

Putting it all together

Werner Herr, CERN



(Version n.n)

http://cern.ch/Werner.Herr/CAS2014/lectures/Praha_review.pdf

Review of the course ...

- What did we learn ?
- What can we do with that ?
- How can we contribute to an accelerator project ?

Review of the course ...

- What did we learn ?
- What can we do with that ?
- How can we contribute to an accelerator project ?



Key issues in an accelerator project

- What is the purpose of the machine ?
- Which resources are available ?
- Basic steps:
 - Choice and definition of parameters
 - Design of the machine
 - Construction of the machine
 - Operation of the machine
- ➔ General tutorial: design a machine with minimum (possibly confusing) information ...

The purpose of the machine

- Not always a single solution for all applications
- Design depends on the purpose
 - Light source
 - Particle physics
 - Medical applications
 - Industrial applications
 - ...



Accelerators in the world (2013):

High-energy and nuclear physics research	120
Synchrotron light sources	> 50
Ion beam analysis	200
Photon or electron therapy	9100
Hadron, ion therapy	> 50
Radioisotope production	550
Ion implantation	> 10000
Neutrons for industry or security	1000
Radiation processing	2000
Electron cutting and welding	4500
Non-destructive testing	650
Total:	> 30000

The choice of the particle and energy

■ Depends on the purpose and availability:

➤ Synchrotron light sources: e^- , e^+

➤ Industrial applications: p , *ions*, ..

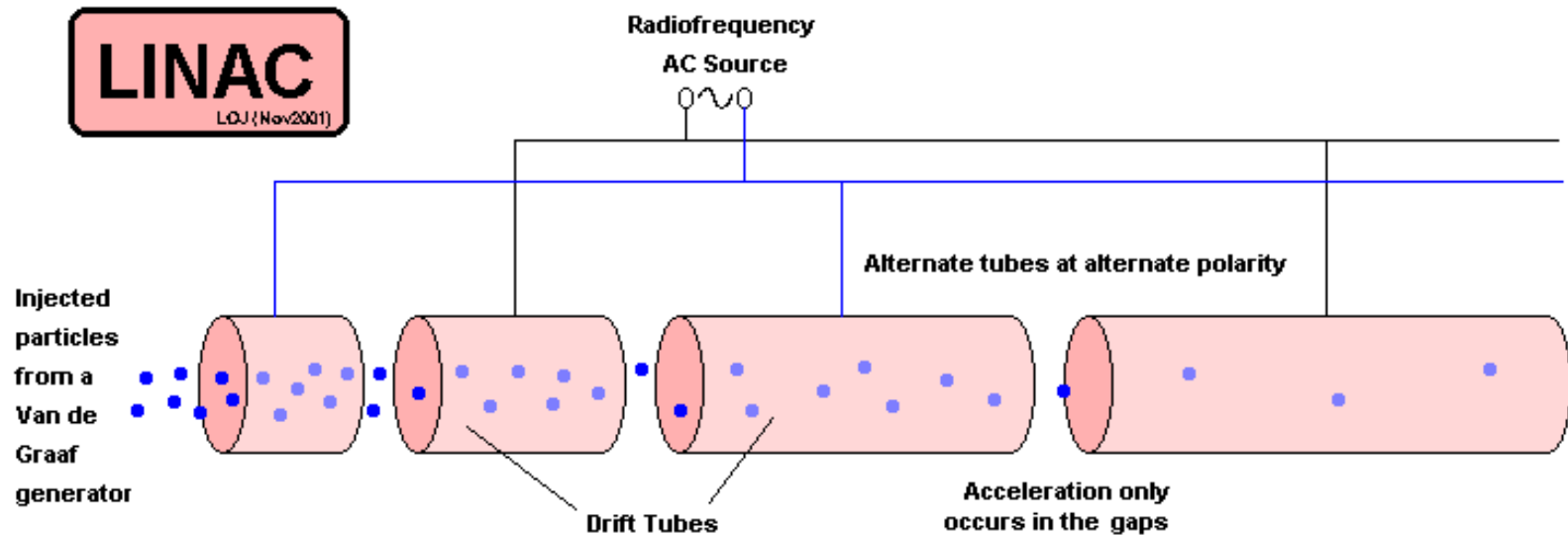
➤ Medical applications: p , e^- , *ions*, ..

➤ HEP experiments: p , \bar{p} , e^- , e^+ , *ions*, ν , μ^\pm , ..

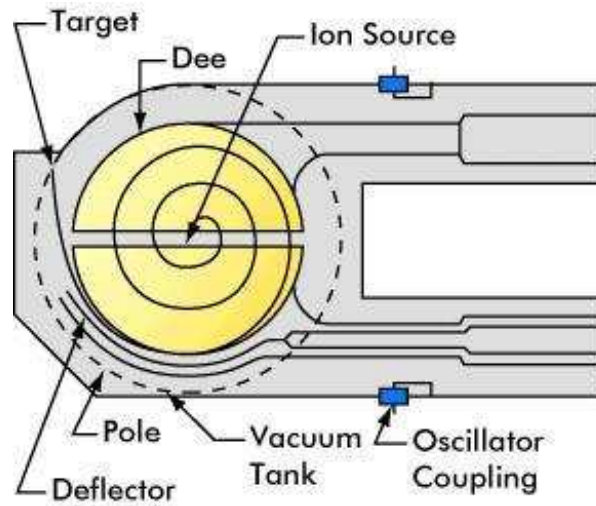
■ Sources are important and some particles are hard to get (\bar{p} , ν , μ^\pm , *ions*, ..)

Different types - linear accelerators

- Single pass
- Low and high energy
- High intensity
- Big size



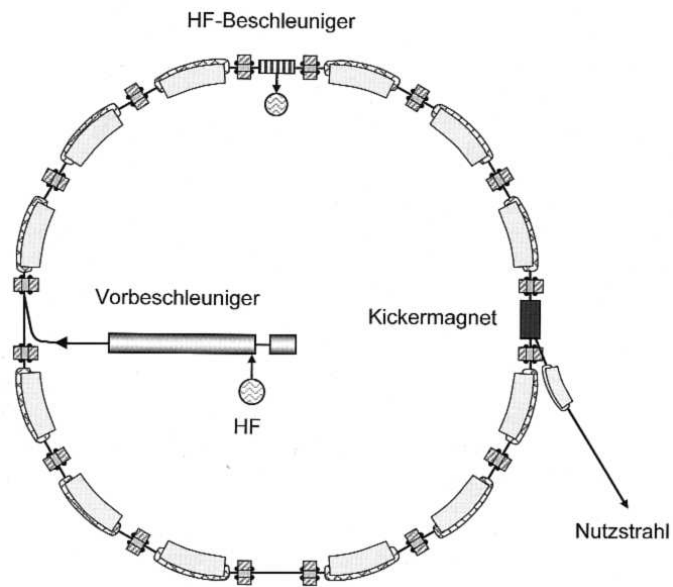
Different types - cyclotrons



- Compact
- Constant field
- Lower energy

Different types - synchrotrons

- Larger
- Constant radius
- High energy



The choice of the type of particles

- Hadrons versus Leptons - two extreme cases ...
- We look at two basic parameters for the choice

Magnetic rigidity:

$$B\rho = p/e = m_0 v \gamma / e$$

Synchrotron radiation losses:

$$U_0 = C_\gamma \cdot E^4 / \rho$$

- Numerical examples:

The choice of the type of particles

Two machines in the same tunnel:

LHC (7000 GeV):	$B = 8.3 \text{ T}$	$U = 0.00001 \text{ GeV}$
LEP (100 GeV):	$B = 0.12 \text{ T}$	$U = 3 \text{ GeV}$

- If you have money for a large magnet system: hadrons
- If you have money for a large RF system: leptons

The choice of the type of machine

■ Depends on type of physics

(assume we want to find dark matter ..)

■ Particle energy as large as possible

➤ Go for a Linac or Synchrotron

➤ For high proton energy: synchrotron

➤ For high lepton energy: synchrotron or linac

➤ For high beam power: FFAG ??

➤ For highest centre-of-mass energy: colliding beams

Why colliding beams ?

■ **Two beams:** $E_1, \vec{p}_1, E_2, \vec{p}_2, m_1 = m_2 = m$

■ $E_{cm} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$

■ **Collider versus fixed target:**

Fixed target: $\vec{p}_2 = 0 \rightarrow E_{cm} = \sqrt{2m^2 + 2E_1m}$

Collider: $\vec{p}_1 = -\vec{p}_2 \rightarrow E_{cm} = E_1 + E_2$

■ **LHC (pp):** 14000 GeV versus ≈ 115 GeV

■ **LEP (e^+e^-):** 210 GeV versus ≈ 330 MeV !!

Luminosity

Together with energy the main deliverable for a collider

Take home formula:

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

To consider:

- Reduction factors (crossing angle, hourglass, ..)
- Peak luminosity
- Integrated luminosity
- 'Useful' luminosity (pile up, levelling, ..)

Circular Colliders:

■ Additional advantages:

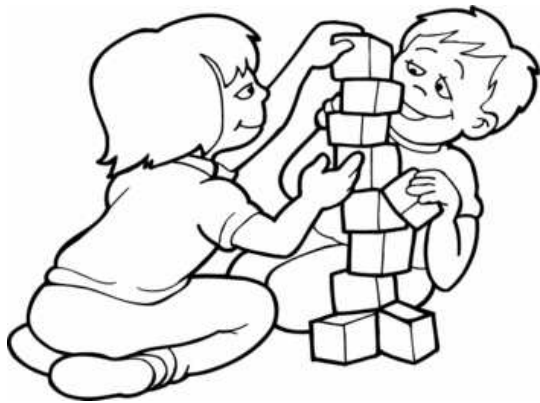
- Particles are "re-used" until they interact

■ Additional difficulties:

- Special lattices
- Insertions
- Additional collective effects
- Require stability for long (24 hrs) time
- Advanced course on accelerator physics (next year)

The required systems

Often deserve dedicated (special) schools:



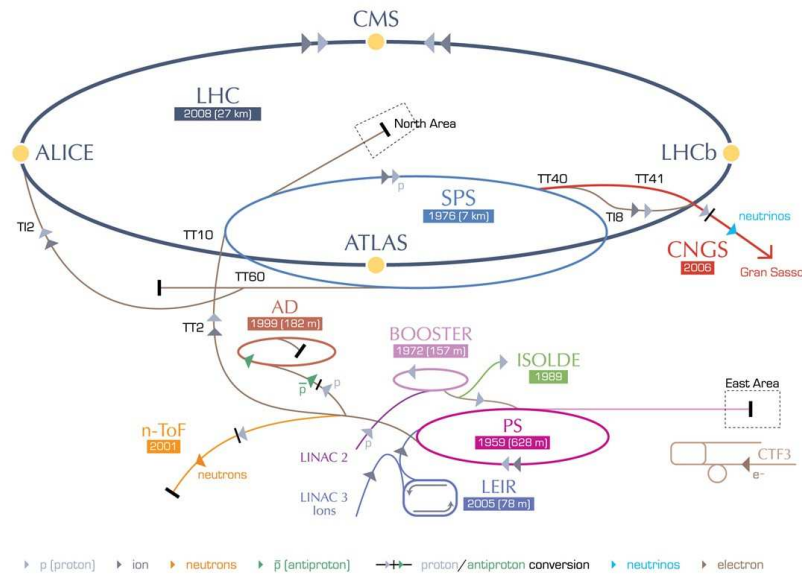
- Magnets: (2009)
- Superconductivity: (2013)
- RF Systems: (1991, 1993, 2000, 2010)
- Diagnostics: (2008)
- Vacuum, cryogenics, metrology: (1992, 1997, 1999, 2002, 2006)
- Power Converters, Control system: (1990, 2004, 2007, 2014)
- Ion Sources: (2012)

The challenges

- **Beam dynamics**
 - **Get the required performance**
 - **Keep the beam in the machine (most critical for hadron storage rings)**
- **Accelerator systems**
 - **Often not commercially available**
 - **Cost and availability**

CERN accelerator complex (2012)

CERN's accelerator complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
 AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight






Why so many accelerators ?

- We cannot accelerate a particle from zero to large momentum in a single machine
 - Several stages needed: "injector complex"
 - Injector complex uses linacs and synchrotrons
 - Typical energy swing ≈ 20
- As example : consider the design of a synchrotron

The choice of the lattice

Purpose of magnet system:

-  Keep the beams on a circle or transport the beams
-  Provide the desired beam parameters (e.g. size) for users and other accelerator components (RF, diagnostics etc.)
-  Keep the beams stable as long as required

The choice of the magnets

■ Lower fields

- Normal conducting
- Maximum 2 T field
- Power (electricity costs !)

■ Higher fields

- Superconducting, (material cost !)
- Fields above 10 T possible
- Low power, but need cryogenic installation

The first piece: choice of the size



Magnetic rigidity:

$$p = m_0 c \beta \gamma \quad \rightarrow$$

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

A handy formula:

$$B[T] \cdot \rho[m] = 3.3356 E[GeV]$$

The choice of fundamental parameters

- If you have **B**: choose **E**, ρ
(e.g. SPS \rightarrow B-field limited to 1.9 T)
- If you have **E**: choose **B**, ρ
(e.g. LEP \rightarrow energy fixed by Z_0 mass)
- If you have ρ : choose **E**, **B**
(e.g. LHC \rightarrow LEP tunnel was already there)

The choice of the size: example

- Assume protons with $E = 500 \text{ GeV}$ and a maximum dipole field of 2 T :
- We have $B[T] \cdot \rho[m] = 3.3356 E[GeV]$
 - ➔ $\rho = 833.9 \text{ m}$
 - ➔ $C = 2\pi\rho = 5239.5 \text{ m}$
- Need some space for other elements (about $1/3$ is a good guess)
- Choose circumference of 9000 m

The choice of the magnets

- We decide to have 120 lattice cells (see later)
- We use 4 dipole magnets per cell, i.e. 480 dipole in total
- Each dipole needs a bending of $2\pi/480 = 0.01309$ rad

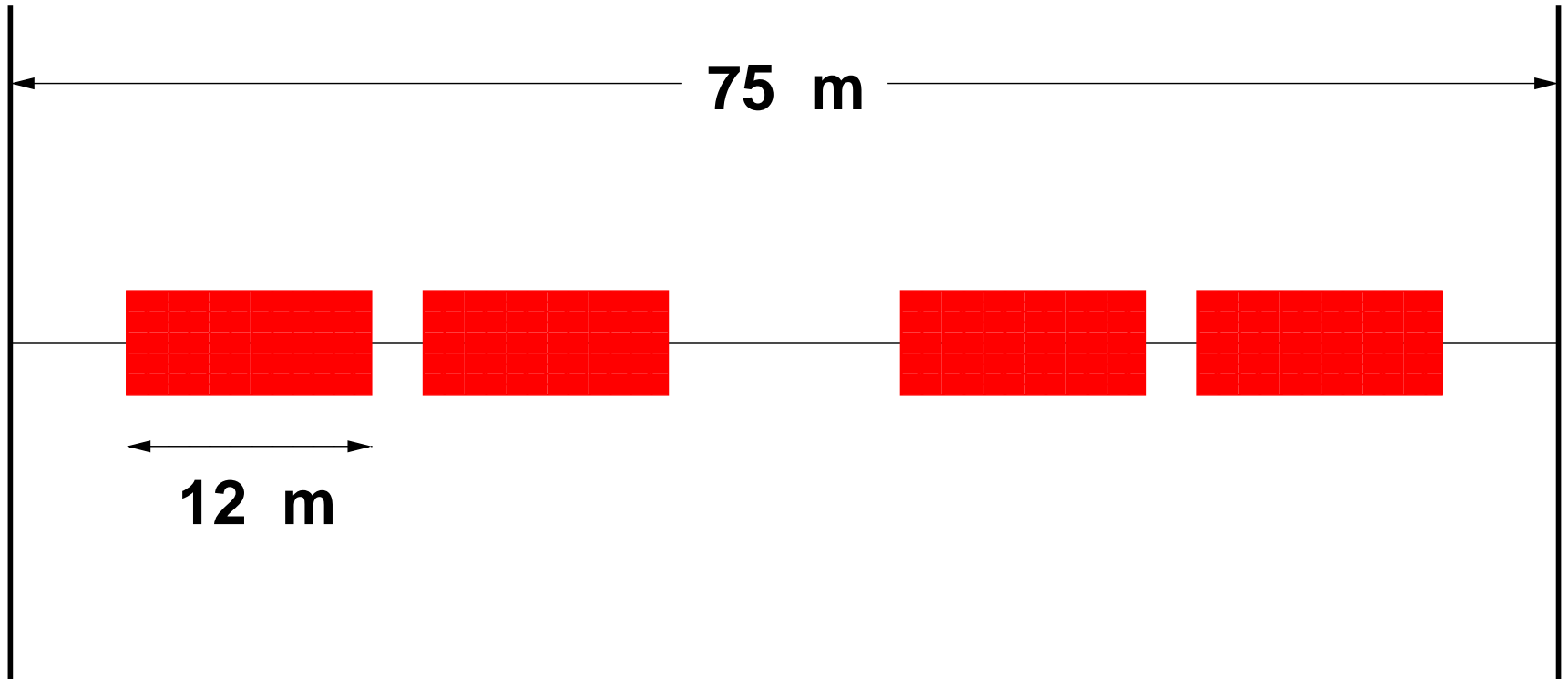
$$B \cdot L = 0.01309 \text{ rad} \cdot 3.3356 \cdot 500 \text{ GeV}$$

- With a dipole length of 12 m, we need a B-field of **1.819 T**
- $480 \cdot 12 \text{ m} = 5760 \text{ m} = 0.64 \cdot 9000 \text{ m}$
- Well within the specification

We have up to now:

- Proton synchrotron with 9000 m circumference
- 480 dipoles in 120 cells
- Each cell is 75 m long, 48 m occupied by dipoles

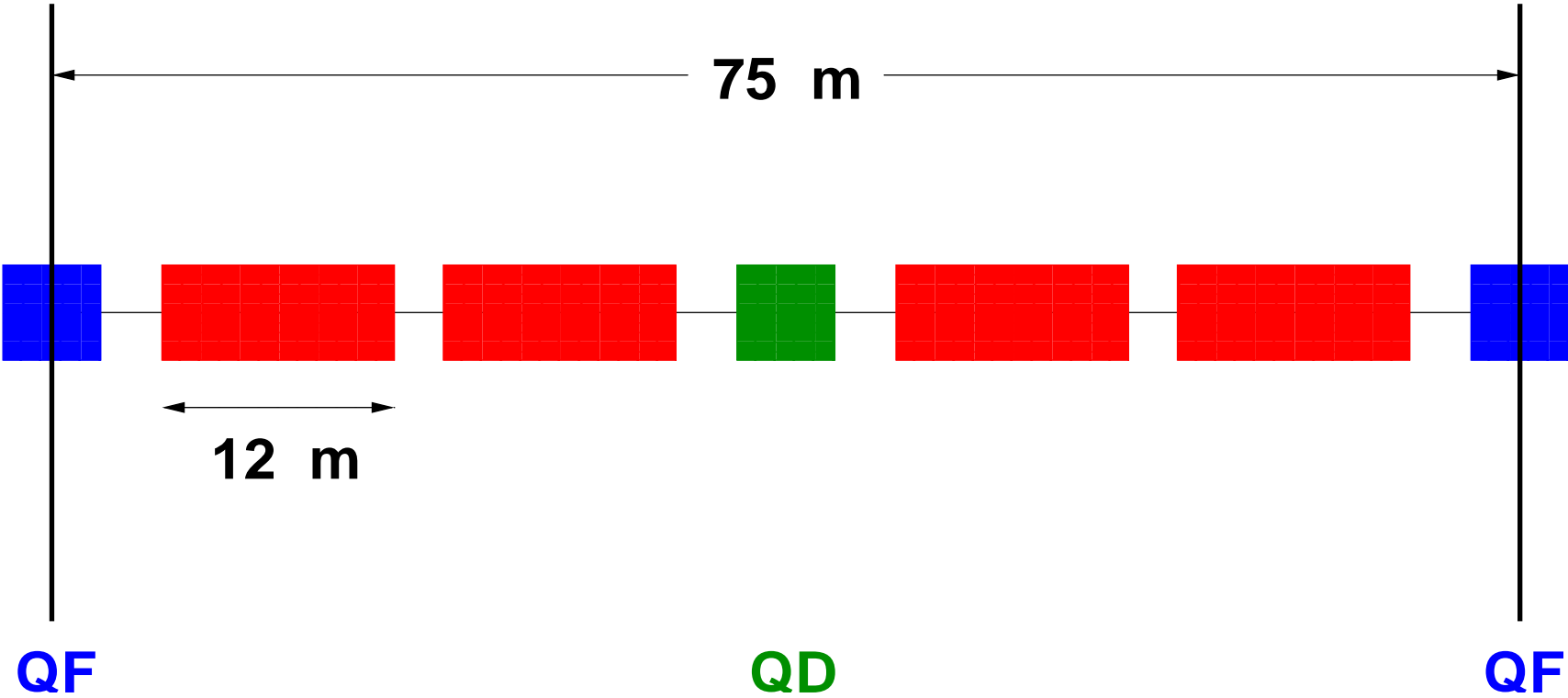
First part of the cell



Complete the cell

- We have to focus the beam !
- The choice to make:
 - The type of lattice
 - Phase advance per cell
- Go for a FODO lattice (we can treat that with the lectures)
- Put a focusing (QF) and defocusing (QD) quadrupole in each cell

Second part of the cell



A FODO cell matrix

$$\mathcal{M}_{cell}^{*}) = \begin{pmatrix} 1 - \frac{L^2}{2f^2} & L(1 + \frac{L}{2f}) \\ (\frac{L^2}{2f^3} - \frac{L}{f^2}) & 1 - \frac{L^2}{2f^2} \end{pmatrix} = \begin{pmatrix} \cos\psi + \alpha\sin\psi & \beta\sin\psi \\ -\gamma\sin\psi & \cos\psi - \alpha\sin\psi \end{pmatrix}$$

L, f → cell length and focusing length of Quadrupole

*) from your exercises ...

 In literature: **L** is sometimes half-length of cell

Basic relations for the cell

$$\sin(\mu/2) = \frac{L_{cell}}{4f}$$

$$\hat{\beta} = \frac{L_{cell}(1+\sin(\mu/2))}{\sin(\mu)}$$

- Phase advance μ determined by focusing f (i.e. quadrupole strength) and cell length L_{cell}
- Maximum $\hat{\beta}$ depends on cell length L_{cell} , larger cells also mean larger $\hat{\beta}$

Rule of thumb: $\hat{\beta} \approx 1.71 \cdot L_{cell}$

Cell parameters

Criteria for cell parameters:

➤ Most common phase advance per cell (μ): 60 and 90 degrees, important for closed orbit and chromaticity correction, insertion design

➤ Maximum β -function ($\hat{\beta}$): important for aperture

$$A(s) = \sqrt{\epsilon \cdot \beta(s)} \qquad \hat{A}(s) = \sqrt{\epsilon \cdot \hat{\beta}(s)}$$



Careful: all these concepts are developed for synchrotrons

Interlude: the emittance saga

■ Definition(s) of emittances seems confusing ...

■ Different for synchrotrons, linacs, sources, ... ?

■ Still, popular to mix:

- Phase space invariants \leftrightarrow phase space volume \leftrightarrow beam emittances !

- Hadrons vs leptons ? Linear or non-linear dynamics ?

- For definition: (x, x') or (x, p_x) ?

⚠ Check what people use for their definition and whether it is correct for your application ...

➡ Useful standard in most cases: $\epsilon = \sigma \cdot \sigma'$

There is still another confusion:

Interlude: the emittance saga

How do these compare ?

1.0 μm

1.0 mm mrad

1.0 π mm mrad

3.14 mm mrad

CERN standard exists (usually ignored by CERN people ...)

In North America: usually defined for 2σ

Basic relations for the machine

Basic relationships for global parameters are available:

$$\text{Tune: } Q = n_{cell} \cdot \mu / 2\pi \quad [\approx 30]$$

$$\langle \beta \rangle \approx R/Q \quad [\approx 50m]$$

$$\alpha \approx 1/Q^2 \quad [\approx 0.0011]$$

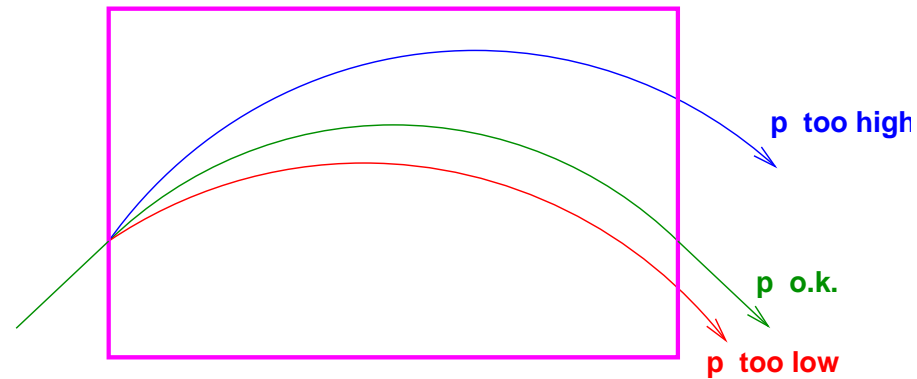
$$\langle D \rangle \approx \alpha \cdot R/Q \quad [\approx 1.6m]$$

$$\gamma_{tr} \approx Q \quad [\approx 30]$$

Detailed lattice design

- From now on a lattice design computer program is required (for details: next CAS)
 - Detailed design and optimization of the optics
 - Design of correction systems (orbit, chromaticity, ..)
 - Effect of off-momentum beams (dispersion and chromaticity)

Dispersion created in dipole magnet



- Correct bending for particles with exact momentum
- Higher momentum particles bend less
- Lower momentum particles bend more

Problems with dispersion

- Emittance increase with radiation
- With momentum error or spread: more aperture required

$$A(s) = \sqrt{\epsilon \cdot \beta(s)} + D(s) \cdot \Delta p/p$$

Example LHC: $D_x \approx 2 \text{ m}$ → effect for momentum offset can be several times the beam size

The good news: it can be controlled ! (see advanced level CAS)

Aperture

Aperture in the machine is always expensive !

Should be small because:

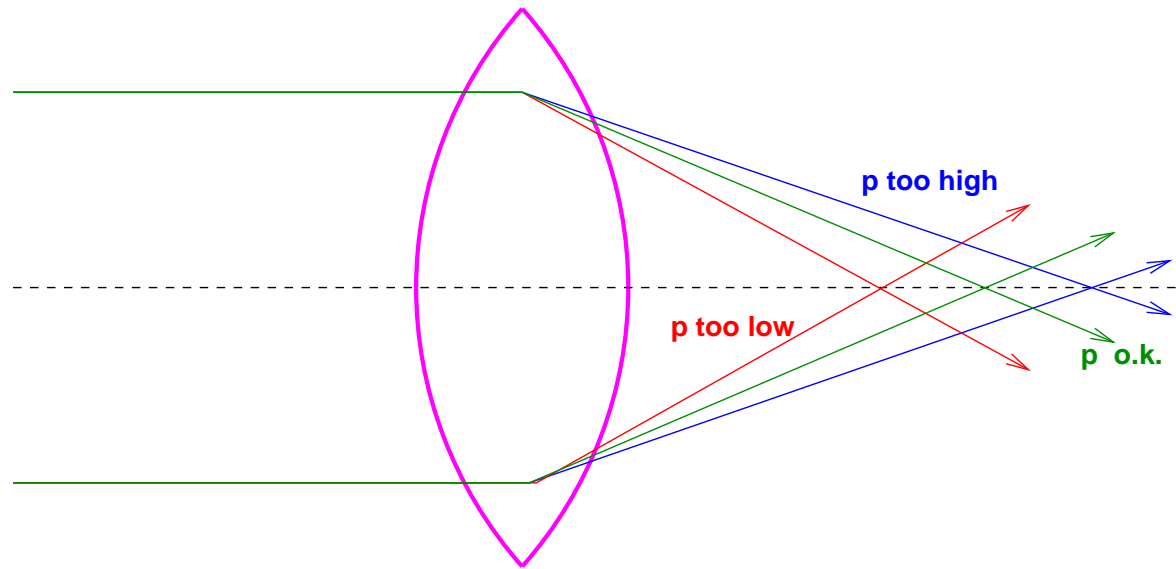
- Cost
- Good field region
- Powering cost
- Available space
- ...

Should be large because:

- Space for injection
- Space for beam size (ϵ, β !)
- Space for orbit
- Impedance
- ...

Requires good compromise between the different requirements

Chromaticity



- For $\Delta Q/(\Delta p/p) < 0$: more focusing, tune is larger
- For $\Delta Q/(\Delta p/p) > 0$: less focusing, tune is smaller

Chromaticity

- Tune change with momentum described by **chromaticity**

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

for $\Delta p / p < 0$ $\Delta Q > 0$ \rightarrow $Q' < 0$

for $\Delta p / p > 0$ $\Delta Q < 0$ \rightarrow $Q' < 0$

Q' is always negative

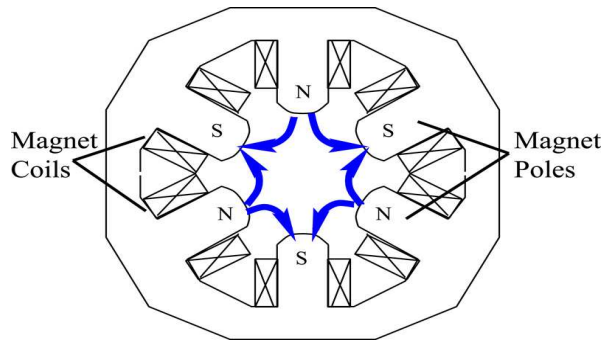
Problems with chromaticity

- Tune spread due to momentum spread (non-linear resonances): should not be too large
- Collective instabilities, for damping (e.g. head-tail modes) might need:
 - Positive chromaticity
 - Negative chromaticity

Q' needs to be controlled !

Correction of chromaticity



- Sextupole has field $\propto x^2$
- Additional focusing for $x > 0$
- Additional defocusing for $x < 0$





- When particles are "sorted" using dispersion:
 - $\Delta p > 0$ focused, $\Delta p < 0$ defocused (SF) or
 - $\Delta p < 0$ focused, $\Delta p > 0$ defocused (SD)
- Sextupoles can correct chromaticity, best with an optics program

Correction of chromaticity

Problems:

-  When chromaticity is very large: large (integrated) strengths required
-  Sextupoles are non-linear: they excite high order resonances ...

To avoid (better: reduce) unwanted effect:

-  Must have more than one type of sextupole in the machine
-  Distribute strength over many sextupoles

(Linear) Machine imperfections

▣ Field errors

▣ Alignment errors (position and tilt)

Orbit and trajectory correction

- Imperfection (e.g. bad alignment) introduce orbit errors
- They must be corrected because
 - Beam may not get around the machine or through the beam line
 - Orbit is too large and causes aperture problems
- Important system for operating the machine



Orbit and trajectory correction



- A measured closed orbit in LHC, 540 beam position monitors

Orbit and trajectory correction

The challenge




-  Find a good set of correctors to get the desired orbit or trajectory
-  Must not disturb other (wanted) properties of the machine

 May require several hundred correctors, sophisticated tools exist




 Most important: good and reliable orbit measurement

RF system

 The RF system has three (main) tasks:

-  Accelerate particles during energy increase (ramp)
-  Replace energy loss due to synchrotron radiation (mainly leptons)
-  Longitudinal focusing of the beam

 Must consider:

-  Appropriate frequencies (Linacs !)
-  Power production and distribution
-  Control of the system

RF system - acceleration

Example synchrotron:

We know from

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

that the energy gain per turn is:

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

when $\Delta B/\Delta t$ is the change of the B-field with time (during ramp).

Since the seen RF voltage is $eV \sin(\Phi_s)$, the minimum required **RF Voltage** is:

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

RF system - acceleration

During the acceleration the particles get faster (for γ not too large) and the RF frequency has to change. For β not close to one, this can be significant.

- Make sure your RF system can accommodate the frequency change
- Check whether you have to make a phase jump (γ_{tr})

RF system - energy replacement





- Energy loss due to synchrotron radiation large for light particles ($\propto \gamma^4$)
- Make sure enough voltage is available to replace the lost energy
- Example: LEP particles lost 3 GeV (of 100 GeV) per turn, minimum seen Voltage 3 GV !!

RF system - longitudinal focusing

- ▣ Longitudinal focusing due to phase stability (watch transition !)
- ▣ Longitudinal emittance must be matched
- ▣ Determines synchrotron tune Q_s and bunch length σ_s , important for machine performance (collider)
- ▣ Both are important for collective instabilities (too high voltage can make bunches too short)

RF system - LINACS

 Demanding, we have:

-  Changing energies, from very low (space charge) to high
-  Choice of frequencies important
-  The choice to make on: structures, RFQ (focusing),
...
-  Parameter matching important

 Watch out for conventions !

Synchrotron radiation

- Accelerated charge radiates energy
- Linear accelerators: radiated power small compared to delivered power
- Circular accelerators: particles bent perpendicular to direction of motion
 - Radiation strongly increased with increasing energy
 - Radiation strongly increased with decreasing bending radius

Synchrotron radiation

- Radiation Power $P_s \propto \frac{\gamma^4}{\rho^2}$
- Energy loss per turn $\Delta E \propto \frac{\gamma^4}{\rho}$
- Important for light particles (e^+/e^-)

A handy formula (for e^+/e^-):

$$\Delta E [keV] = 88.5 \frac{E^4 [GeV^4]}{\rho [m]}$$

- Consequence: e^+/e^- accelerators with **largest energy** have usually the **smallest field** !

The use of synchrotron radiation

- Synchrotron light becomes important application
 - Synchrotron light sources are tunable
 - Deliver high brightness beams
- Properties can be used to manipulate the beam dynamics (damping !)
- New developments and details (e.g. FEL)

Beam transfer

- Beams must be transferred between accelerators or storage rings
- **Beam lines** must conserve the desired properties
 - Beam size increase must be avoided
 - Losses or filamentation must be avoided
- Can be long and must be optically matched to the entry and exit

Injection and extraction

- Accumulating beam in a ring depends on the type of particles
- Extracting beam also depends on purpose:
 - Fast extraction for transfer etc.
 - Slow and resonant extraction
- In all cases: significant loss of beam must be avoided
(e.g. energy transfer to FCC-hh: 0.5 - 1.0 GJ)

Collective effects

- Distinguish 4 different main collective effects (interactions):
 - Particles within a bunch (space charge, intra-beam scattering)
 - A single bunch with the environment (impedance and instabilities)
 - Multiple bunches via the environment (multi bunch instabilities)
 - Between two beams in a collider (next CAS)
- Others: Landau damping (next CAS)
- All these effect can severely limit the bunch intensity

The role of the impedance

- The longitudinal and transverse impedance limit the intensities

Remember:

$$Z_T \approx (2R/b^2) \cdot (Z/n) \text{ (Broad-band impedance)}$$

- Real part: instabilities, energy loss
- Imaginary part: tune shifts

Effects are estimated using the measured or calculated impedance

Collective effects - impedance

- Main issues for collective effects are impedance and particle density:
 - Machine impedance must be well understood and under control
 - Take into account already at design
 - Careful monitoring of impedance required:
- In LEP and LHC every equipment seen by the beam passed through the evaluation procedure

Collective effects - impedance

■ Result of a rigorous and methodical approach:

Machine	year	$ Z/n \Omega$
PS	≈ 1960	> 50
SPS	≈ 1970	≈ 20
LEP	≈ 1989	≈ 0.25
LHC	≈ 2008	≈ 0.10

➤ Reliable codes available

➤ Measurements !



➤ Strong reduction


■ Often contradicting requirements

■ Finance, components

Non-linear effects

The 'real' world:

-  Unwanted: imperfections, ...
-  Wanted (unfortunately): sextupoles (chromaticity correction), octupoles (Landau damping), beam-beam effects (colliders), ...

 Huge development in last 30 years (largely driven by beam dynamics in hadron machines)

 Extensive treatment in advanced school

(we shall deal with contemporary methods !)

Beam instrumentation and diagnostics

The key to a good control of the machine (it is the **ONLY** way to see the beam):

Beam diagnostics



- Measure beam parameters
- Q , Q' , orbit, beam size
- Effect of imperfections (β -beating, ...)
- Control of injection, ...
- ...

Is an art by itself, you never have enough beam diagnostics → advanced level course, special schools

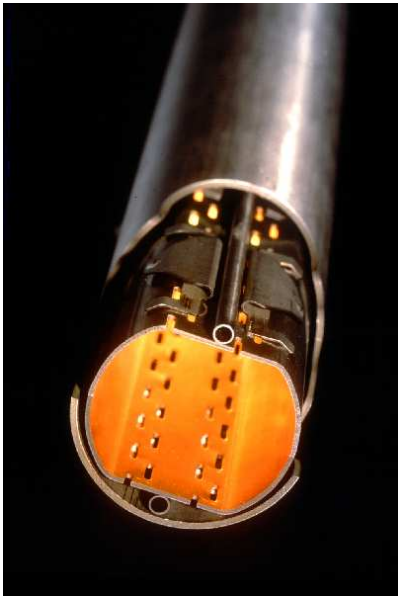
Hardware systems: magnets

- High precision of large range of fields (mT to 10 T)
- Errors (e.g. field errors, etc.) can cause distortions
- Unwanted multipoles must be: avoided, minimized, measured, corrected
- Must provide reproducible fields (hysteresis !)

Additional systems: vacuum

- Must be efficient to keep good vacuum:
 10^{-10} - 10^{-11} mbar
- Important for colliders (long life time)
- Very important for hadron machines (scattering and emittance growth)
- Must operate in cryogenics environment
- Beam can affect vacuum properties: radiation, electron cloud ...

Example: LHC beam screen



- LHC beam screen
- Optimized for:
 - Small impedance !
 - Cooling
 - Aperture
 - Radiation effects
 - ...

Additional systems: Power systems

- Dynamic range (in LHC: ≤ 13000 A)
- Not off the shelf, clear specification required
- High precision: (e.g. Q tolerance $\rightarrow 10^{-4}$ - 10^{-5})
- Tracking and control of several hundred circuits is a challenge
- Errors (e.g. ripple etc.) can cause distortions
- Must provide **accurate**, **reproducible** and **stable** output

Additional systems: cryogenics

■ Relevant for superconducting machine:

- LHC: superconducting magnets (40000 tons at 1.9 K!)
- LEP: superconducting cavities
- Must maintain the machine at constant temperature (for a long time)
- Must not introduce effects on beam (noise)

Additional systems: metrology

- A large machine must be well surveyed (closure)
- Not always easy: LEP/LHC are tilted !
- Alignment of elements is crucial, errors of 0.1 mm affect the closed orbit etc.

The "Introductory" course in a nutshell

- Different types of accelerators
- Relativity and e.m. theory
- Longitudinal and linear transverse dynamics
- Beam diagnostics and instruments
- Imperfections, non-linear effects, resonances
- Transferlines and injection/extraction
- Collective effects, impedances, space charge
- Synchrotron radiation and damping
- Magnets and power systems
- Machine protection
- Additional systems: sources, safety, ..

What is next ?

Advanced Level CAS Course, follow up of this school

- The "core topics" reviewed
- "Hands on" afternoon courses for specific topics, the courses in previous schools (2003 - 2013):
 - 1 Optics design
 - 2 RF measurements
 - 3 Beam diagnostics
- New lectures on special topics

New issues at the next school

- Special lattices and insertions (low emittance, ..)
- RF cavities and LINAC structures
- Magnet design
- More Beam Dynamics (the "real world"):
 - Non-linear beam dynamics, tools, ..
 - Instabilities, impedances, feedback
 - Landau damping
 - Beam-beam effects
 - Machine protection
 - ...
 - ... and it is not only bad !

CAS in 2015

Specialized courses:

Accelerators for medical applications

26.5. - 5.6. 2015, Vienna, Austria

Intensity Limitations in accelerators

November 2015, CERN, Geneva

General course:

Advanced Level Course

Poland