Putting it all together

Werner Herr, CERN

http://cern.ch/Werner.Herr/CAS2010/lectures/Varna_review.pdf

Review of the course ...

- **What did we learn ?**
- **What can we do with that ?**
- **What else do we need to 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**

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 (2007*)):

High-energy physics research	120
Synchrotron light sources	50
Ion beam analysis	200
Photon or electron therapy	9100
Hadron therapy	30
Radioisotope production	550
Ion implantation	9500
Neutrons for industry or security	1000
Radiation processing	2000
Electron cutting and welding	4500
Non-destructive testing	650
Total:	27700

*) R. Hamm at 9th ICFA Seminar, October 2008

The choice of the particle and energy

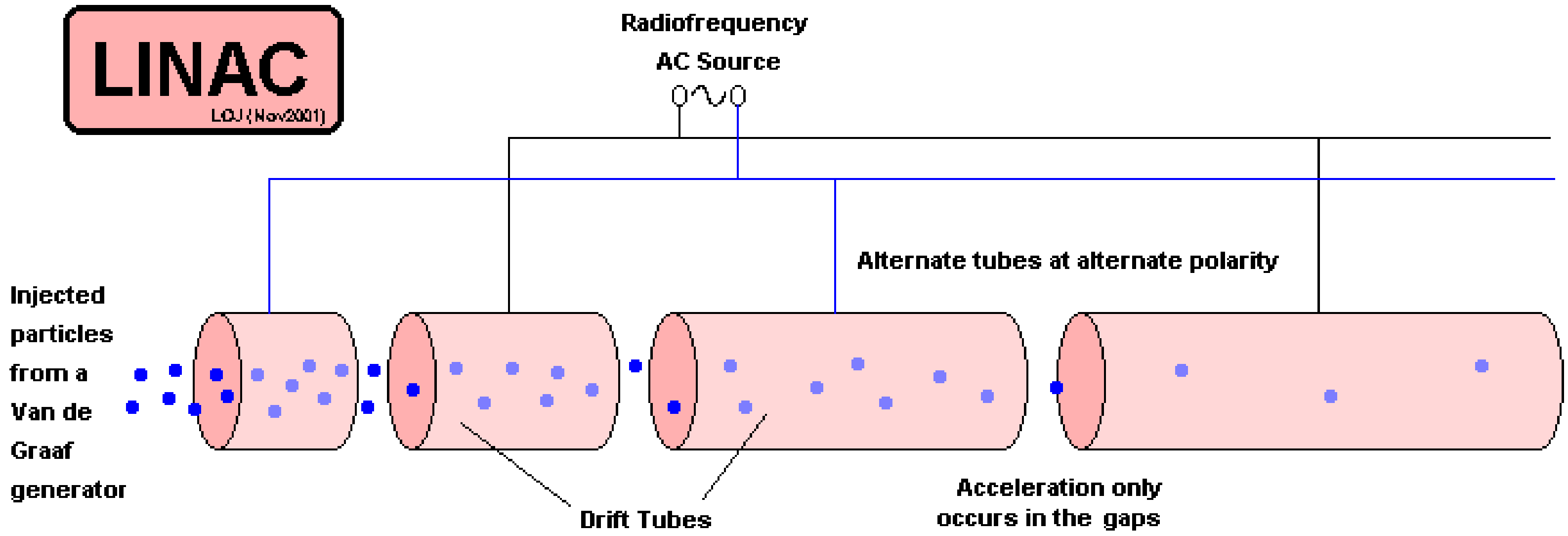
- **Depends on the purpose and availability:**
  - **Synchrotron light sources:** e^-, e^+
  - **Industrial applications:** $p, ions, ..$
  - **Medical applications:** $p, e^-, ions, ..$
  - **HEP experiments:** $p, \bar{p}, e^-, e^+, ions, \nu, \mu^\pm, ..$
- **Sources are important: some particles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

The choice of the particle and energy

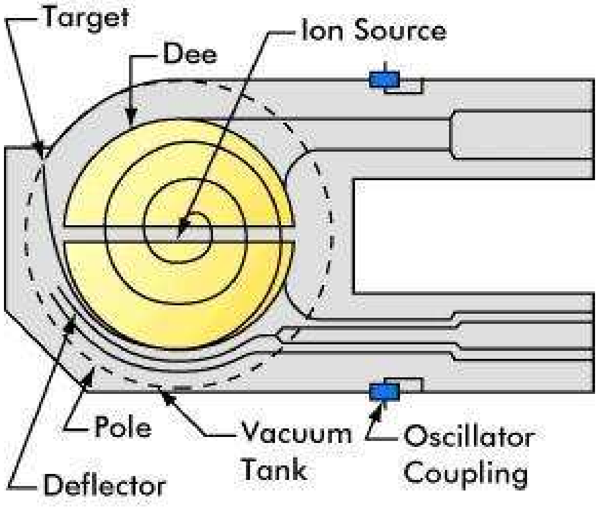
- **Depends on the purpose and availability:**
  - **Synchrotron light sources:** e^-, e^+
  - **Industrial applications:** $p, ions, ..$
  - **Medical applications:** $p, e^-, ions, ..$
  - **HEP experiments:** $p, \bar{p}, e^-, e^+, ions, \nu, \mu^\pm, ..$
- **Sources are important: some particles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

Different types - linear accelerators

- Single pass
- High energy
- High intensity
- Big size

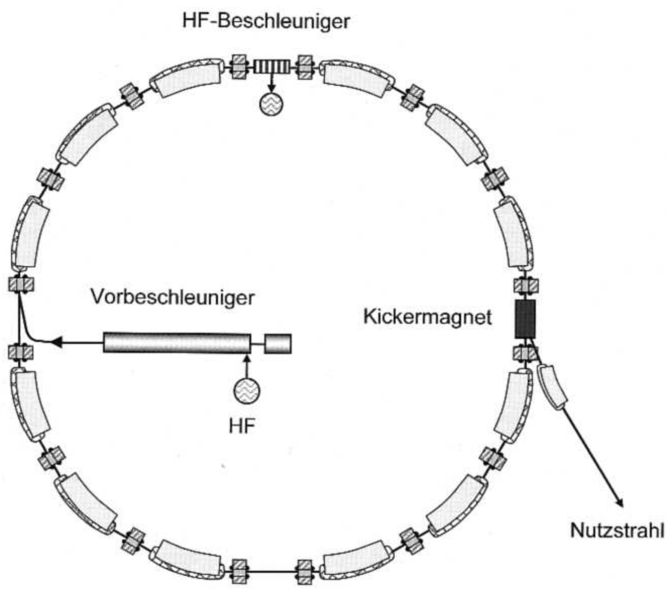


Different types - cyclotrons



- 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:

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

Synchrotron radiation losses:

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

- **Numerical examples:**

The choice of the type of particles

LEP (100 GeV):	B = 0.12 T	U = 3 GeV
LHC (7000 GeV):	B = 8.3 T	U = 0.00001 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
- 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 !!**

Interlude:

- **For collider, additional <u>advantages</u>:**
  - **Particles are "re-used" until they interact**

Interlude:

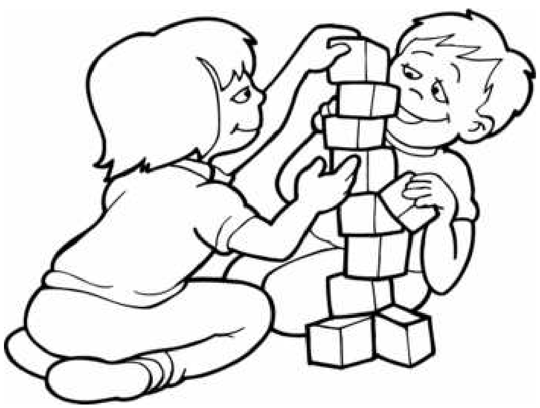
- For collider, additional advantages:
  - Particles are "re-used" until they interact
- For collider, additional difficulties:
  - Special lattices
  - Insertions
  - Additional collective effects
  - → Intermediate course on accelerator physics (next year)

Accelerated particles

- Accelerated particles are fast !
  - They may or may not be relativistic (depends also on particle type !)
  - Must take relativistic properties into account
  - E.g. lifetime, transition, relativistic mass, ...
- Personal recommendation: always do the calculation, in particular for lower energy machines

The required systems

Often deserve dedicated (special) schools:

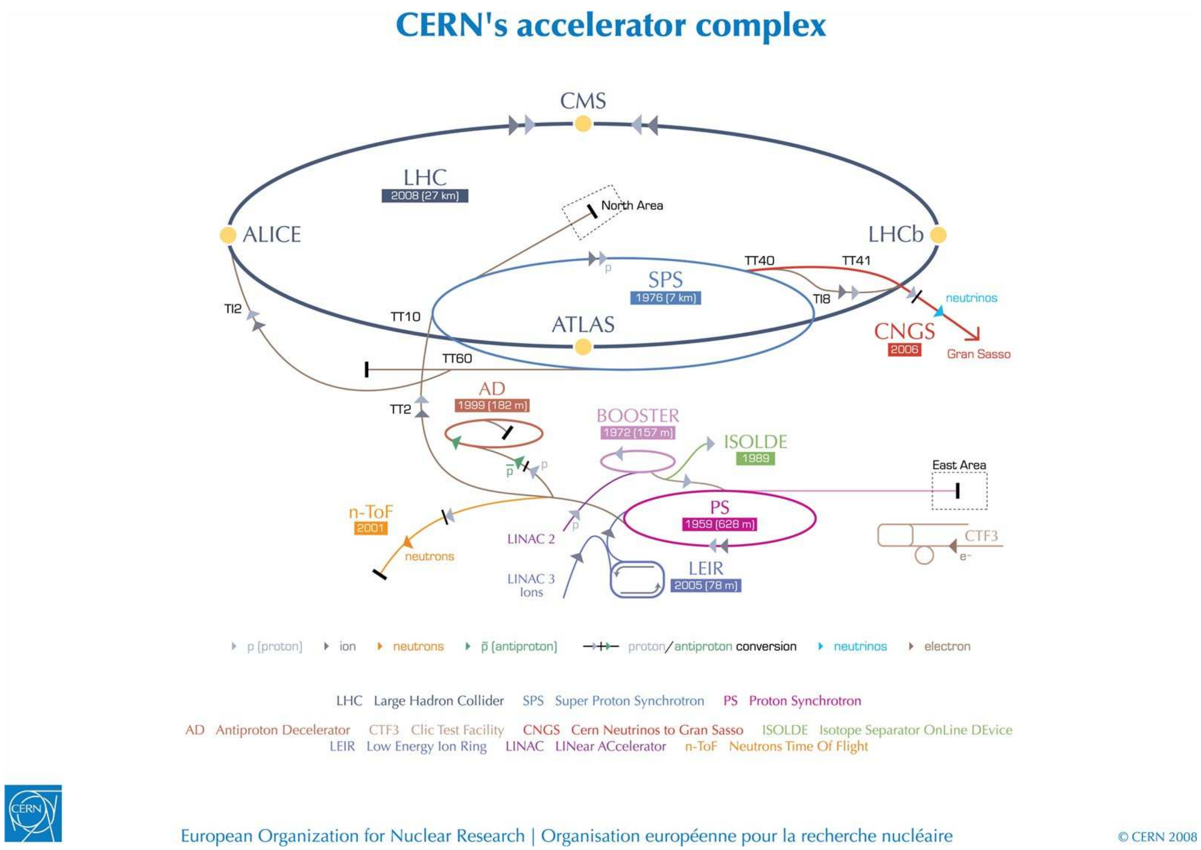


- **Magnets: guide the beams**
- **RF system: accelerate the beams**
- **Diagnostics: measure the beams**
- **Vacuum, power, cryogenics, metrology**
- **Control system**
- **Sources, beam transfer, injection, extraction !**

The required systems

- All systems must work reliably
- Failure of one system can ruin the project
- Communication all important
- Cannot do beam dynamics in isolation

CERN accelerator complex (2010)



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**
- **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**

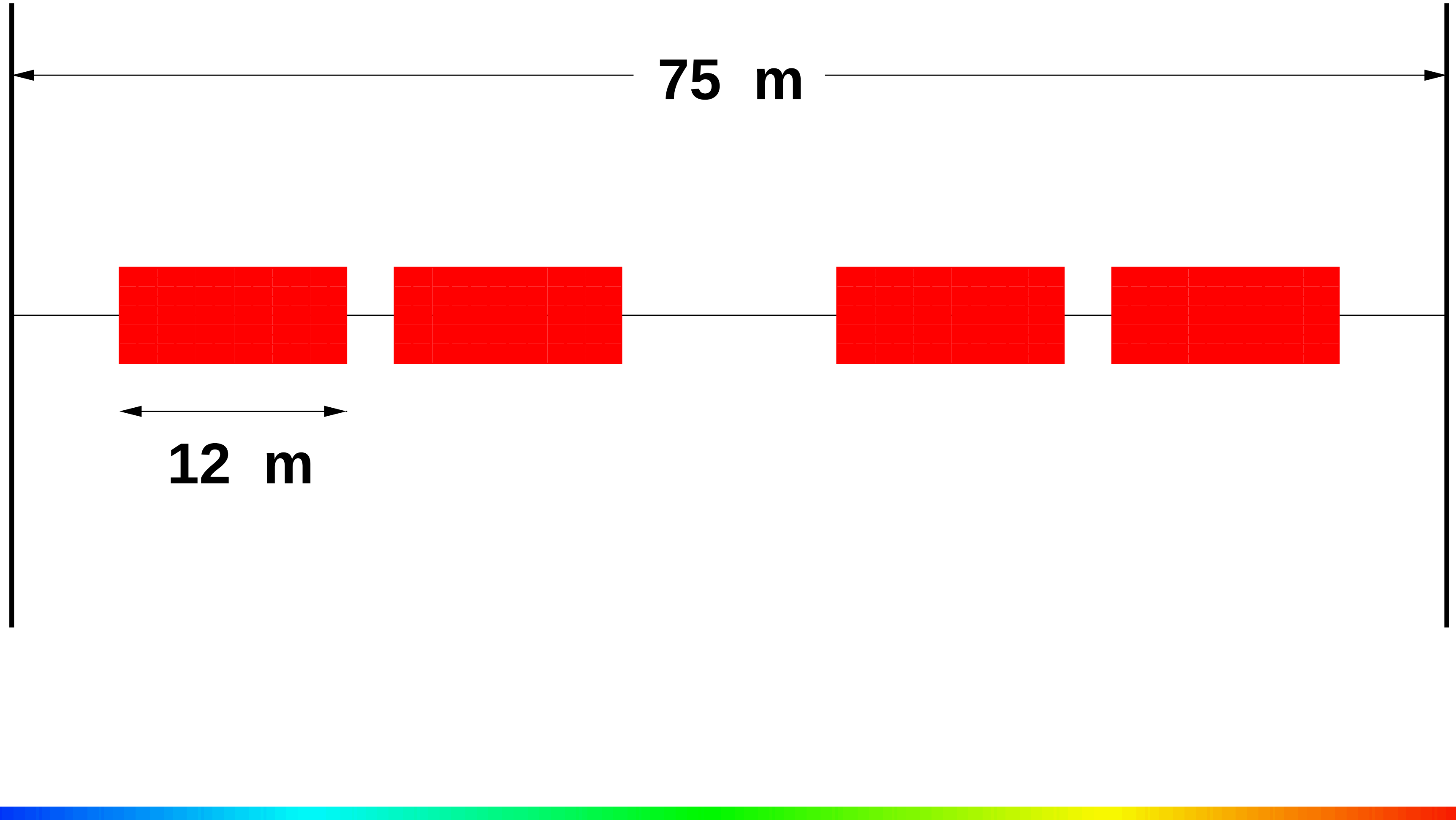
$$B \cdot L = 0.01309 \; rad \;\; \cdot \;\; 3.3356 \;\; \cdot \;\; 500 \; GeV$$

- **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**

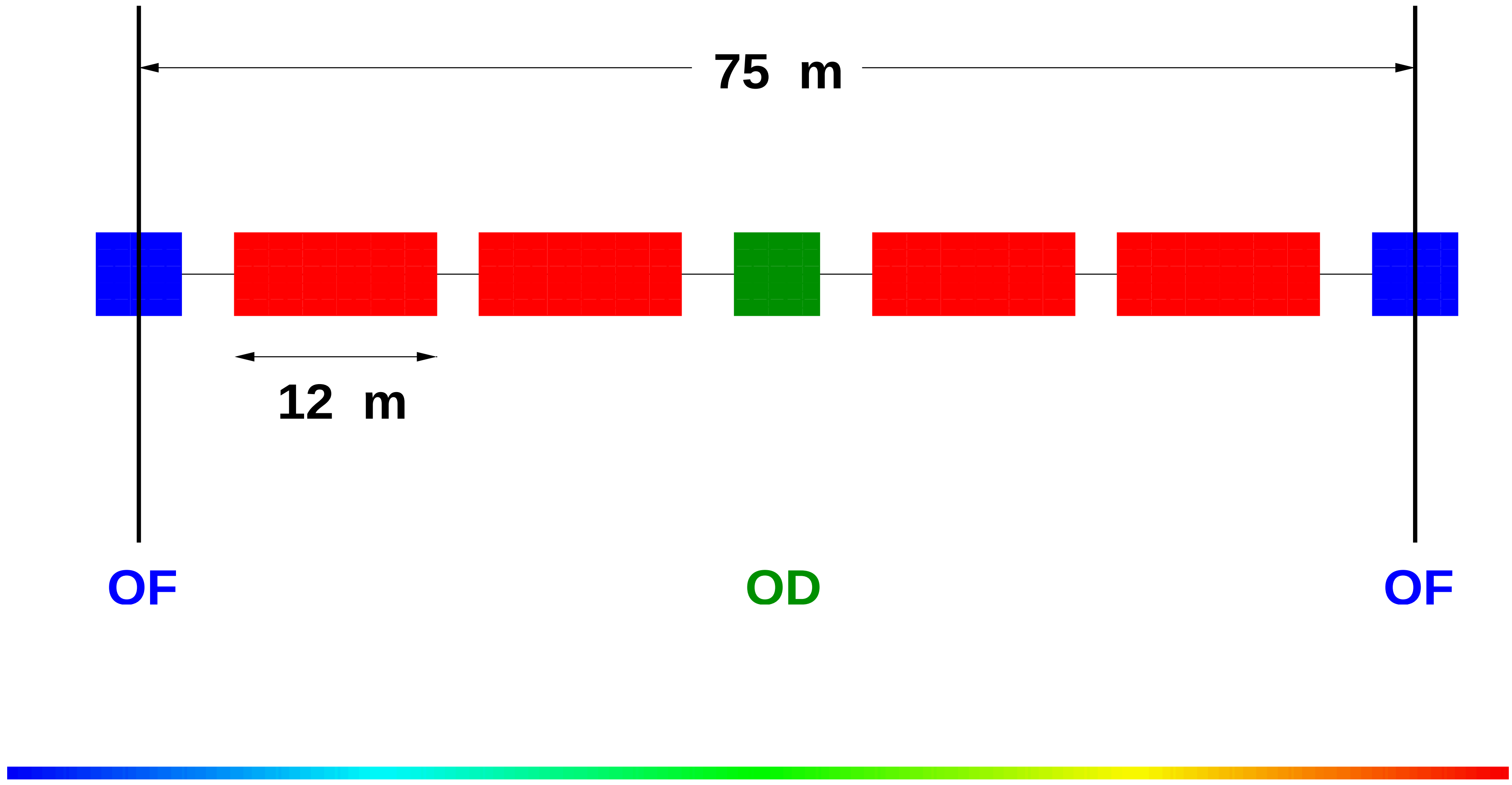
First part of the cell



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)**

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**

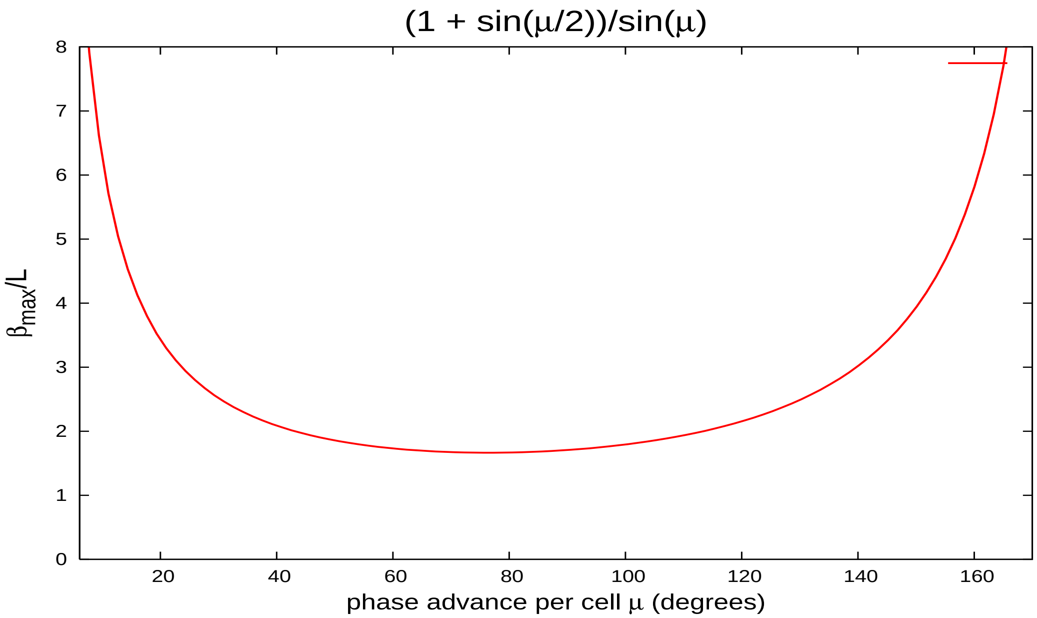
Basic relations for the cell

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

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

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

Cell parameters



Maximum $\hat{\beta}$/L as function of phase advance - should be small enough for aperture

Cell parameters

- **Criteria for cell parameters:**
  - **Phase advance per cell (μ): usually between 60 and 90 degrees, important for closed orbit and chromaticity correction, insertion design**
  - **Maximum β-function ($\hat{\beta}$): important for aperture**
    $A(s) = \sqrt{\epsilon \cdot \beta(s)}$

Basic relations for the machine

Basic relationships for global parameters are available:

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

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

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

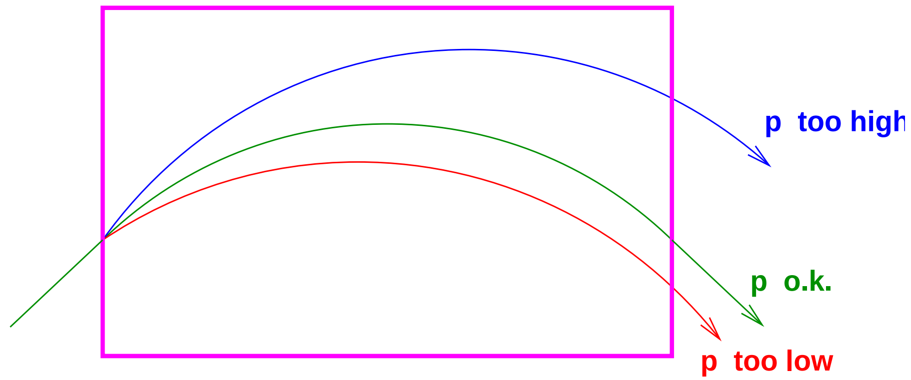
$< D > \;\approx\; \alpha \cdot R/Q \quad [\approx 1.6m]$

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

Detailed lattice design

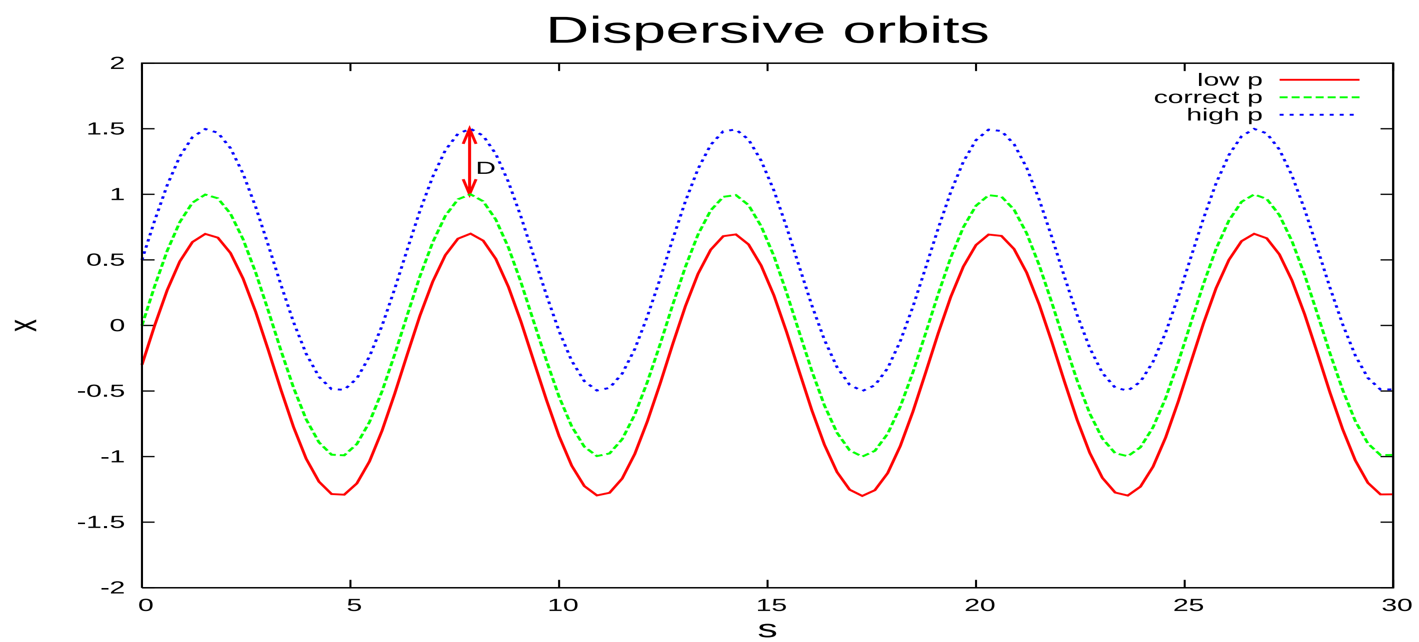
- **From now on a lattice design program is required (for details: next CAS)**
  - **Detailed design and optimization of the optics**
  - **Design of correction systems (orbit, chromaticity, ..)**
  - **Effect of off-momentum beams (dispersion and chromaticity)**

Dispersion created in dipole magnet



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

Dispersion



- **Higher and lower momentum particles on different orbits along the ring**
- **Described by the lattice function dispersion D**

Problems with dispersion

- **With momentum error: more aperture required**
- **With momentum 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**

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**
- **...**

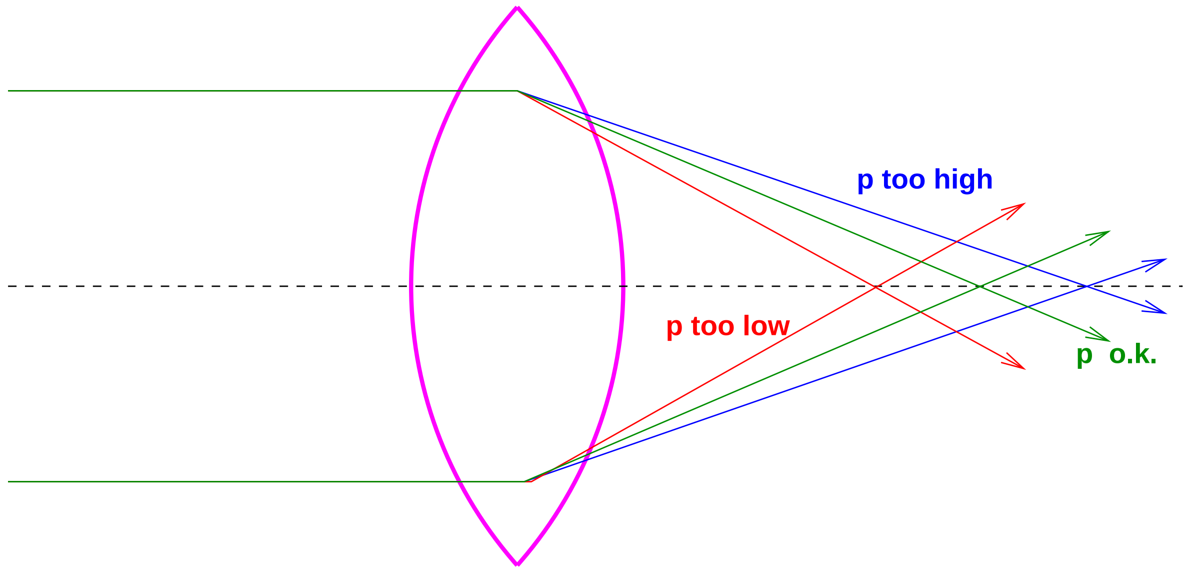
Requires good compromise between the different requirements

Problems with dispersion

- **Offset in other machine elements (quadrupoles, sextupoles, monitors ...)**
- **Can introduce coupling between longitudinal and vertical plane**
- **Dispersion can strongly change damping properties (lepton machines, synchrotron light sources)**

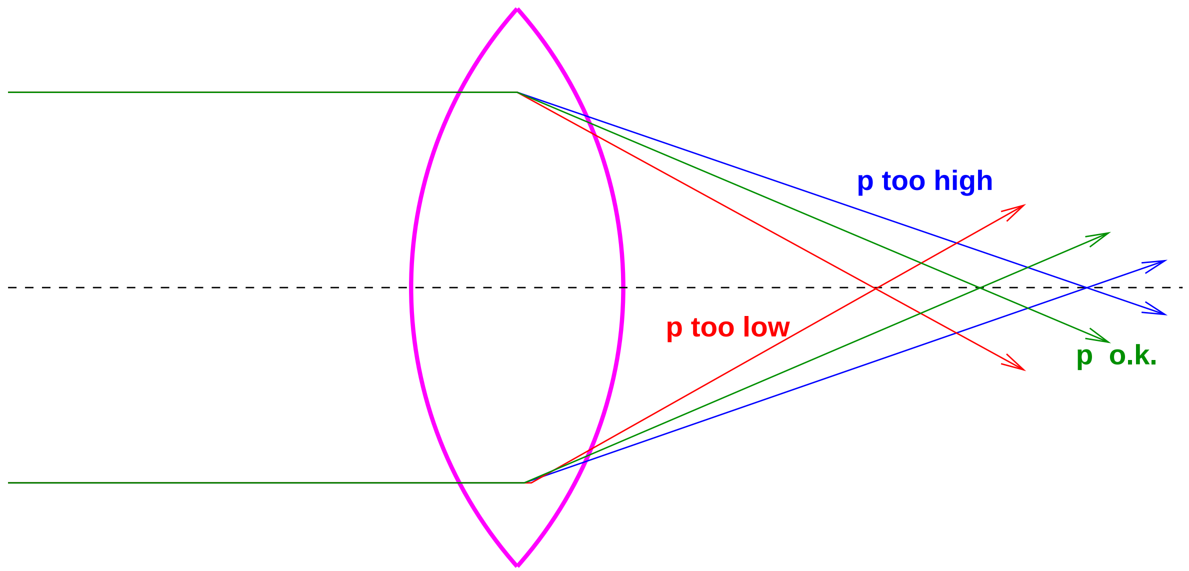
The good news: it can be controlled (see next CAS) !

Chromaticity



- **Focusing** $1/f$ **of a quadrupole depends on momentum**
- **Different focusing leads to different tune**
  $(1/f \;\propto\; sin(\mu/2))$

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

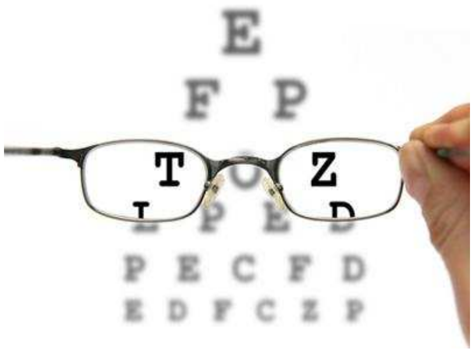
- **Tune spread due to momentum spread (resonances): should be as small as possible**
- **Collective instabilities: should be (slightly) positive**

Q' needs to be controlled !

Problems with chromaticity

- **Tune spread due to momentum spread (resonances): should be as small as possible**
- **Collective instabilities: should be (slightly) positive**

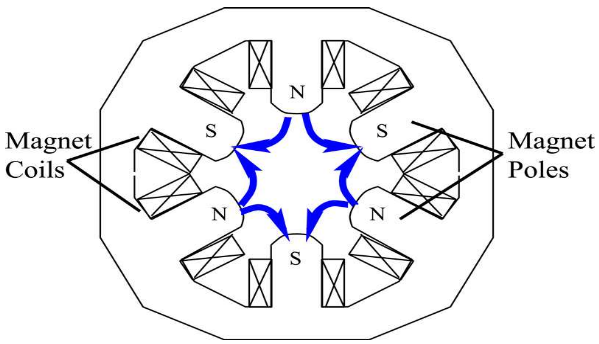
Q' needs to be controlled !



- **Beam not well focused**
- **Need some correction**
- **Our glasses are sextupoles ..**

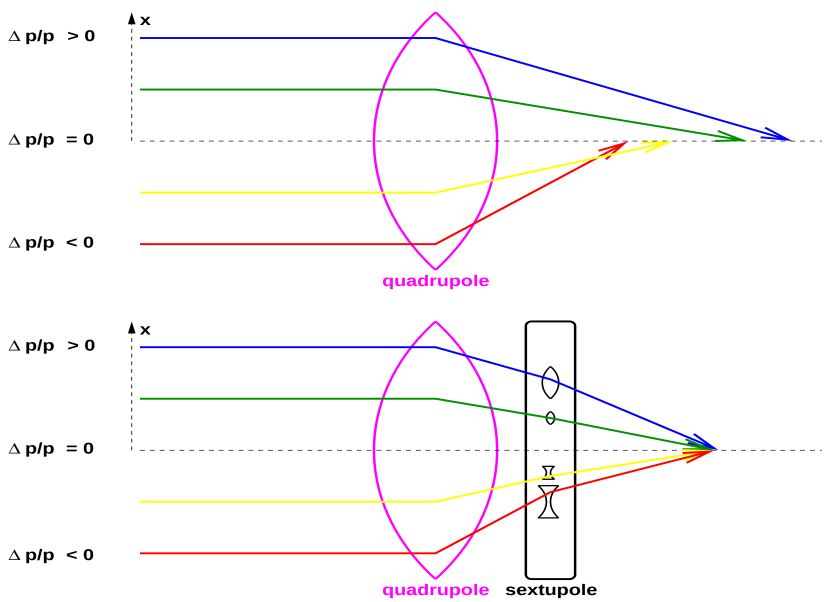
Correction of chromaticity

- 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

Correction of chromaticity - schematic



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

- **Can be computed by hand, better: use a computer program like MAD (next CAS)**

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**

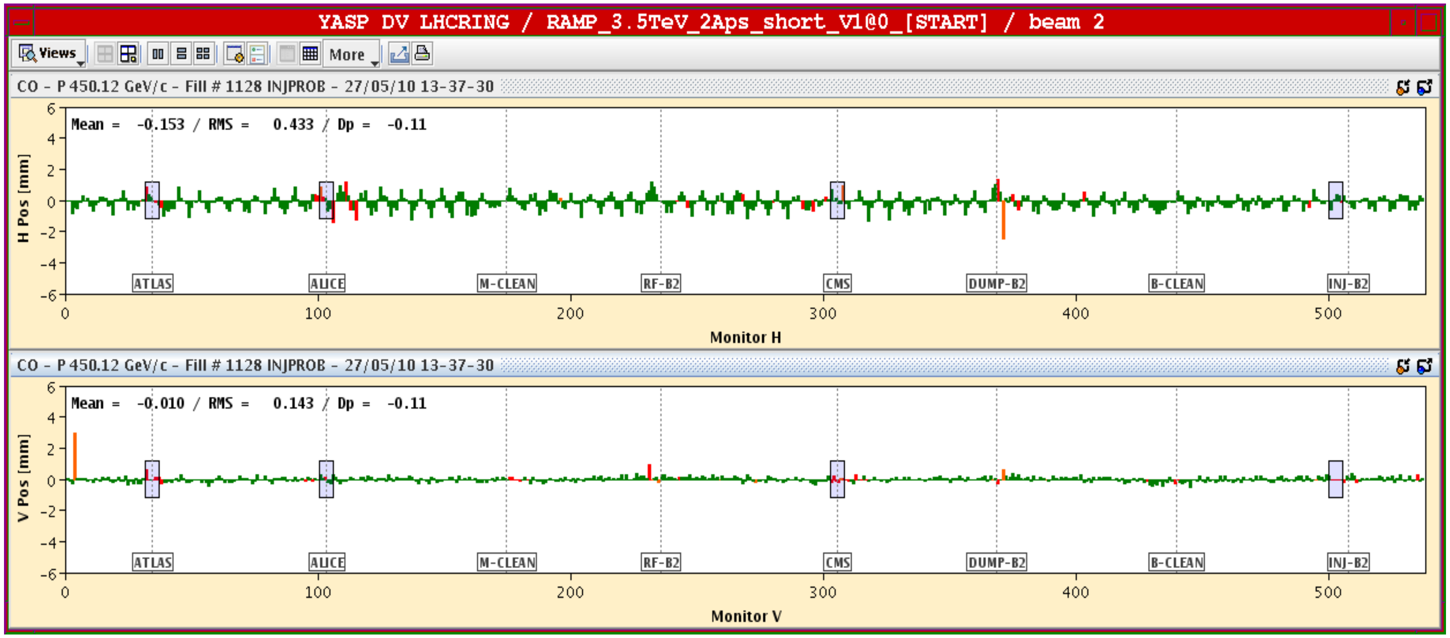
Orbit and trajectory correction

- 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 to large and causes aperture problems
- Important system for operating the machine

Orbit and trajectory correction

- **What is needed:**
  - **Introduce measurement devices (beam position monitors)**
  - **Introduce correction devices (correction dipoles)**
  - **Introduce correction algorithms to test performance**
- **Details and demonstration in next CAS**

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 losss 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**
- **Select harmonic number h (and therefore number of possible bunches) according to requirements**
- **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 !)**
- **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) next CAS**

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**

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 estimated using the measured or calculated impedance

Collective effects

- **From design parameters: desired intensity usually known**
- **We can derive:**
  - **Particle density (emittance, bunch length, ...)**
  - **Maximum longitudinal and transverse impedance**
- **Compute a parameter set allowing the required intensity and performance**

Collective effects - impedance

- **The key: take them into account at design of your machine already**
- **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	≈ 1960	> 50
SPS	≈ 1970	≈ 20
LEP	≈ 1989	≈ 0.25
LHC	≈ 2008	≈ 0.10

  - **Reliable codes available**
  - **Measurements !**
  - **Strong reduction**

- **Often contradicting requirements**
- **Finance, components**

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**
- **Effect of imperfections (β-beating, ...)**
- **Control of injection, ...**
- **...**

Is an art by itself, you never have enough beam diagnostics → intermediate school, special school

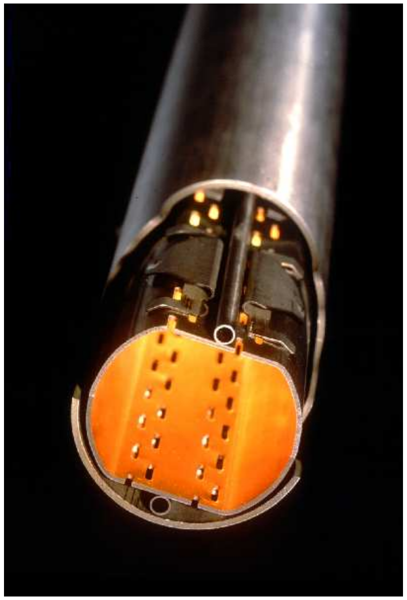
Hardware systems: magnets

- **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: $\leq$ A - 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

- Relativity and e.m. theory
- Introduction to accelerators
- Longitudinal and transverse dynamics
- Imperfections and resonances
- Transferlines and injection/extraction
- Multi-particle effects
- Synchrotron radiation
- Beam diagnostics
- Magnets and power systems
- Additional systems: vacuum, ...

What is next ?

- **Intermediate Level CAS Course**

  is a follow up of this school

- **The ”core topics” reviewed**
- **”Hands on” afternoon courses for specific topics, the courses in previous schools:**
  1. **Optics design**
  2. **RF**
  3. **Beam diagnostics**
- **New lectures on detailed topics**

New issues at the next school

- **Optics design: lattices and insertions**
- **Light sources (lattices, insertions, FELs ..)**
- **Instabilities, space charge effects**
- **Landau damping**
- **Beam-beam effects**
- **RF cavities and LINAC structures**
- **Magnet design**
- **...**

CAS in 2011

- **JOINT US-CERN-ASIA-RUSSIA School**
  Synchrotron Radiation and FEL
  6.4. - 15.4. 2011, Erice, Italy

- **Specialized course:**
  High Power Hadron Machines
  24.5. - 2.6. 2011, Bilbao, Spain

- **General course:**
  Intermediate Level Course
  Autumn 2011, Greece