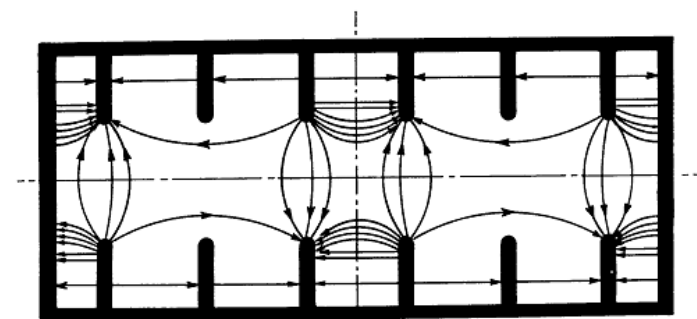
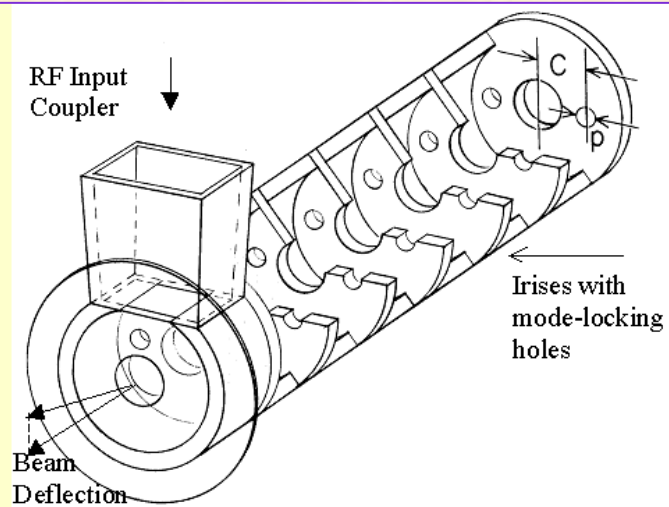


- To mitigate the problem of broken wires in wire-scanners it is possible to replace the wire by a laser.
- This technique called “laser-wire” also allow to reach better resolutions.
- High power lasers (or long integration times) are needed.

Longitudinal properties

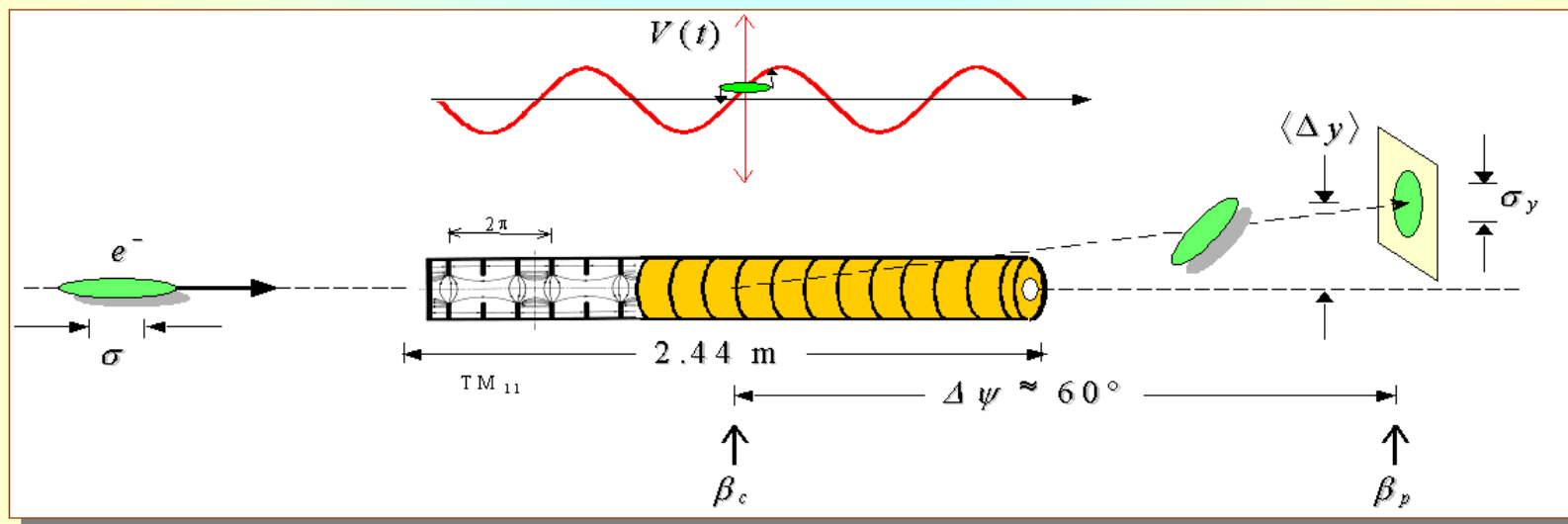


- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsions to the beam it is possible to make it rotate and observe its longitudinal profile.

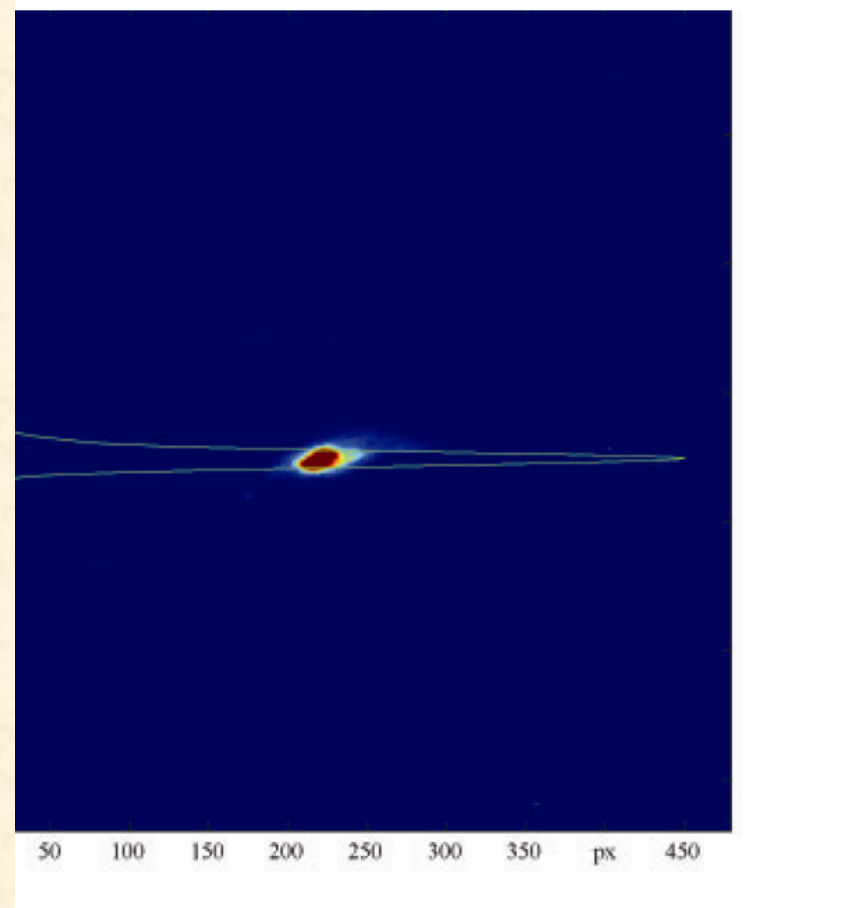
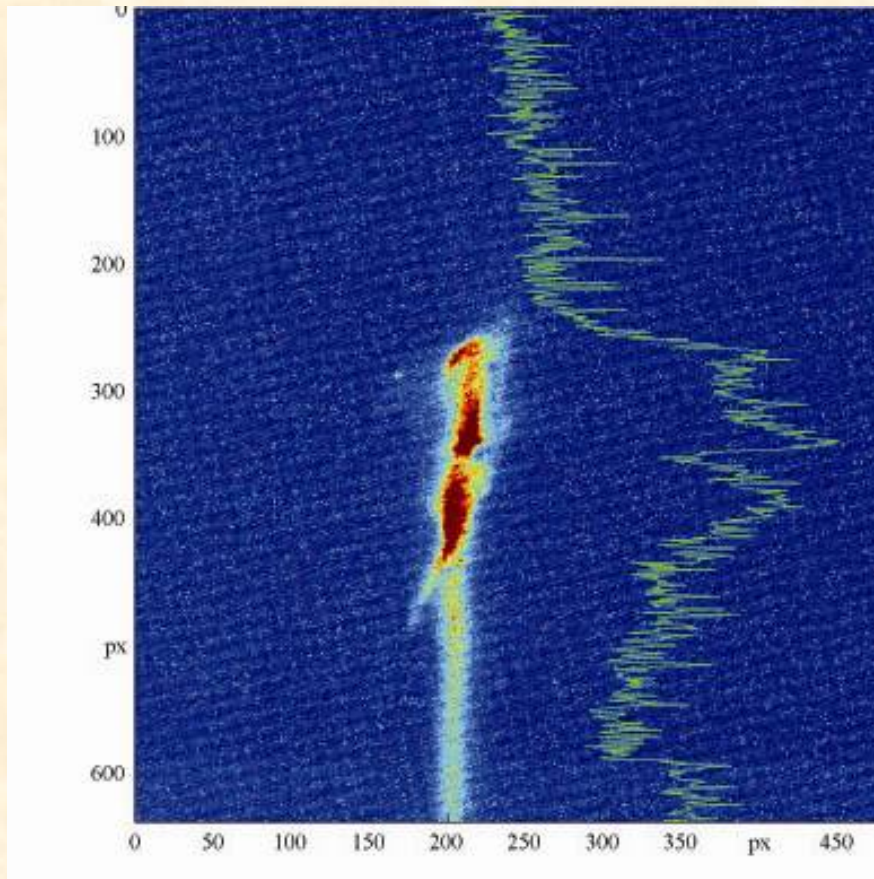


$$V_0 \approx (1.6 \text{ MV/m/MW}^{1/2}) L \sqrt{P_0}$$

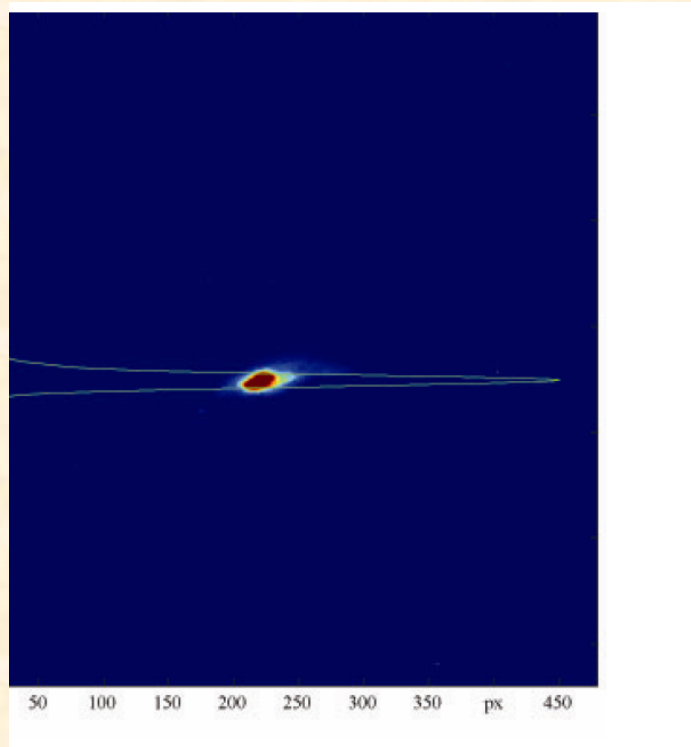
$$\text{bunchlength, } \sigma_z \approx \frac{\lambda_{rf}}{2\pi} \frac{E_s}{|e V_0 \sin \Delta \psi \cos \phi|} \sqrt{\frac{(\sigma_y^2 - \sigma_{y0}^2)}{\beta_d \beta_s}}$$



RF deflector off and on



Deflection calculations



- The transverse kick given by the cavity is

$$\Delta x'(z) = \frac{eV_0}{pc} \sin(kz + \varphi) \approx \frac{eV_0}{pc} \left[\frac{2\pi}{\lambda} z \cos \varphi + \sin \varphi \right]$$

- This leads to an offset

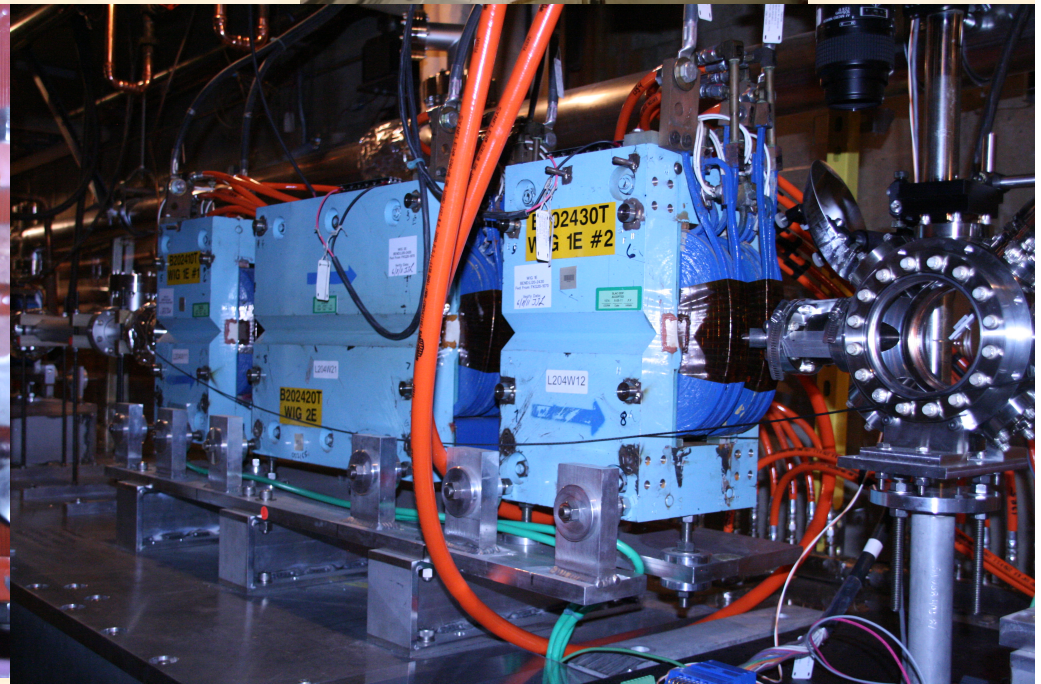
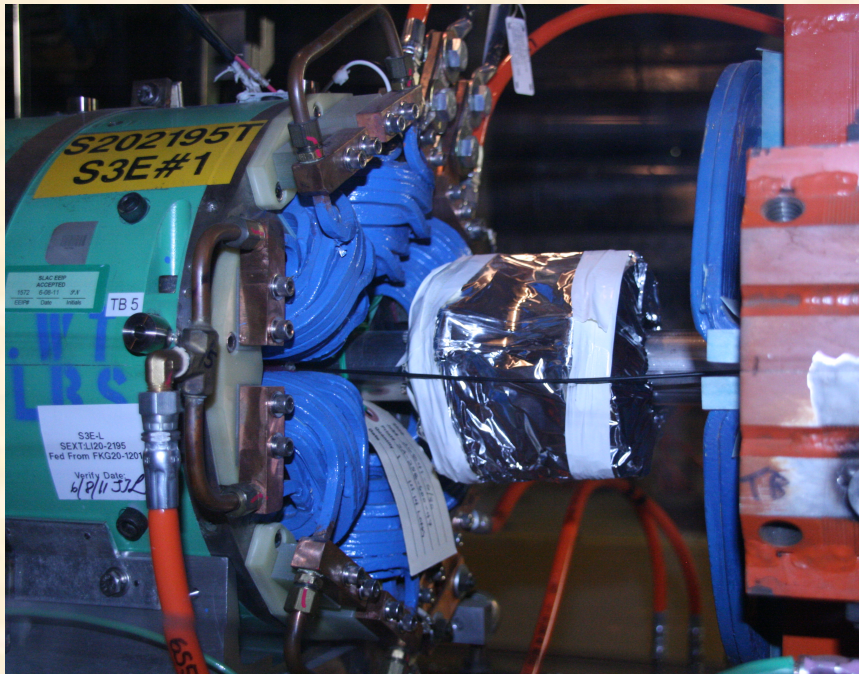
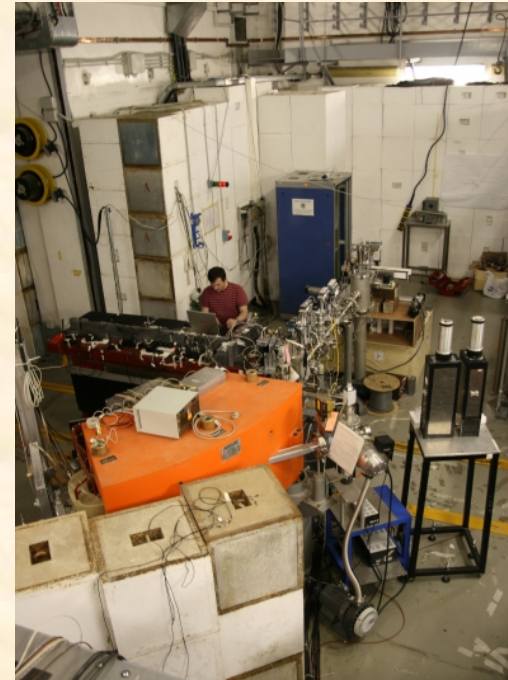
$$\Delta x = \sqrt{\beta_1 \beta_2} \sin \Delta \psi \cdot \Delta \theta$$

- And a resulting beam size

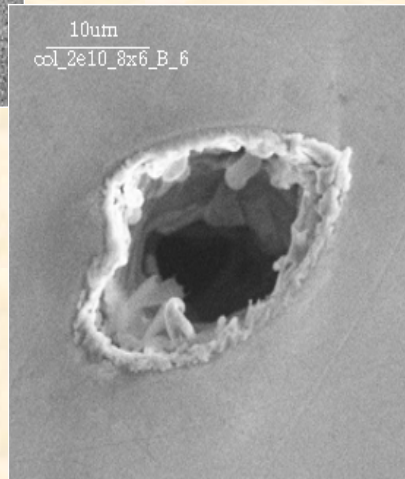
$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2 \beta_d \beta_s \left(\frac{2\pi e V_0}{\lambda \gamma m_e} \sin \Delta \psi \cos \varphi \right)^2}$$

Beam losses

- It is important to monitor the beam losses directly:
- Small beam losses may not be detected by other systems
- Beam losses are a source of radiation and activation
- Most beam losses indicate that there is a problem somewhere.
- In some accelerators on optical fibre is used to track the losses (by induced Cerenkov light).
- Beam loss monitoring is often compulsory to minimize health risks.



Limitation of these monitors



- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

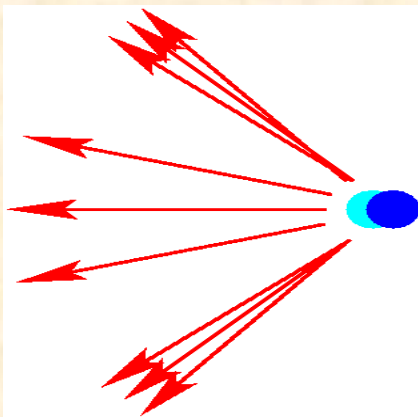
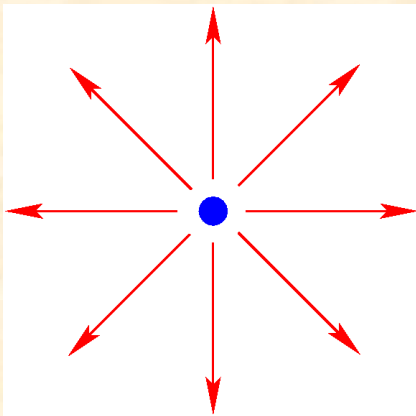
Summary

(particles interaction with matter)

	Interaction with matter
<i>Charge</i>	Faraday cup
<i>Position</i>	Screen
<i>Size or shape (transv.)</i>	Screen or wire-scanner/LW
<i>Size or shape (longit)</i>	RF cavity + screen
<i>Energy</i>	???
Losses	Scintillator

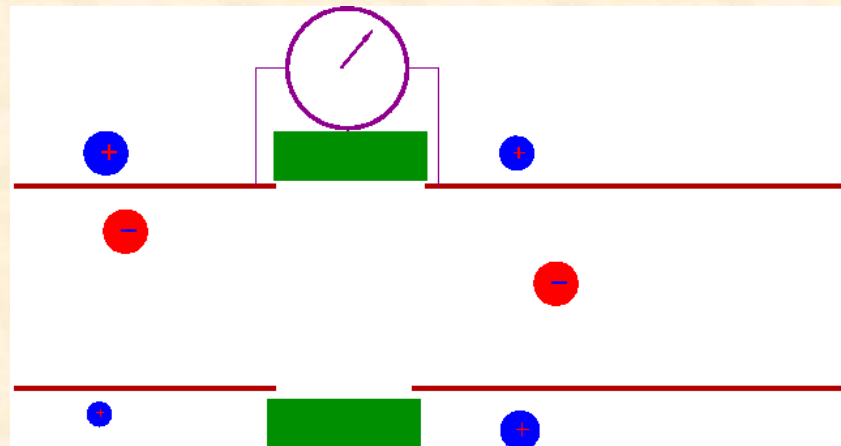
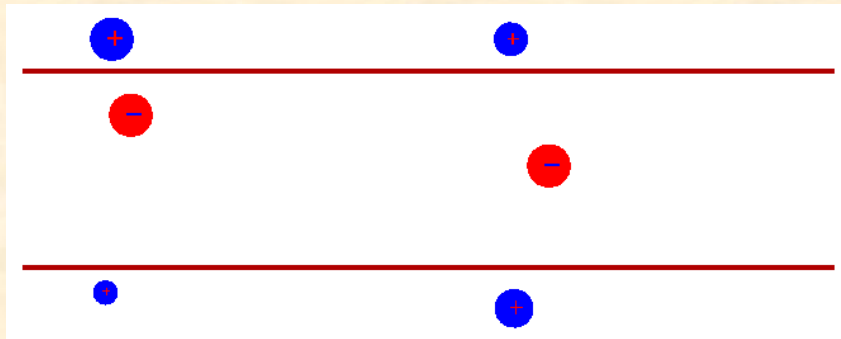
- We have seen that it is possible to build monitors which use the interactions of particles with matter.
- These monitors tend to be destructive: they significantly damage/modify the beam.
- These monitors tend to be simple but can be damaged by high energy and/or high intensity beams.

Charged particle



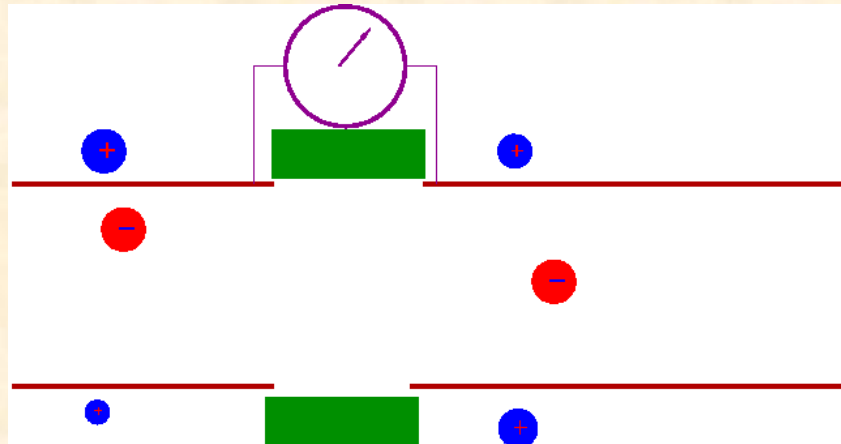
- Any charged particle “radiates”
- These electromagnetic radiations can be detected without disrupting the beam.
- One needs to remember that the beam travels at high speed: the radiations will be contained in a $1/\gamma$ cone.

Beam current monitor



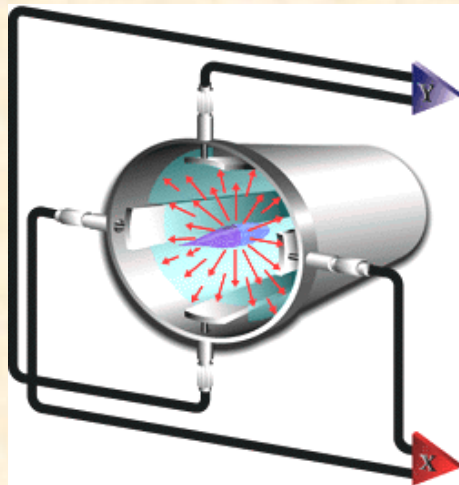
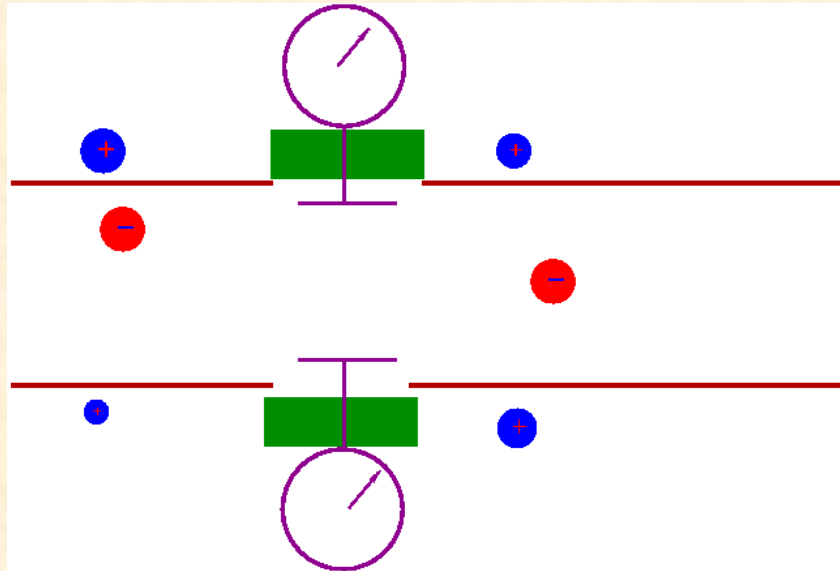
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

Beam current monitor vs Faraday cup



- Both devices have pros and cons.
- A Faraday cup destroys the beam but it gives a very accurate charge measurements
- A Beam current monitor does not affect the beam but must be calibrated.
- Both tend to be used but at different locations along the accelerator.

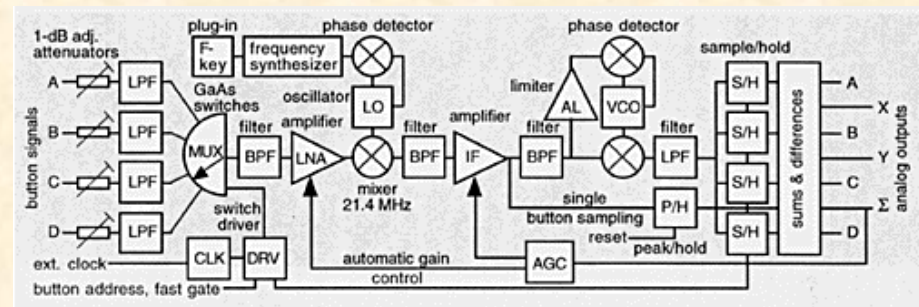
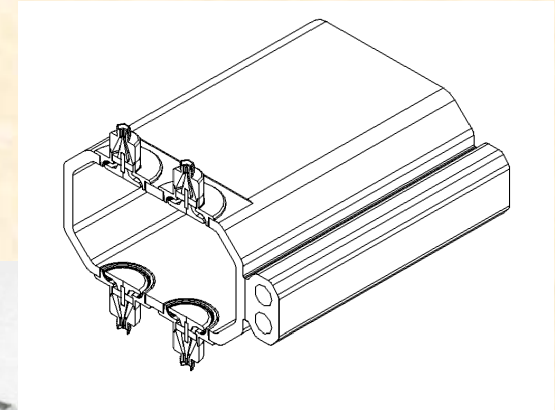
Beam position monitor



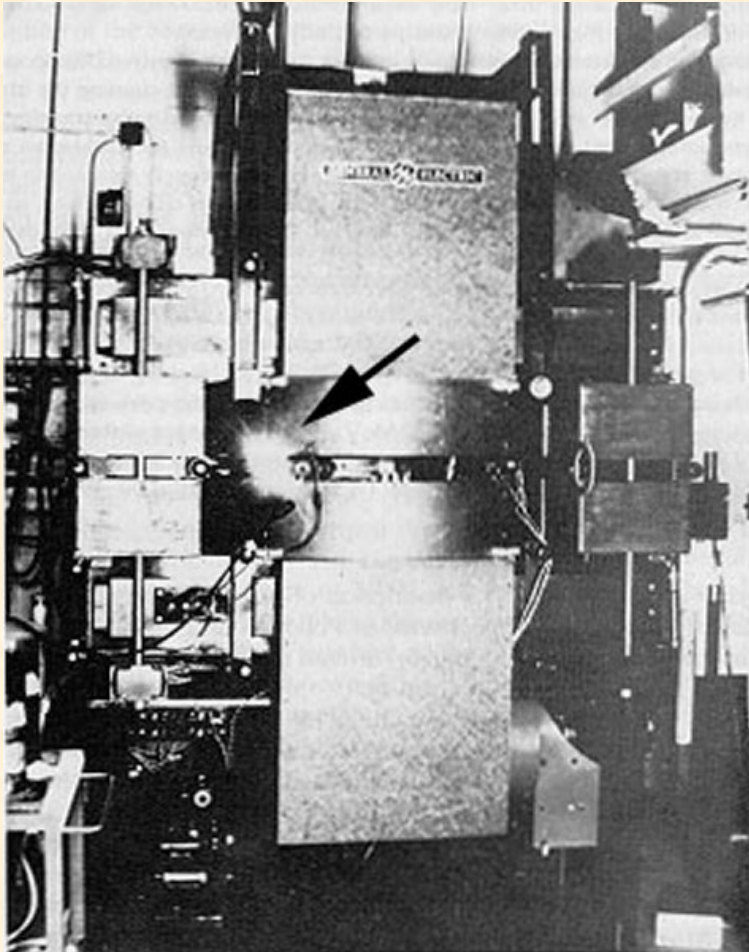
- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

Beam Position Monitor (2)

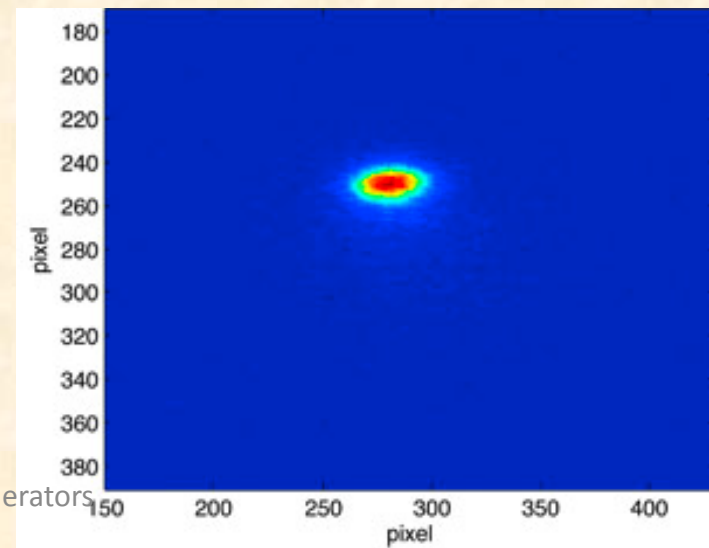
- BPM are one of the most common diagnostic at an accelerator.
- They exist on many different configurations.
- At synchrotrons it is not possible to have electrodes in the horizontal plane so the electrodes have to be above or below the beam.
- Although the basic principle is simple, very advanced electronics are used to get the best possible precision.
- In typical synchrotrons there is a large number of BPMs, about 1 every 4 meters in the ring!



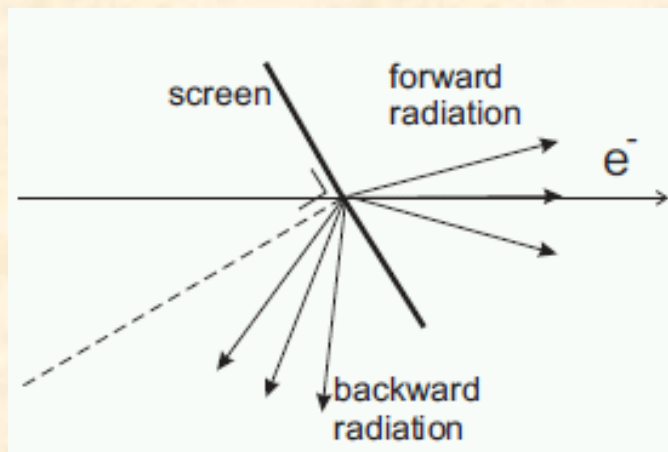
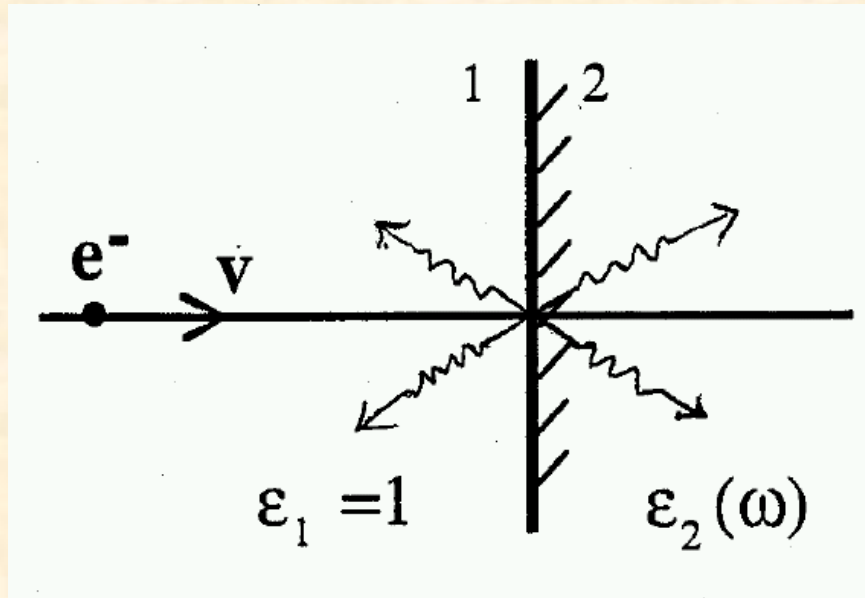
Synchrotron radiation



- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.

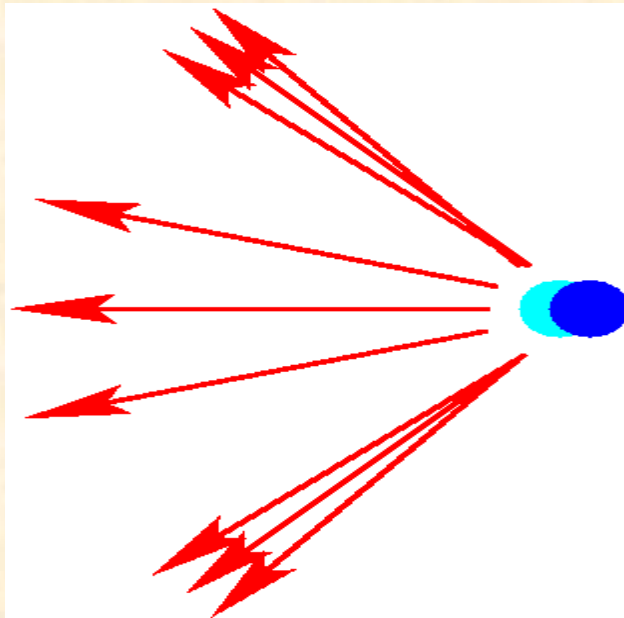


Optical Transition Radiation



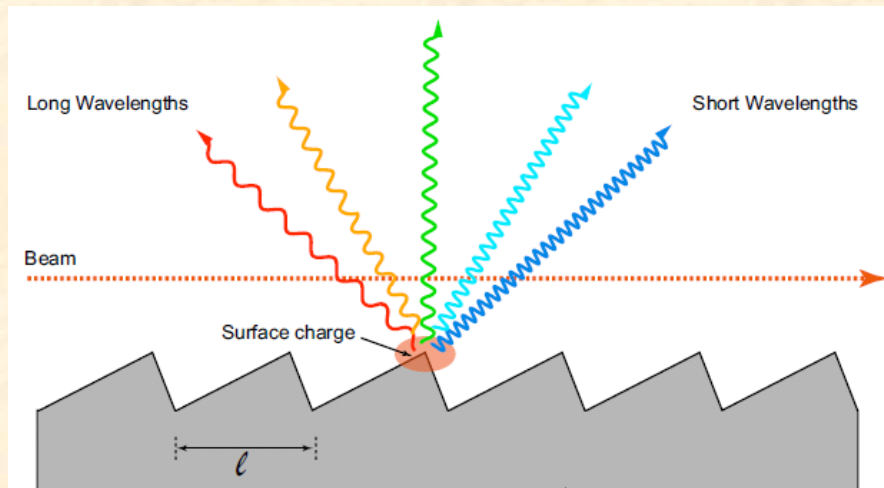
- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape (and possibly other things).
- As this is a surface effect, very thin (non disruptive) screens can be used.

Optical Diffraction Radiation



- It is also possible to use a screen to reflect the wake created by the charged particles bunch.
- This technique is called ODR.
- It is even less disruptive than OTR.

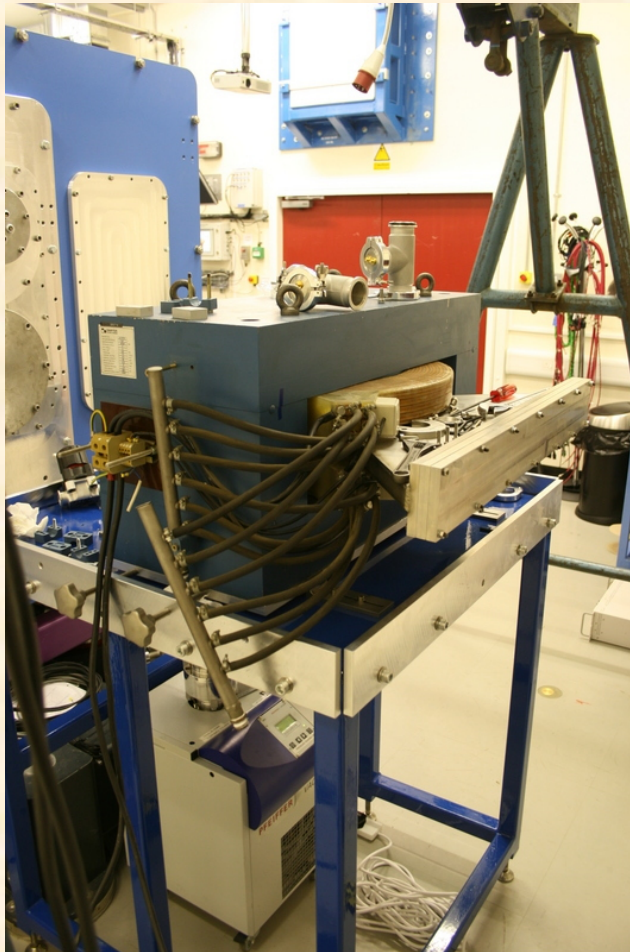
Longitudinal profiles



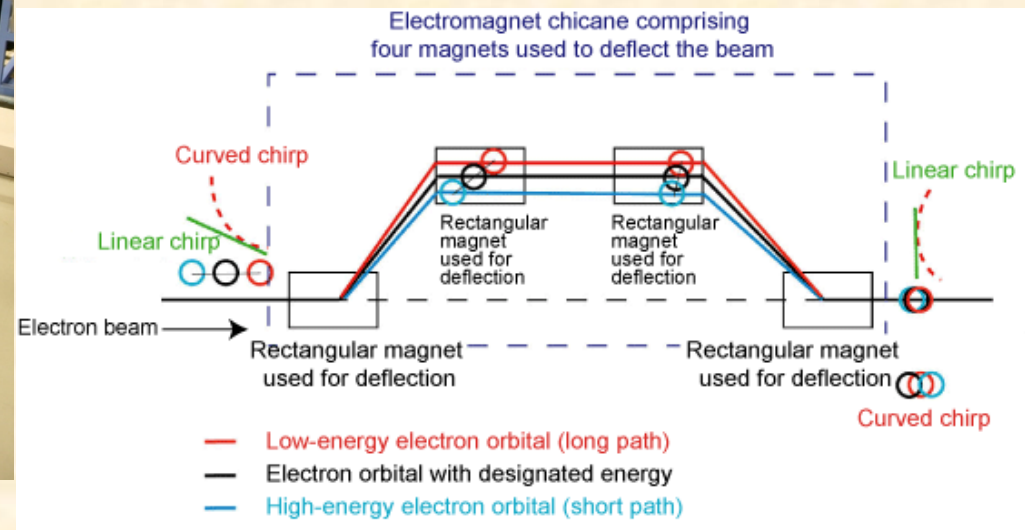
- Longitudinal profiles of short beams are one of the most difficult measurement.
- Several techniques use radiation induced by the beam.
- In the Smith-Purcell method a grating is used.
- The beam interacts coherently with the grating and emits radiation.
- The intensity and wavelength of this radiation depends on the longitudinal profile of the beam.
- Most longitudinal profile measurement techniques actually measure the Fourier transform of the beam
=> reconstruction needed!

$$\left(\frac{dI}{d\Omega d\omega} \right)_{N_e} (\Omega, \omega) = \left(\frac{dI}{d\Omega d\omega} \right)_{sp} (\Omega, \omega) \cdot [N_e + N_e(N_e + 1) |F(\omega)|^2]$$

Energy measurements



- To measure (or select) the energy of the particles a bending magnet is often the best solution.
- This can be done in an “energy chicane”.



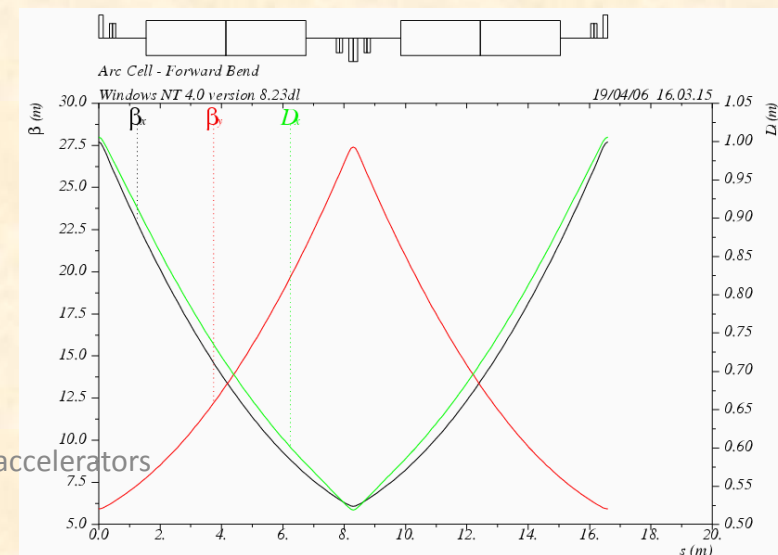
Diagnostics overview

	Interaction with matter	Radiation
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transverse)	Screen or wire-scanner	Synchrotron radiation or optical transition radiation
Size or shape (longitudinal)	RF cavity + screen	Radiation detectors (eg: Smith-Purcell)
Energy		Bending magnet
Losses	Scintillator	

Emittance measurement: Multi screen/wire method

- The emittance is not directly an observable.
- The beam size is an observable.
- By measuring the beam size at several locations it is possible to fit the best emittance.
- The beam size can be measured by using screens or wires.

$$\sigma = \sqrt{\epsilon(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$

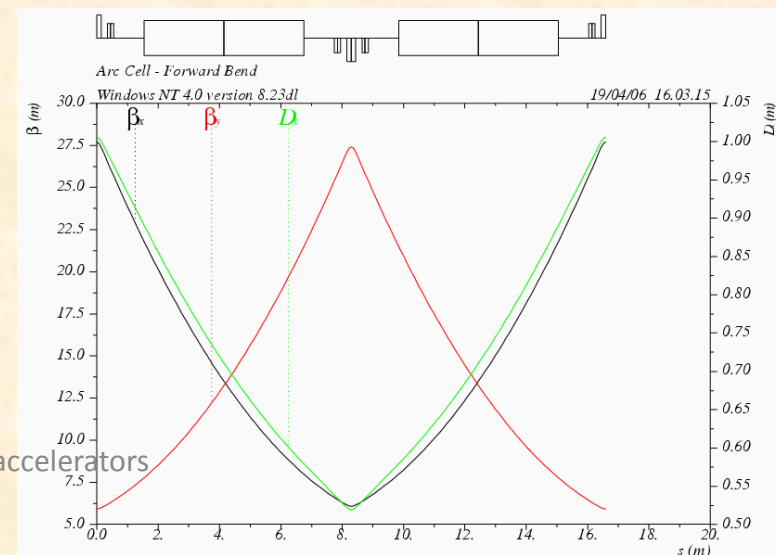


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Diagnostics

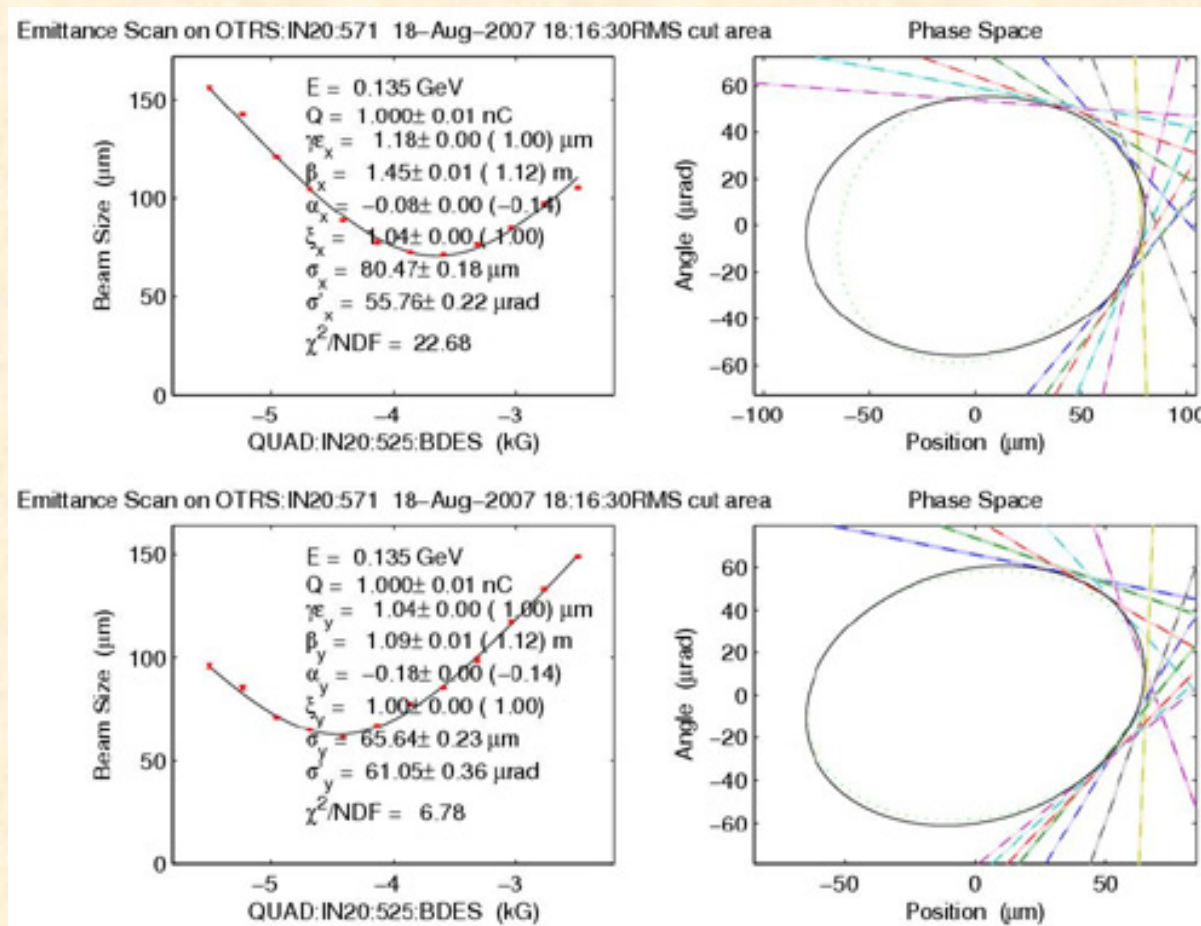
Quad scan

- The emittance can also be measured by changing the strength of a quadrupole and measuring the location at a fixed position.
- This modifies the beta function of the beam and once again this can be fitted to find the best emittance value.

$$\sigma = \sqrt{\epsilon(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$

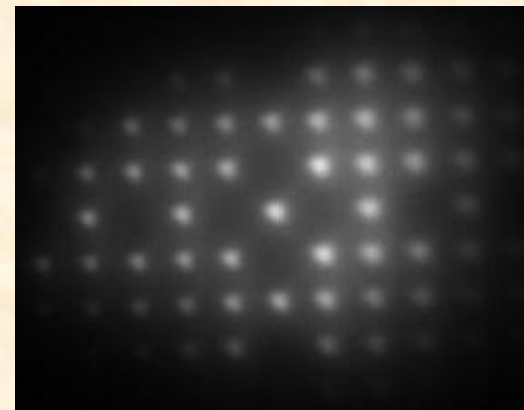
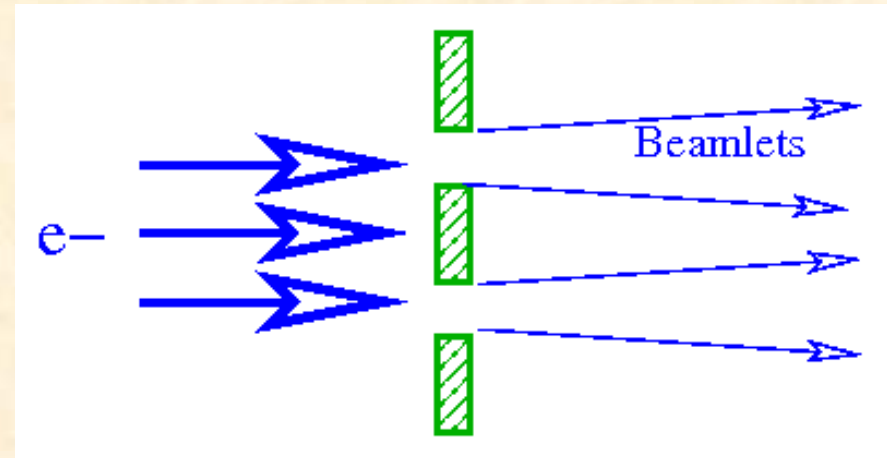


Quad scan emittance measurement



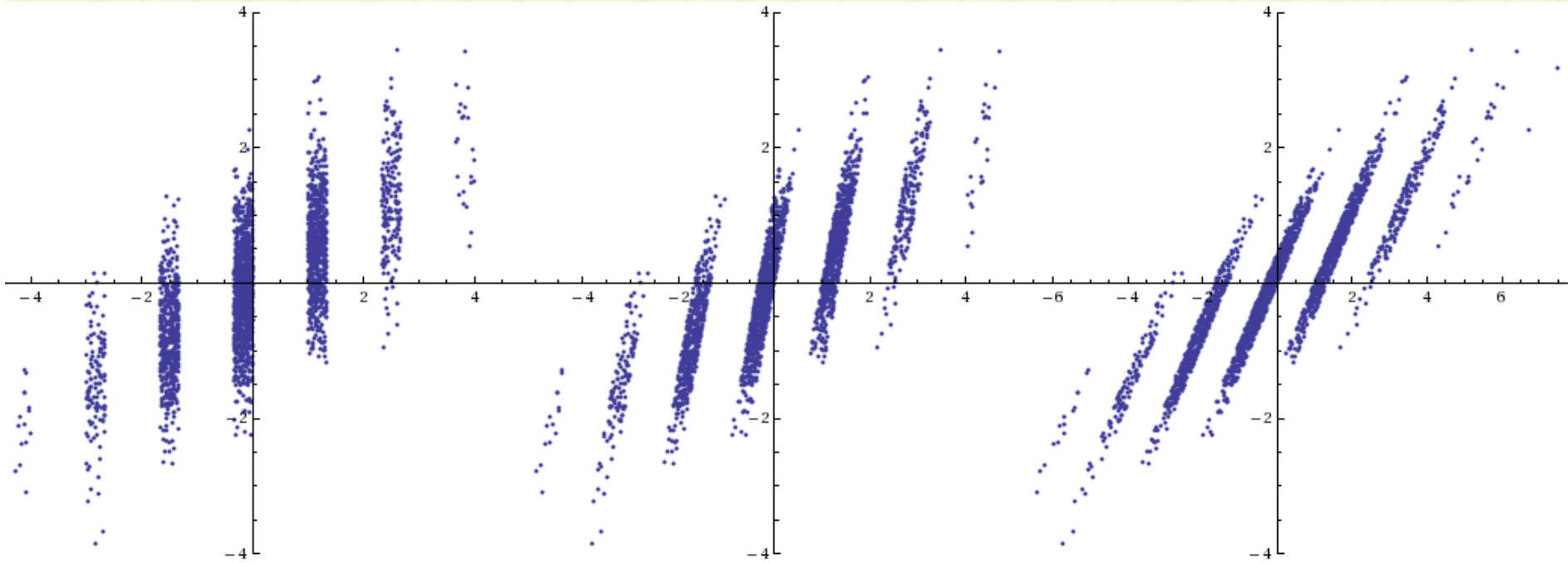
Pepper-pot (1)

- A grid of dense material inserted in the beam path will split the beam in several beamlets.
- The transverse position at which these beamlets were created is known (it is the position of the grid).
- A measurement of the size of the beamlets downstream gives access to the beam divergence.
- The beam size plus the beam divergence can be combined to give the value of the emittance.



Pepper-pot measurement of the transverse emittance of a van de graaff

Pepper-pot (2)



- In the phase space, the effect of pepper-pot is shown above:
 - The beam is sampled at given x positions
 - After the pepper-pot, the beam drifts
- The measurement must be made close enough so that the beamlets do not overlap.
- The Pepper-pot method is a destructive single-shot technique (the beam is destroyed after the measurement but a single pulse is enough to make the measurement).
- It is used a low energy, for example for the study of particle gun properties.

Diagnostics summary

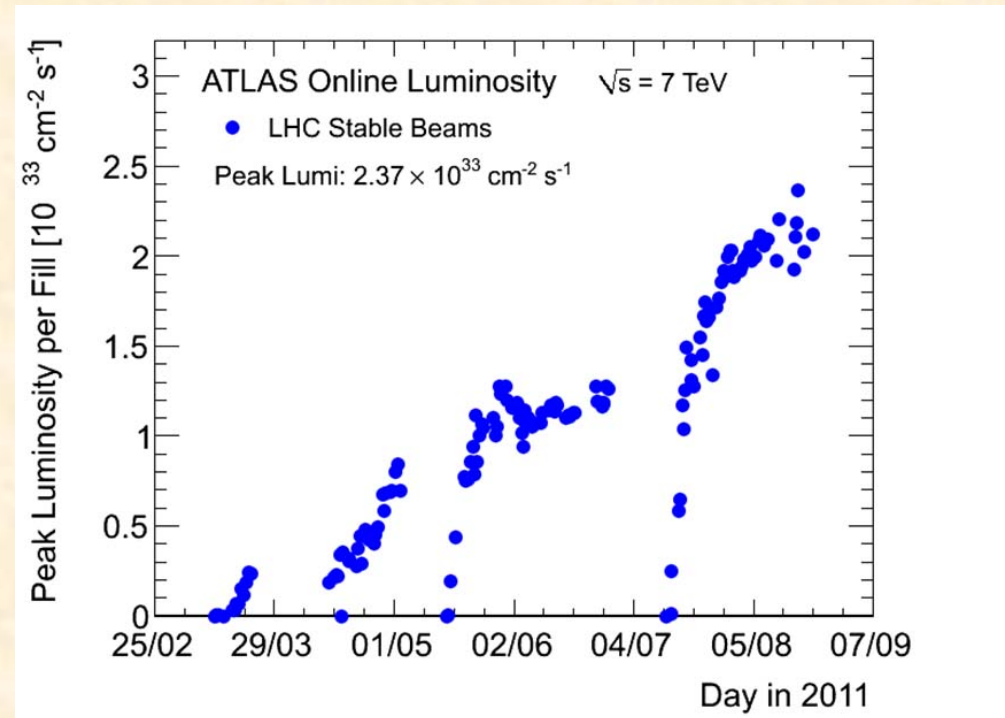
- The properties of a particle beam can be measured, either:
 - through its interactions with matter (destructive measurement)
 - or by detecting the radiation measurements (almost non perturbative measurement)
- The more accurate the measurement has to be the more precise/expensive the measuring equipment will be.
- Diagnostics for particle accelerators are an active research area with conferences dedicated to the topic every year.



EXAMPLE OF ACCELERATOR: THE LHC

A complex enterprise

- Beyond the particle physics challenges associated with the construction of the detectors and the analysis of the data, building and operating the LHC machine was also an immense challenge involving a large number of skills.
- The machine has not yet reached its full potential and the engineers running it improve its performance all the time.

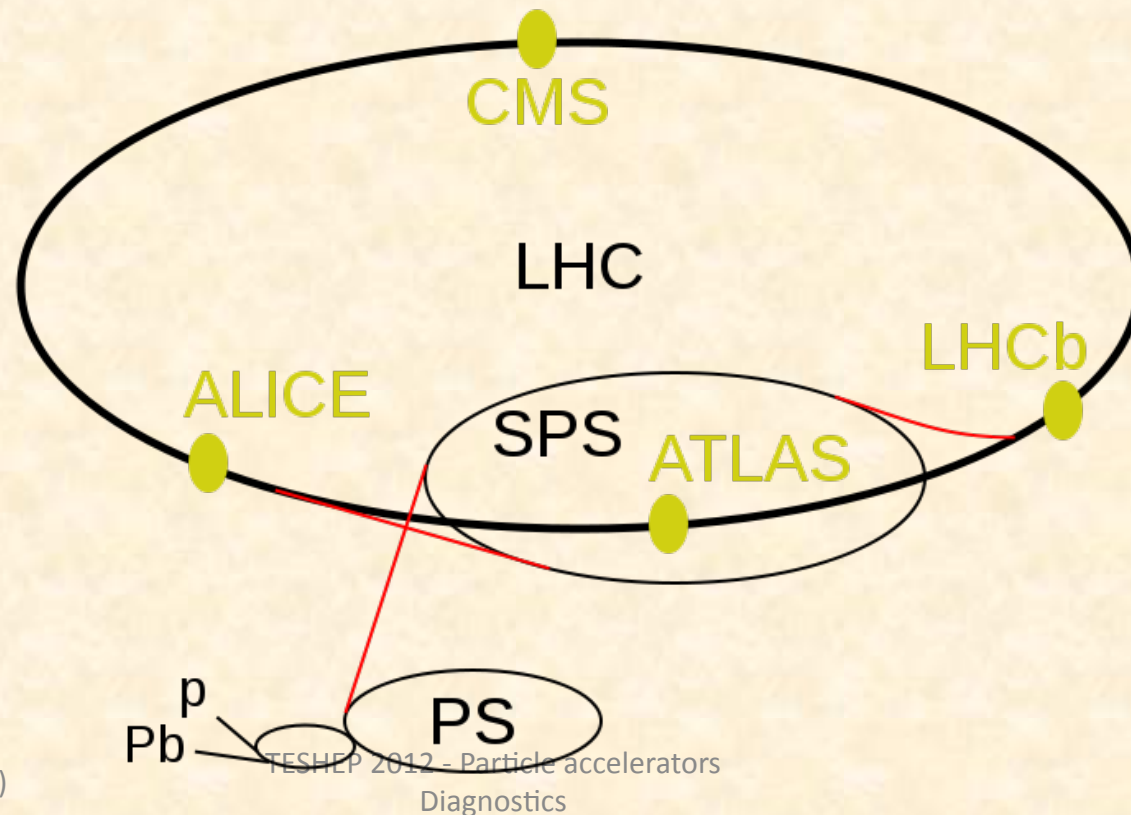


References: <http://lhc.web.cern.ch/lhc/LHC-DesignReport.html> and

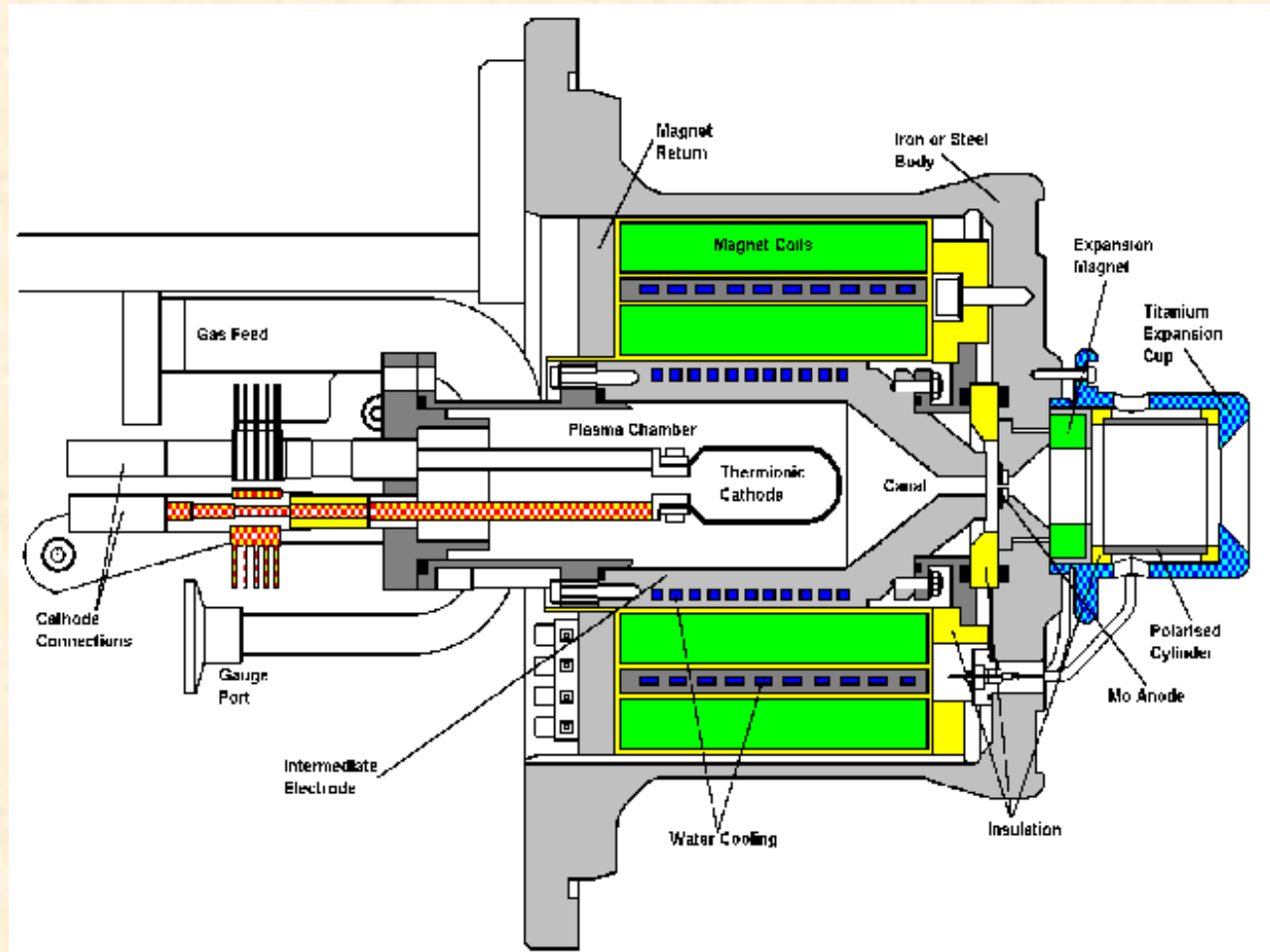
« The LHC Machine, Lyndon Evans and Philip Bryant 2008 *JINST* **3** S08001 doi:10.1088/1748-0221/3/08/S08001 »

The injection chain

- Particles can not directly be produced and accelerated in the LHC, several preliminary steps are necessary.
- Let's follow a proton from the source to the collisions...

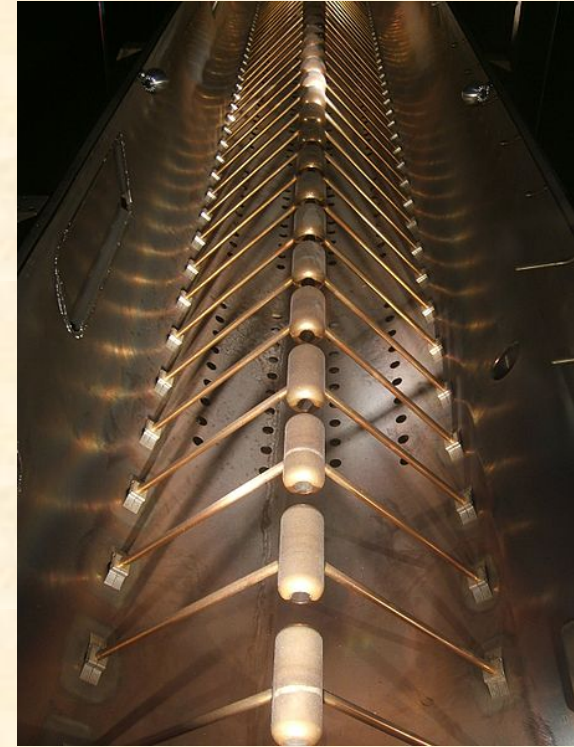
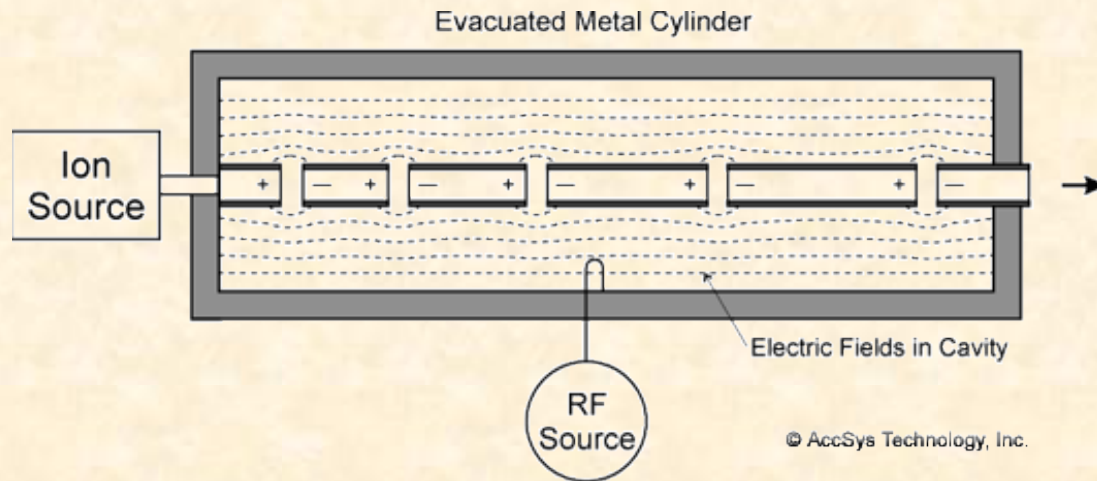


Proton source



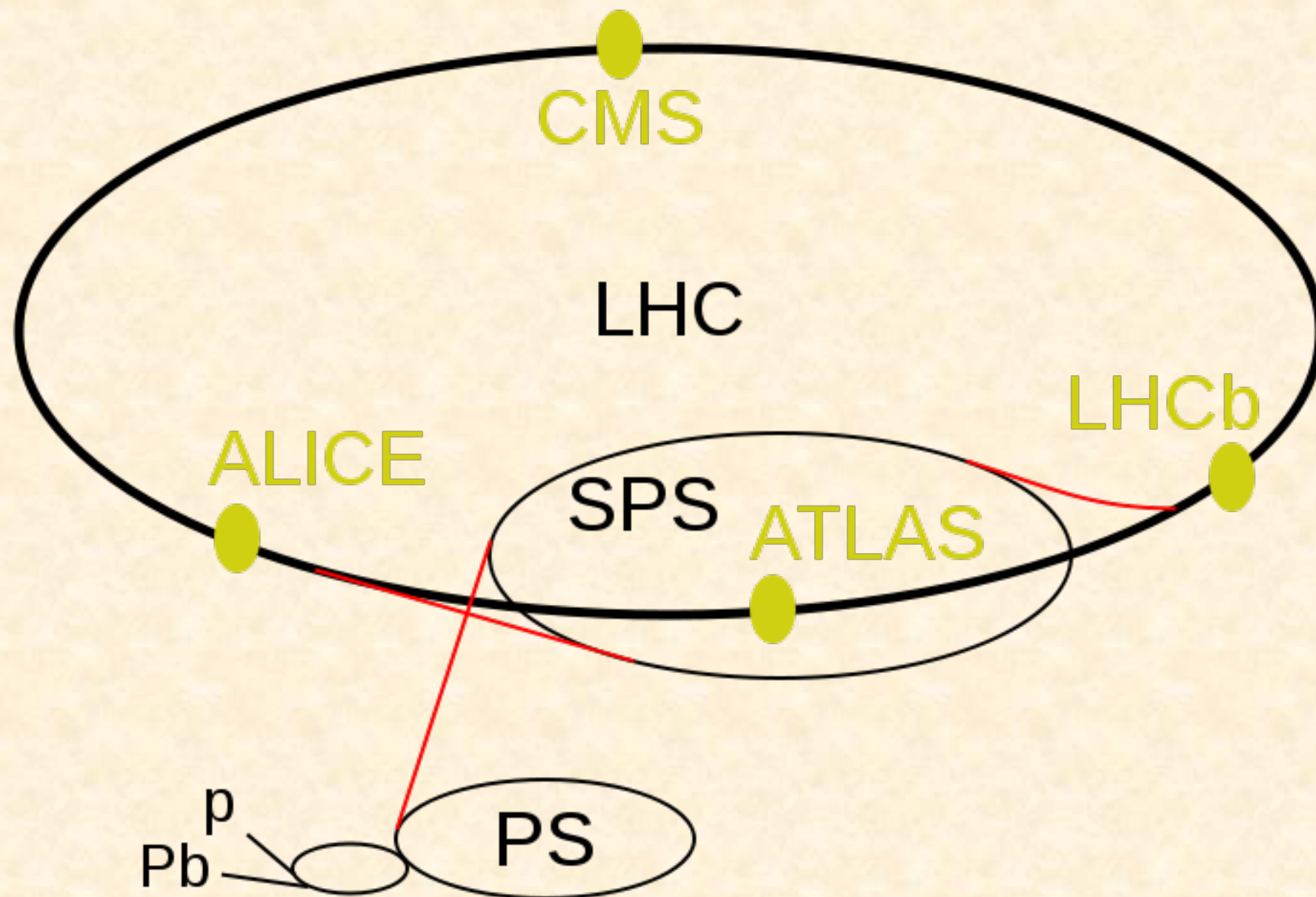
- Particles are extracted by ionisation of hydrogen as in a device called “Duoplasmatron Proton Ion source”

Linac



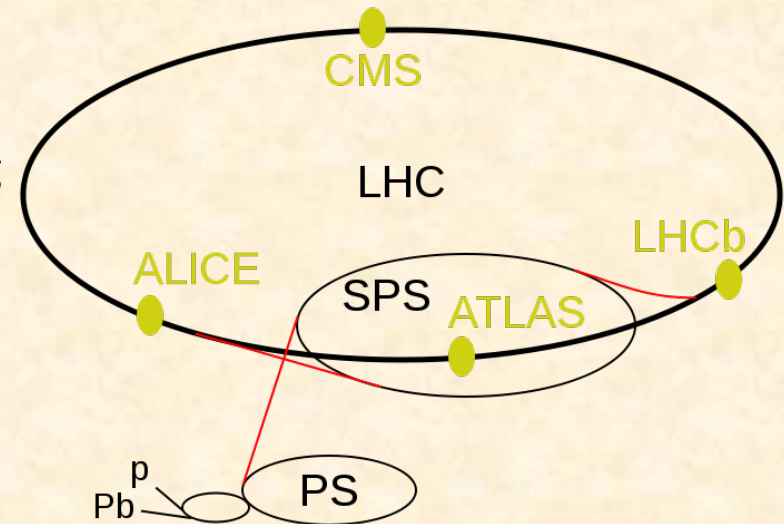
- After the source the protons are accelerated in a linac.
- As the protons gain speed they travel longer distance in a RF cycle and therefore the length of the tubes must be increased.
- At the end of the Linac the protons reach an energy of 50 MeV.



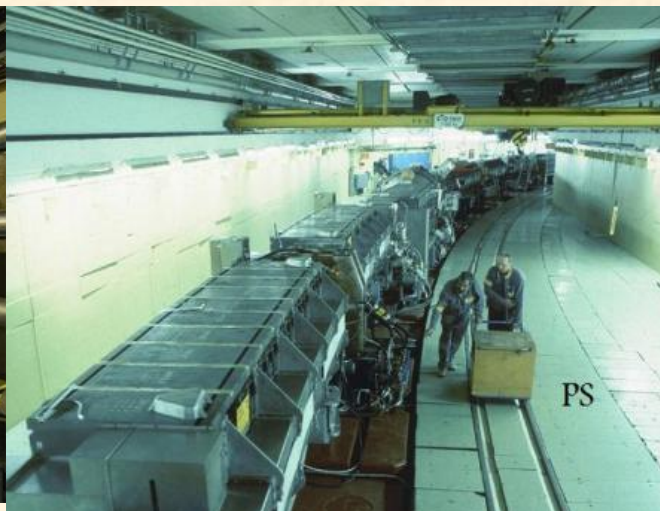


Pre-acceleration rings

- At 50 MeV the energy of the protons is too low to be injected in the LHC.
- Several intermediate rings are necessary to bring their energy to the LHC injection energy.
- To save space the first of these rings, the PS booster is made of 4 rings stacked on to each other!
- All these rings use pulsed magnets which allow to change the beam configuration very quickly.
- The PS was built in 1959, the PSB in 1972 and the SPS in 1976.



Nicolas Delerue, LAL (CNRS)

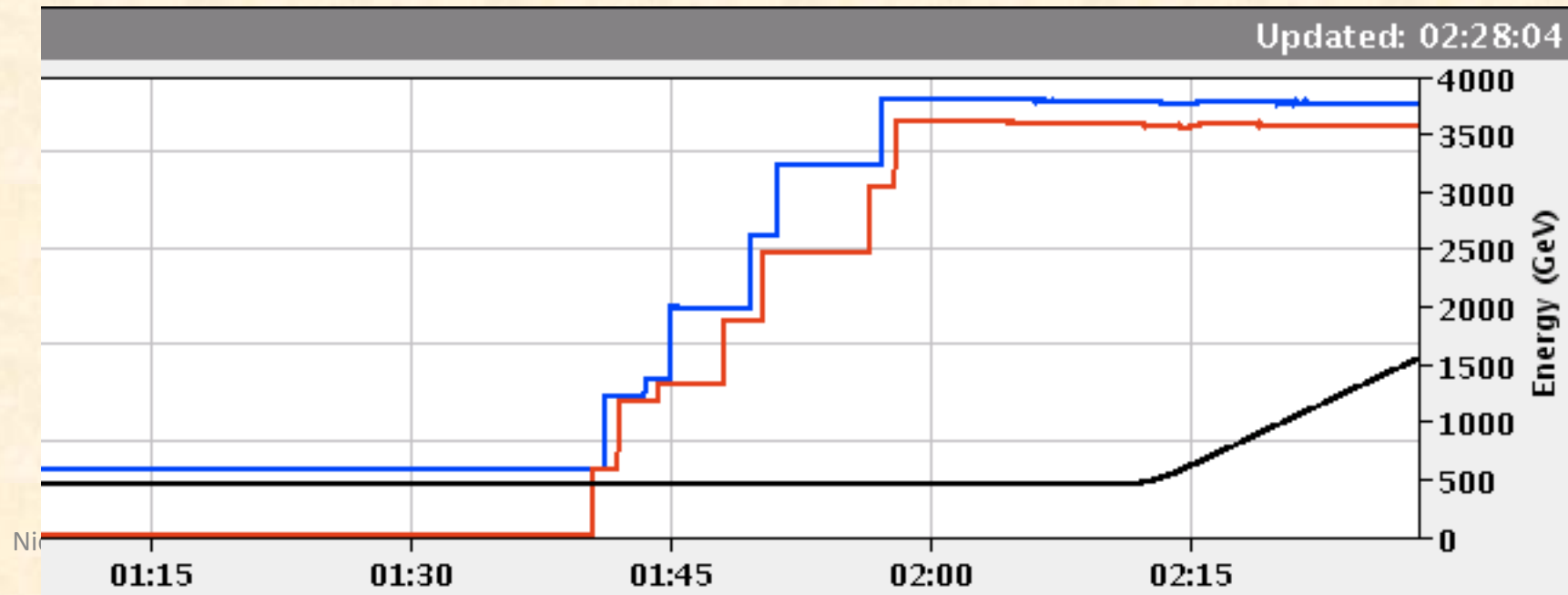


TESHEP 2012 - Particle accelerators
Diagnostics



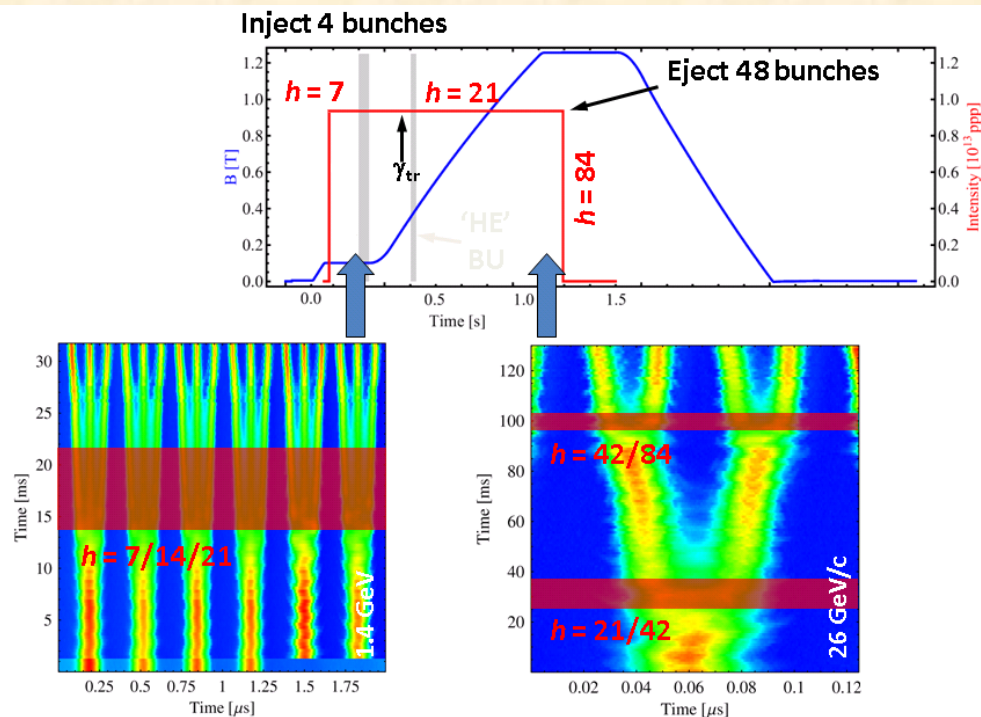
Why pre-acceleration rings?

- In a synchrotron the strength of the magnets must be increased when the energy of the particles is increased.
- It is cheaper to have magnets (and power supplies) with a limited dynamic range.
- As the energy of the beam increases its emittance (and therefore its size) decreases.
Early accelerators in the acceleration chain must have a wide aperture whereas the LHC has a small aperture (a bunch from the Linac would not fit in the LHC).

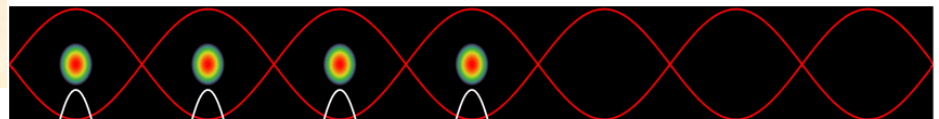


Protons bunch splitting

- Another purpose of the PS is to adapt the bunch structure from the Linac to the requirements of the LHC.
- The RF of the PS is used to split 8 proton bunches into 84 bunches!

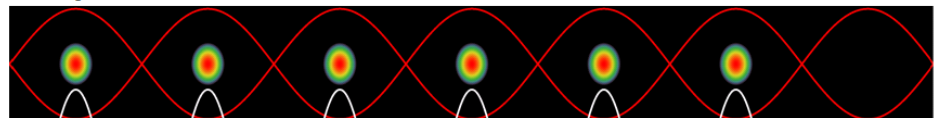


1. Inject four bunches

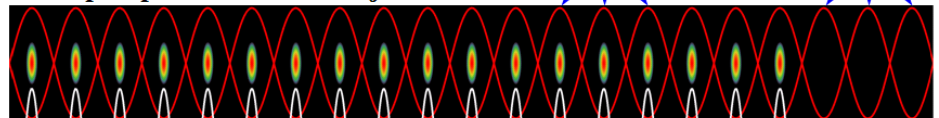


Wait 1.2 s for second injection

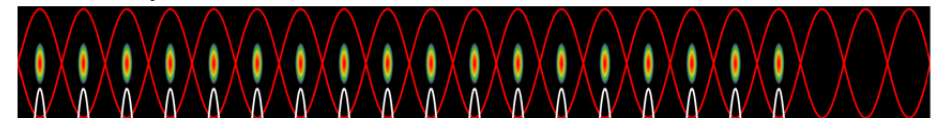
2. Inject two bunches



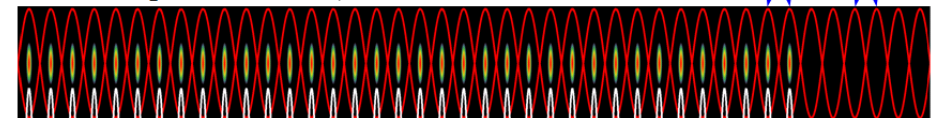
3. Triple split after second injection



1. Coarse synchronization with SPS ($h1$, move batch)

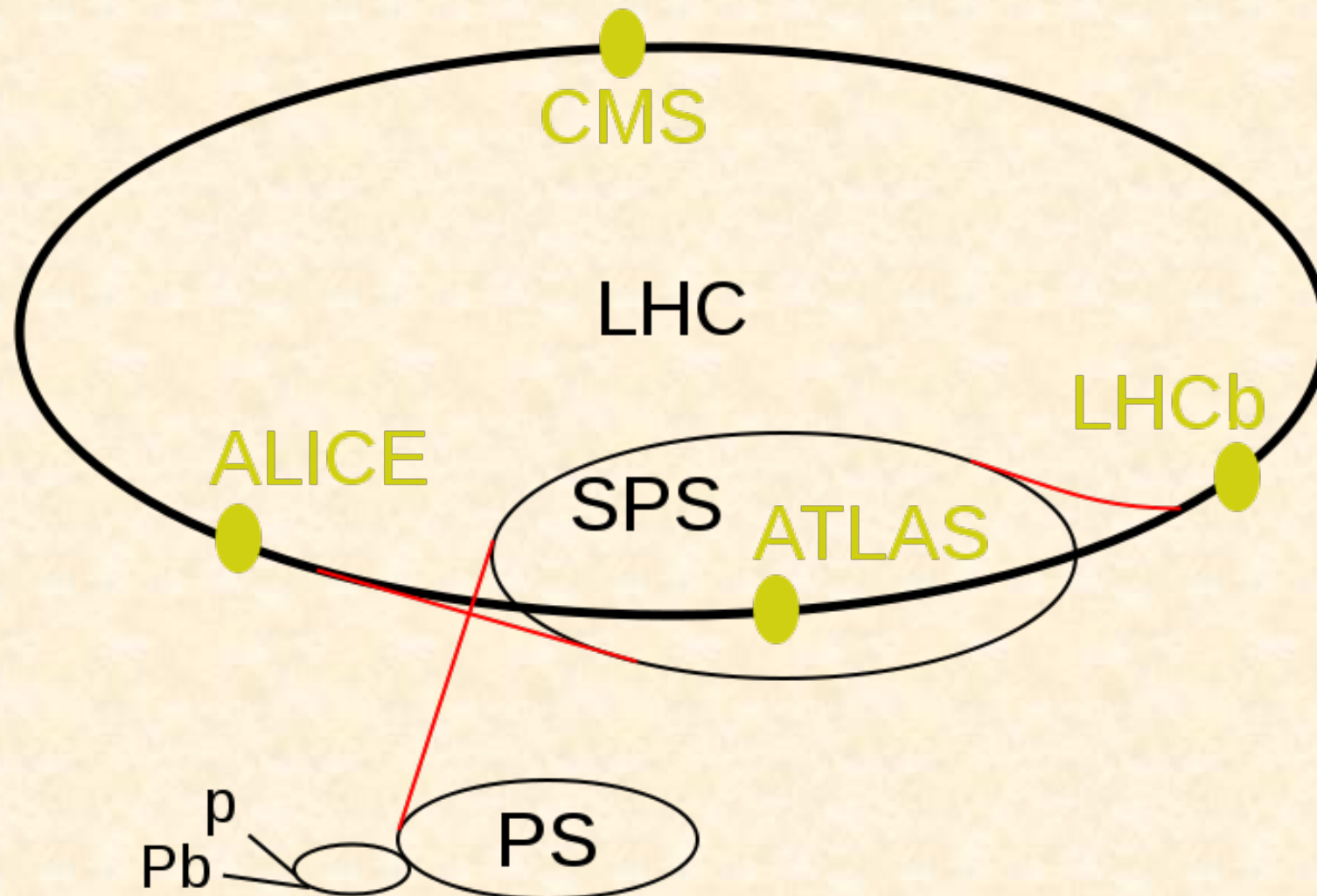


2. Double split ($h42 \rightarrow h84$)



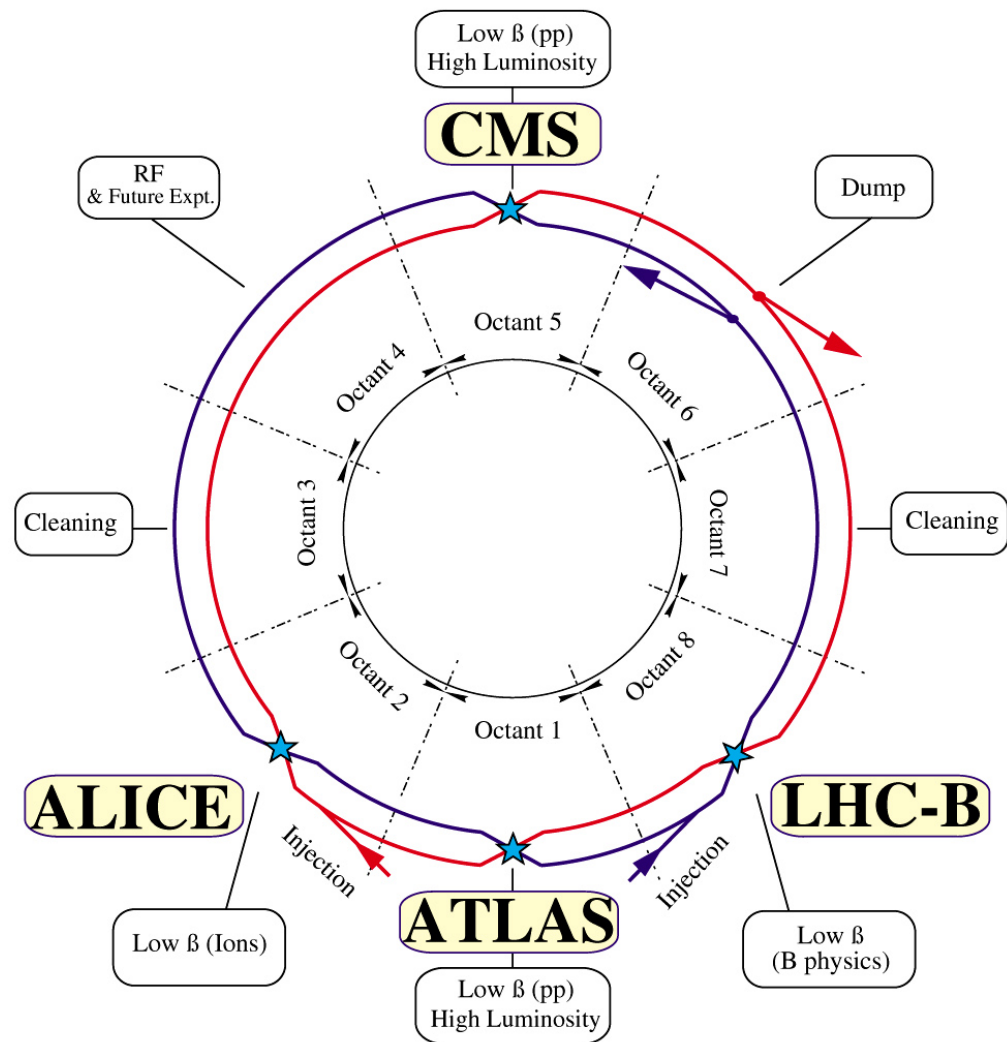
3. Fine synchronization, bunch rotation $\rightarrow$ Extraction!

The LHC itself



The LHC

- Circumference: 26659m
- Injection energy: 450 GeV
- 9300 magnets (1232 dipoles, 858 quadrupoles,...)
- Power consumption: 180MW



Collimators

- Some particles do leave the main orbit and get lost.
- To minimize damages by these stray particles (for example in the HEP detectors) collimators are placed around the ring.

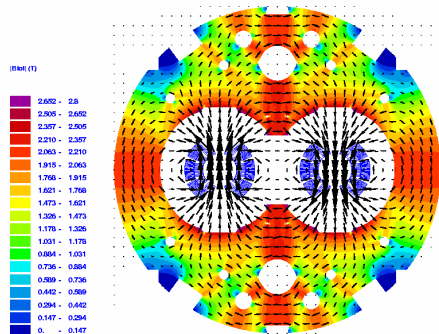
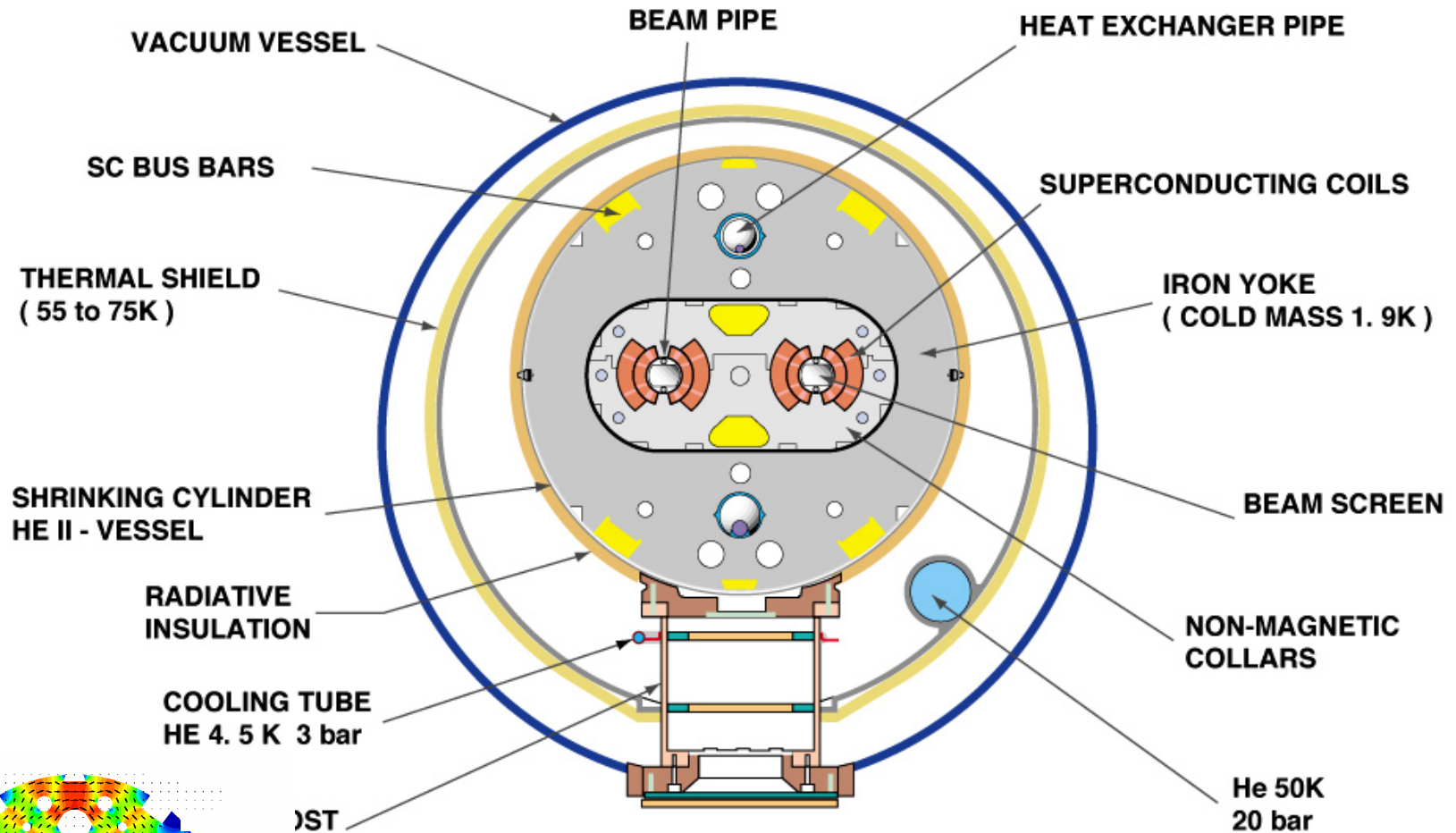
Magnets

- One of the challenges of the LHC is to give to the 7 TeV protons a circular orbit.
- The magnetic rigidity defines how strong the magnetic field must be to bend particles of a given energy.
- At 7 TeV and with a bending radius of 2.8km this requires a very intense magnetic field: 8.3 Tesla!
- This is a very intense magnetic field.
- To achieve it without using too much power, the coils have to be superconducting.

$$\frac{p}{q} = B\rho$$

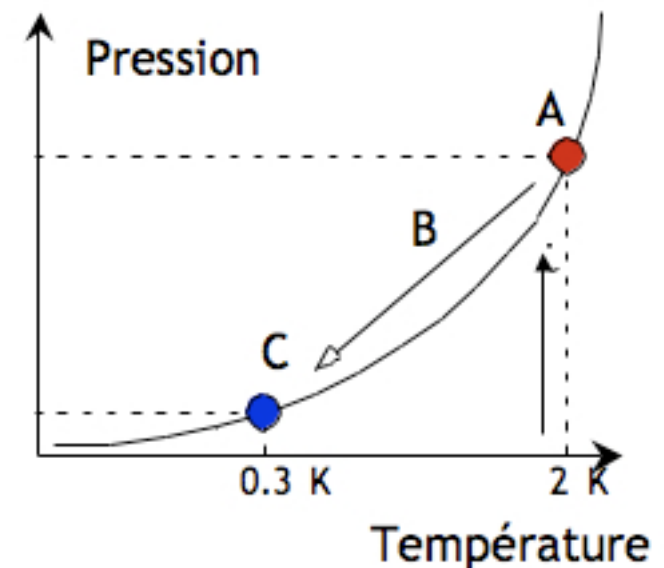
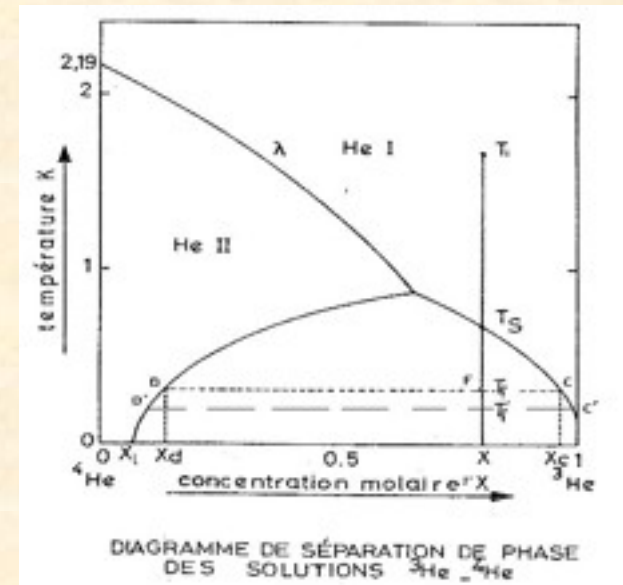
$$B\rho = 3.3p(\text{GeV}/c)$$

CROSS SECTION OF LHC DIPOLE



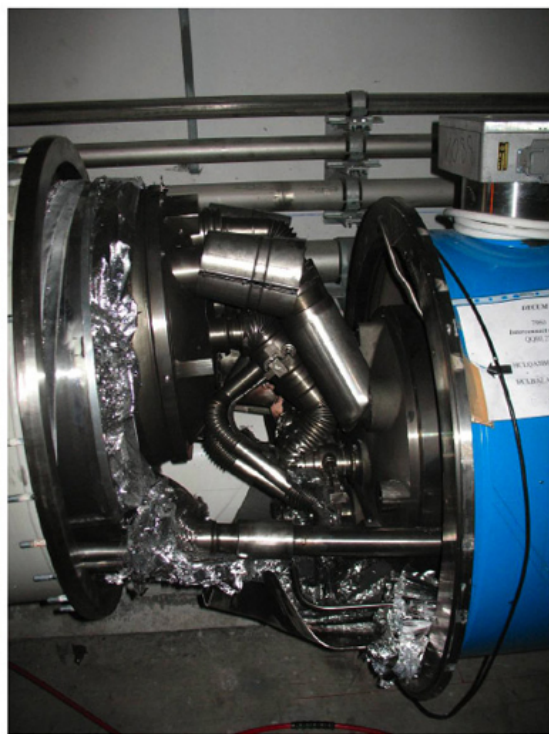
Cryogenics

- To keep all the magnets superconducting they must be kept at all time below 4K.
- All the LHC magnet are cooled to 1.9K.
- It is not possible to reach such temperature simply by liquefying helium. The phase transition between Helium II and Helium I must be used (using a mix of Helium-3 and Helium-4).
- Cooling a large metallic object from room temperature to 1.9K without breaking it is a complex operation that takes several weeks.
- If a superconducting magnet is suddenly brought back to normal conducting (eg due to heating), the magnetic energy is suddenly released => quench.
- Therefore an important safety margin must be kept to prevent/minimize quenches.



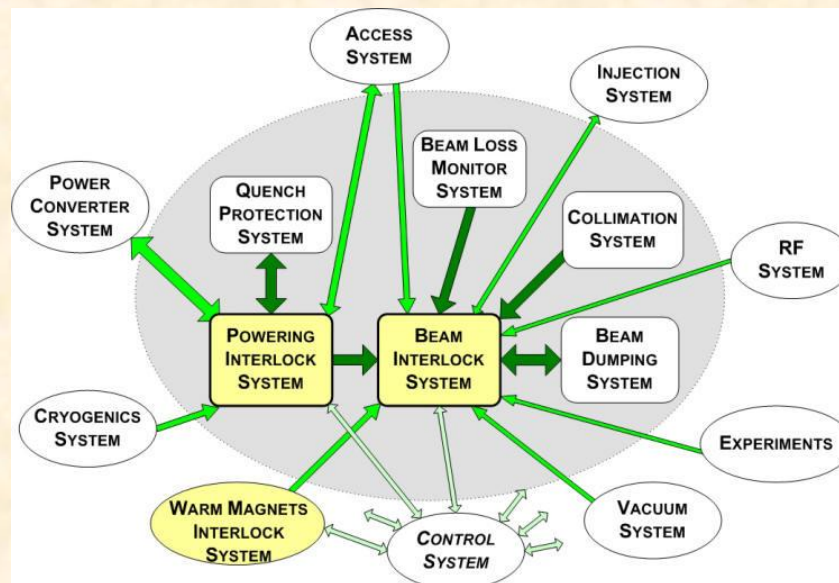
Quench

- Unfortunately a large quench occurred in September 2008.
- This was due to the resistance of a bus bar (connector) being a few nano-ohms too high.



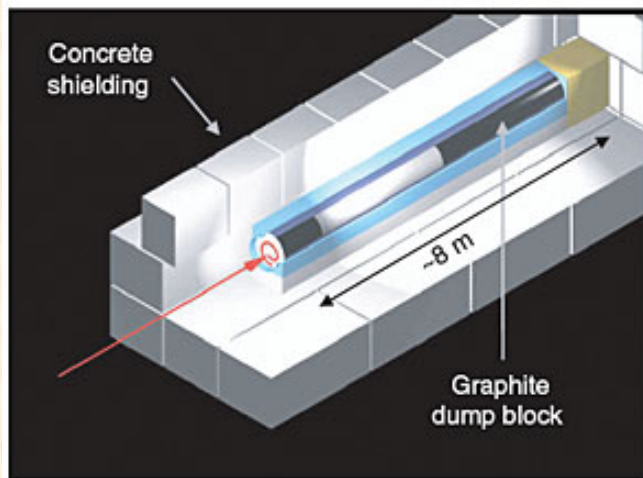
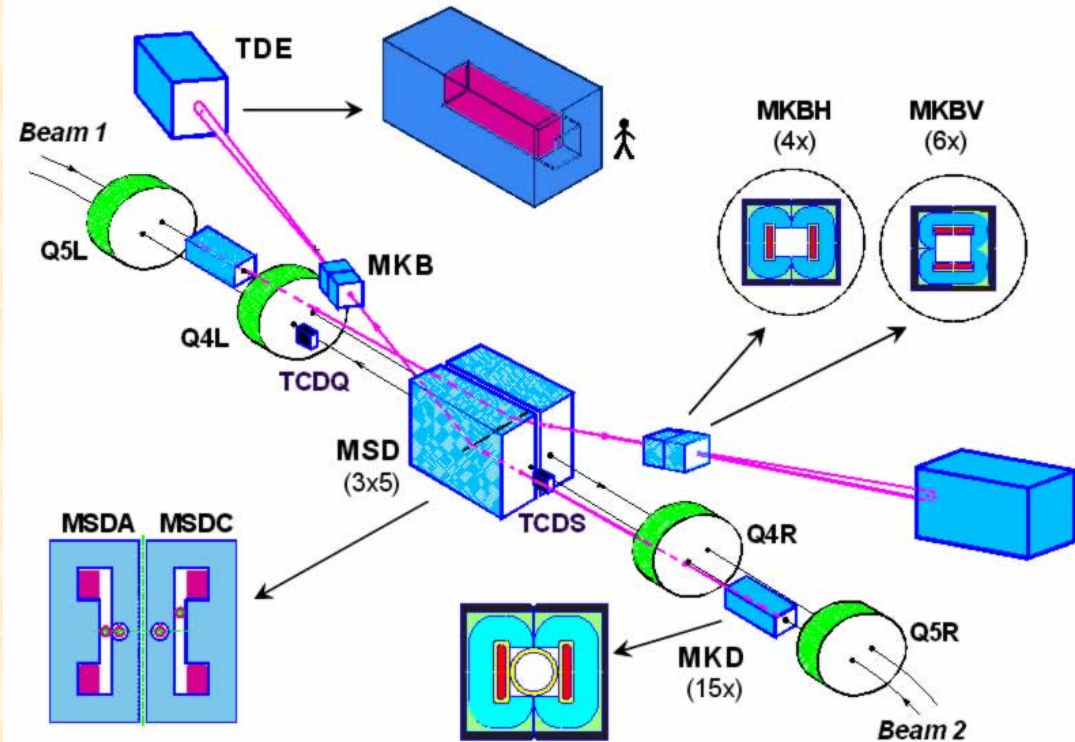
Machine protection system

- The LHC beams carry the same amount of energy than a jumbo plane at take-off!
- If a beam is sent on the beam pipe accidentally it could make serious damages!
- A complex “machine protection system” is used to monitor the machine at all time and prevent injection or dump the beam if a fault is detected.
- A system of flags and permits is used to prevent any situation that might led to significant damages.



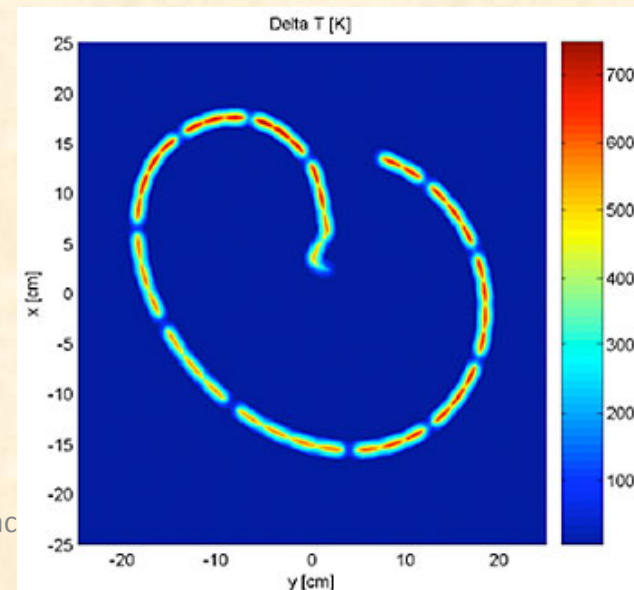
How to get rid of the beams?

- With so much energy stored in the beams they have to be disposed of with care.
- A special area “dumps” has been designed and instrumented for this purpose.
- All the energy can not be disposed of on a single point.



Nico

2012 - Particle ac
Diagnostics



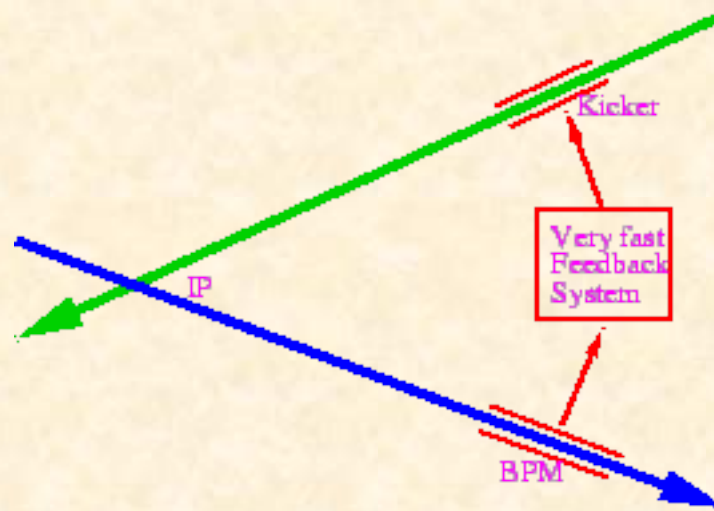
Vacuum

- Collisions between protons and residual gas in the accelerator will reduce the beam's lifetime.
=> Very stringent requirements (10^{-10} mbar $\sim 10^{-8}$ Pa).
- Use of a special coating (Non Evaporable Getter - NEG) on the beam pipe that “absorbs” residual gas.

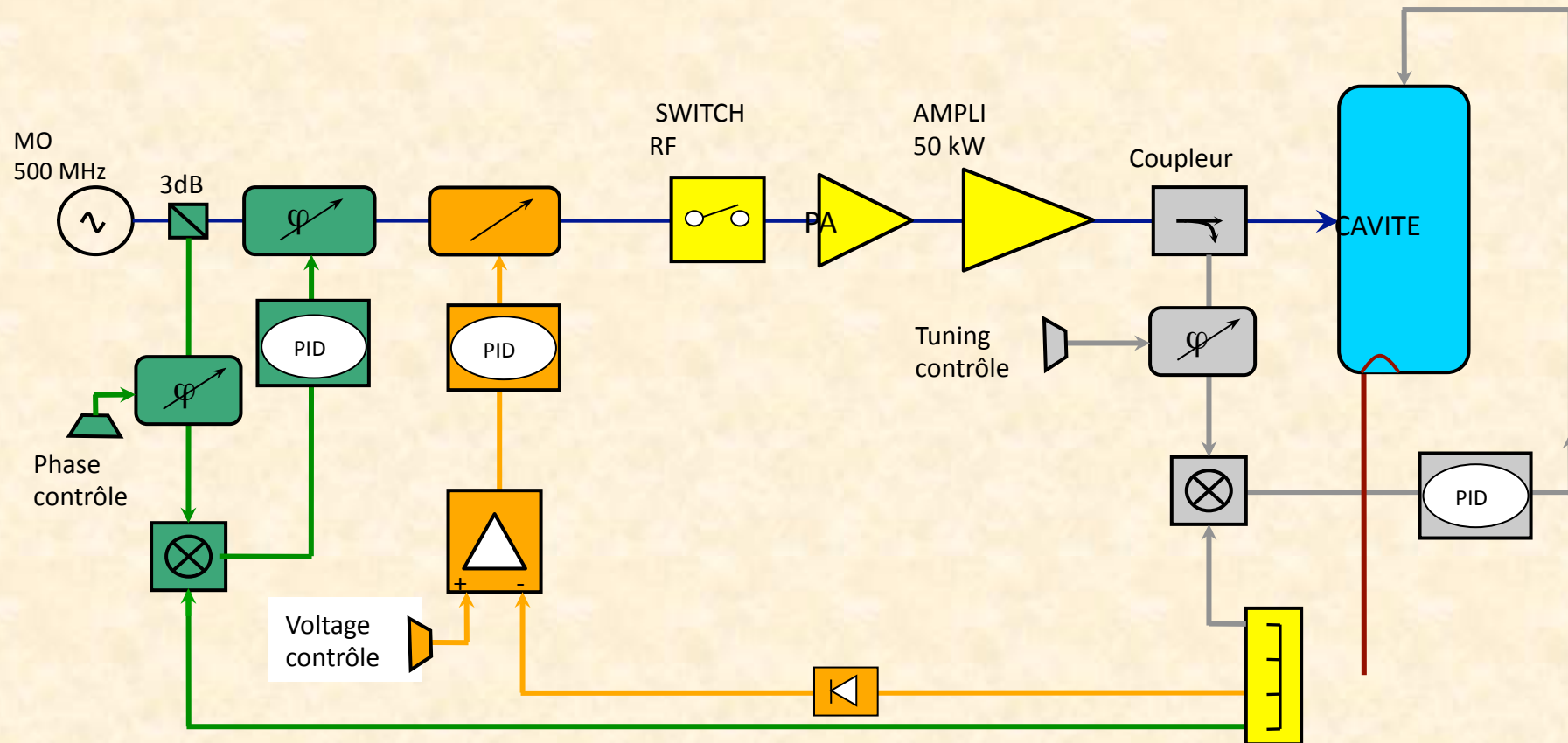
GAS	Nuclear scattering cross section(cm²)	Gas density (m⁻³) for a 100 hour lifetime	Pressure (Pa) at 5 K, for a 100 hour lifetime
H ₂	$9.5 \cdot 10^{-26}$	$9.8 \cdot 10^{14}$	$6.7 \cdot 10^{-8}$
He	$1.26 \cdot 10^{-25}$	$7.4 \cdot 10^{14}$	$5.1 \cdot 10^{-8}$
CH ₄	$5.66 \cdot 10^{-25}$	$1.6 \cdot 10^{14}$	$1.1 \cdot 10^{-8}$
H ₂ O	$5.65 \cdot 10^{-25}$	$1.6 \cdot 10^{14}$	$1.1 \cdot 10^{-8}$
CO	$8.54 \cdot 10^{-25}$	$1.1 \cdot 10^{14}$	$7.5 \cdot 10^{-9}$
CO ₂	$1.32 \cdot 10^{-24}$	$7 \cdot 10^{13}$	$4.9 \cdot 10^{-9}$

Feedback systems

- Can you react to a change in 1ms?
- In an accelerator that is already several thousand turns.
- Feedback systems are used to correct fast environmental changes.

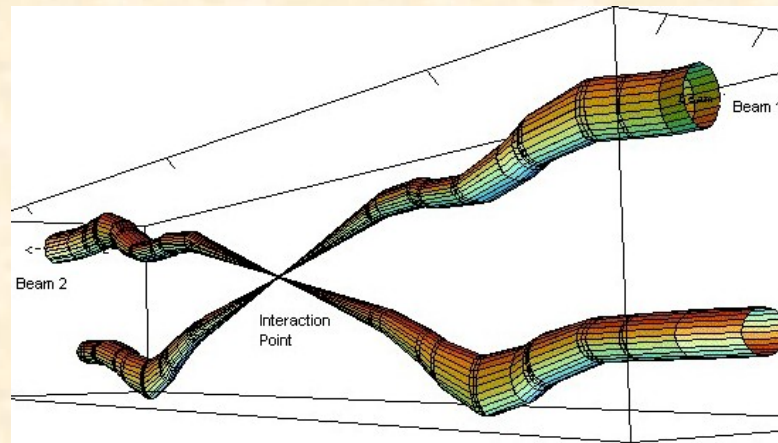


Feedback (2)

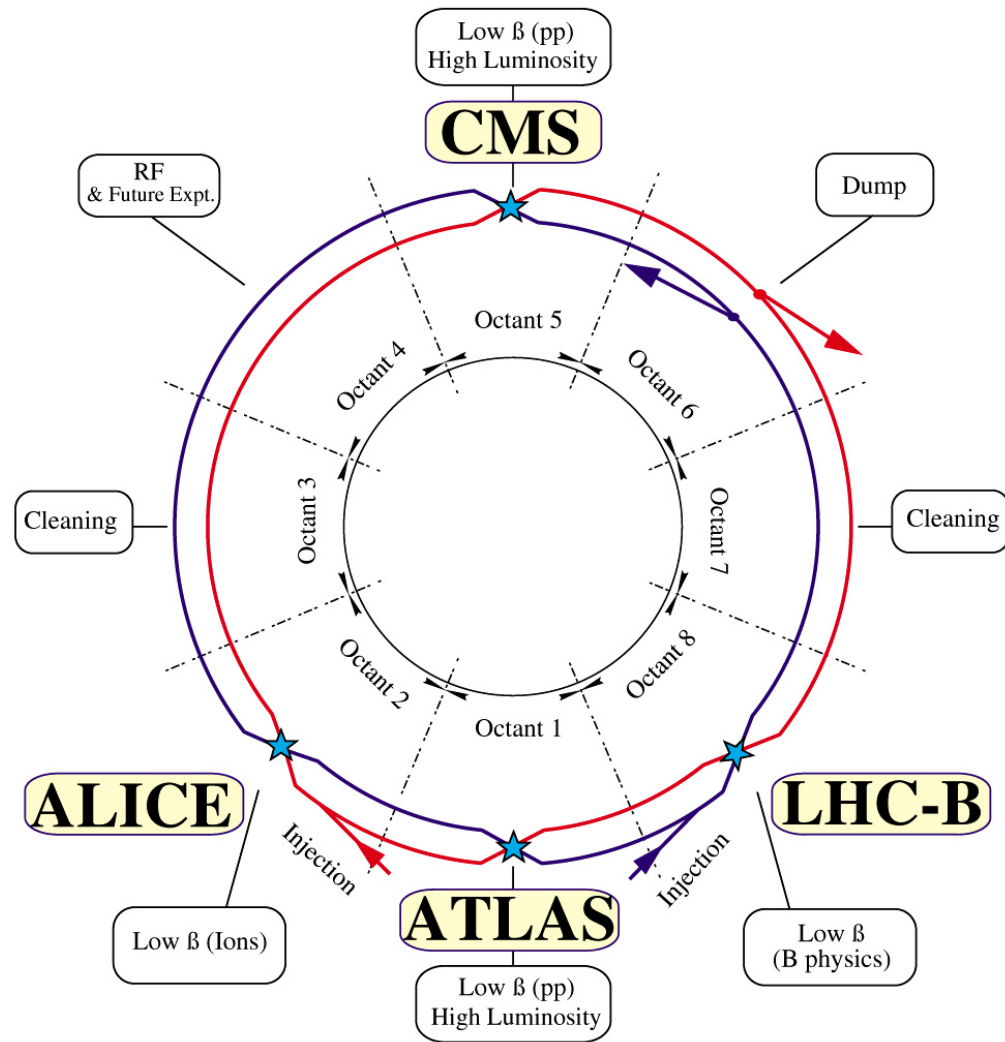


Collisions

- Special magnets near each interaction point allow to control the focussing (or not of the beam at that point).
- LHCb has requested a lower pile-up than the other experiments => different tuning and flat luminosity during the run.



LHC LAYOUT

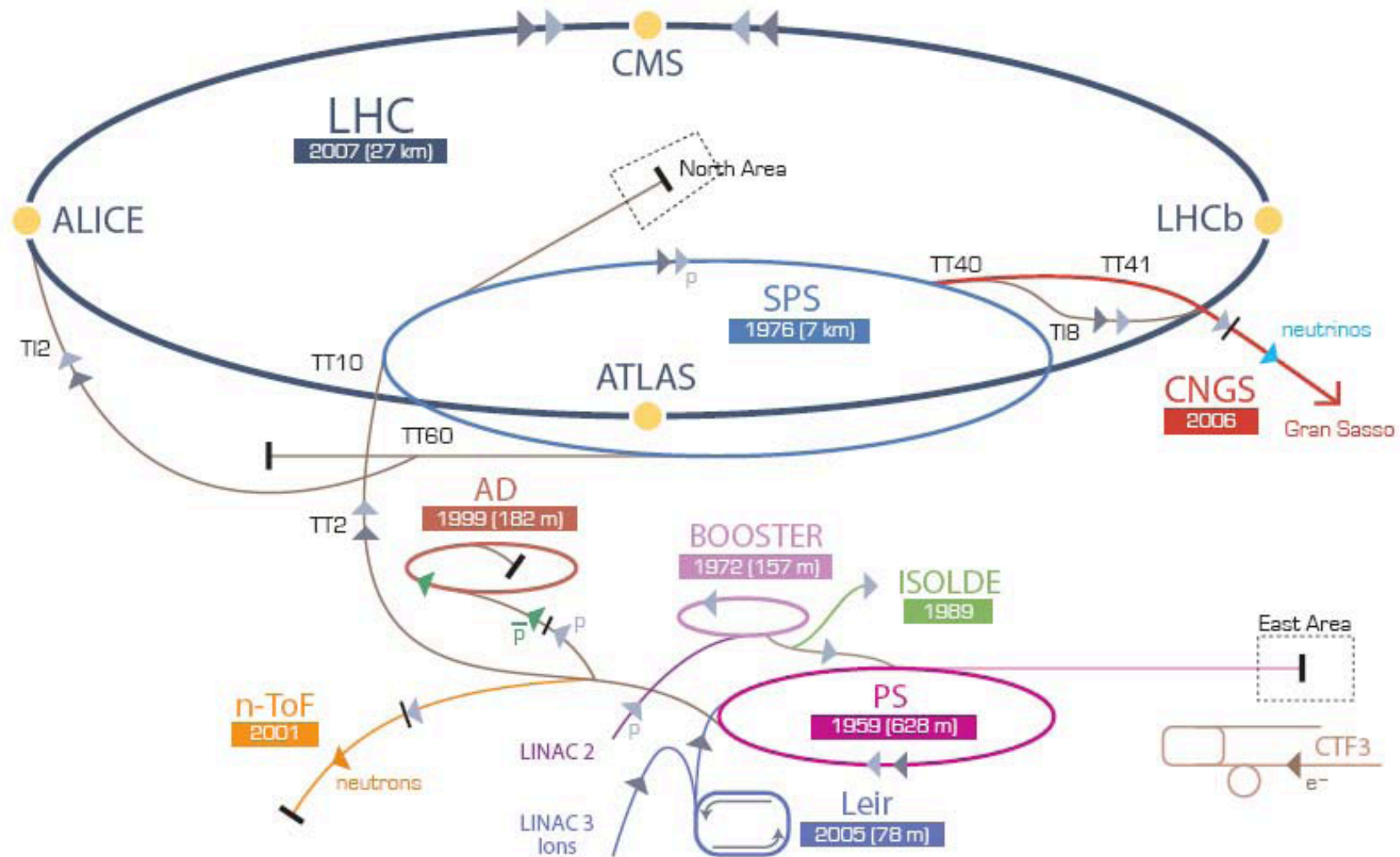


Summary

- To control an accelerator you need to “see” what is happening:
 - where is the beam?
 - what are its properties?
- There are 2 main types of diagnostics:
 - diagnostics that use interactions between the particles and matter
 - diagnostics that look at the radiation emitted by the bunch
- The operation of an accelerator is very complex and requires the control of a large number of parameters.

THE JOURNEY OF A PROTON FROM THE SOURCE TO THE LHC

(Courtesy of D.Manglunki - BE/OP/CERN)

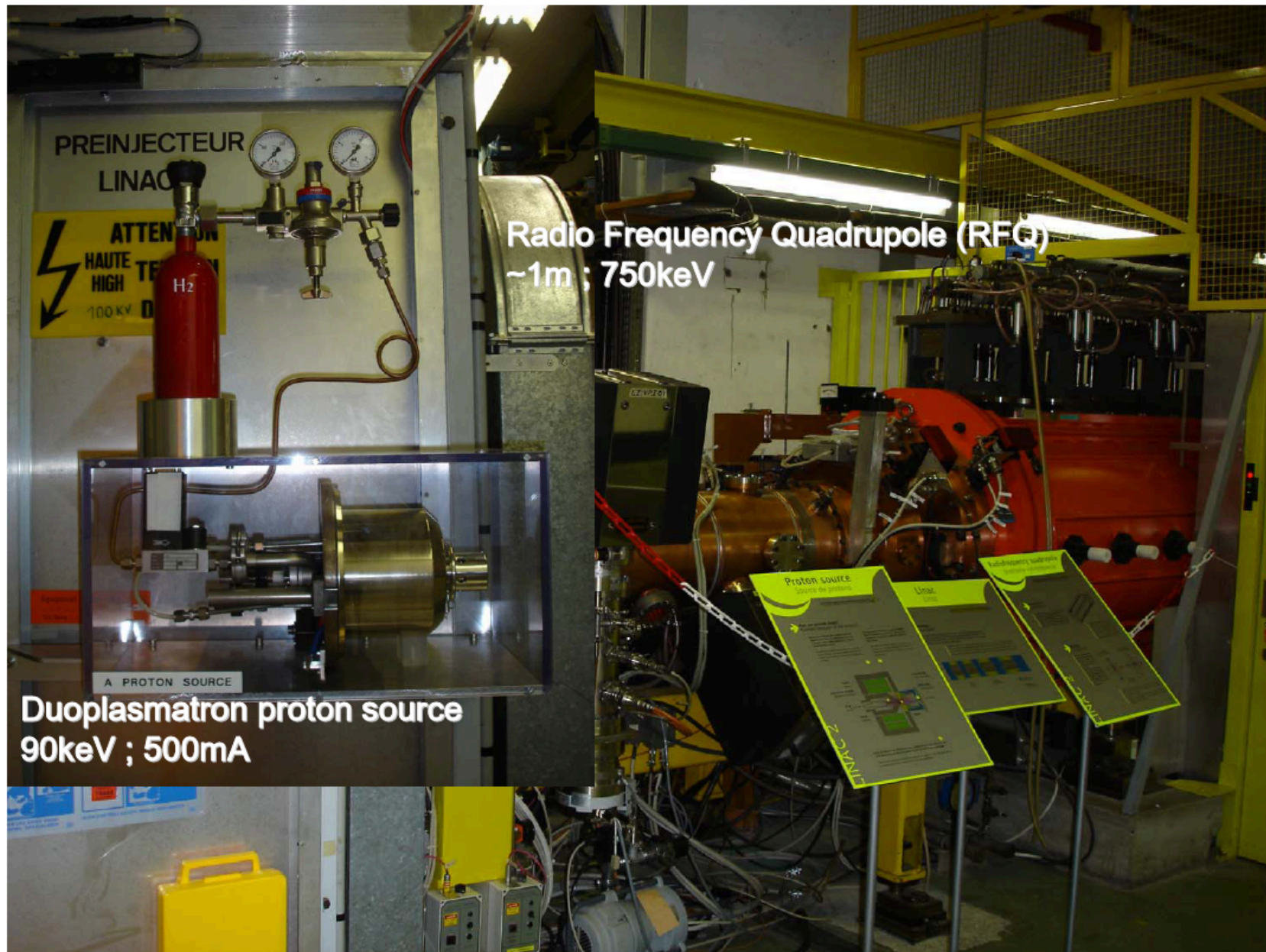


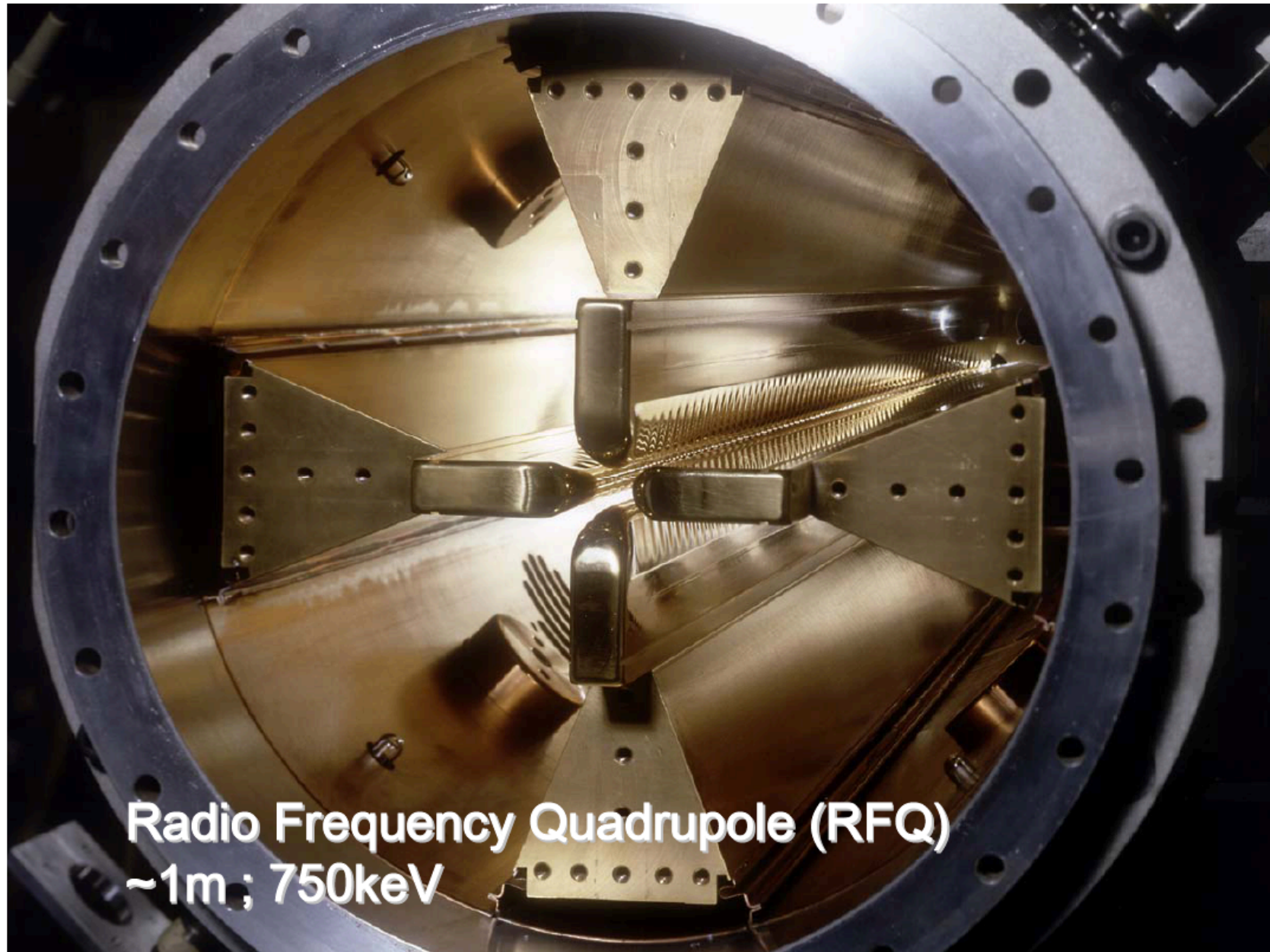
▶ p [proton] ▶ ion ▶ neutrons ▶ $\bar{p}$ [antiproton] ▶ proton/antiproton conversion ▶ neutrinos ▶ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

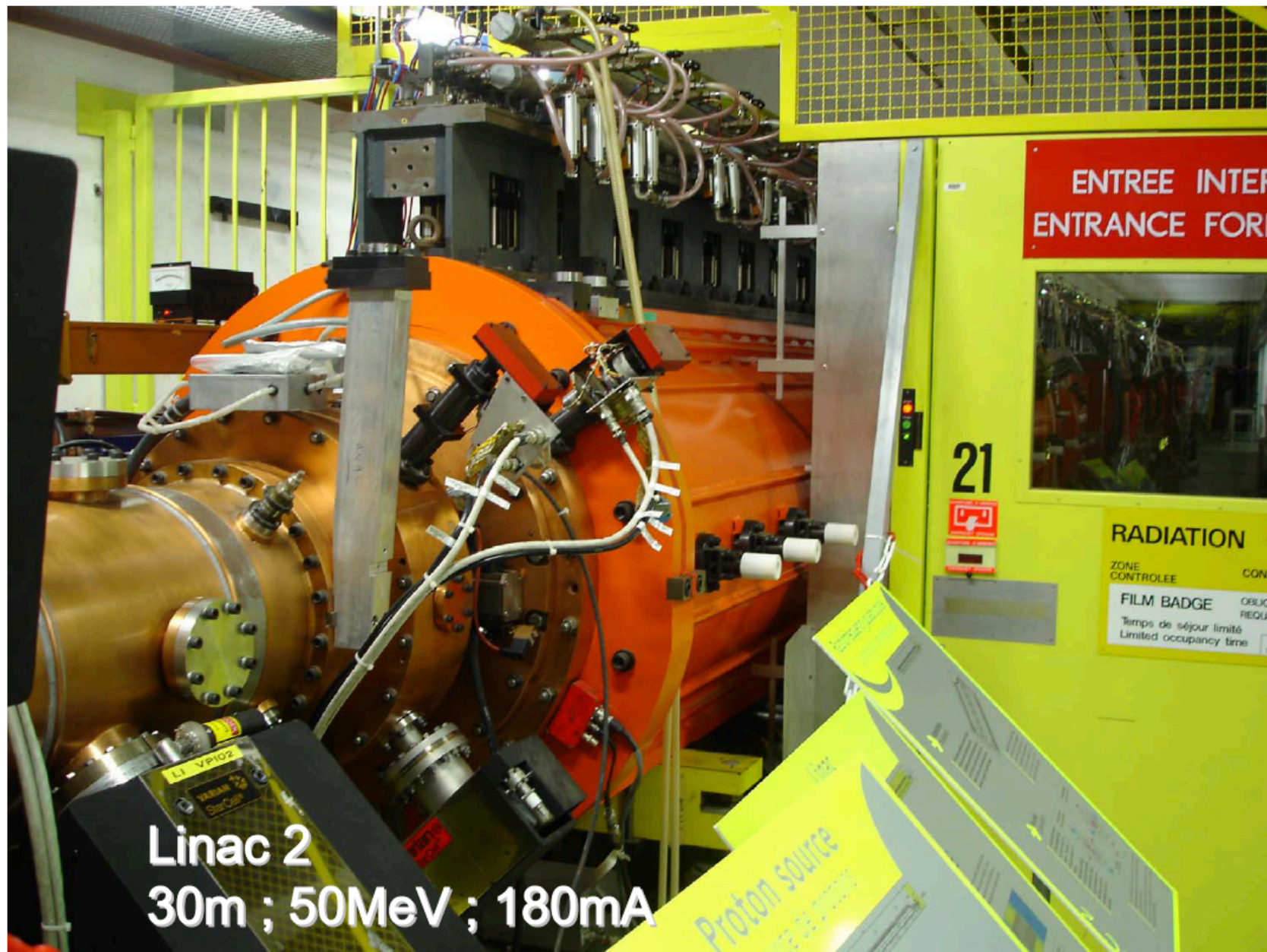
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

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

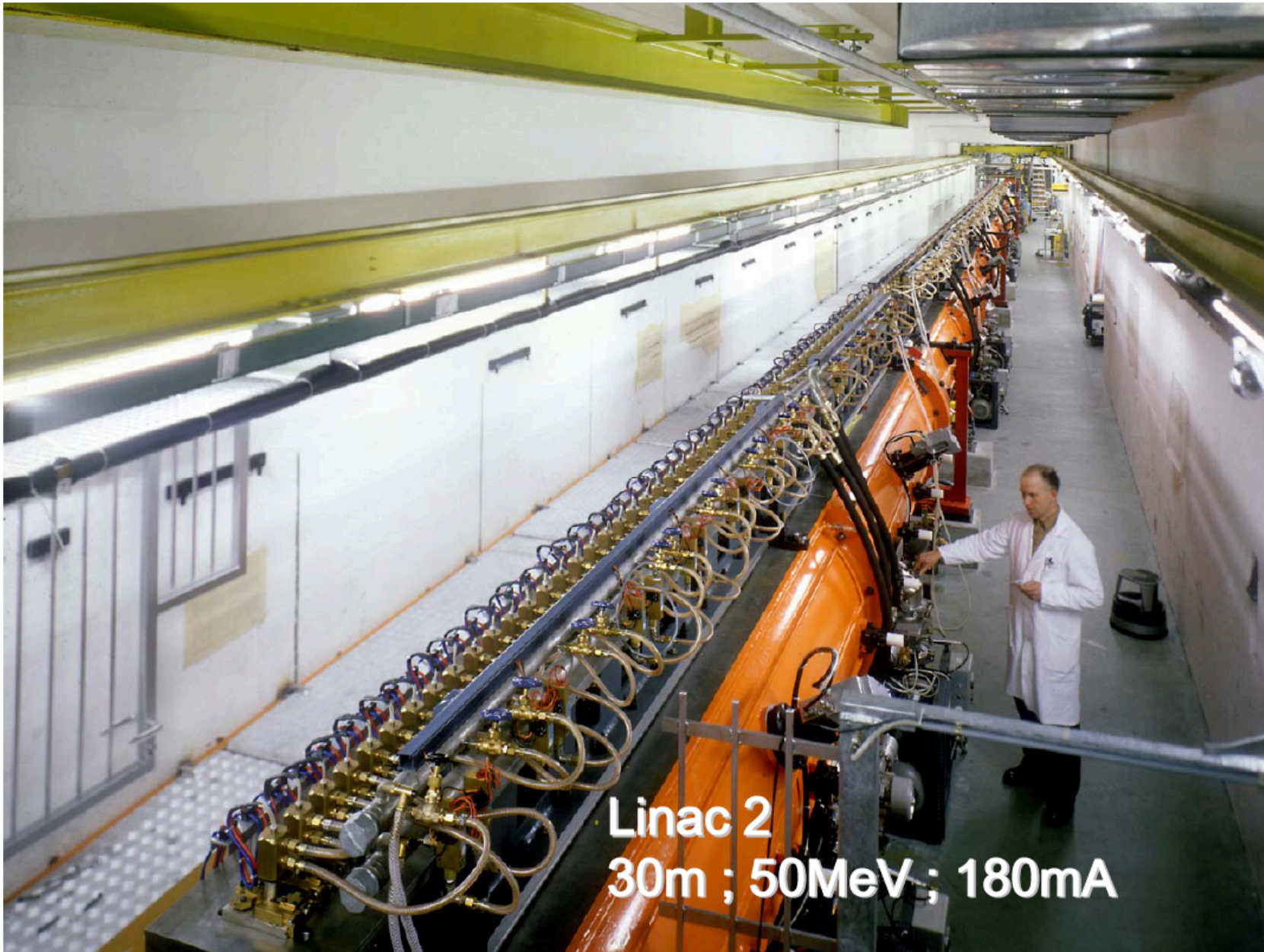




Radio Frequency Quadrupole (RFQ)
~1m ; 750keV



Linac 2
30m ; 50MeV ; 180mA



Linac 2
30m ; 50MeV ; 180mA

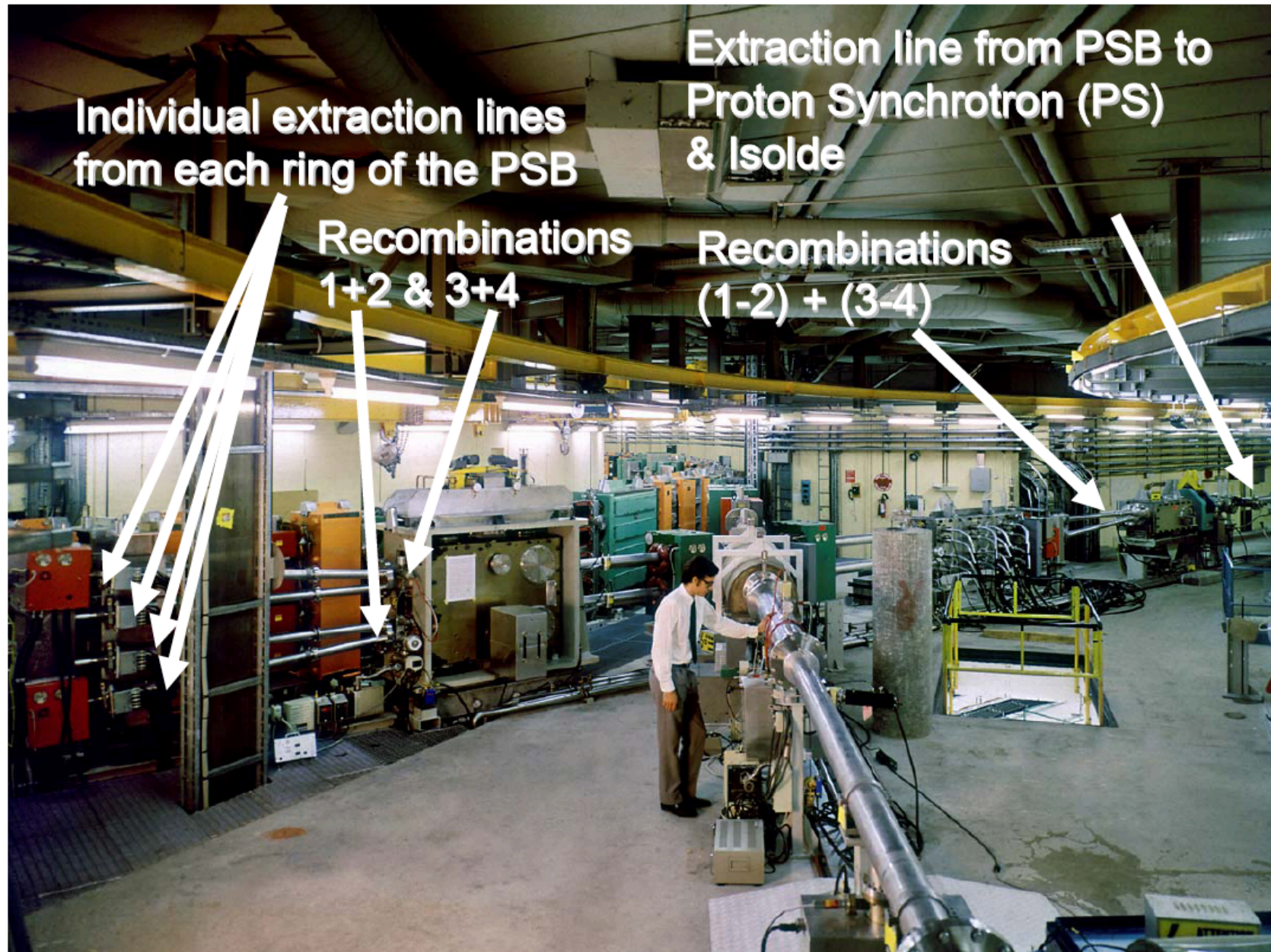


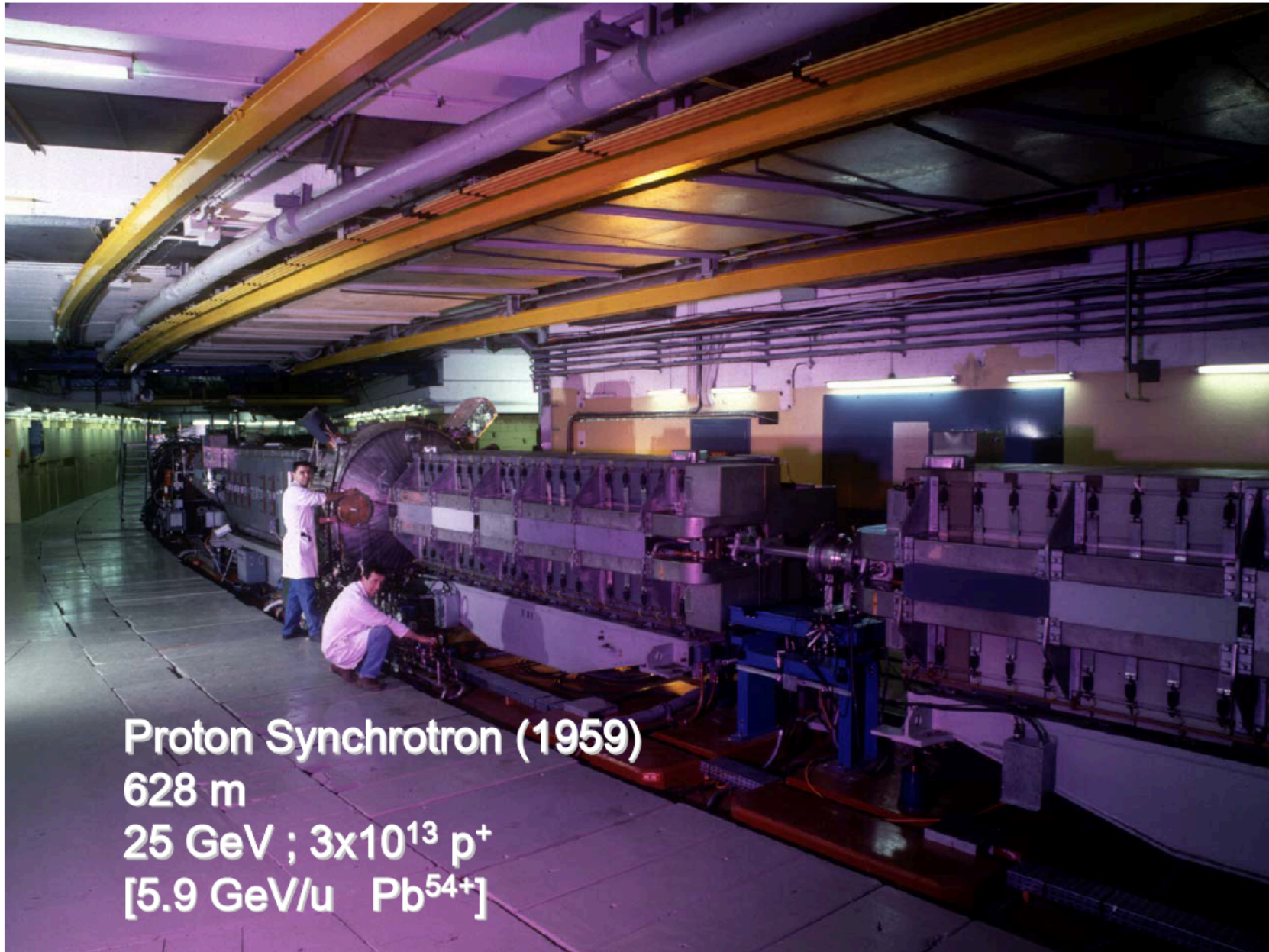
PSB distributor

Transfer line from Linac 2 to Proton Synchrotron Booster (PSB)

Proton Synchrotron Booster
4 rings ; 157m each
1.4GeV ; 10^{13} p⁺/ring







Proton Synchrotron (1959)

628 m

25 GeV ; 3×10^{13} p^+

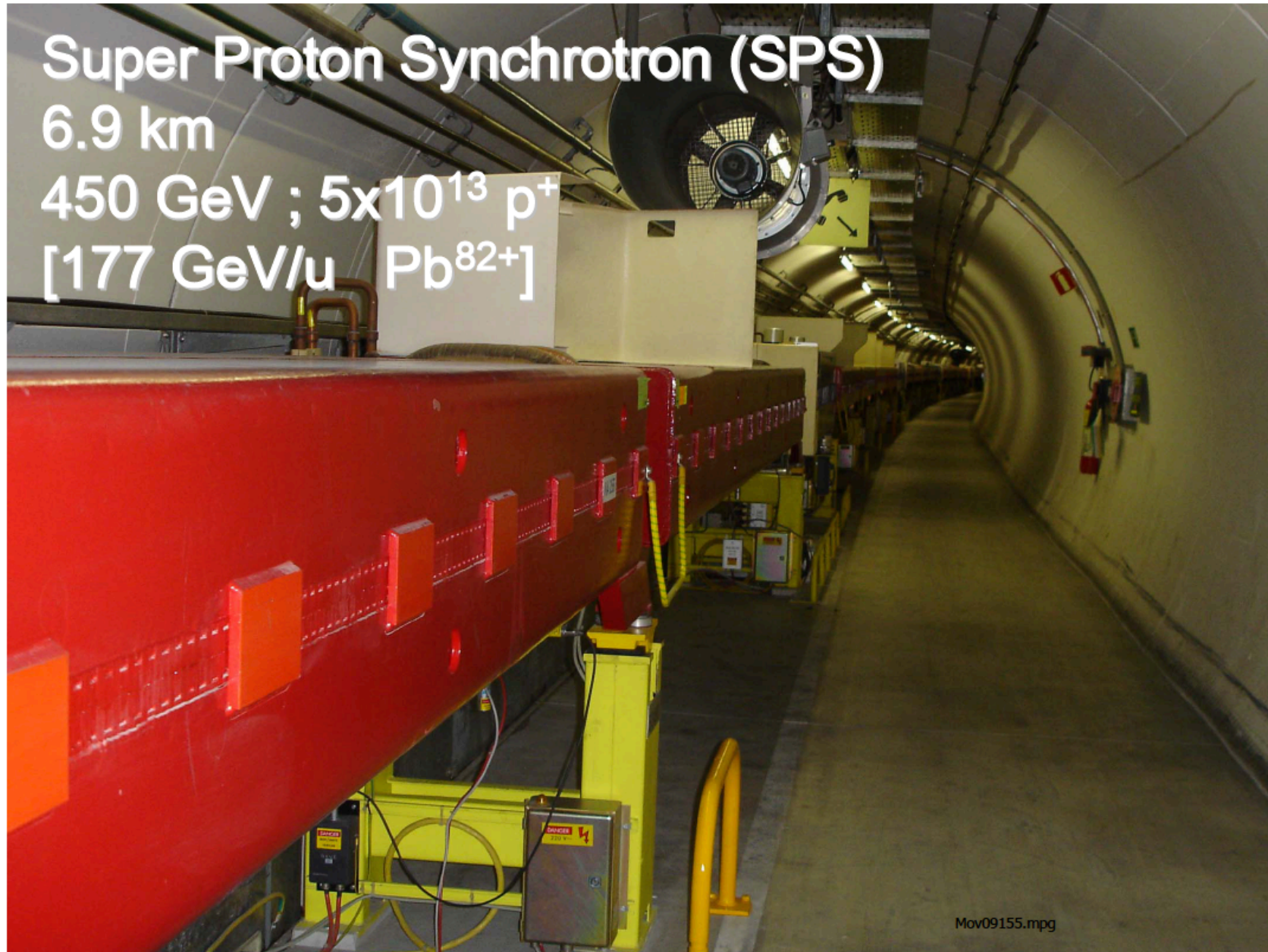
[5.9 GeV/u Pb^{54+}]

Super Proton Synchrotron (SPS)

6.9 km

450 GeV ; 5×10^{13} p⁺

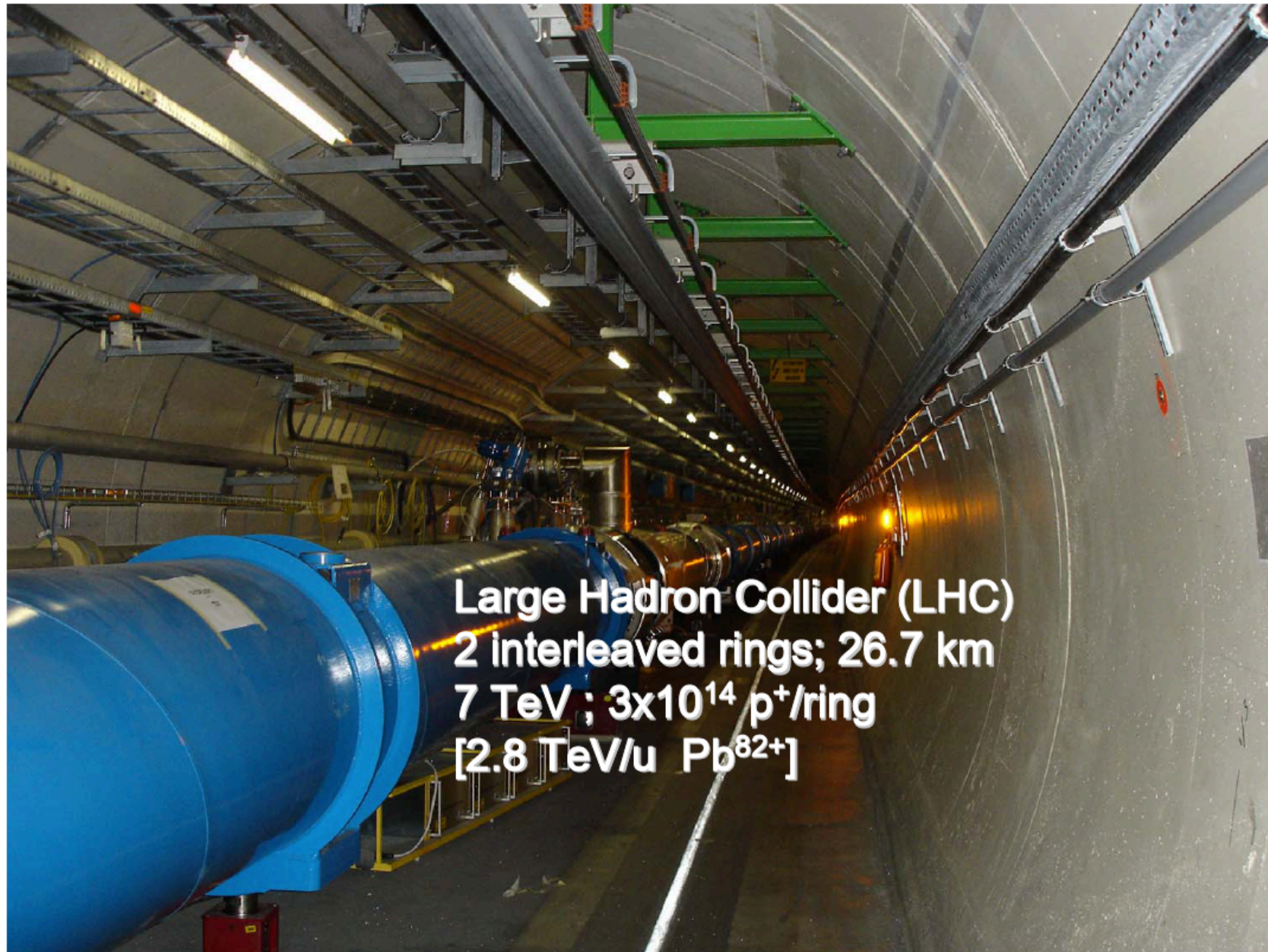
[177 GeV/u Pb⁸²⁺]



Mov09155.mpg



T18 counter-clockwise transfer line from SPS to LHC



Large Hadron Collider (LHC)
2 interleaved rings; 26.7 km
7 TeV ; 3×10^{14} p⁺/ring
[2.8 TeV/u Pb⁸²⁺]