Longitudinal Dynamics

$$F = e\,(E + v \times B)$$

Acceleration

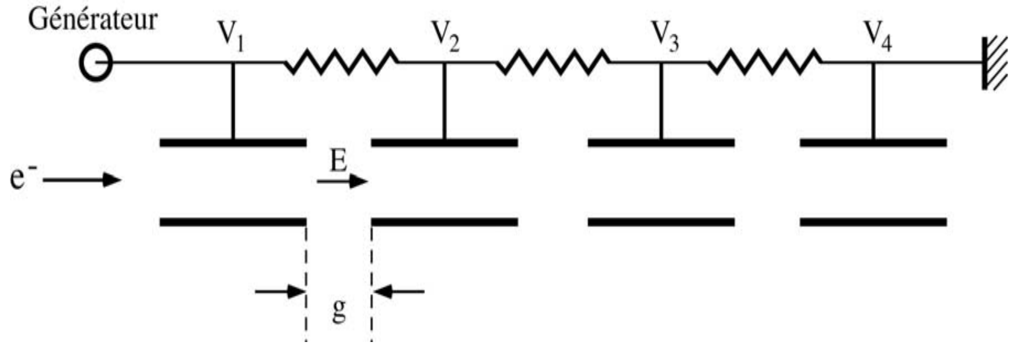
The accelerator has to provide kinetic energy to the charged particles, i.e. increase the momentum of the particles. To do this, we need an electric field E, preferably in the direction of the momentum of the particles

Electrostatic accelerator

Gain: n.e.ΔV

Limit: $V_G = \Sigma V_i$

Sparks !

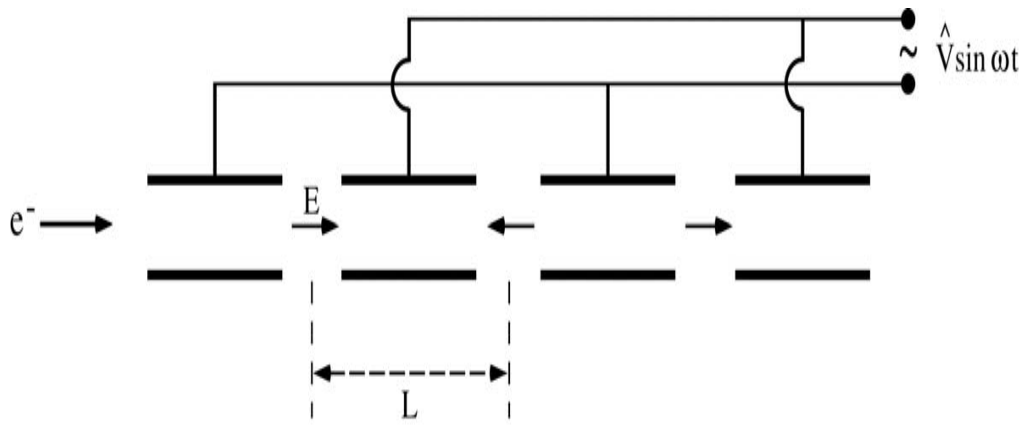


Rather use RF fields !

RF accelerating fields:

Wideroe structure

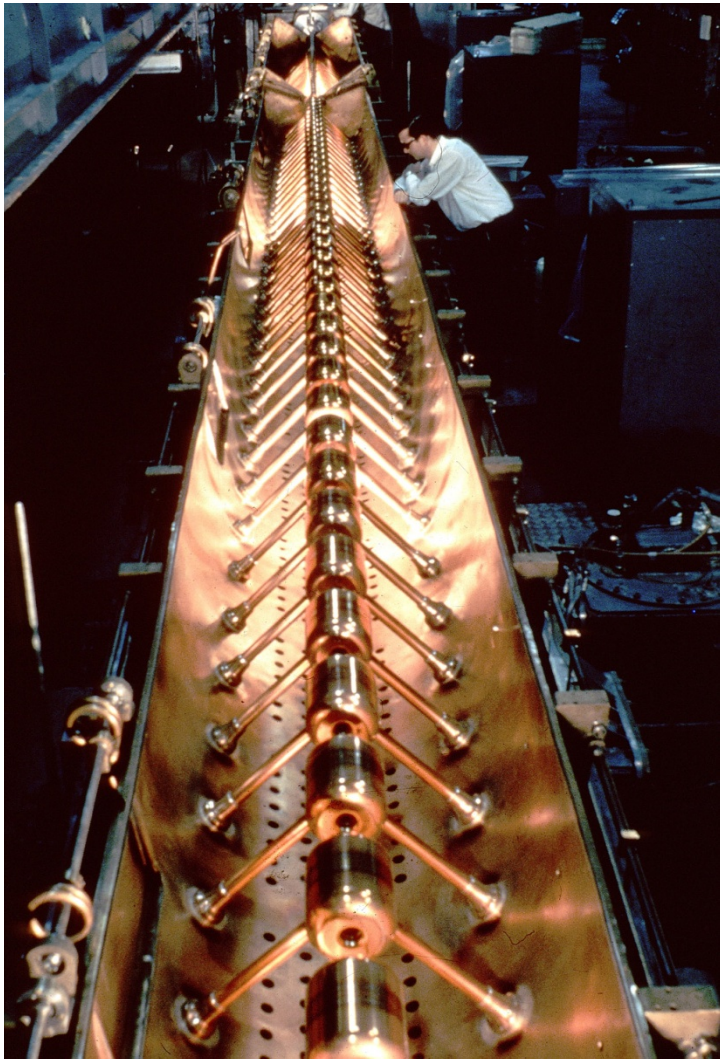
Synchronism: L = vT/2



As the speed of the particles increases, the length of the drift tubes has to increase ! Efficiency !

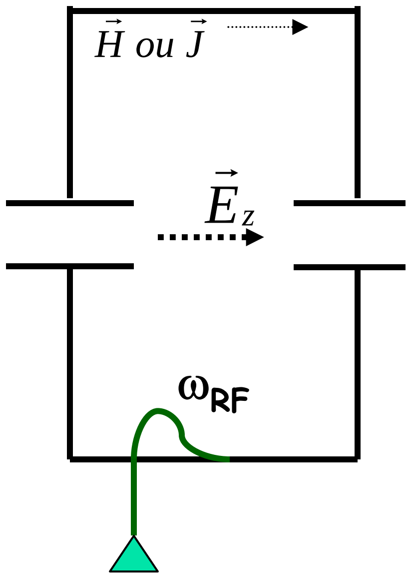
Low energy linac:

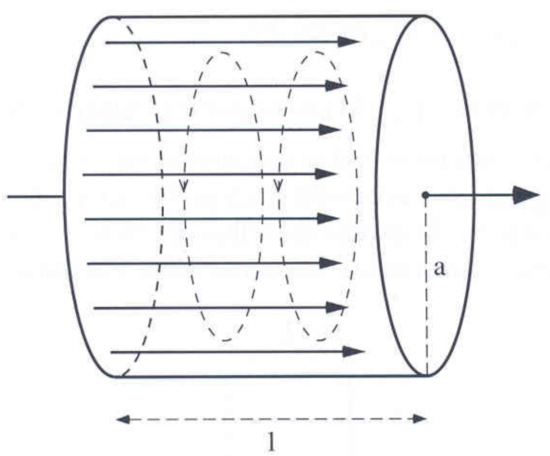
Linear structure
in use at CERN



Resonant cavities (1)

The resonance frequency of the cavity is adapted (matched) to the frequency of the RF generator.



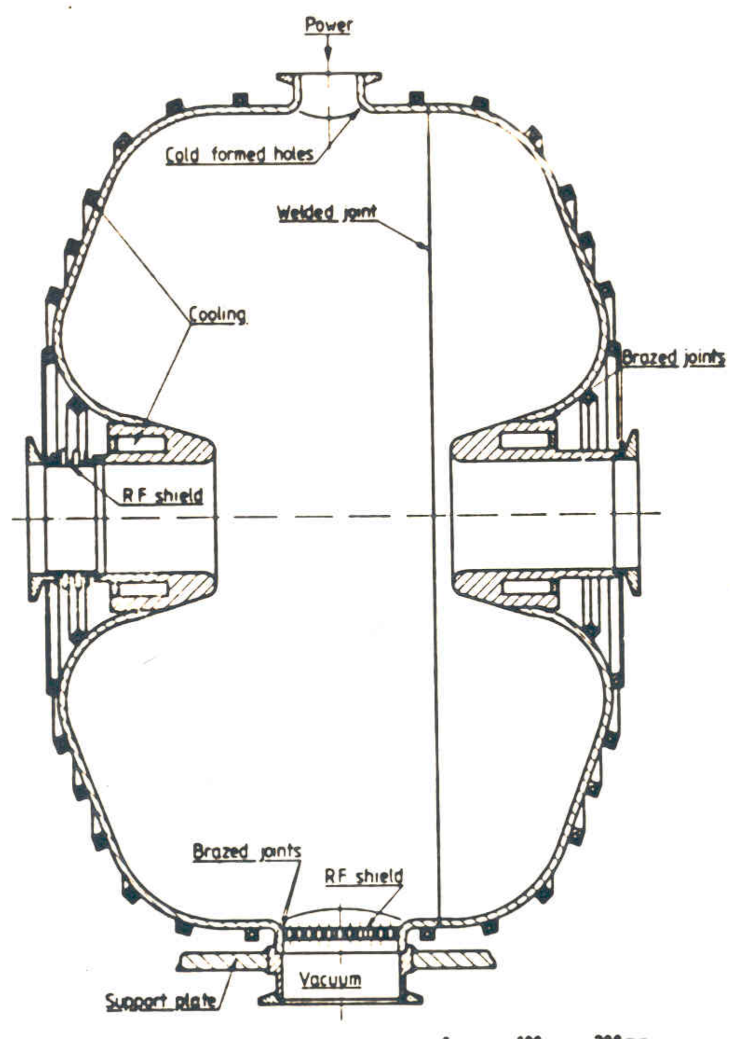


Resonant cavities (2)

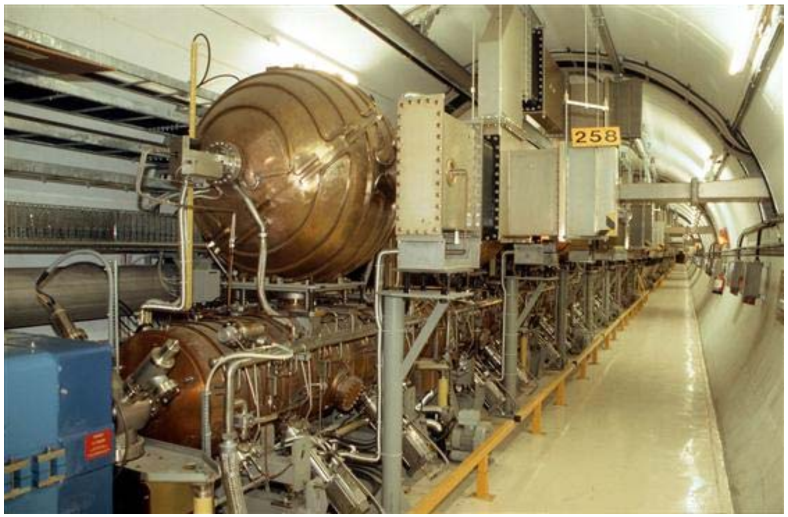
Real geometry is more sophisticated to improve the performance of the cavity

Nose: E in the vicinity of the symmetry axis

Rounding: losses, multipacting

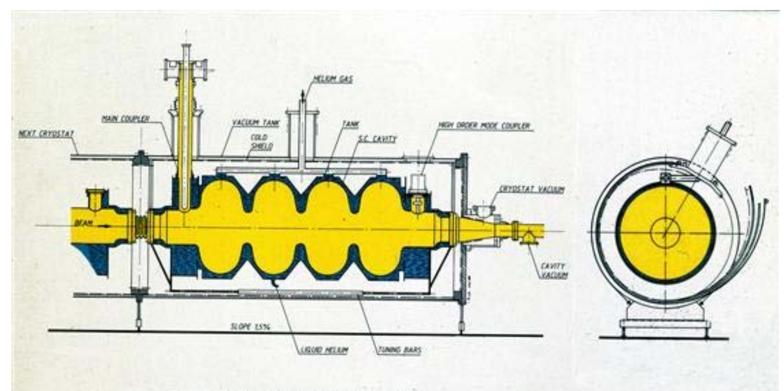


RF cavities:



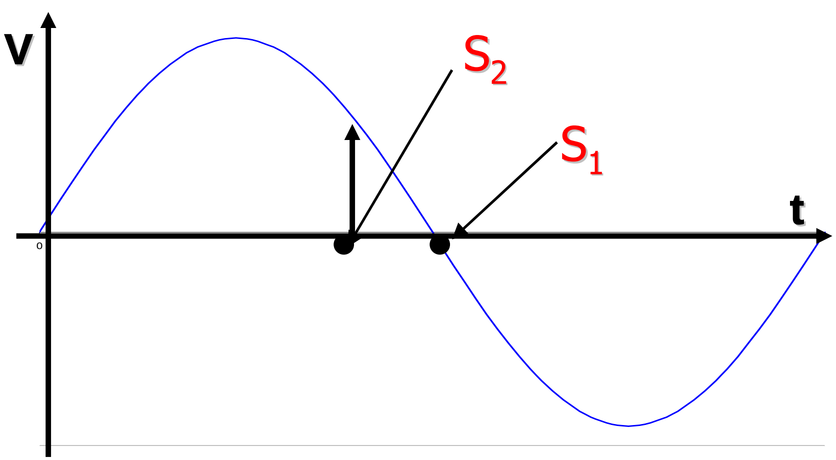
LEP "NC"

LHC "SC"



Acceleration or compensation

- We have to provide energy to the particles either to accelerate them or to compensate for the losses accumulated during one turn.
- This energy is not provided by electrostatic plates, but by RF cavities.
- The ideal particle has to arrive at the cavity exactly at the same moment turn after turn (synchroneous particle).



Equilibrium:

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

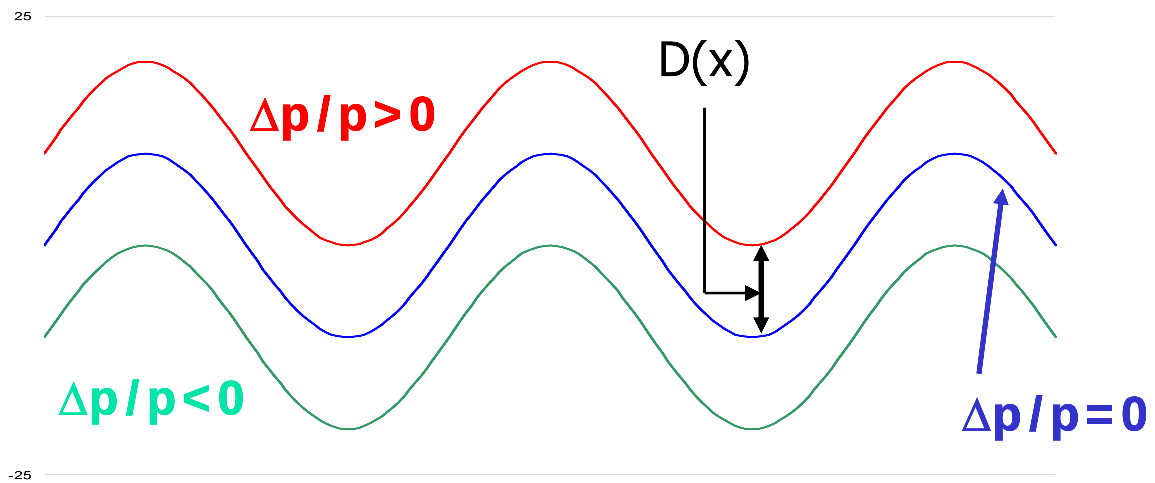
Off momentum particles ($\Delta p/p \neq 0$)

Effect from Dipoles

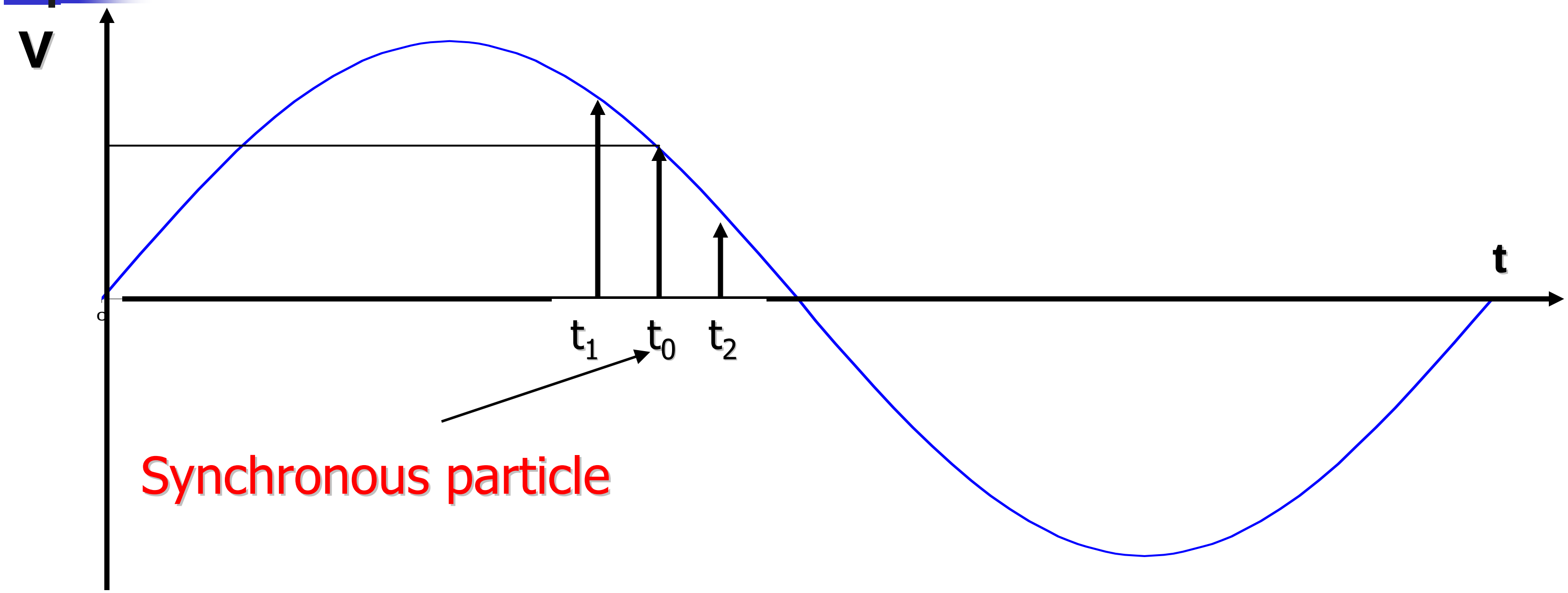
- If $\Delta p/p > 0$, particles are less bent in the dipoles ➔ should spiral out !
- If $\Delta p/p < 0$, particles are more bent in the dipoles ➔ should spiral in !

No!

There is an equilibrium with the restoring force of the quadrupoles

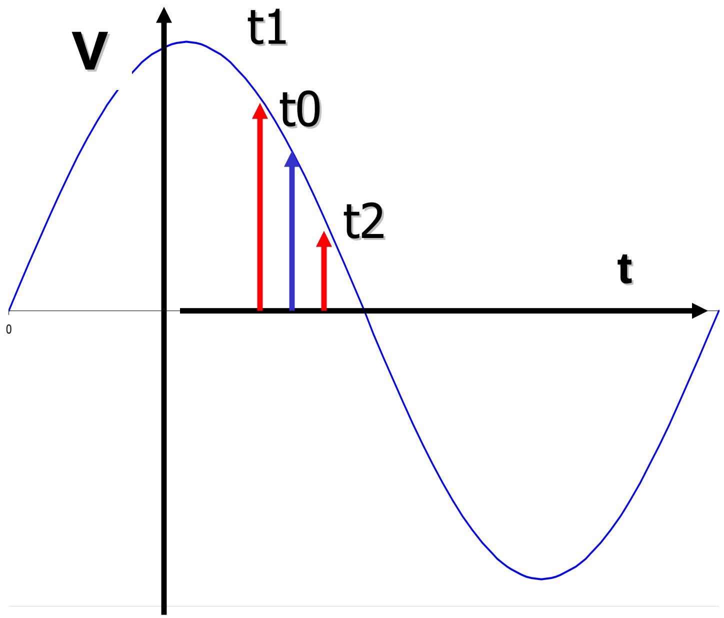


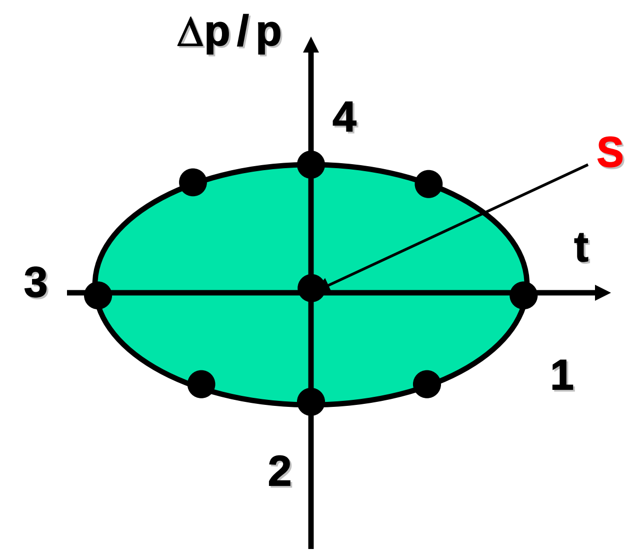
Off momentum particles



On momentum particle arrives at t_0 ➔ $V = V_0$ ➔ o.k.
$\Delta p/p > 0$ have a longer path ➔ arrive late, e.g. t_2 ➔ $V_2 < V_0$
$\Delta p/p < 0$ have a shorter path ➔ arrive early, e.g. t_1 ➔ $V_1 > V_0$

Synchrotron oscillations





1) Correct energy but late, not enough voltage ➔ will loose energy.
2) On time, correct voltage, on short orbit ➔ will gain energy.
3) Correct energy but early, too large voltage will gain ➔ energy.
4) On time, correct voltage, on long orbit ➔ will loose energy.

Synchrotron oscillations

- In the longitudinal plane, particles also perform oscillations, the synchrotron oscillations.
- These oscillations are characterised by the synchrotron tune Q_s.
- The frequency of the synchrotron oscillations is very different from that of the betatron oscillations:

$Q_\beta > 1$ $Q_s << 1$

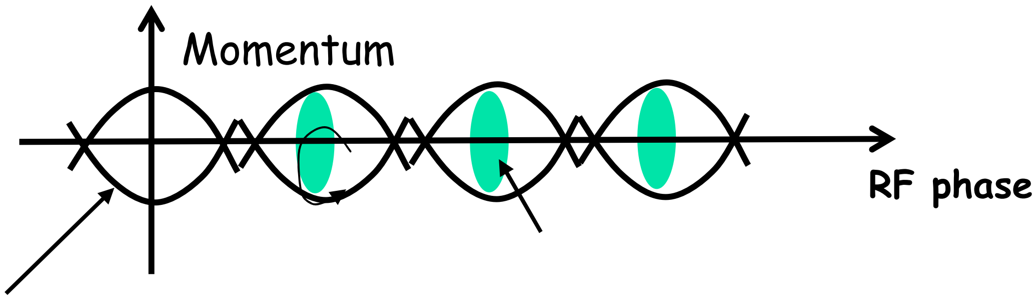
The RF system imposes limits on t (i.e. t_1 and t_2) and $\Delta p/p$ for which the particles are stable and perform synchrotron oscillations within the bunch. Outside these limits the particles are lost.

The RF cavities restore energy losses, ensure correct energy of the beam(s) and maintain particles grouped into bunches longitudinally.

The bunches of particles:

The RF system creates bunches of particles

With f_{RF} = h . f_{rev} , we could thus have "h" bunches of particles circulating in the machine.



LHC: h= 35640

f_{RF} = 400 MHz

V_{RF} = 16 MV

2808 bunches per beam

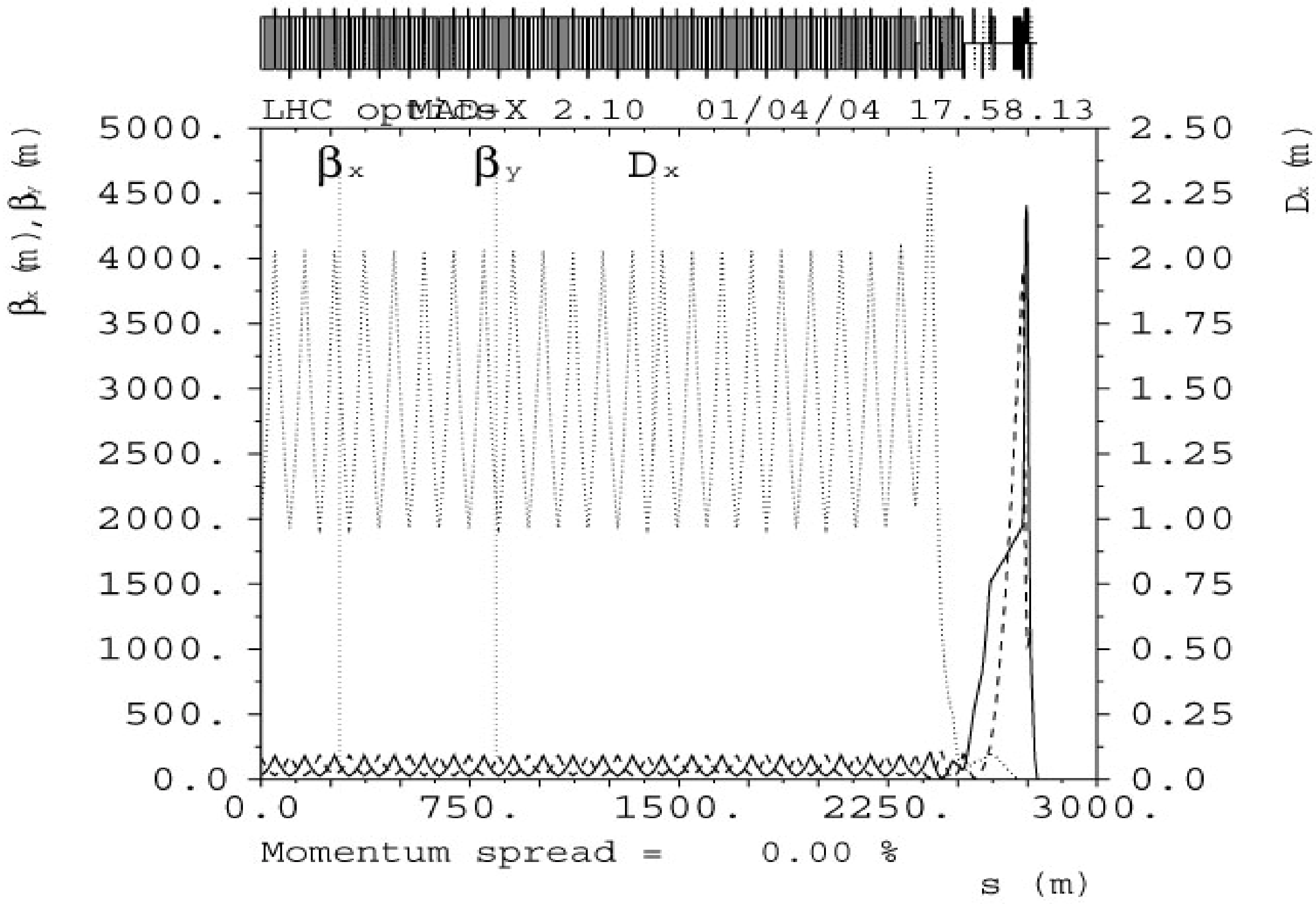
Closed orbit distortions

$$x(s) = (\beta_i\, \beta(s))^{1/2}/(2\sin(\pi Q))\ .\ \theta_i\ .\ \sin(\phi(s) - \phi_i)$$

$$x'(s) = (\beta_{i\,,}\beta(s))^{1/2}/(2\sin(\pi Q))\ .\ \theta_i\ .\ \cos(\phi(s) - \phi_i)$$

- Any imperfection or perturbation of the guide field will distort the closed orbit, which, so far was the theoretical axis of the machine.
- The ideal particle will no longer go straight down the centre of the vacuum chamber, but will follow a perturbed closed orbit (still closing on itself).
- The betatron oscillations of the particles will be superimposed to this distorted closed orbit ➔ Aperture and non-linearities.

Beta function in a real machine



Aperture:

Aperture is a key parameter which has to be defined at a relatively early stage! It deserves a lot of attention!

Apert. small

Global cost,
Powering cost,
Multipoles,
good field region,
available space,
Power supplies, …

Apert. large

Injection steering,
closed orbit,
emittance at injection,
Impedance, …

Closed orbit, Magnets and PCs

- In modern machines (aperture is very expensive), it is therefore essential to control the closed orbit with great care

LHC: Δx, Δy < 4 mm and r.m.s. < 0.5 mm

- In low-beta insertions (very large beta values before and after the I.P.), imperfections or perturbations of the guide field can have dramatic consequences (vacuum chamber, non-linear fields).

The stability and the accuracy of the magnets/power converters is one of the key ingredients to ensure the expected performance of the machine !

Stability !

How do the stability and the accuracy of the Magnets affect the accelerator?

- Accuracy of the energy of the beam(s) : dipoles

- Modify the tunes of the machine : quadrupoles

- Perturb the closed orbit of the machine : field errors/fluctuations

Synchrotron Radiation

Synchrotron radiation

- Charged particles bent in a magnetic field emit synchrotron radiation!

with $\gamma = E/E_0 = m/m_0$ and m_0 is the rest mass

Energy loss:

$$eU_0 = A \,.\, \gamma^4/\rho$$

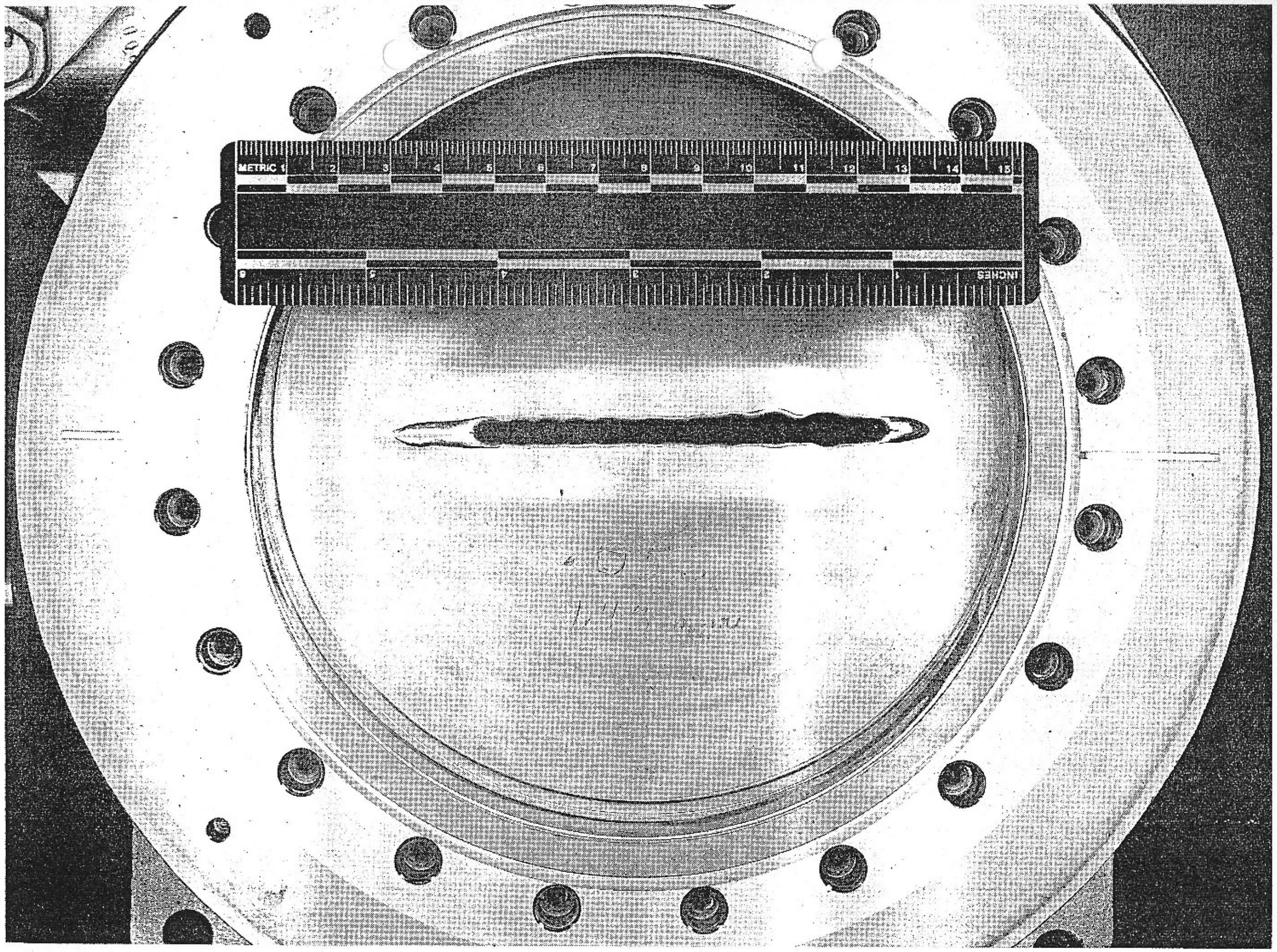
m_0 proton = 0.938 GeV/c^2

m_0 electron = 0.511 MeV/c^2

$(m_{o\text{-}p}/m_{o\text{-}e})^4 = (1836)^4 \cong 10^{13}$

Collider	B (T)	E/beam (GeV)	γ	eU_0 (GeV)
LEP ($e^+ e^-$)	0.12	100	196000	2.92
LHC (p-p)	8.3	7000	7500	0.00001

The power is all too real !



ig. 12. Damaged X-ray ring front end gate valve. The power incident on the valve was approximately 1 kW for a duration estimated to 2–10 min and drilled a hole through the valve plate.

L. Rivkin

CAS-Trieste2005

Hadrons vs. Leptons (circular machine)

Two extreme cases:

Magnetic rigidity:
$B\rho = mv/e = p/e$

↓

LEP (100 GeV): B = 0.12 T
LHC (7 TeV): B = 8.3 T

Synchrotron radiation losses:
$eU_0 = A \cdot \gamma^4/\rho$

↓

LEP (100 GeV): U_0 = 3 GeV
LHC (7 TeV): U_0 = 0.00001 GeV

Remember: For warm magnets (not SC): $B \leq 2$ T

The Performance

e.g. for colliders: the Luminosity

$dN/dt = L \times \sigma$

$[1/s] = [1/(cm^2.s)] \times [cm^2]$

$$L = N_1.N_2.f.k/(4.\pi.\sigma_x.\sigma_y)$$

with:

$N_{1,2}$ = Number of particles per bunch

f = revolution frequency

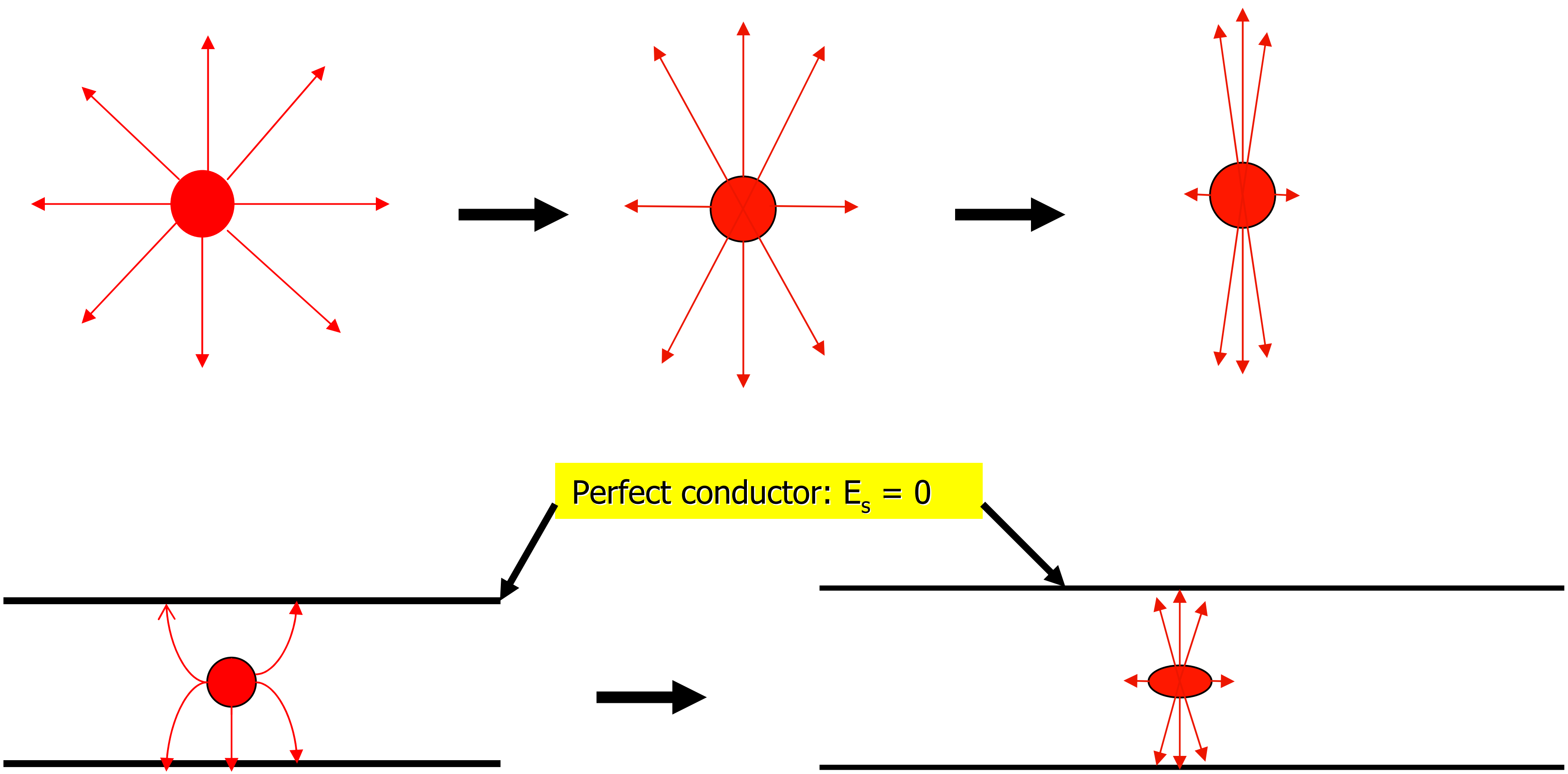
k = number of bunches

$\sigma_{x,y}$ = horixontal and vertical beam size

Maximise the bunch Intensity

$$L = N_1.N_2.f.k/(4.\pi.\sigma_x.\sigma_y)$$

Intensity: Impedance $Z_L(\omega)$ (1)



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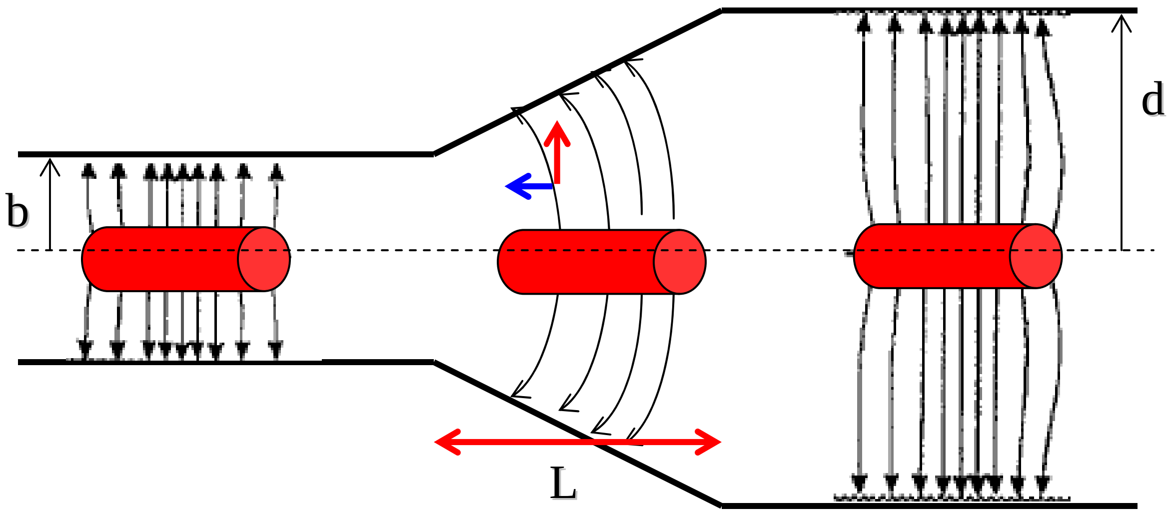
Impedance $Z_L(\omega)$ (2)

- If conductor is not perfect, or, even worse, if $b \neq$ const.



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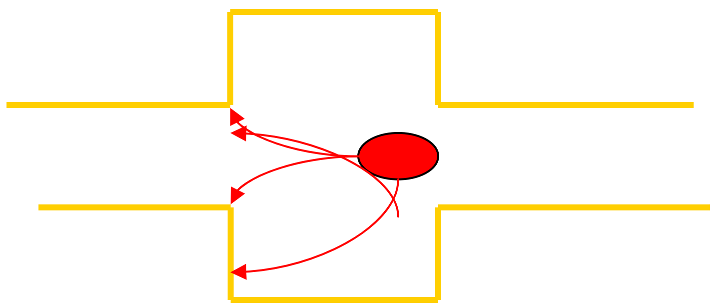
$E_s \neq 0$ => there is an interaction between the beam and the wall!

Impedance $Z_L(\omega)$ (3)

Worst case: abrupt changes in the cross-section of the pipe:



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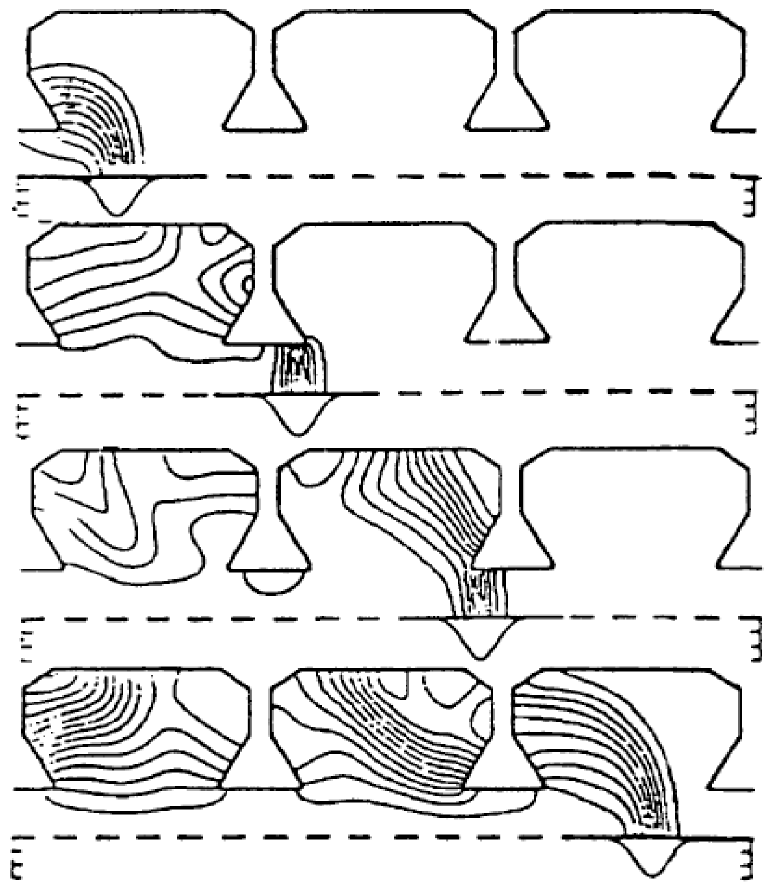
The beam looses energy (heating problems), but the induced fields can act back on the bunch or on the following bunches:

=> Instabilities!

Induced fields

e.m. fields induced in the RF cavities during the passage of a bunch.
The fields can act back either on the bunch itself or, on the following bunches



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Impedance $Z_L(\omega)$ (4)

Not surprisingly: $I_{max} \propto 1/Z_L(\omega)$

- Select carefully the materials you are using.
- Avoid any (unnecessary) change in the cross-section.
- When variations of the cross-section are unavoidable, use smooth tapers ($\alpha \leq 15°$).

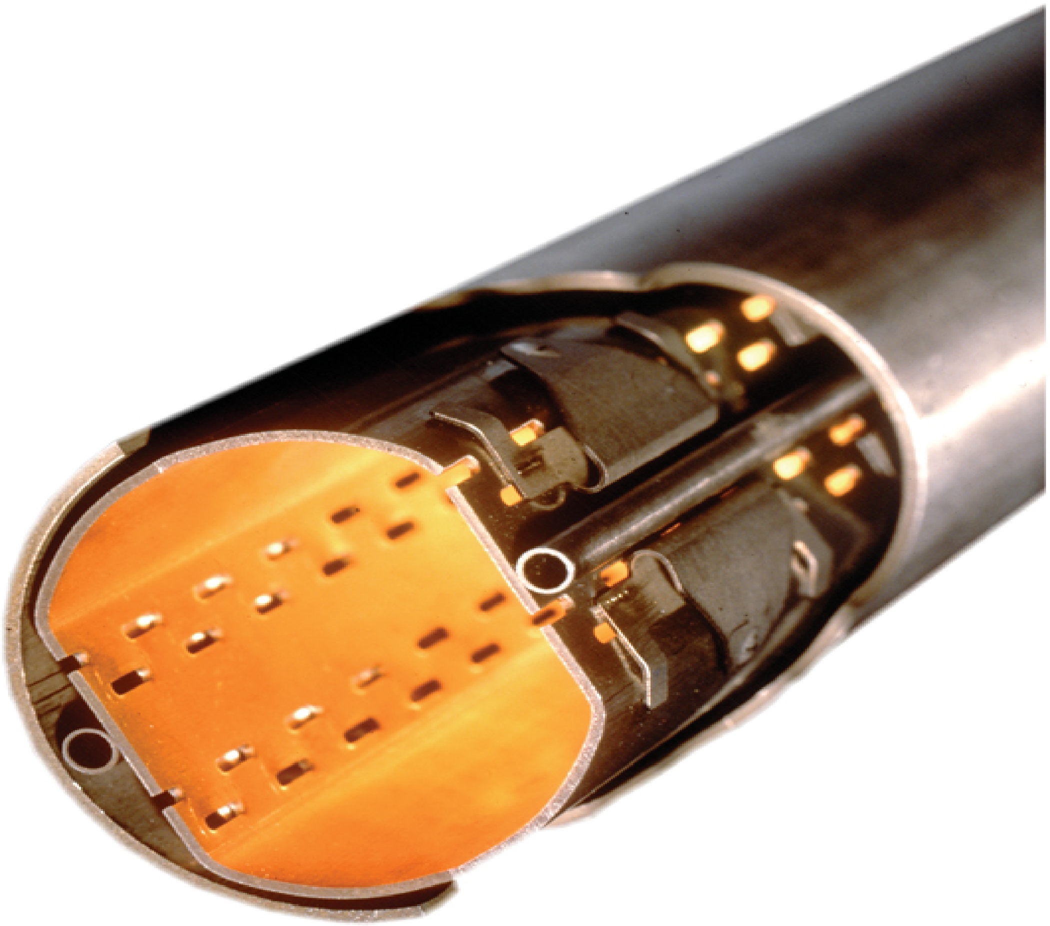
$Z_L(\omega)$ is a complex function. The quality of the design is characterised by the value of $|Z/n|$ with $n=\omega/\omega_0$.

|Z/n| as a function of time:

Machine	$\|Z/n\|$ [Ω]
PS (~ 1960)	> 50
SPS (~ 1970)	~ 20
LEP (~ 1990)	~ 0.25 (1.0)
LHC (~ 2009)	~ 0.10 (0.25)

LHC Beam-Screen (material)

- Without proper Cu-coating of the beam-screen, nominal intensity foreseen for the LHC could not circulate in the machine!



Transverse Impedance $Z_T(\omega)$

- In case of a broad-band impedance, there is a very convenient relation between the longitudinal and the transverse impedances, namely:

$$Z_T(\omega) = (2R/b^2) \, . \, |Z_L(\omega)/n| \qquad [\Omega/m]$$

This relation clearly shows that magnets designers, vacuum experts and financial considerations might favour solutions which are opposite to those of accelerator physicists!

The only solution is to understand each other's constraints and to find the best possible compromise.

Minimise the beam sizes

$$L = N_1.N_2.f.k/(4.\pi.\sigma_x.\sigma_y)$$

Optimal performance:

- Highest possible bunch intensity (N^2)
- Number of bunches k
- Minimise beam size ➔ decrease β function !

Create special zones around the experiments:

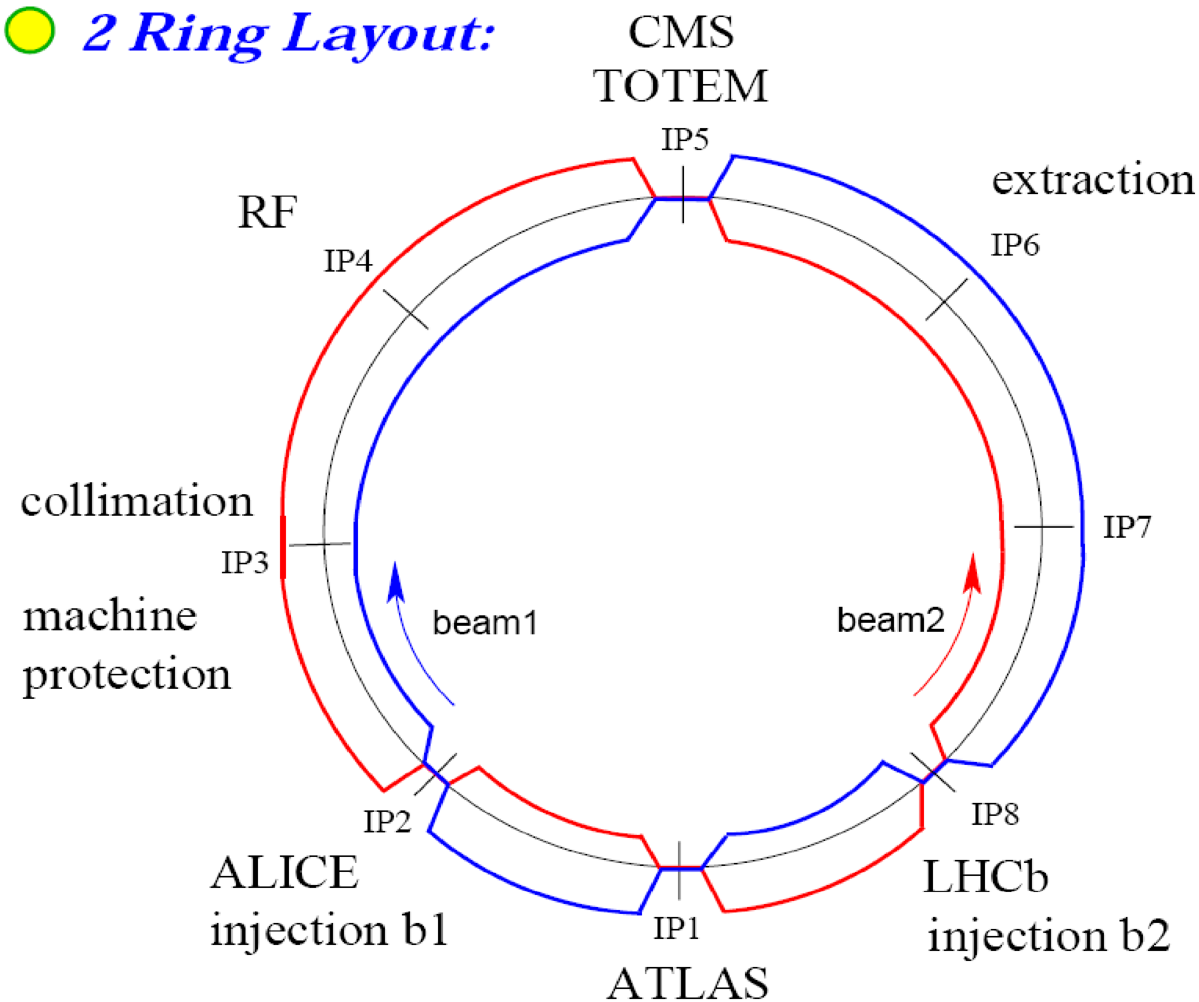
The Insertions !

The insertions:

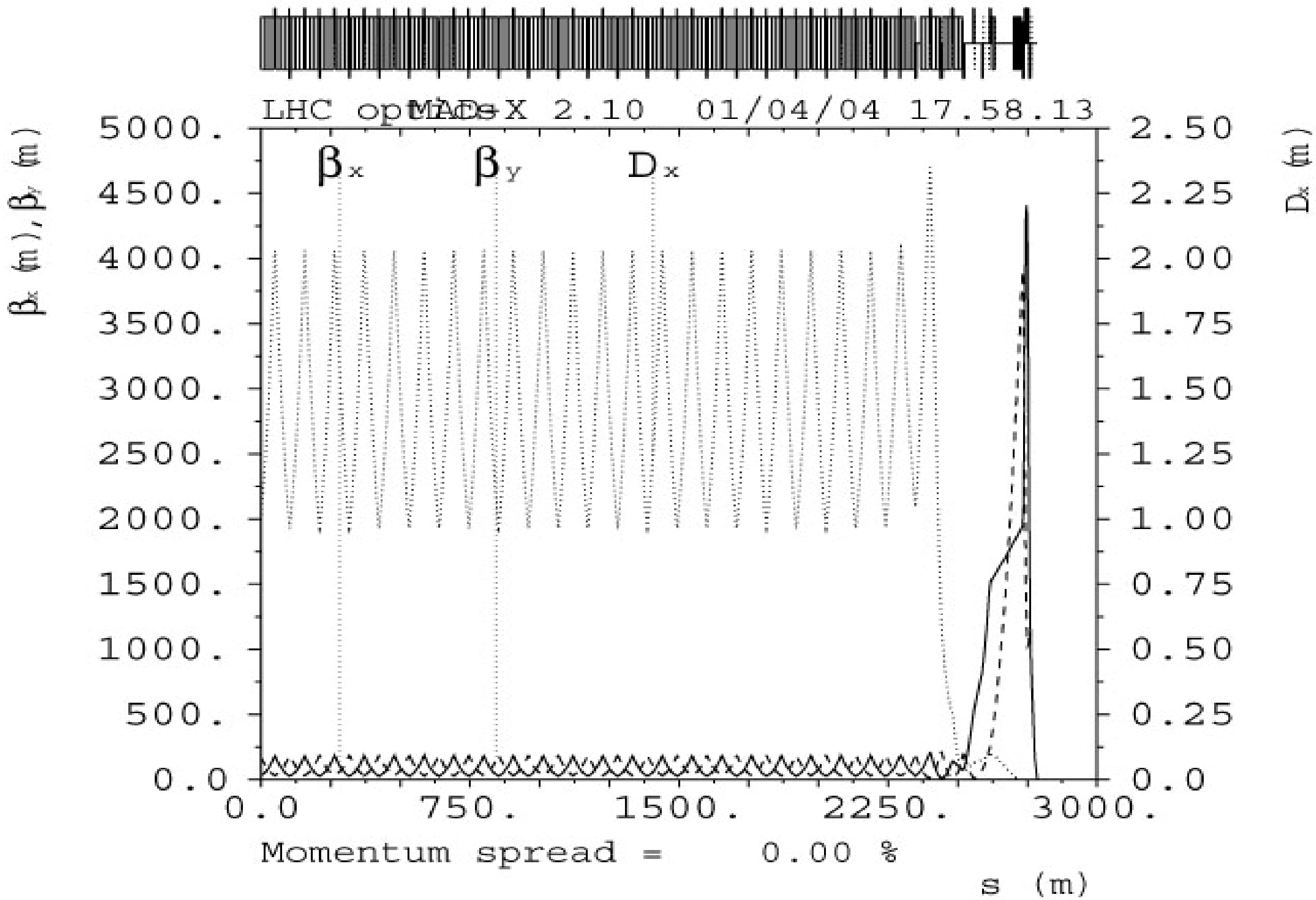
- Break the periodic structure of the arc at a selected place.
- « Insert » a straight section with the experiment in the middle.
- Each straight section is composed of (L+R):
    - Dispersion suppressor (a few dipoles and quadrupoles)
    - Section with quadrupoles to strongly squeeze the beam

LHC insertions:

- ***2 Ring Layout:***

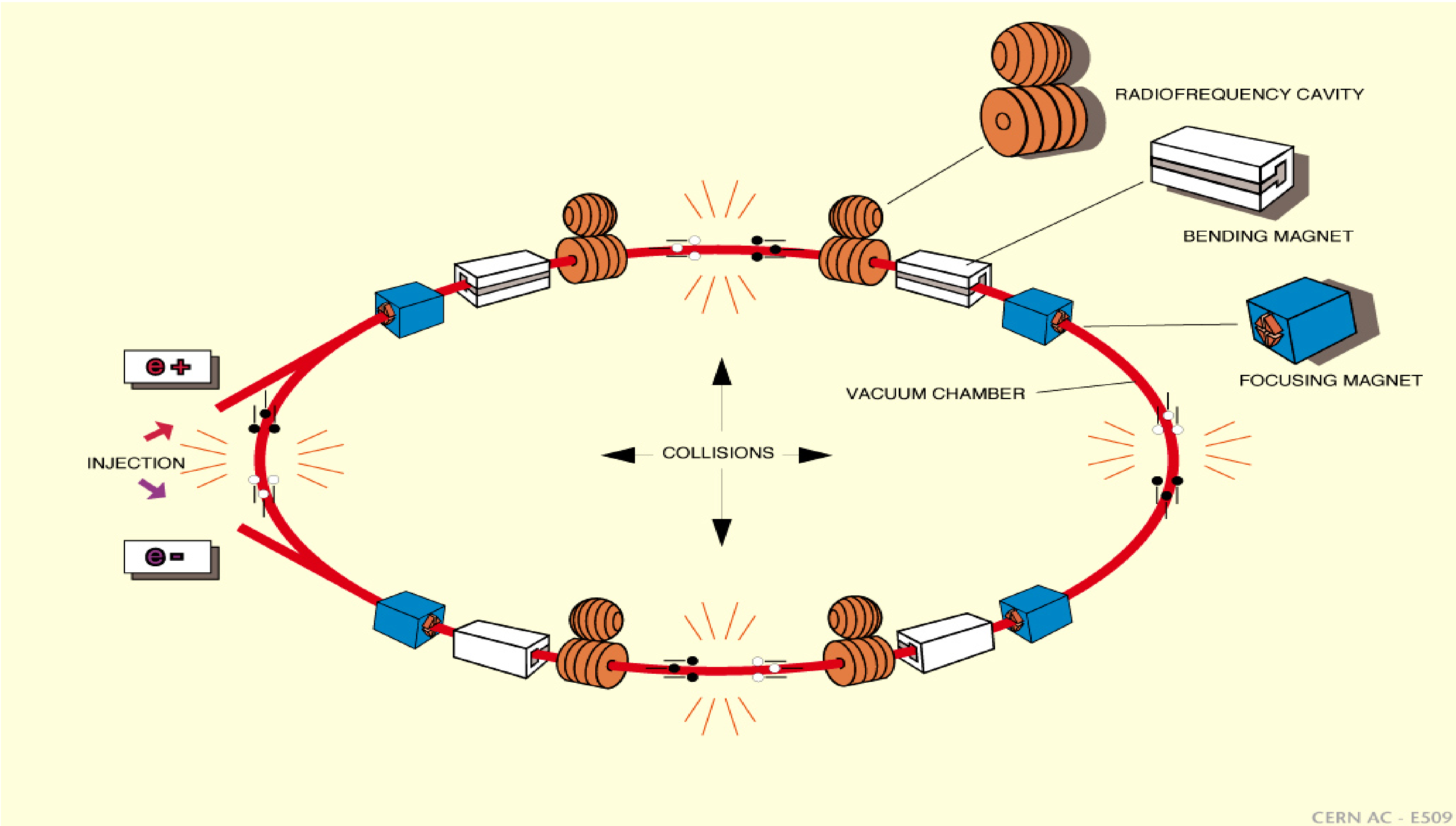


β at the Interaction Point (IP):



Summary …

High energy collider:



Particle Physics and the rest of the field …

Accelerators in the world (2002)

Basic and Applied Research		Medicine	
High-energy phys.	120	Radiotherapy	7500
S.R. sources	50	Isotope Product.	200
Non-nuclear Res.	1000	Hadron Therapy	20
Industry			
Ion Implanters	7000		
Industrial e- Accel.	1500	Total:	17390

Courtesy: W. Mondelaers JUAS 2004