Introduction to Accelerators

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Why an Introduction?

- The time where each accelerator sector was working alone in its corner is definitively over!
- Modern machines are at the limit of technology, so that individual (ideal) requests often cannot be fulfilled.
- The only solution is to find a reasonable compromise, which implies for each sector to understand the (sometimes extreme) requests from the other sectors, and to be able to explain its (sometimes extreme) requests to the other sectors:

  (e.g. beam dynamics <-> magnets <–> Power Converters)

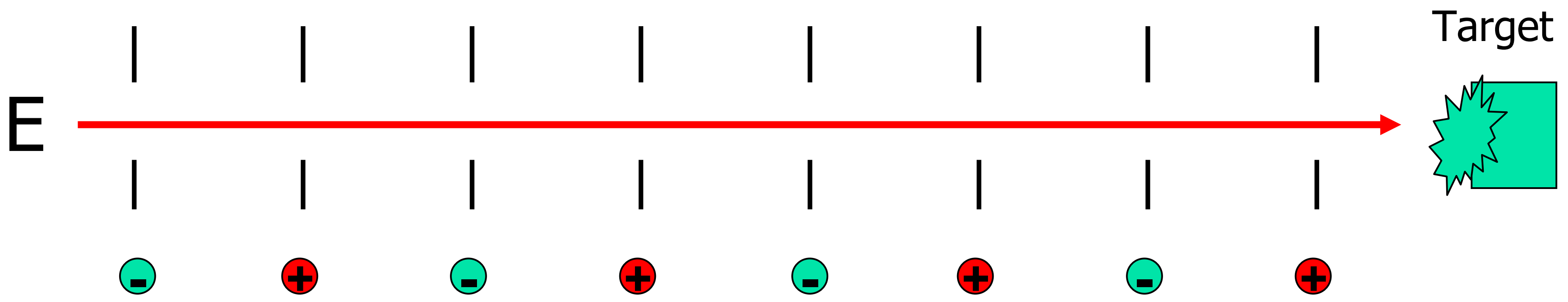
- This lecture is an attempt to introduce a few basic concepts of transverse beam dynamics, which might be useful for vacuum considerations.

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

Ideal linear machines (linacs)



Available Energy : $E_{c.m.} = m \cdot (2+2\gamma)^{1/2} = (2m.(m+E))^{1/2}$

with $\gamma = E/E_0$

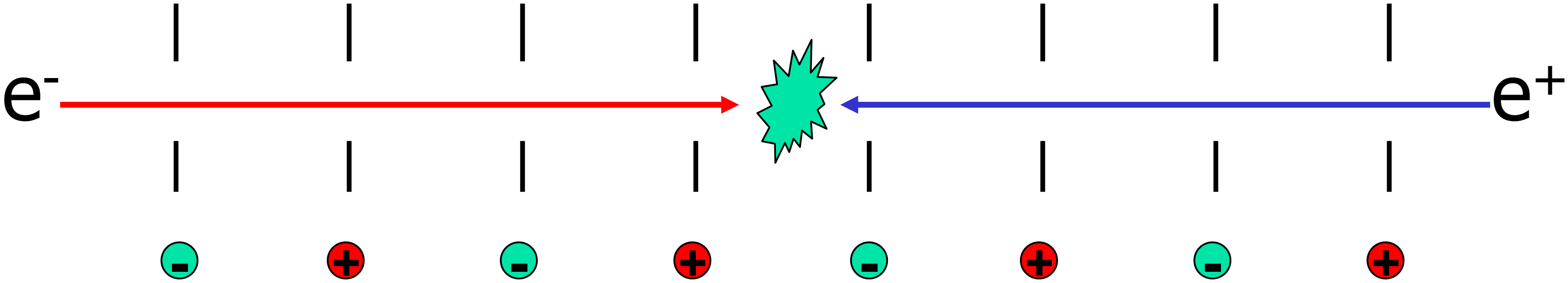
Advantages: Single pass

High intensity

Drawbacks: Single pass

Available Energy

Improved solution for $E_{c.m.}$



Available Energy : $E_{c.m.} = 2m\gamma = 2E$

with $\gamma = E/E_0$

Advantages: High intensity

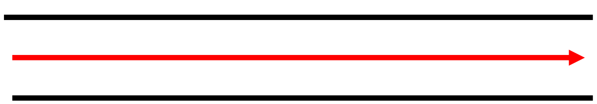
Drawbacks: Single pass

Space required

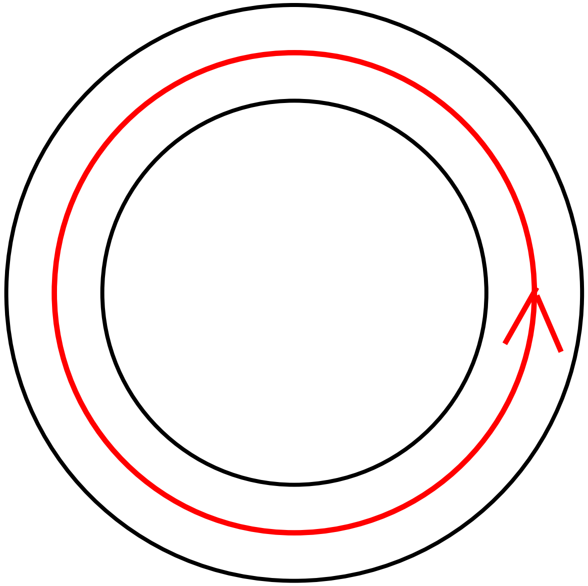
Keep particles: circular machines

Basic idea is to re-use the particles or keep them in the machine.

Move from the linear design



To a circular one:

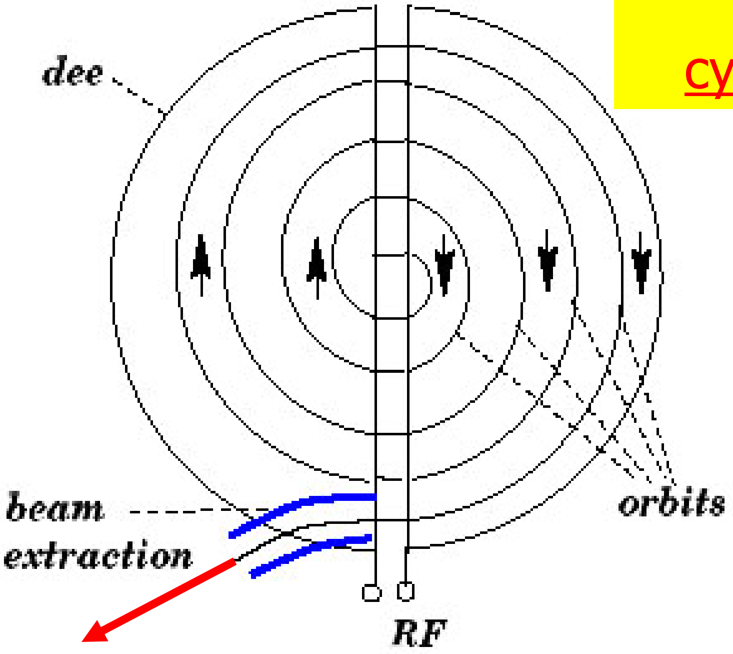


- Need Bending
- Need Dipoles!

Circular machines ($E_{c.m.} \sim (mE)^{1/2}$)

fixed target:

cyclotron



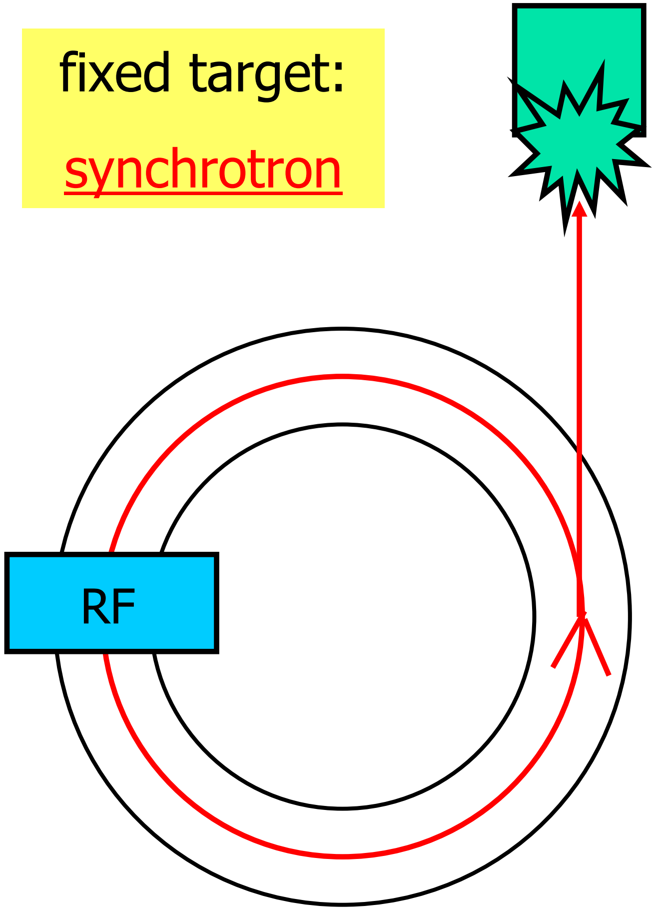
huge dipole, compact design,

B = constant

low energy, single pass.

fixed target:

synchrotron



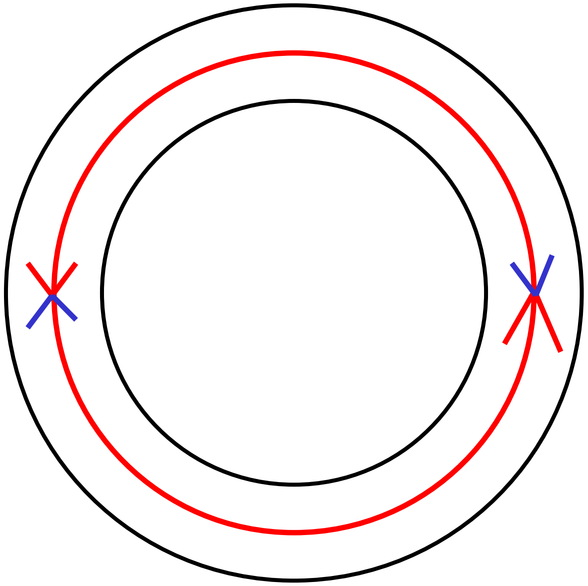
varying B, small magnets, high energy

Colliders ($E_{c.m.}=2E$)

<u>Colliders:</u>

electron – positron

proton - antiproton



Colliders with the same type of particles (e.g. p-p) require two separate chambers. The beam are brought into a common chamber around the interaction regions

Ex: LHC

8 possible interaction regions

4 experiments collecting data

Question: What about LHC physics with fixed target?

Beam Dynamics

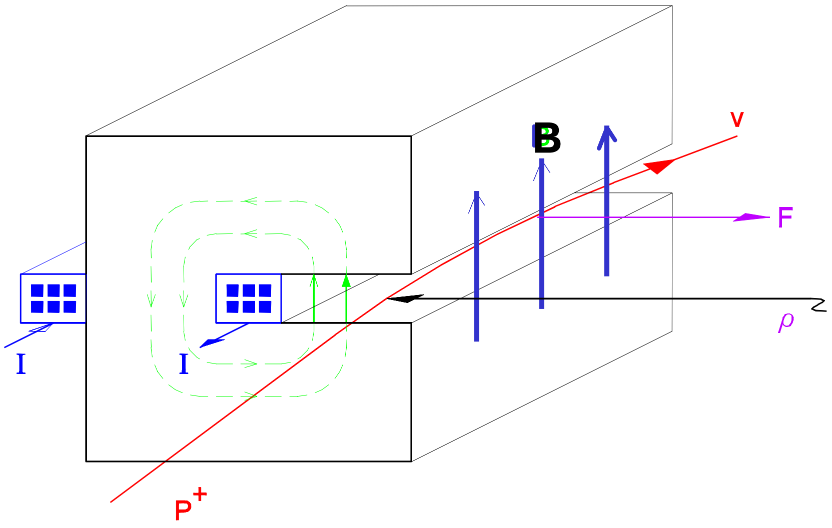
A particle is described by:

- Its azimuthal position along the machine: s
- Its momentum: p
- Its horizontal position: x
- Its horizontal slope: x'
- Its vertical position: y
- Its vertical slope: y'

i.e. a sixth dimensional phase space

$$(s, p, x, x', y, y')$$

Circular machines: Dipoles



Classical mechanics:

Equilibrium between two forces

Lorentz force	Centripetal force
$F = e.(\underline{v} \times \underline{B})$	$F = mv^2/\rho$

$$evB = mv^2/\rho$$

$$p = m_0.c.(\beta\gamma)$$

Magnetic rigidity:

$$B\rho = mv/e = p/e$$

Relation also holds for relativistic case provided the classical momentum mv is replaced by the relativistic momentum p

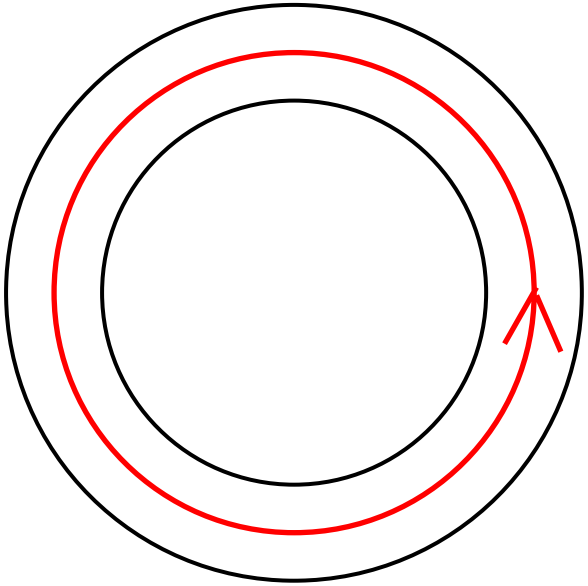
Simple but fundamental relation!

- If you already have a site and you know the physics (E) to be achieved -> you know the magnets required (SC or warm).
- If you have the site and do not want to go for SC magnets -> you know the energy range you can cover (fixed target or collider).
- Now, check LHC physics with fixed target….!

Ideal circular machine:

- Neglecting radiation losses in the dipoles
- Neglecting gravitation

ideal particle would happily circulate on axis in the machine for ever!



Unfortunately: real life is different!

Gravitation: Δy = 20 mm in 64 msec!	
Alignment of the machine	Limited physical aperture
Ground motion	Field imperfections
Energy error of particles and/or $(x, x')_{inj} \neq (x, x')_{nominal}$	
Error in magnet strength (power supplies and calibration)	

From Ideal to Real machines…

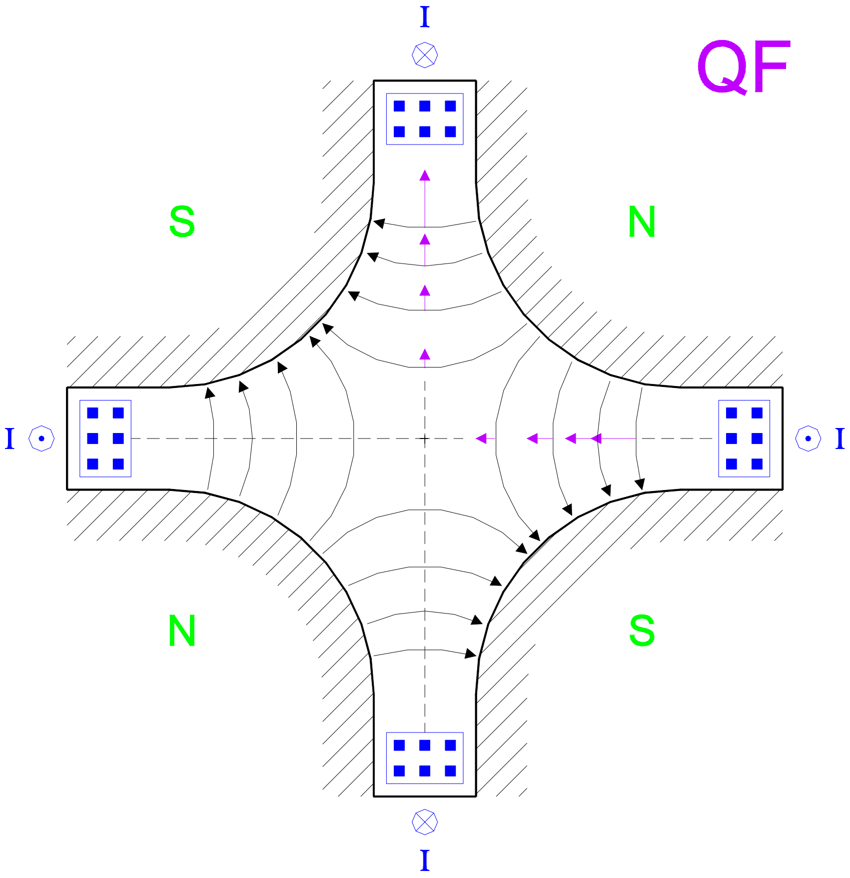
- Most of the particles are NOT ideal particles

$$(x,x',y,y',p) \neq (x,x',y,y'p)_{ideal}$$

- ➢ Sooner or later these particles will hit the walls and will be lost!

- How can we keep these particles within the vacuum chamber?

Focusing with quadrupoles



$$F_x = -g.x$$

$$F_y = g.y$$

Force increases linearly with displacement.

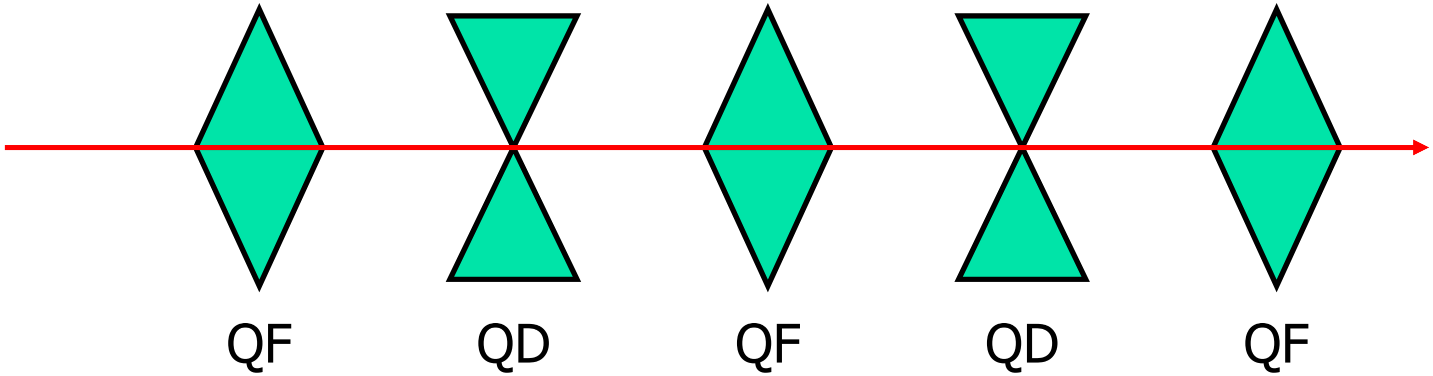
Unfortunately, effect is opposite in the two planes (H and V).

Remember: this quadrupole is focusing in the horizontal plane but defocusing in the vertical plane!

Alternating gradient focusing

Basic new idea:

Alternate QF and QD

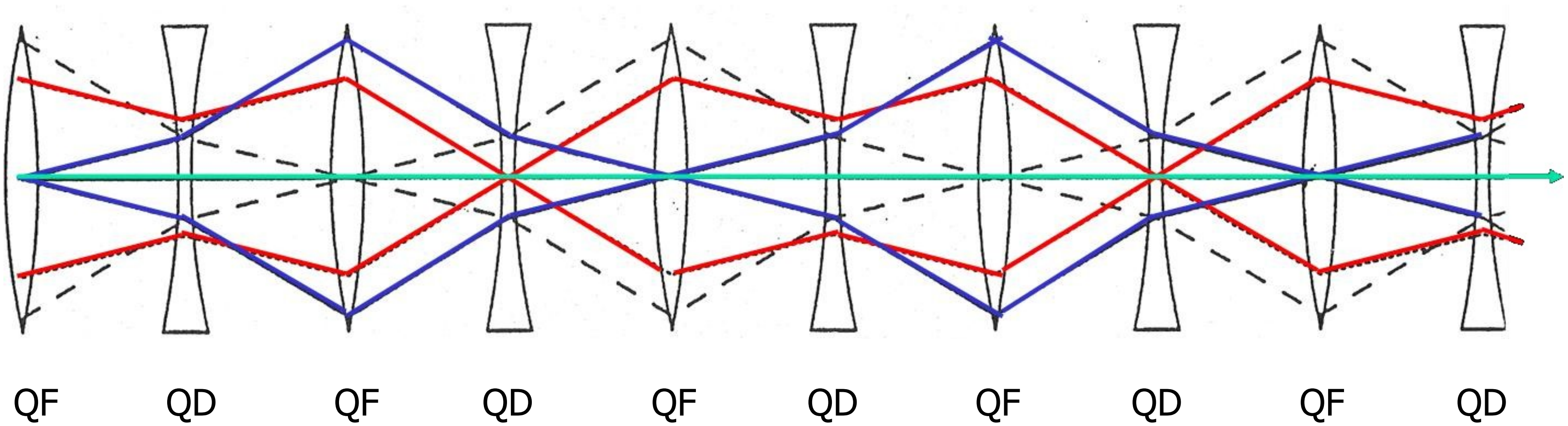


Let us first consider a « non-ideal » injection in position and slope

(x, x′) or (y, y′)

Alternating gradient focusing

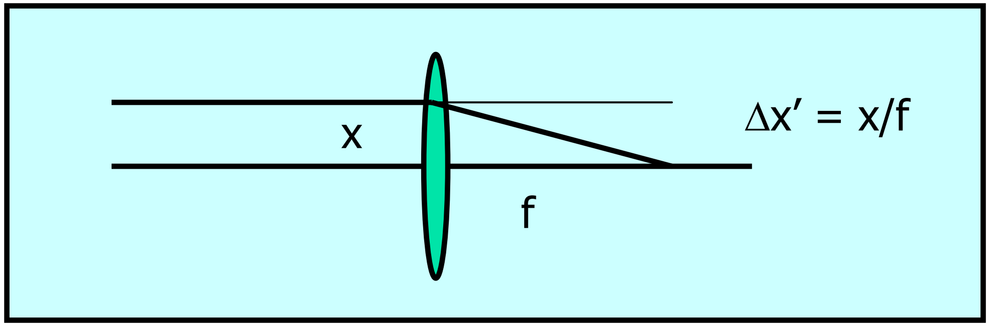
It can be shown that a section composed of alternating focusing and defocusing elements has a **net focusing effect**, provided the quadrupoles are correctly placed. What happens to « non-ideal » particles?



The « non-ideal » particles perform an oscillation around the « ideal » trajectory.

Thin lens analogy of AG focusing

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{out} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_{in}$$



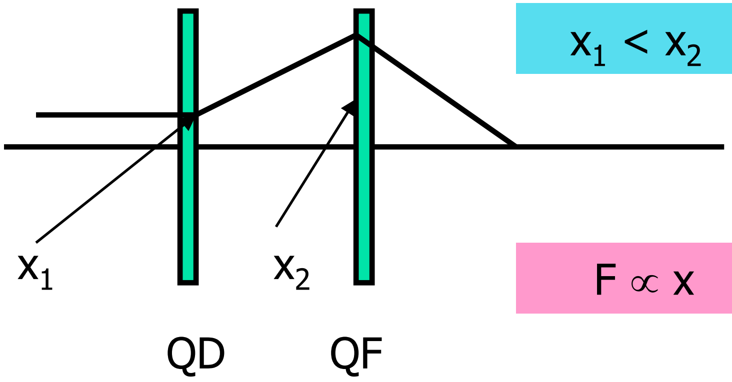
$$X_{out} = x_{in} + 0.x'_{in}$$
$$x'_{out} = (-1/f).x_{in} + x'_{in}$$

$$\text{Drift} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

$$\text{QF-Drift-QD} = \begin{pmatrix} 1-L/f & L \\ -L/f^2 & 1+L/f \end{pmatrix}$$

Initial: $x = x$ and $L < f$
$x' = 0$

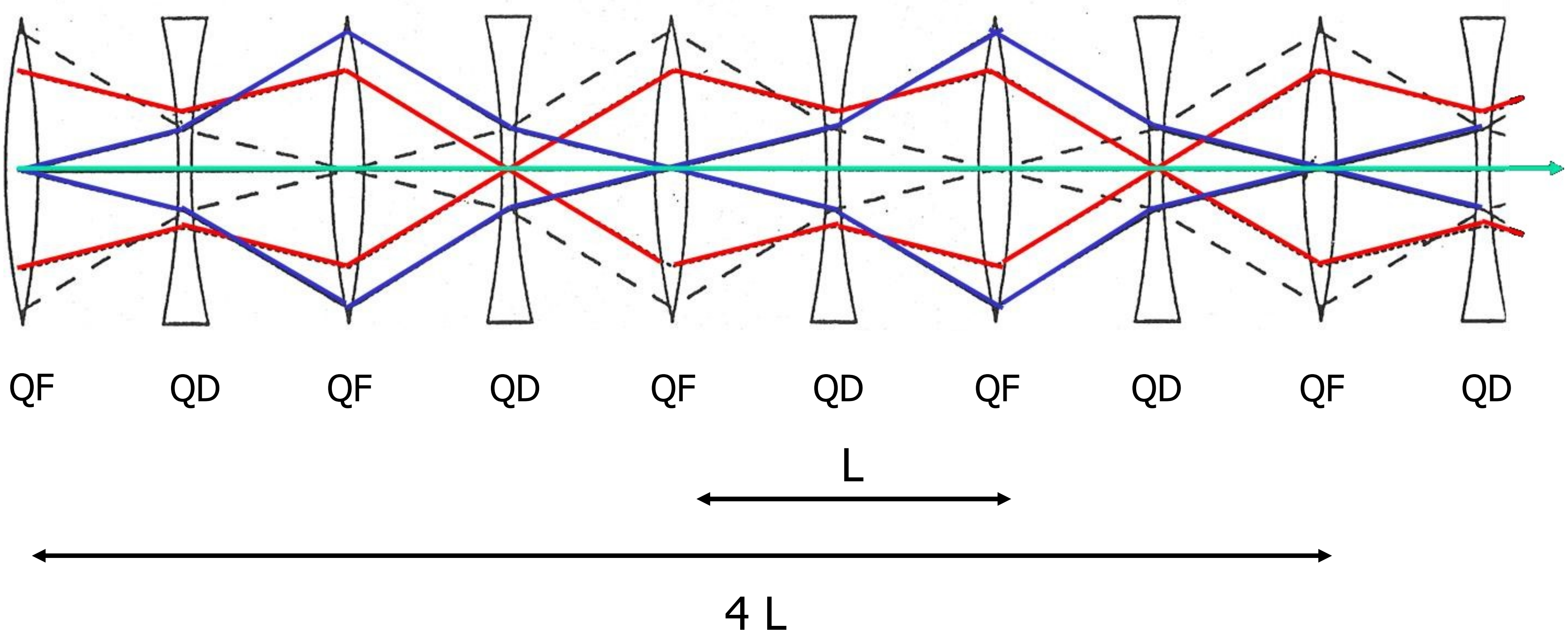
More intuitively:



$x_1 < x_2$

$F \propto x$

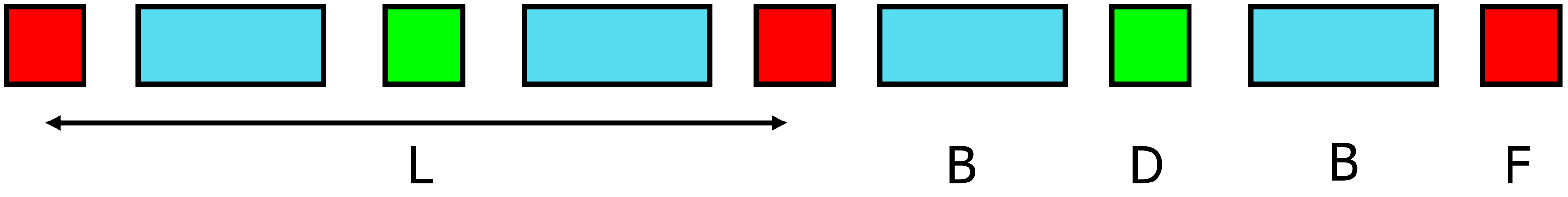
The FODO cell:



One complete oscillation in 4 cells ⇒ 90°/ cell ⇒ $\mu = 90°$

Real circular machines (no errors!)

The accelerator is composed of a periodic repetition of FODO cells:



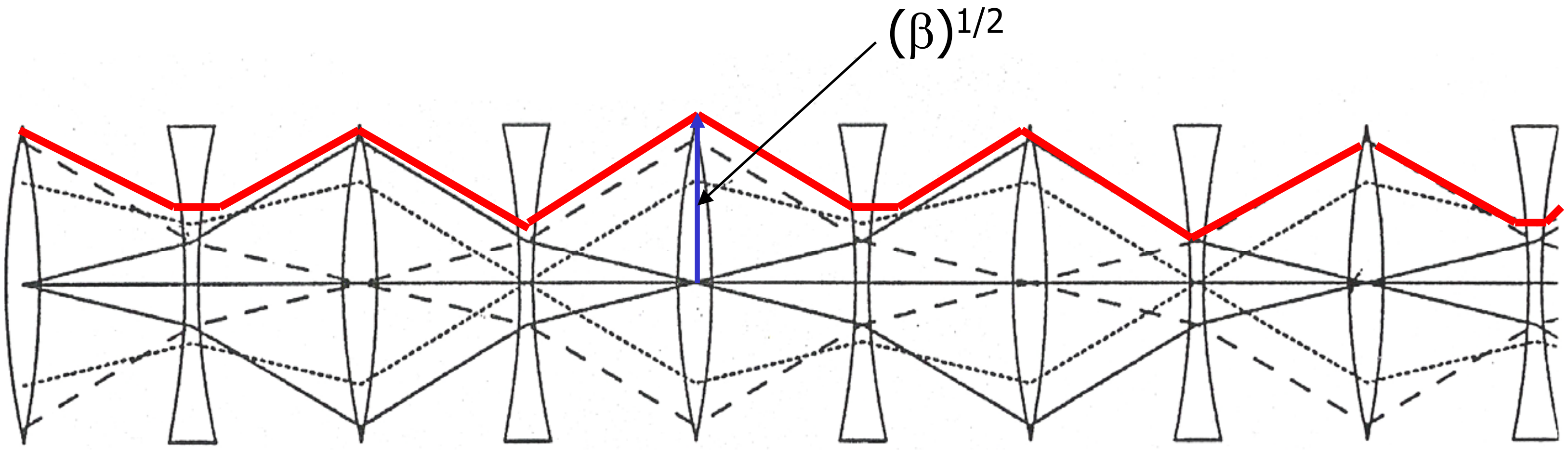
- The phase advance per cell μ can be modified, in each plane, by varying the strength of the quadrupoles.

- The ideal particle will follow a particular trajectory, which closes on itself after one revolution: the closed orbit.

- The real particles will perform oscillations around the closed orbit.

- The number of oscillations for a complete revolution is called the Tune Q of the machine (Qx and Qy).

The beta function $\beta(s)$



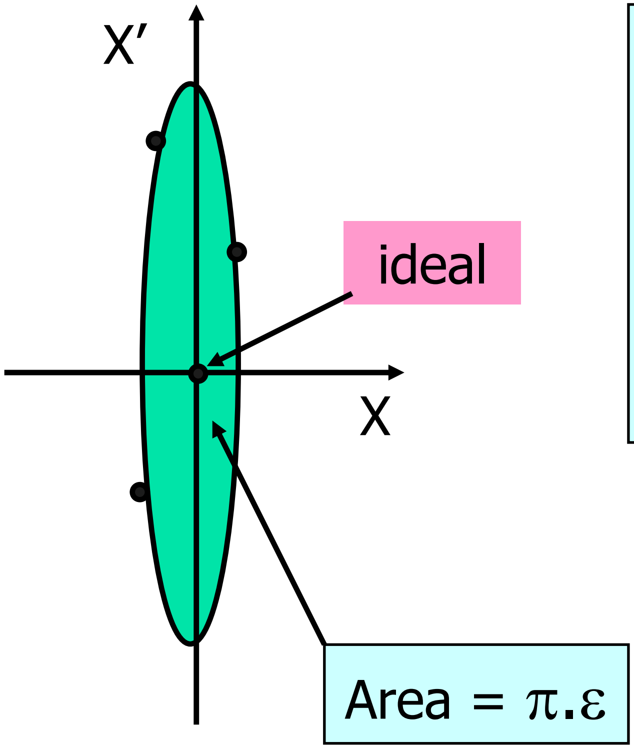
The β-function is the envelope around all the trajectories of the particles circulating in the FODO lattice.

The β-function has a minimum at the QD and a maximum at the QF, ensuring the net focusing effect of the lattice.

It is a periodic function in the FODO lattice. The oscillations of the particles are called betatron motion or betatron oscillations.

Phase space at some position (s)

- Select the particle in the beam with the largest betatron motion and plot its position vs. its phase (x vs. x′) at some location in the machine for many turns.

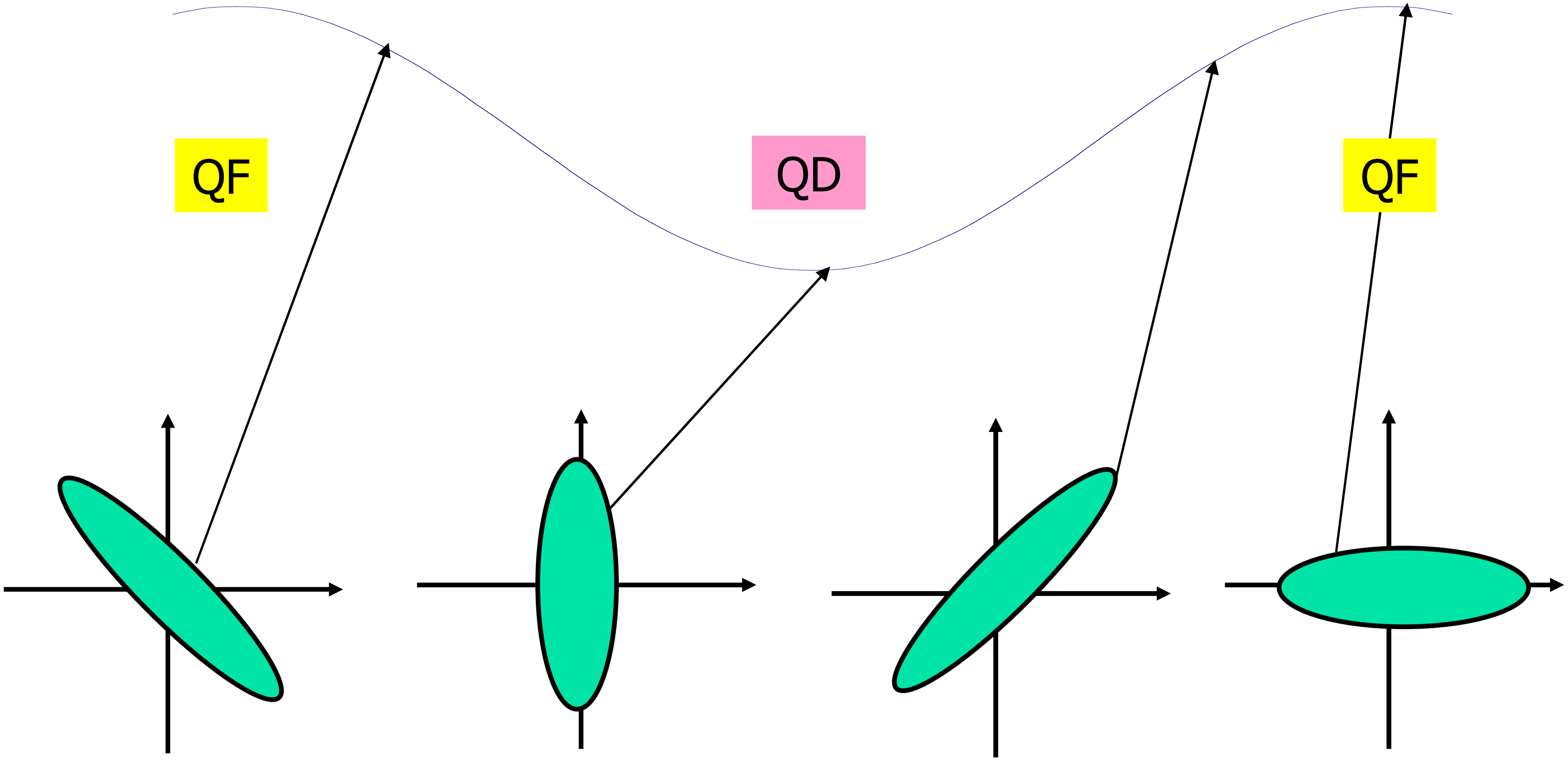


- ε Is the emittance of the beam [π mm mrad]
- ε is a property of the beam (quality)
- Measure of how much particle depart from ideal trajectory.
- β is a property of the machine (quadrupoles).

Beam size [m]

$$\sigma(s) = (\varepsilon.\beta(s))^{1/2}$$

Emittance conservation



The shape of the ellipse varies along the machine, but its area (the emittance ε) remains constant for a given energy.

Recapitulation

- The fraction of the oscillation performed in a FODO cell is called the phase advance μ per cell (x or y).
- The total number of oscillations over one full turn of the machine is called the betatron tune Q (x or y).
- The envelope of the betatron oscillations is characterised by the beta function $\beta(s)$. This is a property of the quadrupole settings.
- The quality of the (injected) beam is characterised by the emittance ε. This is a property of the beam and is invariant around the machine.
- The r.m.s. beam size (measurable quantity) is $\sigma = (\beta.\varepsilon)^{1/2}$.

What about a « non-ideal » injection energy $\Delta p/p \neq 0$?

Off momentum particles:

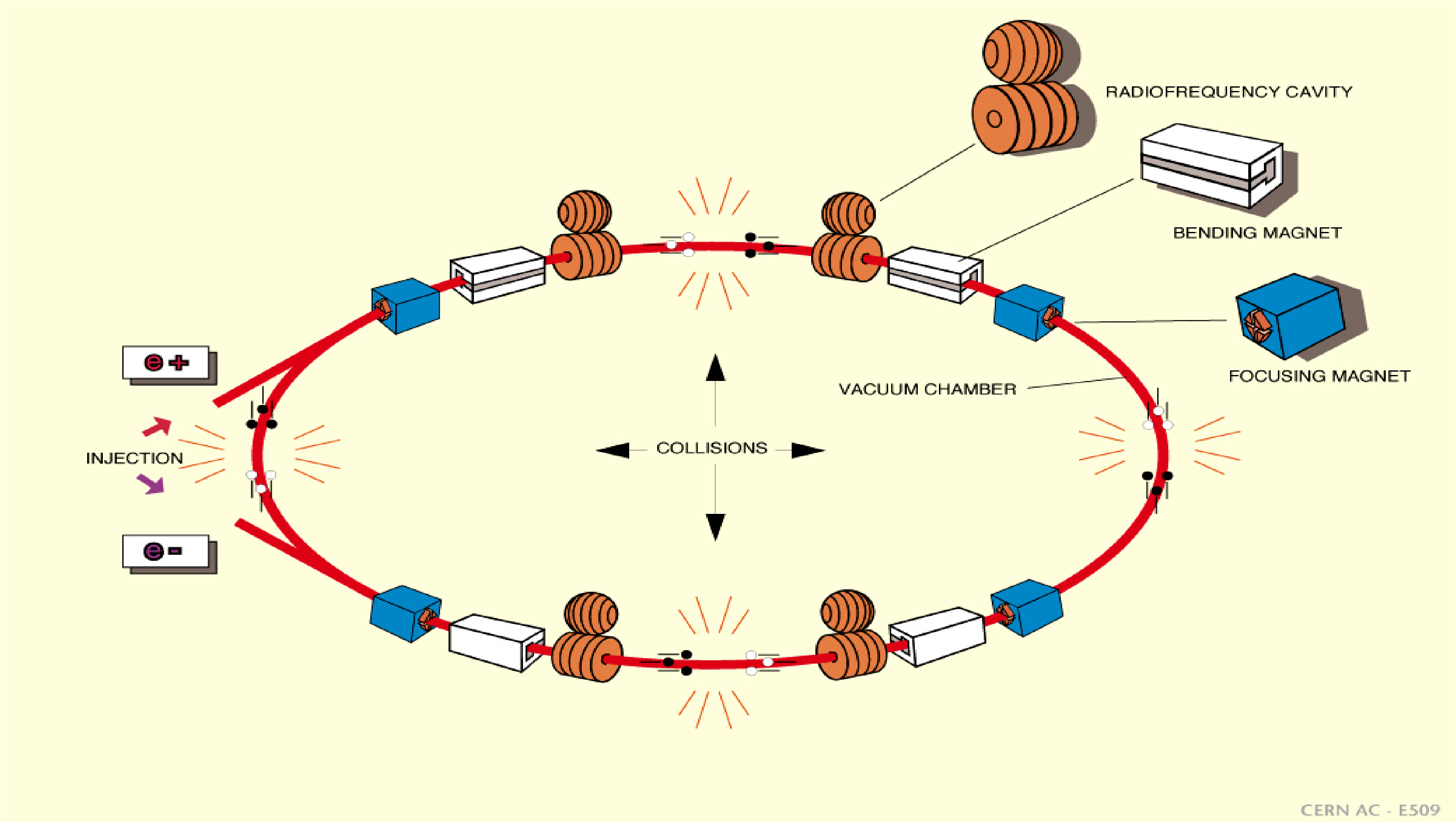
- For particles with $\Delta p/p \neq 0$, the magnets induce other important effects like:

The dispersion (dipoles)

The chromaticity (quadrupoles)

These effects will not be treated in this lecture!

Real high energy collider



Vacuum and Accelerators

- In HEP, accelerators are used to produce:

  - Collisions (fixed target or colliders)
  - Synchrotron light

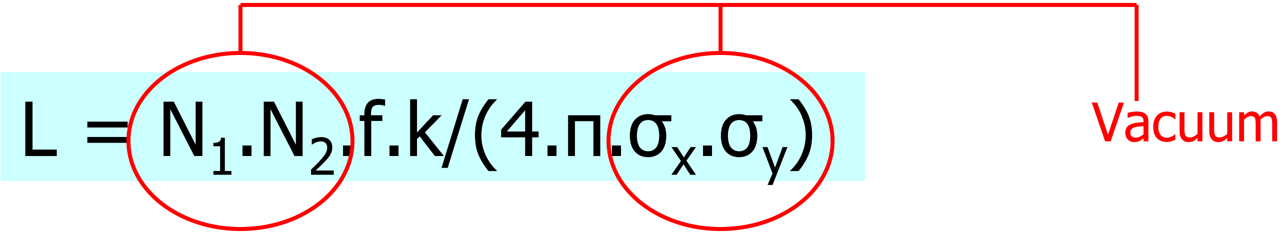
This requires:

  - High intensities
  - As small as possible beams
  - As long as possible runs

e.g. for colliders: the Luminosity

$$dN/dt = L \times \sigma$$

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



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

Vacuum

with:

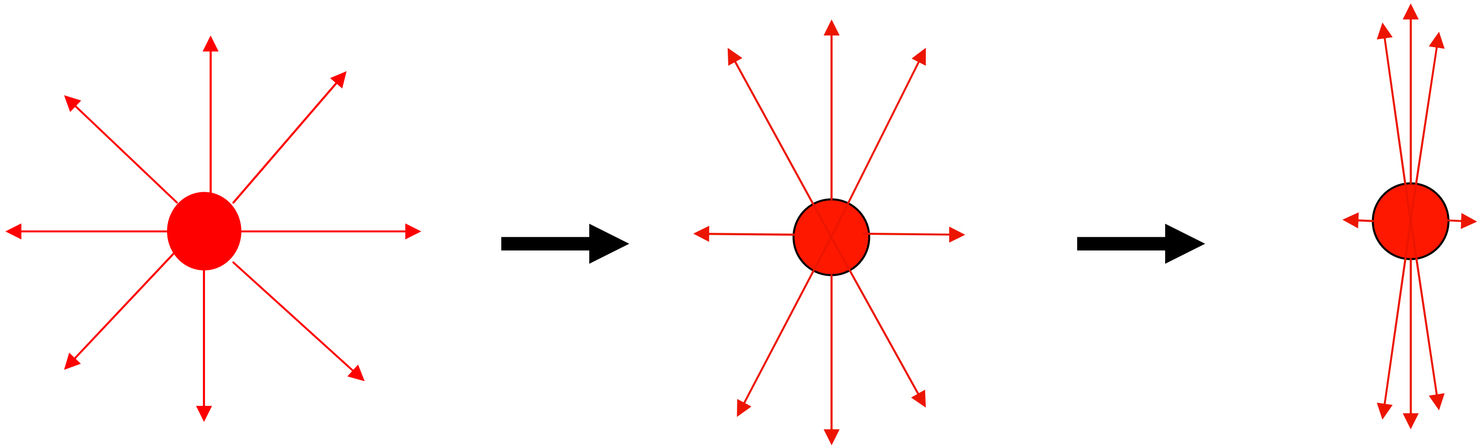
$N_{1,2}$ = Number of particles per bunch

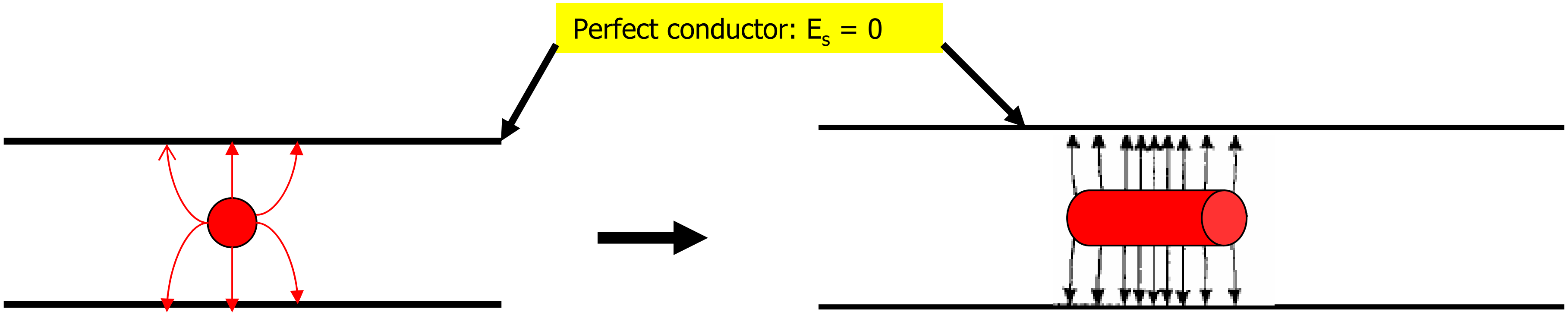
f = revolution frequency

k = number of bunches

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

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





Perfect conductor: $E_s = 0$

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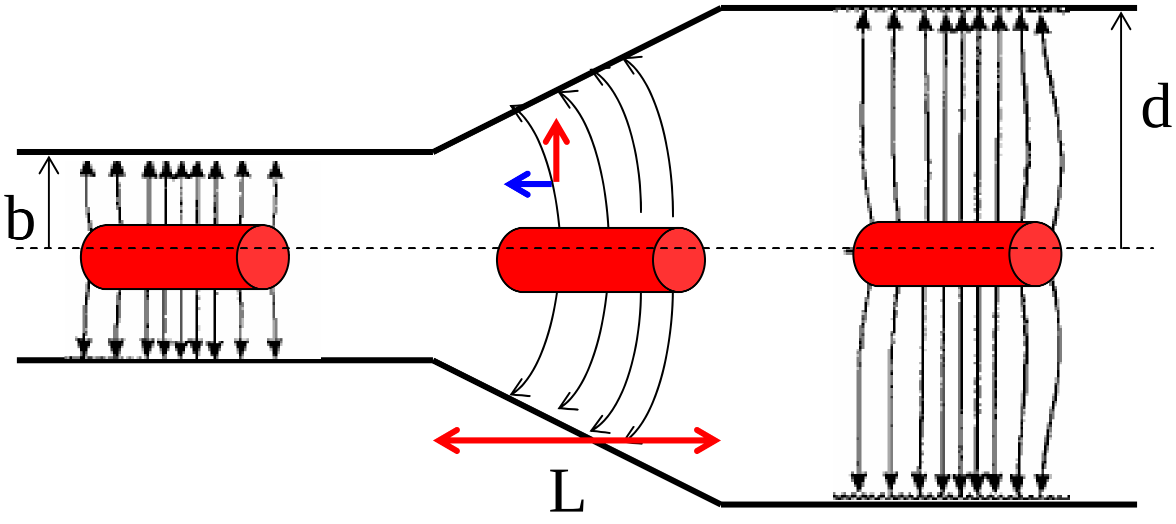
Impedance $Z_L(\omega)$ (2)

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



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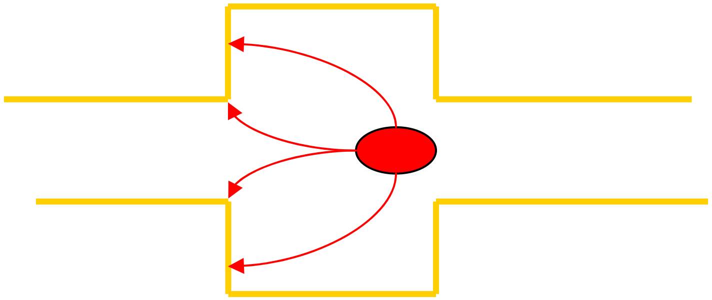
$E_s \neq 0$ => there is an interaction between the beam and the wall!

Impedance $Z_L(\omega)$ (3)

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



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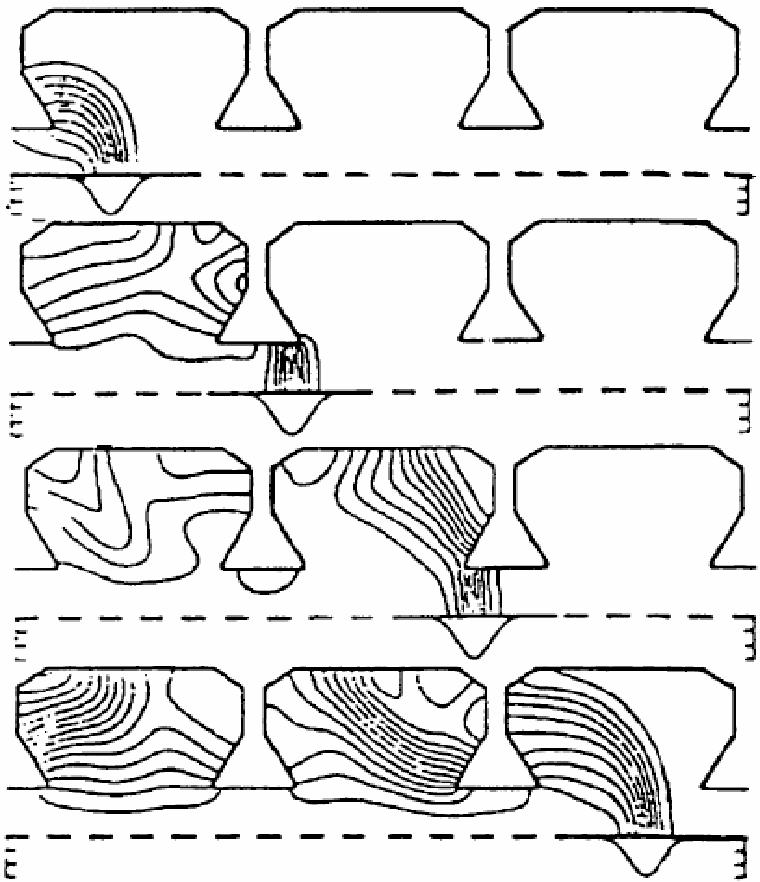
The beam looses energy (heating problems), but the induced fields can act back on the bunch or on the following bunches:

=> 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	$\lvert Z/n \rvert$ [Ω]
PS (~ 1960)	> 50
SPS (~ 1970)	~ 20
LEP (~ 1990)	~ 0.25 (1.0)
LHC (~ 2007)	~ 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:

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

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.

Vacuum: beam sizes and Lifetime

- A “poor” vacuum can affect the beam in different ways:
  - Blow-up of the beam sizes (performance).
  - Induce losses by deflecting particles outside the aperture (lifetime):
    - Physical aperture
    - Dynamic aperture
    - RF acceptance

Gas scattering

- Particles scatter with residual gas molecules in the vacuum chamber:

➢ Two main SINGLE particle effects:

  - Elastic collisions (particles deflected resulting in increase of betatron oscillation => apertures!).
  - Inelastic collisions (particles loose energy either by energy transfer to the residual gas molecule or by photon emission – Bremsstrahlung effect => RF acceptance)

Elastic scattering

- Apertures are very important for elastic scattering.
- The lifetime at a given position (s) in the machine for elastic scattering behaves like:

$$\tau \propto 1/\langle \beta_s \, P_s \rangle$$

i.e. inversely proportional to the product of gas partial pressure and the beta function => pumping at places with large beta functions is appropriate!

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:

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

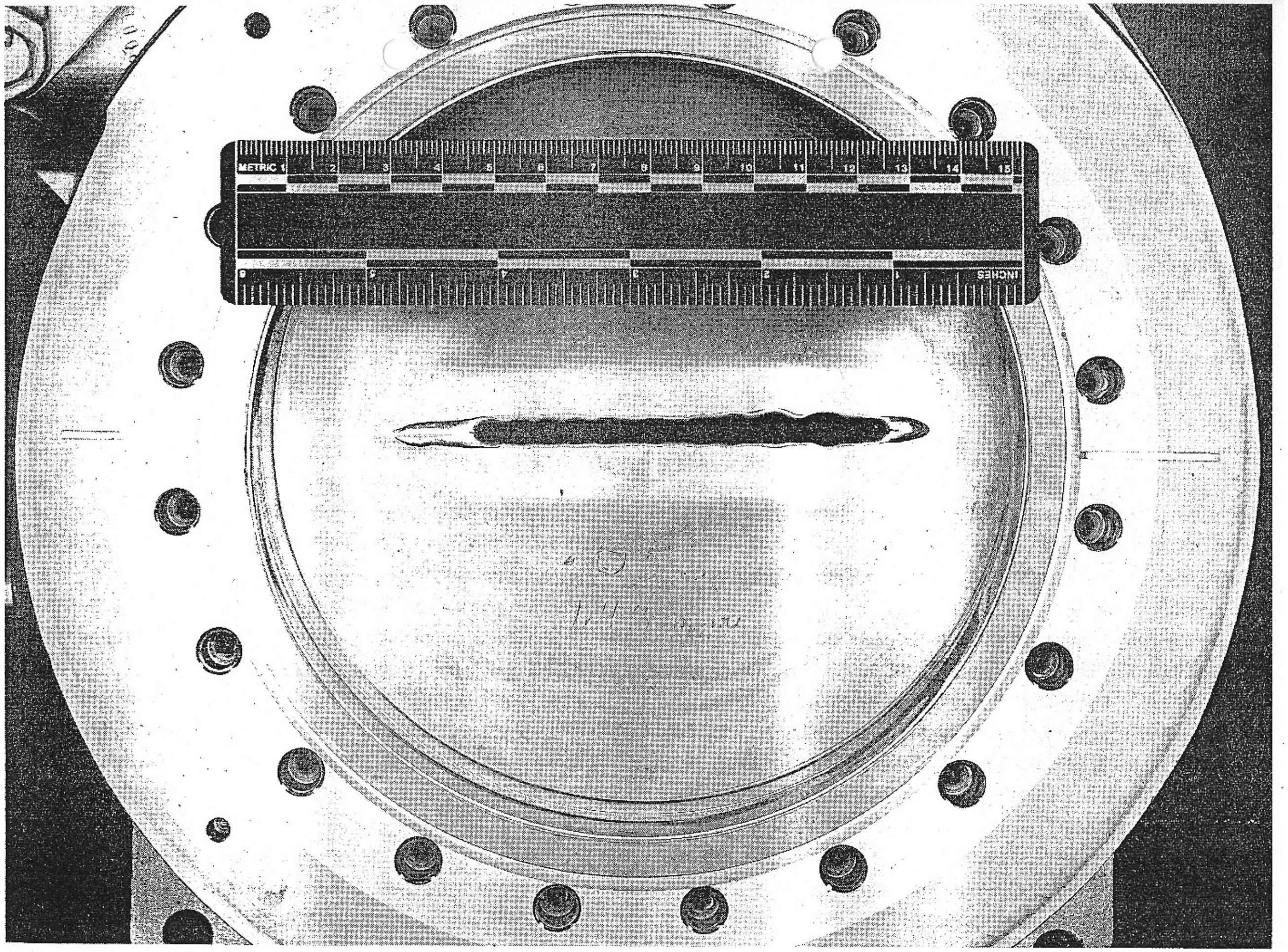
m_0 proton = 0.938 GeV/c^2

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

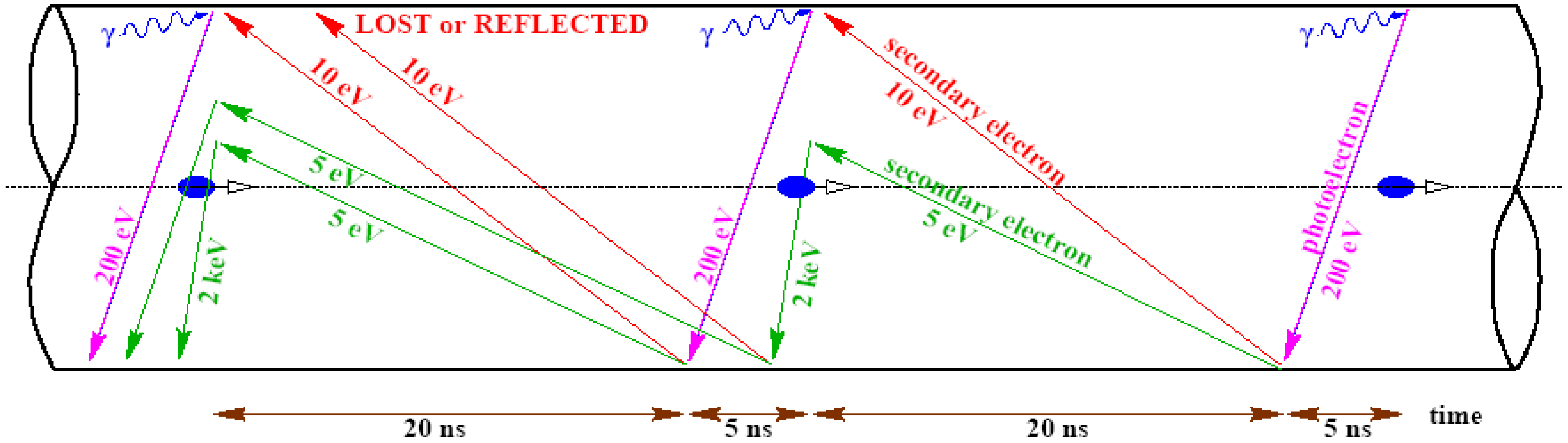
Synchrotron radiation (2)

Desorption of gas molecules by synchrotron radiation is the main source of residual gas in synchrotron light sources!

$$P_\gamma \propto E^4/\rho^2$$

E-cloud effect

- Accumulation of electrons which can perturb the circulating beam.



➢ Strongly depends on intensity, bunch spacing and surface conditioning…

Conclusions

- Vacuum design has to take into account the accelerator physics constraints (and vice-versa).
- On top of considering beam-gas interactions, the choice of the correct materials and of the most appropriate geometry is essential in the design phase of the vacuum system.
- A poor vacuum design will definitively affect the optimal operation of the accelerator (apertures, instabilities).

➢ I hope to have convinced you that the time where experts from individual fields were working alone is definitively over !