

Introduzione agli acceleratori di particelle

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Material from presentations by:

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Synchrotron

- Frequency modulated but also B -field increased **synchronously** to match energy and keep revolution radius constant.
- Magnetic field produced by several bending magnets increases with momentum. For high energies:

$$p = eBr \text{ and } p\left[\frac{\text{GeV}}{c}\right] \cong 0.3B[\text{T}]r[\text{m}]$$

- Practical limitations for magnetic fields => high energies only at large radius
- Need large bending radius and **super-conducting magnets to reach very high energies as in the LHC: 8.3 T and bending radius of 2.9km to reach 7 TeV**

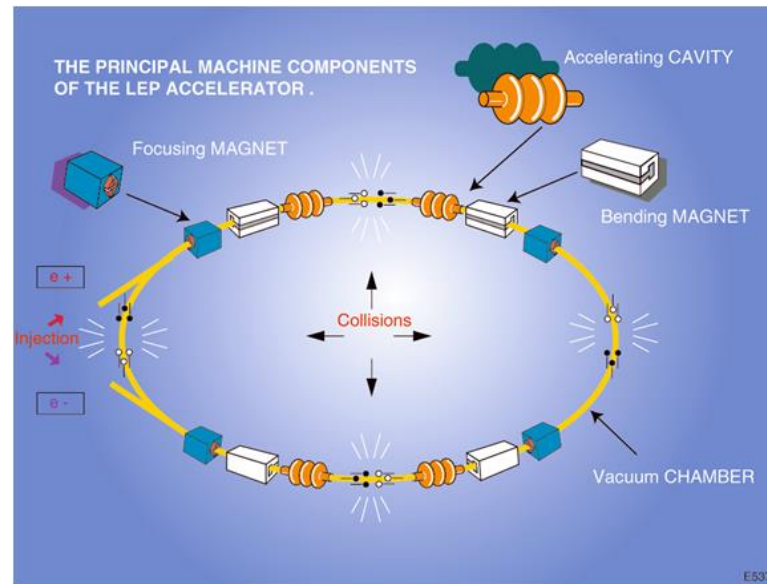


Summary of Circular Machines

Machine	RF frequency f	Magnetic Field B	Orbit Radius ρ	Comment
Cyclotron	constant	constant	increases with energy	Particles out of synch with RF; low energy beam or heavy ions
Iso-Cyclotron	constant	varies	increases with energy	Particles in synch, but difficult to create stable orbits
Synchro-cyclotron	varies	constant	increases with energy	Stable oscillations
Synchrotron	varies	varies	constant	Flexible machine, high energies possible

Main Components of an Accelerator

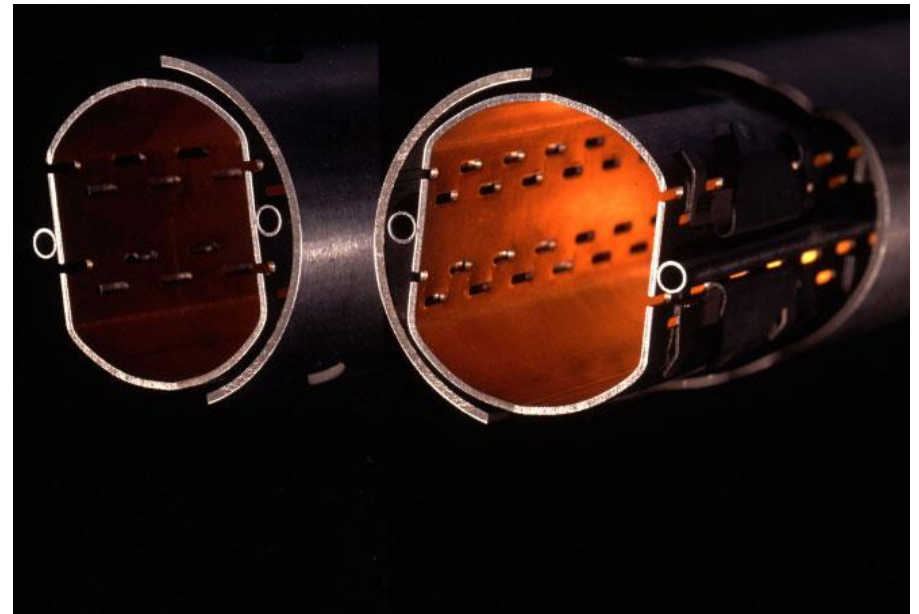
- Employs a vacuum chamber in which the particles travel
- Employs electric fields to impart energy to (accelerate) the particles
- Employs magnetic fields to steer and focus the beam
- Makes collisions either against a fixed target, or between two beams of particles.



Vacuum System

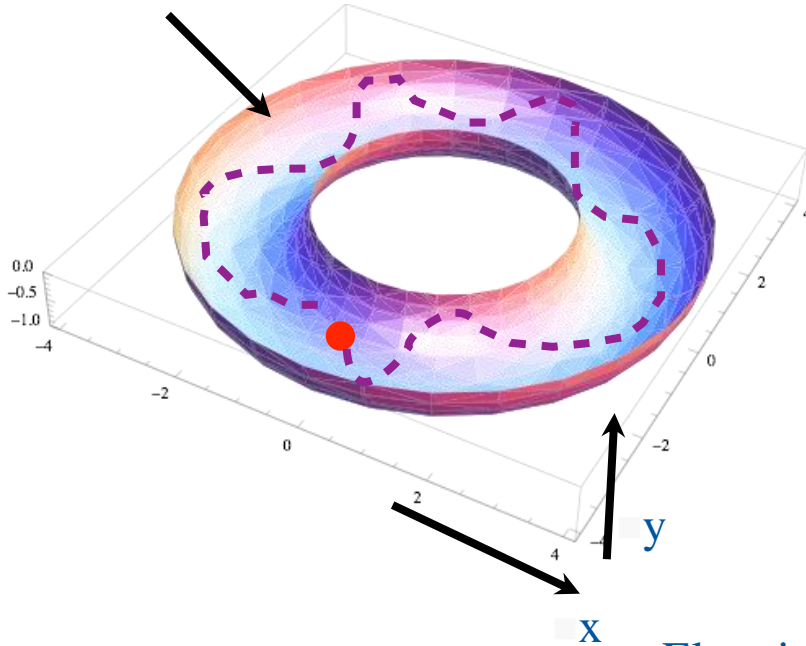
- Beam particles travel inside a metal pipe (also known as the beam pipe). This is kept at an ultrahigh vacuum to minimise the amount of gas present to avoid collisions between gas molecules and the particles in the beam.

■ Ultrahigh vacuum $<10^{-10}$ Torr $\sim 10^{-13}$ atm



How an accelerator works ?

Accelerator



- **Goal:** keep enough **CHARGED** particles confined in a well defined volume to accelerate them for a sufficiently long time (**ms - hours**)
- **How ? Lorentz Force!**

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

Electric field accelerates particles

Particles of different energy (speed) behave differently

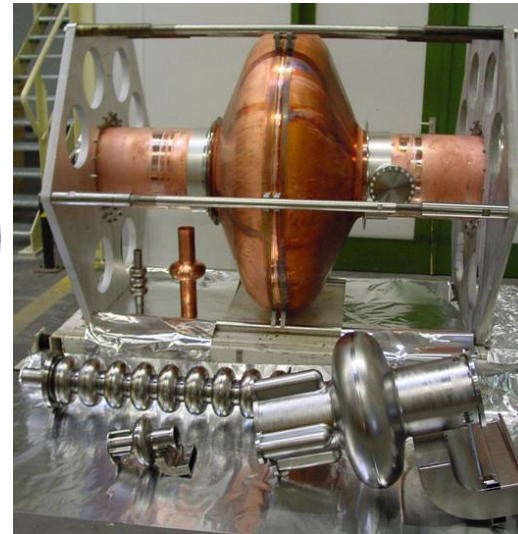
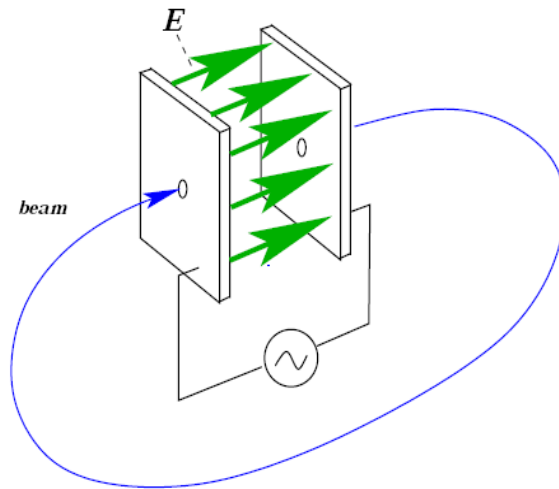
Magnetic field confines particles on a given trajectory

■ An **accelerator** is formed by a sequence (called **lattice**) of:

- Magnets** → Magnetic Field
- Accelerating Cavity** → Electric Field

Acceleration (RF) System

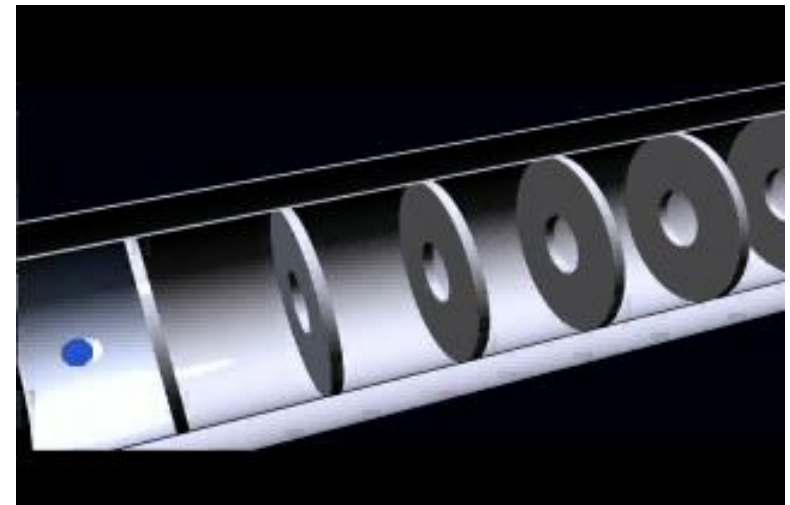
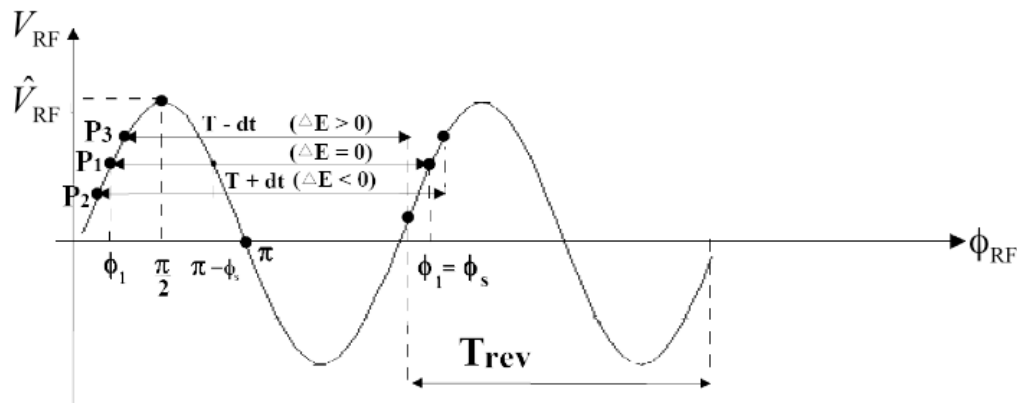
- Radiofrequency (RF) electric fields provide acceleration to a beam of particles. RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles.



Acceleration

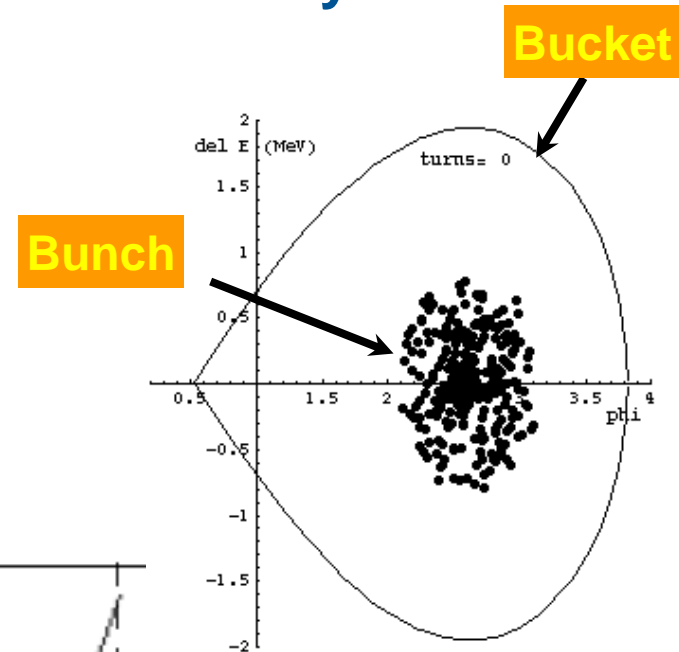
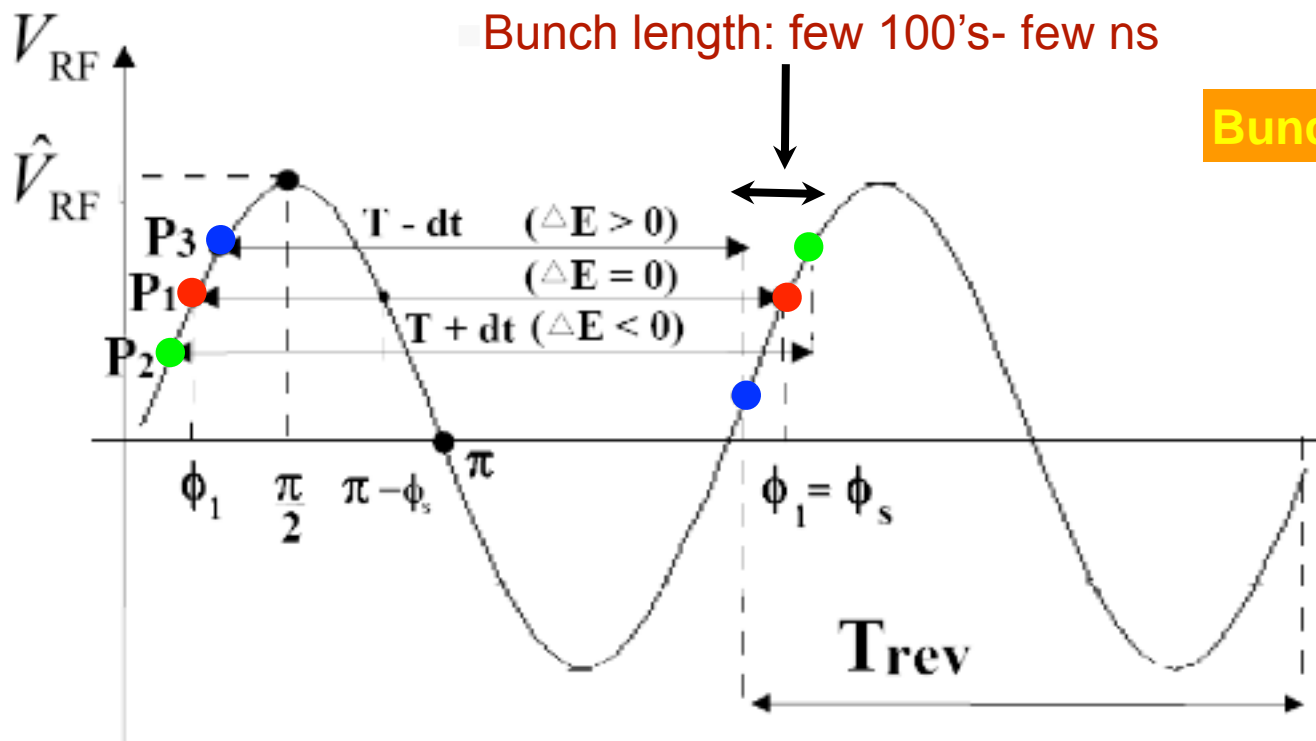
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- Particles are accelerated by an RF (radio frequency) electric field which is confined in cavities.
- The electric field varies in time as a sinus wave in such a way, that at each revolution, the particle comes back at the RF to see the acceleration $\rightarrow f_{\text{RF}} = h f_{\text{rev}}$



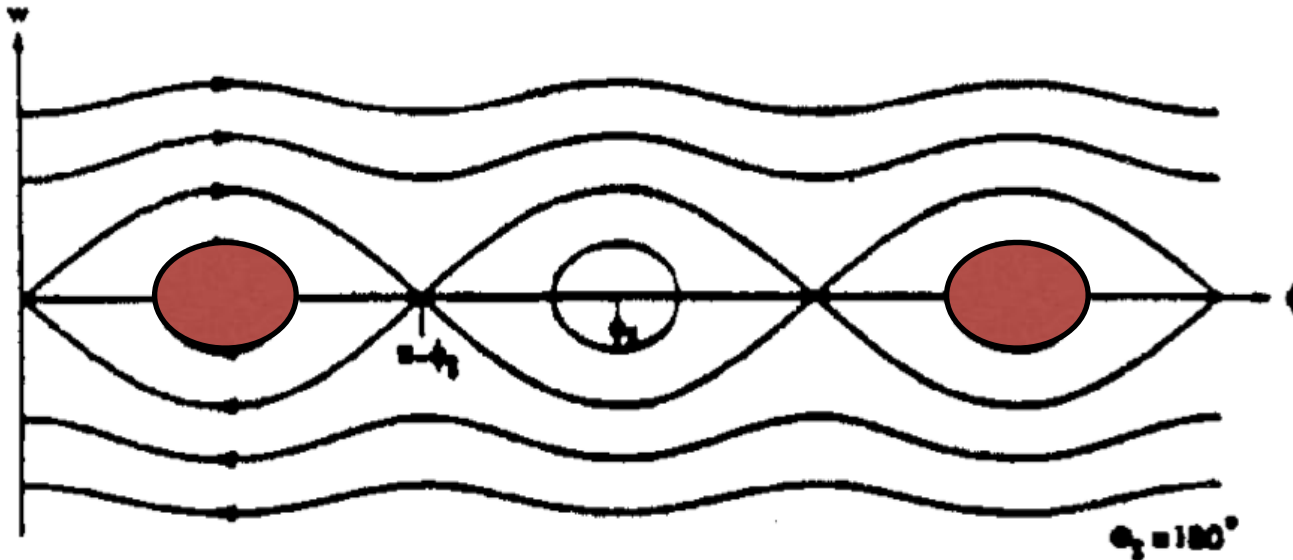
Longitudinal focusing, a pendulum ...

- Particles are confined within a range in phase and energy called **BUCKET** and are grouped into **bunches** by the electric field.



- One machine turn \sim some (hundred) microseconds

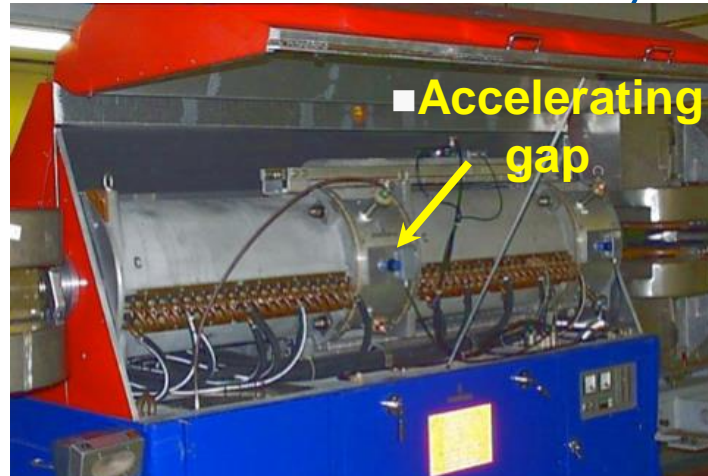
A chain of buckets



- Number of buckets:
- *possible positions along the machine circumference where **there could be a bunch.***
- In the example: 3 buckets and 2 bunches $\rightarrow h=3$

RF cavities in the CERN PS

The dimension of the cavity changes with the RF wave length



10 MHz RF cavity of the PS



Six 200 MHz Cavities



13 MHz cavity



40 MHz cavity



80 MHz cavity

RF system LHC

- 16 MV/beam
- ACCELERATION TAKES TIME (20 mins)
- What is the energy gain per turn?
 - Injection at 450 GeV
 - Ramp to 7000 GeV
 - Circumference 27 km
 - Ramp time = ~20 mins

0.52 MV

- How long is a wave?

- $f_{RF} = 400 \text{ MHz}$

75 cm



RF acceleration (LHC)

RF Cavity 2013



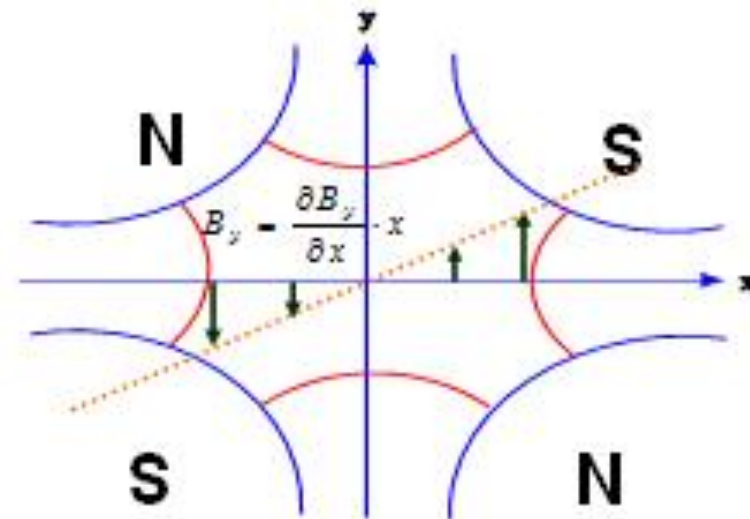
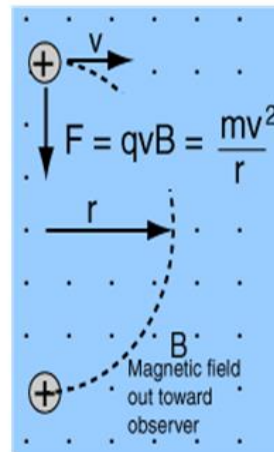
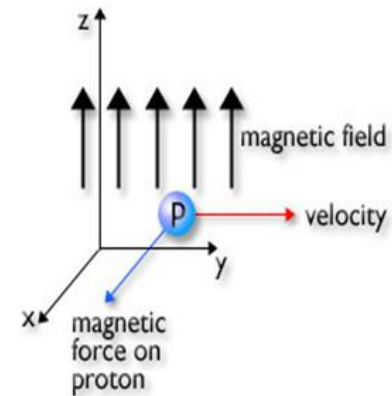
■ 16/10/2014

■ G. Arduini - Italian Teacher Programme
2014 - Accelerators

■ 13

Magnets

- Two main types of magnets:
 - **Dipole magnets** to bend the path of a beam of particles that would otherwise travel in a straight line. The **more energy a particle has, the greater the magnetic field needed** to bend its path → larger energy implies larger circumferences or stronger magnetic fields
 - **Quadrupole magnets** are used to focus a beam, gathering all the particles closer together (like lenses are used to focus a beam of light).



Beam guidance (dipoles)

- Consider only a uniform magnetic field \mathbf{B} in the direction perpendicular to the particle motion over a length l . From the ideal trajectory and after considering that the transverse velocities $v_x \ll v_s, v_y \ll v_s$, we have that the radius ρ and angle α of curvature are

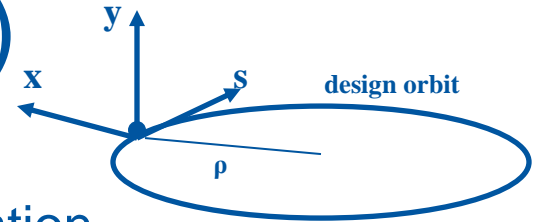
$$\rho = \frac{pc}{qB} = \frac{\beta E}{qB} \qquad \alpha = \frac{qBl}{pc}$$

- We define the **magnetic rigidity** $B\rho \equiv \frac{q}{pc}$
- In more practical units $\beta E_{tot} [GeV] = 0.2998 |B\rho| [Tm]$
- For ions with charge multiplicity Z and atomic number A , the energy per nucleon is

$$\beta \bar{E}_{tot} [GeV/u] = 0.2998 \frac{Z}{A} |B\rho| [Tm]$$



Beam focusing (quadrupoles)



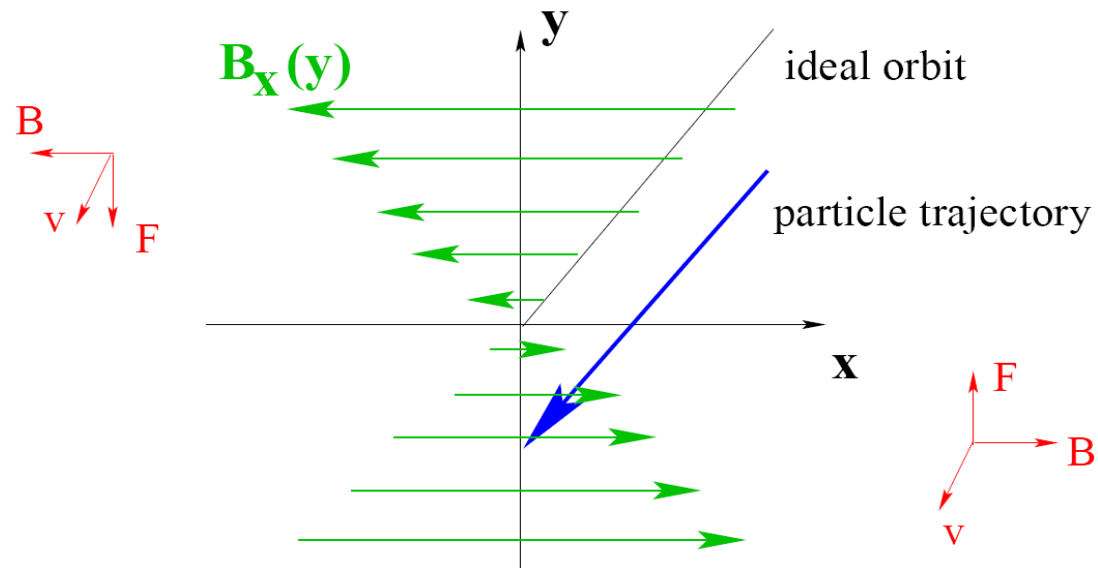
- Consider a particle in the design orbit.
- In the horizontal plane it does an harmonic oscillation

$$x = x_0 \cos(\omega t + \phi) \quad \text{with frequency } \omega = \frac{v_s}{\rho}$$

- The horizontal acceleration is described by $\frac{d^2x}{ds^2} = \frac{d^2x}{v_s^2 dt^2} = -\frac{1}{\rho^2}x$
- There is a **weak focusing** effect in the horizontal plane.

- In the vertical plane, only force is gravitation. The particle will be displaced vertically following the usual law $\Delta y = \frac{1}{2}g\Delta t^2$

- Setting $g = 10 \text{ m/s}^2$, the particle will be displaced by **18mm** (LHC dipole aperture) in **60ms** (a few hundreds of turns in LHC)



- Need of **focusing!**



Focusing elements

- Magnetic element that deflects the beam by an angle proportional to the distance from its centre (equivalent to ray **optics**) provides focusing.

- For a focal length f the deflection angle is $\alpha = -\frac{y}{f}$

- A magnetic element with length l and with a gradient g has a field $B_x = gy$ so that the deflection angle is $\alpha = -\frac{qgy l}{pc} = -\frac{qgy l}{\beta E}$

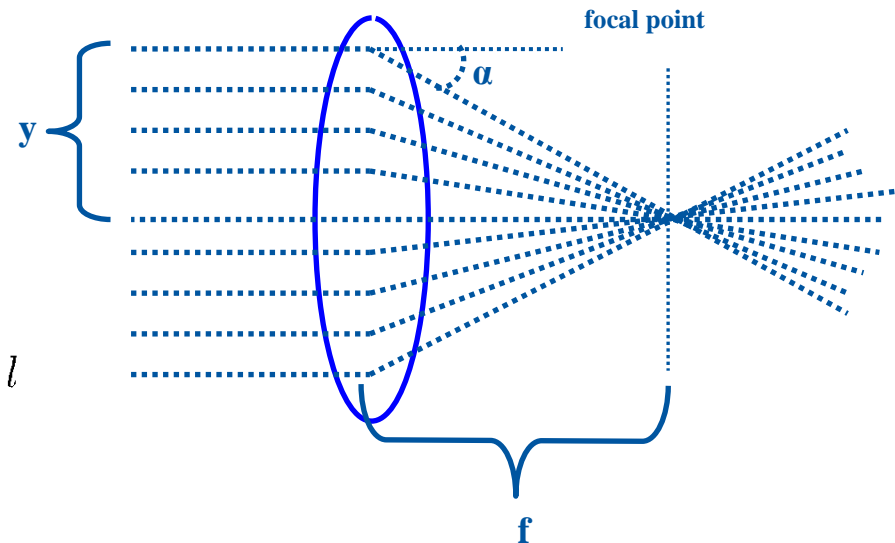
- The normalised focusing strength

$$k = \frac{qg}{\beta E}$$

- In more practical units, for **Z=1**

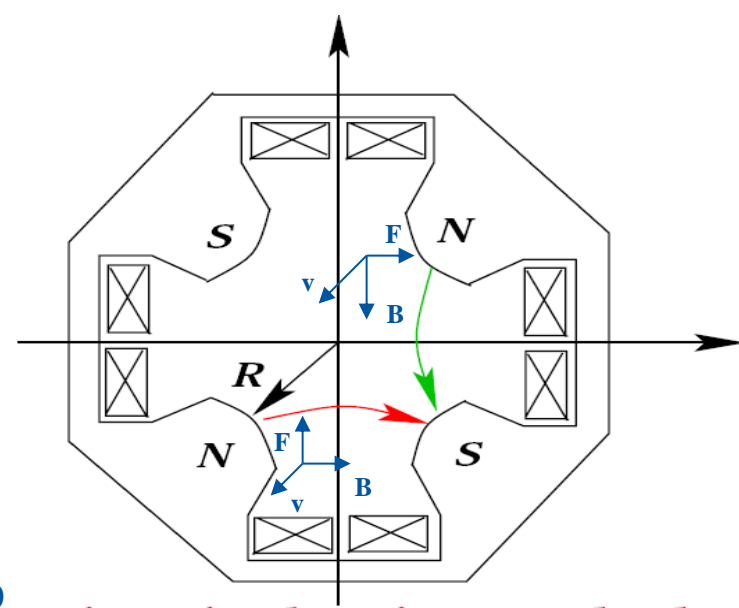
$$k[m^{-2}] = 0.2998 \frac{g[T/m]}{\beta E[GeV]}$$

- The focal length becomes $f^{-1} = k l$
and the deflection angle is $\alpha = -k y l$



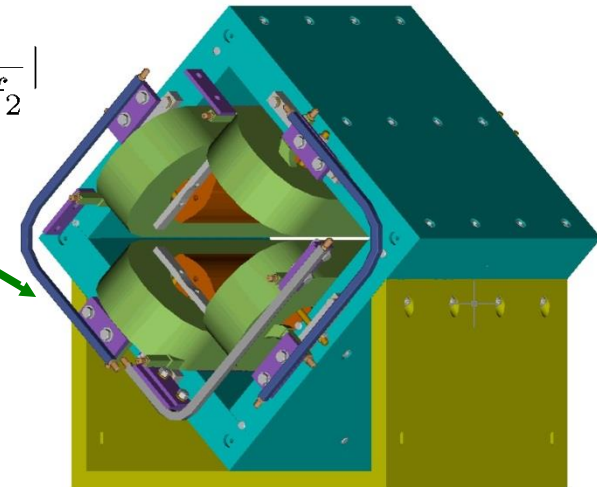
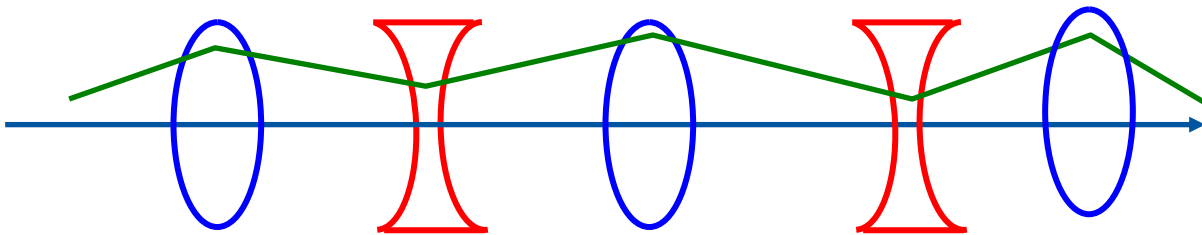
Quadrupoles

- Quadrupoles are focusing in one plane and defocusing in the other
- The field is $(B_x, B_y) = g(y, x)$
- The resulting force $(F_x, F_y) = k(y, -x)$
- Need to alternate focusing and defocusing to control the beam (**alternating gradient focusing**)
- From optics we know that a combination of two lenses with focal lengths **f1** and **f2** separated by a distance **d**
- If $f_1 = -f_2$, there is a net focusing effect, i.e.

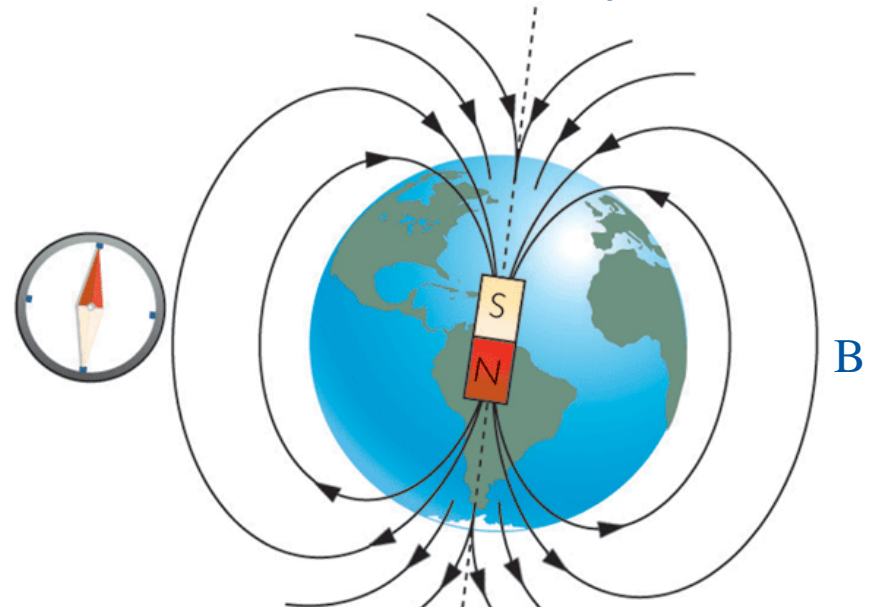
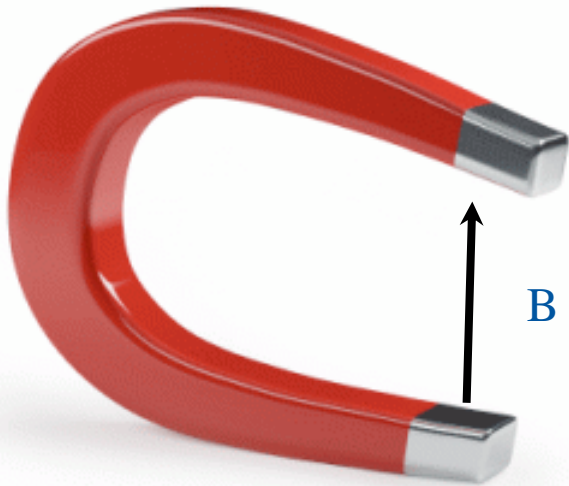


$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$\frac{1}{f} = \left| \frac{d}{f_1 f_2} \right|$$

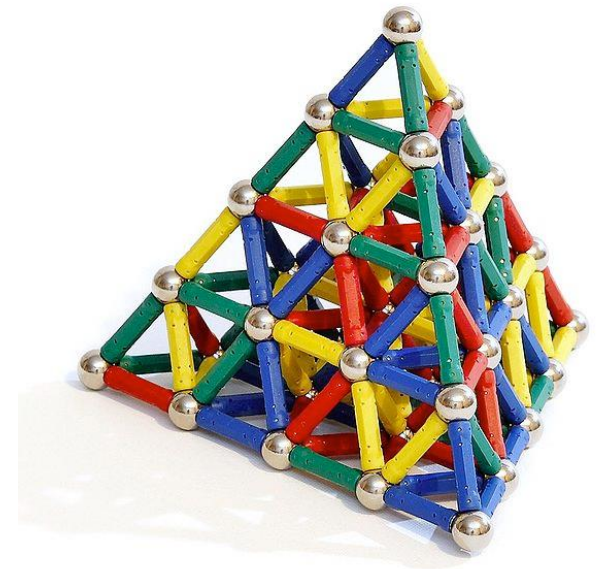


Two dipoles and magnets you should know very well



■ **Earth Magnetic Field : ~ 0.6 Gauss**

■ **Typical SPS dipole field: ~ 20000 Gauss (2Tesla)**



Magnets

- Normal conducting magnets:
 - field dominated by the magnetization of the iron yoke
 - Maximum fields limited to less than 2 Tesla (~40000 the terrestrial magnetic field)



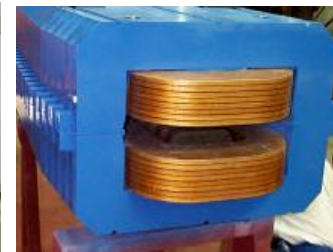
ANK



ALBA



ELETTR



SLS



SPRING-8



SOLEI

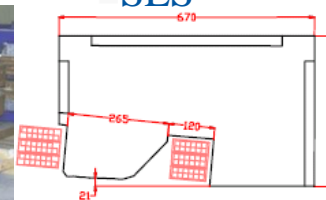


DIAMOND



CLS

Gap=45 mm B= 1.35 T G= 3.8T/m



ASP



SPEAR3

Gap = 50 mm B= 1.4 T G= 3.6 T/m



Classical mechanics.... spring with a mass

$$F = ma = m \frac{d^2x}{dt^2} = -kx$$

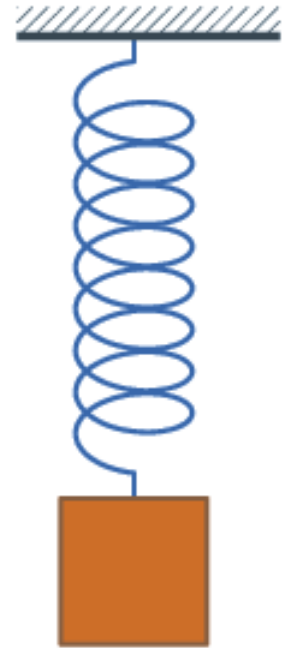
with k the spring constant and m the mass

Solution of the equation of motion is a periodic function:

$$x(t) = A \cos(2\pi f t + \phi)$$

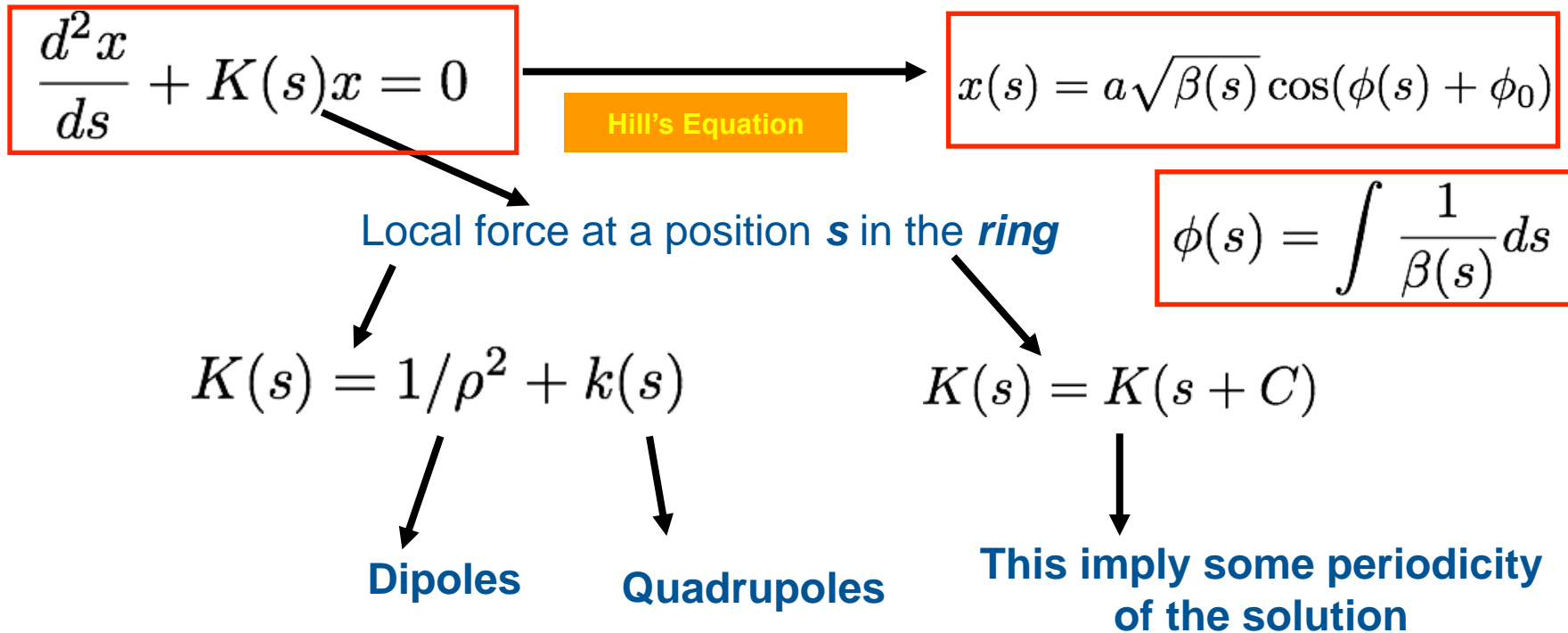
■ with $1/\text{period}$ equals to

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$



Equation of motion (transverse)

- Equation of motion of a particle in a circular accelerator composed by a sequence of elements, each one eventually with a k at a position s of the ring, repeated at every C



Envelope of the betatronic motion (Twiss parameters)

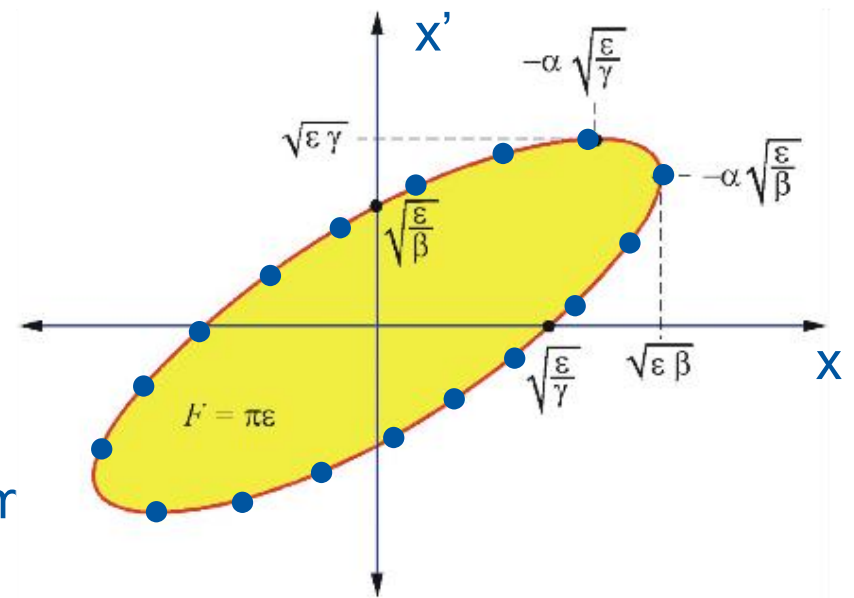
Defining $x'(s) = \frac{dx}{ds}$ (beam divergence) it can be demonstrated that

$$\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2 = \varepsilon$$

where:

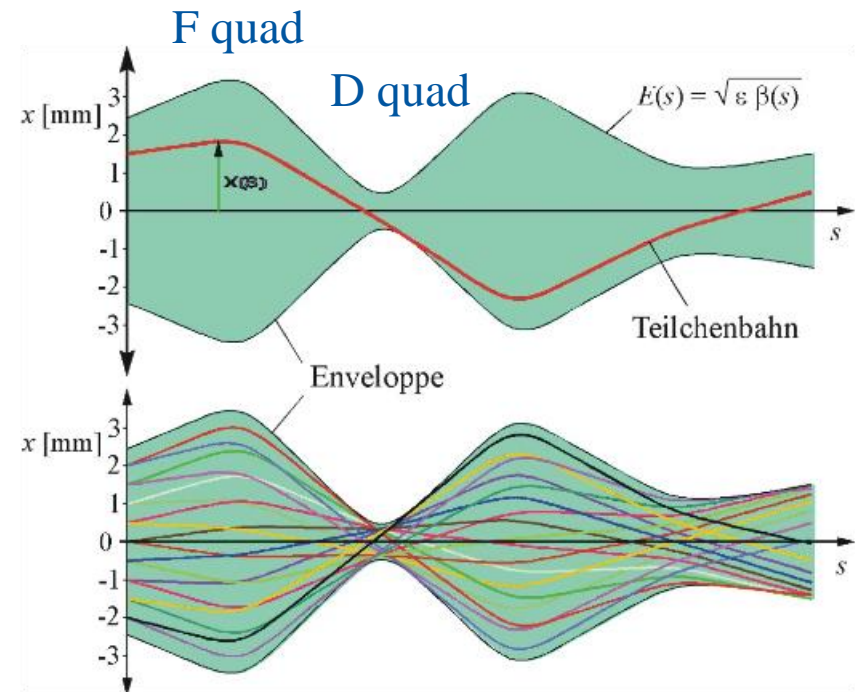
- $\alpha(s) \equiv -\frac{1}{2} \frac{d\beta}{ds}$
- $\gamma(s) \equiv \frac{1+\alpha^2(s)}{\beta(s)}$
- $\varepsilon \equiv a^2$

Twiss parameters (α , β , γ) at a given position and emittance ε in the ring provide a complete description of the motion of the particles and of the beam envelope



Definition of envelope

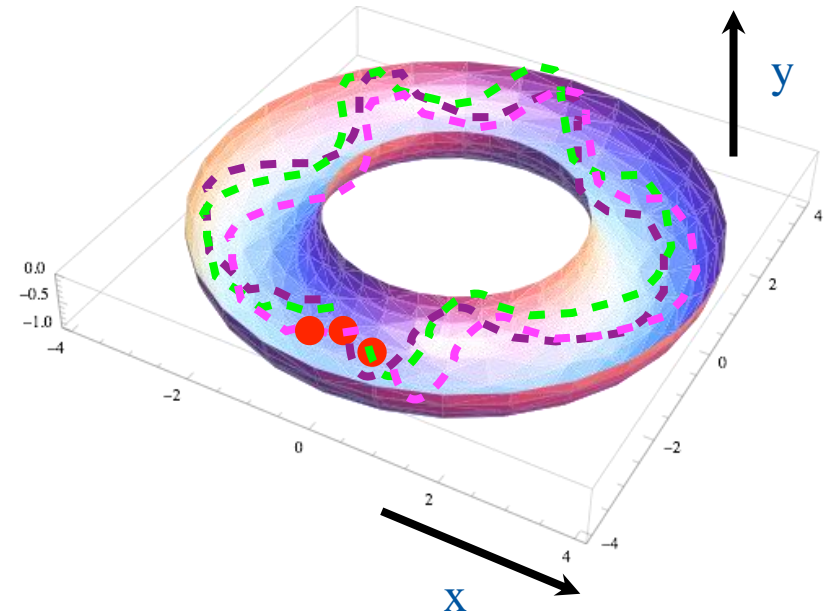
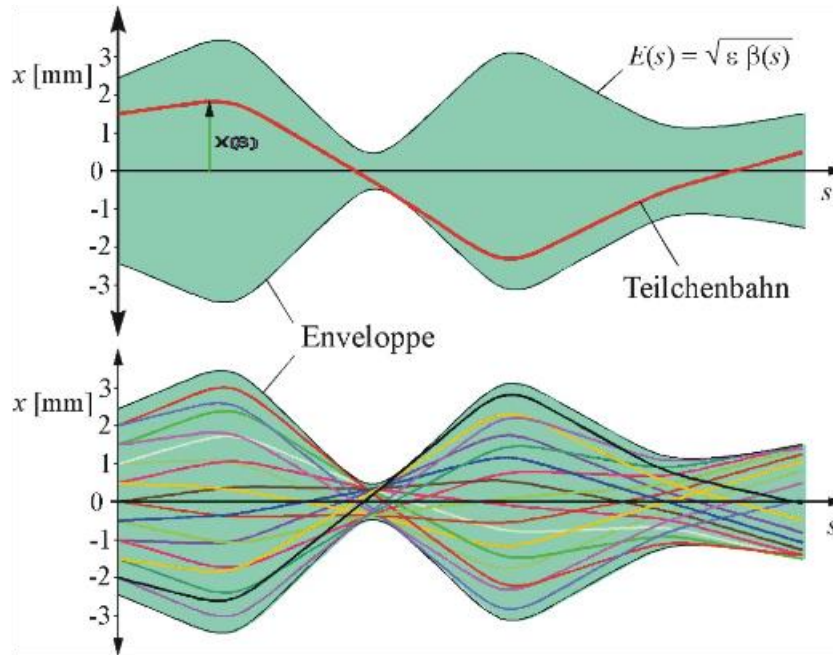
- The beam envelope can be defined for example as the maximum amplitude for which the particle remains in the machine vacuum chamber.



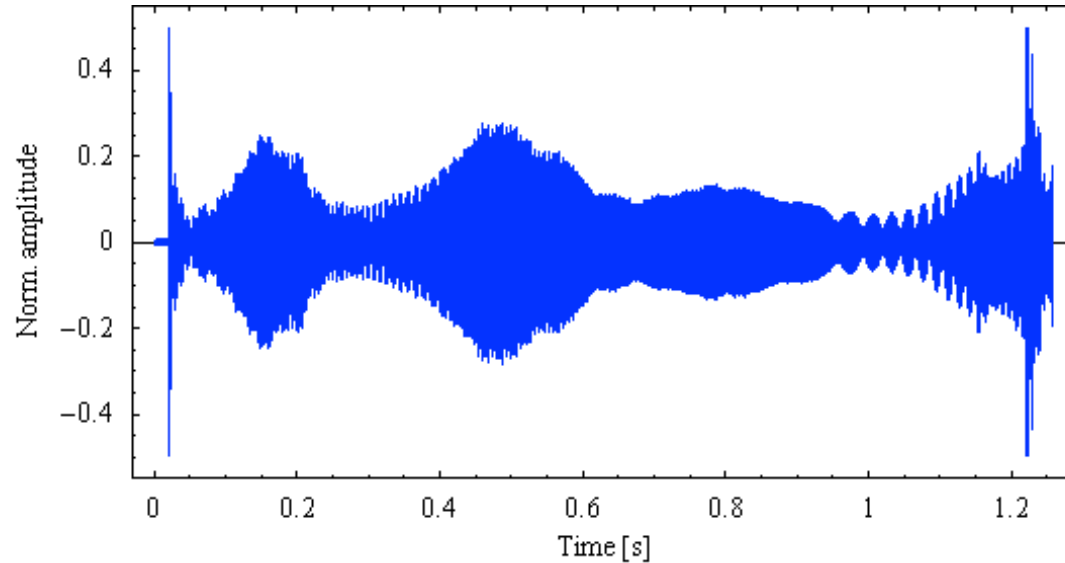
Beam physical dimension

Tune

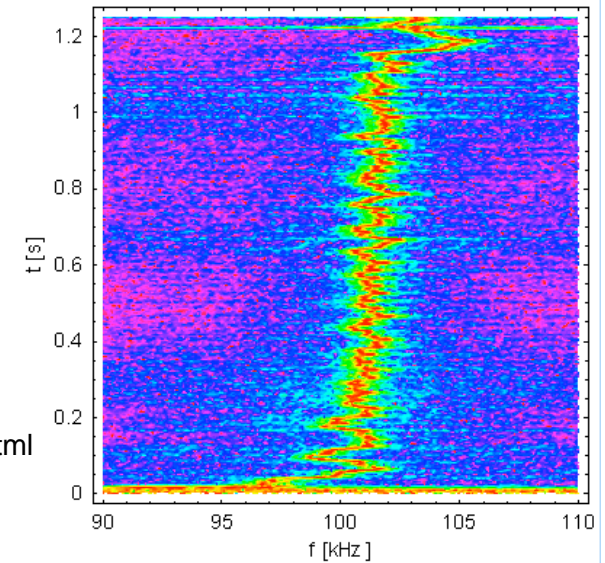
- Tune Q: number of oscillations (called betatronic) in the xx' plane a particle does in one machine turn.
- $$Q = \frac{\phi(s+C) - \phi(s)}{2\pi}$$
- The tune depends on the quadrupoles settings



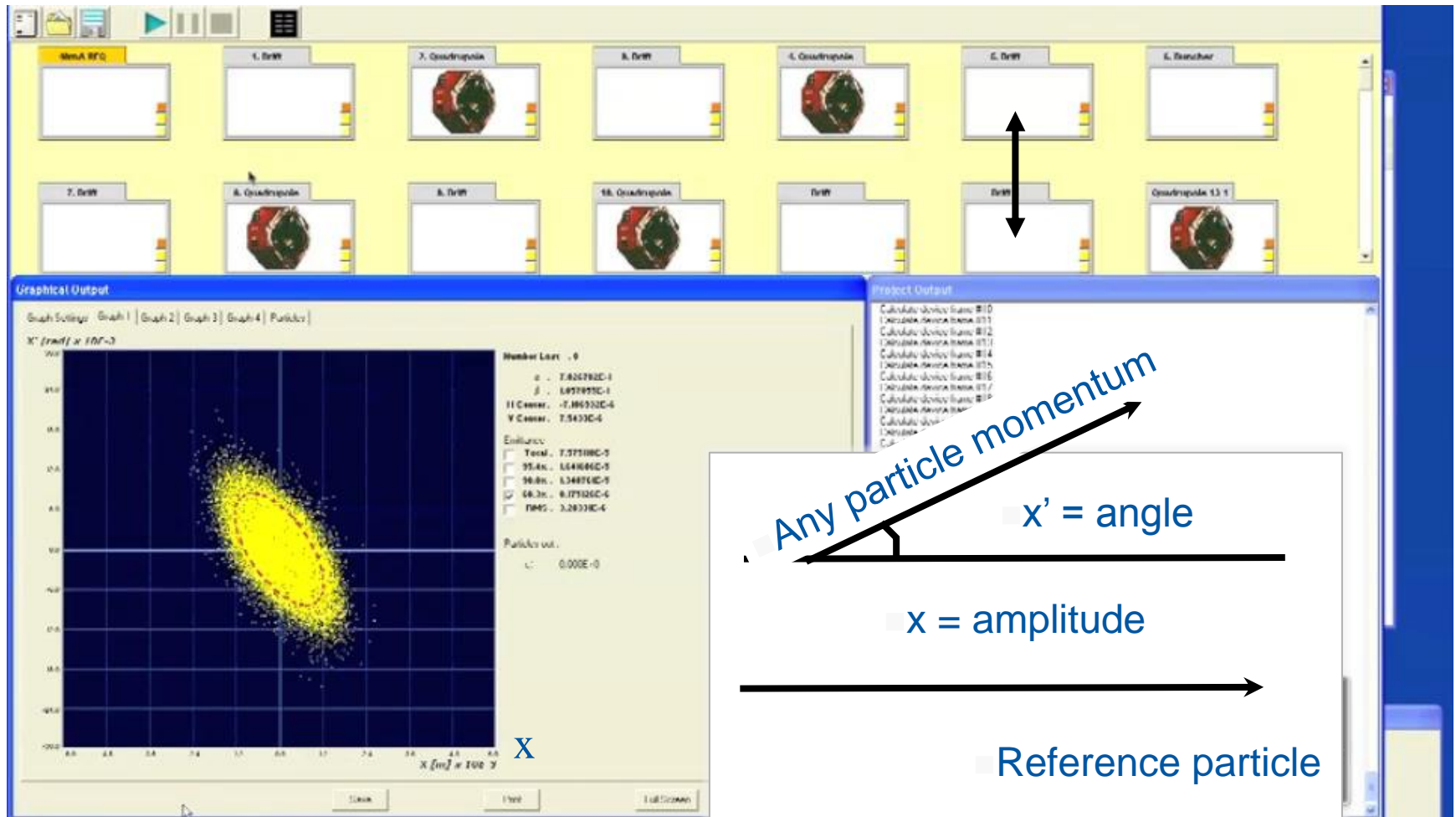
Tune: number of betatron oscillation in the transverse plane



<http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html>



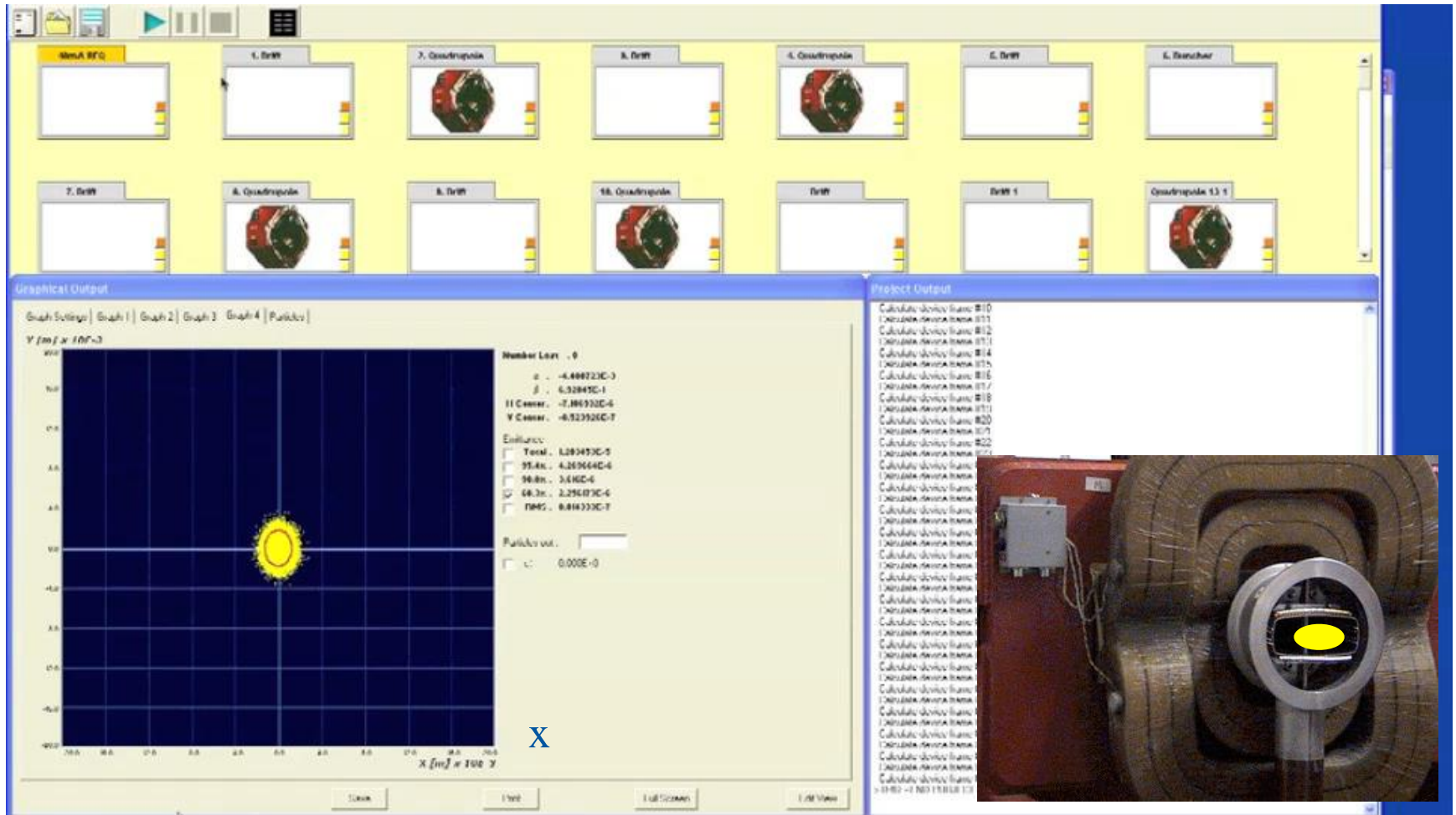
Particle transport in a lattice (phase space)



X'

X

Particle transport in a lattice (real space)

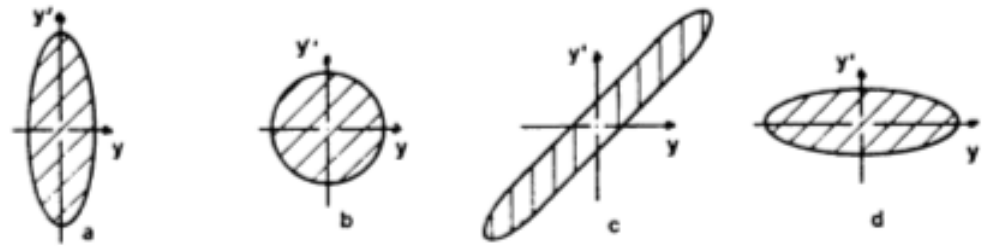


y

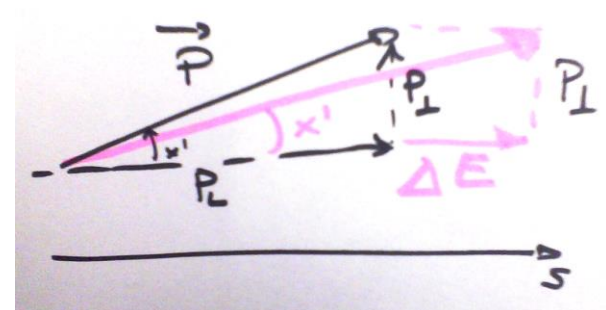
x



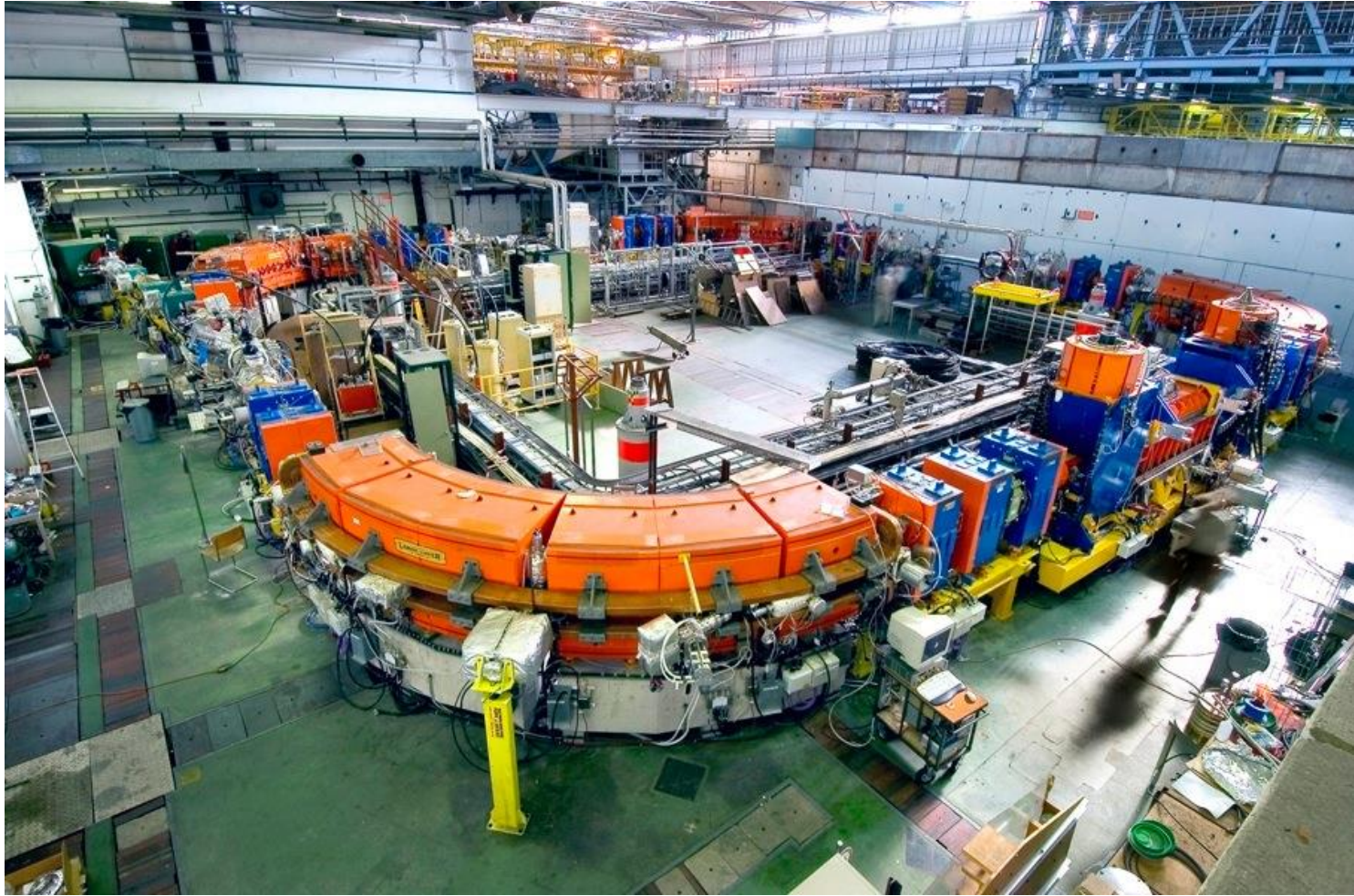
Liouville theorem



- Theorem: In the vicinity of a particle, the particle density in phase space is a constant if the particle move in an external magnetic field or in a general field which the force do not depend upon velocity the beam is like an incompressible fluid in phase space
- Implications:
 - a. the emittance is conserved when the beam is transported via a magnetic system. The ellipse is distorted/streched but its surface is conserved.
 - b. the emittance is NOT conserved if we accelerate, except if we normalize the emittance wrt to $\beta\gamma$ (relativistic). x' is reduced by the acceleration.

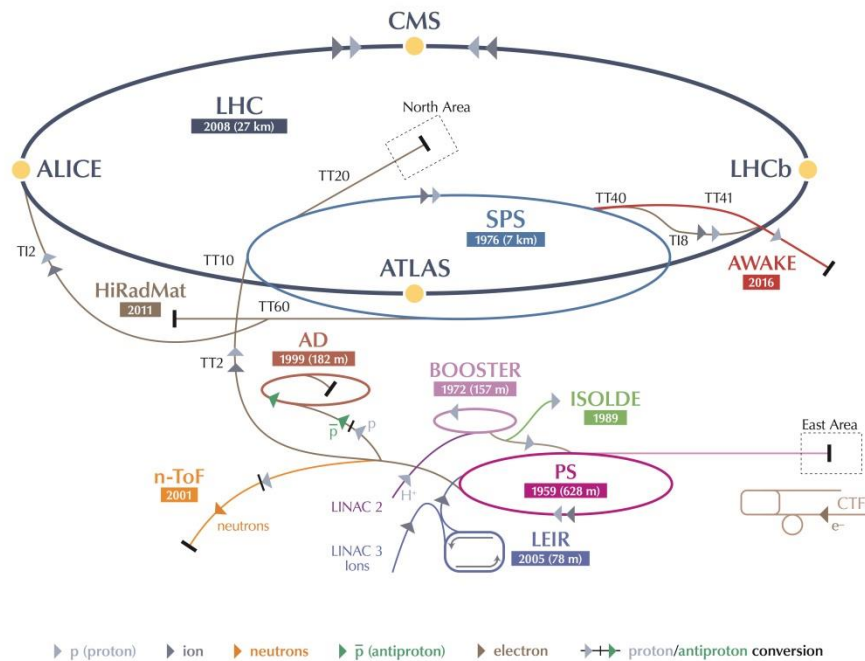


A synchrotron at a glance: LEIR



CERN Accelerators

CERN's Accelerator Complex



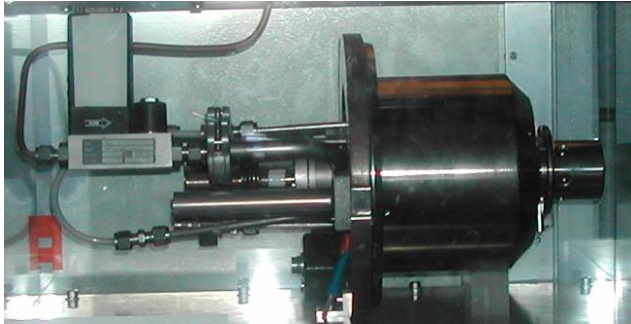
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
 AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

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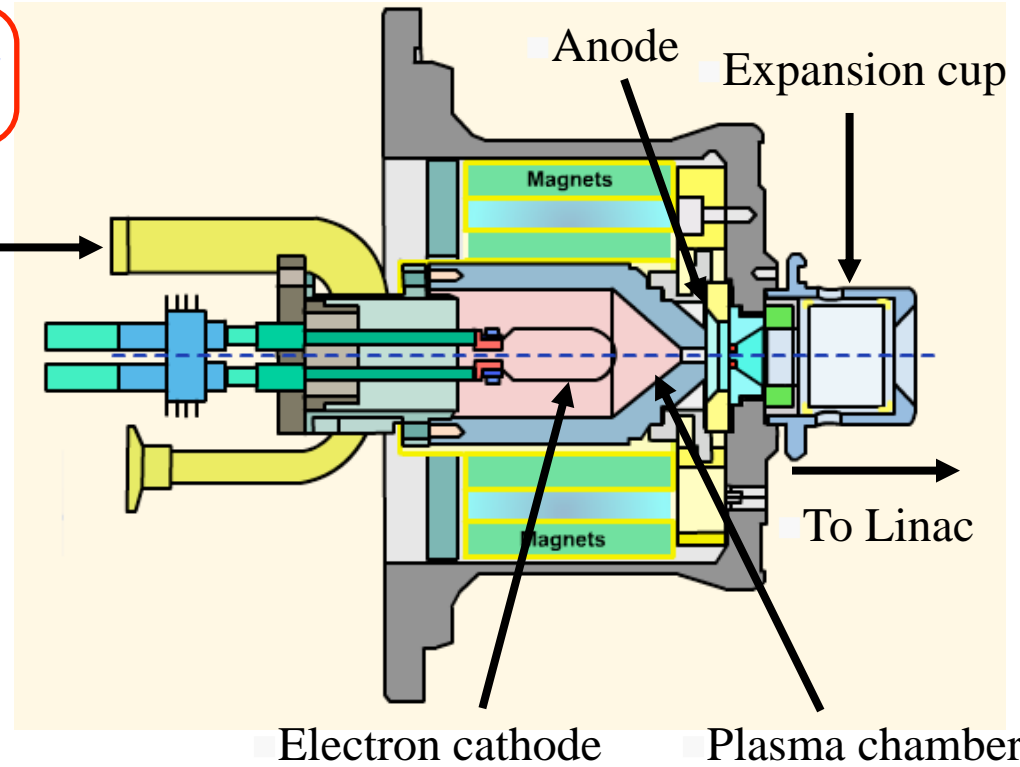


How to get protons: duoplasmatron source

Protons are produced by the ionization of H_2 plasma enhanced by an electron beam



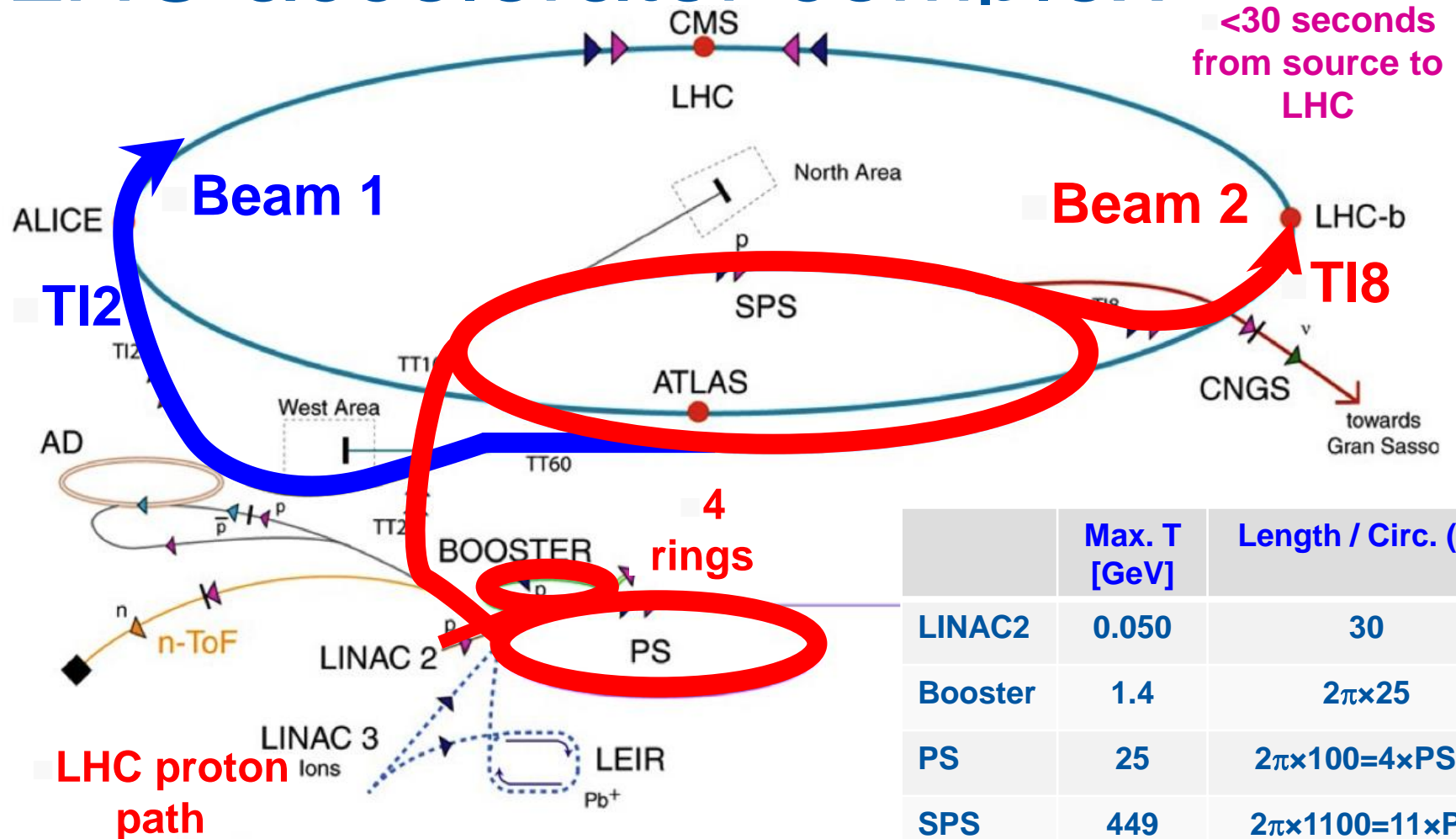
Hydrogen supply (one lasts for 6 months)



Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % of the speed of light, $v \approx 4000 \text{ km/s}$

The SPACE SHUTTLE goes only up to 8 km/s

LHC accelerator complex

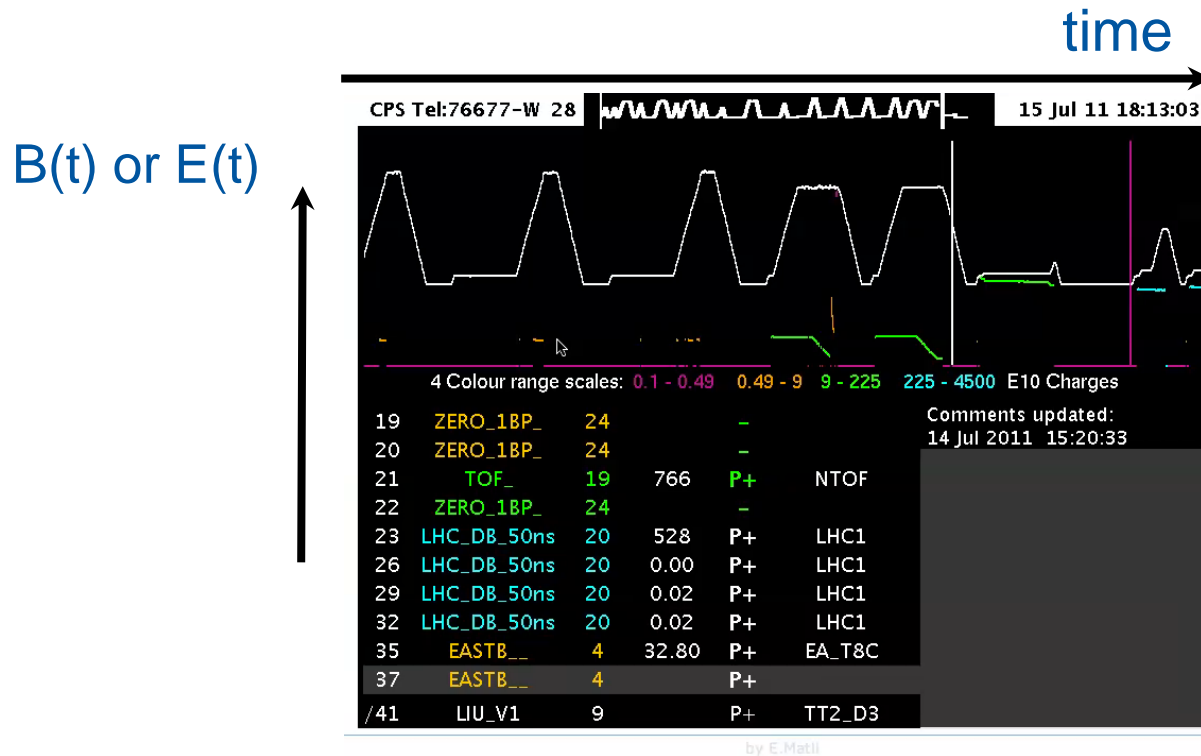


<30 seconds from source to LHC

	Max. T [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	$2\pi \times 25$
PS	25	$2\pi \times 100 = 4 \times \text{PSB}$
SPS	449	$2\pi \times 1100 = 11 \times \text{PS}$
LHC	6999	$26'657 = 27/7 \times \text{SPS}$

- ▶ protons
- ▶ antiprotons
- ▶ ions
- ▶ electrons
- ▶ neutrons
- ▶ neutrinos
- AD Antiproton Decelerator
- PS Proton Synchrotron
- SPS Super Proton Synchrotron
- LHC Large Hadron
- n-ToF Neutron Tim
- CNGS CERN Neutri

An example of cycling machine: the CERN-PS



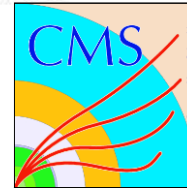
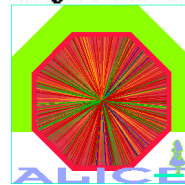
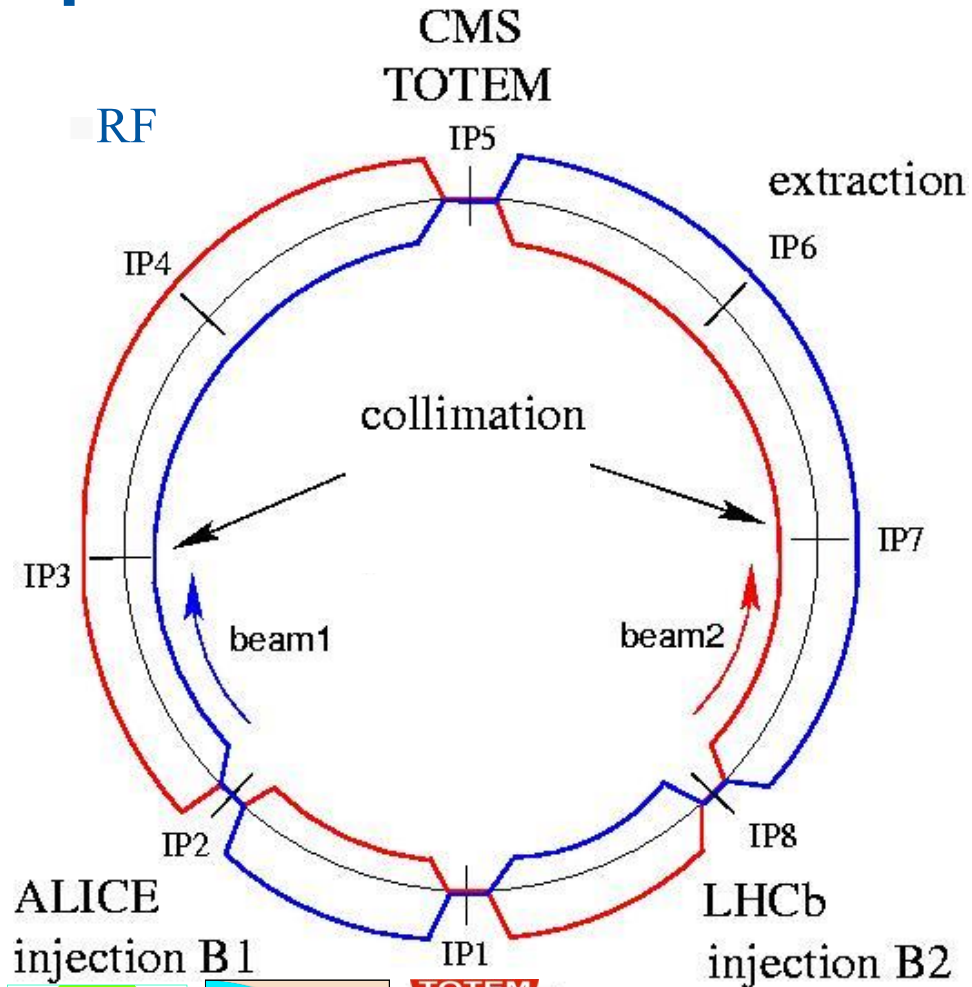
$$\frac{dB}{dt} = 24 \text{ G/ms}$$

- **PS is a slow synchrotron: pulses every 1.2 s (or multiples)**
- PS radius: 100 m
- Injection: B = 1013 G (0.1013 T) E = 1.4 GeV
- Extraction (max): 12000 G (1.2T) E ~ 26 GeV

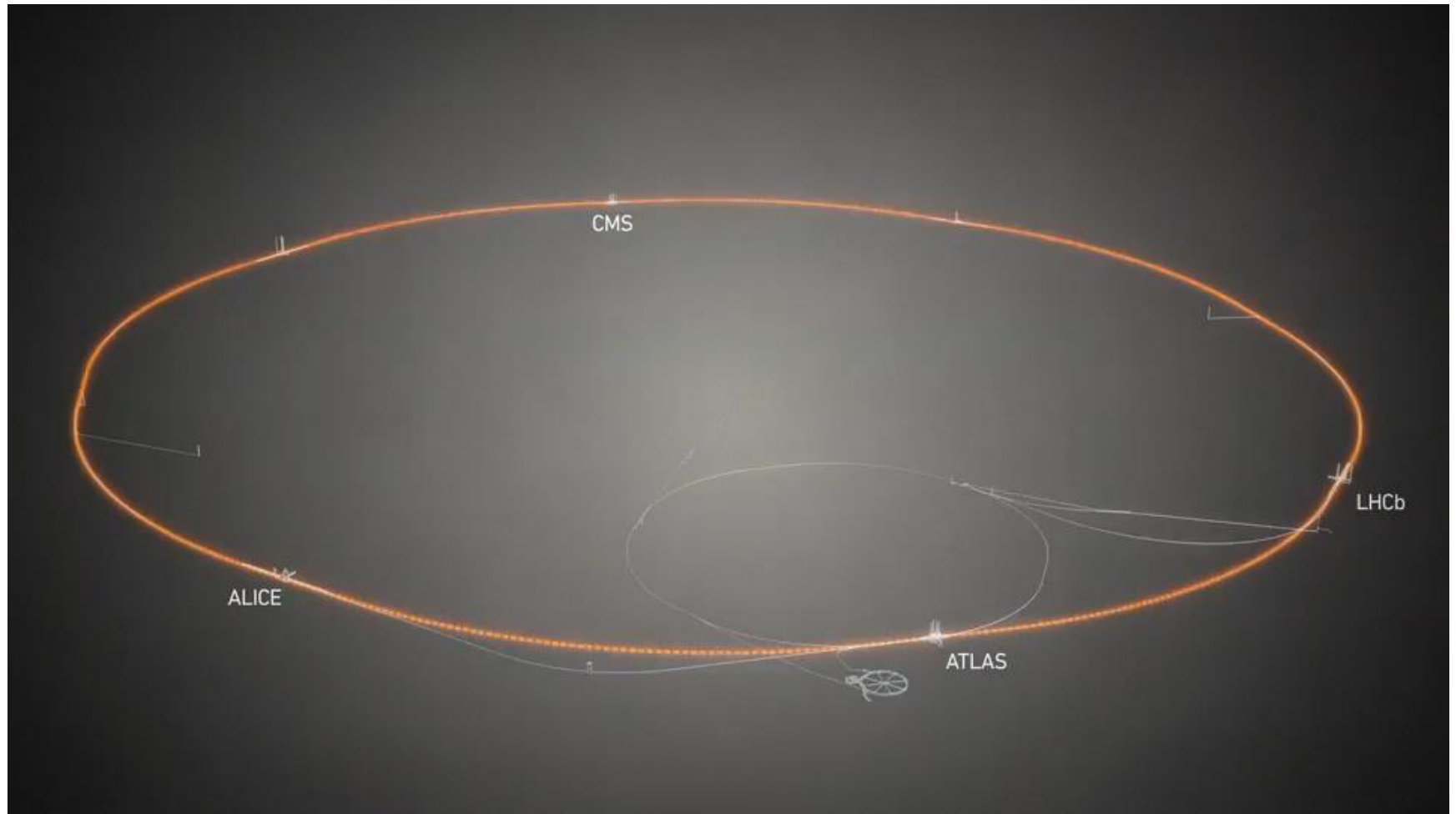


LHC layout and parameters

- Total length 26.57 km, in the former LEP tunnel.
- 8 arcs (sectors), ~2.8 km each.
- 8 long straight sections (700 m each).
- beams cross in 4 points.
- 2-in-1 magnet design with separate vacuum chambers → p - p (or ion/ion or p /ion) collisions.



The LHC



Why a collider?

Two particles have equal rest mass m_0 .

The Centre of Mass Energy

$E_{CM} = c\sqrt{(\mathbf{P}_1 + \mathbf{P}_2)^2}$ is invariant and it represent the energy available for the generation of the collision products.

- $|\mathbf{P}|c = \sqrt{E^2 - \mathbf{p}^2c^2} = m_0c^2$ is invariant.



• $\mathbf{P}_1c = (E, \mathbf{p}c)$

$\mathbf{P}_2c = (m_0c^2, \mathbf{0})$

Fixed Target: one particle at rest, total energy is E .



• $\mathbf{P}_1c = (E, \mathbf{p}c)$

$\mathbf{P}_2c = (E, -\mathbf{p}c)$

Collider: Particles with opposite momenta

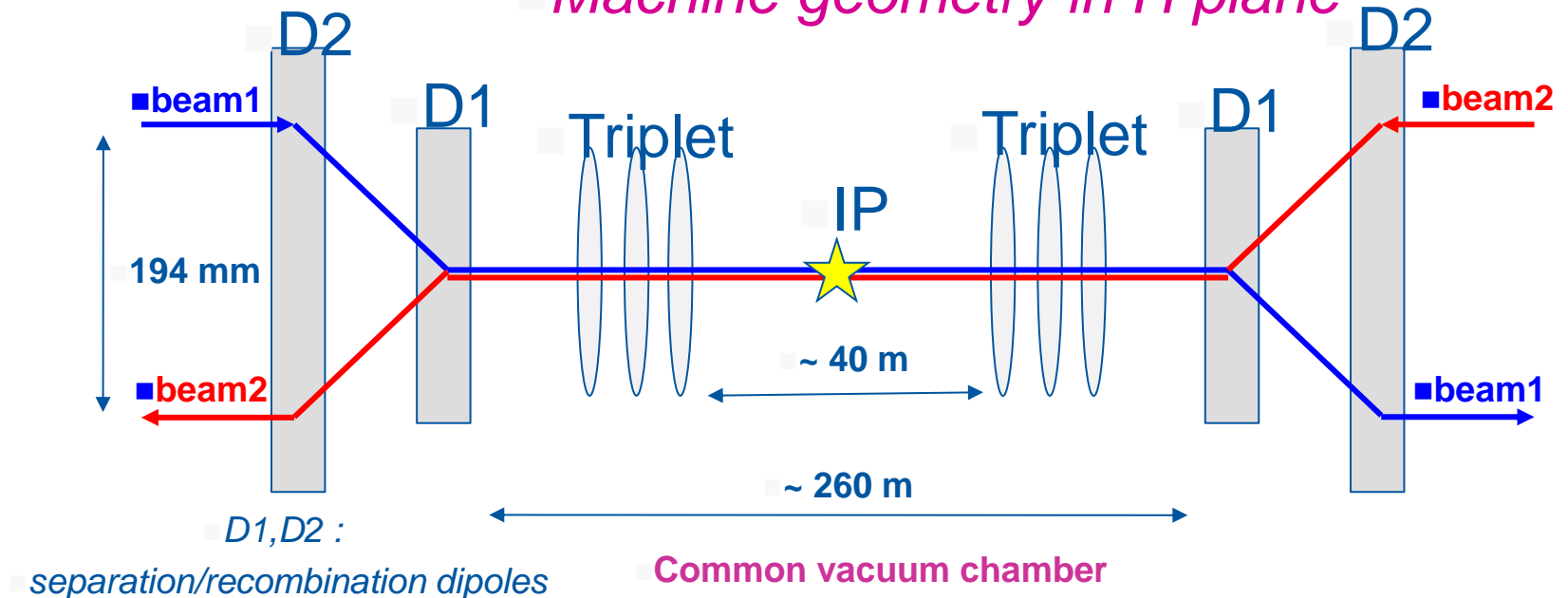
- **Fixed Target:** $E_{CM} = \sqrt{2m_0c^2(m_0c^2 + E)}$
- **Collider:** $E_{CM} = 2E$

In order to get a CoM energy of 100GeV we need a beam of 5328 GeV for a fixed target experiment or two colliding beams of 50 GeV each!!!

Interaction regions geometry

- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane,
 - The beams move from inner to outer bore (or vice-versa),
 - The triplet quadrupoles are used to focus the beam at the IP.

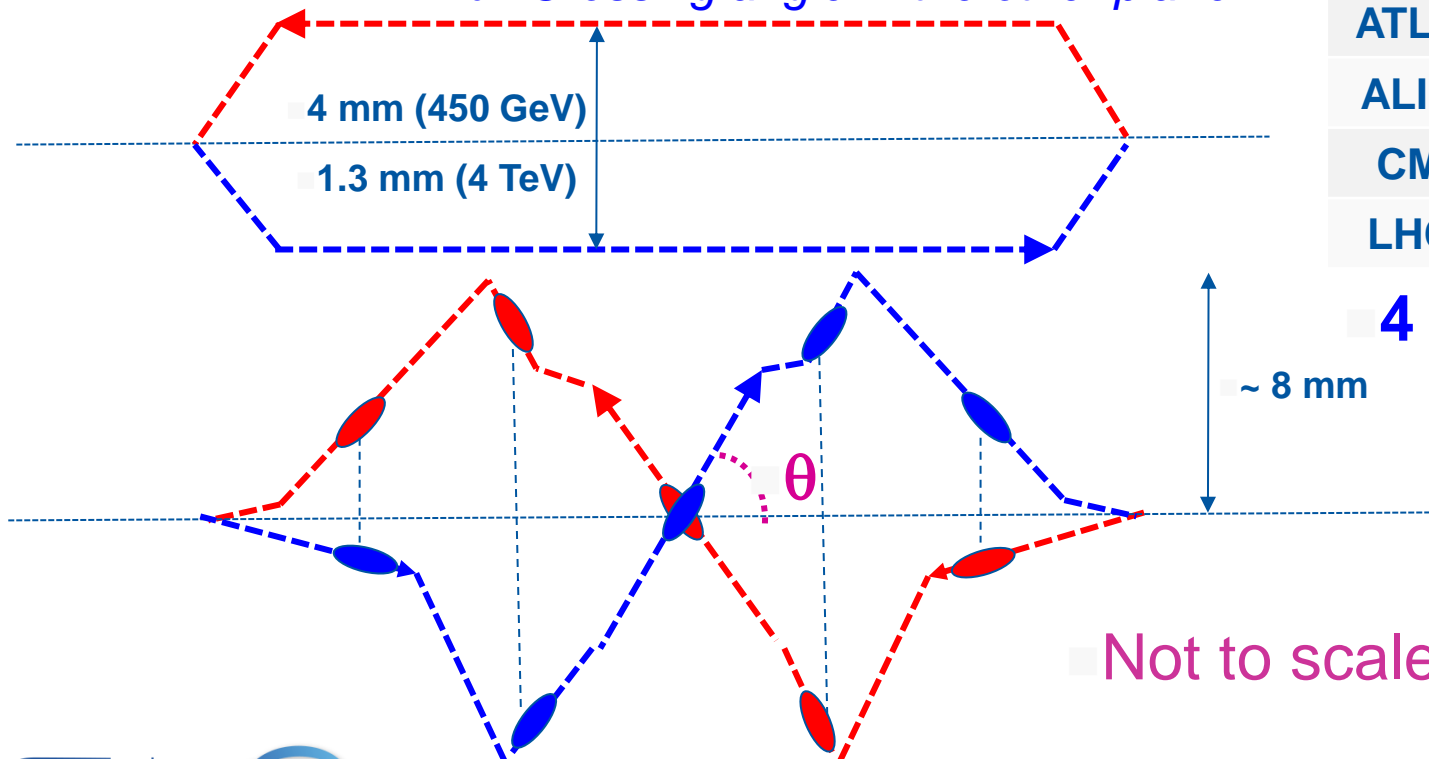
Machine geometry in H plane



Separation and crossing

Because of the tight bunch spacing and to prevent undesired parasitic collisions in the region where the beams circulate in the common vacuum chamber:

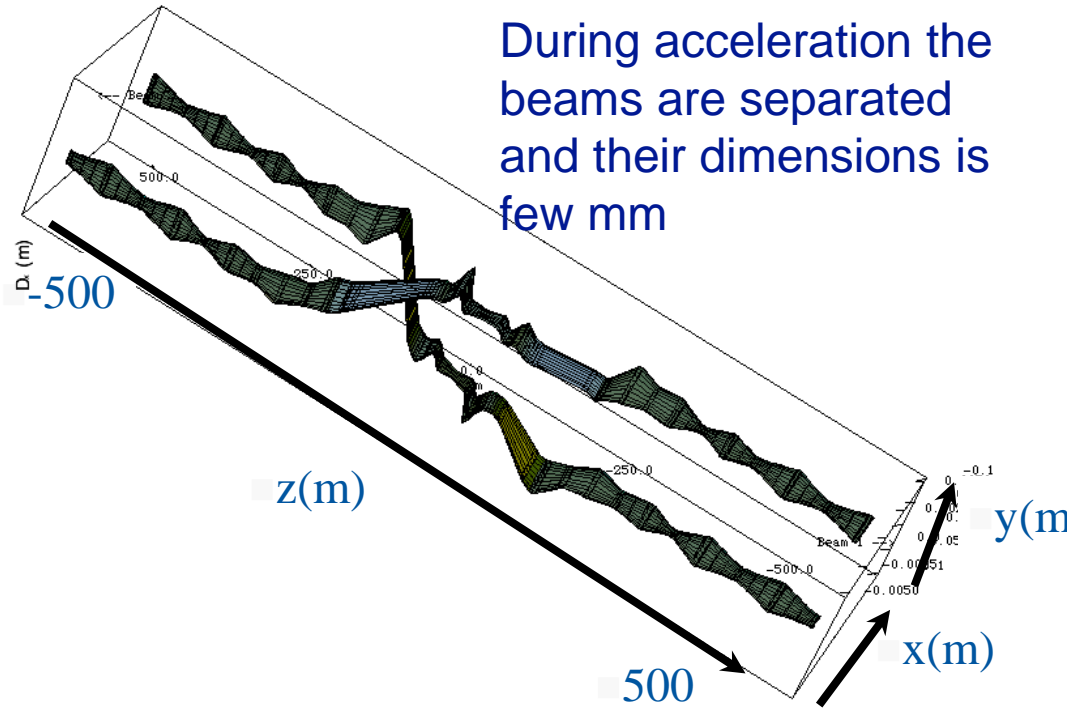
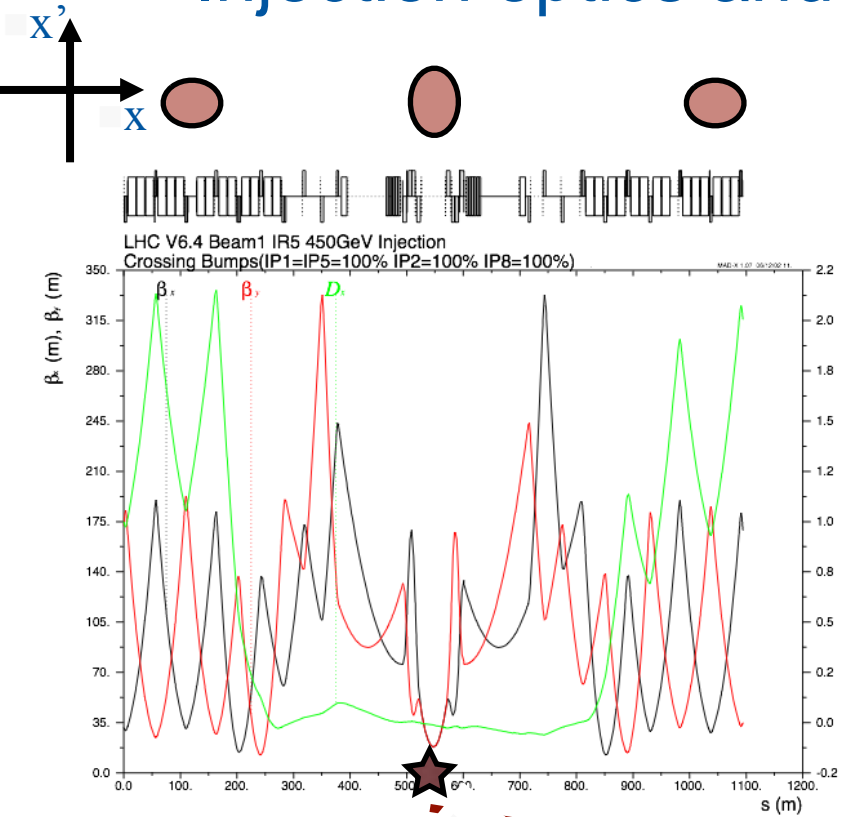
- *Parallel separation in one plane (mostly effective at the IP), which is collapsed to 0 when the beams are colliding,*
- *Crossing angle in the other plane.*



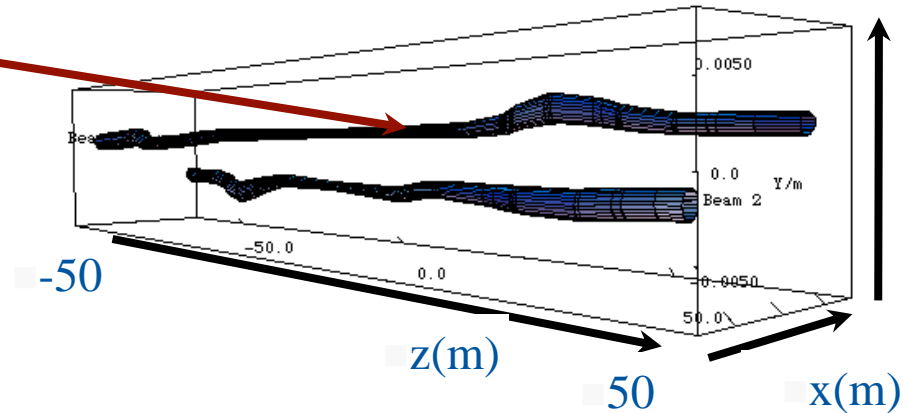
	α (μrad)
ATLAS	-145 / ver.
ALICE	145 / ver.
CMS	145 / hor
LHCb	90 / ver

4 TeV / 2012 !

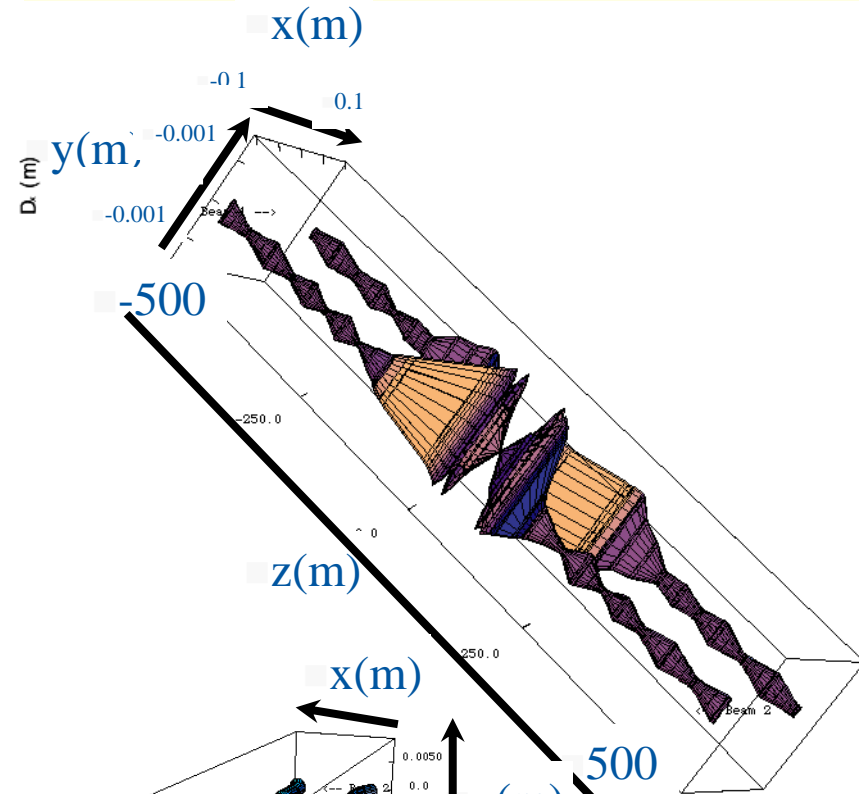
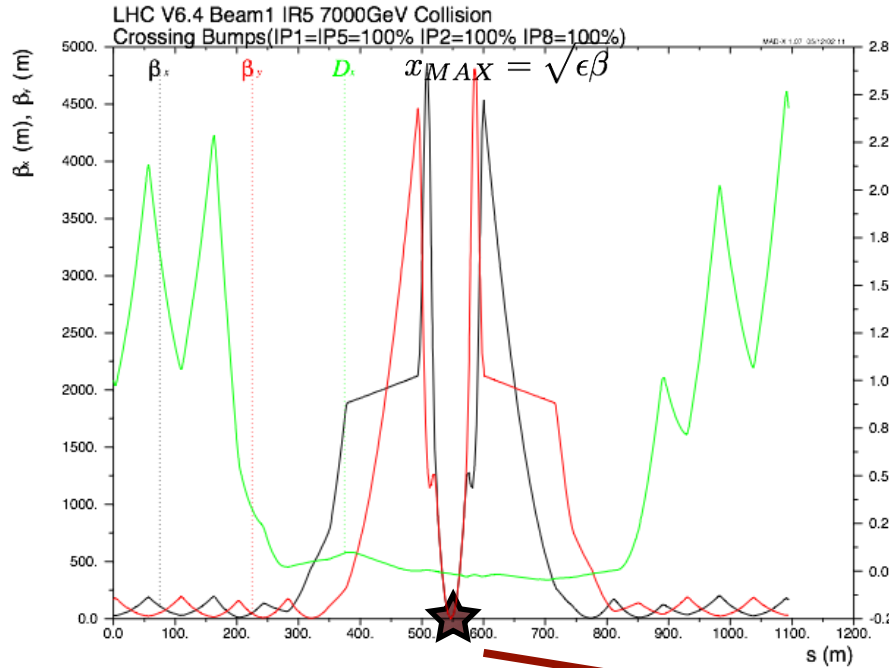
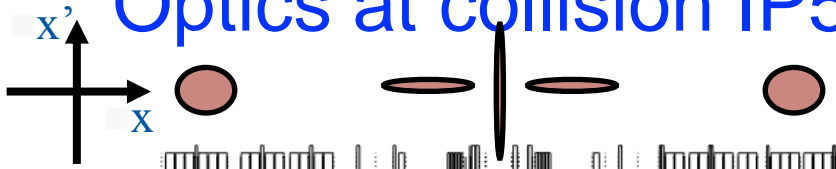
Injection optics and during acceleration IP5(CMS)



Interaction point

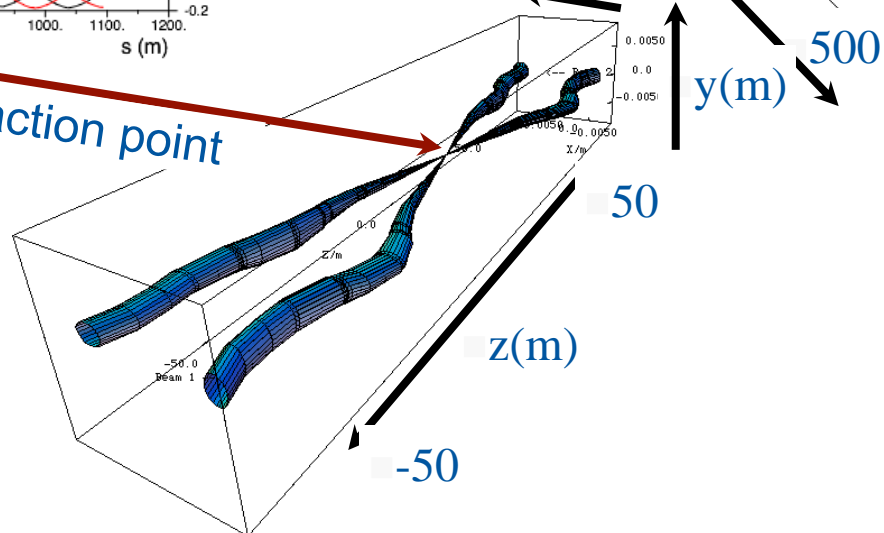


Optics at collision IP5- CMS



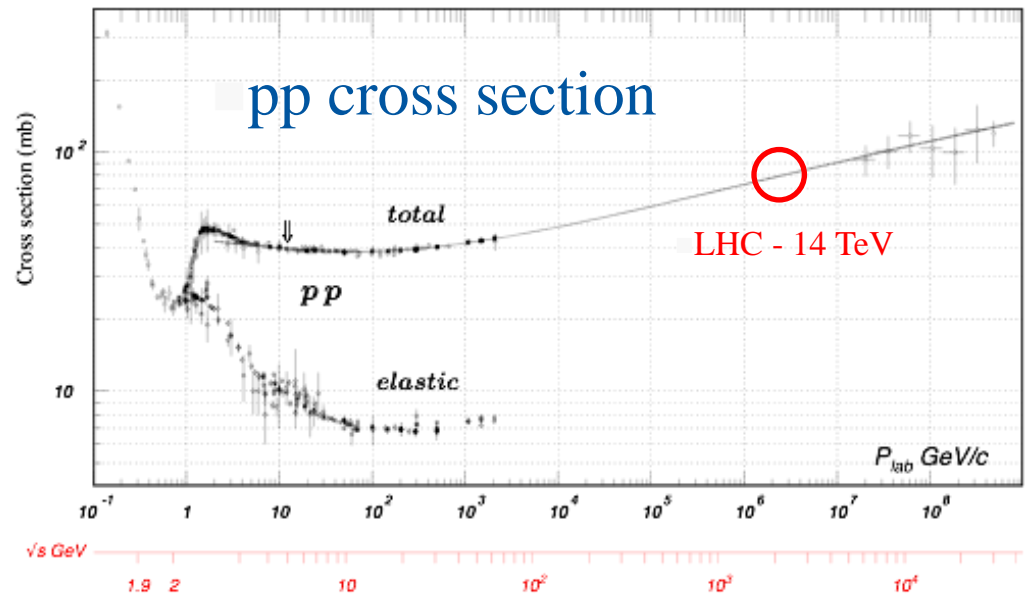
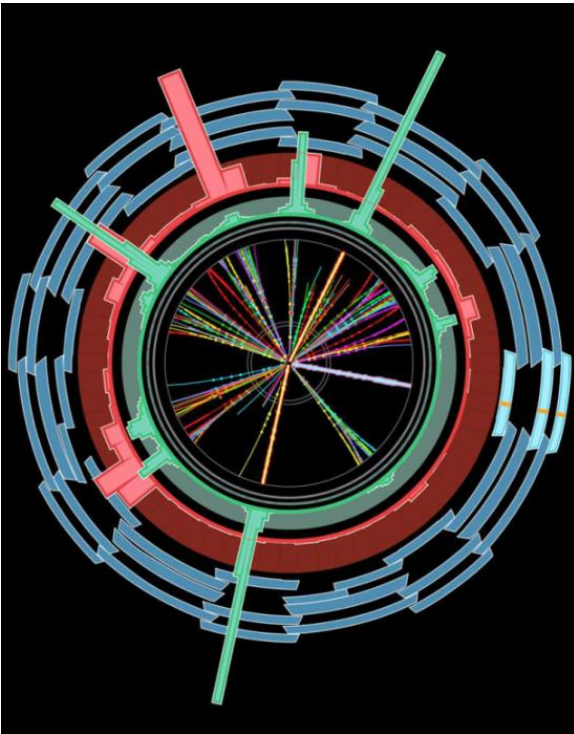
At collision the beams are “squeezed” down to few microns at the interaction point

Interaction point



More luminosity

$$\frac{dN_{event}}{dt} = L\sigma_{event}$$



Luminosity

$$L = \frac{kN_b^2 f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{kN_b^2 f \gamma}{4\pi\beta^* \varepsilon^*} F$$

$$\sigma_x^* \sigma_y^* = \frac{\beta^* \varepsilon^*}{\gamma} \text{ (Round beams)}$$

- $\gamma = E/m$, f is the revolution frequency (11.25 kHz) defined by the circumference ($v \sim c!!$)
- k is the number of colliding bunch pairs,
- N_b is the bunch population,
- σ is the beam size at IP
- ε^* is the normalized emittance
- β^* the betatron (envelope) function at the IP
- F is a reduction factor due to the crossing-angle



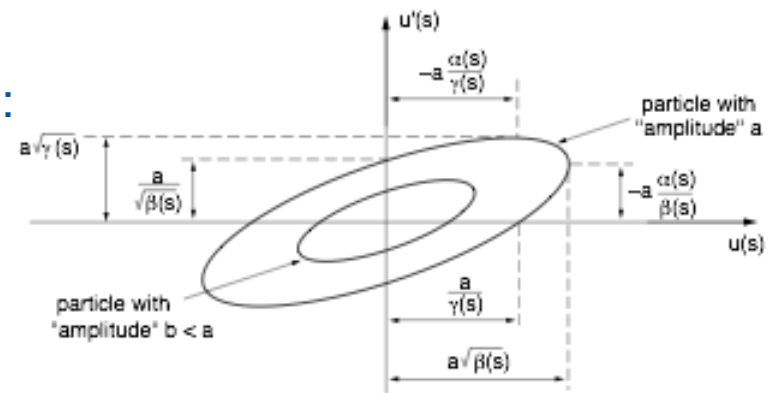
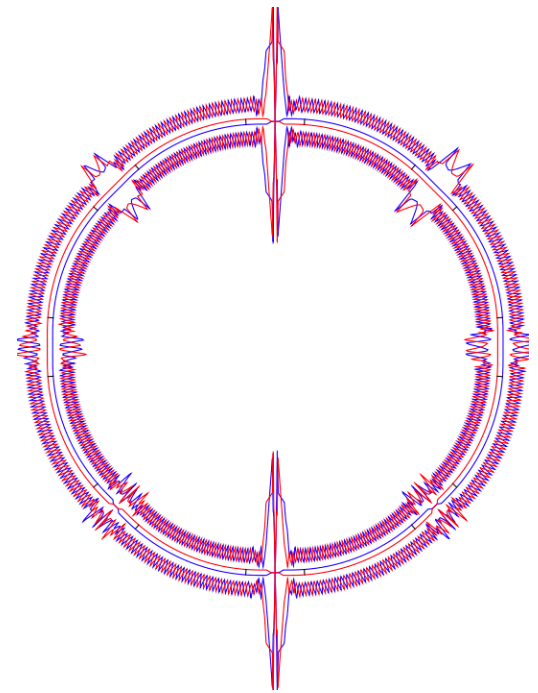
Beam size

$$\sigma = \sqrt{\beta \varepsilon}$$

- β = optical function defined at each point of the machine by strength of the quadrupoles. β^* is the value of the β function at the IP which is a focal point for the machine optics.
- ε = **emittance**: phase space area. As we move around the machine the shape of the phase space ellipse will change as $\beta(s)$ but the area of the ellipse ($\pi\varepsilon$) does not change (Liouville). ε shrinks naturally as we go up in energy (p_s increases, p_t doesn't) **normalized emittance** ε^* :

$$\varepsilon^* = \varepsilon \beta \gamma$$

- Ideally constant across the injector chain essentially defined at the proton source!!

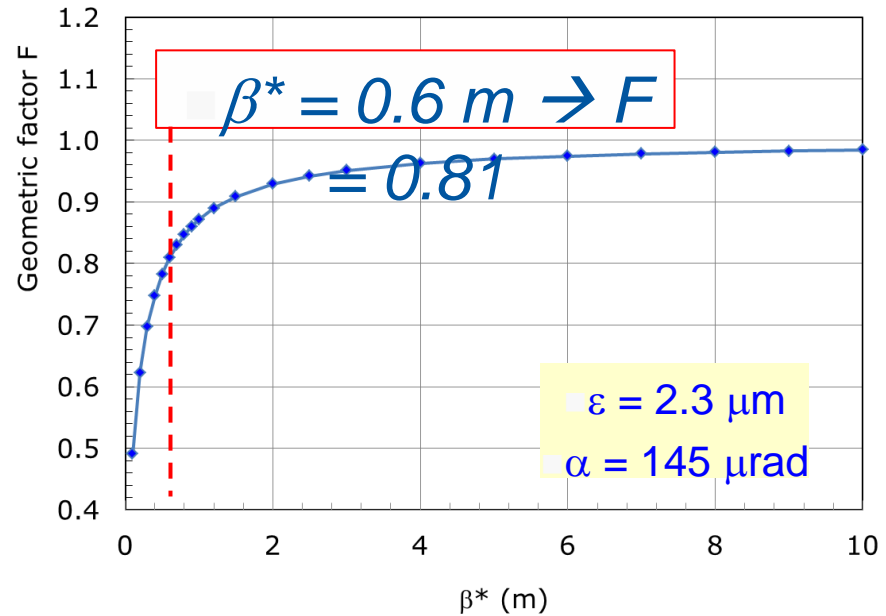
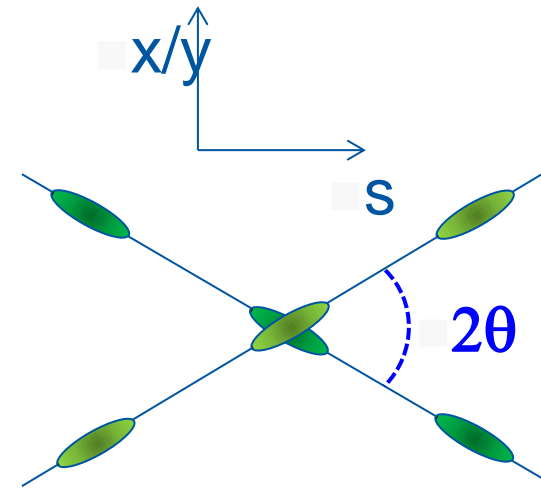


Crossing angle

- Drawbacks:
 - Due to the small beam size the luminosity geometric reduction factor due to bunch length σ_s and crossing angle becomes significant for low β^*

$$F = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_{x/y}} \tan \theta \right)^2}}$$

- Reduction of the aperture
- Long range beam-beam interactions
- and others (e.g. synchro-betatron resonances,...)



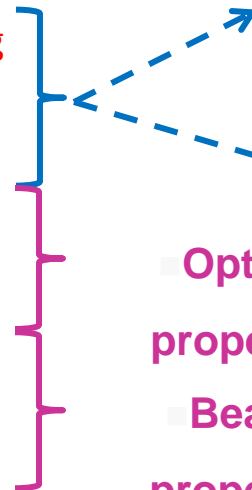
Luminosity

$$L = \frac{kN_b^2 f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{kN_b^2 f \gamma}{4\pi\beta^* \varepsilon^*} F$$

$$\sigma_x^* \sigma_y^* = \frac{\beta^* \varepsilon^*}{\gamma}$$

To maximize L:

- Many bunches (k) → **tight bunch spacing**
- Many protons per bunch (N_b)
 - Small beam sizes $\sigma_{x,y}^*$
 - **Small β^***
 - **Small emittance ε^***



High beam “brightness” N_b/ε^*
 (particles per phase space volume)

→ **Injector chain performance !**

■ Small envelope

→ **Strong focusing !**

■ Optics property

■ Beam property



What limits β^* ?



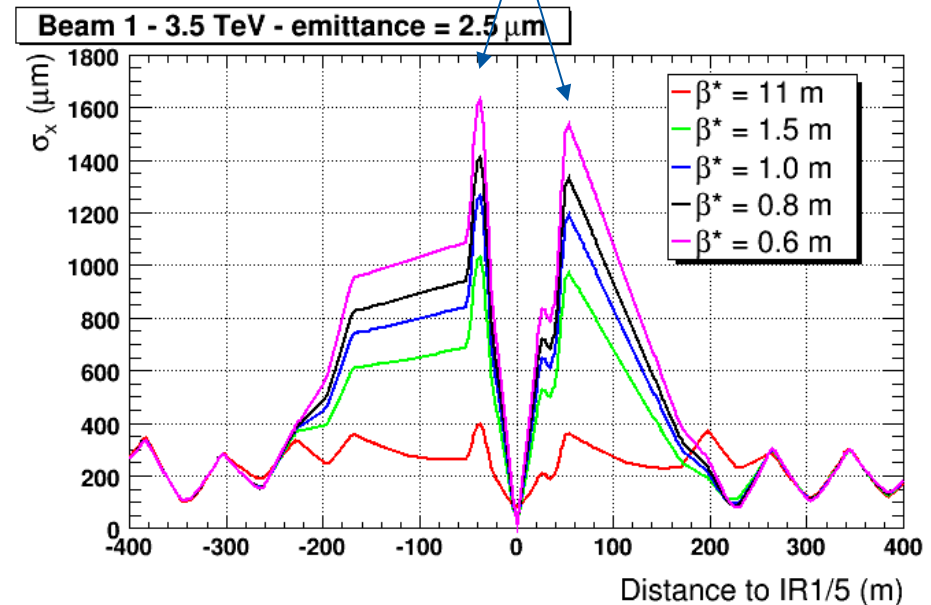
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Limits on β^*

In the high luminosity IRs, the triplet quadrupoles define the machine aperture limit for squeezed beams, β^* is constrained by:

$$\sigma_{triplet} \propto \sqrt{\frac{\epsilon}{\beta^* \gamma}}$$

- the beam envelope
- the crossing angle



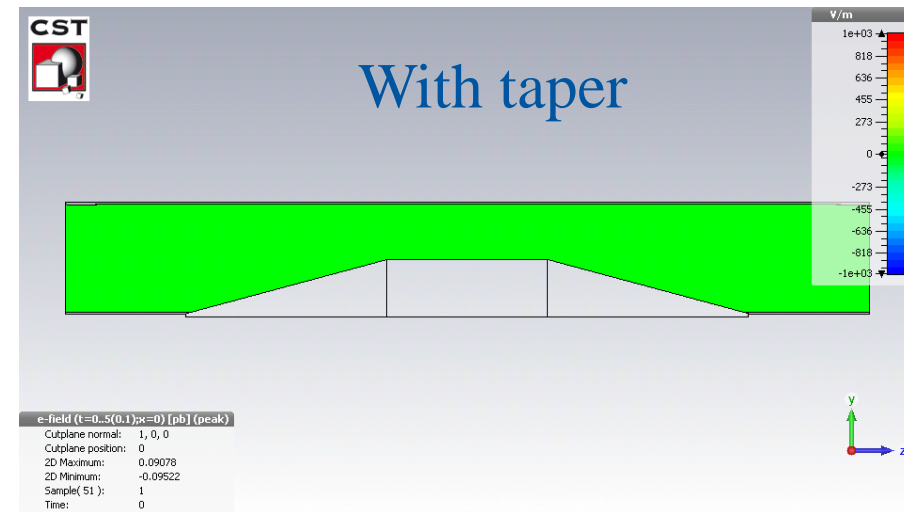
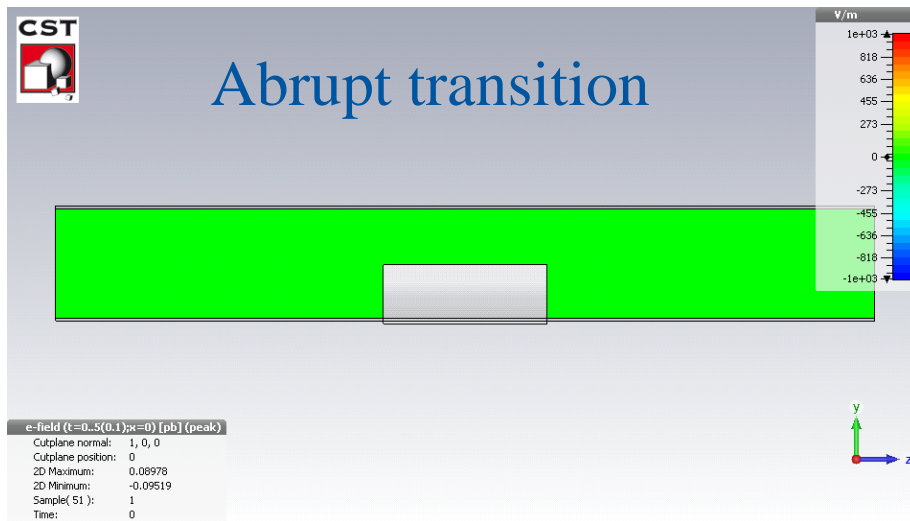
What limits the number and population of the bunches?



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Wake fields and Impedances

- **Intense bunches generate** electromagnetic (EM) fields when passing inside a structure (e.g. Carbon collimators – opening of ~ 1 mm!!!)
- \rightarrow results in an EM force, called **wake field** in time domain, beam-coupling **impedance** in frequency domain.

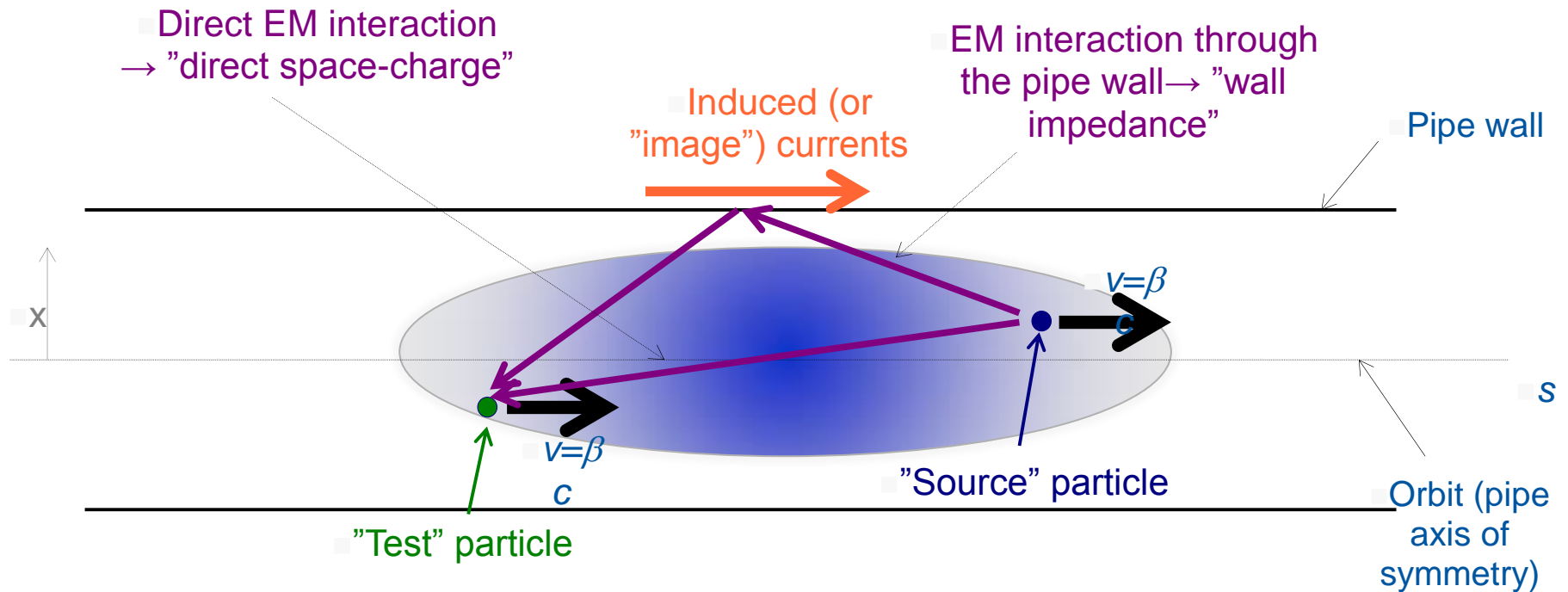


- Avoid the abrupt transition for the beam fields at the location of the beam passage (taper)
- Reduce the resistivity of the material

B. Salvant

Wake fields and instabilities

- Wake fields can couple the head and tail of a bunch

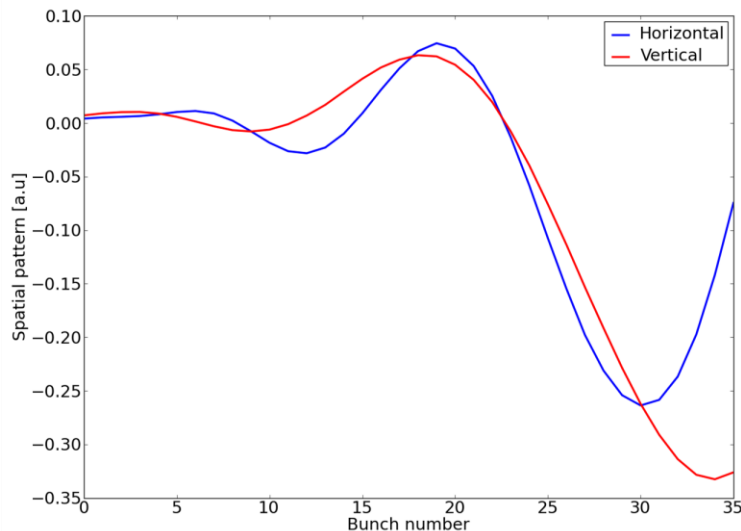


Wake fields and Instabilities

- Many bunches (up to 2800 with 25 ns spacing)



- Bunches can interact together (or even the head of each bunch can interact with the tail of the bunch) and in some cases begin to oscillate.
- Example with 36 bunches in the LHC: oscillation pattern along the bunch train (simulation result):



→ Coupled-bunch instabilities

N. Mounet



Beam instabilities

- In 2012 instabilities have become more critical due to higher bunch intensity and **tighter collimators settings**. The LHC is one of the few machines where instabilities are more critical at high energy.
- Interplay between impedance (mostly due to collimators) and two-beams phenomena (mostly beam-beam)
- **Cures:**
 - **Transverse feedback ('damper')** that measures the oscillations and sends corrective deflections,
 - **Non-linear magnetic fields (sextupoles, octupoles, beam-beam)** that produce a frequency spread among particles – kill coherent motion



Beam-beam effects

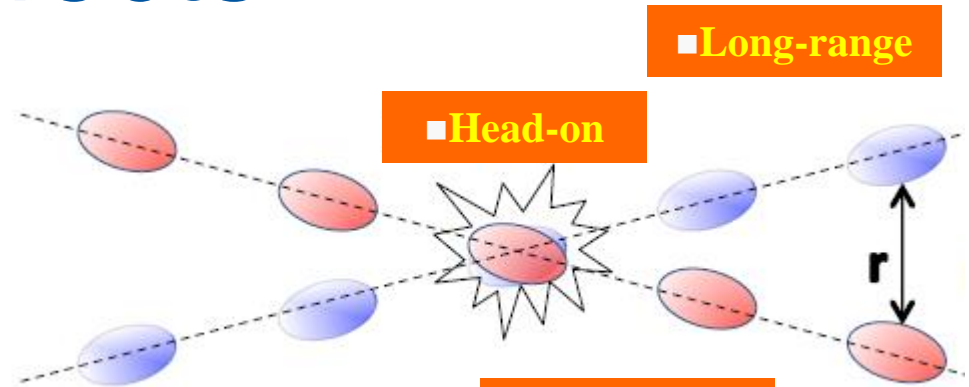
Strong non linear fields when counter-rotating beams are sharing vacuum chamber.

→ spread in betatronic frequencies → risk of overlapping resonances driven by magnetic errors

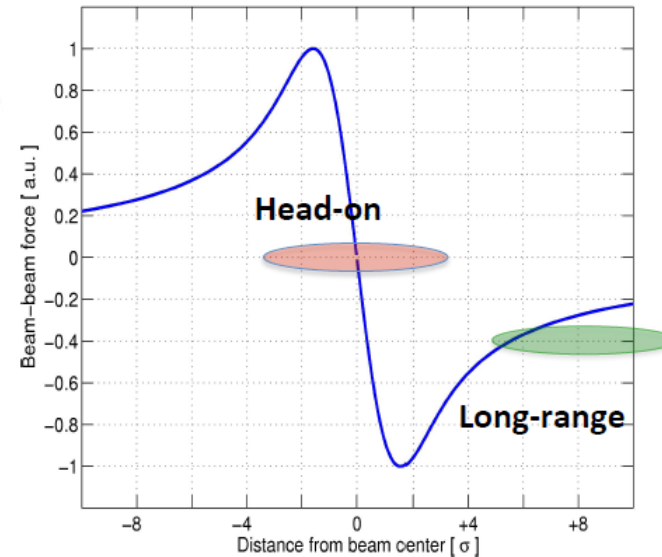
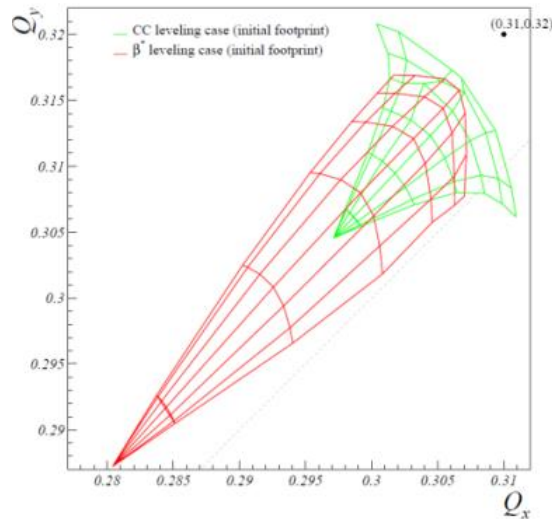
Minimize magnetic errors → Paid off for the LHC

Devise correction schemes and sorting → Paid off for the LHC

Initially expected to have limit at $\Delta Q_{BB} \sim 0.005/IP$



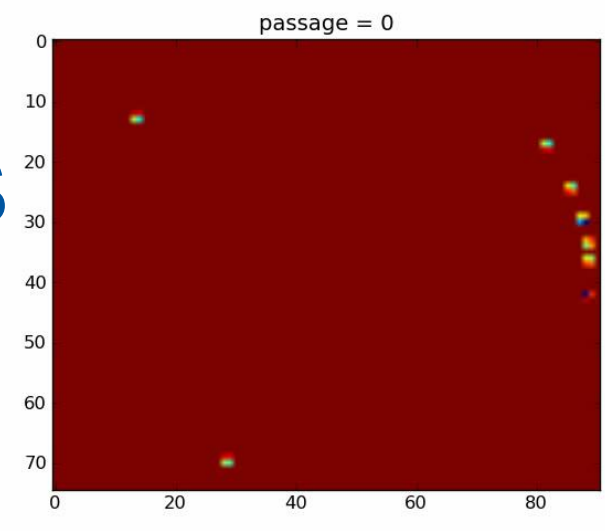
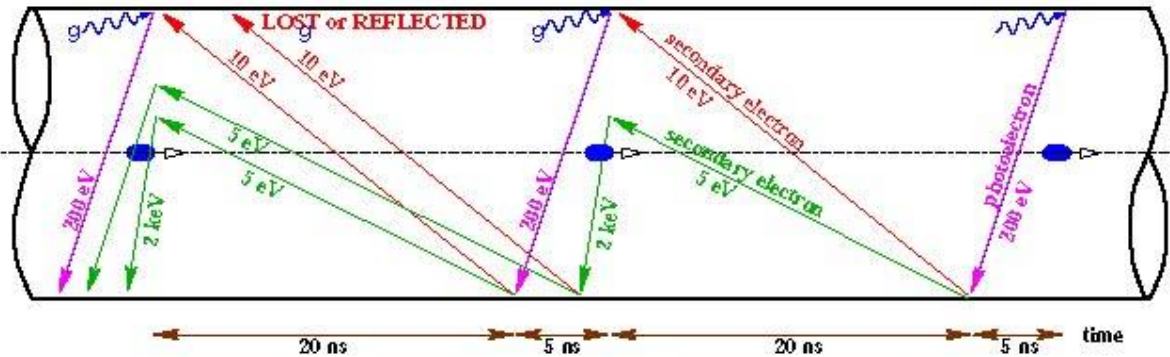
$$\Delta Q_{bb} \propto \frac{1}{N_b}$$



■ S. Fartoukh



Electron cloud effects



■ F. Ruggiero

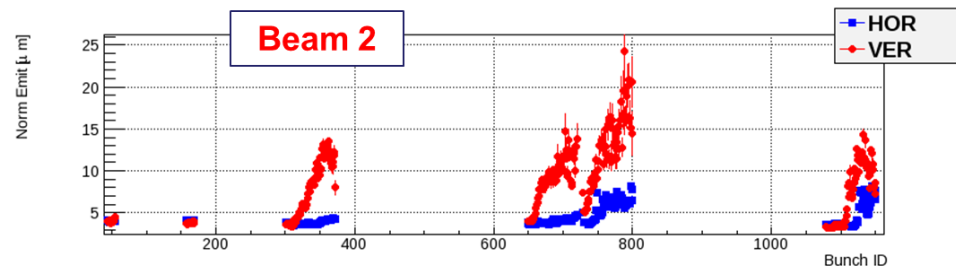
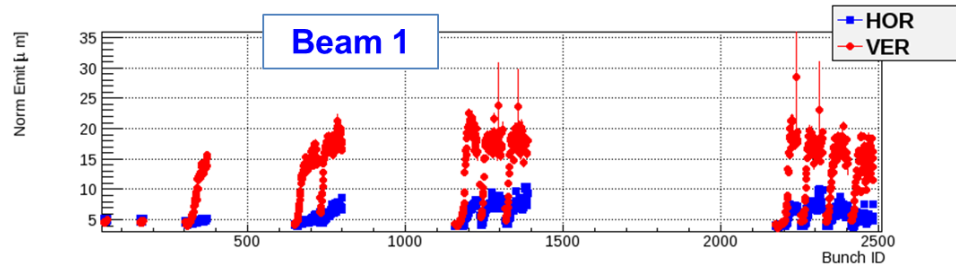
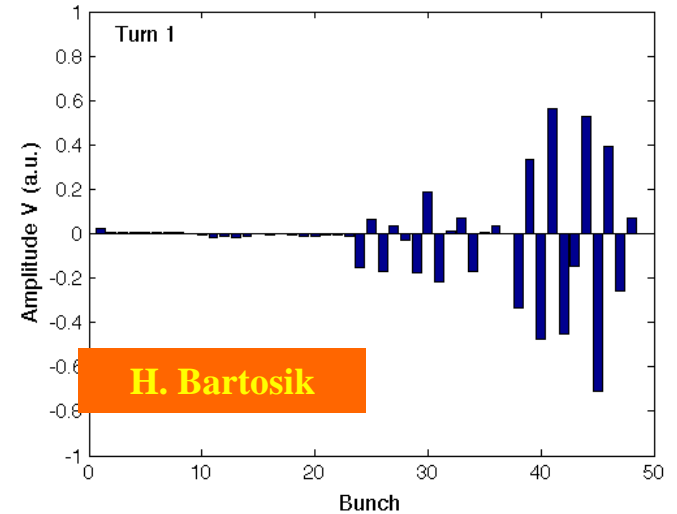
Secondary emission yield [SEY]

$SEY > SEY_{th} \rightarrow$ avalanche effect (multipacting)
 SEY_{th} depends on bunch spacing and population

- Electron cloud effects occur both in the warm and cold regions, their intensity increases rapidly for shorter bunch spacing. Observed as soon as we started to inject bunch trains (150 \rightarrow 75 \rightarrow 50 \rightarrow 25 ns spacing):
 - Vacuum pressure rise (interlock levels, beam losses...)
 - Single-bunch and multi-bunch instabilities \rightarrow beam size growth
 - Incoherent beam size growth
 - Heat load on the cryogenics

Electron cloud effects

- Fields induced by electrons act like wake fields (more complex) that couple different bunches along the train and head&tail of each bunch and have similar adverse effects on beam stability as impedances.
- As a result of that emittance blow-up and beam losses



Cures for electron cloud effects

- At the time of the construction of the LHC:
 - NEG coating → would require activation to $>200\text{ °C}$ → impractical
 - Conditioning by beam-induced electron bombardment (“scrubbing”) leading to a progressive reduction of the SEY as a function of the accumulated electron dose → tested in the laboratory (on Cu surfaces) and in the SPS (Stainless Steel vacuum chambers) → **Chosen strategy for the LHC operation with bunch trains – but it takes time!! (in particular for 25 ns operation)**
- More recently a-C coating has been successfully tested in the SPS showing SEY as low as 1.1 → possible implementation for HL-LHC (interaction regions)



The technology of LHC



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LHC: Some Challenges

Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37 million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field. Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field. 1ppm resolution
Beam Intensity (A)	0.5	$2.2 \cdot 10^{-6}$ loss causes quench
Beam Stored Energy (MJ)	362	Results from high beam energy and high beam current.. 1MJ melts 2kg Cu
Magnet Stored Energy (MJ)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

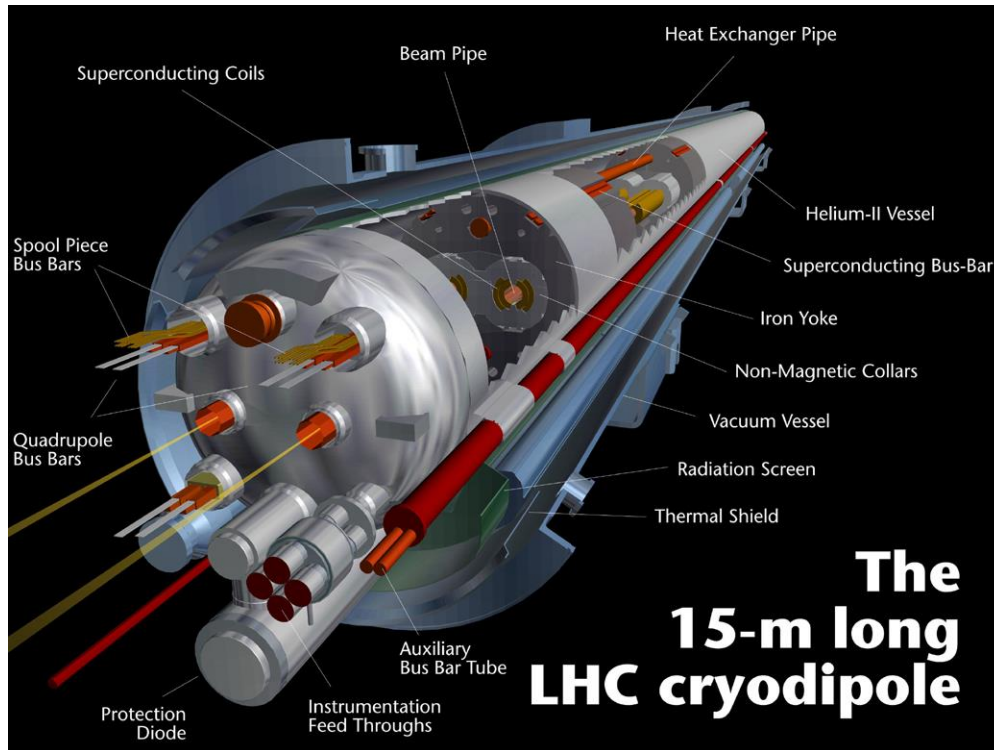


LHC dipole magnet

1232 dipole magnets.

B field 8.3 T (11.8 kA) @ 1.9 K (super-fluid Helium) – after incident operated up to ~4.7 T → interconnect consolidation during Long Shut-down 2013-2014

2 magnets-in-one design : two beam tubes with an opening of 56 mm.



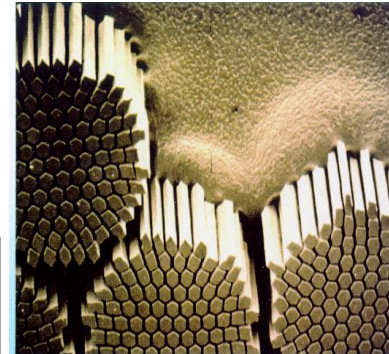
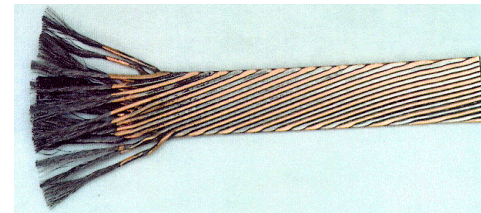
Operating challenges:

- *Dynamic field changes at injection.*
- *Very low quench levels ($\sim \text{mJ/cm}^3$)*



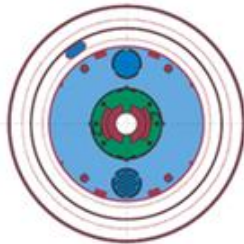
Magnets

- SC magnets:
 - field generated by a suitable distribution of current, properly arranged around the beam aperture:
 - **tight constraints in coil position:** 0.1 mm inaccuracy in the coil position can give rise to important field error that would affect beam quality and lifetime
 - **stability within few μm** needed to avoid cable movement that could lead to transition to normal conducting state
 - SC magnet technology relies heavily on the ability to produce technical SC materials in the form of high current cables.

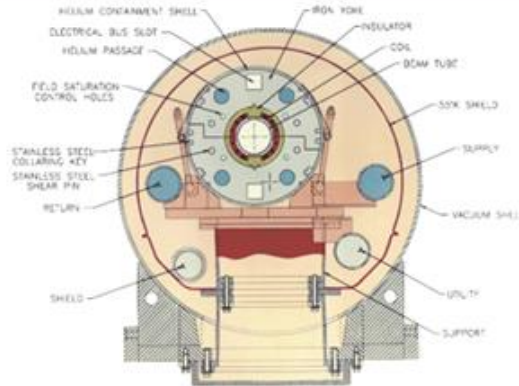


SC Dipoles from Recent Colliders

DIPOLE MAGNETS



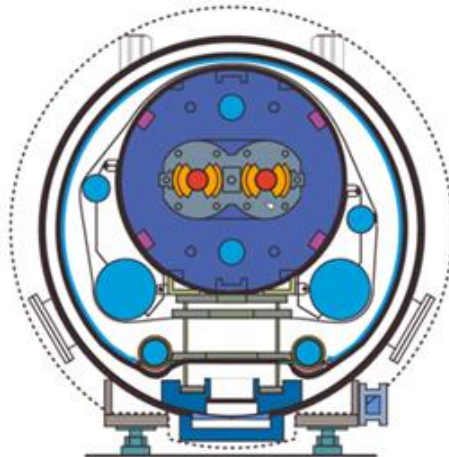
HERA
 $B = 4.7 \text{ T}$
 BORE : 75 mm



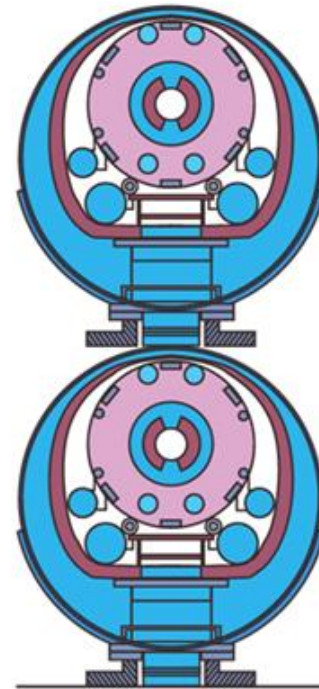
RHIC
 $B = 3.5 \text{ T}$
 Bore : 80 mm



TEVATRON
 $B = 4.5 \text{ T}$
 Bore : 76 mm



LHC
 $B = 8.3 \text{ T}$
 Bore : 56 mm

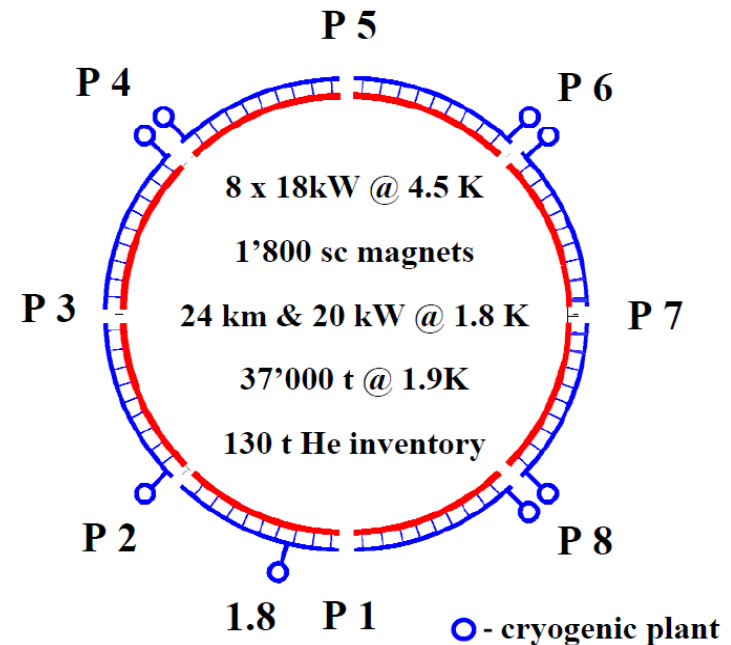
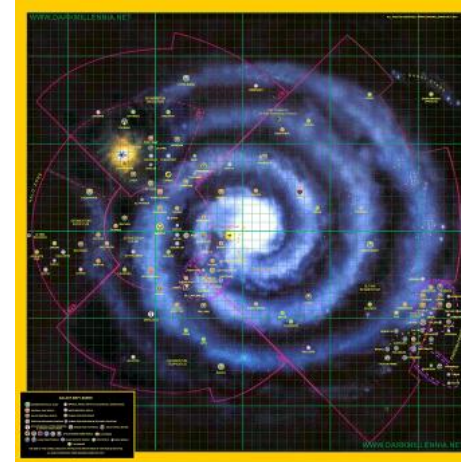


SSC
 $B = 6.6 \text{ T}$
 Bore : 50-50 mm

CERN AC - HE 109 RHIC 2001/09/20

One of the coldest places in the universe...

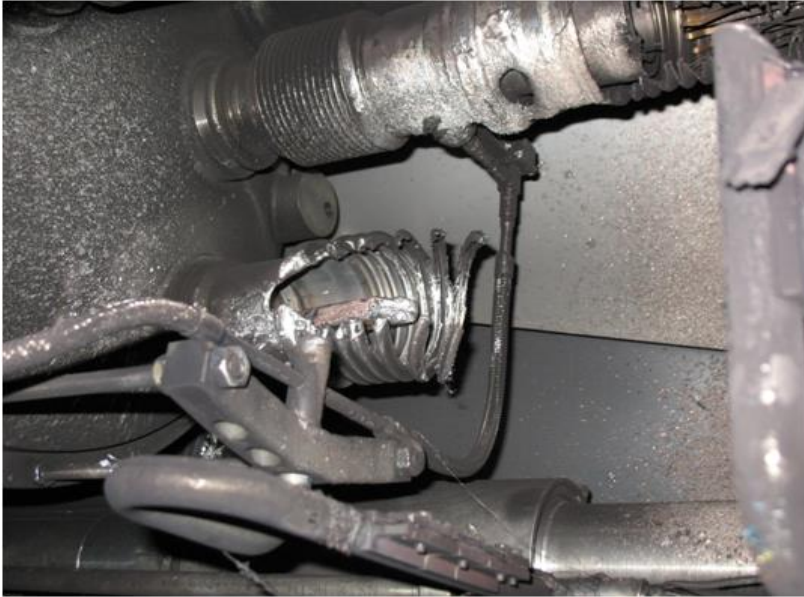
- Superconducting magnets with a field of 8.3 Tesla are cooled by superfluid helium at 1.9 K (corresponds to $-271\text{ }^{\circ}\text{C}$) along 20 km
- Large cooling plants for magnet cooling at 1.9 K, 4.5 K and higher temperatures



Protection of Superconducting Magnets

- A superconductor is such only when it operates below its critical surface. Once in normal conducting state, e.g., because of a sudden temperature increase caused by internal mechanical energy release or a beam loss, the superconductor generates resistive power, causing a thermal runaway “quench”.
- SC accelerator magnets, tend to have **large stored magnetic energy**. (LHC → 10 GJ).
- Local dissipation of energy has the potential to lead to material damage and loss of electrical insulation
 - SC magnets must be protected against quench by detecting any irreversible resistive transition (quench detection electronics) and discharging the magnet
 - **very precise measurement of the resistance across the SC coils (< mV resolution in a very EM noisy environment!)**

Protection of Superconducting Magnets



Nimitz class aircraft carrier (90 000 tons)
at battle-speed of 30 Knots
Energy = $\frac{1}{2} mv^2 \sim 10\text{GJ}$



RF systems

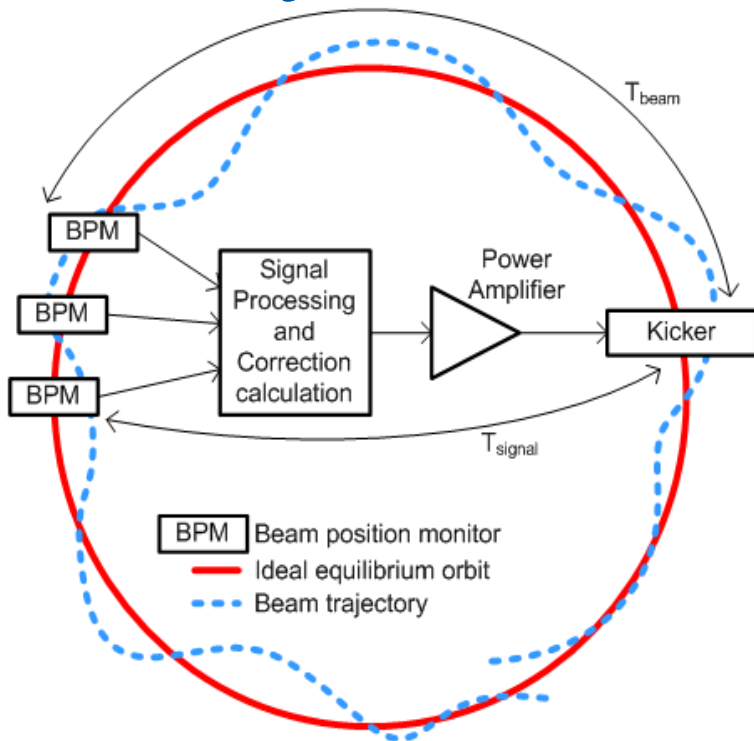
- 8 **Superconducting** cavities/beam delivering an accelerating field of **5.5 MV/m** and a total accelerating voltage per turn of **16 MV**
- Fine synchronization of the drive signals and loops to the **10^{-12} s level**



LHC 400MHz Klystron Installation

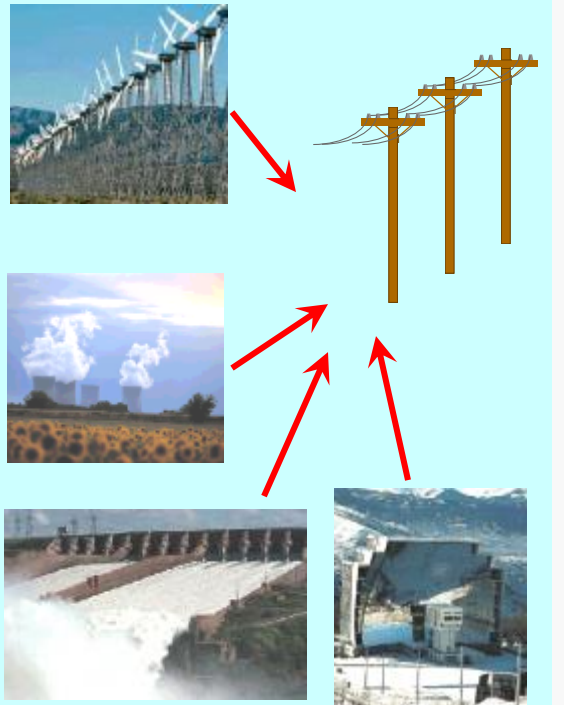
LHC 400MHz SC cavities

RF systems

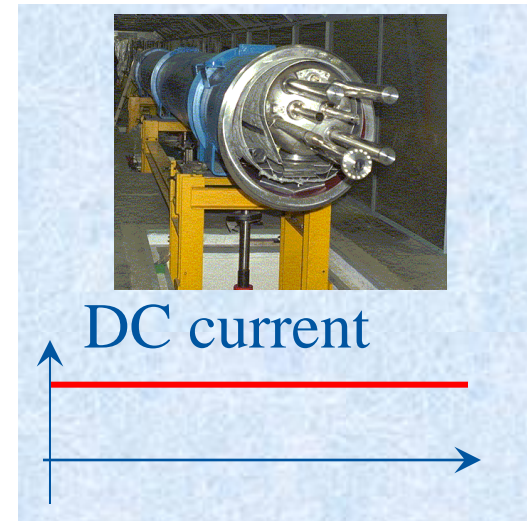


- LHC Transverse Feedback system: bunch-by-bunch/turn-by-turn measurement and correction of the trajectory of individual bunches
- 20 MHz bandwidth.
- ± 7.5 kV maximum voltage on two electrodes spaced by 50 mm

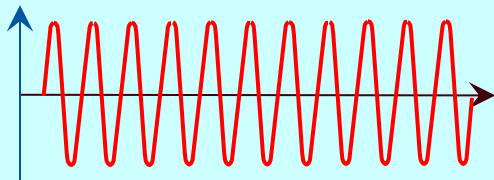
Power converters



The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for accelerator equipment powering



50 or 60 Hz ; AC



Power converters

PC-V6-4: General Information

Last_modif 24/3/2003

Optics version	Eq.Code	Current		Voltage		Module		Mains Input		Losses		Dimensions			Provisional Quantity	
		Type	kA	Steady V	Boost V	I mod A	I tot kA	Peak kW	Peak kVA	Water kW	Air kW	Length m	Depth m	Height m		Equiv. No. Racks
6-4 01	RPTE		13.000	10	±180											8
6-4 02	RPHE		13.000	13	±5											16
6-4 03	RPHF		8.000	6	±2											20
6-4 04	RPHG		6.000	6	±2											132
6-4 05	RPHH		4.000													40
6-4 10	RPMB		0.600													1
6-4 11	RPMC		0.600													
6-4 12	RPMB		0.600													
6-4 13	RPMC		0.600													
6-4 14	RPLB		0.120													
6-4 15	RPMC		0.120													
6-4 16	RPLA		0.060													
6-4 20	RPTL		0.650													
6-4 21	RPTF		0.810													
6-4 22	RPTG		0.810													
6-4 23	RPTM		1.000													
6-4 24	RPTI		6.500													
6-4 25	RPTN		1.000	±180												3
6-4 30	RPTJ		20.000	±26	0	26	1	20.000	20.000	621.2	795.1	75.9	25.3			1
6-4 31	RPHK		20.500	18	0	18	7	3.250	22.750	417.8	454.1	43.9	4.9			1
6-4 32	RPTH		33.000	170	0	170	1	33.000	33.000	6062.1	7609.1	339.1	113.0			1
6-4 40	RPTK		0.040	100000	0	100000	1	0.040	0.040	4240.1	5300.9	180.1	60.0			4

Number of Converters: > 1700
 Total Current : 1860 kA
 Steady State Input : 63 MW
 Peak Input : 85 MW
 Underground volume \cong 1700 m³
 Surface volume \cong 300 m³

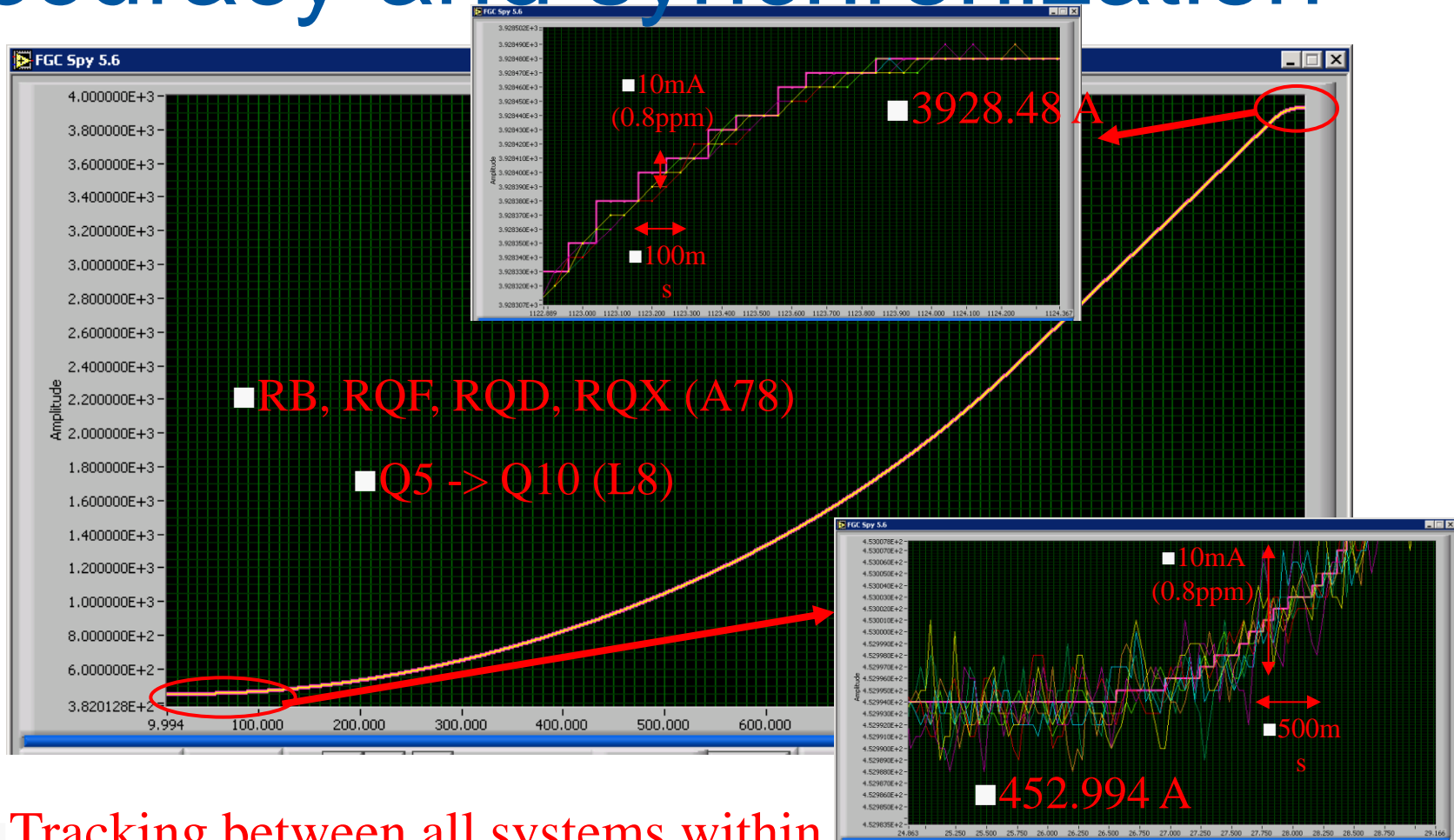
Total Current required
1861 kA

Steady State Input 63018 kW
 Peak Input 85906 kW

Total Number of PCs 1719

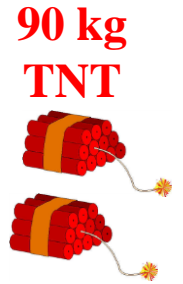
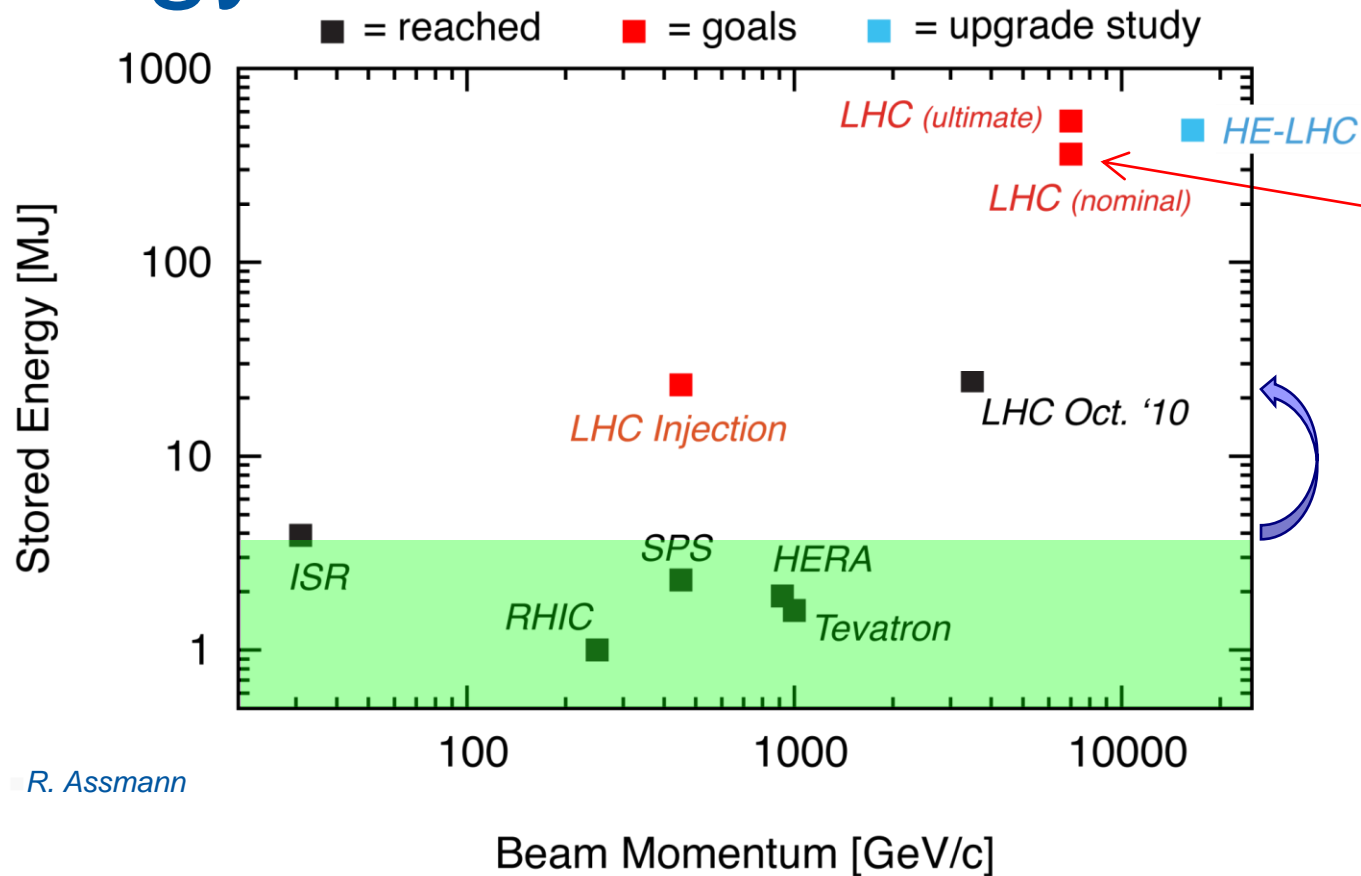


Accuracy and synchronization



■ Tracking between all systems within measurement noise

Energy stored in one beam



R. Assmann

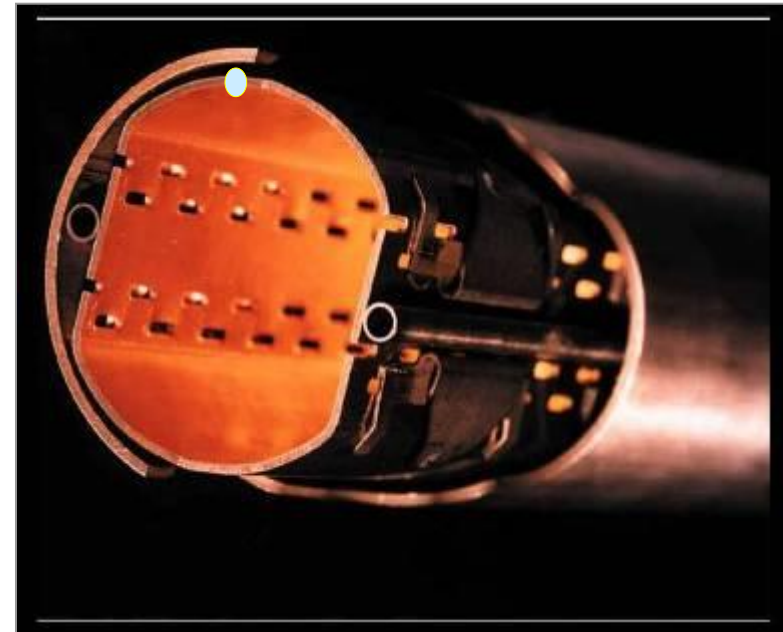
Energy stored in one beam



- 3000000000000000 ($=3 \cdot 10^{14}$) protons in each beam
- Kinetic Energy of 200 m Train at 155 km/h \approx 360 Million Joule
 - Stored energy per beam is 360 Million Joule

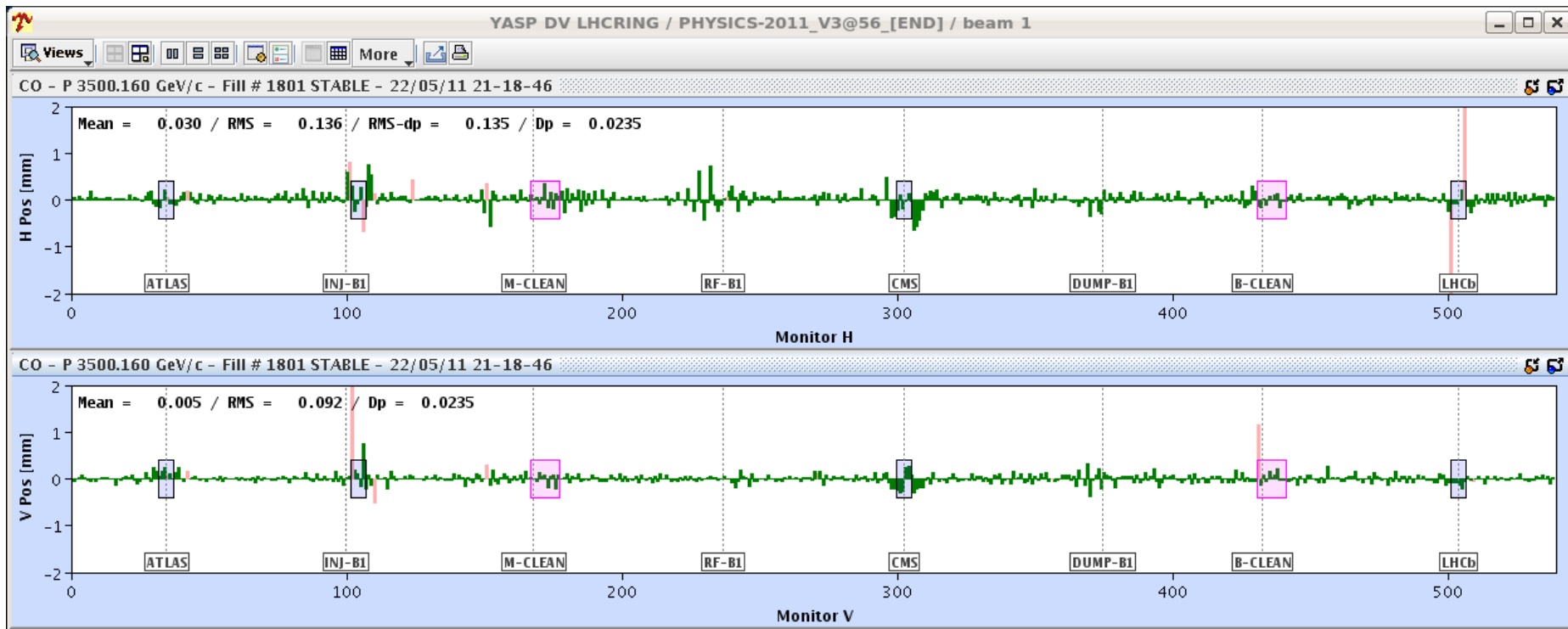
Risk of damage from beam

- Beams with the energy of a fast speed train are running through the beam tube with the speed of light
- 10000 magnets keep the beams in the center of the beam tube
- In case of magnet failure, the beams hit the accelerator equipment in a very short time, 1/1000 of a second
- This must **never happen**.



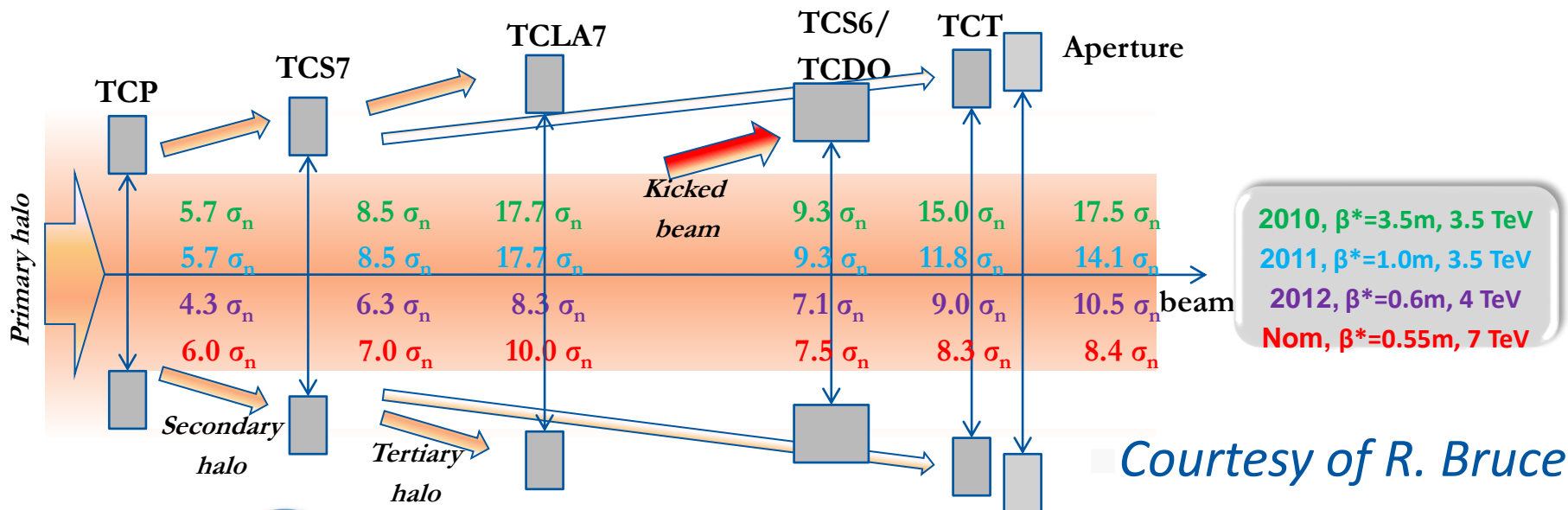
LHC Beam Position Monitors

- Very precise orbit measurement is necessary to safely operate the machine. Precision are of the order of ~ 100 μm all around the 27 km of the ring. Total of **1182** BPMs for the LHC and its Transfer Lines

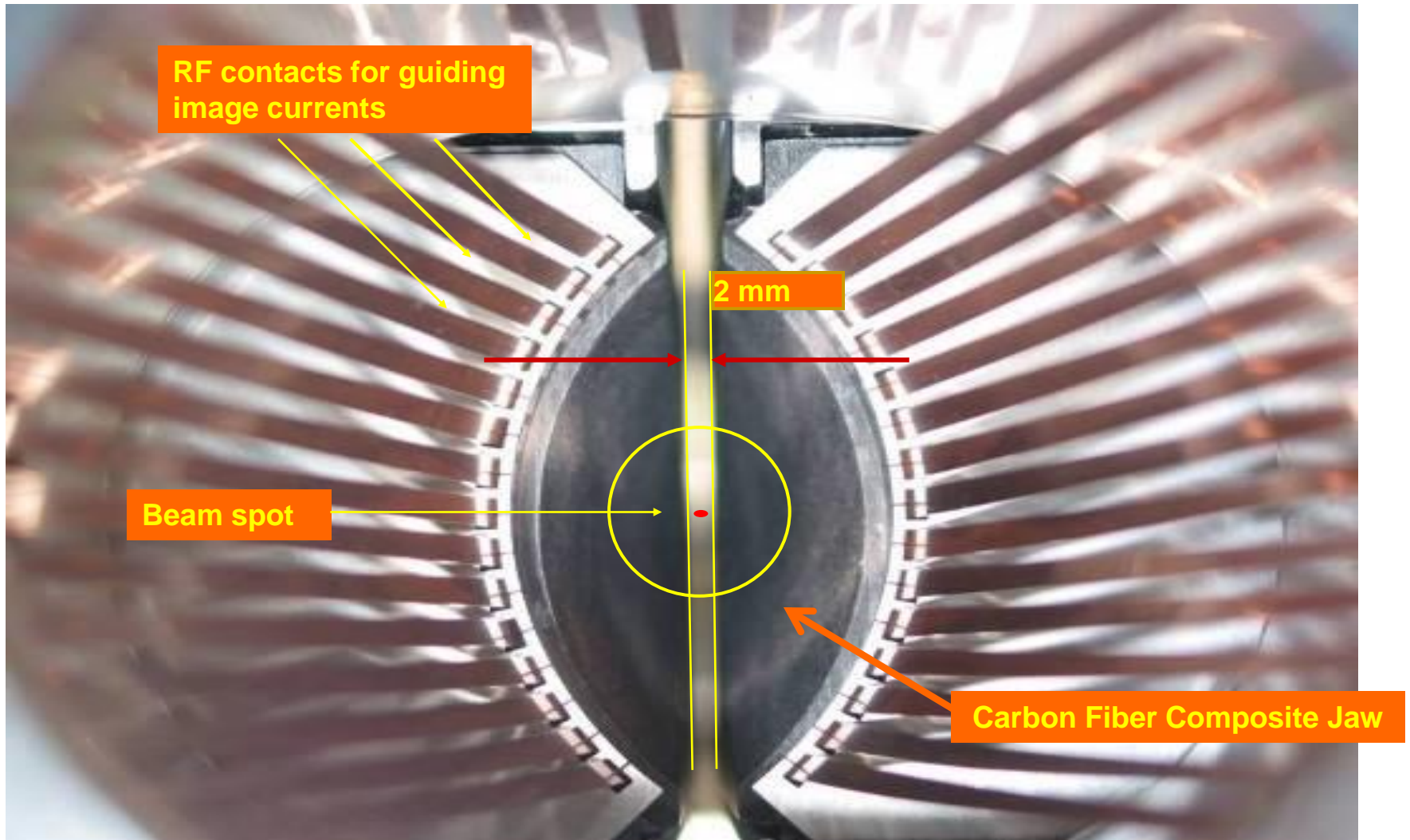


Collimation system

- Complex and high performance multi-stage collimation system.
- Collimation hierarchy has to be respected in order to achieve satisfactory **protection and cleaning**.
- Lower β^* implies tighter collimator settings as well as alignment, beam sizes and orbit well within tolerance. **We could do it only after having gained experience in orbit and optics controls and thanks to the small emittance delivered by the injectors.**
- **Smaller β^* implies tighter collimator settings**



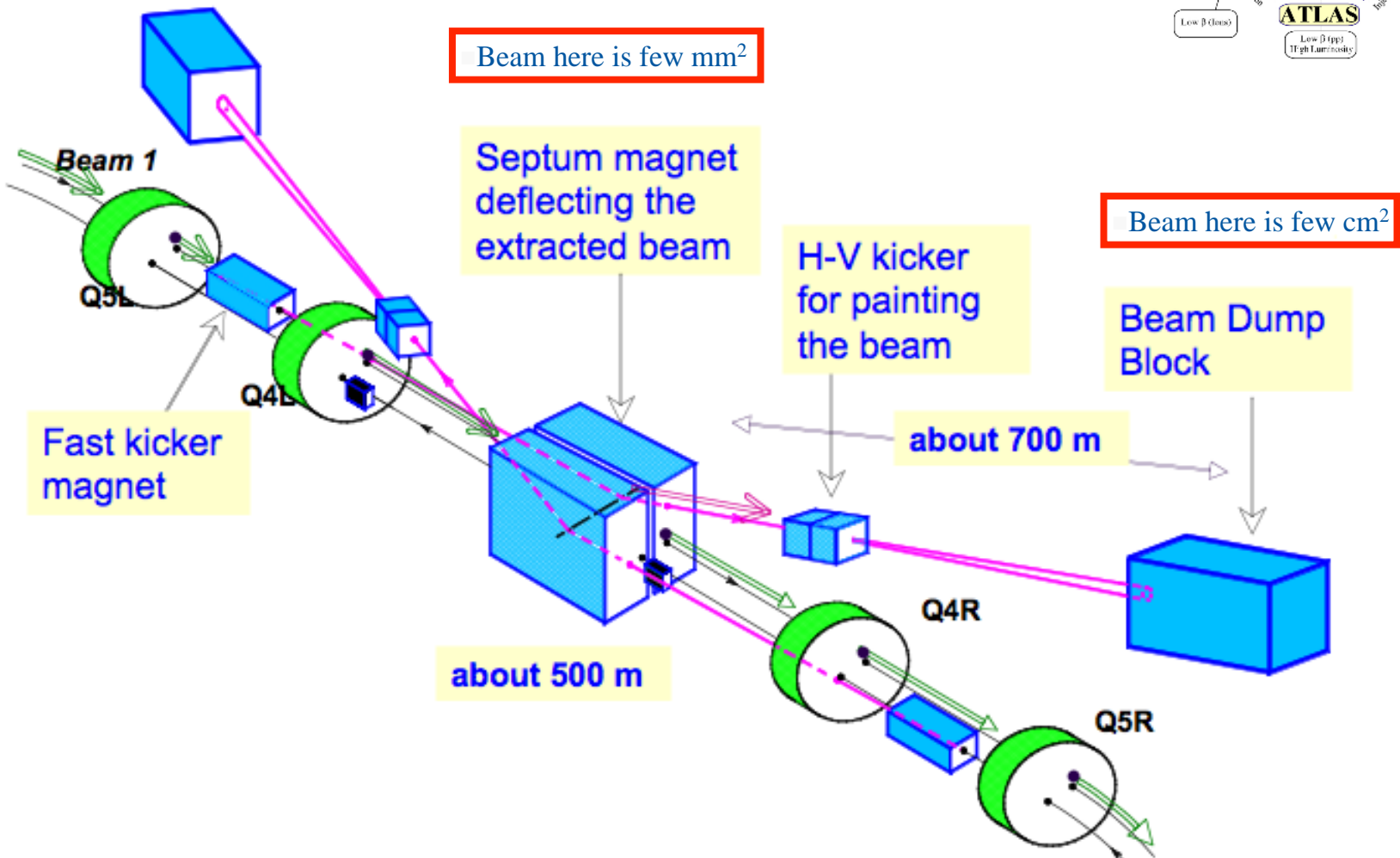
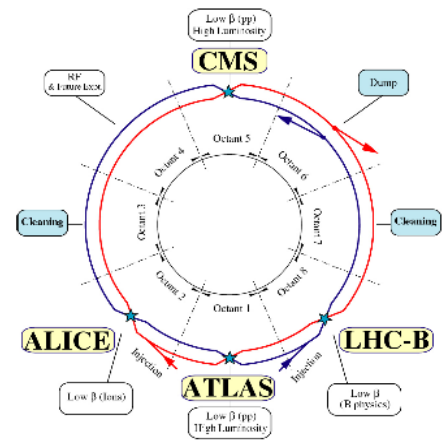
Collimators



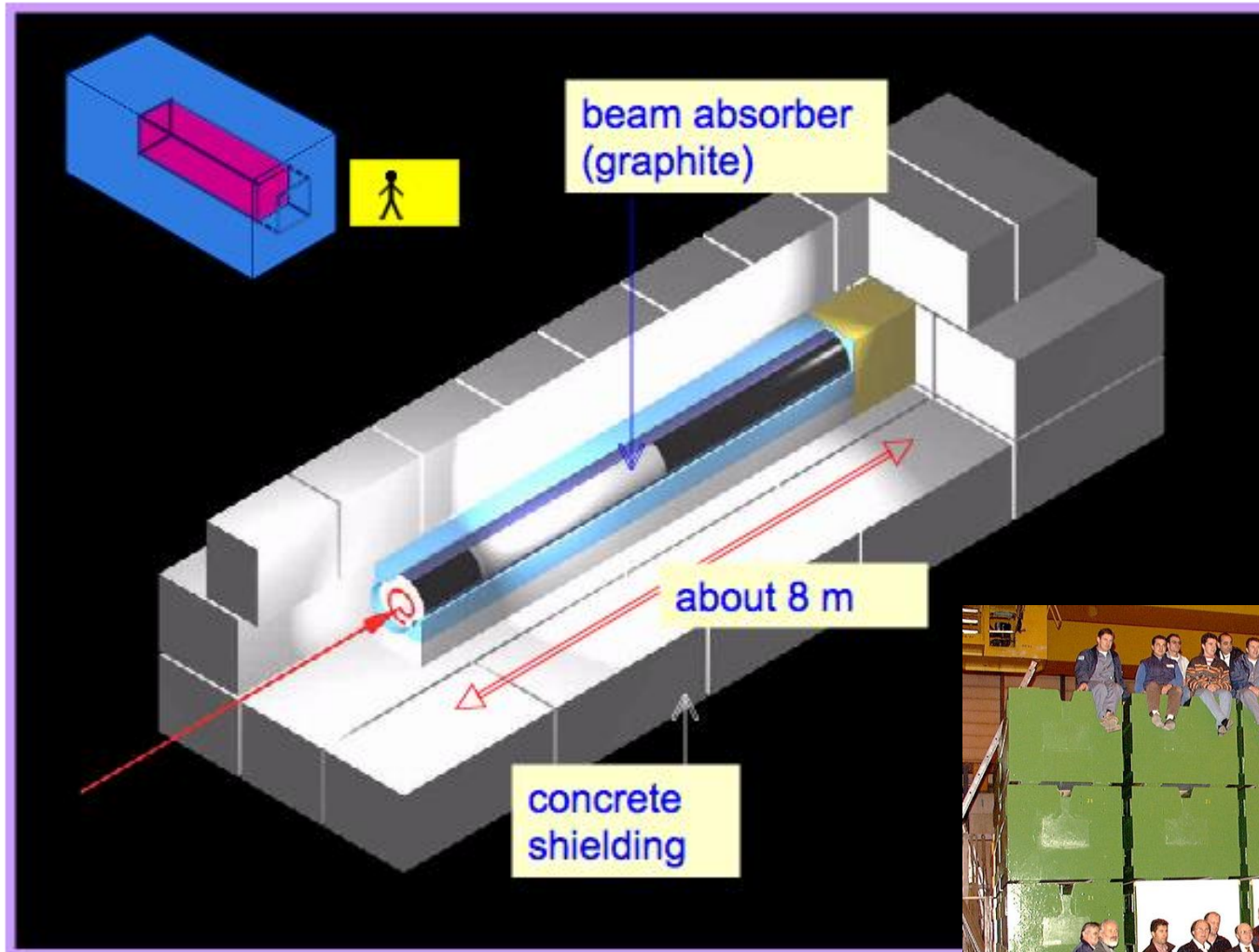
Beam extraction, emergency or not...

At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn.

Beam dump built to absorb full power at full energy.



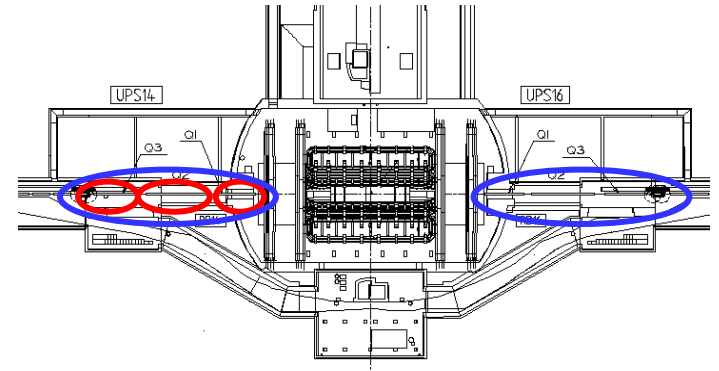
Scheme of one of the beam absorbers



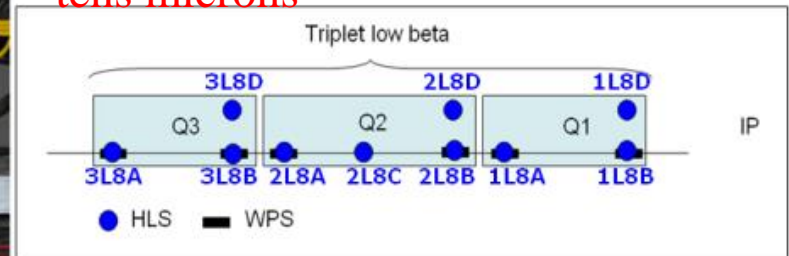
Survey and Alignment

- Very tight tolerances in absolute and relative accuracy for the positioning of the accelerator components imposed by:
 - beam dynamics (e.g. quadrupole magnet misalignments give rise to trajectory distortion of the circulating beam)
 - mechanical and geometrical issues influencing the aperture available for the circulating beam.
- Position, orientation, shape and the size of all major accelerator components must be measured **to accuracies not needed in any other domain.** In order to position a component, a reference system (frame) must be defined, and transferred to the accelerator tunnel.

Survey and Alignment

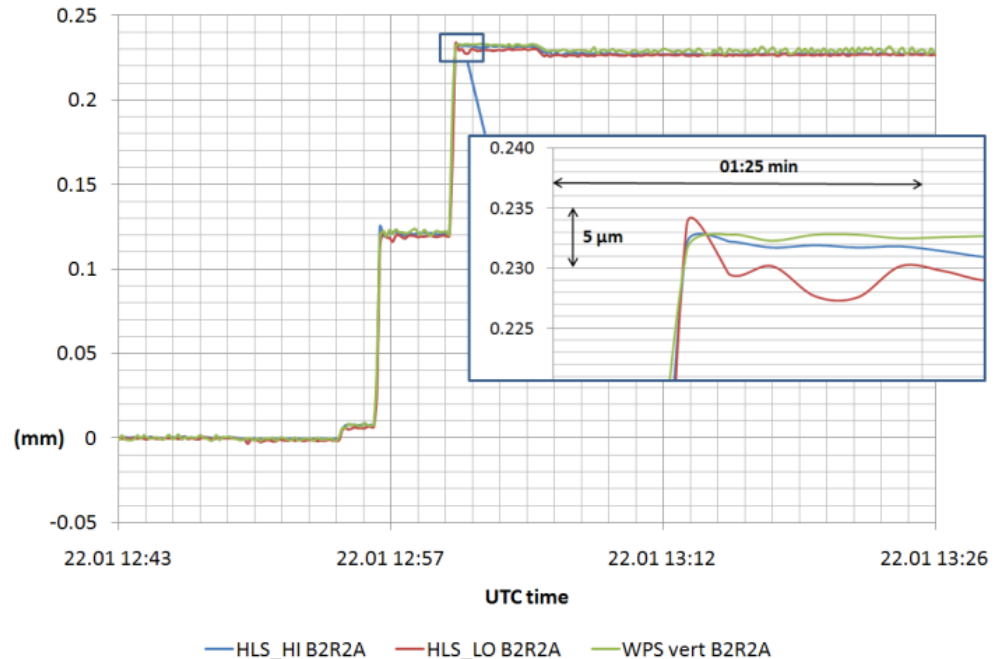


- **VERY TIGHT TOLERANCES:**
- Relative alignment Left/Right (~50 m distance): ± 0.5 mm (3σ)
- Stability of the positioning of a quadrupole inside its triplet: **few tens microns**



Survey and Alignment

Case of a remote displacement: resolution of the sensors



■ Displacement of 220 μm monitored within 5 μm

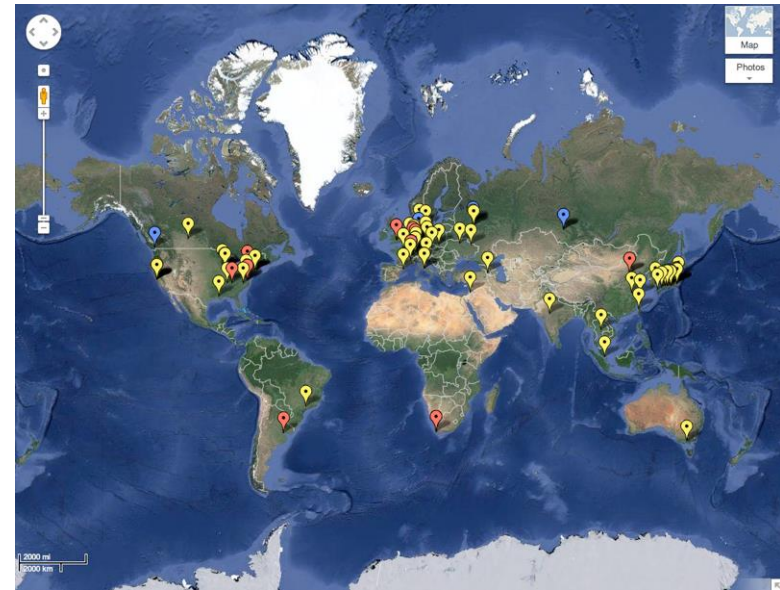
■ Hydrostatic Levelling System (HLS) based on communicating vessels principle

■ Wire Positioning System (WPS) based on stretched Carbon wire



Accelerators in the world

- Accelerator for research are a small fraction of the overall number: more than 30000 now



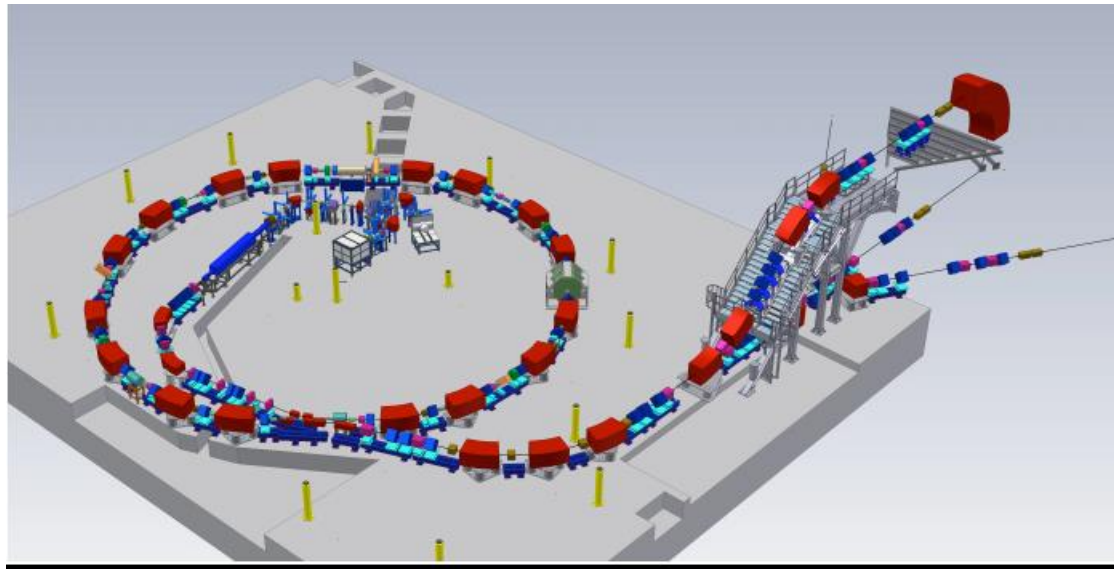
Accelerators for Everyday's life

- Particle accelerators are also used in many different applications such as **material analysis and modification and spectrometry** especially in environmental science
- About half of the world's 15,000 accelerators are used as ion implanters, for **surface modification and for sterilization and polymerization**
- The ionization arising when charged particles are stopped in matter is often utilized for example in **radiation surgery and therapy of cancer**. At hospitals about 5,000 electron accelerators are used for this purpose.
- Accelerators also produce **radioactive elements that are used as tracers in medicine, biology and material science**
- In material science, ion and electron accelerators are used to produce neutrons and photons over a wide range of energies. Well-defined beams of photons are for example increasingly used for **lithography in order to fabricate the very small structures required in electronics**.



Accelerators for Everyday's life

- Not far from here (Pavia – south of Milan) an accelerator is operating in a Hospital (CNAO) to allow cancer therapy with proton and ion beams (hadron-therapy) providing one of the most advanced tools in radiation therapy.



- CERN has contributed to design of this machine and some of its components

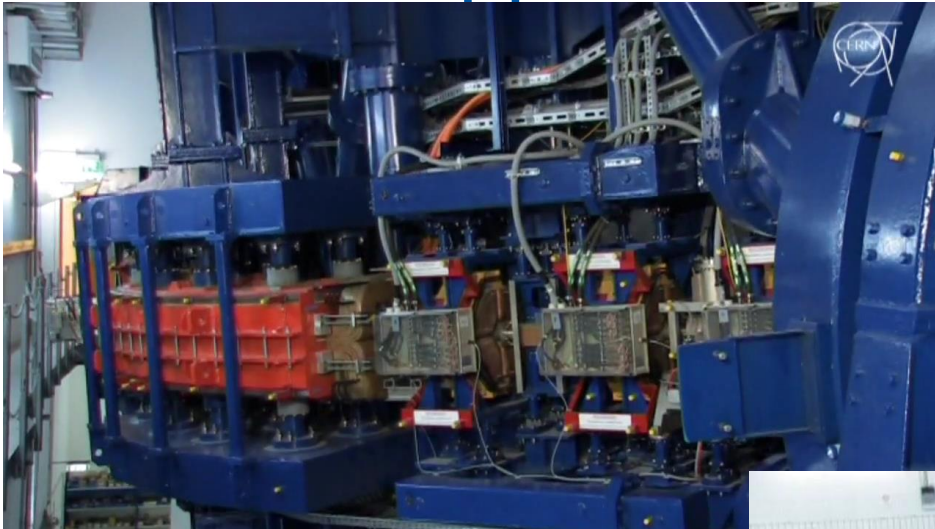
Medical applications



Medical applications



Medical Applications

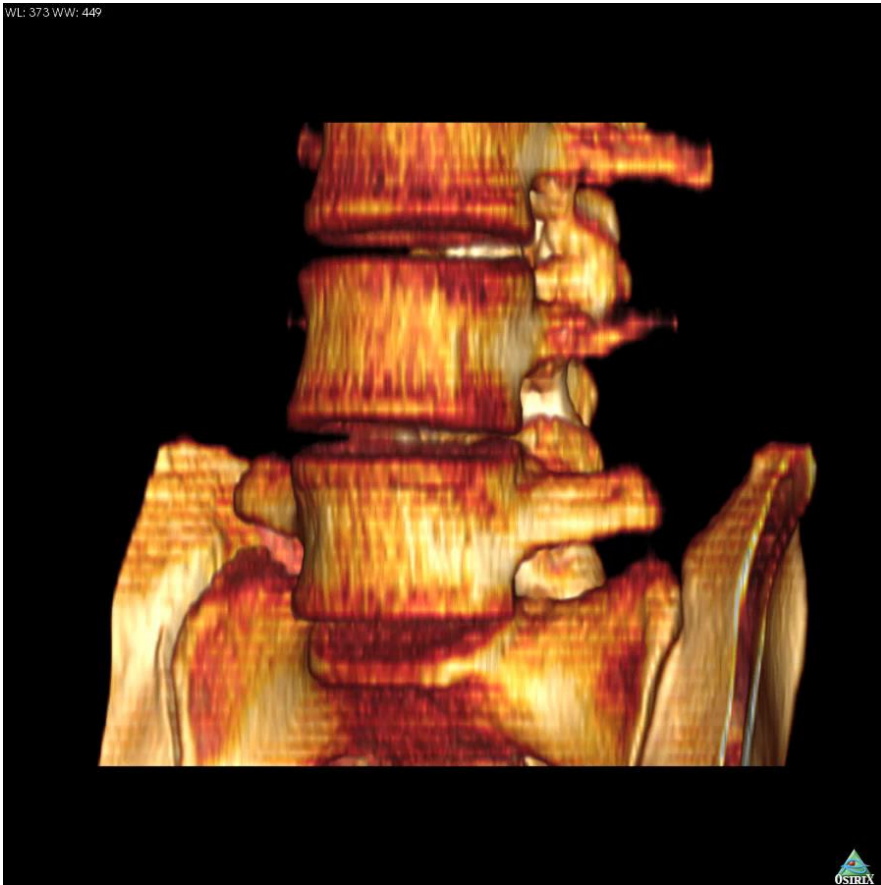


Heidelberg Ion Therapy Facility (HIT)

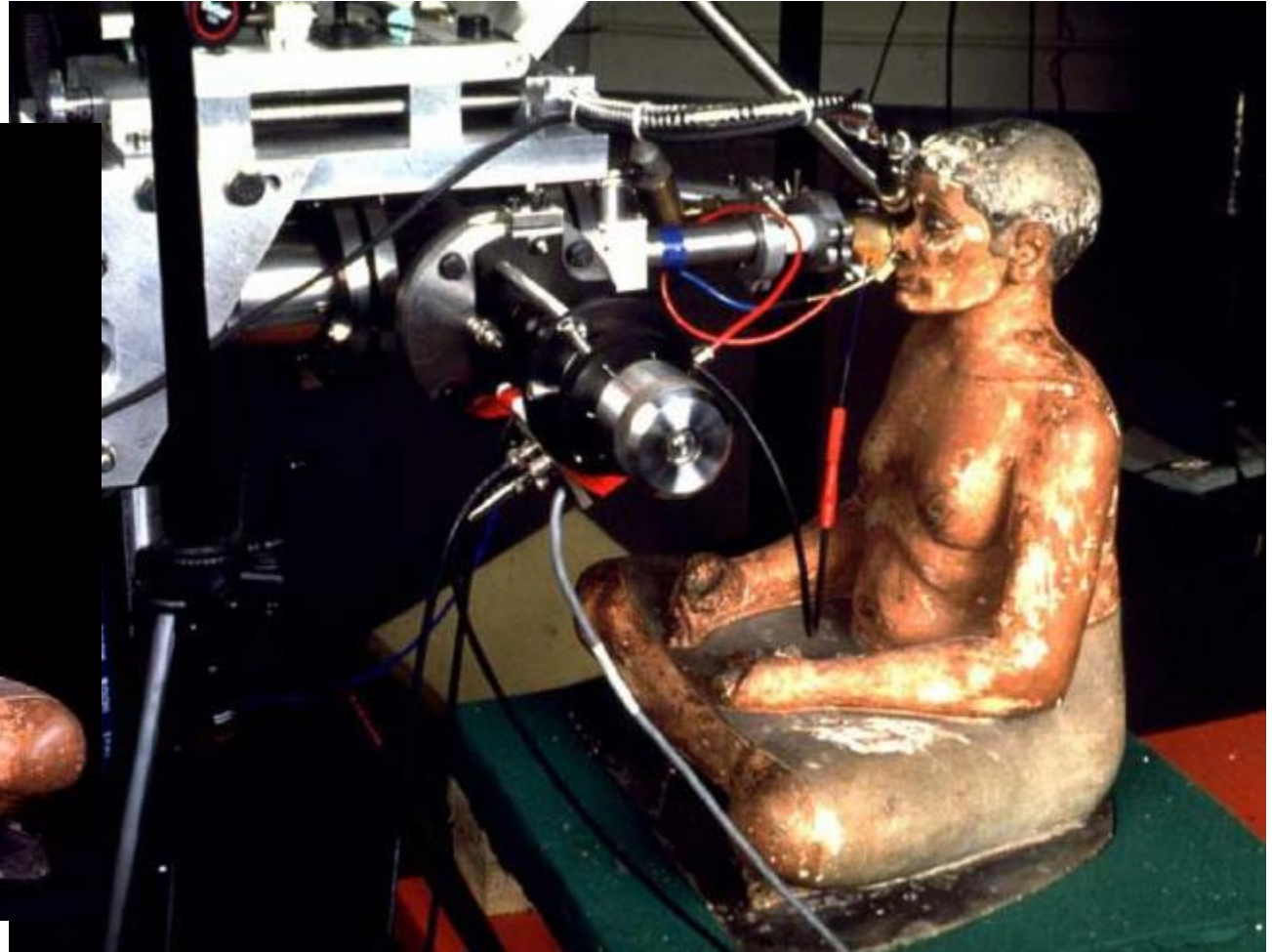
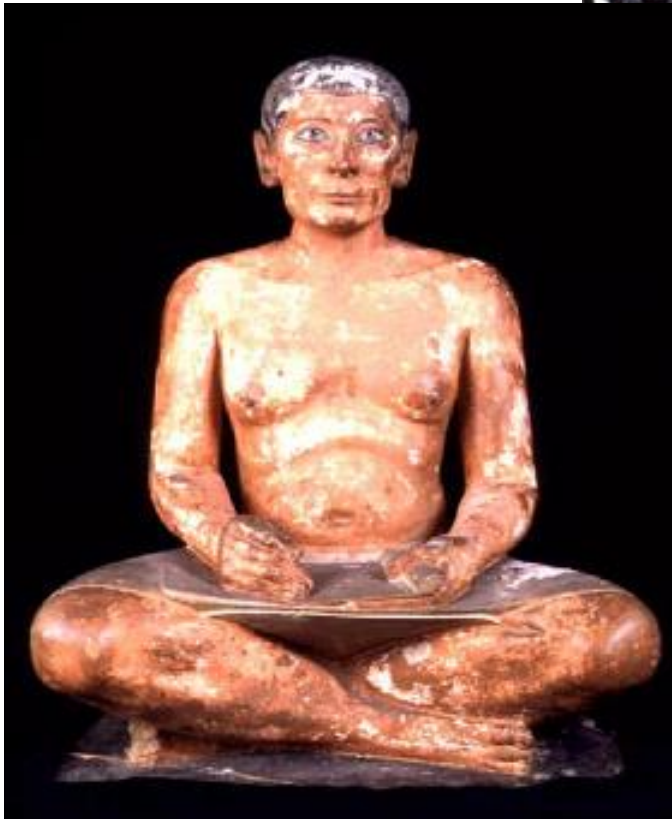


Medical imagery

- A CT (computerized tomography) scanner, or CAT (computerized axial tomography).
- x-ray machine plus detector, both rotating around the patient



Application of Louvre Tandem: composition of scribe eyes

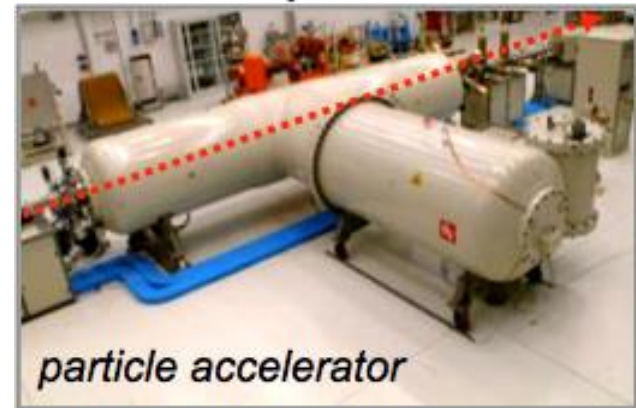
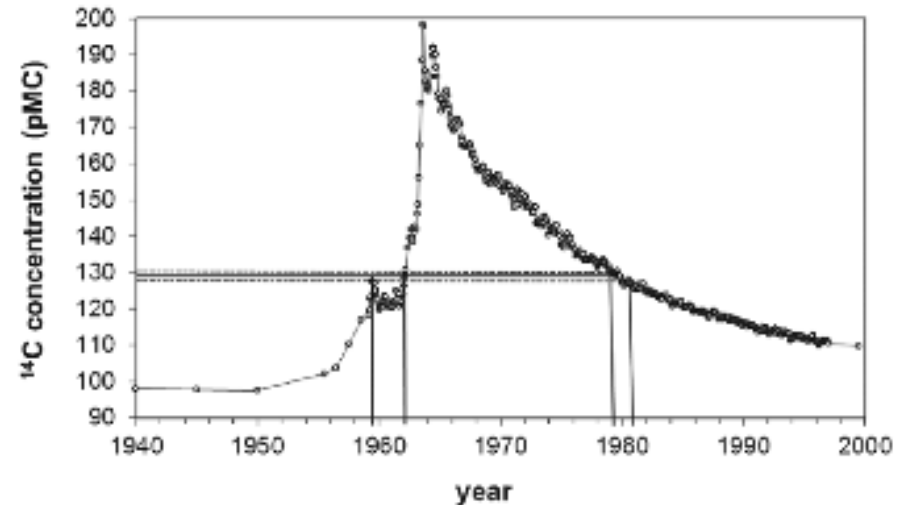


Discovering forgeries of modern art by the ^{14}C Bomb Peak

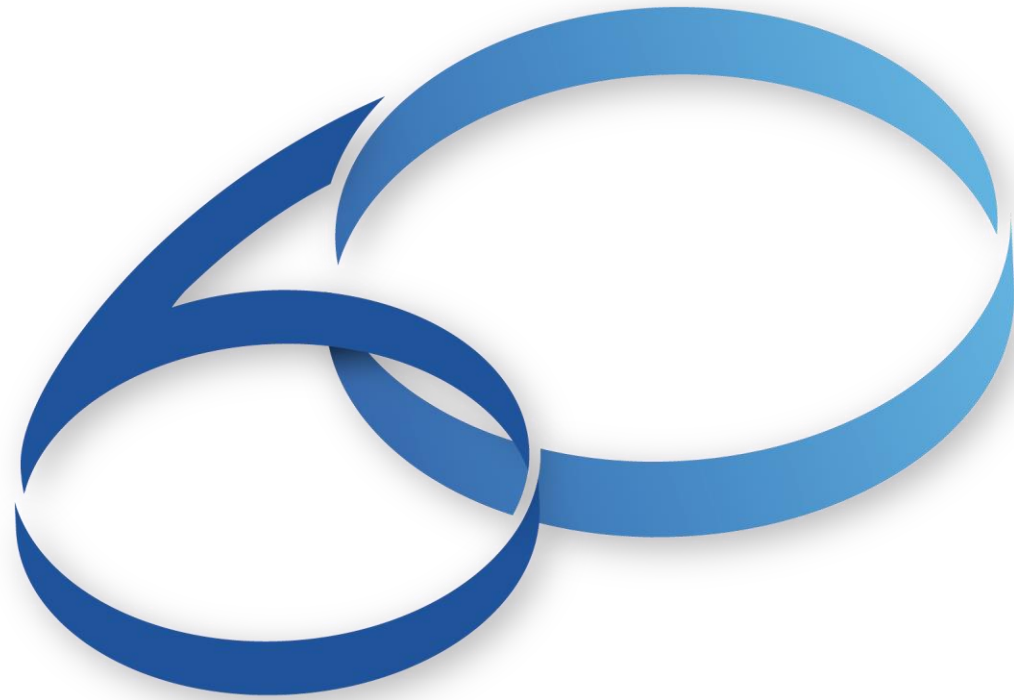


Contraste de formes, Fernard Leger (?)
Peggy Guggenheim Collection, Venice.

Accelerator Mass Spectrometry (AMS) to measure rare isotopes abundance with 3MV Tandetron accelerator of INFN-LABEC in Florence.



particle accelerator



YEARS / ANS **CERN**