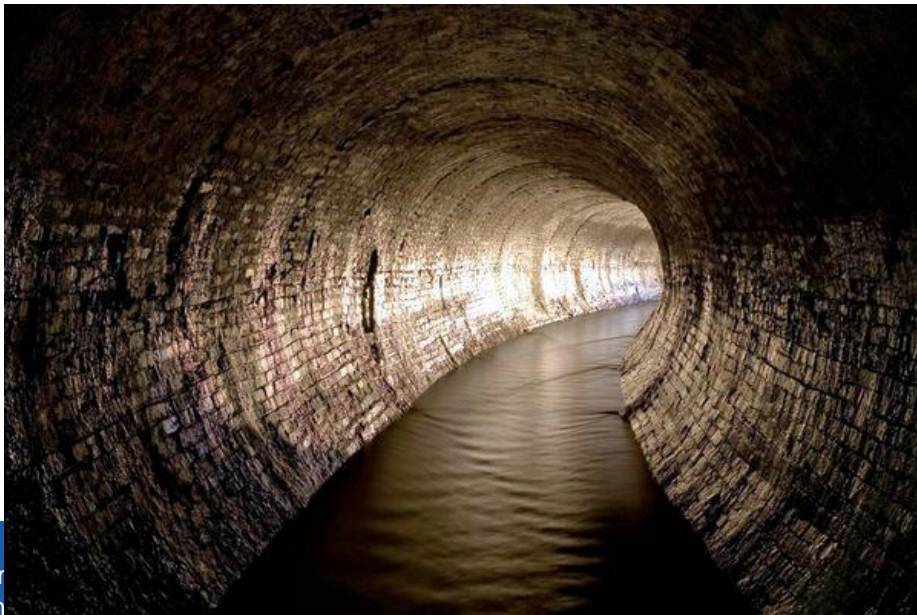


# Building Blocks of an accelerator



1) A particle source

3) A series of guiding and storage devices



2) An accelerating system



Everything under vacuum



# 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.

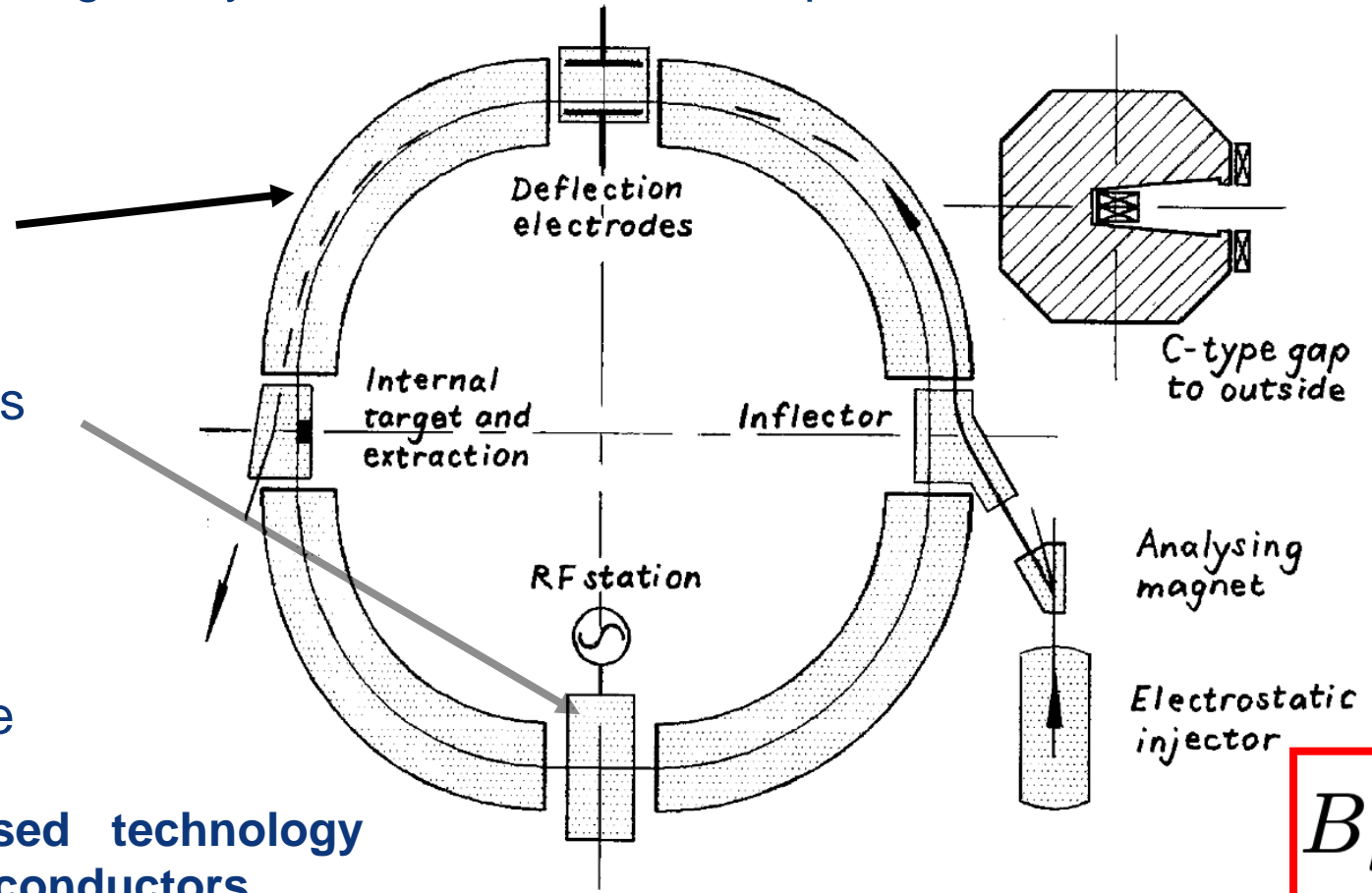
$B = B(t)$  magnetic field from the bending magnets

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

$e$  electric charge

$\rho$  constant radius of curvature

Bending strength limited by used technology to max  $\sim 1$  T for room temperature conductors



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

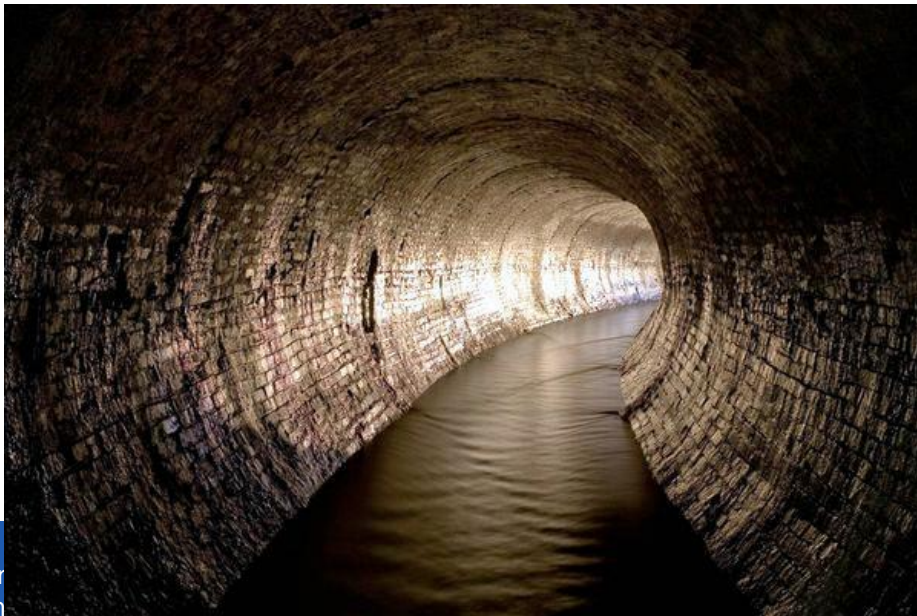
Particle rigidity:

# Building Blocks of an accelerator



1) A particle source

3) A series of guiding and storage devices



2) An accelerating system

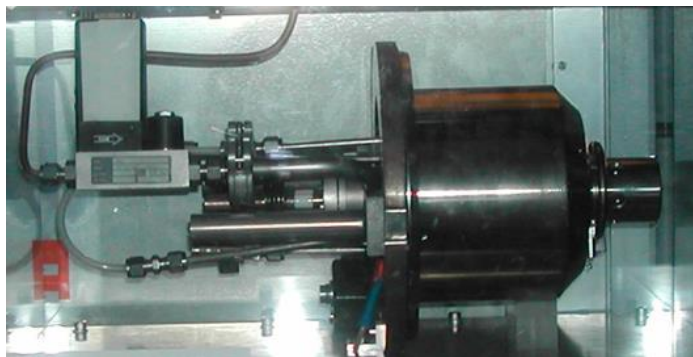


Everything under vacuum



# How to get protons: duoplasmatron source

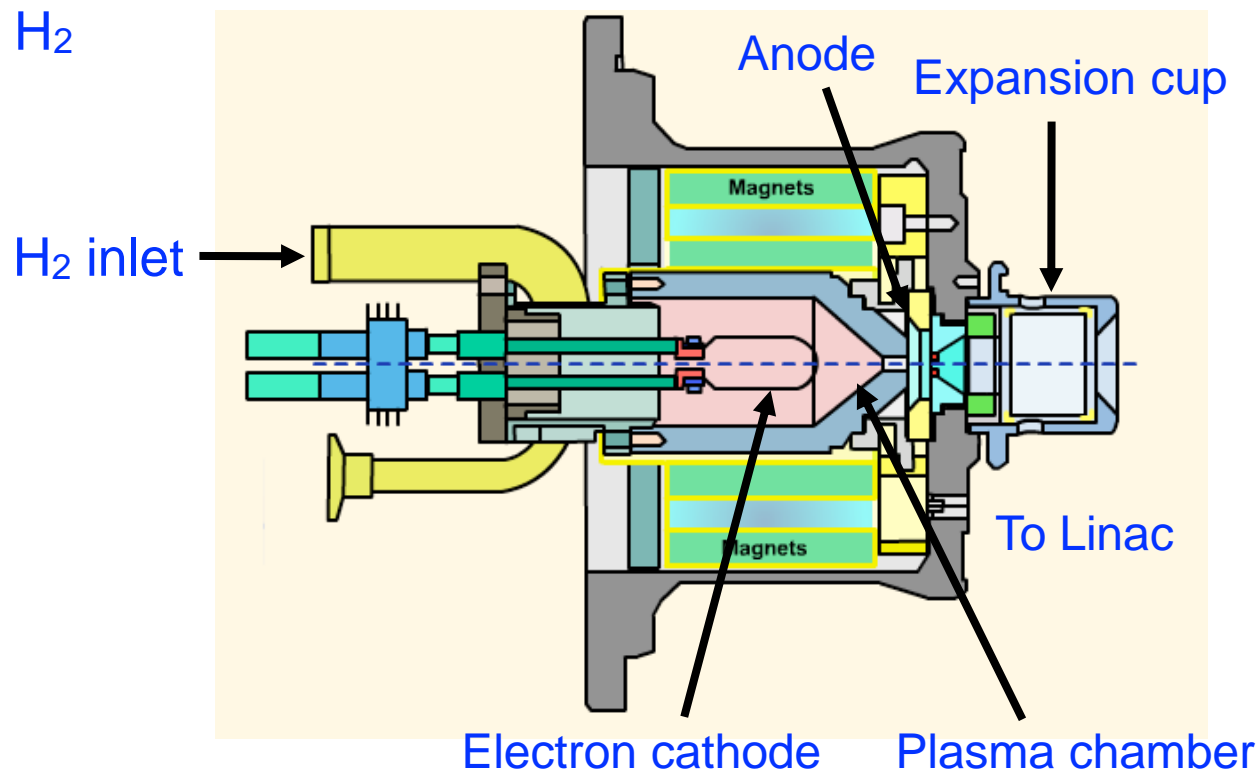
Protons are produced by the ionization of H<sub>2</sub> plasma enhanced by an electron beam



Hydrogen supply (one lasts for 6 months)



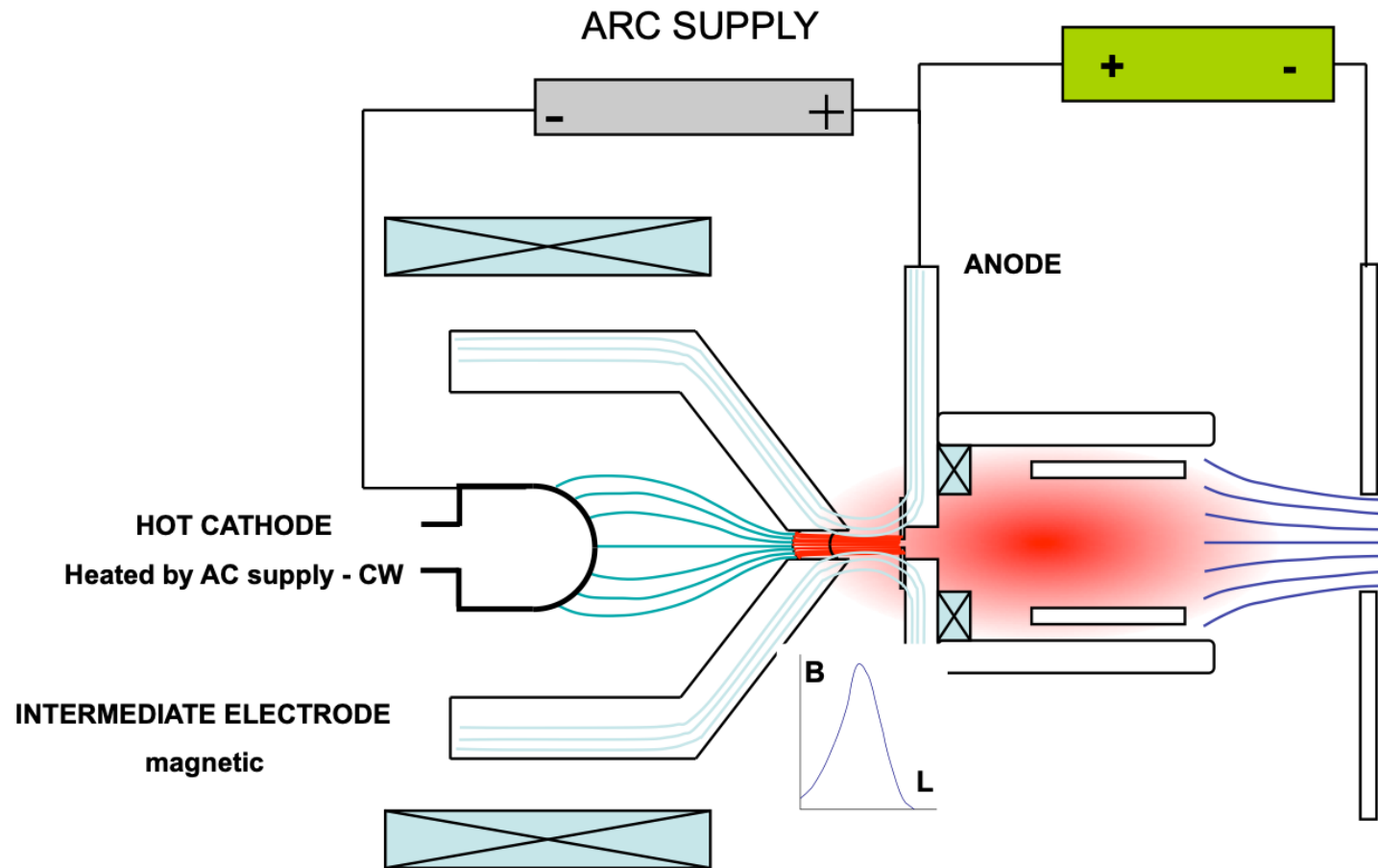
Back of the source



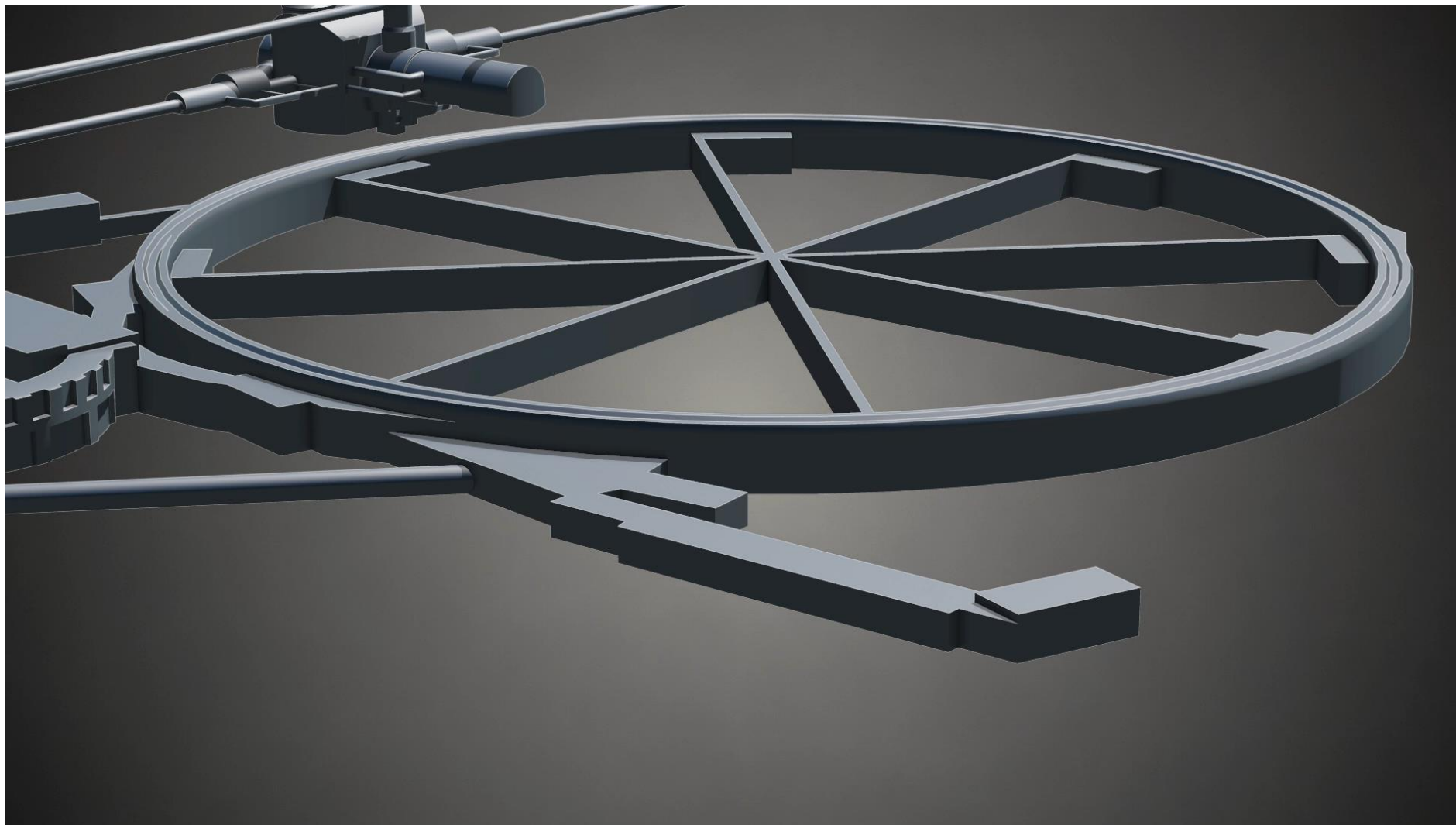
Proton exiting from the about 1 mm<sup>2</sup> hole have a speed of 1.4 % c,  $v \approx 4000$  km/s

The SPACE SHUTTLE goes only up to 8 km/s  
**Today we have an H<sup>+</sup> source, 2<sup>nd</sup> level lectures**

# Source electrical scheme



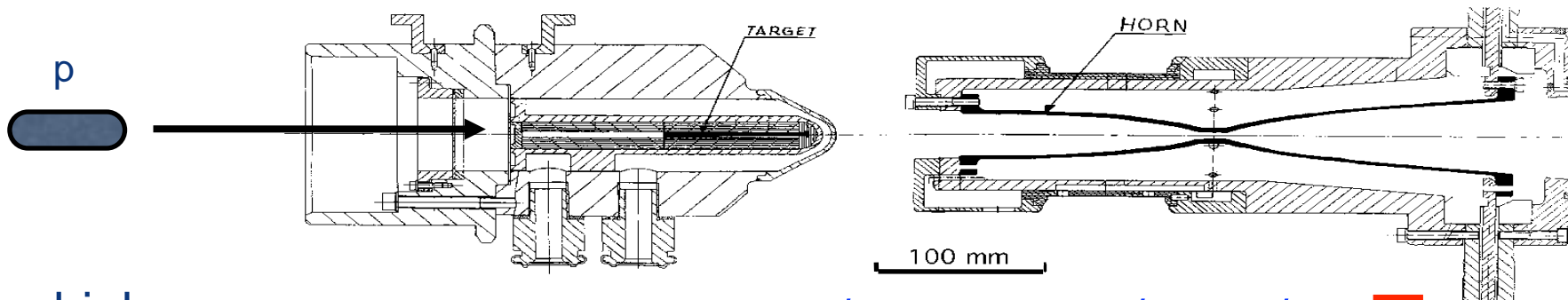
*Courtesy R. Scrivens*



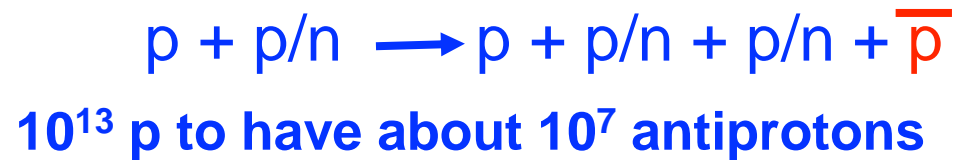
## Cern Control Center: first LHC day



# How to get antiprotons



Starting from high energy  $p$   
and with a very low efficiency



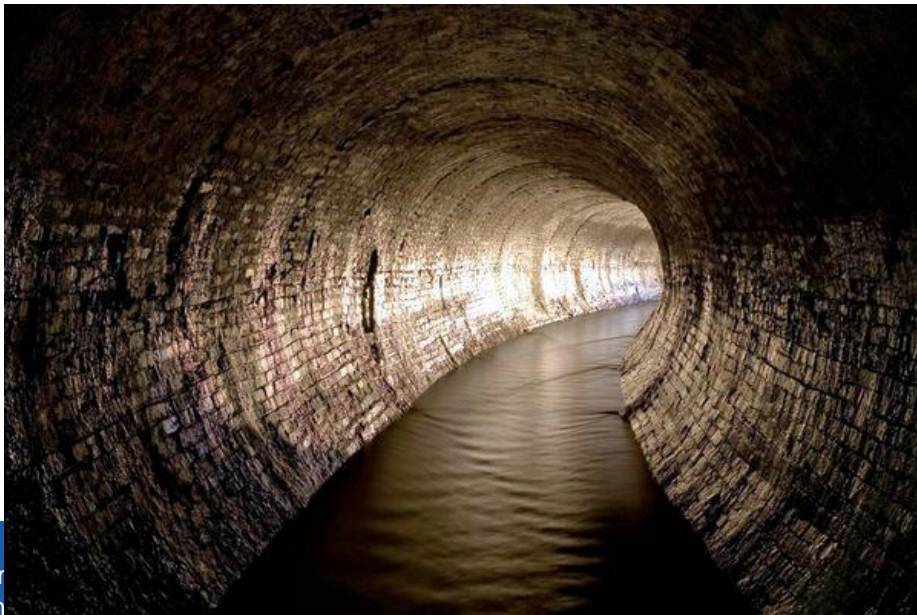


# Building Blocks of an accelerator



1) A particle source

3) A series of guiding and storage devices



2) An accelerating system

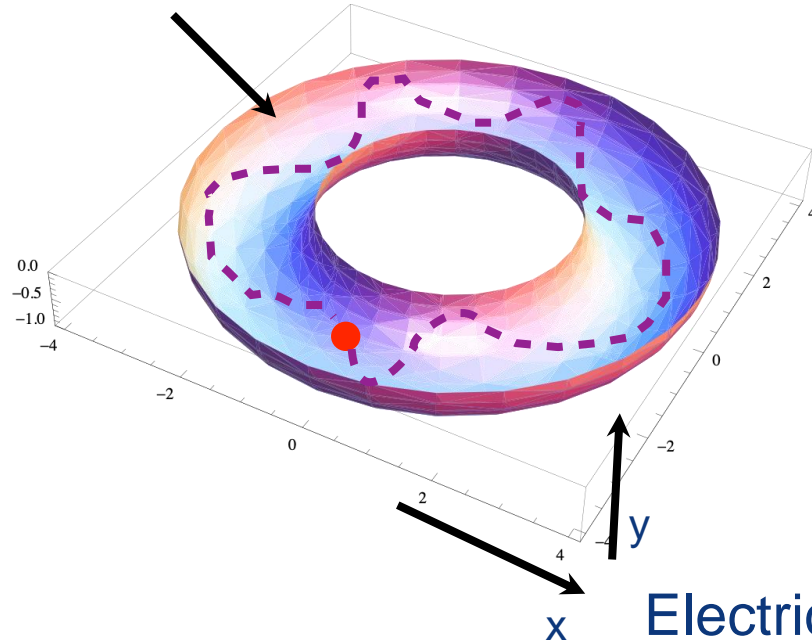


Everything under vacuum



# How an accelerator works ?

*Accelerator*



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

**How ? Lorentz Force!**

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

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

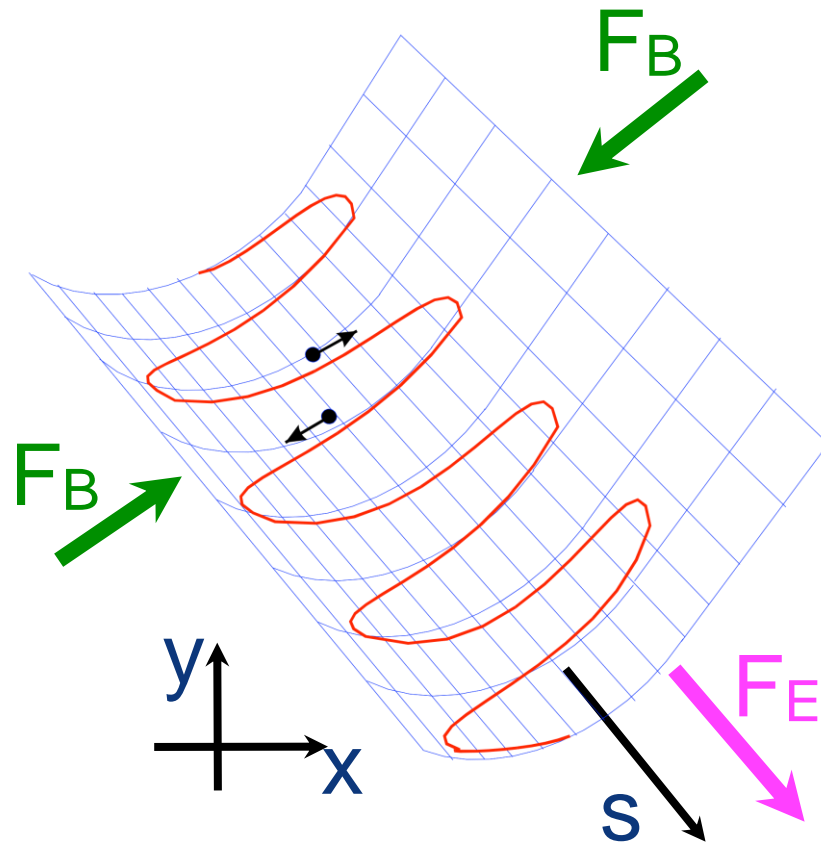
*An **accelerator** is formed by a sequence (called **lattice**) of:*

*a) **Magnets** → **Magnetic Field***

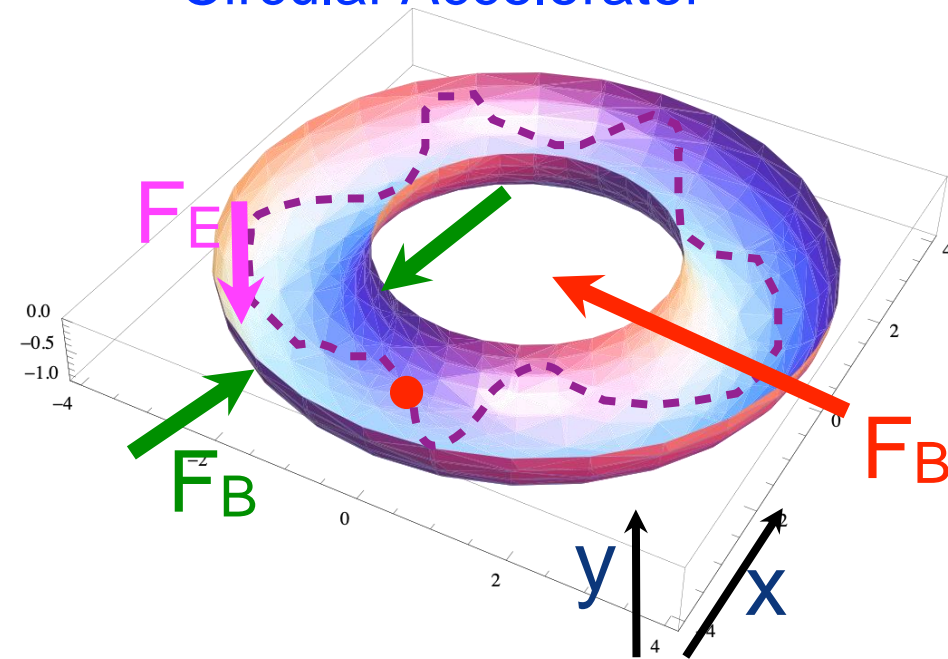
*b) **Accelerating Cavity** → **Electric Field***

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

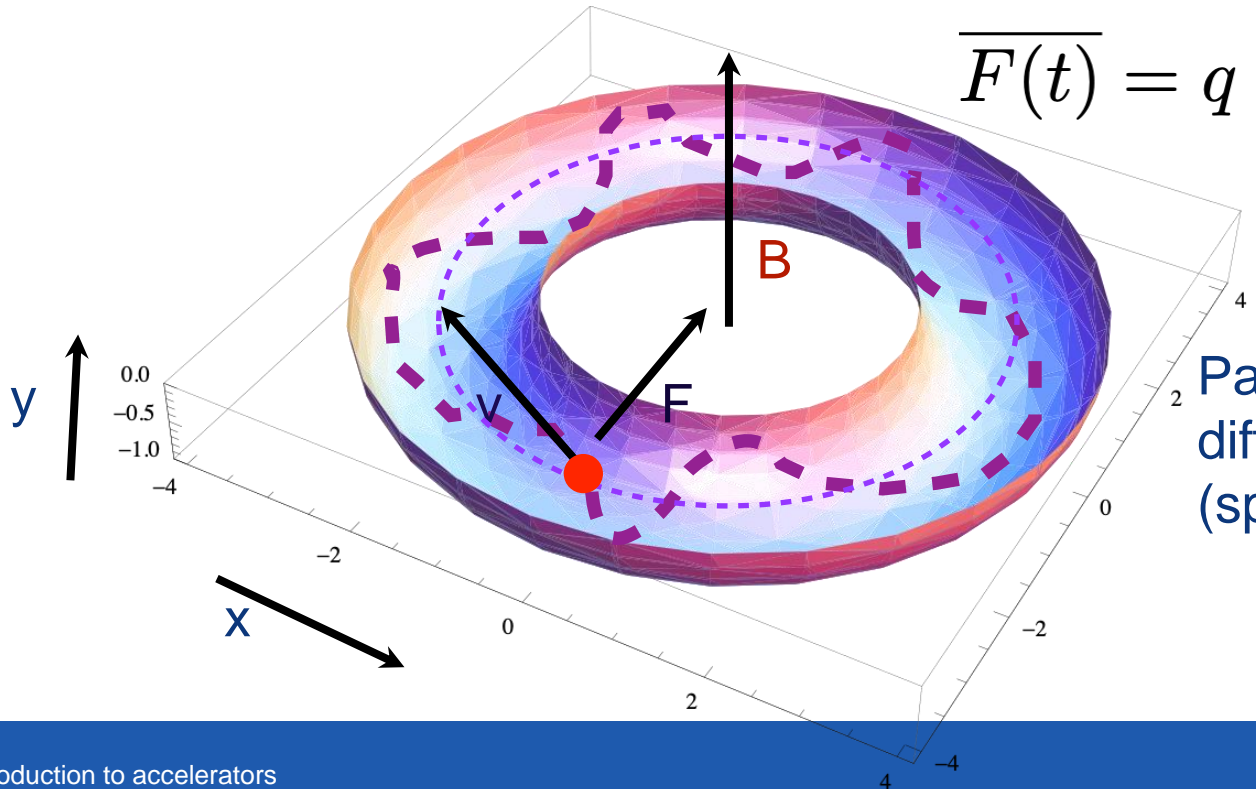
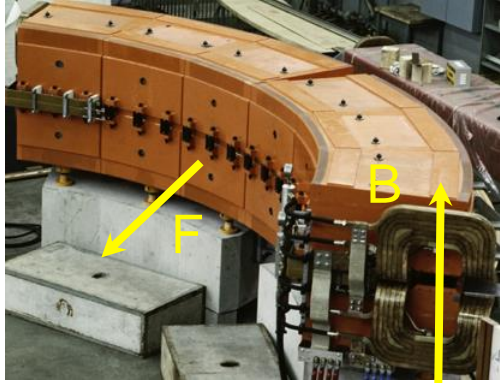
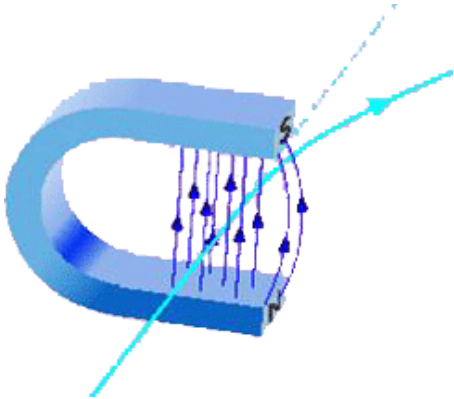
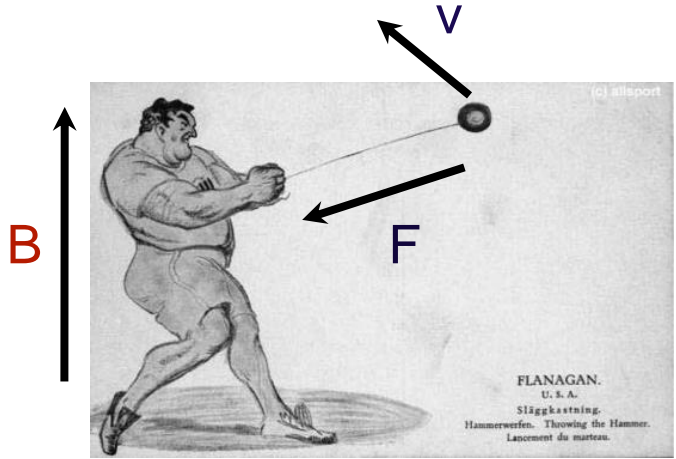
Linear Accelerator



Circular Accelerator



# How an accelerator works ? A dipole

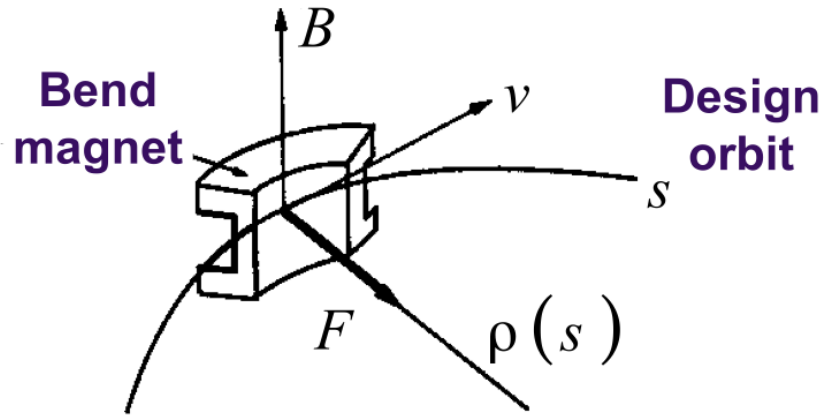


$$\overline{F(t)} = q \left( \overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)} \right)$$

Particles of different energy (speed) behave differently

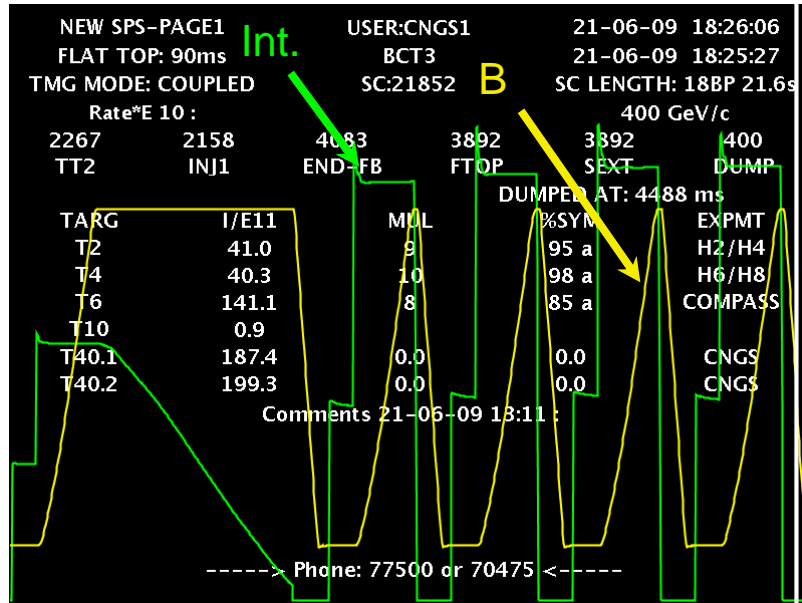
Magnetic field confines particles on a given trajectory

# Dipoles



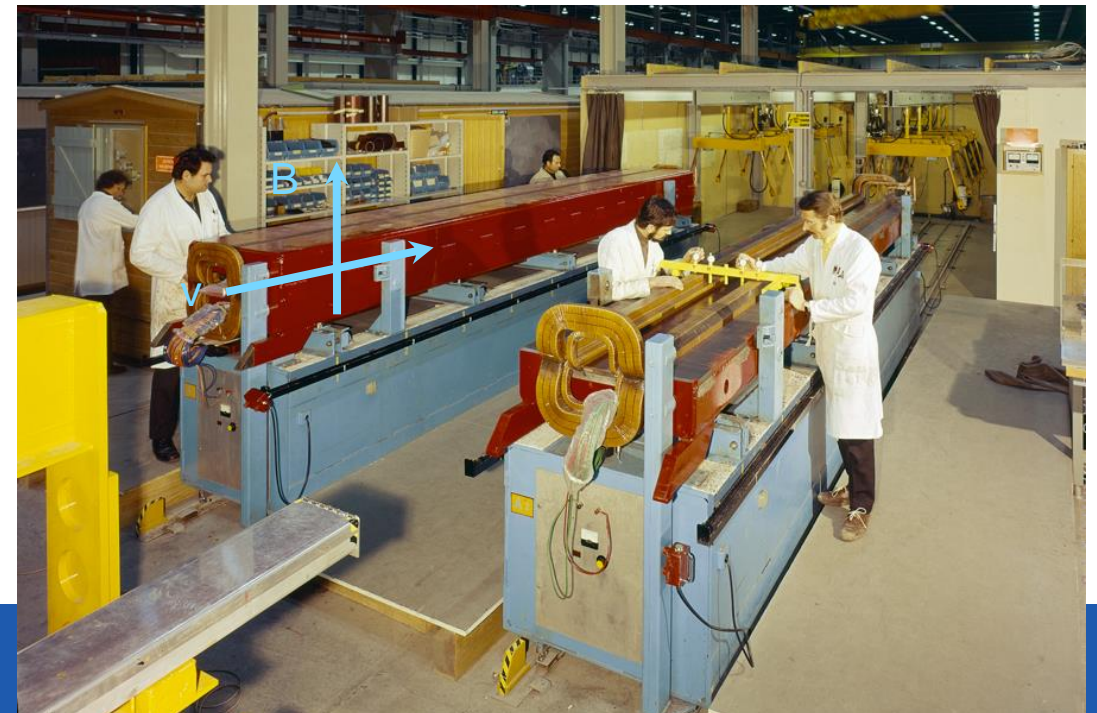
Force given by the vertical magnetic field compensates the centrifugal force to keep the particles on the central trajectory, i.e. in the center of the beam pipe.

A fast dipole, able to deflect the beam in few  $\mu\text{s}$  is called **kicker**. A kicker is used to extract the beam from the machine.

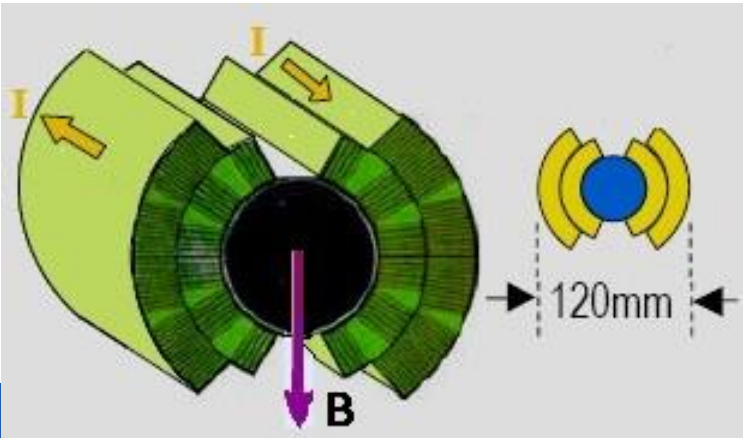
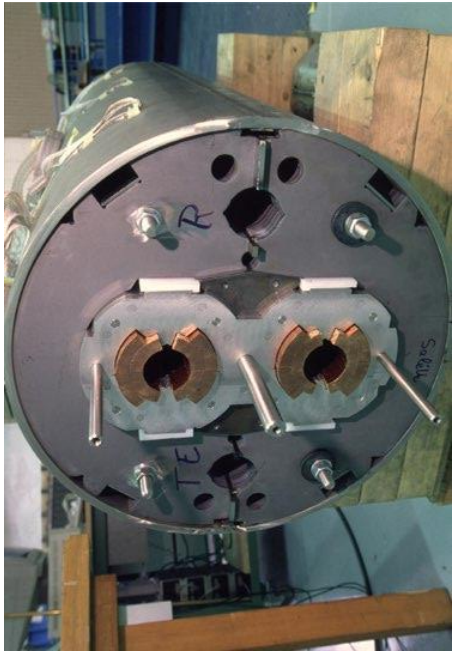
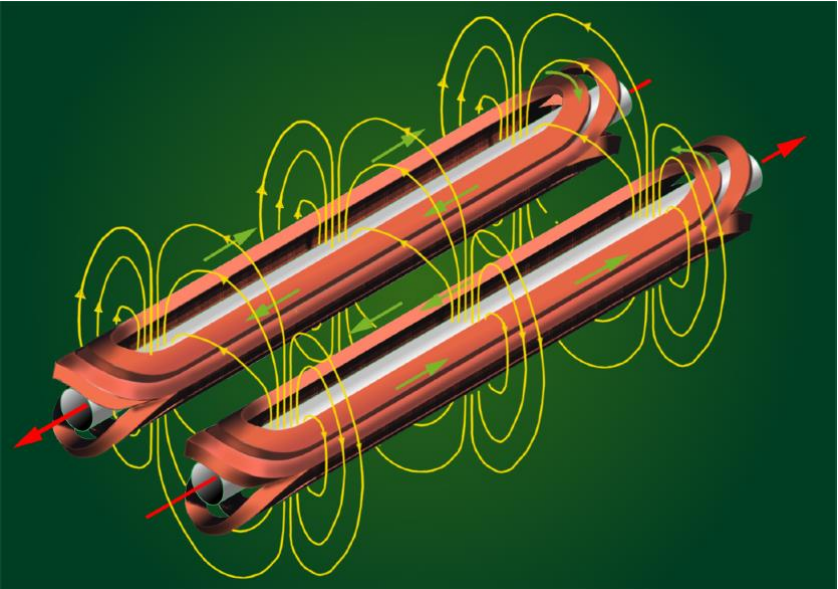


time (s) [21.6 s]

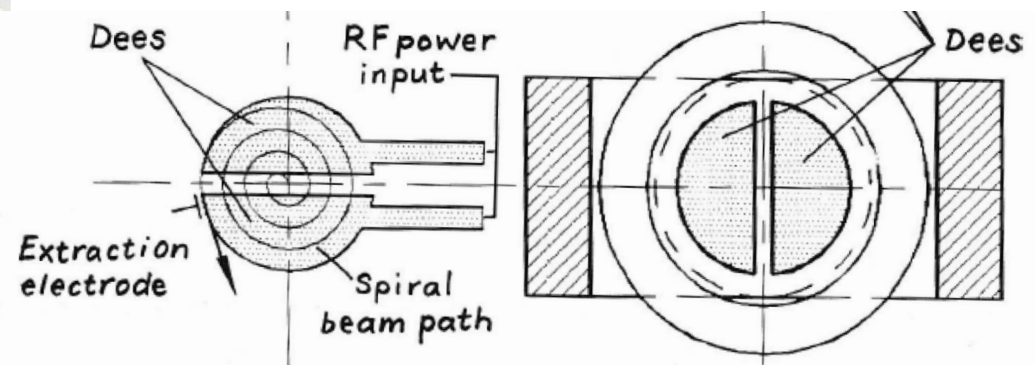
CERN-SPS dipoles, in total about 500



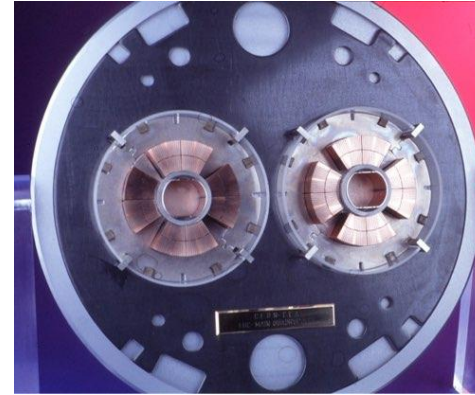
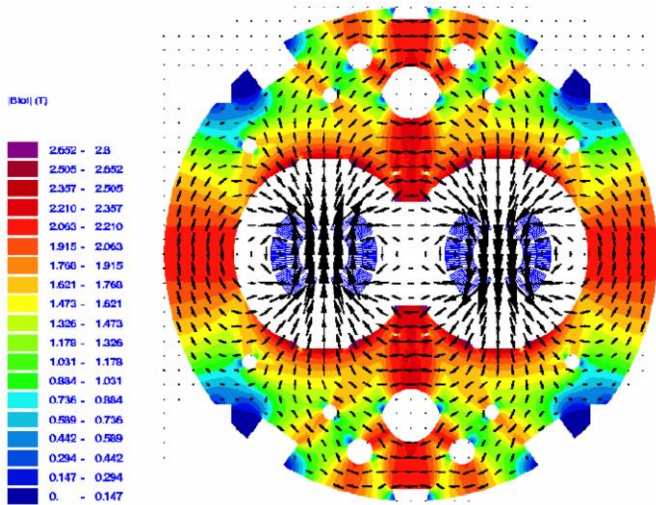
# B-field right hand rule



# The first cyclotron and the Berkeley one



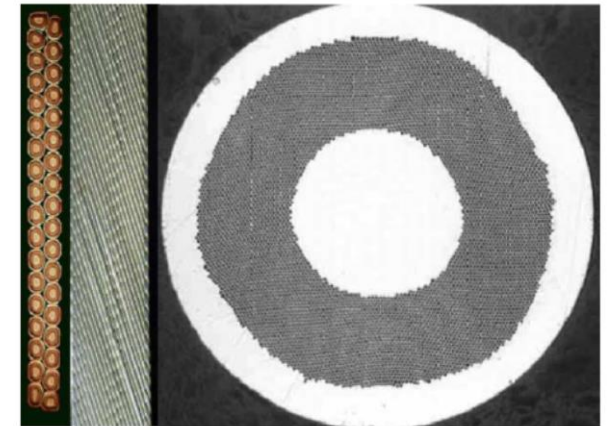
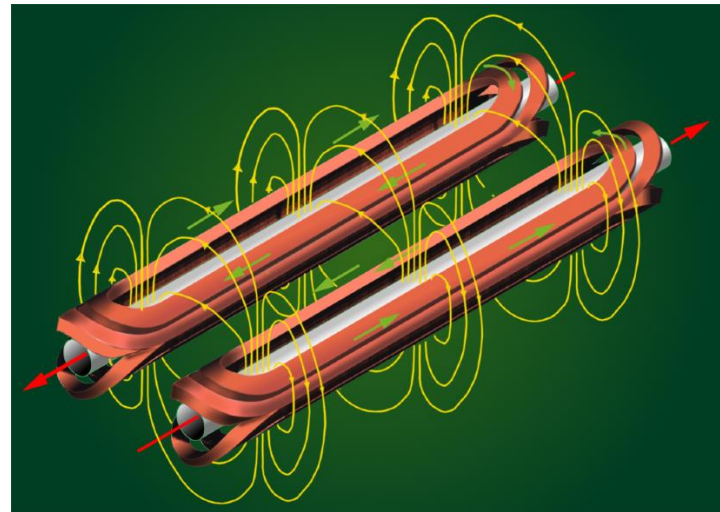
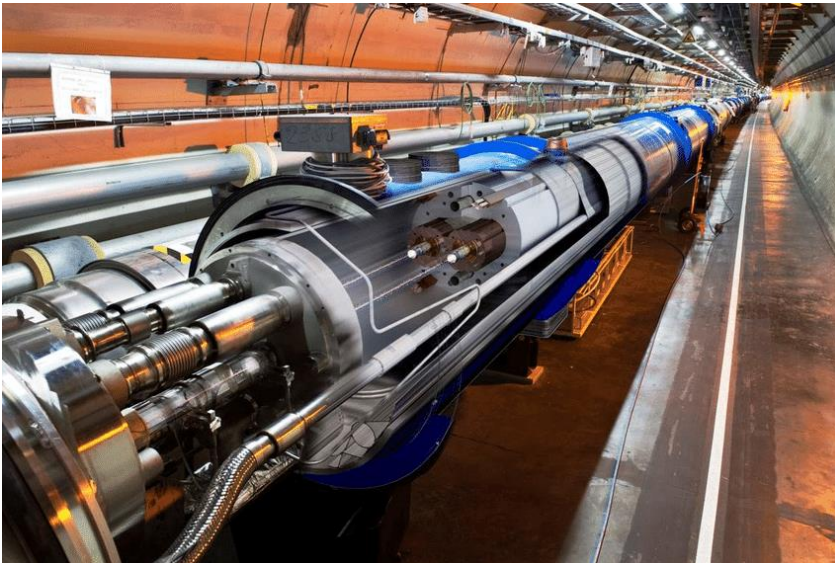
# Two-in-one magnet design



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

1232 dipoles  
15 m long  
11800 A

Nb –Ti **superconducting** cable in a Cu matrix  
**LHC lives at 1.9 - 2 K**



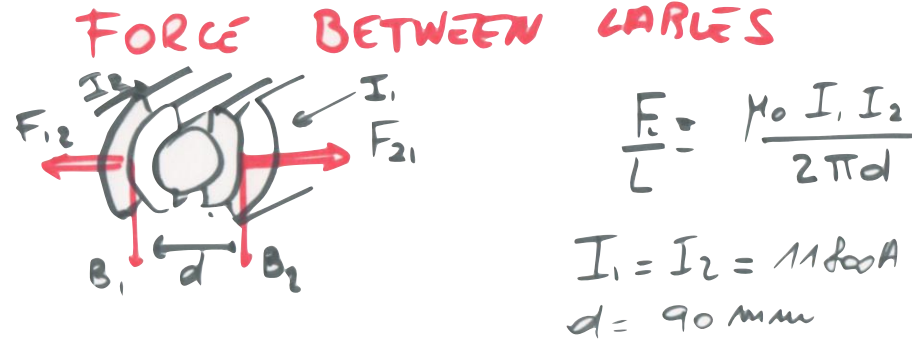


# LHC dipoles



**Max Current:** ~ 11800 A  
**Max Field (7 TeV) :** 8.33 T  
**Temperature:** ~ 2 K  
**Tot. Energy stored:** ~10 GJ

**To compare**  
 Current at home : 15 A  
 Earth magnetic Field: 25-65  $\mu$ T  
 Temperature : 297.15 K (24 C)



$$F_c/L = 310 \text{ N/m}$$

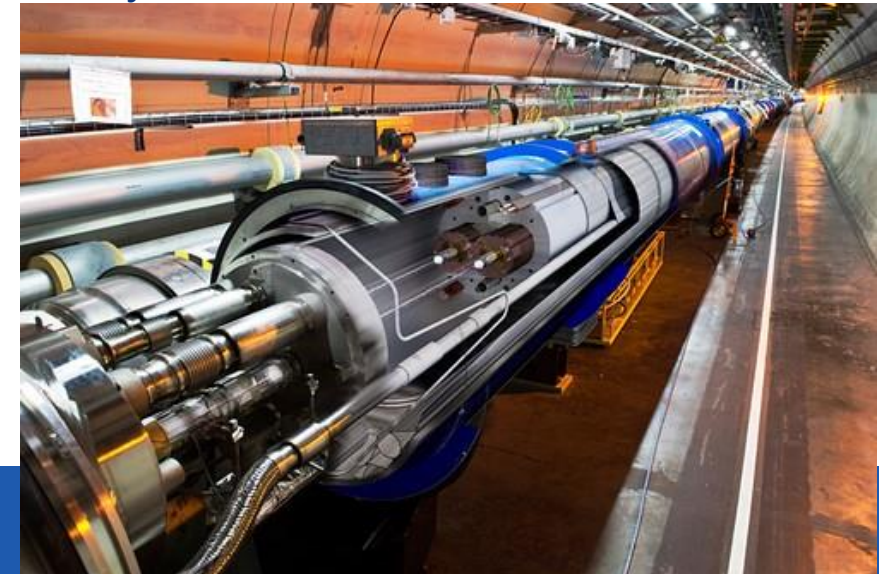
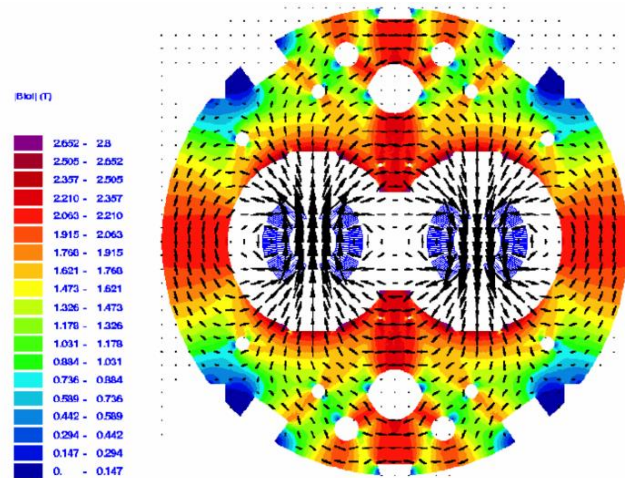
2 SETS OF 80 CABLES

$$F_{TOT} = 80 \cdot 80 \cdot 310 \sim 2 \cdot 10^6 \text{ N/m}$$

The force generated by this at liftoff

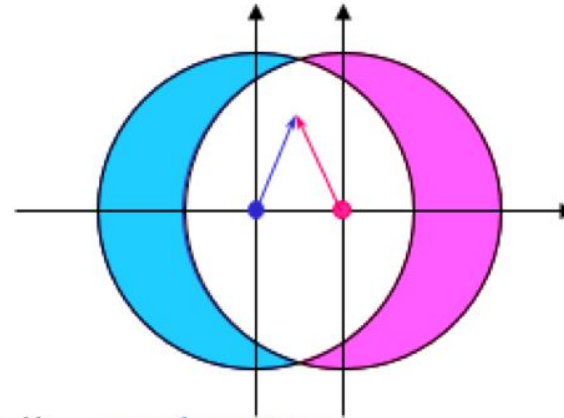
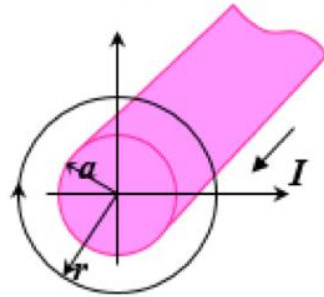
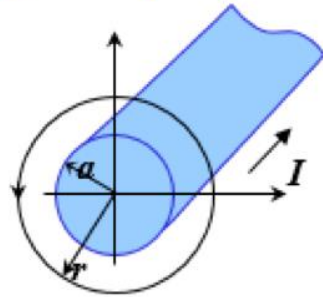


At every meter of this between the cables....



# The $\cos \phi$ coil

- Consider now the field generated by two wires
  - They carry equal currents in opposite directions



- Now consider the geometry with the two wire partially overlapping
  - The current in the overlap is zero
  - The magnetic field in the overlap is uniform and directed along  $y$

•  $B_x = B_{1x} + B_{2x}$

$$B_{1x} = -\frac{\mu_0}{2} J_1 r_1 \sin f_1$$

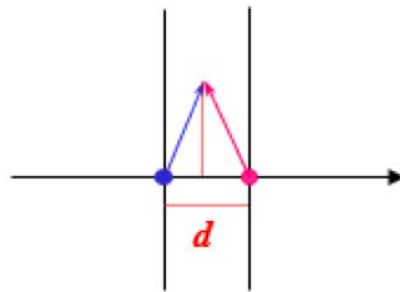
$$B_{2x} = -\frac{\mu_0}{2} J_2 r_2 \sin f_2$$

$$B_x = \mu_0 \frac{|J|}{2} (r_1 \sin f_1 - r_2 \sin f_2)$$

$$r_1 \sin f_1 = r_2 \sin f_2$$

$$B_x = 0$$

$$B_y = \mu_0 \frac{|J| d}{2}$$



$$B_y = B_{1y} + B_{2y}$$

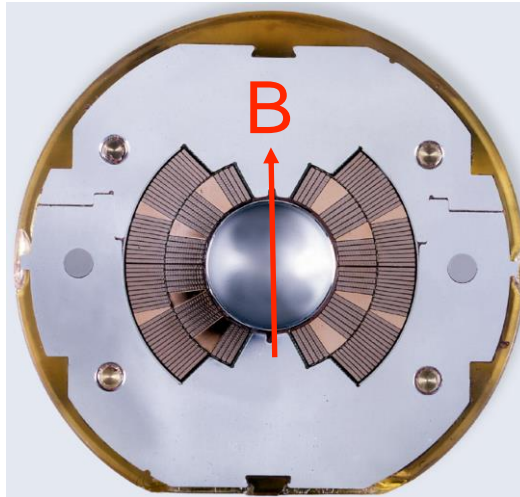
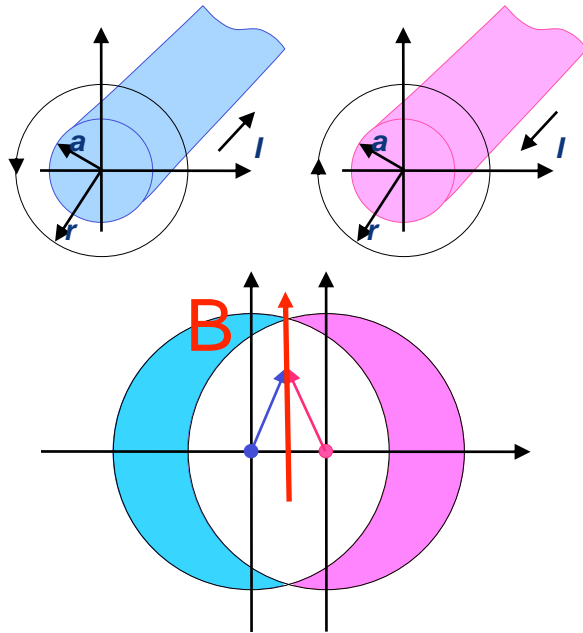
$$B_{1y} = \frac{\mu_0}{2} J_1 r_1 \cos f_1$$

$$B_{2y} = \frac{\mu_0}{2} J_2 r_2 \cos f_2$$

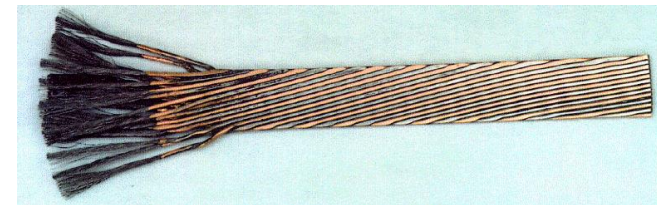
$$B_y = -\mu_0 \frac{|J|}{2} (r_1 \cos f_1 - r_2 \cos f_2)$$

$$r_1 \cos f_1 - r_2 \cos f_2 = d$$

# Cosθ coil of main dipoles



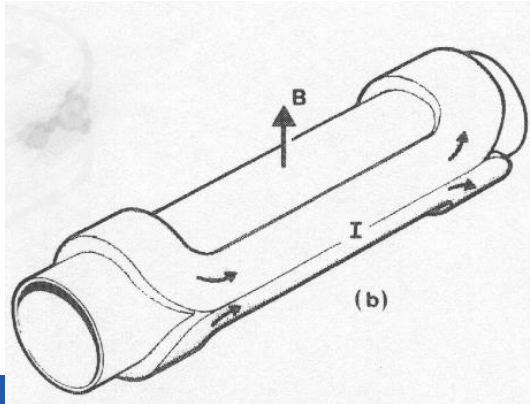
A 2D cosθ current distribution generates a quasi-perfect vertical field in the aperture between the two conductors.



$$I = I_0 \cos \vartheta$$

$$B_\vartheta = \frac{\mu_0 I_0}{2 r_0} \cos \vartheta \quad B_x = 0$$

$$B_\vartheta = \frac{\mu_0 I_0}{2 r_0} \sin \vartheta \quad B_y = \frac{\mu_0 I_0}{2 r_0}$$



Dipolar Vertical field

# CENTRIFUGAL FORCE

$$v \sim c \quad \boxed{F_c = \frac{mc^2}{r}} \quad F_c = \frac{E}{r}$$

$$N_{\text{DIPOLÉS}} = 1232 \quad L_{\text{DIPOLÉS}} = 14,3 \text{ m}$$

$$L_{\text{TOT, DIP}} = 1232 \times 14,3 = 17618 \text{ m}$$

$$\text{BENDING RADIUS} \rightarrow r_b = \frac{17618 \text{ m}}{2\pi}$$

$$r_b = 2804 \text{ m}$$

$$F_c = \frac{7 \text{ TeV}}{2804 \text{ m}} \Rightarrow F_c = \frac{1,12 \cdot 10^{-6} \text{ J}}{2804 \text{ m}}$$

$$\boxed{F_c = 4 \cdot 10^{-10} \text{ N}}$$

# Force scale (from Wikipedia)

Factor (N)	Value	Item
$10^{-47}$	$3.6 \times 10^{-47}$ N	Gravitational attraction of the proton and the electron in hydrogen atom <sup>[1]</sup>
$10^{-30}$	$8.9 \times 10^{-30}$ N	Weight of an electron <sup>[1]</sup>
$10^{-26}$	$1.6 \times 10^{-26}$ N	Weight of a hydrogen atom <sup>[1]</sup>
$10^{-24}$ yoctonewton (yN)	5yN	Force necessary to synchronize the motion of a single trapped ion with an external signal measured in a 2010 experiment <sup>[2][3]</sup>
$10^{-22}$	170 yN	Force measured in a 2010 experiment by perturbing 60 beryllium-9 ions <sup>[4][5]</sup>
$10^{-15}$ femtonewton (fN)		
$10^{-14}$	~10 fN	Brownian motion force on an <i>E. coli</i> bacterium averaged over 1 second <sup>[6]</sup>
	~10 fN	Weight of an <i>E. coli</i> bacterium <sup>[7][8]</sup>
$10^{-13}$	~100 fN	Force to stretch double-stranded DNA to 50% relative extension <sup>[6]</sup>
$10^{-12}$ piconewton (pN)	~4 pN	Force to break a hydrogen bond <sup>[6]</sup>
	~5 pN	Maximum force of a molecular motor <sup>[6]</sup>
$10^{-11}$		
$10^{-10}$	~160 pN	Force to break a typical noncovalent bond <sup>[6]</sup>
$10^{-9}$ nanonewton (nN)	~1.6 nN	Force to break a typical covalent bond <sup>[6]</sup>
$10^{-8}$	$8.2 \times 10^{-8}$ N	Force on an electron in a hydrogen atom <sup>[1]</sup>
$10^{-7}$	$2 \times 10^{-7}$ N	Force between two 1 meter long conductors, 1 meter apart by the definition of one ampere
$10^{-6}$ micronewton ( $\mu$ N)	1–150 $\mu$ N	Output of FEEP ion thrusters used in NASA's Laser Interferometer Space Antenna <sup>[9]</sup>
$10^{-4}$		
$10^{-3}$ millinewton (mN)		
$10^{-2}$	19-92 mN	Thrust of the NSTAR ion engine tested on NASA's space probe Deep Space 1 <sup>[10]</sup>
$10^{-1}$		

$$\vec{F}_c = q \cdot \vec{v} \wedge \vec{B}$$

$$B = F_c / (q \cdot v)$$

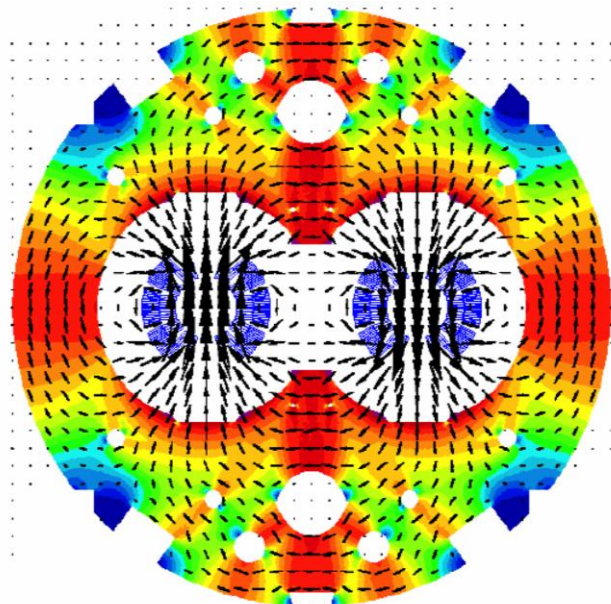
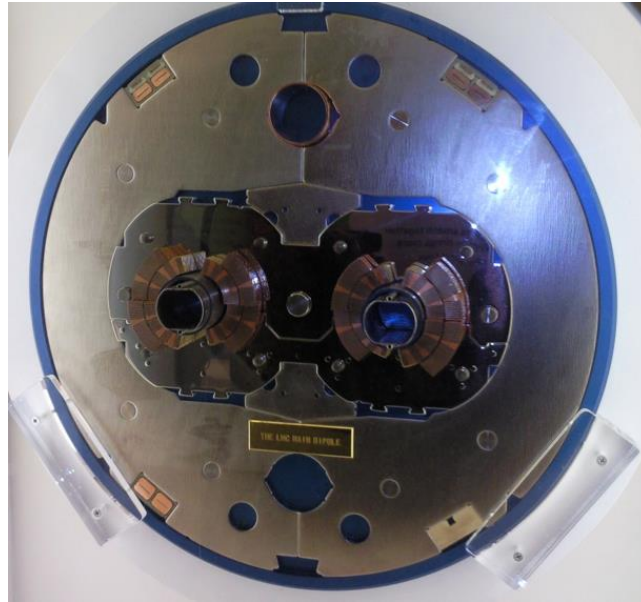
$$F_c = 4 \cdot 10^{-10} \text{ N}$$

$$q = 1,602 \cdot 10^{-19} \text{ C}$$

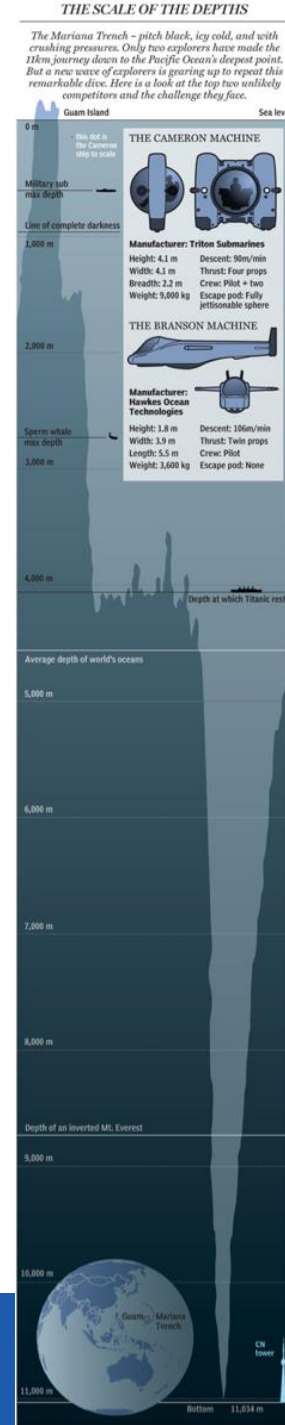
$$v \sim c$$

$$B \sim 8,33 \text{ T}$$

# Pressure on conductors ~ 110 MPa



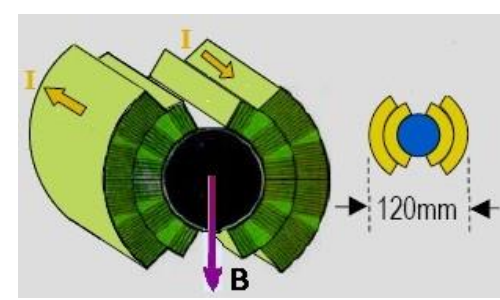
About same pressure  
at the bottom of  
Mariana trench:  
11 000 m of water



# DIPOLÉS

$$B = \frac{\mu_0 I}{2\pi d}$$

BIOT-SAVART



Average distance between cables and beam pipe center

$$d = 2 \cdot r \quad r = 45 \text{ mm}$$

$$I \sim 11 \text{ kA} \Rightarrow B_c \sim 0,05 \text{ T per cable}$$

$$B_{\text{DIPOLÉ}} = 1,33 \text{ T} \Rightarrow N_{\text{CABLE}} = \frac{B_{\text{DIPOLÉ}}}{B_{\text{CABLE}}}$$

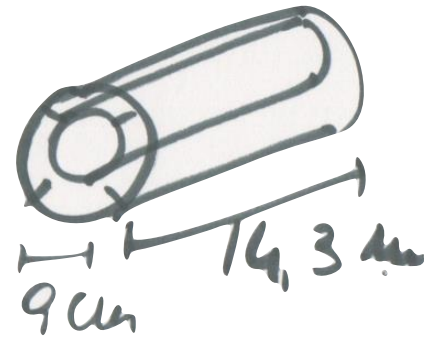
$$N_{\text{CABLE}} = \frac{1,33 \text{ T}}{0,05 \text{ T}} \sim 160$$



# DIPOLE INDUCTANCE

$$\Phi = N \cdot B \cdot S$$

TURN                  FIELD



$$\Phi = \mu_0 \cdot 8,33 \text{ T} \cdot (14,3 \text{ m} \cdot 0,09 \text{ m}) \approx 1000 \text{ Wb}$$

$$\Phi = L \cdot I$$

$$L = \frac{1000 \text{ Wb}}{11000 \text{ A}} \sim 0,1 \text{ H}$$

## STORED ENERGY

$$E_D = \frac{1}{2} L I^2$$

PER DIPOLE

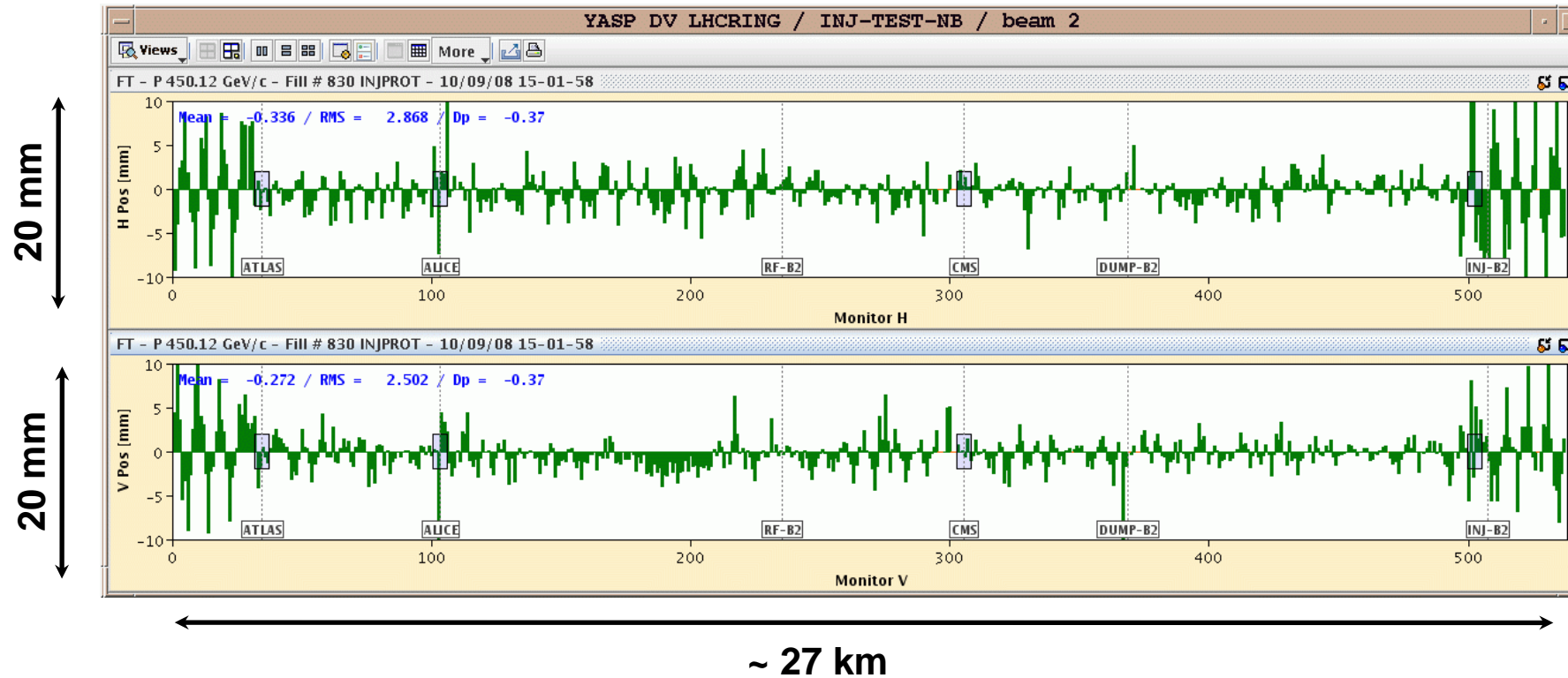
$$E_d \approx 7 \text{ MJ}$$

$$N_d = 1232$$

$$E_{\text{total}} \approx 9 \text{ GJ}$$

# Real LHC orbit - correction of dipolar error

Real orbit taken the 1st day of the LHC

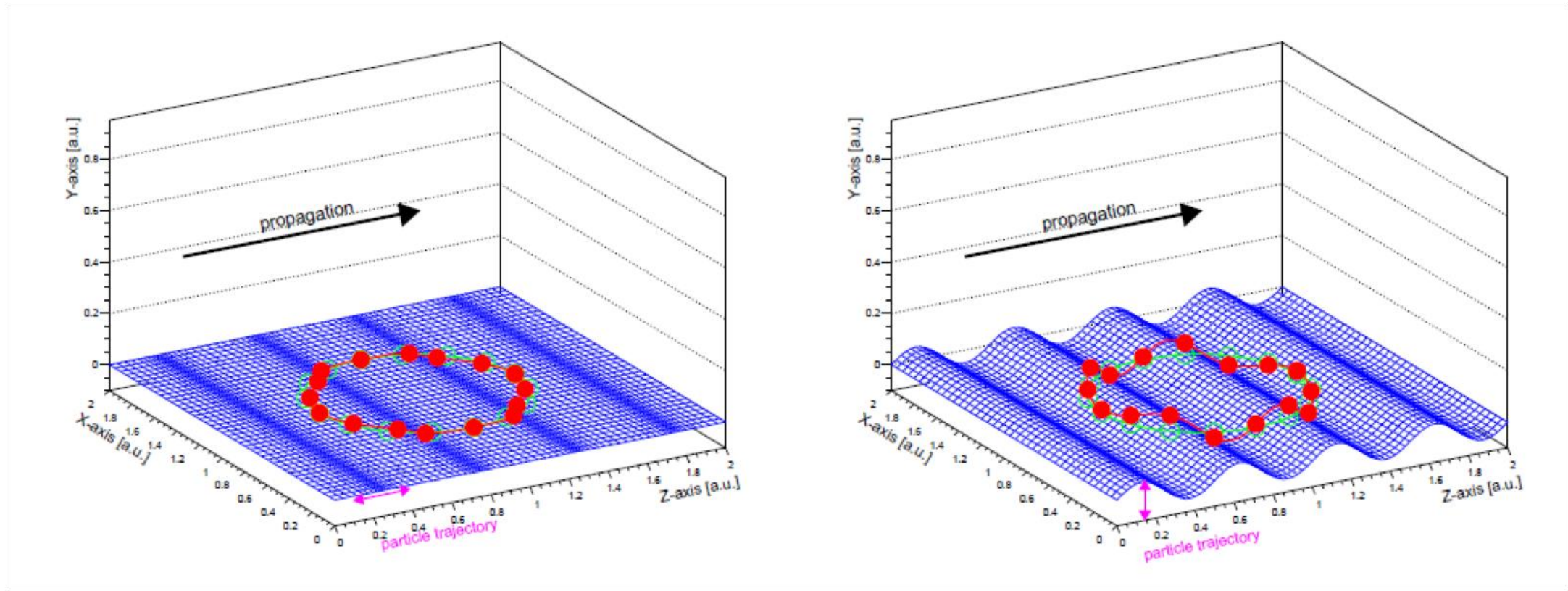


**Please notice:**  
**Horizontal and vertical scale are different by 6 orders of magnitude**

Courtesy of J. Wenninger

# Impact of Earthquakes on LHC (not only)

The impact on LHC of seismic waves depends on amplitude, wavelength (lattice resonances), wave type (longitudinal, transverse)

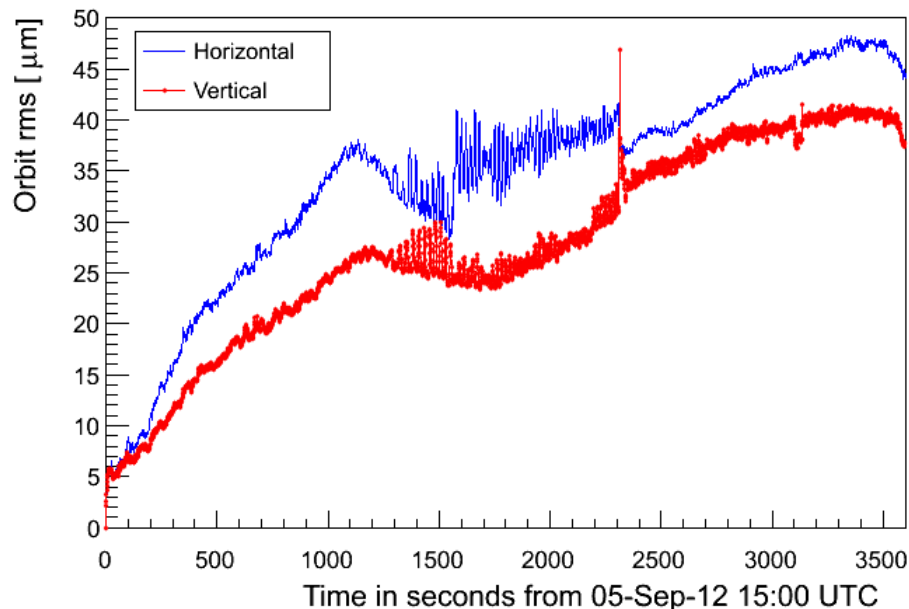
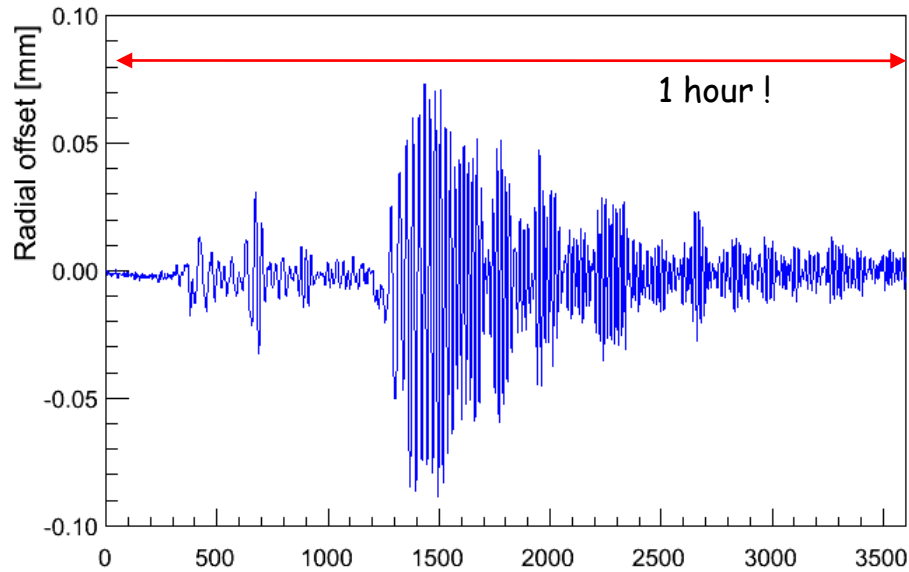


# An earthquake in Costa Rica

- By scanning the logging data M. Fitterer found a candidate earthquake of magnitude 7.6 that occurred in Costa Rica during **fill 3032**.
- UTC time of the earthquake :
  - 05/09/2012 14:42:10
- Arrival of the first waves at CERN ~15:06 UTC.



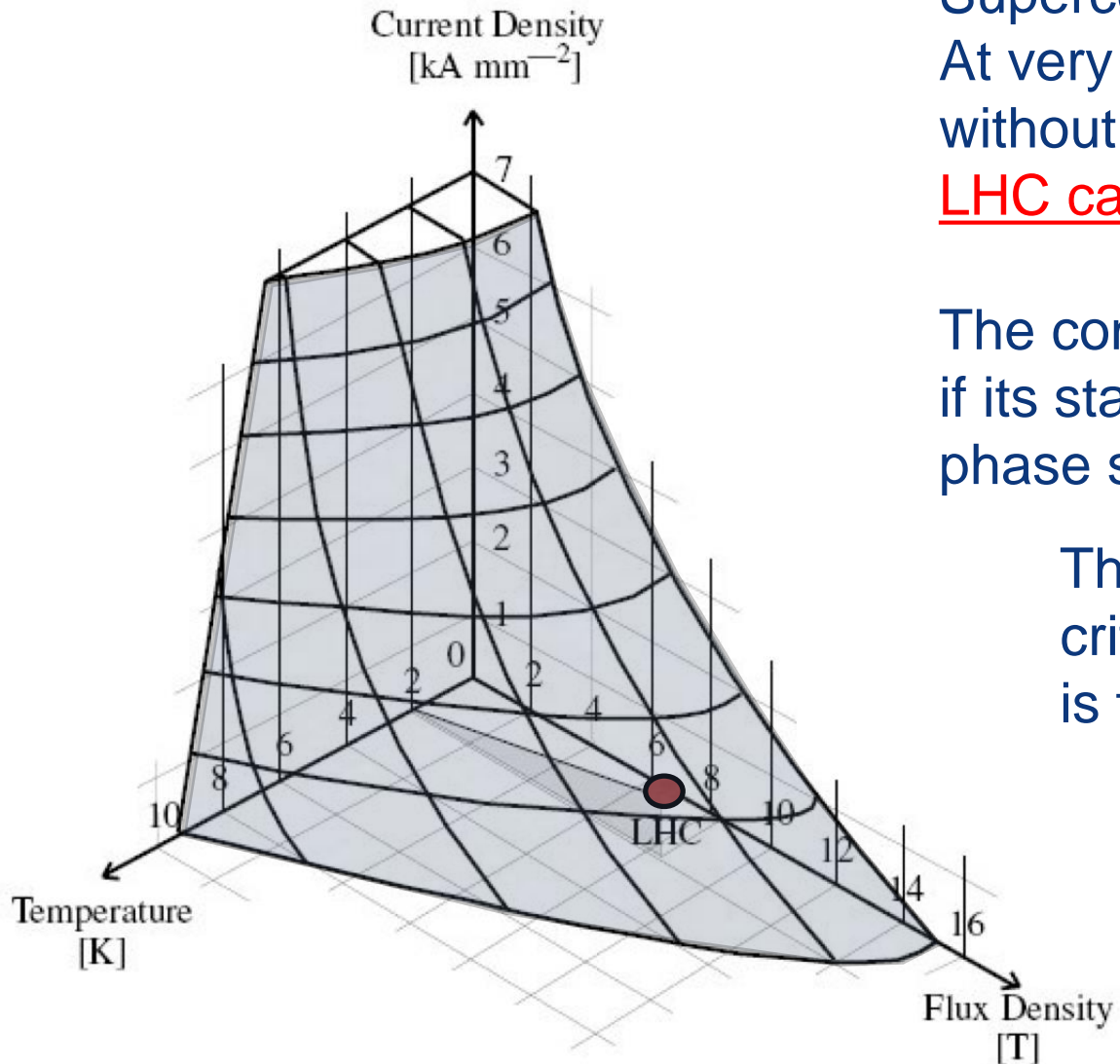
# Costa Rica earthquake – orbit response



- Earthquake visible on the ring radius for over 1 hour.
- The first waves (6 km/s) seemed to affect the LHC mainly radially – but it is also weaker.
- The second type of waves (4 km/s) is visible in radial and transverse.

From J. Wenninger

# 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)

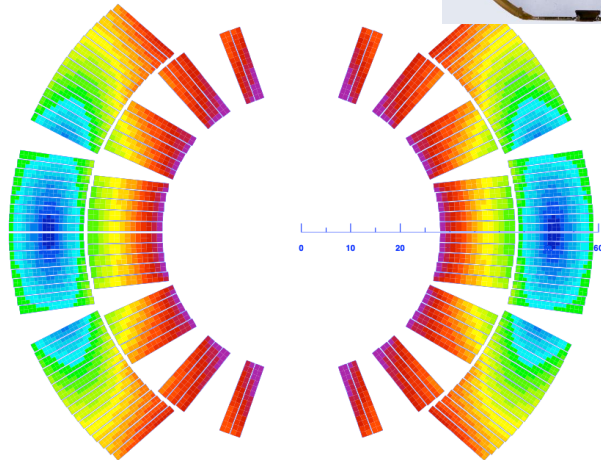
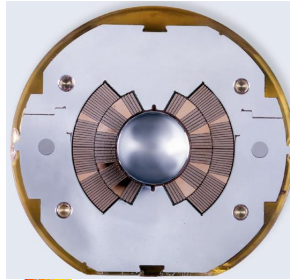
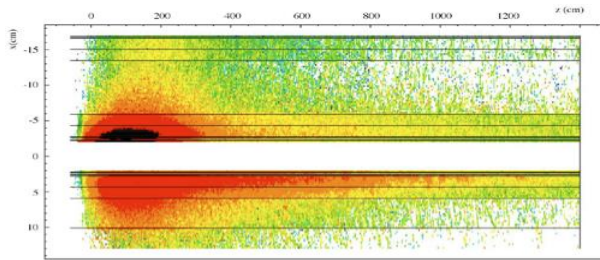
Transition to a normal conducting state is called magnet quench

What can increase the temperature in a magnet ?

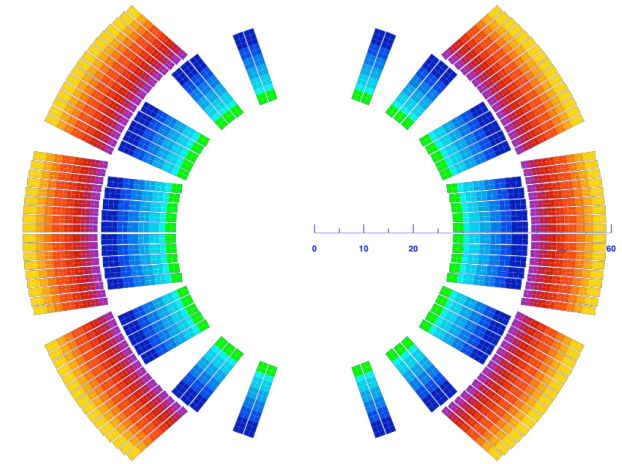
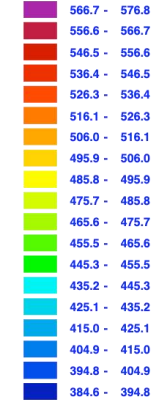
# V. V. S. Introduction to Superconductivity II

Beam losses can eat the temperature margin because of energy deposition

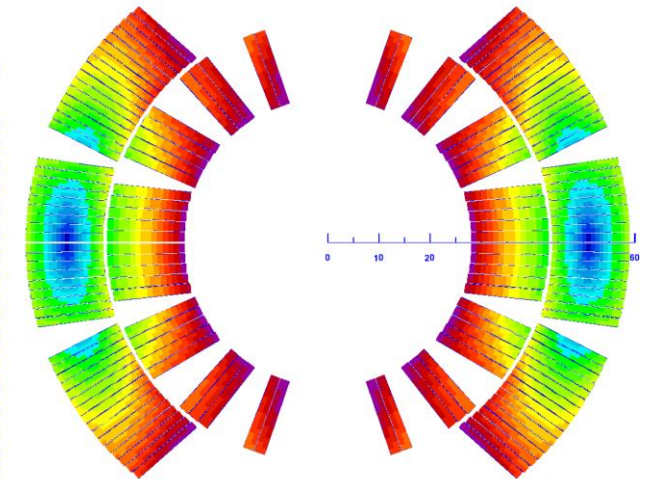
Limit of accepted losses:  $\sim$  10 mW/cm<sup>3</sup> to avoid  $\Delta T > 2$  K, the temperature margin



LI (A/mm<sup>2</sup>)



Temperature margin [K]



Courtesy of Stephan Russenschuck

# How much is $10 \text{ mW/cm}^3$ ?



A fluorescent (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  $56 \text{ mW/cm}^3$ .

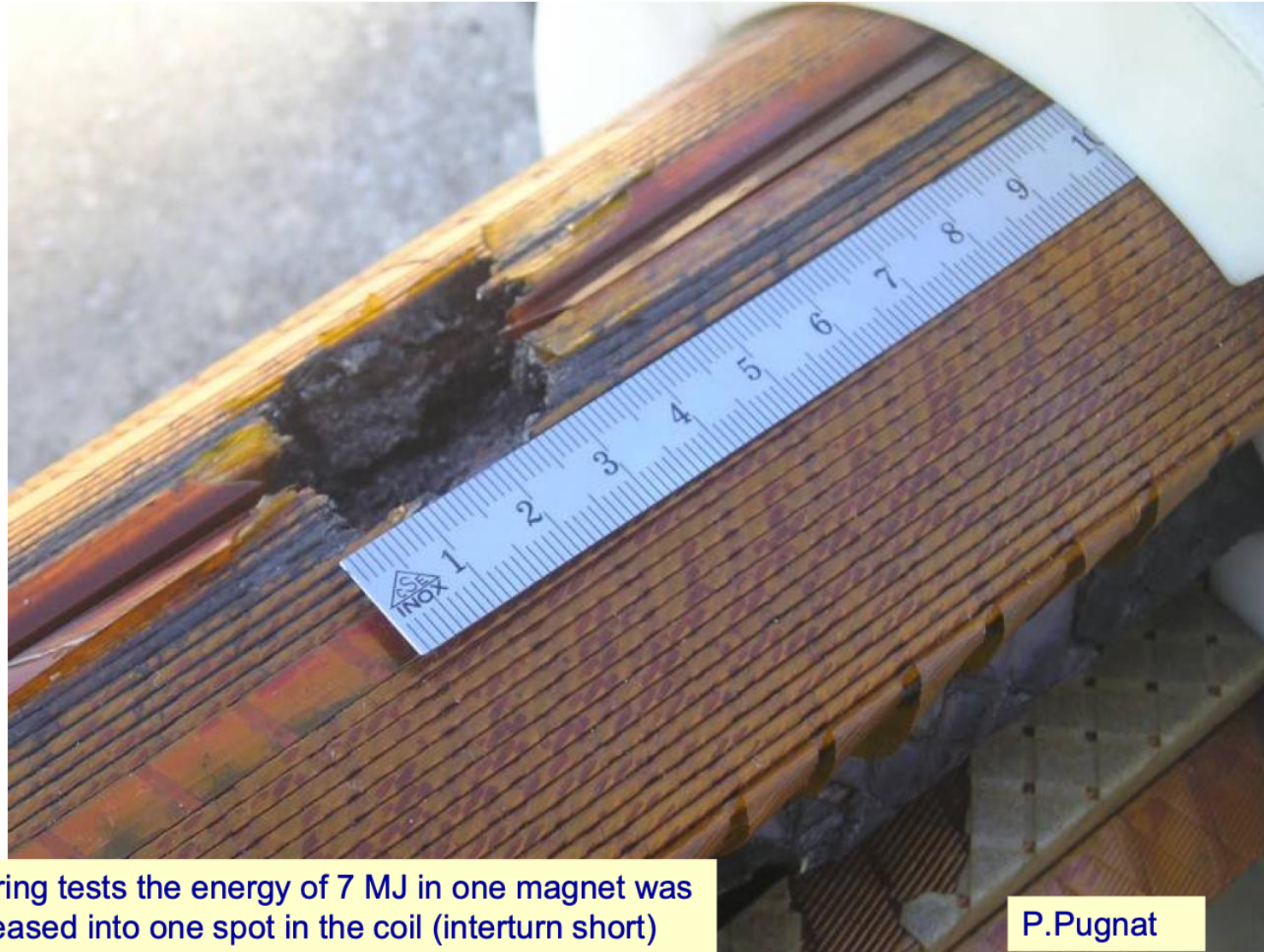
**The power of a neon tube can quench about 5 LHC dipoles at collision energy... because one does not need  $10 \text{ mW/cm}^3$  for the entire volume of a magnet, but for about  $1 \text{ cm}^3$ .**

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





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



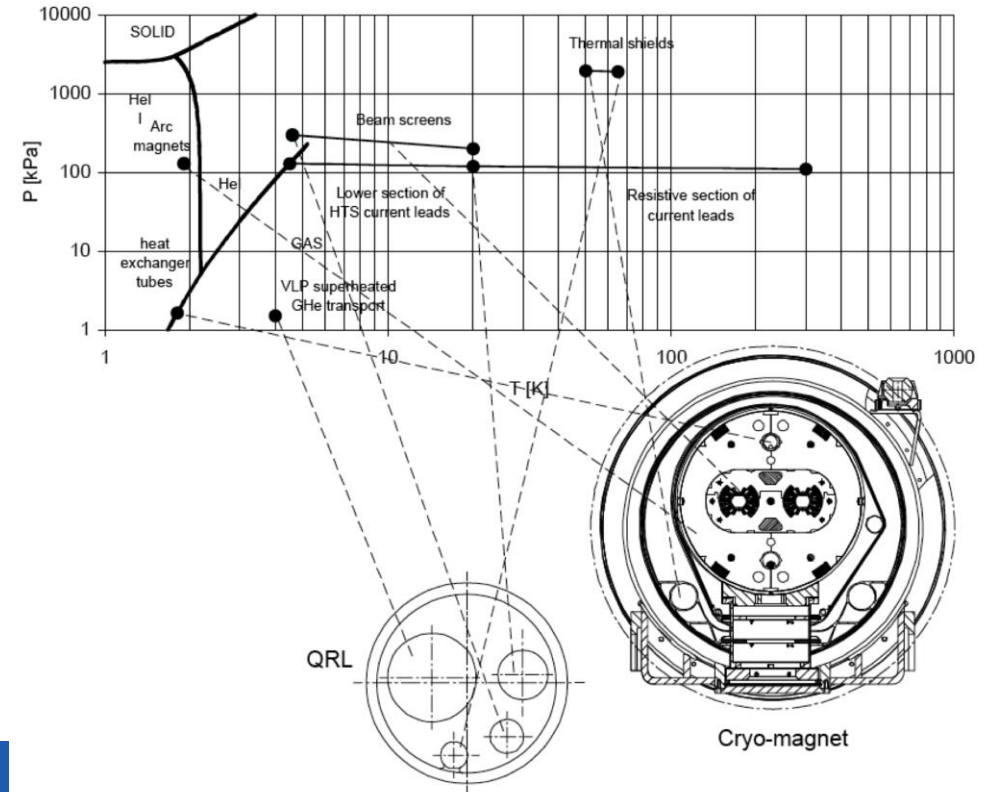
During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short)

P.Pugnat

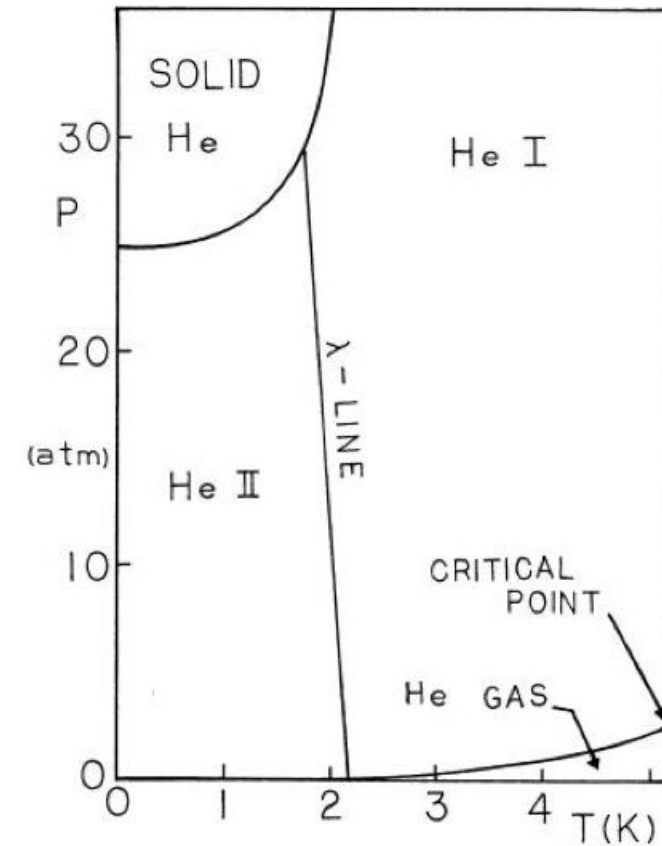
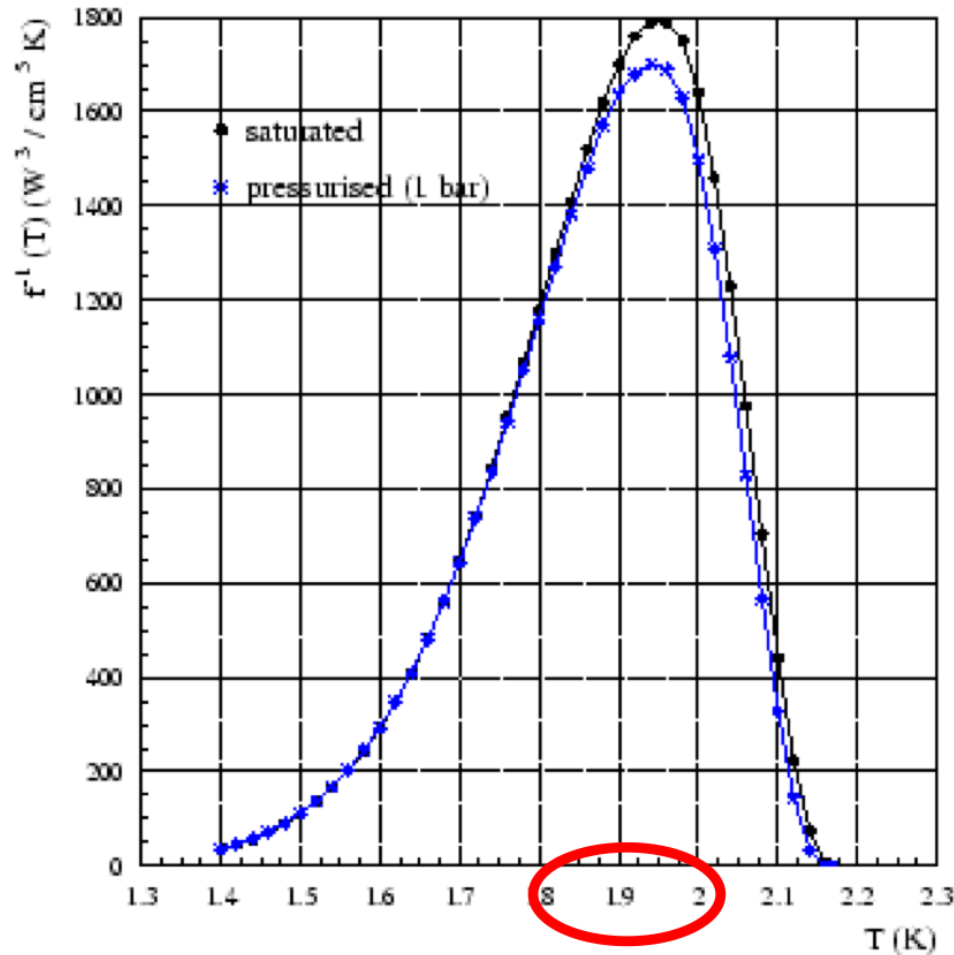
# Second, one has to cool the LHC ....

LHC cryogenics needs 40,000 leak-tight pipe junctions.

12 million litres of liquid nitrogen are vaporised during the initial cooldown of 31,000 tons of material and the total inventory of liquid helium is 700,000 l (about 100 tonnes).

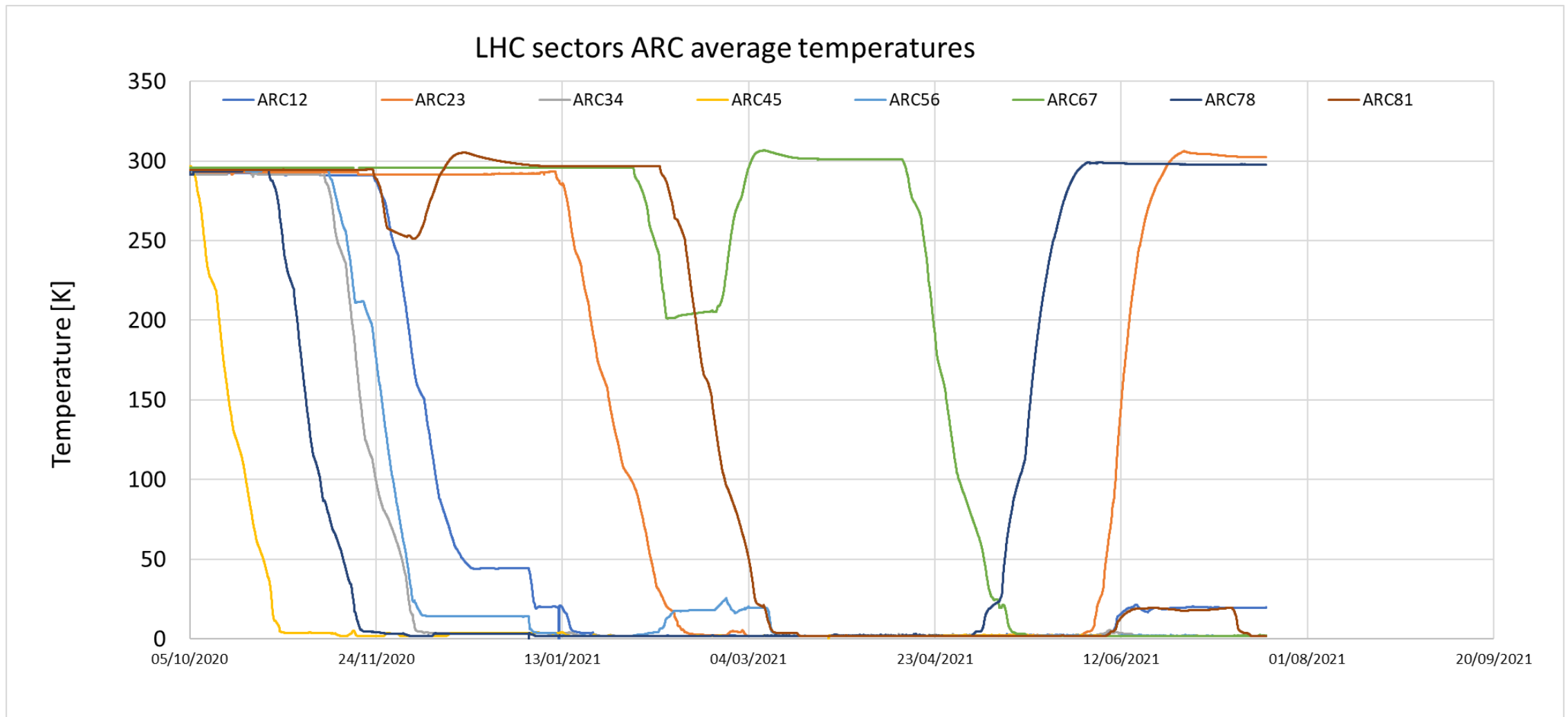


# Why helium ?



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

# Cooling the LHC (and re-warming due to some surprises...)

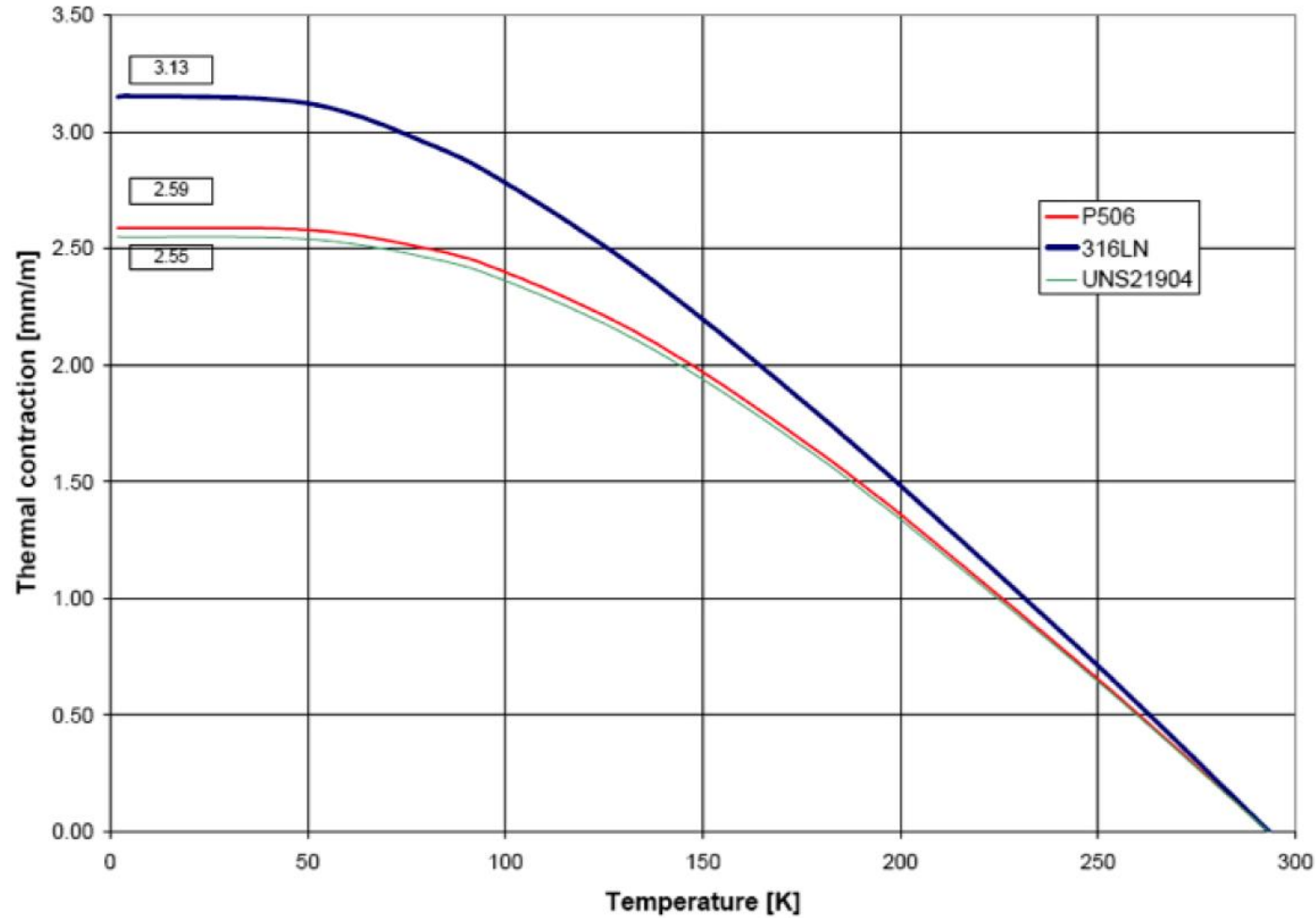


# Different working places, similar temperatures..



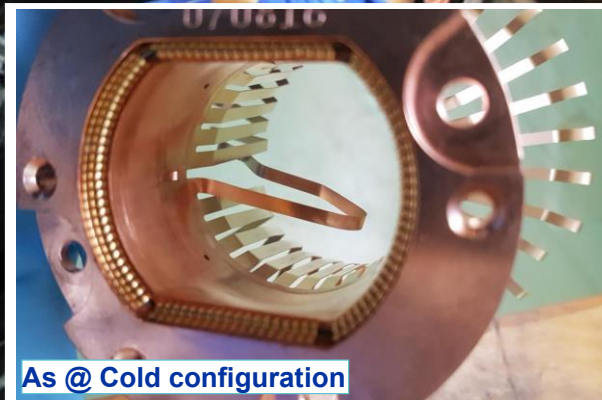
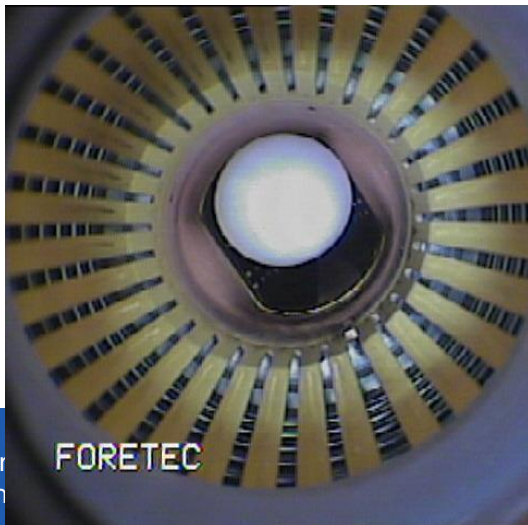
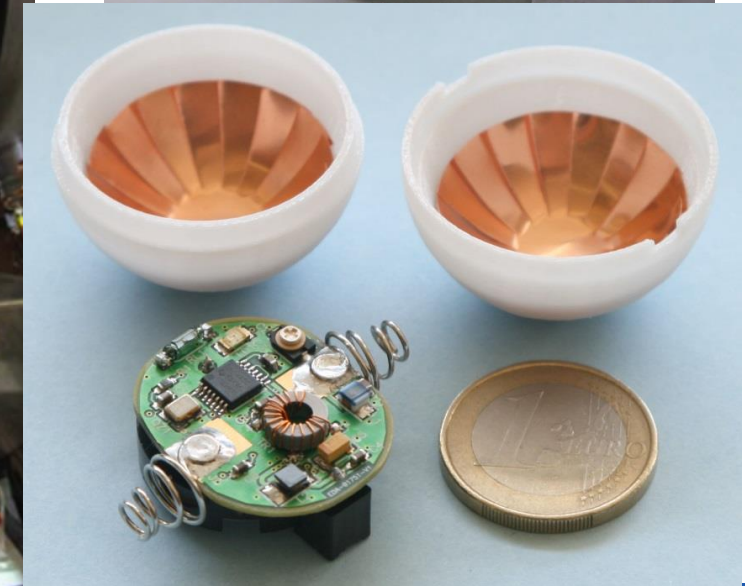
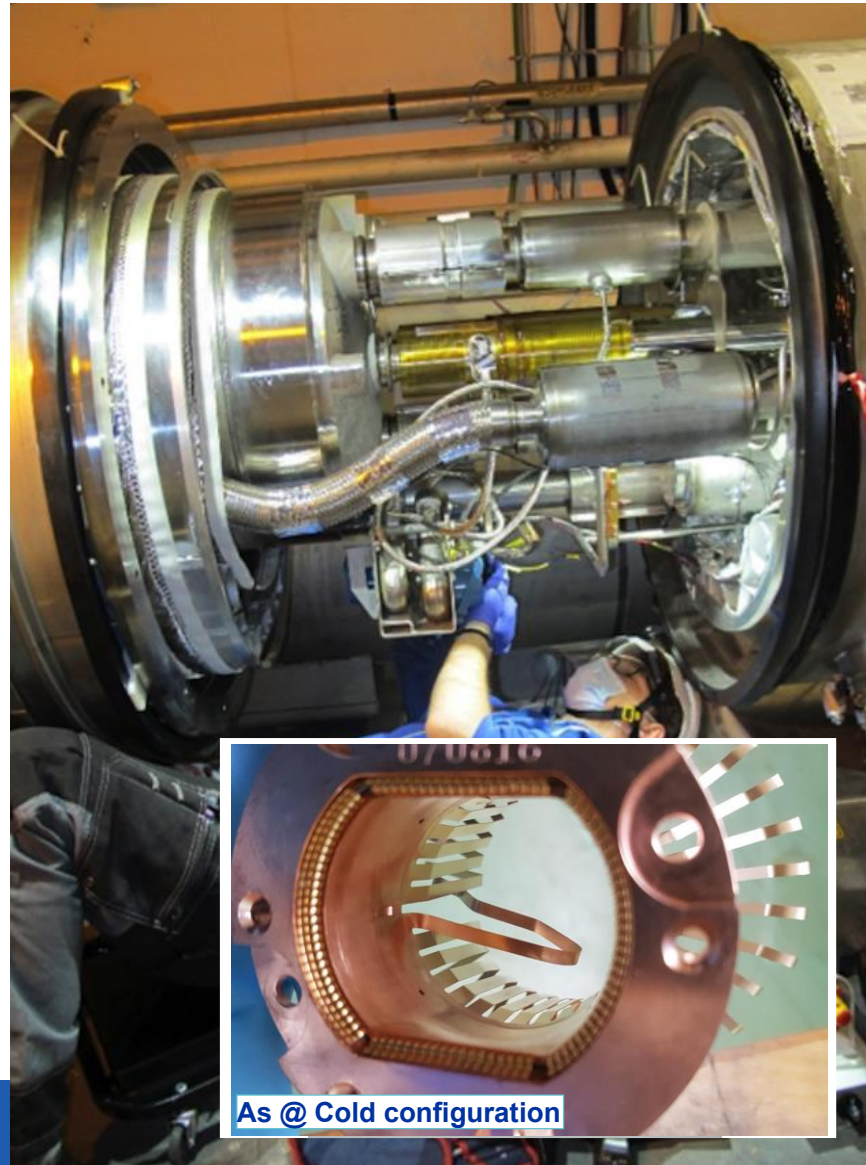
*Credits: NASA*

# The magnets shrinks due to temperature...

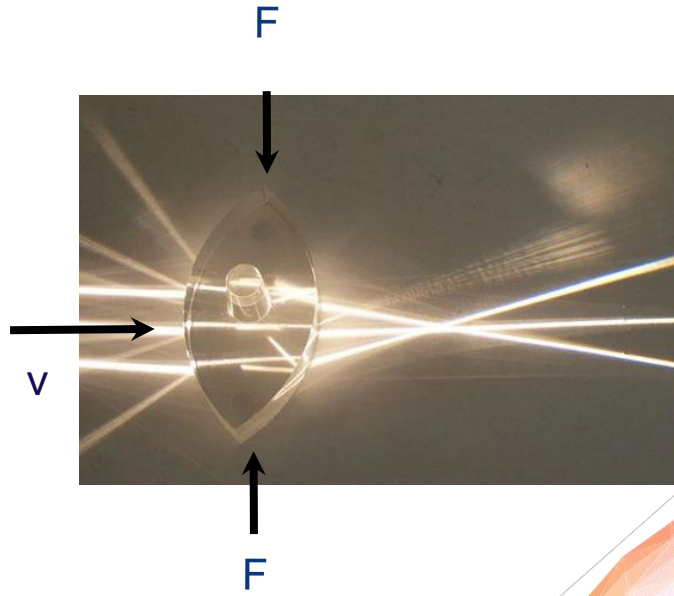


# Anything inside? “Ping-pong” 40 MHz RF ball

40 MHz transmitter

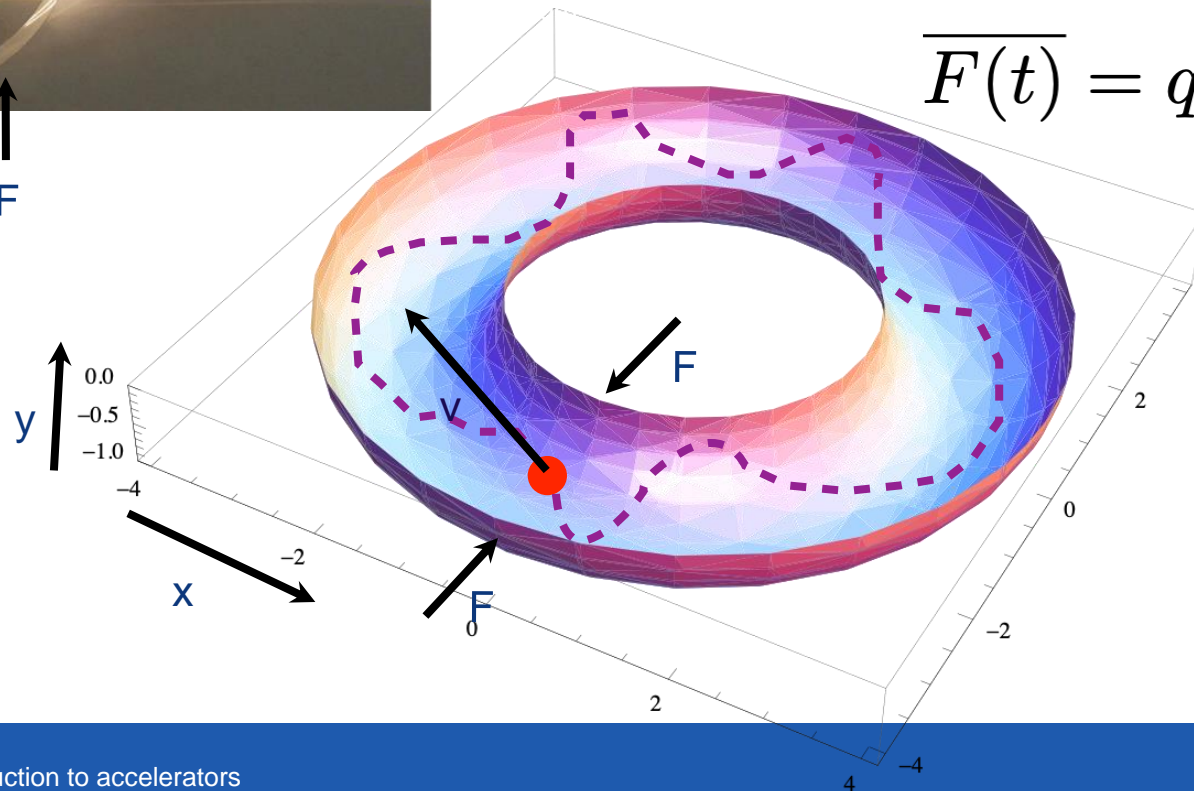


# How an accelerator works ?



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

*How ? Lorentz Force!*



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

Particles of different energy (speed) behave differently

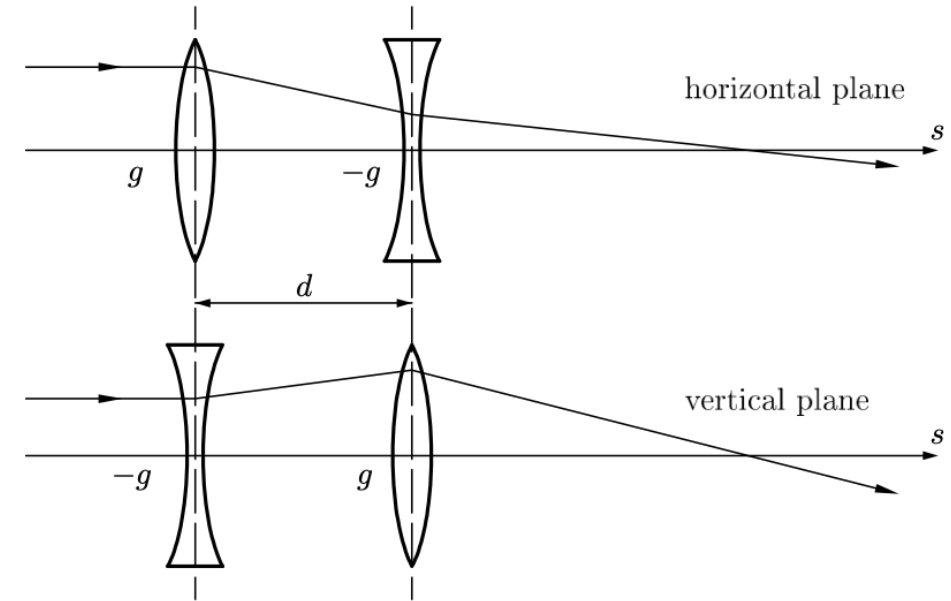
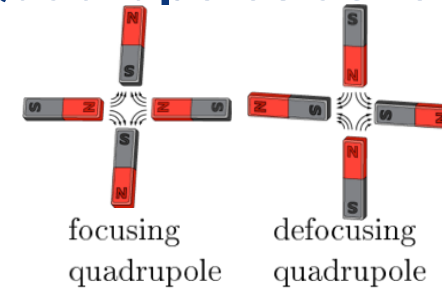
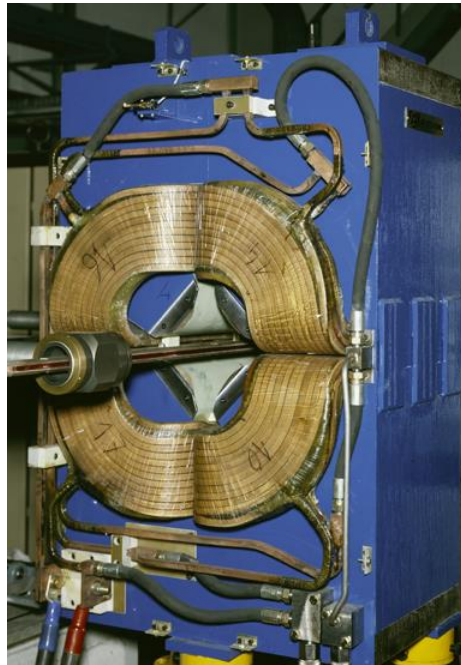
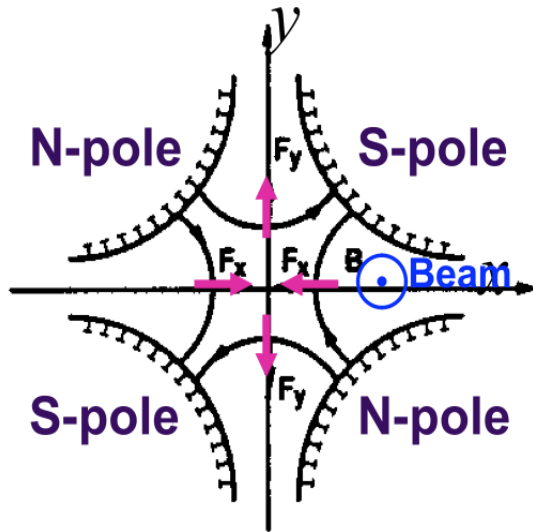
Magnetic field confines particles on a given trajectory



# 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 Gradient quadrupoles) the beam dimension is kept small (even few  $\mu\text{m}^2$ ).

## QUADRUPOLE



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

Typical lattice is FODO, focusing-drift-defocusing

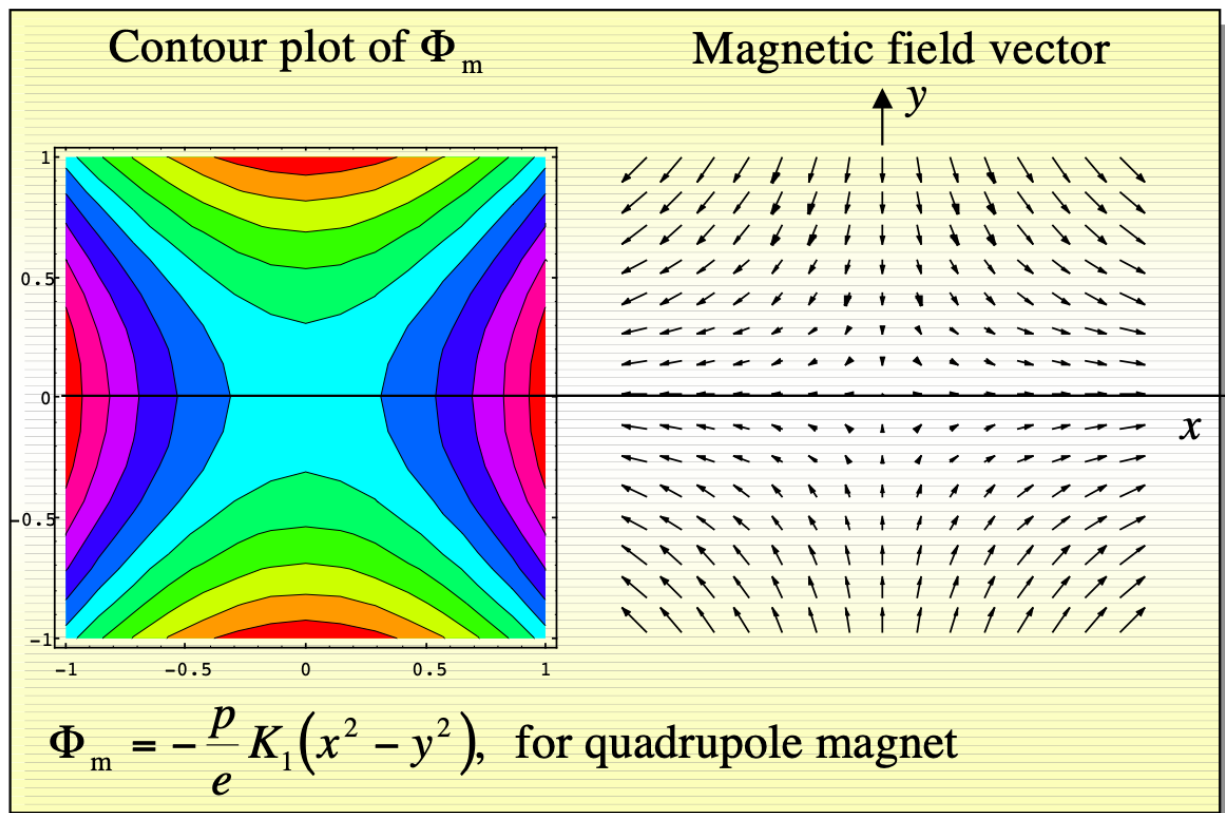
# Quadrupole field

$$B = - \nabla \Phi_m$$

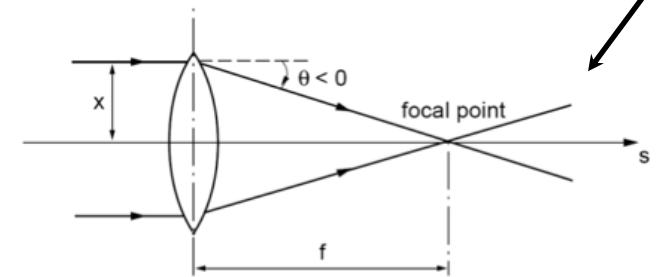
$$\Phi_m = \text{Vector potential}$$

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.



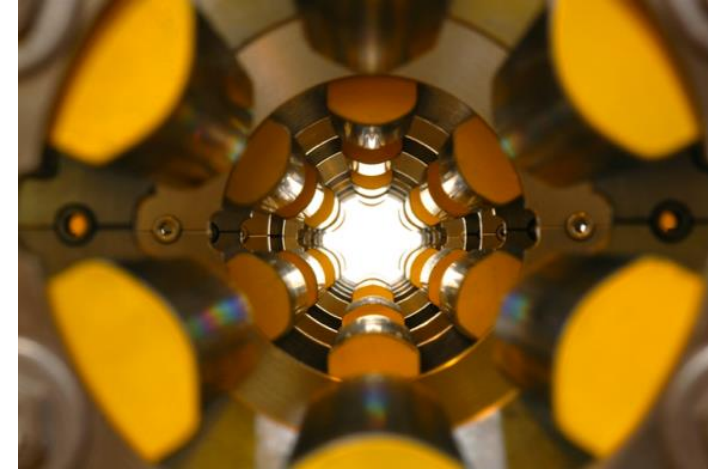
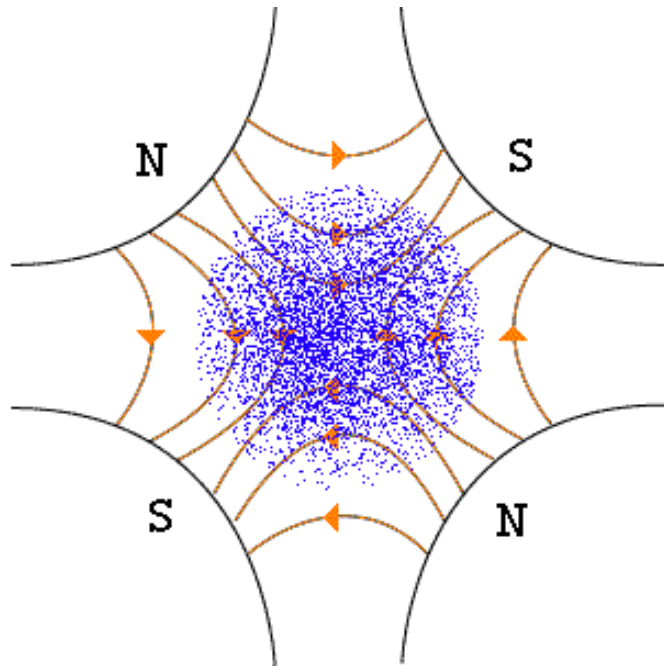
$$l K = - \frac{l}{B\rho} \frac{\partial B}{\partial x} = \frac{1}{f}$$



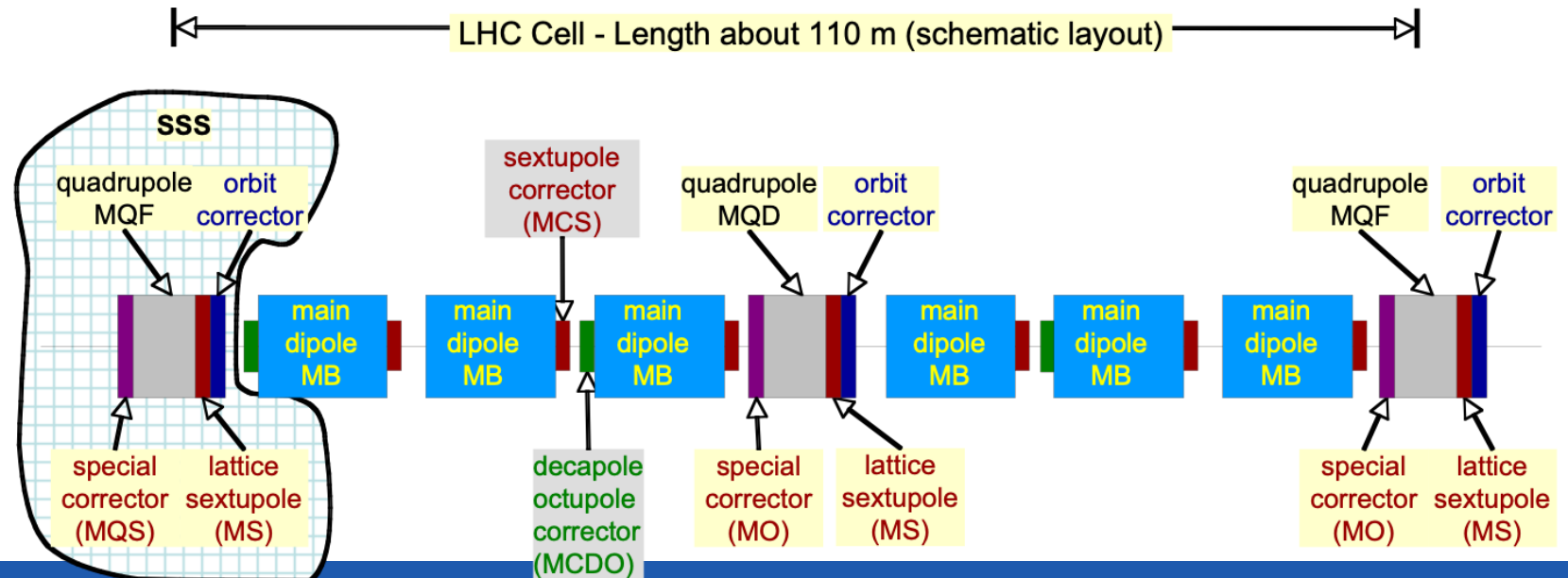
$$\tan \theta = -\frac{x}{f}$$

# Example of FODO lattice

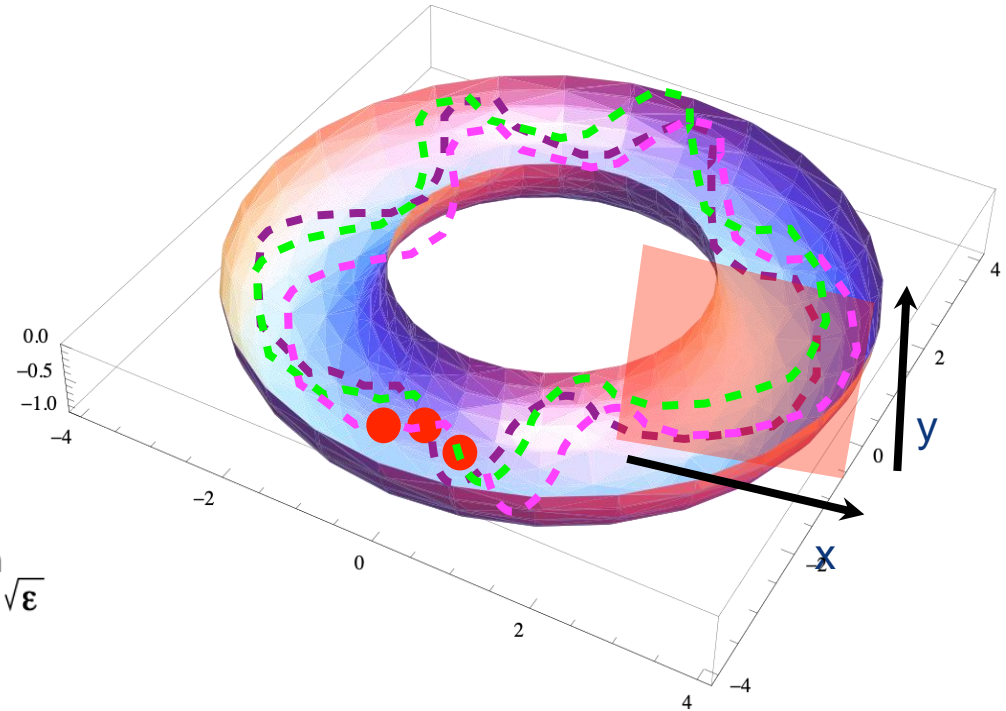
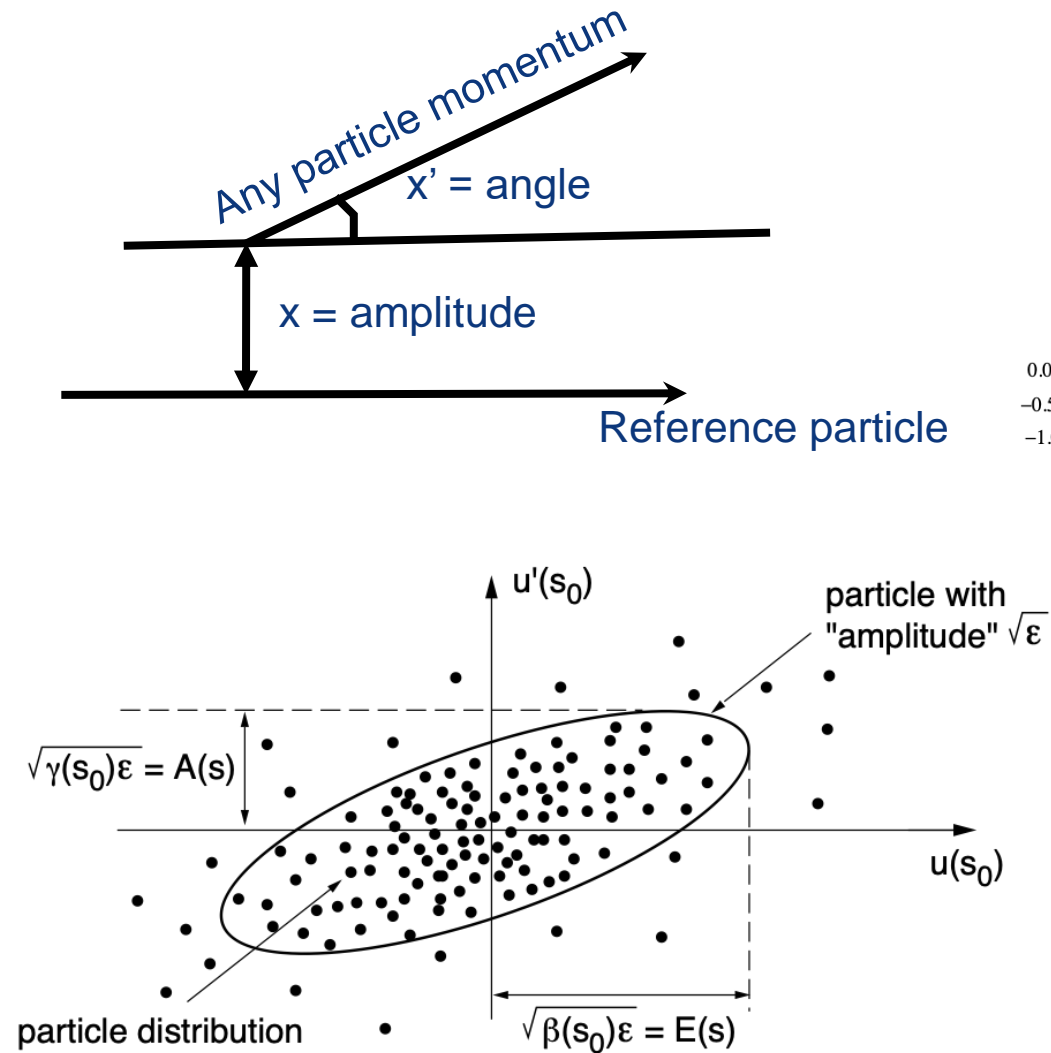
The beam point of view - Those are sextupoles - Six poles



Diamond light source - UK



# 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

# Classical mechanics.... spring with a mass

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

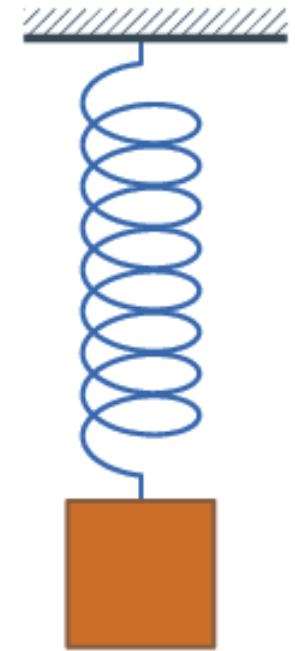
with  $k$  the spring constant and  $m$  the mass

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  $s$ .

$$\frac{d^2 x}{ds^2} + K(s)x = 0 \xrightarrow{\text{beer} = \text{solution}} x(s) = a\sqrt{\beta(s)} \cos(\phi(s) + \phi_0)$$

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

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

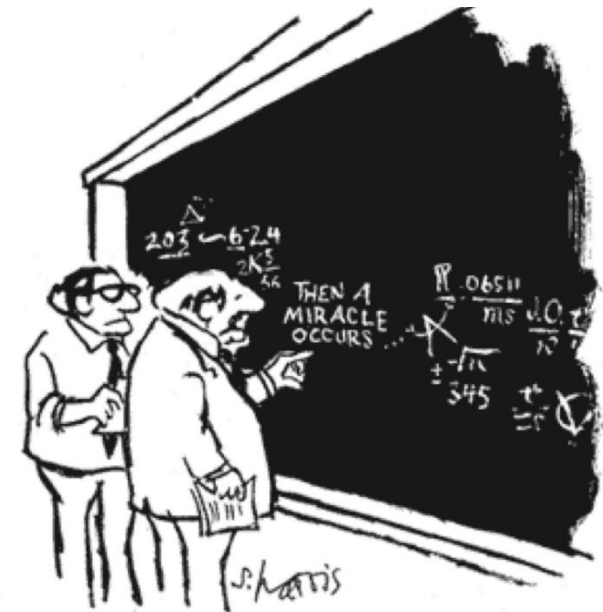
Dipoles

Quadrupoles

forget them for a moment

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

This imply periodicity of the solution



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

# 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**.

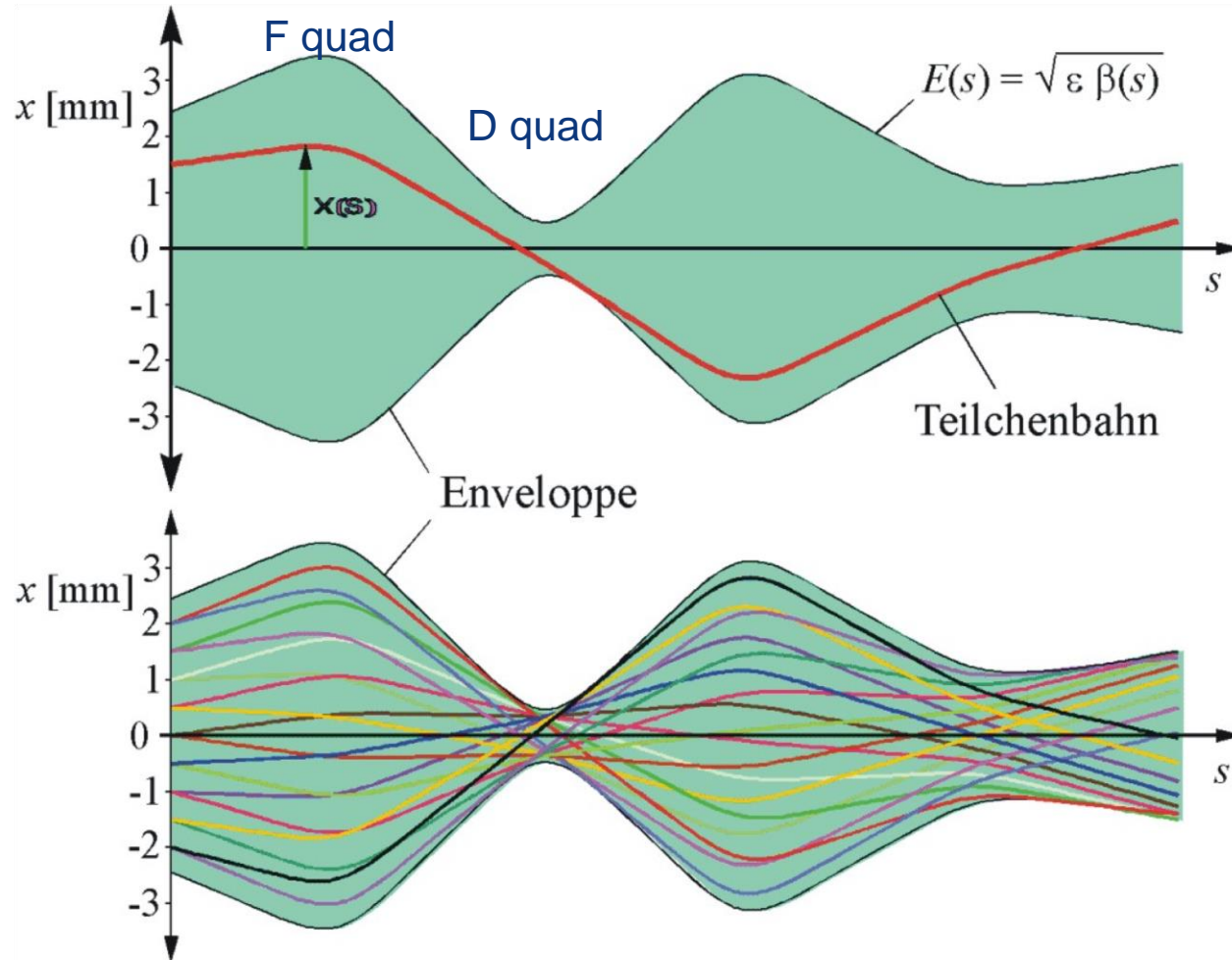
Every section of an accelerator has a constant k, so alone would be similar to an harmonic oscillator

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

is called the **phase advance**

# Definition of envelope

*Beam physical dimension*



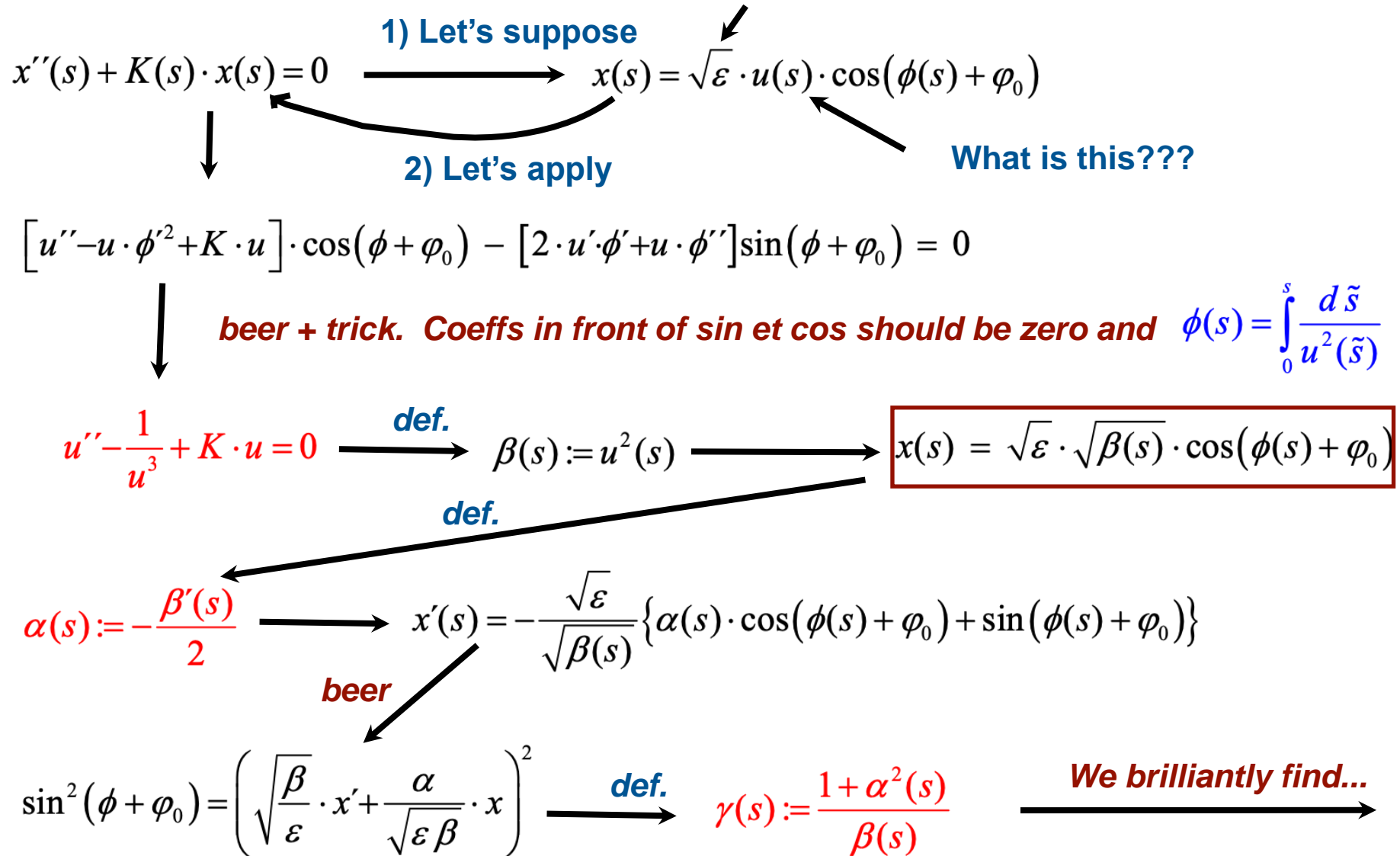
$$E(s) = \sqrt{\epsilon \beta(s)}$$

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



## Nearly no beer ... full proof ...

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



# ..... what we wanted...

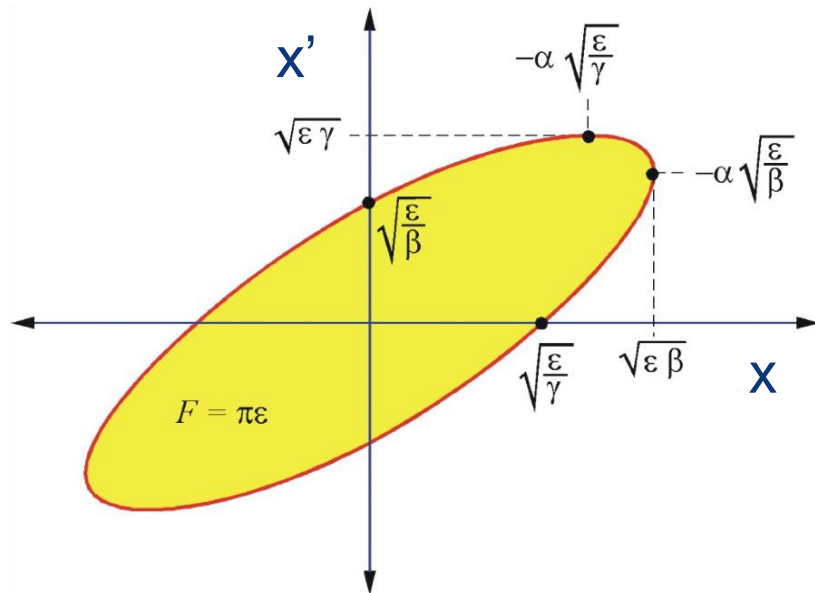
*oh surprise...*

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

**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:**

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

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

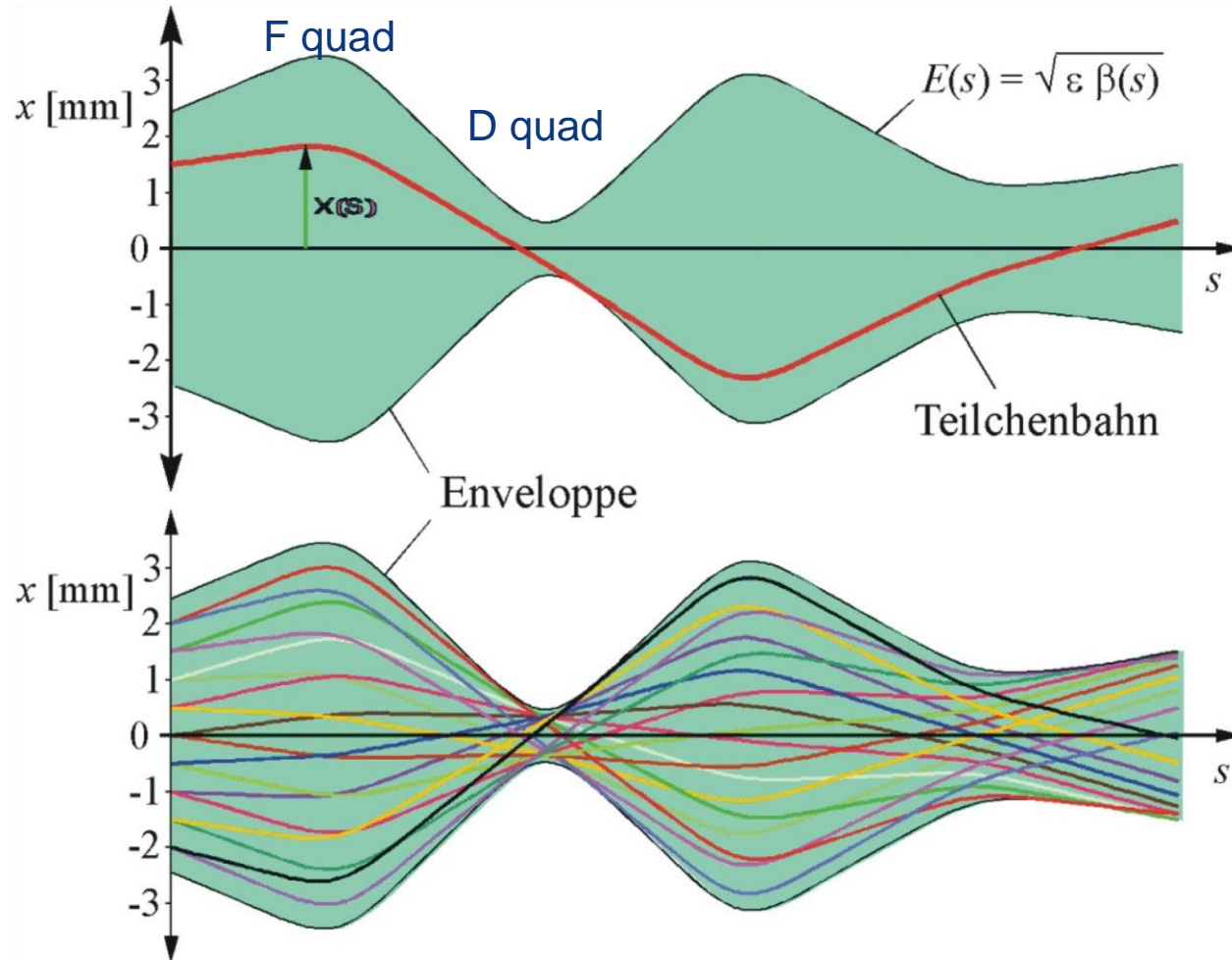
$$\beta(s)$$



**Those are not  
the relativistic  
homonyms**

# Definition of envelope

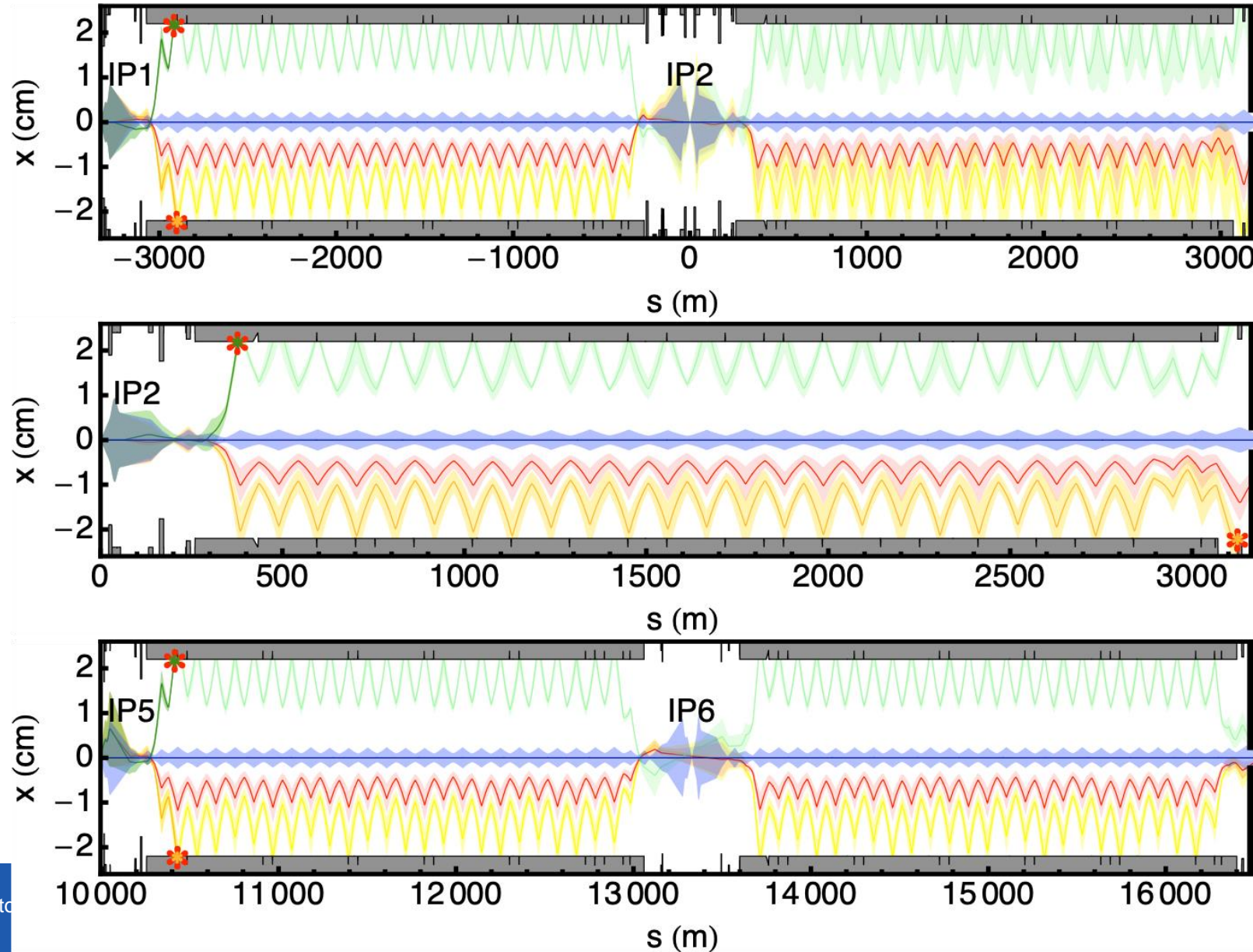
*Beam physical dimension*



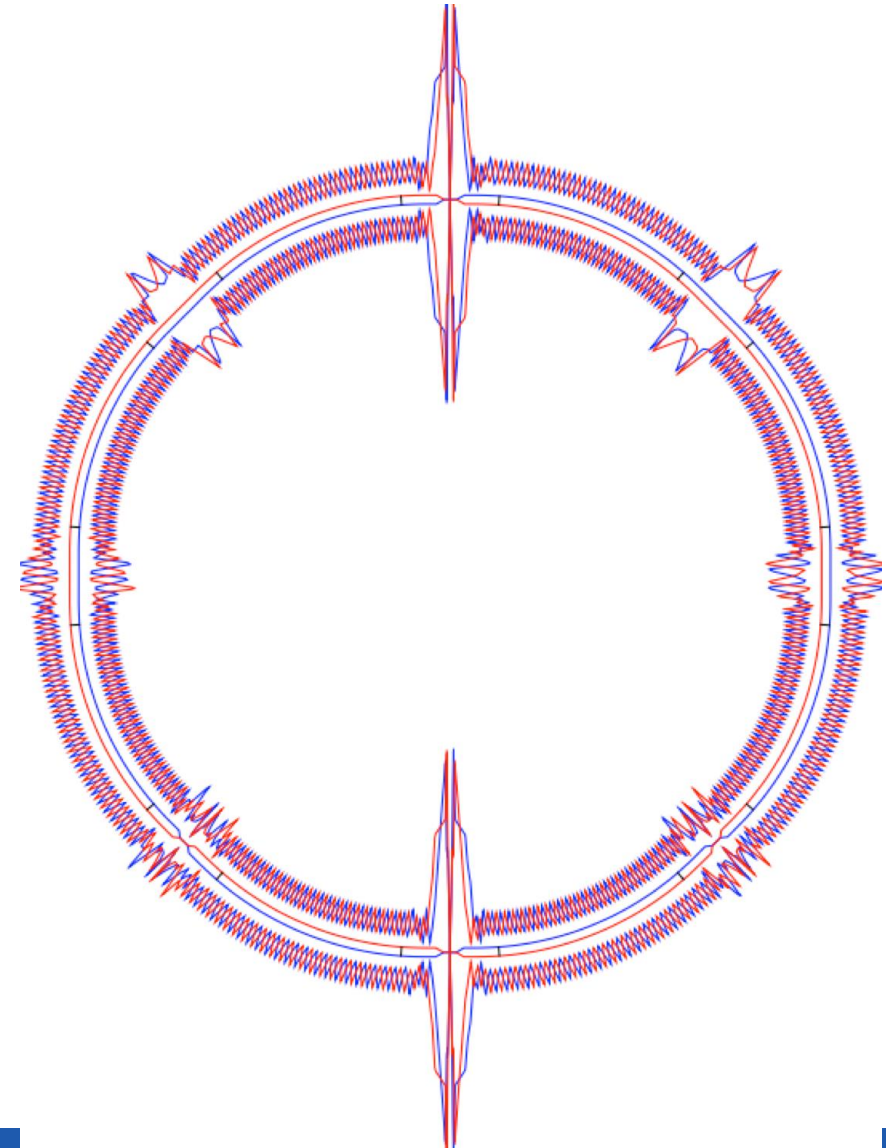
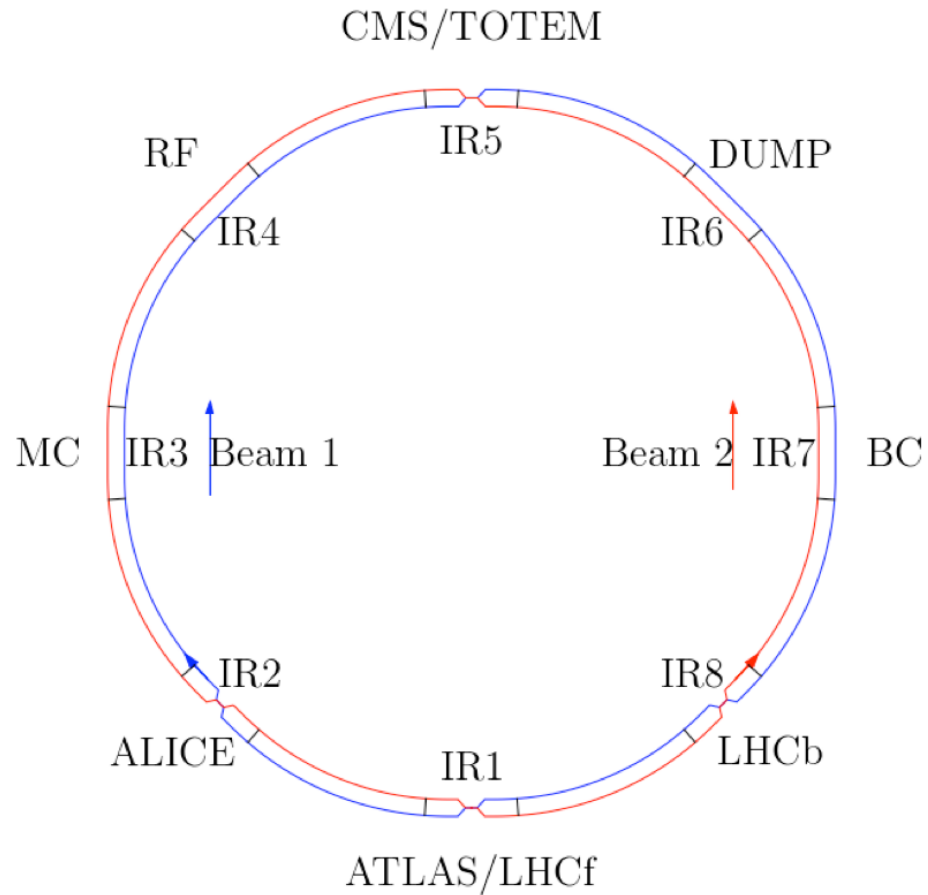
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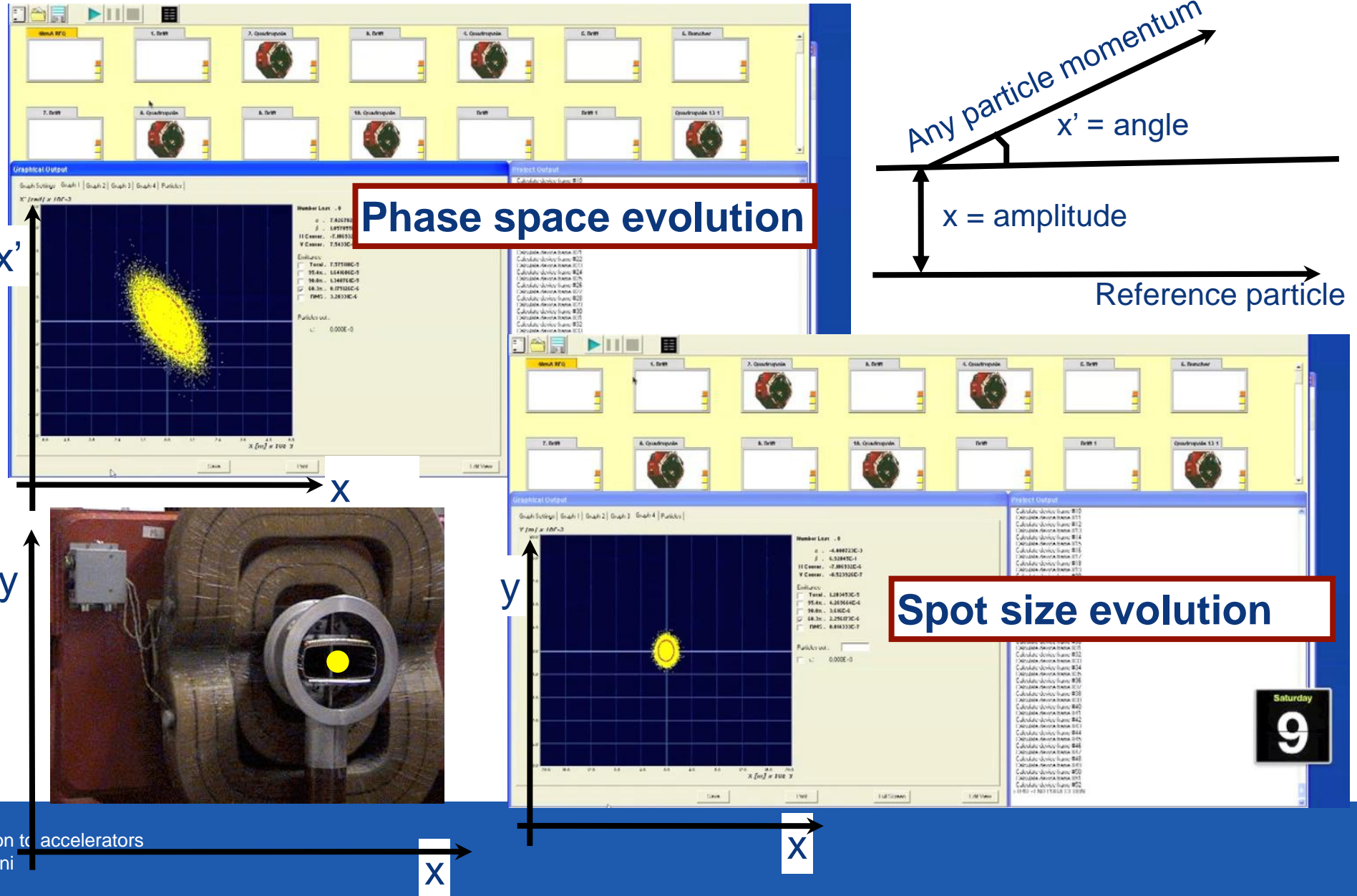
# Envelope around the LHC



# The first LHC collision optics in one slide



# Particle transport in a lattice



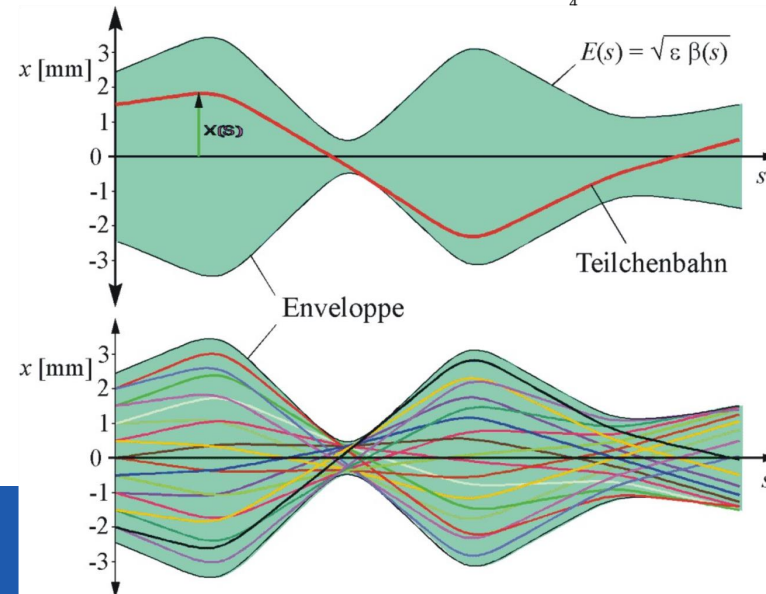
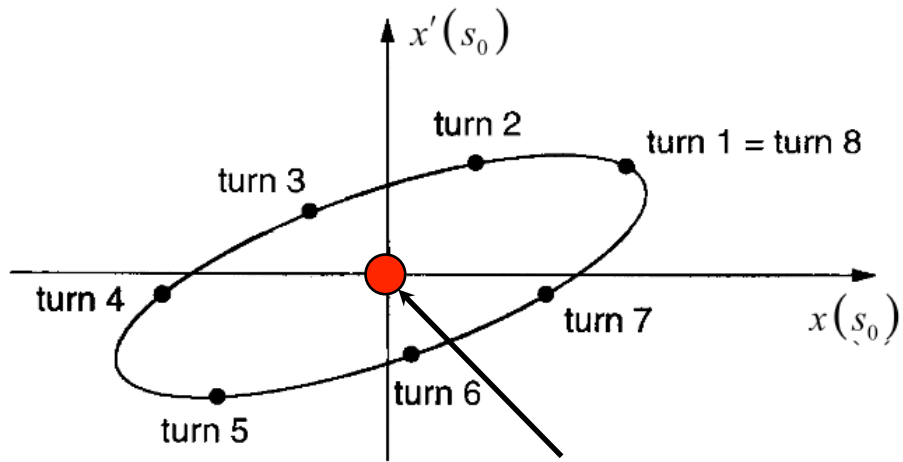
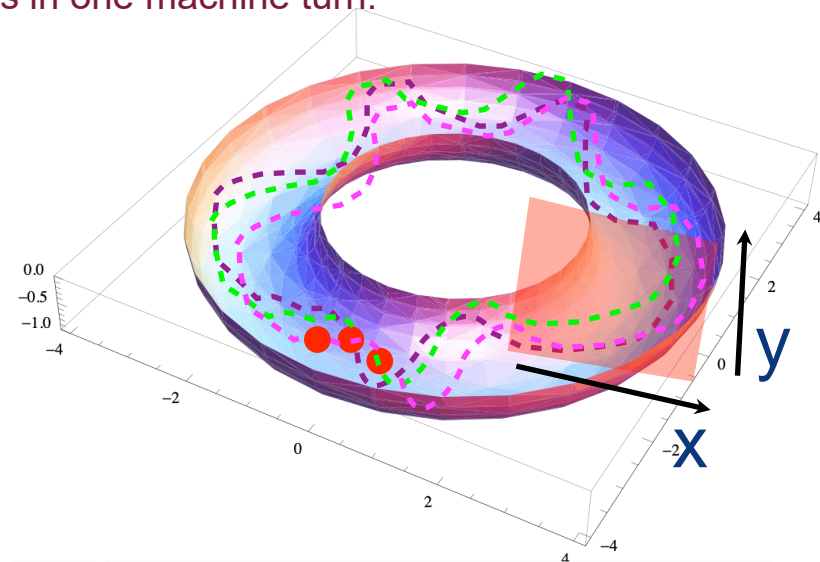
# Tune

## 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

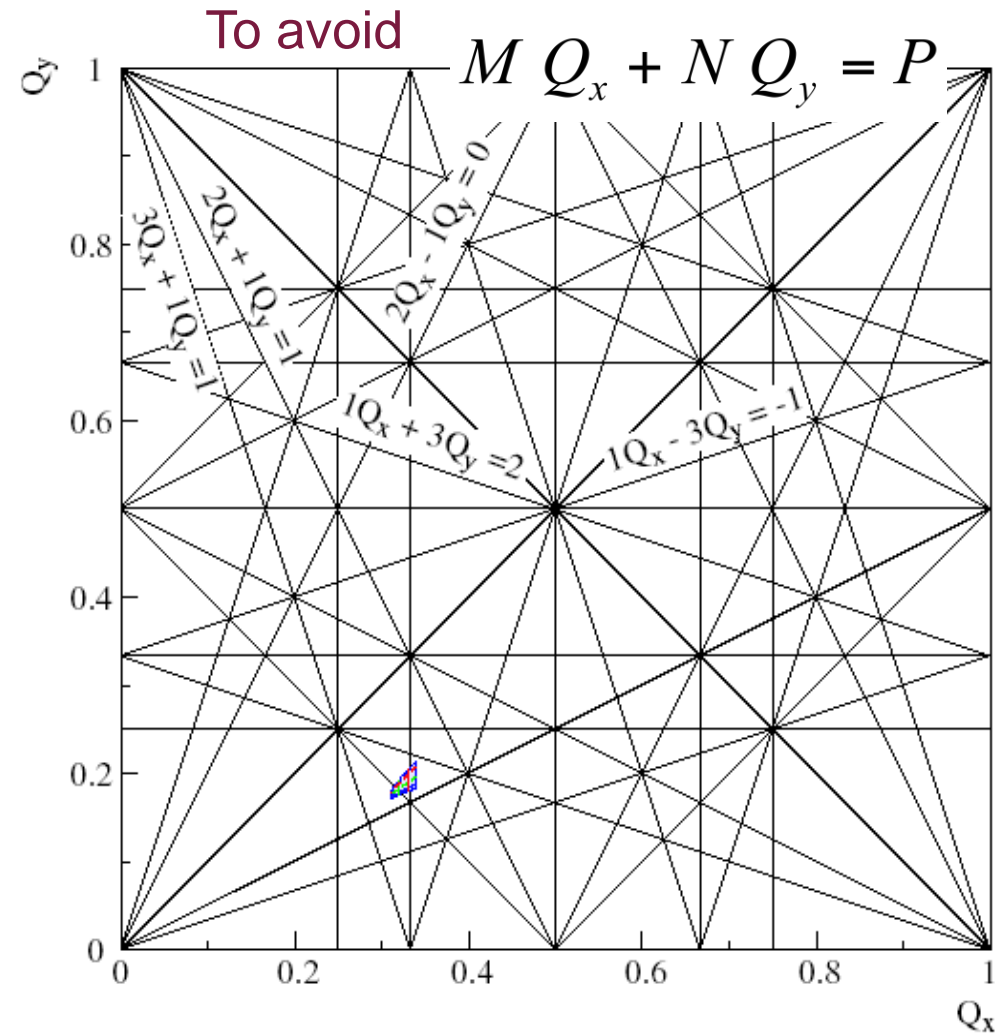
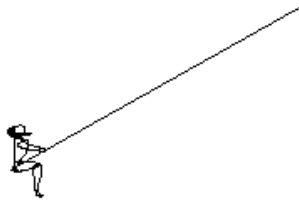
$$Q_x = \frac{1}{2\pi} \oint \frac{ds}{\beta_x(s)}$$



# Tune and resonances

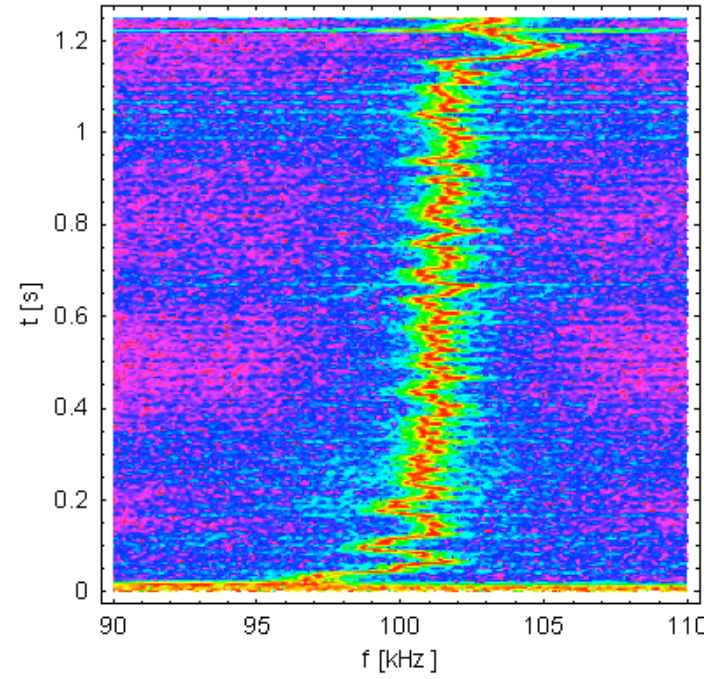
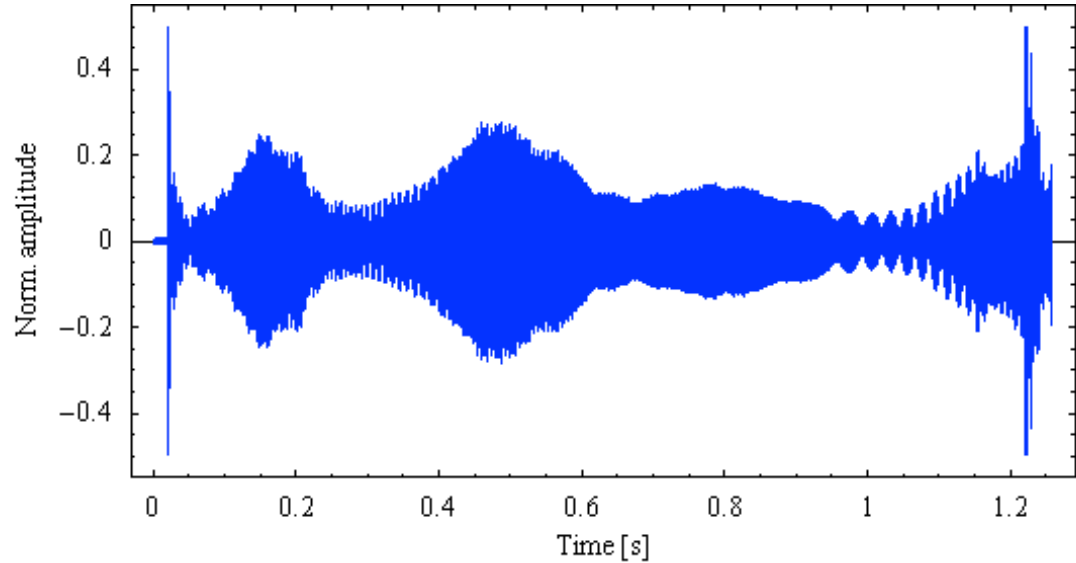
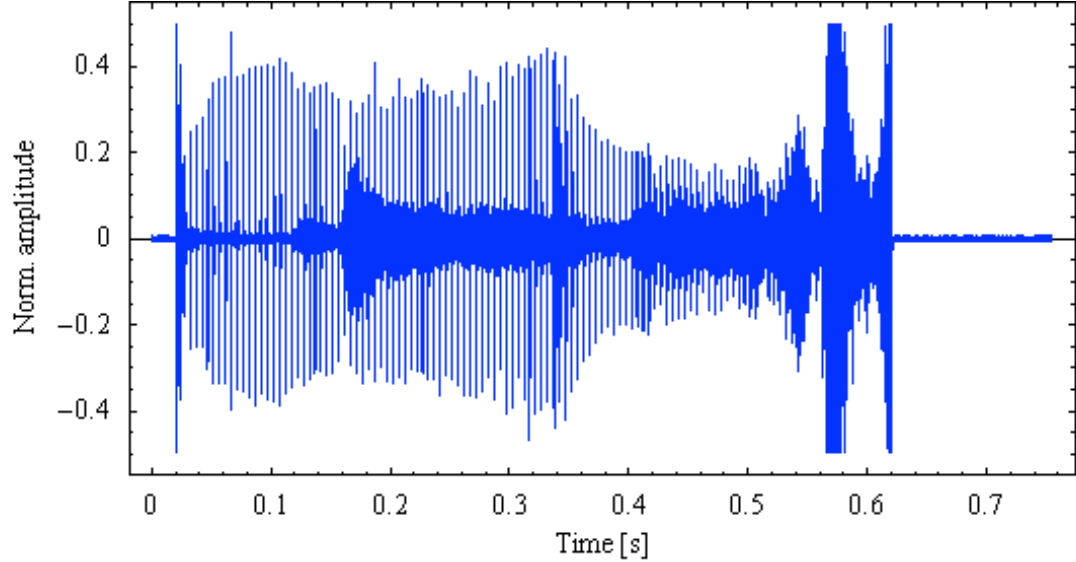
Like on a swing, to keep the oscillations bounded in amplitude, one has to avoid to excite the beam in a resonant way.

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



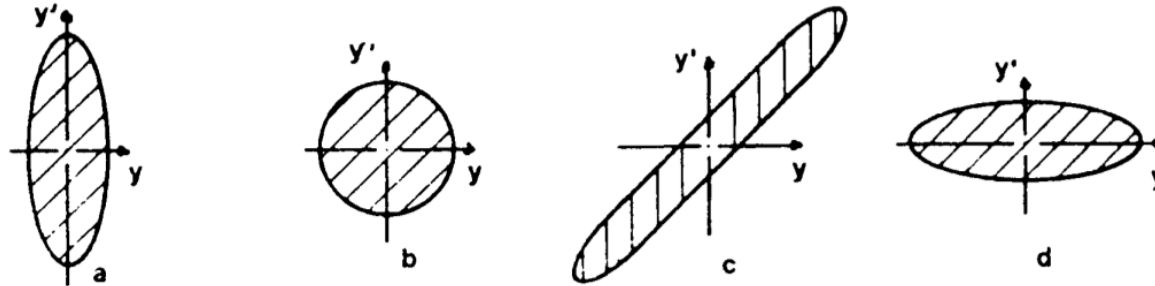
<http://mgasior.web.cern.ch/mgasior/pro/3D-BBQ/ps.html>

# 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

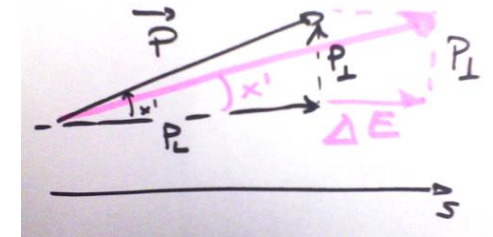


**The ellipse is distorted/stretched but the surface is conserved.**

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

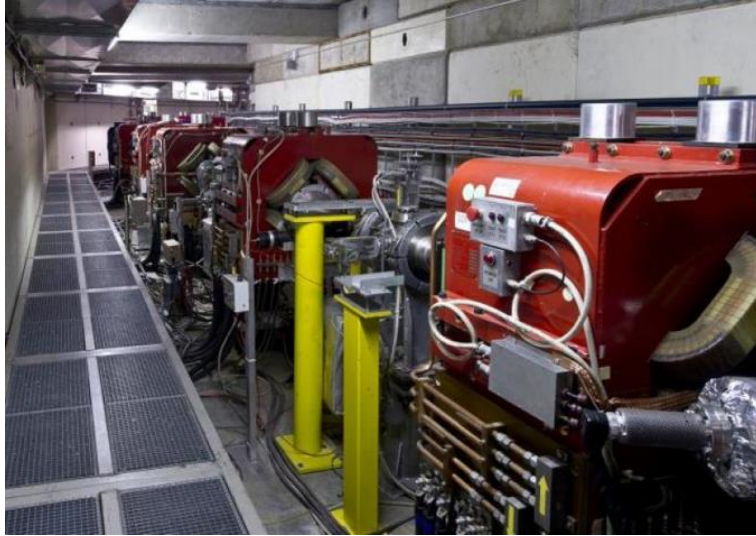
$$\epsilon_{norm} = \epsilon_{phys} * \beta_{rel} * \gamma_{rel}$$

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

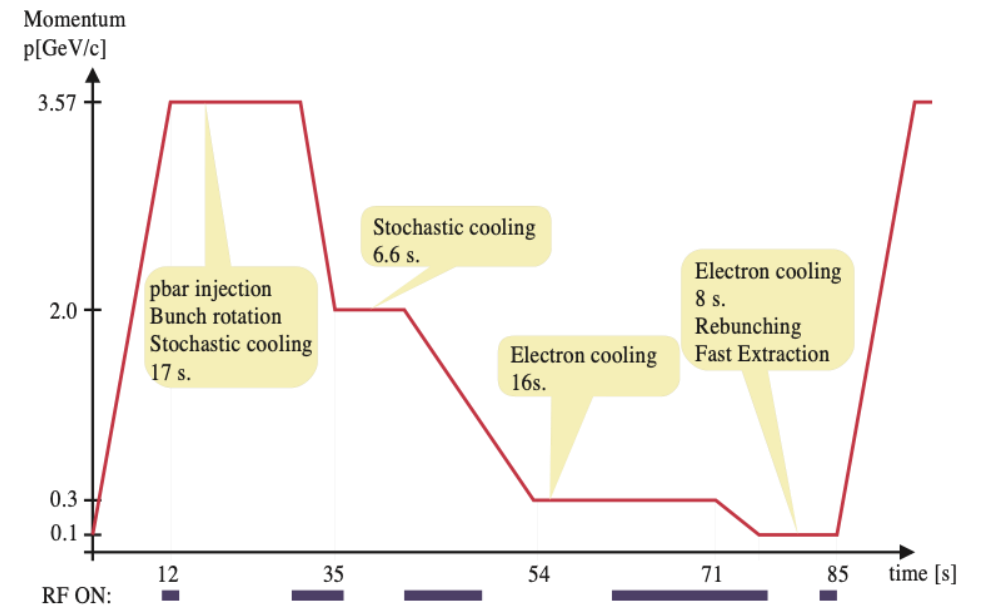
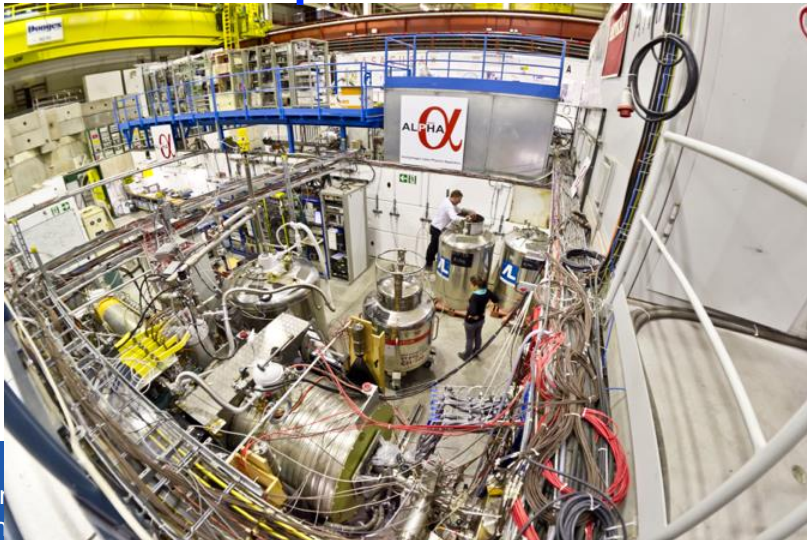


# AD (Antiproton decelerator)

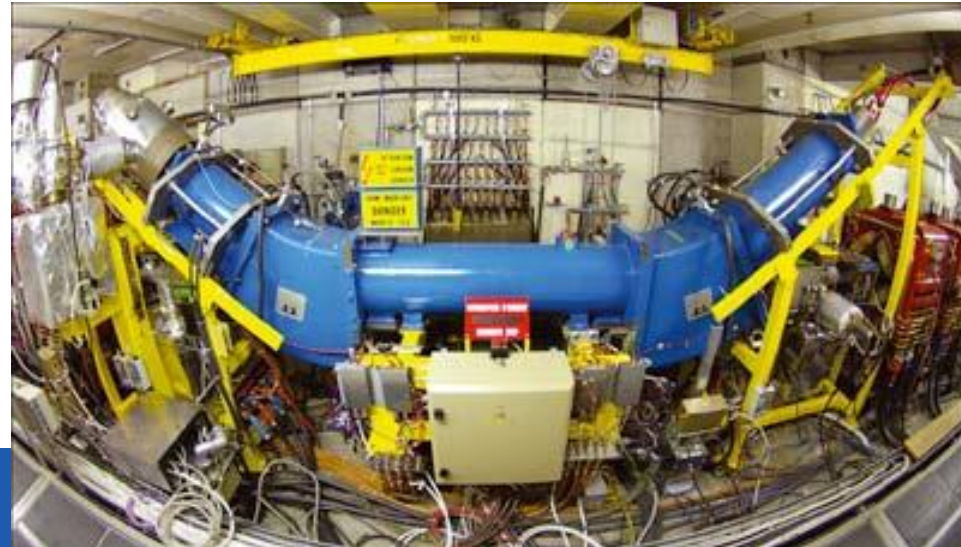
## Lattice quadrupoles



## Experiments

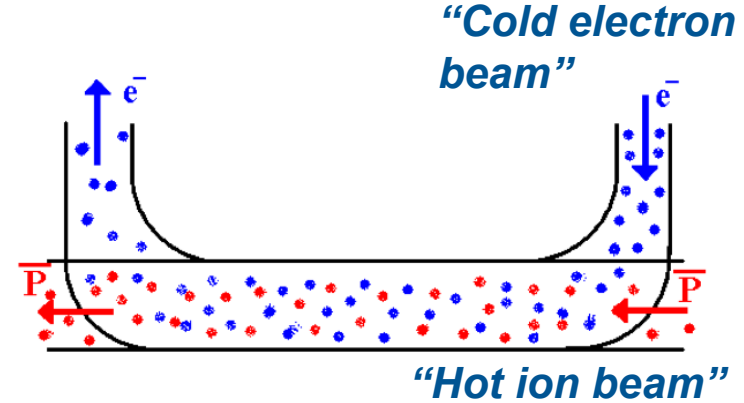


## Electron cooler



# Electron cooling

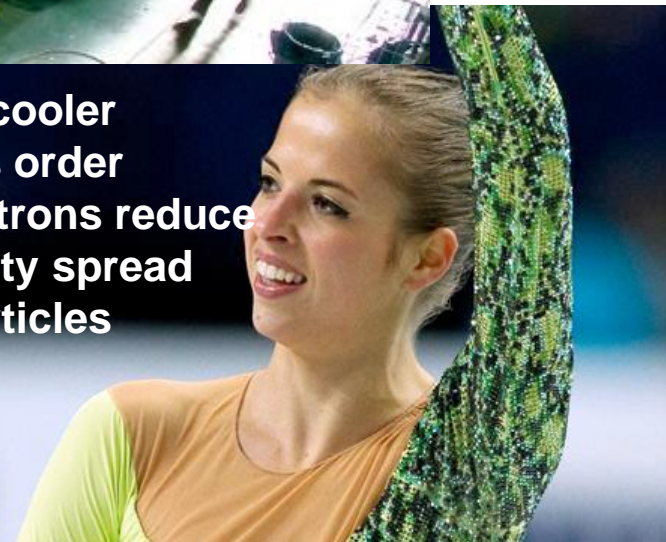
Hot and large emittance beam



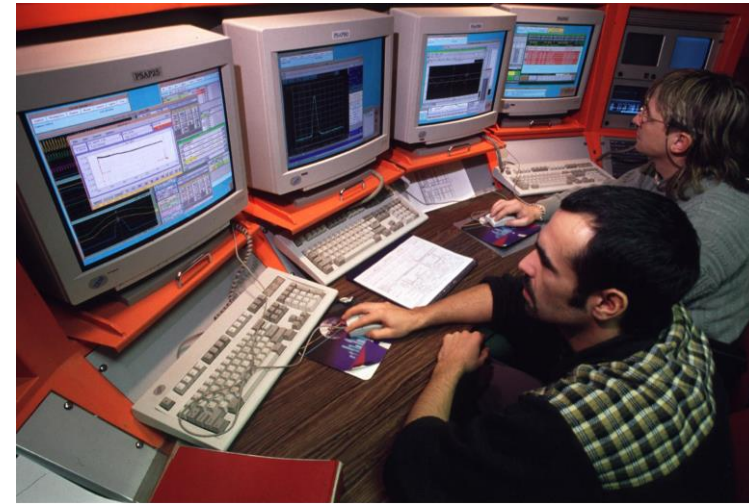
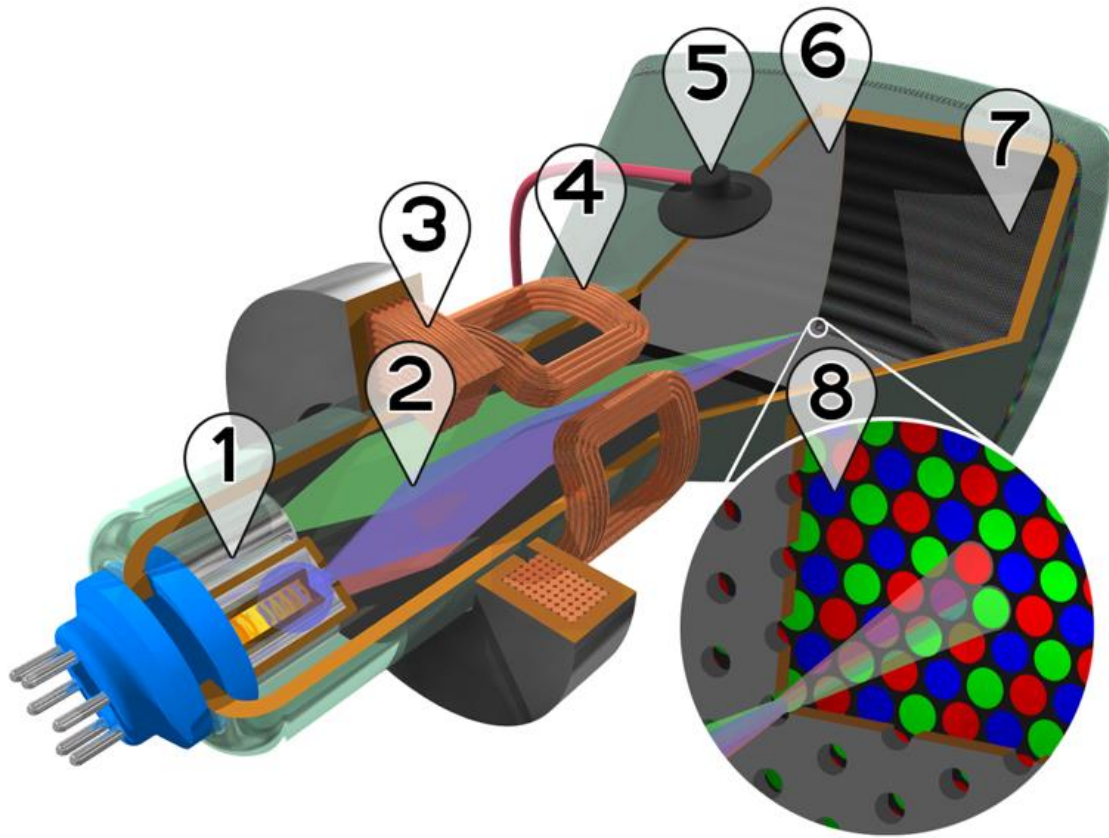
Cold and small emittance beam



Electron cooler increases order  
Cold electrons reduce the velocity spread of hot particles



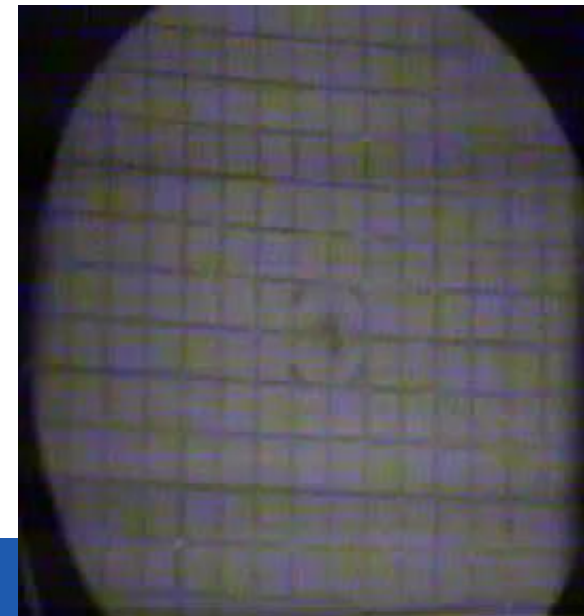
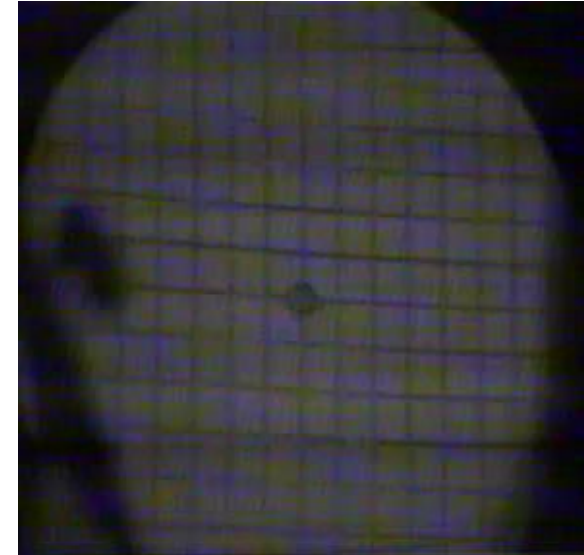
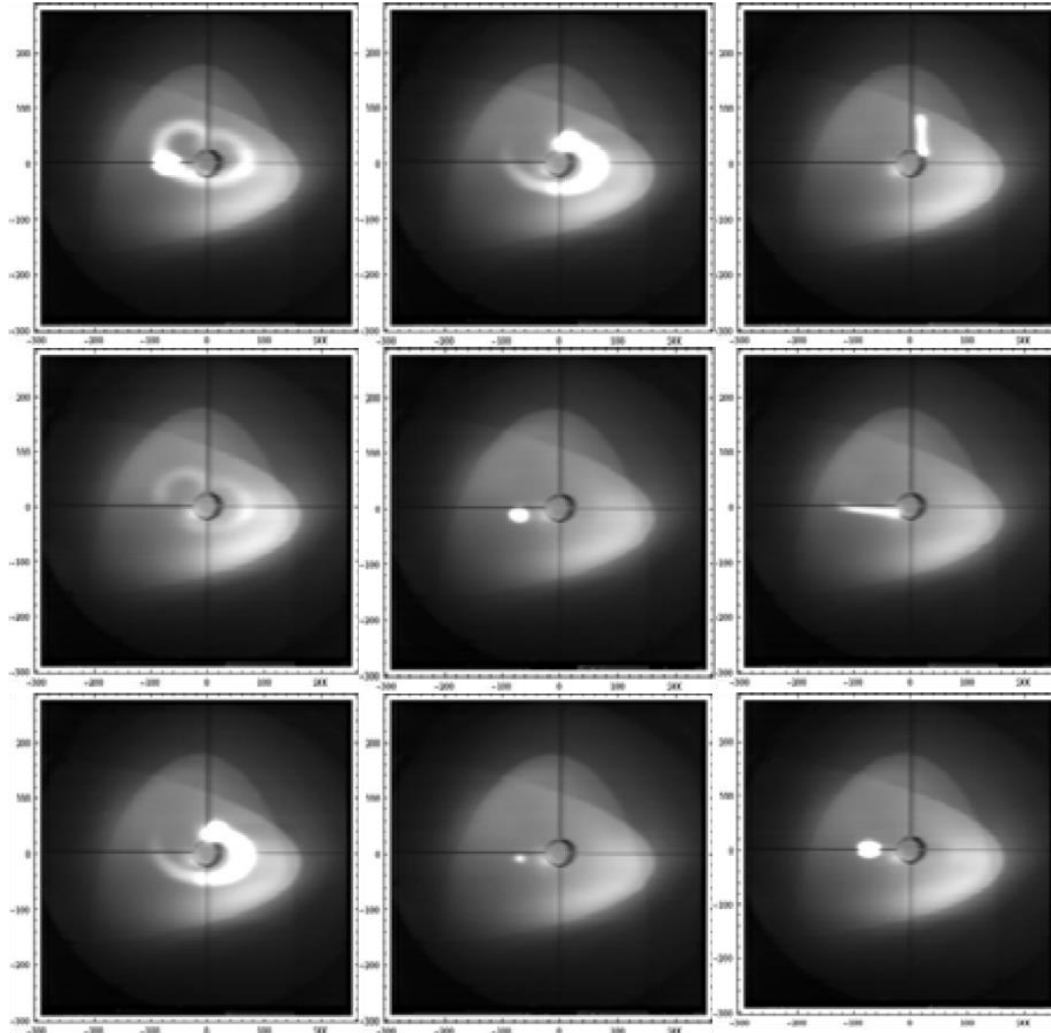
# Summary: an accelerator that you know very well



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

# Real beam images

Courtesy of B. Goddard



# Apples vs Antiapples: protons vs antiprotons (matter vs antimatter)



Does matter fall?



And what about antimatter?

We still not not fully understand matter vs. antimatter in the universe, and by the way gravity neither ...

# First part summary

- **Dipoles** bend charged particles in the accelerator
- **Quadrupoles** focus particles and define the beam **tune**
  
- The emittance is the space occupied by the particles in the  $xx'$  plane
- The envelope is defined by the quadrupoles via the beta function

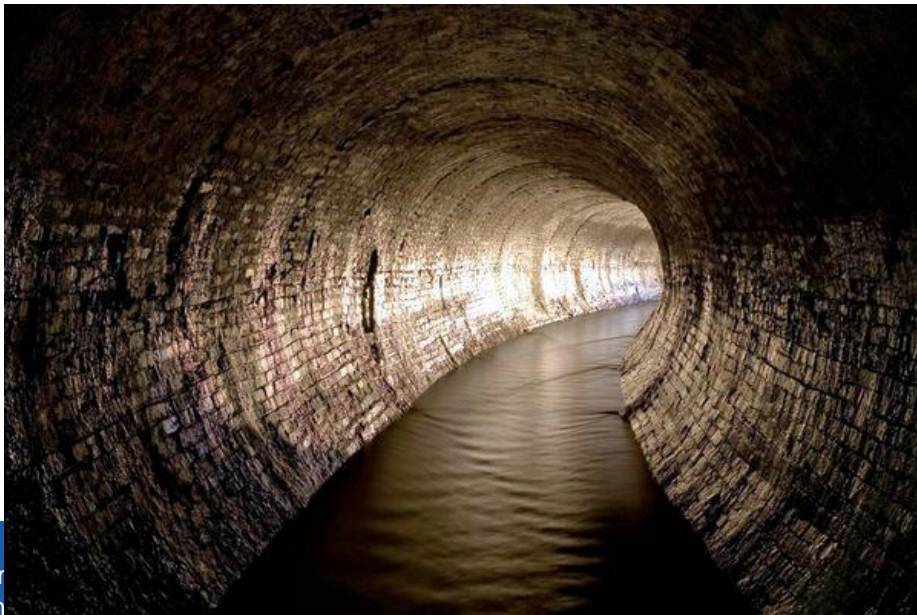


# Building Blocks of an accelerator



1) A particle source

3) A series of guiding and storage devices



2) An accelerating system



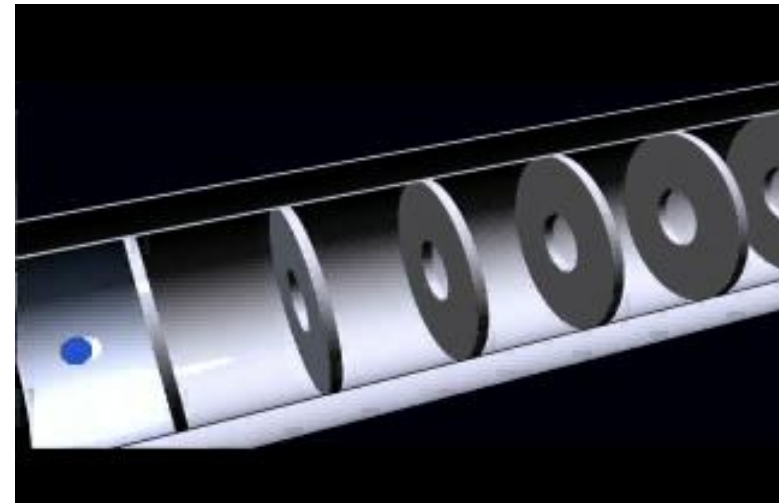
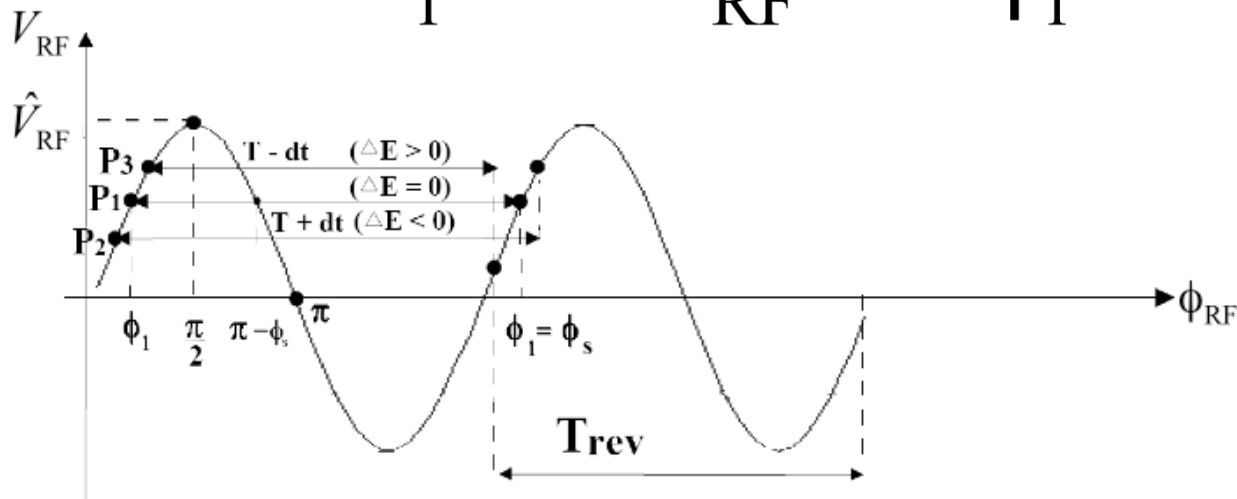
Everything under vacuum



# 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.**

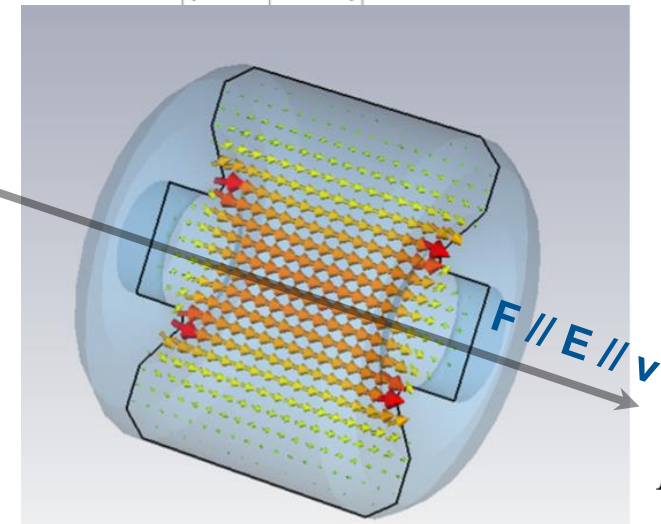
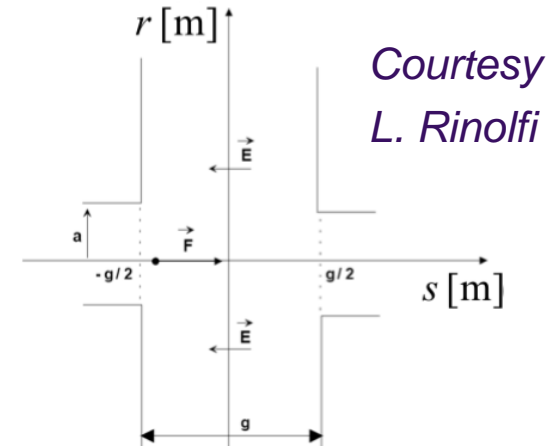
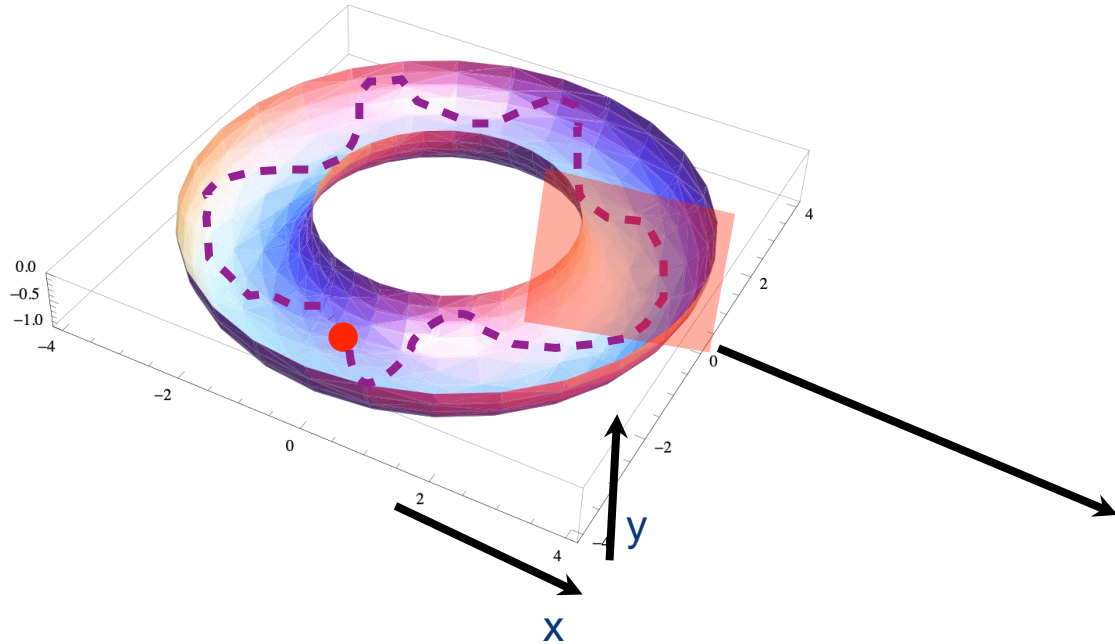
$$\Rightarrow \Delta E_1 = e \hat{V}_{RF} \sin \phi_1$$



# Acceleration I

Acceleration again with Lorentz force:

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



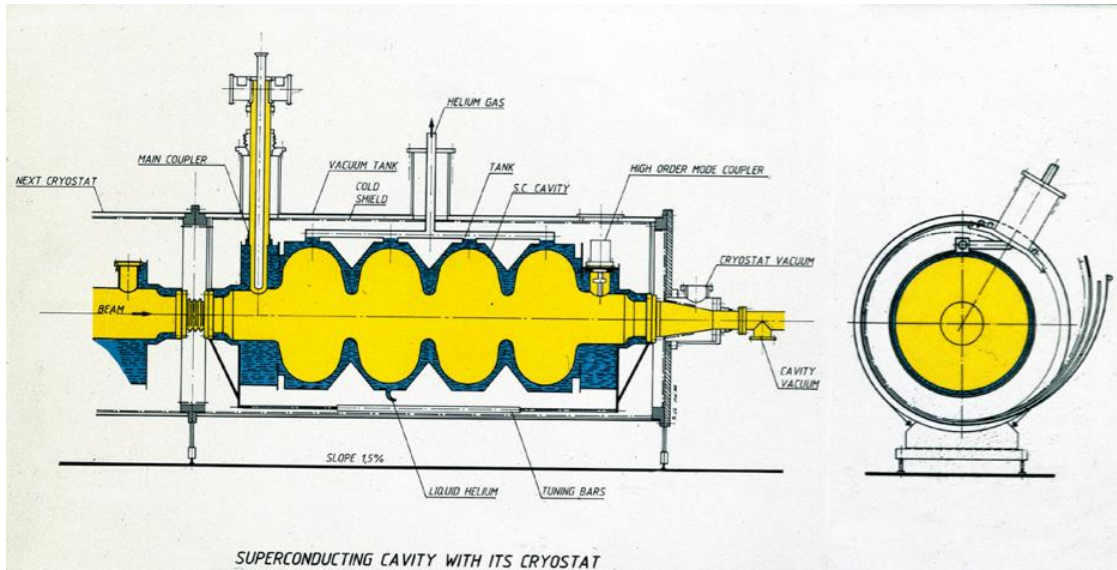
In a well defined part of the accelerator, a **RF (radio frequency) cavity** generates an **electric field parallel to the velocity of a zero divergence particle**.

The cavity itself acts as a resonator.

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

*B. Salvant  
N. Biancacci*

# RF systems, LEP, LHC



Example for LHC:

485 keV gain per turn  
ACCELERATION TAKES TIME

How long is a wave?

$f_{cav} = 400 \text{ MHz}$

$\lambda = c / f_{cav} \sim 75 \text{ cm}$

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

Example for LEP:

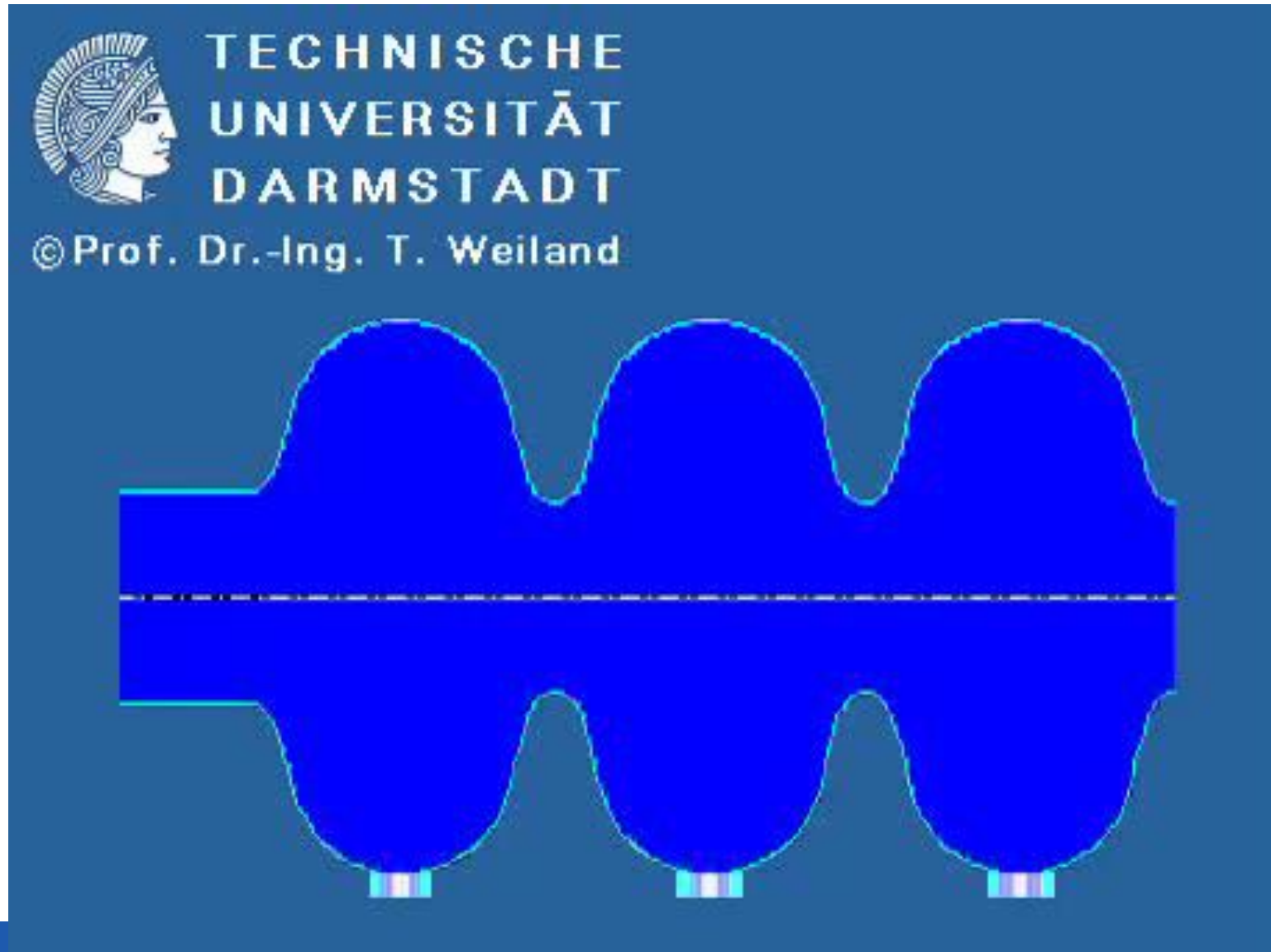
120 cavities (room temperature) at 352 MHz, provided over 300 MV circumferential voltage (! that's why we do not bend with E fields...)

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



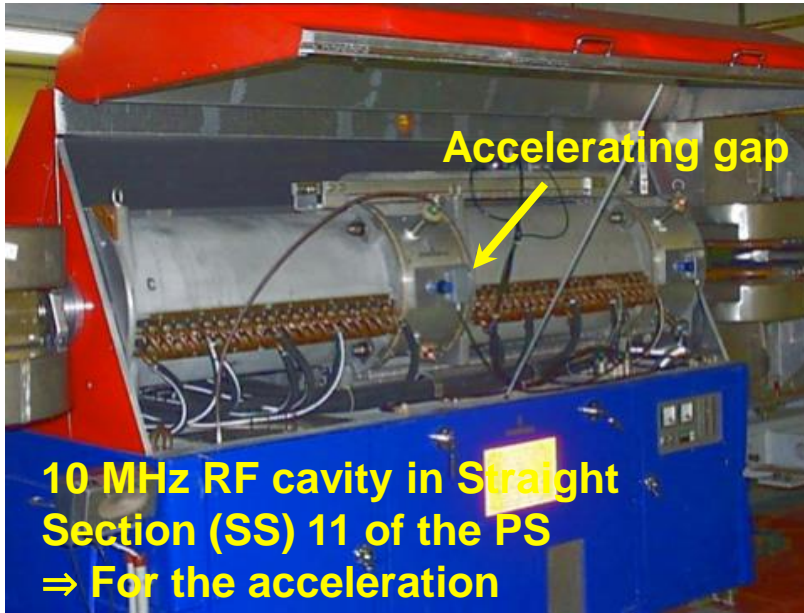
RF Cavity 2013

# Electromagnetic field of bunch in a cavity



# Example of RF cavities in the PS

The dimension of the cavity changes with the RF wave length



# Some italian radios (Provincia di Vicenza)

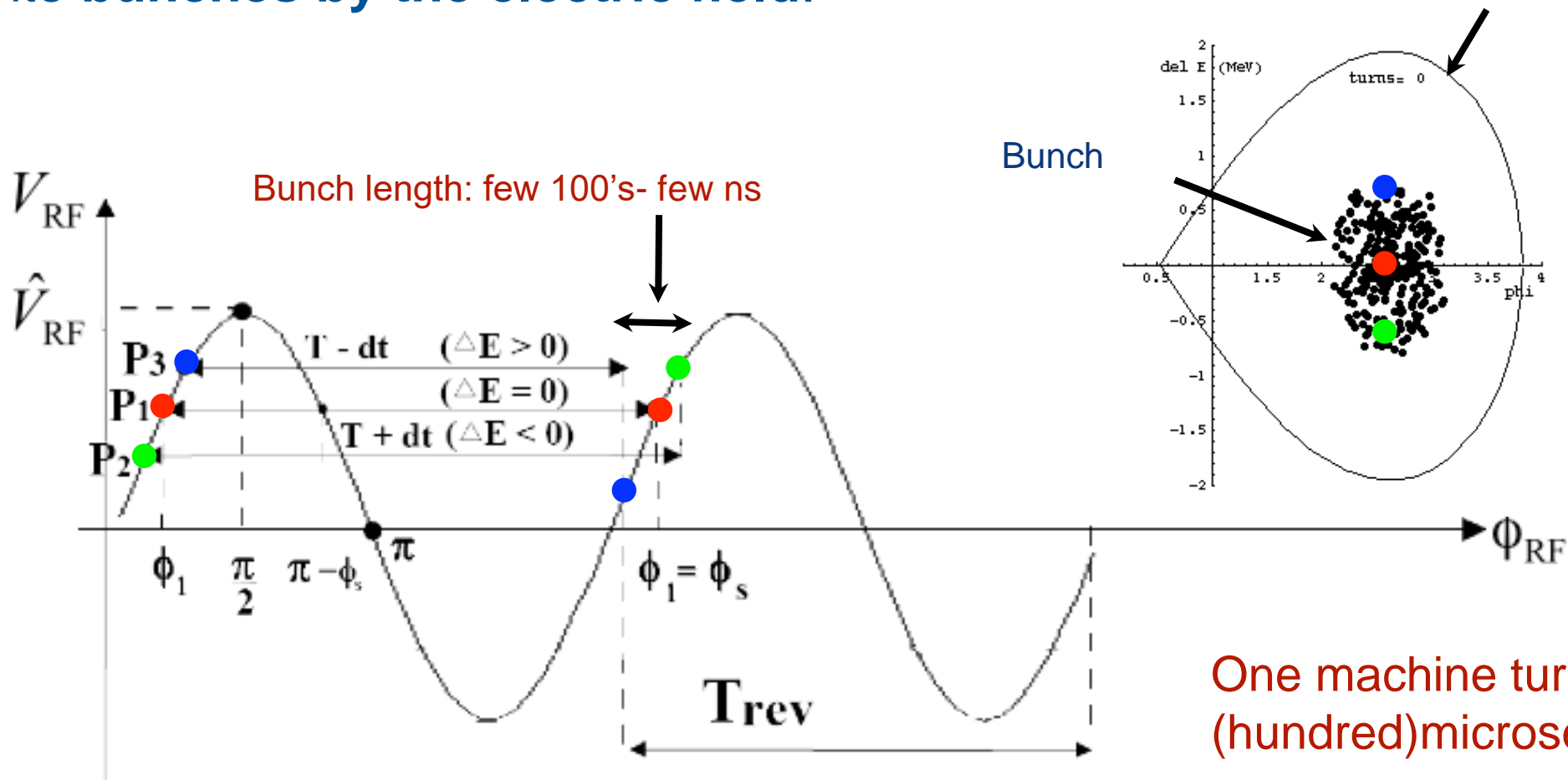
(Mhz)	nominativo
87.60	EASY NETWORK
87.85	RADIO CAPITAL
88.10	RAI, RADIO UNO
88.40	RADIO PADOVA
88.70	RADIO RICERCA REALTA' (CIRC. MARCONI)
89.00	RAI, RADIO DUE
89.30	RADIO DEEJAY
89.60	BELLISSIMA FM
89.90	RAI, RADIO TRE
90.20	RADIO OREB (CIRCUITO MARCONI)
90.40	BUM BUM ENERGY
90.65	RADIO PICO
90.80	RADIO RICERCA REALTA' (CIRC. MARCONI)
90.90	RADIO COMPANY
91.10	RADIO SOLE
91.30	RADIO SORRISO
91.60	RADIO PITERPAN
91.60	RADIO BIRIKINA

(Mhz)	nominativo
97.70	RADIO COLLINA STUDIO UNO
97.95	RADIO FOLLIA
98.20	RADIO CAPITAL
98.45	BUM BUM NETWORK
98.60	RAI, RADIO TRE
98.70	EASY NETWORK
99.00	TRV TELE RADIO VENETA
99.30	RADIO PITERPAN
99.55	RADIO PRINCIPESSA
99.80	RDS, RADIO DIMENSIONE SUONO
100.05	RSB RADIO SAN BONIFACIO
100.25	RCA - RADIO CITY ANTENNA UNO
100.50	RADIO COMPANY
100.80	RMC, MONTECARLO
101.00	RADIO BLU
101.30	RCA - RADIO CITY ANTENNA UNO
101.50	RADIO ITALIA SOLO MUSICA ITALIANA



# Longitudinal focusing, a pendulum ...

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



One machine turn ~ some (hundred)microseconds

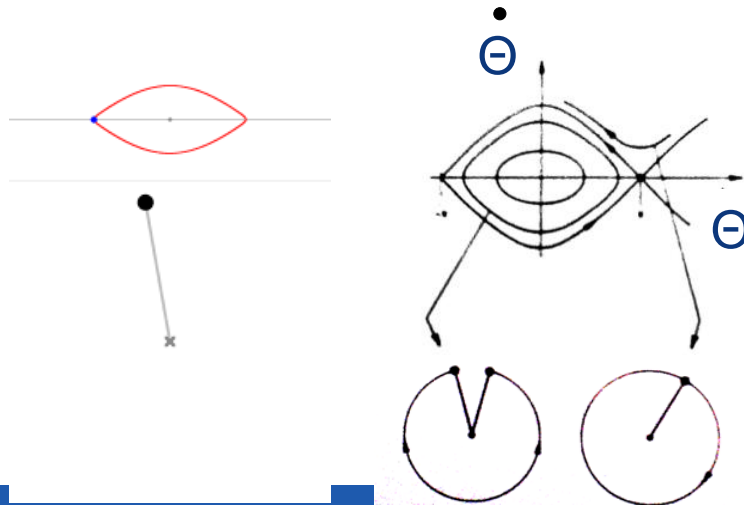
# Longitudinal dynamics

## Classical mechanics.... oscillating pendulum

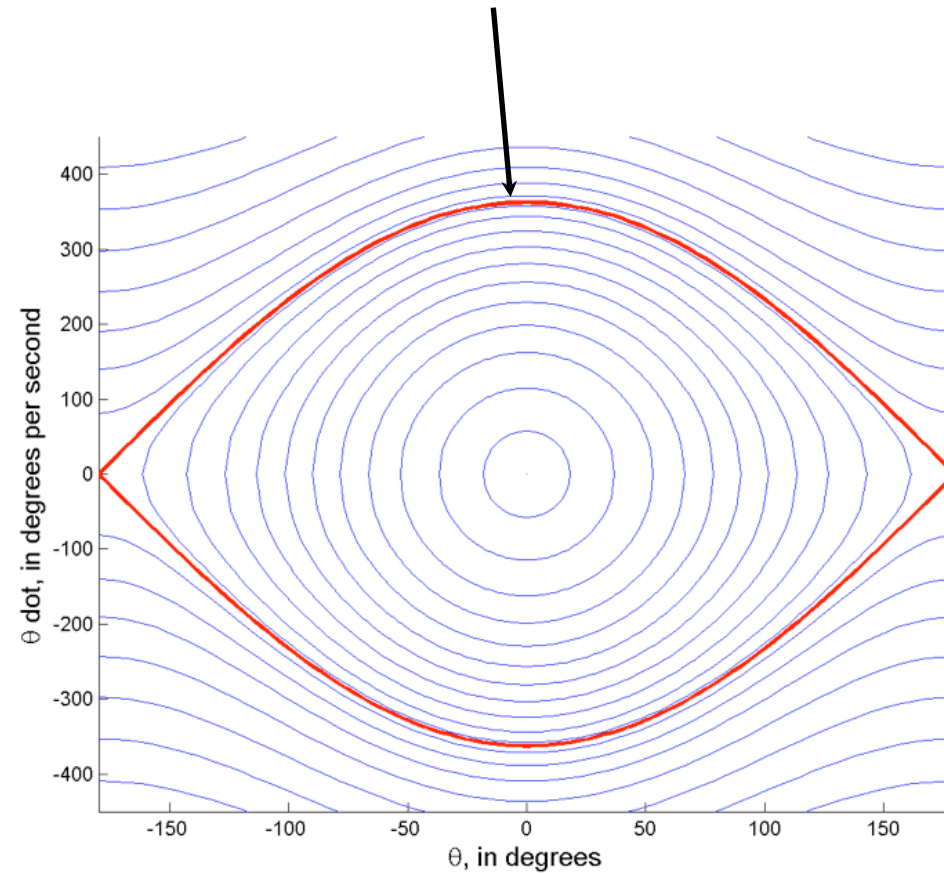
$$\frac{d^2\theta}{dt^2} + \frac{g}{l} \sin\theta = 0$$

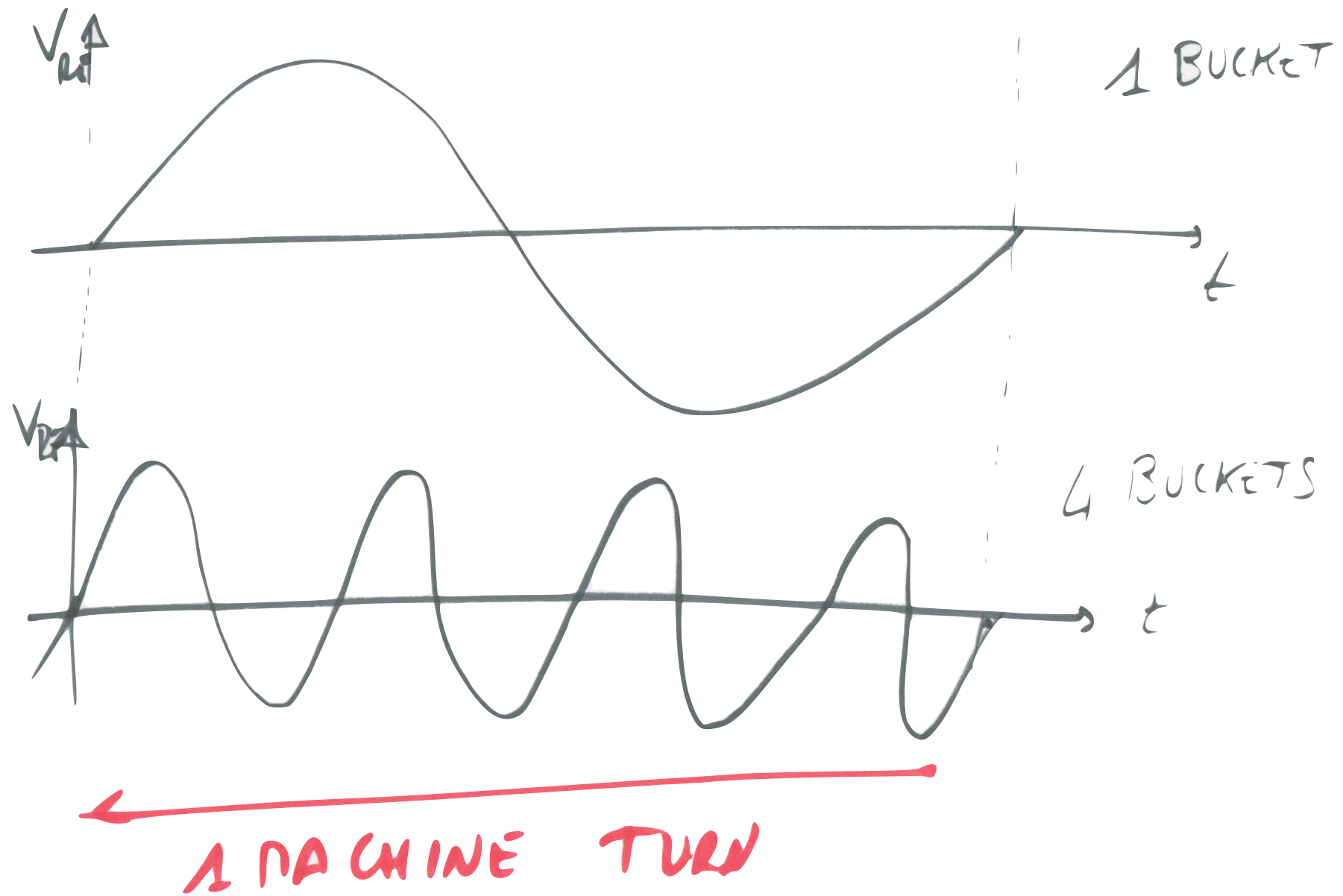


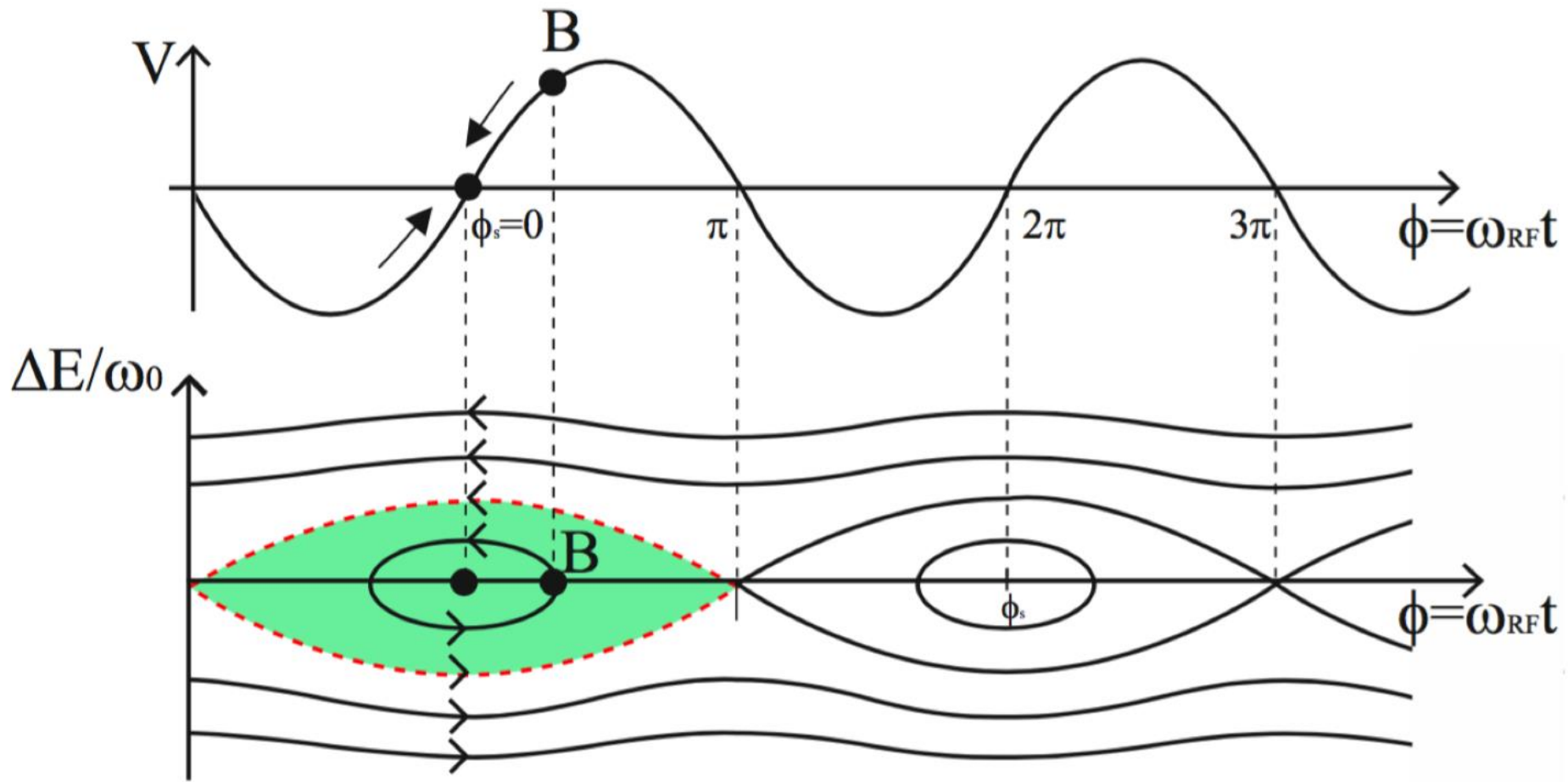
Constant force:  
g = acceleration of gravity  
l = pendulum length



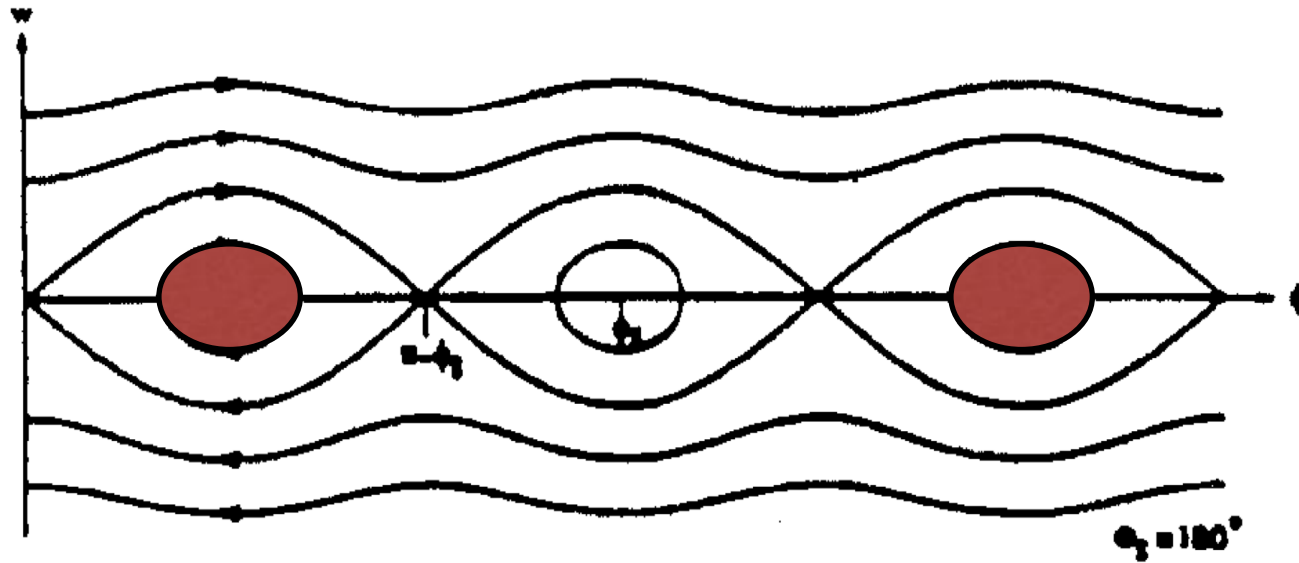
The movement is stable only inside the separatrix







# A chain of buckets



Courtesy  
E. Wilson

Number of buckets:

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

In the example: 3 buckets and 2 bunches

# From wavelength to meters

Frequency	Wavelength
1 MHz	300 meters
10 MHz	30 meters
50 MHz	6.0 meters
100 MHz	3.0 meters
200 MHz	1.5 meters
300 MHz	1.0 meter
400 MHz	0.75 meters
500 MHz	0.6 meters
600 MHz	0.5 meters
700 MHz	42.9 cm
800 MHz	37.5 cm
900 MHz	33.3 cm
1.0 GHz	30 cm

PS

SPS

LHC



Circumference increases

Bunches are shorter

More bunches

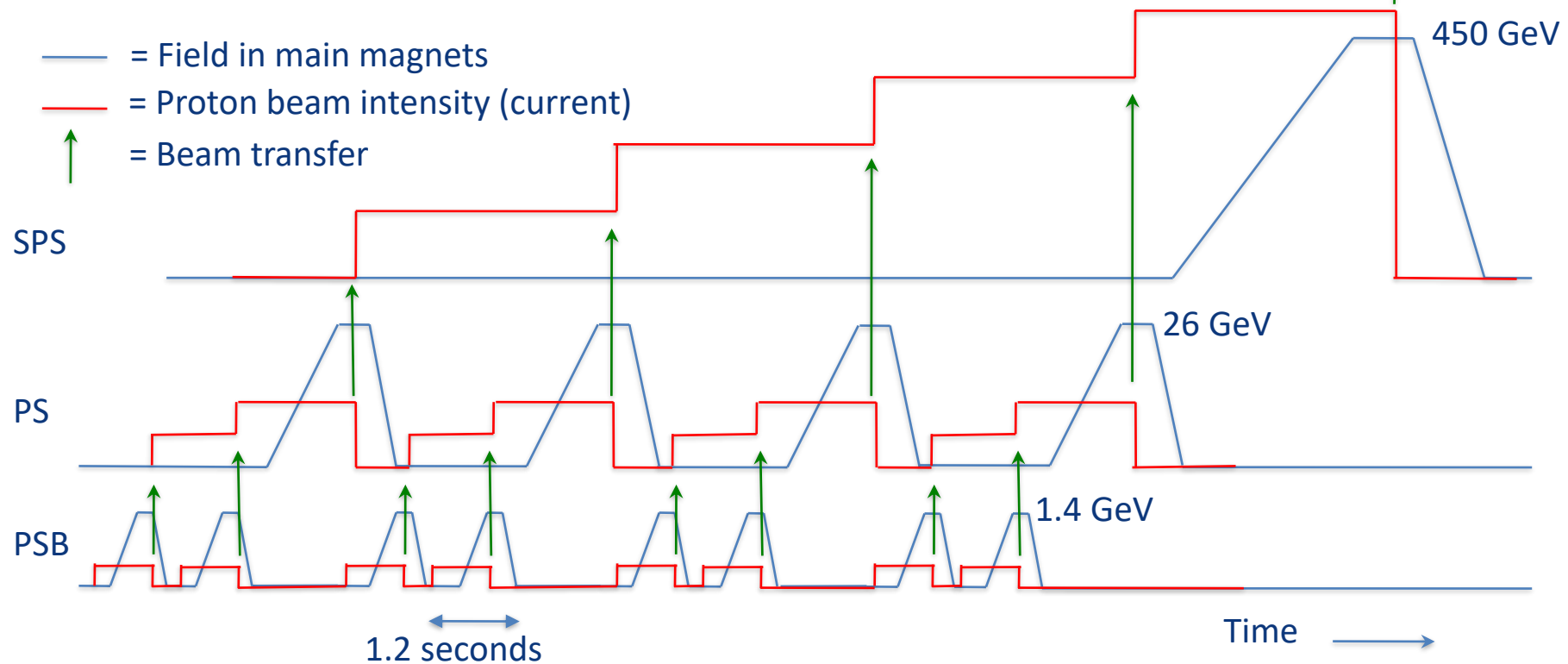
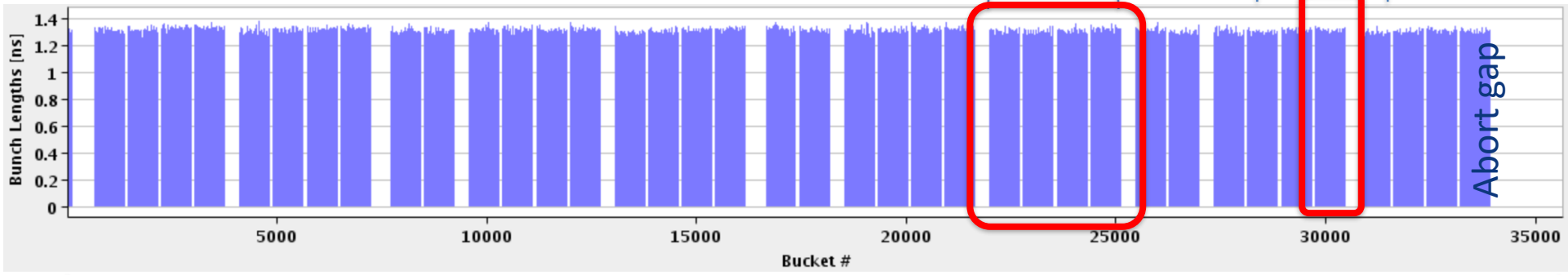
Q: Why I want a lot of bunches in the LHC?

# How many buckets are in the LHC?

- $f_{RF} = 400 \text{ MHz}$        $f_{RF} = h \times f_{rev}$
- $f_{rev} = \beta c / (2\pi R)$
- $2\pi R = 26659 \text{ m}$
- Harmonic Number:  $h = f_{RF} / f_{rev}$
- $h = (400 \cdot 10^6) / (c / 26659)$
- Harmonic Number  $\approx 35640$  — number of buckets
  
- Q: why we have only 2808 bunches ?
- Q: why bunches spaced by 25 ns?
- Q: why bunches at all ?

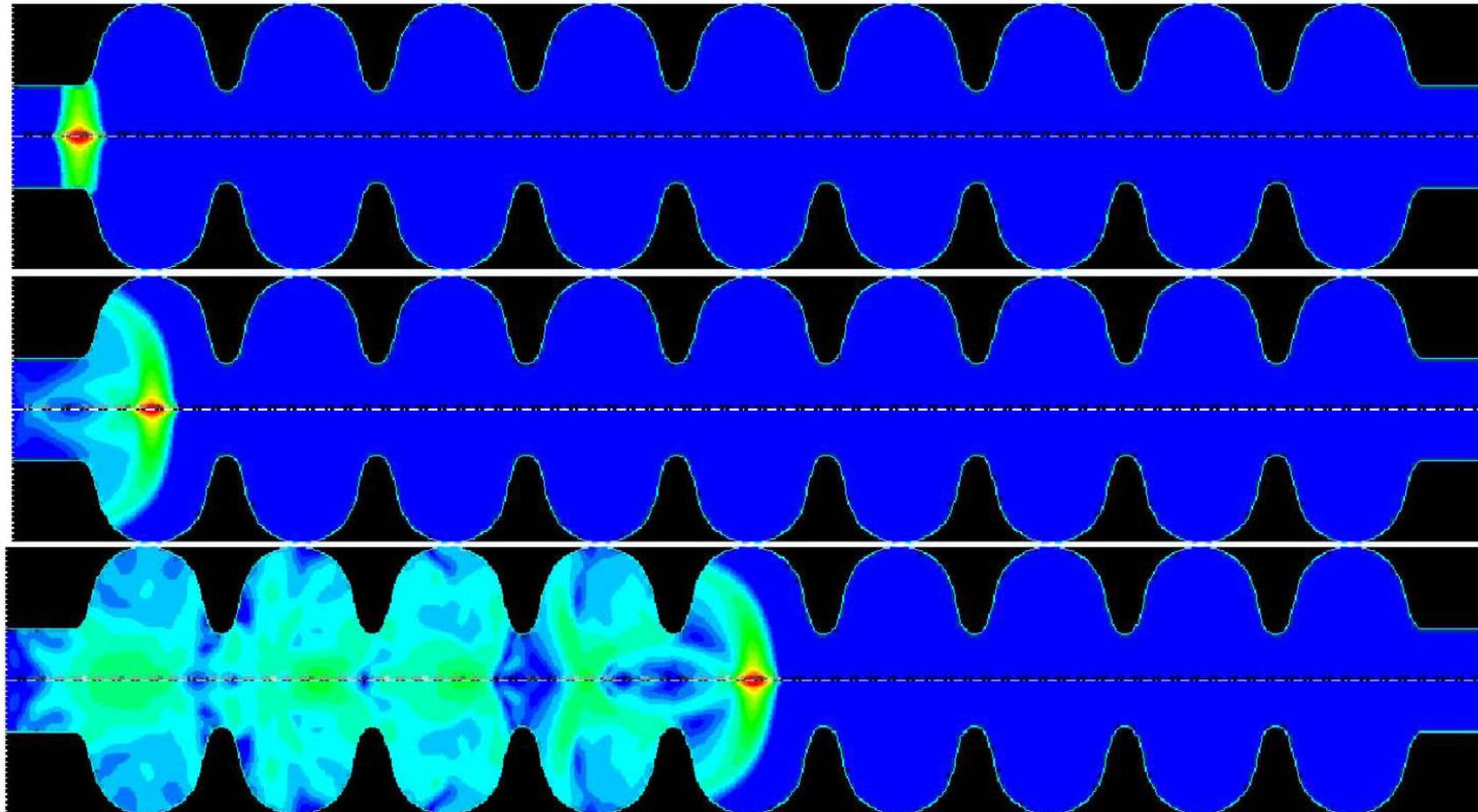
# LHC and Injectors – 50 ns

1 SPS batch (144 bunches)      1 PS batch (36 bunches)





# Induced field inside a cavity from a bunch passage



D. Trines, Bodrum 2007

Following bunch “feels” the presence of the previous one due to induced electromagnetic field

# Summary

- **Dipoles** bend charged particles in the accelerator
- **Quadrupoles** focus particles and define the beam **tune**
- **RF cavities** accelerate the beam
  
- The emittance is the space occupied by the particles in the  $xx'$  plane
- The envelope is defined by the quadrupoles via the beta function