Putting it all together…

D. Brandt, CERN

Global Review

- What did we learn ?
- Can we really start some useful work with this ?
- Some (subjective) personal comments/hints …

What machine for what Project?

- Whatever the project, it is likely that the choice of your machine will be influenced by:

- ➢ The specific purpose of the machine (SLS, HEP,…).
- ➢ The availability of some already existing facilities (upgrade).
- ➢ The required final energy.

The final energy

Example: a machine for particle physics

- Remember: The center of mass energy E_{cm} is given by

(with $\gamma = E/E0$):

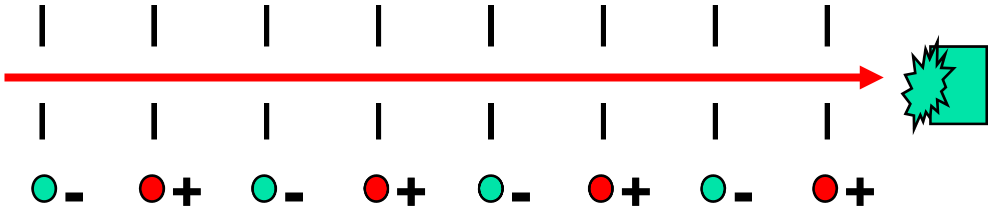
$E_{cm} \propto m \,.\, (2\gamma+2)^{1/2}$ for fixed target

$E_{cm} \propto 2m\gamma = 2E$ for a collider

- High energy not required ➔ linacs or cyclotrons (fixed target)

- High energy required ➔ linacs or synchrotrons (fixed target or collider)

Linacs and Cyclotrons

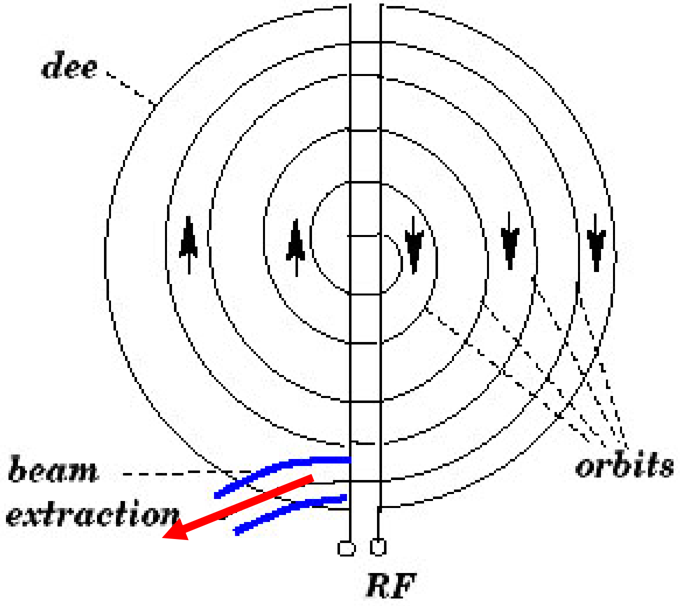


Single pass, high intensities, high energy possible

huge dipole, compact design,

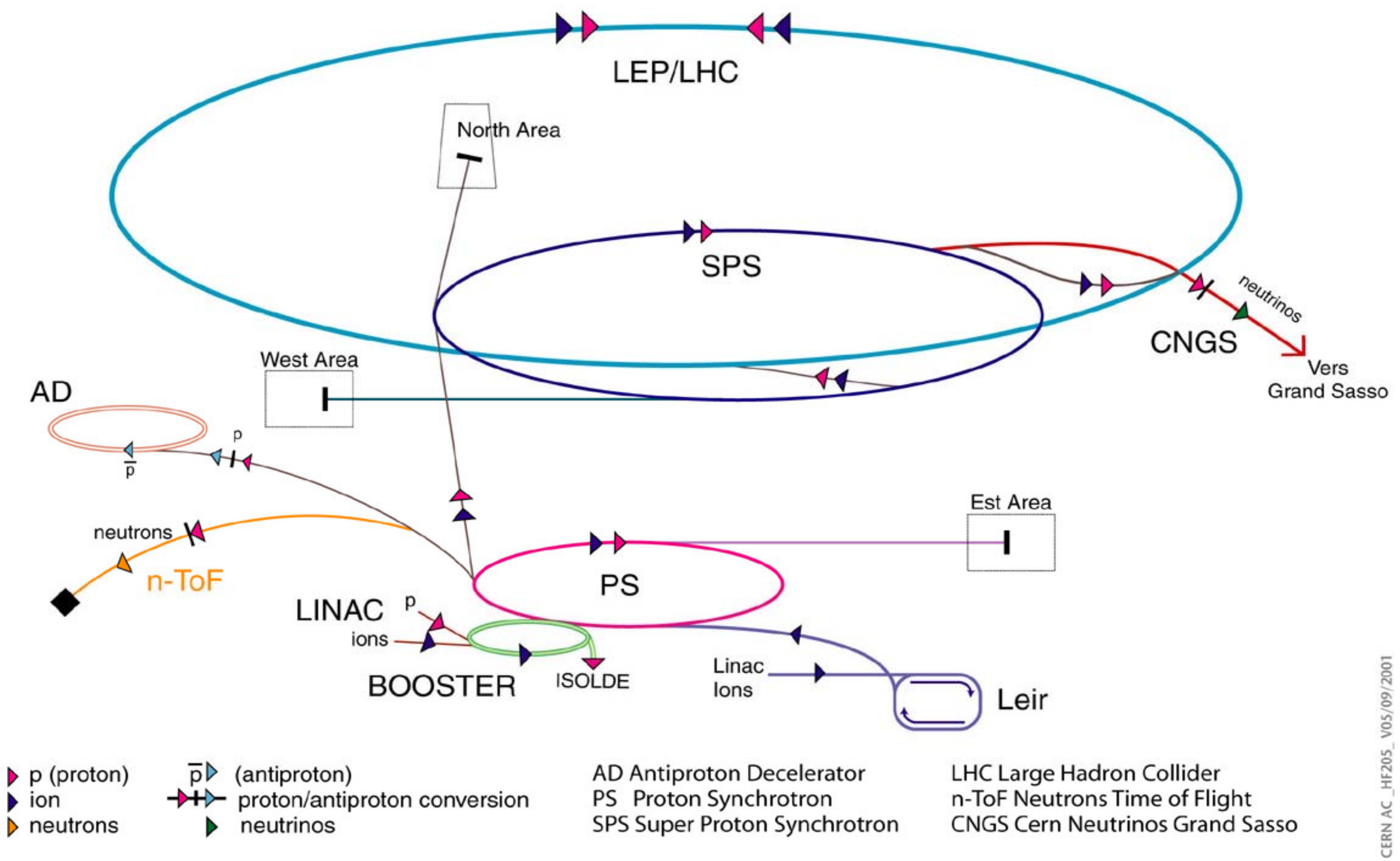
B = constant

single pass and low energy !



Synchrotrons …

Accelerator chain of CERN (operating or approved projects)



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

Fundamental relation:

At this very early stage, you will have to use the fundamental relation:

$p = m_0.c.(\beta\gamma)$ →

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

Why fundamental ?

Constraints:

E and ρ given ➡ Magnets defined (**B**)

Constraints:

E and **B** given ➡ Size of the machine (ρ)

Constraints:

B and ρ given ➡ Energy defined (**E**)

Interesting homework:

Compute machine parameters for LHC physics with fixed target:

- ➢ Compute Energy (momentum) required for equivalent E_{cm}

Keeping the existing
LHC tunnel (R fixed)

➔ B = ?

Keeping the existing
LHC magnets (B fixed)

➔ R = ?

What type of particles?

- The choice of the type of particles is intimately linked to the dedicated application. For high energy circular machines, synchrotron radiation and the available magnet strength will be the important parameters. Possible candidates:
    - Electrons and/or positrons (synchrotron radiation in circular machines)
    - Protons (magnet strength)
    - Antiprotons, neutrinos (available intensities)
    - Ions (sources)
    - Muons (future machines)

Hadrons vs. Leptons (circular machine)

Two extreme cases:

Magnetic rigidity:

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

Synchrotron radiation losses:

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

LEP (100 GeV): $B = 0.12$ T

LHC (7 TeV): $B = 8.3$ T

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

End of step 1:

So, at this stage, with your given boundary conditions and a single (simple) relation, you already know:

- The type of your machine
- The energy of your machine
- The type of particles
- The size of your machine
- The type of your magnets (SC or conventional)
- … and the radiation losses

NB: Size of the real machine

- Required kinetic energy of the beam is known: E_{kin}
- Available field in the dipoles is given: B [T]
- Evaluate additional space required for injection, extraction, acceleration, collisions… => $(L_{bend}/L_{tot}) = A$

$(E_{kin} = 450\ \text{Gev},\ B = 1.9\ \text{T},\ A = 2/3)$

- Compute momentum p: $p^2c^2 = (E_{tot}^2 - E_0^2)$: p=450.93 GeV/c

- Compute ρ: $B\rho = 3.3356\ p$: $\rho = 791.64$ m

- Compute R: ρ/A ➔ Circumference of the machine $C=2\pi R$

$R = 1187.5$ m $C = 7461.2$ m

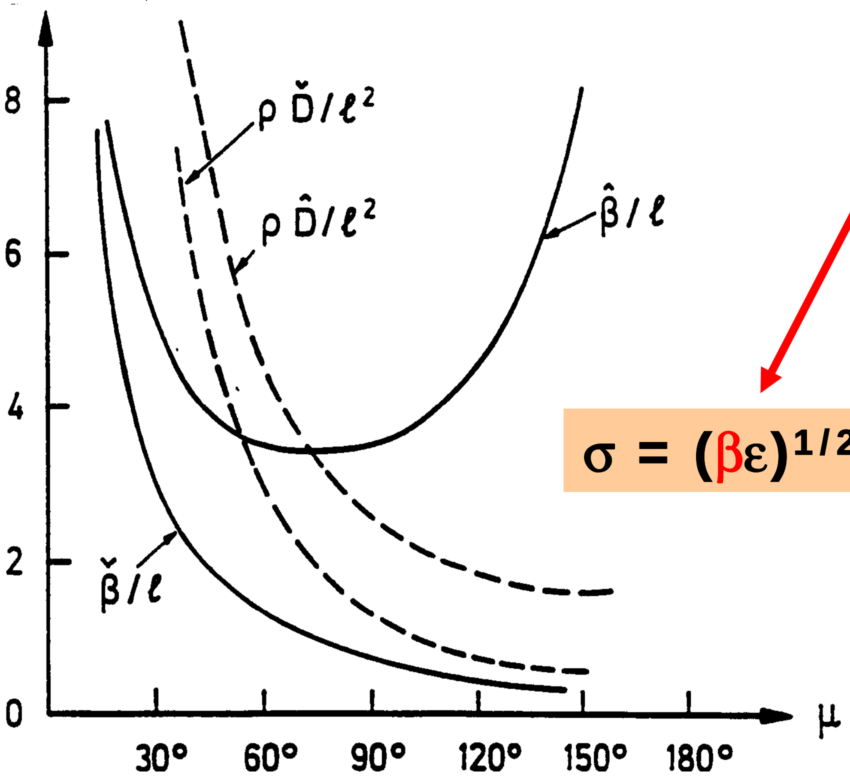
Step 2: Choice of the lattice

- ➢ If you are working on a conventional machine, then you are very likely to use a standard FODO lattice. For the FODO cells, the lectures on « Transverse Dynamics » directly apply.

- ➢ If your synchrotron has insertions (injection, extraction, RF, low-β, experiments), then you will need an « Optics program » to adapt (match) these specific regions to the FODO/periodic cells.

- ➢ If you are working on a Synchrotron Light Source (very small emittance, insertion devices) you will opt for a special lattice (CAS Intermediate course). For such a case, the use of a dedicated « Optics program» is probably unavoidable.

The phase advance per cell μ



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

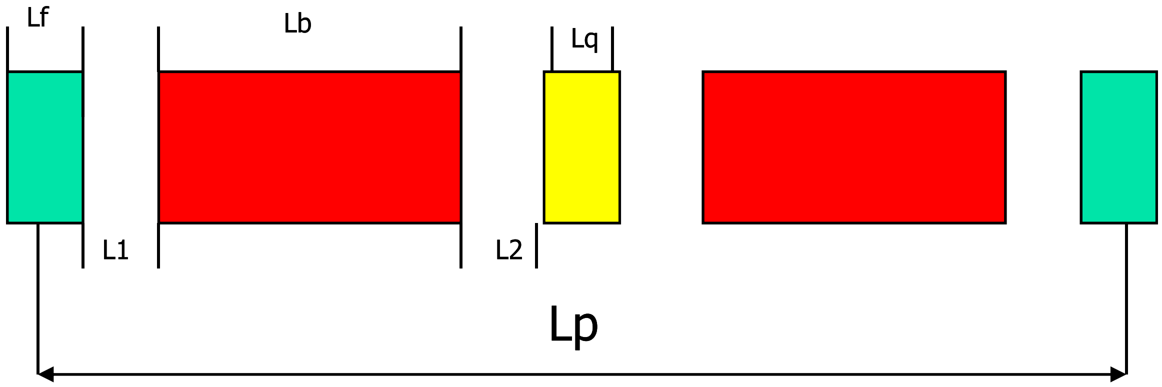
E. Wilson's lecture, CAS Sesimbra 2002

- Aperture expensive ➔ μ between 60 and 90 degrees.
- Closed orbit correction
- Chromaticity correction with a reasonable number of sextupole families

Some phase advances are advantageous for the lattice design (Intermediate level)

$60^\circ < \mu > 90^\circ$

Geometry of the FODO cell



The length of a periop Lp = 2 (L1+L2+Lb) + Lf +Lq

Obvious checks: $2\pi R = Np \times Lp$

$2\pi\rho = Nb \times Lb$

The Twiss Parameters

Matrix for the FODO cell (mid-F to mid-F):

$$M = \begin{pmatrix} 1-L^2/2f^2 & 2L(1+L/2f) \\ (-L/2f^2)(1-L/2f) & 1-L^2/2f^2 \end{pmatrix} = \begin{pmatrix} \cos\mu + \alpha \sin\mu & \beta \sin\mu \\ -\gamma \sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$$

$\cos\mu = 1 - L^2/2f^2$

$\sin(\mu/2) = L/2f$

$\beta_{max} = 2L\,(1+\sin(\mu/2))/\sin\mu$

$\alpha = 0$

Aperture optimisation:

Start reversed process by defining β_{max}

More general case …

- You will need an « Optics program » to compute the lattice of your machine (e.g. MAD-X, more detailed tuition on « Optics design » and how to use the « Optics code » belongs to the Intermediate level CAS course with a dedicated afternoon course (12-14 hours)).

Get the correct Optics

- ➢ Match your insertions.
- ➢ Correct the chromaticity
- ➢ Compensate coupling

Predict the performance

- ➢ Compute Tunes vs. Momentum
- ➢ Perform tracking with errors
- ➢ Evaluate the dynamic aperture

A few useful checks…

- Although the « Optics code » will provide you all the required parameters, it is always recommended to perform a few very basic checks (garbage IN, garbage OUT ↔ the program does what YOU asked it to do).

Useful checks:

$<\beta> \approx R/Q$

$\alpha \approx 1/Q^2$

$<D> = \alpha R \approx R/Q^2$

$\gamma_{tr} \approx Q$

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

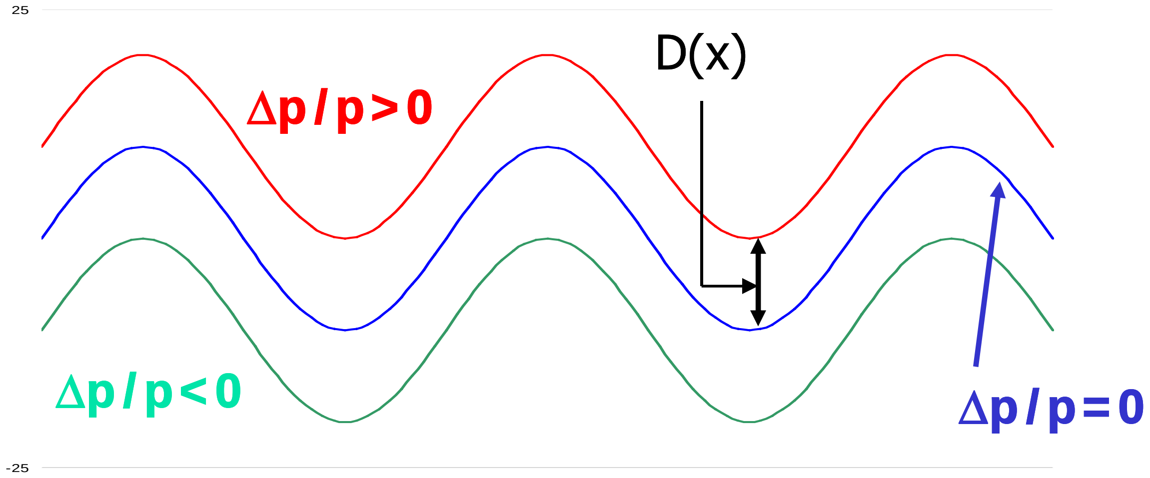
Effect from Dipoles

- 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 !

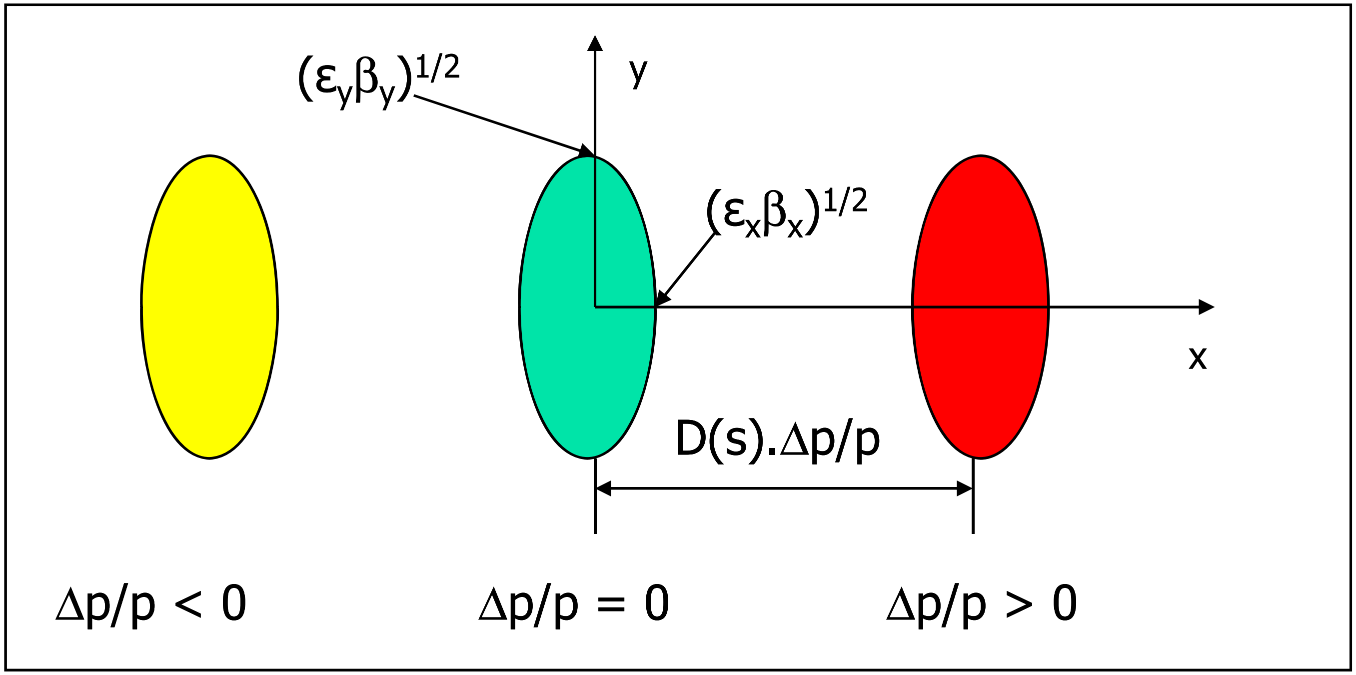
No!

There is an equilibrium with the restoring force of the quadrupoles



Dispersion

In general:



Only extreme values of $\Delta p/p$ are shown.

The vacuum chamber must accomodate the full width.

VH: $A_y(s) = (\varepsilon_y\beta_y(s))^{1/2}$ and HW: $A_x(s) = (\varepsilon_x\beta_x(s))^{1/2} + D(s).\Delta p/p$

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, …

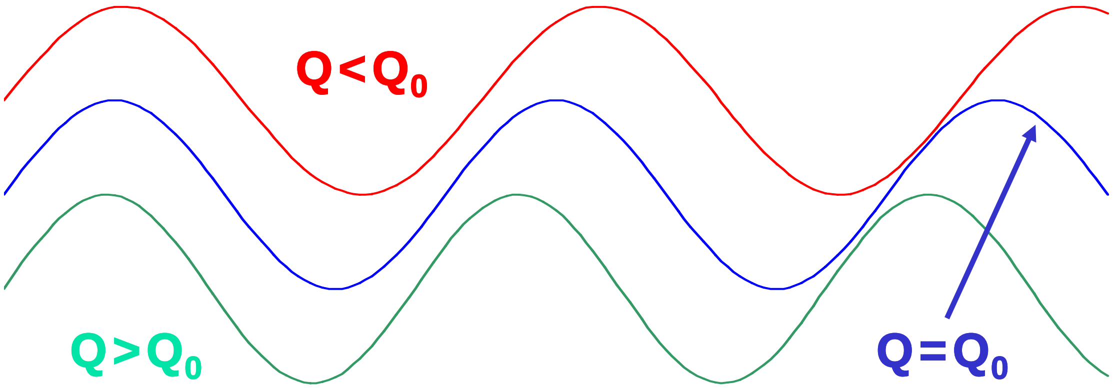
Off momentum particles ($\Delta p/p \neq 0$)

Effect from Quadrupoles

- If $\Delta p/p > 0$, particles are less focused in the quadrupoles **lower Q !**

- If $\Delta p/p < 0$, particles are more focused in the quadrupoles ➔ **higher Q !**

Particles with different momenta would have a different betatron tune $Q=f(\Delta p/p)$!



The chromaticity Q′

- The tune dependence on momentum is of fundamental importance for the stability of the machine. It is described by the chromaticity of the machine Q′:

$$Q' = \Delta Q / (\Delta p/p)$$

- ➢ For relativistic particles, the chromaticity has to be positive (stability)!
- ➢ The natural chromaticity of the machine is negative!
- ➢ The chromaticity has to be corrected and kept under control.

➢ This is achieved by means of sextupoles

Natural chromaticity…

- Take a particle and slightly increase its momentum:

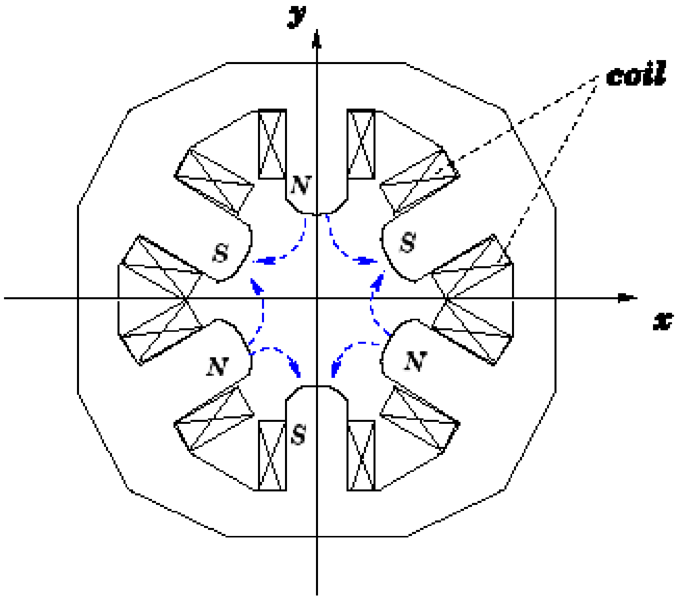
  ➔ $\Delta p/p > 0$ ➔ $\Delta Q < 0$ ➔ $Q' < 0$

- Take a particle and slightly decrease its momentum:

  ➔ $\Delta p/p < 0$ ➔ $\Delta Q > 0$ ➔ $Q' < 0$

Natural Q′ is always negative !

The sextupoles (SF and SD)

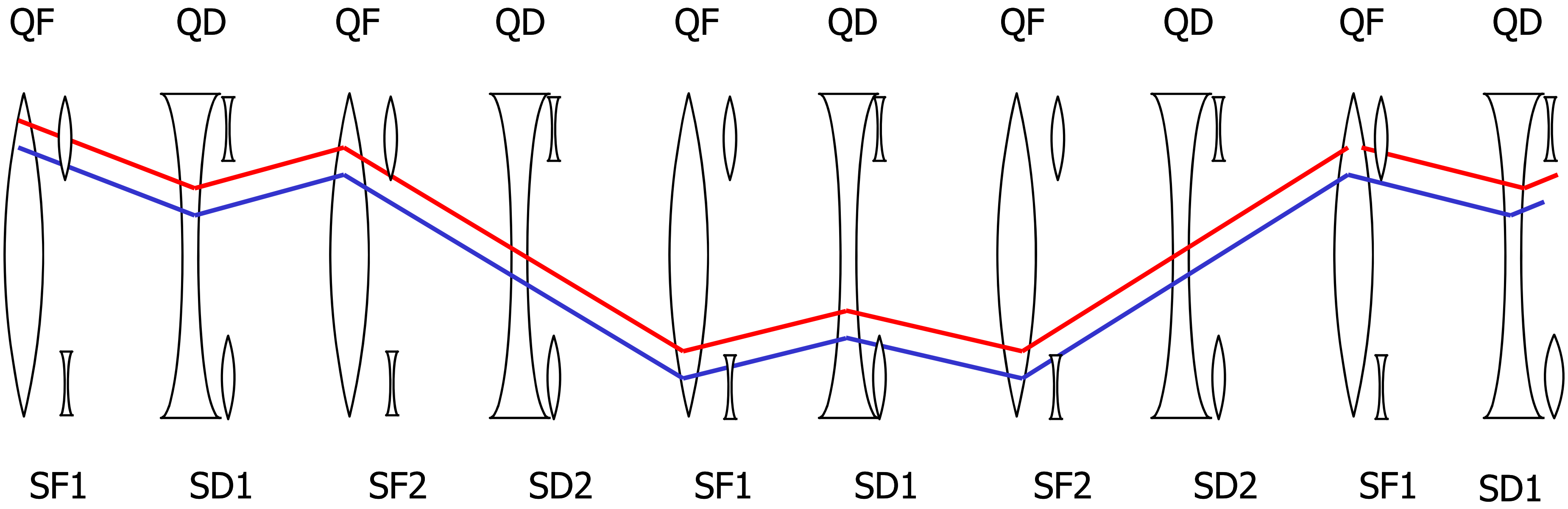


- $\Delta x' \propto x^2$

- A SF sextupole basically « adds » focusing for the particles with $\Delta p/p > 0$, and « reduces » it for $\Delta p/p < 0$.

- The chromaticity is corrected by adding a sextupole after each quadrupole of the FODO lattice.

Chromaticity correction



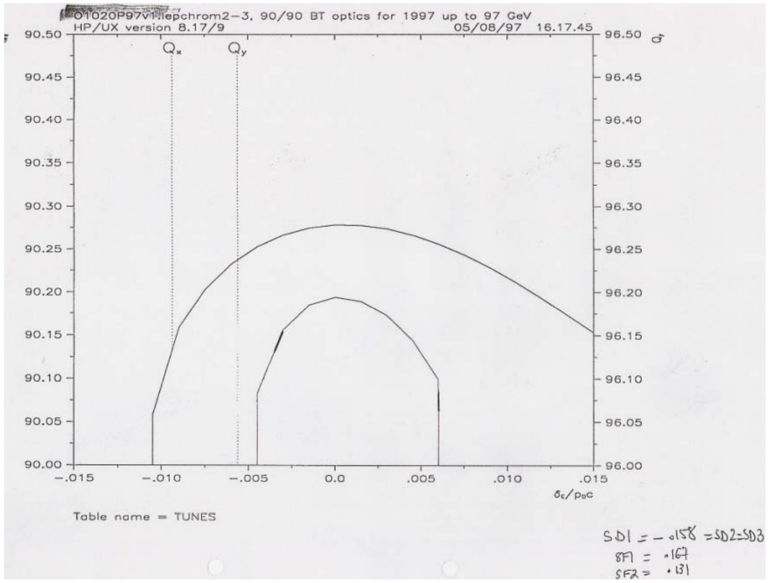
The undesired effect of sextupoles on particles with the nominal energy can be avoided by grouping the sextupoles into « families ».

Nr. of families:

N = (k * 180 °)/μ = Integer

e.g. 180 °/ 90 ° = 2

Tune vs. momentum



Correction with 1 sextupole family:

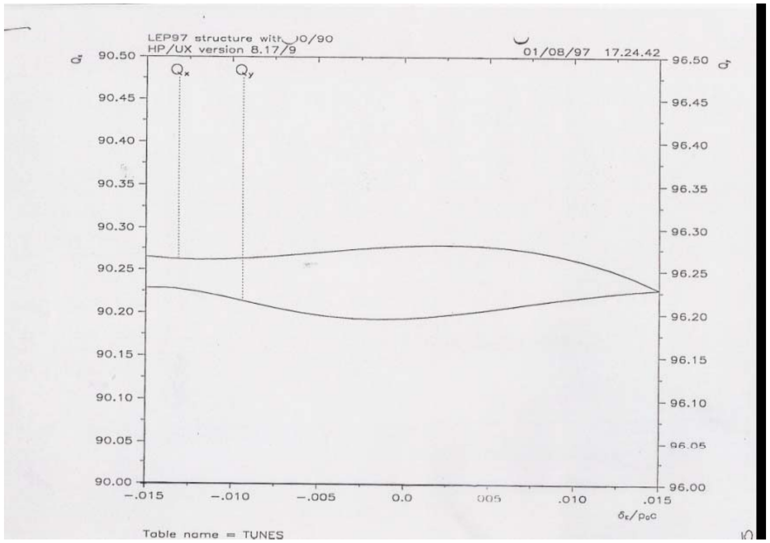
Bad!

Off momentum particles rapidly cross the integer (Qy!).

Correction with 2 sextupole families:

Excellent!

Tunes remain almost constant over the whole range of momentum!



Step 3: the RF frequency

$\beta = pc / E$

$f_0 = \beta c / C$

$f_{RF} = h \cdot f_0$

Check γ_{tr} !

- If Accelerator chain ➔ try to keep the same frequency.
- Look what is available on the market.
- If cavities too big ➔ $f_{RF} \uparrow$ ➔ $h \uparrow$
- Injection/extraction may impose constraints on the bunch spacing.

$\Delta f / f_{min}$	f_{RF} [MHz]	V [kV/m]	
> 2	1 – 10	≤ 10	Ferrite, good longit. accept.
< 0.01	10 – 100	10 – 50	
<< 0.01	> 100	>> 50	Resonators

2 elements of the injector chain

Our « test » machine

	E [GeV]	pc [GeV]	β	fo [kHz]	$\Delta f / f_{min}$
Injection	26.938	26.92	0.9994	40.156	0.0006
Extraction	450.938	450.93	0.999982	40.180	

A smaller machine in the chain (B=1.5 T, C=228.35 m)

	E [GeV]	pc [GeV]	β	fo [kHz]	$\Delta f / f_{min}$
Injection	0.949	0.1453	0.153	200.95	5.5
Extraction	10.938	10.898	0.9963	1308	

Required RF voltage

- $\Delta E_{turn} = e\ \rho\ (\Delta B/\Delta t)\ C$

=> $V_{min} = (\Delta E_{turn}) / e \sin(\phi_s)$

- $\Delta E_{turn} = e\ V \sin(\phi_s)$

Easier:

Request (A_B / A_b) = (Bucket Area / Bunch Area) = 2 ➔ V_{max}

Easy capture at injection: $(\Delta E/E)_{beam} = (\Delta E/E)_{Bucket}$

Step 4: Collective effects

- Interaction between the particles within a bunch (space charge, watch out at injection energy!).

- Interaction between the bunch and the environment (impedance).

- Interaction between the different bunches via the environment (multi-bunch instabilities)

- There are other collective effects to be considered when the beams are colliding! (CAS Intermediate course)

- Taking into account the collective effects at the design phase is a relatively new procedure (~ LEP). The creation of an "Impedance Police Team" proved to be very useful for LEP and vital for LHC!

Procedure:

- Expected performance of the machine defined ➔ required intensities known.
- Compute maximum longitudinal (Z/n) and transverse (Z_T) impedances which allow for these intensities.
- Make sure your Impedance Police Team has sufficient scientific credit to manage (unavoidable) conflicts with component designers and Finance Committee:

Remember: $Z_T = (2R/b^2) \cdot (Z/n)$ (Broad-band Impedance)

Magnets + Finance want **b** ↓ and Collective Effects want **b** ↑

Remember about the vacuum chamber of insertion devices !!!

The Impedance Police Team

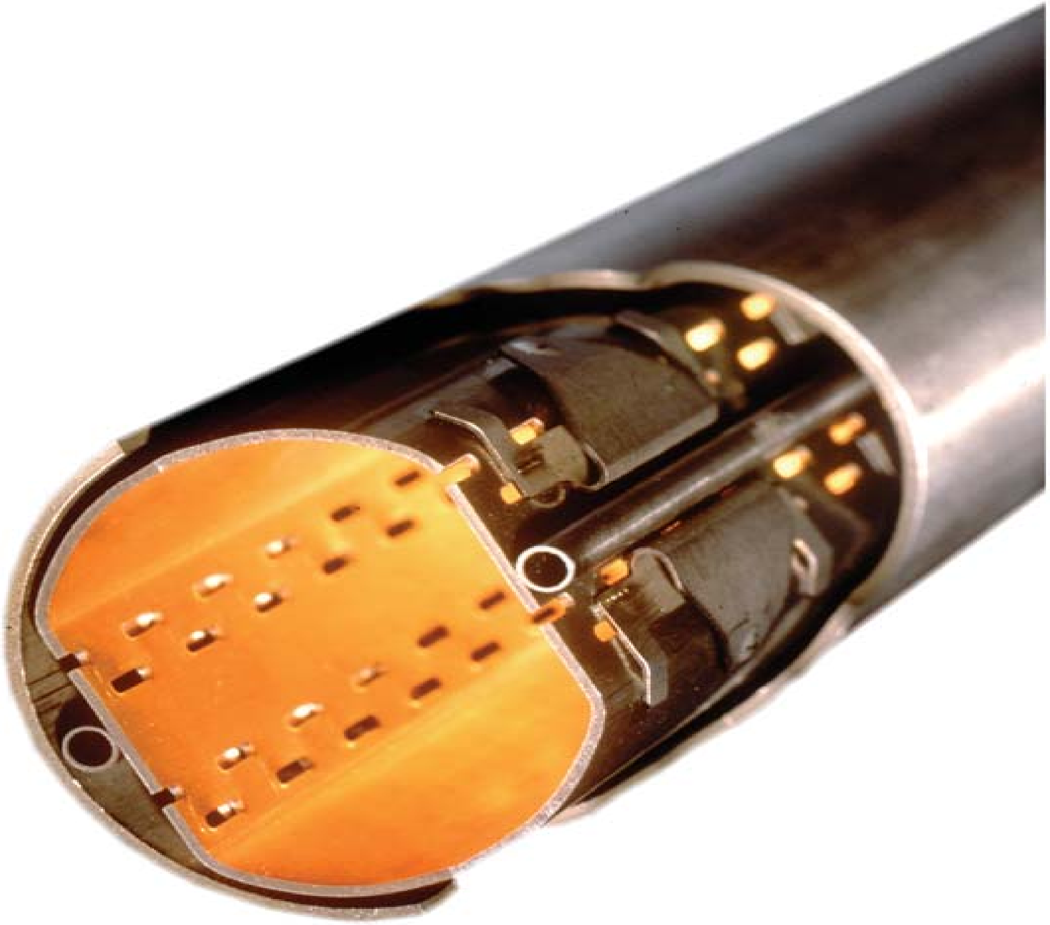
- Every single object visible by the beam should be submitted for approval to the Impedance Police Team.
- The team evaluates by means of dedicated programs the longitudinal and transverse impedances of the object.
- The team approves or proposes modifications for the object.
- Once approved, the object is included in the Impedance budget of the machine, which is regularly updated.
- For each update, ALL the instability thresholds are re-evaluated.
- The time domain codes yield the corresponding wakefields to be used for further multi-particle simulations.
- The frequency domain codes yield BB-impedances or single resonant modes (narrow-band impedances) which will be used to compute instabilities, but also power deposition in the different elements of the machine (essential for SC machines).

|Z/n| as a function of time:

Machine	|Z/n| [Ω]
PS (~ 1960)	> 50
SPS (~ 1970)	~ 20
LEP (~ 1990)	~ 0.25 (1.0)
LHC (~ 2008)	~ 0.10 (0.25)

LHC “beam-screen”

- Without this additional Cu layer, the nominal intensity foreseen for the LHC could not circulate in the machine!



About Impedances…

➢ One often refers to |Z/n| but, please, remember that the impedance is a Complex function !

➢ Values quoted for (Z/n) are in fact |Z/n| to be inserted in handy criteria for longitudinal stability (e.g. KS criterion).

The real part

yields the instability growth times or the energy losses

related to the impedance

(Damping, Feedback)

The imaginary part

yields

the tune shifts

caused by the impedance

(Resonances)

Step 5: Beam Instrumentation

➢ We have seen the basic components used for beam diagnostics (more detailed tuition belongs to the Intermediate level CAS course with a dedicated afternoon course (12-14 hours)).

➢ Once the machine is closed, the instruments available from the beam instrumentation represent the only possibility to « see » the beam! Seems obvious but is often forgotten!

➢ Beam Instrumentation is often a good candidate when costs reductions are envisaged. Think twice before abandoning such instruments (e.g. BPMs).

Magnets and Power Converters

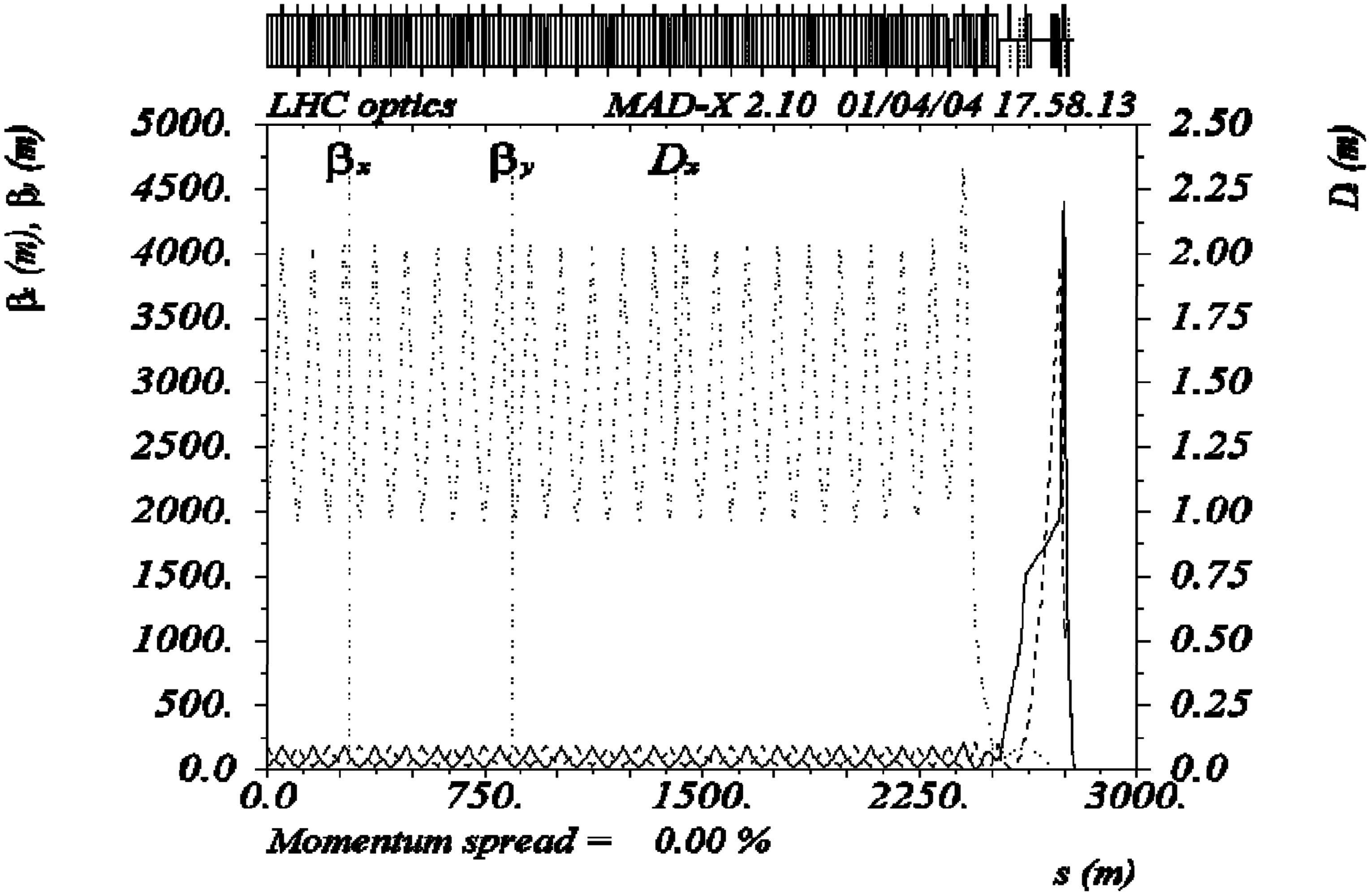
- Errors in Magnets or Power Converters (misalignments, field, current, ripples) can induce severe “distortions” of the closed orbit:

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

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

- The accuracy and the reproducibility (specifications) of these elements is crucial for the performance of the machine.

Beta function in a real machine



Step 6: Summary "Introductory"

- Relativity, E.M. Theory
- Introduction to Accelerators (types, physics, applications)
- Longitudinal and Transverse Dynamics
- Beam Diagnostics
- Linear Imperfections, Low Order Resonances
- Transfer Lines, Injection and Extraction
- Multi Particle Effects
- Synchrotron Radiation, Electron Dynamics and SLS
- Vacuum, Apertures, Particle Sources
- Computational Tools for Accelerator Physicists

The next step is …

- **The Intermediate Level CAS course**, which is the logical follow-up of the Introductory level:

- The “core topics” are re-visited in some more details.
- The “Afternoon courses” propose to discover a specific topic and to study it in detail (Optics Design, Beam Instrumentation, RF methods).
- New topics are introduced:

New topics:

➢ Plenary talks on the topics retained for the Afternoon courses	
➢ Insertions, Special lattices, Non-linearities	
➢ Lattices for Light Sources, Insertion devices, FELs	
➢ Sources of emittance growth (lifetime)	
➢ Longitudinal and transverse instabilities, space charge effects	
➢ Landau damping	➢ Dynamics with damping
➢ Luminosity	➢ Beam-beam effects
➢ RF cavities, Linac structures	➢ Accelerator Magnet design

CAS in 2009 …

Specialised course on

« Magnets »

(resistive magnets)

Bruges, Belgium, 16-25 June 2009

You are more than welcome …

Accelerator Physics course

« Intermediate level »

GSI and TU Darmstadt

Darmstadt, Germany, September 2009

and please let your colleagues know !

By the way …

CAS and the CERN Member States …