Introduction to accelerators

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SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

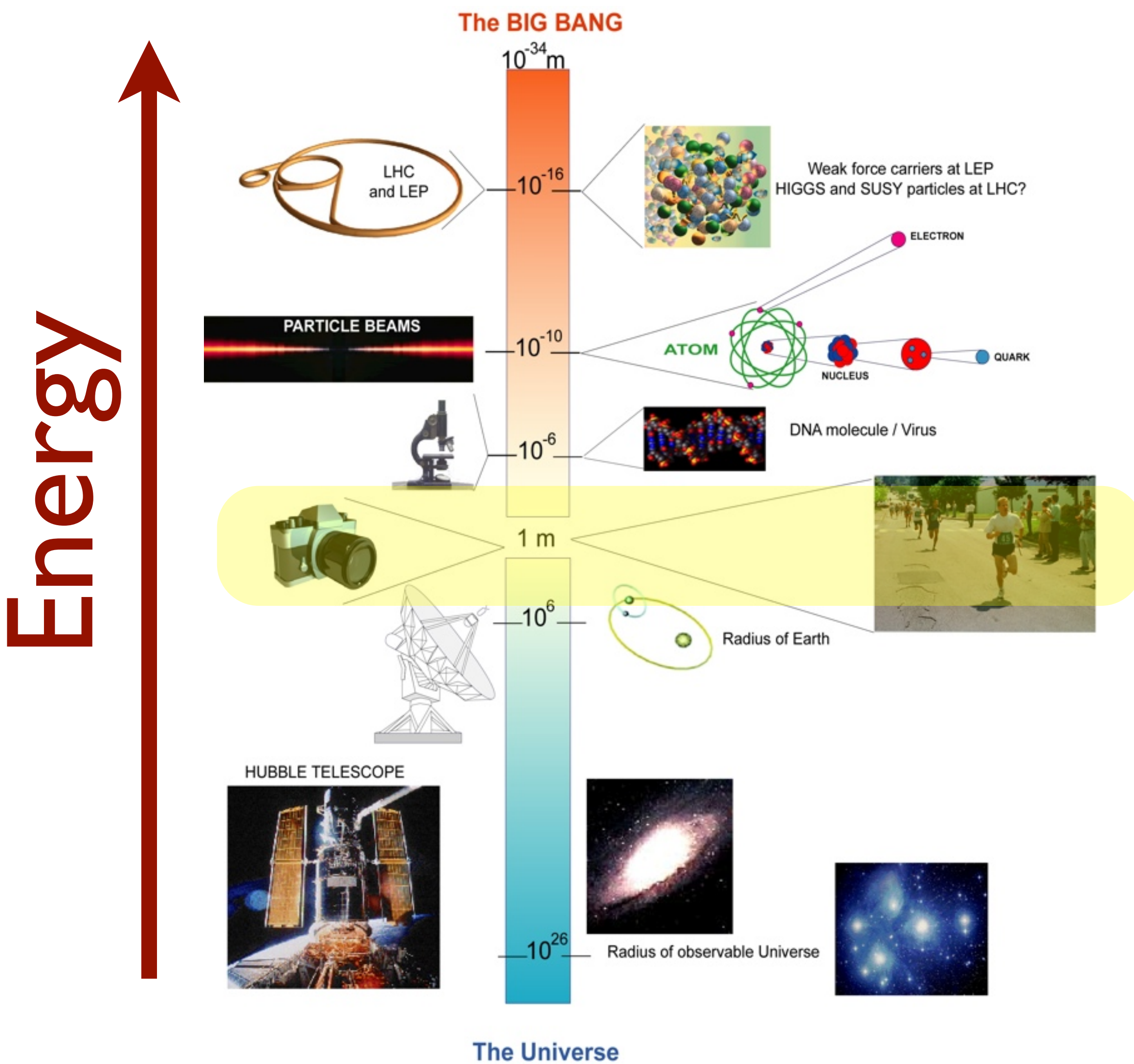
Press Release PR/56
12 February, 1960

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

The right instrument for a given dimension



Wavelength of probe radiation should be smaller than the object to be resolved

$$\lambda << \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy of Radiation
Atom	10^{-10} m	0.00001 GeV (electrons)
Nucleus	10^{-14} m	0.01 GeV (alphas)
Nucleon	10^{-15}m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons)

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.

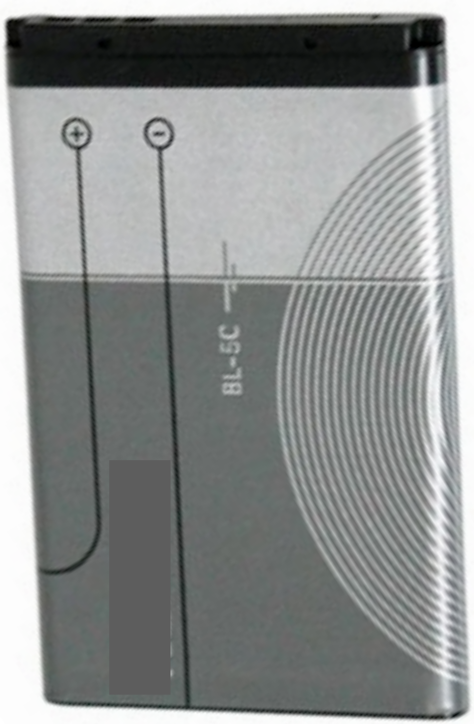
"electronic eyes"

The typical energy of our life is eV

So, how we can reach the energy/dimension of the big bang?

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.

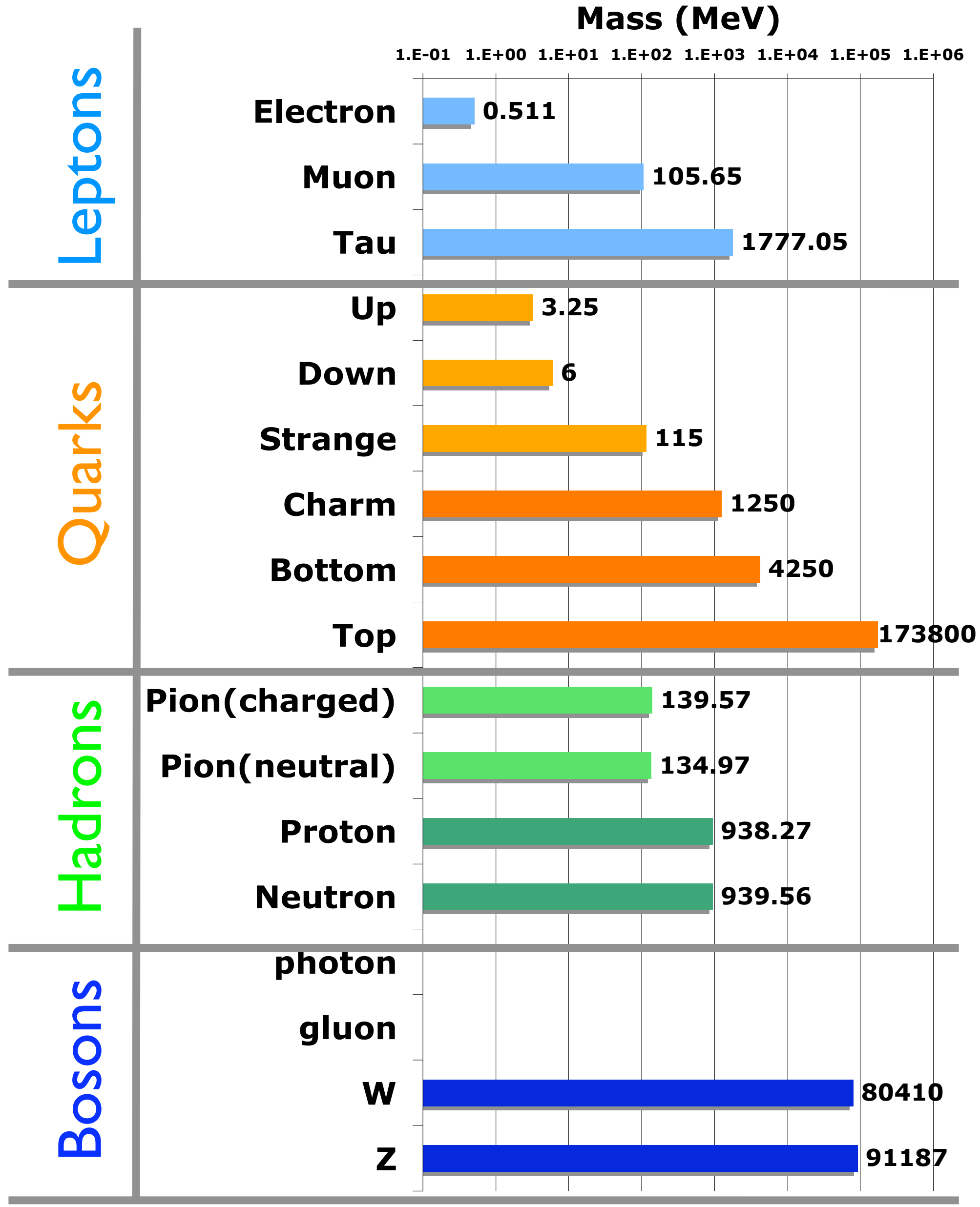
Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to

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

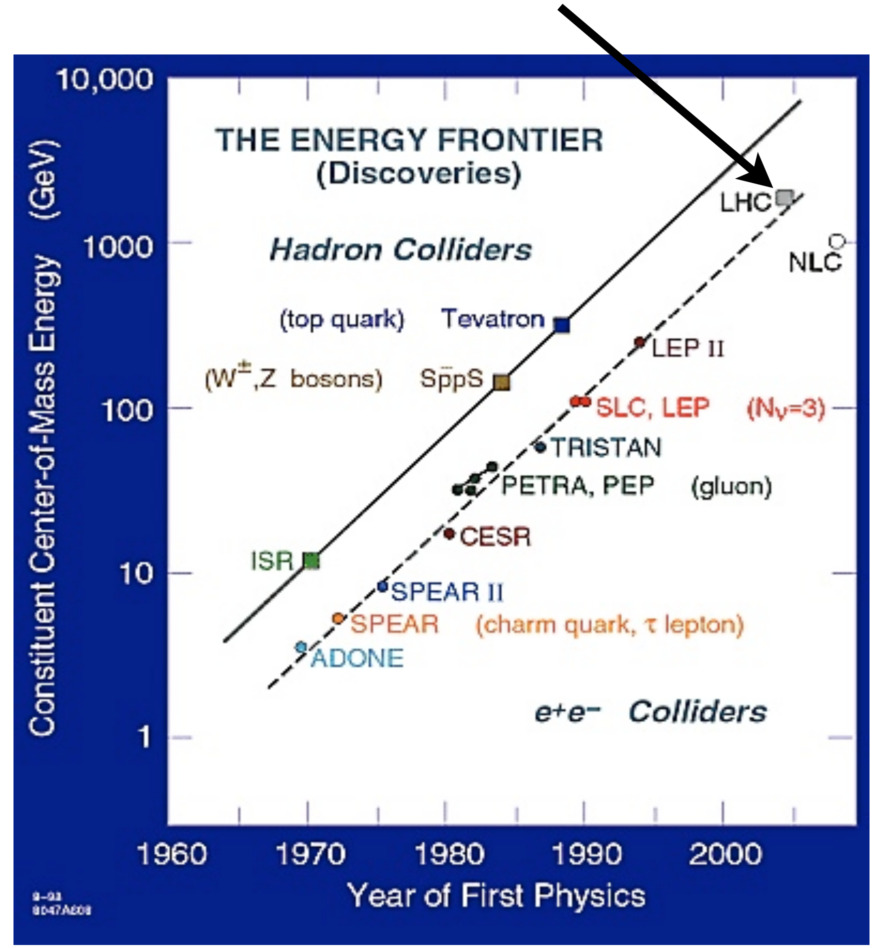
12 000 000 m ~ THE EARTH DIAMETER

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



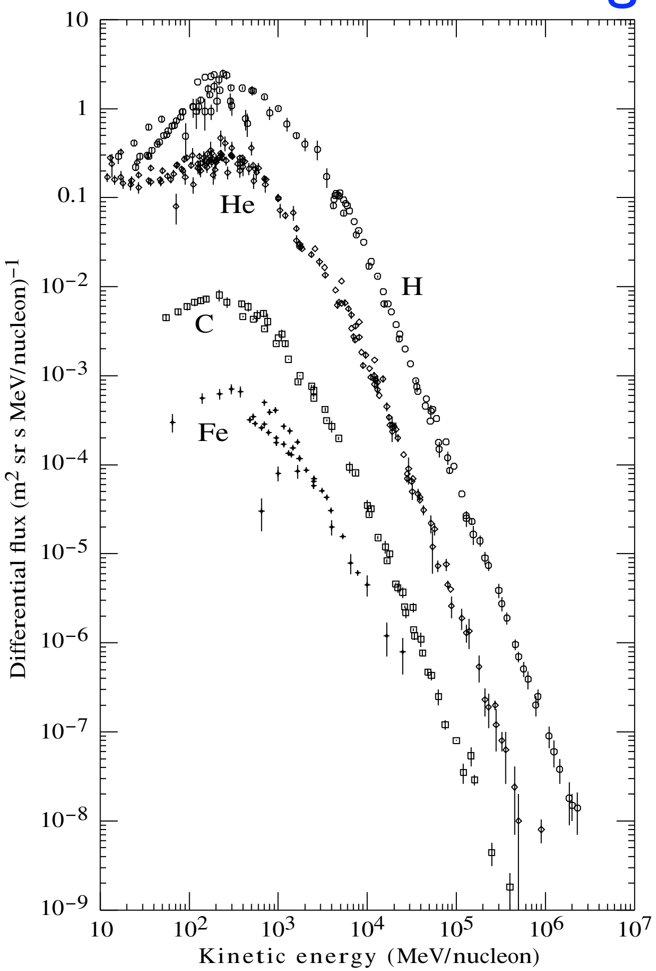
Constant increase in energy to discover heavier and heavier particles or very rare processes

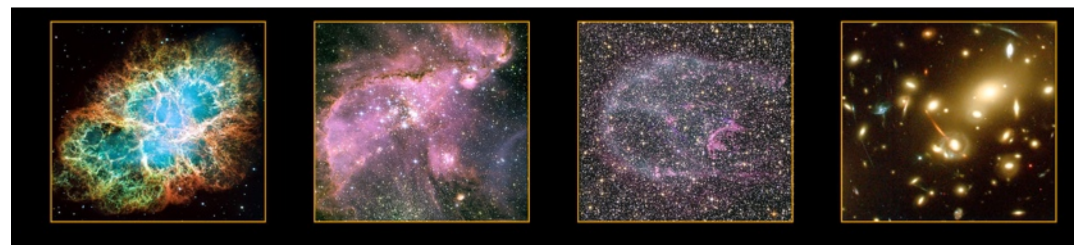
Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\overline{p}$ as Tevratron, p-p as LHC)

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.



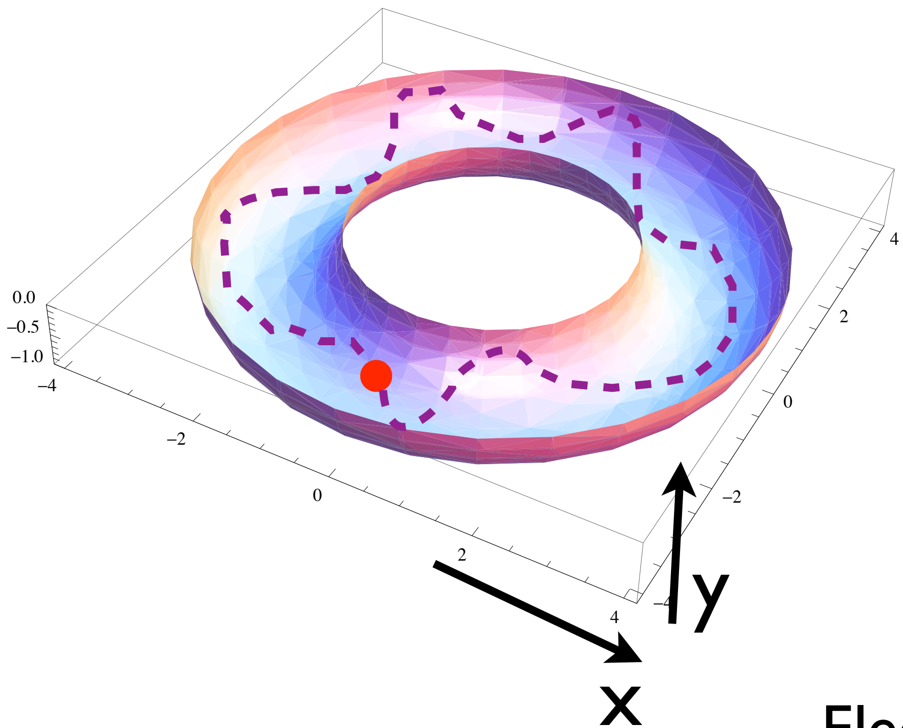


The cosmo is already doing collisions with different mechanisms:

while I am speaking about
66 10^9 particles/cm^2/s are traversing your body, with this spectrum before being filtered by the atmosphere.

The universe is able to accelerate particles up to 10^6 MeV protons

How an accelerator works ?



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

b) Accelerating Cavity

Synchrotron (1952, 3 GeV, BNL)

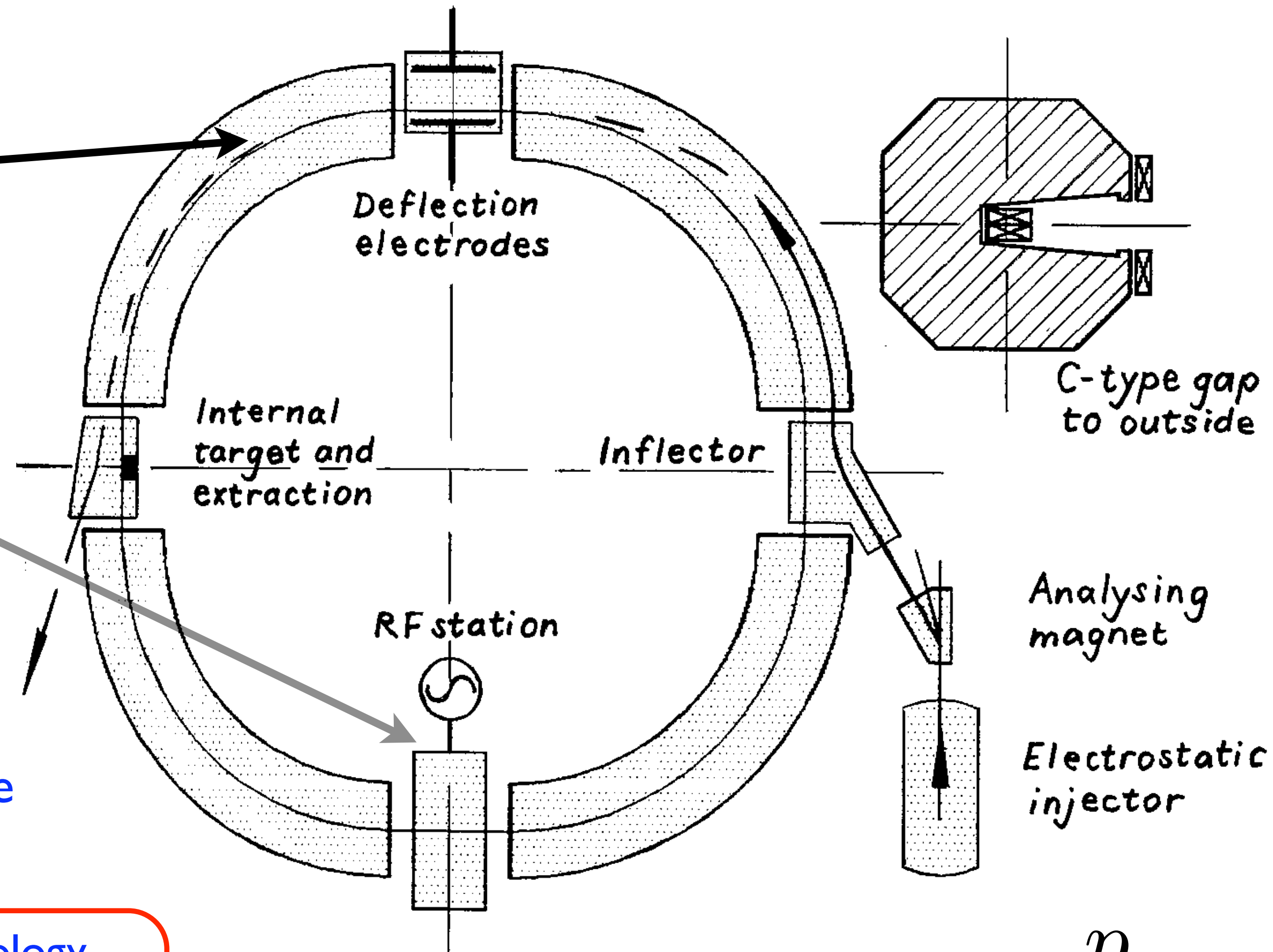
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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

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

e electric charge

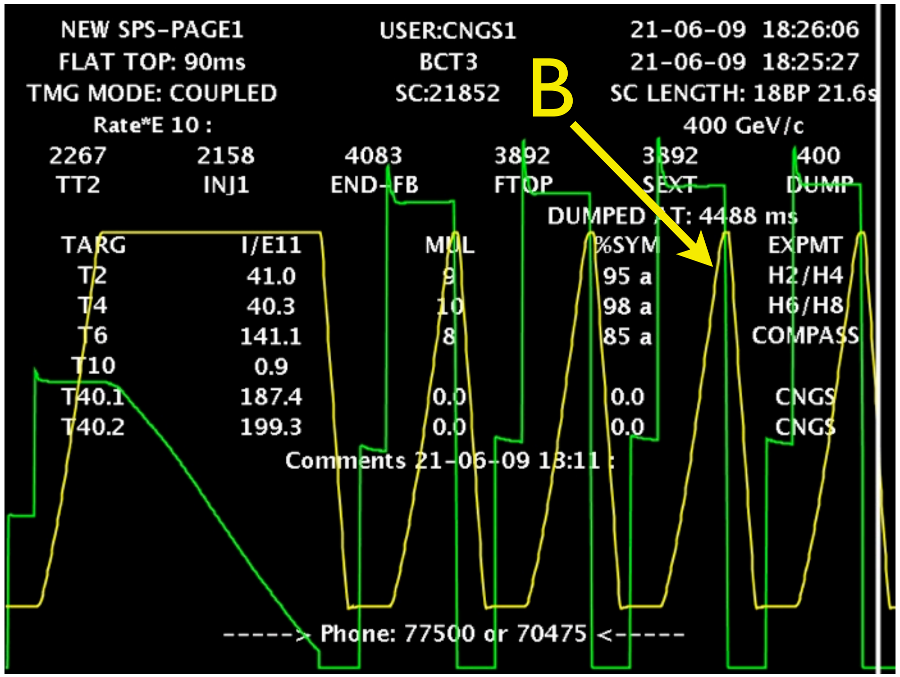
ρ constant radius of curvature



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

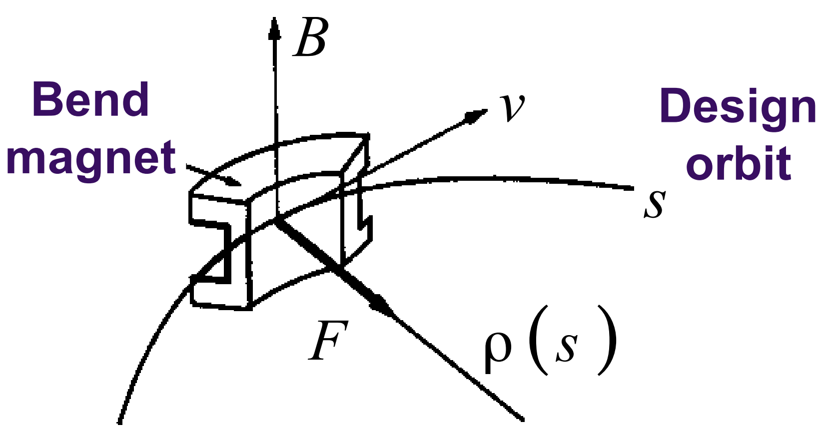
Particle rigidity: $B\rho = \frac{p}{e}$

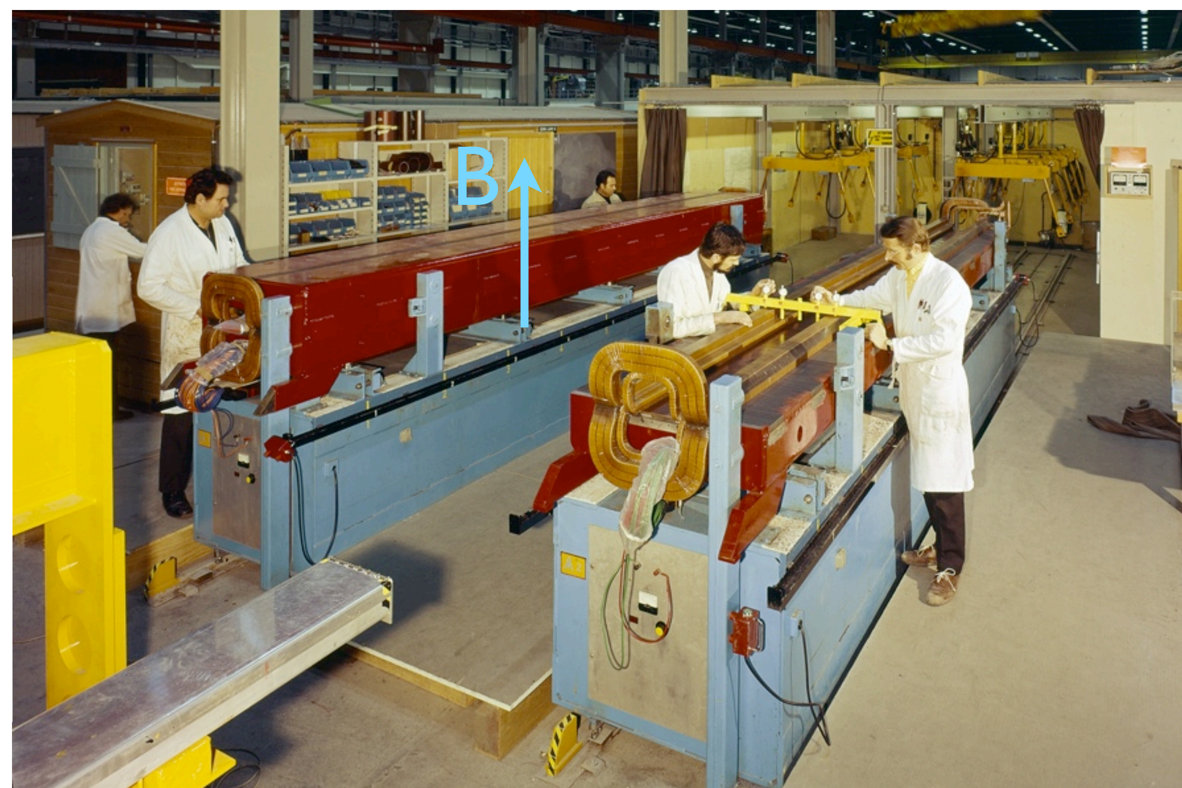
Dipole



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.

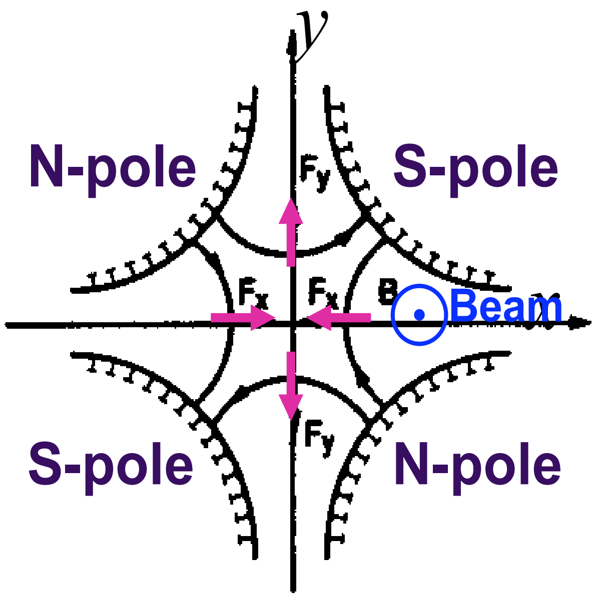
Once the beam accelerates, the magnetic field is increased synchronously

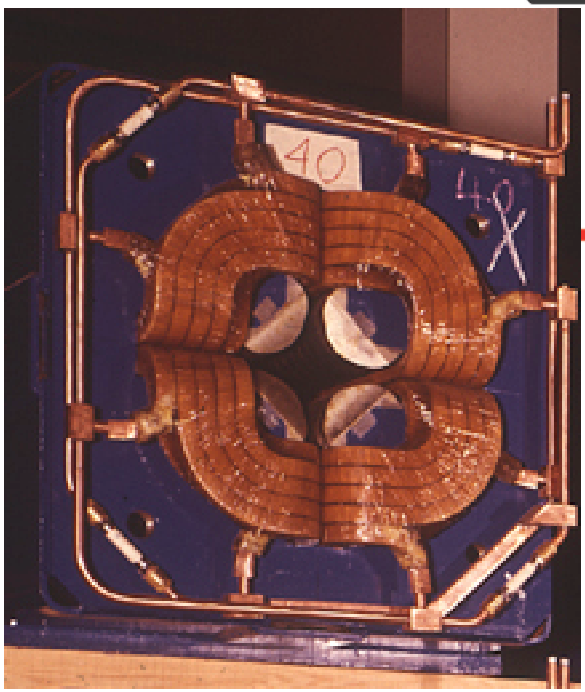


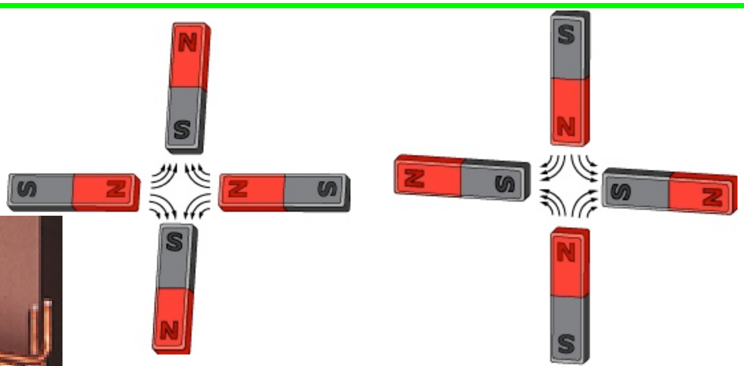


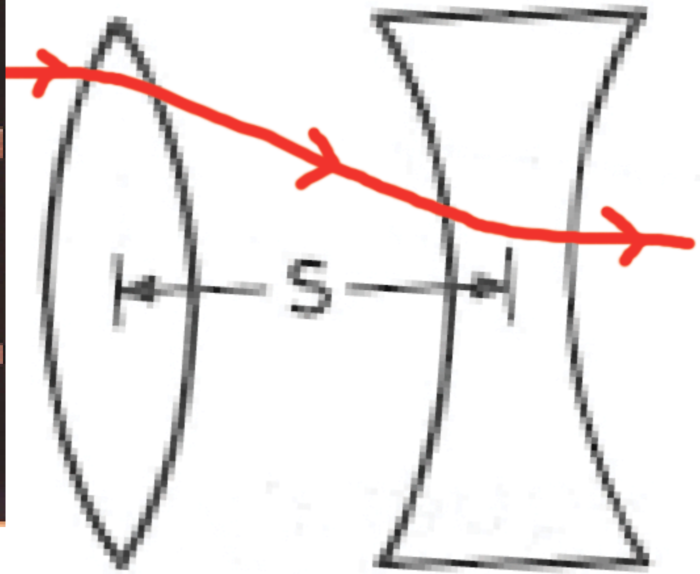
Synchrotrons: strong focusing machine

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).







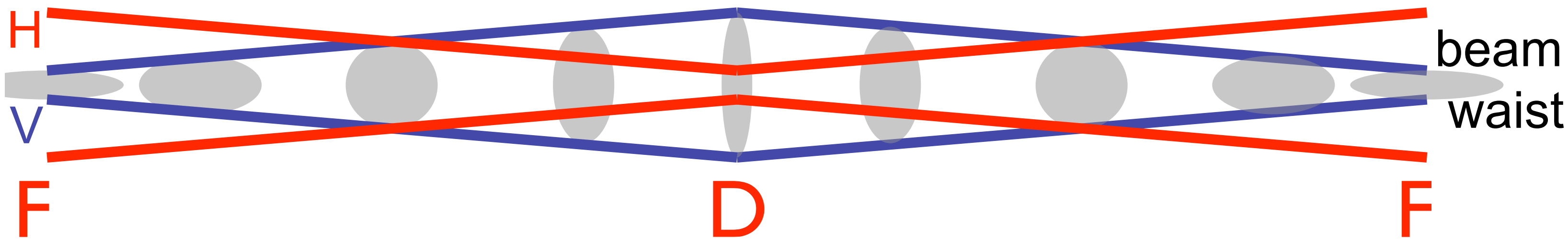


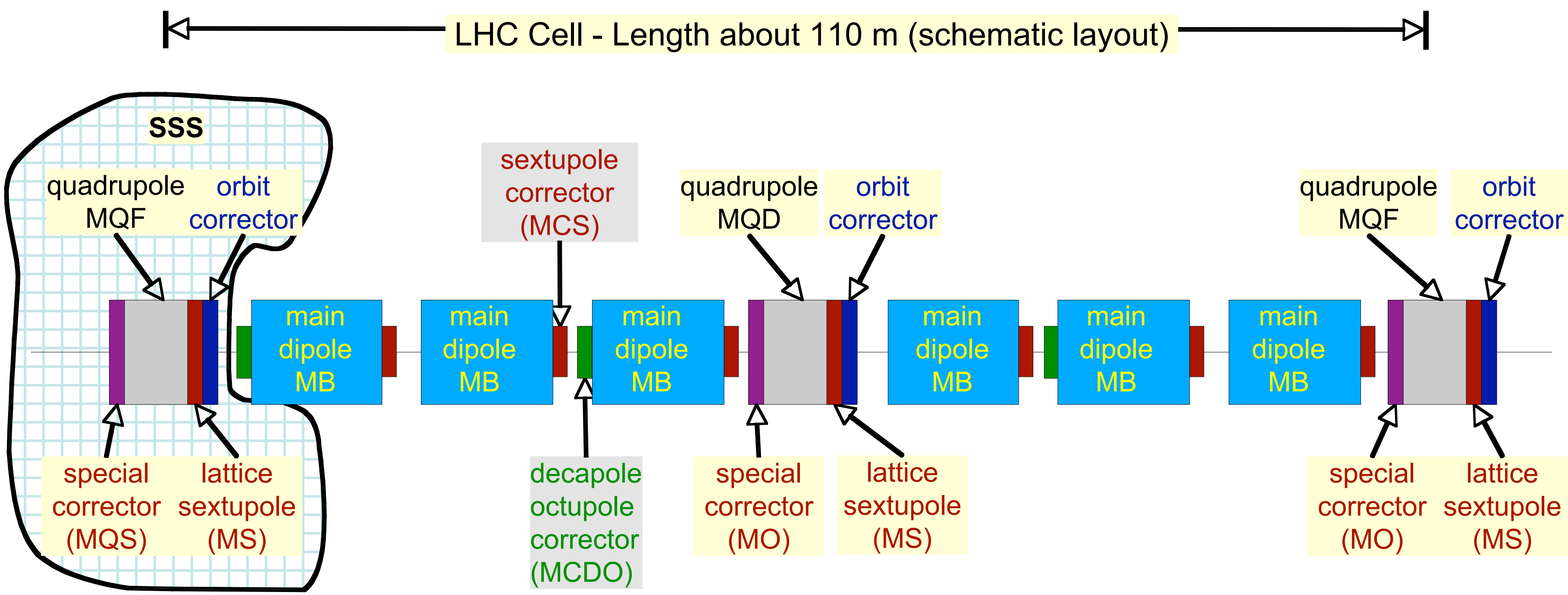
B field is focusing in one plane but defocusing in the other.

Typical lattice is FODO, focusing-drift-defocusing

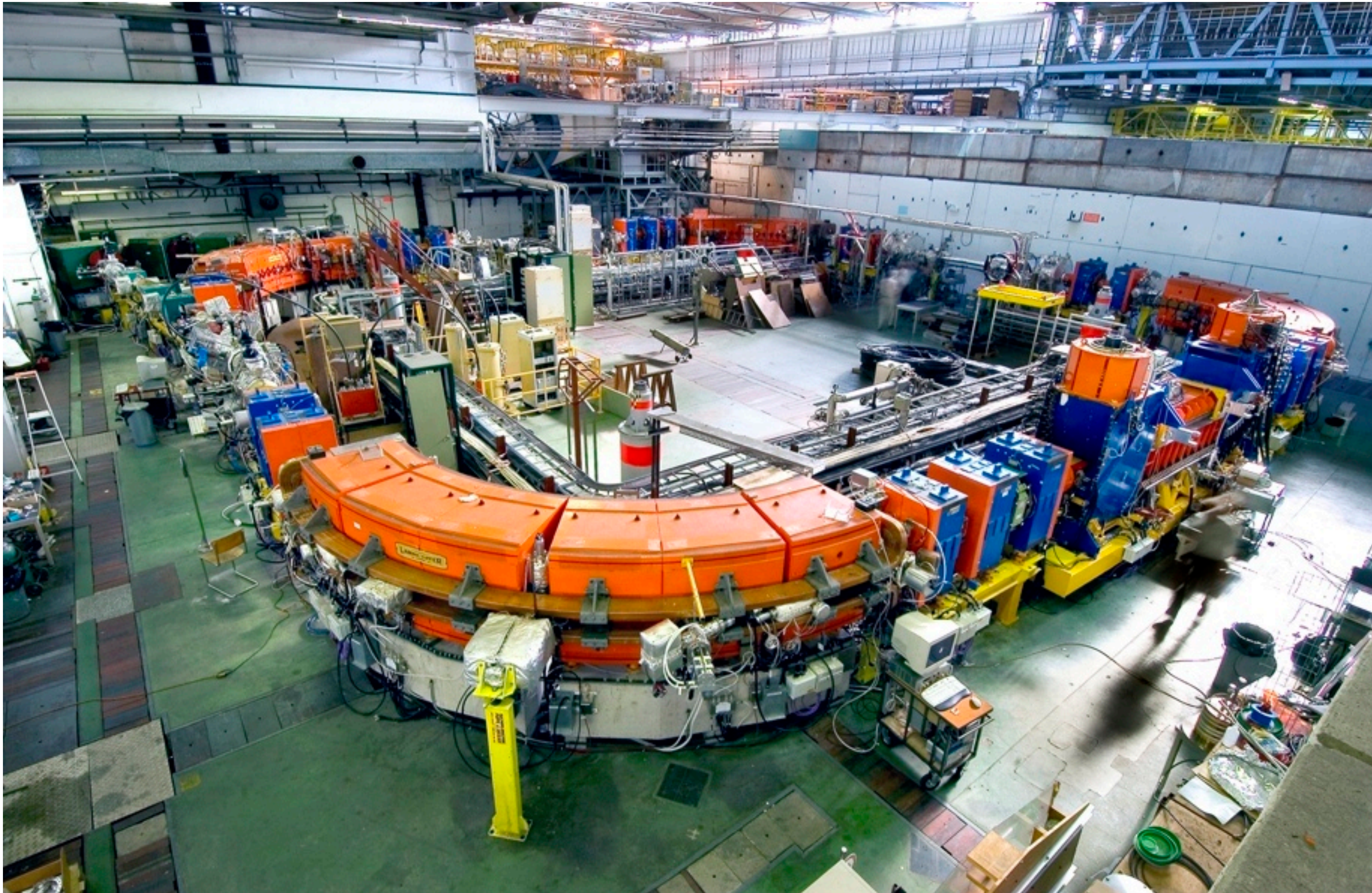
An example of a lattice: LHC cell

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





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



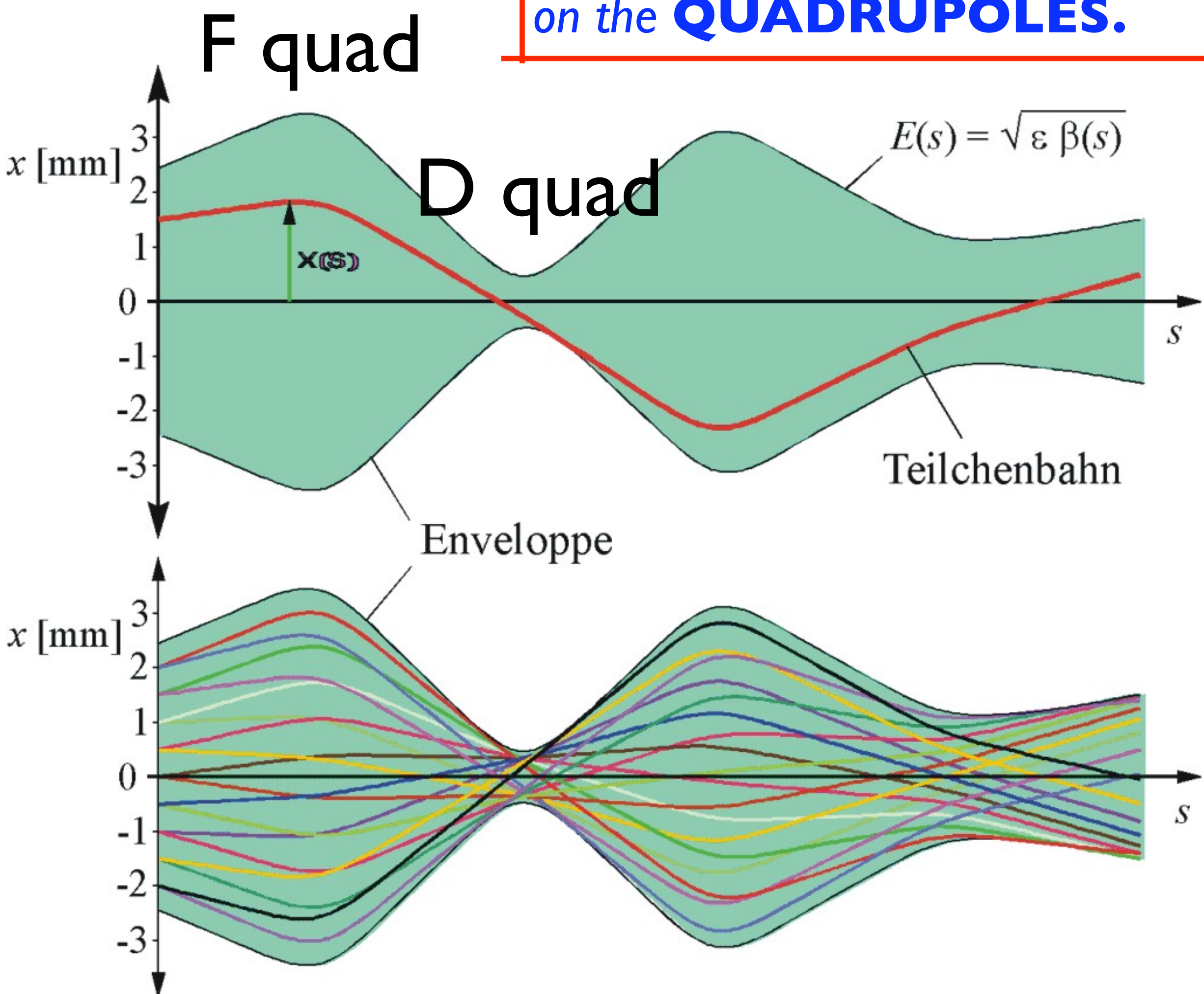
Definition of beam emittance and enveloppe

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

Beam physical dimension

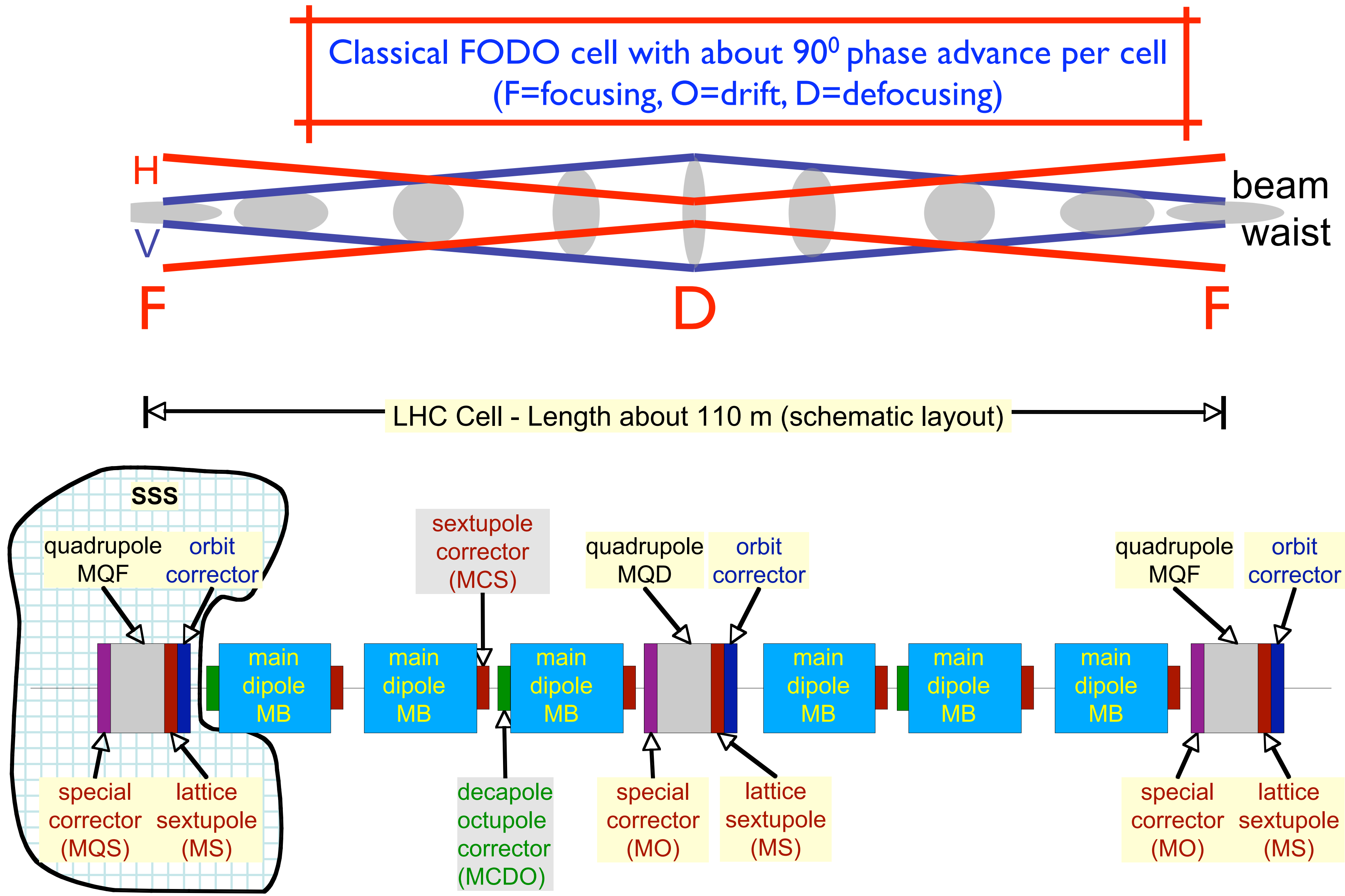
Optical machine parameter that depends on the lattice of the machine, in particular on the ***QUADRUPOLES.***

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

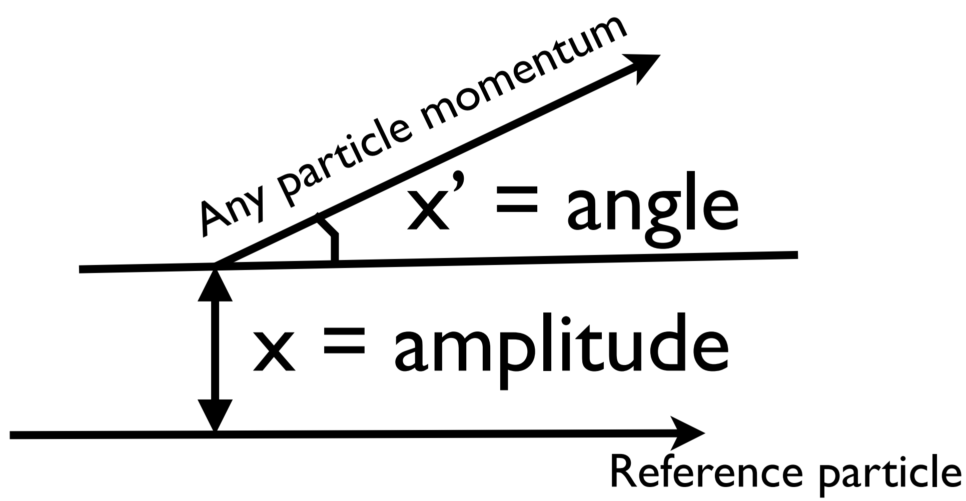


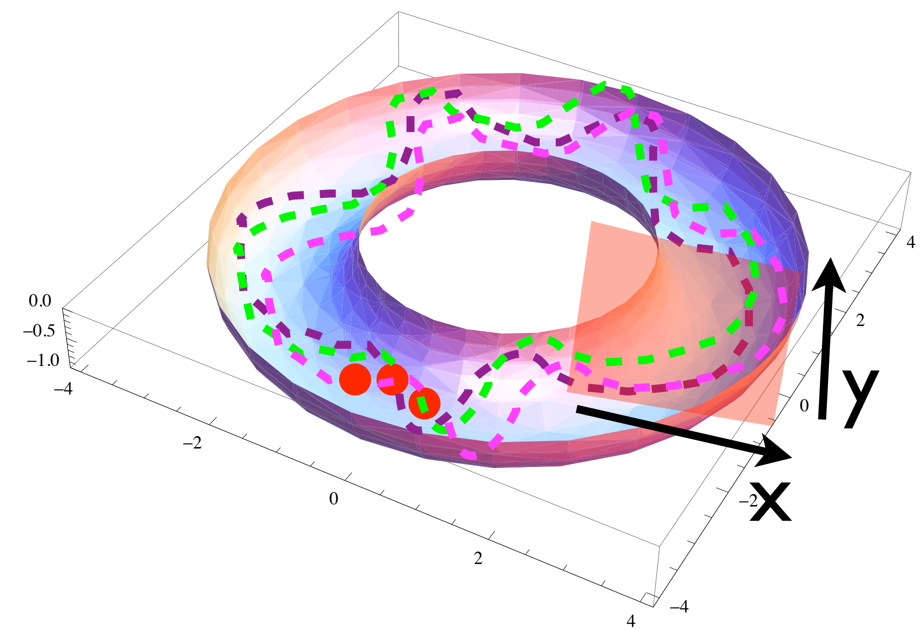
The enveloppe is defined as the maximum amplitude for which the particle remains in the machine vacuum chamber.

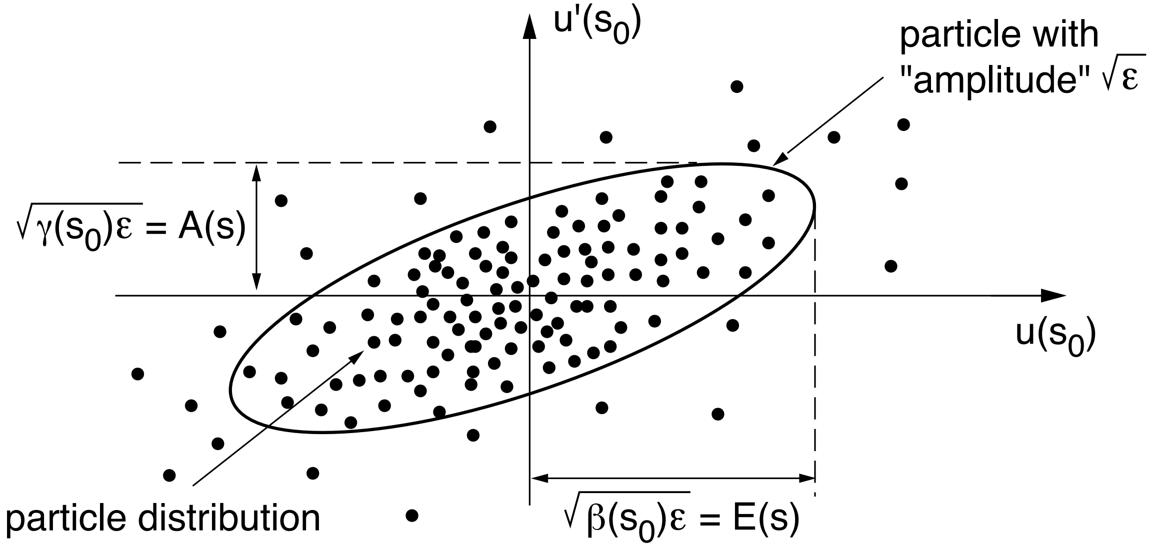
An example of a lattice: LHC cell



Our reference frame: xx', the phase space





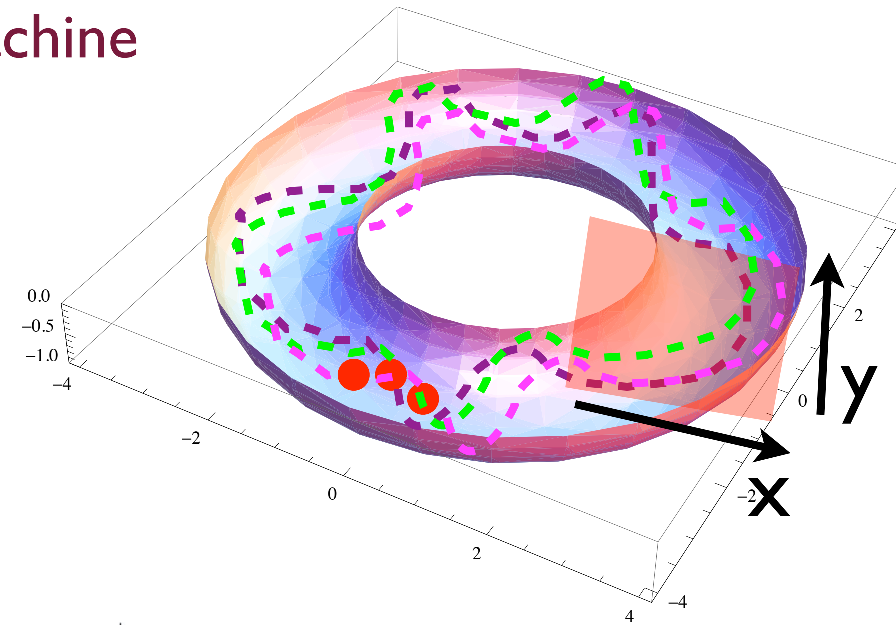


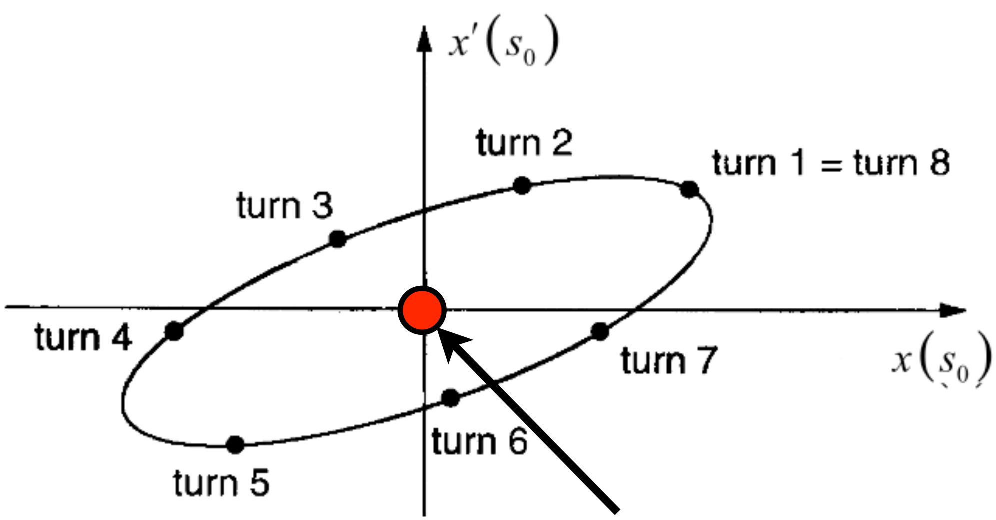
The space occupied in the xx' (or yy') plane by the beam at a given position in the machine is defined as Emittance

Tune

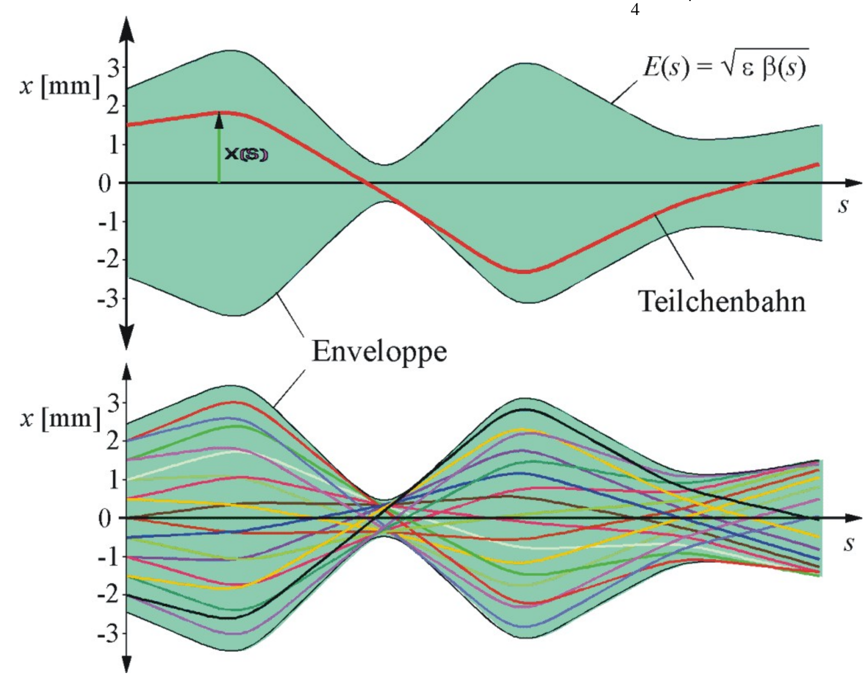
Tune: number of oscillations (called betatronic) in the xx‘ plane a particle does in one machine turn.

The tune depends on the quadrupoles setting





Reference particle

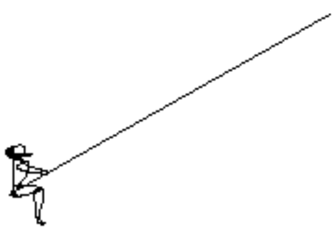


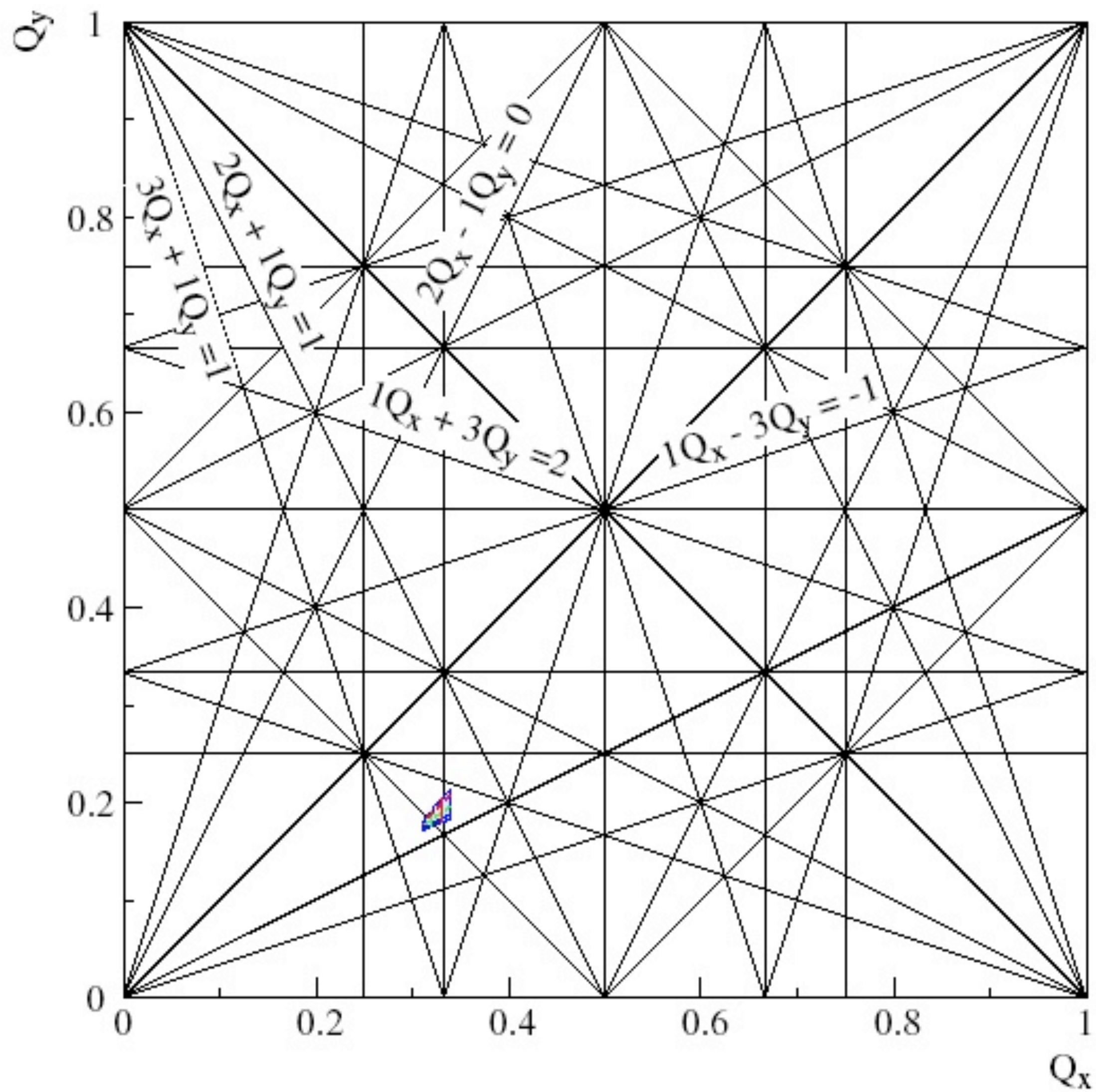
Tune and resonances

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

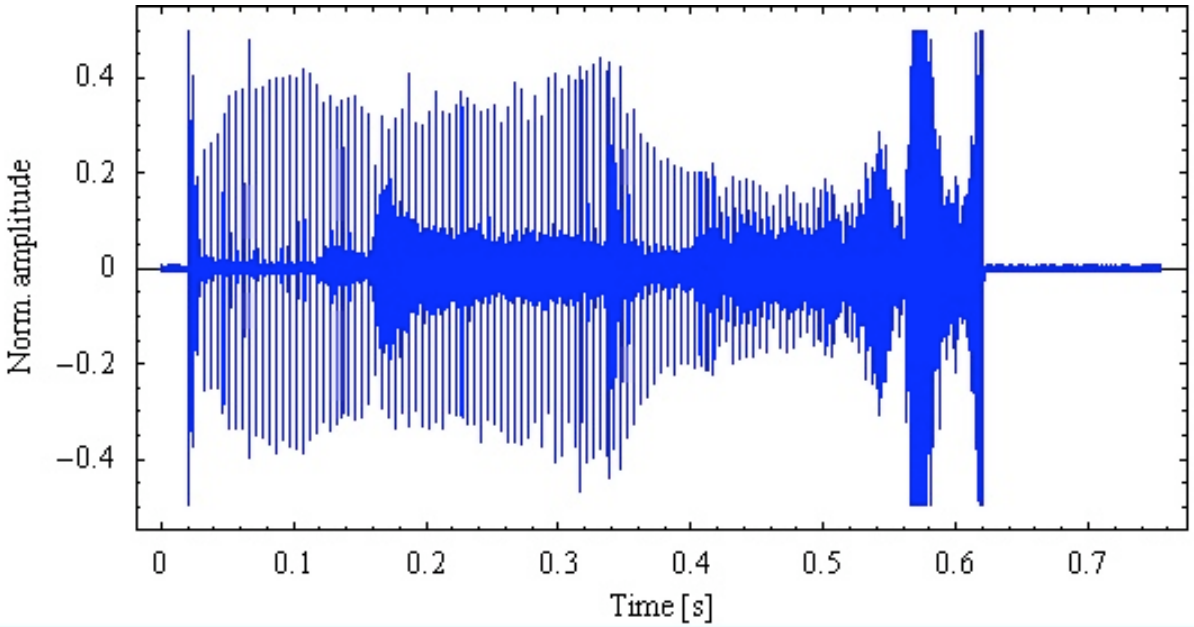
Like on a “balançoire”, to keep the oscillations bounded in amplitude, one has to avoid to excite the beam in a resonant way.

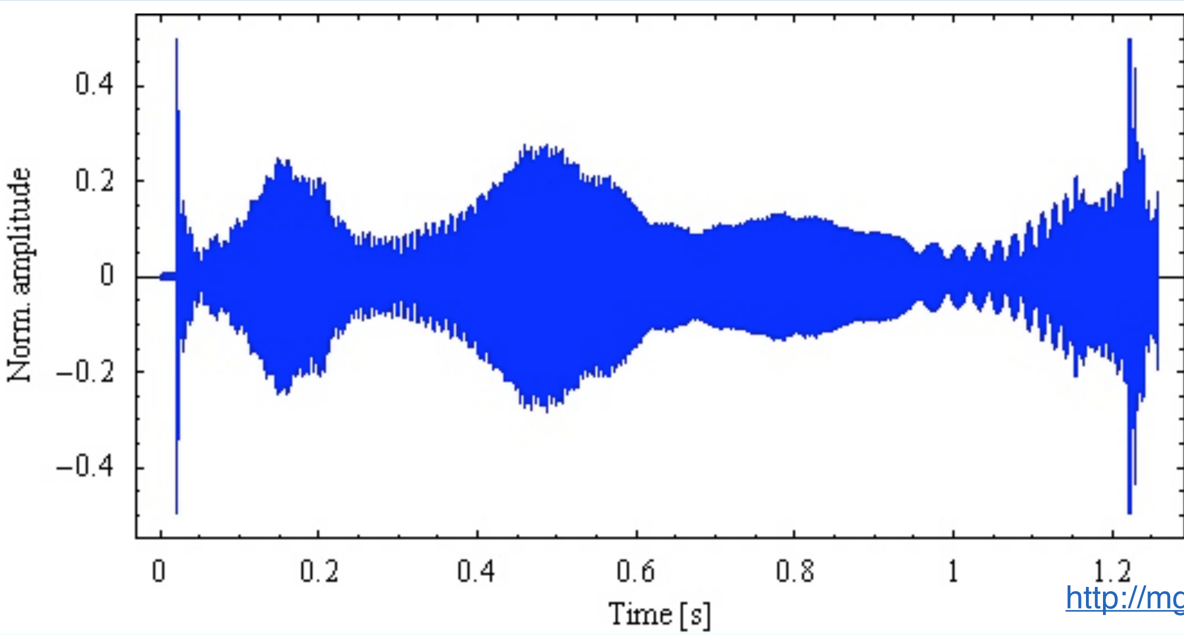
The tune has to be far away from some values, like exciting the beam with the same force at each turn

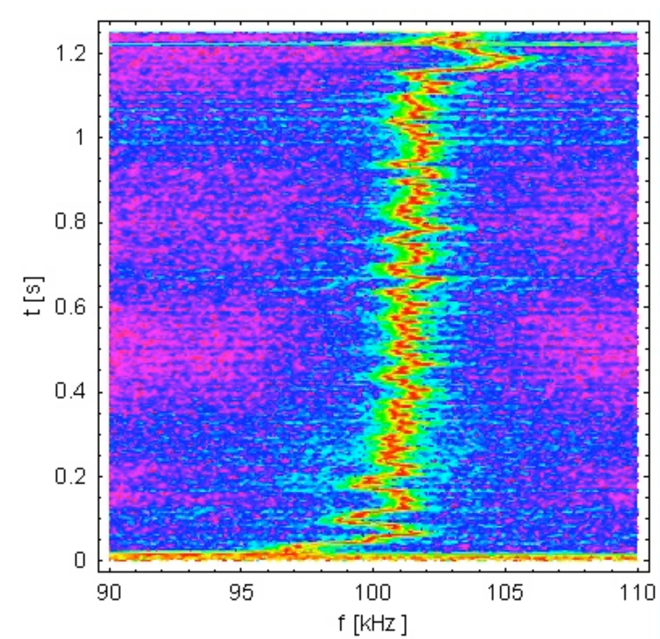




Tune: number of betatron oscillation in the transverse plane



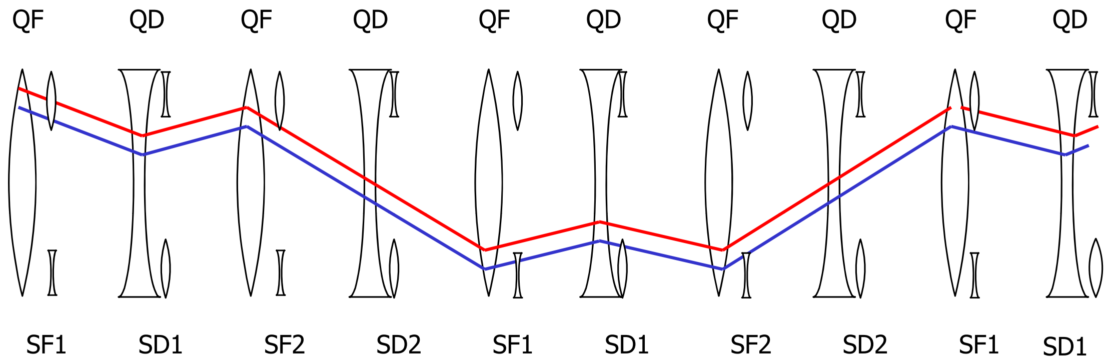


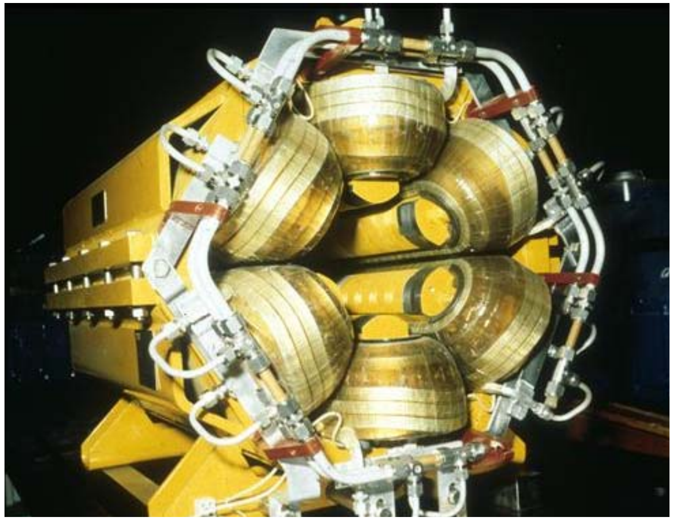


http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html

Chromaticity

- If the energy of a particle is different from the energy of the reference particle, the quadrupoles will focus less or more, so the tune will change according to the energy, as if the accelerator suffer from ASTIGMATISM (or MIOPHY).
  - This is defined as CHROMATICITY
  - Since one want to avoid crossing resonances, the CHROMATICITY has to be kept small and corrected.
  - This can be done by using SEXTUPOLE, which are like quadrupoles which, but, thanks to the lattice design, can focus differently different energies

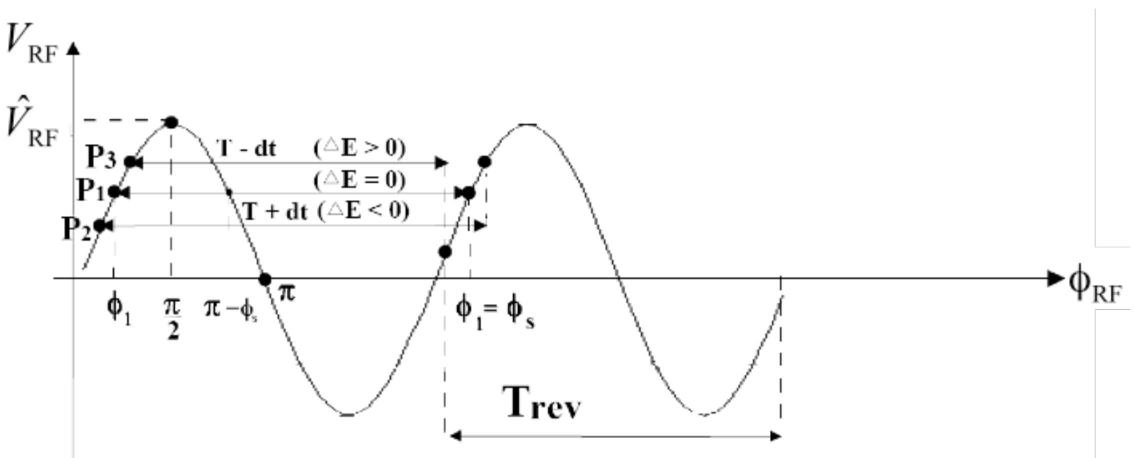


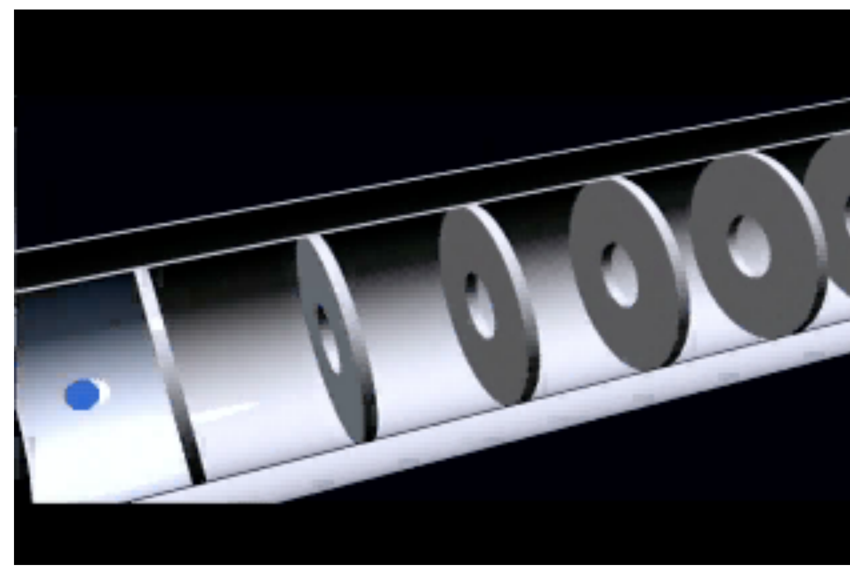


Acceleration

- 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.**

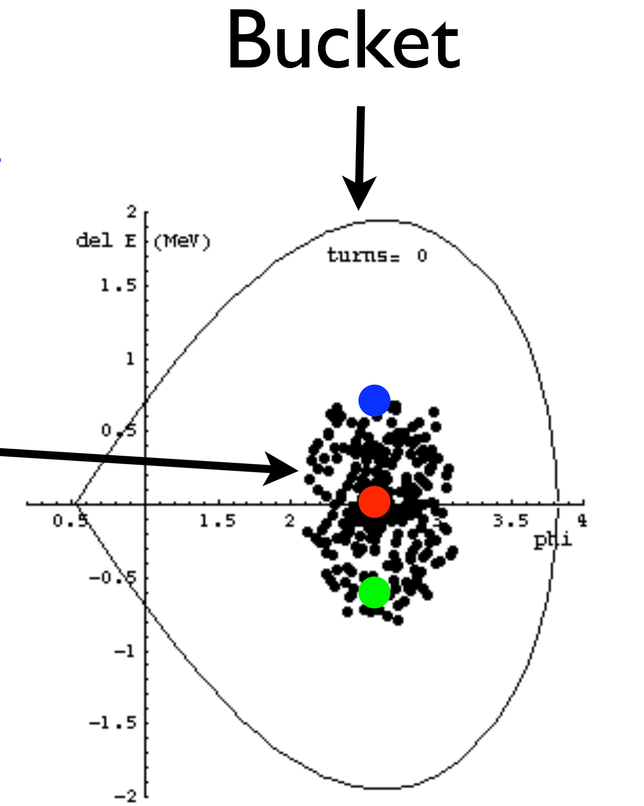
$$\Rightarrow \Delta E_1 = e\,\hat{V}_{RF}\,\sin\phi_1$$

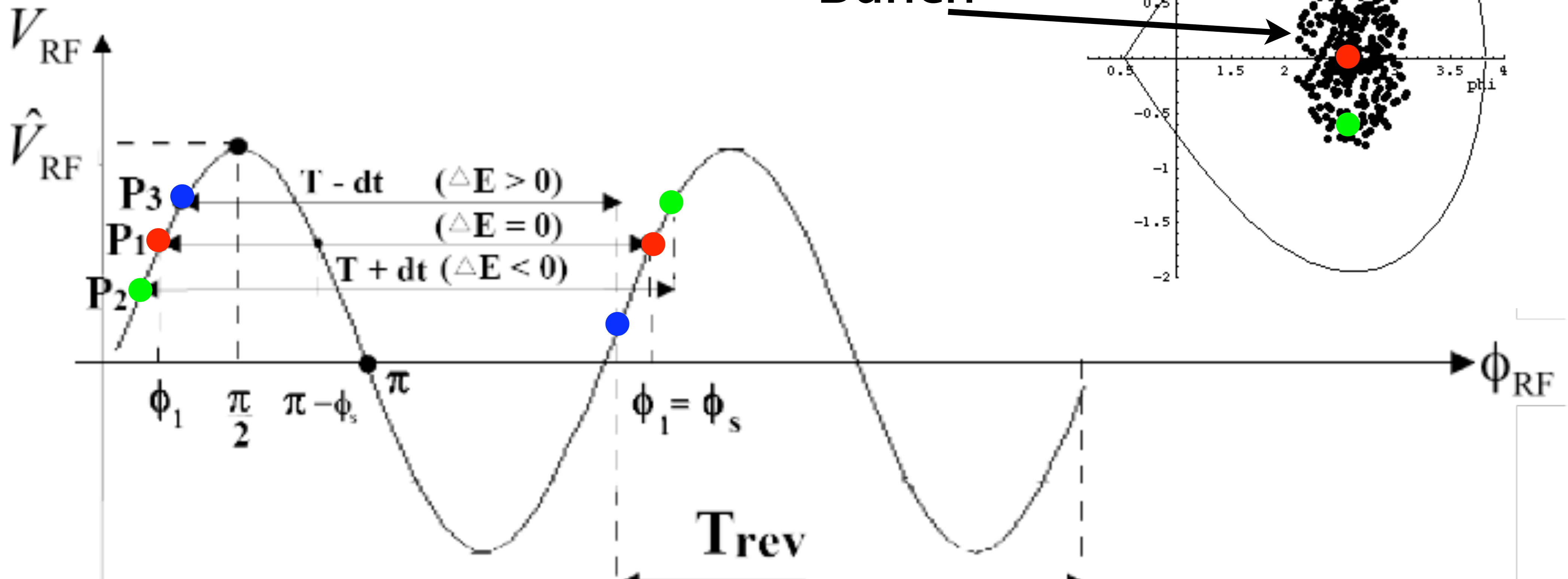




Longitudinal focusing

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





One machine turn ~ some microseconds

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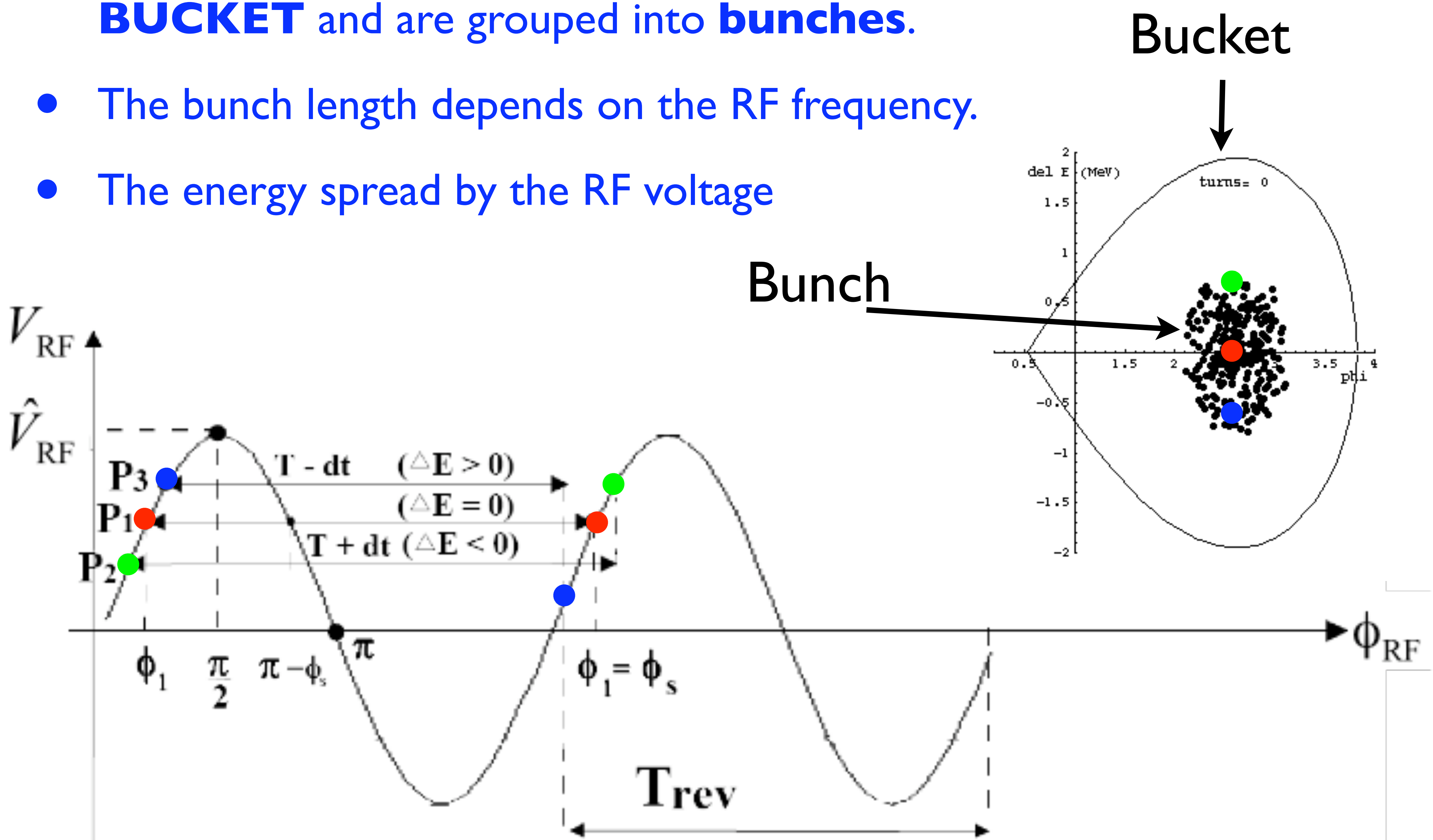
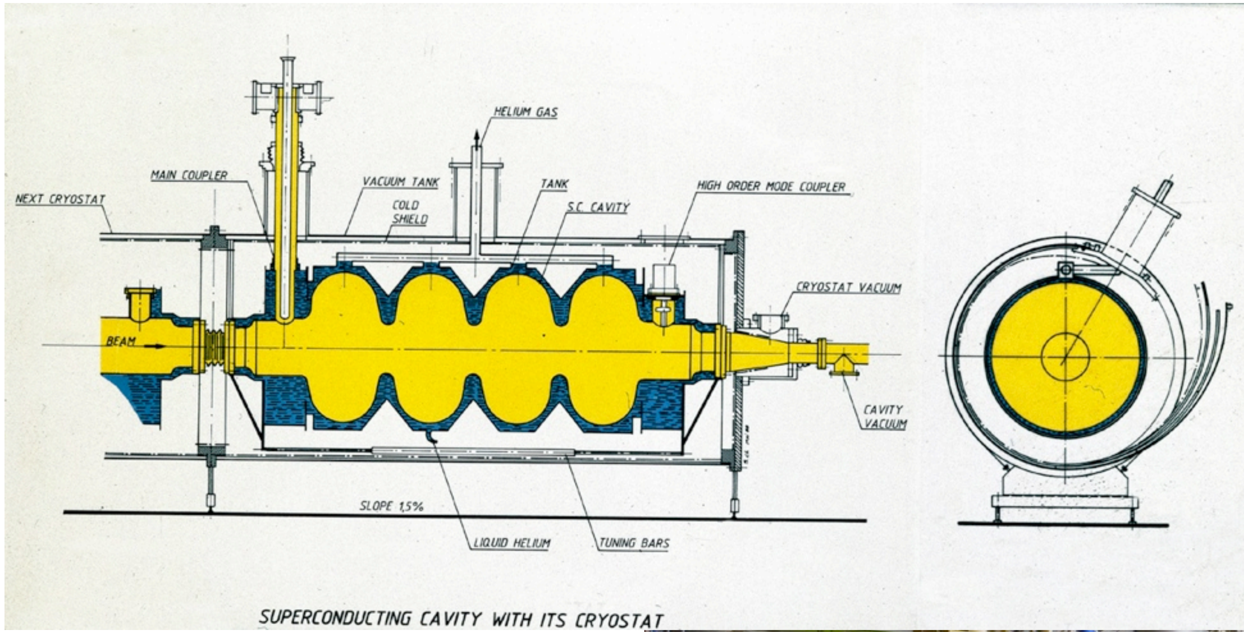
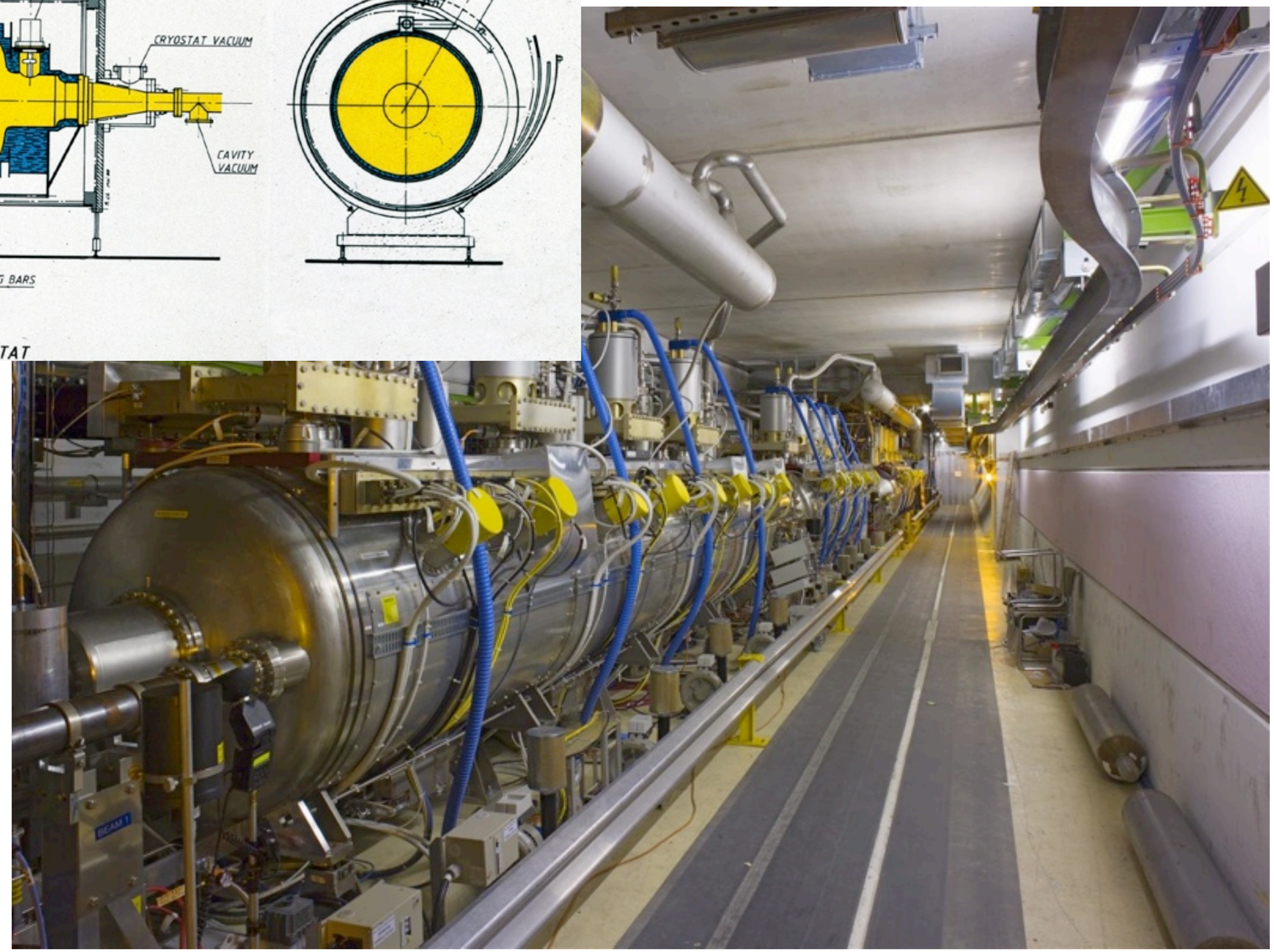


One machine turn ~ some microseconds

RF system


HELIUM GAS
MAIN COUPLER
VACUUM TANK
TANK
HIGH ORDER MODE COUPLER
NEXT CRYOSTAT
COLD SHIELD
S.C CAVITY
CRYOSTAT VACUUM
BEAM
CAVITY VACUUM
SLOPE 1,5%
LIQUID HELIUM
TUNING BARS
SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT



First part summary

- **Dipoles** bend charged particles in the accelerator
- **Quadrupoles** focus particles and define the beam **tune**
- **Sextupoles** keep the tune spread (Chromaticity) due to an energy spread small
- **RF cavities** accelerate the beam

- The emittance is the space occupied by the particles in the xx' plane
- The enveloppe is defined by the quadrupoles via the beta function

What is the LHC ?

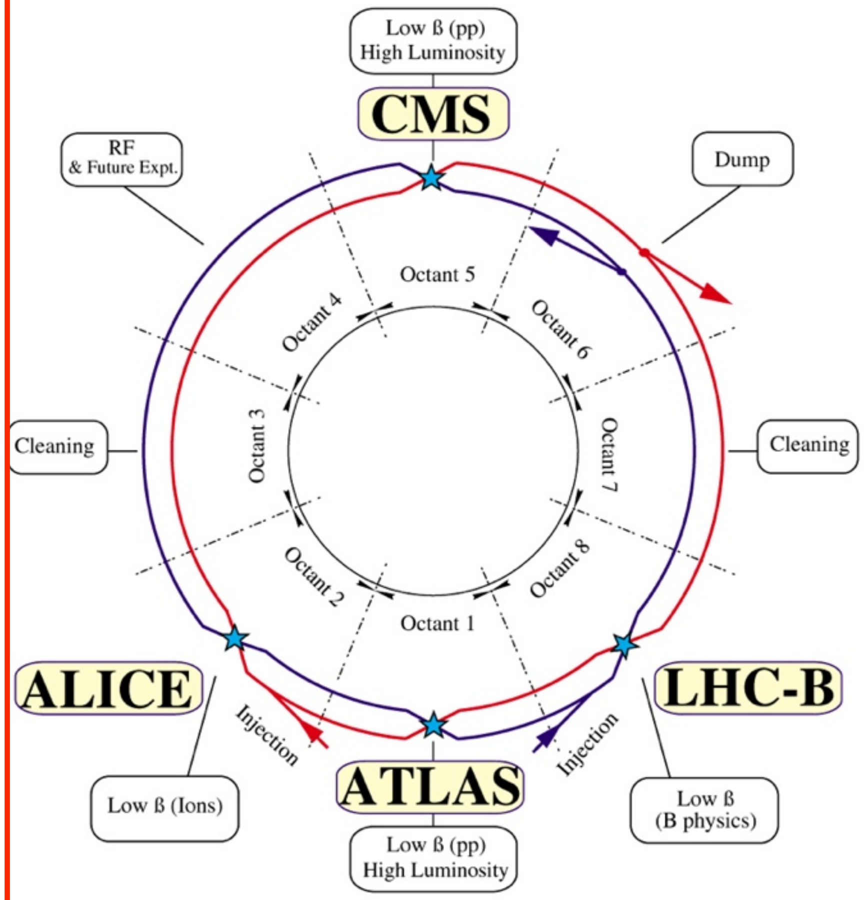
LHC: Large Hadron Collider

LHC *is a* ***collider*** *and* ***synchrotron storage ring:***
ILC is a collider but is not a synchrotron storage ring

Large: high energy needs large bending radius *due to the maximum magnetic field existing technology can produce*
26.7 km circumference

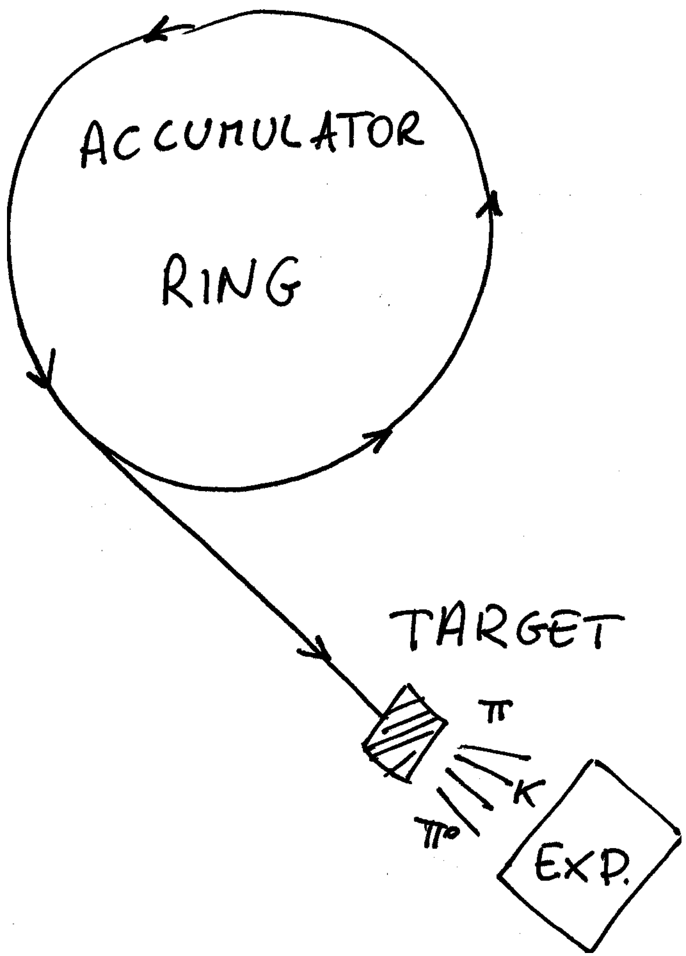
Hadrons: p p collision ⇒ synchrotron radiation and discovery machine.

Collider: particles are stored in two separated rings which are synchrotrons, and accelerated from injection energy (450 GeV) to 7 TeV.
At 7 TeV the two beams are forced to cross in collision points to interact.
The beams are stored at 7 TeV for few 10 h to produced collisions. When the intensity is too low, the two rings are emptied and the process of injecting, accelerating, storing and colliding is restarted, until one finds the higgs or supersymmetry... then one needs a bottle of Champaign and a nobel price ...

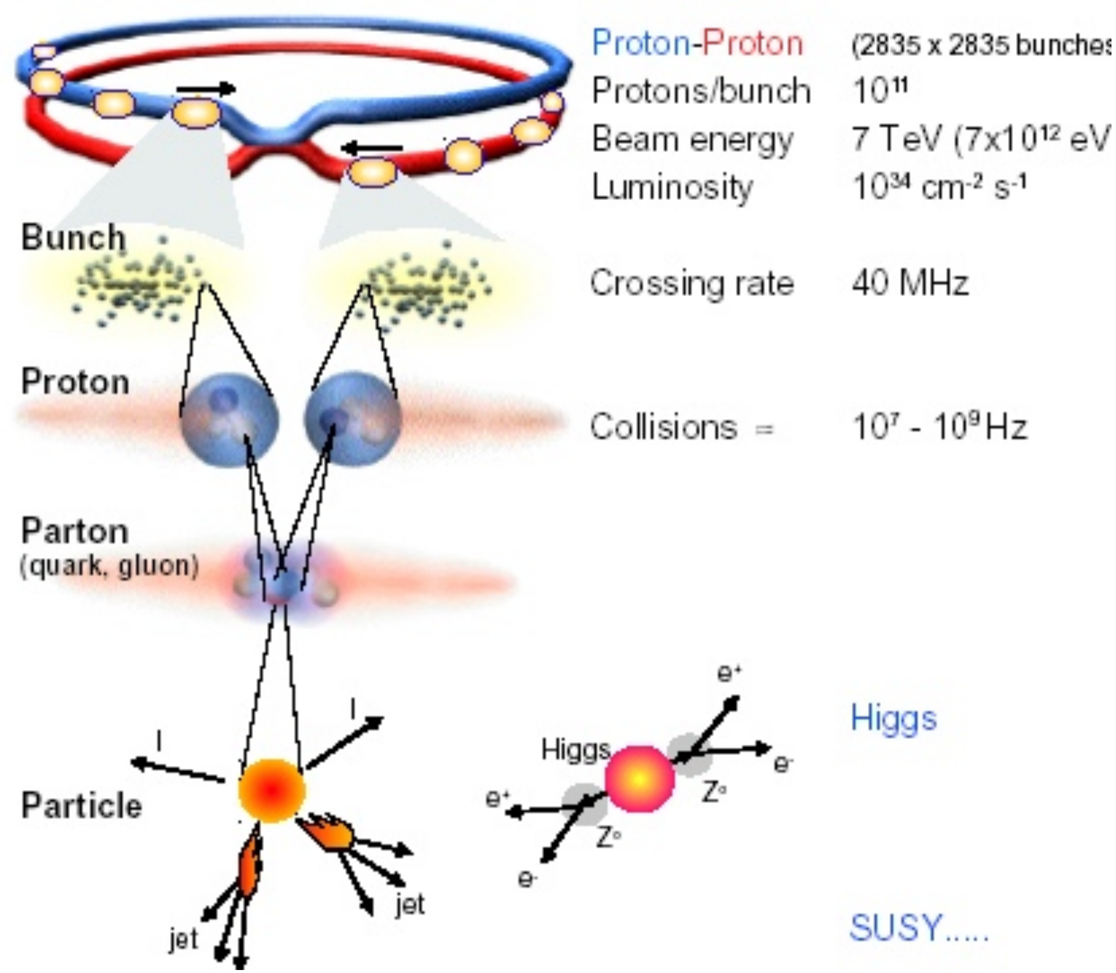


Different approaches: fixed target vs collider

Fixed target



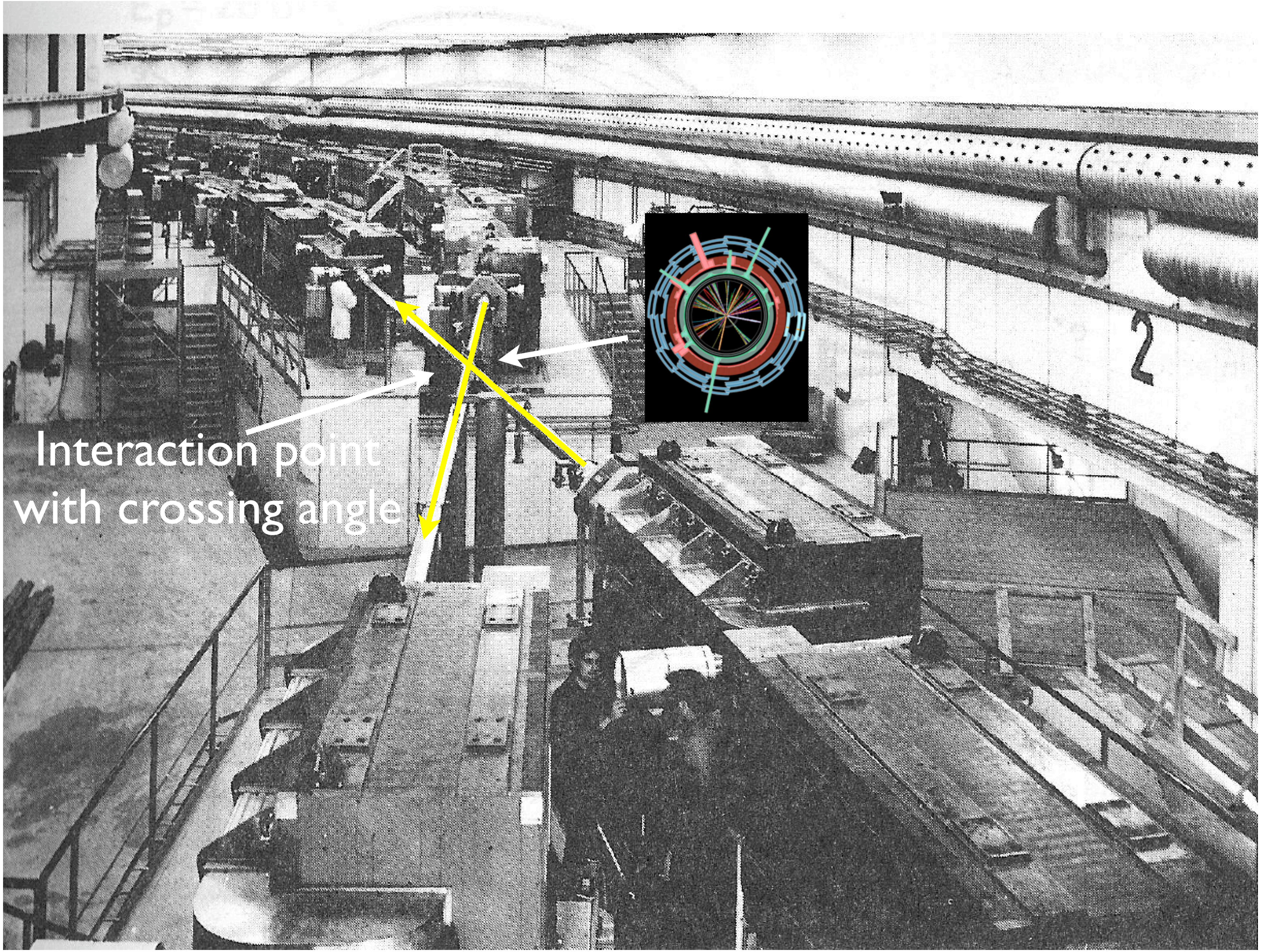
Storage ring/collider



$$E_{CM} = \sqrt{2\left(E_{beam} mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

This usually is defined as $\sqrt{s}$

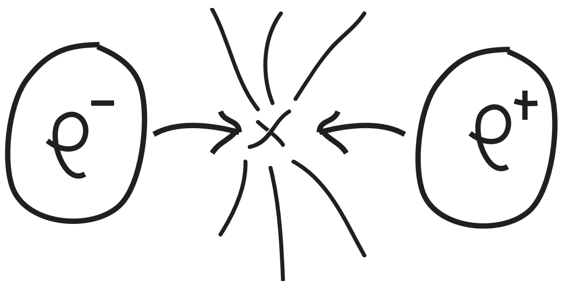
ISR, the first proton-proton collider

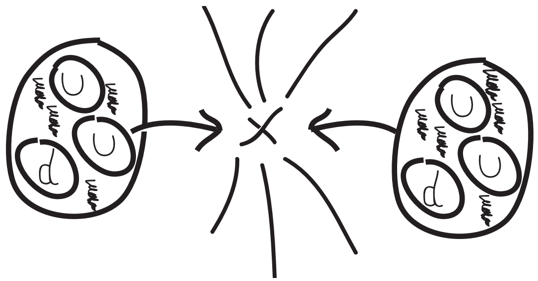


The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons





The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

Cons: above a certain energy is no more possible to use electrons because of too high synchrotron radiation

The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll (about 2 TeV at LHC) < 2 Eb (14 TeV)

Pros: with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

4th power of the energy
(2nd power)$^{-1}$ of the bending radius
(4th power)$^{-1}$ of the particle mass

$r_0 = \frac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

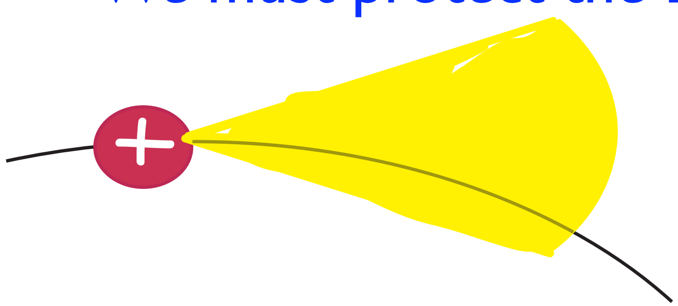
ρ particle bending radius

Energy lost per turn per particle due to synchrotron radiation:

e- ≈ some GeV (LEP)

p ≈ some keV (LHC)

We must protect the LHC coils even if energy per turn is so low



Power lost per m in dipole: some W
Total radiated power per ring: some kW

CERN accelerator complex overview

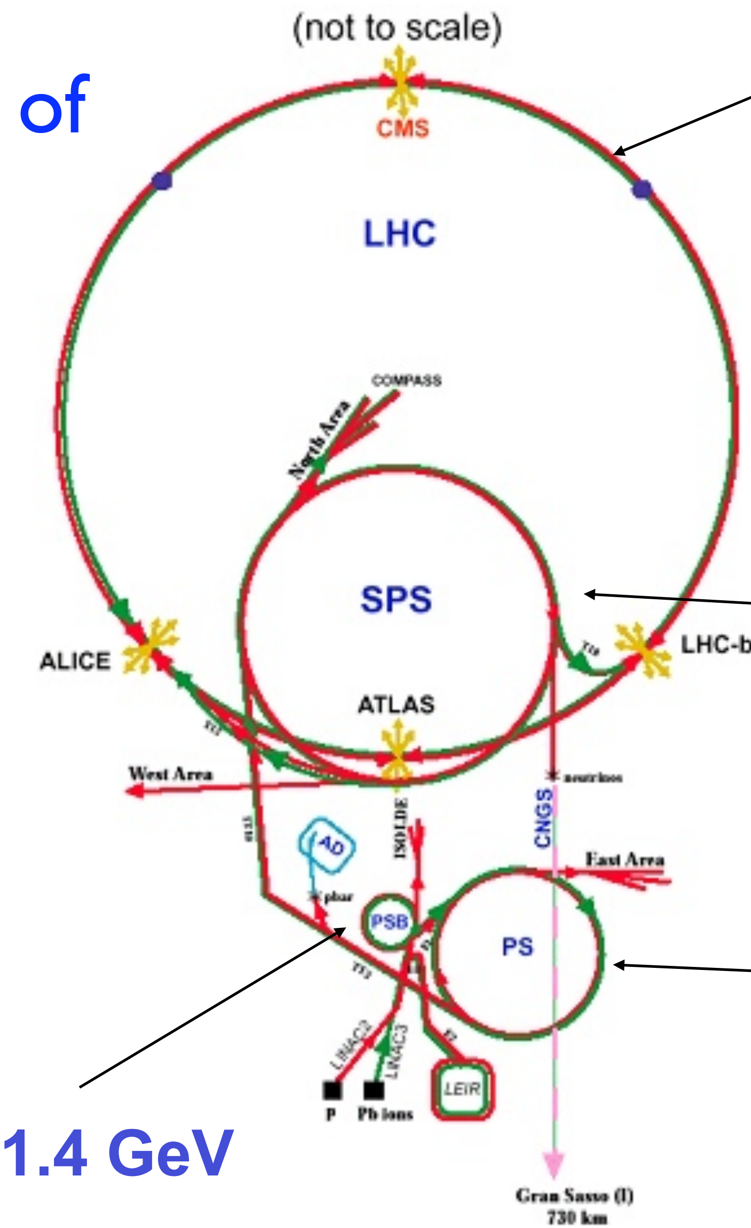
Chain/sequence of accelerators

450 GeV /c – 7 TeV /c

26 - 450 GeV/c

1.4 GeV – 26 GeV/c

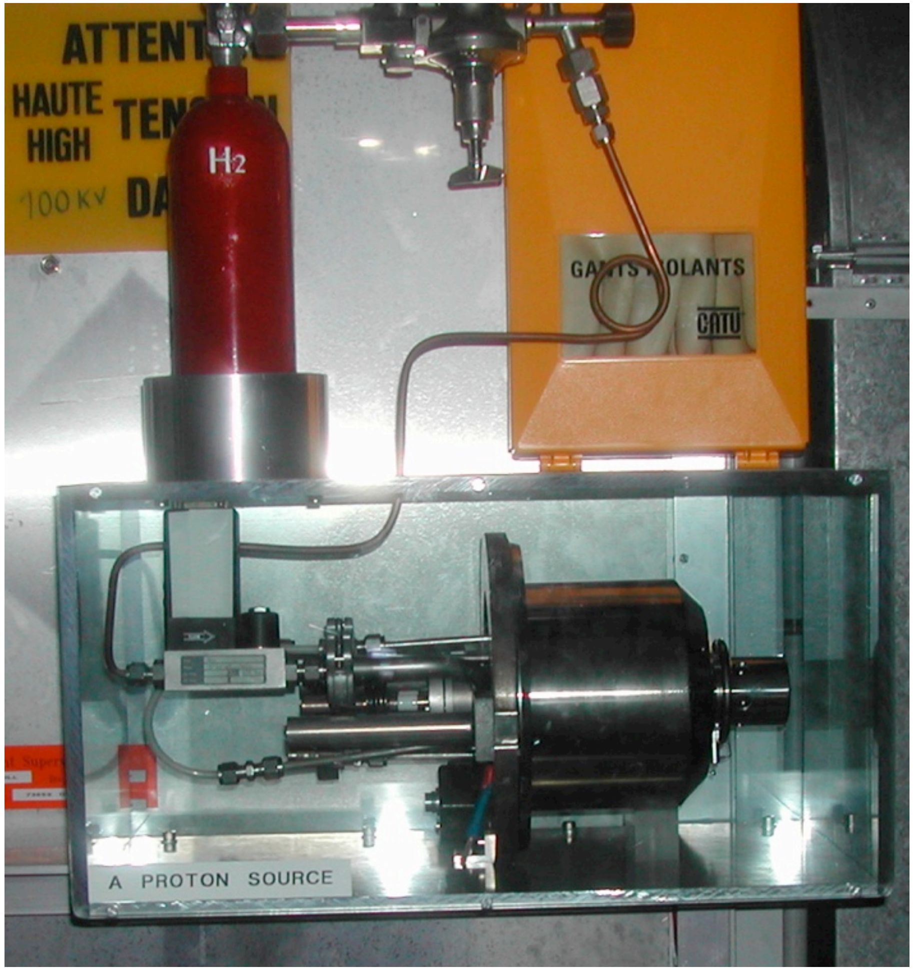
50 MeV – 1.4 GeV

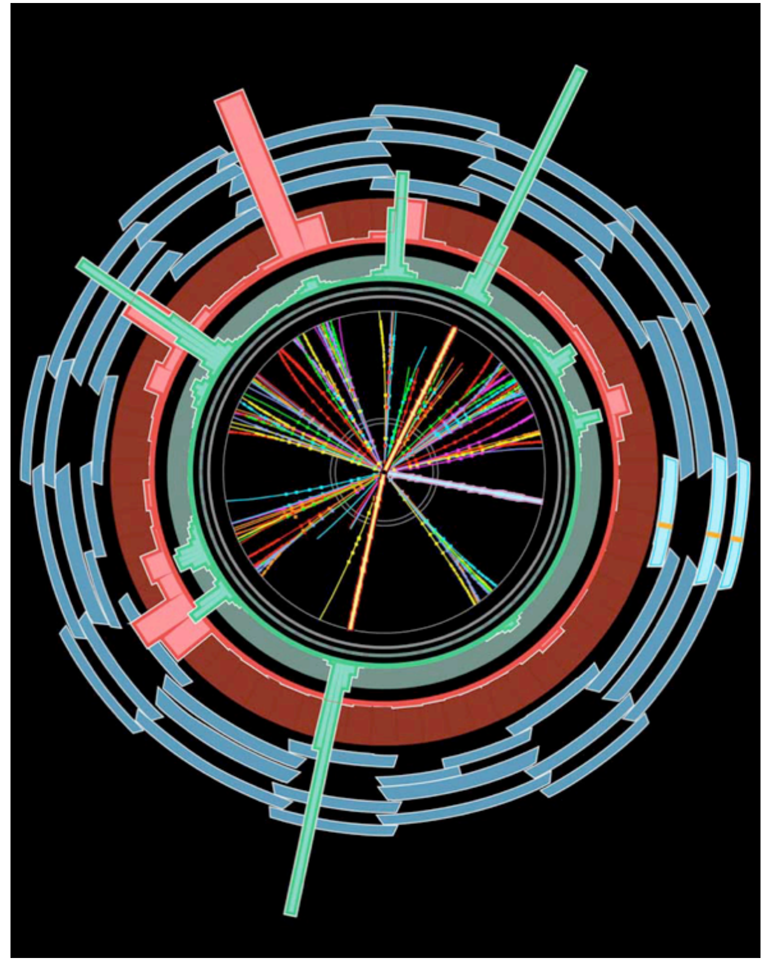


- protons
- antiprotons
- ions
- neutrinos to Gran Sasso (I)

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

Basically the injector chains brings you ...

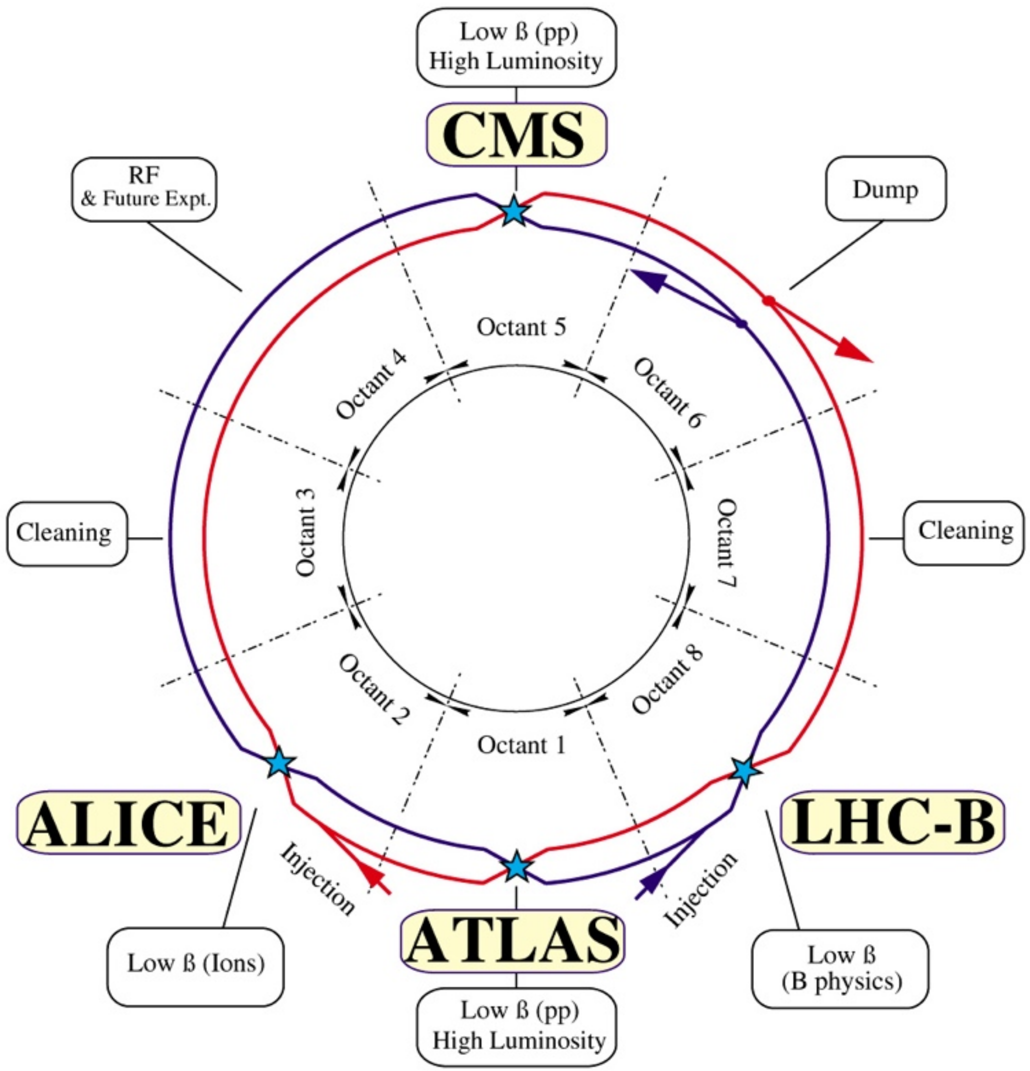




from nearly a bottle of hydrogen

to a little bit before this

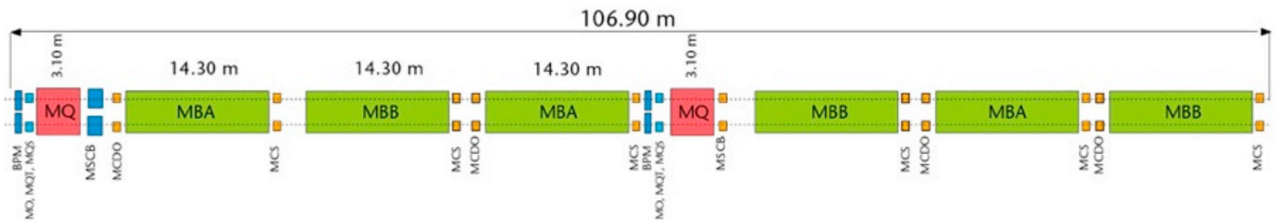
LHC layout and few parameters



Particle type	protons (heavy ions, Pb82+)
Energy	450 GeV (injection) 7 TeV (collision energy) 2,75 TeV/u (ions collision)
Circumference	26658 m
Revolution frequency	11,245 kHz
Number of rings	1 (two-in-one magnet design)
Number of accelerators	2 (2 independent RF system)
Interaction Points (IP) or Collision Points or Low beta insertions	4 (ATLAS, CMS, ALICE, LHCb)
Cleaning insertions or collimation insertions	2
Beam dump extractions	2
RF insertion	1

LHC cost ~1,899.64 MEUR, without the tunnel... ONE F1 season costs about 1,500 MEUR

Basics components of the LHC



Regular ARC

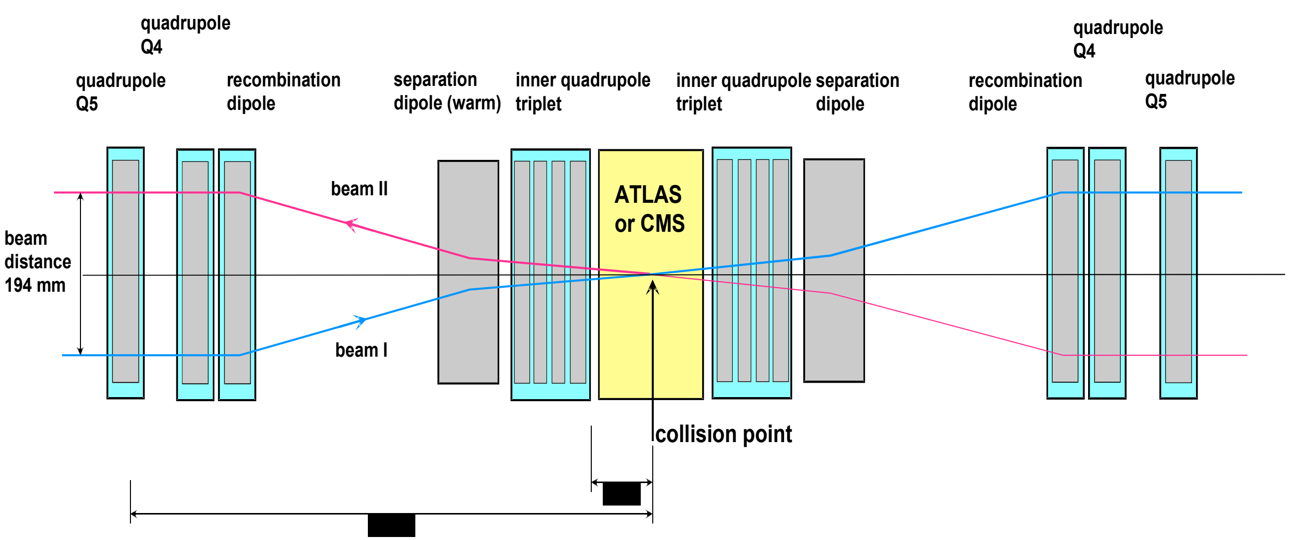
MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

HF226 - v10/99

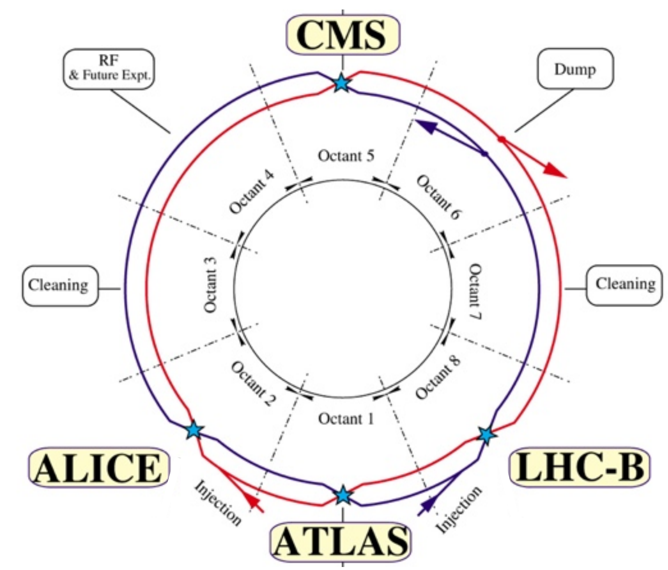
Synchrotron:
a) dipoles to bend particles with increasing field vs time i.e. vs energy

b) quadrupoles to focus the beam and keep it in the aperture

c) interaction point with final focusing to collide the two beams



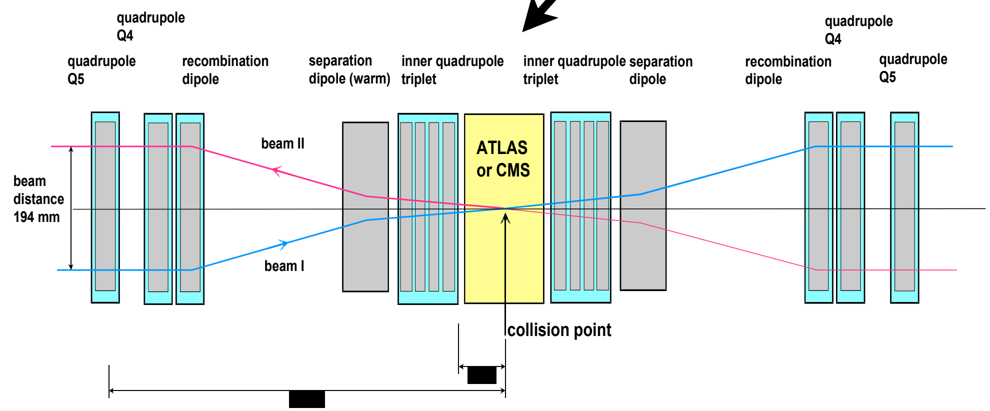
Example for an LHC insertion with ATLAS or CMS



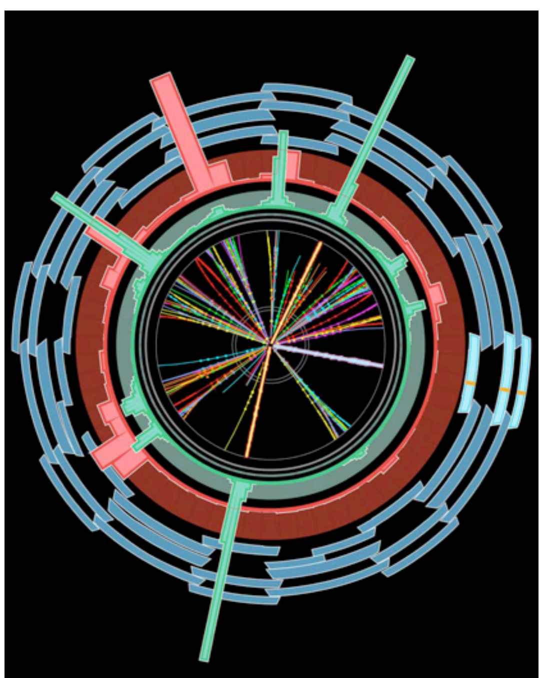
Interaction points

Luminosity

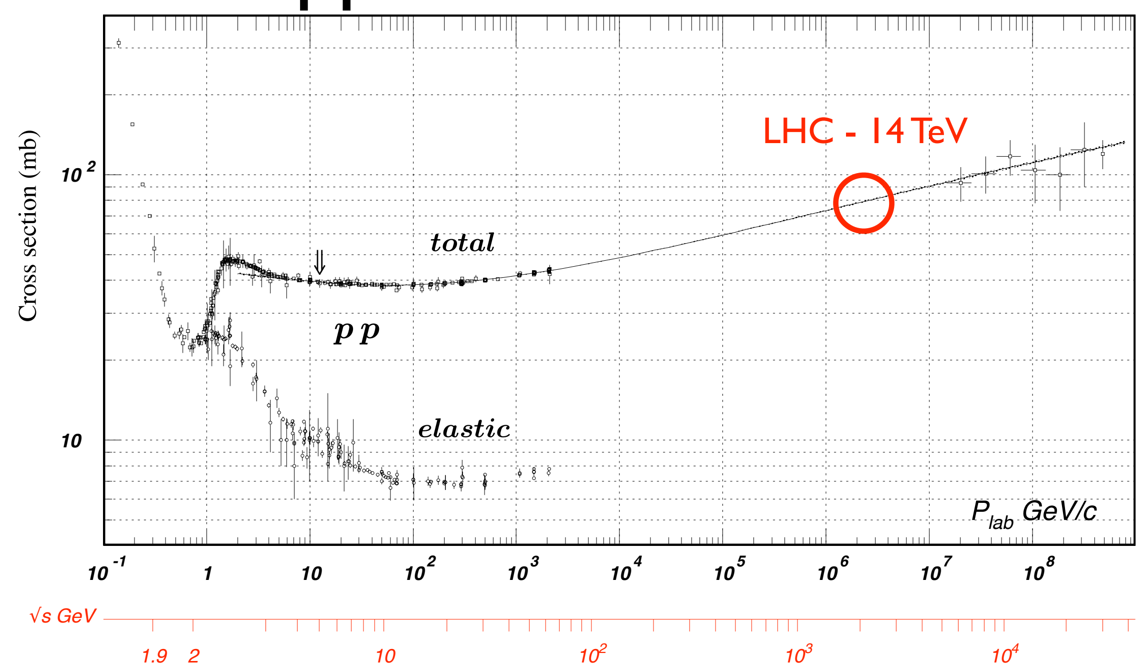
$$N_{event} = L\sigma_{event}$$



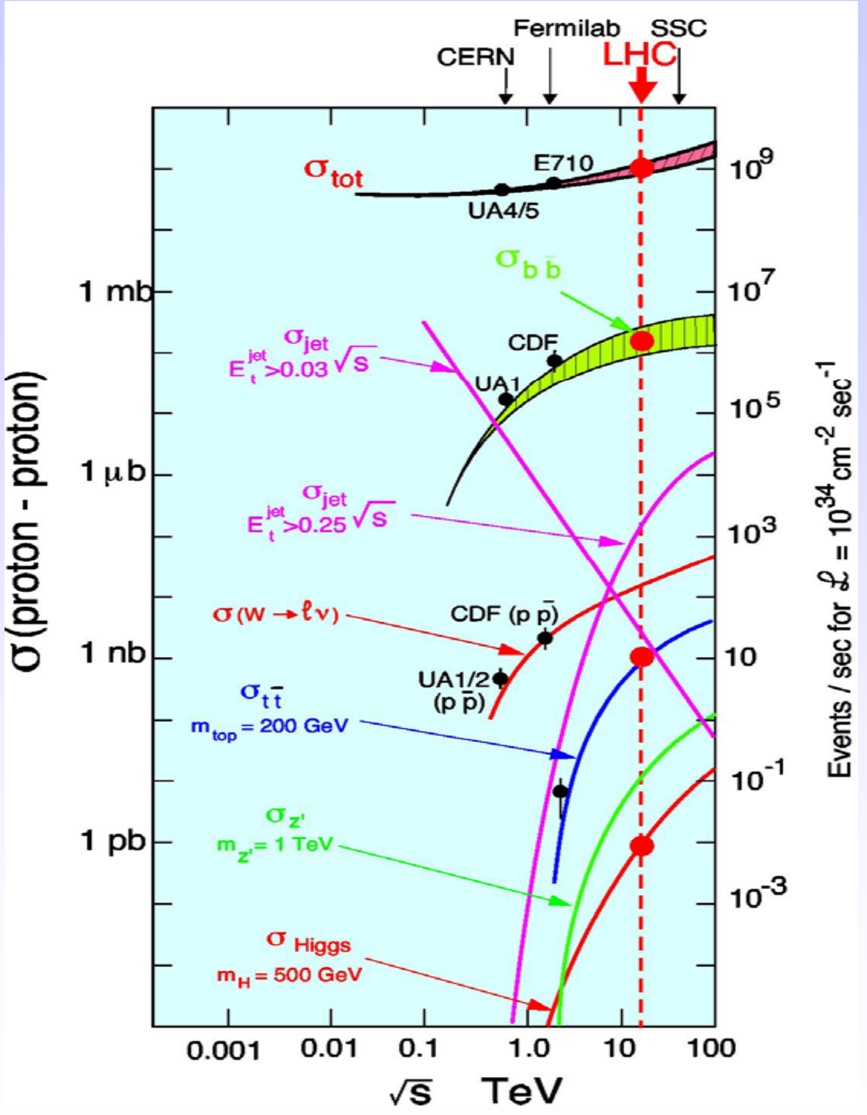
Example for an LHC insertion with ATLAS or CMS



pp cross section



Cross Sections and Production Rates



Rates for $L = 10^{34}\ cm^{-2}\ s^{-1}$: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	$5\ 10^6$ / s 8 / s
• $W \to e\,\nu$ • $Z \to e\,e$	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

The only problem: you have to detect them !

Luminosity

Number of particles per bunch
$N_{beam1} * N_{beam2} = N^2$

Revolution frequency

Number of bunches

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

Geometric Reduction factor due to crossing angle

Beam dimension at the IP

$$\sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}}$$

At first look, the smaller the better

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*} \right)^2}$$

Definition of beam emittance

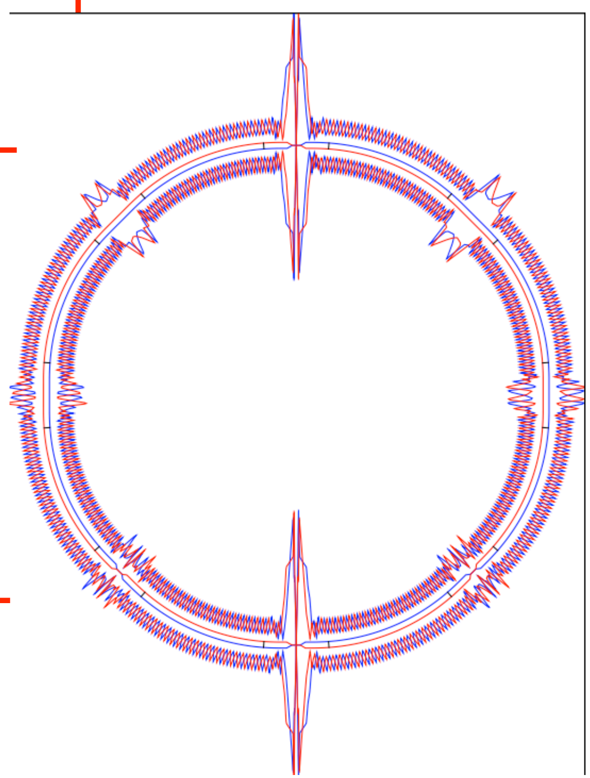
$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y} \cdot \epsilon_{x,y}}$$

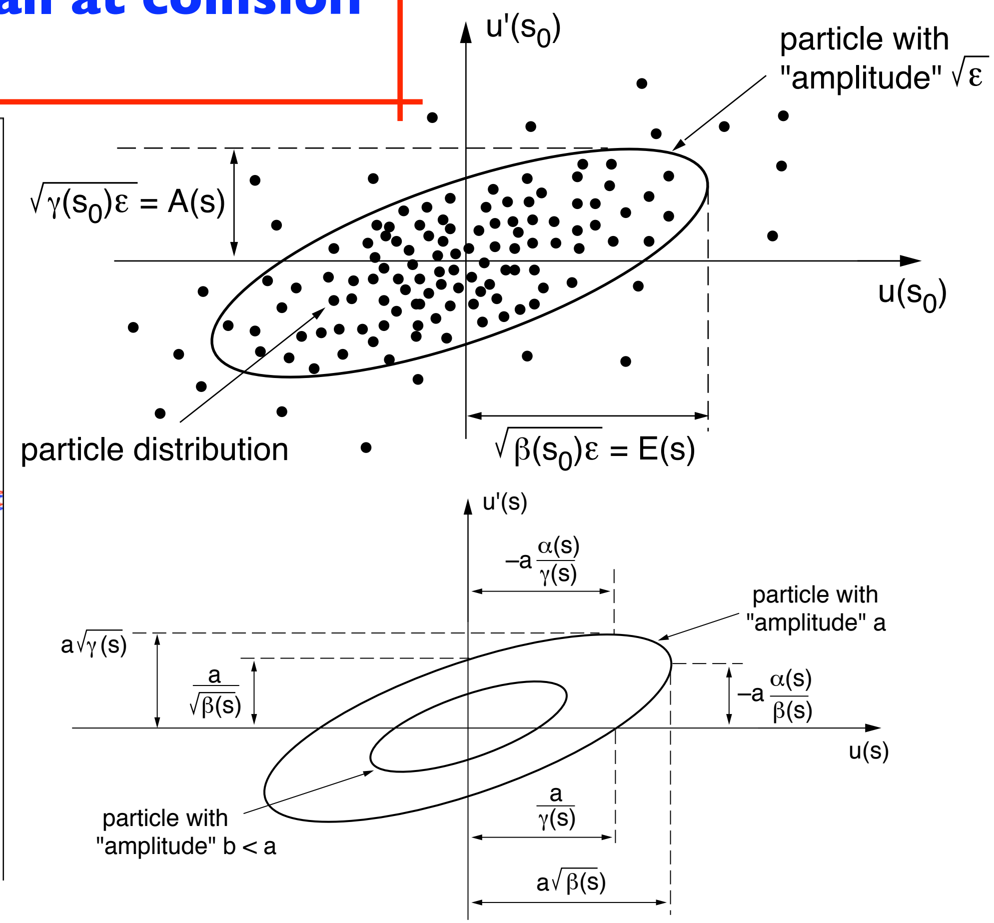
Beam physical dimension

Optical machine parameter that depends on the lattice of the machine, in particular on the ***QUADRUPOLES.***
Beta has to be small at collision at the IP

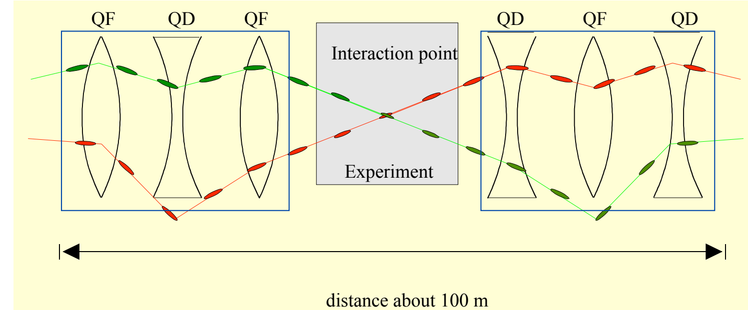
Emittance: *Parameter which describes the spread of the particles in the phase space (xx') or (yy').*

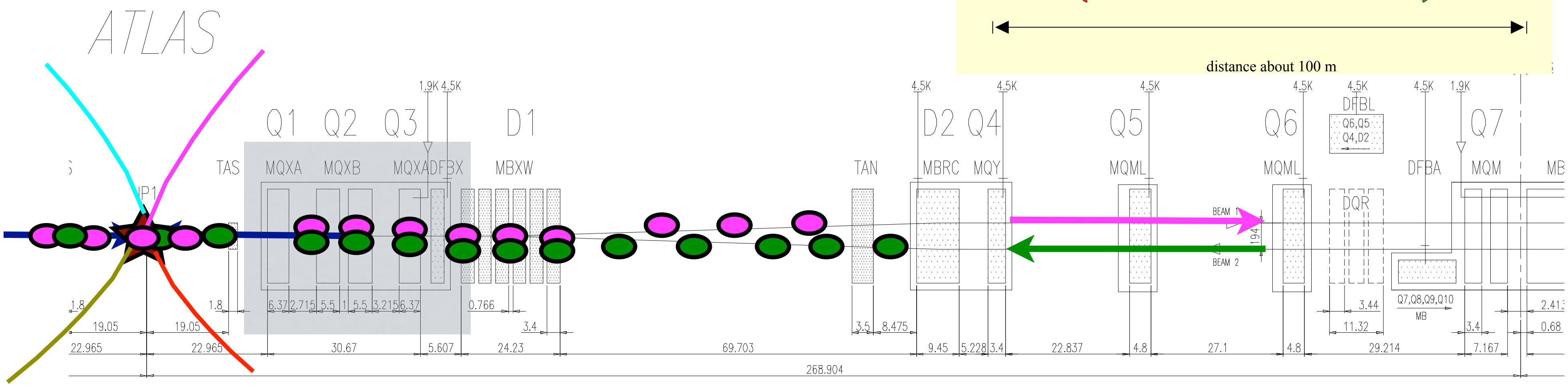
By knowing the setting of the quadrupoles and the beam emittance, one can compute the beam dimension in the entire LHC

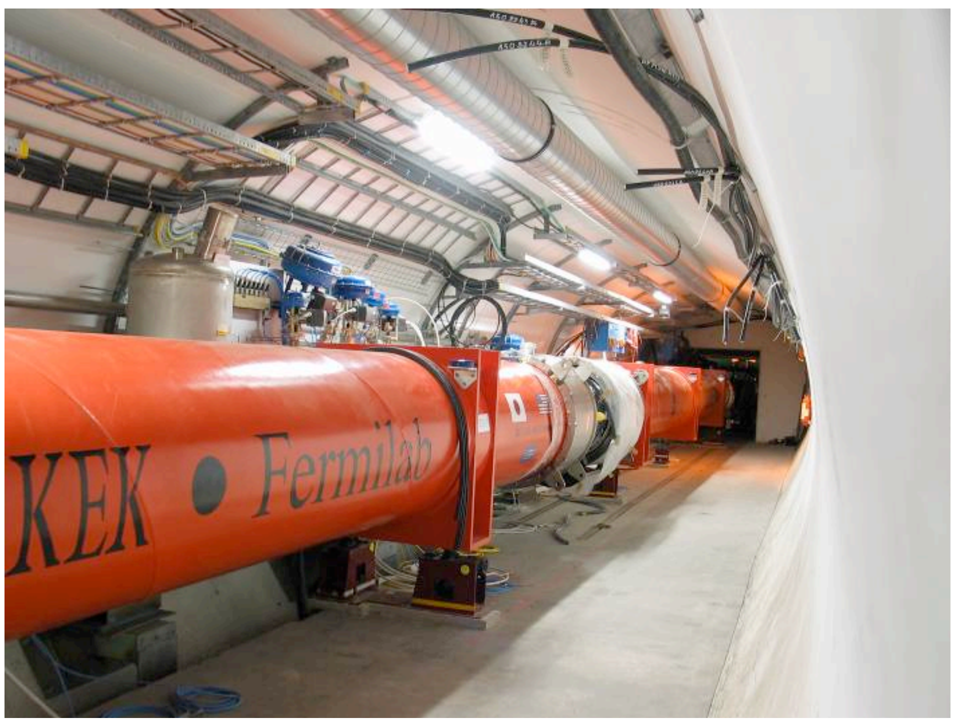




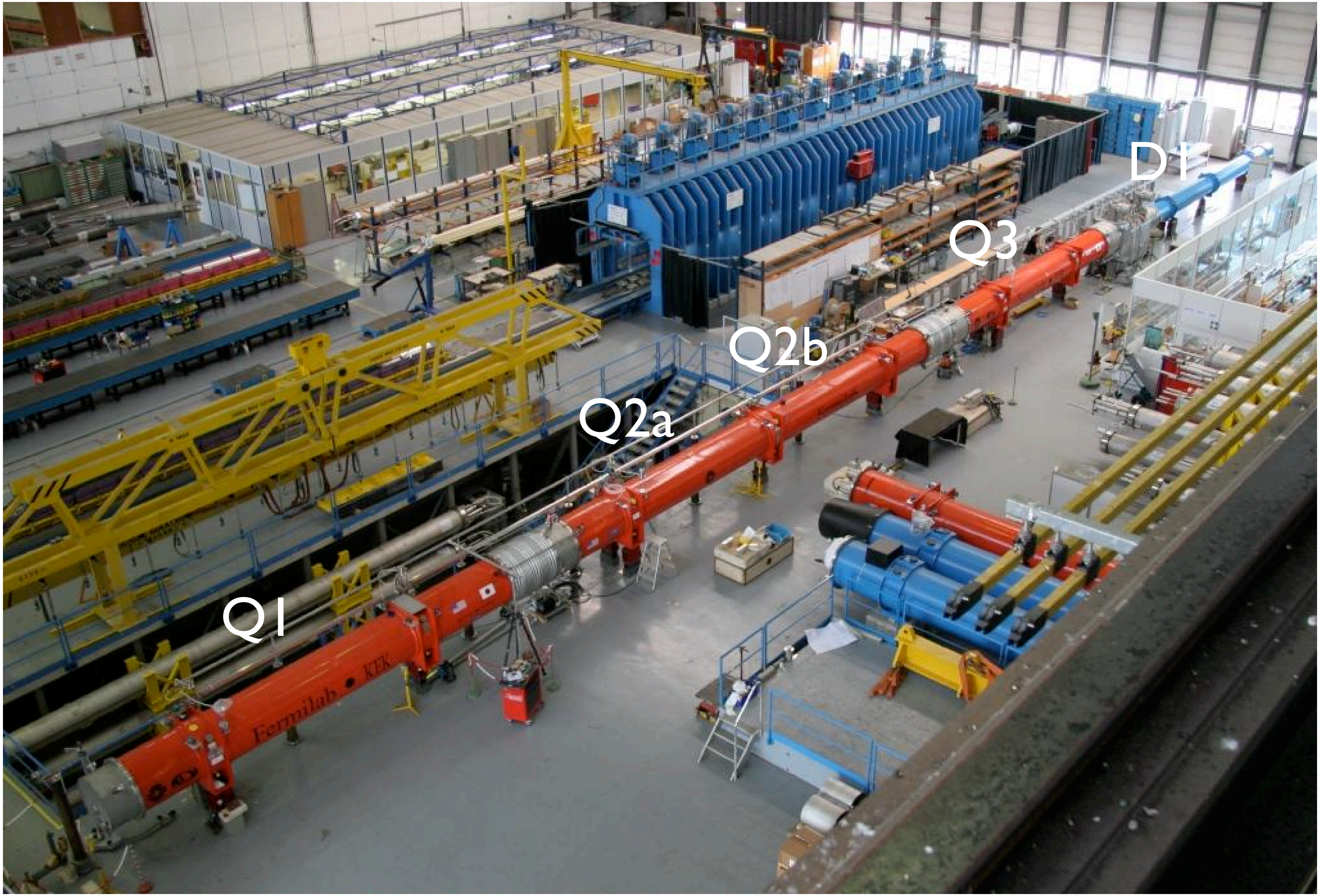
Inner triplet: final focusing
⇒ how to make the beam small at the IP





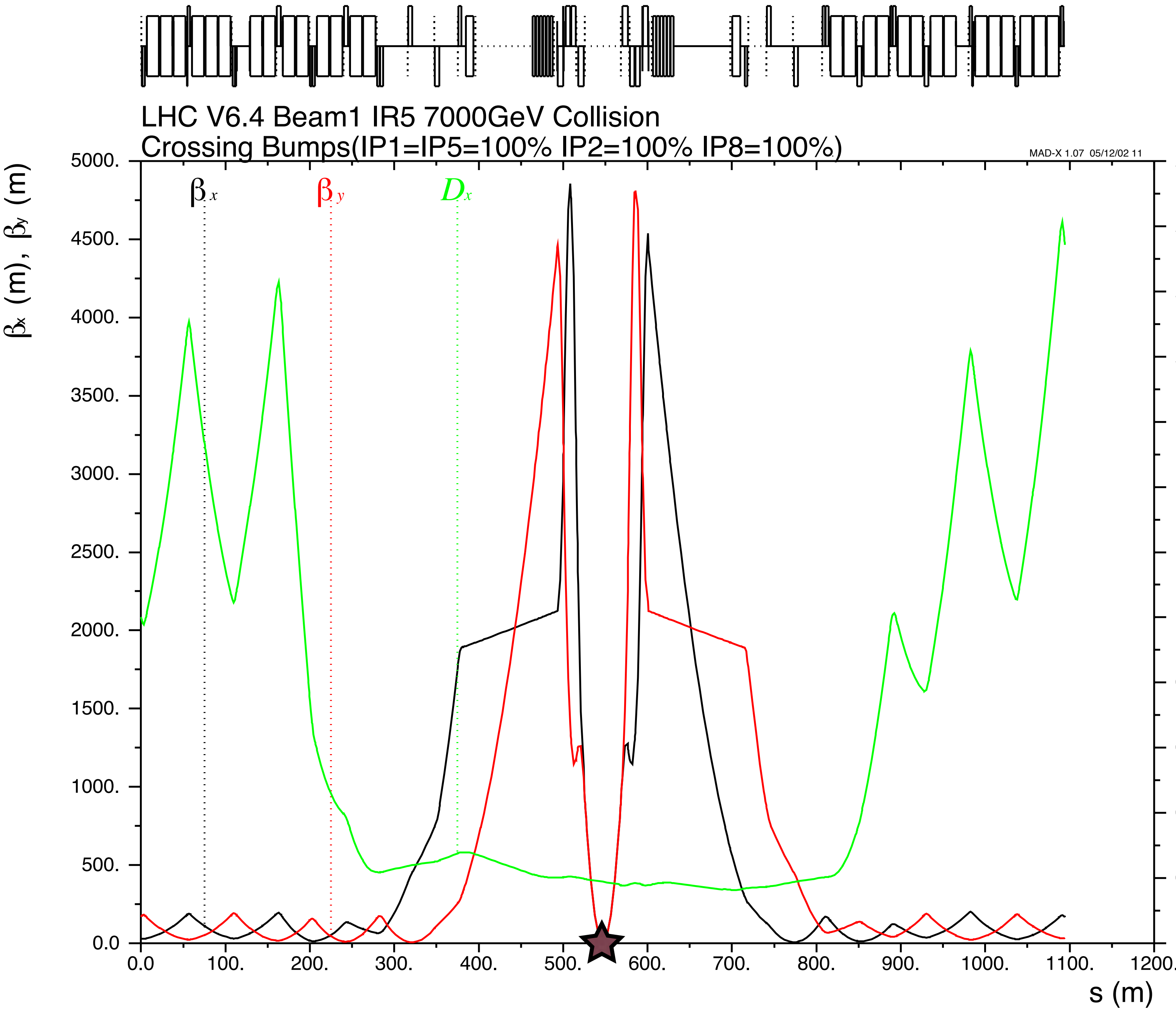


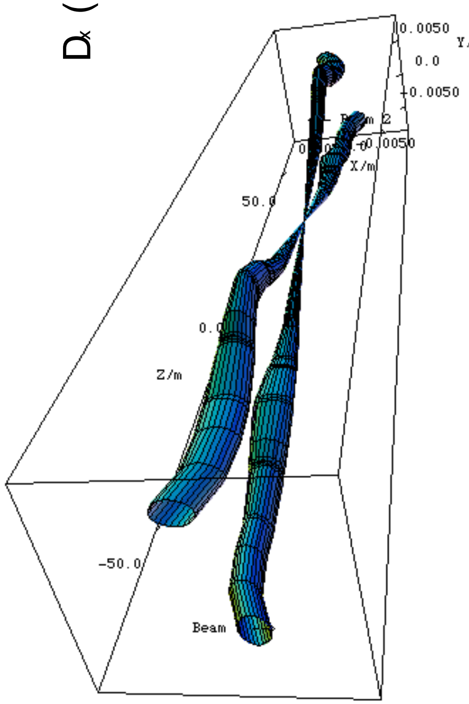
Triplets before lowering in the tunnel



Optics at collision IP1- ATLAS, only beam 1

$$x_{MAX} = \sqrt{\epsilon\beta}$$





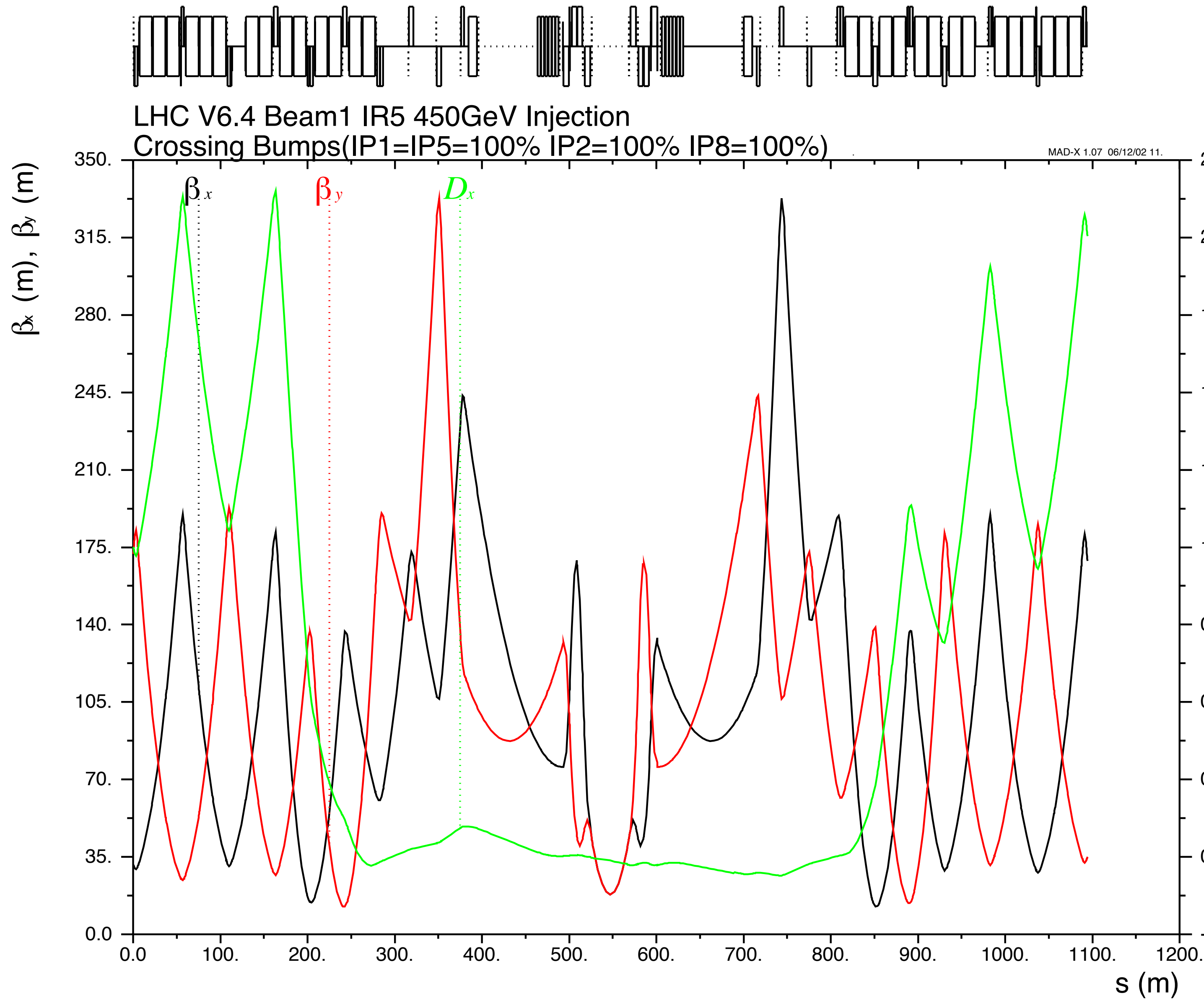
Bmax in the triplets ⇒ 5 Km

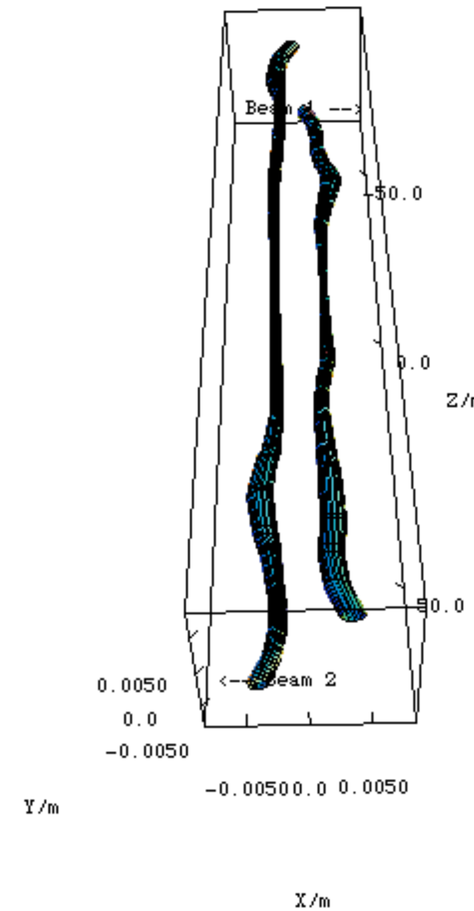
Bmin in the IPs = 0.55 m

Zero dispersion

Vertical crossing

Injection optics and during accelleration IP1- ATLAS, only beam 1





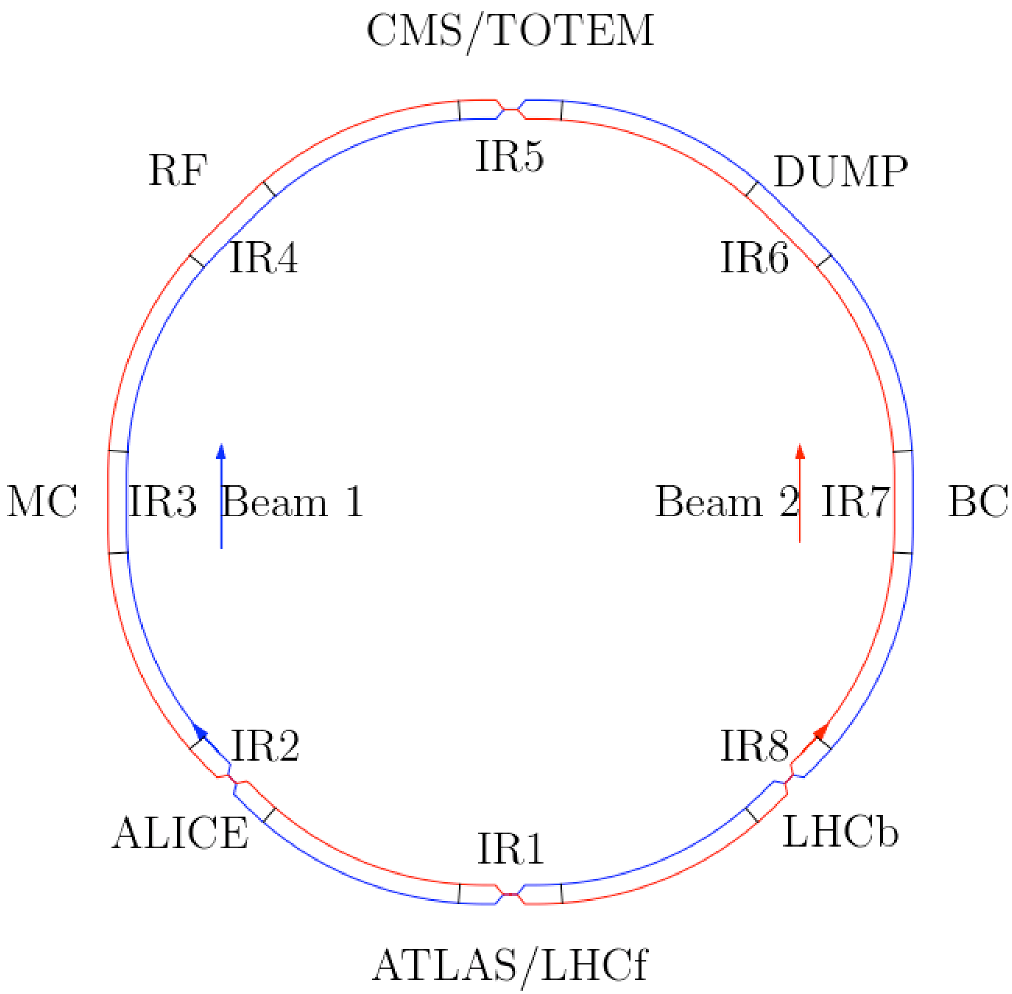
Bmax outside triplets

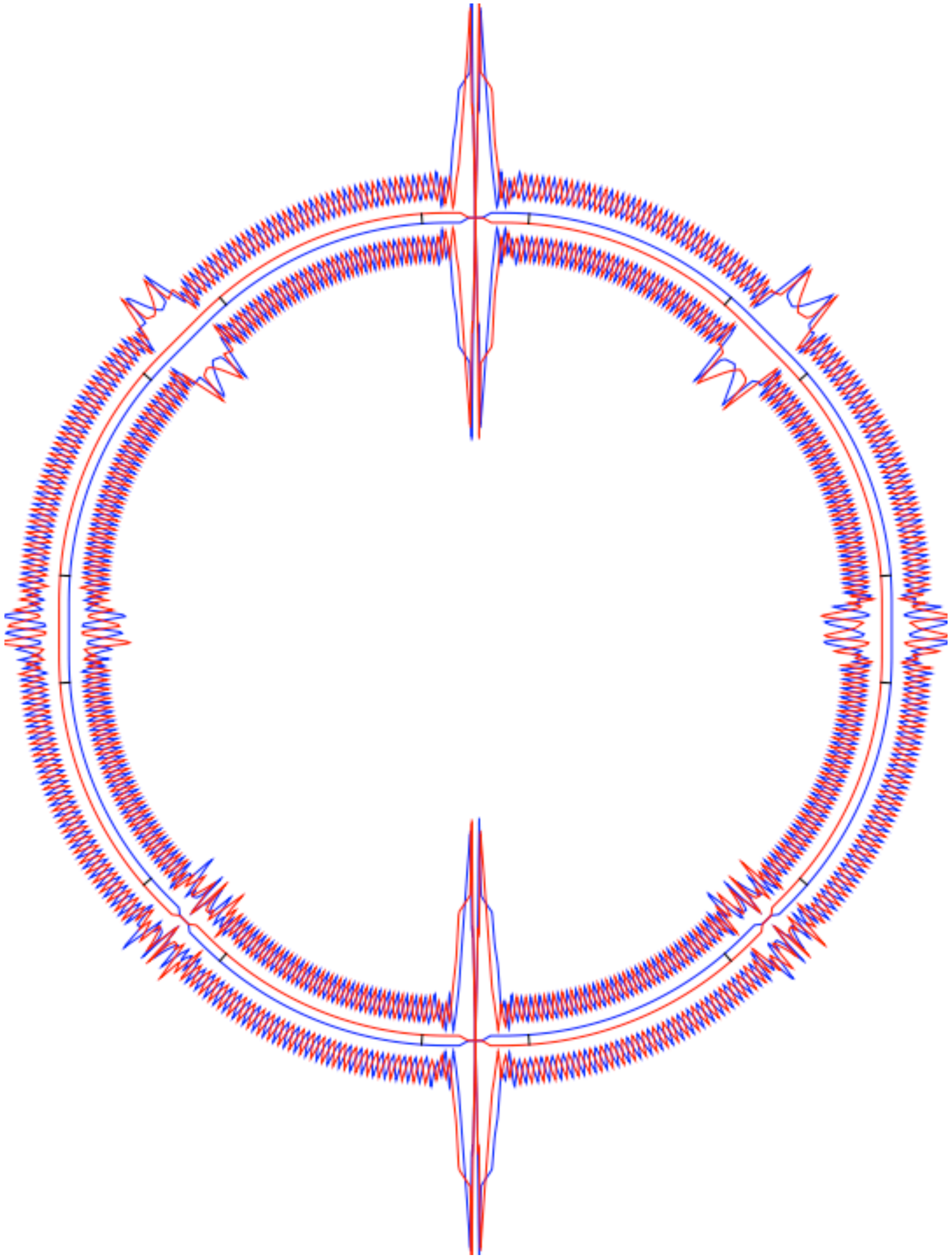
Bmin in the IPs = 11 m

Zero dispersion

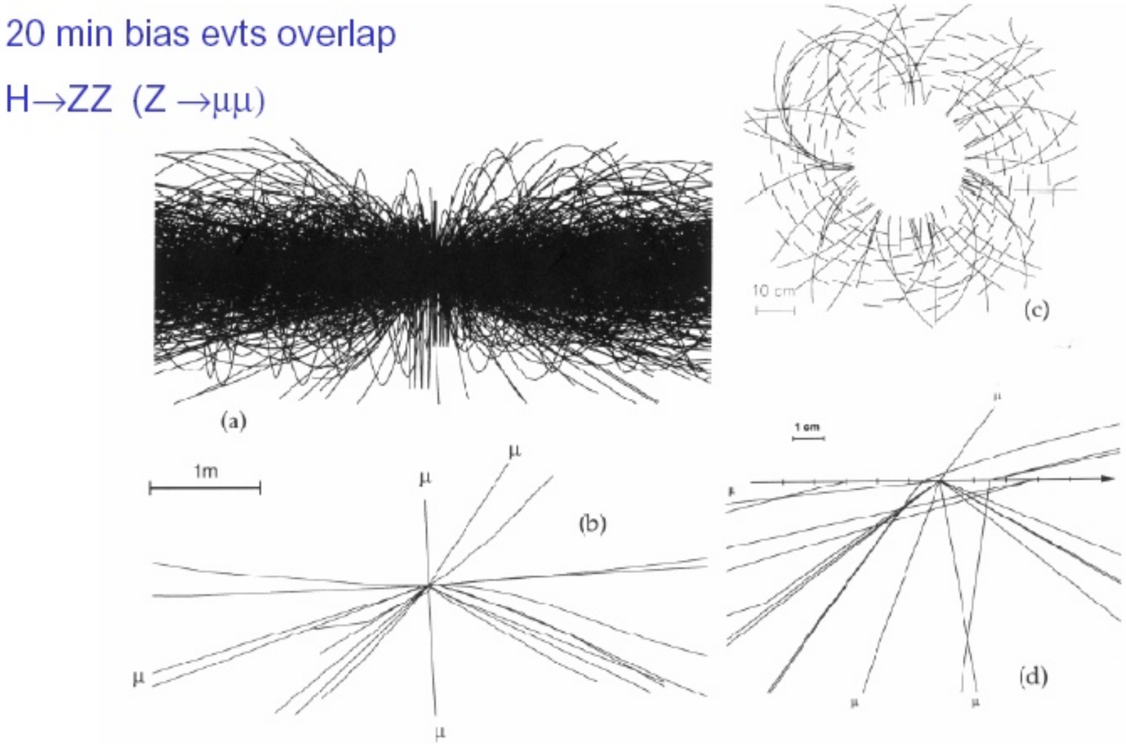
Vertical separation

The LHC optics in one slide





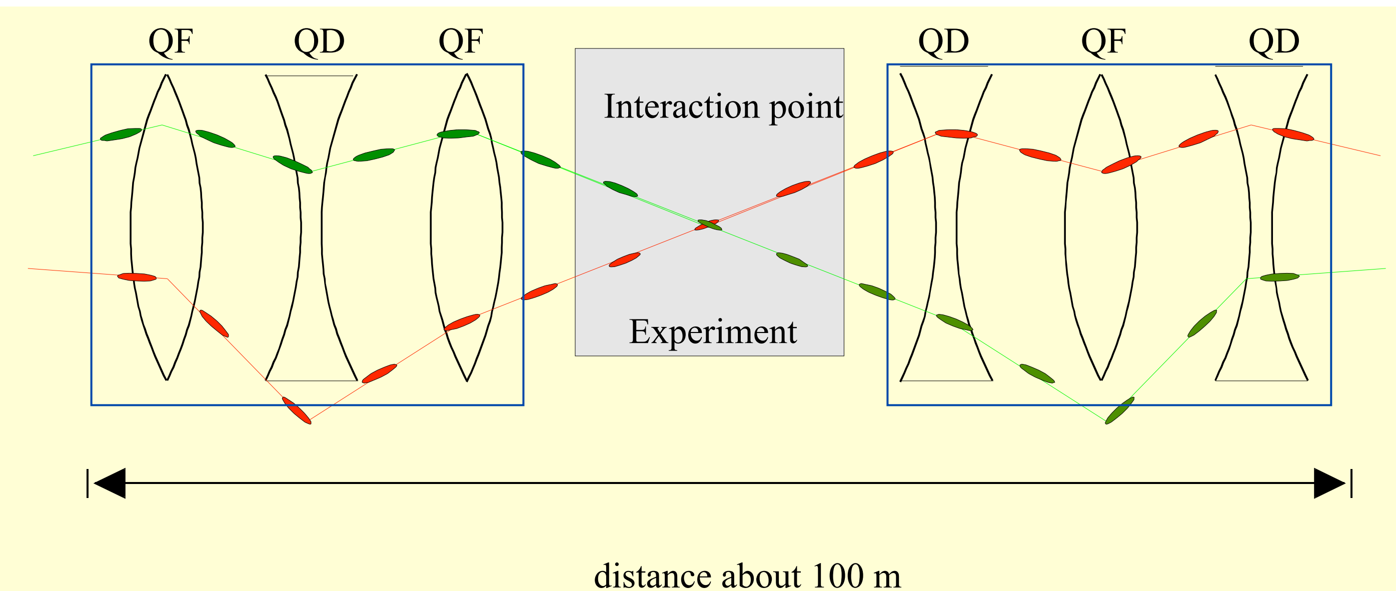
Crossing angle



Angle @ IP to avoid that the 2808 bunches collides in other places than the IP in the LSS.

~ 30 unwanted collision per crossing

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*} \right)^2}$$

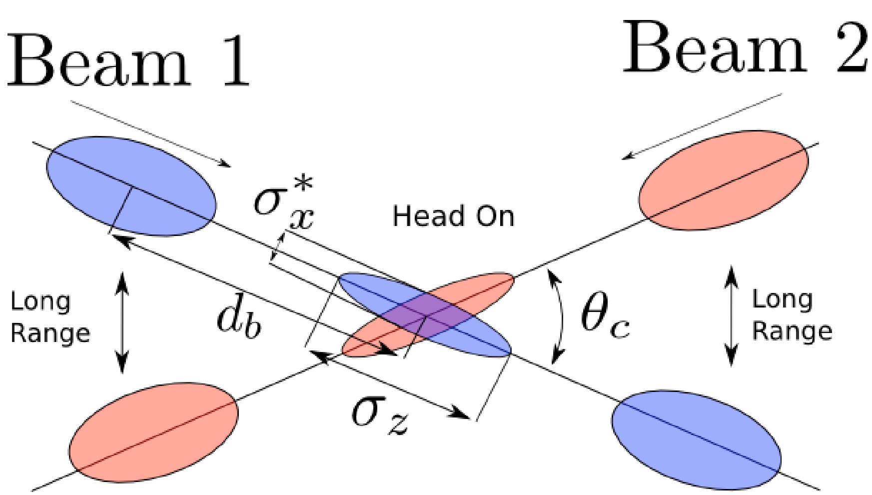


Θc	crossing angle	285 μrad
σz	RMS bunch length	7.55 cm
σ*	RMS beam size (ATLAS-CMS)	16.7 μm
F	L reduc. Factor	0.836

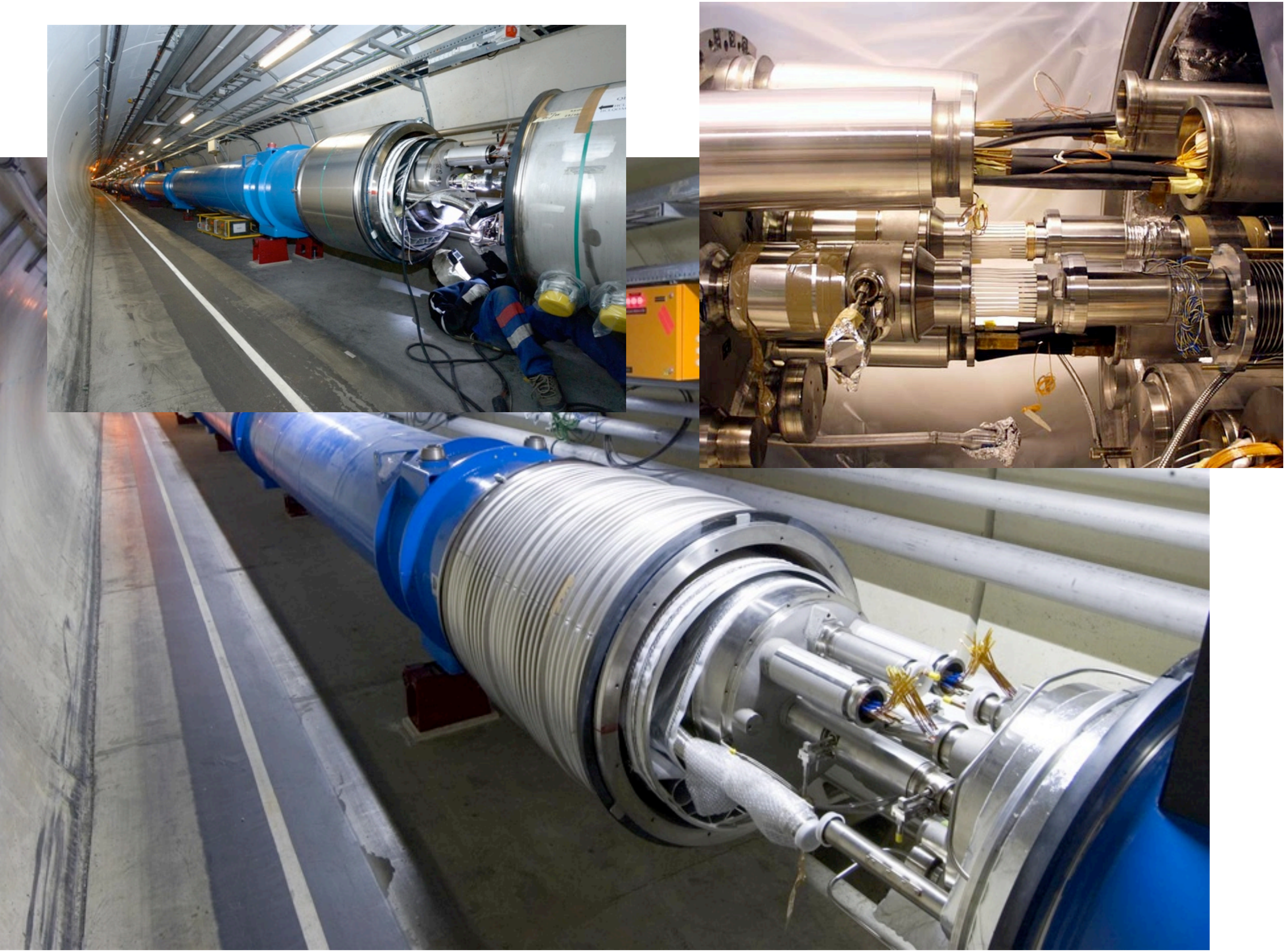
Few LHC numbers ...

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F$$

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}$$



Luminosity	1 10^{34} /cm²/s (IP1 IP5)
Particle per bunch	1,15 10^{11}
Bunches	2808
Revolution frequency	11,245 kHz
Crossing rate	40 MHz
Nomalised Emittance	3.75 μm rad
β-function at the collision point	0.55 m
RMS beam size @ 7 TeV at the IP1-5	16.7 μm
Circulating beam current	0.584 A
Stored energy per beam	362 MJ



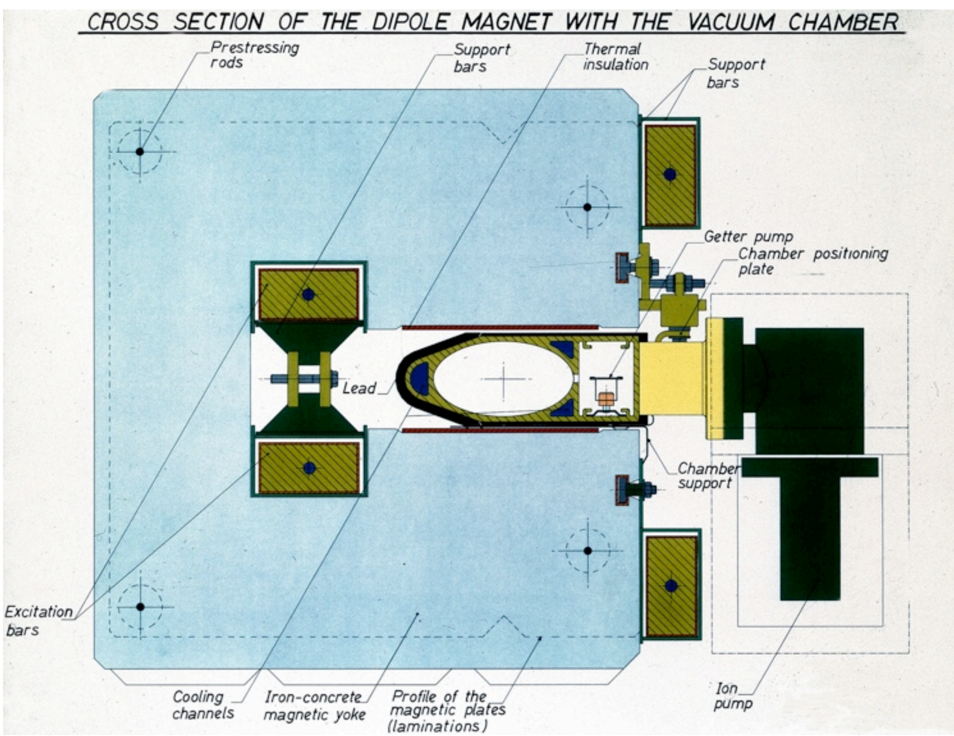
LEP vs LHC: Magnets, a change in technology

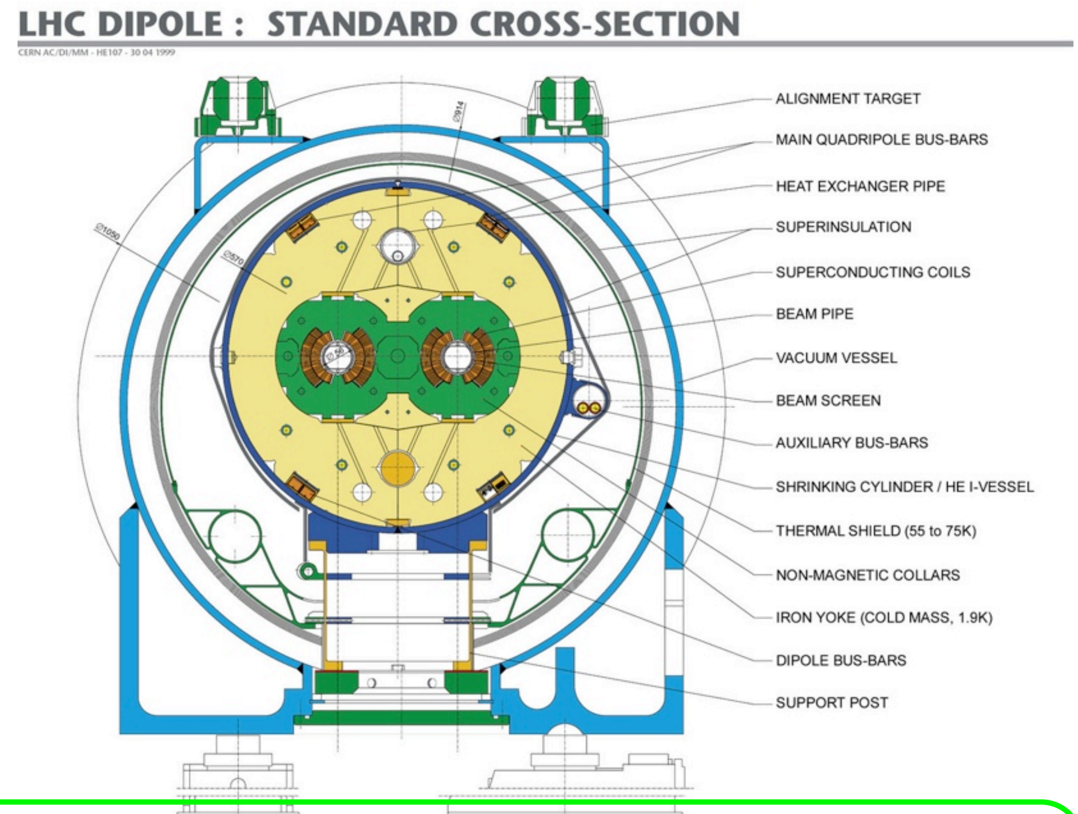
Bending Field → ***p(TeV) = 0.3 B(T) R(Km)***

(earth magnetic field is between 24 mT and 66 mT)

Tunnel R ≈ 4.3 Km LHC 7 TeV → B ≈ 8.3 T → ***Superconducting coils***

LEP 0.1 TeV → B ≈ 0.1 T → ***Room temperature coils***



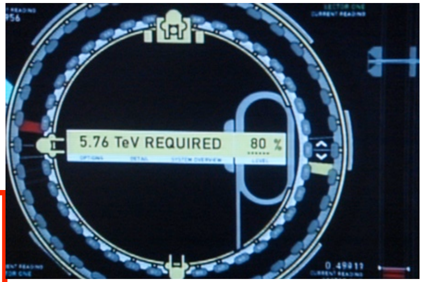


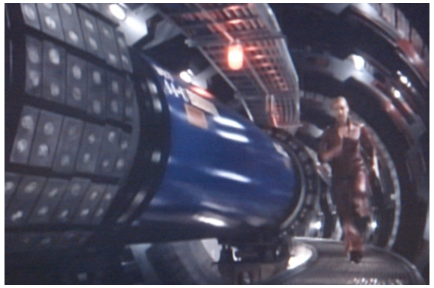
Protons can go up in energy more than electrons because they ***emit less synchrotron radiation.*** Bending (dipoles) and focusing (quadrupoles) strengths require high magnetic fields generated by superconductors

INTERLUDE:
THE TERMINATOR-3 ACCELERATOR

We apply some concepts to the accelerator shown in Terminator-3 [Columbia Pictures, 2003]

- Estimation of the magnetic field
  - Energy = 5760 GeV
  - Radius ~30 m
  - Field = 5760/0.3/30 ~ 700 T (a lot !)





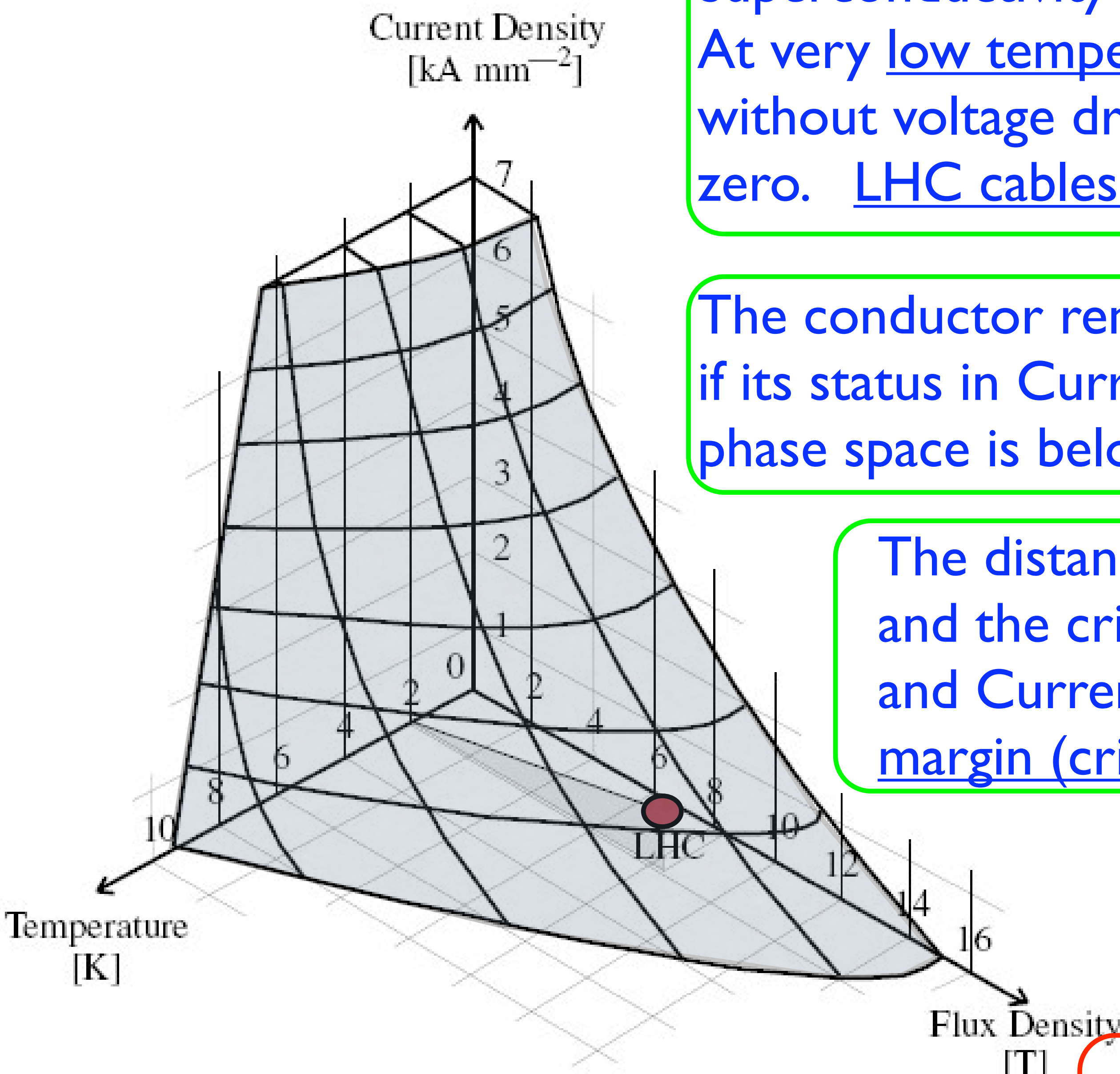
Energy of the machine (left) and size of the accelerator (right)

- Why the magnet is not shielded with iron ?
  - Assuming a bore of 25 mm radius, inner field of 700 T, iron saturation at 2 T, one needs 700*25/2=9000 mm=9 m of iron … no space in their tunnel !
  - In the LHC, one has a bore of 28 mm radius, inner field of 8 T, one needs 8*25/2=100 mm of iron
- Is it possible to have 700 T magnets ??

A magnet whose fringe field is not shielded

From E. Todesco CERN Summer student lecture

Very, very short introduction to Superconductivity for accelerators



Superconductivity is a property of some materials. At very low temperature they can carry currents without voltage drop, i.e. their resistivity goes to zero. LHC cables: Nb-Ti working at 1.9 K

The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the Critical Surface

The distance between the working point and the critical surface for a fixed B field and Current Density is the temperature margin (critical temperature)

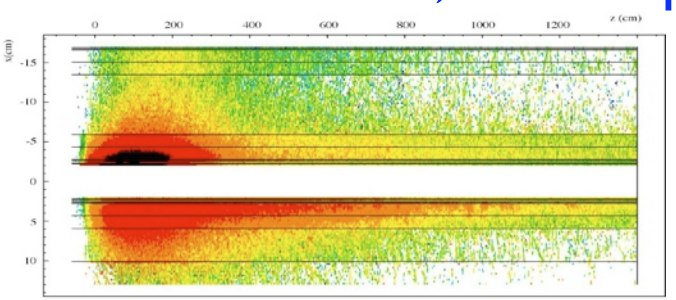
Transition to a normal conducting state is called magnet quench

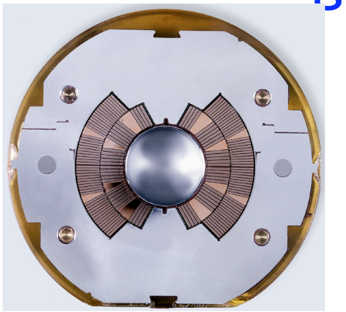
What can increase the temperature in a magnet ?

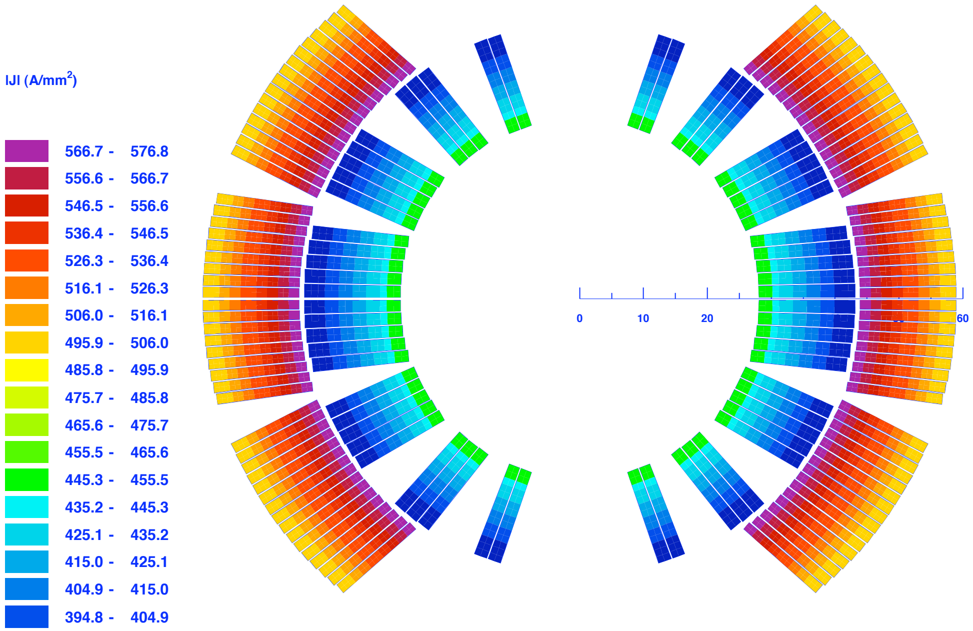
V. V. S. Introduction to Superconductivity II

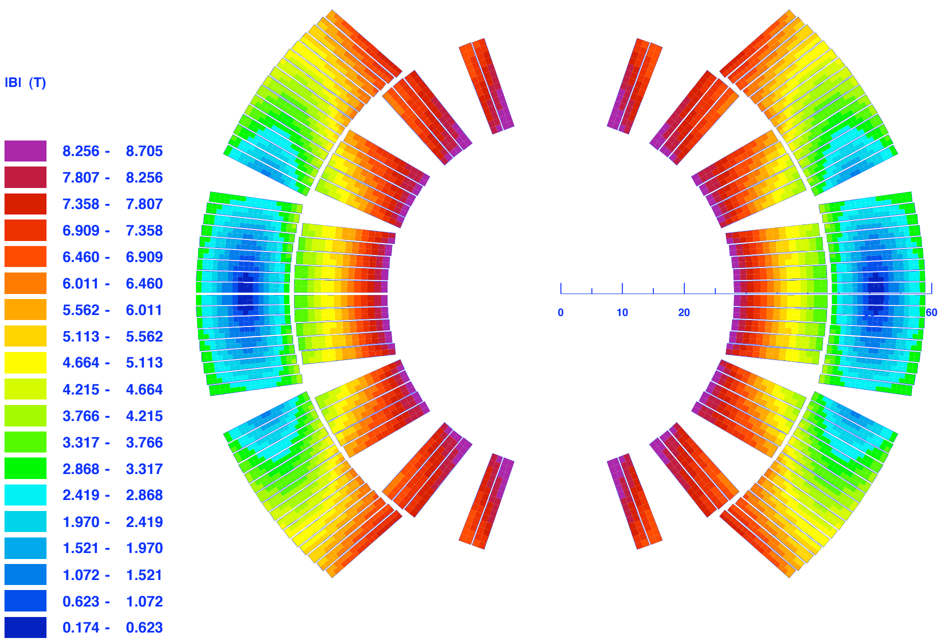
Beam losses can eat the temperature margin because of energy deposition

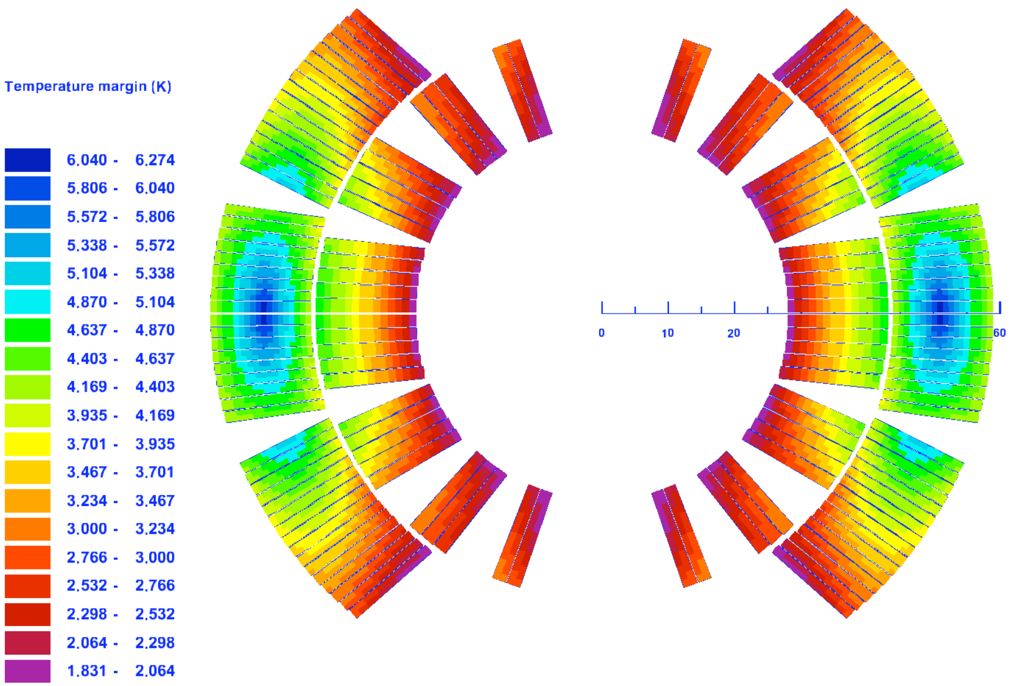
Limit of accepted losses: ~ **<u>10 mW/cm³</u>** to avoid ΔT> 2 K, the temperature margin











Courtesy of Stephan Russenschuck

How much is 10 mW/cm^3 ?

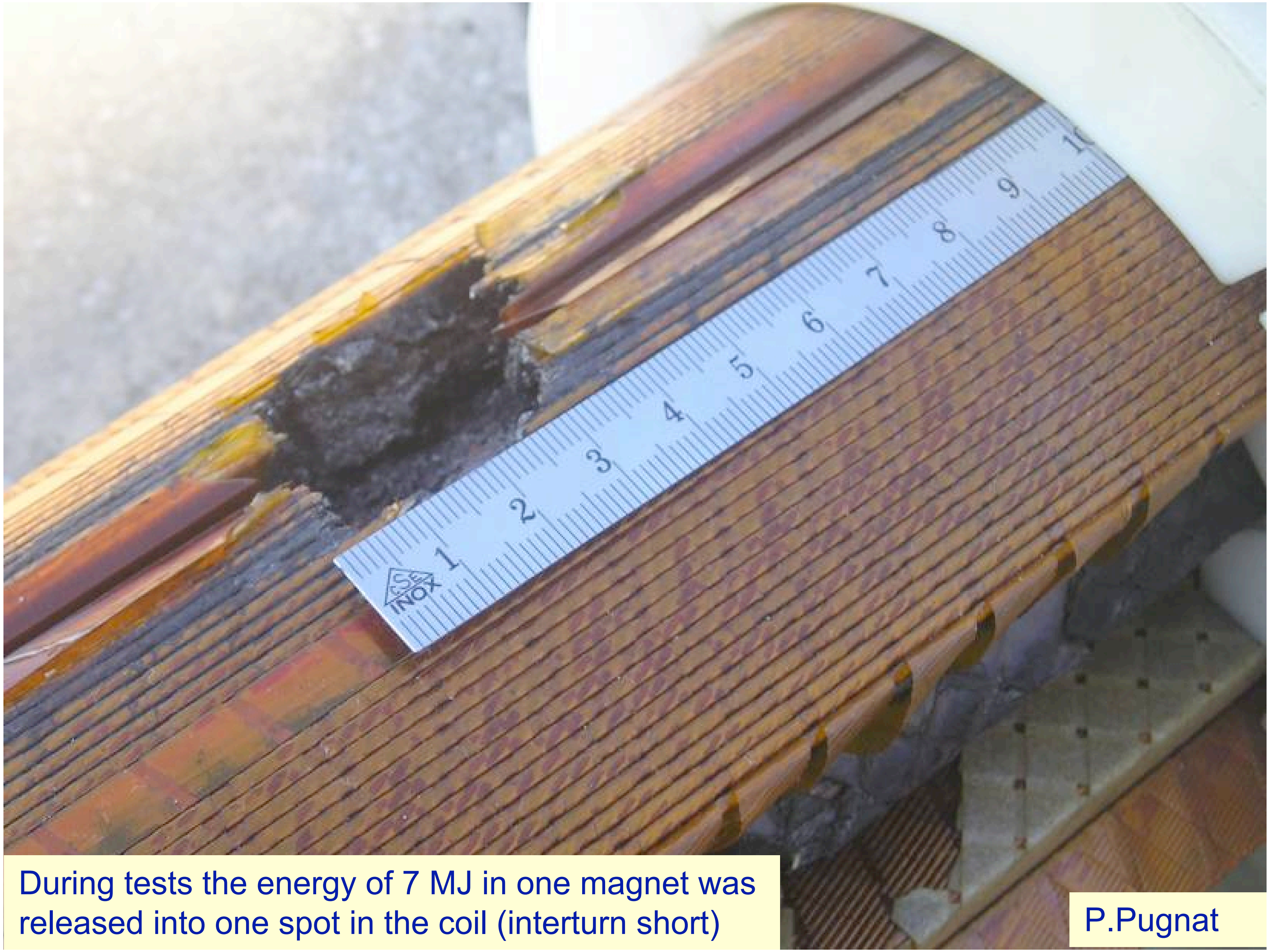
A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

This makes a power density of about 56 mW/cm^3.

The power of a neon tube can quench about 5 LHC dipoles at collision energy.... because one does not need 10 mW/cm^3 for the entire volume of a magnet, but for about 1 cm^3.

If you do the same basic computation with a normal 100 W resistive bulbs is even worst

When something goes wrong.... bad quench...

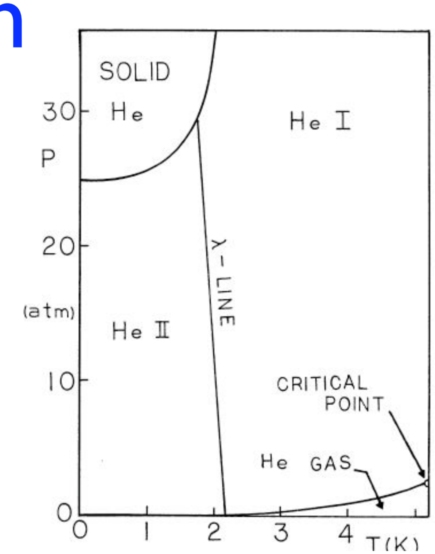


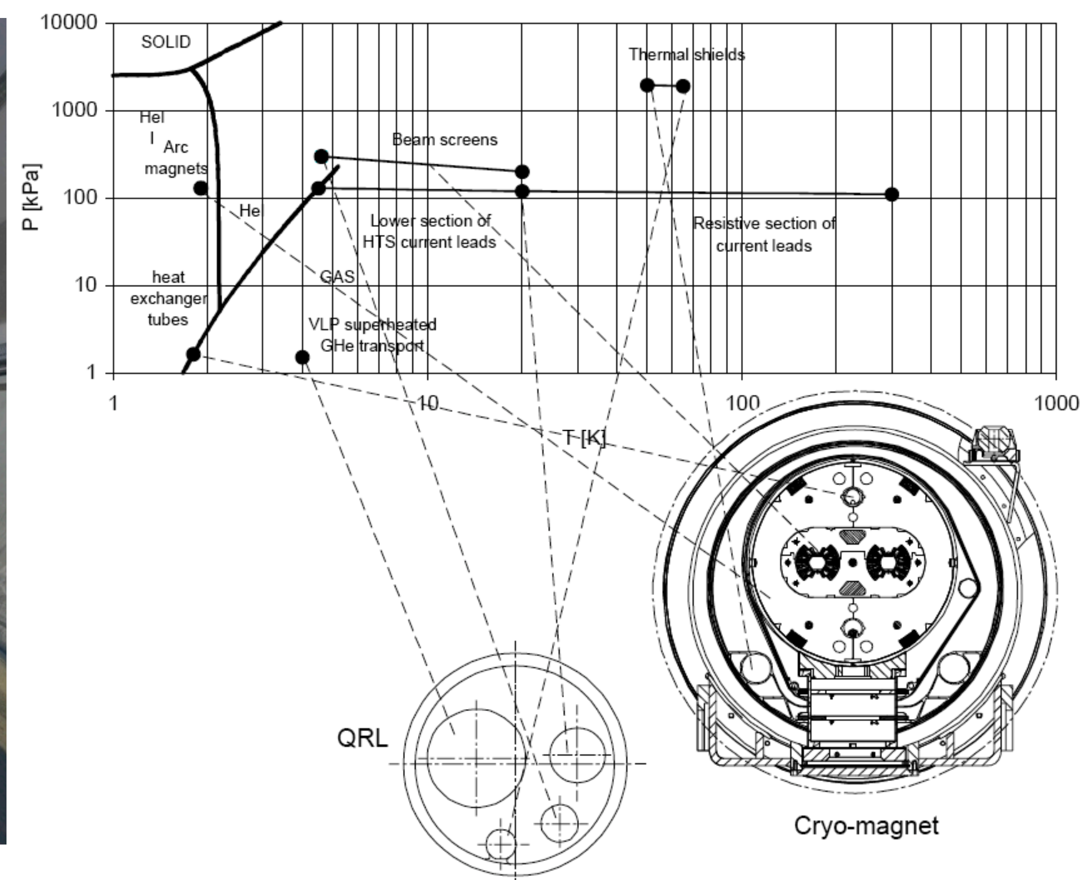
During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

P.Pugnat

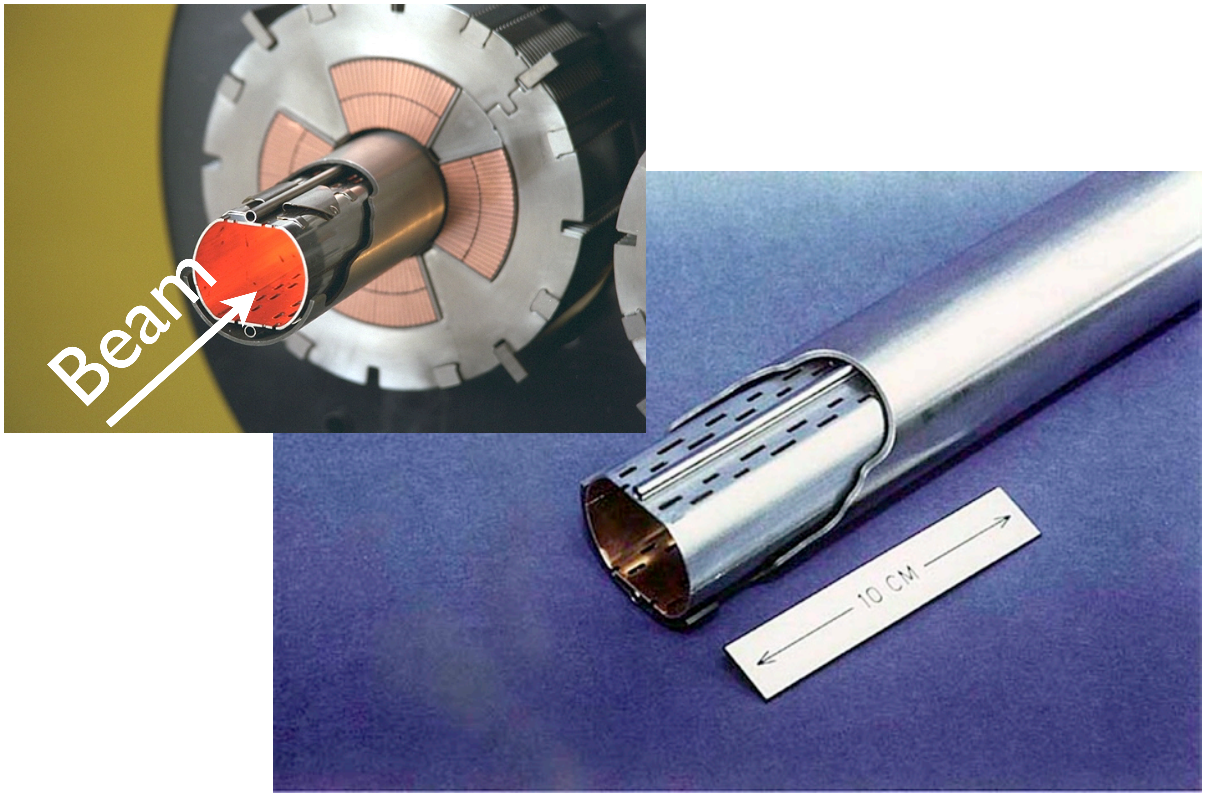
Which coolant ? Liquid superfluid helium

LHC cryogenics will need 40,000 leak-tight pipe junctions. 12 million litres of liquid nitrogen will be vaporised during the initial cooldown of 31,000 tons of material and the total inventory of liquid helium will be 700,000 l (about 100 tonnes)





LHC beam screen with cooling pipes



Beam screen to protect Superconducting magnets from Synchrotron radiation.

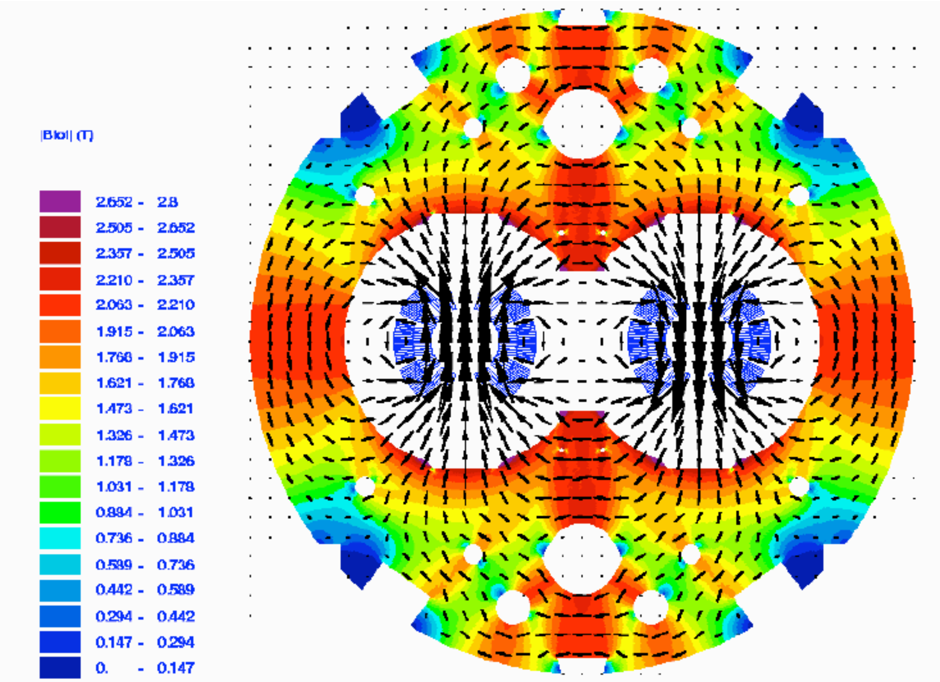
Holes for vacuum pumping

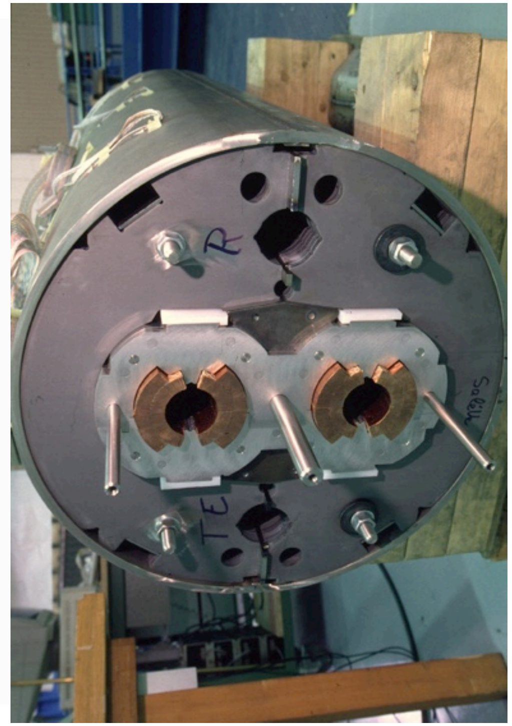
Atmosphere pressure = 750 Torr
Moon atmospheric pressure = 5 10^{-13} Torr

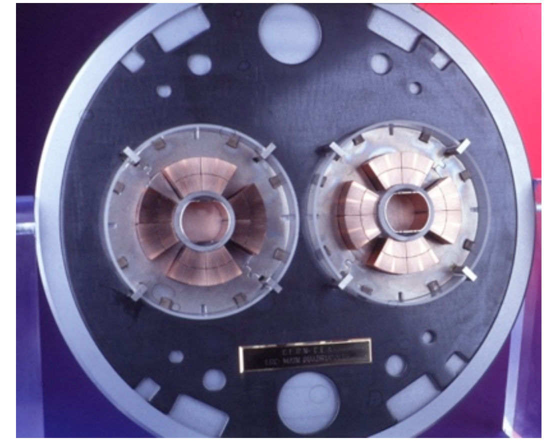
Vacuum required to avoid unwanted collision far from the IPs and decrease the Luminosity

Typical vacuum: 10^{-13} Torr
There is ~6500 m^3 of total pumped volume in the LHC, like pumping down a cathedral.

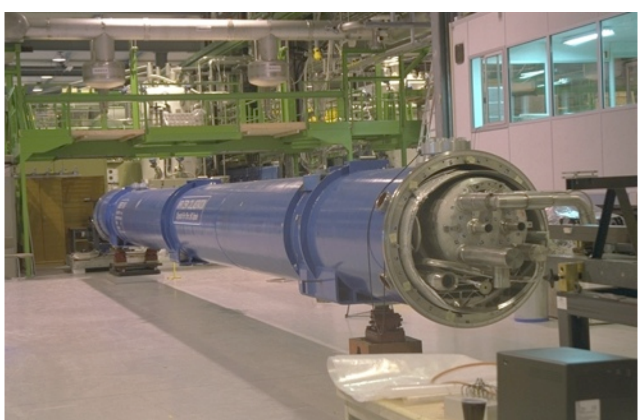
Two-in-one magnet design

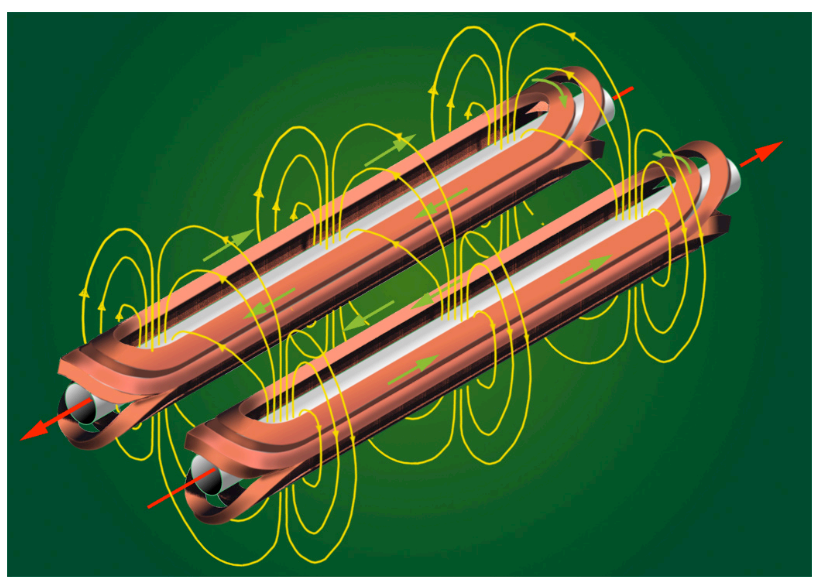




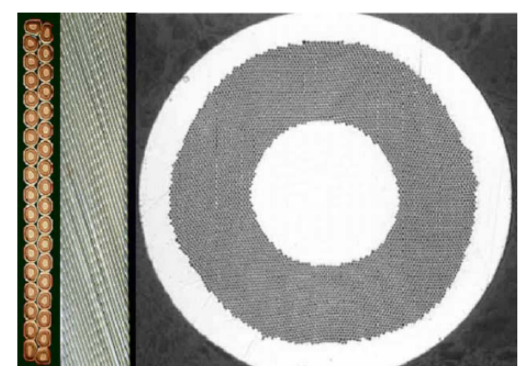


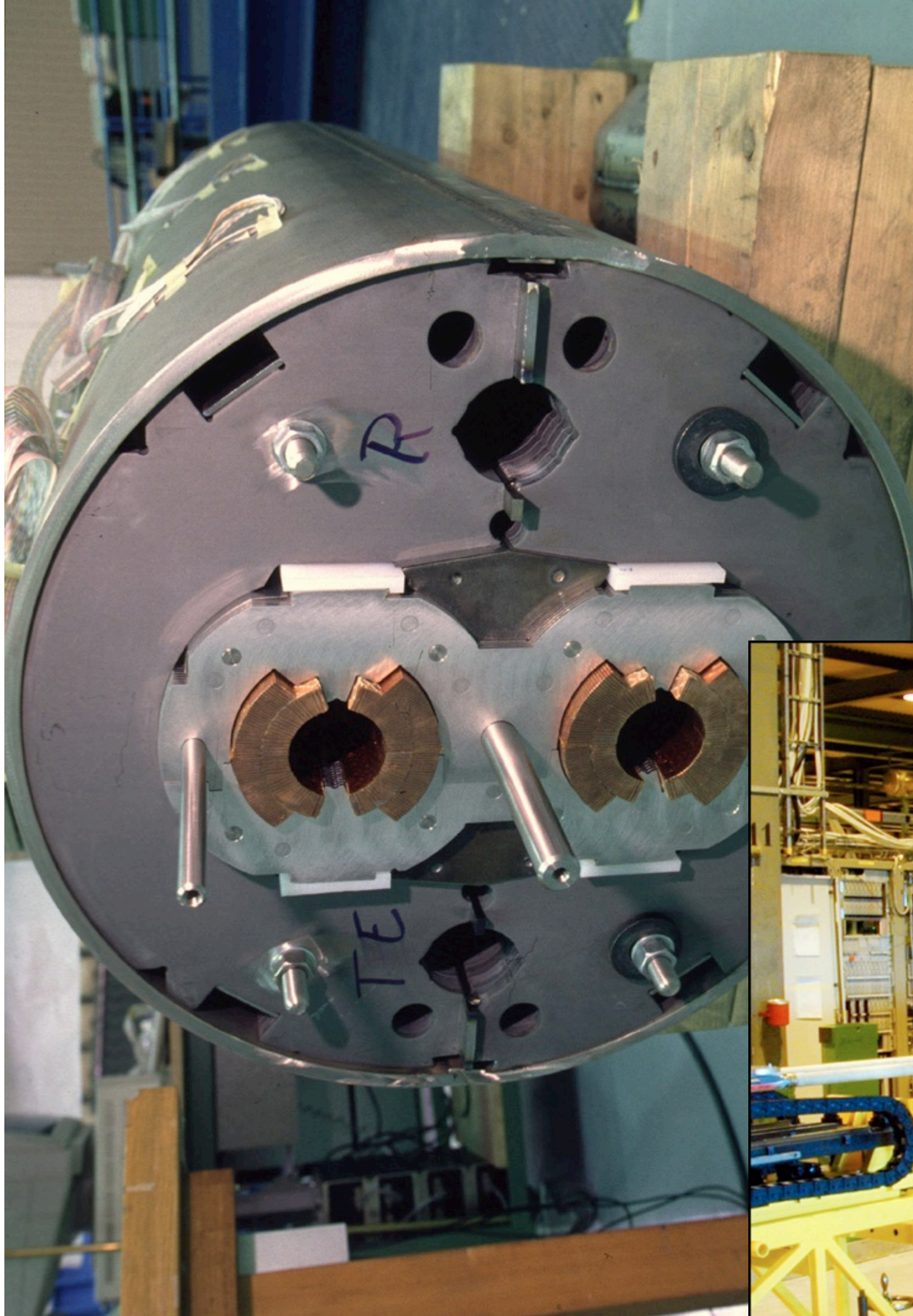
The LHC is one ring where two accelerators are coupled by the magnetic elements.





Nb -Ti superconducting cable in a Cu matrix





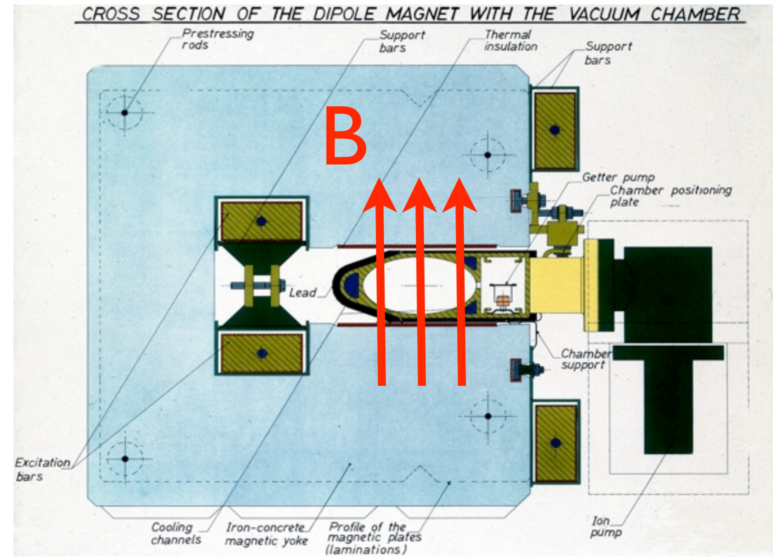
At 7 TeV:

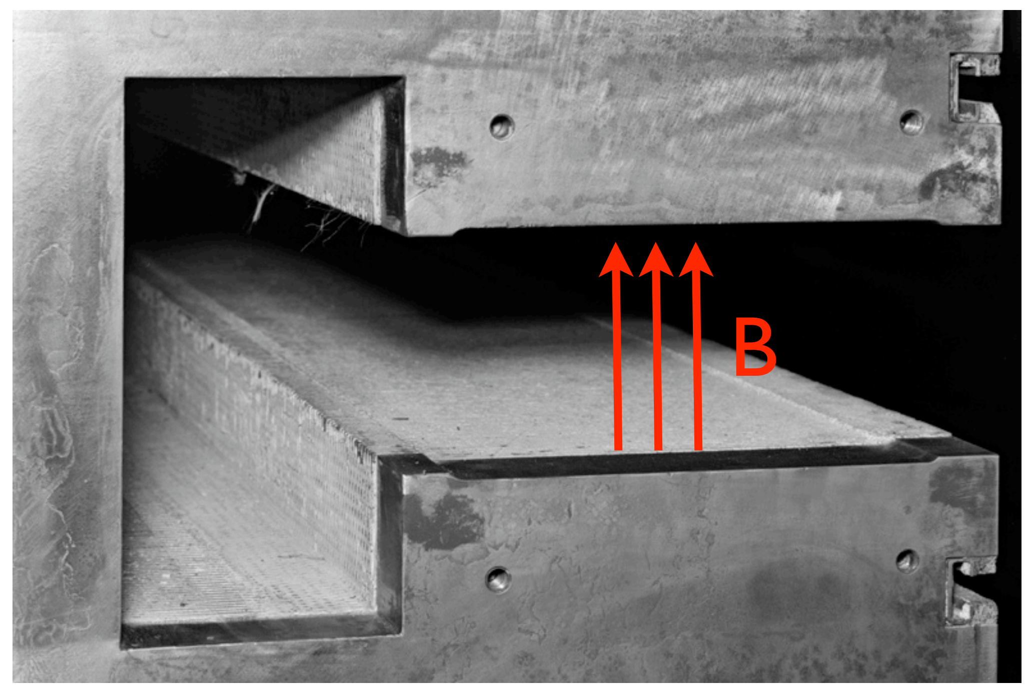
I_{max} = 11850 A Field=8.33 T
Stored energy= 6.93 MJ
Weight = 27.5 Tons
Length =15.18 m at room temp.
Length (1.9 K)=15 m - ~10 cm

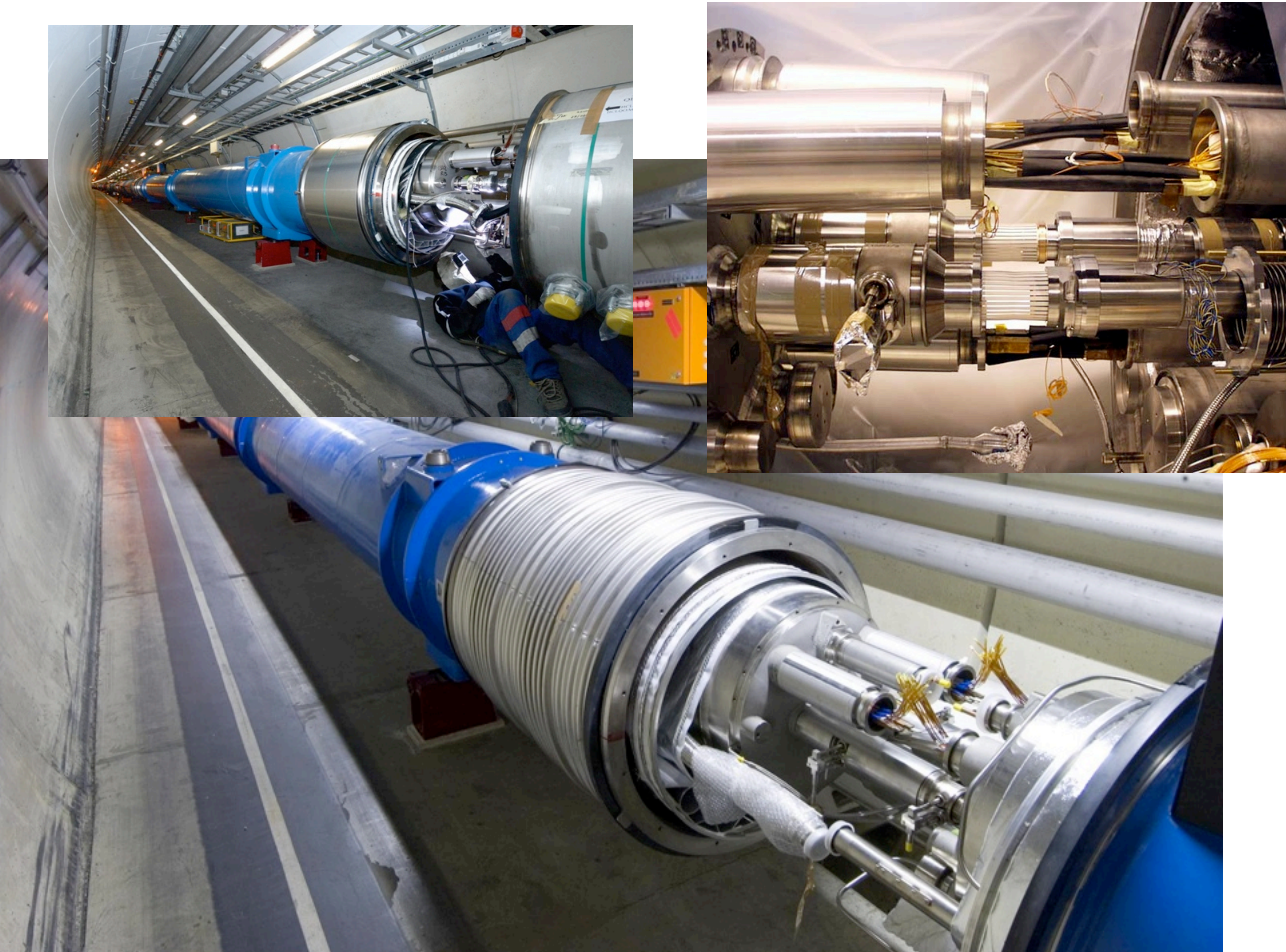
Test bench for magnetic measurements at 1.9 K

PS: they are not straight, small bending of 5.1 mrad

From LEP to the LHC, iron-concrete yoke ...

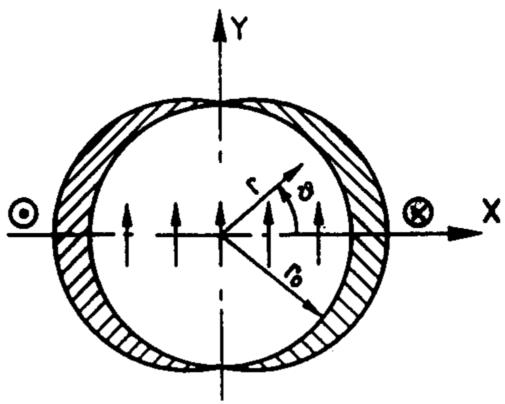


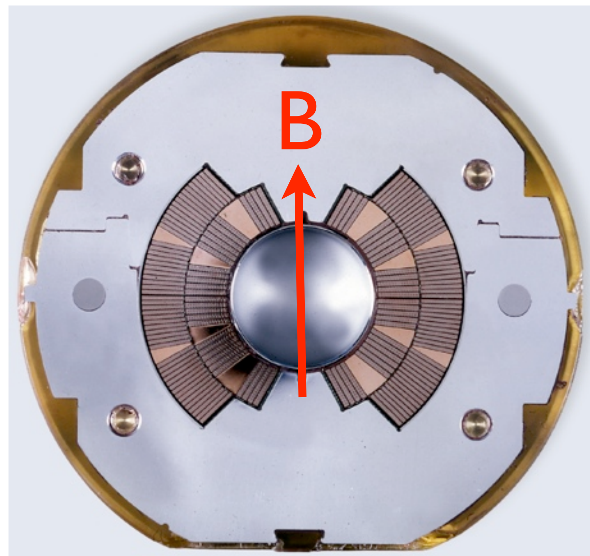




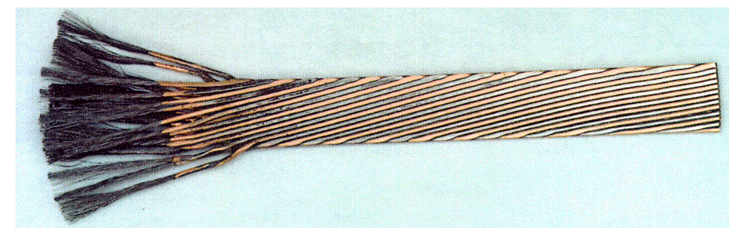
Cosθ coil of main dipoles

Cos nϑ





A 2D cosθ current distribution generates a quasi-perfect vertical field in the aperture between the two conductors.

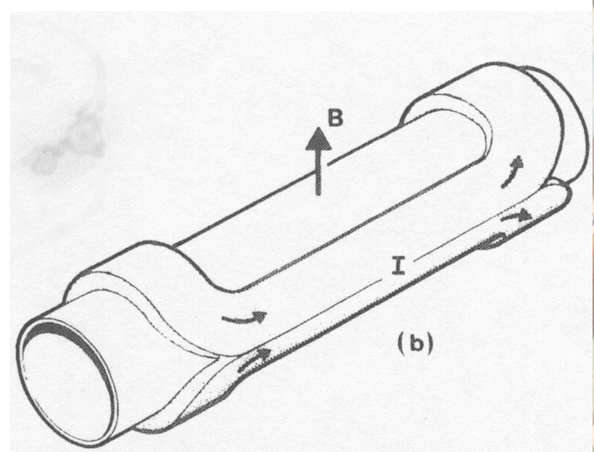


$$I = I_o \cos \vartheta$$

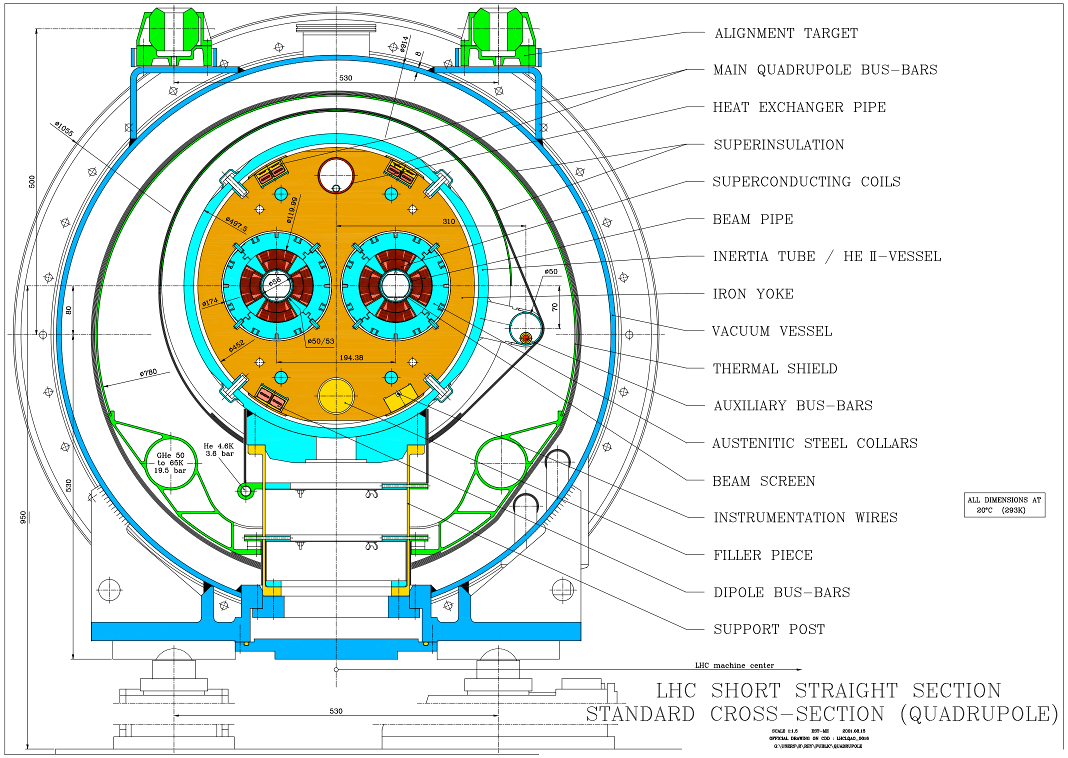
$$B_\vartheta = \frac{\mu o \ I_o}{2 \ r_o} \cos \vartheta \qquad B_x = o$$

$$B_\vartheta = \frac{\mu o \ I_o}{2 \ r_o} \sin \vartheta \qquad B_y = \frac{\mu o \ I_o}{2 \ r_o}$$

Dipolar Vertical field



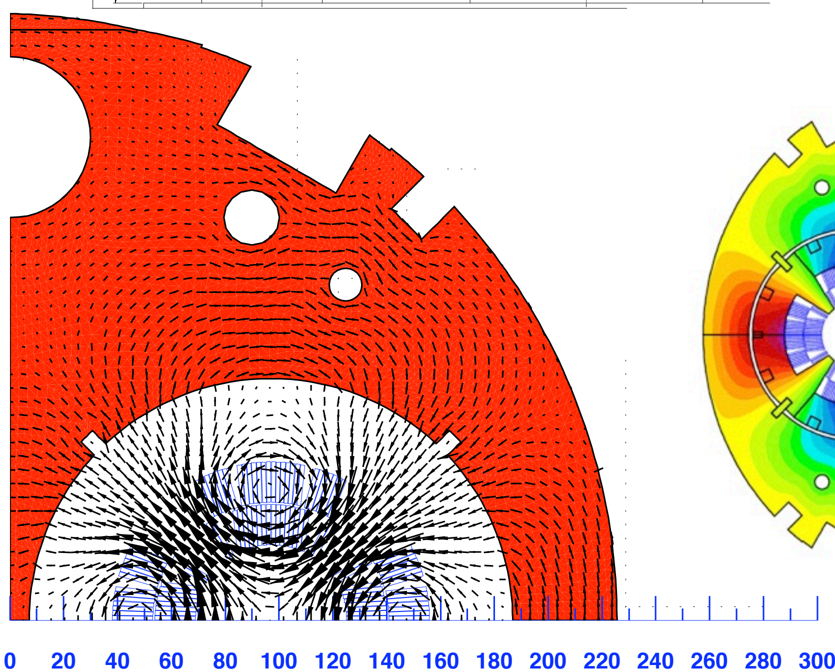
Quadrupoles are also two-in one

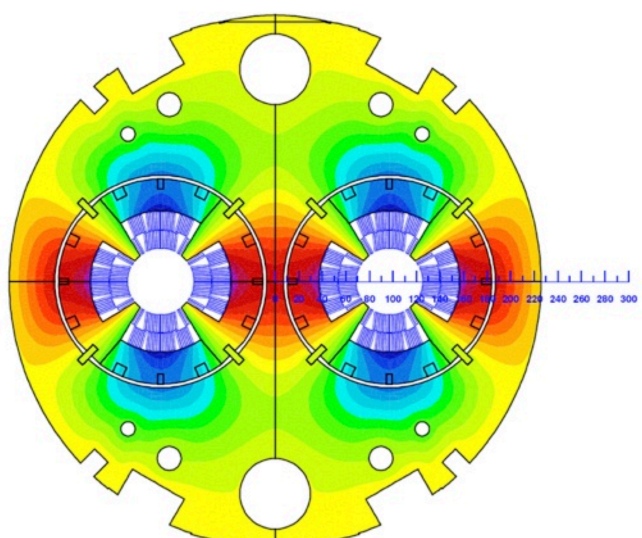


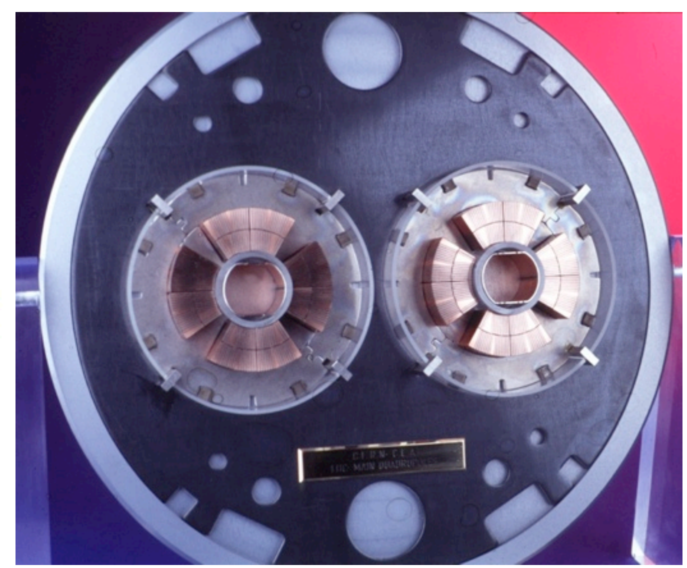
At 7 TeV:

I_{max} = 11850 A
Field=225 T/m

Weight = 6.5 Tons
Length =3.1 m

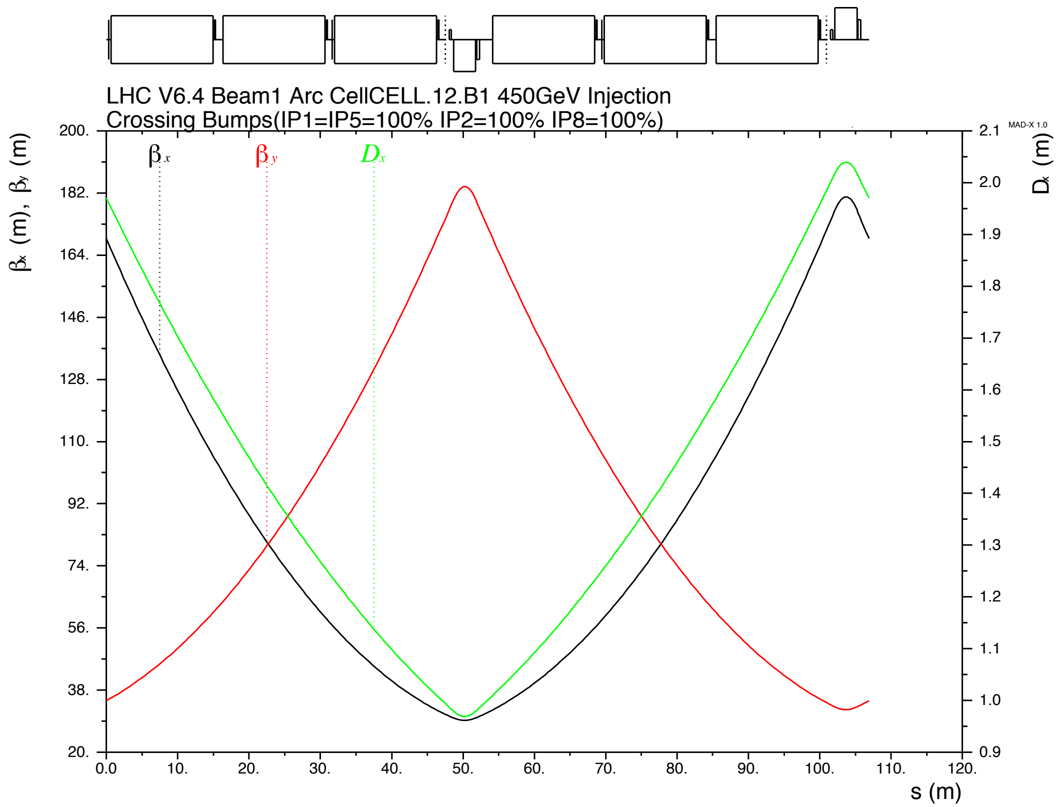


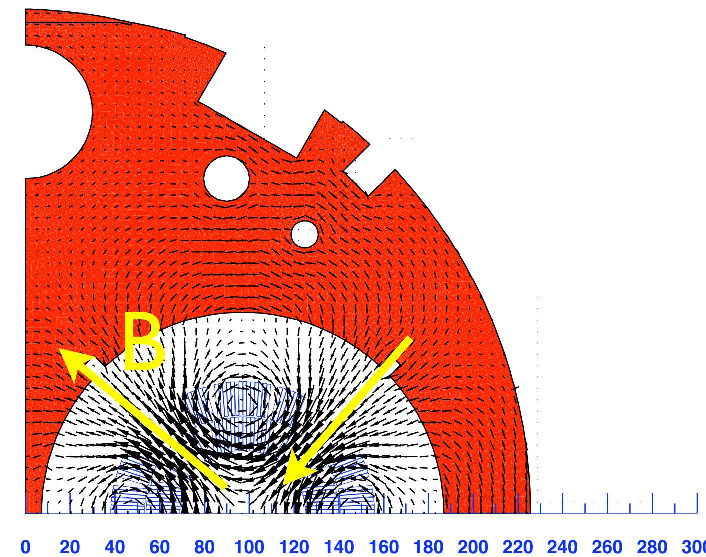


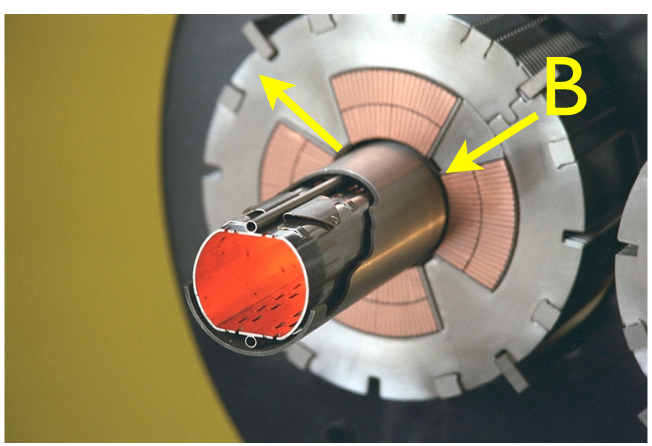


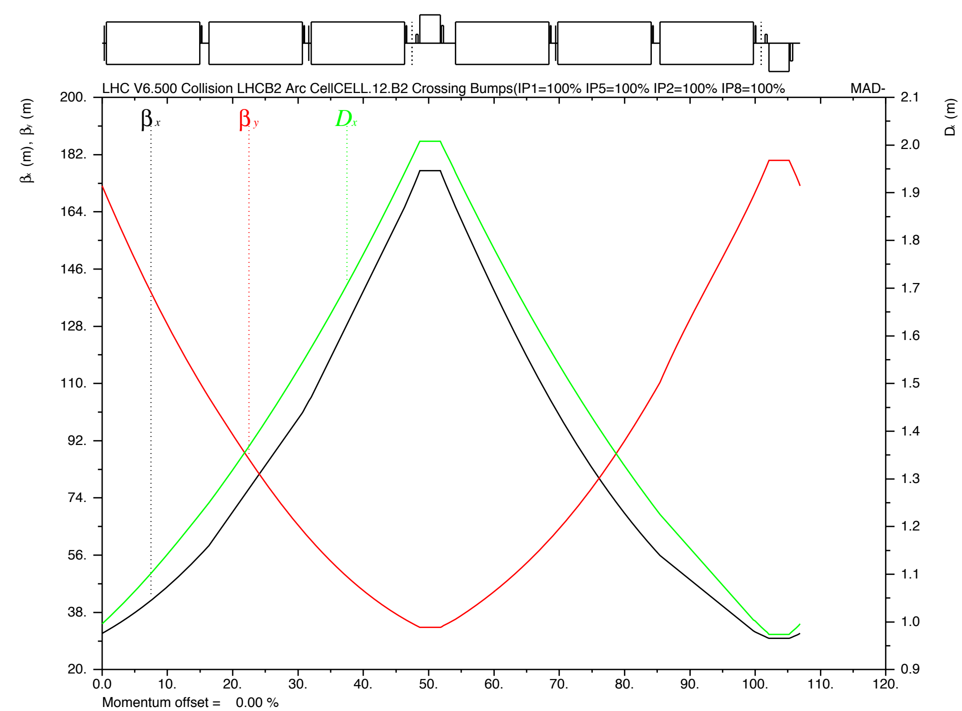
Quadrupoles being assembled before installation

Arc cell at injection for beam 1 and beam 2



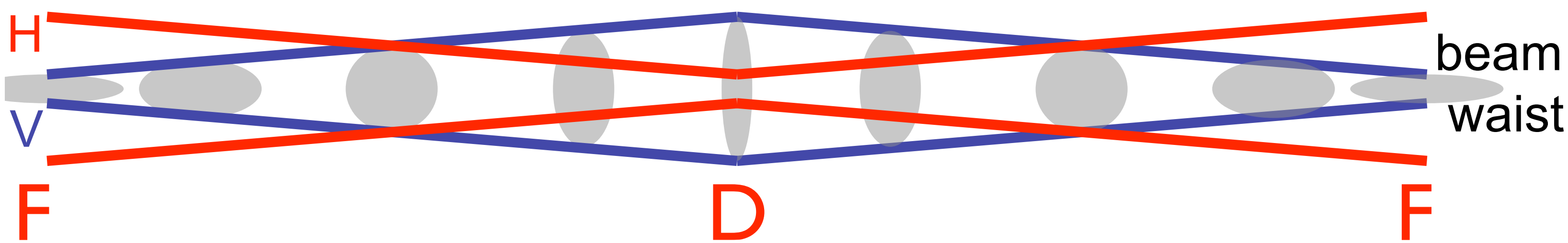


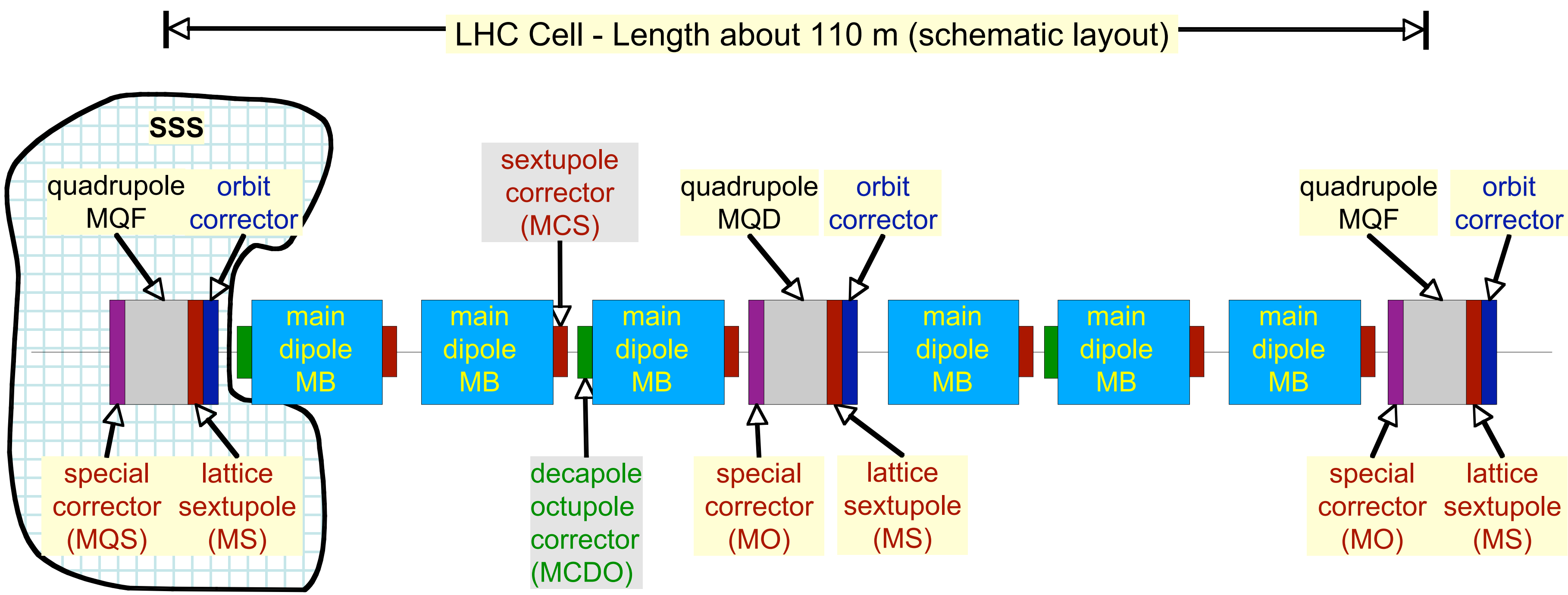




An example of a lattice: LHC cell

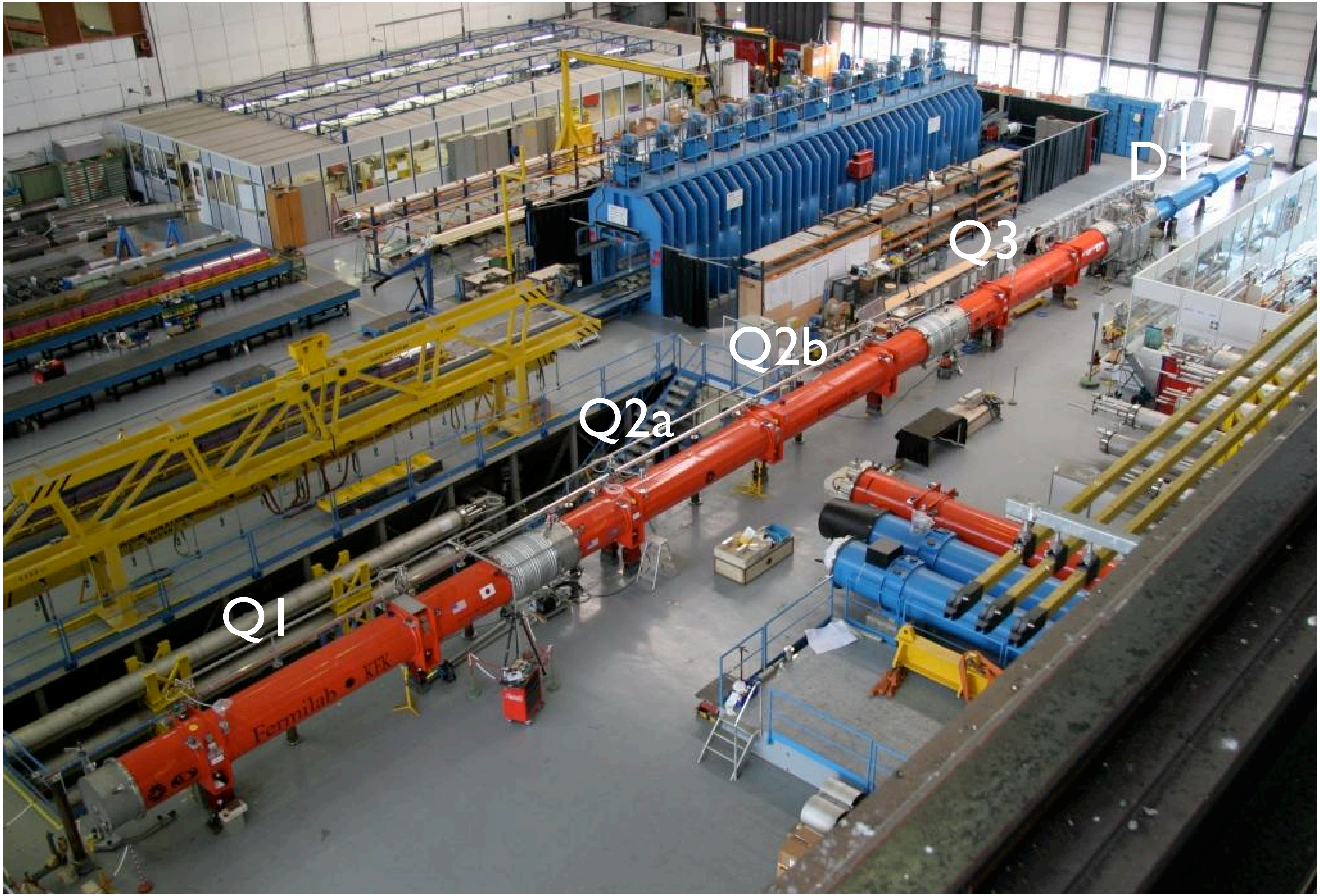
Classical FODO cell with about 90^0 phase advance per cell
(F=focusing, O=drift, D=defocusing)





One LHC test CELL on surface

Triplets before lowering in the tunnel



Working point choice

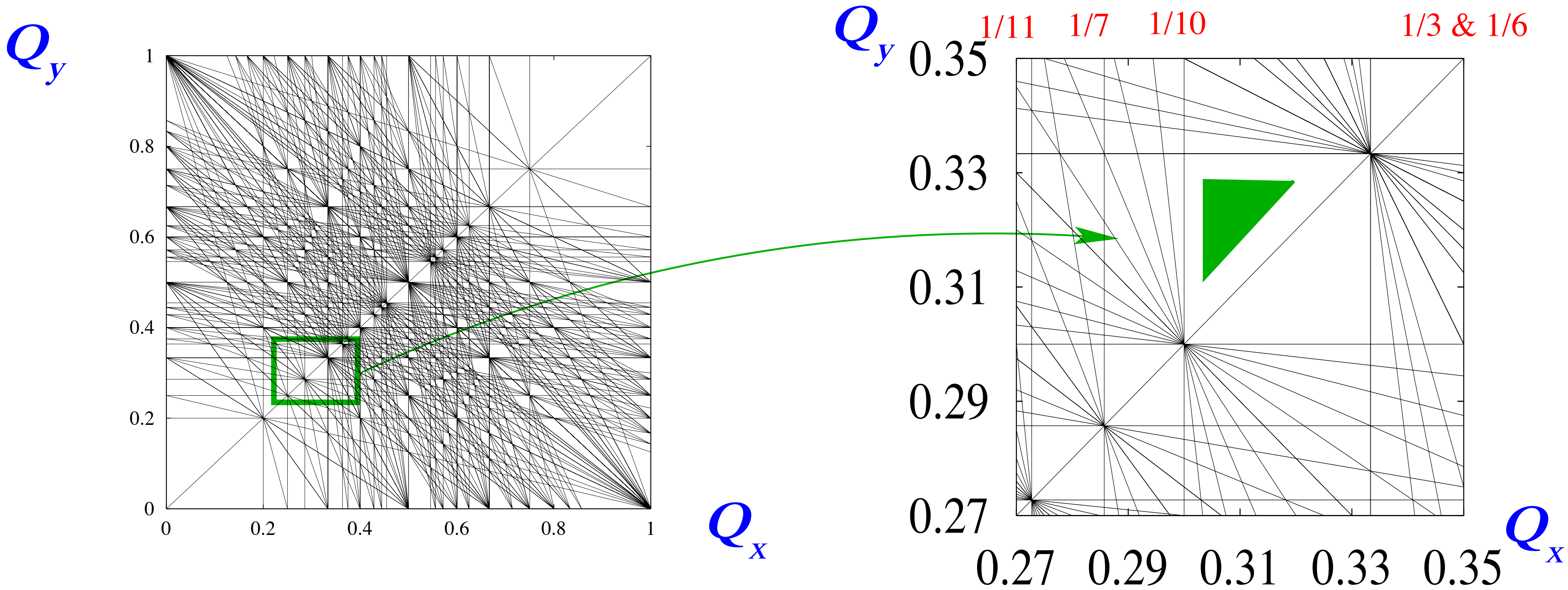
Tune: number of betatron oscillations in the x-x' (Qx) or y-y' (Qy) plane per machine turn.
An integer number in Qx or Qy correspond to a 2π rotation in the phase space. Not interesting in term of resonance instabilities.
Usually fractional tune is quoted, meaning what rest of the tune after subtracting the integer part.

From previous experience (Hera, Tevatron)
Avoid resonances n+m < 12

Working point → Qx and Qy.
LHC working point:
Q_x=64.28, Q_y=59.31

Choose region of (Qx,Qy) with enough free space from resonances

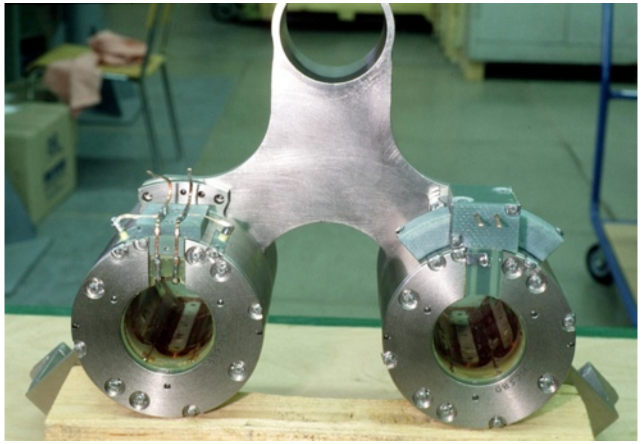
Resonances: nQx + mQy = p "n+m" → resonance order→



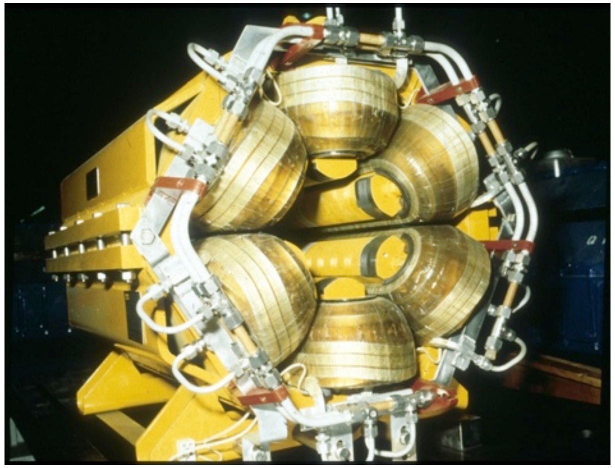
Two zoo of the multipoles and orbit correctors

Name	Quantity	Purpose
MB	1232	Main dipoles
MQ	400	Main lattice quadrupoles
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

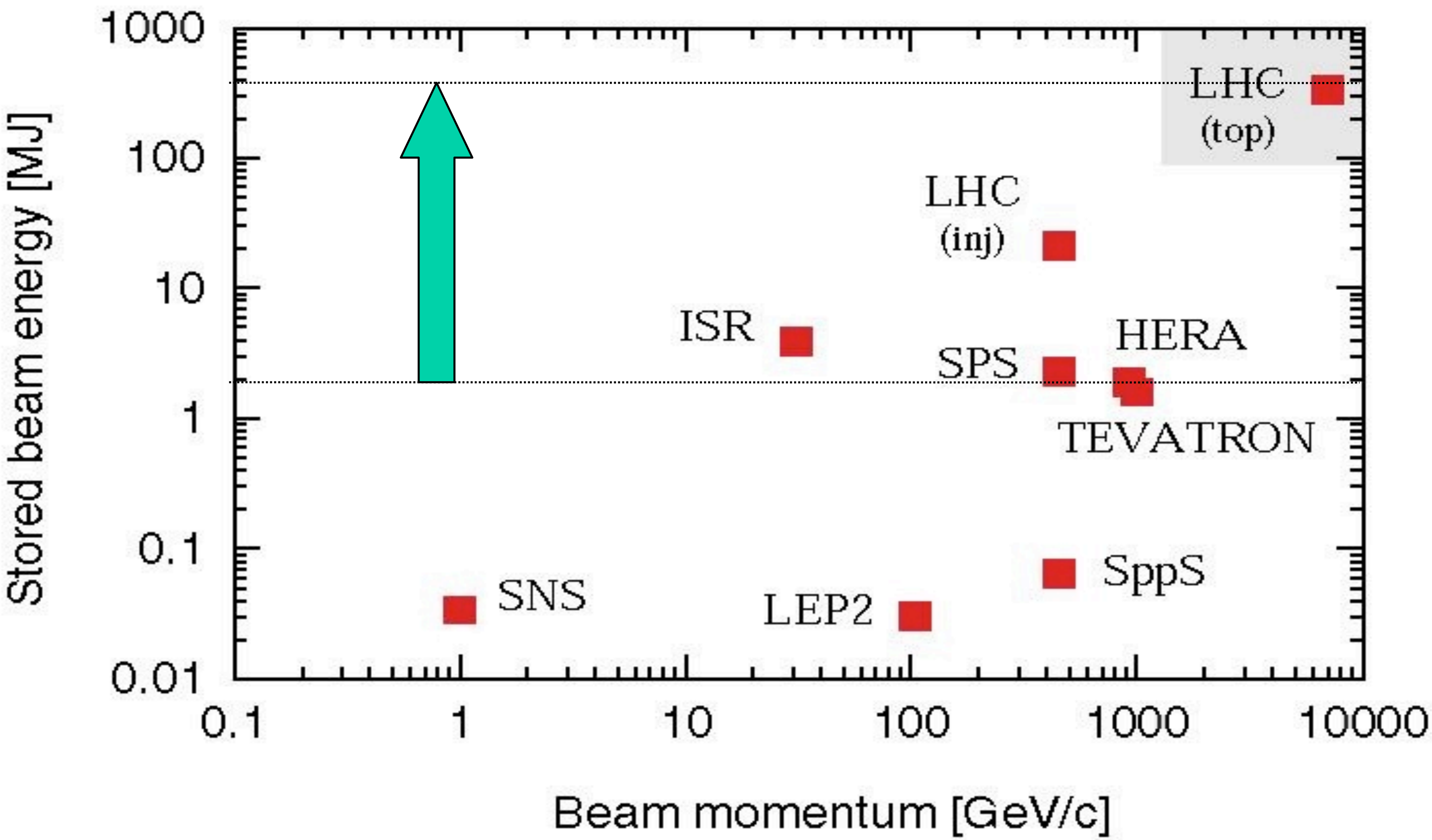
LHC sextupole



LEP sextupole



LHC: the issue of stored beam energy



Why do we have to protect the machine ?

Why do we have to protect the machine ?

Total stored beam energy at top energy (7 TeV), nominal beam, 334 MJ (or 120 kg TNT)
Nominal LHC parameters: $1.15\ 10^{11}$ protons per bunch
2808 bunches
0.5 A beam current

British aircraft carrier:
HMS Illustrious and Invincible weigh 20,000 tons all-up and fighting which is 2×10^7 kg.
Or the USS Harry S. Truman (Nimitz-class) - 88,000 tons.

Energy of nominal LHC beam = 334 MJ or 3.34×10^8 J

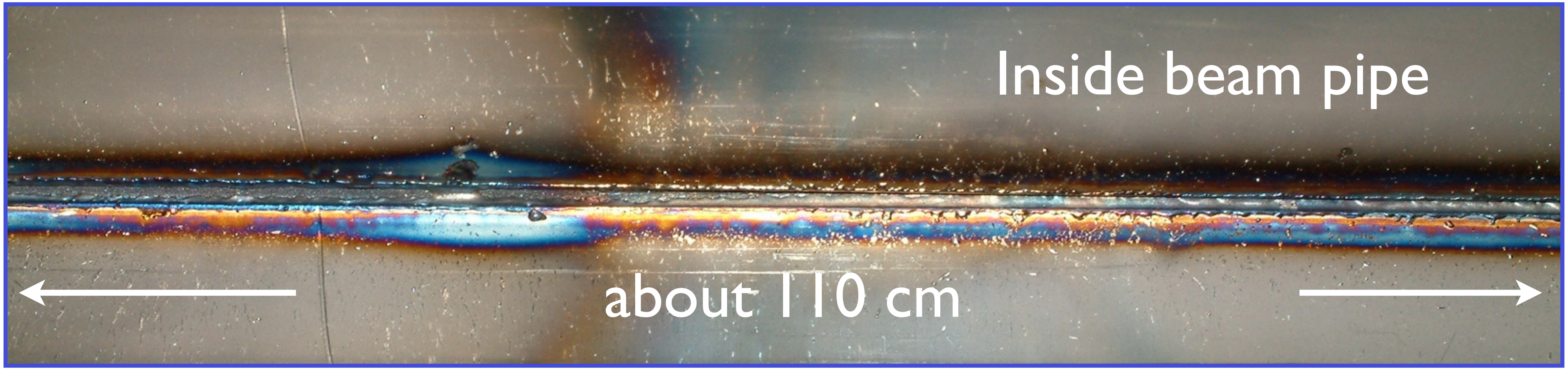
which corresponds to the aircraft carrier navigating
at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

So, what if something goes wrong?

What is needed to intercept particles at large transverse amplitude or with the wrong energy to avoid quenching a magnet?

3 years ago something went wrong during a test ...

LHC extraction from the SPS
450 GeV/c, 288 bunches
Transverse beam size 0.7 mm (1 σ)
1.15 x 10^{11} p+ per bunch, for total intensity of 3.3 x 10^{13} p+
Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)

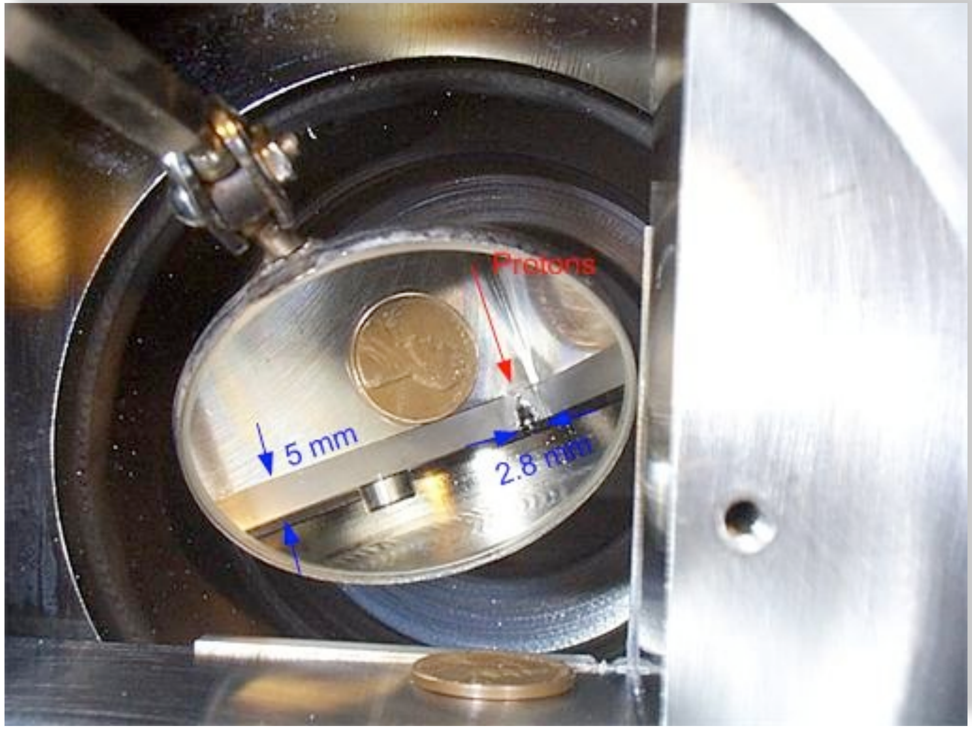


B.Goddard CERN AB/BT

Tevatron accident in 2003 (courtesy of N. Mokhov)

Accident caused by uncontrolled movement of beam detectors
(Roman Pots) which caused a secondary particle shower
magnet quench → no beam dump → damage on approximatively 550 turns

Tungsten collimator. Tmelting = 3400 ^{O}C



1.5 m long stainless steel collimator

Experiment simulating beam-losses

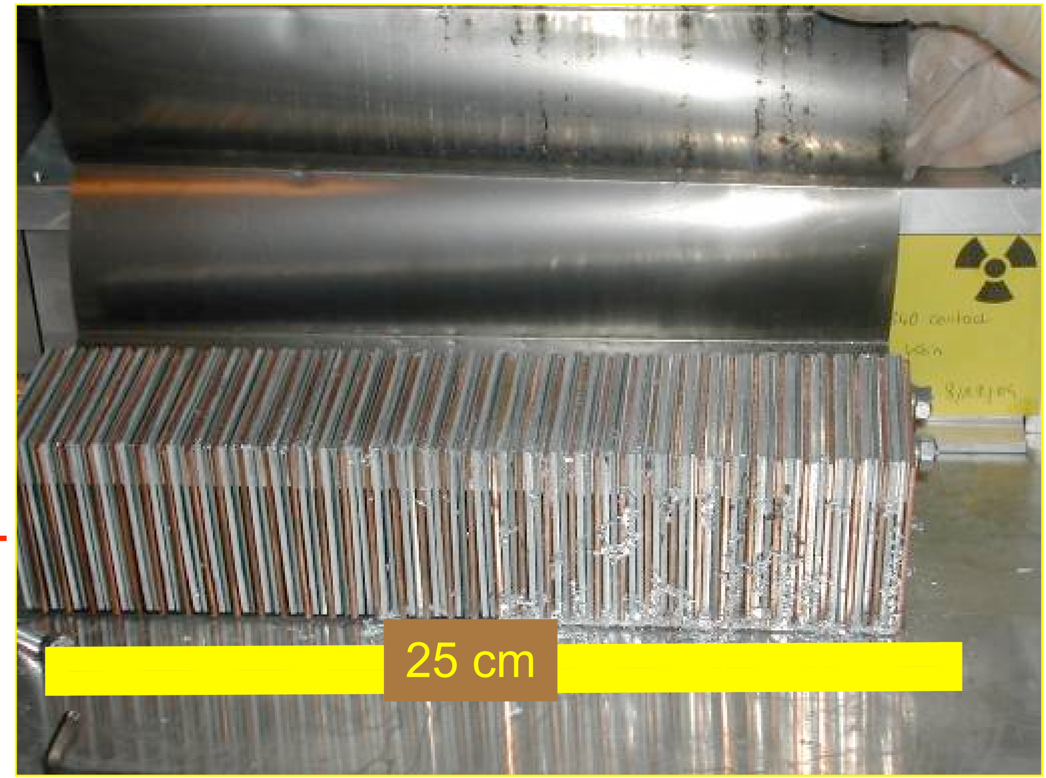
Controlled SPS experiment

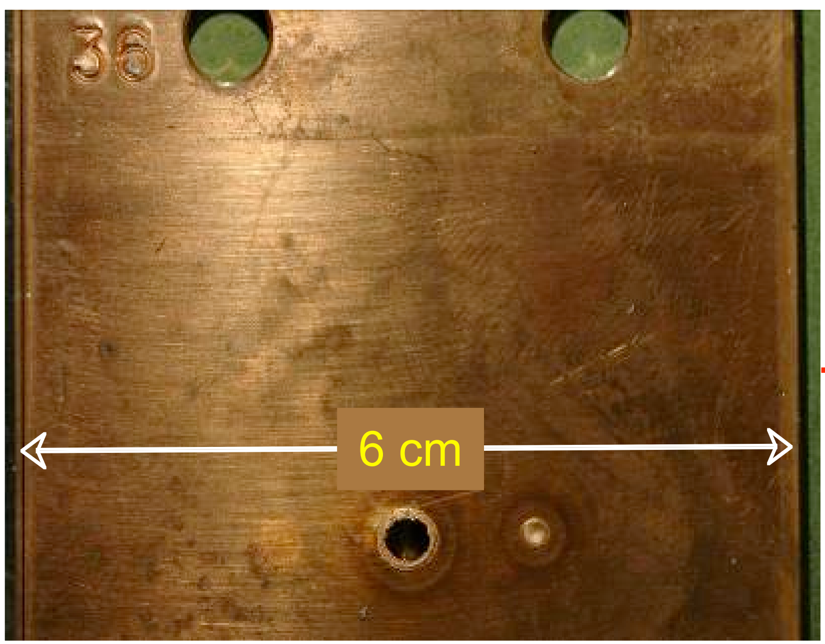
$8*10^{12}$ protons ⇒ 0.1% full LHC power

Clear damage

Beam size σx/y = 1.1 mm/0.6 mm

$2*10^{12}$ protons ⇒ below damage limit





0.1 % of the full LHC beams

Aim of the experiment:

1. test on different material the possible damage cause by beam-loss

2. test the codes used for predict possible damages in the real machine

From V. Kain

Collimation system for machine protection

Two sections in LHC dedicated to beam cleaning:

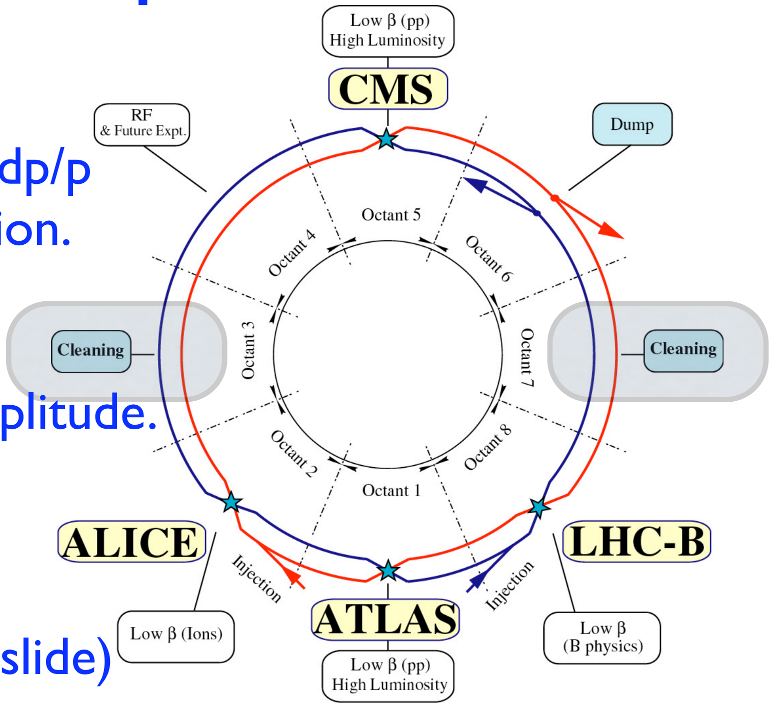
IR3 momentum cleaning → remove particles with too large dp/p ($> \pm 10^{-3}$) thanks to large dispersion.

$$\Delta x = D\frac{\Delta p}{p}$$

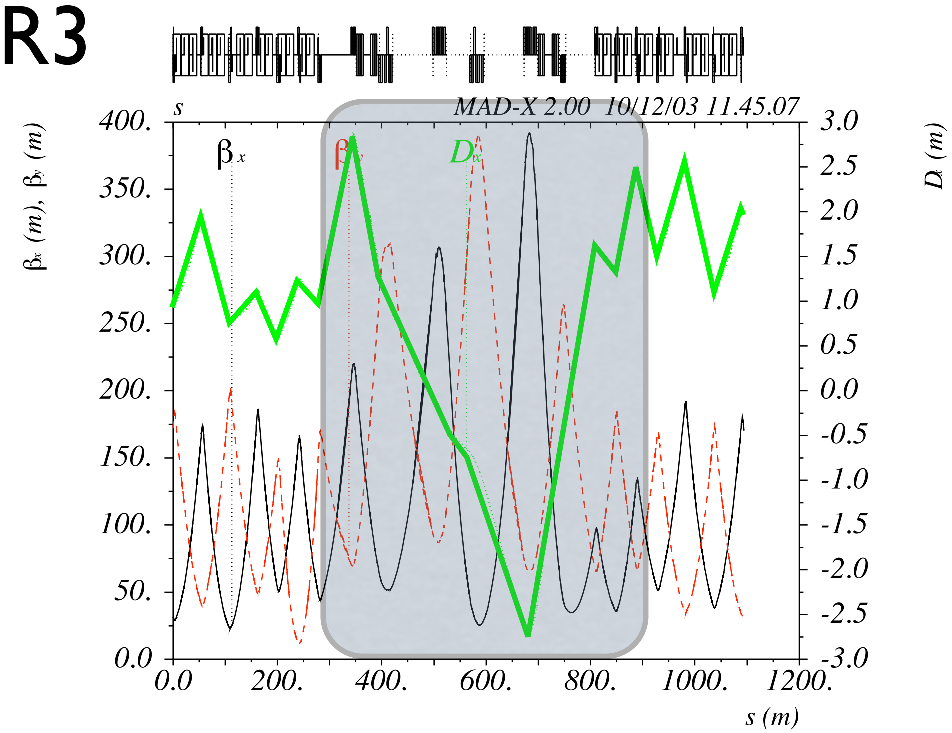
IR7 betatron cleaning → remove particles at too large amplitude. Dispersion as small as possible.

$$x_{MAX} = \sqrt{\epsilon\beta}$$

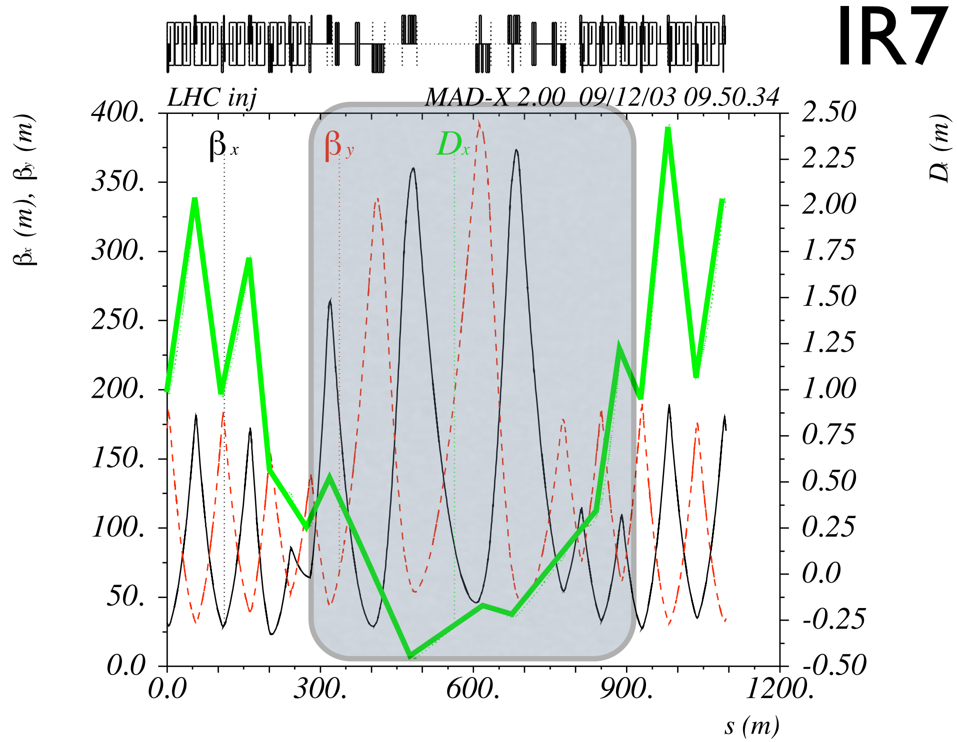
Done by intercepting particle with 2 stage collimation (next slide)



IR3

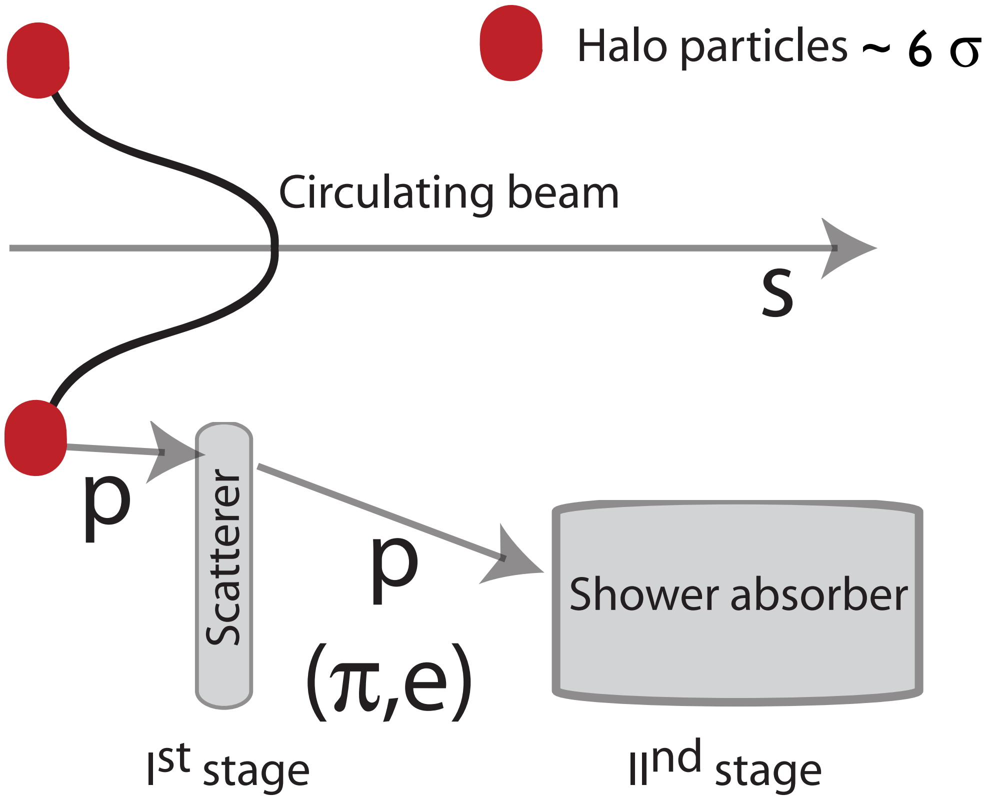


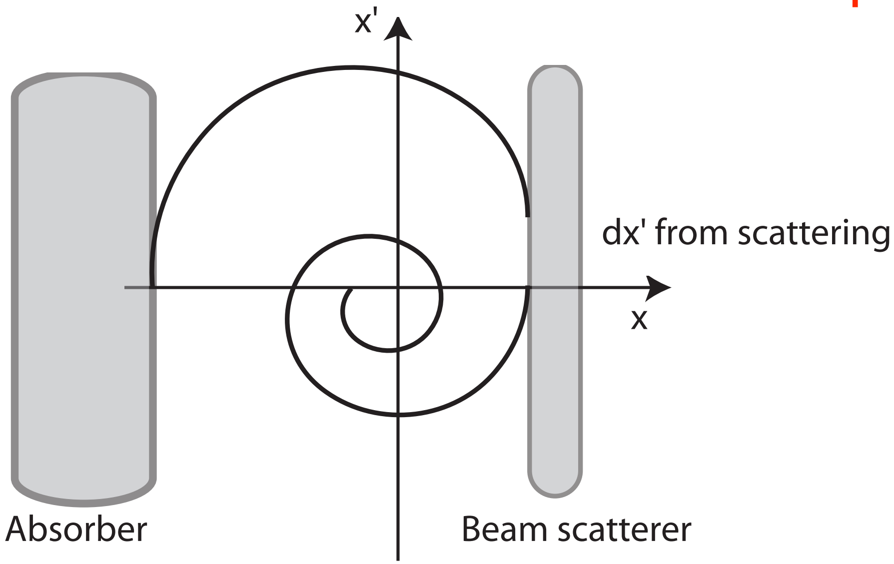
IR7

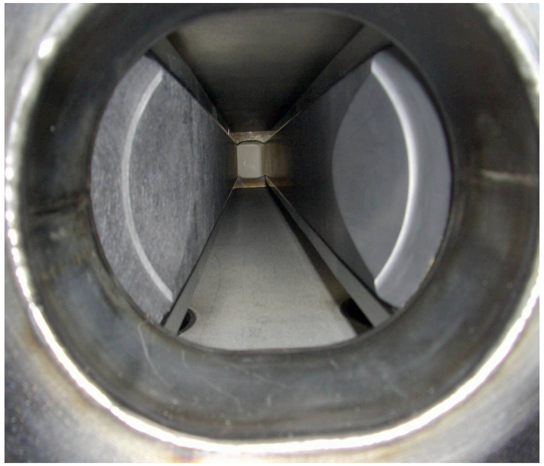


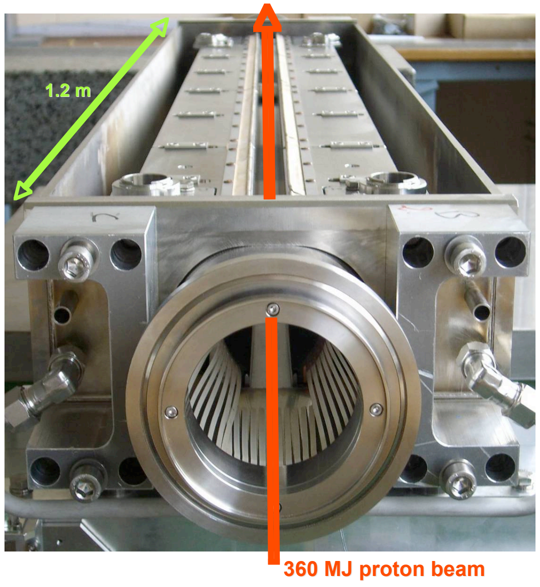
2 stage collimation

A) Low Z material scatters halo particles
B) High Z and low Z catch the primary or secondaries
C) In total, 95 % of the energy is spread over 250 m, with a very low energy density, and not in a cold region.









Movable collimators, they to be robust

Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

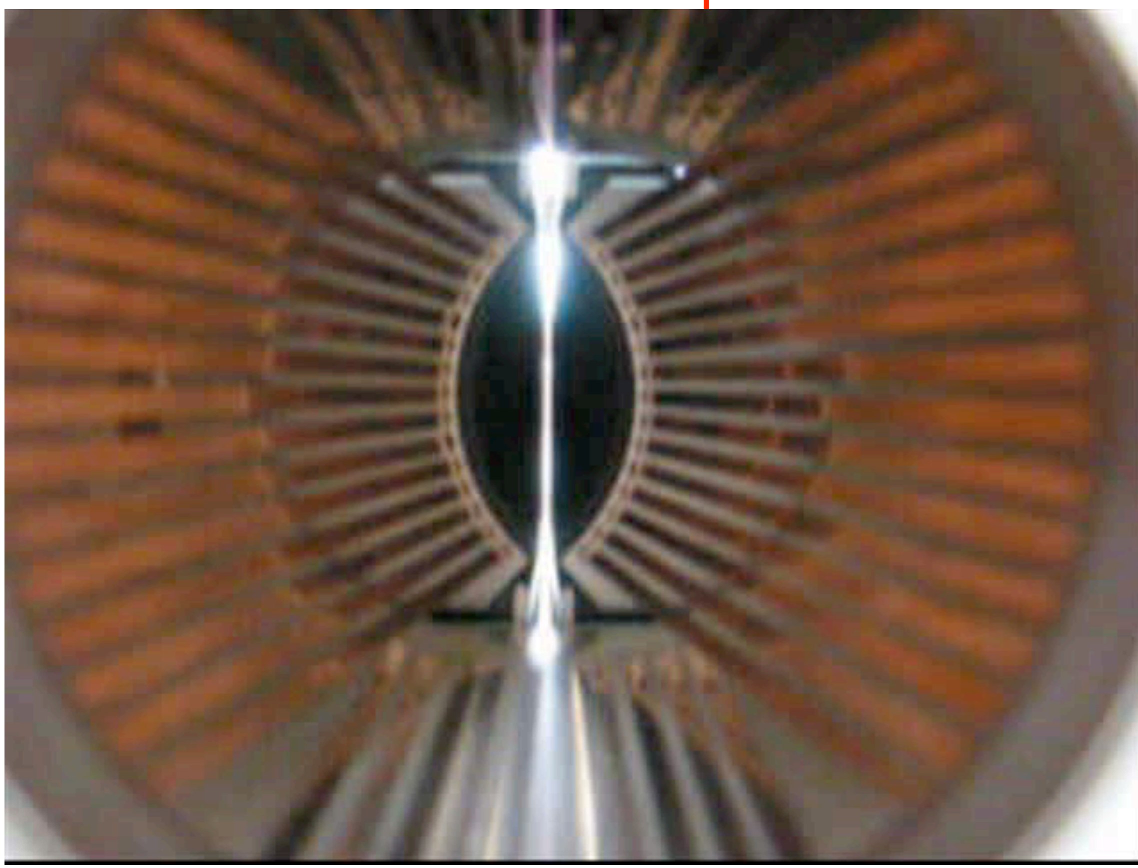
SPS experiment:

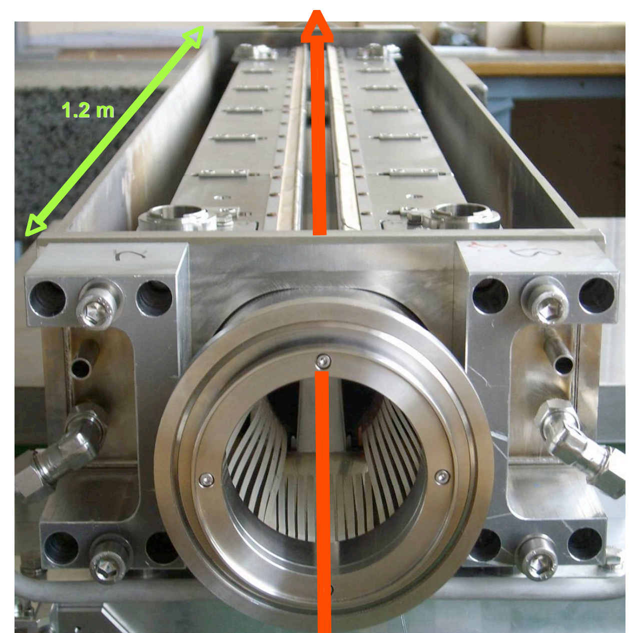
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms)
on CC jaw ⇒ full design CASE

equivalent to about 1/2 kg of TNT

from S. Redaelli





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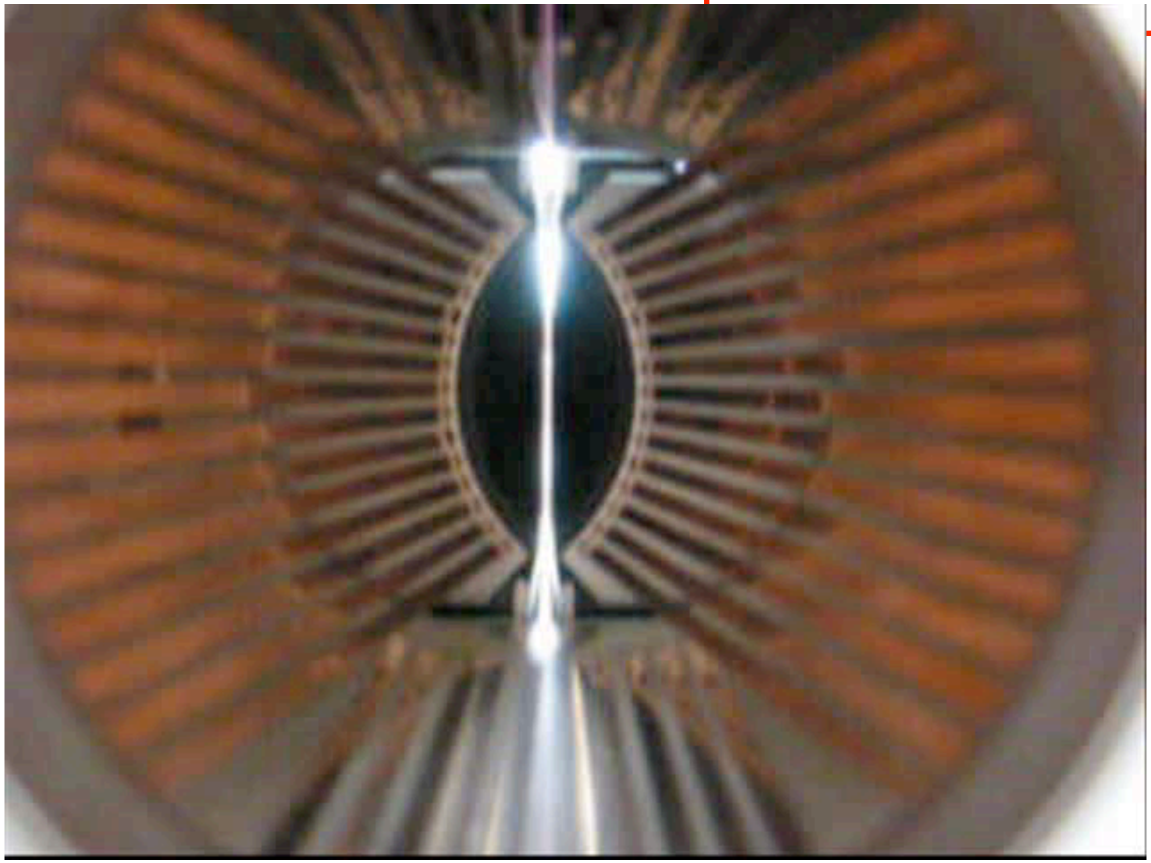

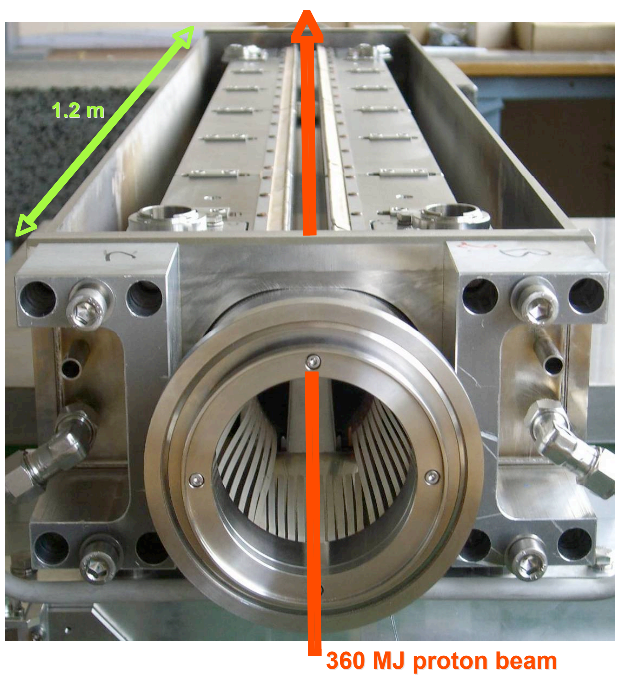

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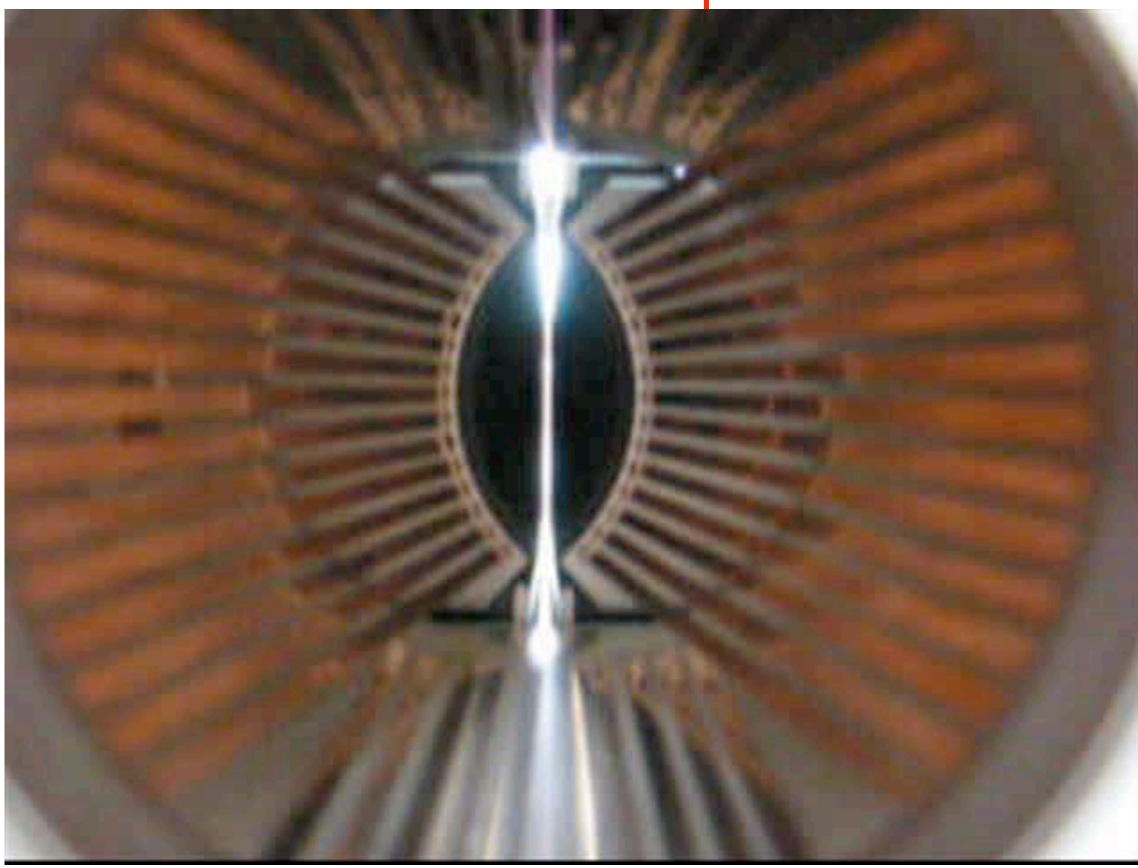
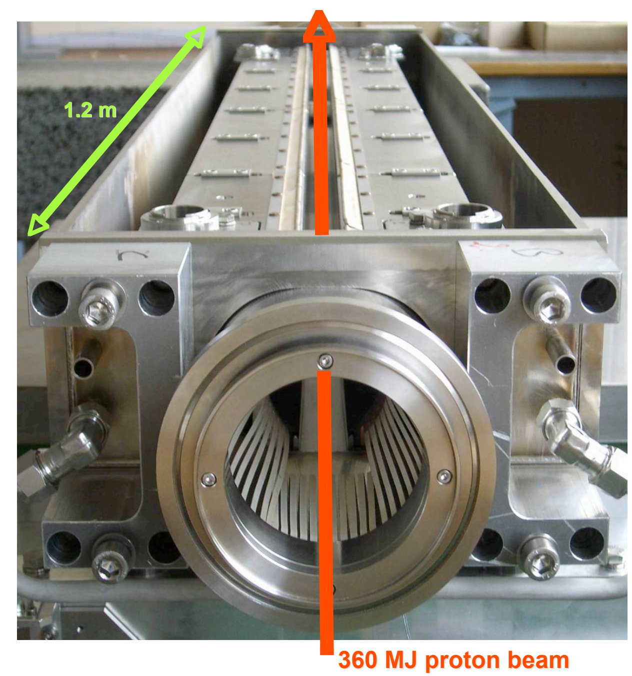
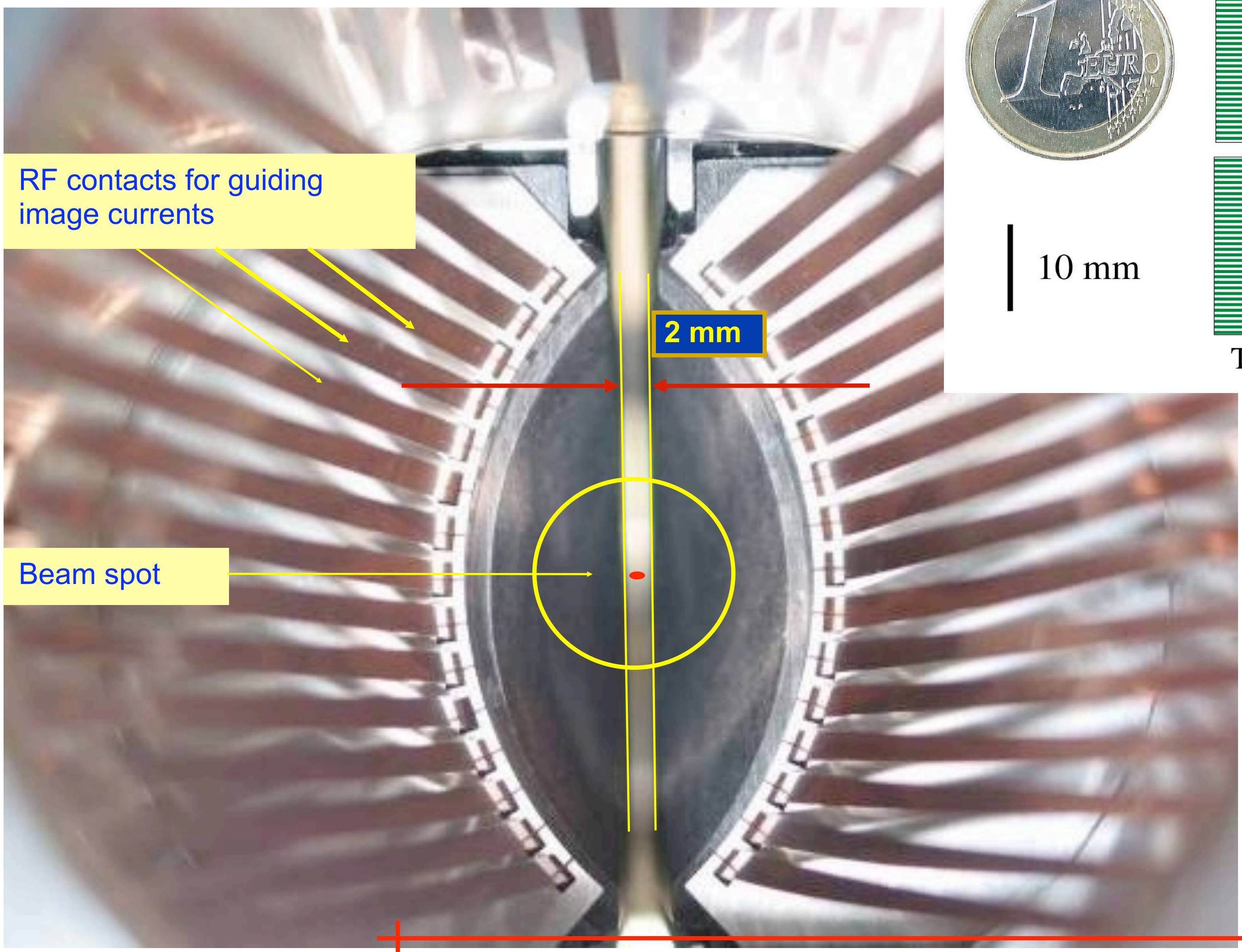
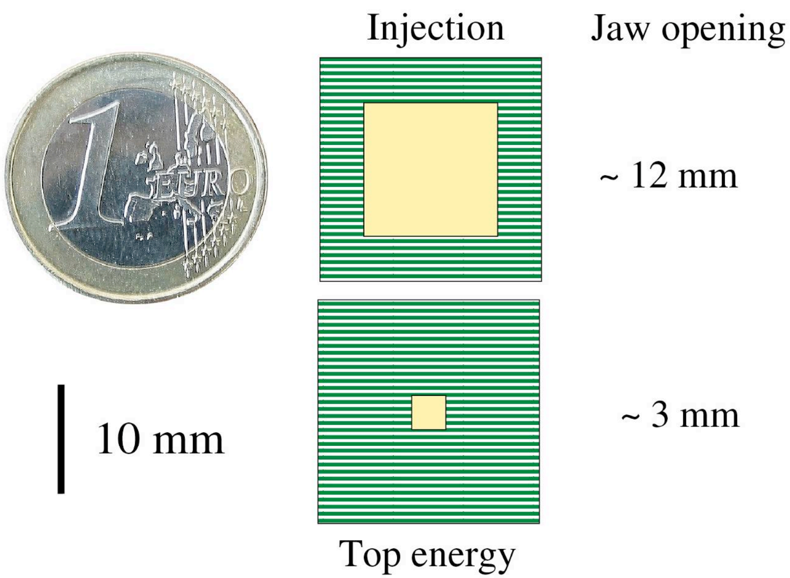




At 7 TeV, beam really small, 3σ diam. ~ 1.2 mm



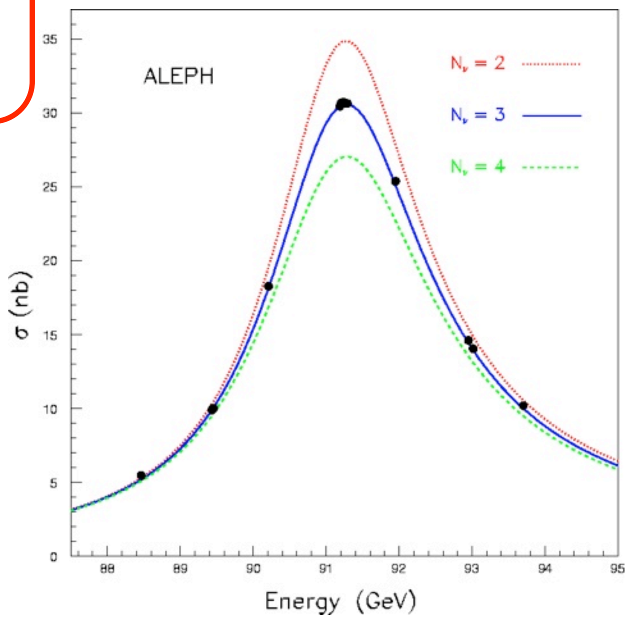


Precision required for collimator movements about 25 μm

Collimator in the tunnel during installation

What can influence an accelerator?

The physics case:
the Z mass at LEP has been measured with an error of 2 MeV.
Energy of the accelerator has to be know better than 20 ppm.



Energy measurements obtained by during last years of LEP operation

Nominal (GeV)	E_{CM} (LEP) (GeV)
181	180.826 ± 0.050
182	181.708 ± 0.050
183	182.691 ± 0.050
184	183.801 ± 0.050
Combined	182.652 ± 0.050

What can influence the energy of a collider?

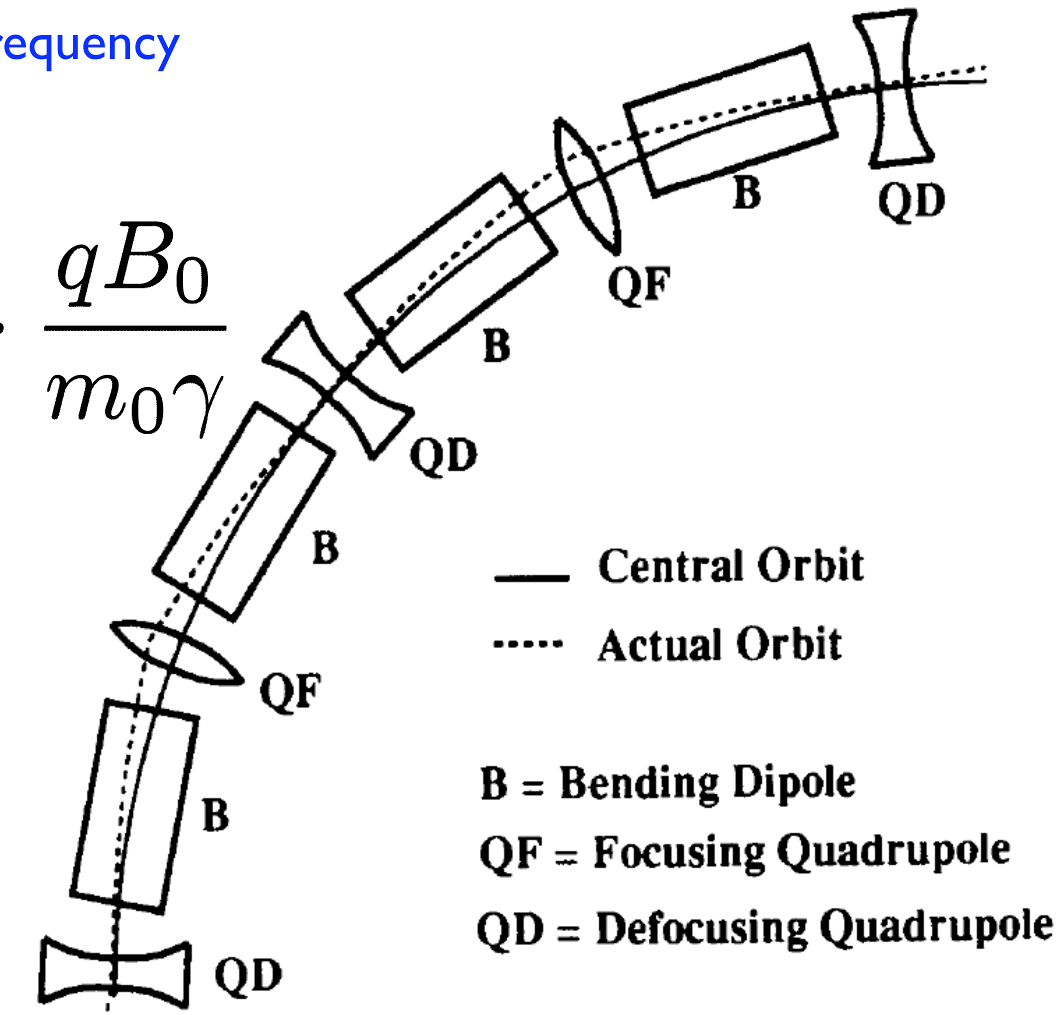
"Rappel"of strong focusing synchrotron optics

Stable orbit is bent by the main dipoles, centered in the quadrupoles, no field

Energy fixed by bending strength and cavity frequency

$$f_{RF} = h \cdot f_{rev}$$

$$f_{rev} = \frac{v}{C_c} = \frac{v}{2\pi\rho} = \frac{1}{2\pi} \cdot \frac{qB_0}{m_0\gamma}$$



A variation of the Circumference C induces changes in the energy proportional to α, the momentum compaction factor.

$$\frac{\Delta E(t)}{E_0} = -\frac{1}{\alpha} \frac{\Delta C(t)}{C_c}$$

In LEP $\alpha = 1.86\ 10^{-4}$ a small variation the circumference induces a large variation in energy

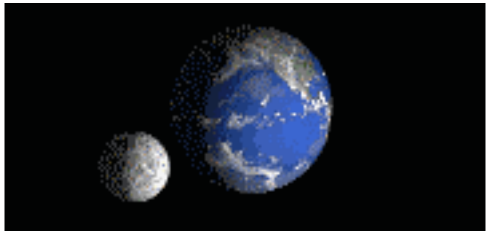
see trasp. Elias

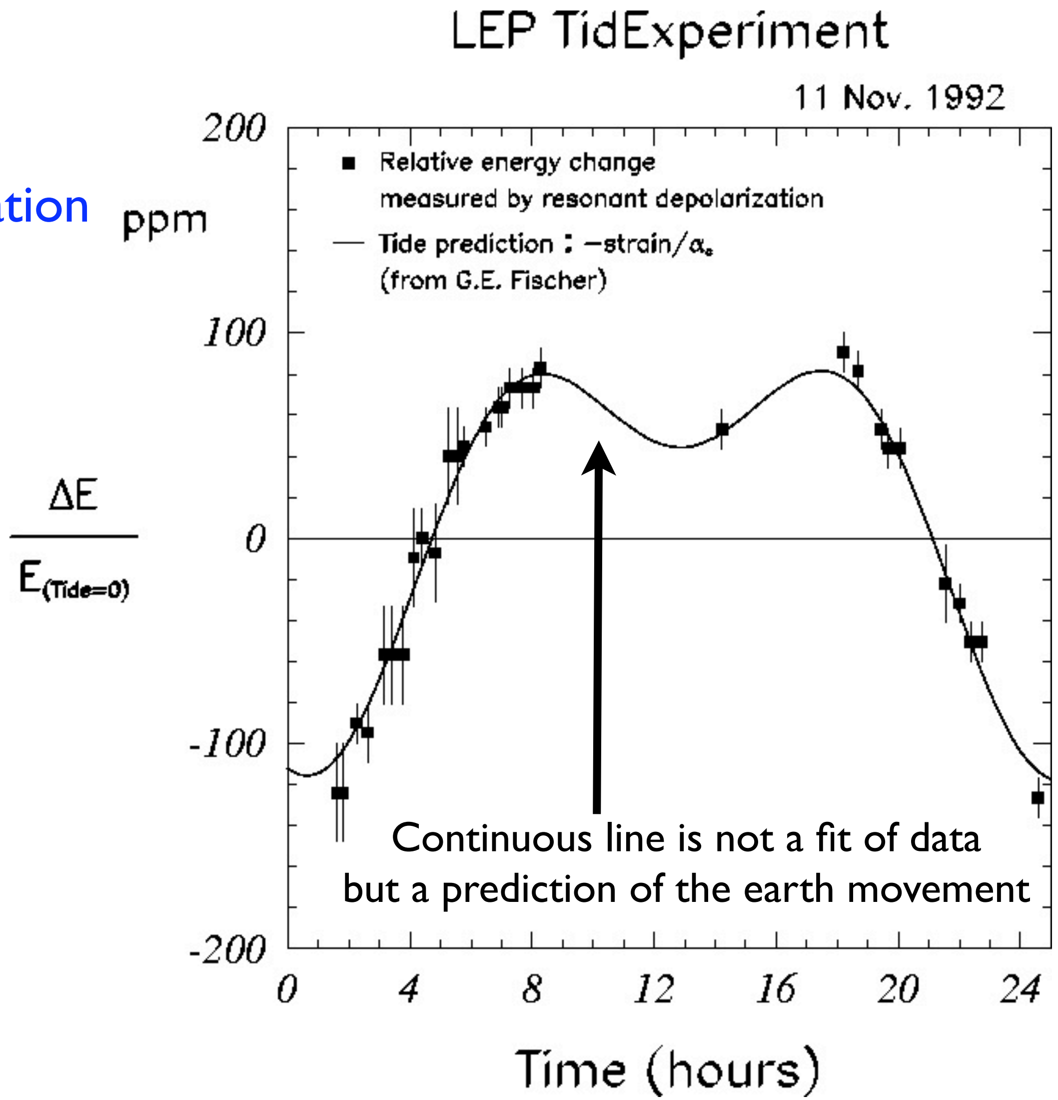
Moon tides can change earth geometry

Moon induces a earth deformation similar to water tide.

Total deformation of the LEP about 4 mm
Energy variation of 100 ppm

The 12 h cycle is due to the earth deformation

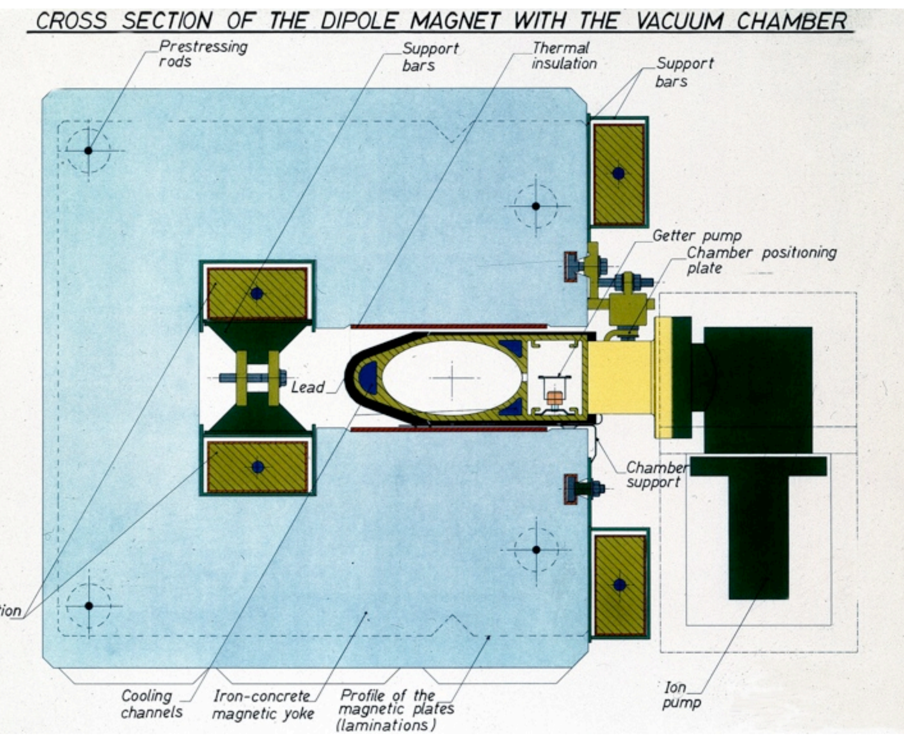


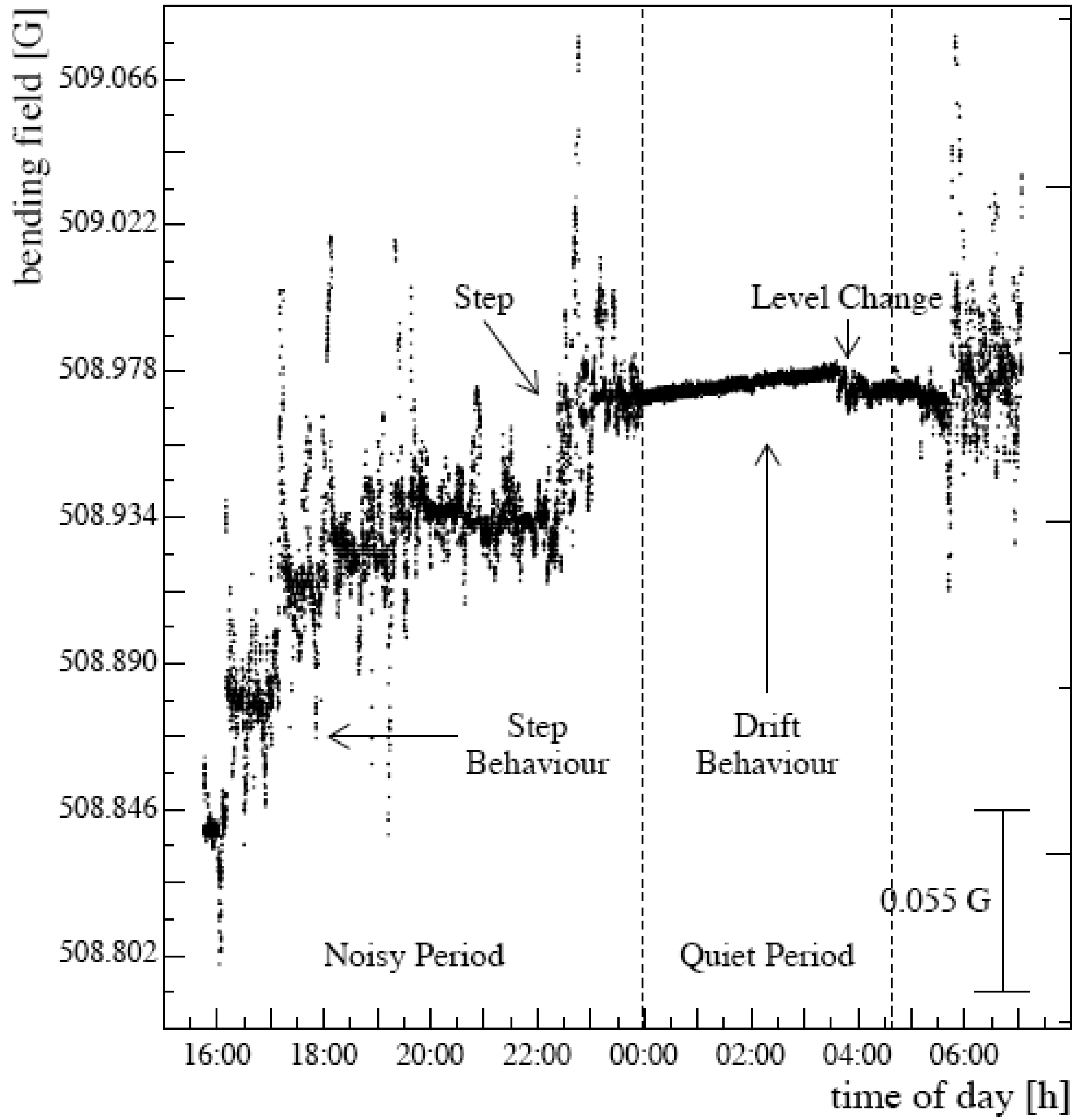


The effect is modulated by the different tide intensities and by the SUN tides

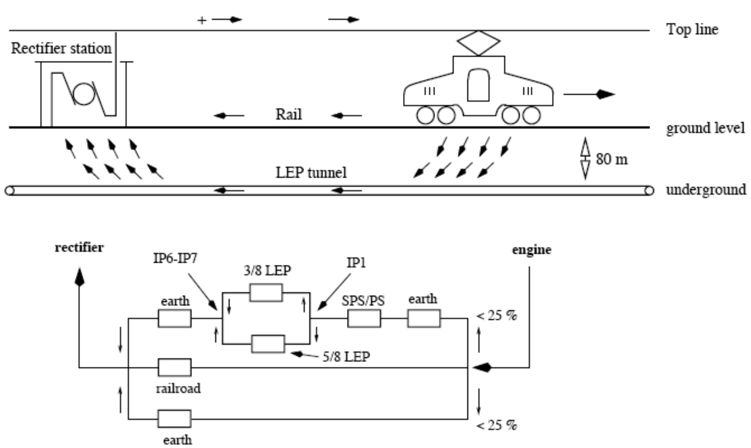
The problem: an accelerator is not in the middle of nothing

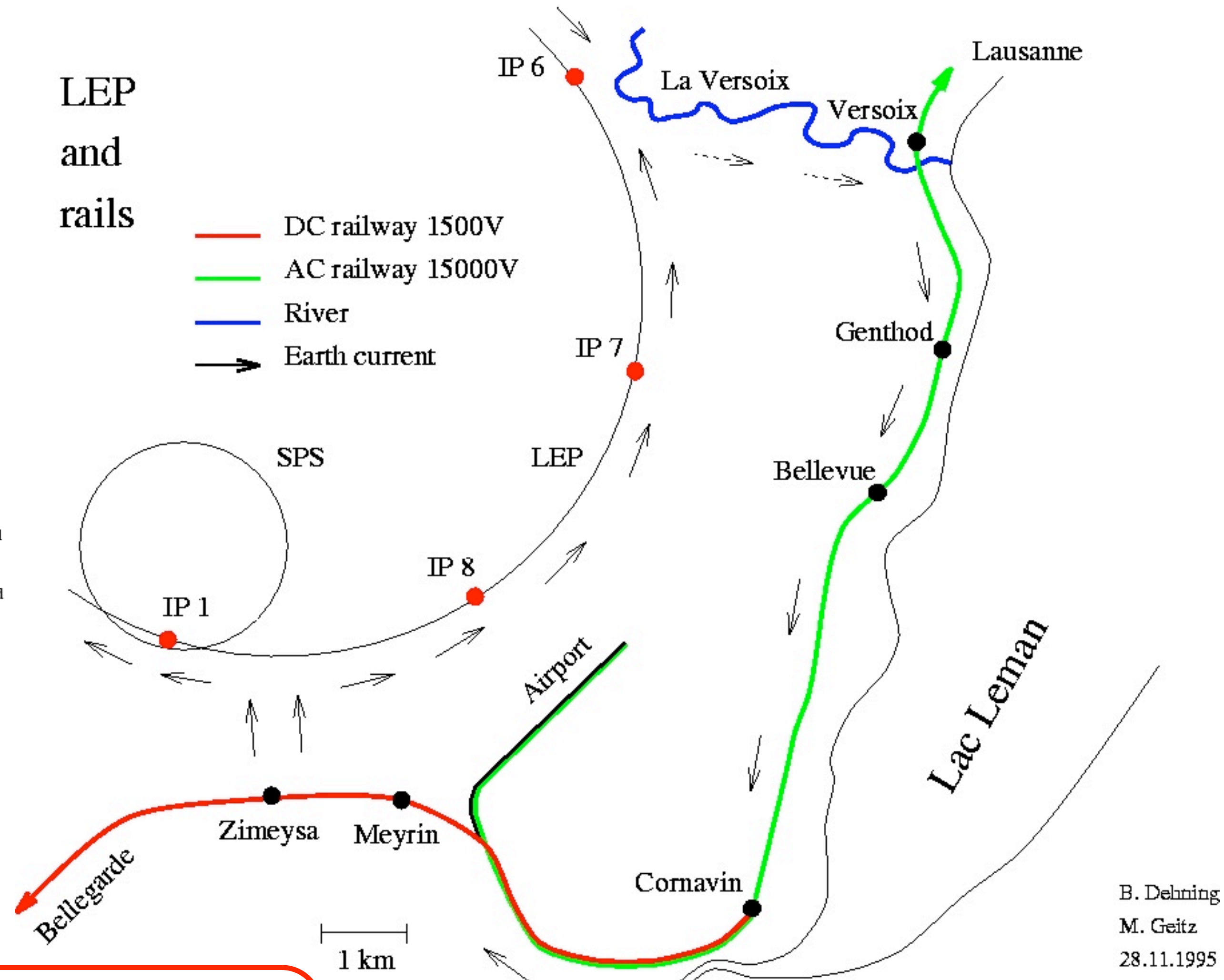
Observed variation of the bending strength of the LEP dipoles during the day





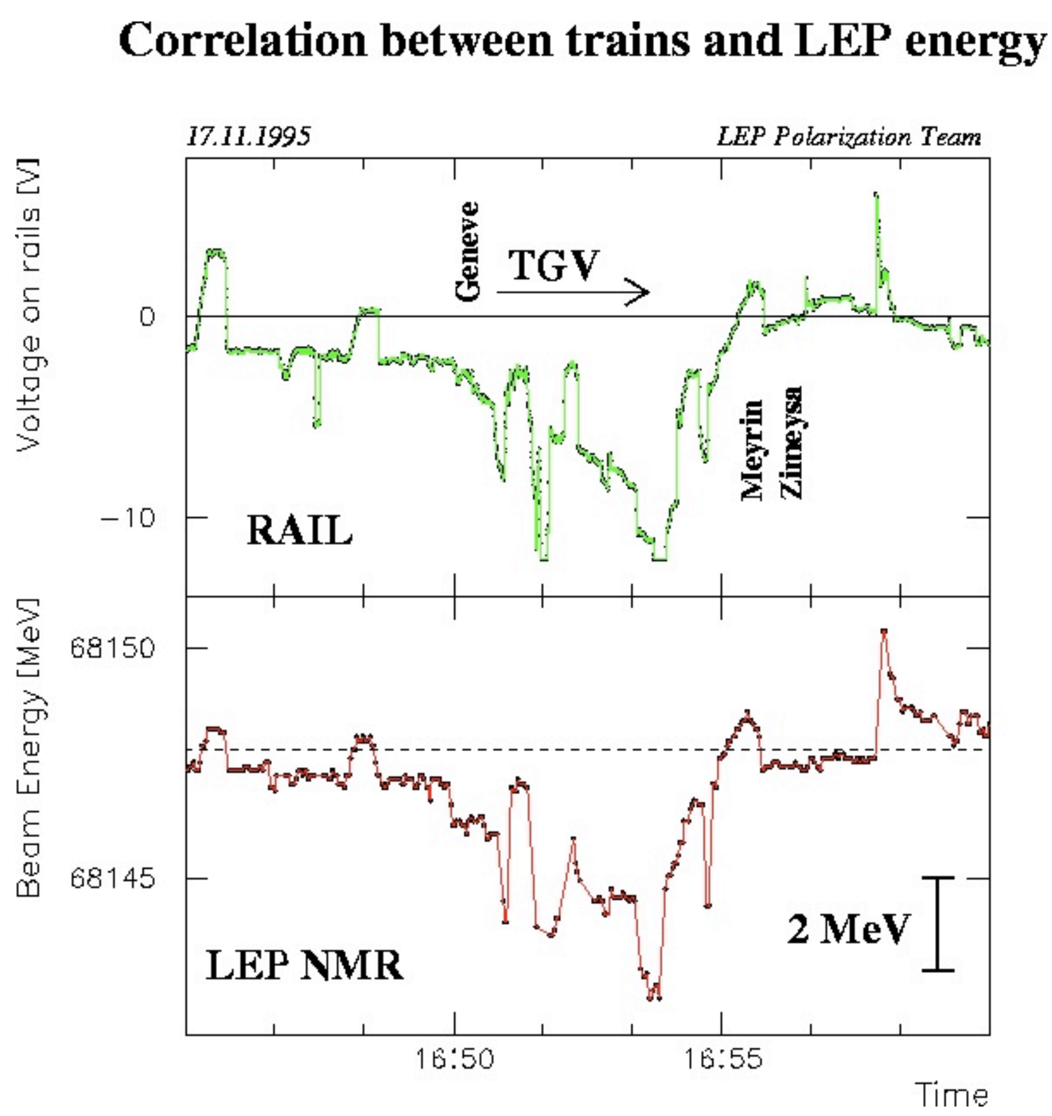
Influence of train leakage current





LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

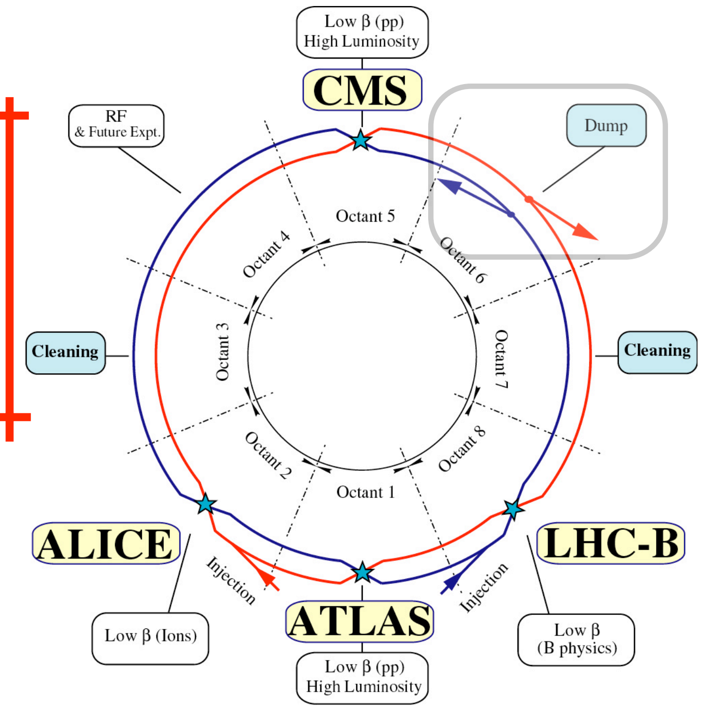
The evidence, TGV to Paris at 16:50 ...

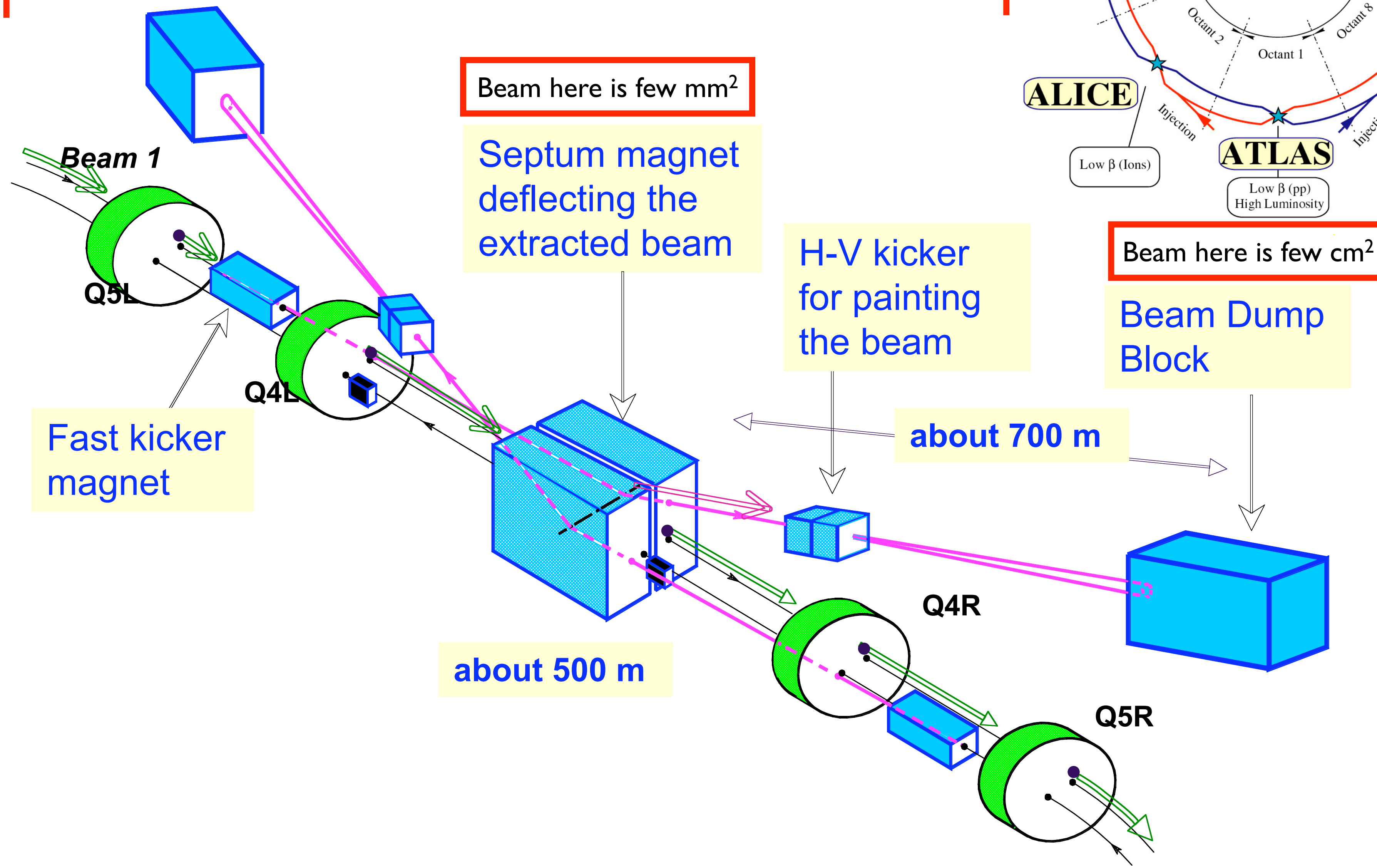


Thanks for your attention!!!

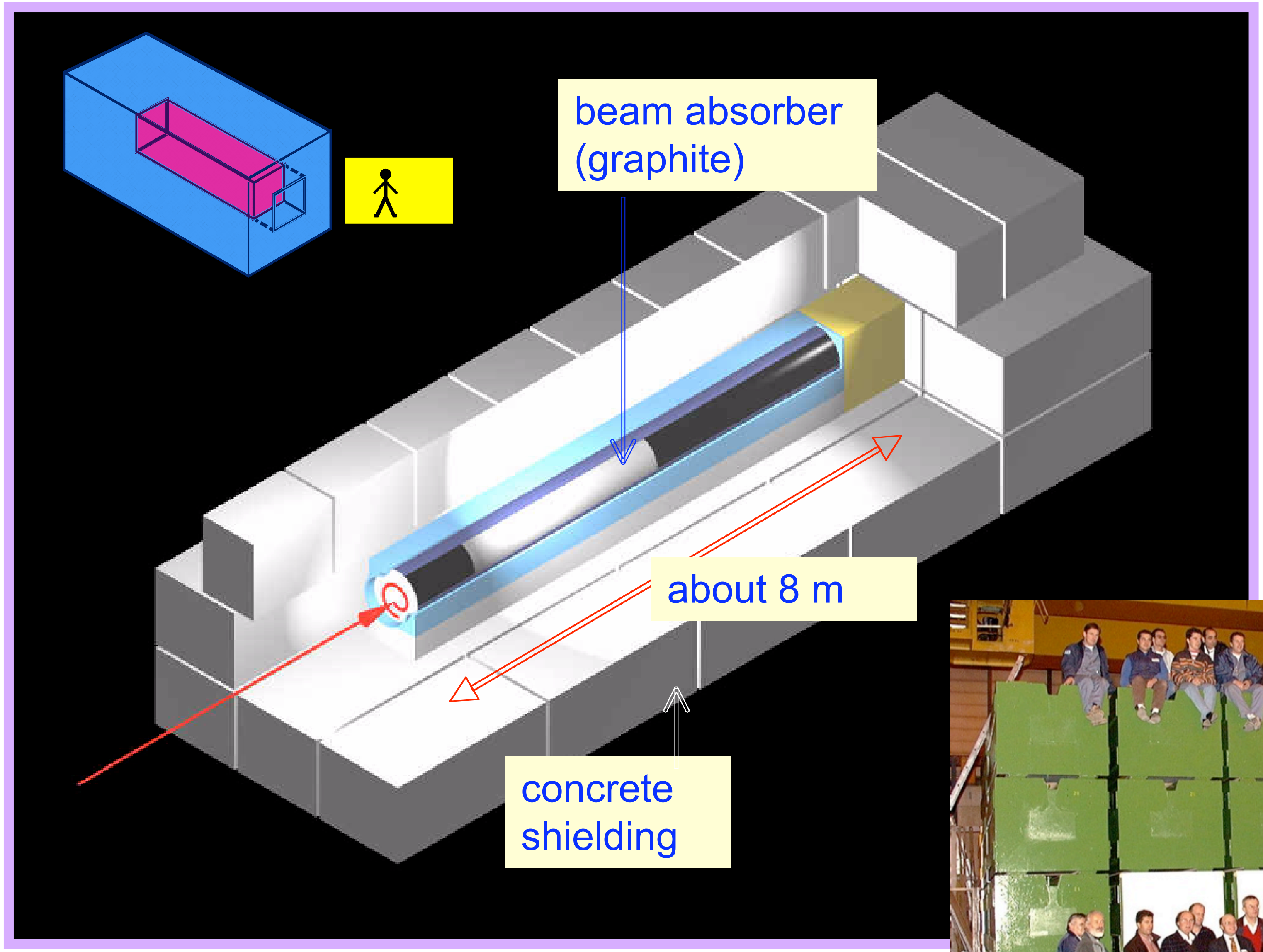
Beam extraction, emergency or not...

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 absorbe full power at full energy.





Scheme of one of the beam absorbers



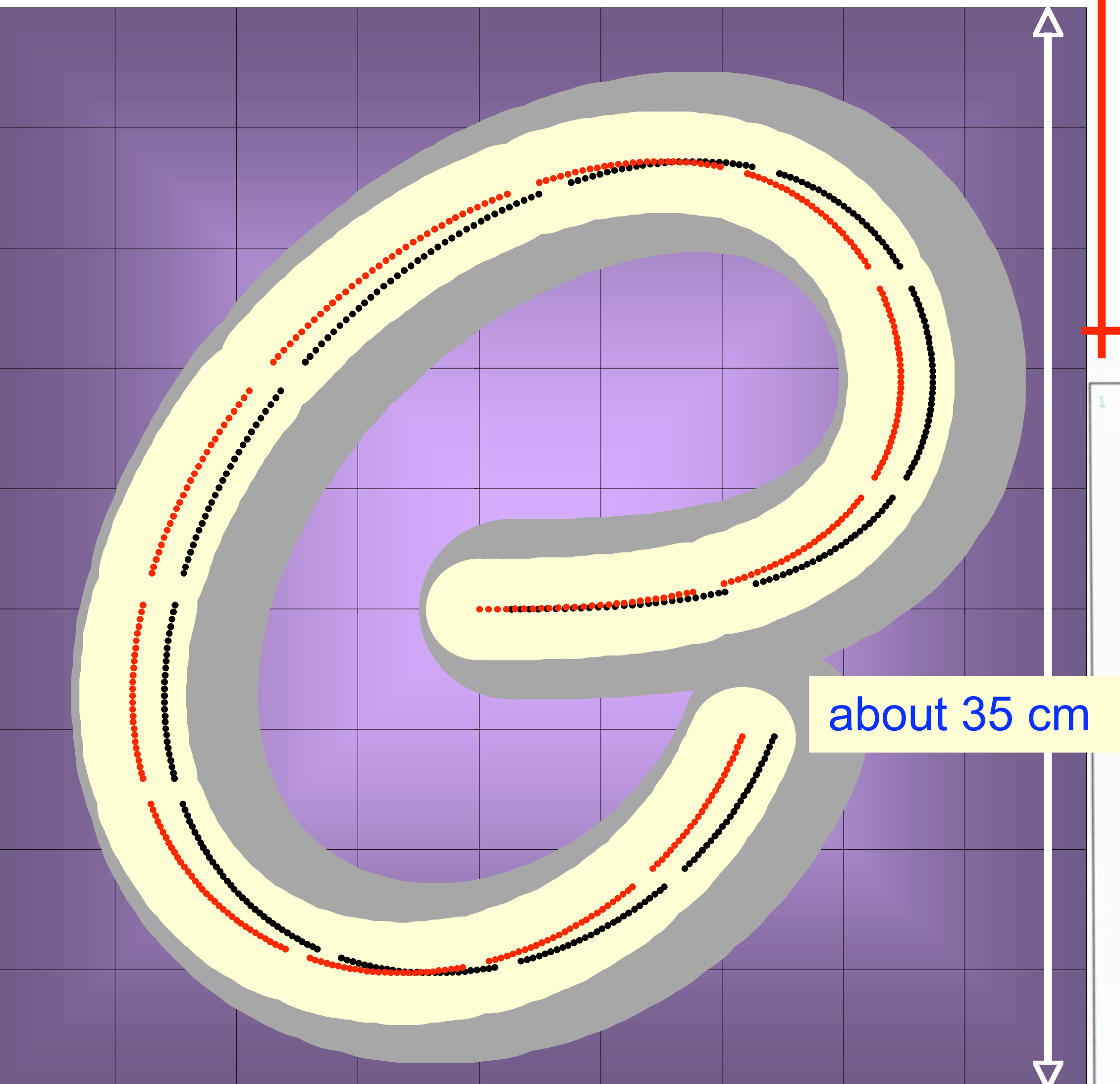
L.Bruno

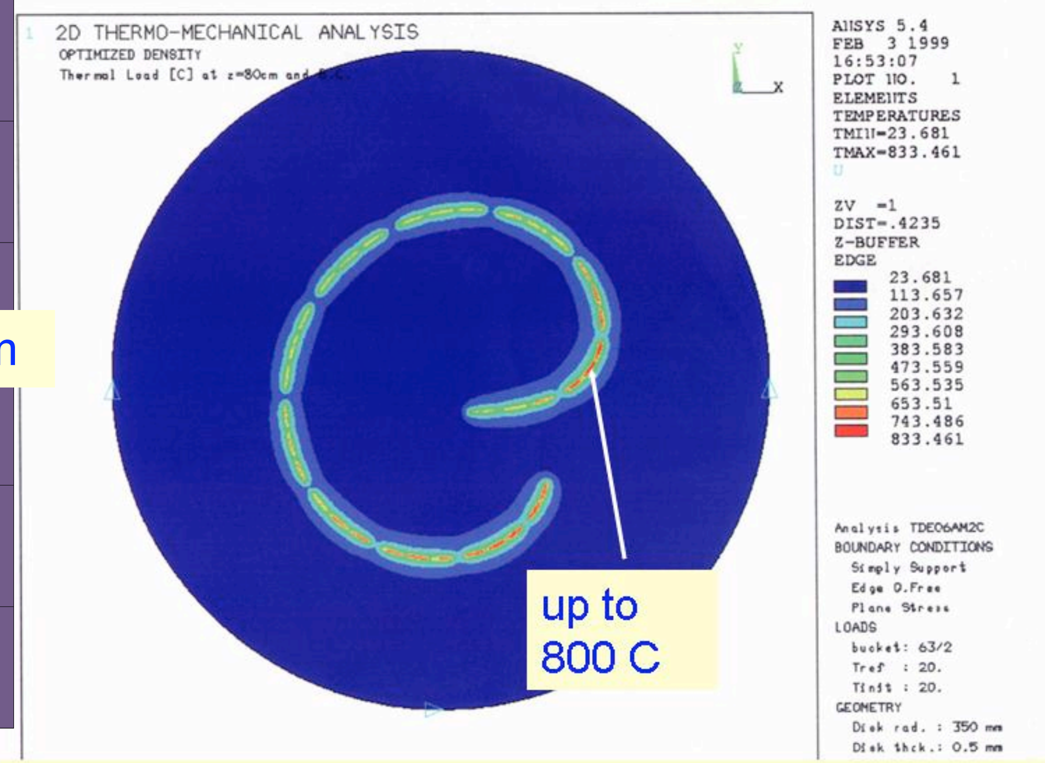
Spot size on the beam dump

To reduce energy deposition peak, proton swept by fast kickers to for a spiral on the transverse face of the dump.

Beam impact in less than 0.1 ms

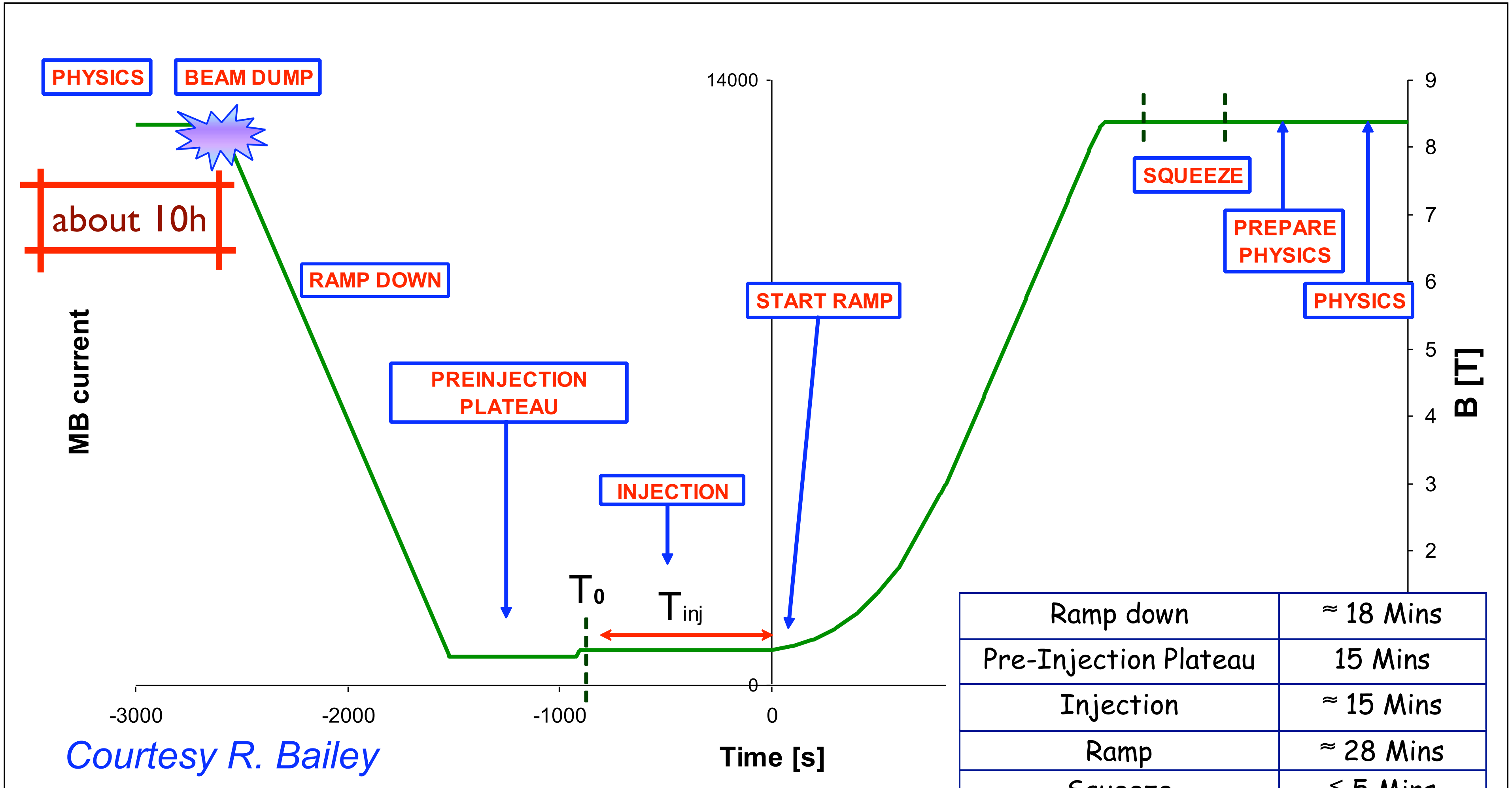
Even like this, maximum temperature rise about 800 C.





L.Bruno: Thermo-Mechanical Analysis with ANSYS

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

From previous experience, at least 6 attempts before a good physics fill

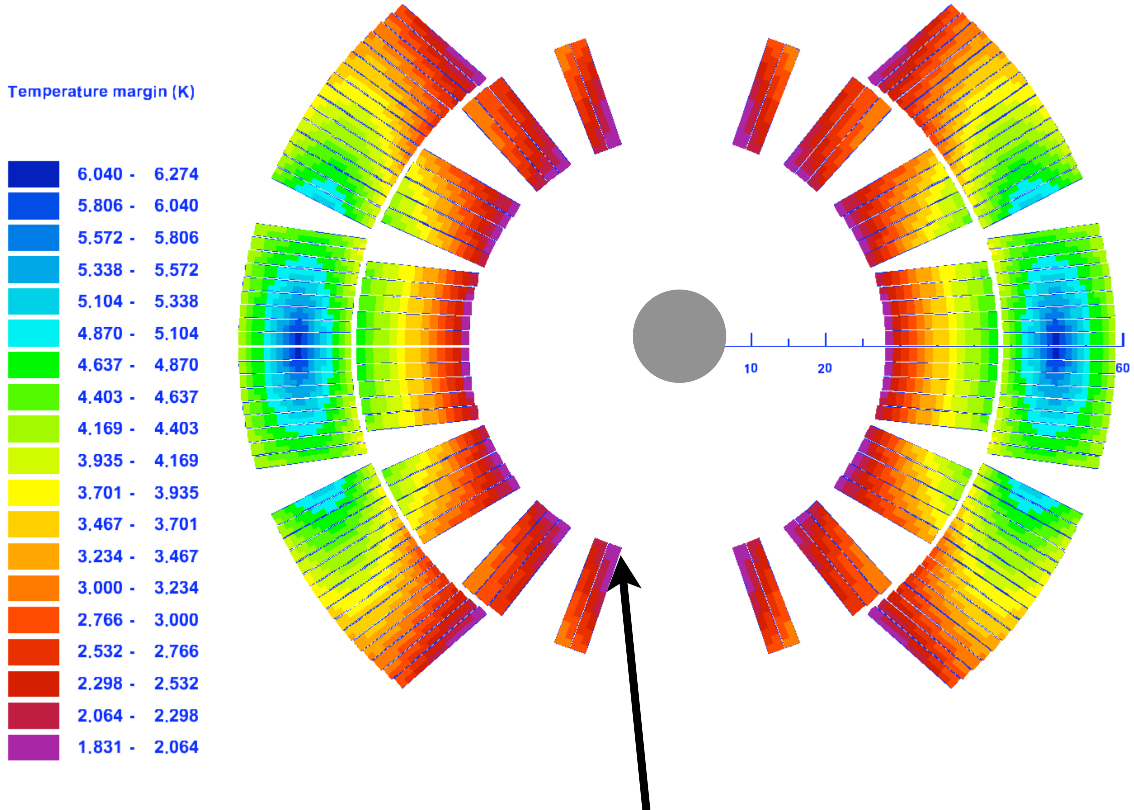
Few numbers for dipoles

Injection B (0.45 TeV energy)	Current at injection field	Nominal B (7 TeV energy)	Current at nominal field	Stored energy (2 apertures) at 8.33 T	Ultimate field	Maximum quench limit of the cold mass	Magnetic length at 1.9 K and at nominal B	Bending radius 1.9 K	Total mass
0.54 T	763 A	8.33 T	11850 A	6.93 MJ	9.00 T	9.7 T	14312 mm	2803.98 m	~ 27.5 t

		r [m]	B [T]	E [TeV]
FNAL	Tevatron	758	4.40	1.000
DESY	HERA	569	4.80	0.820
IHEP	UNK	2000	5.00	3.000
SSCL	SSC	9818	6.79	20.000
BNL	RHIC	98	3.40	0.100
CERN	LHC	2801	8.33	7.000
CERN	LEP	2801	0.12	0.100

The length of the LHC dipoles (15 m) has been determined:
by the best design for the tunnel geometry and installation and
by the maximal dimensions of (regular) trucks allowed on European roads.

Temperature margin and quenches....



Lower temperature margin near the beam !

Limiting beam losses:
10^8 p/m at small grazing angle
for a total circulating intensity of 3.3 10^{14} p

Other possible sources of quenches:

1. ***mechanical friction***, for example during current ramp, between the conductors. Few μm are enough. Magnets are "trained" before installation and they keep memory of the training at least since the next quench.

2. ***failure of the cooling system.*** Depending on the case of failure, magnets can heat up slowly or not...

but every dipole stores about 7 MJ at collision

the stored energy is about 350 MJ per beam

So, one need:

1. *to exclude the magnet from the ARC powering*, since all the magnets are IN SERIES per ARC.

2. *to discharge fast the power of the quenching magnet octant (time constant about 100 s)*, and dispersing by heating up the magnet the power that otherwise will accumulate near the quenching zone.

3. *to extract the beam as fast as possible*, meaning within one turn from the quench detection, before risking to damage mechanically the machine with the beam.

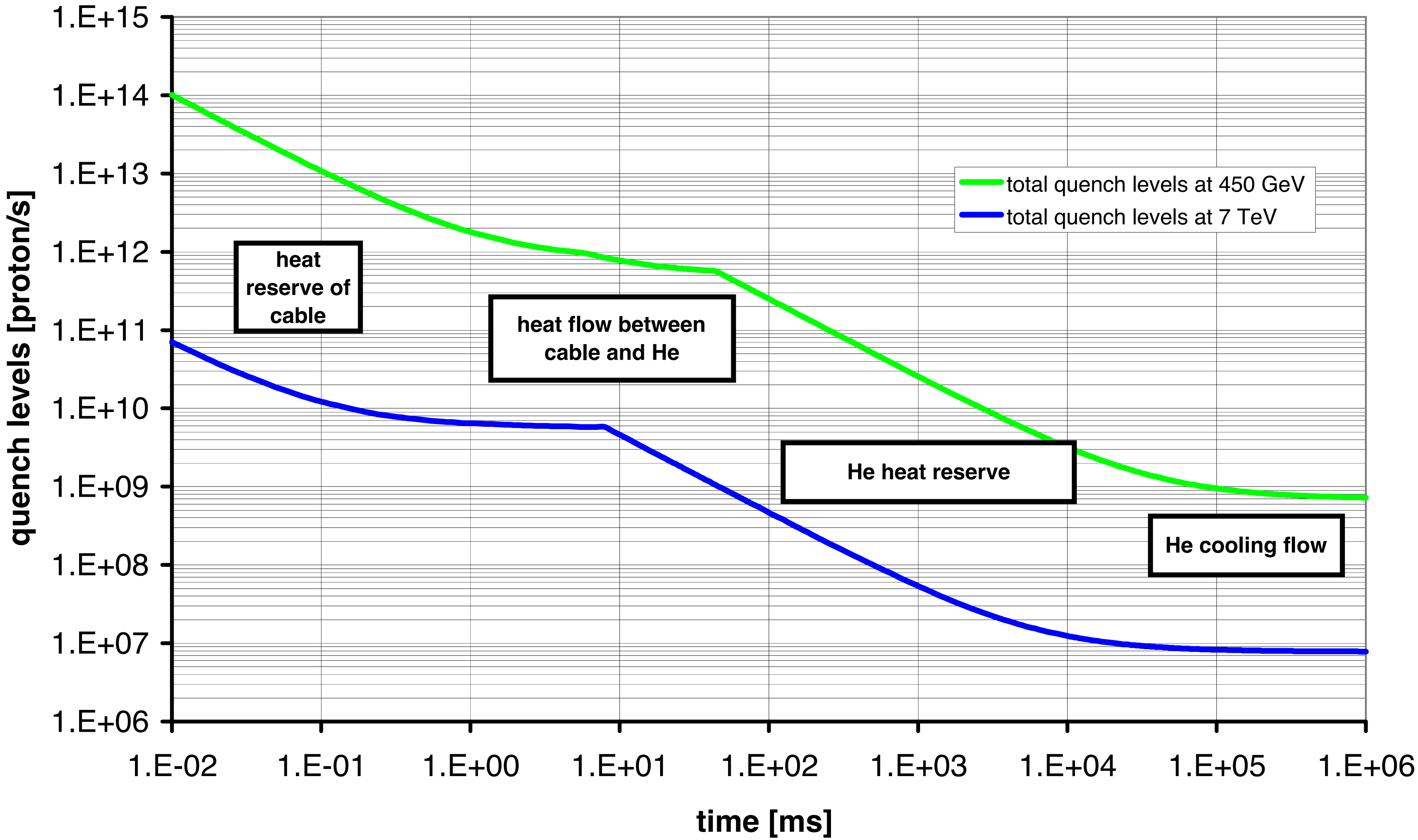
The different time scale of the two processes helps:

1 beam turn every ~ 90 μs while a *quench develops on at least few ms*. However, quench detection, power extraction and beam extraction has to be fast and reliable.

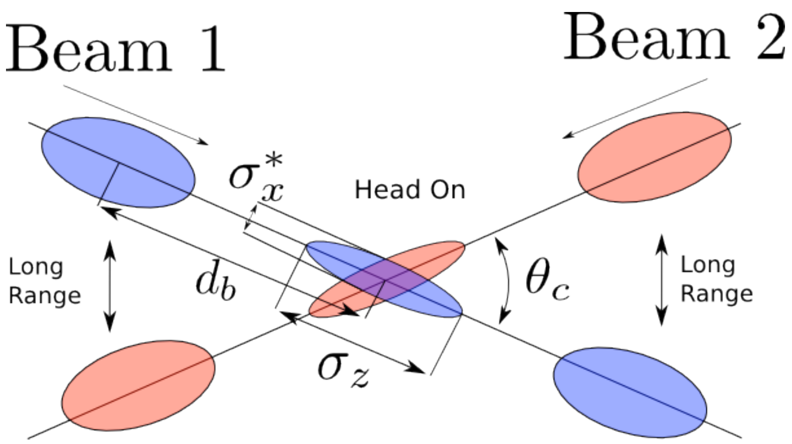
Quench levels are varying with energy ....

In a synchrotron, the magnetic field increases with energy to keep particles on the circular trajectory. This means that both the current as the field are larger at 7 TeV than at 450 GeV.

The Temperature margin is the reduced, one can loose less particles....



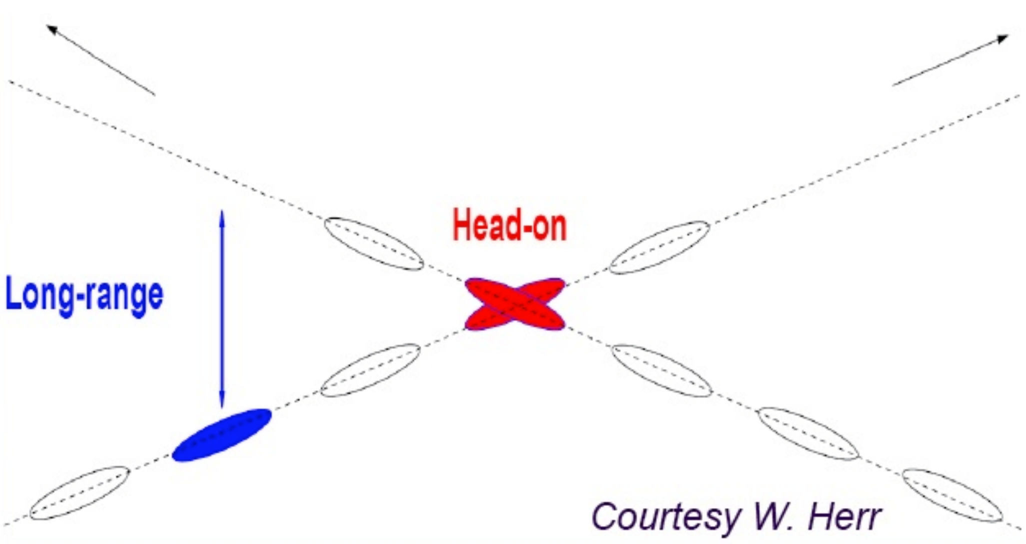
Beam-Beam interaction



The two beams travels one near the other at the IP

The electromagnetic field generated by one beam is felt by other ⇒ Beam-Beam

Three classes of beam-beam effects:
A)Long range
B) Packman bunches
C) Head-on

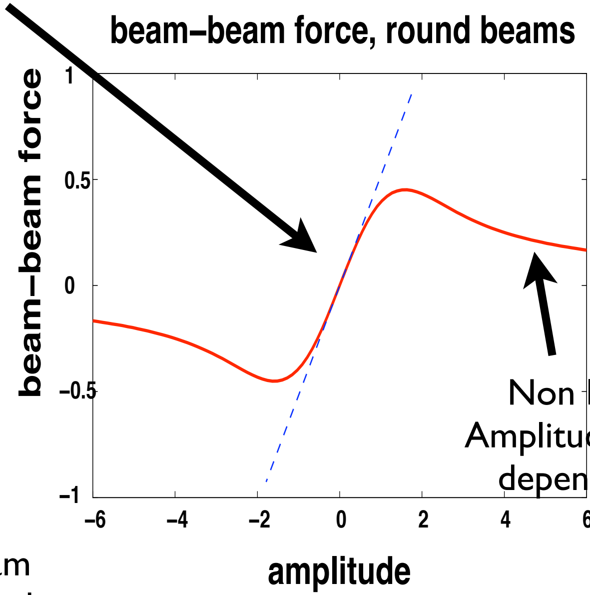


Packman bunches are the bunches of one beam that at the IP don't see a correspondant bunch of the other beam.

As a results, for them the tune, orbit and chromaticity will be different from the other bunches ....

Beam beam tune spread

Quadrupole-like component



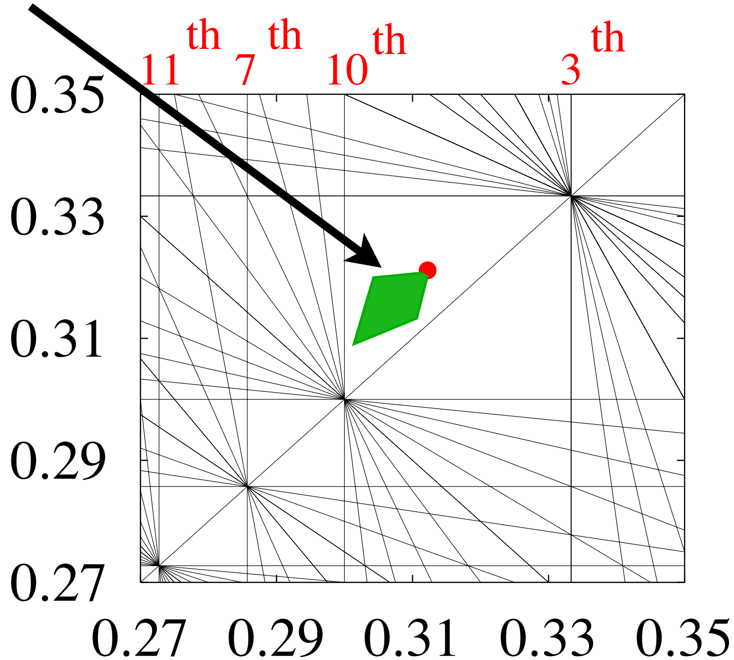
Non linear Amplitude-force dependence

Max beam-beam tune shift ⇒ not more than 0.015 to avoid crossing resonances

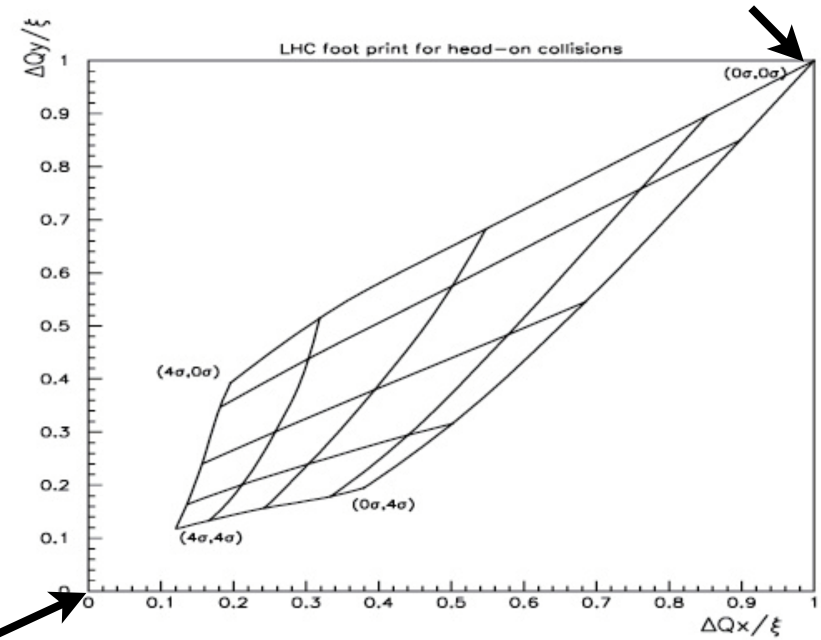
$$\Delta Q = \frac{N_2 \cdot r_p}{4\pi \cdot \gamma \cdot \epsilon} = \xi_{beam-beam}$$

So N_2=intensity per bunch should be small and ε=emittance should be big, *exactly the opposite to have large Luminosity*. An optimum has to be chosen

Beam-beam tune-spread



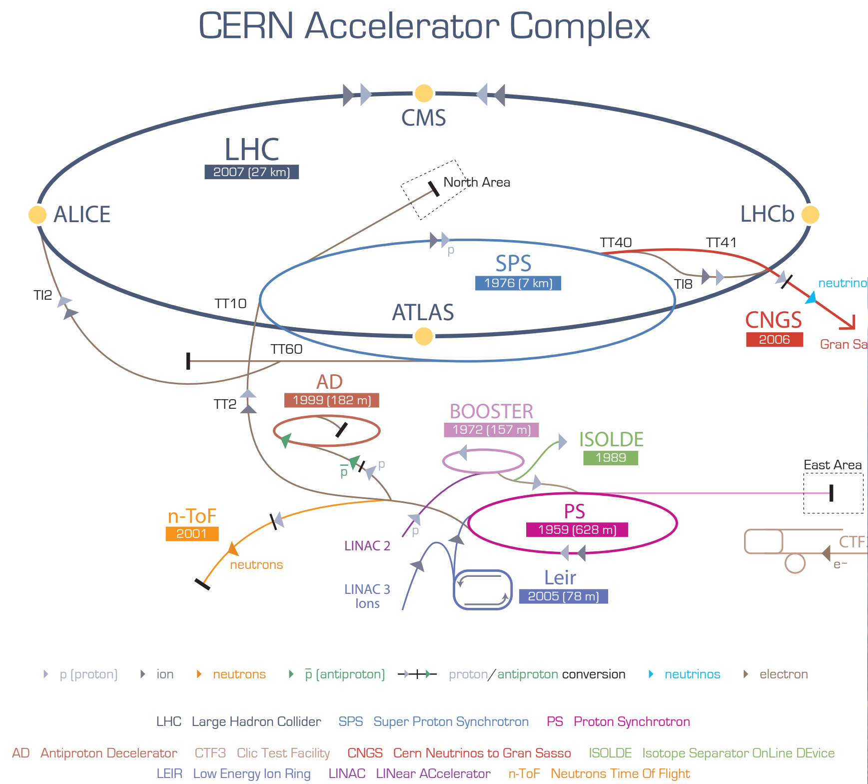
Max beam-beam

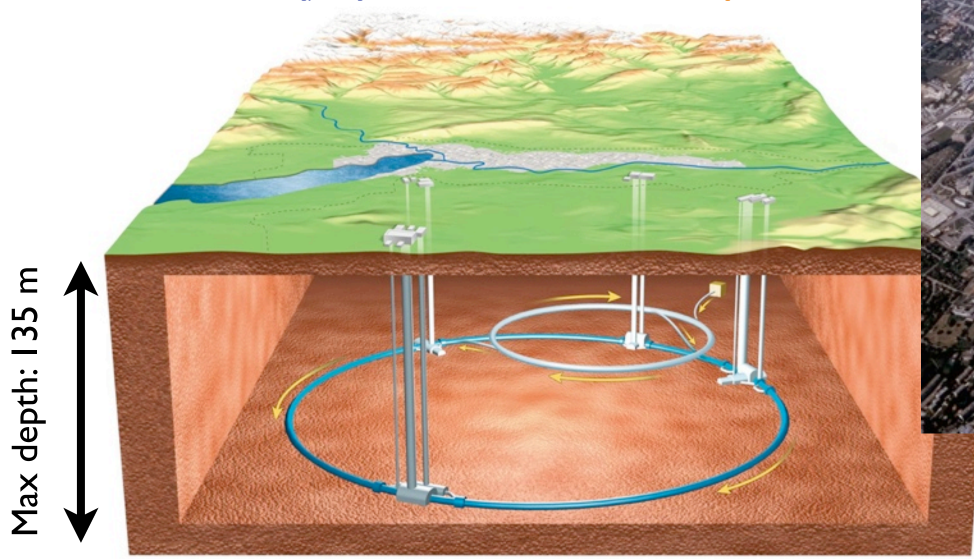


No beam-beam

Where is the LHC ?

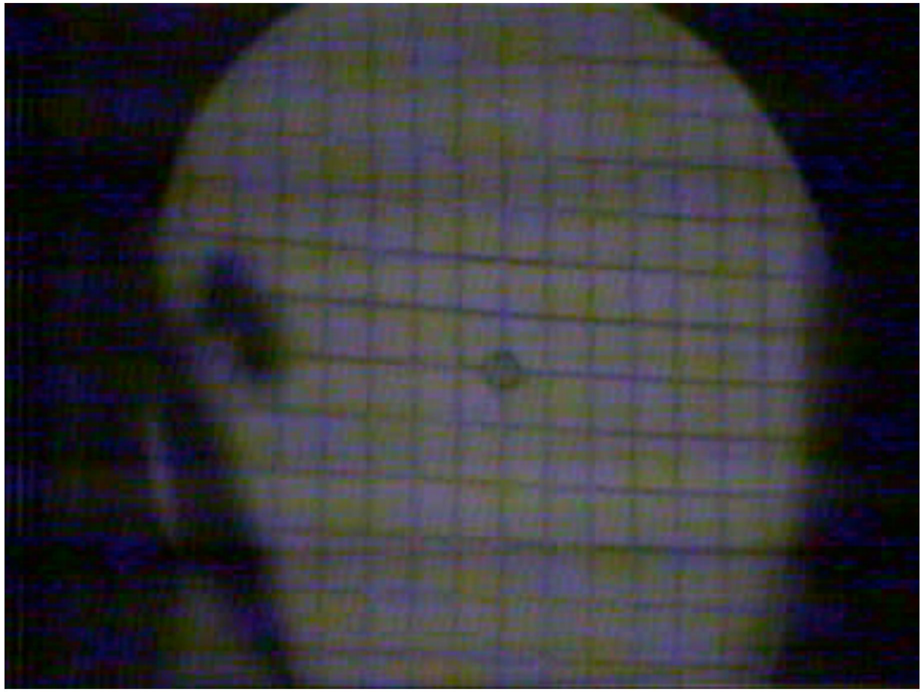
Intersection point	Tunnel		LEP 200	LHC
	Depth (m)	Slope (%)		
I (Meyrin)	82.0	1.23	Injection in arcs	ATLAS
II (St Genis)	45.3	1.38	L3 and RF	ALICE and Injection
III (Crozet)	97.5	0.72		Cleaning
IV (Echenevex)	137.6	0.36	ALEPH and RF	RF
V (Cessy)	86.6	1.23		CMS
VI (Versonnex)	95.0	1.38	Opal and RF	Dump
VII (Ferney)	94.0	0.72		Cleaning
VIII (Mategnin)	98.8	0.36	Delphi and RF	LHC-B and Injection

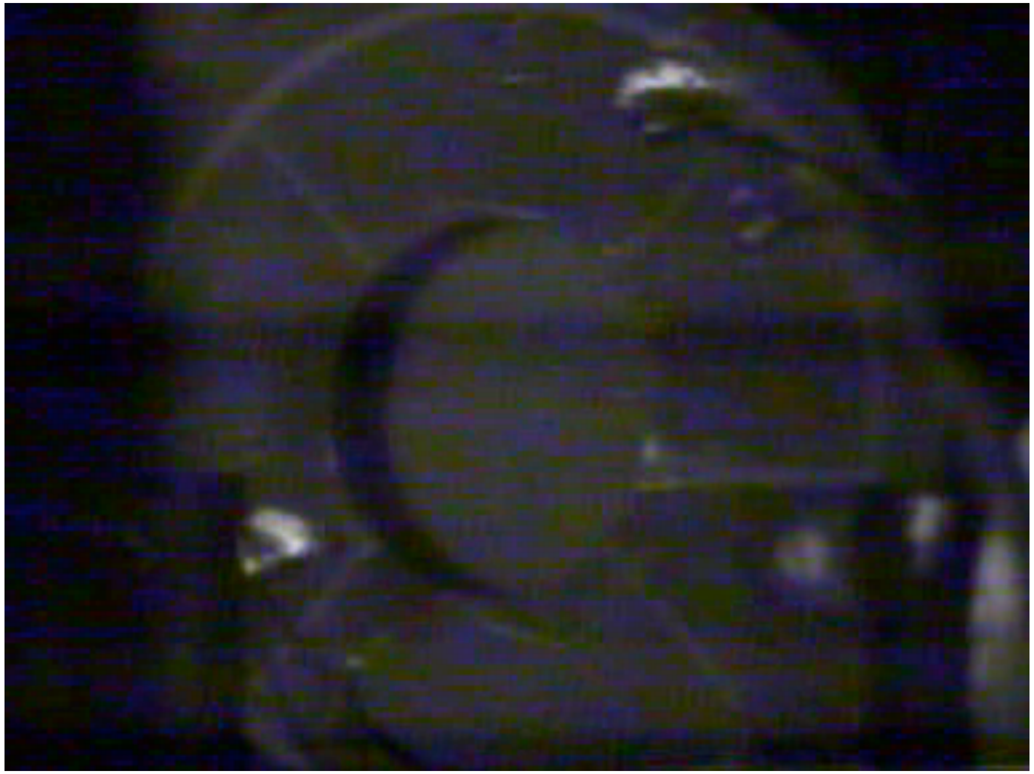


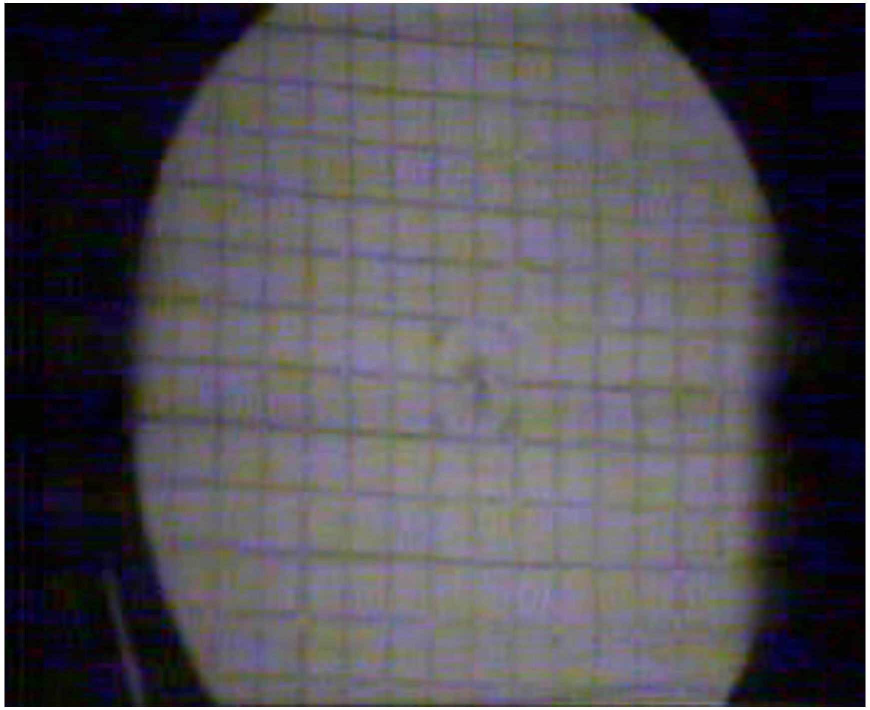


London tube: 24 m depth

Beam Hitting detector screens







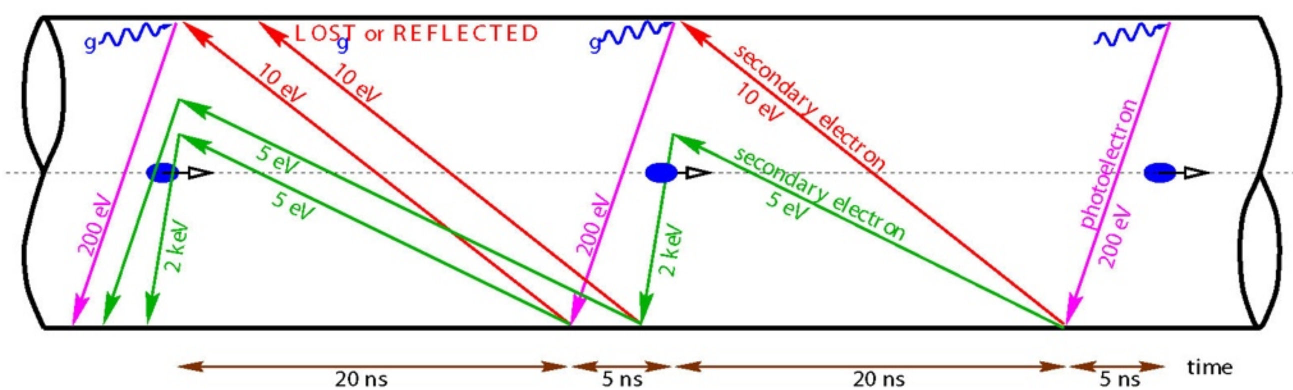
Electron clouds

Electron cloud in the vacuum beam pipe can be created by "avalanche" process :

1. few primary e^- generated by as photoelectrons, from residual gas ionization, extract by Synchrotron radiation
2. p+ bunches accelerate e^- (this depends from the bunch separation, i.e. 25 nsec in the LHC)
3. e^- impact on the wall and extract secondary e^-

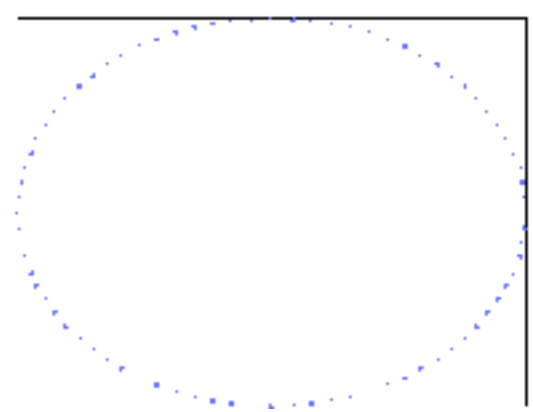
and so on ... and the cloud can generate:

a) heating of the beam pipe ⇒ magnet heating b) beam instabilities



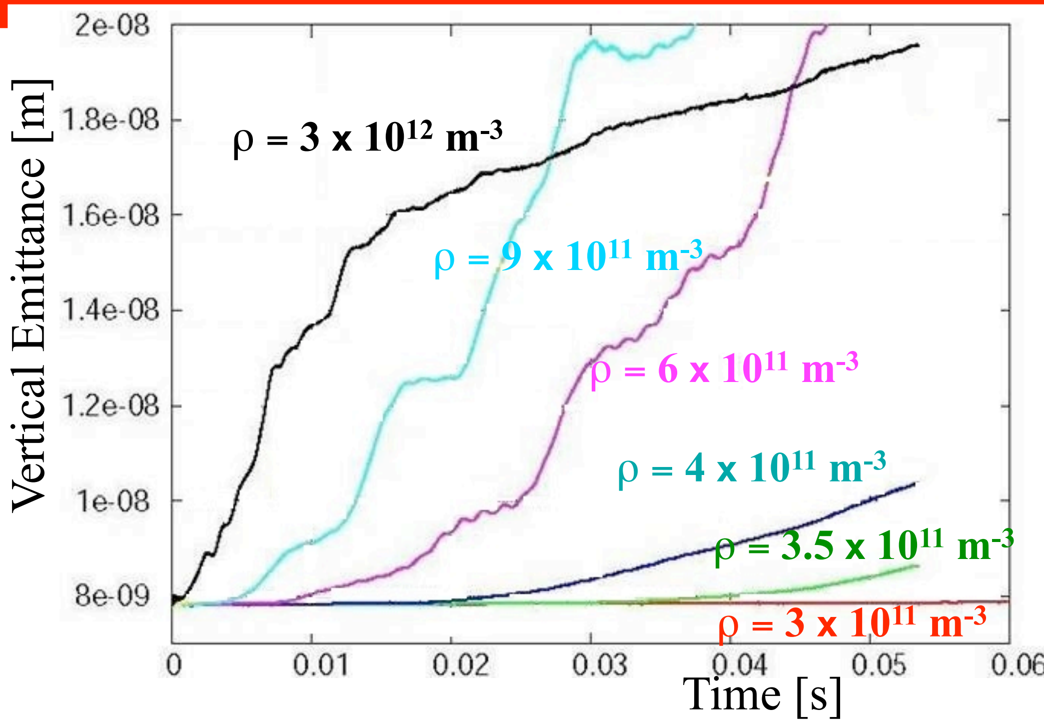
(Courtesy F.Ruggiero)

Animation from O. Brüning simulation
→ 10 subsequent bunch passages
Color describes the formation of the electron cloud

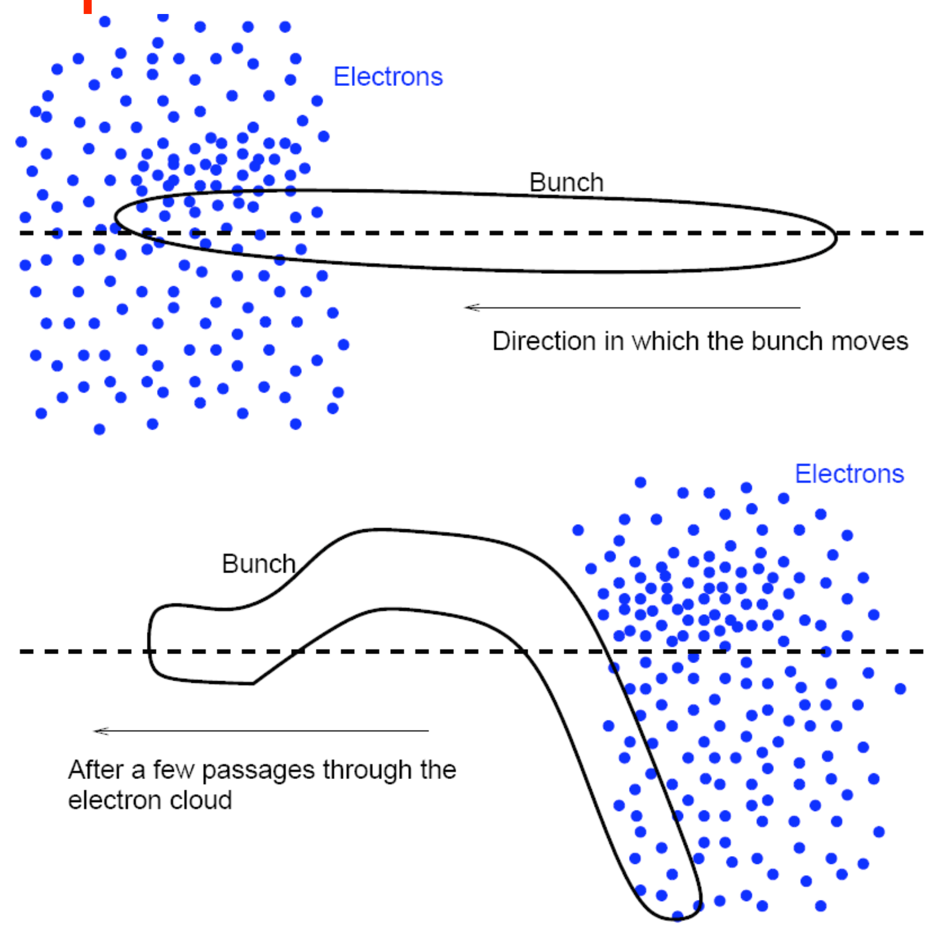


Electron clouds issues on beam

1. Bunch passage, electrons accumulated near beam centroid
2. If there is offset between head and tail:
   - → tail feels transverse electric field created by head
   - → tail become unstable
3. Particles mix longitudinally
   - → also head can become unstable (above threshold)

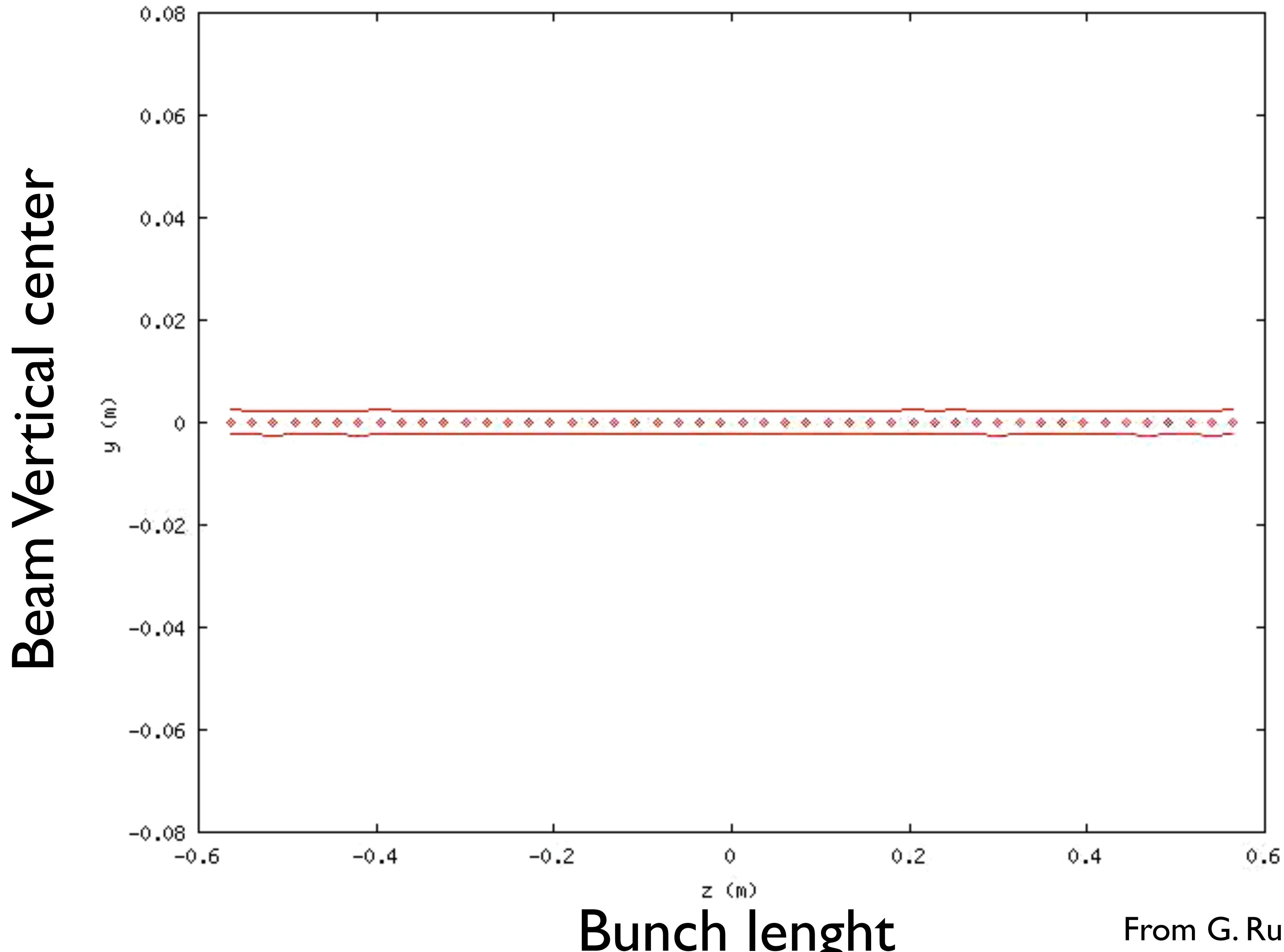


Vertical emittance vs. time, for different EC densities @ LHC injection



From E. Benedetto

Simulation of SPS experiment, 500 turn



From G. Rumolo