Introduction to CERN/accelerators/LHC

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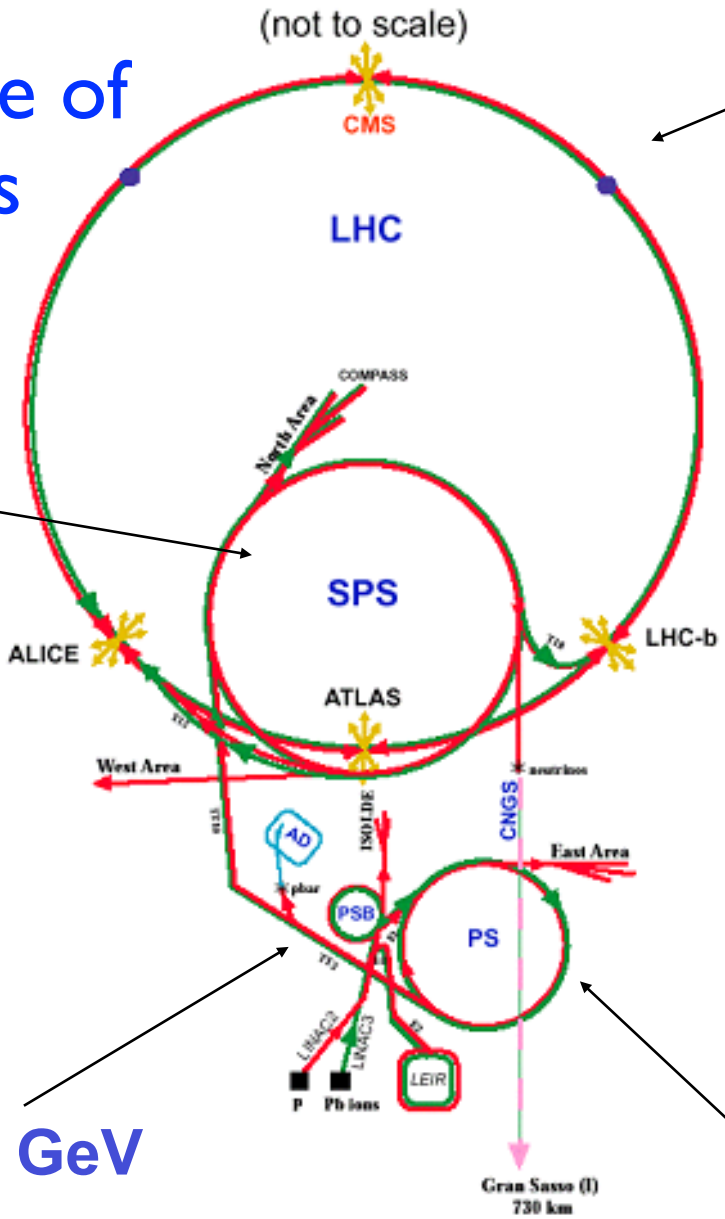
CERN accelerator complex overview

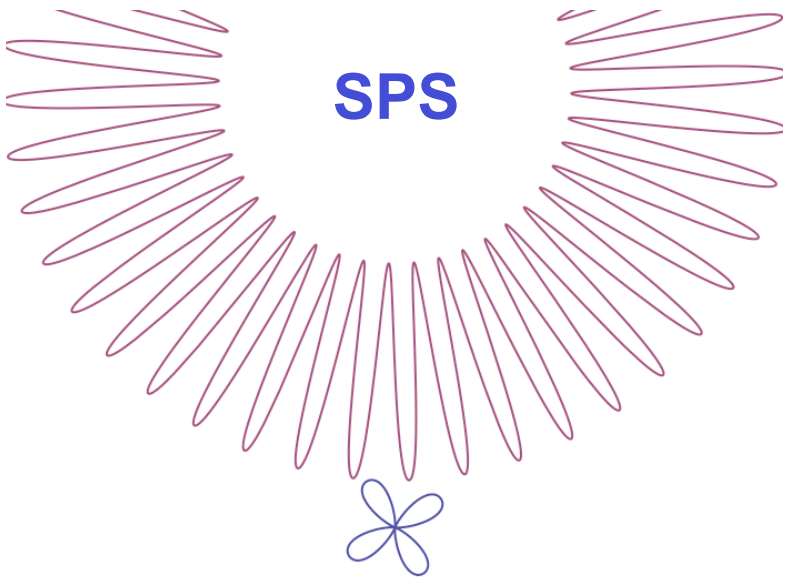
Chain/sequence of accelerators

450 GeV /c – 7 TeV /c

26 - 450 GeV/c



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso



50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

Press Release PR/56
12 February, 1960

It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC.

Small detail... Bohr was not completely right, the "new" elementary particles are not elementary but mesons, namely formed by quarks

Interlude: a brief recall of energy scales

- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
  - Energy[GeV], Momentum [GeV/c], Masses [GeV/c^2]
    (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a rule of thumb: **0.511 MeV/c^2** (electron mass) corresponds to about **9.109 10^{-31} kg**

An Example about energy scales: my cellular phone battery.

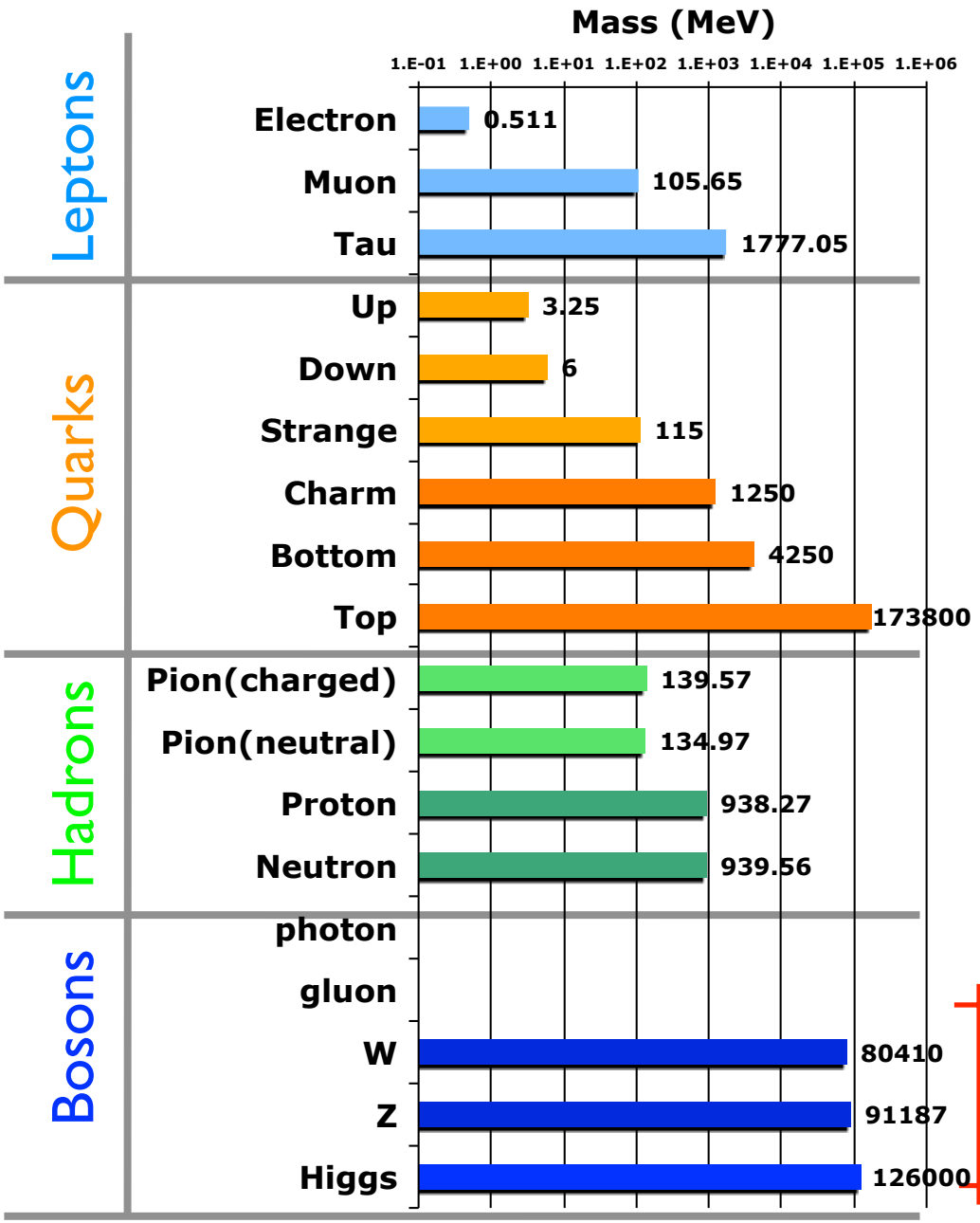
Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to a proton mass:

1 GeV/3.7 eV = 270 270 270 batteries
270 270 270 batteries * 0.045 m ~ 12 000 000 m

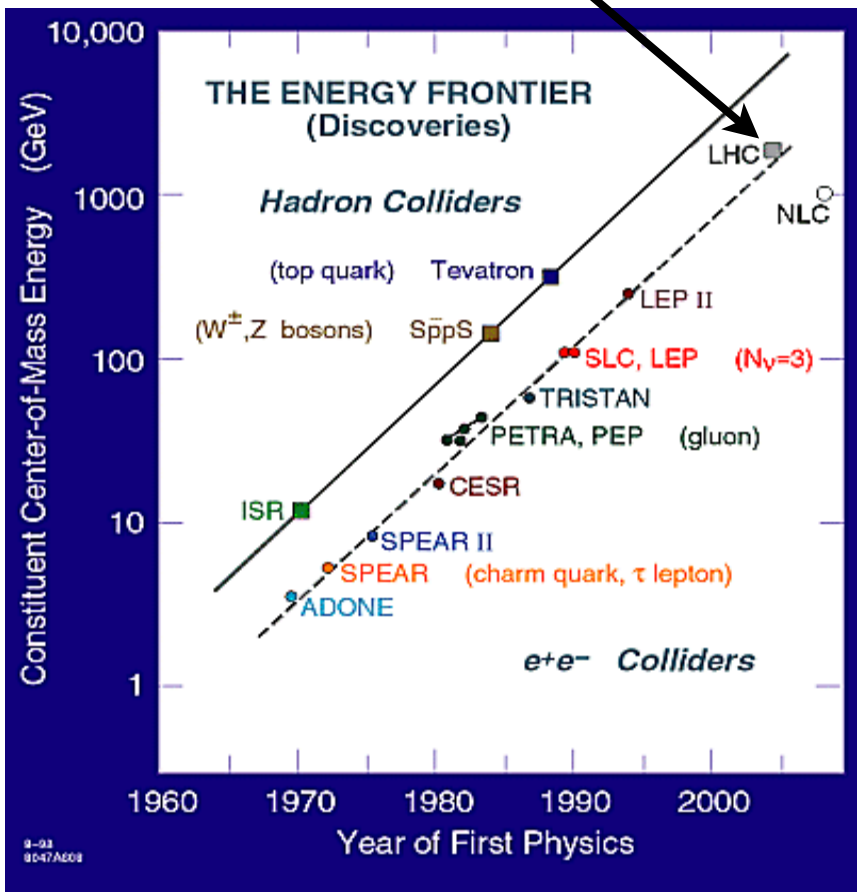
12 000 000 m ~ THE EARTH DIAMETER

Obviously one has to find a smarter way to accelerate particles to high energies instead of piling up cellular phone batteries ....

History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe



Constant increase in energy to discover heavier and heavier particles or very rare processes

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\bar{p}$ as Tevratron, p-p as LHC)

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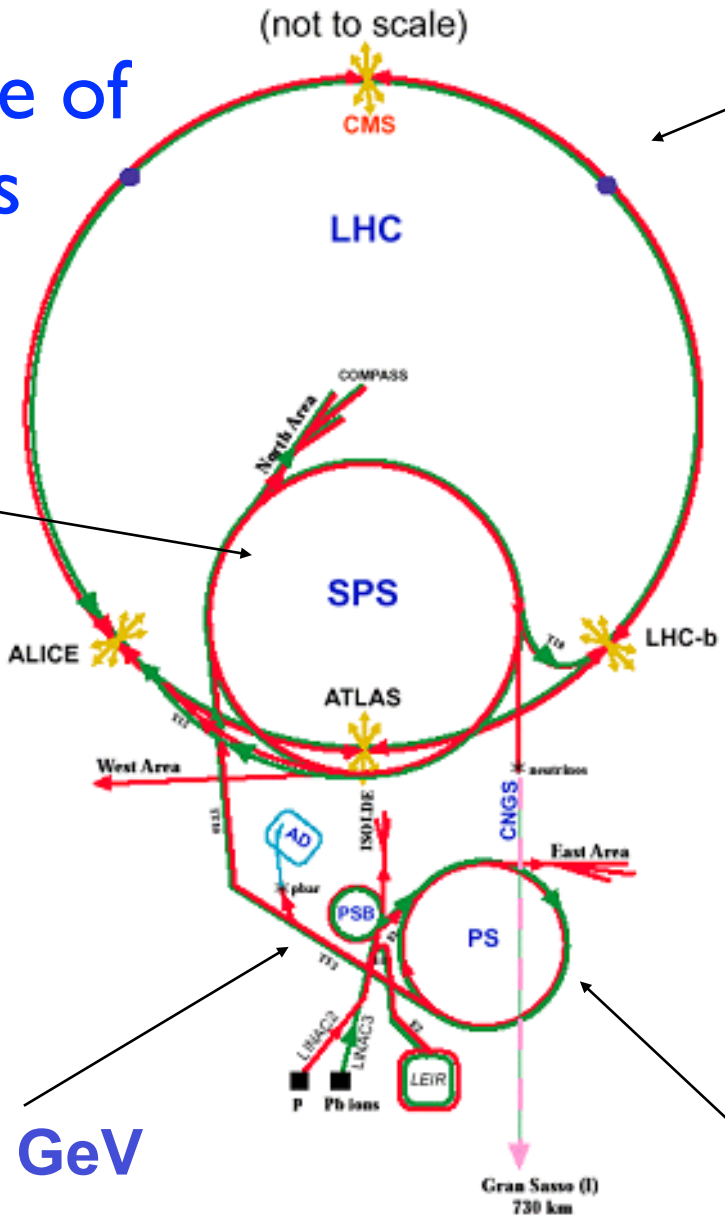

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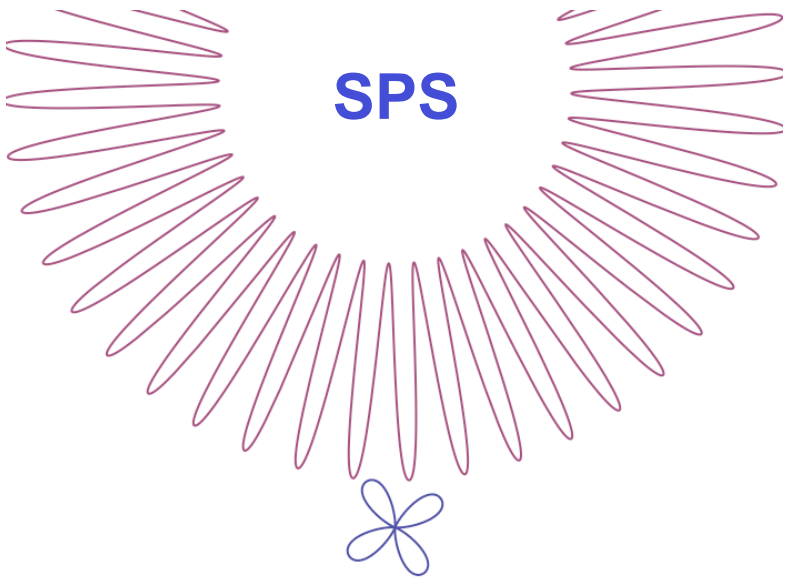

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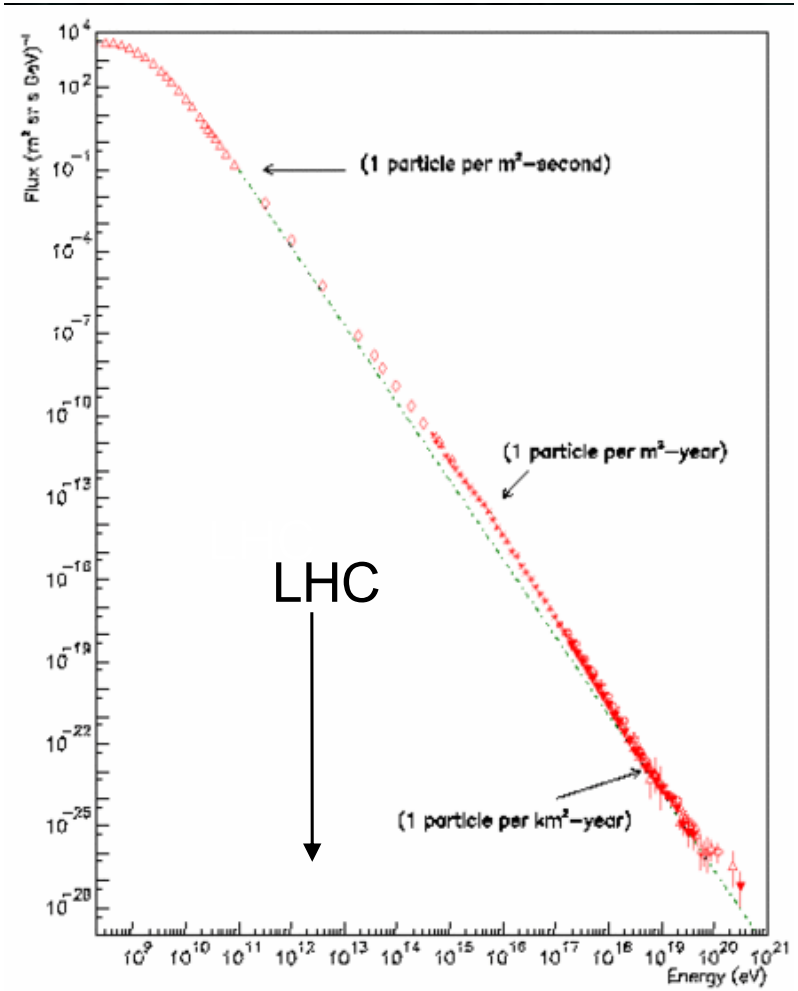
Why particle accelerators ?

- *Why accelerators?:* need to produce under <u>controlled conditions</u> HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT

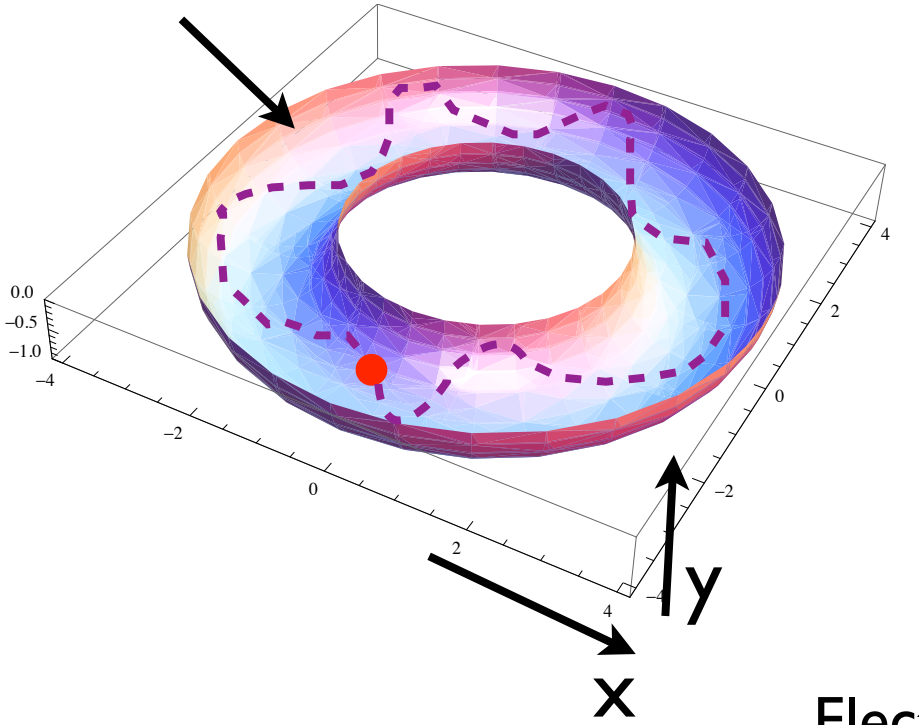
- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.



The cosmos accelerates already particles more than the TeV
While I am speaking about **66 10^9 particles/cm²/s** are traversing your body, about 10^5 LHC-equivalent experiment done by cosmic rays
With a space distribution too dispersed for today's HEP physics!

How an accelerator works ?

Accelerator



Goal: keep enough particles confined in a well defined volume to accelerate them.

How ? Lorentz Force!

$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

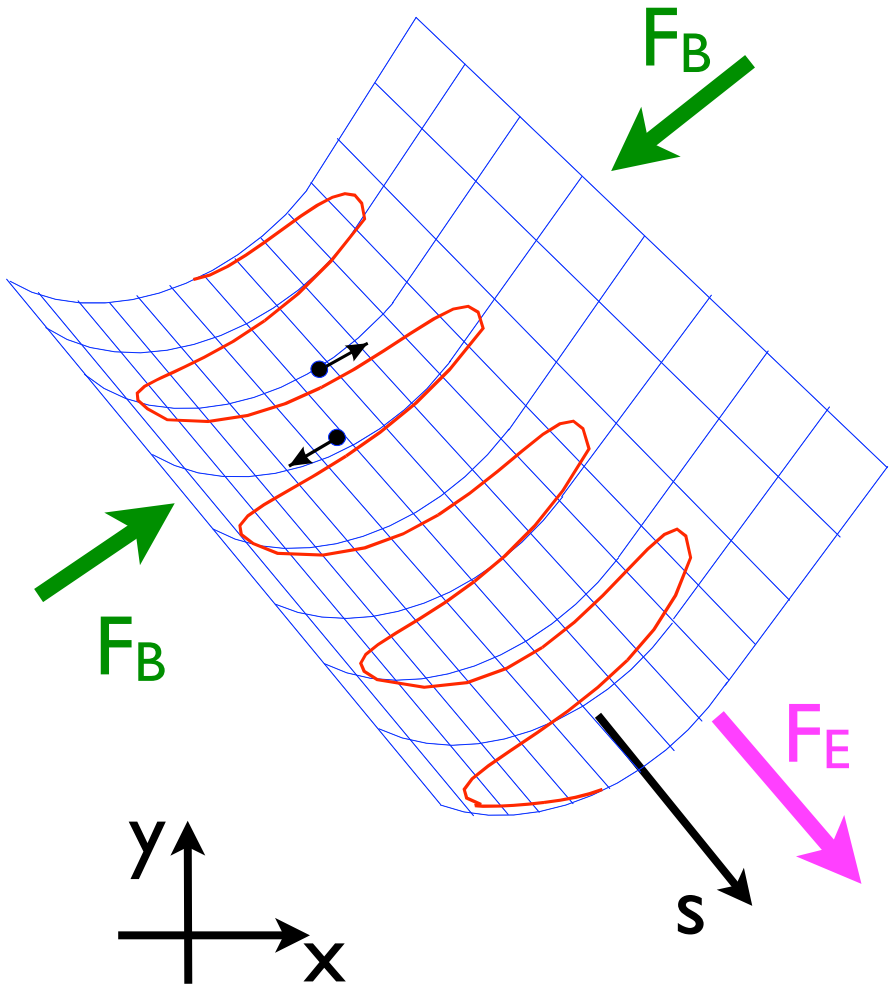
*An **accelerator** is formed by a sequence (called **lattice**) of:*

a) Magnets → Magnetic Field

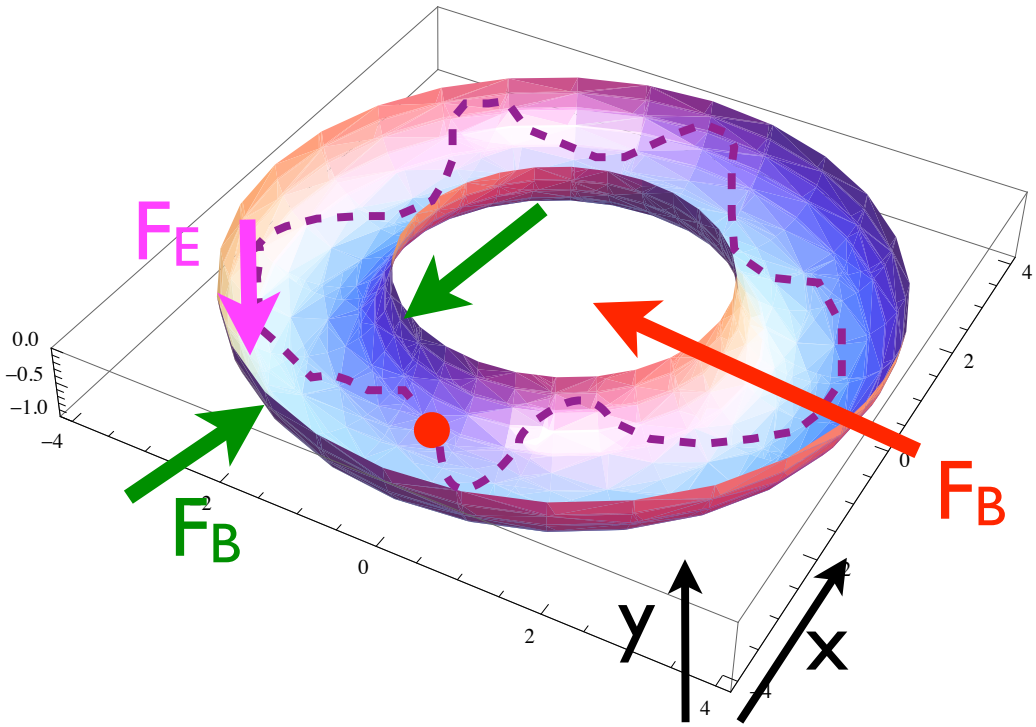
b) Accelerating Cavity → Electric Field

$$\overline{F(t)} = \underbrace{q\left(\overline{E(t)}\right.}_{F_E} + \underbrace{\left.\overline{v(t)} \otimes \overline{B(t)}\right)}_{F_B}$$

Linear Accelerator



Circular Accelerator



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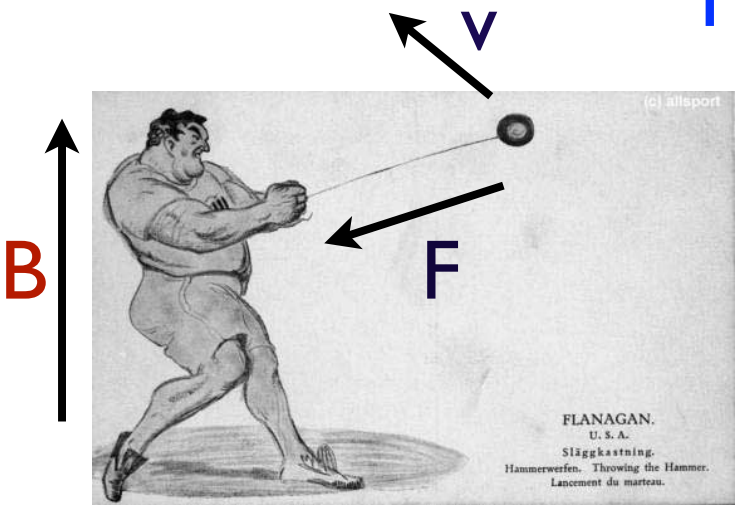

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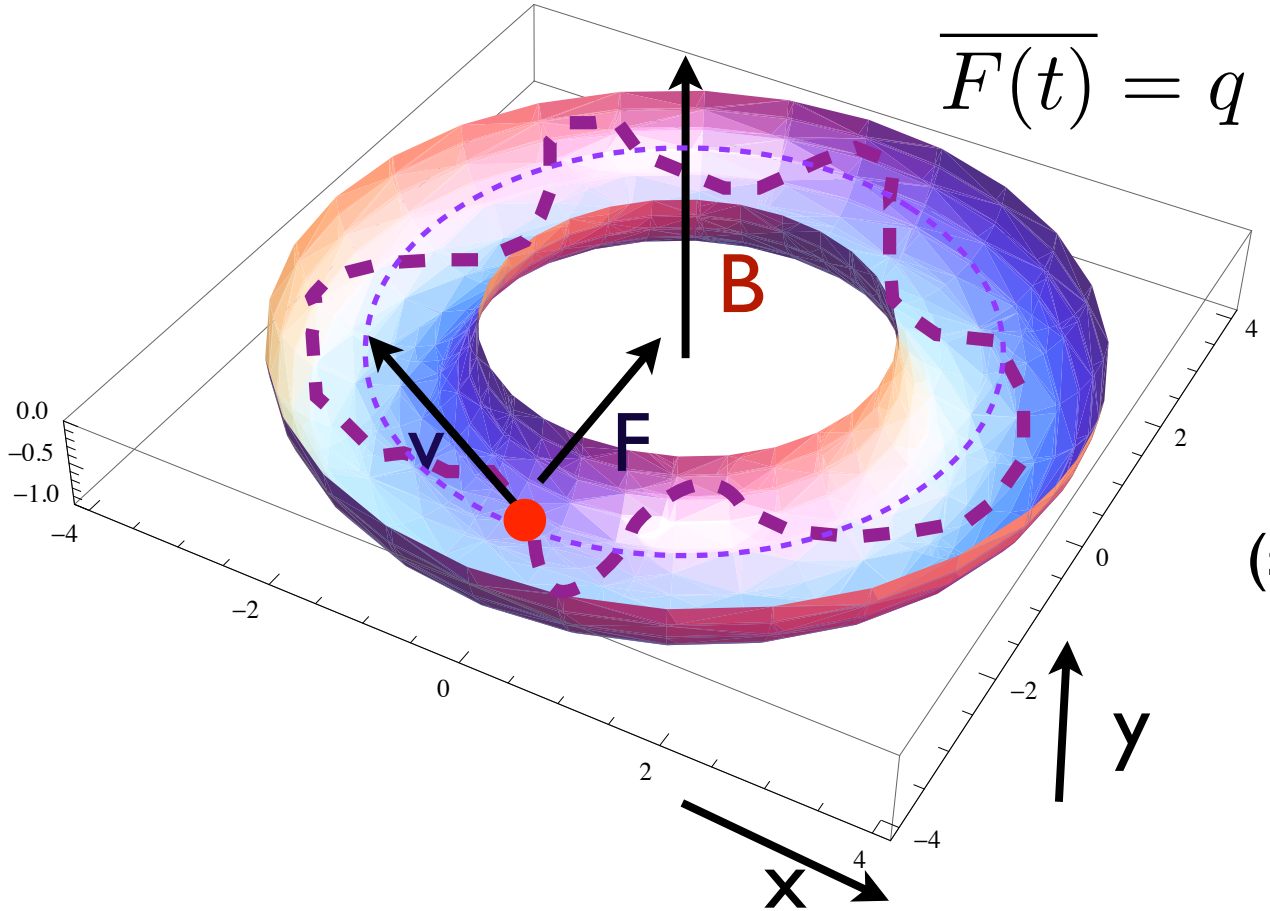

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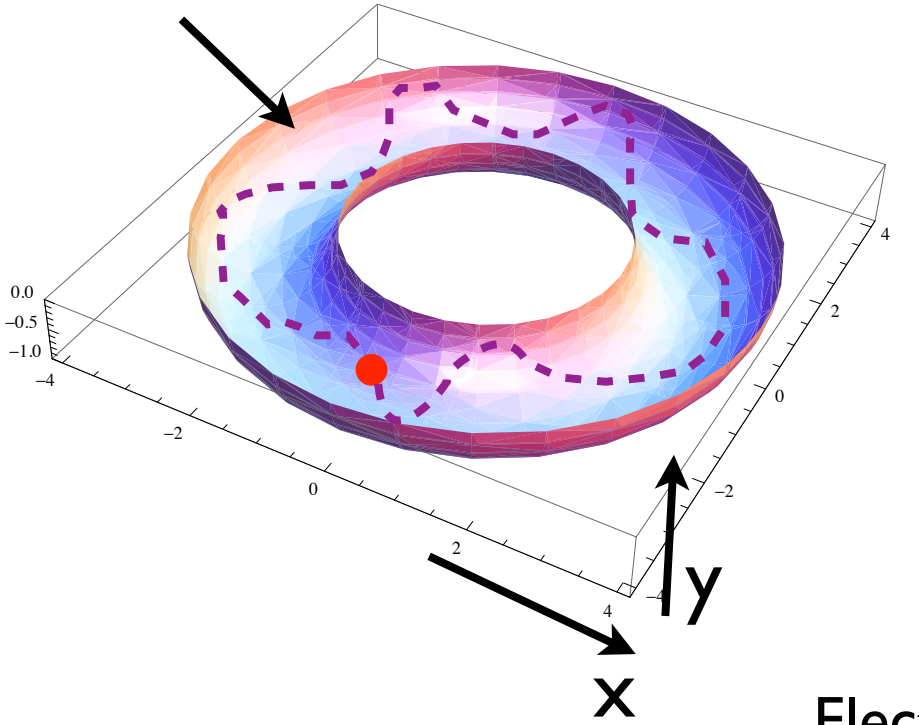

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Synchrotron (1952, 3 GeV, BNL)

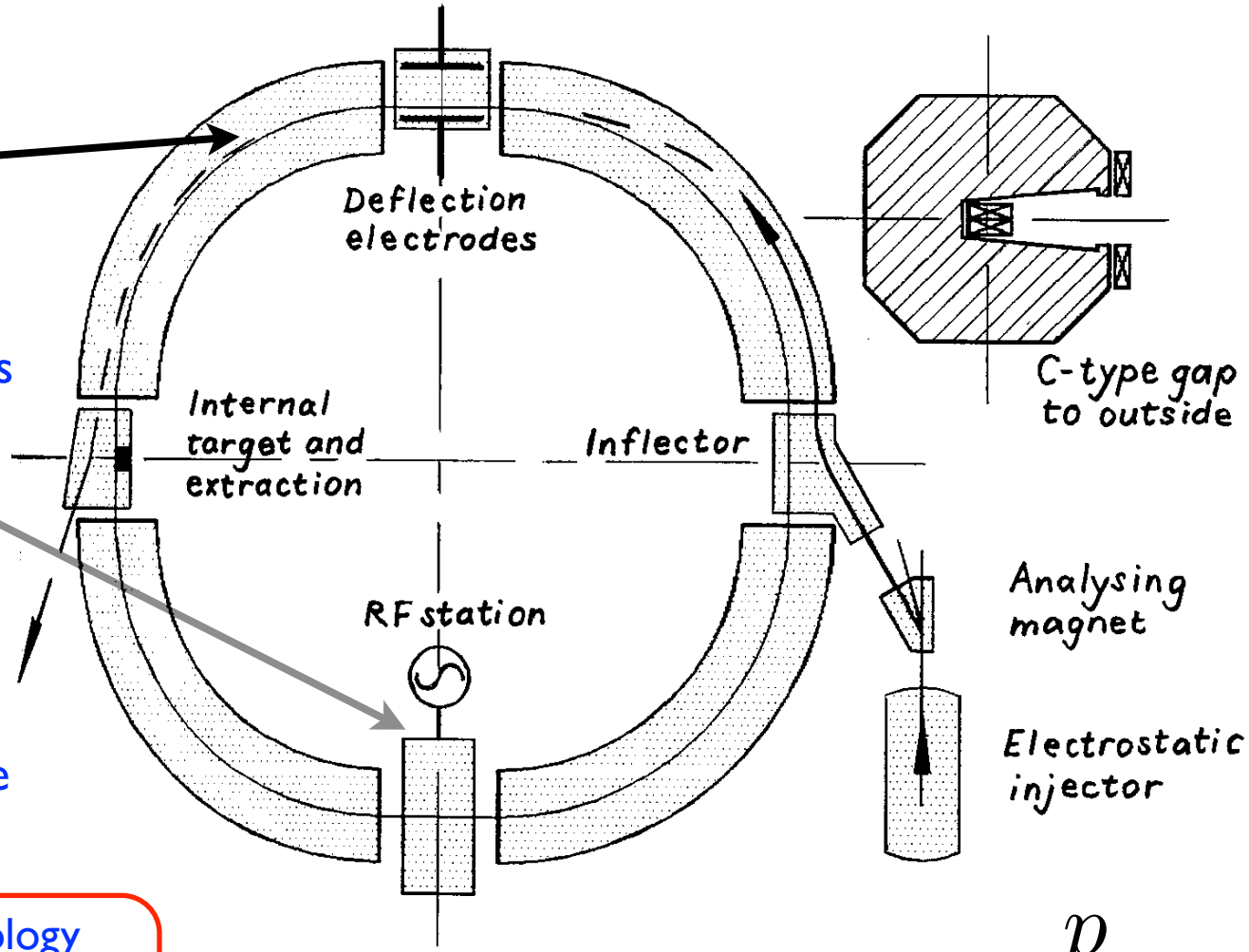
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

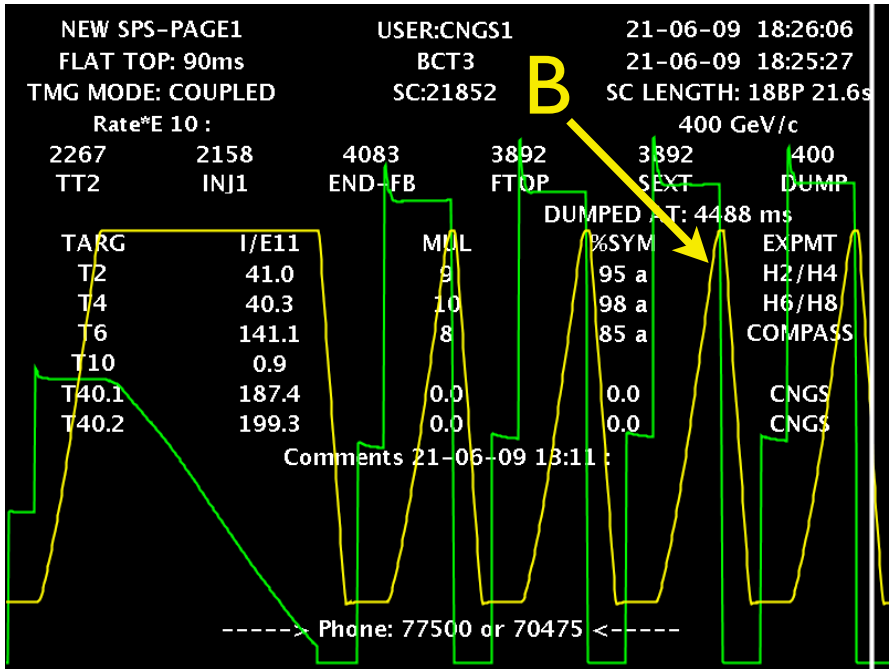
ρ constant radius of curvature



Bending strength limited by used technology to max ~ 1 T for room temperature conductors

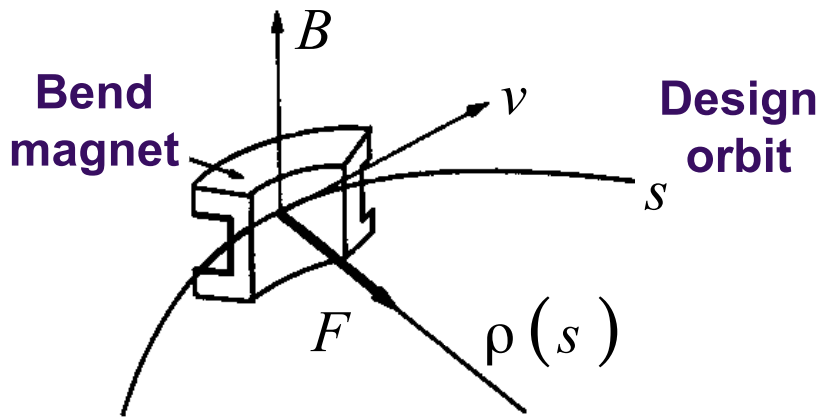
Particle rigidity: $B\rho = \frac{p}{e}$

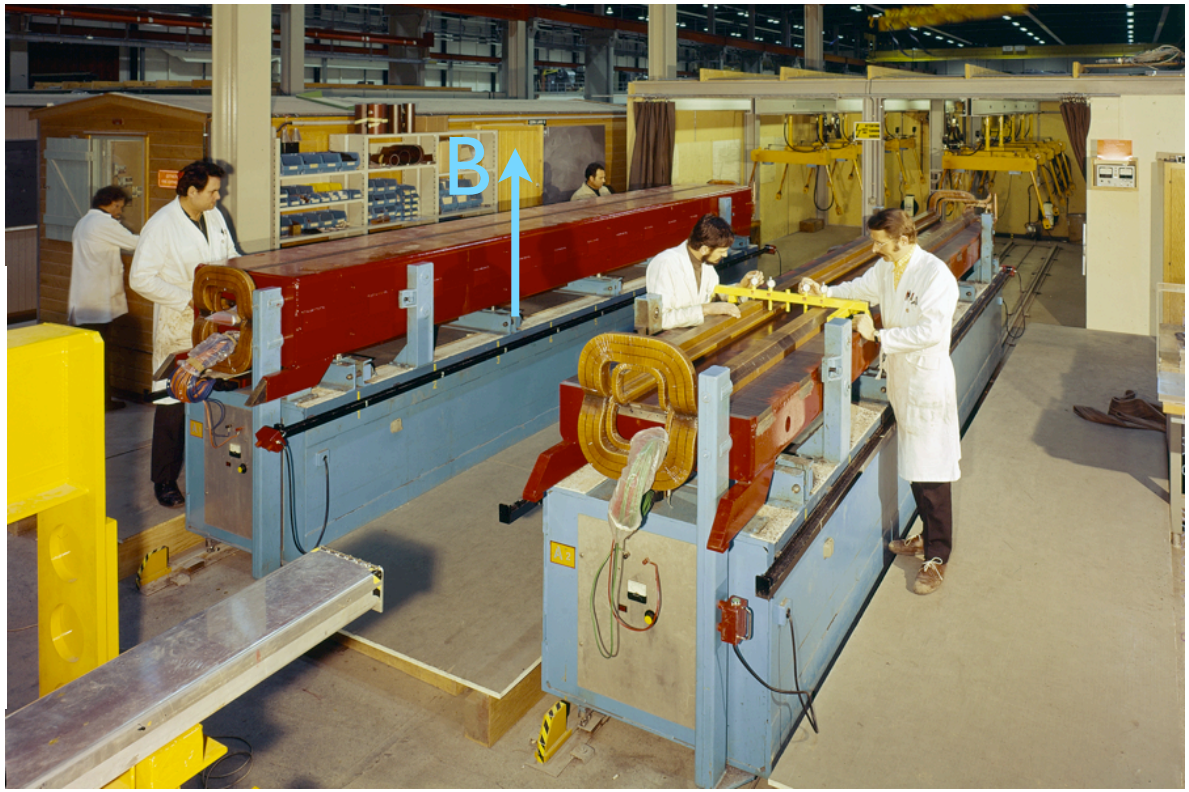
Dipole



Force given by the vertical magnetic field compensate the centrifugal force to keep the particles on the central trajectory, i.e. in the center of the beam pipe.

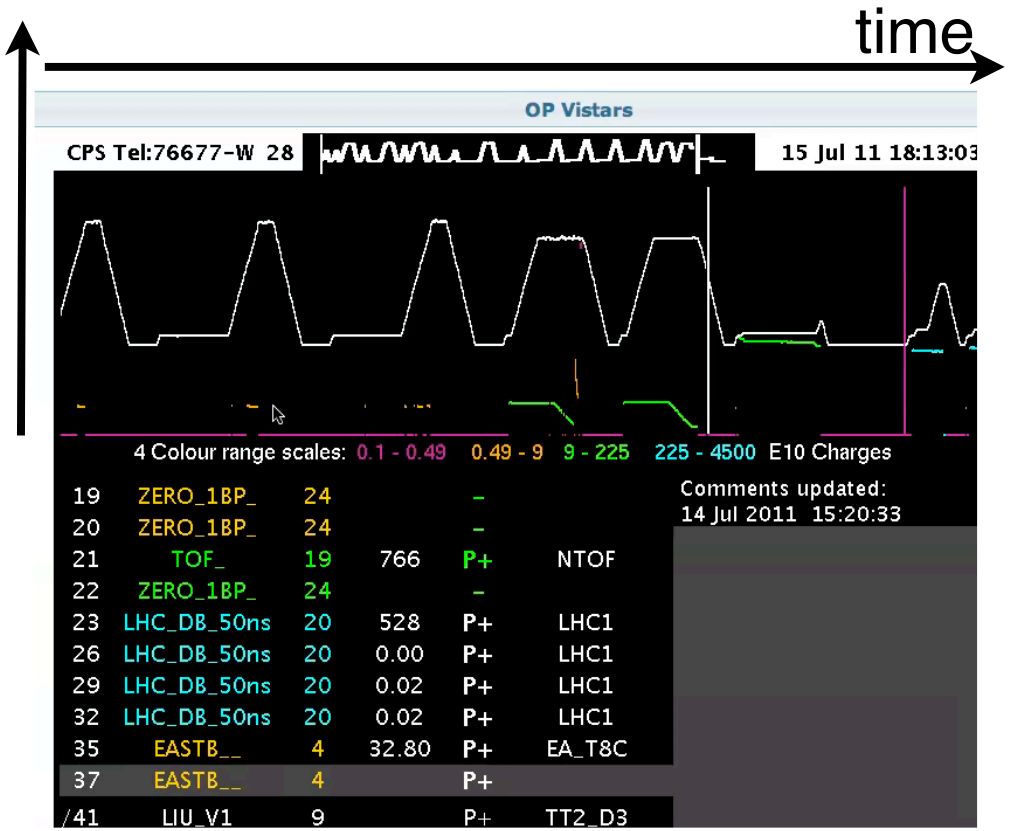
Once the beam accelerates, the magnetic field is increased synchronously





An example of cycling machine: the CERN-PS (Proton Synchrotron)

B(t) or E(t)



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

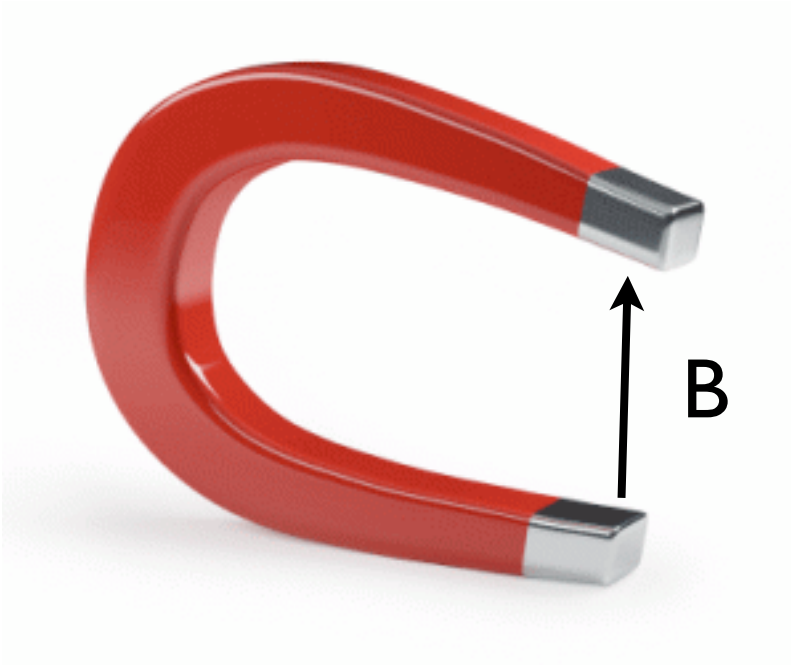
PS is a slow synchrotron: pulses every 1.2 s (or multiples)

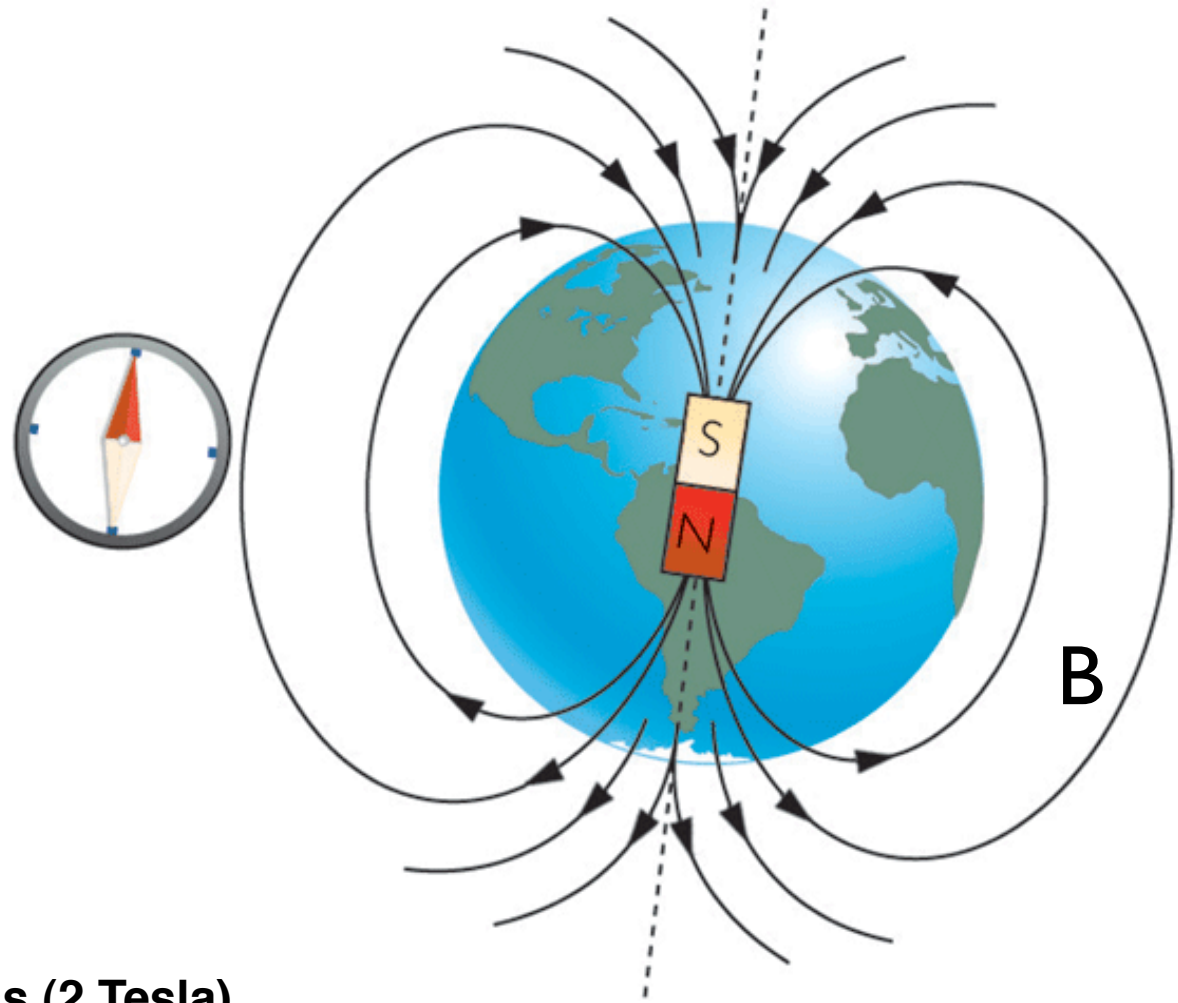
PS radius: 100 m

Injection: B = 1013 G (0.1013 T) E = 1.4 GeV

Extraction (max): 12000 G (1.2T) E ~ 26 GeV

Two dipoles you should know we well

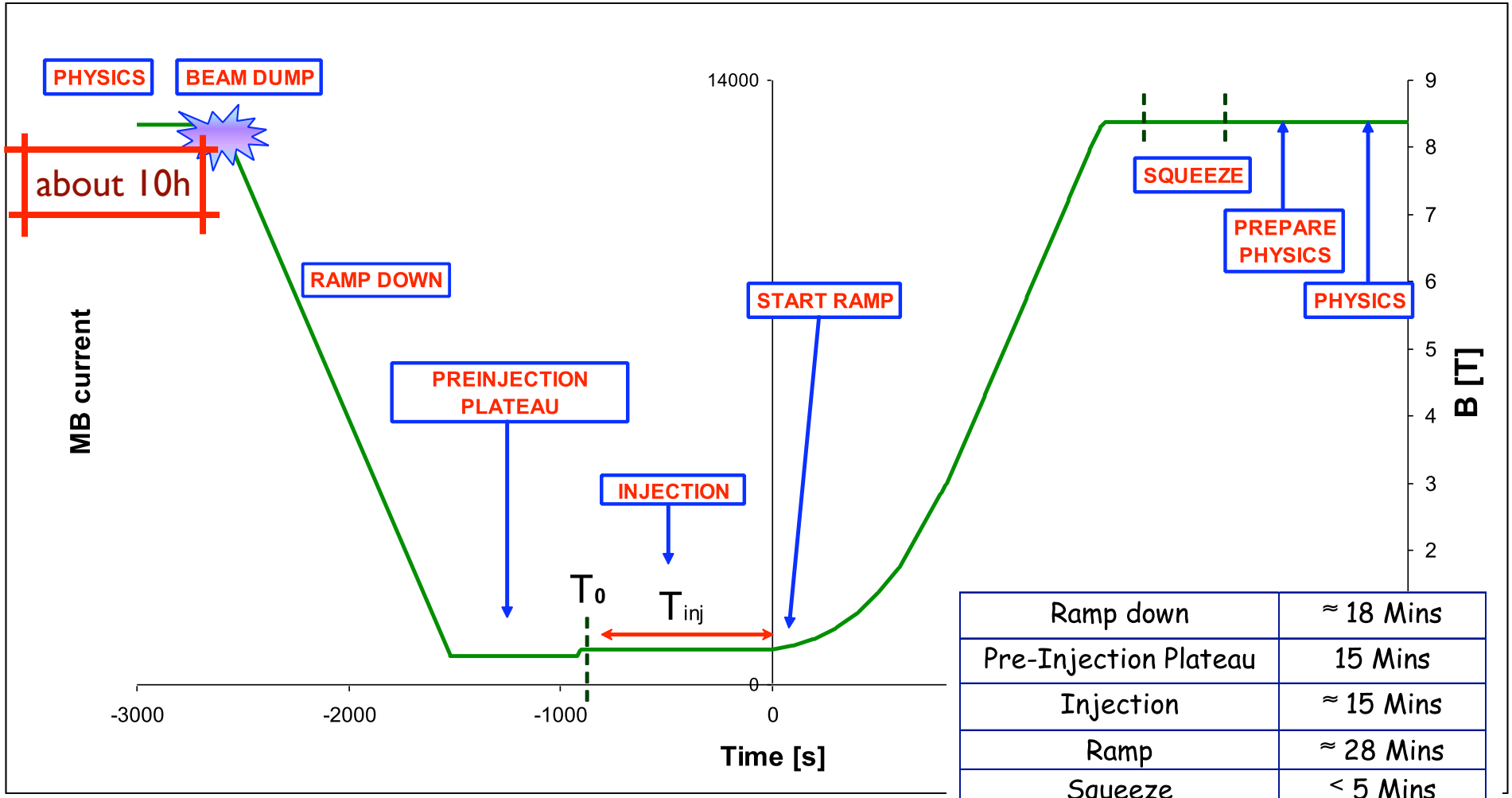




Earth Magnetic Field : ~ 0.6 Gauss

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

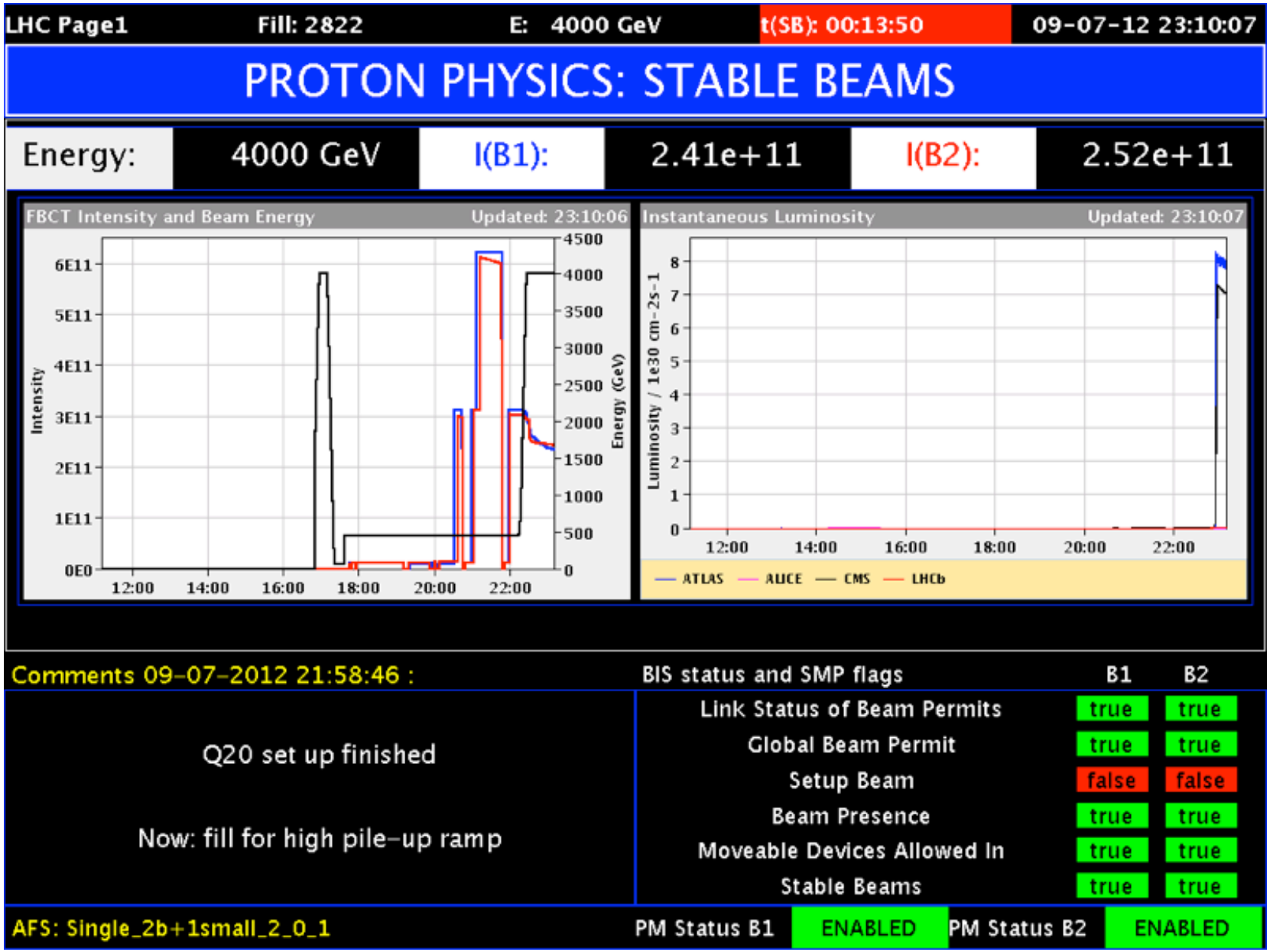
Typical LHC Operational cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

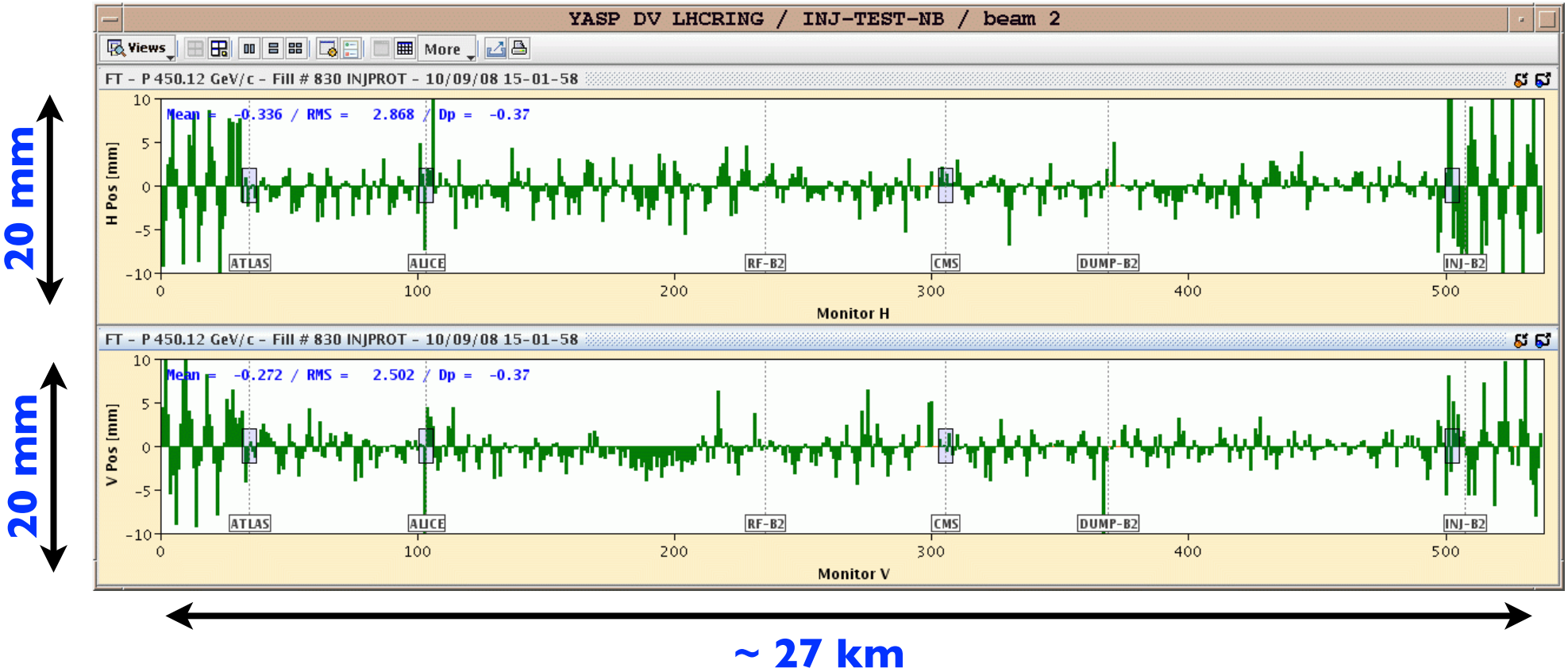
Courtesy R. Bailey

LHC Operational page



Real LHC orbit - correction of dipolar error

Real orbit taken the 1st day of the LHC



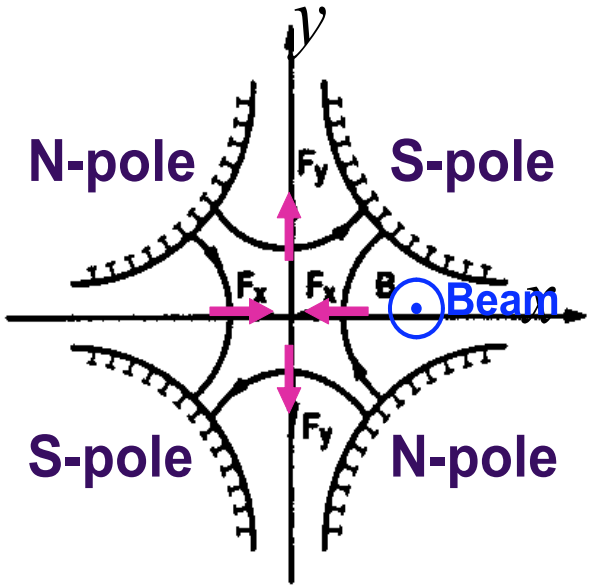
Courtesy of J. Wenninger

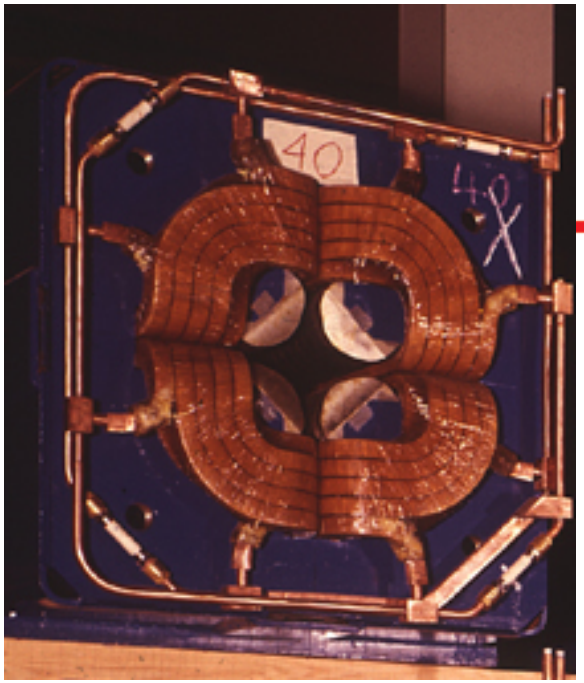
Please notice:
Horizontal and vertical scale are different by 6 orders of magnitude

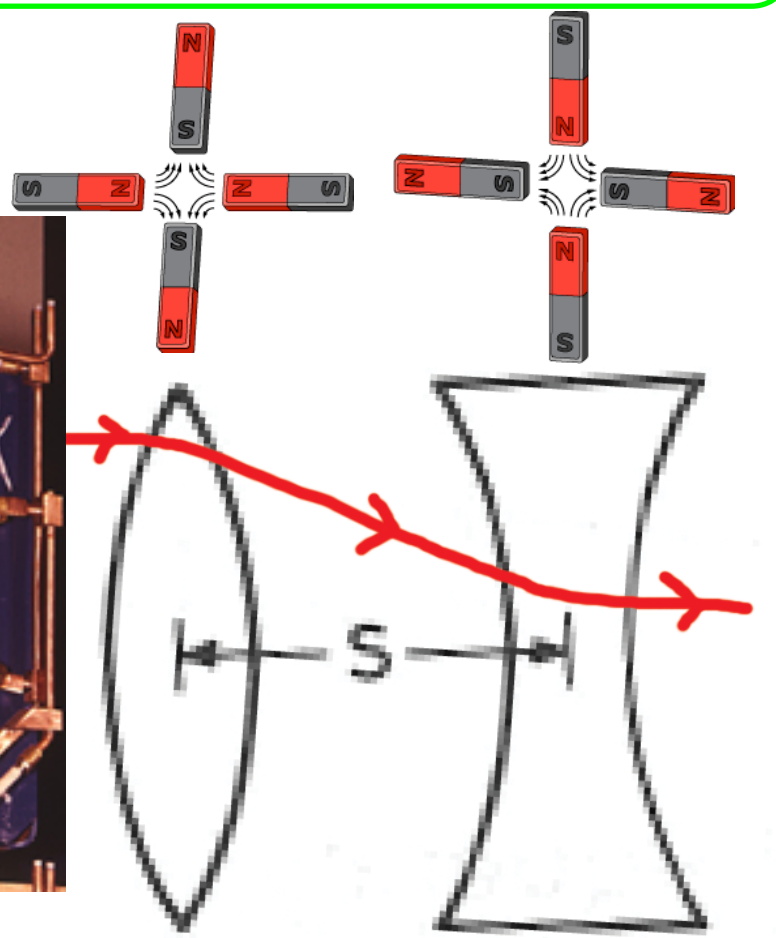
Synchrotrons: strong focusing machine

Dipoles are interleaved with quadrupoles to focus the beam.
Quadrupoles act on charged particles as lens for light. By alternating focusing and defocusing lens (Alternating Grandient quadrupoles) the beam dimension is kept small (even few mum^2).

QUADRUPOLES



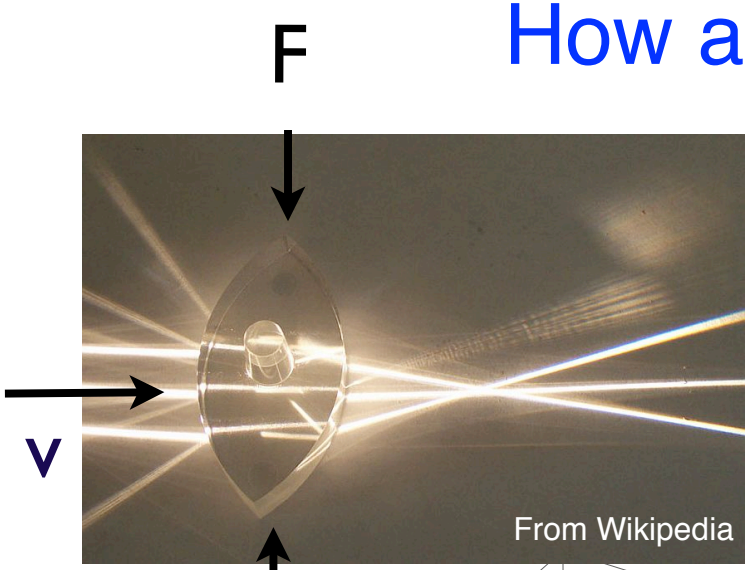




B field is focusing in one plane but defocusing in the other.

Typical lattice is FODO, focusing-drift-defocusing

How an accelerator works ?



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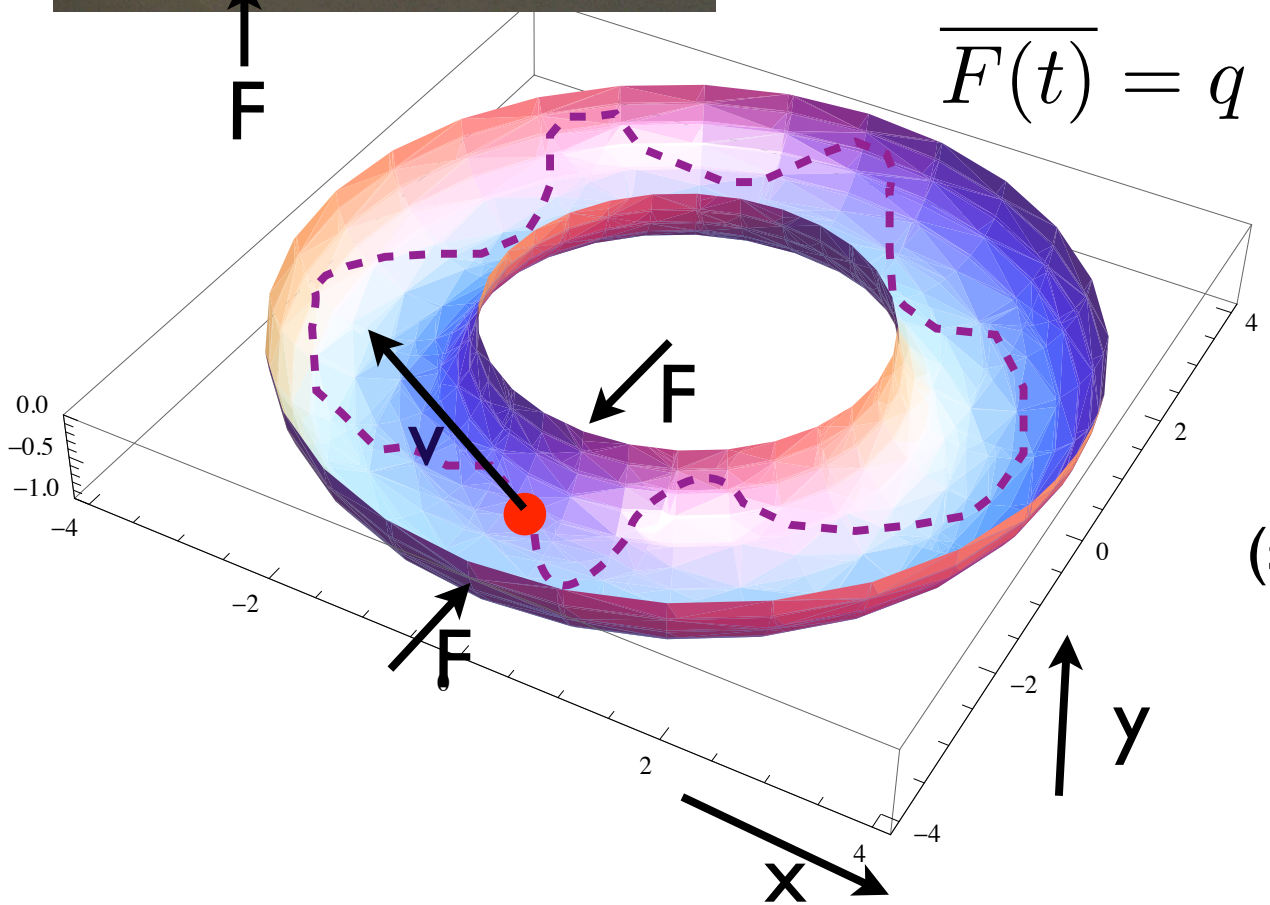
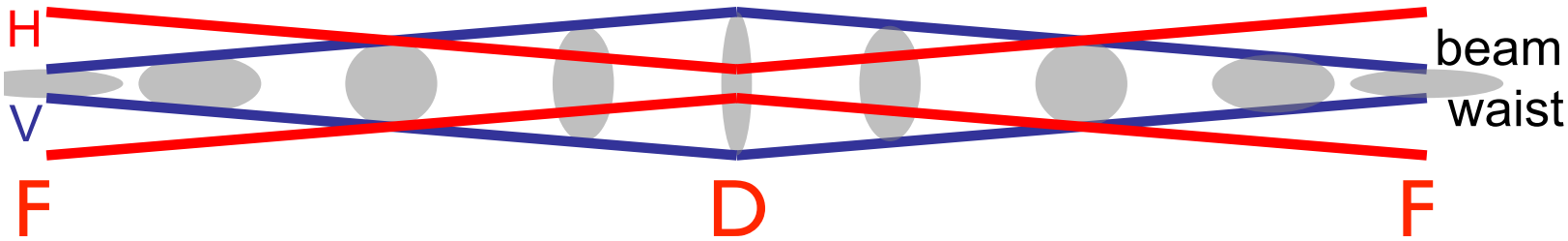


Particles of different energy (speed) behave differently

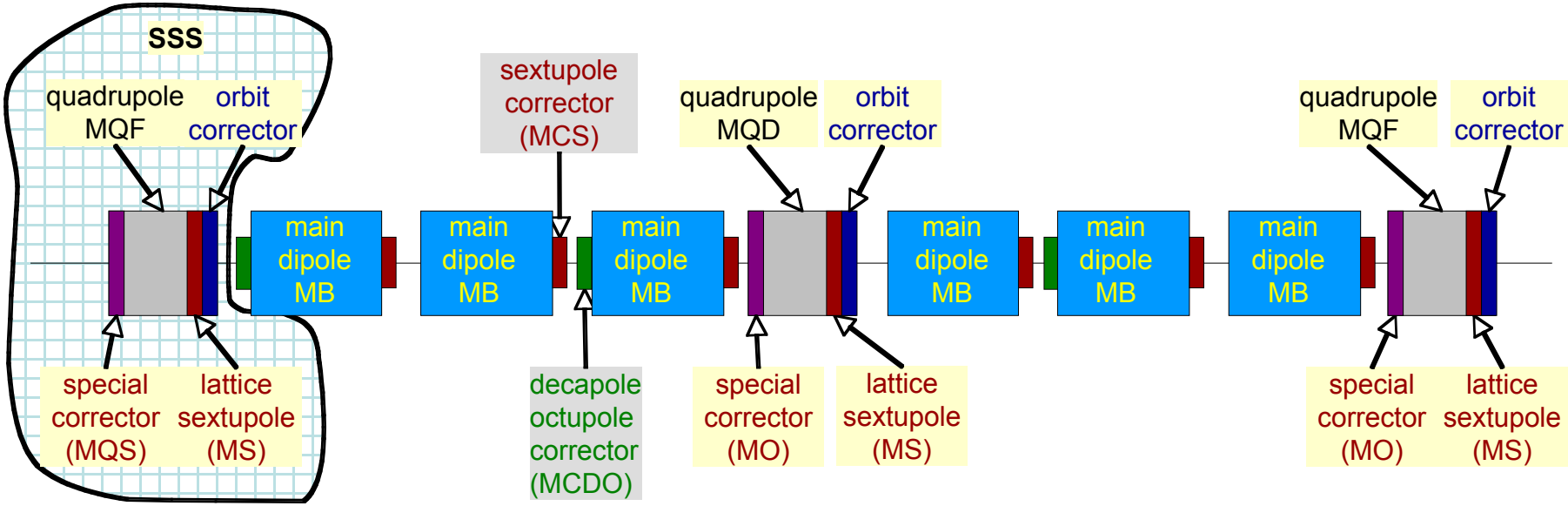
Magnetic field confines particles on a given trajectory

An example of a lattice: LHC cell

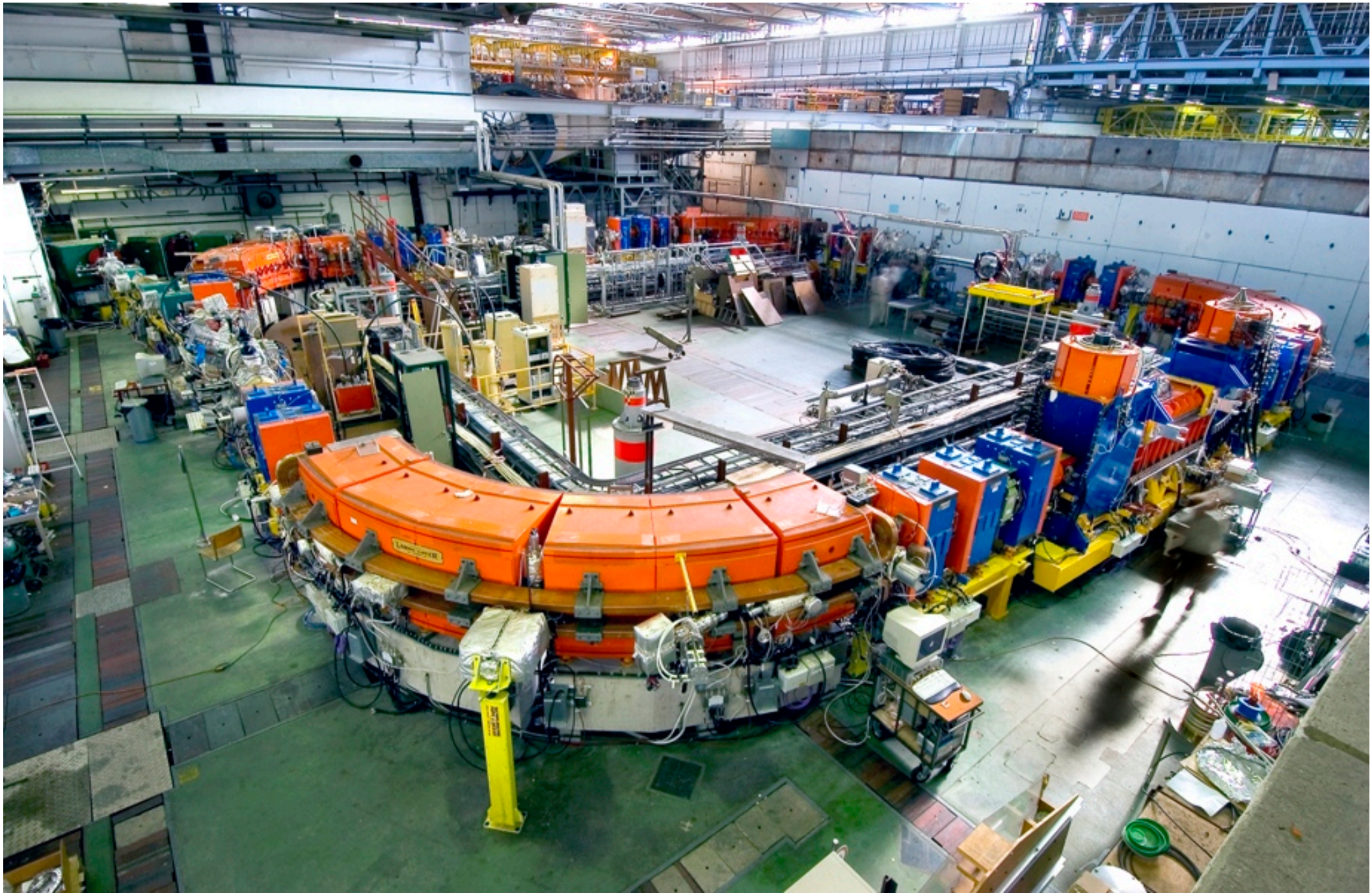
Classical FODO cell with about 90^0 phase advance per cell
(F=focusing, O=drift, D=defocusing)



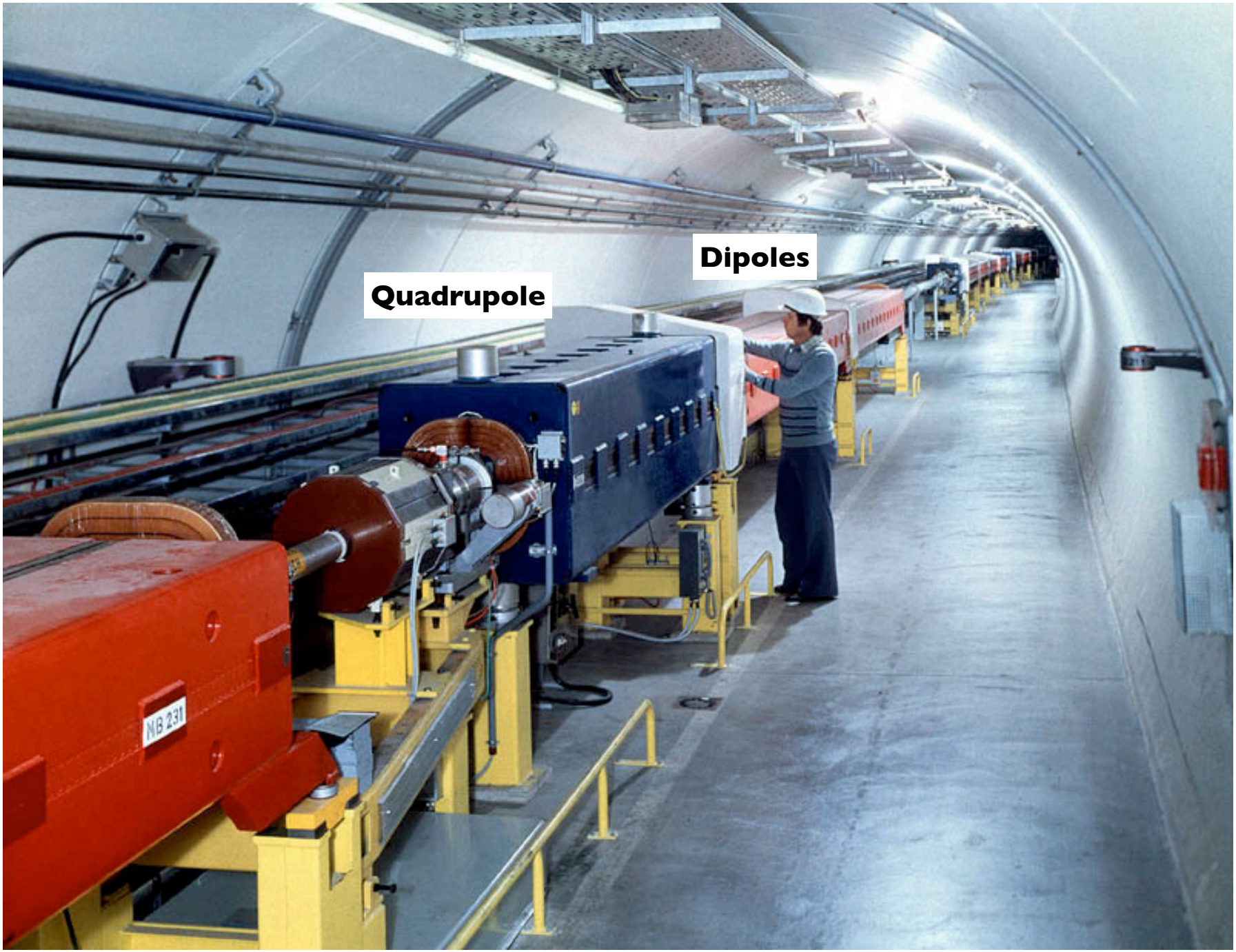
LHC Cell - Length about 110 m (schematic layout)



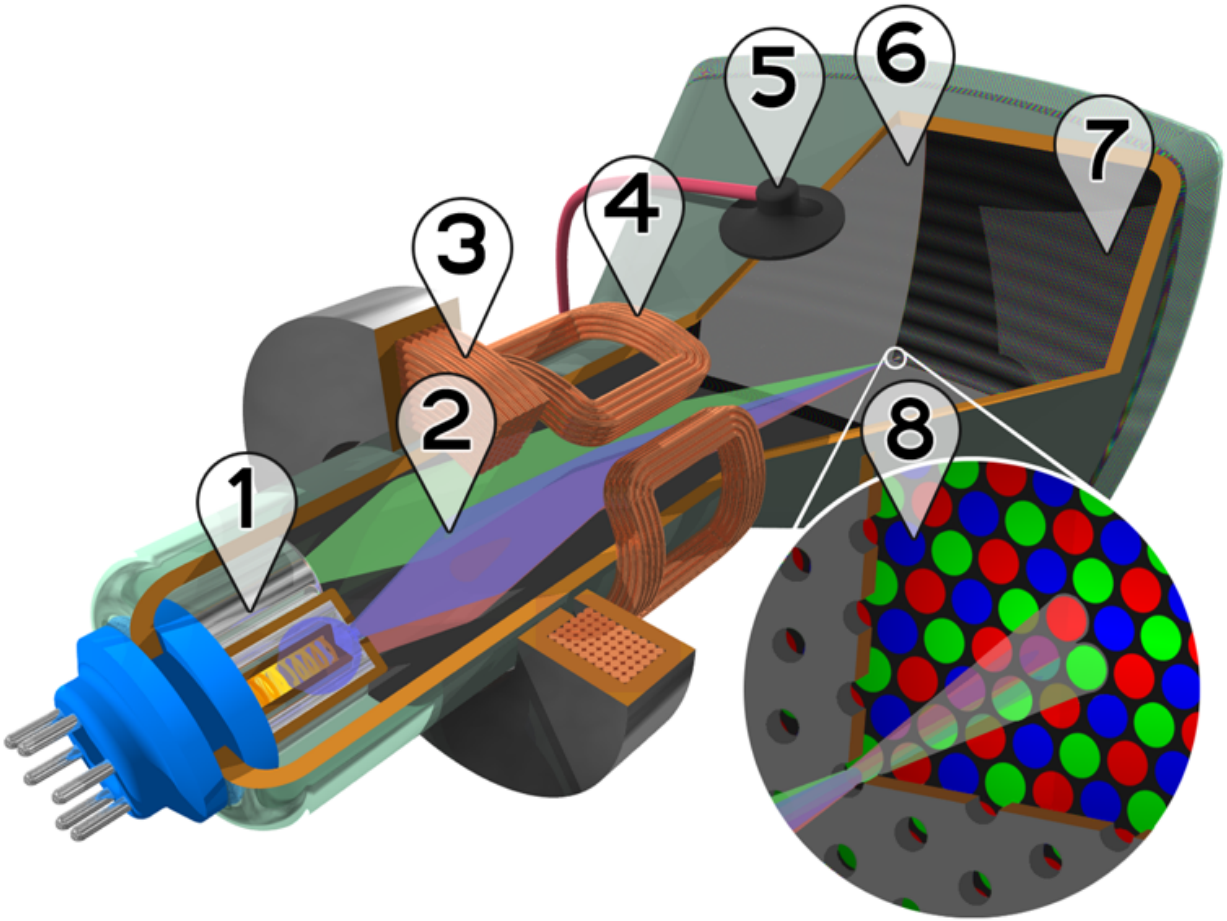
A synchrotron in a view: LEIR (Low Energy Ion Ring)



The SPS tunnel



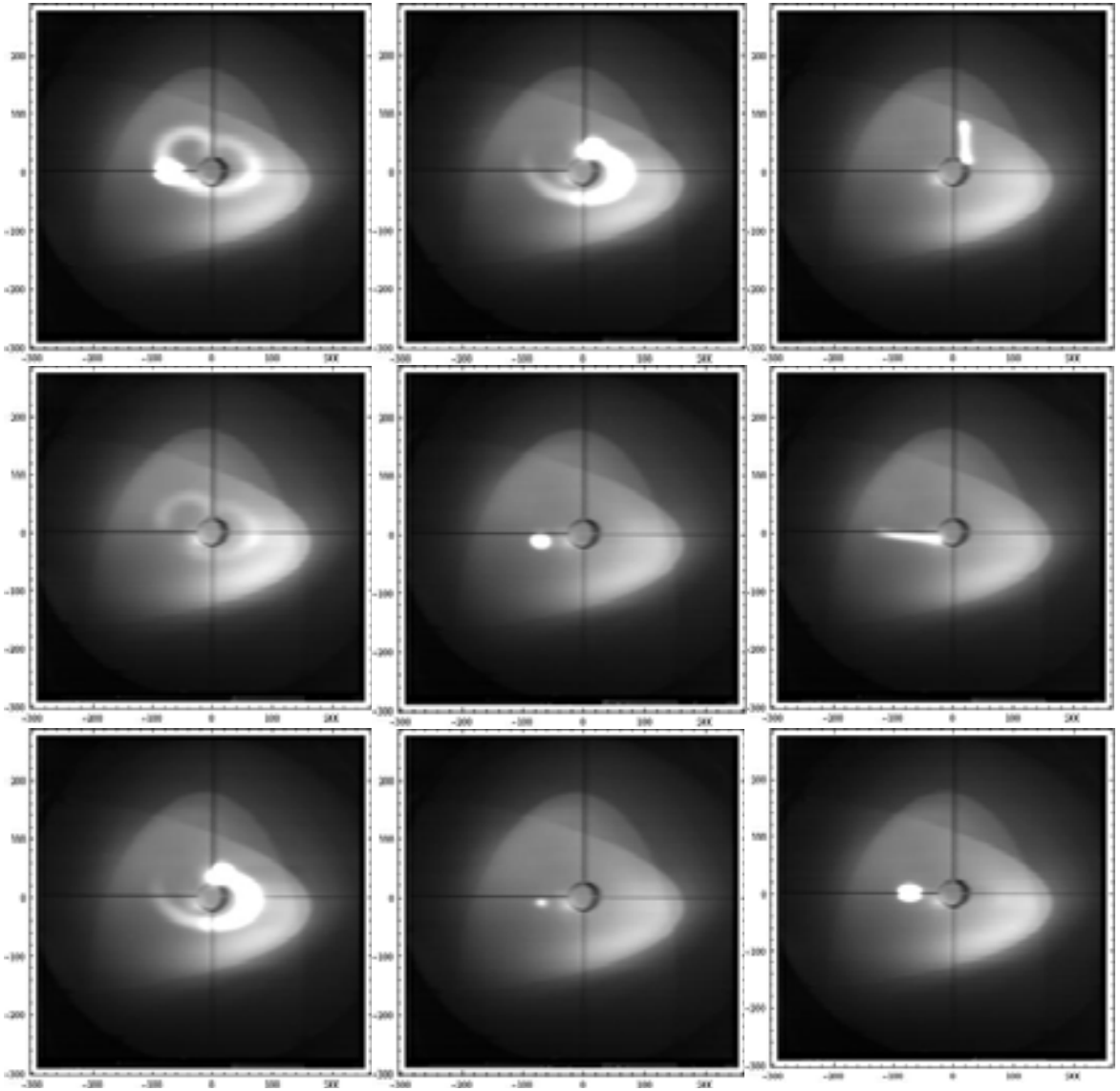
An accelerator that you know very well

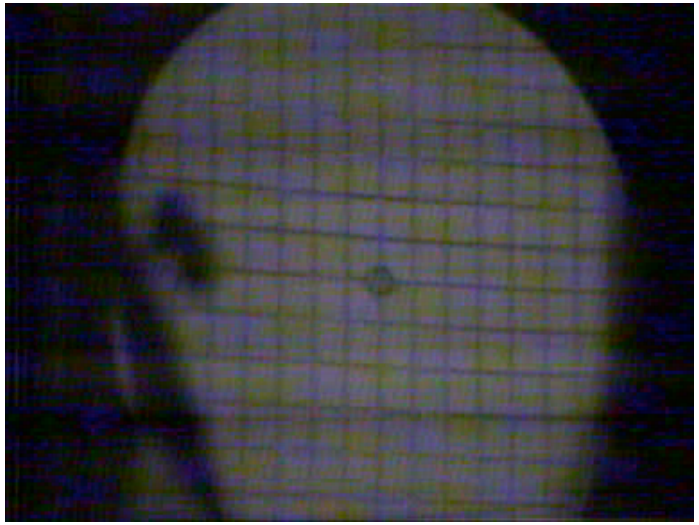


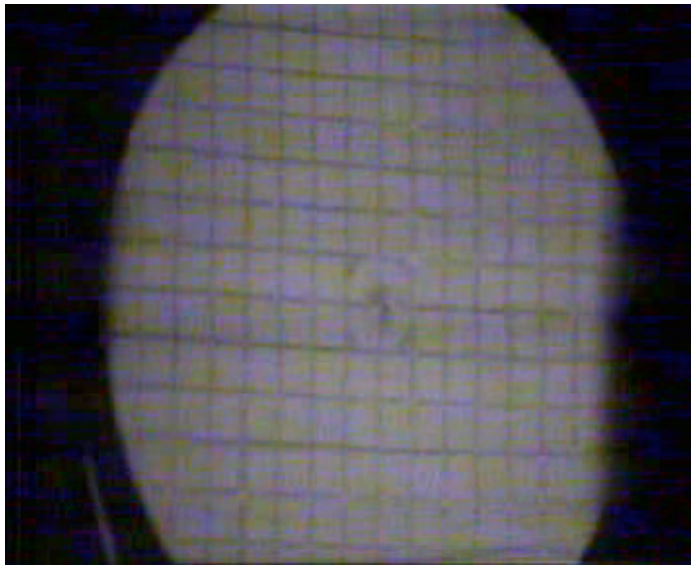
1. **Three Electron guns** (for red, green, and blue phosphor dots)
2. **Electron beams**
3. **Focusing coils**
4. **Deflection coils**
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen

From Wikipedia

Real beam images

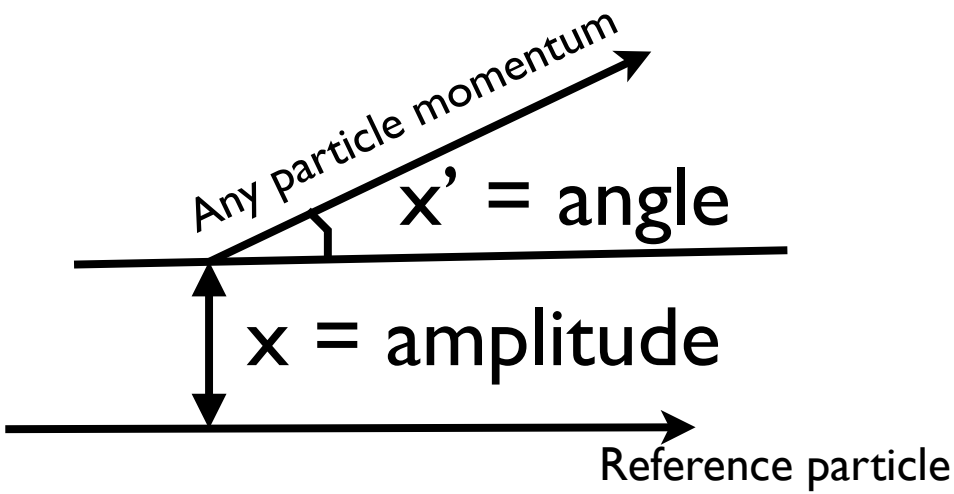


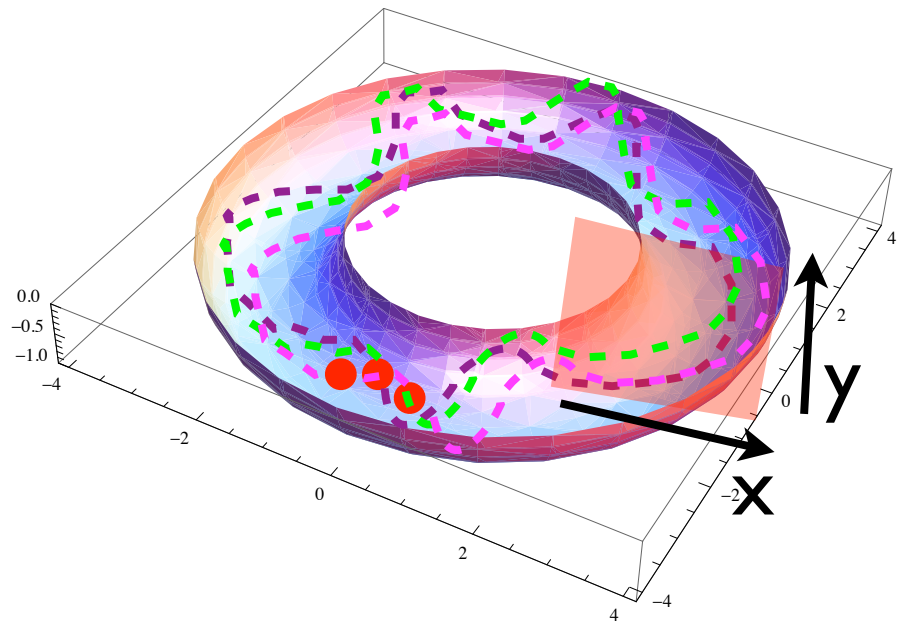


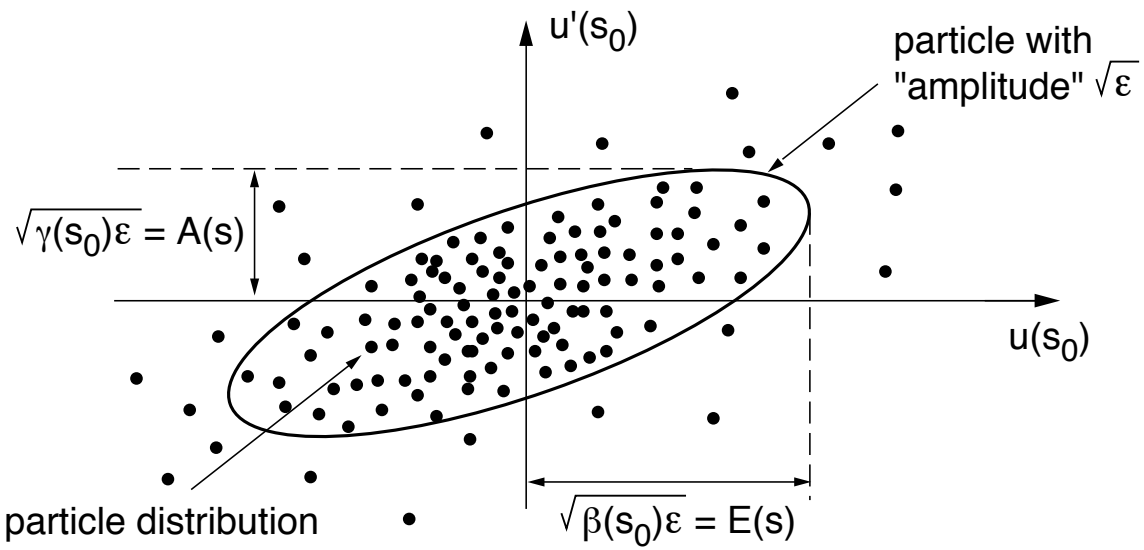


Courtesy of B. Goddard

Our reference frame: xx', the phase space







The space occupied in the xx' (or yy') plane by the beam at a given position in the machine is defined as Emittance

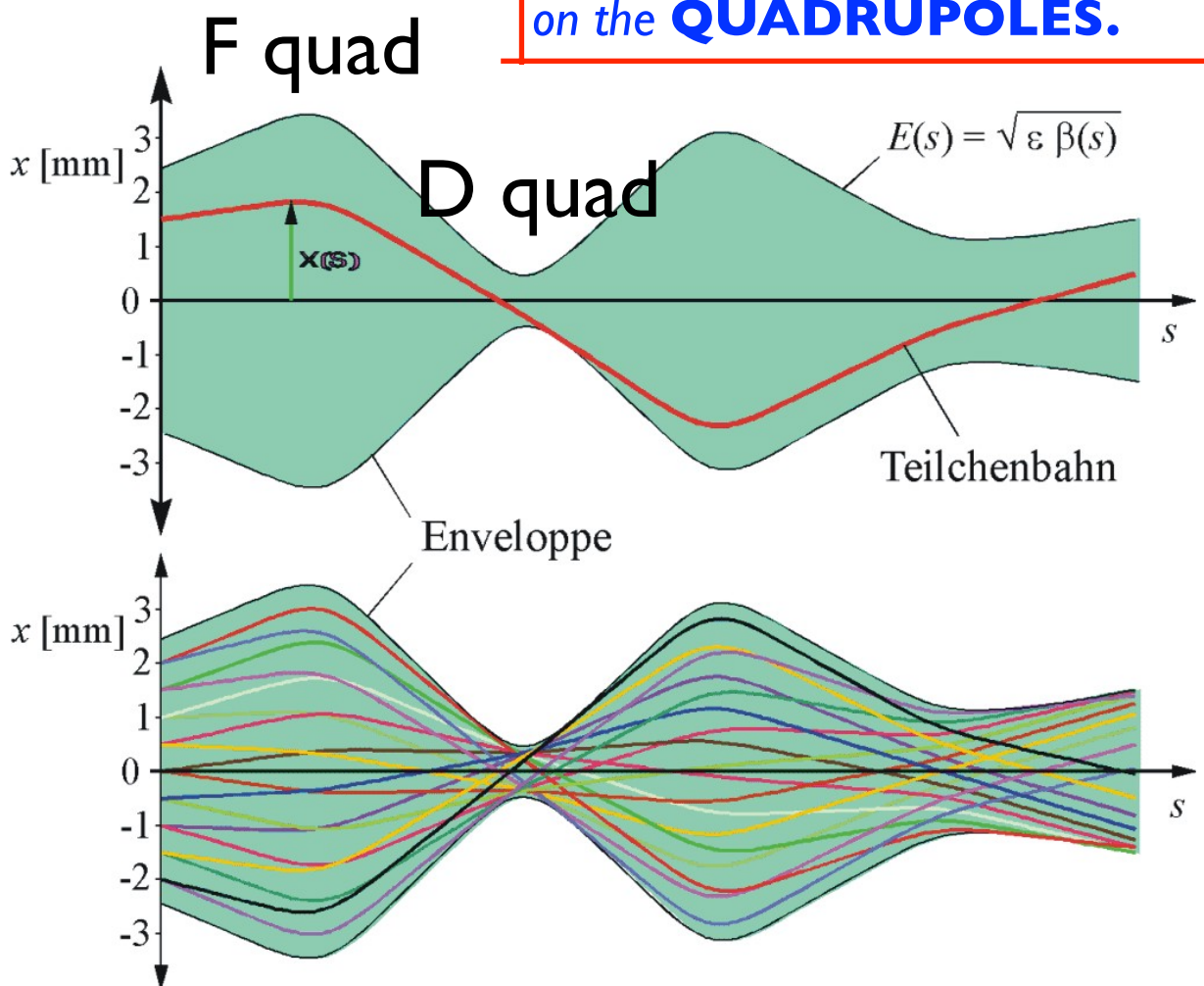
Definition of beam emittance and enveloppe

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y}}$$

Beam physical dimension

Optical machine parameter that depends on the lattice of the machine, in particular on the ***QUADRUPOLES.***

Emittance: *Parameter which describes the spread of the particles in the phase space (xx') or (yy').*



The enveloppe is defined as the maximum amplitude for which the particle remains in the machine vacuum chamber.

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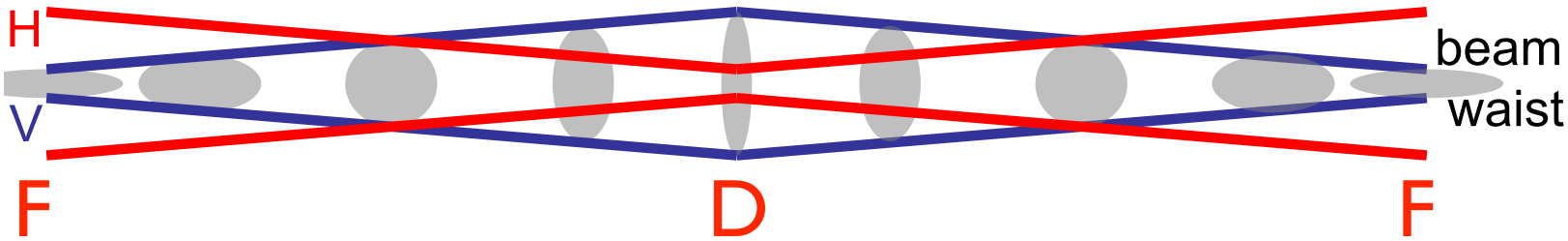

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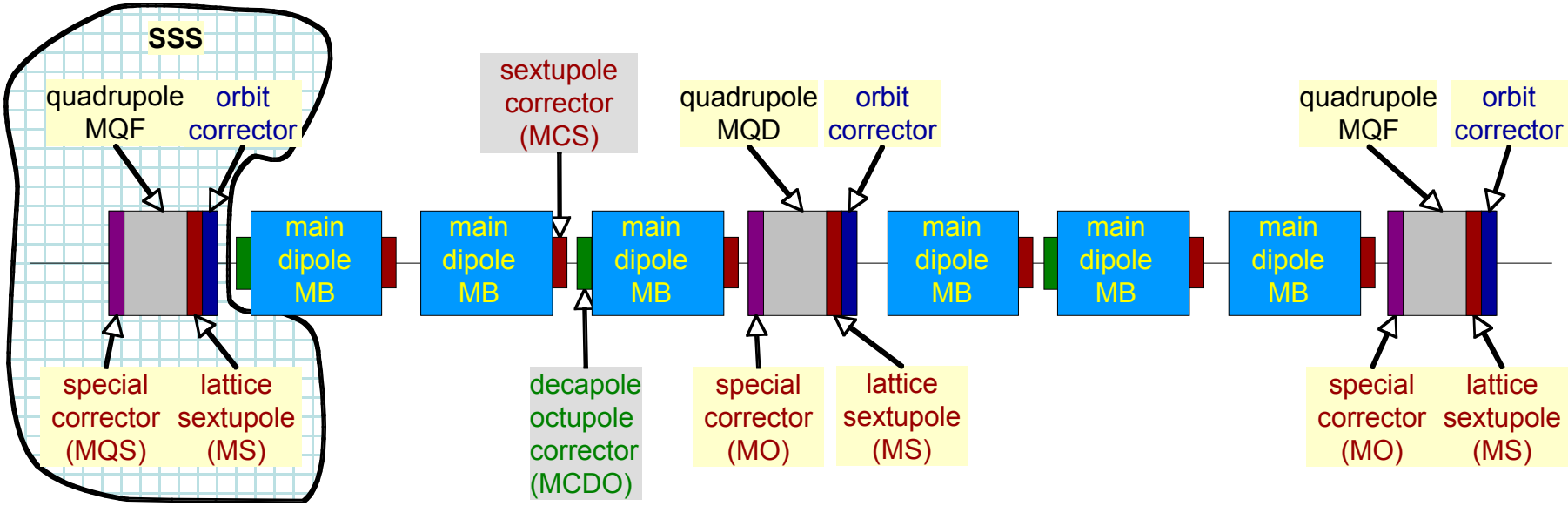
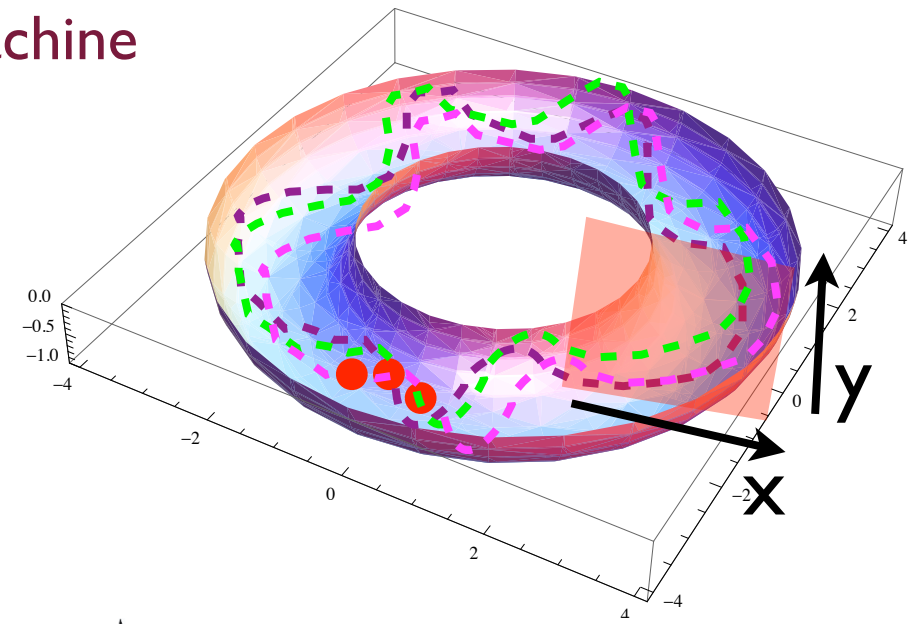
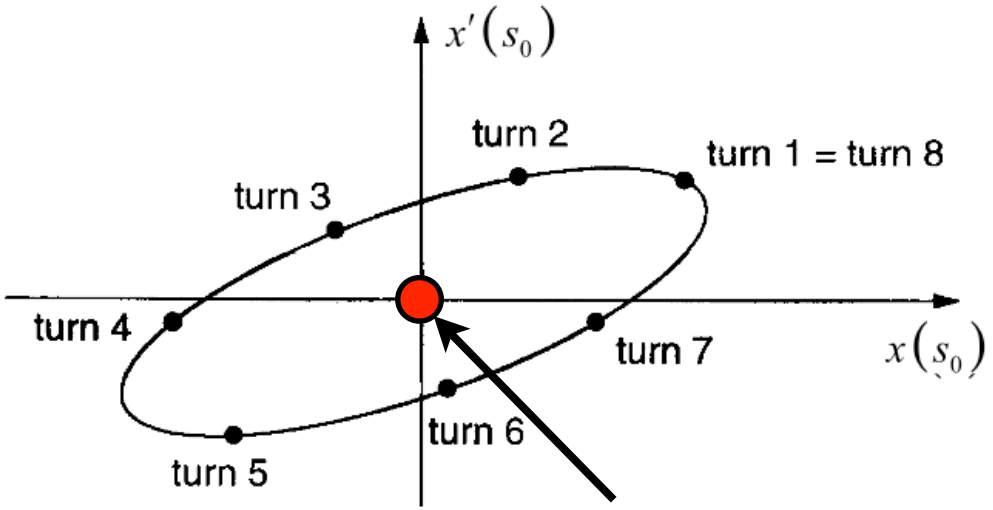


Tune

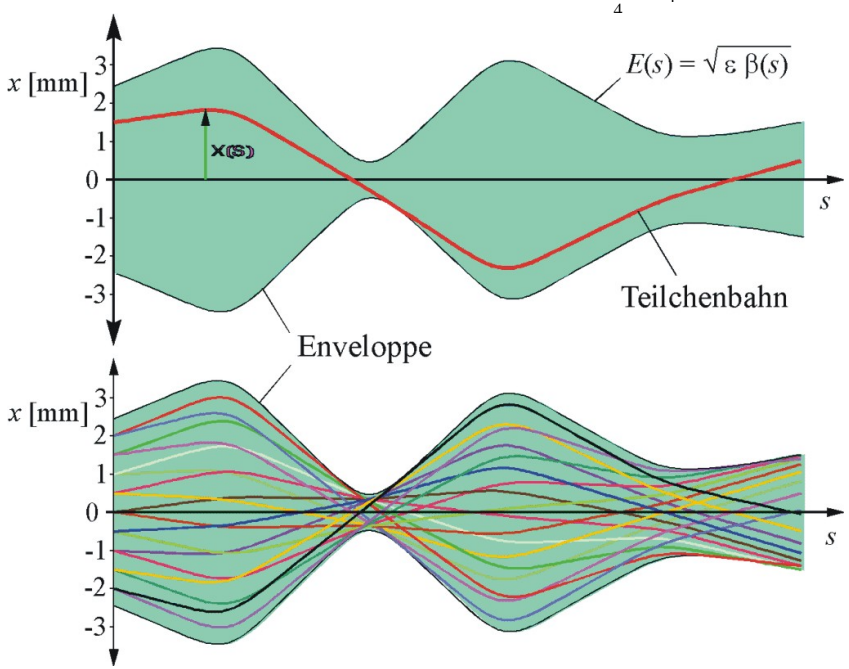
Tune: number of oscillations (called betatronic) in the xx‘ plane a particle does in one machine turn.

The tune depends on the quadrupoles setting





Reference particle

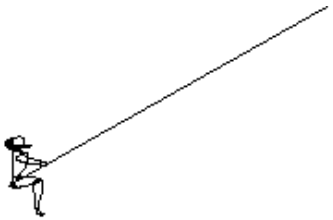


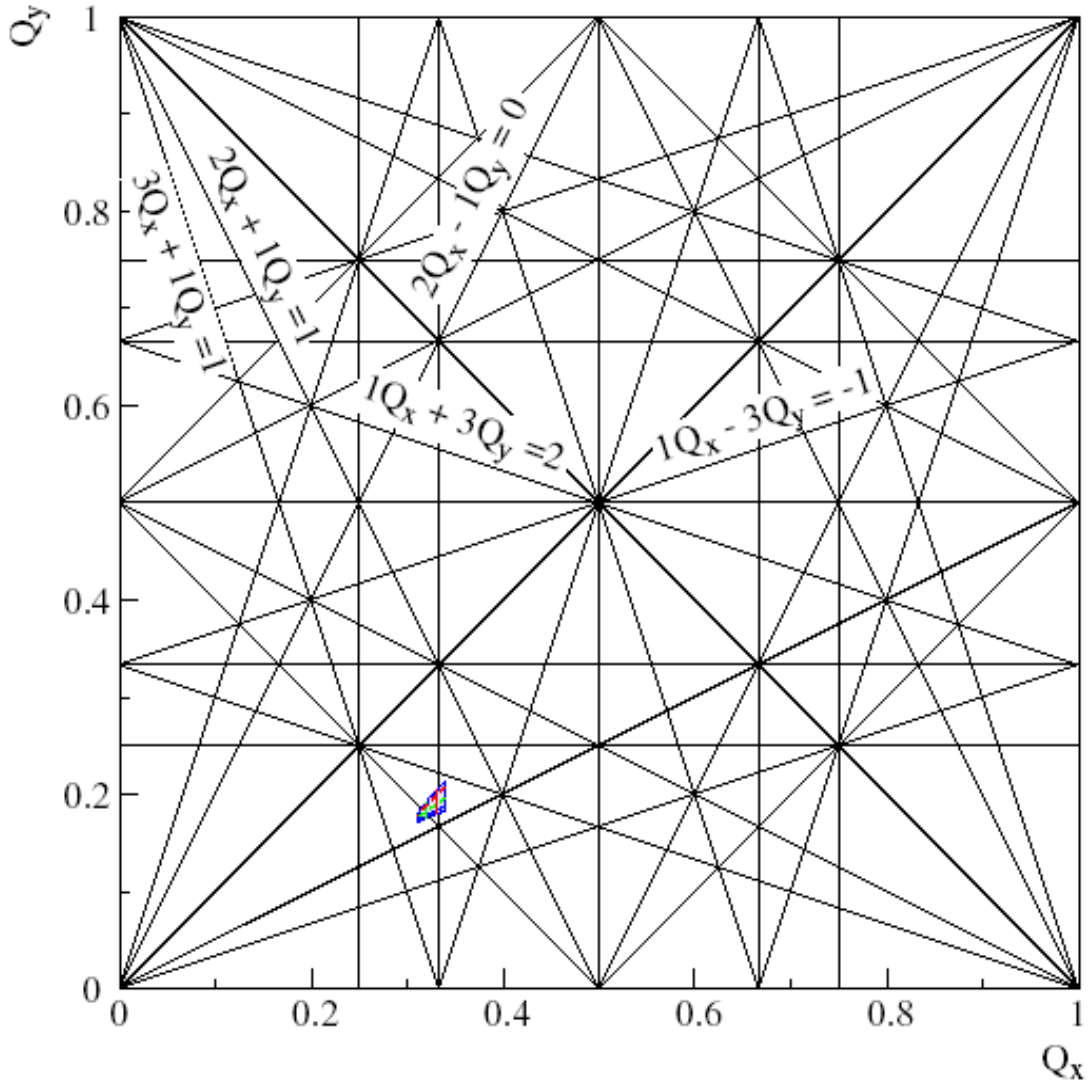
Tune and resonances

To avoid $M\,Q_x + N\,Q_y = P$

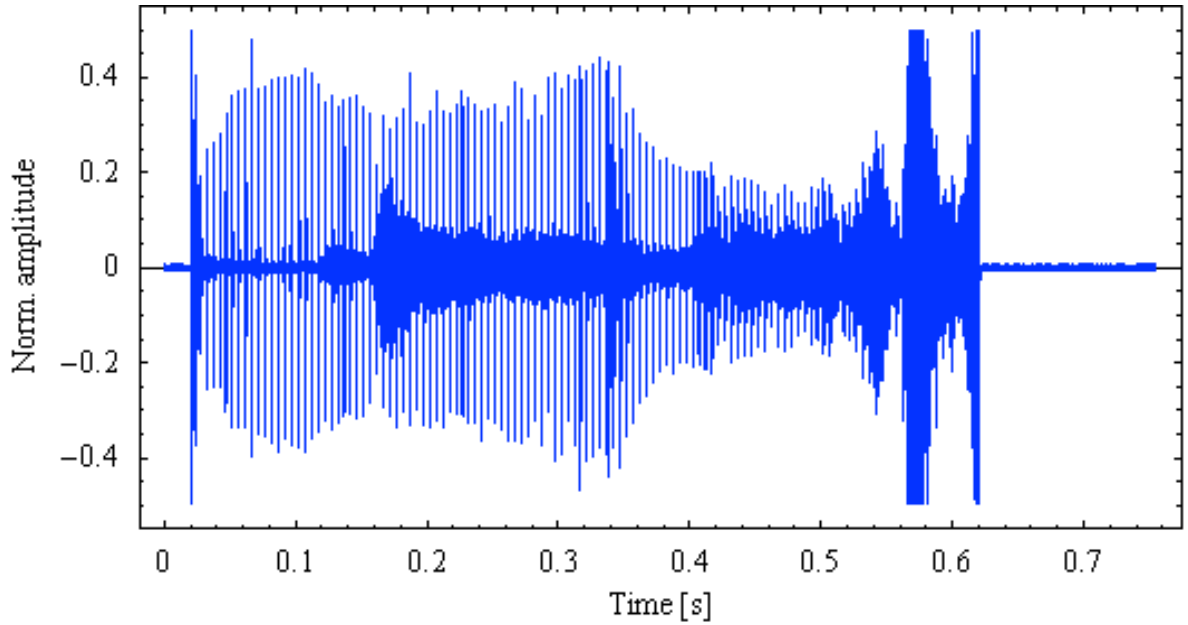
Like on a "balançoire", to keep the oscillations bounded in amplitude, one has to avoid to excite the beam in a resonant way.

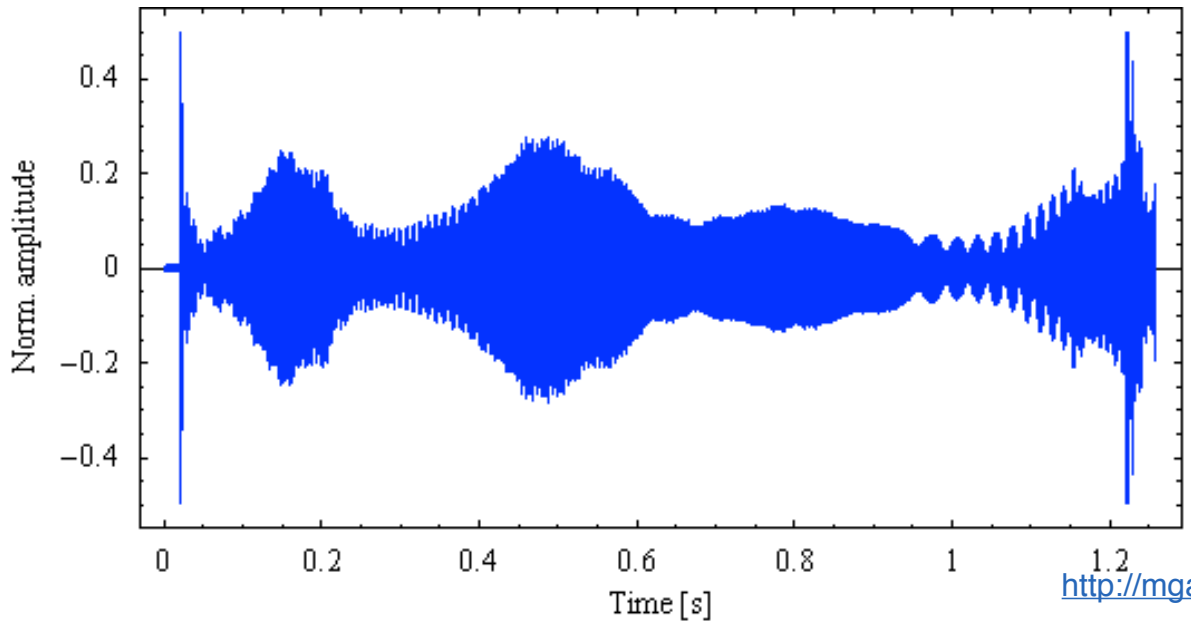
The tune has to be far away from some values, like exciting the beam with the same force at each turn

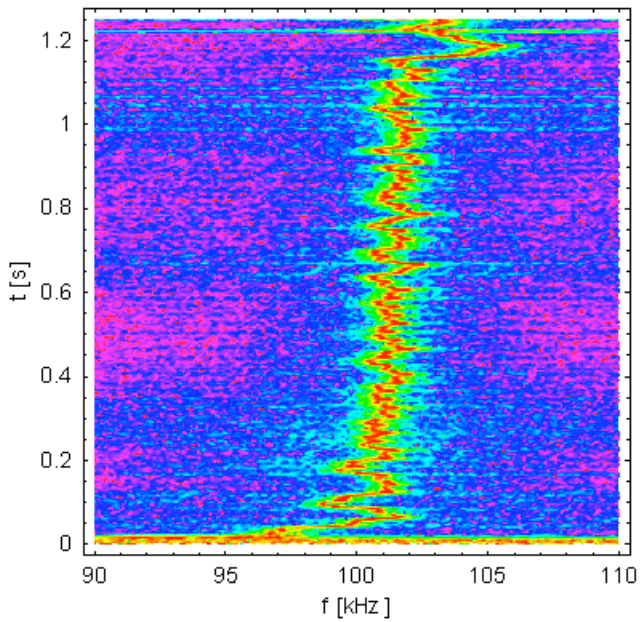




Tune: number of betatron oscillation in the transverse plane

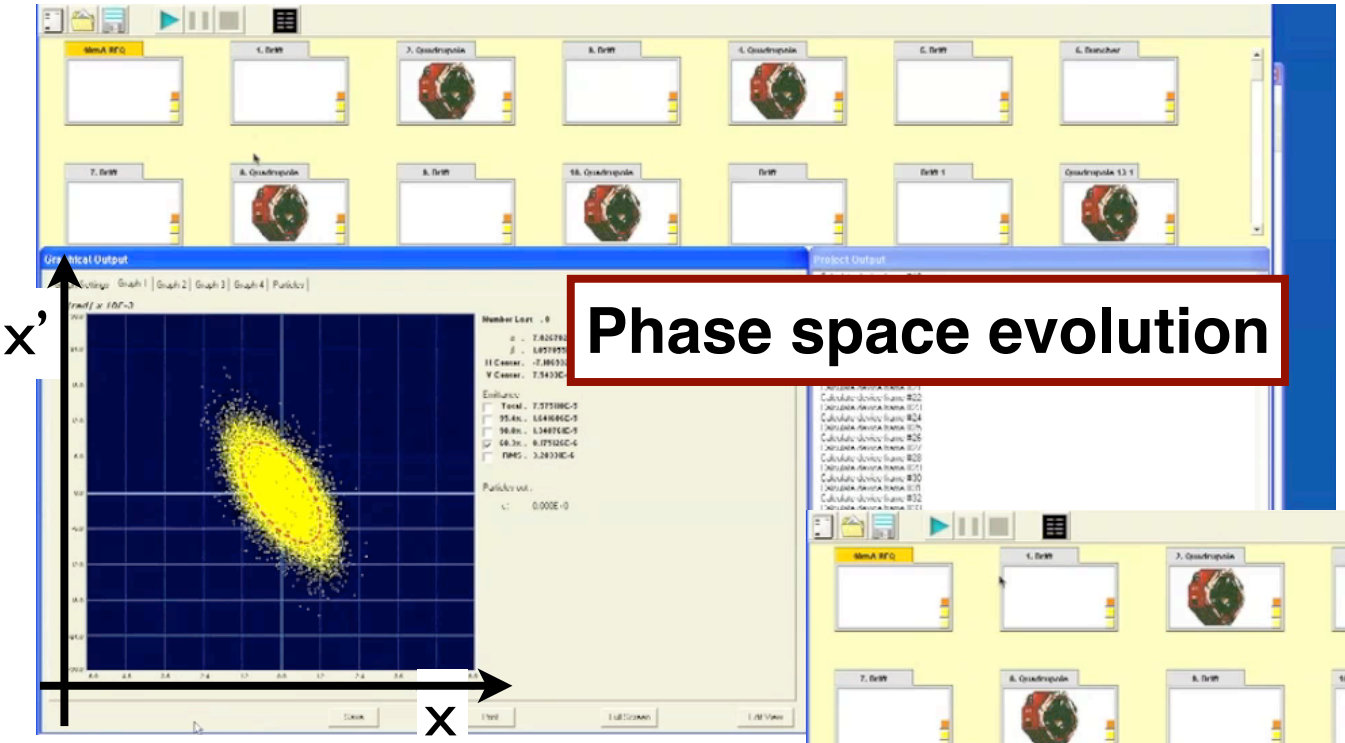


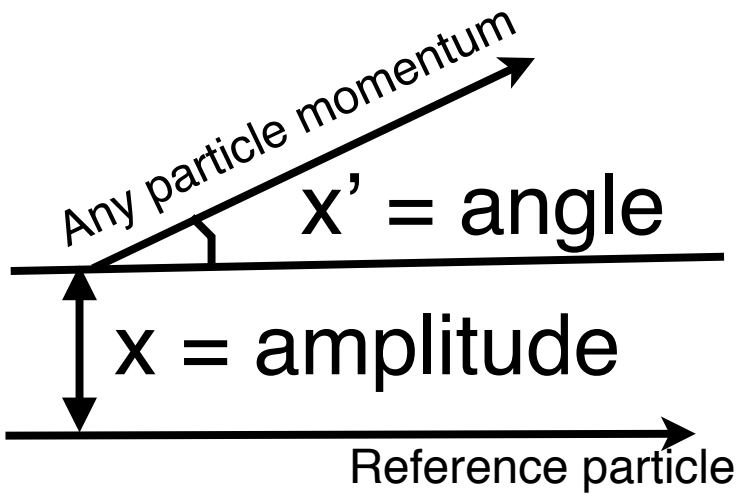


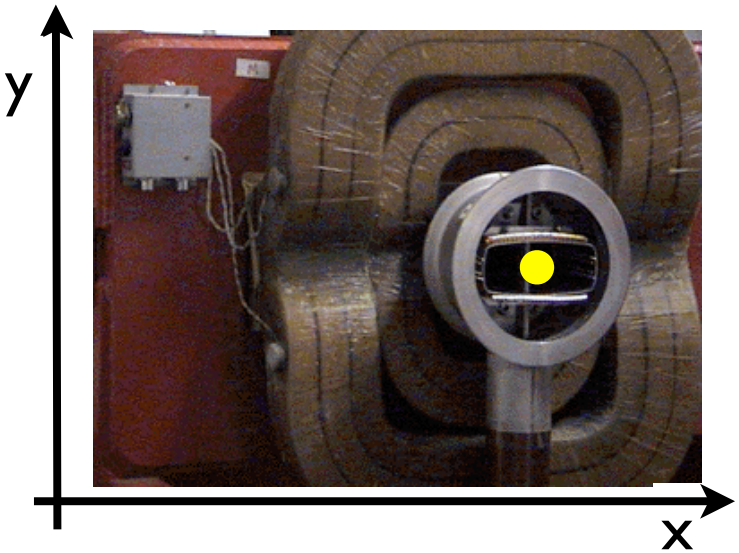


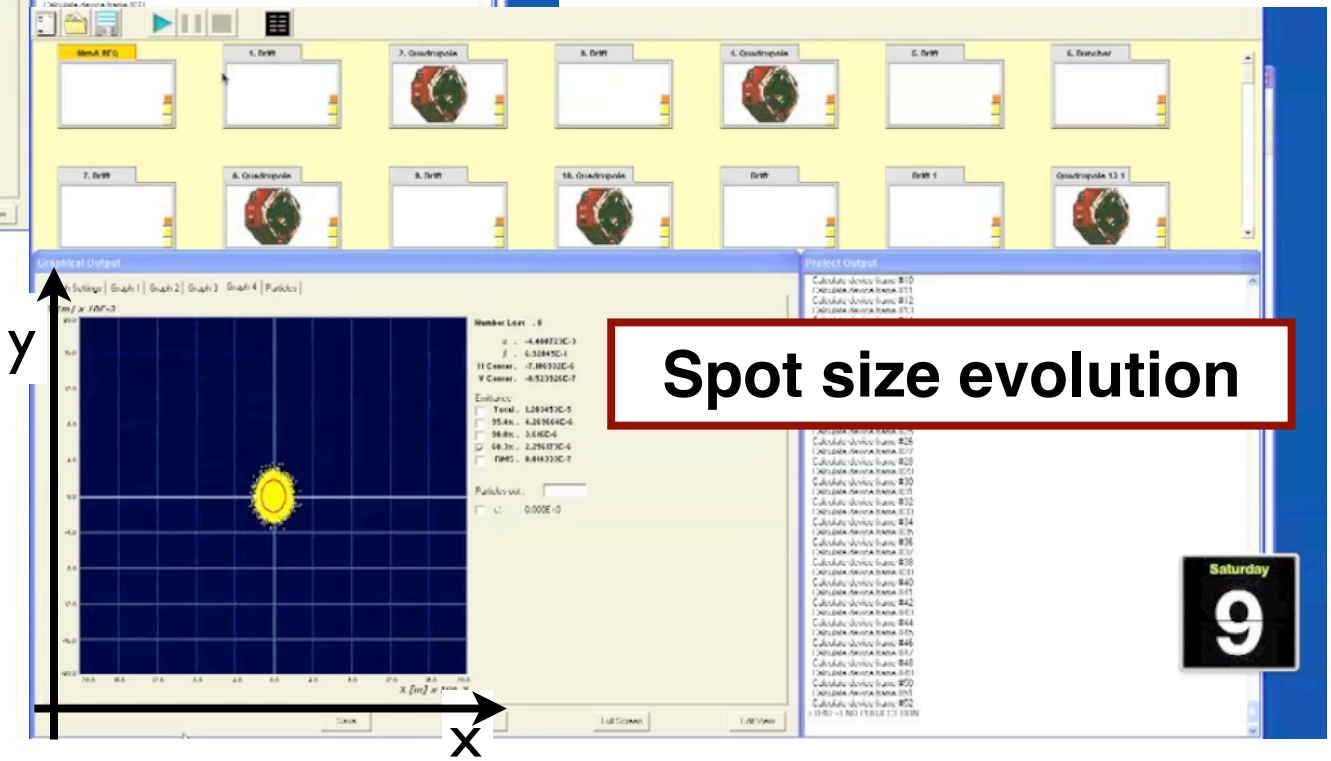
http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html

Particle transport in a lattice





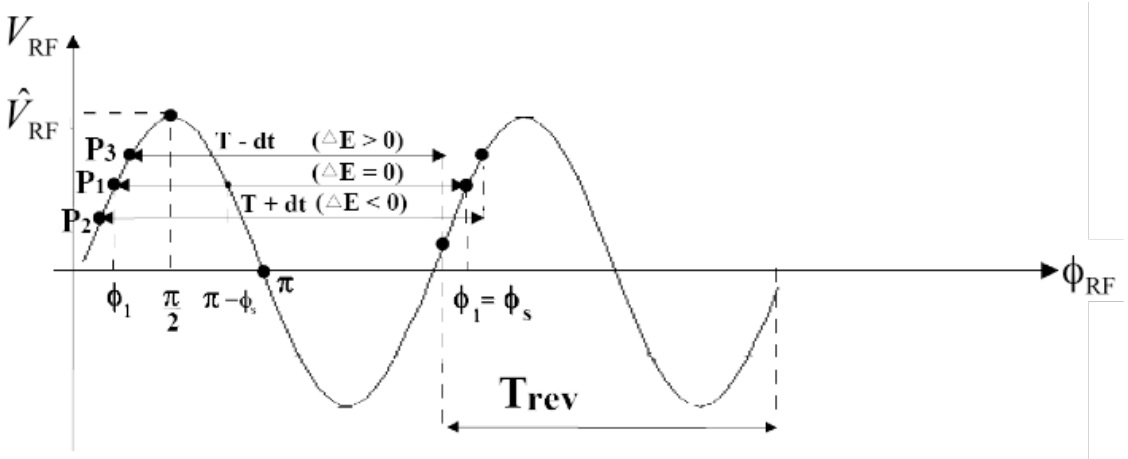


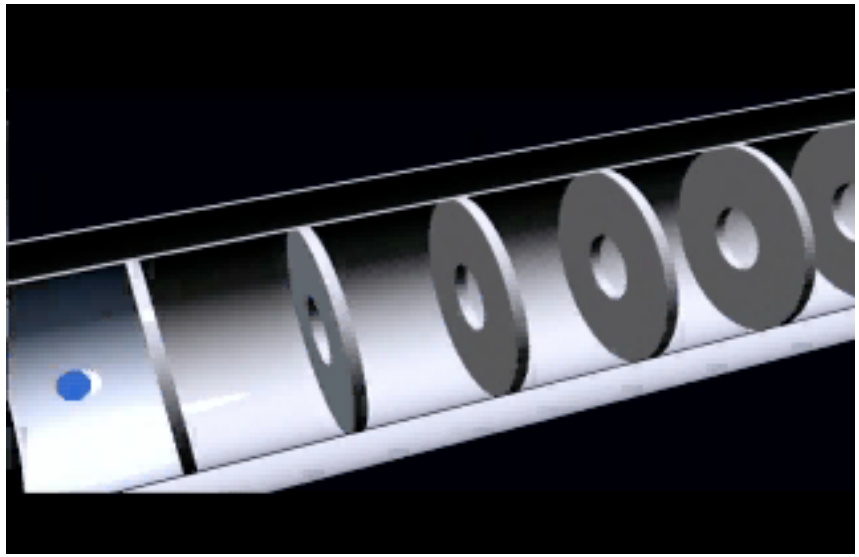


Acceleration

- 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.**

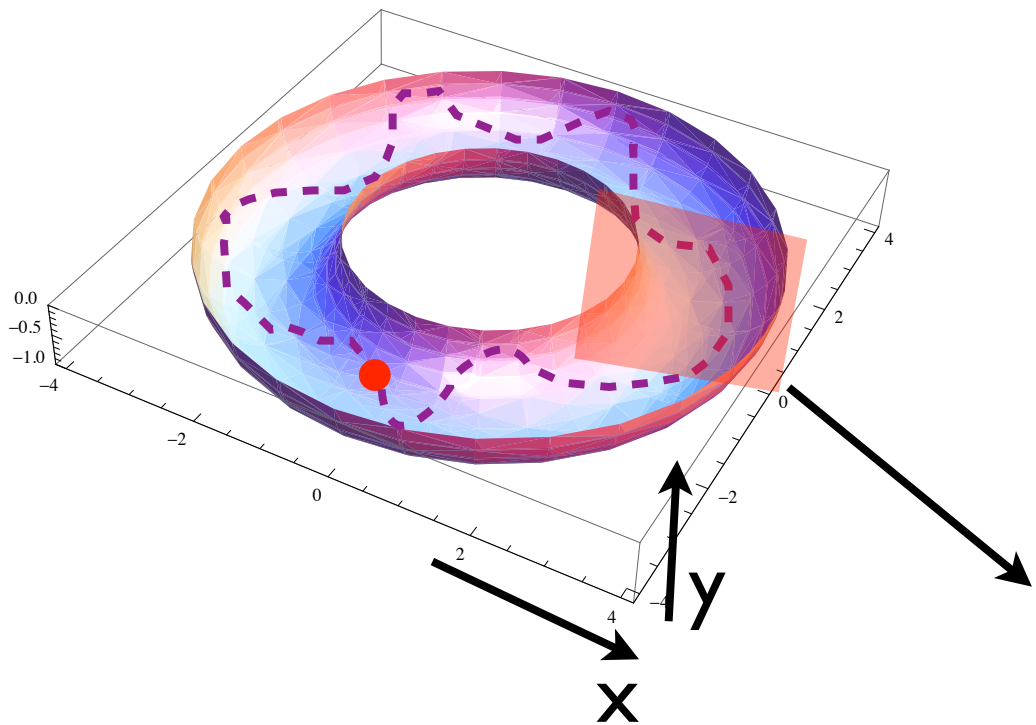
$$\Rightarrow \Delta E_1 = e\,\hat{V}_{\mathrm{RF}}\,\sin\phi_1$$

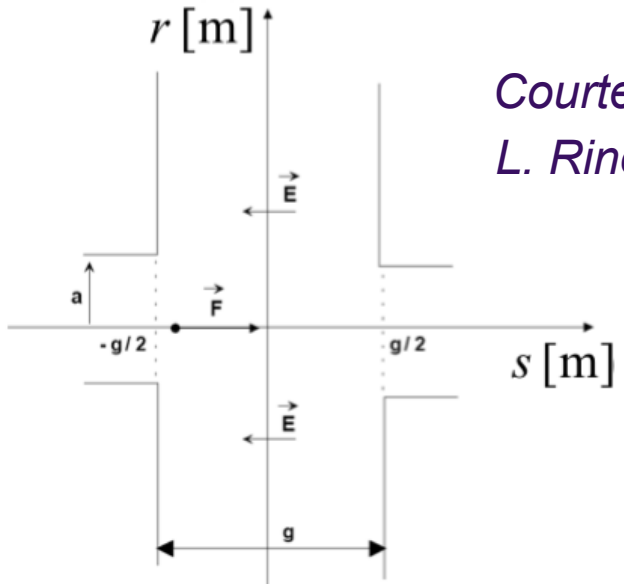




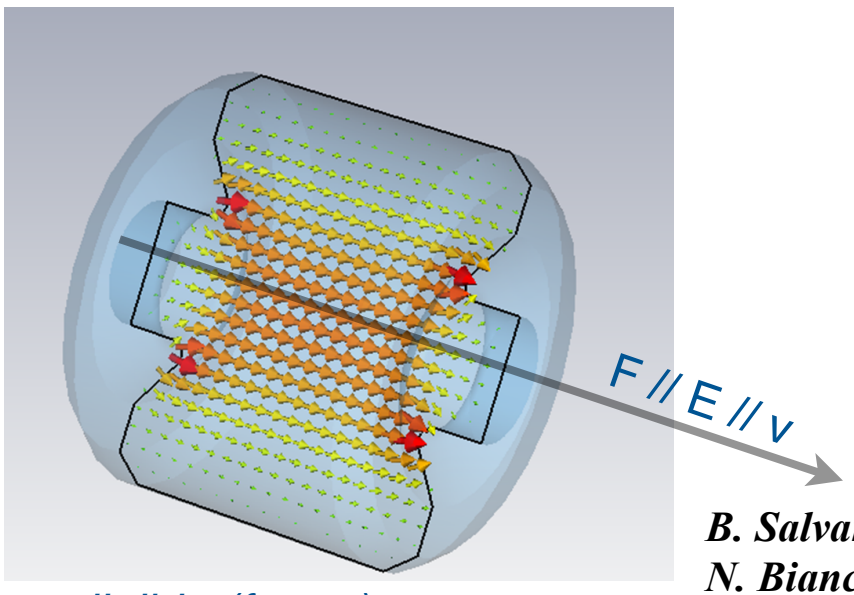
Acceleration I

Acceleration again with Lorentz force: $$\overline{F(t)} = q\left(\overline{E(t)} + \cancel{\overline{v(t)}} \otimes \cancel{\overline{B(t)}}\right)$$





Courtesy L. Rinolfi

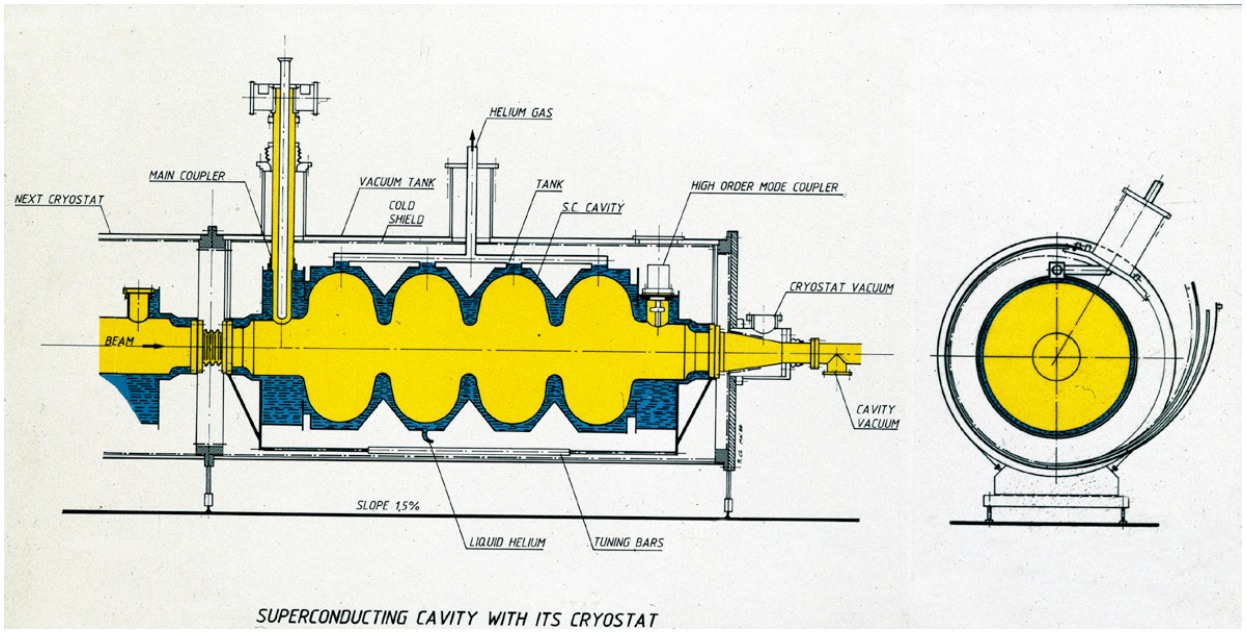


B. Salvant
N. Biancacci

In a well defined part of the accelerator,
a RF (radio frequency) cavity generates an electric field parallel to the velocity of a zero divergence particle.
The cavity itself acts as a resonator.

Obs: The magnetic field associated to the RF wave is negligible (for us).

RF systems, LEP, LHC



Example for LHC:

485 keV gain per turn
ACCELERATION TAKES TIME

How long is a wave?
fcav= 400 MHz

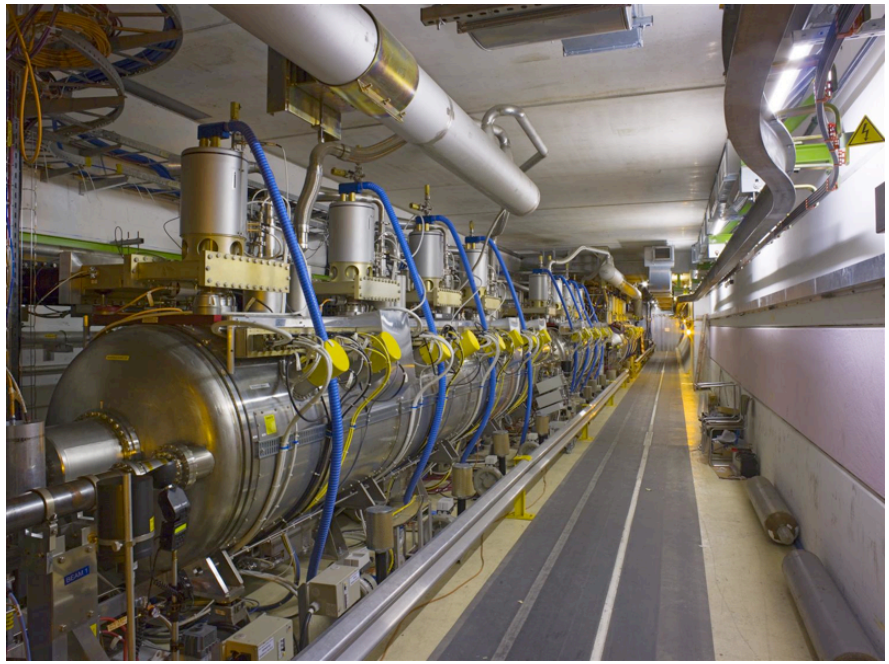
λ= c / fcav ~ 75 cm

A typical cavity can provide from few kV/m few MV/m

Example for LEP:

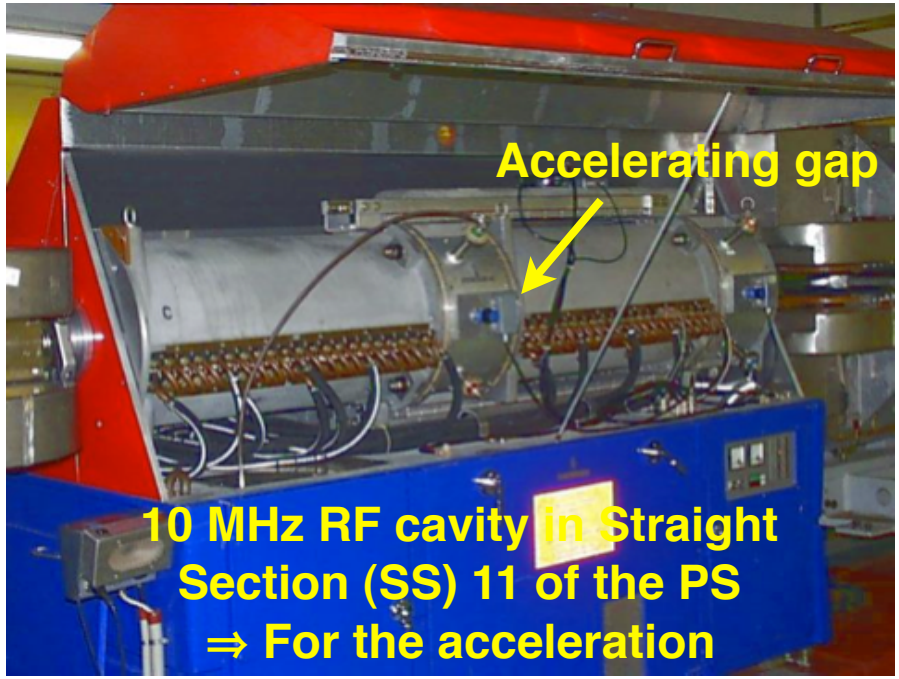
120 cavities (room temperature) at 352 MHz,
provided over **300 MV circumferential voltage**
(! that's why we do not bend with E fields...)

Then, the new superconducting RF provided
2000 MV circumferential voltage
(LEP was 27 km circumference, basically filled by RF cavities)



Example of RF cavities in the PS

The dimension of the cavity changes with the RF wave length

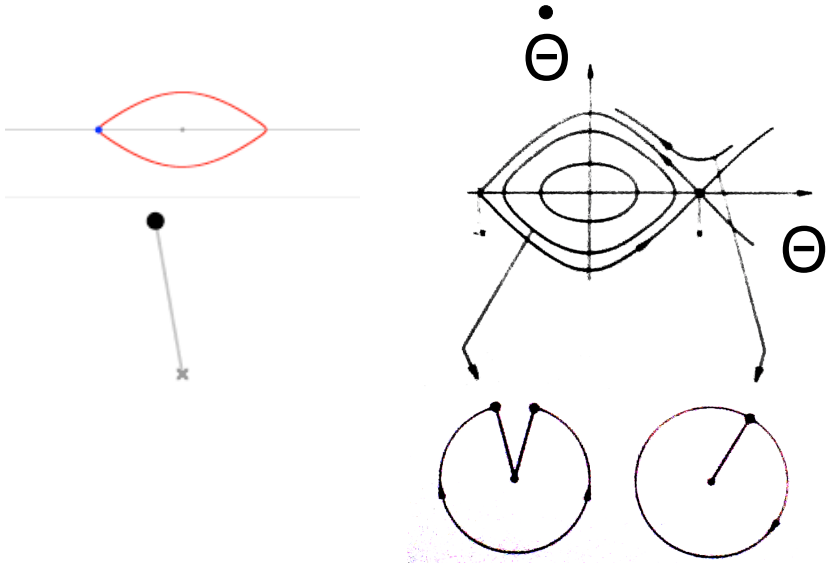


World Radio Switzerland: 88.4 MHz

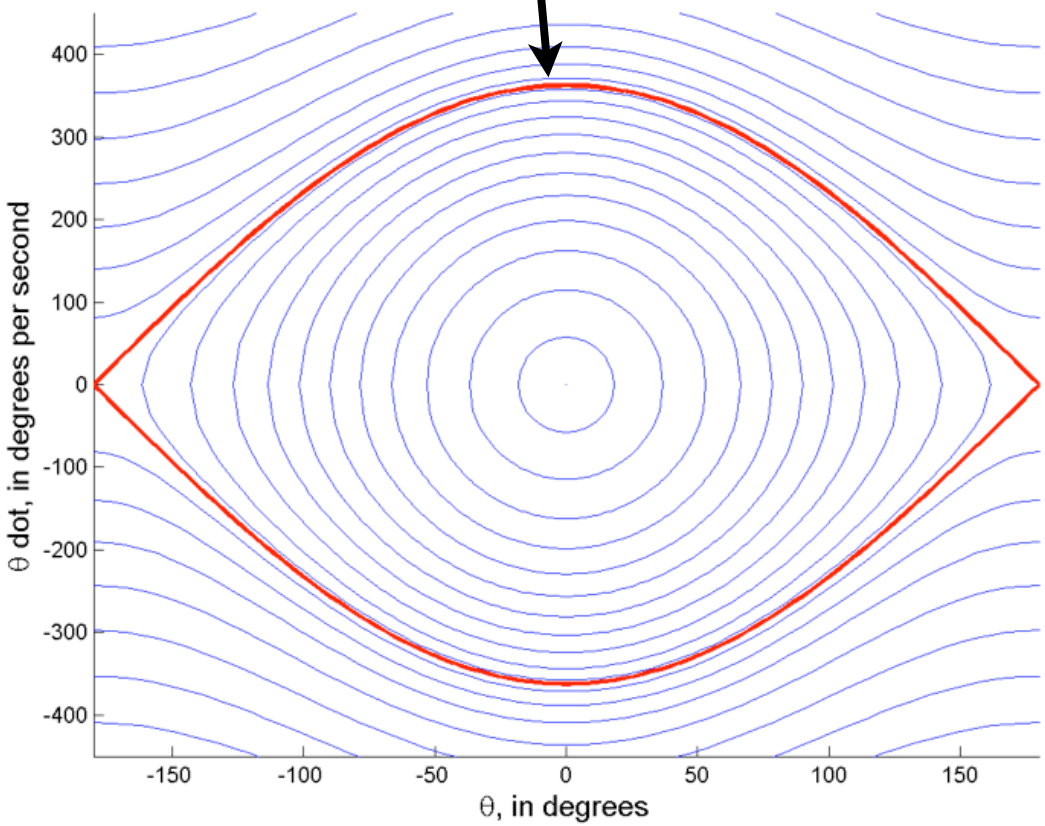
Longitudinal dynamics
Classical mechanics.... oscillating pendulum

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin\theta = 0$$

Constant force:
g = acceleration of gravity
l = pendulum length

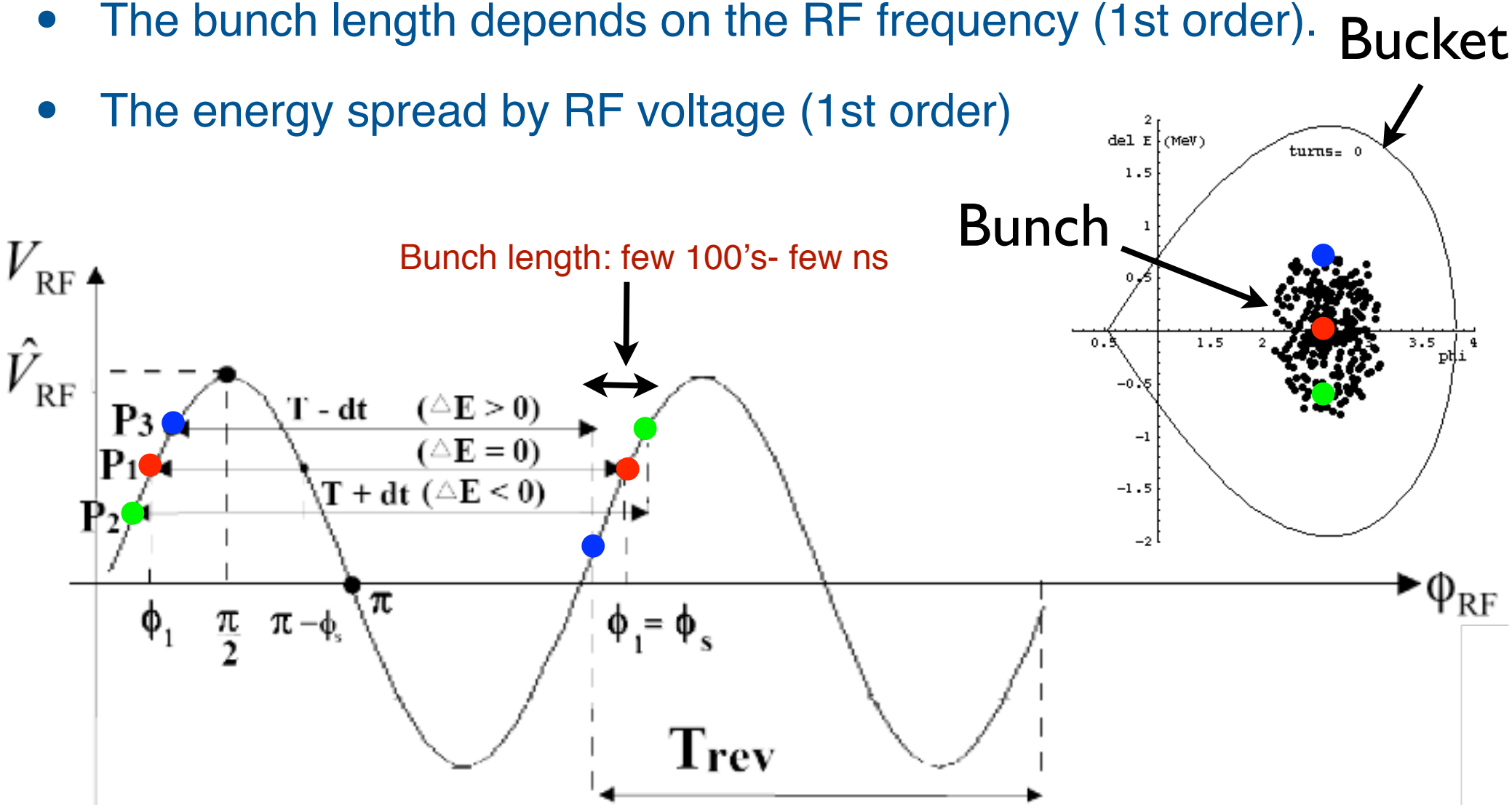


The movement is stable only inside the separatrix



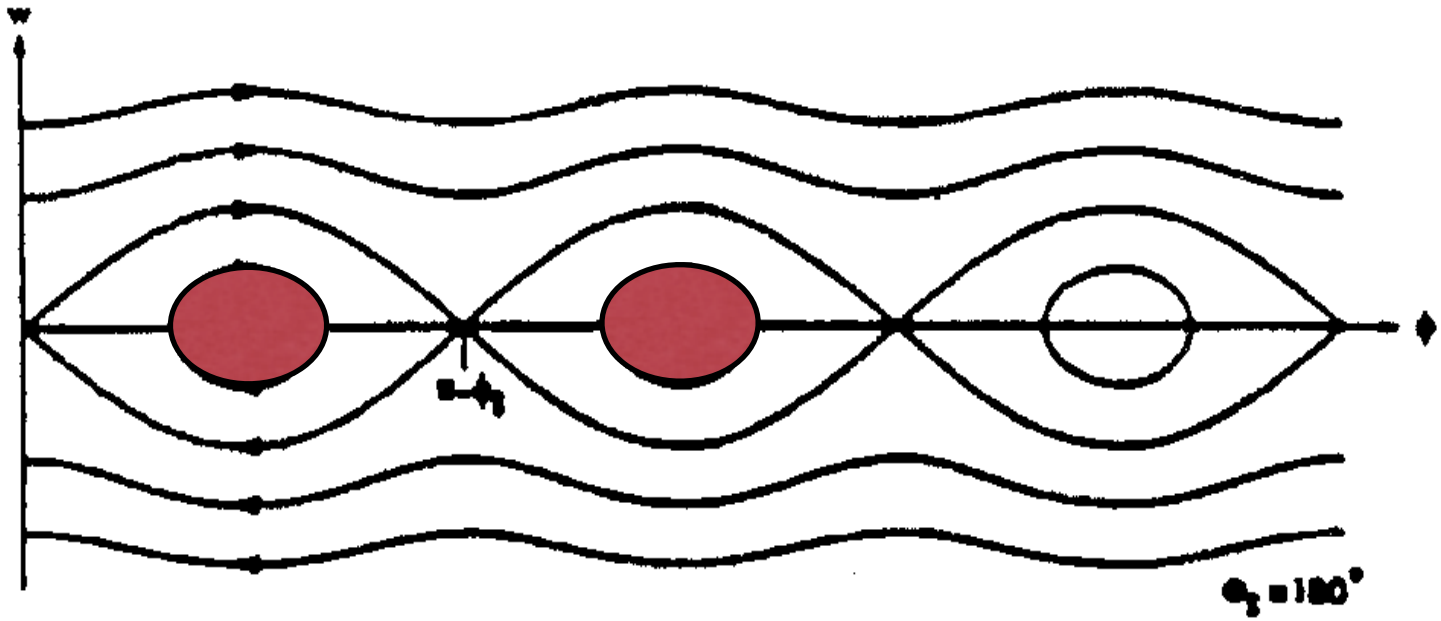
Longitudinal focusing, as the pendulum ...

- Particles are confined within a range in phase and energy called **BUCKET** and are grouped into **bunches by the electric field**.
- The bunch length depends on the RF frequency (1st order).
- The energy spread by RF voltage (1st order)



One machine turn ~ some (hundred)microseconds

A chain of buckets



Courtesy
E. Wilson

Number of buckets:

possible positions along the machine circumference where ***there could be a bunch.***

In the example: 3 buckets and 2 bunches

Summary part I ....

- **Lattice of a machine:**
  - sequence of *dipoles* (to bend), *quadrupoles* (to focus), and *RF cavities* (to accelerate or keep the beam bunched)
- **A synchrotron** is an accelerator where:
  - Magnetic fields and energy change in a synchronous way to keep the beam on a fixed radius of curvature
- **The beam is described by:**
  - *Transverse emittance*: surface occupied on the (displacement, divergence) plane by a group of particles
  - *Longitudinal emittance*: surface occupied on the (time, energy) plane by a group of particles defined as a bunch sitting in a bucket

[redacted]