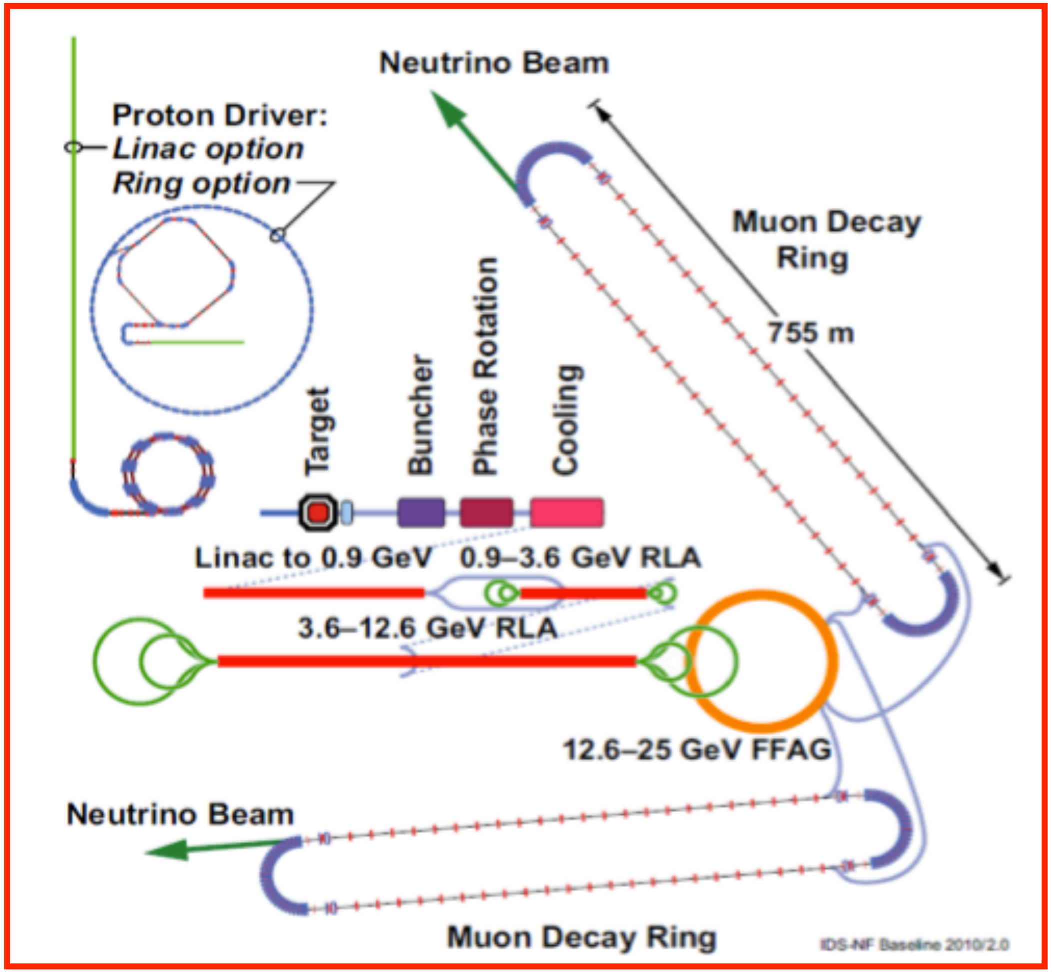
Introduction to accelerators: application to neutrino beams

Simone Gilardoni CERN-BE/ABP
Simone.Gilardoni@cern.ch

Lecture goals/outline

Goal: present the basic concepts of accelerator physics to understand also the Nufact/Beta beam/Superbeam design



day 1-2)

Introduction to accelerators
Beam transverse dynamics
Superconductivity for accelerators

day 2-3)

Longitudinal beam dynamics
Collective effects

day 2-3)

Superbeam design
Neutrino Factory design
Beta beams design

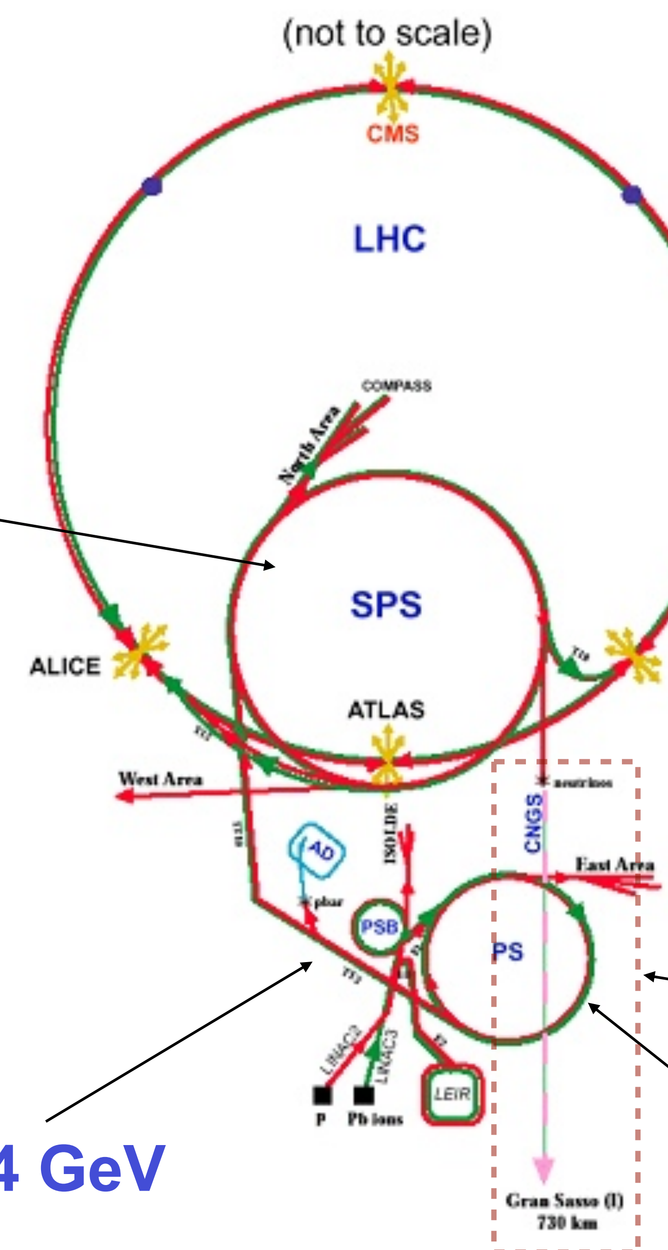
Whenever possible, example taken from existing machine, like LHC, CNGS.
Attempt to mix reality with a bit of theory

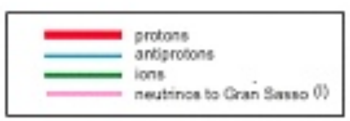
These lectures are not meant to be a MONOLOGUE

Existing facility as example: the CERN accelerator complex overview

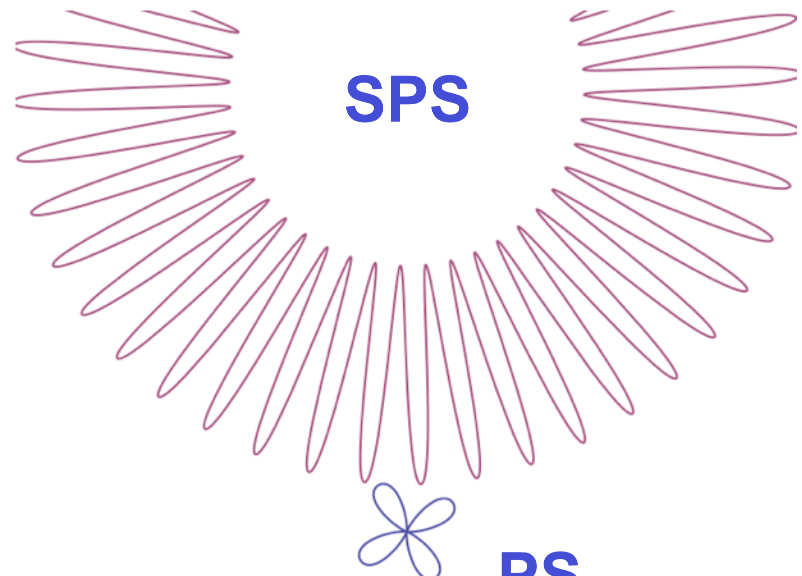
450 GeV /c – 7 TeV /c

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



CNGS, the CERN neutrino beam

50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c

Mathematical approach of the lectures

TEST:

$$D_n = \beta_C \sin n\phi_C * \delta_{\text{supr}} * \sum_{i=1}^{n} \cos\left(i\phi_C - \frac{1}{2}\phi_C \pm \varphi_m \right) * \sqrt{\frac{\beta_m}{\beta_C}} -$$
$$- \cos n\phi_C * \delta_{\text{supr}} * \sum_{i=1}^{n} \sqrt{\beta_m \beta_C} * \sin\left(i\phi_C - \frac{1}{2}\phi_C \pm \varphi_m \right)$$

$$D_n = \sqrt{\beta_m \beta_C} * \sin n\phi_C * \delta_{\text{supr}} * \sum_{i=1}^{n} \cos\left((2i-1)\frac{\phi_C}{2} \pm \varphi_m \right) -$$
$$- \sqrt{\beta_m \beta_C} * \delta_{\text{supr}} * \cos n\phi_C \sum_{i=1}^{n} \sin\left((2i-1)\frac{\phi_C}{2} \pm \varphi_m \right)$$

Remembering the trigonometric gymnastics shown above we get

$$D_n = \delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \sin n\phi_C * \sum_{i=1}^{n} \cos\left((2i-1)\frac{\phi_C}{2} \right) * 2\cos\varphi_m -$$
$$- \delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \cos n\phi_C \sum_{i=1}^{n} \sin\left((2i-1)\frac{\phi_C}{2} \right) * 2\cos\varphi_m$$

$$D_n = 2\delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \cos\varphi_m \left\{ \sum_{i=1}^{n} \cos\left((2i-1)\frac{\phi_C}{2} \right) * \sin(n\phi_C) - \right.$$
$$\left. - \sum_{i=1}^{n} \sin\left((2i-1)\frac{\phi_C}{2} \right) * \cos(n\phi_C) \right\}$$

$$D_n = 2\delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \cos\varphi_m \sin(n\phi_C) \frac{\sin\frac{n\phi_C}{2} * \cos\frac{n\phi_C}{2}}{\sin\frac{\phi_C}{2}} -$$
$$- 2\delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \cos\varphi_m * \cos(n\Phi_C) * \frac{\sin\frac{n\Phi_C}{2} * \sin\frac{n\Phi_C}{2}}{\sin\frac{\Phi_C}{2}}$$

$$D_n = \frac{2\delta_{\text{supr}} * \sqrt{\beta_m \beta_C} * \cos\varphi_m}{\sin\frac{\phi_C}{2}} \left\{ 2\sin\frac{n\phi_C}{2} \cos\frac{n\phi_C}{2} * \cos\frac{n\phi_C}{2} \sin\frac{n\phi_C}{2} - \right.$$
$$\left. - (\cos^2\frac{n\phi_C}{2} - \sin^2\frac{n\phi_C}{2}) \sin^2\frac{n\phi_C}{2} \right\}$$

Method proposed by B. Holzer,
see CERN summer student lectures

replace by ...

"after some TLC transformations" ***... or ...*** ***" after some beer"***

Linus security blanket

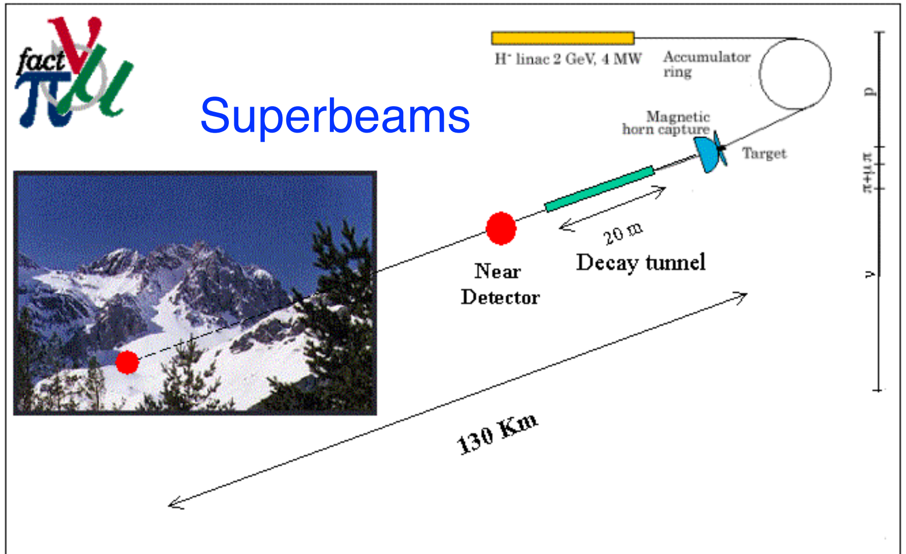
I'll use a minimum of math for the ones who fill better and to prove at least the basics principles

I'll try to notice if you arrive at this stage during the lectures..

"Ipse dixit (he himself said it)" means: I have no time to explain the subject in details,
I give you a reference in case, the details in that case are not fundamental for the understanding

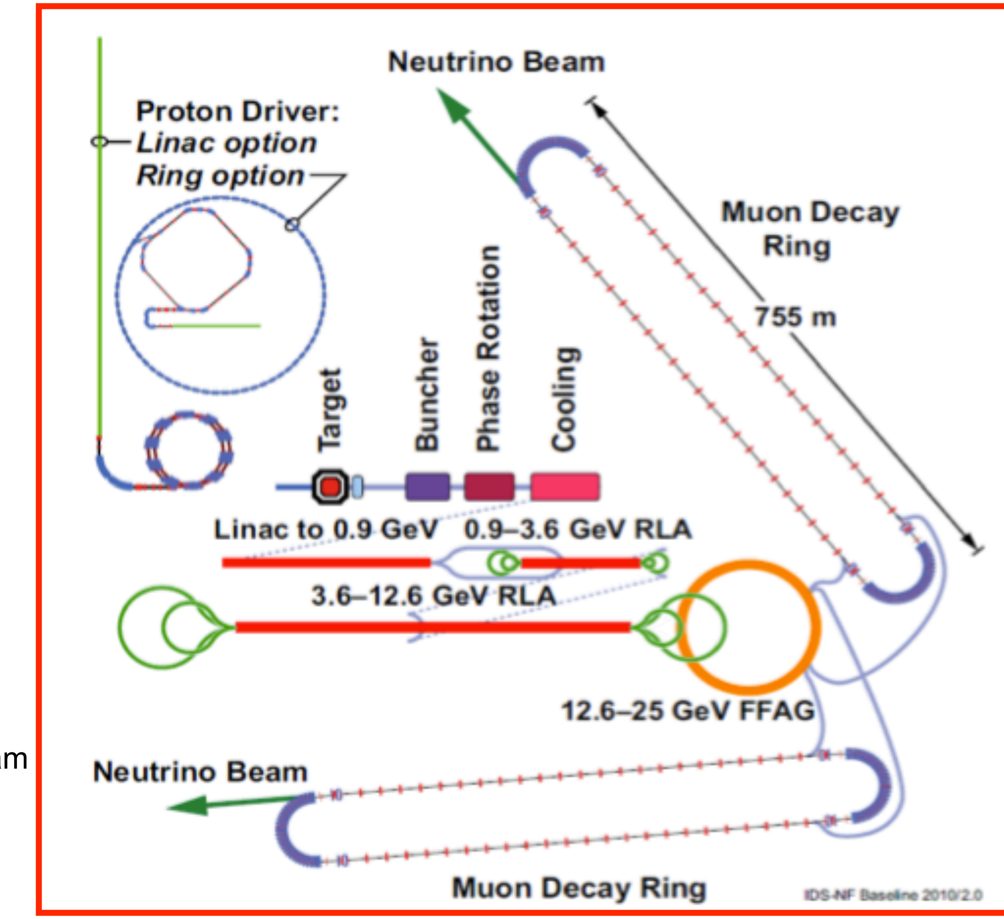
What we would like to understand ...

Superbeams

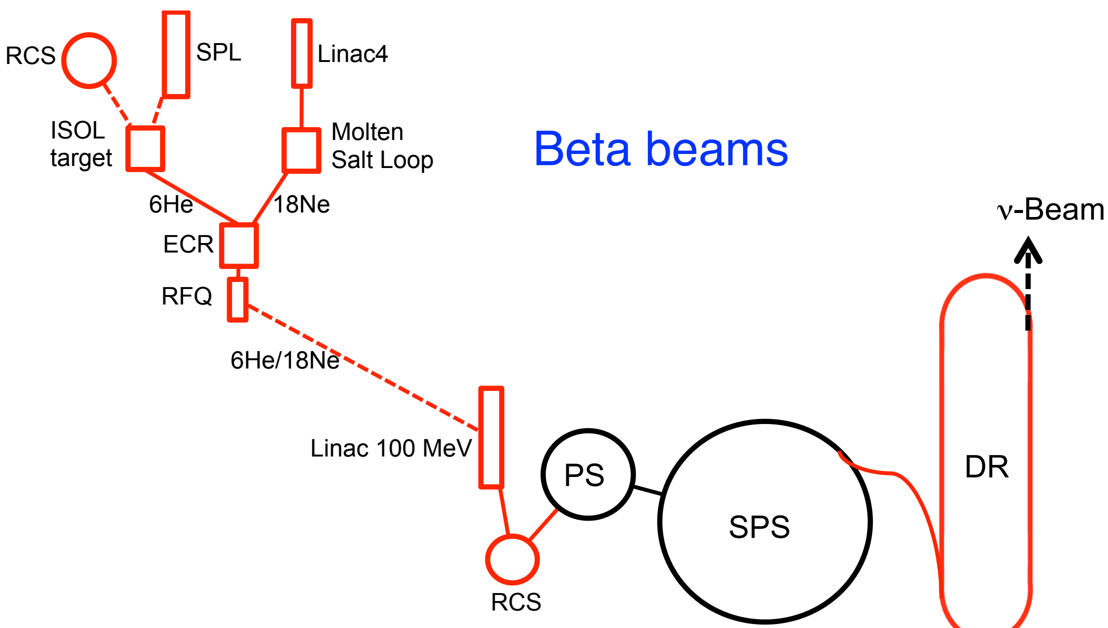


A possible layout of a Low Energy Neutrino Super Beam

Nufact

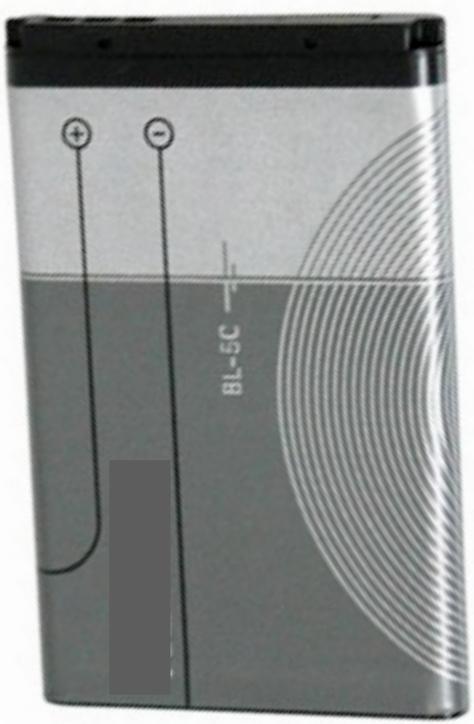


Beta beams



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

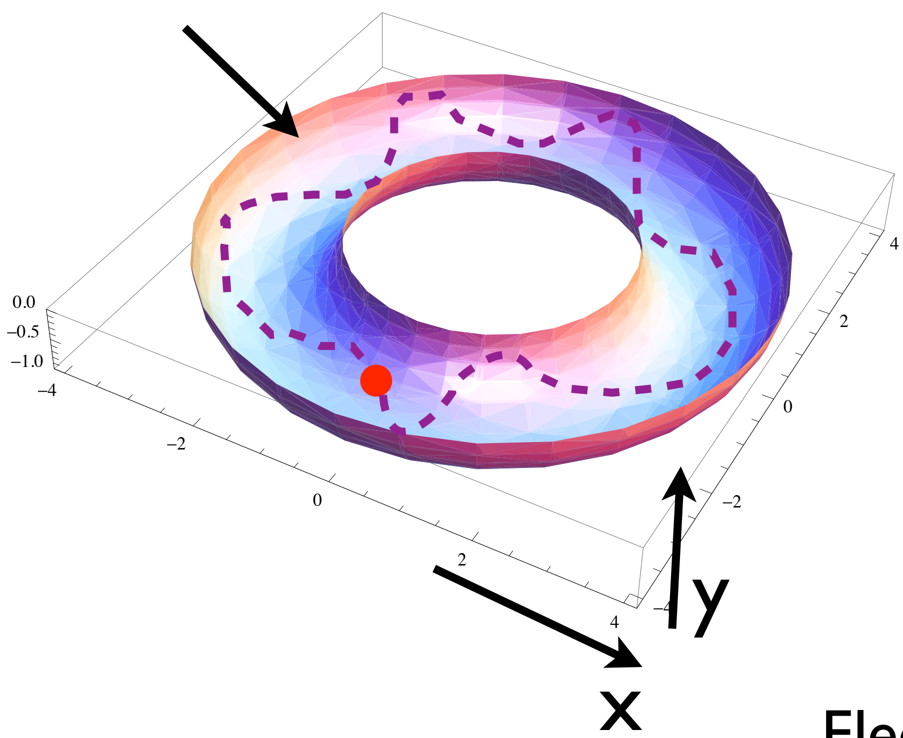
To accelerate an electron to an energy equivalent to a proton mass:

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 ....

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

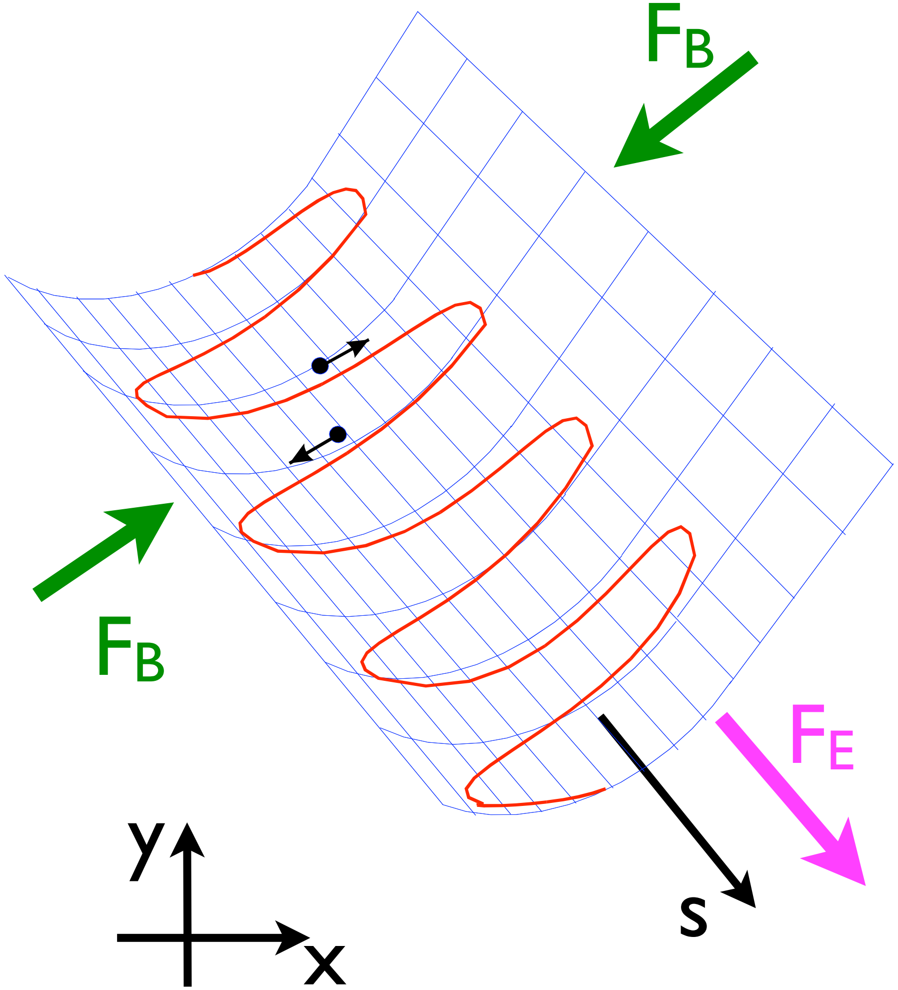
*An **accelerator** is formed by a sequence (called **lattice**) of:*

a) Magnets → Magnetic Field

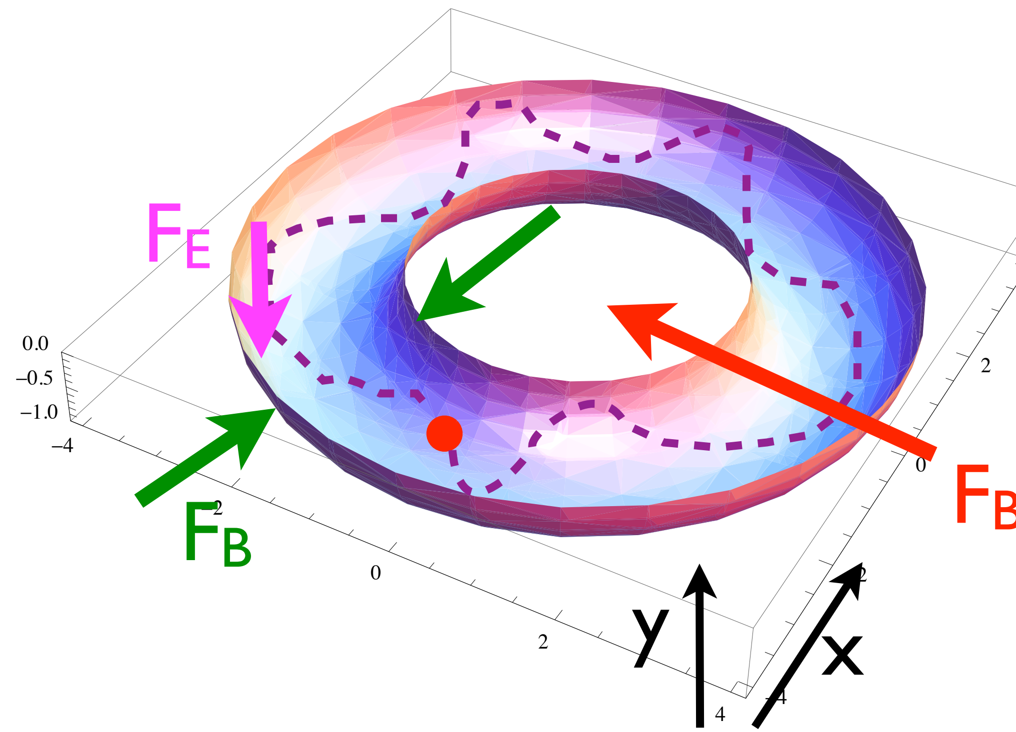
b) Accelerating Cavity → Electric Field

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

Linear Accelerator

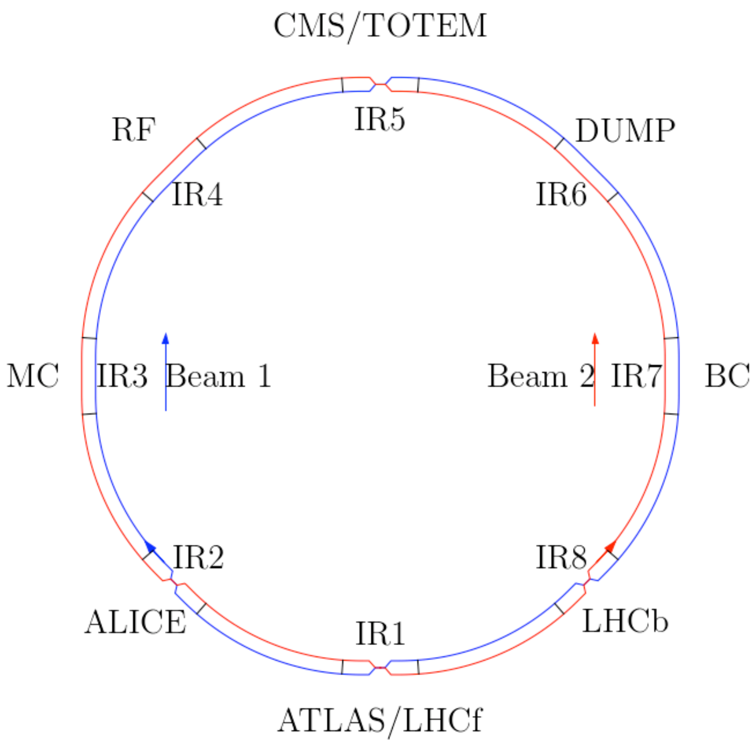


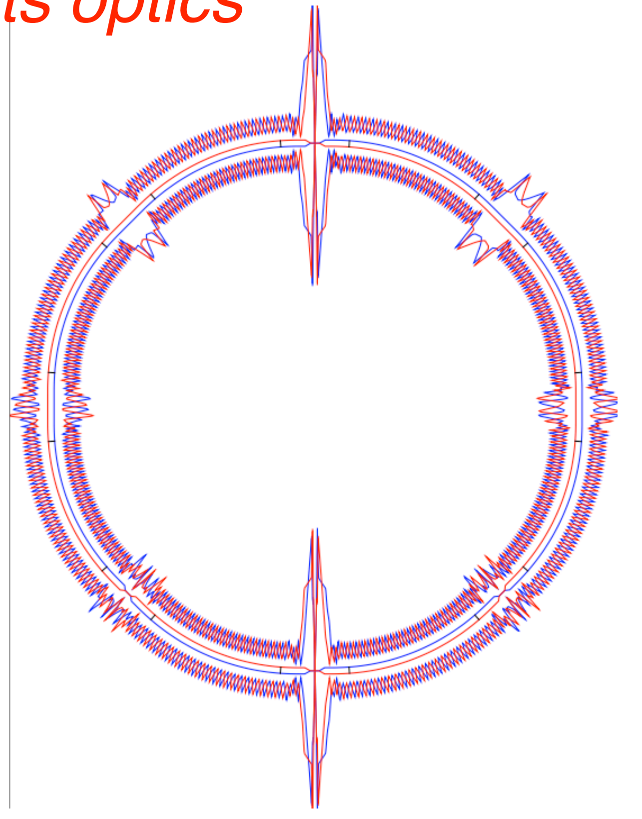
Circular Accelerator



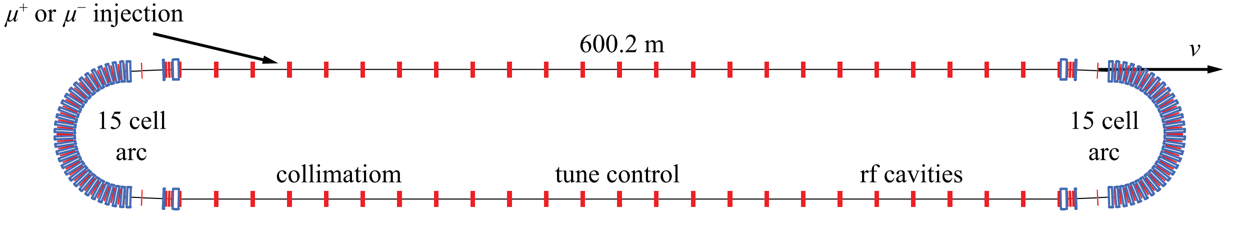
Today lectures... let's go circular

LHC, the ring and its optics

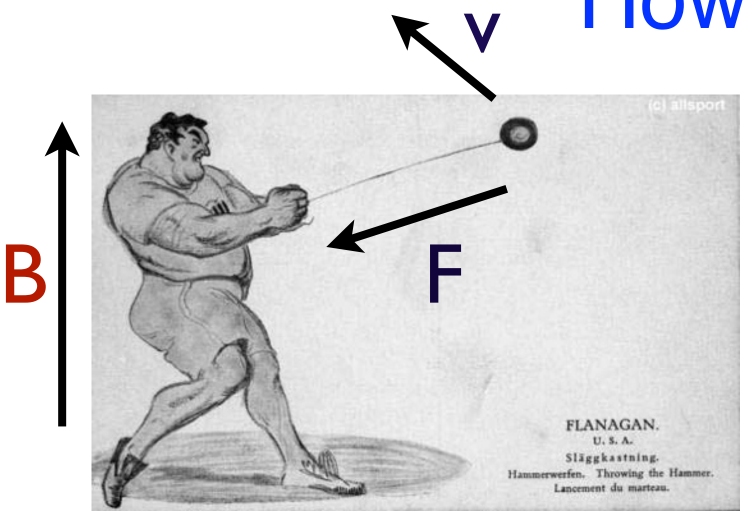




Nufact storage ring



How a circular accelerator works ?



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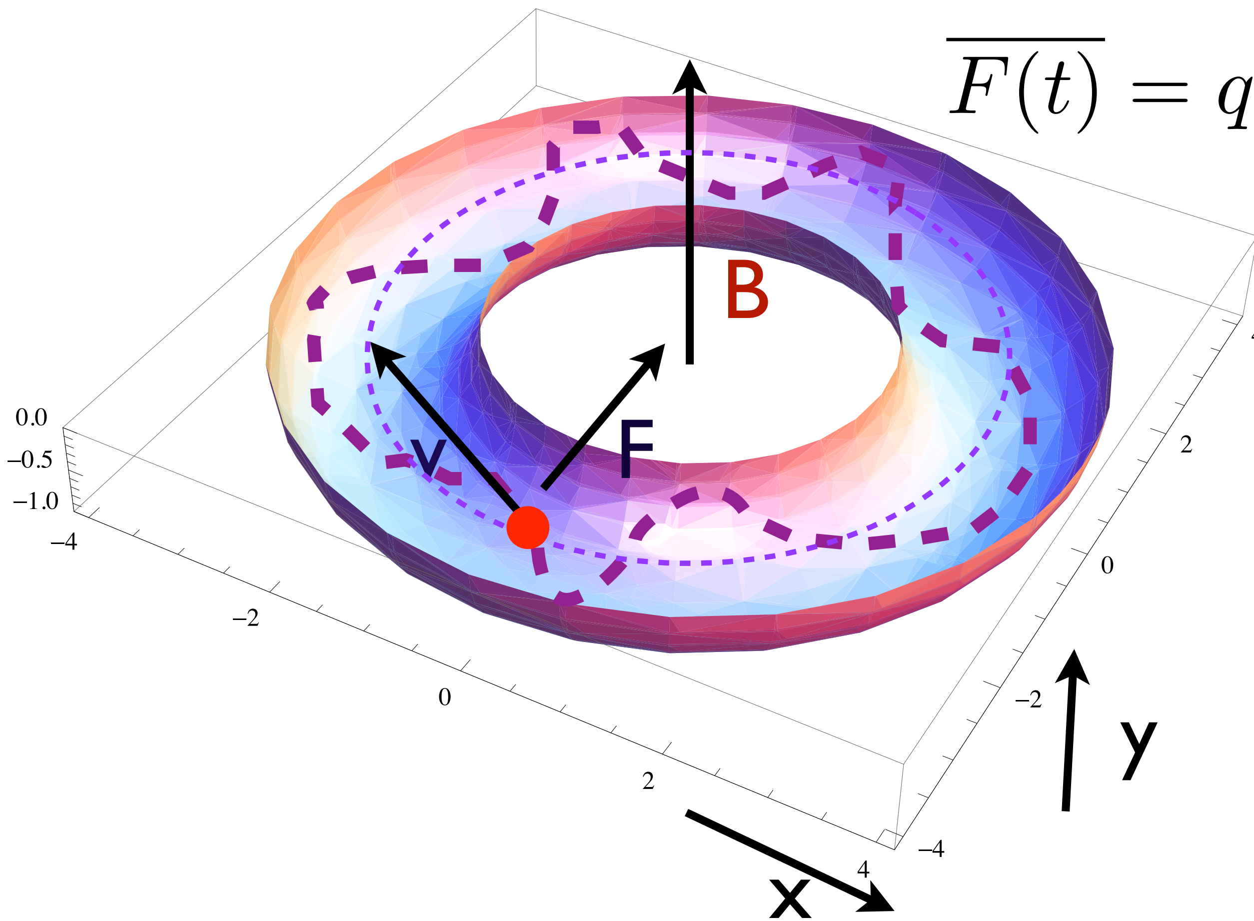
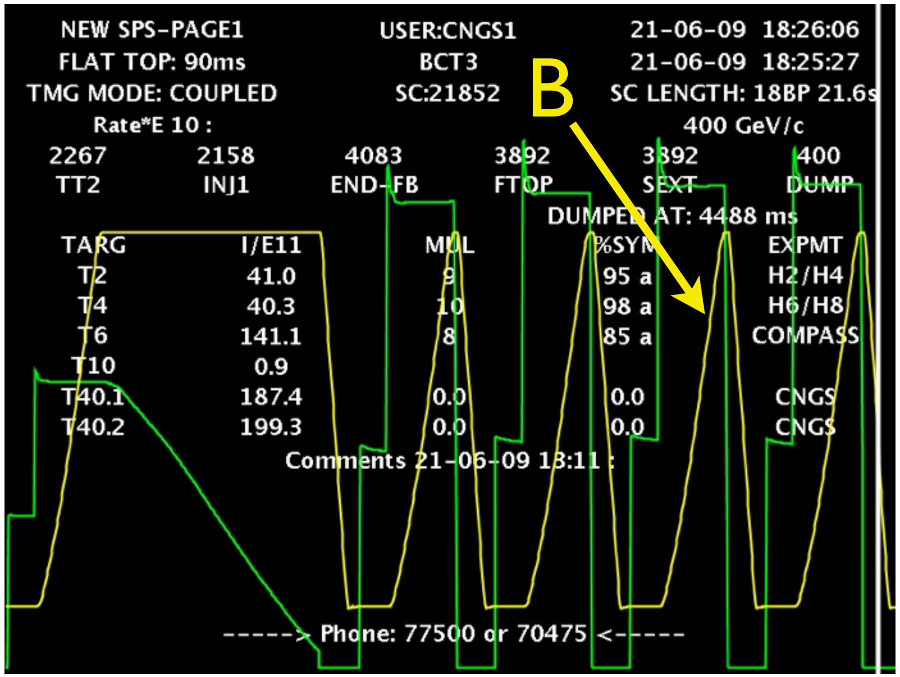


Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

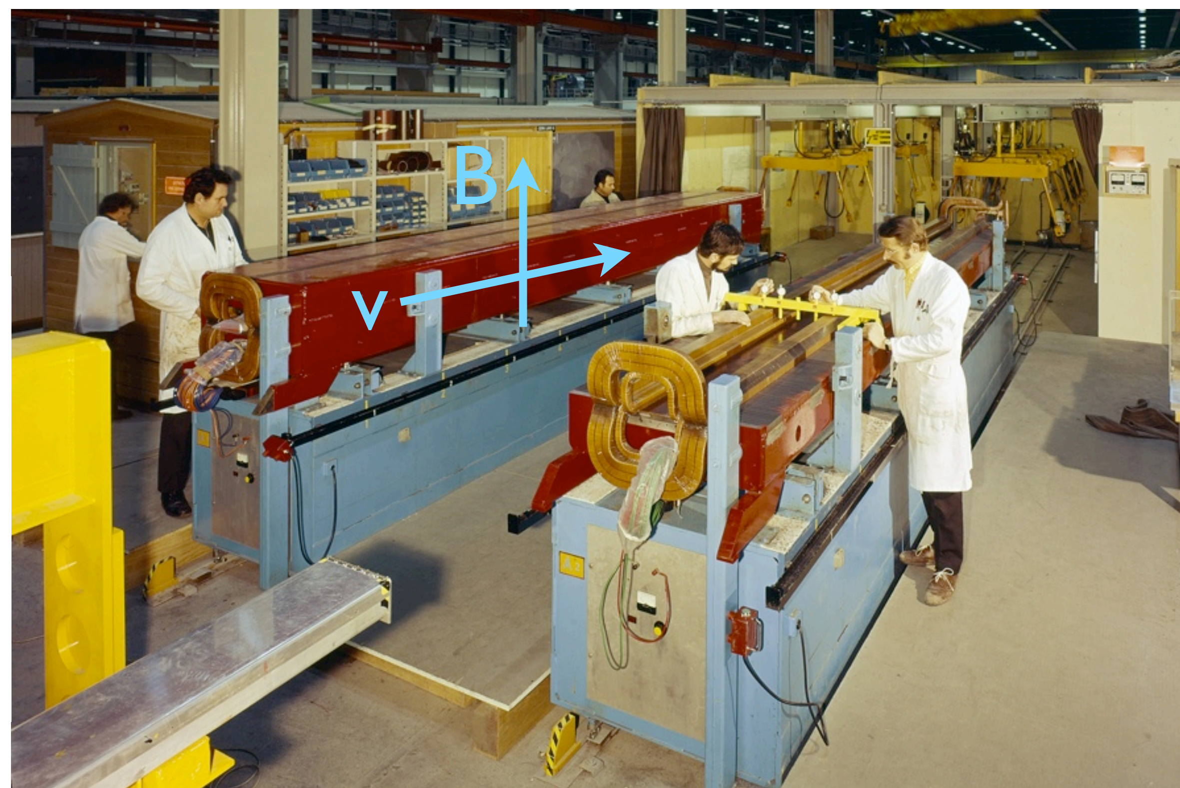
Dipole

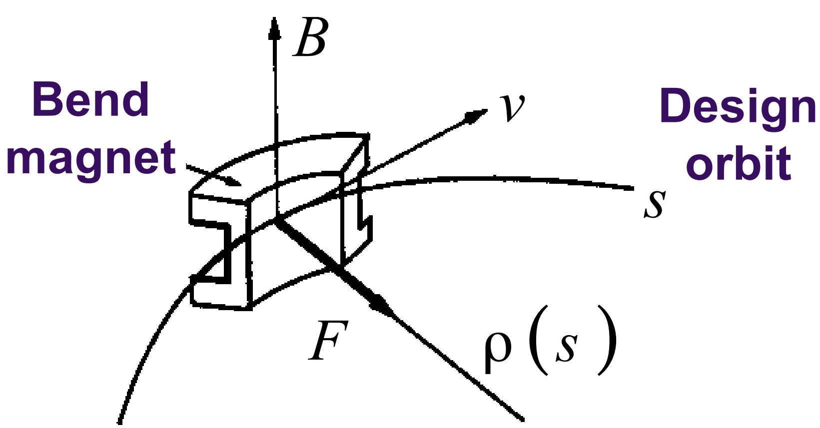


Force given by the vertical magnetic field compensates the centrifugal force to keep the particles on the central trajectory, i.e. in the center of the beam pipe.

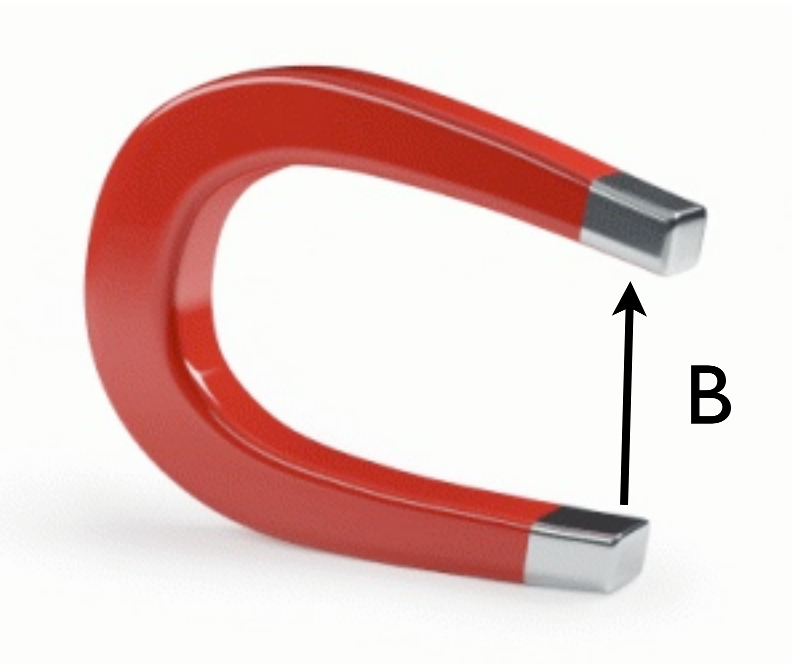
Once the beam accelerates, the magnetic field is increased synchronously

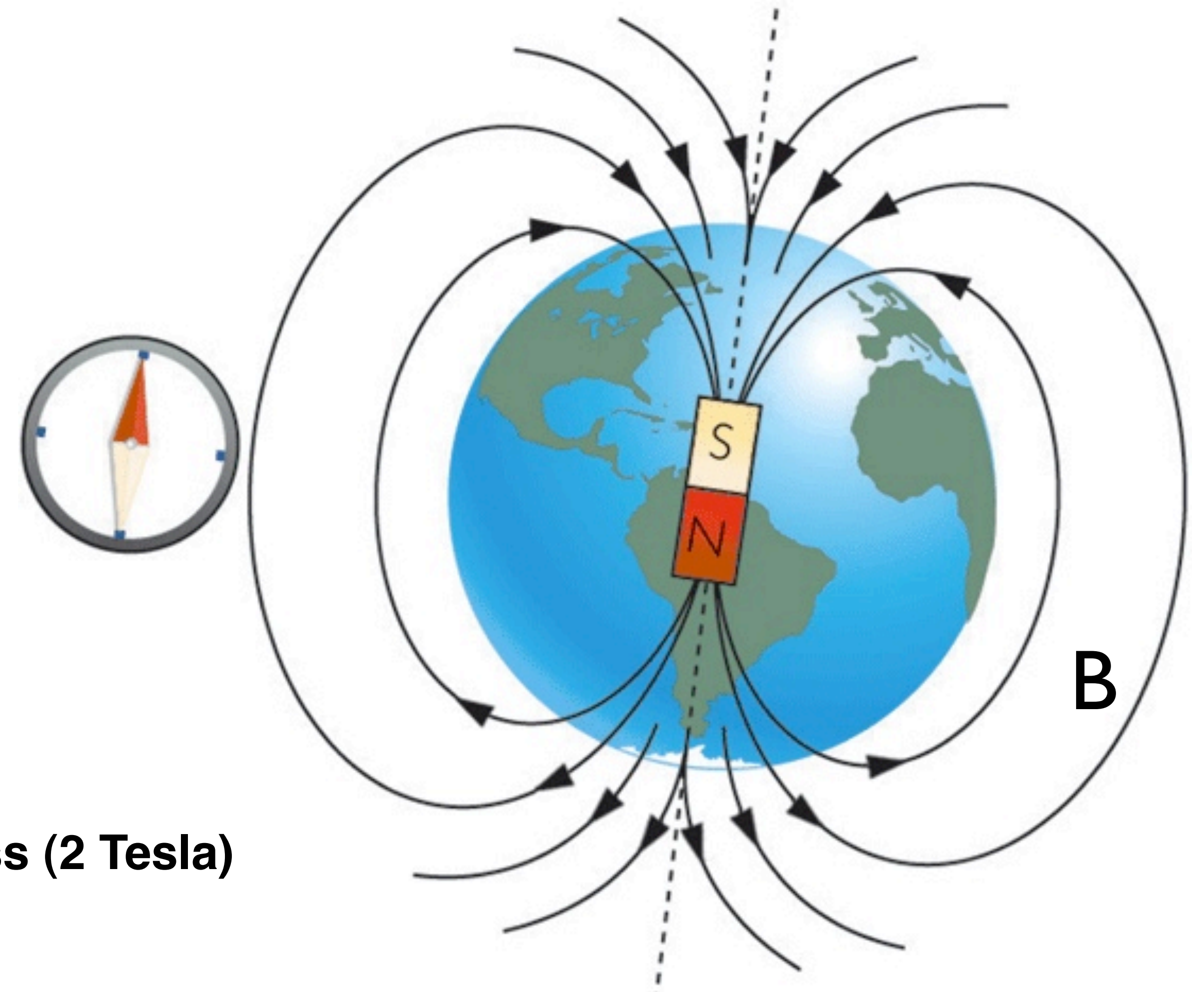
SPS dipoles, in total about 500





Two dipoles you should know we well





Earth Magnetic Field : ~ 0.6 Gauss

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

Typical magnet current required: 1 kA

Synchrotron (1952, 3 GeV, BNL)

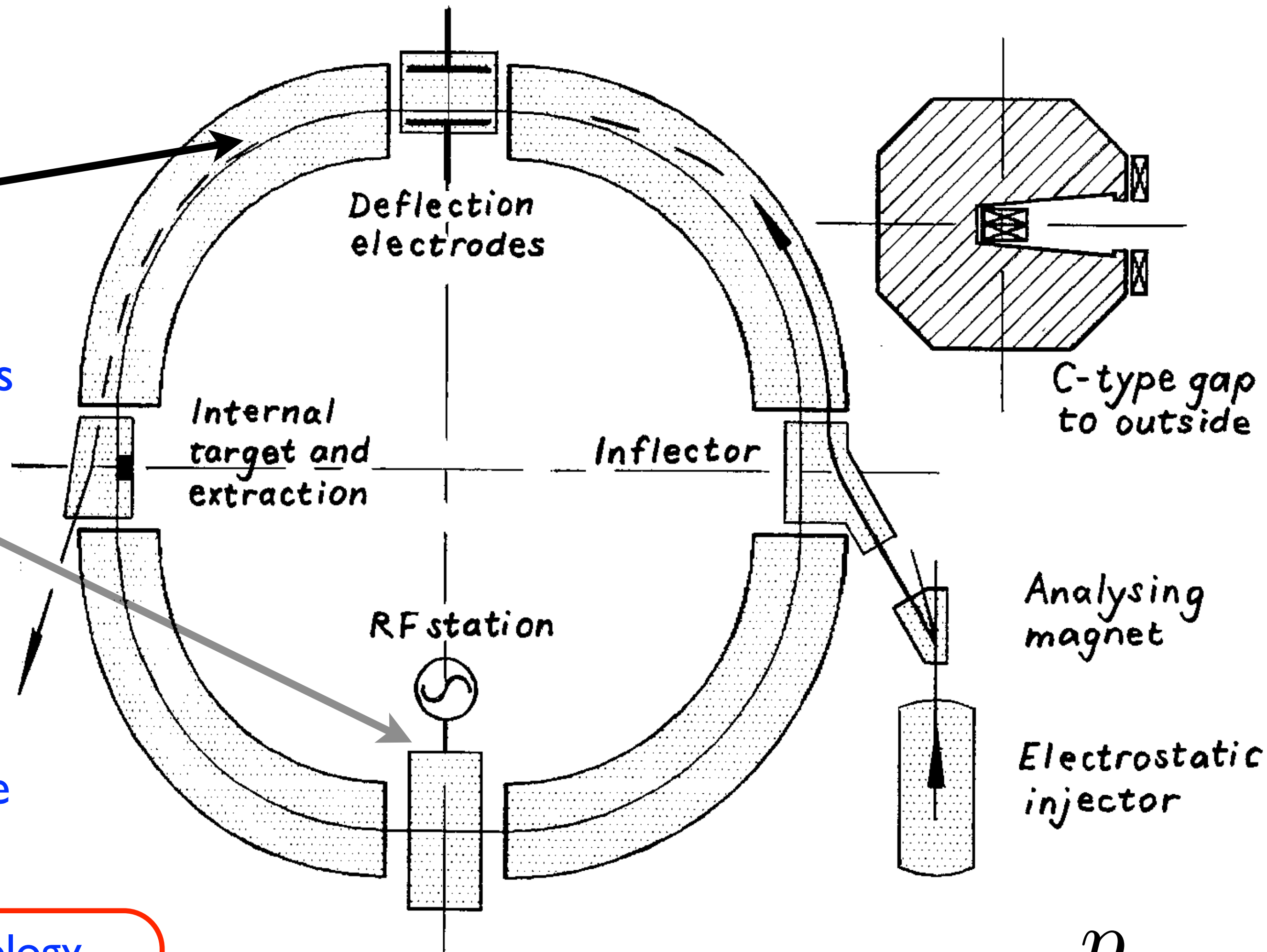
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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

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

e electric charge

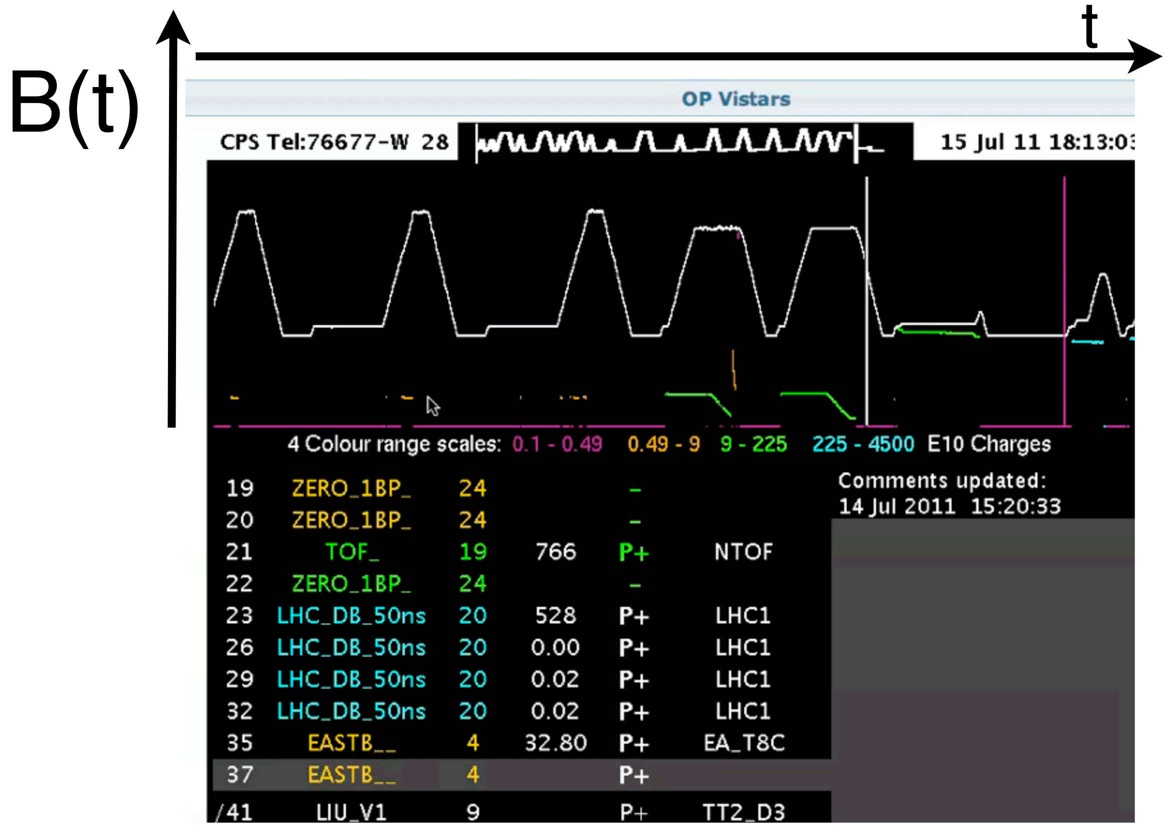
ρ constant radius of curvature



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

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

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



PS: first synchrotron ever build with Quadrupoles

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

Inj. field: 1013 G, extraction 12000 G

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

RCS: Rapid cycling synchrotron, few 100 ms to ramp the magnets

Beam rigidity vs E and B fields

$$\vec{F} = e\cdot\left(\vec{E} + \vec{\mathrm{v}}\times\vec{B}\right)$$

Lorentz Force

$$\vec{F}_\perp = \gamma m_0 c\dot{\vec{\beta}}_\perp = e\cdot\left(\vec{E}_\perp + \vec{\beta}c\times\vec{B}\right) \stackrel{!}{=} \gamma m_0\frac{\mathrm{v}^2}{R}$$

Lorentz Force **Centrifugal force**

Why bend particles with magnetic fields and not electric fields at high energy ?

$$eRB_\perp = p = e\frac{1}{\mathrm{v}}RE_\perp$$

Ultrarelativistic particles: $v \approx c \Rightarrow RB_\perp = 1\ \mathrm{Tm} \Leftrightarrow RE_\perp \approx 300\ \mathrm{MV/m}$

Simple magnet

Very high voltage (max few MV/m)

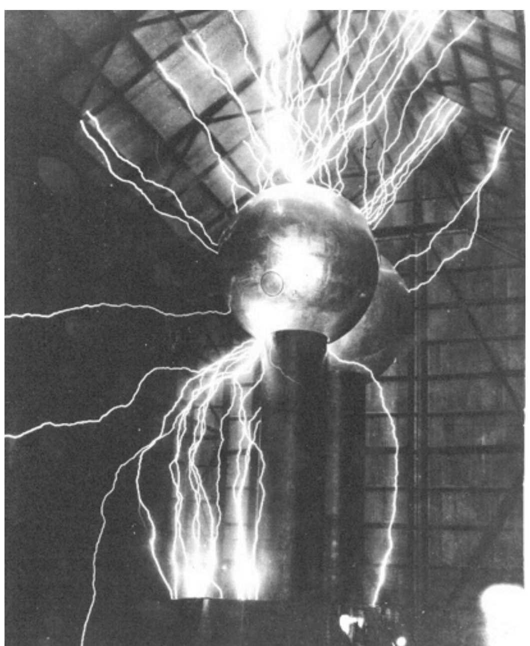
Van De Graaf electrostatic generator (1928)

A flavor how to get 10 MV/m ....

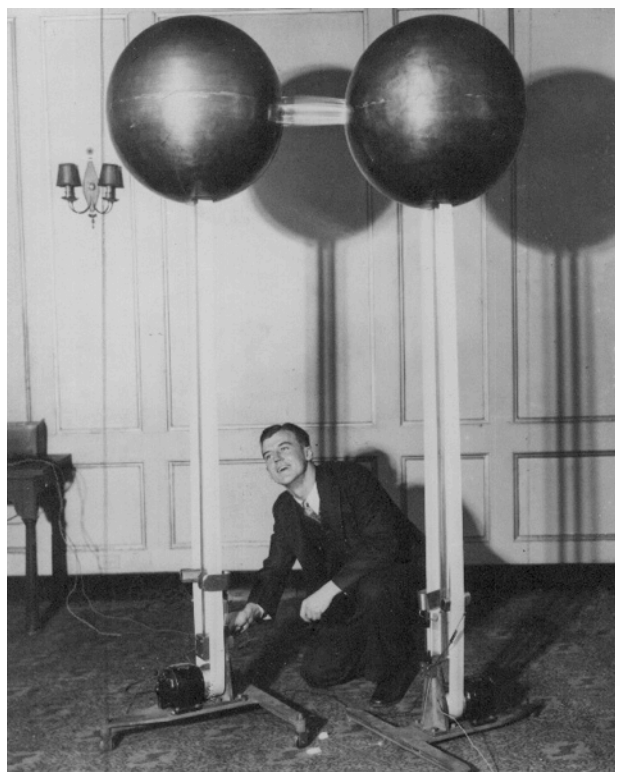
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: **10 MV**

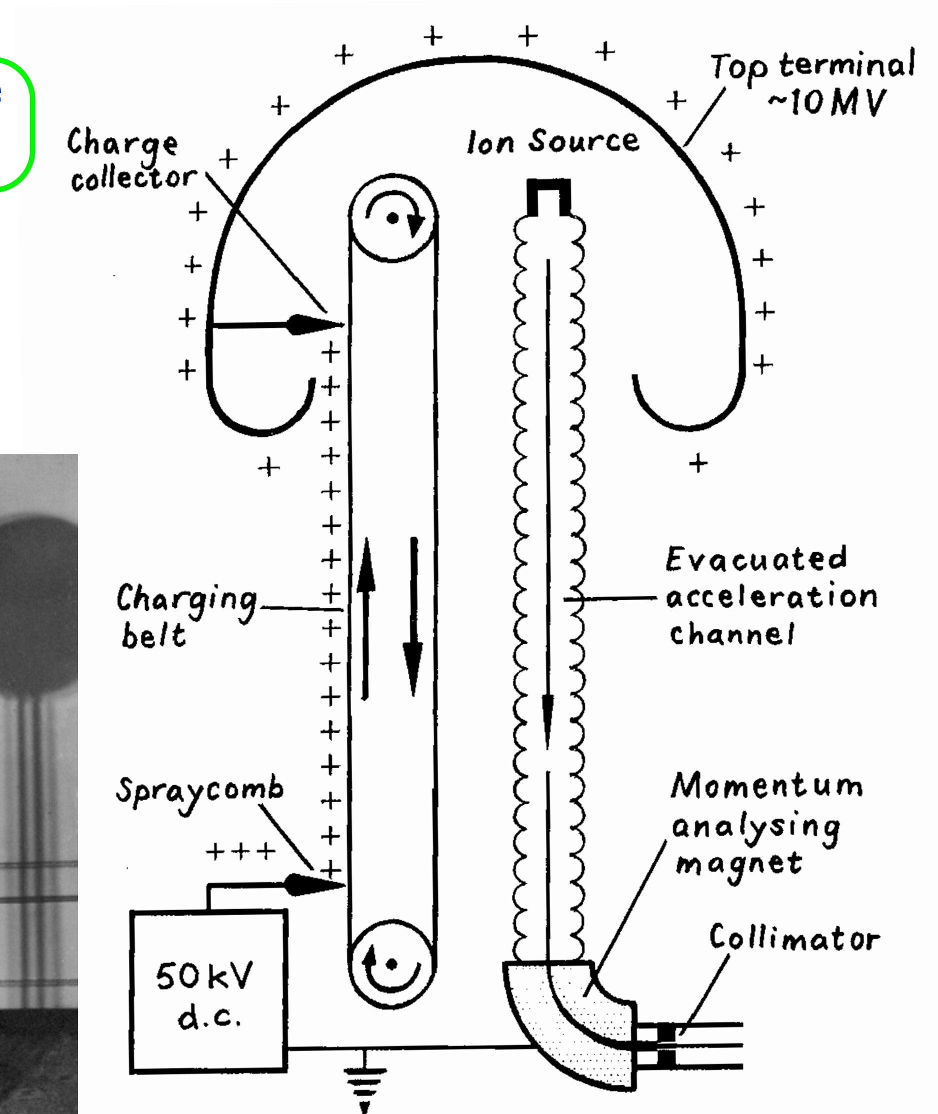
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



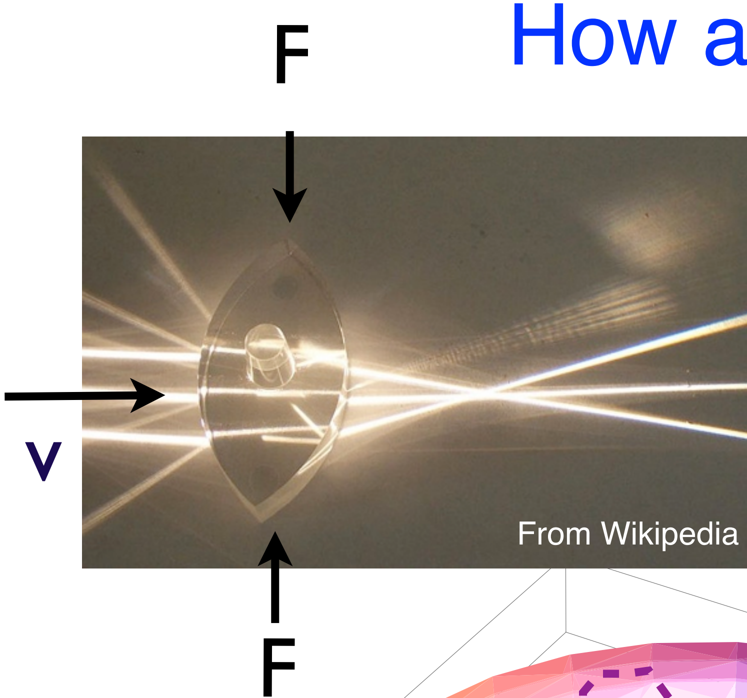
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



R. J. VAN DE GRAAFF WITH FIRST GENERATOR



How an accelerator works ?



Goal: keep enough particles confined in
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Magnetic field confines
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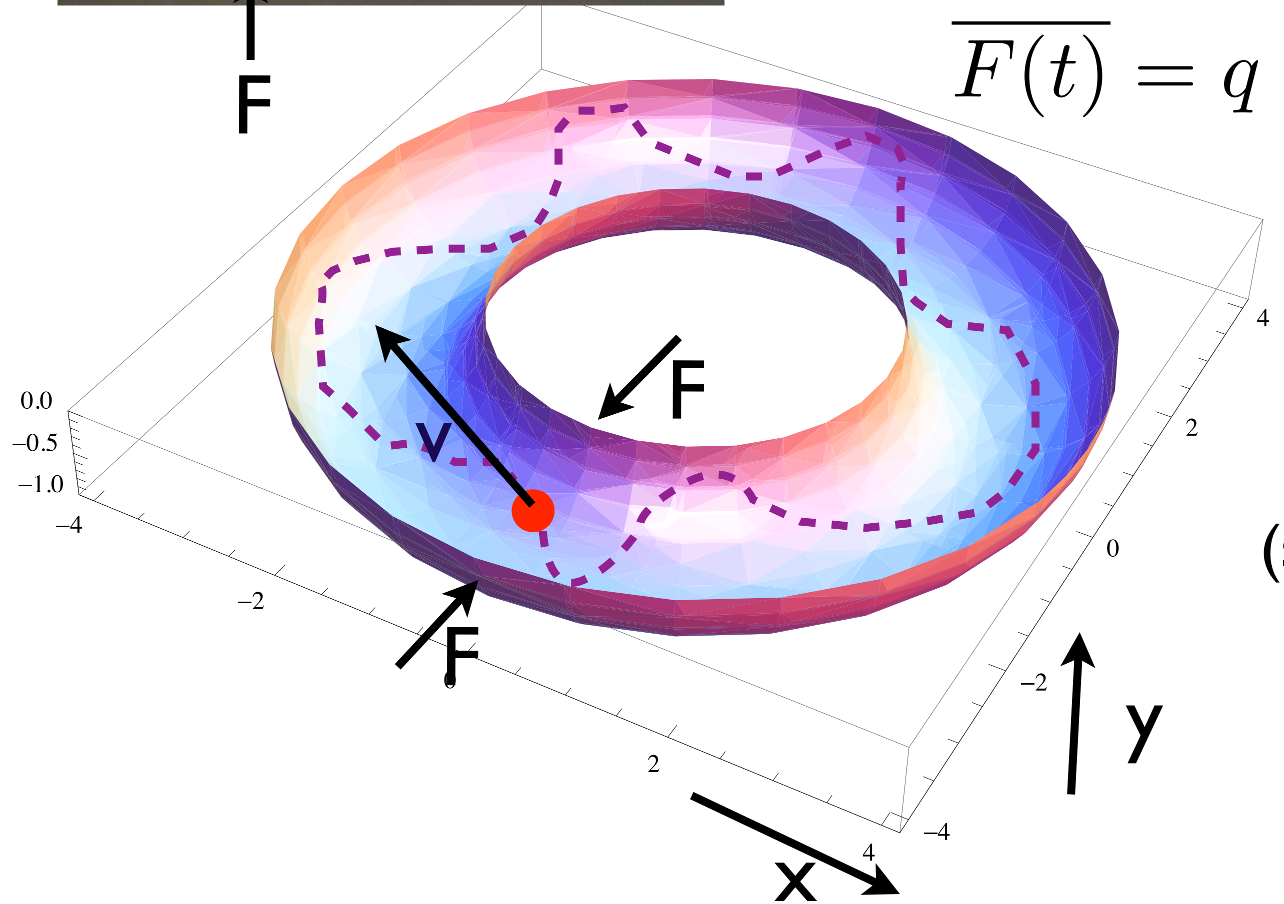
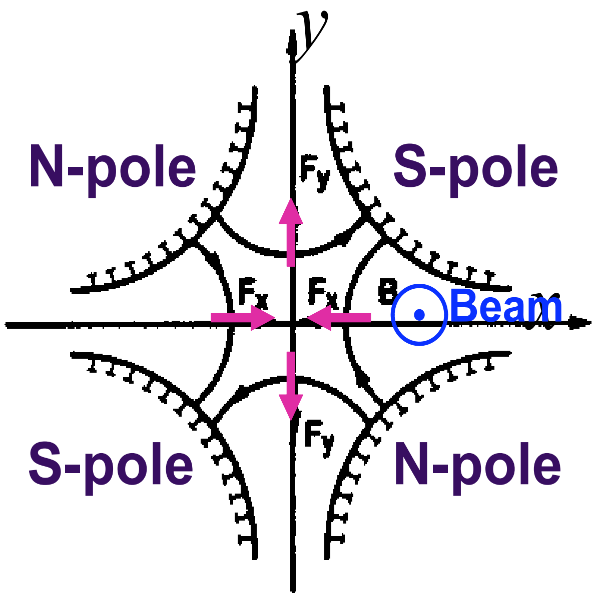
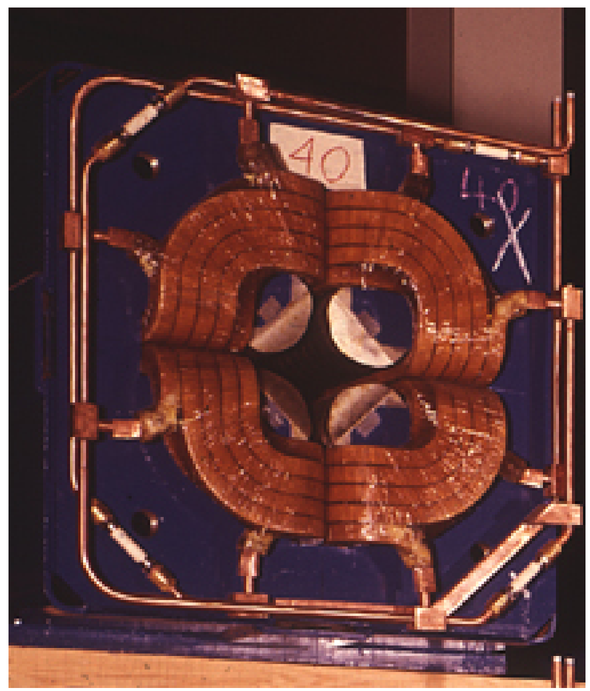


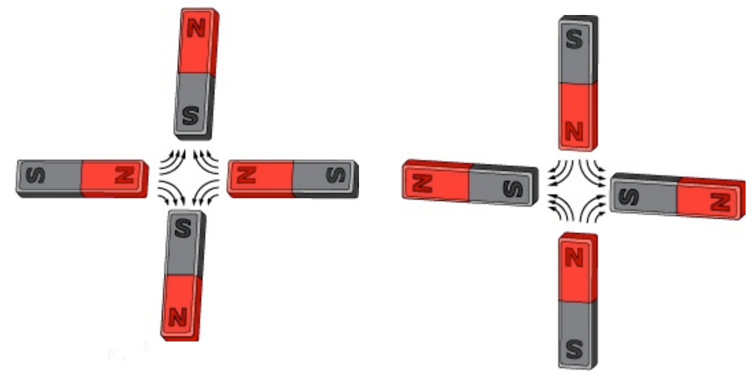
Synchrotrons: strong focusing machine

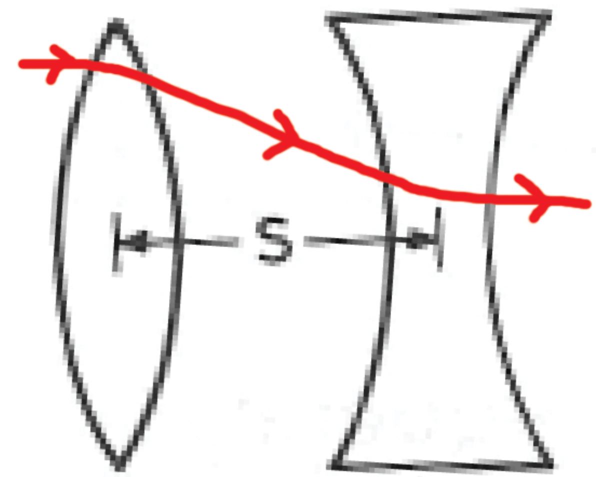
Dipoles are interleaved with quadrupoles to focus the beam.
Quadrupoles act on charged particles as lens for light.
By alternating focusing and defocusing lens
(Alternating Grandient quadrupoles) the beam dimension is kept small (even few mum^2).

QUADRUPOLES









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

Typical lattice is FODO, focusing-drift-defocusing

Quadrupole field

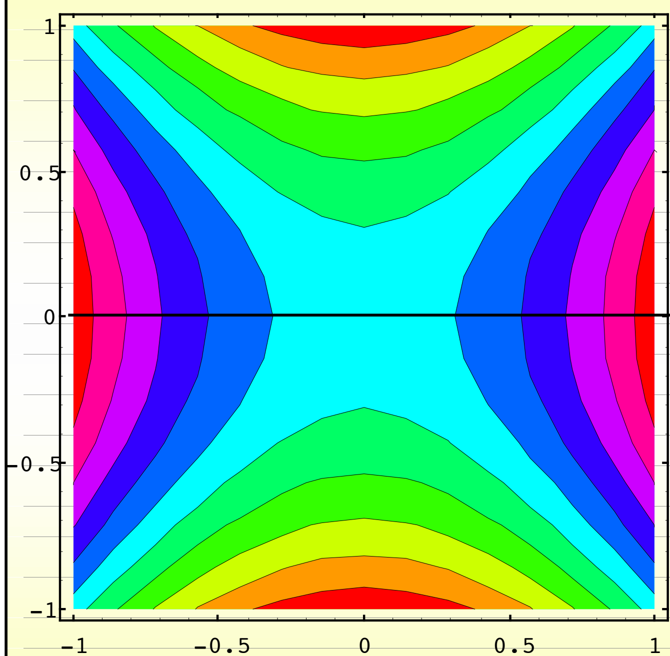
$$B = -\nabla \Phi_m$$

Φ_m **= Vector potential**

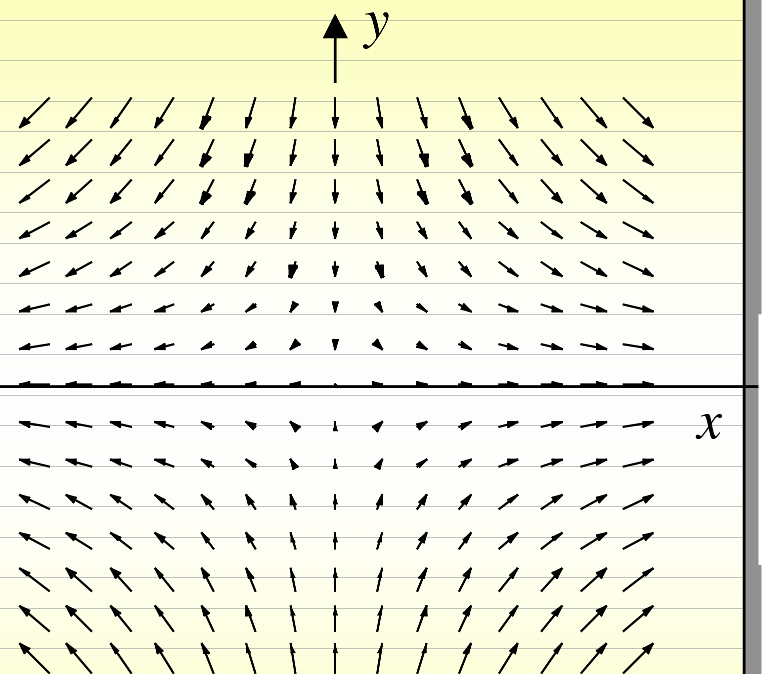
The field increases linearly with the distance from the center of the magnet

Obviously, K, the gradient, has a sign. By convention + means focusing quadrupole in the horizontal plane.

Contour plot of Φ_m

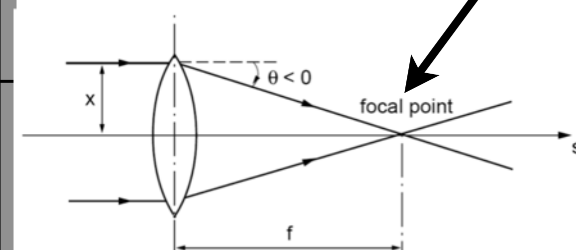


Magnetic field vector



$$\Phi_m = -\frac{p}{e} K_1 \left(x^2 - y^2\right), \text{ for quadrupole magnet}$$

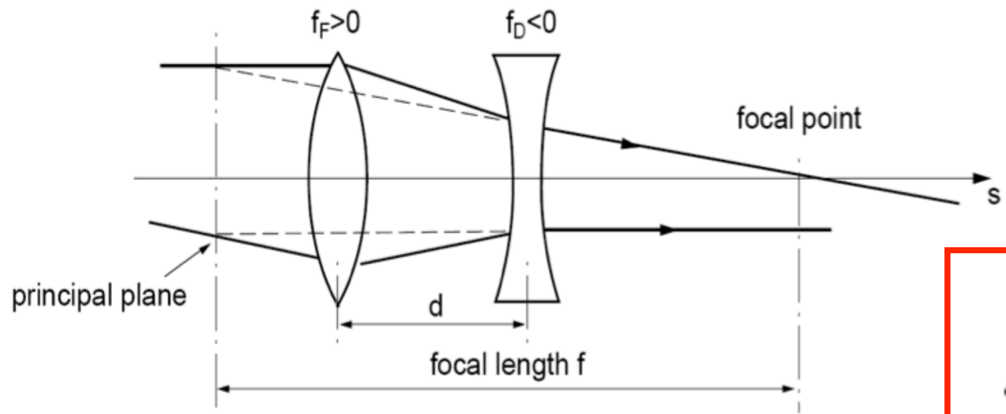
$$l\,K = -\frac{l}{B\rho}\frac{\partial B}{\partial x} = \frac{1}{f}$$



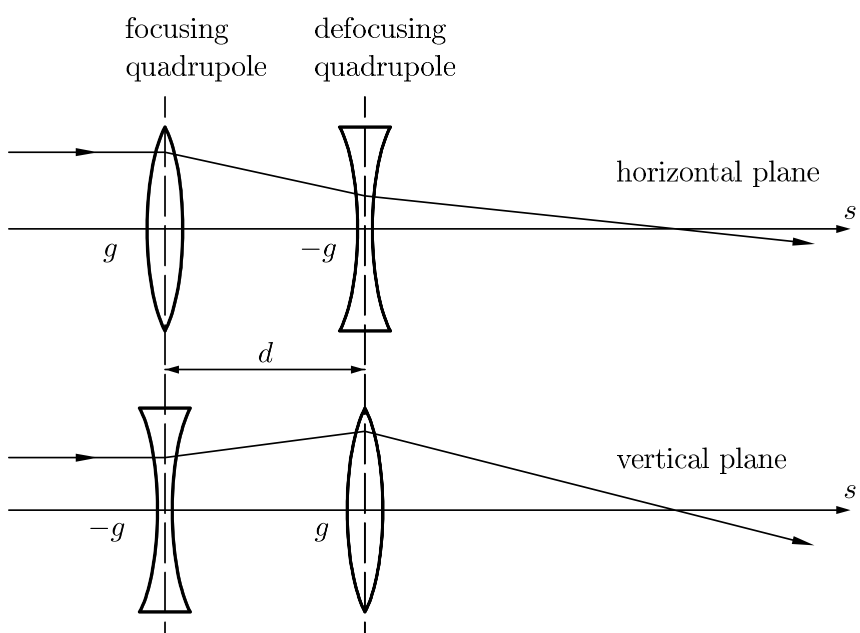
$$\tan\theta = -\frac{x}{f}$$

FODO structure

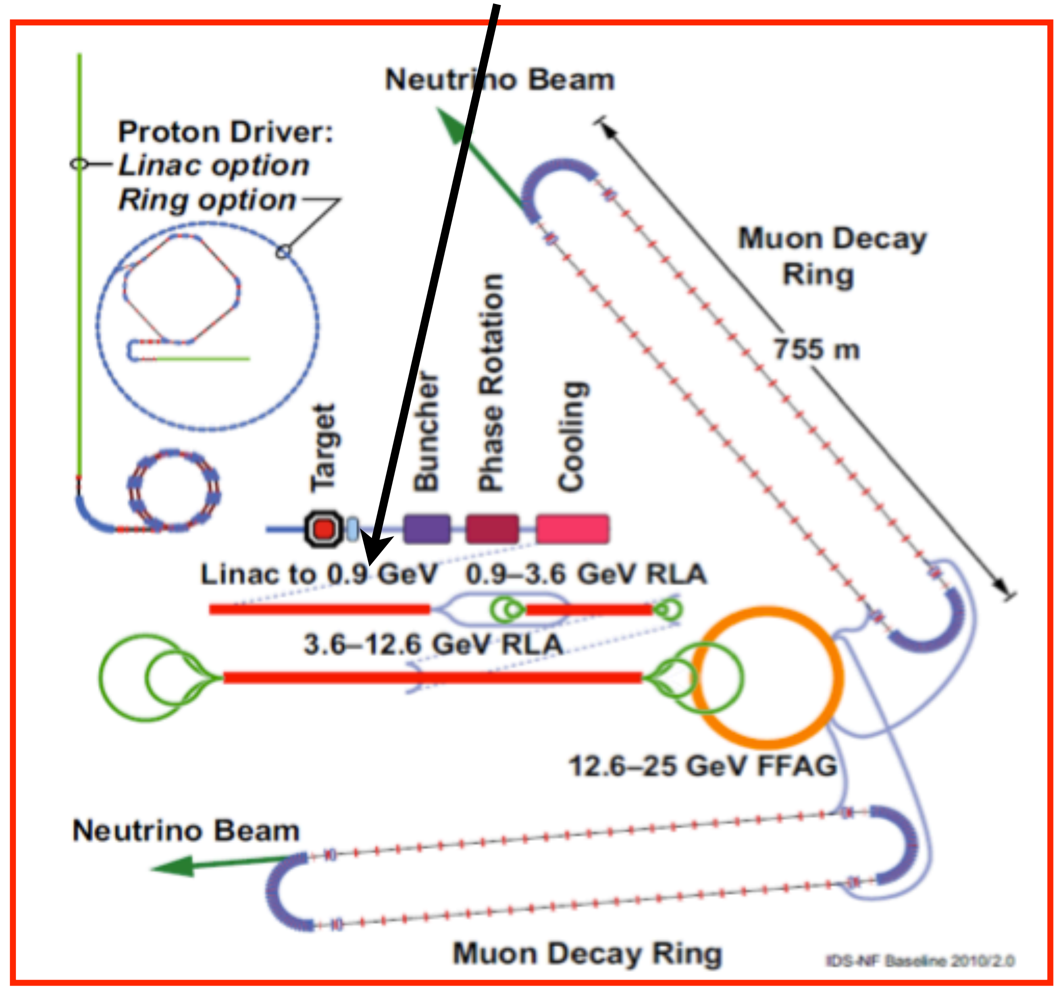
The FODO structure allows the focussing in both plane as in classical optics.



$$f = \frac{f_F^2}{d} > 0 \left(\text{when } f_D = - f_F \right)$$

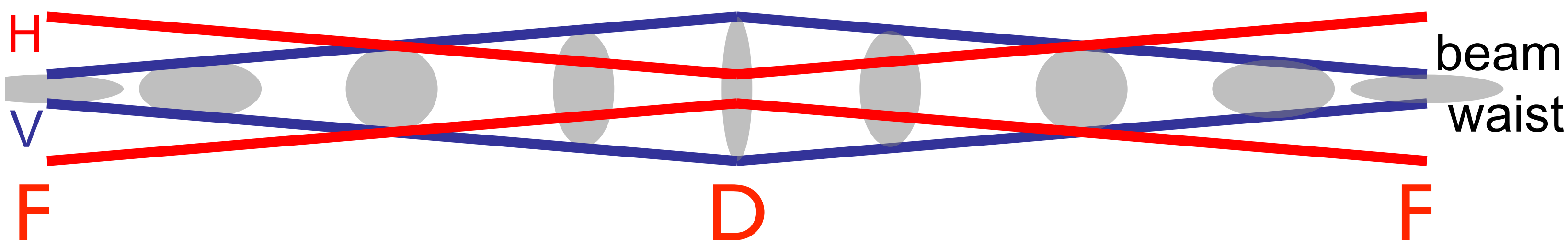


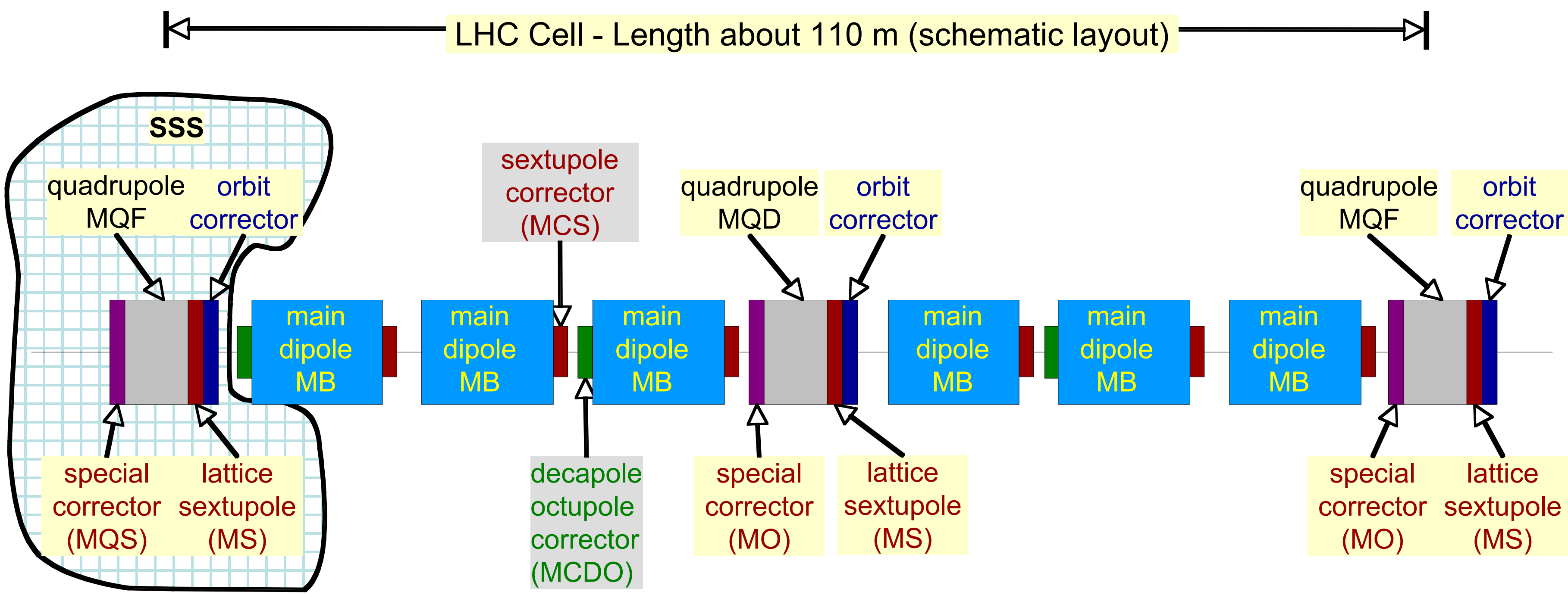
Quadrupolar focusing basically everywhere after this point...



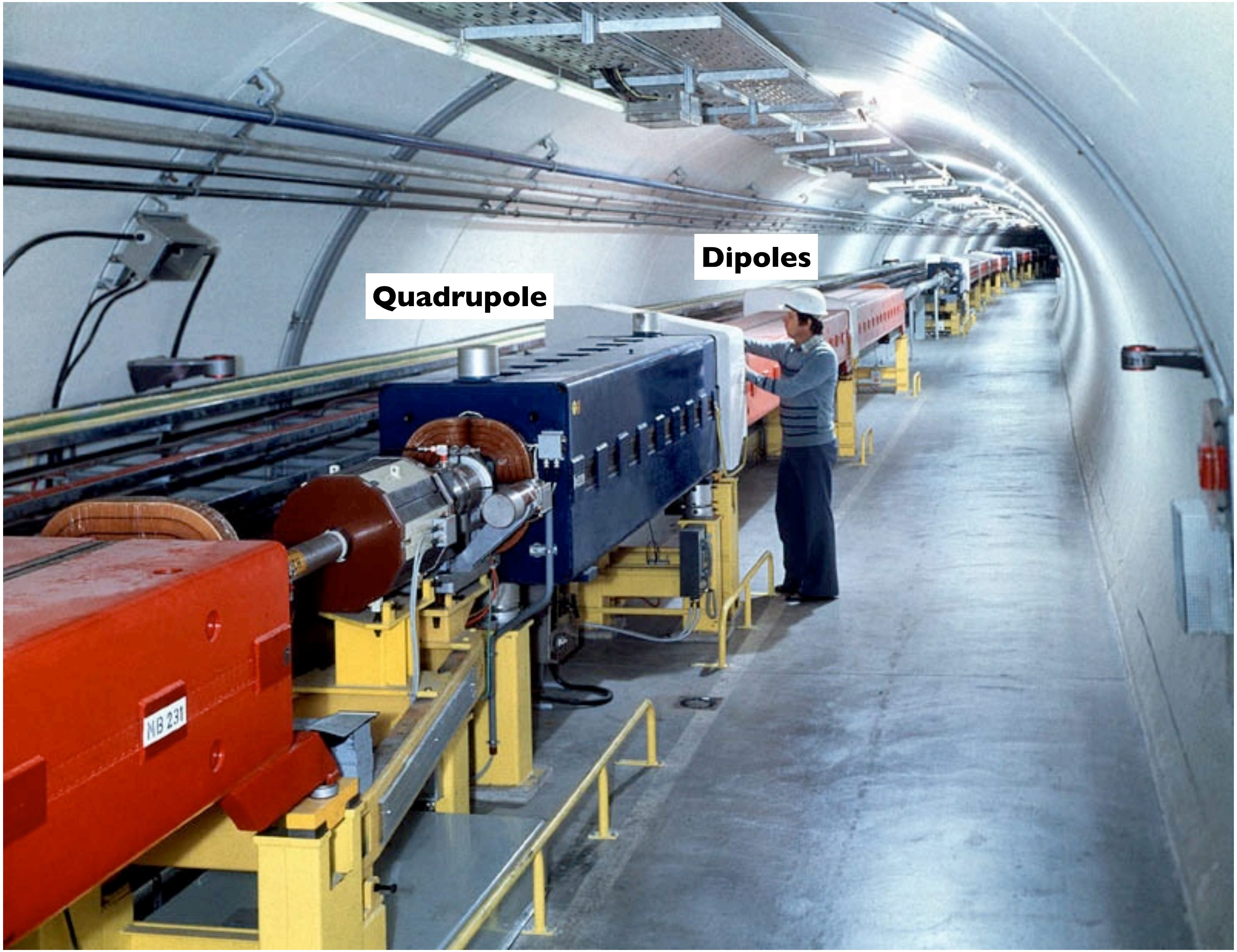
An example of a lattice: LHC cell

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

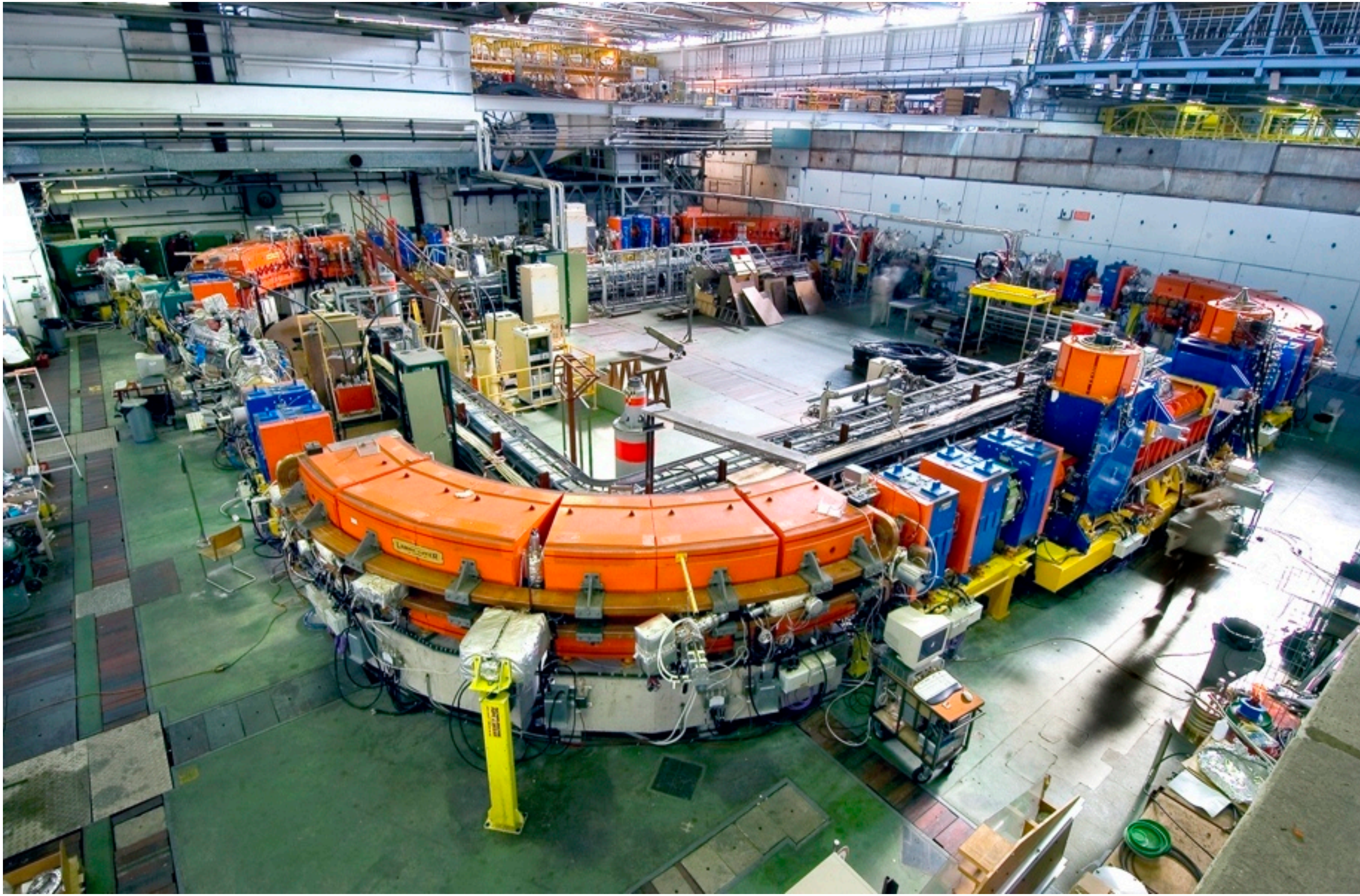




The SPS tunnel

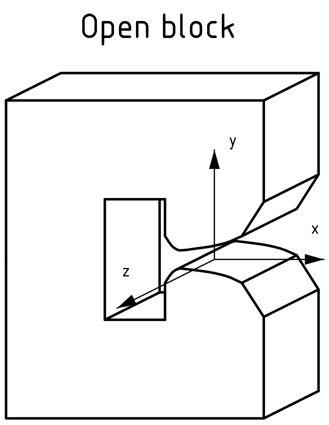


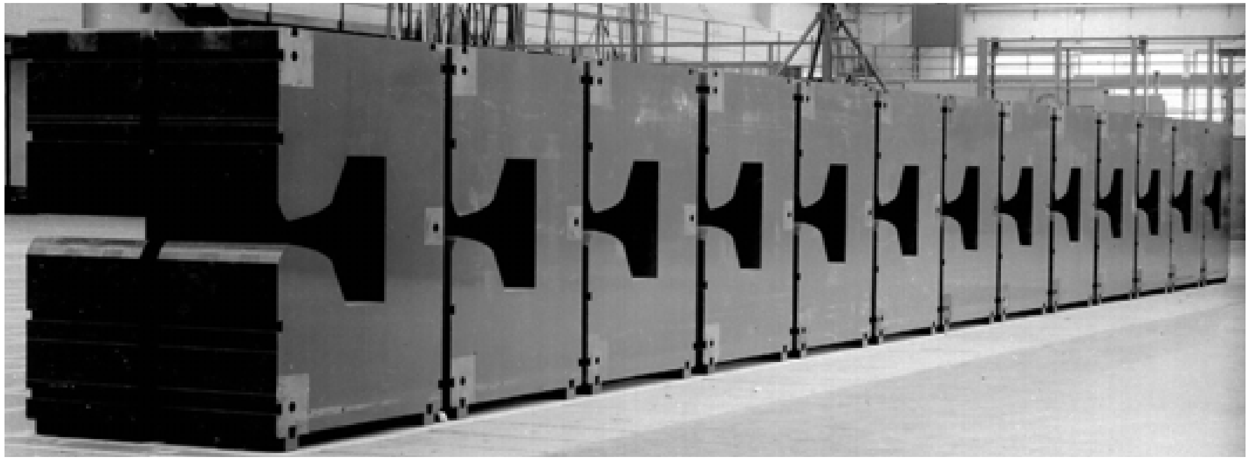
A synchrotron in a view: LEIR (Low Energy Ion Ring)

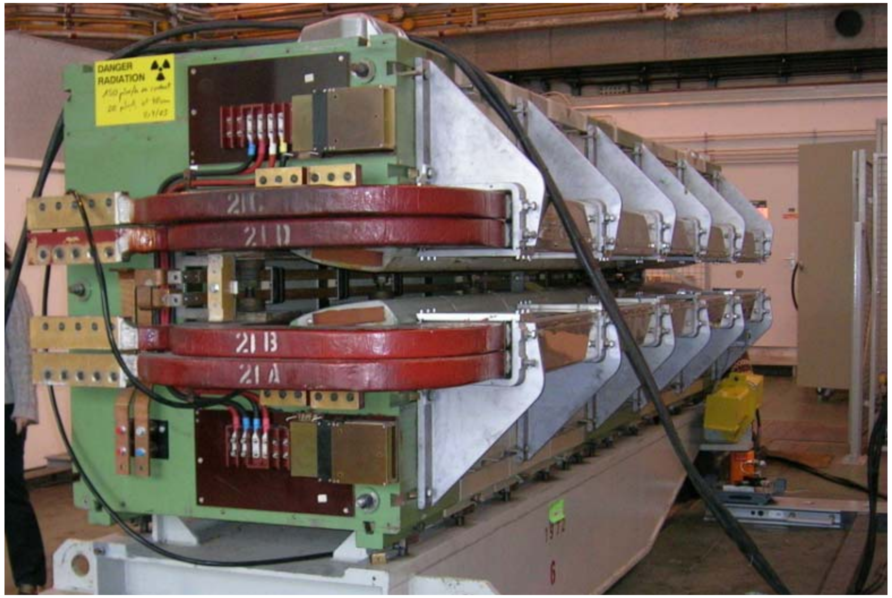


Combined function magnets

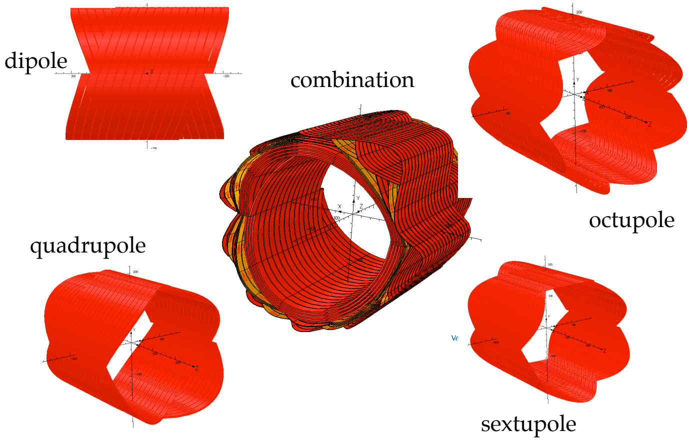
Some accelerators, like the PS have combined function magnets, i.e., quadrupolar and dipolar component is generated in a single magnets



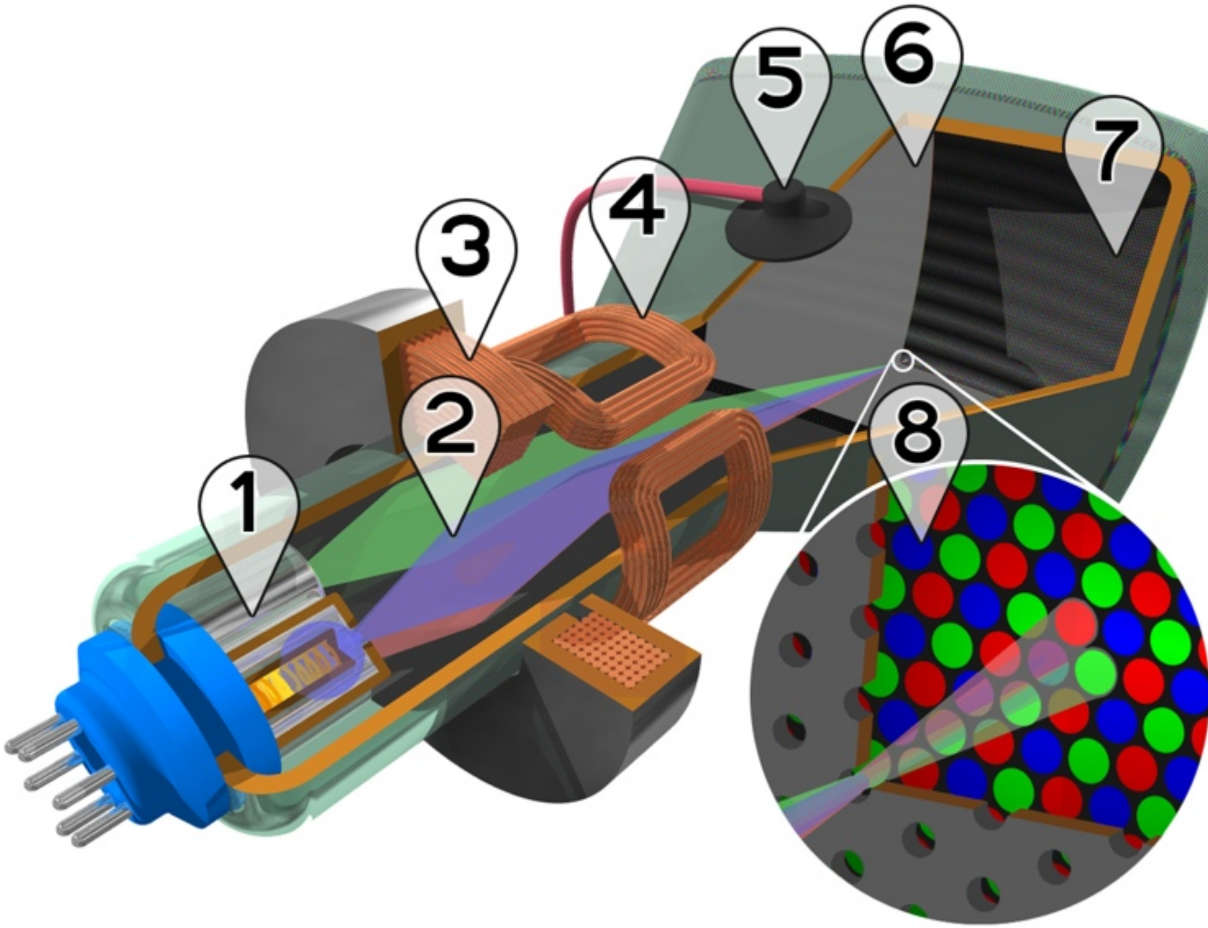




See later for FFAGs (Fixed Field Alternating Gradients accelerators)



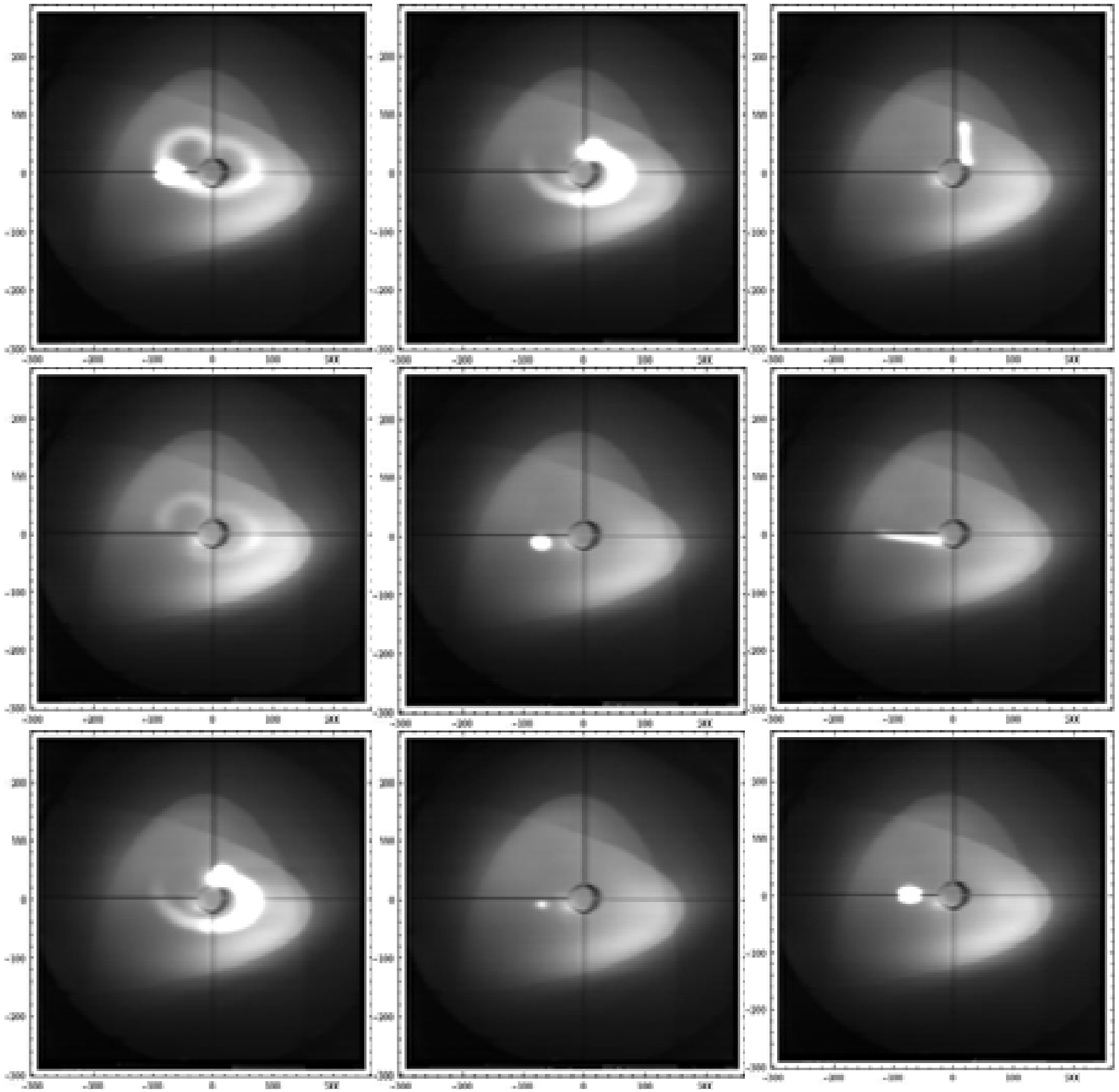
An accelerator that you know very well

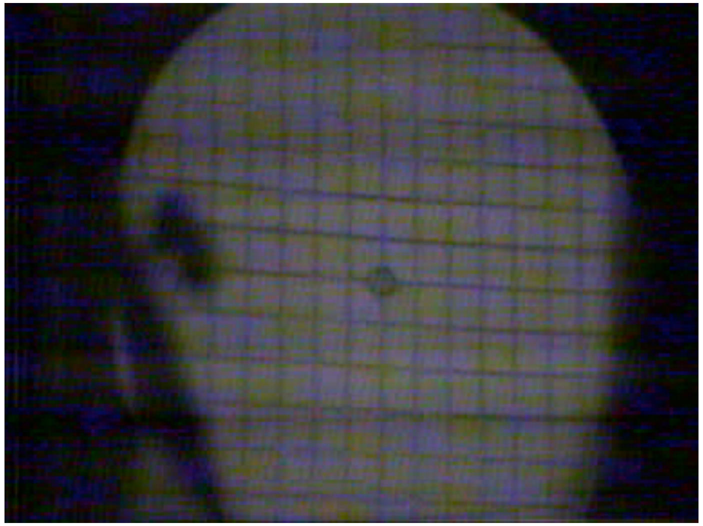


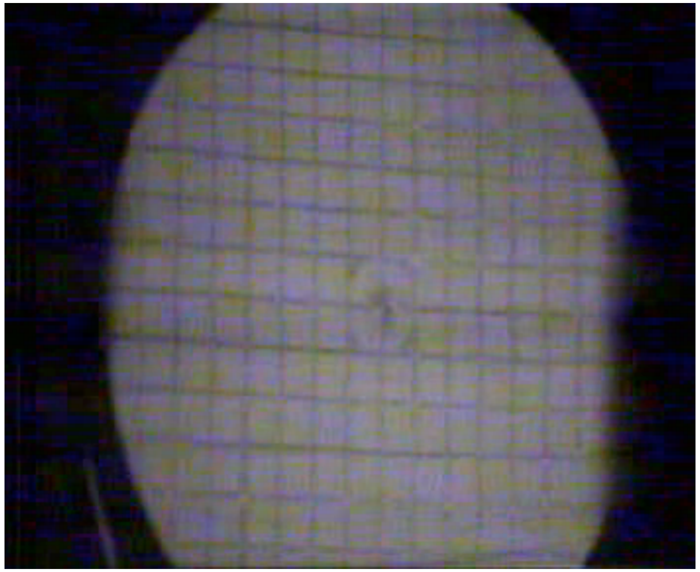
1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated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

From Wikipedia

Real beam images

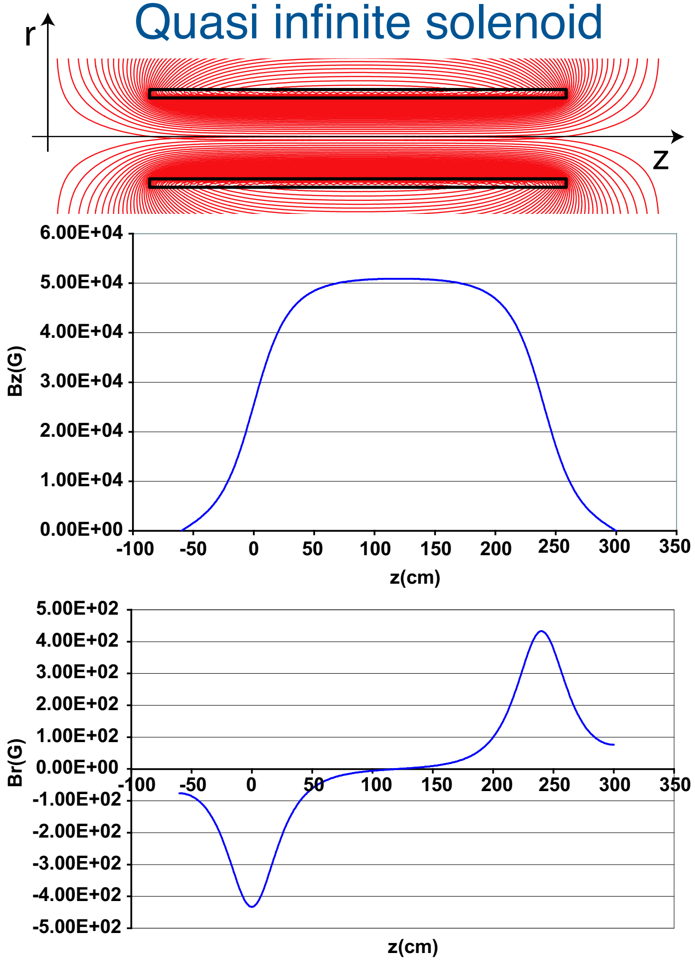


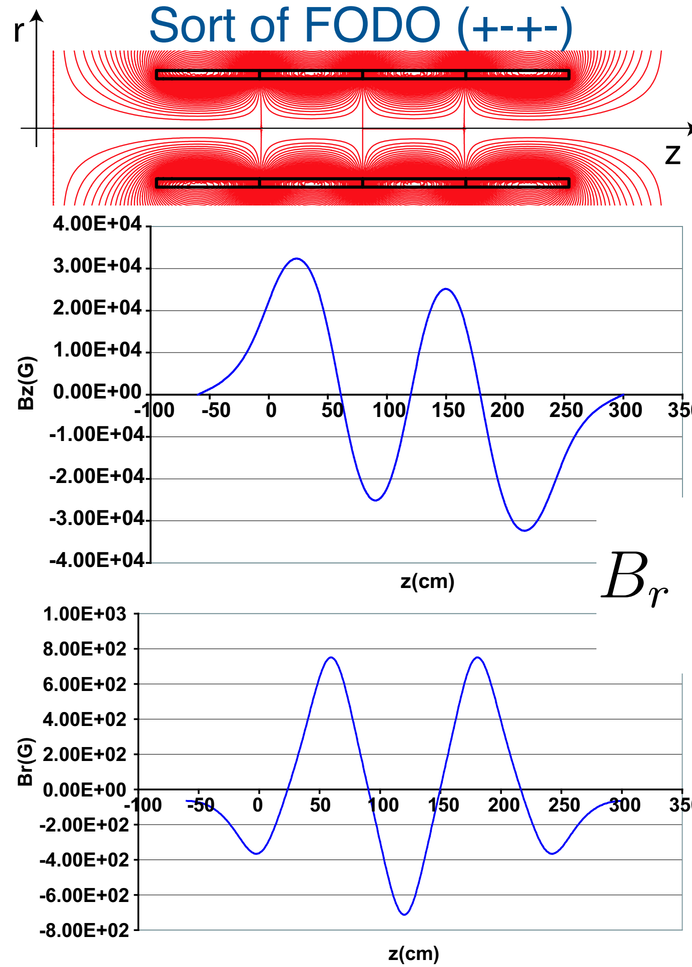




Courtesy of B. Goddard

Beam transport with solenoids





$$B_r = -\frac{r}{2}\frac{\partial B_z(z)}{\partial z}$$

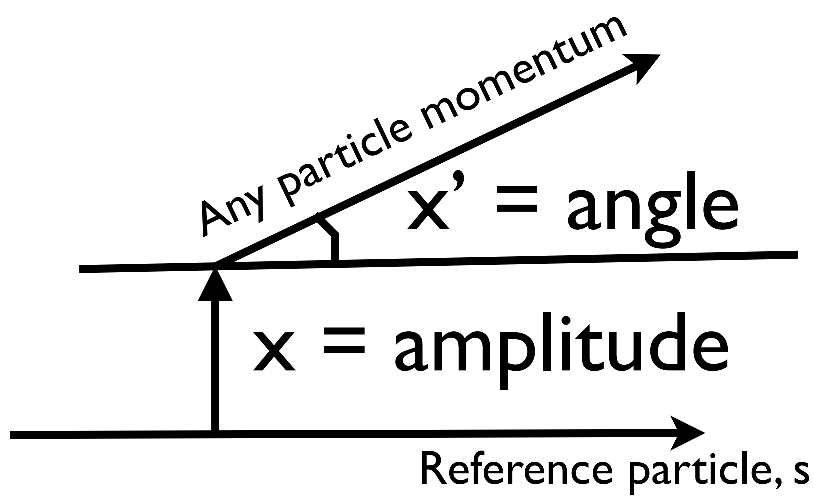
For low energy beams, beam transport can be done using solenoids (**remember for low energy part of the Neutrino Factory**)

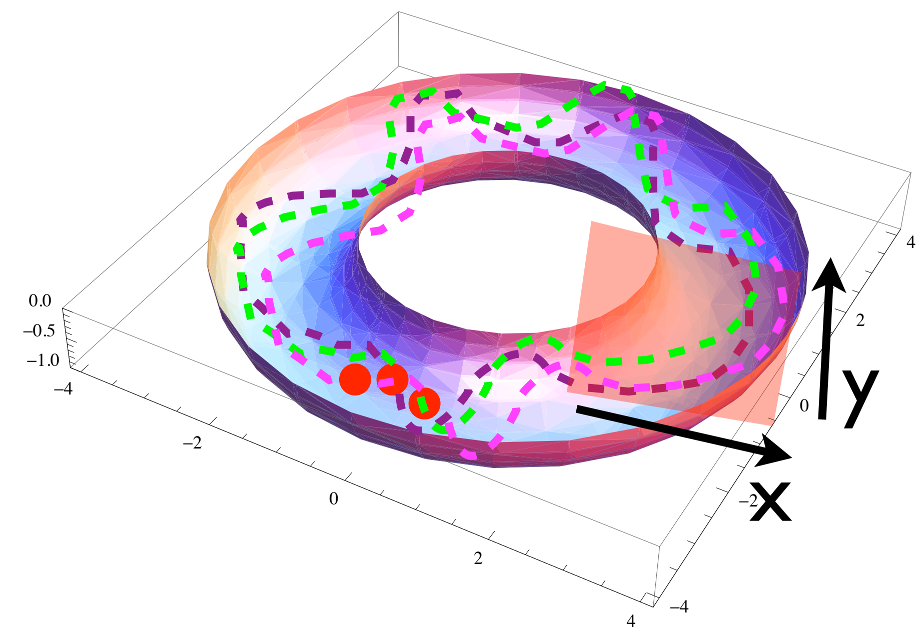
In the transport, the transverse momentum in conserved for the zone at constant field:

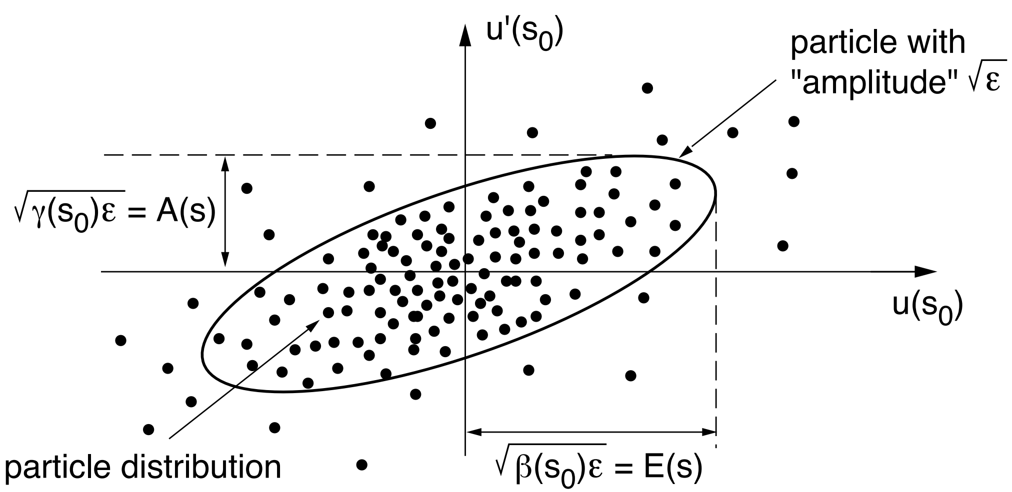
$$B\rho^2 = const$$

$$\frac{B}{{p_T}^2} = const$$

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**

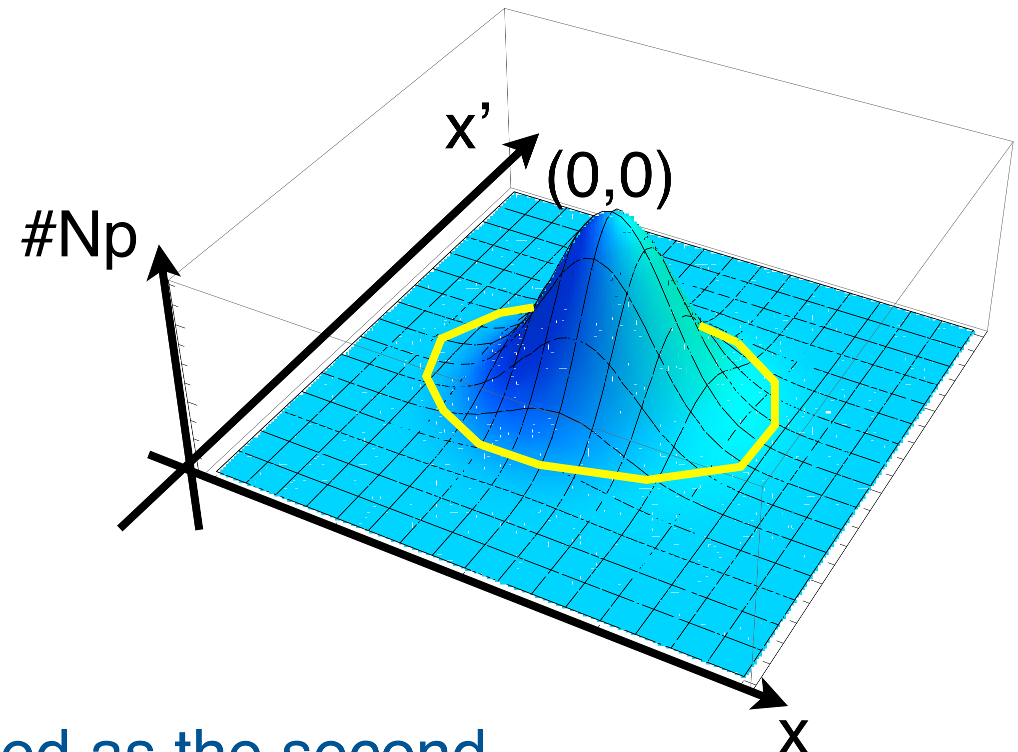
The occupied phase space is an ellipse

Emittance: statistical definition

Let's consider a centered beam:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = 0$$

$$\bar{x'} = \frac{1}{N}\sum_{i=1}^{N} x_i' = 0$$



Def: The physical emittance is defined as the second order momentum of the particle distribution

$$\varepsilon = \frac{1}{N}\sqrt{\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left(x_i x_j' - x_j x_i'\right)^2} = \frac{1}{N}\sqrt{2\sum_{i=1}^{N}\sum_{j=1}^{N} A_{ij}^{\,2}}$$

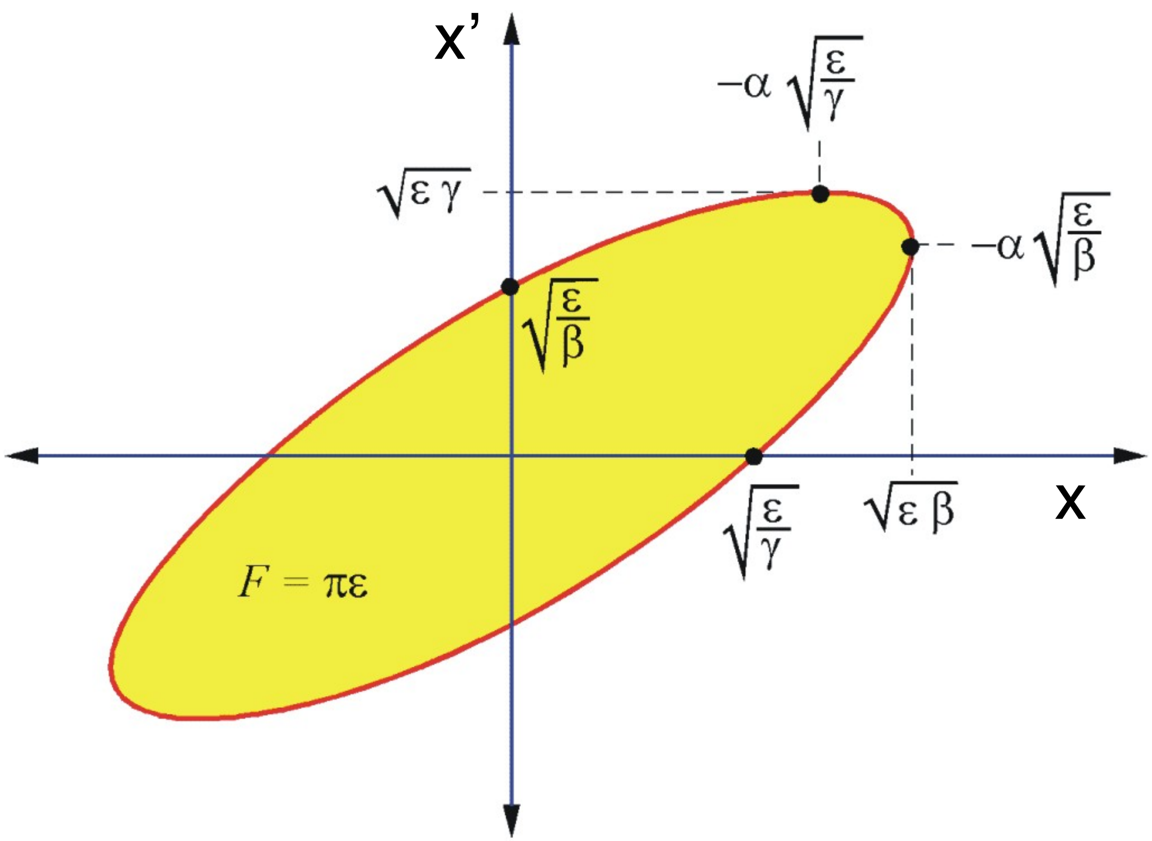
Units of the emittance: [mm mrad] (typically)

The beam ellipse

The beam ellipse is described by convention by 3 parameters
the **TWISS PARAMETERS** **:** α, β, γ

The ellipse equation takes the form:

$$\gamma x^2 + 2\alpha\, x x' + \beta x'^{\,2} = \epsilon$$



Beta is NOT v/c

Gamma is NOT E/m

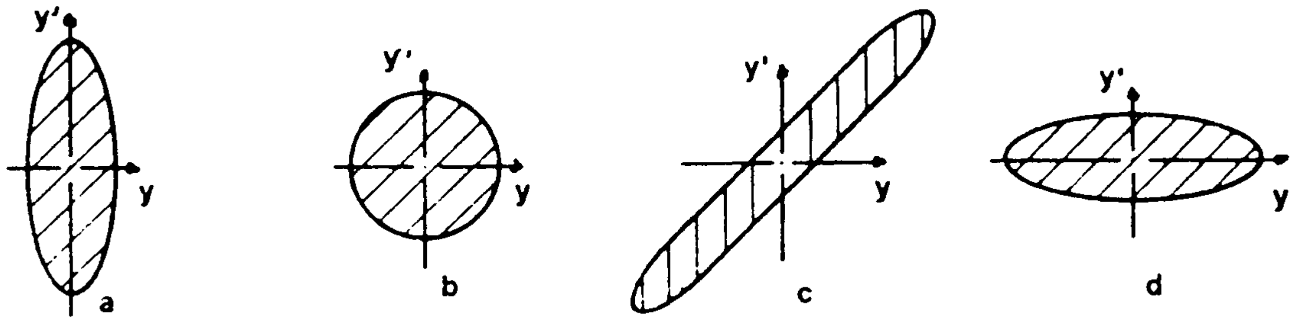
This is an unfortunate choice of our predecessors for which I cannot be blamed ....

THE LAW: Liouville theorem

Theorem: In the vicinity of a particle, the particle density in phase space is a constant if the particle move in an external magnetic field or in a general field which the force do not depend upon velocity (*ipse dixit*...), i.e., **the beam is like an incompressible fluid in phase space**

Implications:

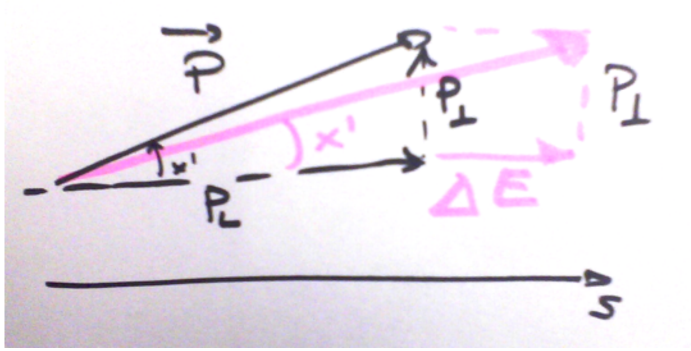
a) the emittance is conserved when the beam is transported via a magnetic system



The ellipse is distorted/streched but the surface is conserved.

b) the emittance is **NOT** conserved if we accelerate, except if we normalize the emittance wrt to βγ (relativistic). **x' is reduced by the acceleration.**

$$\epsilon_{norm} = \epsilon_{phys} * \beta_{rel} * \gamma_{rel}$$

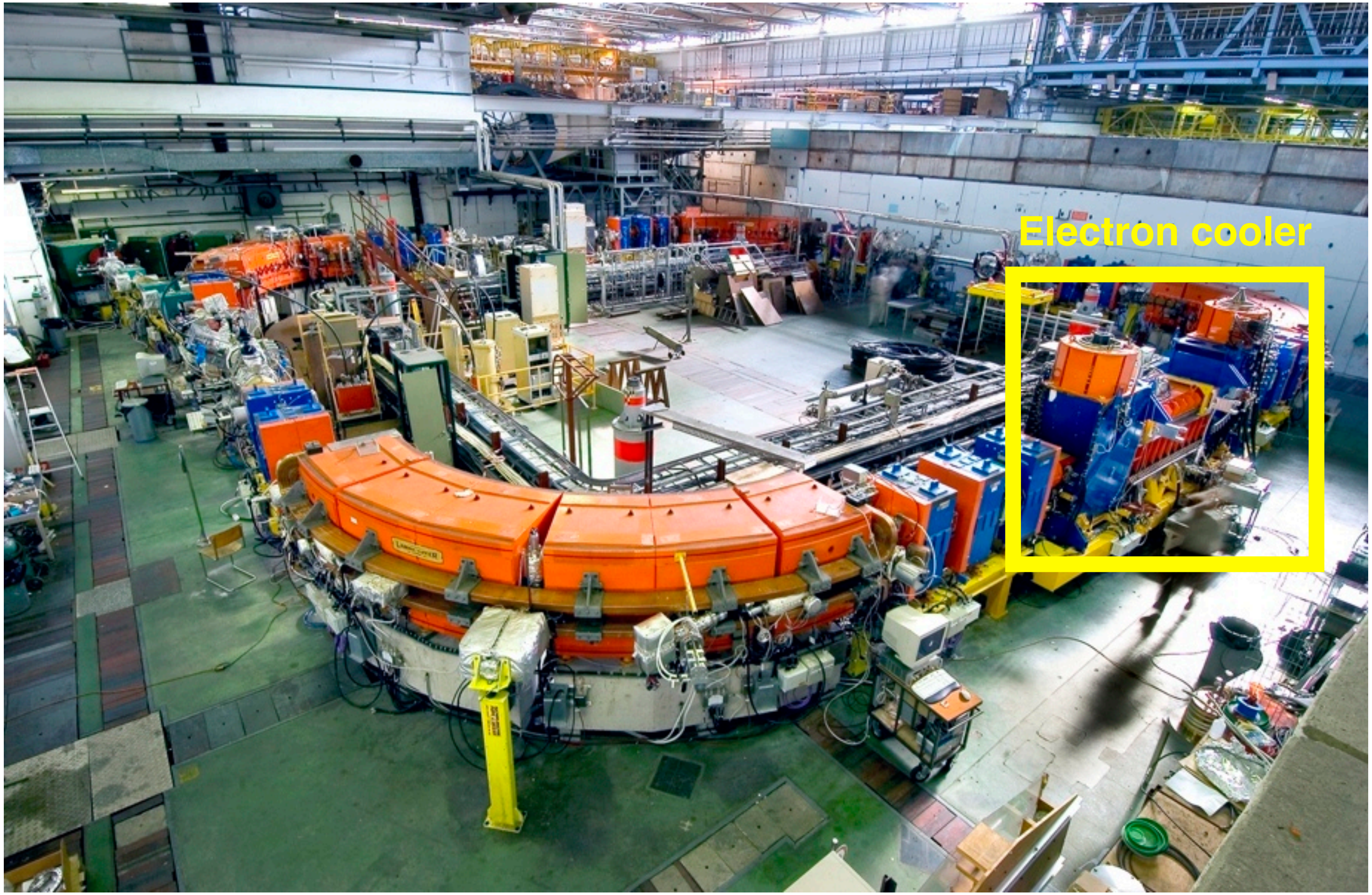


c) if we want to reduce emittance at constant energy, we have to “cheat”: **BEAM COOLING**

Beam cooling

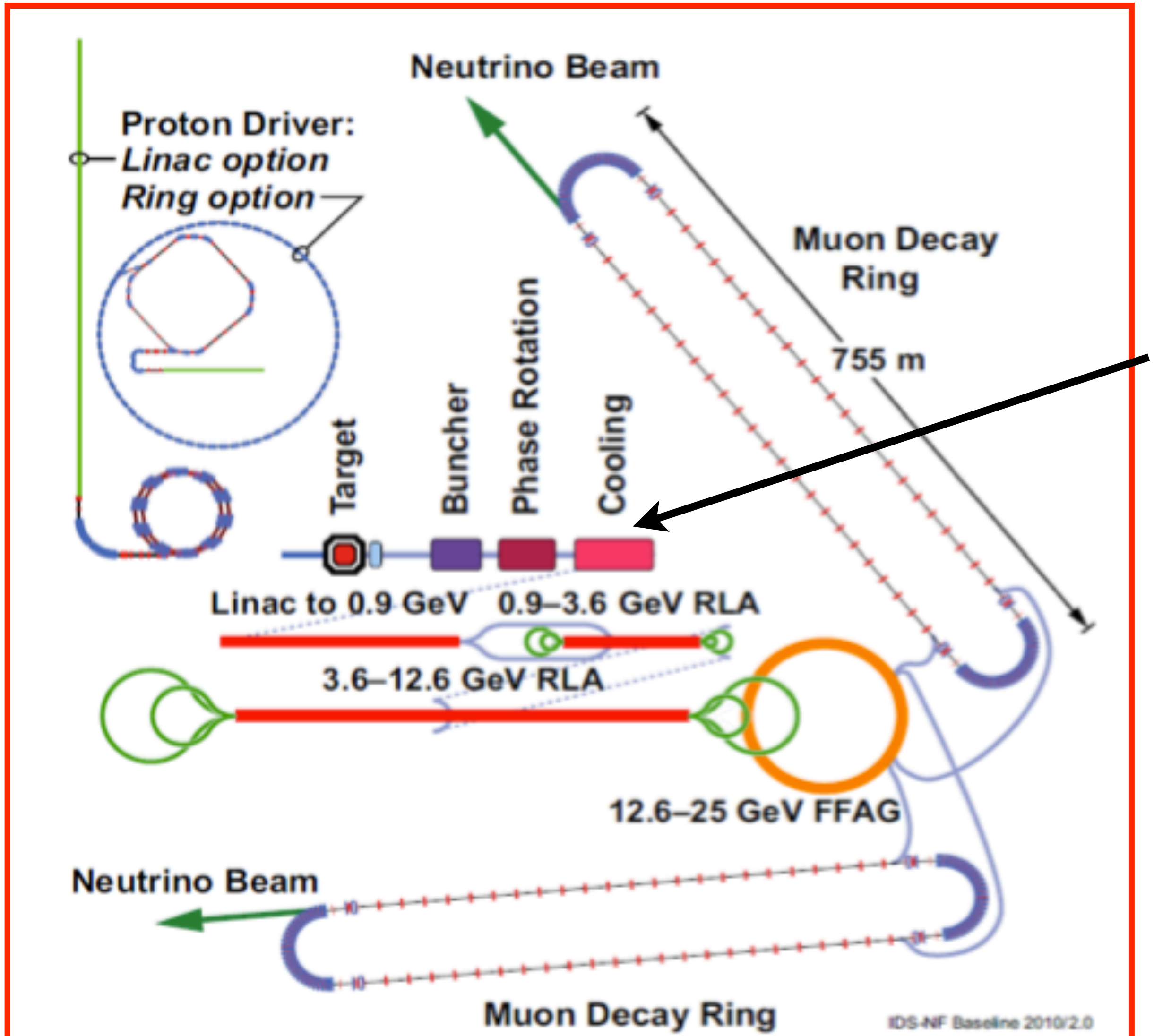
An low intensity ion beam is accumulated in the storage ring. To reduce the emittance, a very intense mono-energetic electron beam is sent parallel to the ion beam.

The large emittance ion beam is like an hot fluid which is cooled by the very ordinate electron beam. Same as putting one near another two fluids at different temperatures



Why emittance is so important?

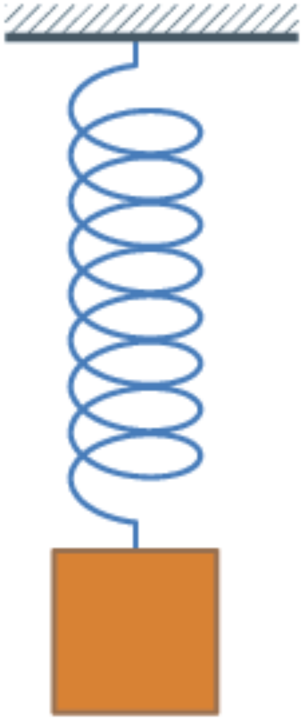
See in a moment, determine the beam dimension from the optics/lattice design



Here we want to reduce beam emittance to be able to feed the rest of the accelerator complex

Classical mechanics.... spring with a mass

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



with *k* the spring constant and *m* the mass

Solution of the equation of motion is a periodic function:

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

with 1/period equals to

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

Equation of motion, not too in details

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

***Hill's equation: pendulum-like with non-constant spring force wrt to *s*.**

$$\frac{d^2x}{ds} + K(s)x = 0$$

beer **= solution** →

$$x(s) = a\sqrt{\beta(s)}\cos(\phi(s) + \phi_0)$$

Local force at a position ***s*** in the ***ring***

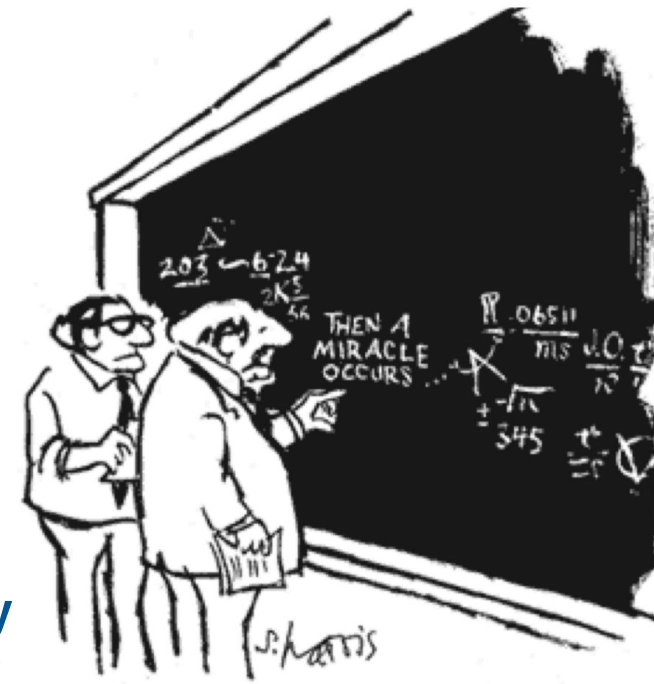
$$K(s) = 1/\rho^2 + k(s)$$

Dipoles → **forget them for a moment**

Quadrupoles

$$K(s) = K(s + C)$$

This imply periodicity of the solution



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

me too... in a moment...

***there was a Mr. Hill, an astronomer**

Solution of Hill's equation

$$x(s) = a\sqrt{\beta(s)}\cos(\phi(s) + \phi_0)$$

this "probably" contains k

Spring solution

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

this contains k and m

This actually... look alike should not be there...
The beta function is a product of the locally changing force in the accelerator, i.e., of the quadrupoles. Every section of an accelerator has a constant k, so alone would be similar to an harmonic oscillator

By definition (*ipse dixit...*)**:** $$\phi(s) = \int \frac{1}{\beta(s)} ds$$

is called the *phase advance*

Relationship between beam ellipse and beta

Nearly no beer **... full proof ...**

if the emittance is a surface this can be an amplitude (I am cheating... I know)

1) Let's suppose

$$x''(s) + K(s)\cdot x(s) = 0 \quad \longrightarrow \quad x(s) = \sqrt{\varepsilon}\cdot u(s)\cdot\cos\left(\phi(s)+\varphi_0\right)$$

2) Let's apply

What is this???

$$\left[u'' - u\cdot\phi'^2 + K\cdot u\right]\cdot\cos\left(\phi+\varphi_0\right) - \left[2\cdot u'\cdot\phi' + u\cdot\phi''\right]\sin\left(\phi+\varphi_0\right) = 0$$

beer + trick. Coeffs in front of sin et cos should be zero and $\phi(s) = \int_0^s \frac{d\tilde{s}}{u^2(\tilde{s})}$

$$u'' - \frac{1}{u^3} + K\cdot u = 0 \quad \xrightarrow{\textit{def.}} \quad \beta(s) := u^2(s) \quad \longrightarrow \quad \boxed{x(s) = \sqrt{\varepsilon}\cdot\sqrt{\beta(s)}\cdot\cos\left(\phi(s)+\varphi_0\right)}$$

def.

$$\alpha(s) := -\frac{\beta'(s)}{2} \quad \longrightarrow \quad x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta(s)}}\left\{\alpha(s)\cdot\cos\left(\phi(s)+\varphi_0\right) + \sin\left(\phi(s)+\varphi_0\right)\right\}$$

beer

$$\sin^2\left(\phi+\varphi_0\right) = \left(\sqrt{\frac{\beta}{\varepsilon}}\cdot x' + \frac{\alpha}{\sqrt{\varepsilon\,\beta}}\cdot x\right)^2 \quad \xrightarrow{\textit{def.}} \quad \gamma(s) := \frac{1+\alpha^2(s)}{\beta(s)}$$

We brilliantly find... $\longrightarrow$

..... what we wanted...

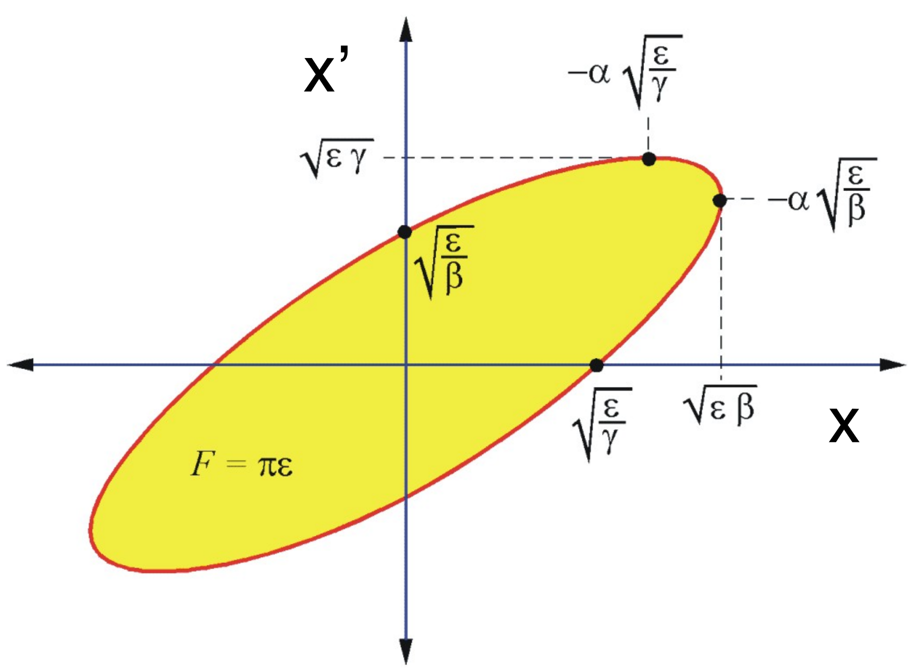
oh surprise... →

$$\gamma x^2 + 2\alpha\, x x' + \beta x'^{\,2} = \epsilon$$

Learned:

a) definition of Twiss parameters comes from the equation of motion and beta function

b) The dynamics is really on/within an ellipse



Twiss parameters:

$$\alpha(s) := -\frac{\beta'(s)}{2}$$

$$\gamma(s) := \frac{1+\alpha^2(s)}{\beta(s)}$$

$$\beta(s)$$

Those are not the relativistic homonyms

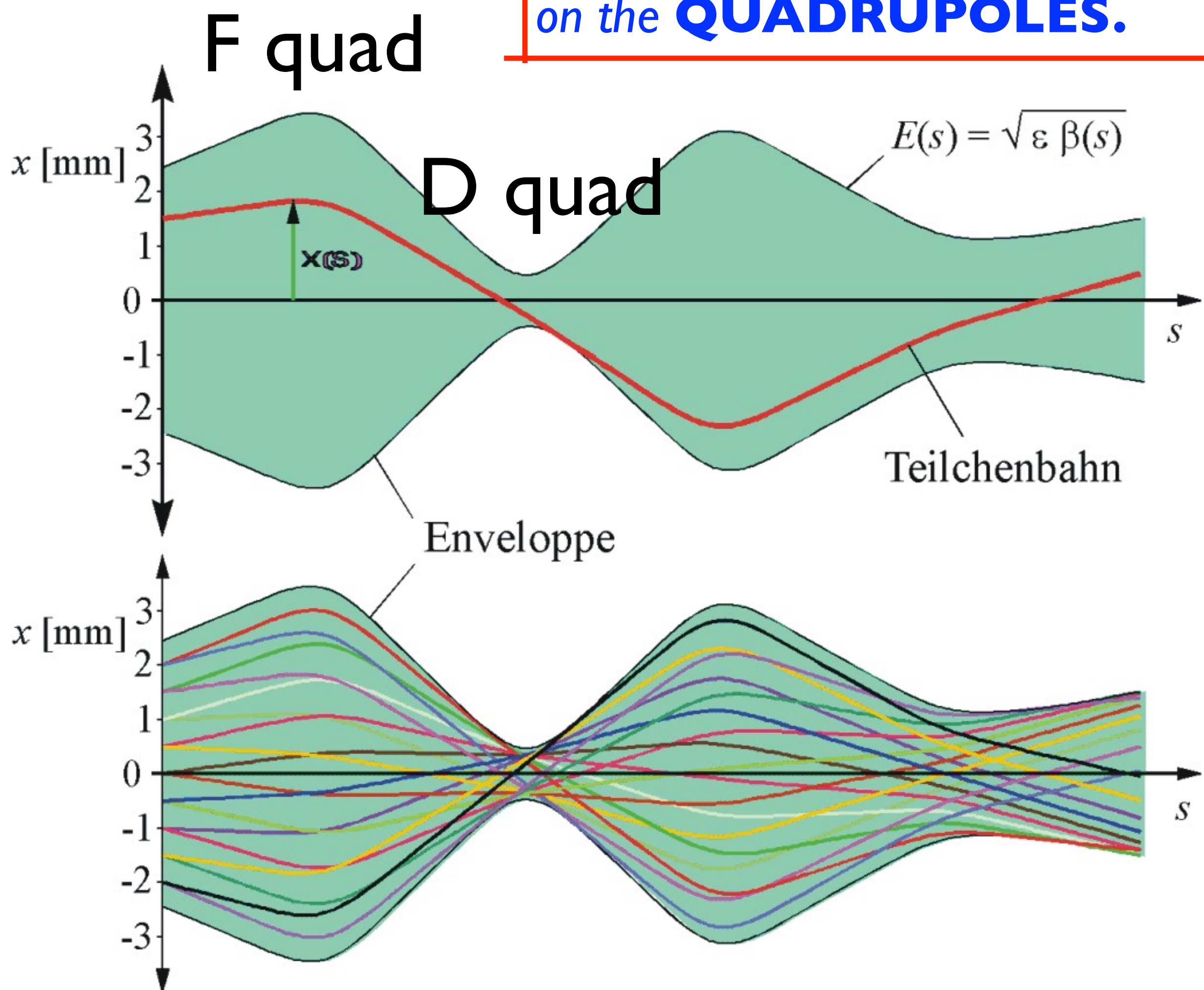
Definition of envelope

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

Beam physical dimension

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

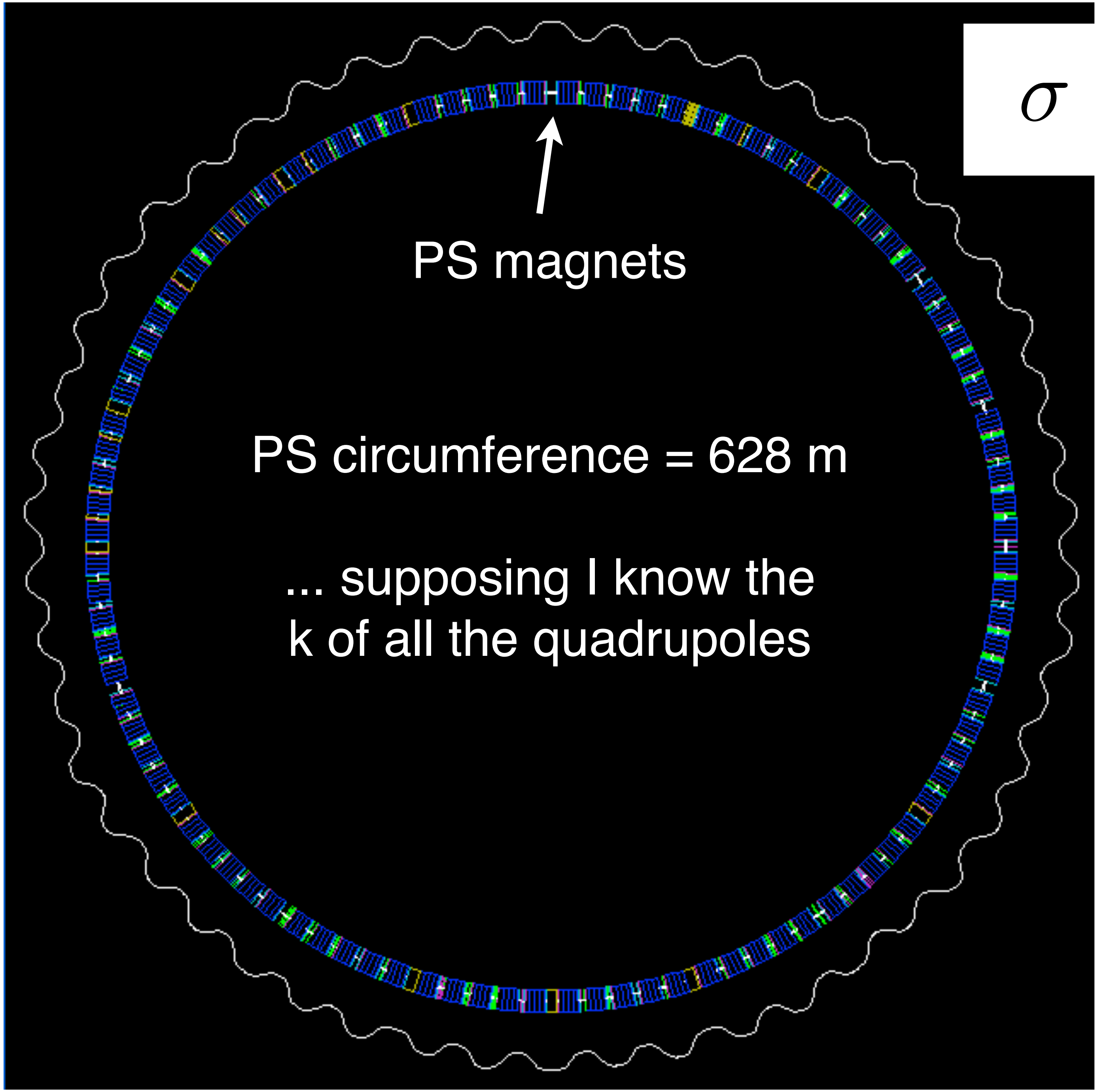
Emittance: *Parameter which describes the* ***spread*** *of the particles in the phase space (xx') or (yy').*



The **envelope** is defined as the maximum amplitude for which the particle remains in the machine vacuum chamber at a given position *s*.

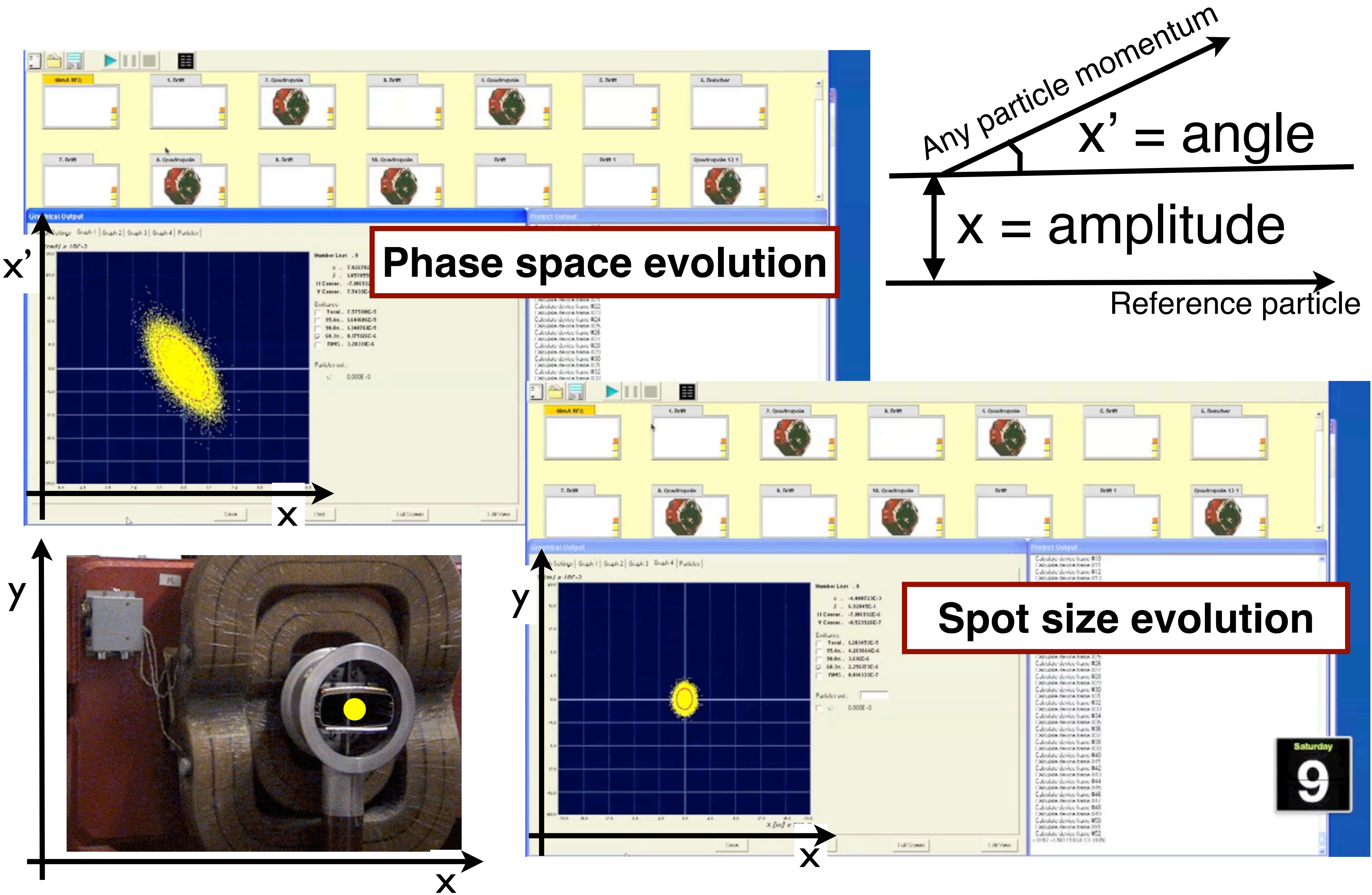
The envelope can be determined by the beta function and by the beam emittance

Envelope of PS beam



$$\sigma \propto \sqrt{\beta}$$

Particle transport in a lattice

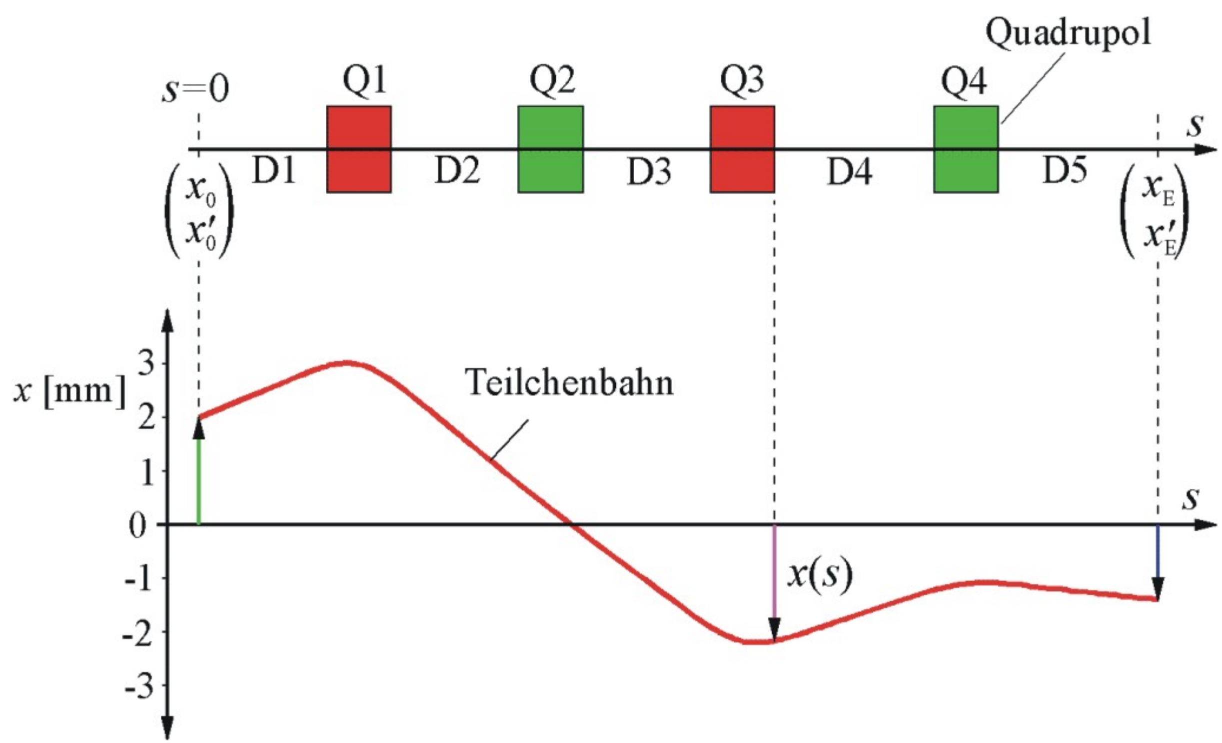


How the transport is computed

Every element of a machine, drift and quadrupoles, can be described AT FIRST ORDER by a **TRANSFER MATRIX (2x2 or 4x4)**, equivalent and deduced from the equation of motion.

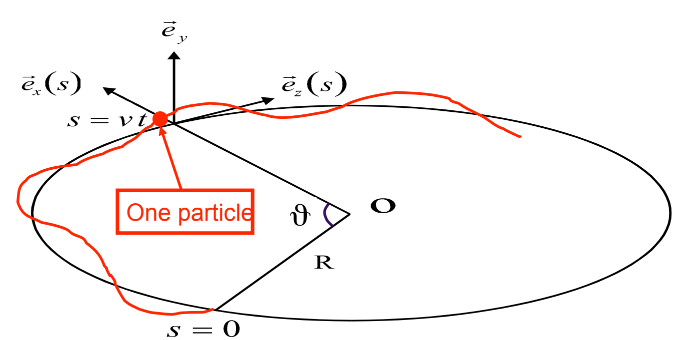
$$\begin{pmatrix} x \\ x' \end{pmatrix}_f = M \begin{pmatrix} x \\ x' \end{pmatrix}_i$$

Phase space	Position	Drift	Dipole	Quadrupole
horizontal	$\vec{X}(s) = \begin{pmatrix} x \\ x' \end{pmatrix}$	$\mathbf{M}_d = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\mathbf{M}_D = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\mathbf{M}_Q = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$



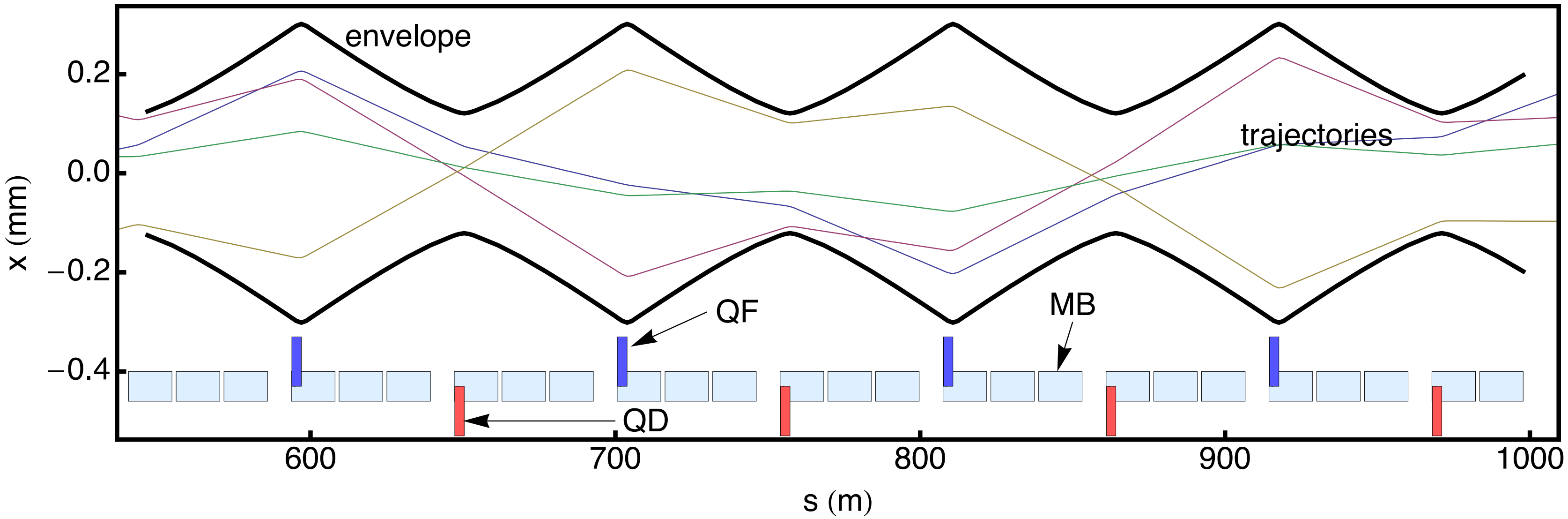
$$\vec{X}_E = \mathbf{M}_{D5} \cdot \mathbf{M}_{Q4} \cdot \mathbf{M}_{D4} \cdot \mathbf{M}_{Q3} \cdot \mathbf{M}_{D3} \cdot \mathbf{M}_{Q2} \cdot \mathbf{M}_{D2} \cdot \mathbf{M}_{Q1} \cdot \mathbf{M}_{D1} \cdot \vec{X}_0$$

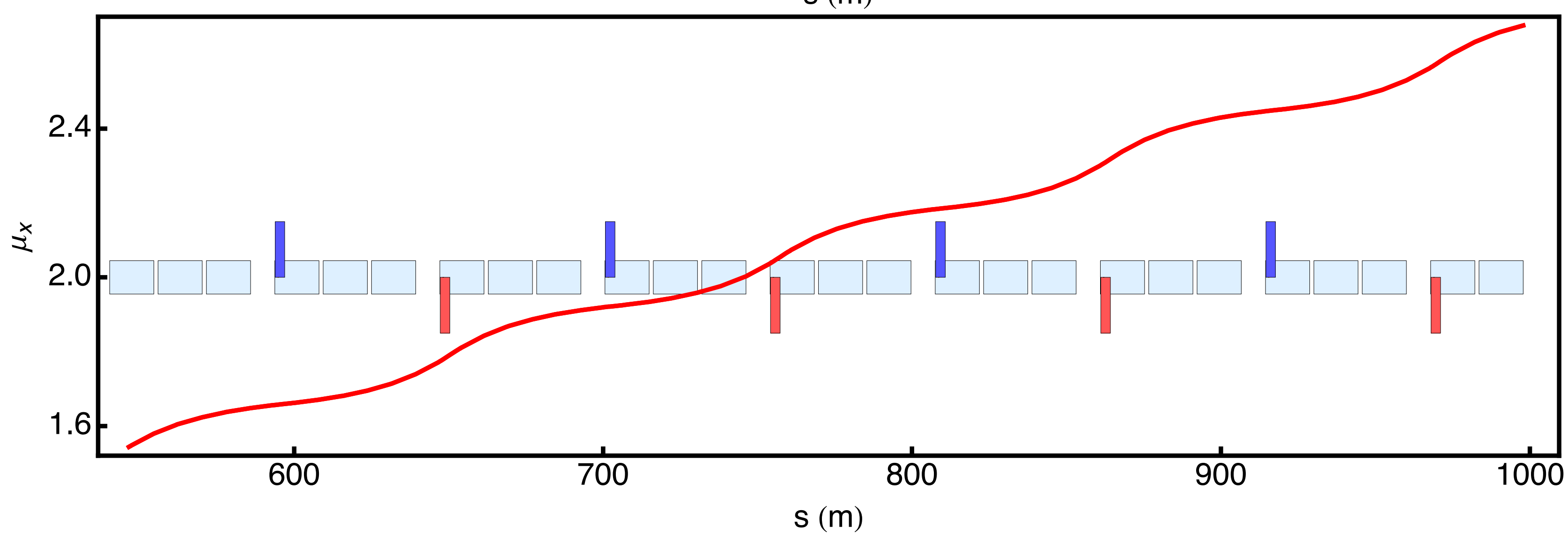
Obs: A dipoles is like a drift since the reference frame is turning with the central trajectory, i.e., the reference frame is following the bent trajectory



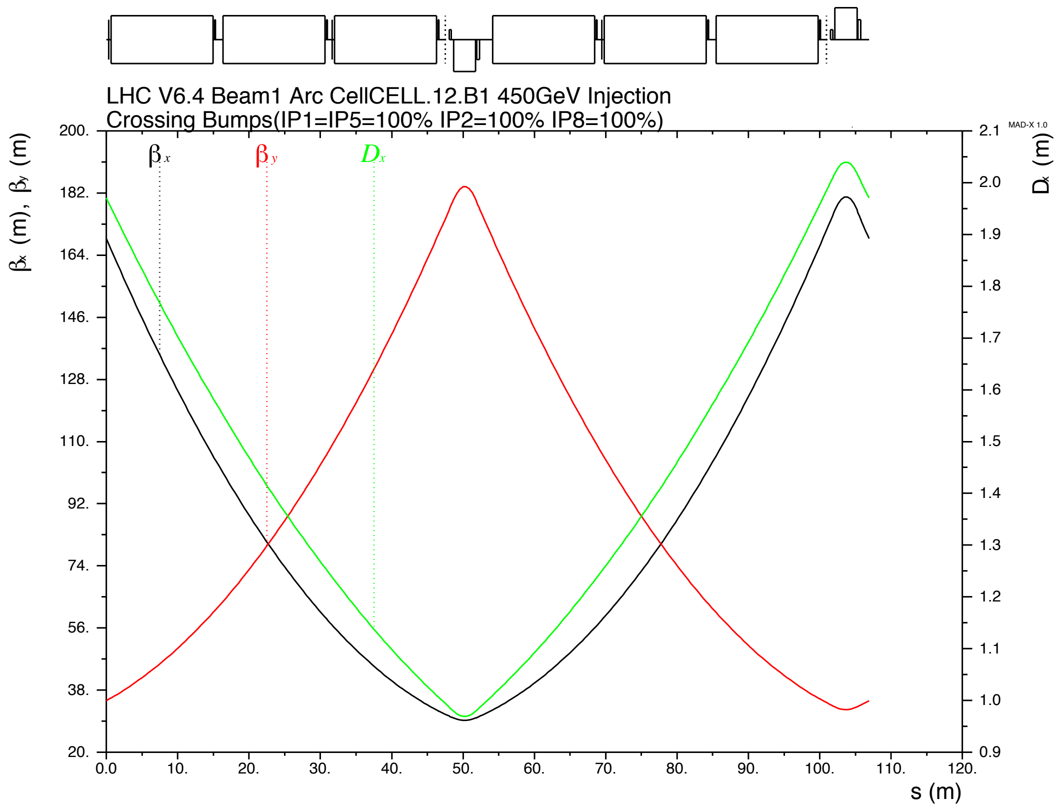
Ray tracing and envelope in the LHC

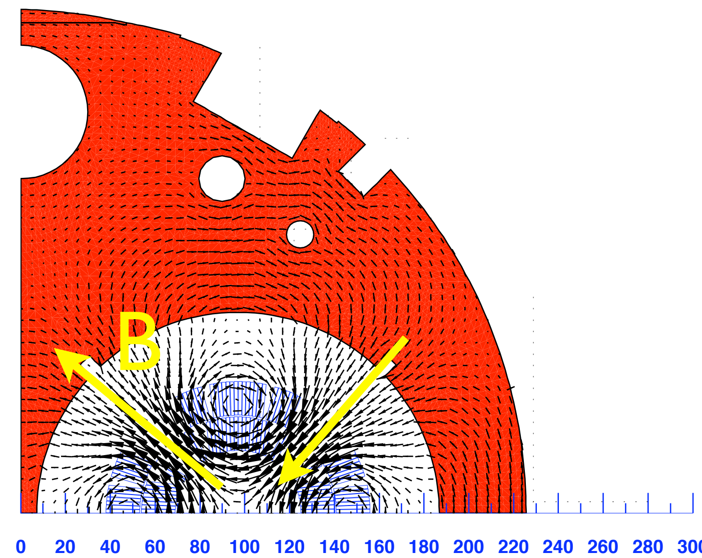
The same apply for a machine like the LHC

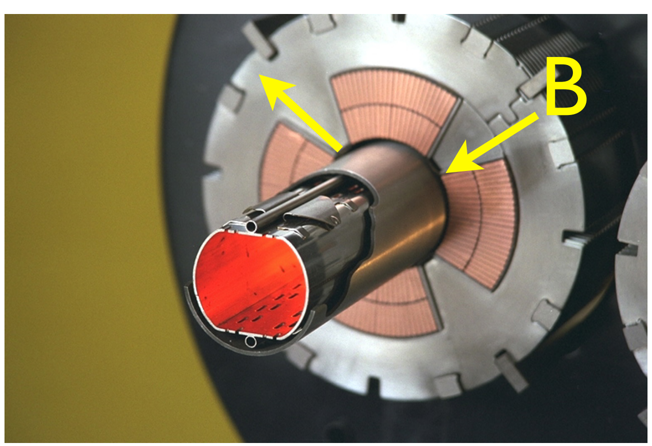


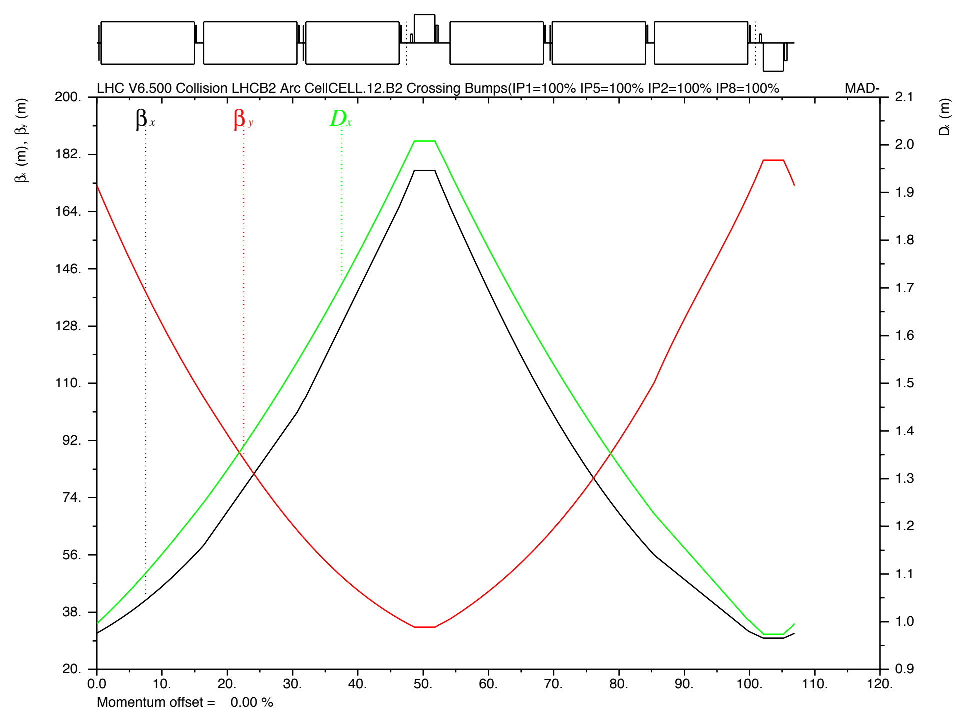


Arc cell at injection for beam 1 and beam 2





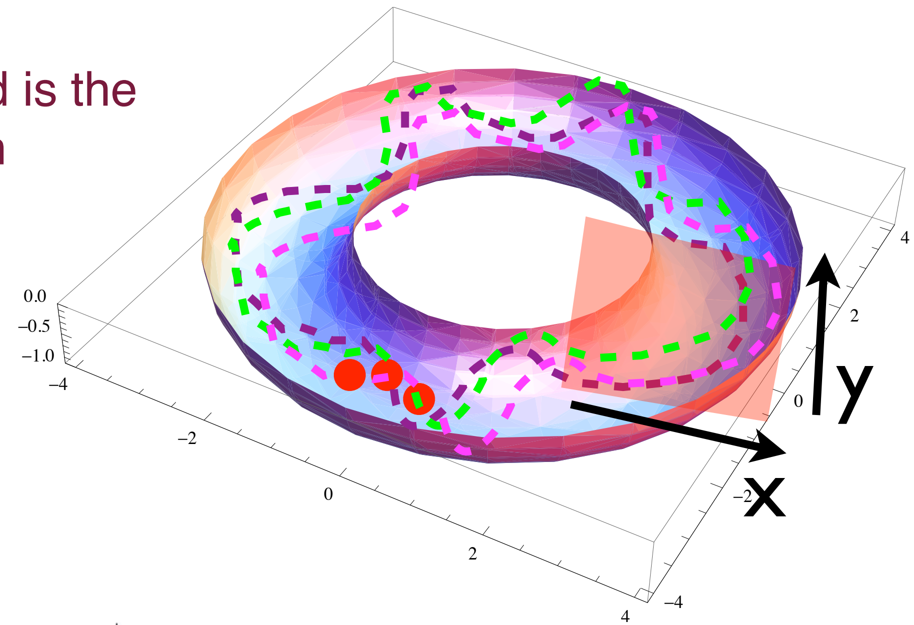




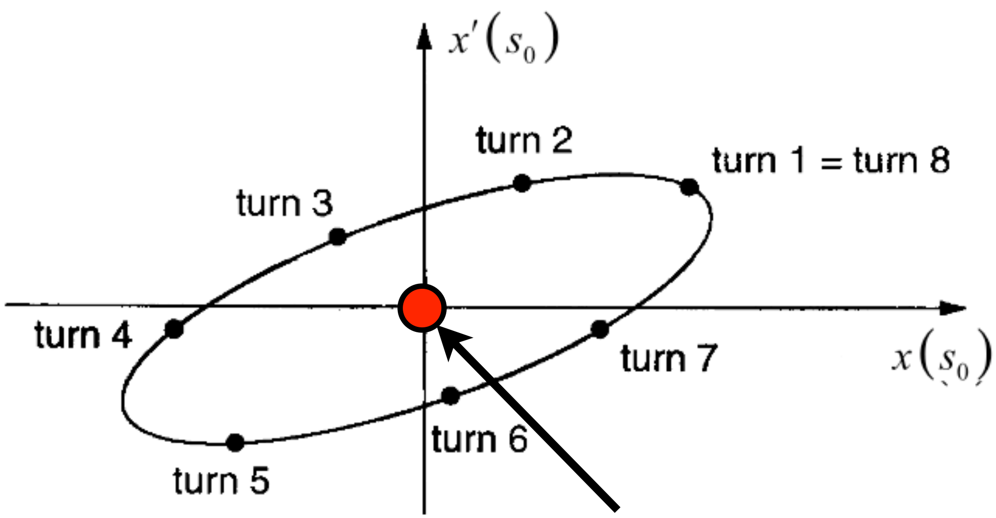
Tune

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

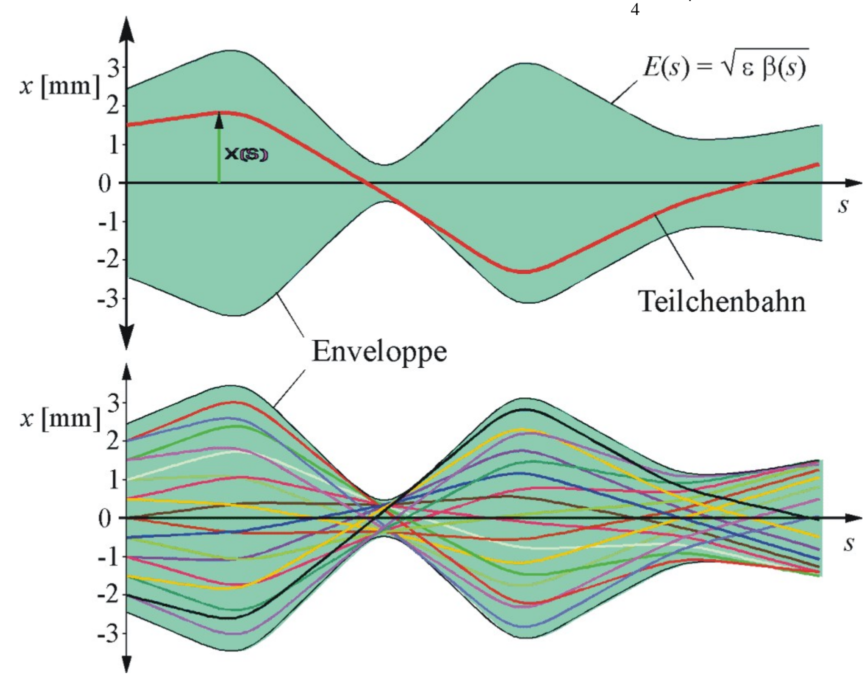
The tune depends on the quadrupoles settings and is the integral of the phase advance on one machine turn



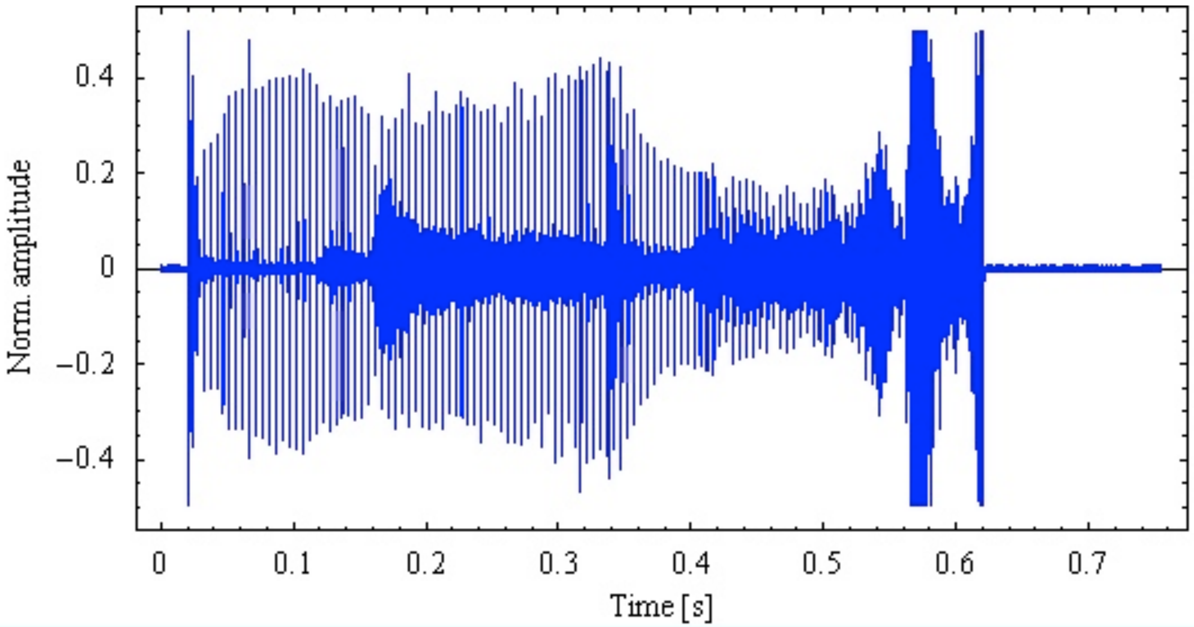
$$Q_x = \frac{1}{2\pi} \oint \frac{ds}{\beta_x(s)}$$

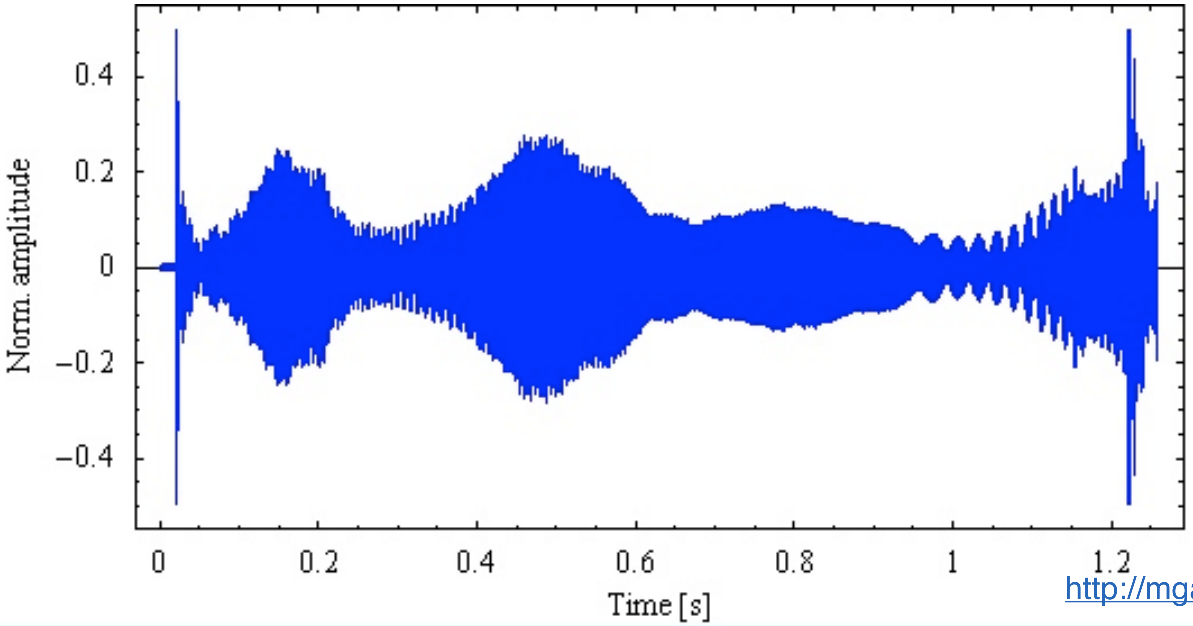


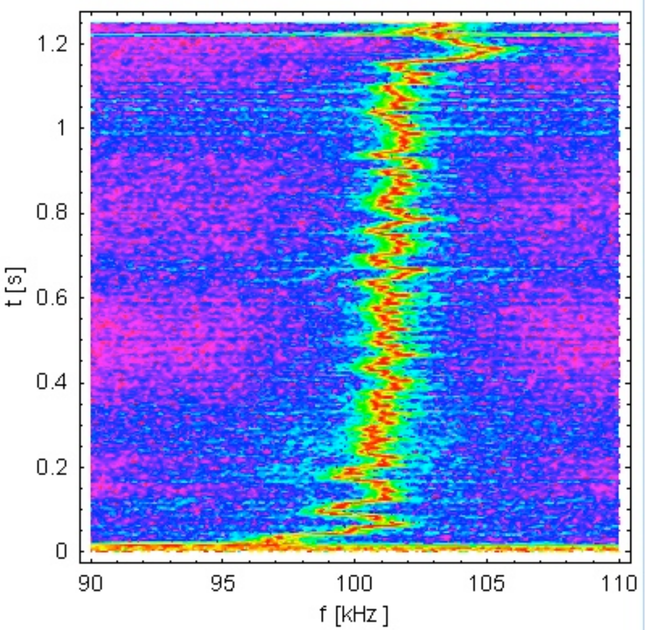
Reference particle



Tune: number of betatron oscillation in the transverse plane







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

Machine imperfections ....
Real LHC orbit - correction of dipolar error

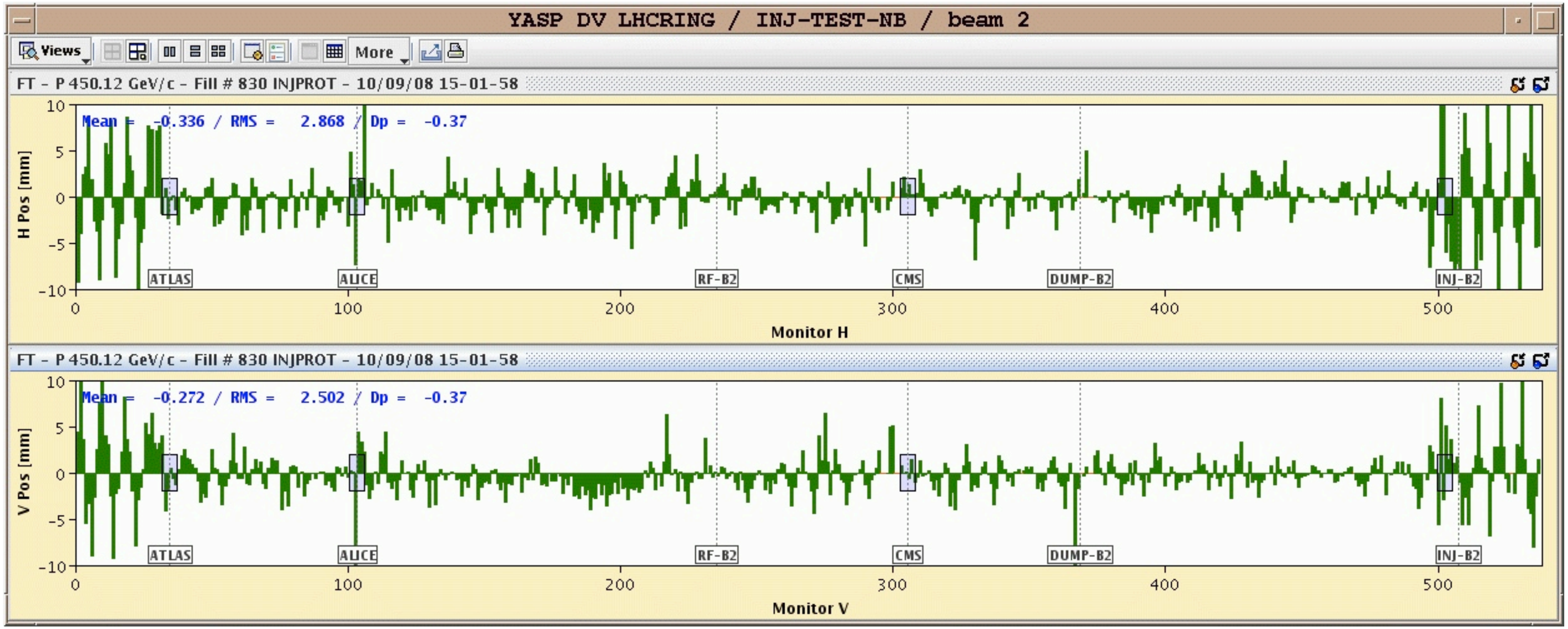
LHC average momentum at injection = 450.5 ± 0.2 GeV

⇒Dipole error Δb1 between rings ≈ 1.5×10^{-4}

⇒Δb1 among 8 sectors ≈ 3×10^{-4}

Courtesy of J. Wenninger

Machine imperfections ....
Real LHC orbit - correction of dipolar error



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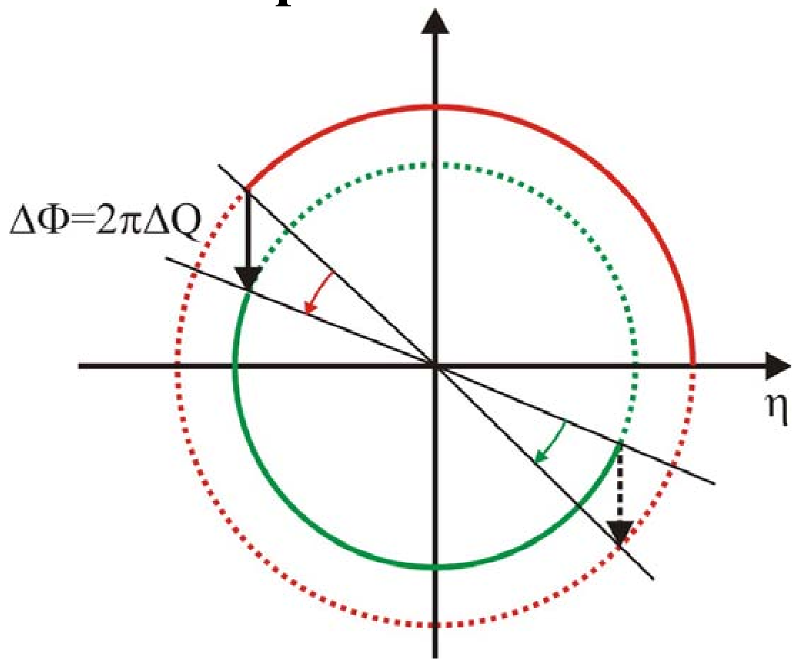
Courtesy of J.Wenninger

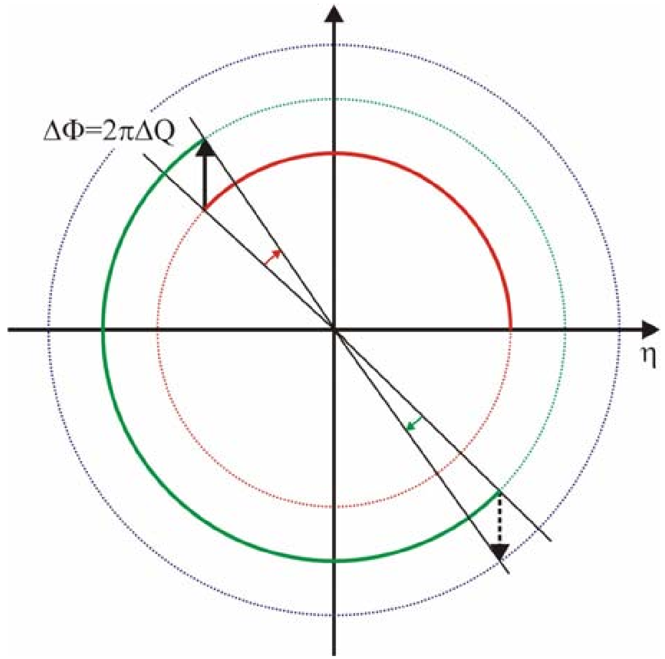
Machine imperfections

Magnetic errors can cause beam losses/instability if appears as certain multipoles of the tune

Dipole Errors:



Gradient Errors:

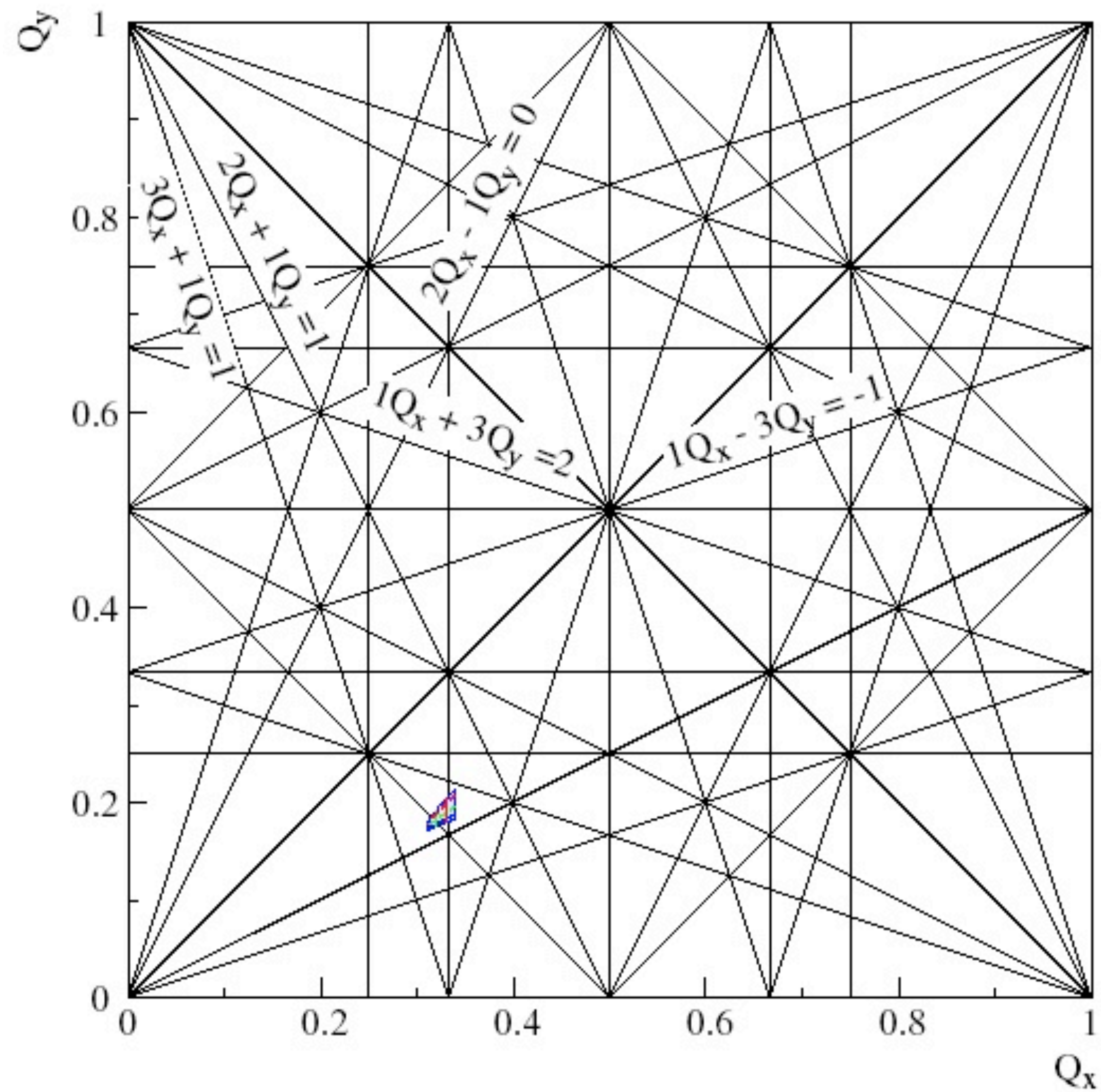


resonance type	driving multipole
integer resonance: $Q = n$	dipole errors
half-integer resonance $2 \cdot Q = n$	quadrupole errors
third-integer resonance $3 \cdot Q = n$	sextupole errors

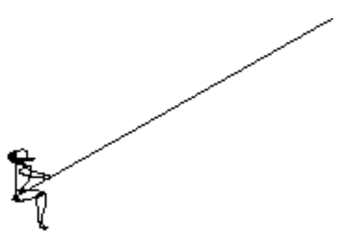
Tune and resonances

To be avoided $M\,Q_x + N\,Q_y = P$

Like on a "**swing**", to keep the oscillations bounded in amplitude, one has to avoid to excite the beam in a resonant way, in particular due to magnets imperfections.



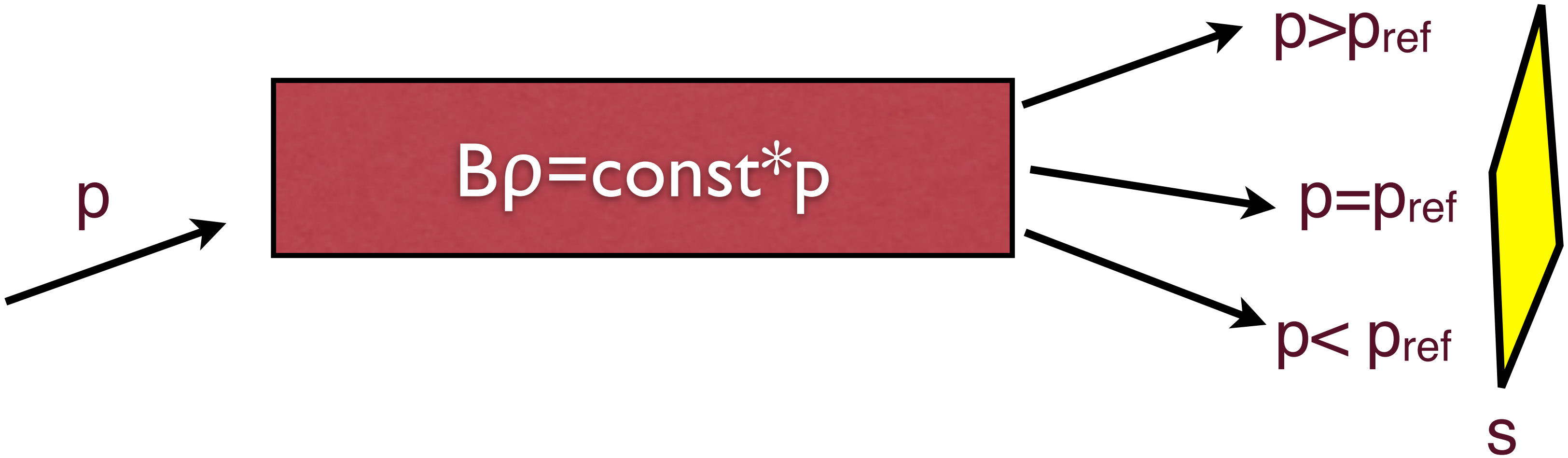
The tune has to be far away from some values, like exciting the beam with the same force at each turn (dipolar errors)



Dispersion

So far, beam considered monoenergetic, in fact, it is not ...

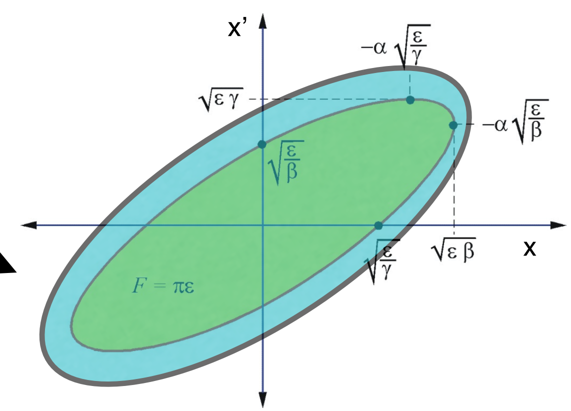
Bending strength of the dipoles depends on the energy



Dispersion **D** at position ***s*** parametrize the different amplitude **x** due to the difference in energy

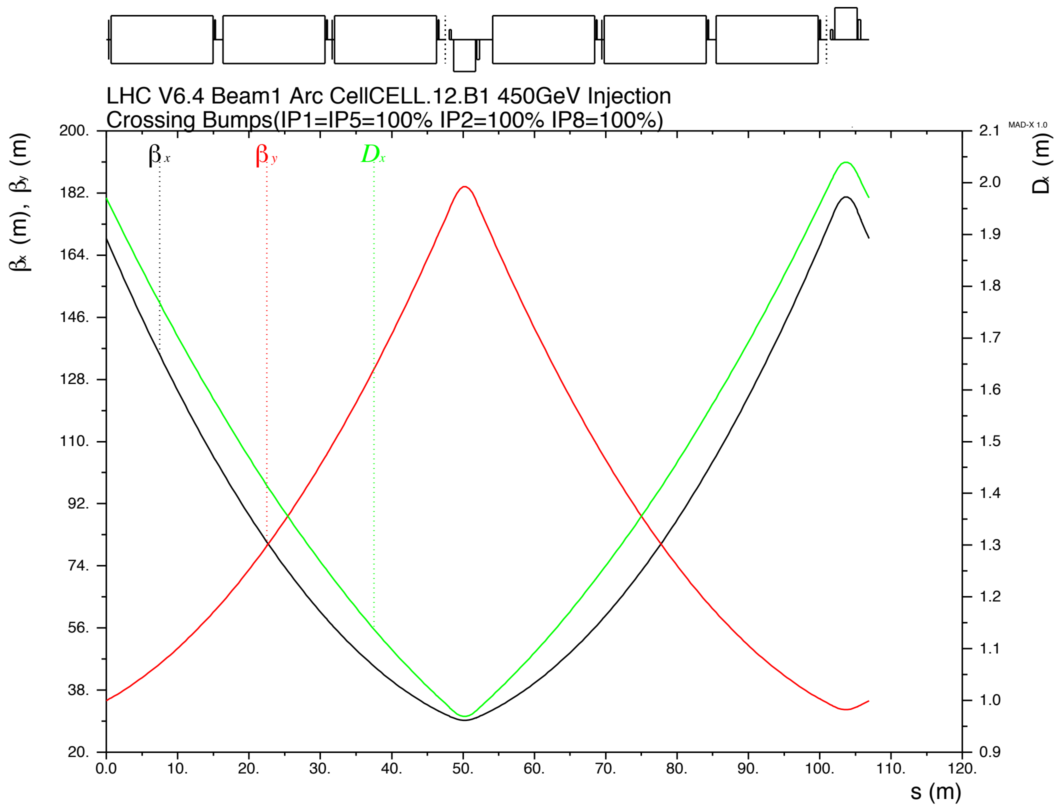
$$\frac{\Delta x}{x} = D\,\delta \quad \delta = \frac{\Delta p}{p}$$

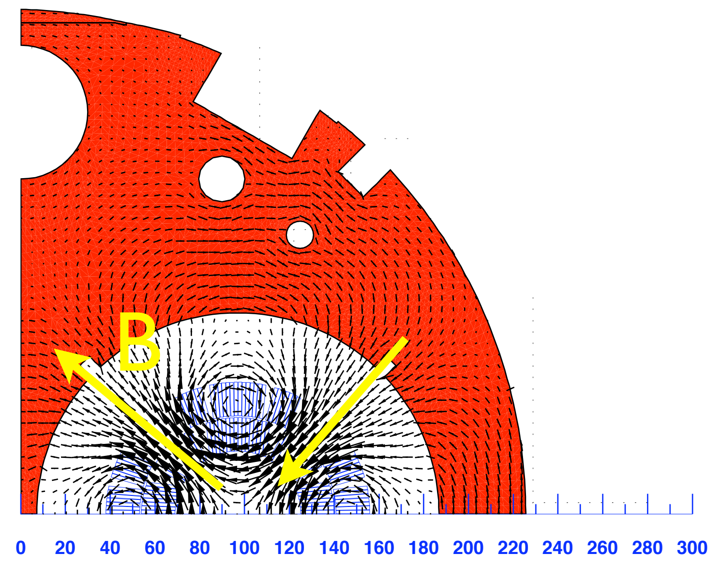
The dispersion changes also the beam ellipse

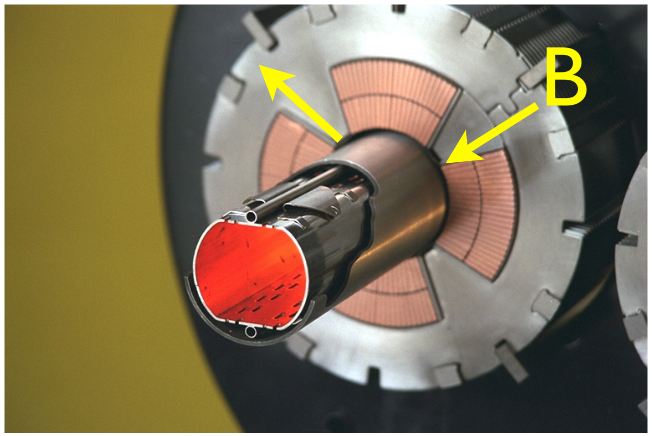


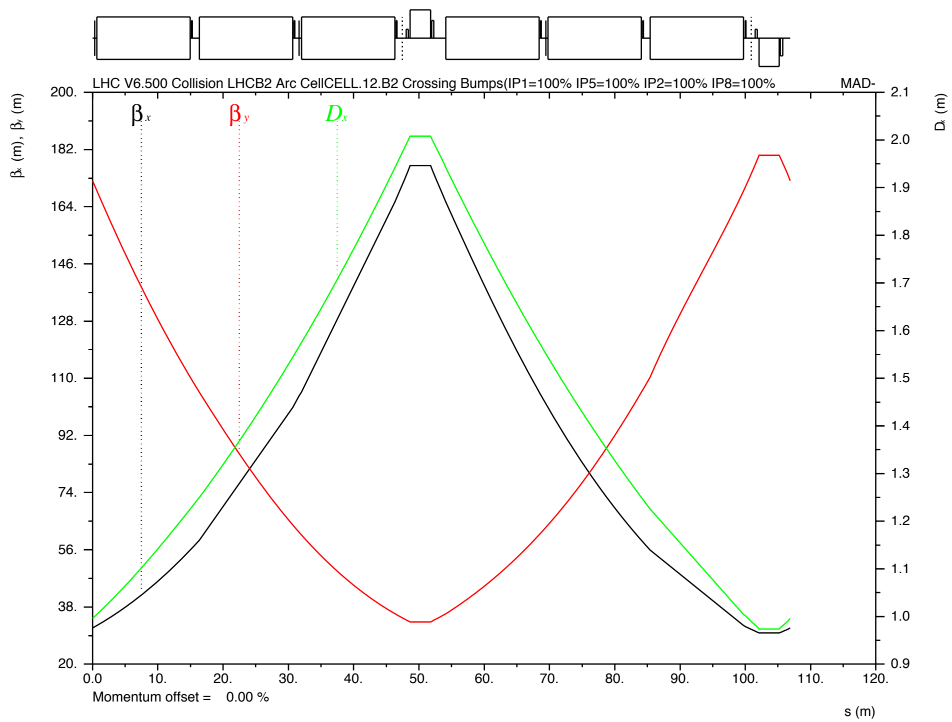
$$\sigma_x(s) = \sqrt{\epsilon_x \beta_x(s) + \langle \delta^2 \rangle D_x^2(s)}.$$

Arc cell at injection for beam 1 and beam 2



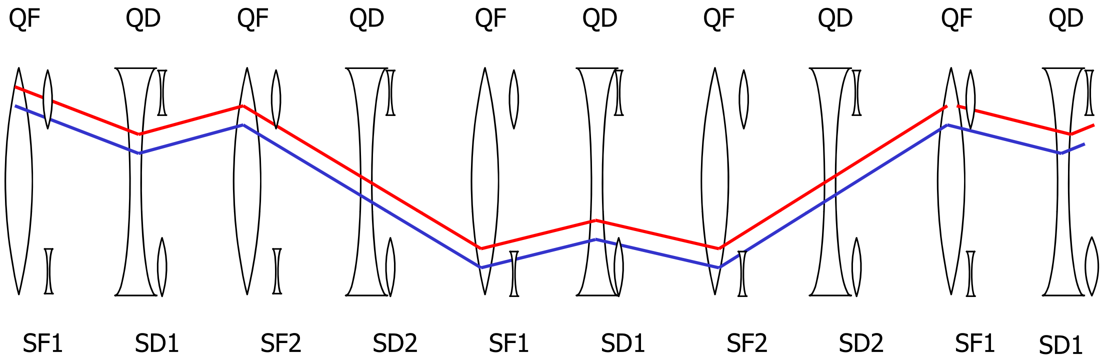


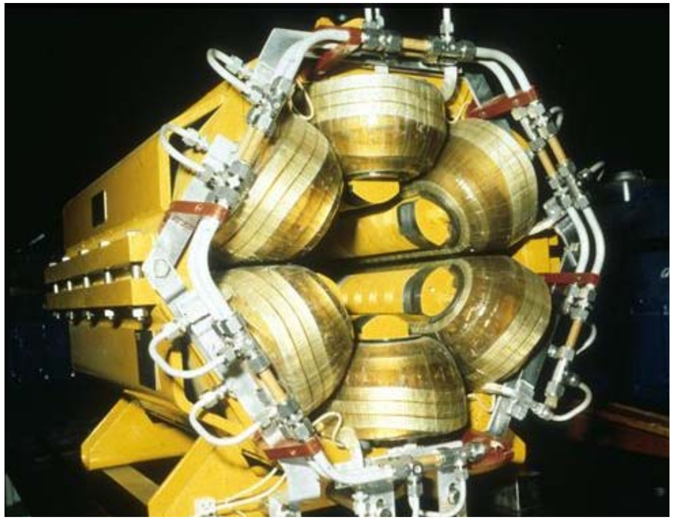




Chromaticity

- 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 ξ $$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$$
- Since one want to avoid crossing resonances, the CHROMATICITY has to be kept small and corrected.
- This can be done by using SEXTUPOLES, thanks to the lattice design, can focus differently different energies





Actually ... that's chromaticity...

$$k = \frac{g}{p/e}$$

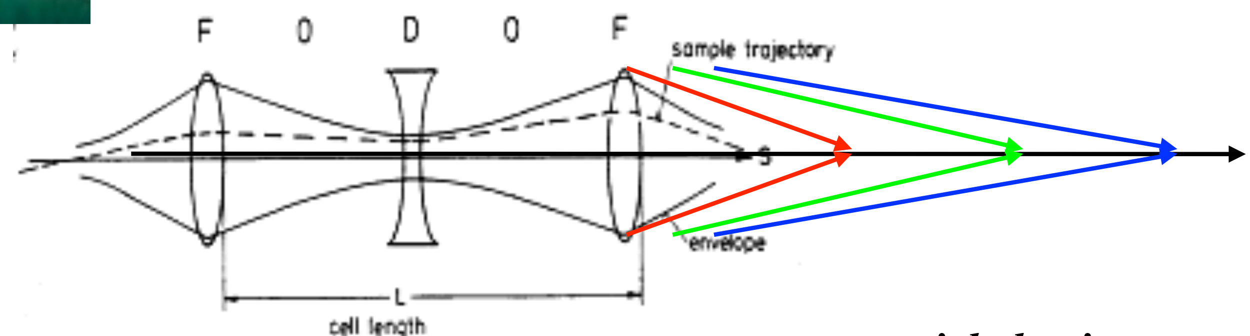


Figure 29: FODO cell

particle having ...

to high energy

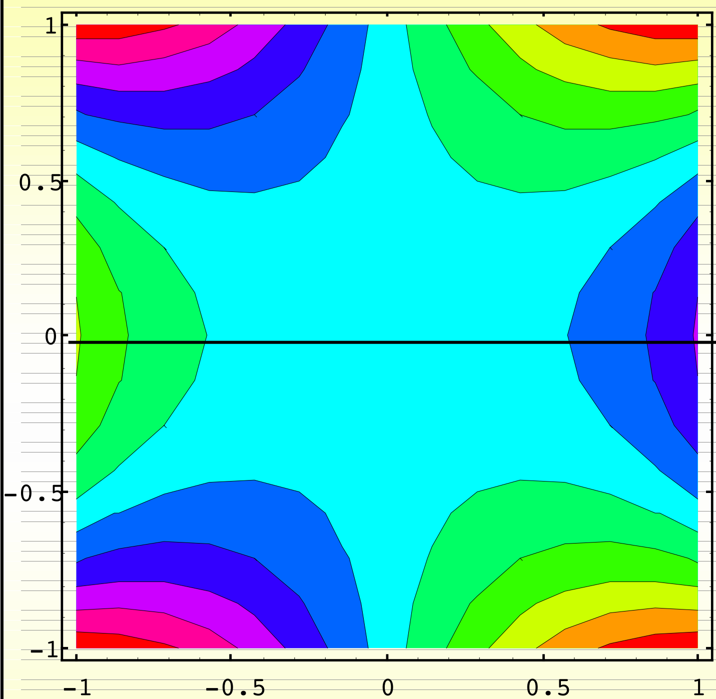
to low energy

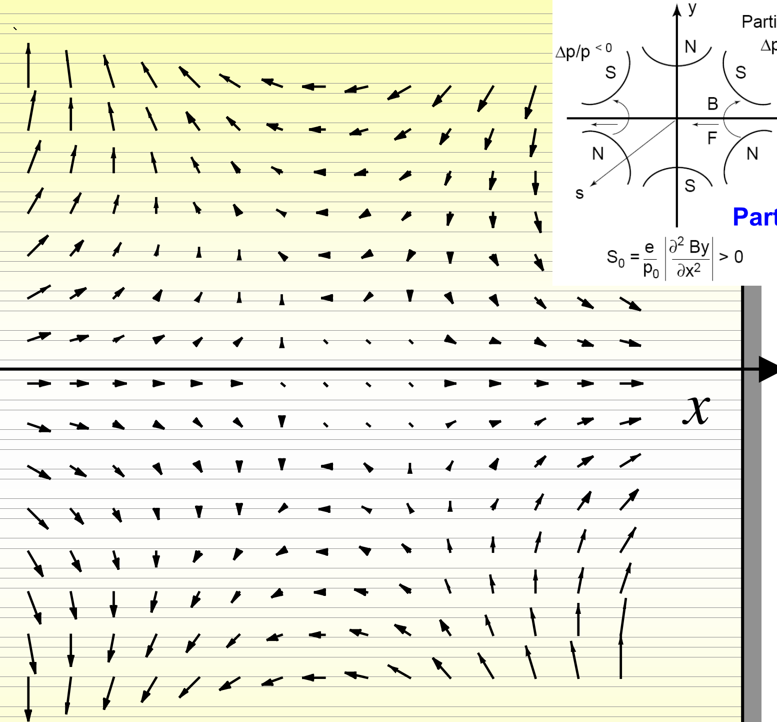
ideal energy

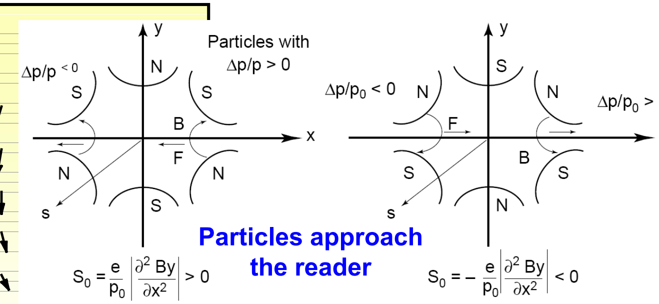
Sextupoles

$$B = -\nabla \Phi_m \qquad \Phi_m = \text{Vector potential}$$

The force changes with the distance, and couples vertical and horizontal plane



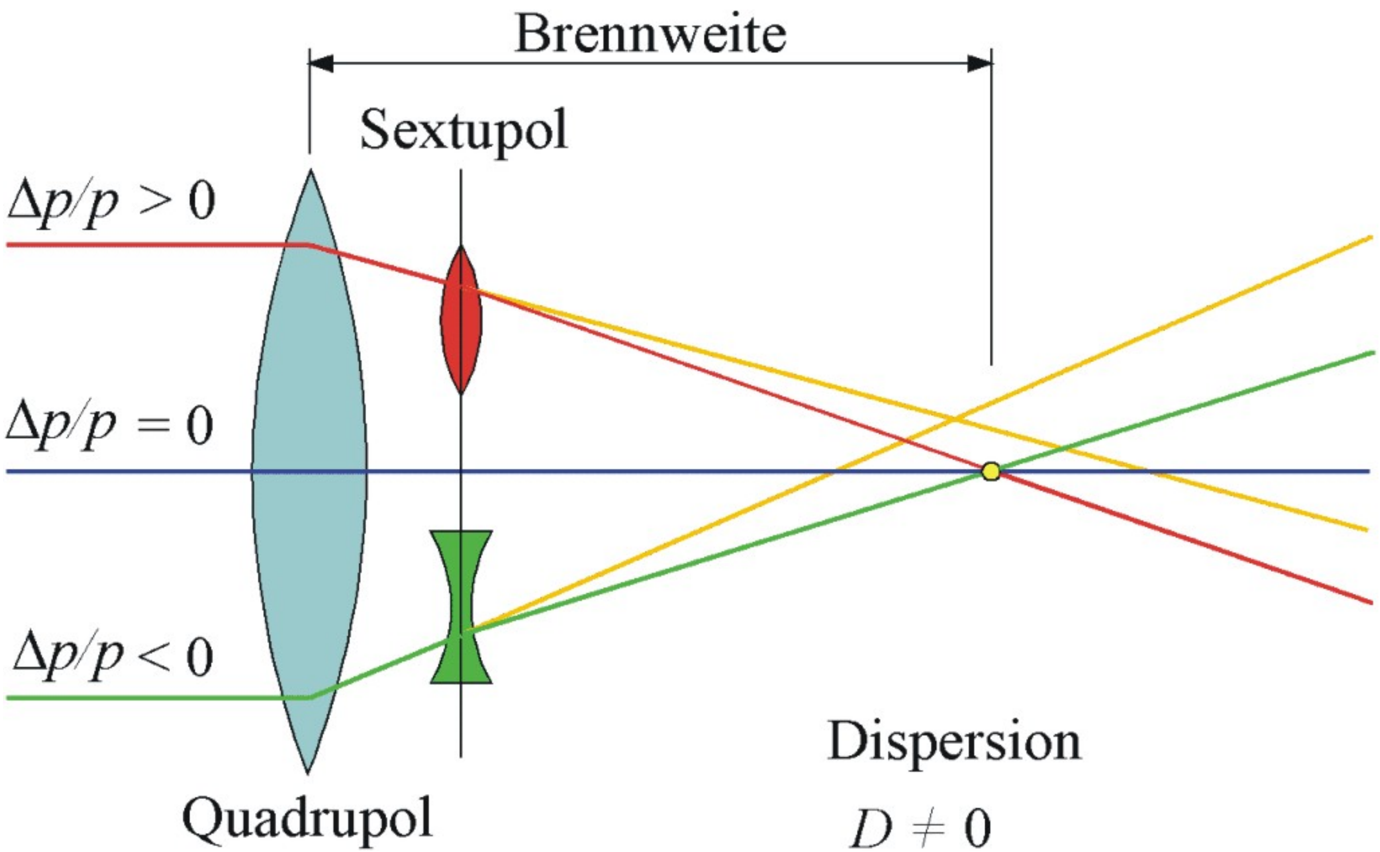




$$\Phi_m = -\frac{p}{e} K_2\left(x^3 - 3xy^2\right), \quad \text{for sextupole magnet}$$

Chromaticity correction scheme

In a region where Dispersion is not zero, the sextupoles uses the correlation between energy and displacement to correct the different focal point for the different energies



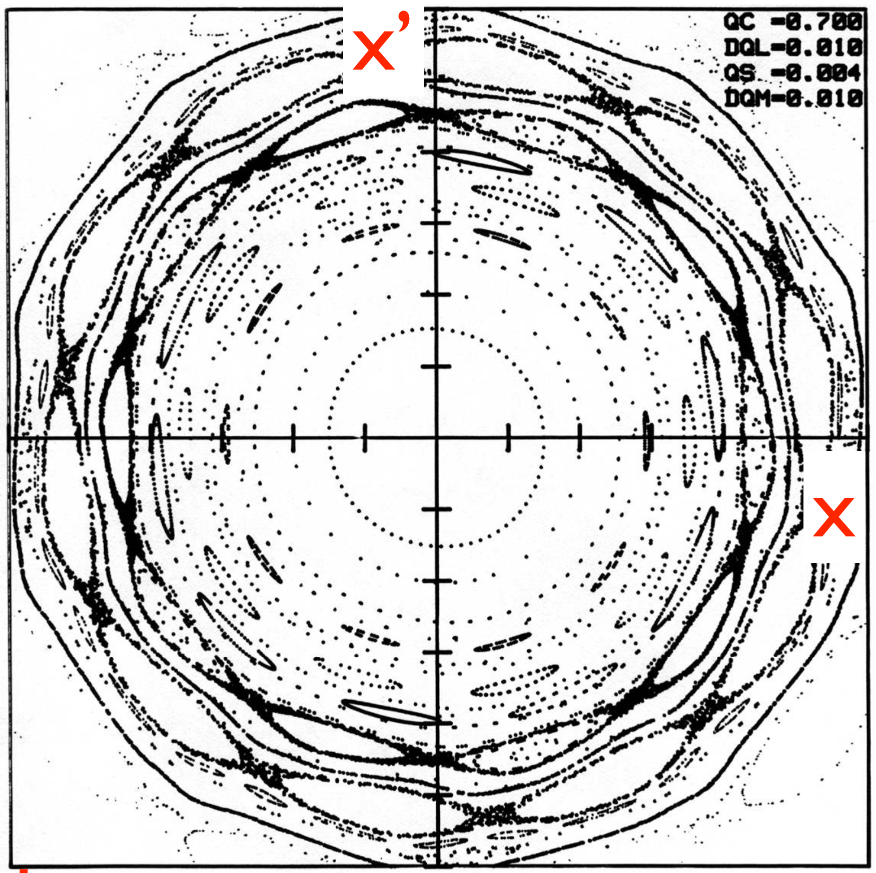
Why chromaticity is bad? In fact not all the time, but due to $\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$ particles with large energy errors could intercept some resonances

Dynamical Aperture

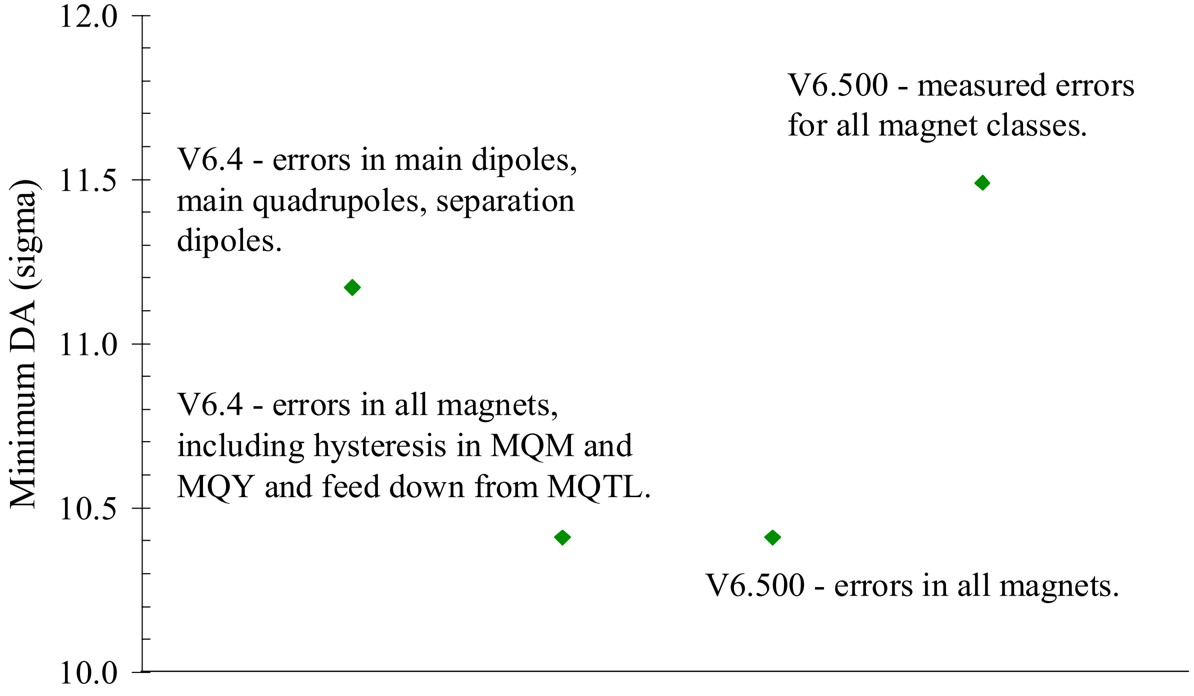
Dynamic aperture (DA) is largest region of phase space where stable motion occurs.
Computed by particle tracking simulating different sets of machine imperfection due to:

(A) machine alignement/mechanical aperture

(B) **multipoles generated by the magnets (see sextupoles...)**

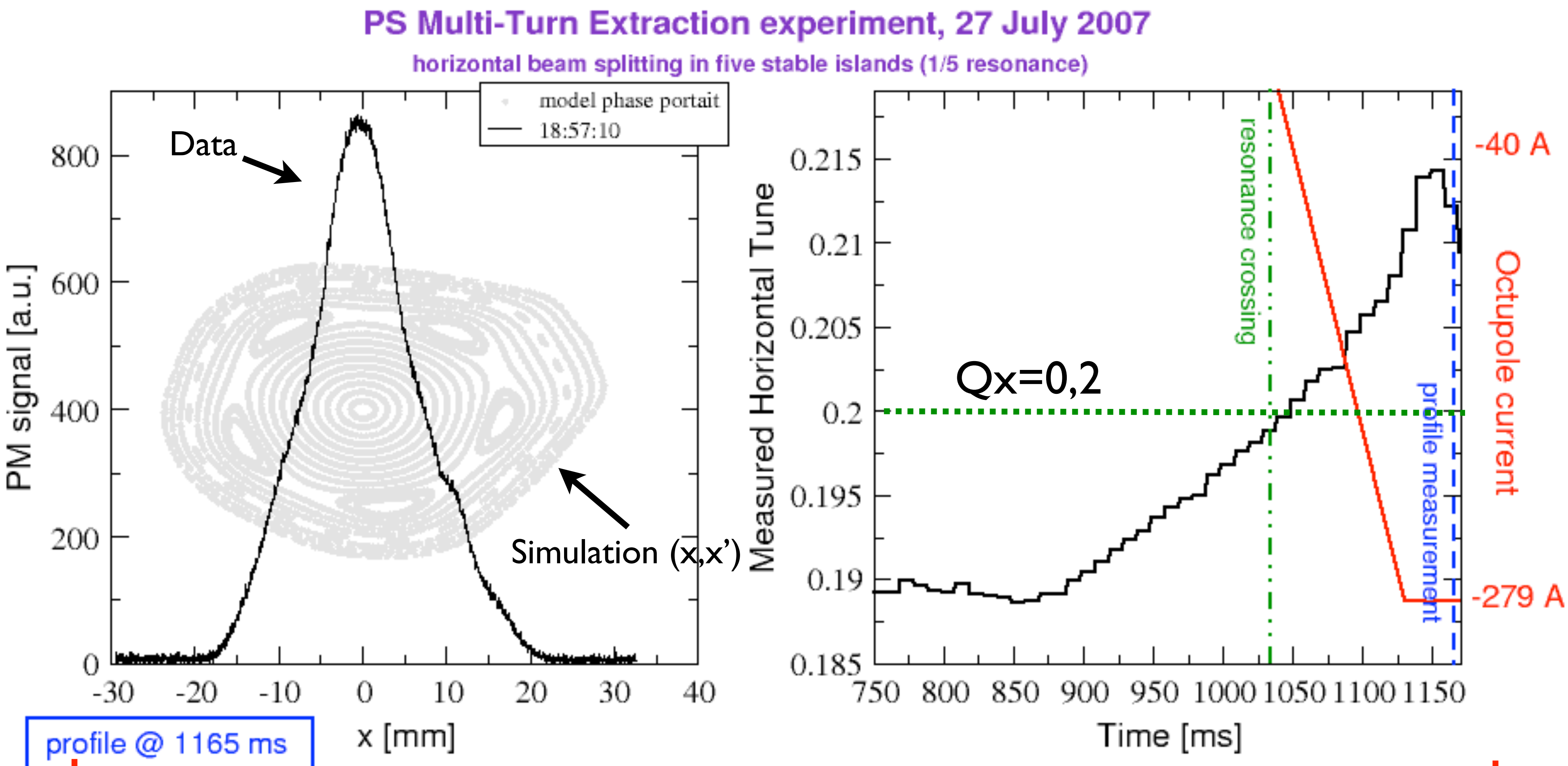


Dynamic aperture for different LHC "realisation"



In the transverse phase space, one cannot really see an ellipse which describes the normal betatronic phase space in a FODO lattice. Islands and chaotic (both in mathematical sense as in how it looks like) motion appear due to fields that vary with amplitudes (x) ⇒ Multipoles

In fact, if can control properly the non-linearities you can even split up the beam



Experiment done in the PS at 14 GeV/c (not @ the LHC) to show the splitting in *5 islands* of the beam by using sextupoles and octupoles and crossing the *1/5 resonance, i.e. Qx=0,2*

If this not done not under controlled conditions, losses appear

If one can produce multibeams, one can for sure produce tails in a nice gaussian beam profile...

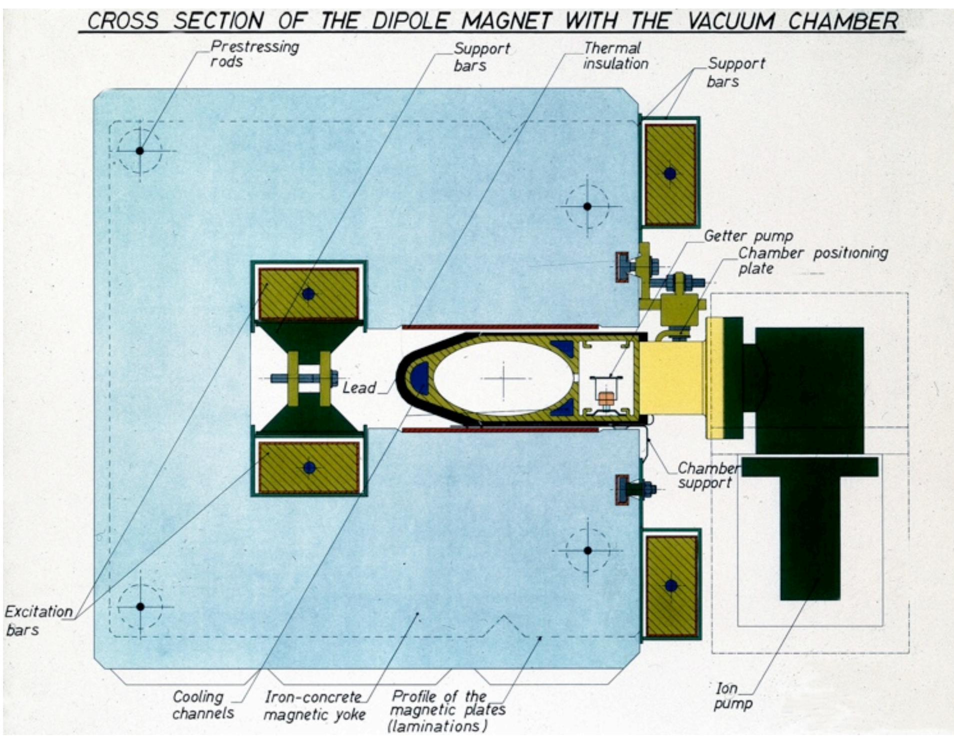
Magnets, a change in technology when energy increases

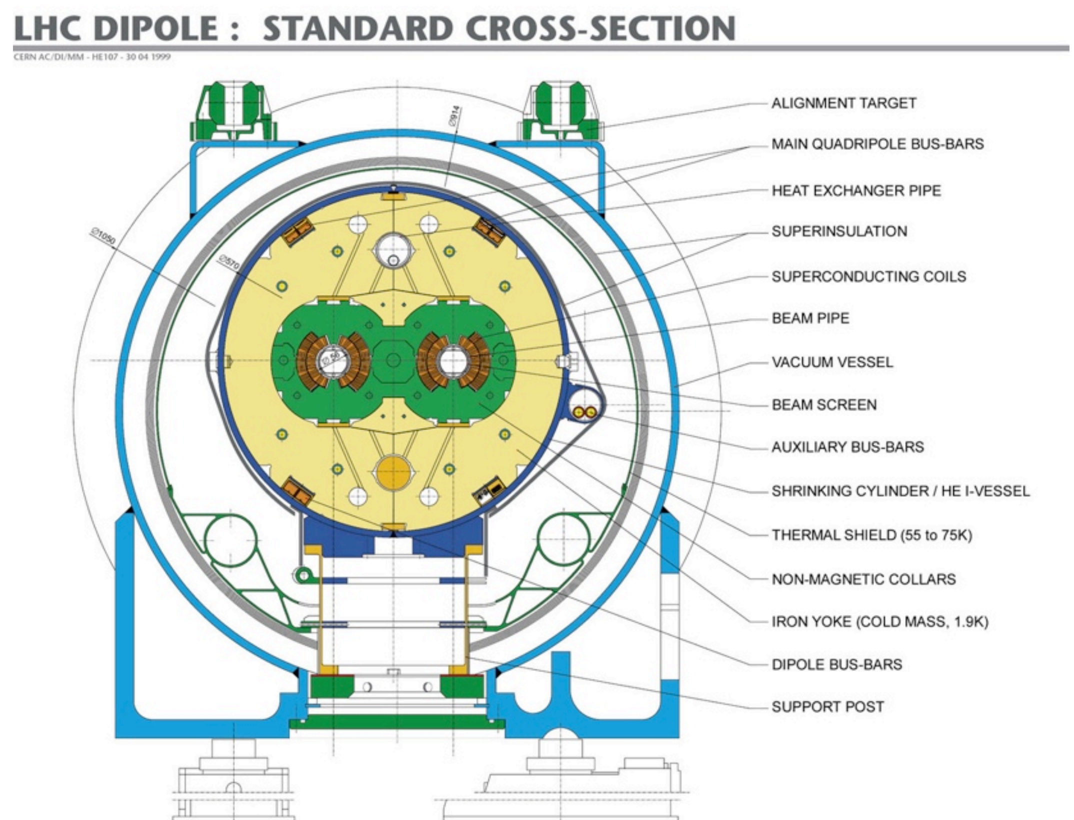
Bending Field → ***p(TeV) = 0.3 B(T) R(Km)***

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

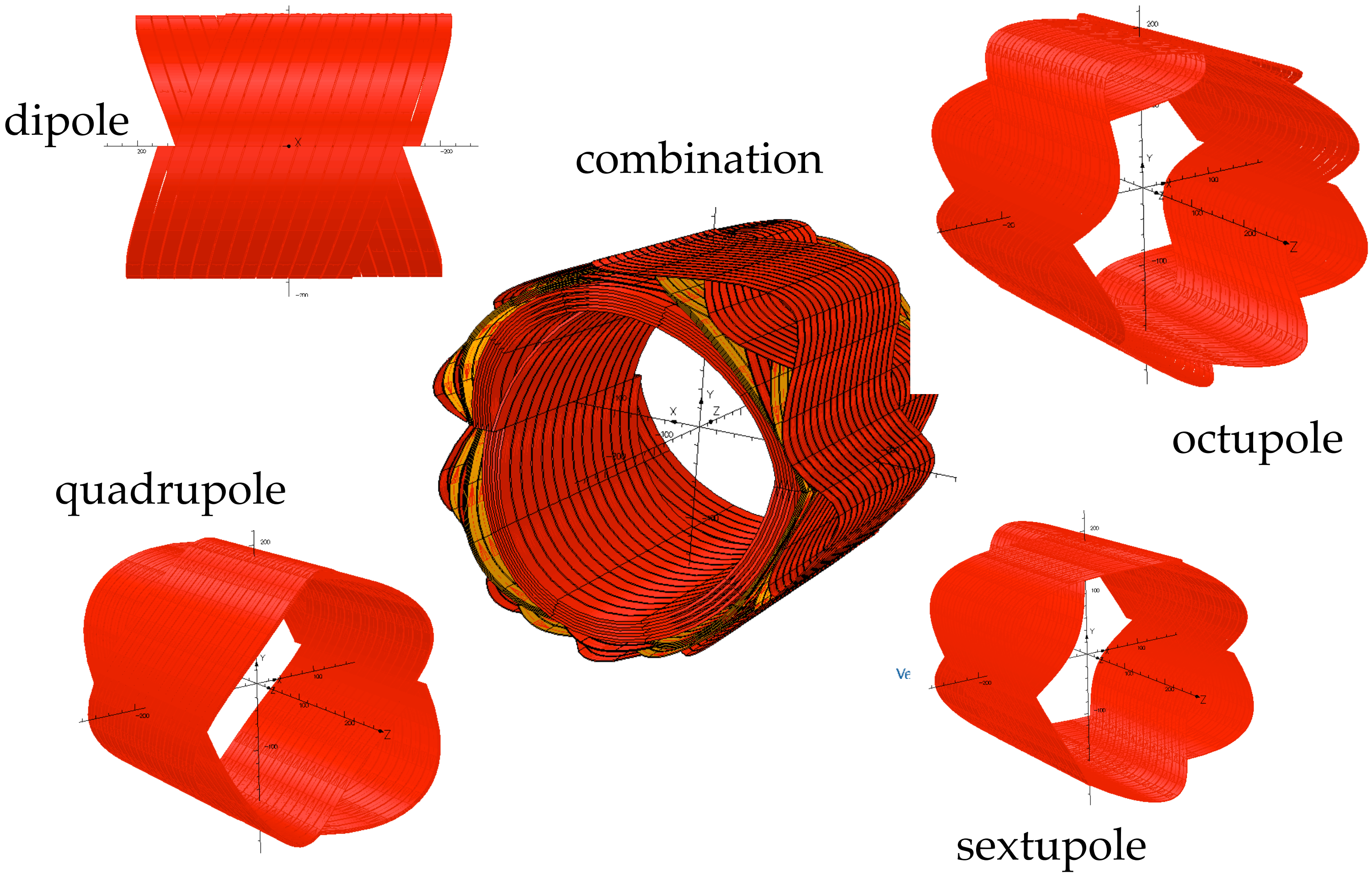
Tunnel R ≈ 4.3 Km LHC 7 TeV → B ≈ 8.3 T → ***Superconducting coils***

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



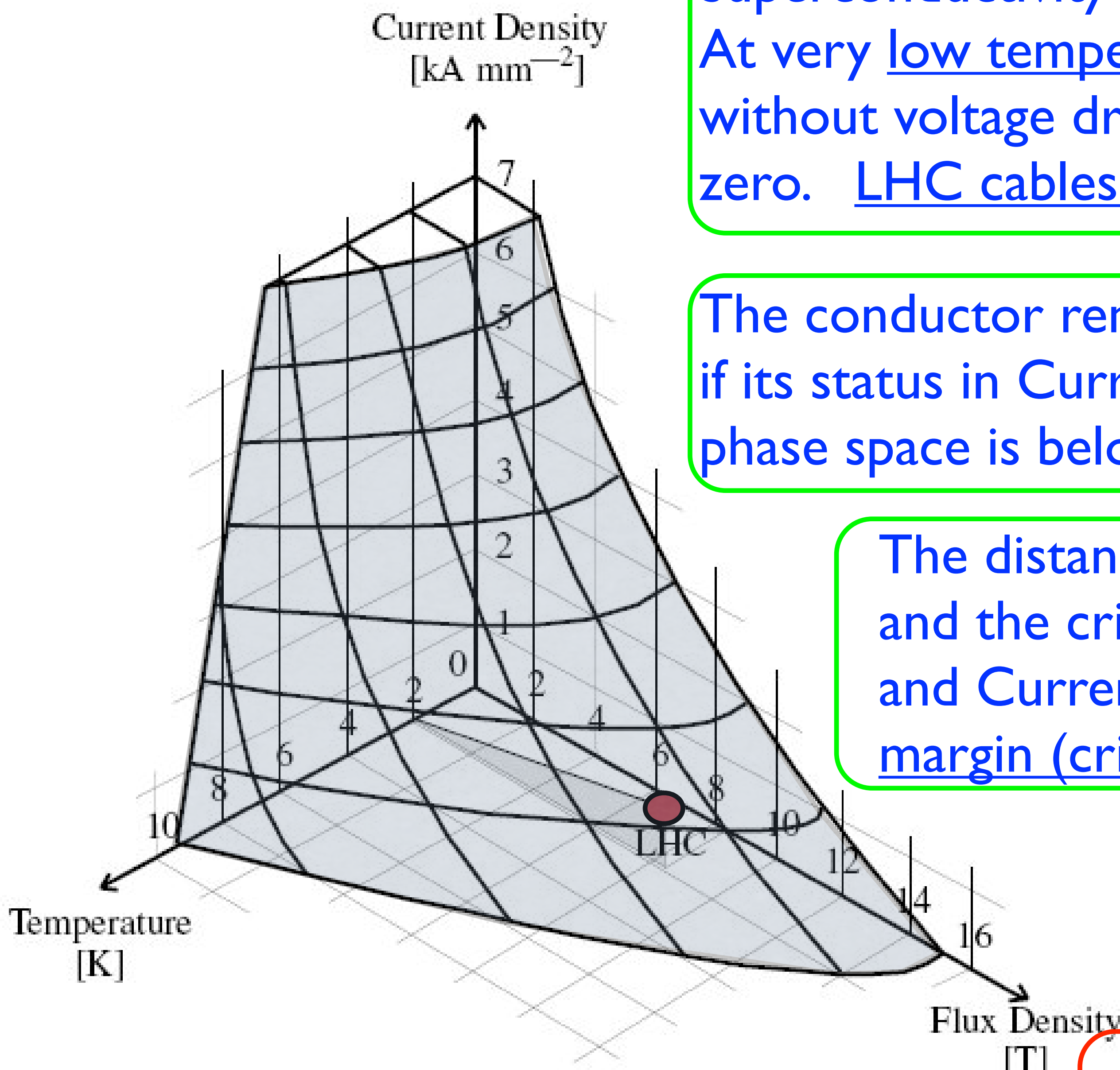


Remember for combined function magnets...



Why this shape ?

Very, very short introduction to Superconductivity for accelerators



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

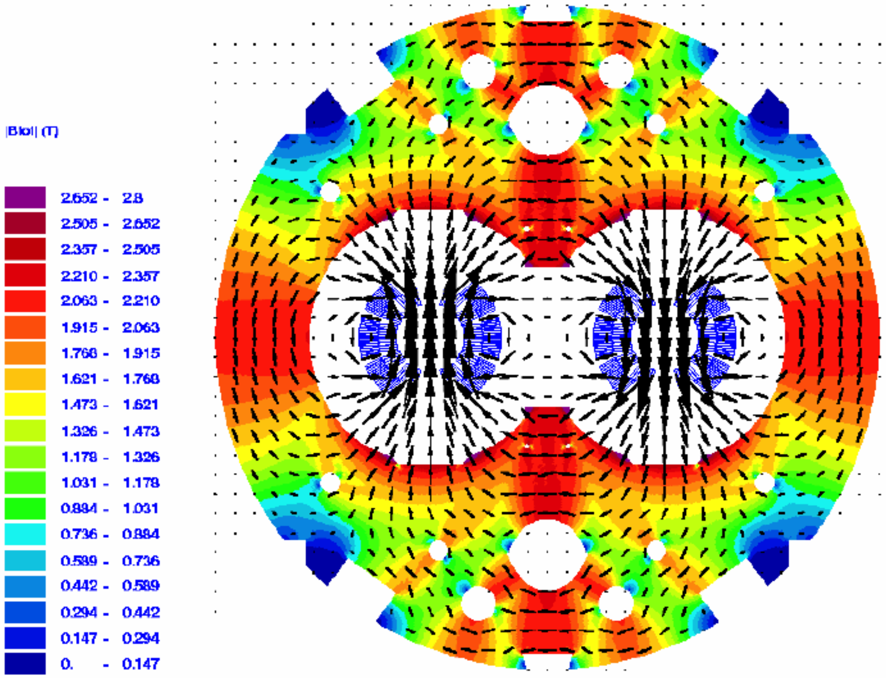
The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the <u>Critical Surface</u>

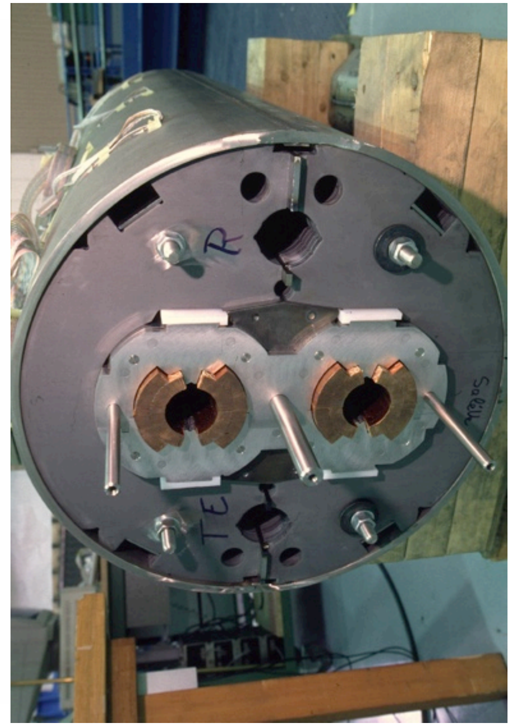
The distance between the working point and the critical surface for a fixed B field and Current Density is the <u>temperature margin (critical temperature)</u>

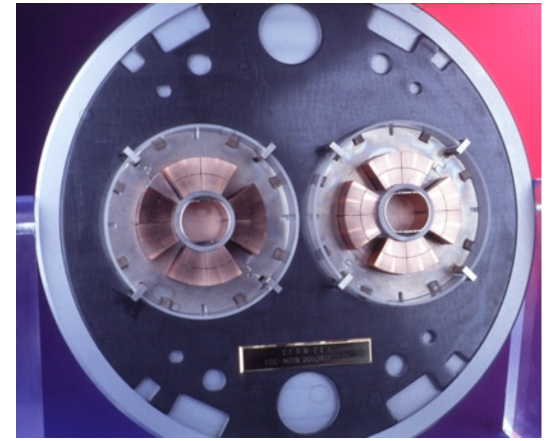
Transition to a normal conducting state is called <u>magnet quench</u>

What can increase the temperature in a magnet ?

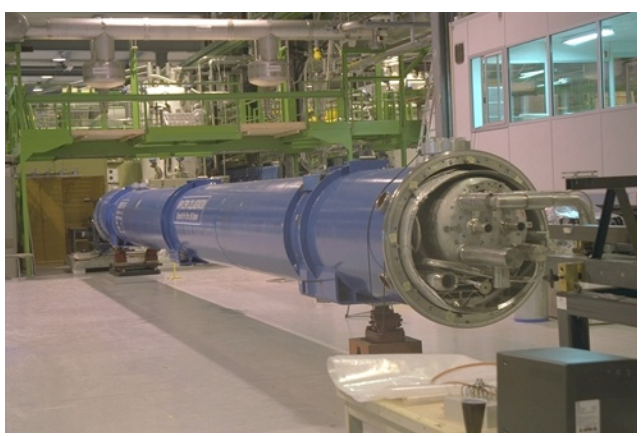
Two-in-one magnet design

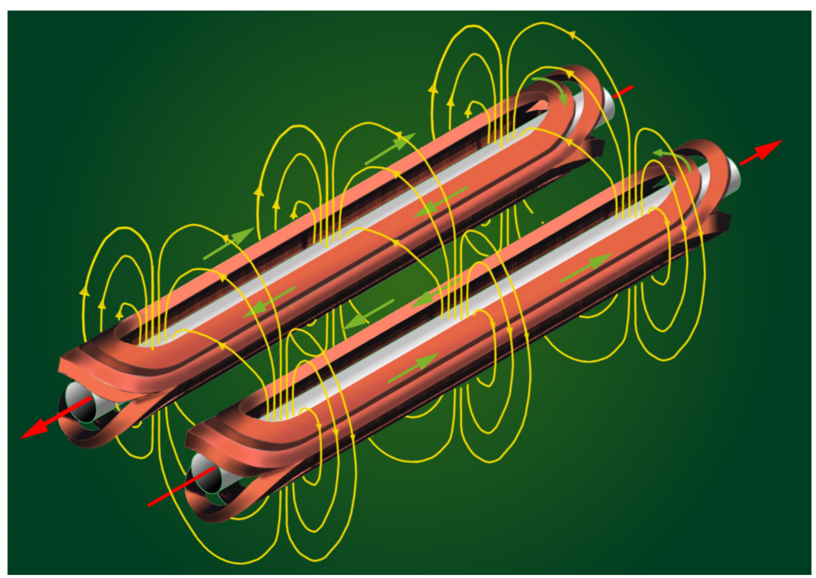




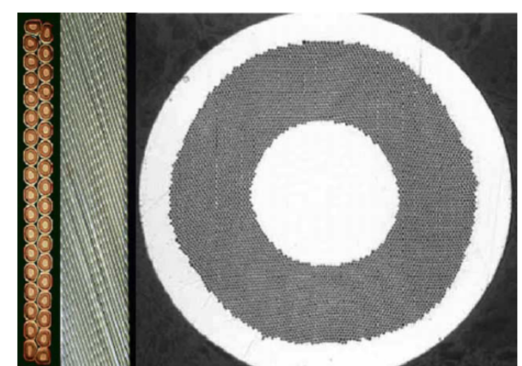


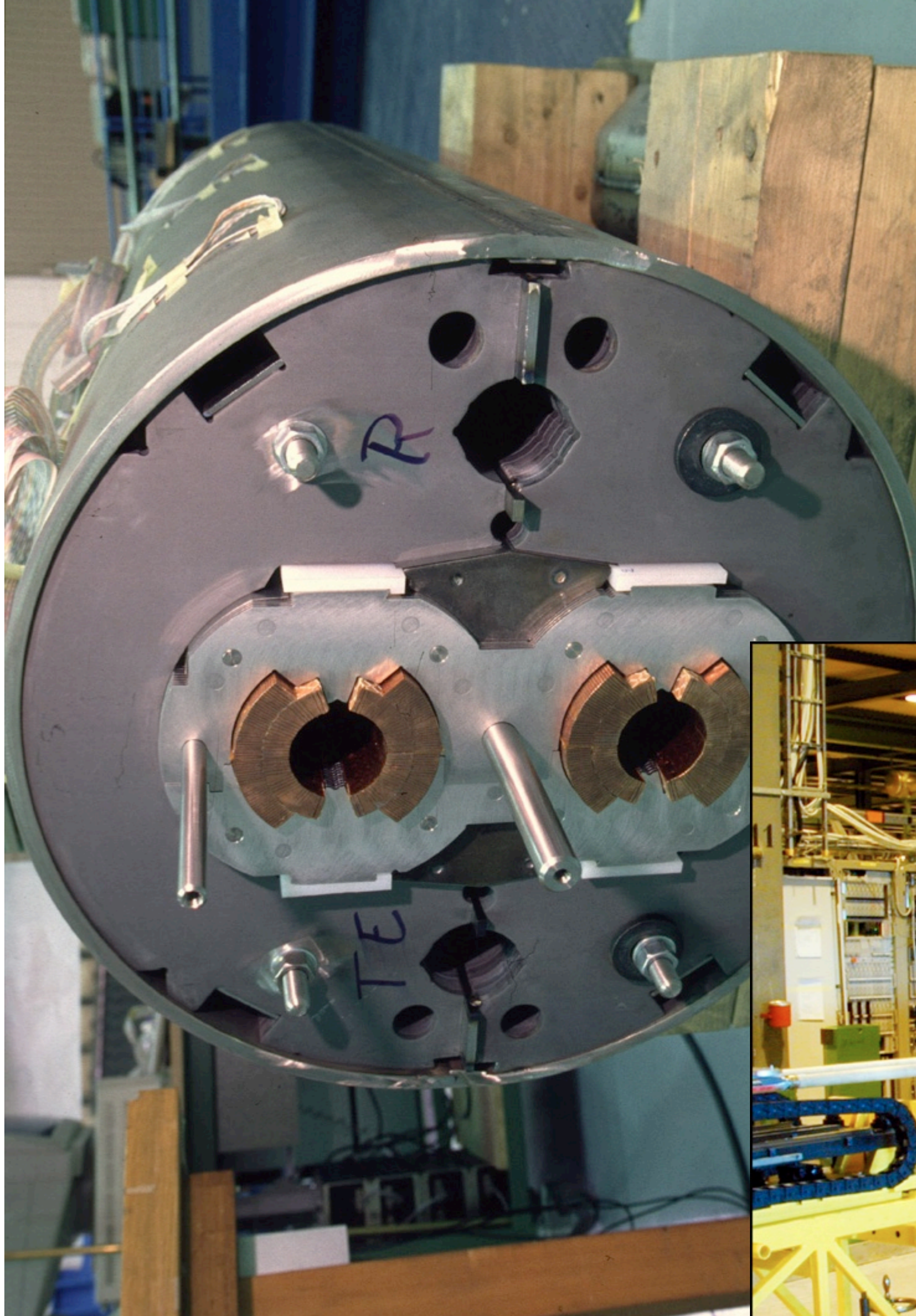
The LHC is <u>one ring</u> where <u>two accelerators</u> are coupled by the magnetic elements.





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

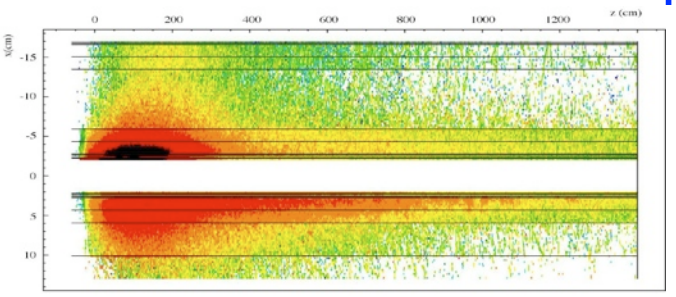
Test bench for magnetic measurements at 1.9 K

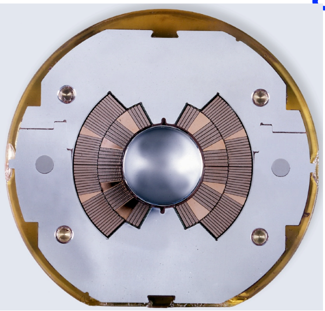
PS: they are not straight, small bending of 5.1 mrad

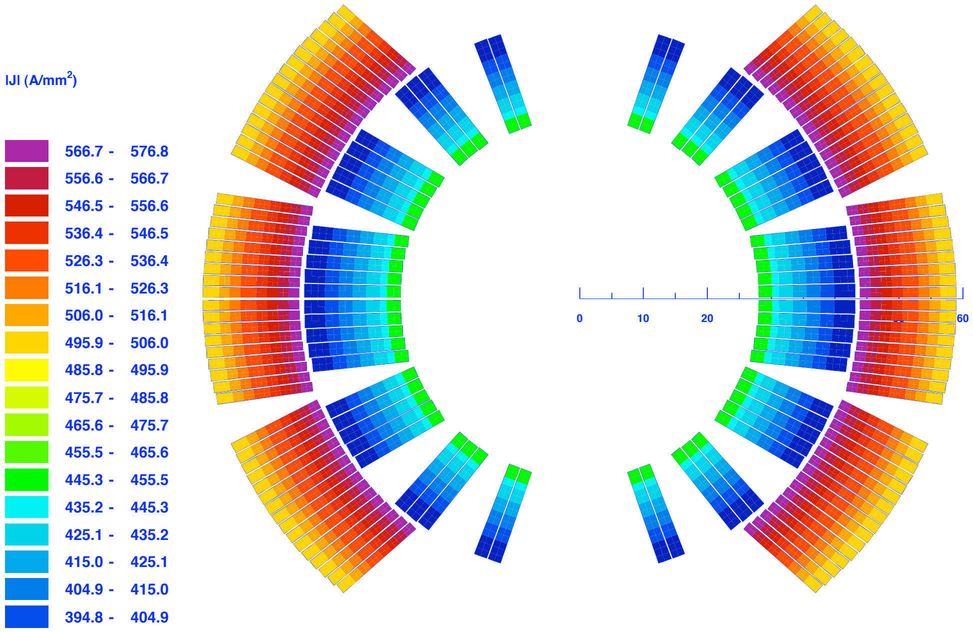
V. V. S. Introduction to Superconductivity II

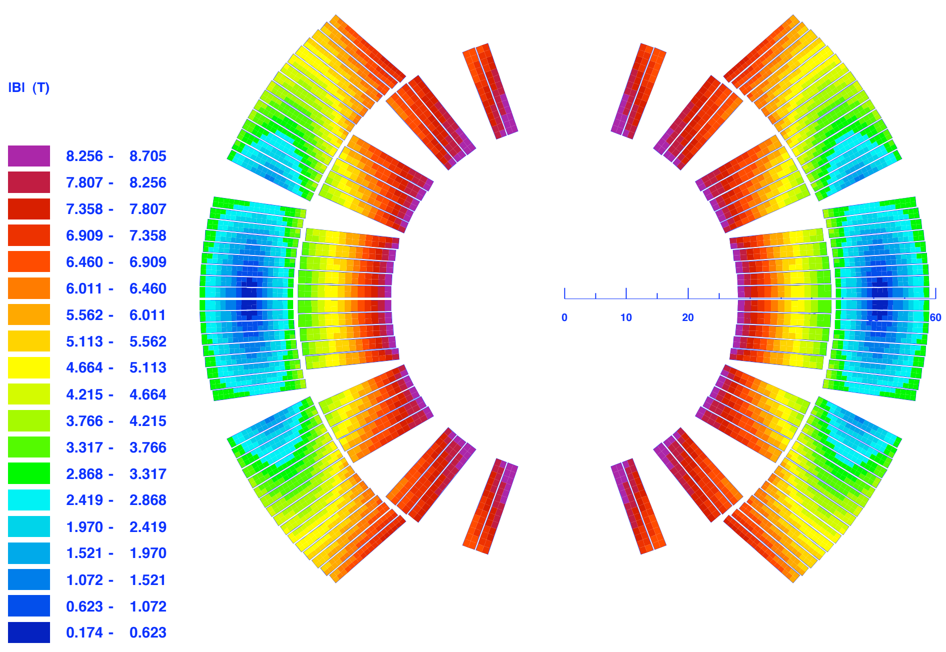
Beam losses can eat the temperature margin because of energy deposition

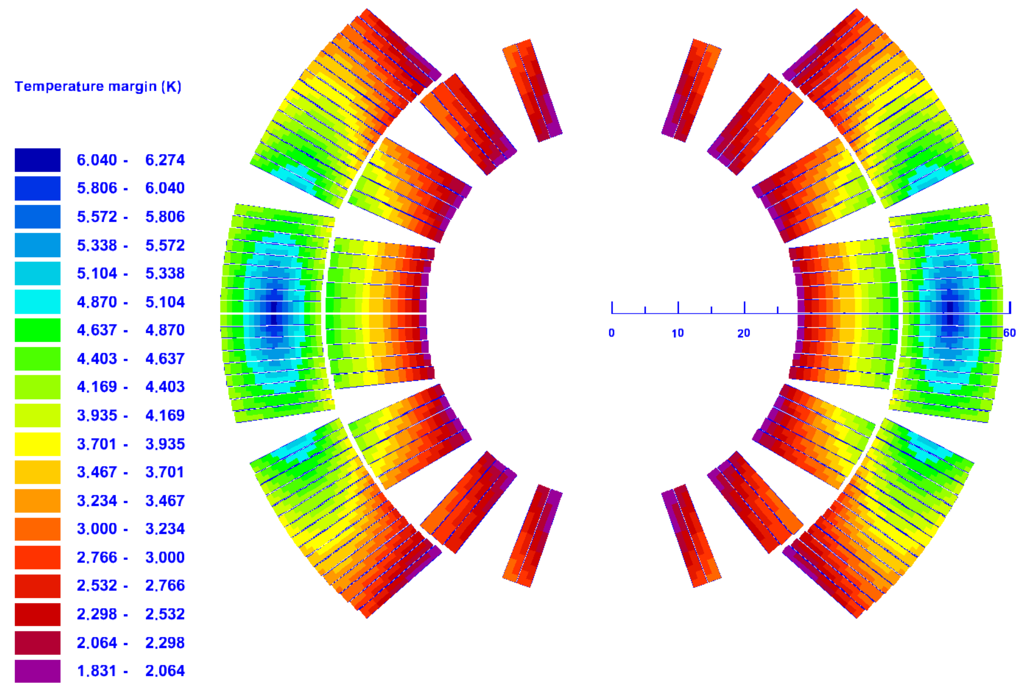
Limit of accepted losses: ~ **10 mW/cm³**
to avoid ΔT> 2 K, the temperature margin









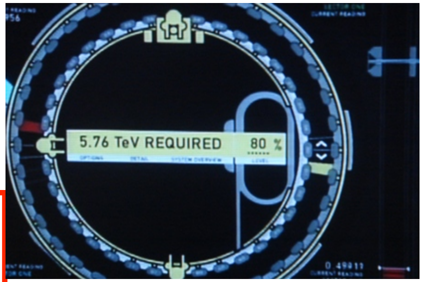


Courtesy of Stephan Russenschuck

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

How much is 10 mW/cm³ ?

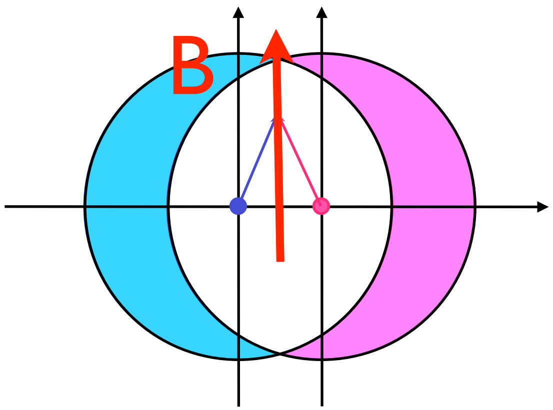
A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

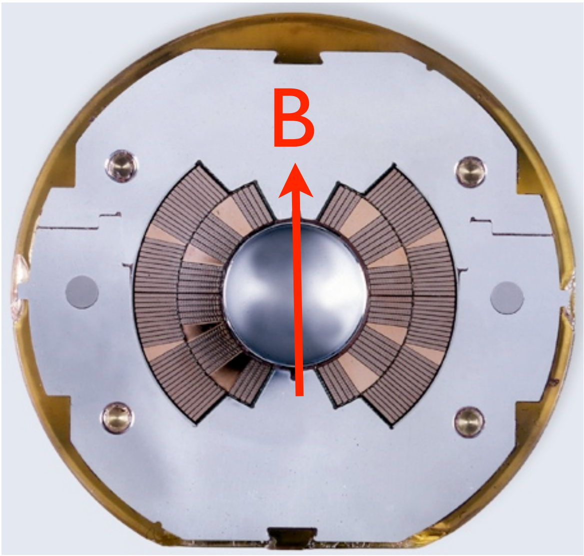
This makes a power density of about 56 mW/cm^3.

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.

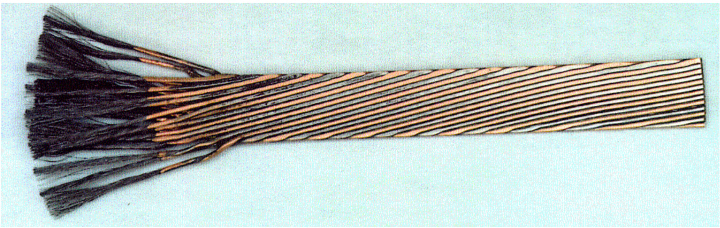
If you do the same basic computation with a normal 100 W resistive bulbs is even worst

Cosθ coil of main dipoles





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

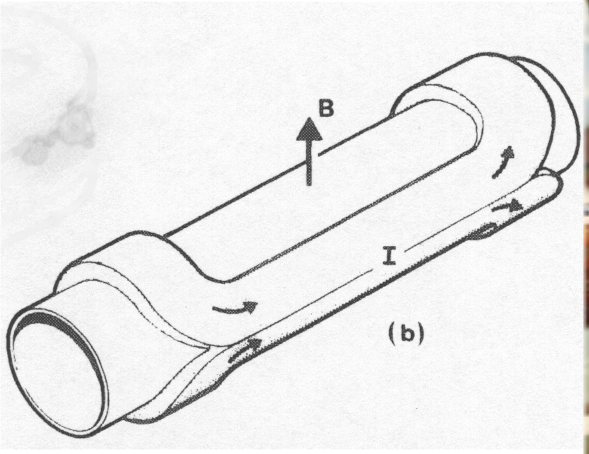


$$I = I_o \cos\vartheta$$

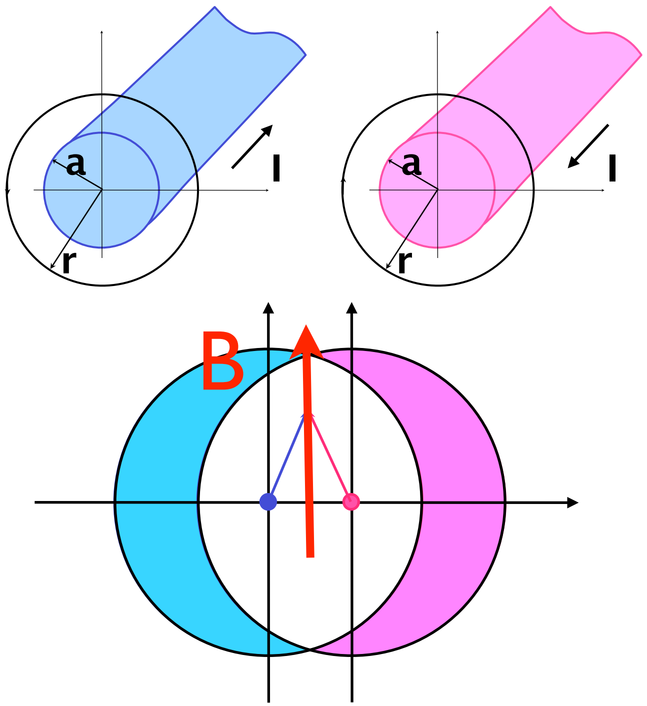
$$B_\vartheta = \frac{\mu o \; I_o}{2 \; r_o} \cos\vartheta \qquad B_x = o$$

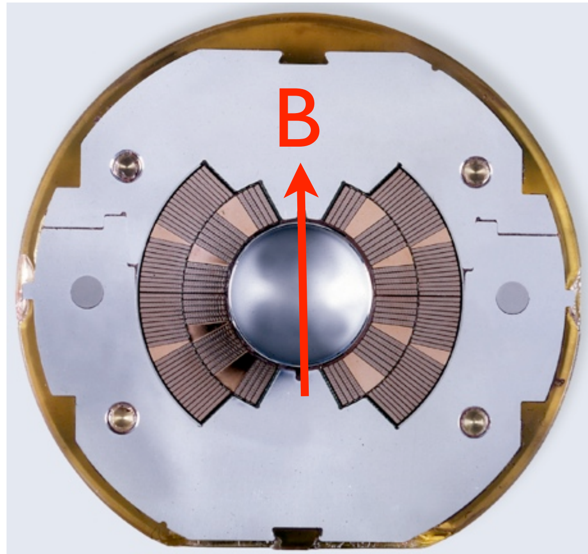
$$B_\vartheta = \frac{\mu o \; I_o}{2 \; r_o} \sin\vartheta \qquad B_y = \frac{\mu o \; I_o}{2 \; r_o}$$

Dipolar Vertical field



Cosθ coil of main dipoles





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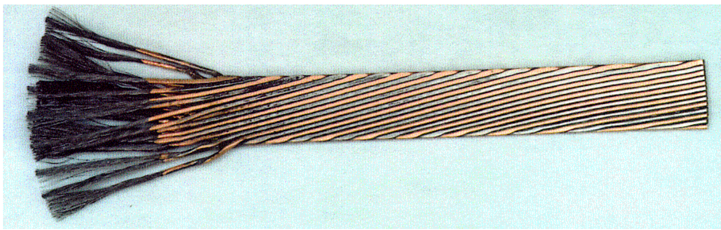

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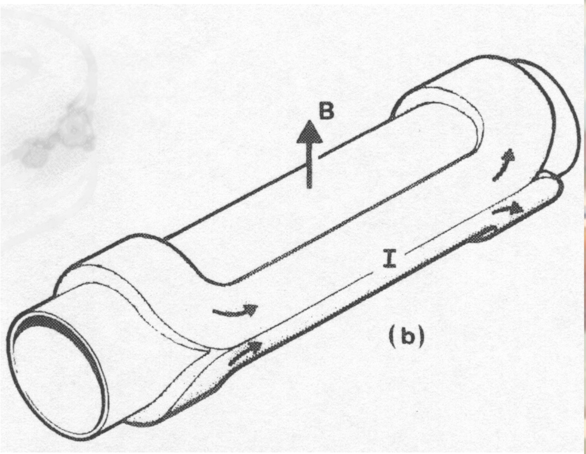
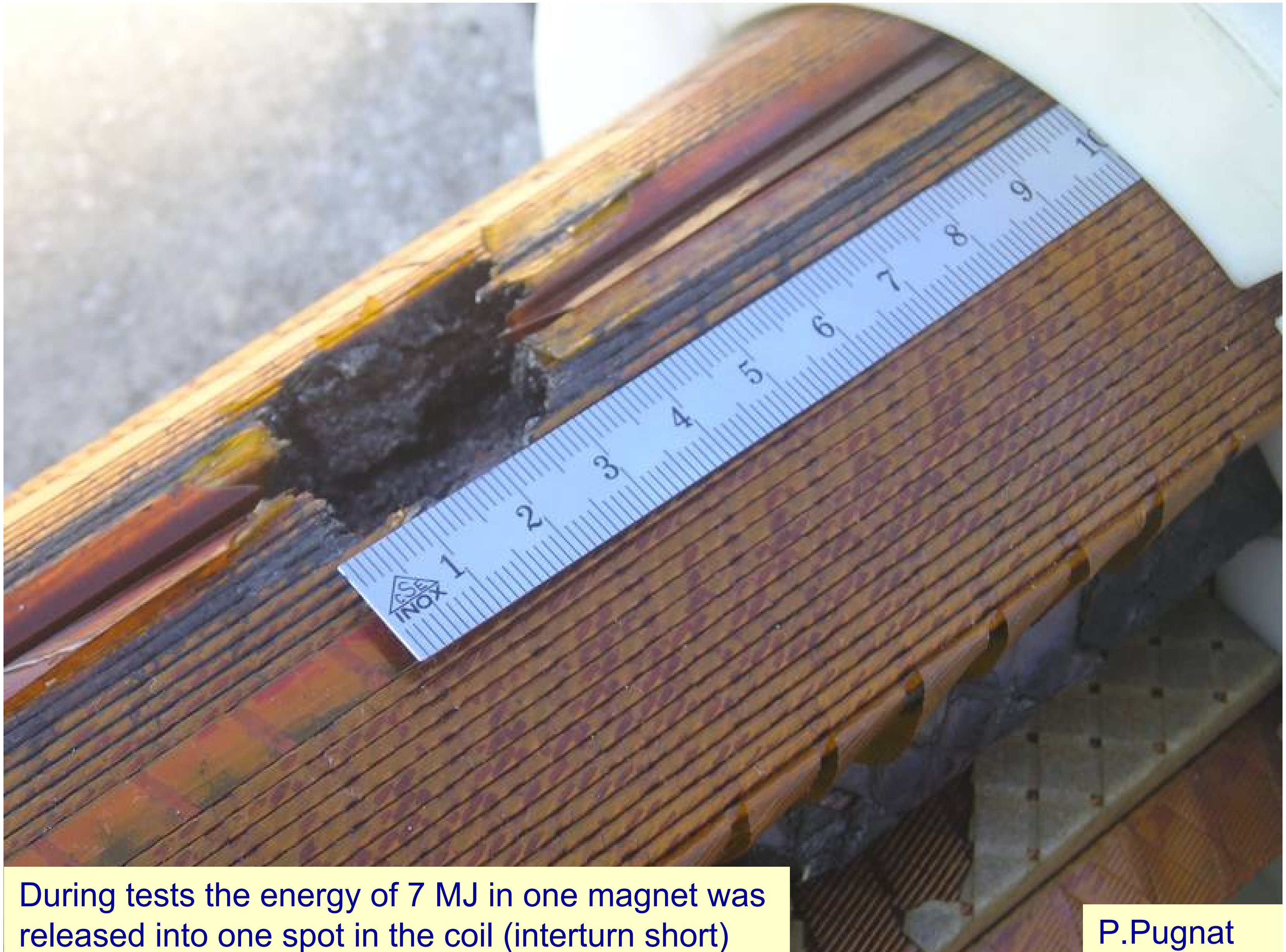
Dipolar Vertical field



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

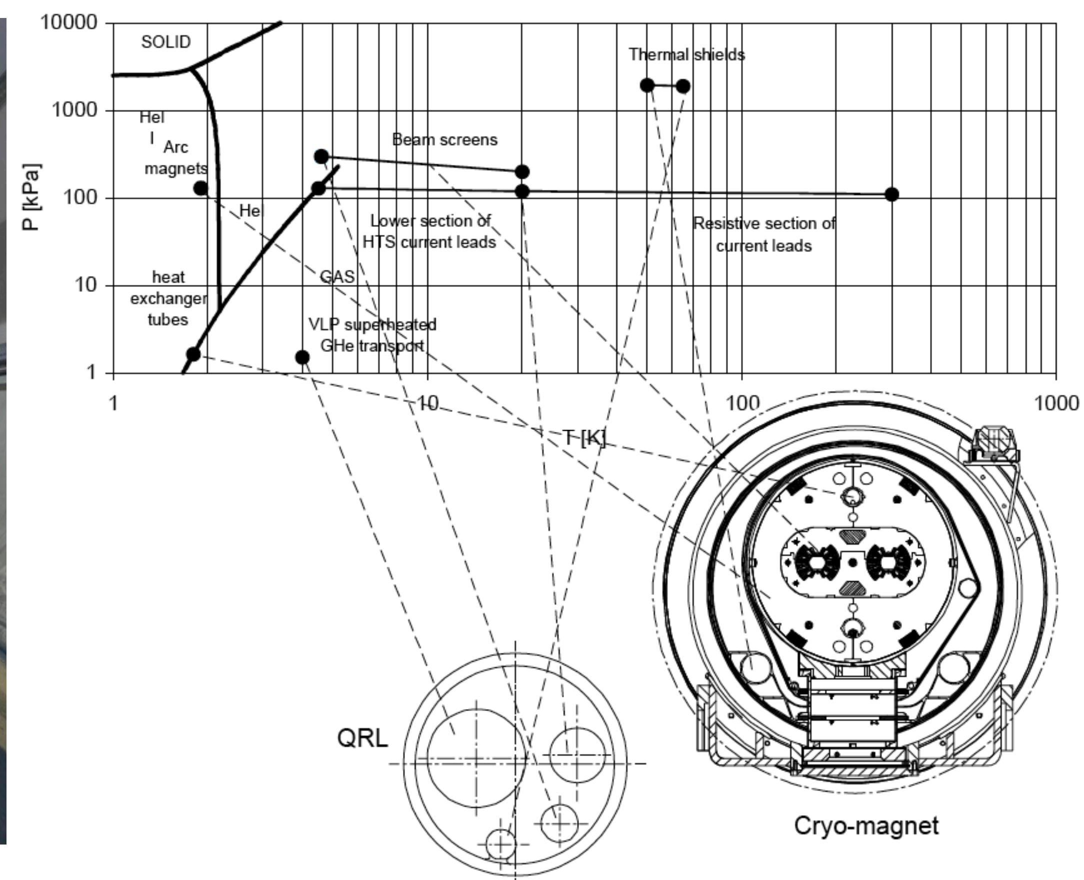


During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

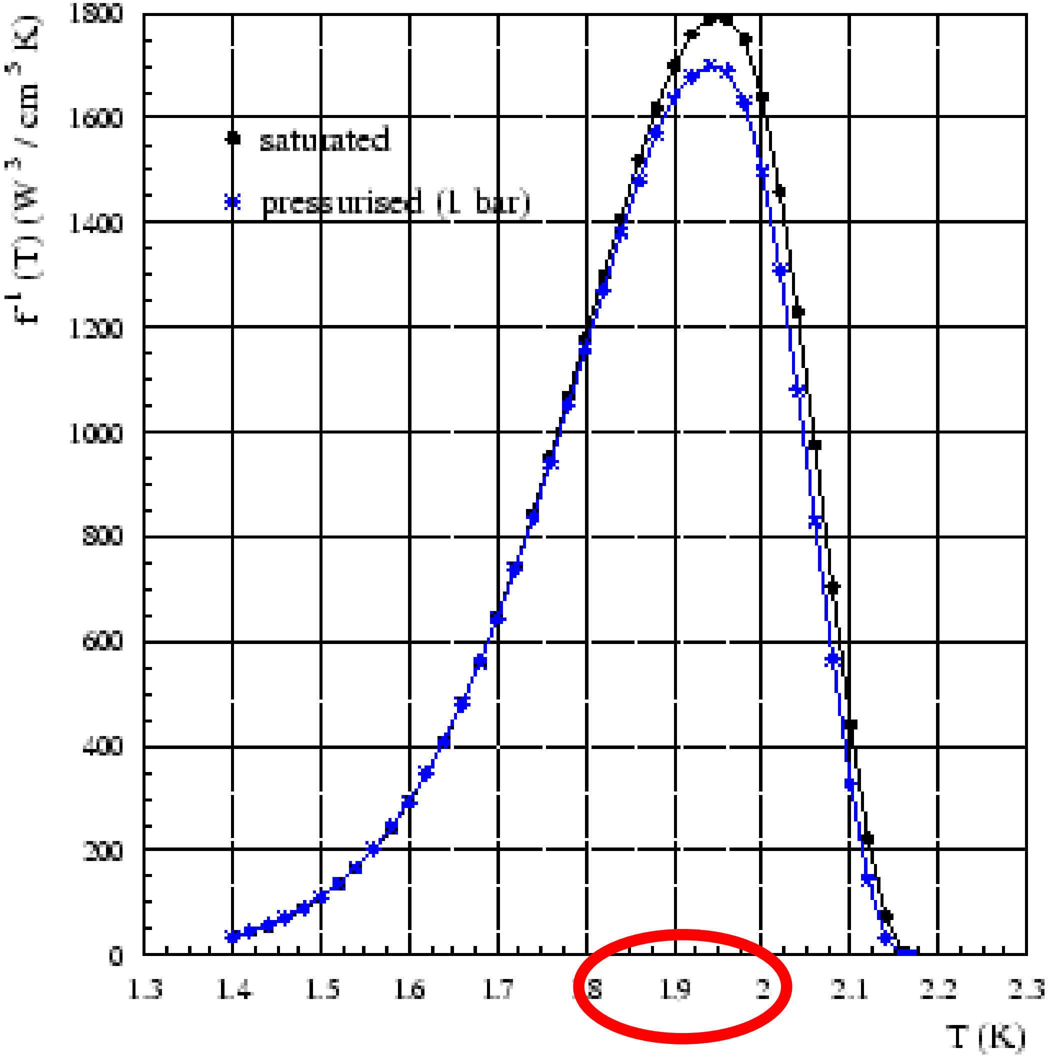
P.Pugnat

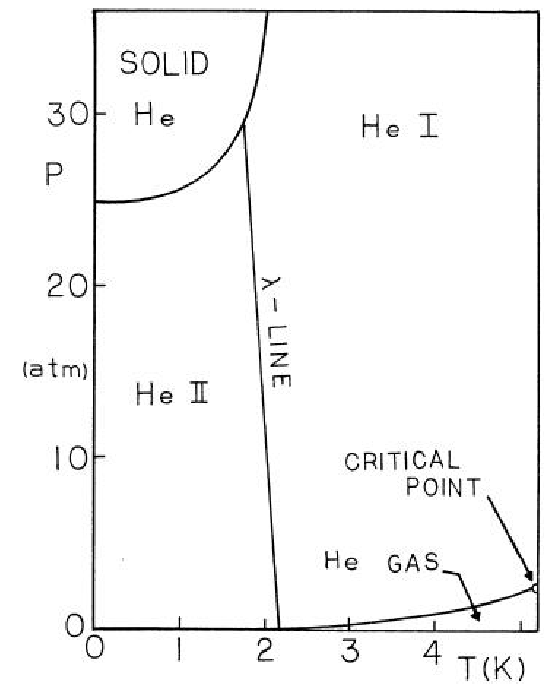
Which coolant ? Liquid superfluid helium

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).



Why helium ?

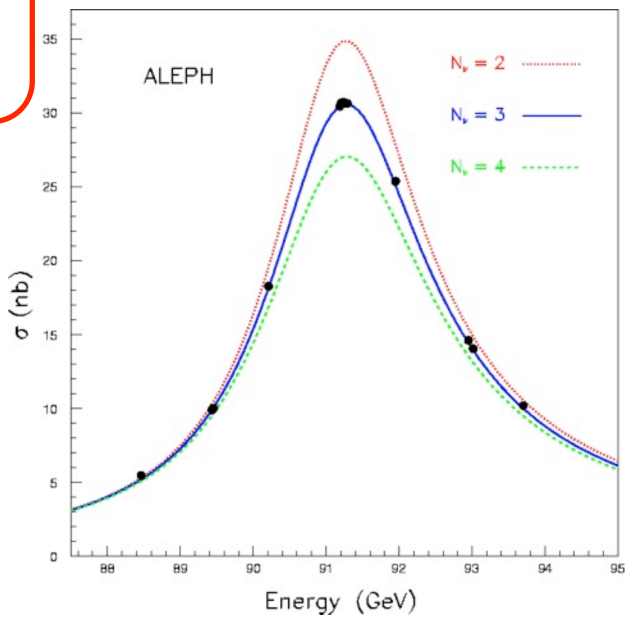




He at 1.8-2 K has a very large thermal conductivity and very low viscosity

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.



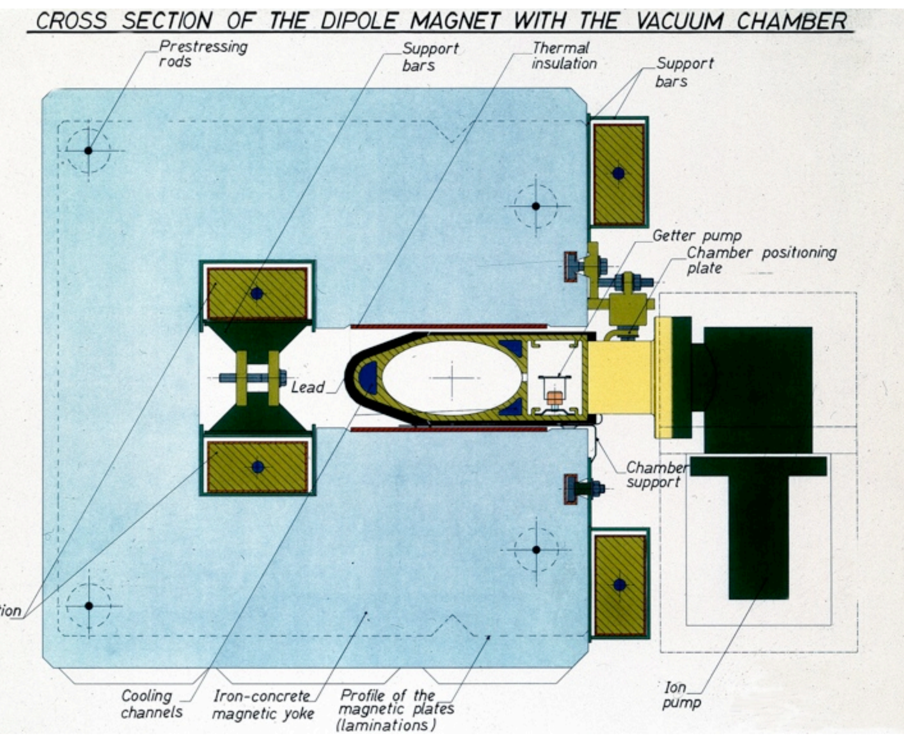
Energy measurements obtained by during last years of LEP operation

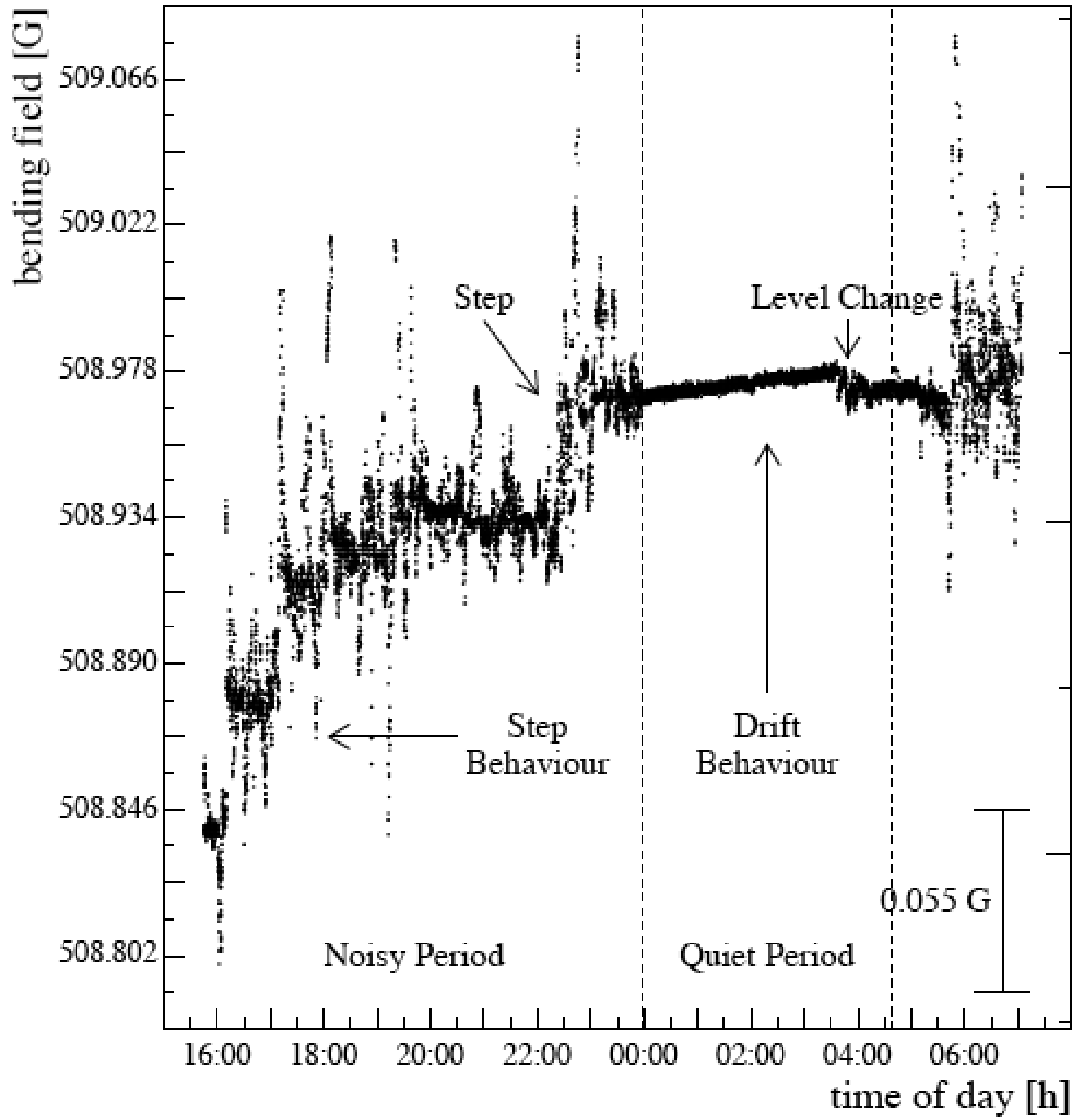
Nominal (GeV)	E_{CM} (LEP) (GeV)
181	180.826 ± 0.050
182	181.708 ± 0.050
183	182.691 ± 0.050
184	183.801 ± 0.050
Combined	182.652 ± 0.050

What can influence the energy of a collider?

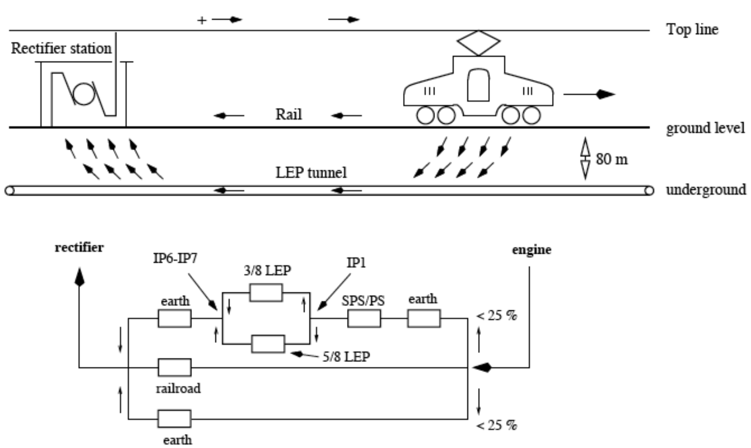
The problem: an accelerator is not in the middle of nothing

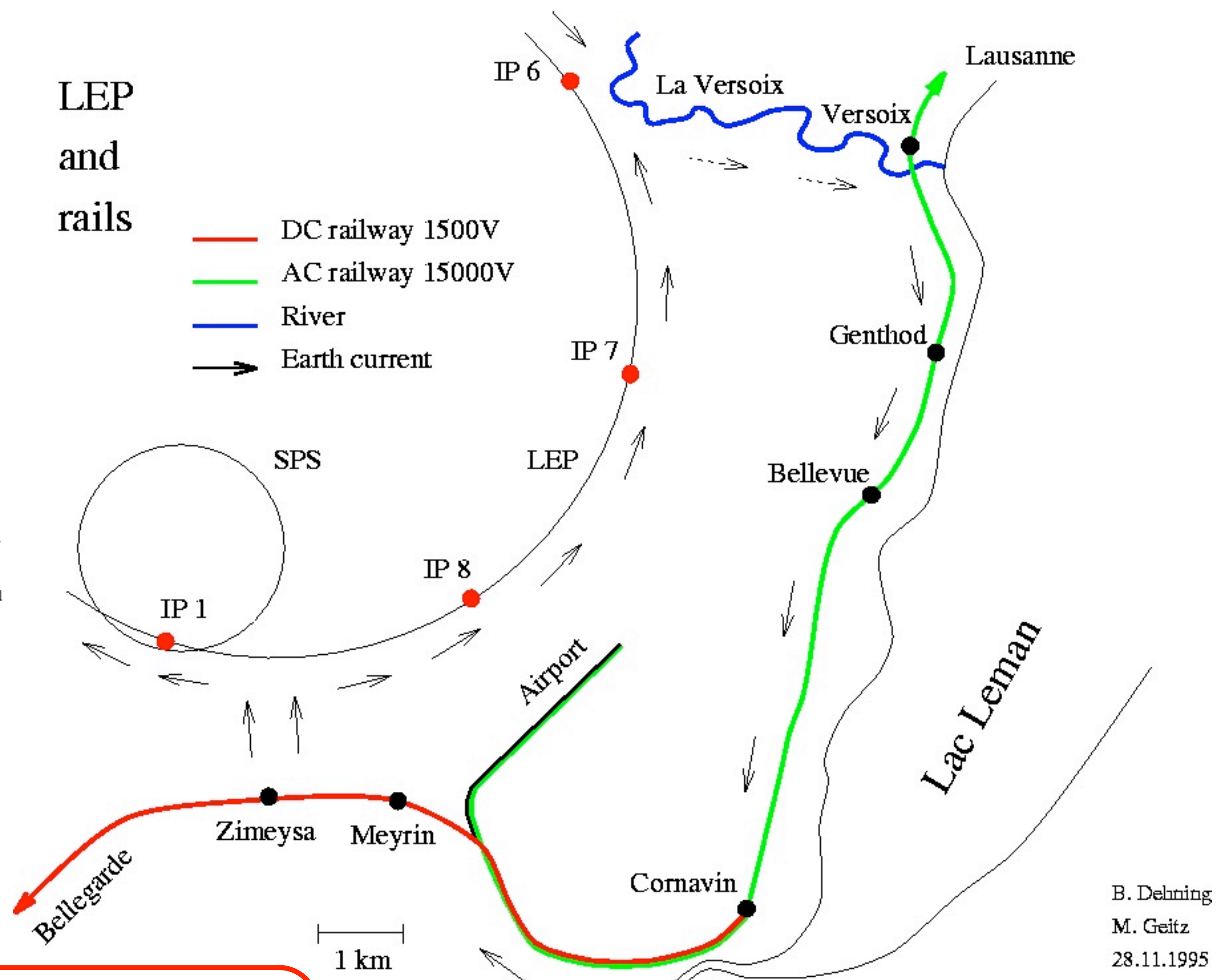
Observed variation of the bending strength of the LEP dipoles during the day





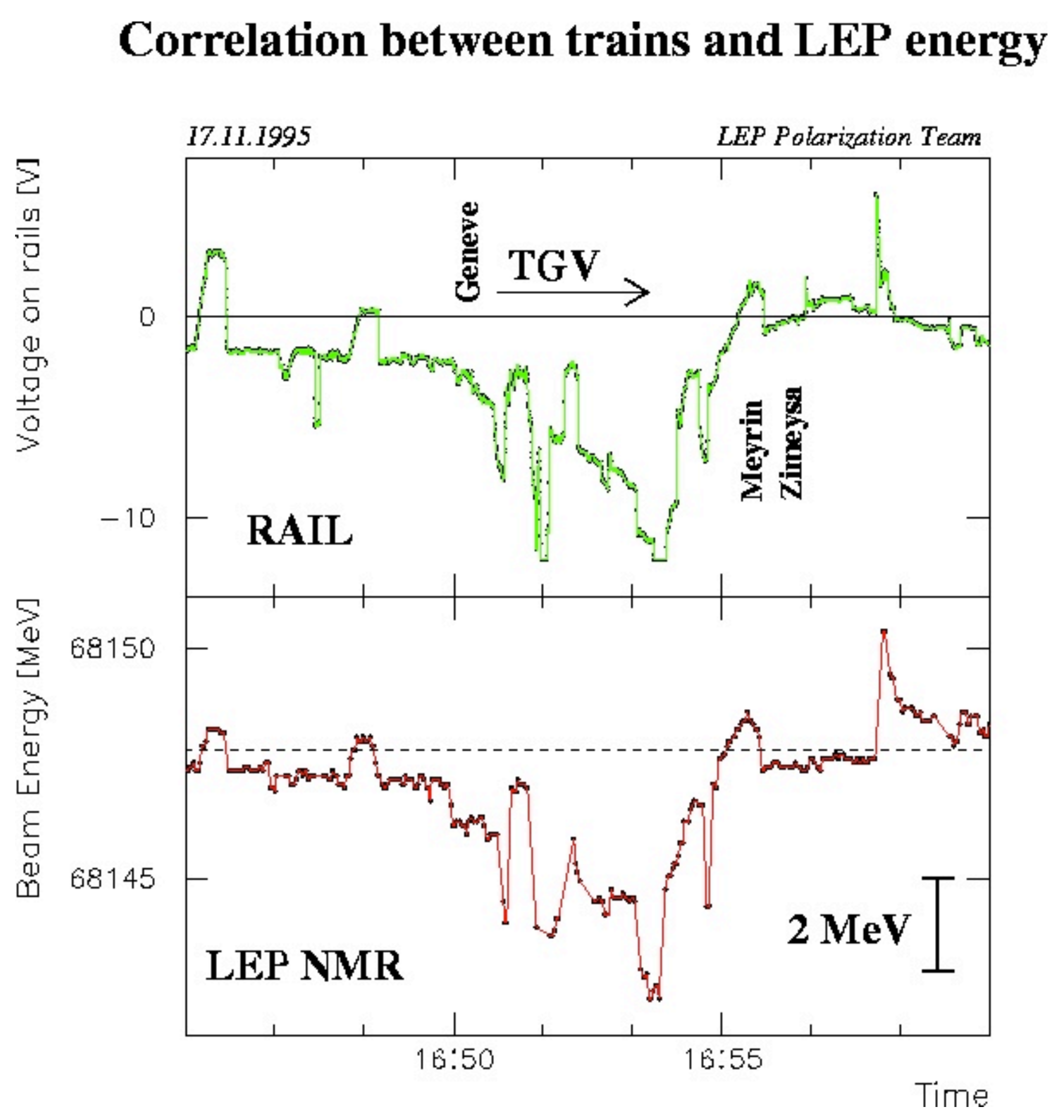
Influence of train leakage current





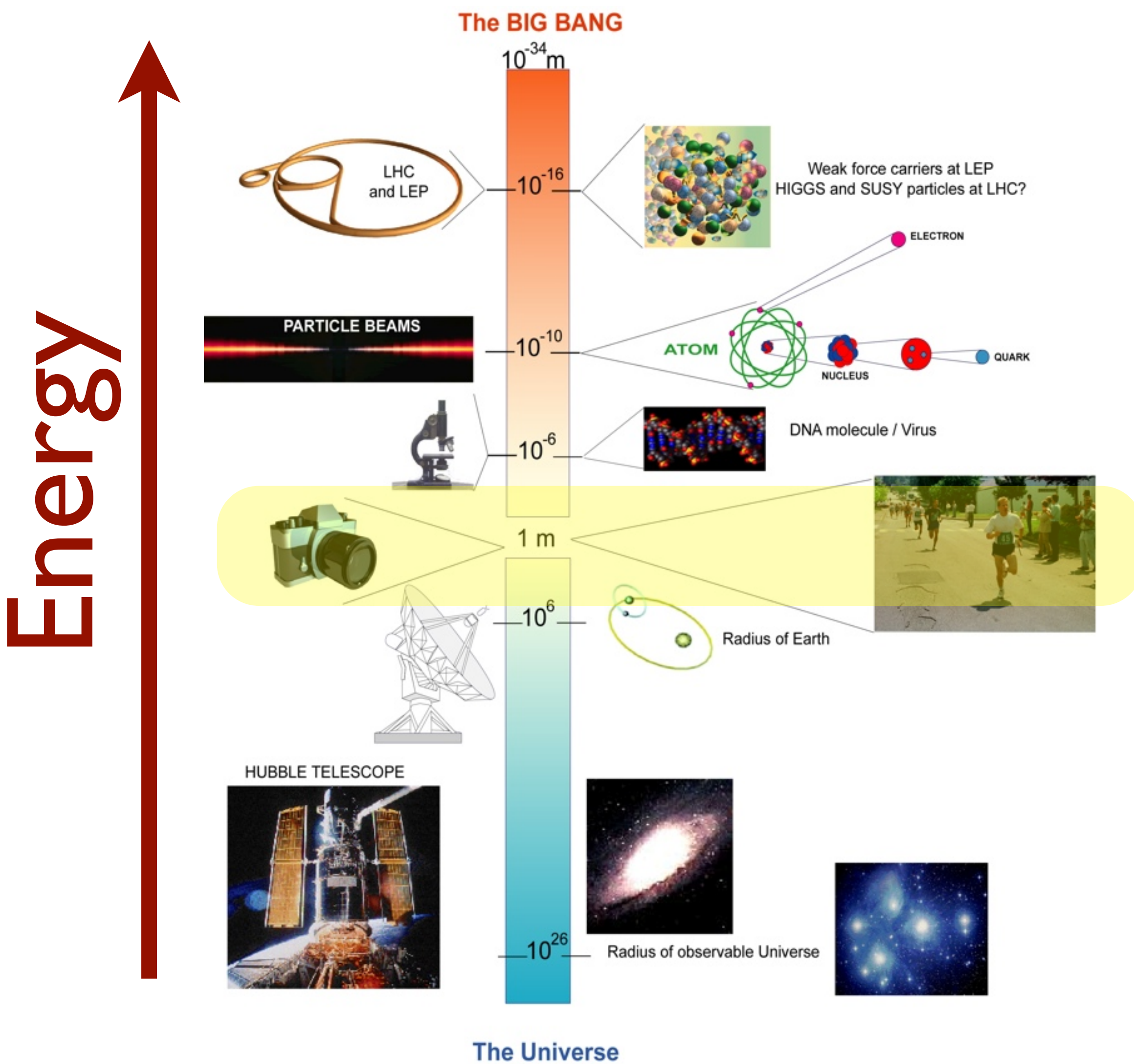
LEP beam pipe as ground for leakage current.
Variation of the dipole field due to the current .
Change in energy following the SNCF train table

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



[redacted]

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

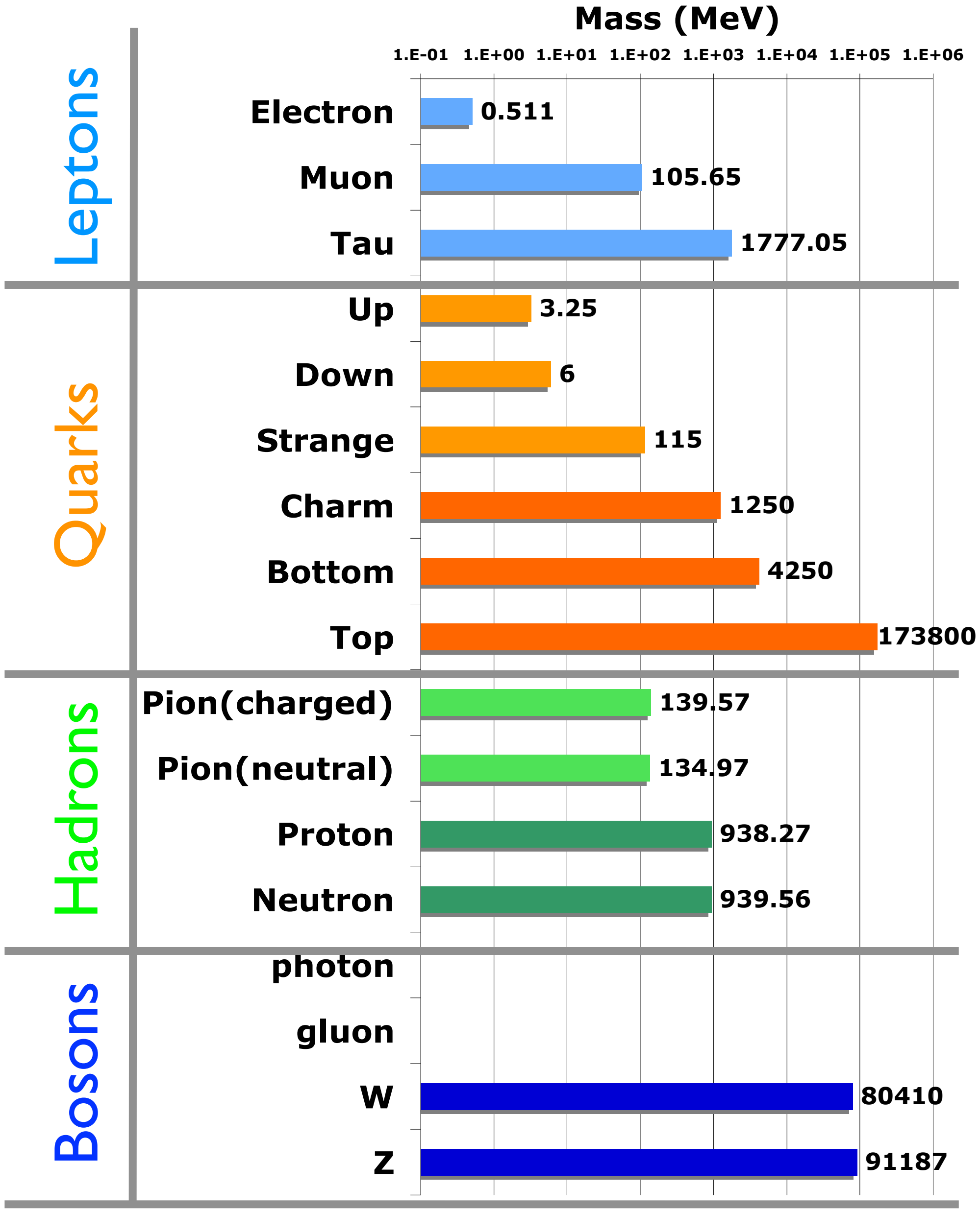
Need accelerators for higher energies.

"electronic eyes"

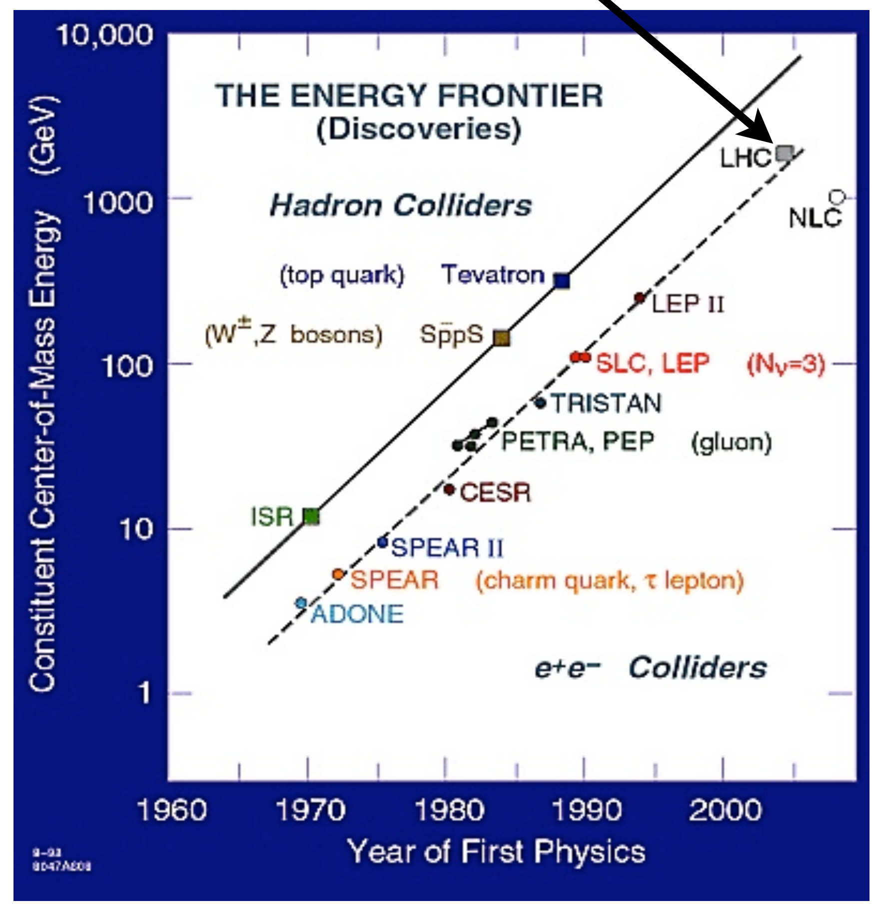
The typical energy of our life is eV

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

History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

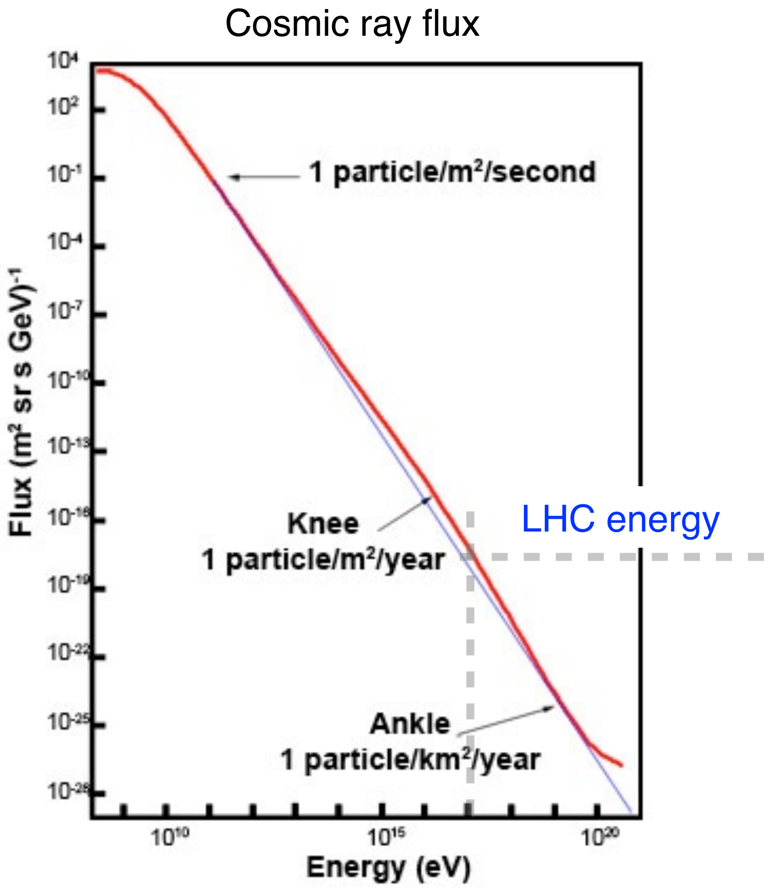


Constant increase in energy to discover heavier and heavier particles or very rare processes

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)

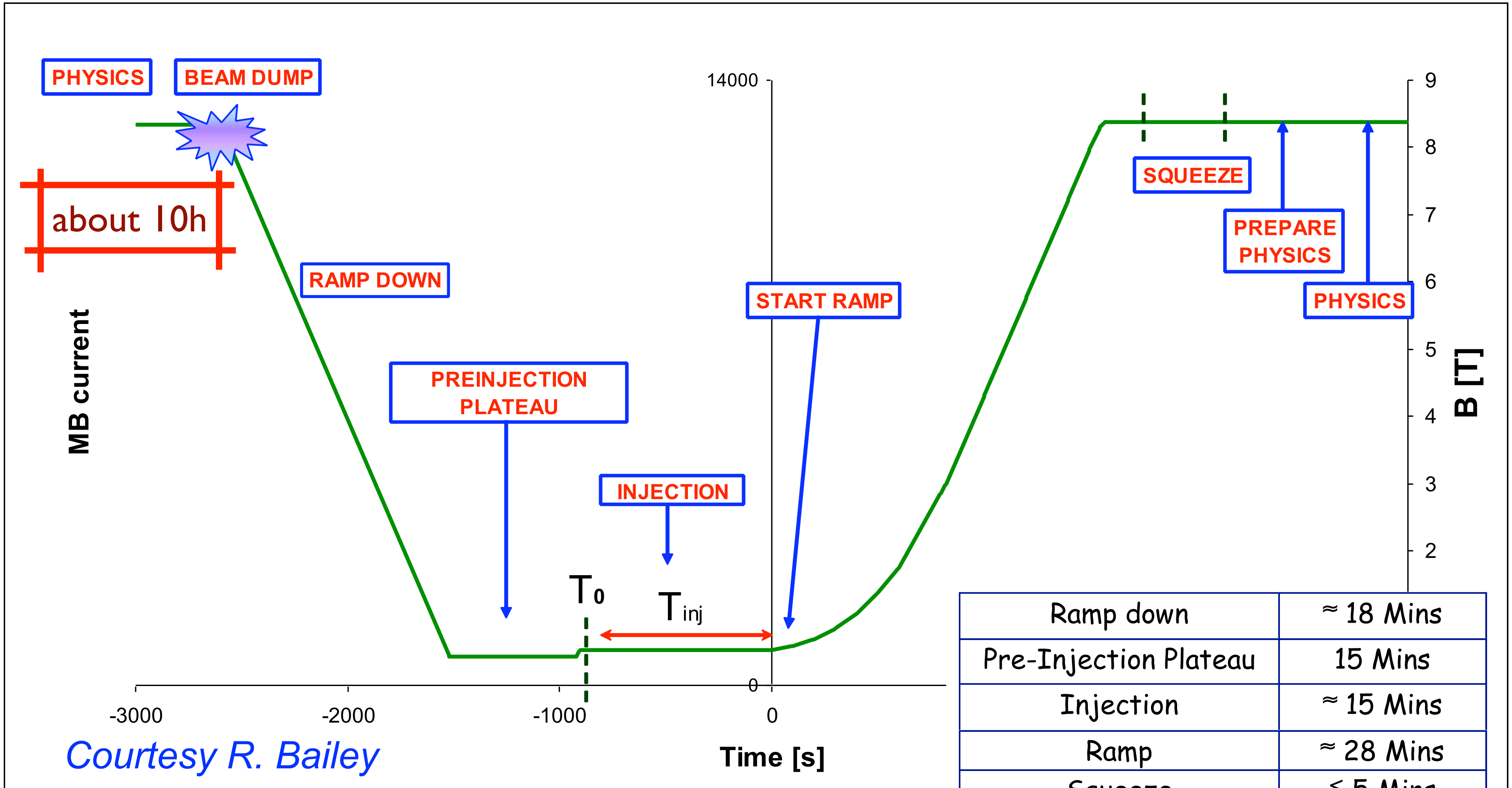
Why particle accelerators ?

- *Why accelerators?:* need to produce under controlled conditions 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/cm^2/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!

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