Putting it all together

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(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):

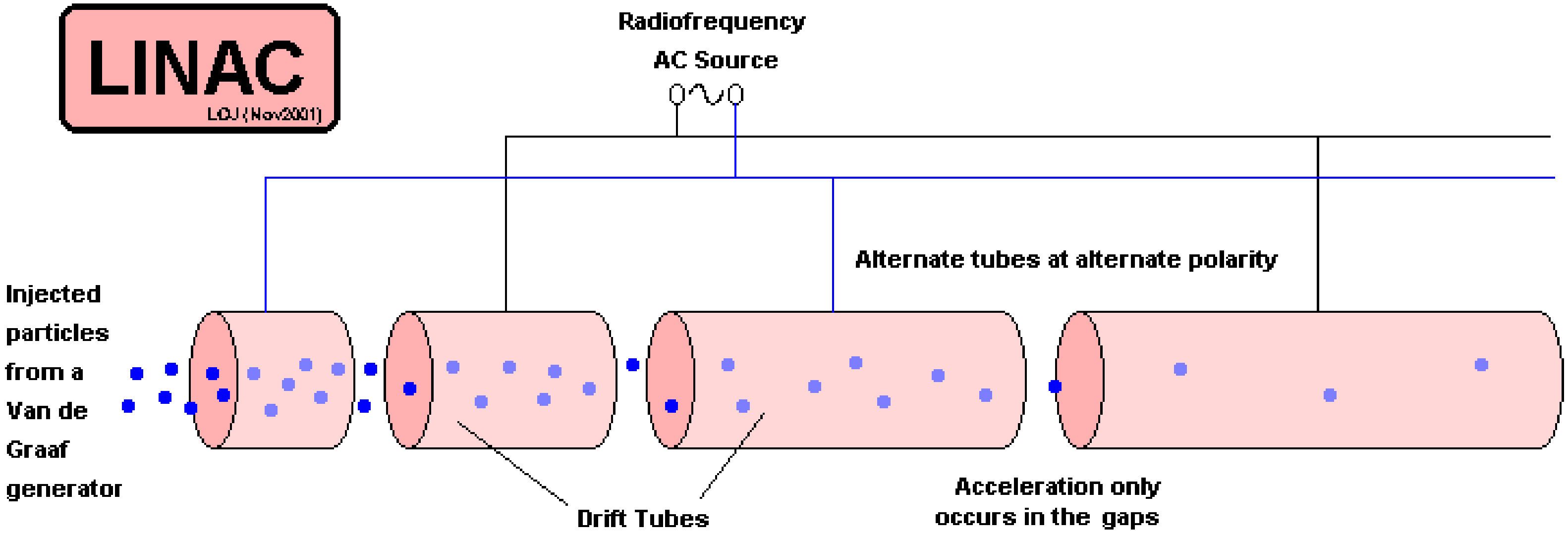
High-energy and nuclear physics research	**120**
Synchrotron light sources	**$>$ 50**
Ion beam analysis	**200**
Photon or electron therapy	**9100**
Hadron, ion therapy	**$>$ 50**
Radioisotope production	**550**
Ion implantation	**$>$ 10000**
Neutrons for industry or security	**1000**
Radiation processing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

The choice of the particle and energy

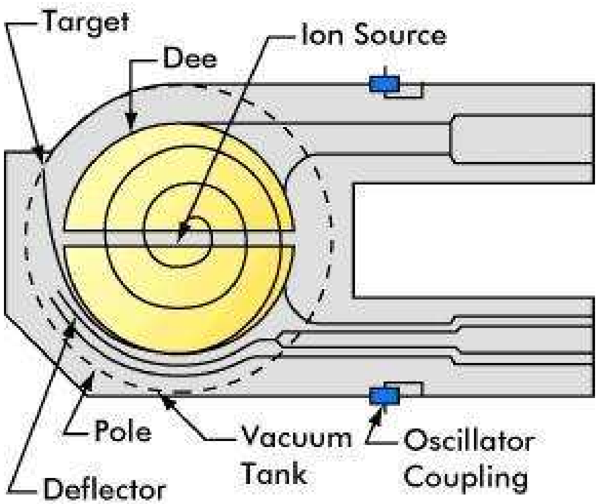
- **Depends on the purpose and availability:**
  - **Synchrotron light sources:** e^-, e^+
  - **Industrial applications:** $p, ions, ..$
  - **Medical applications:** $p, e^-, ions, ..$
  - **HEP experiments:** $p, \bar{p}, e^-, e^+, ions, \nu, \mu^\pm, ..$
- **Sources are important and some particles are hard to get ($\bar{p}, \nu, \mu^\pm$, ions, ..)**

Different types - linear accelerators

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

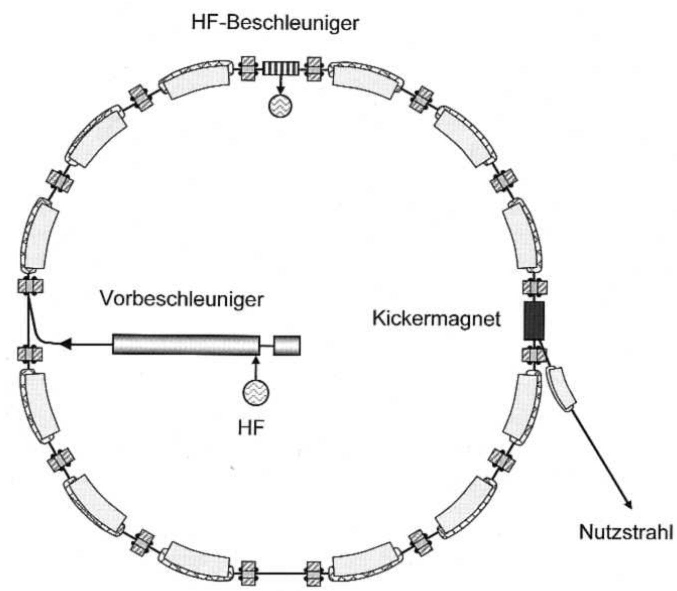


Different types - cyclotrons



- 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 T**	**U = 0.00001 GeV**
LEP (100 GeV):	**B = 0.12 T**	**U = 3 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: $\vec{p_2} = \mathbf{0}$ → $E_{cm} = \sqrt{2m^2 + 2E_1 m}$

  Collider: $\vec{p_1} = -\vec{p_2}$ → $E_{cm} = E_1 + E_2$
- **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, ..)**

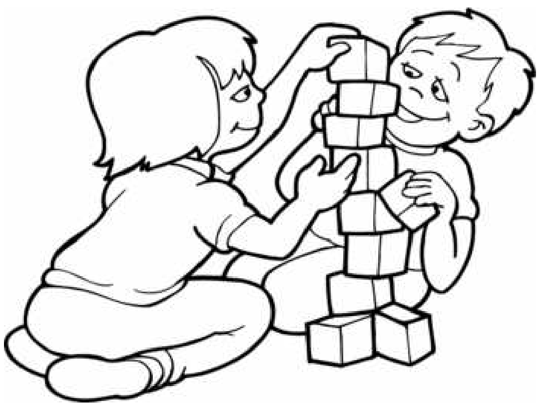
Circular Colliders:

- Additional <u>advantages</u>:
  - Particles are ”re-used” until they interact
- Additional <u>difficulties</u>:
  - 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:

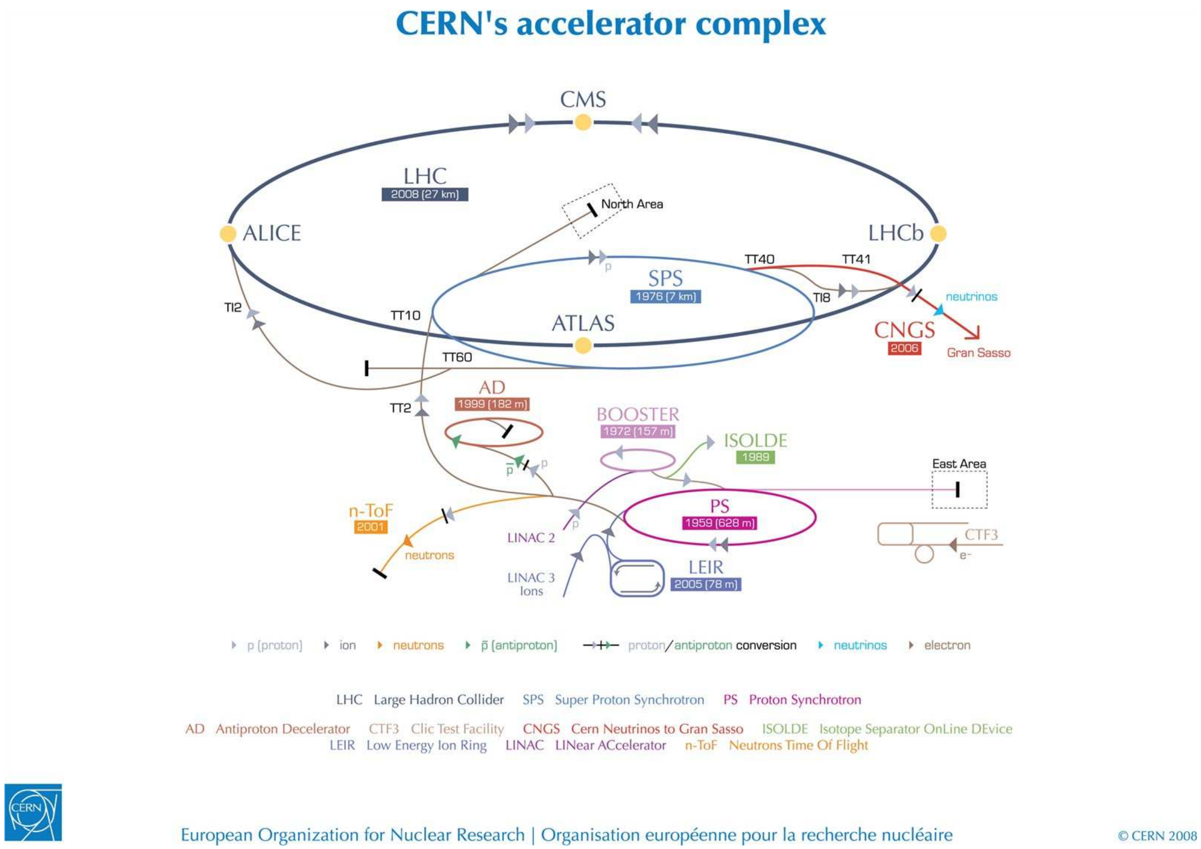


- **Magnets: (2009)**
- **Superconductivity: (2013)**
- **RF Systems: (1991, 1993, 2000, 2010)**
- **Diagnostics: (2008)**
- **Vacuum, cryogenics, metrology: (1992, 1997, 1999, 2002, 2006)**
- **Power Converters, Control system: (1990, 2004, 2007, 2014)**
- **Ion Sources: (2012)**

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)



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 $\approx$ 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:

$$p = m_0 c \beta \gamma$$ ➡

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

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

The choice of the size: example

- **Assume protons with E = 500 GeV and a maximum dipole field of 2 T:**
- **We have** $B[T] \cdot \rho[m] = 3.3356\ E[GeV]$
  - ➡ $\rho = 833.9\ m$
  - ➡ $C = 2\pi\rho = 5239.5\ m$
- **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**

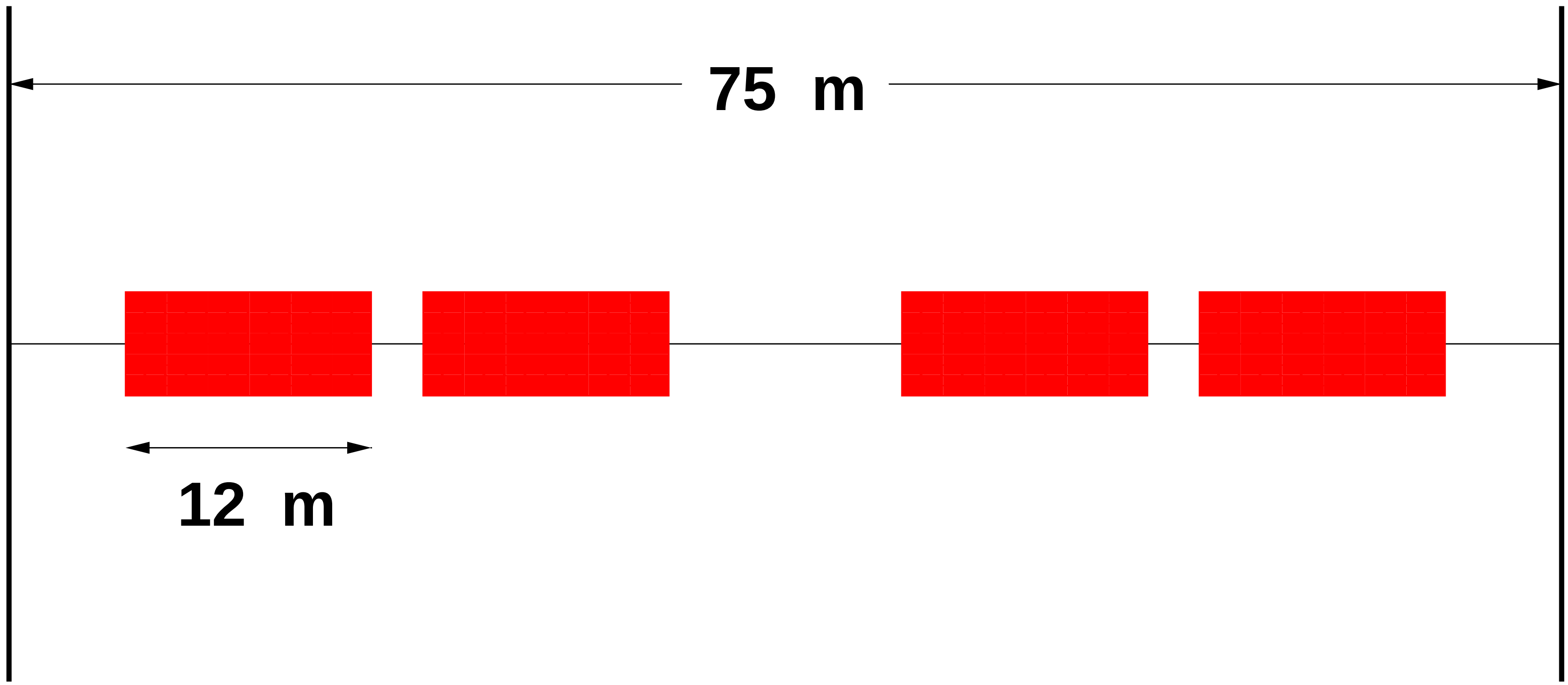
$$B \cdot L = 0.01309\ rad\ \cdot\ 3.3356\ \cdot\ 500\ GeV$$

- **With a dipole length of 12 m, we need a B-field of 1.819 T**
- $480\ \cdot\ 12\ m$ = **5760 m = 0.64·9000 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**

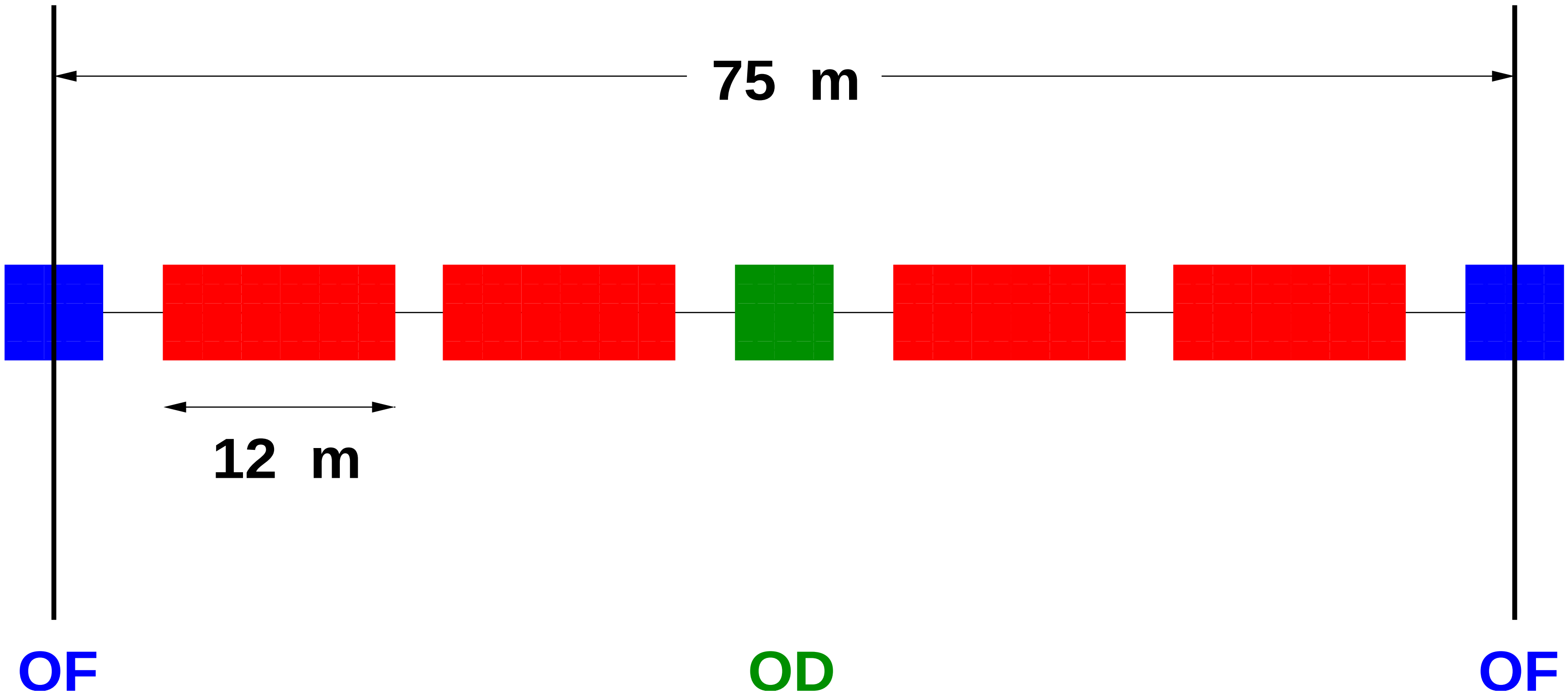
First part of the cell



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 <u>synchrotrons</u>**

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:

Tune: $Q = ncell \cdot \mu/2\pi$ [≈ 30]

$< \beta > \approx R/Q$ [$\approx 50m$]

$\alpha \approx 1/Q^2$ [≈ 0.0011]

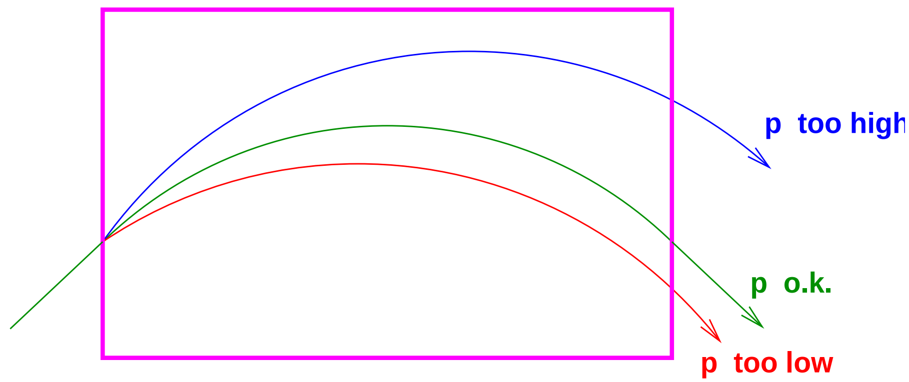
$< D > \approx \alpha \cdot R/Q$ [$\approx 1.6m$]

$\gamma_{tr} \approx Q$ [≈ 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 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:

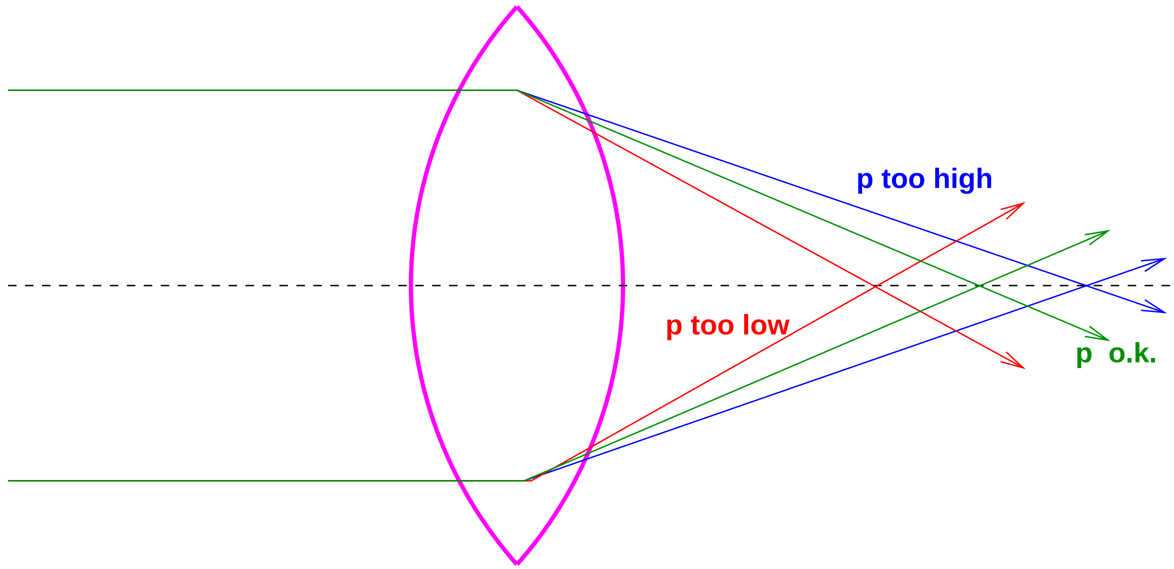
- Cost
- Good field region
- Powering cost
- Available space
- ...

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

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

Q' **is always negative**

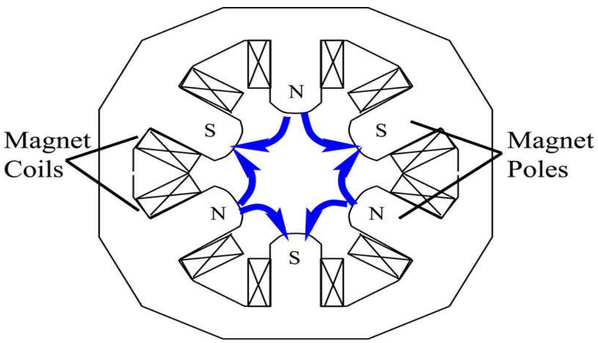
Problems with chromaticity

- **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**

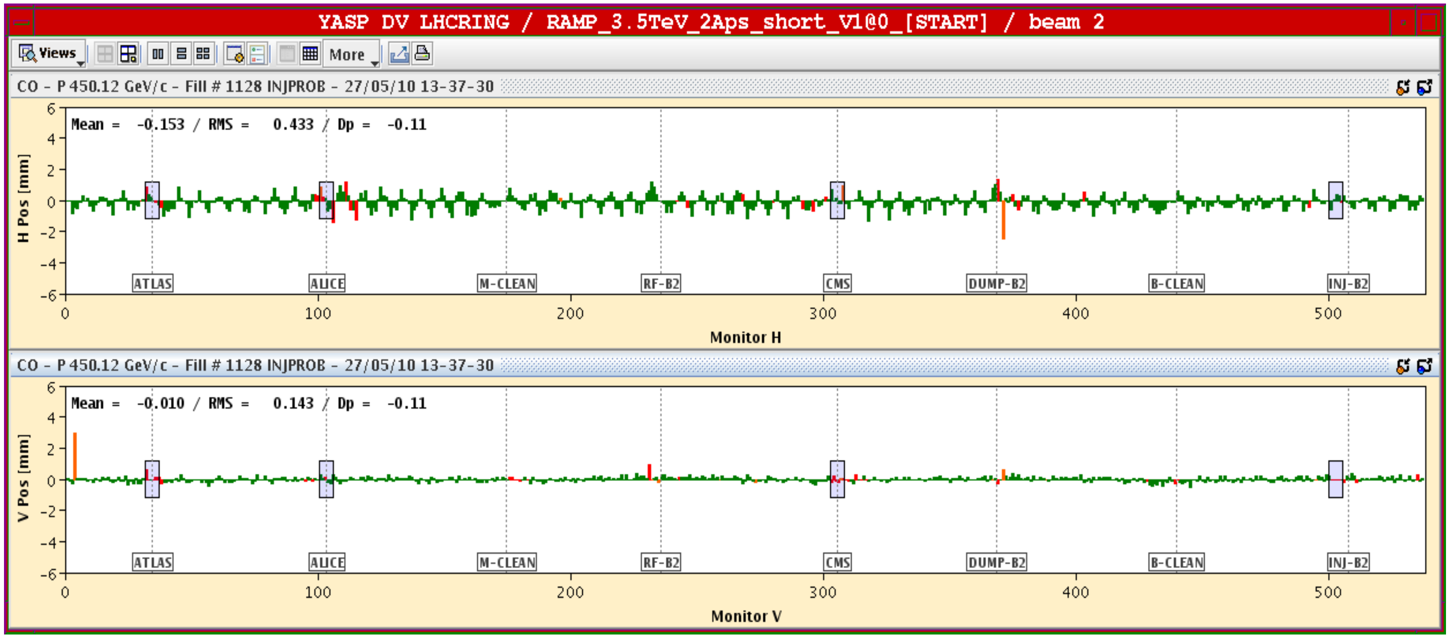
(Linear) Machine imperfections

- **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:

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

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**
- **<u>Linear</u> accelerators: radiated power small compared to delivered power**
- **<u>Circular</u> 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 transfered 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:

  $Z_T \approx (2R/b^2) \cdot (Z/n)$ **(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	$\|Z/n\|$ Ω
PS	$\approx$ 1960	$>$ 50
SPS	$\approx$ 1970	$\approx$ 20
LEP	$\approx$ 1989	$\approx$ 0.25
LHC	$\approx$ 2008	$\approx$ 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

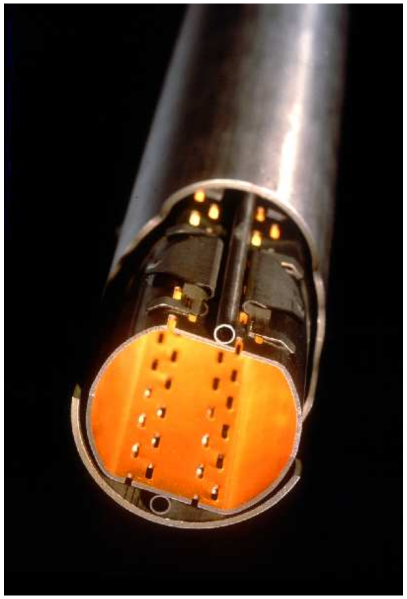
Hardware systems: magnets

- **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: $\leq$ 13000 A)**
- **Not off the shelf, clear specification required**
- **High precision: (e.g. Q tolerance → 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