Putting it all together

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(http://cern.ch/Werner.Herr/CAS2016_LECTURES/Budapest_review.pdf)

Review of the course ...

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

Reading and Studying Material - personal selection

[1] **This Course and all references therein**

[2] **Proceedings of other CAS courses,**

Some textbooks:

[3] **A. Wolski,** *Beam Dynamics in High Energy Particle Accelerators*, **Imperial College Press, London, 2014.**

[4] **A. Chao,** *Lecture Notes on topics in Accelerator Physics*, **SLAC, 2001.**

[5] **H. Wiedemann,** *Particle Accelerator Physics*, **Vol 1+2, Springer, Heidelberg, 1993.**

Review of the course ...

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

First (hopefully positive) experience was the tutorial ...

Lectures 2016:

Preliminaries	5 hours
Beam dynamics	18
Accelerator systems and technology	12
Applications and accelerator types	7
Seminars	2
Total:	44

Preliminaries:

- **Introduction to accelerators and overview**
- **Electromagnetism and Relativity**
- **Motion in electromagnetic fields**

Intended to provide a common basis

Introduction:

- **Different types of accelerators**

  Choice usually depends on:

  - **Application and cost**
  - **Types of particles and energy**

- **Basic Concepts and keywords**

Electromagnetism and Relativity

- Review Maxwell's equations
- Application to accelerators, cavities, wave guides, ...
- Basic principles of relativity and invariants
- Consequences: time dilation, Lorentz contraction, ...
- Introduction of 4-vectors
- Transformation of fields of moving charges, Lorentz force, kinematics
- Basic concepts for multi particle systems

Motion in electromagnetic fields:

Objective was to get a generic formulation of the motion of charged particles through any electromagnetic field.

- **Provides the standard tool to construct sequences of elements, e.g. in beam lines, linacs, rings, ...**
- **Should be independent of the type of machine and application (electromagnetic elements have a life on their own)**

Can we find a most general, but easy to use formalism ?

The immaculate Hamiltonian:

- **Describes exactly the magnetic fields**
- **Provides directly the equations of motion (not just forces etc.) → makes your life a lot easier**
- **Identical formalism for linear and non-linear maps**
- **Not treated here: is the foundation for the analysis of non-linear effects, advanced course next year**

  (Unthinkable without this formalism)
- **Bonus: Hill's equation comes for free, not by wild guessing**

Do not let you get scared by older colleagues !

Relativistic Hamiltonian of a particle in an electro-magnetic field:

$$H(\vec{x},\vec{p},t) = c\sqrt{(\vec{p} - e\vec{A}(\vec{x},t))^2 + m_0^2c^2} + e\Phi(\vec{x},t)$$

where $\vec{A}(\vec{x},t)$**,** $\Phi(\vec{x},t)$ **the vector and scalar scalar potential**

Using canonical variables (2D) and the design path length s **as independent variable (bending in x-plane) and no electric fields:**

$$H = -(1+\frac{x}{\rho}) \cdot \sqrt{(1+\delta)^2 - p_x^2 - p_y^2} + \frac{x}{\rho} + \frac{x^2}{2\rho^2} - \frac{A_s(x,y)}{B_0\rho}$$

where $\delta = (p_{old} - p_0)/p_0$ **is relative momentum deviation and** $A_s(x,y)$ **longitudinal component of the vector potential.**

We obtain 2 first order equations of motion:

$$\frac{\partial H}{\partial q_j} = -\dot{p_j} = -\frac{dp_j}{dt}, \qquad \frac{\partial H}{\partial p_j} = \dot{q_j} = \frac{dq_j}{dt}$$

Hamiltonian (for large machine) ..

$$\mathcal{H} = \overbrace{\frac{p_x^2 + p_y^2}{2(1+\delta)}}^{kinematic} - \overbrace{\underbrace{\frac{x\delta}{\rho}}_{dispersive} + \underbrace{\frac{x^2}{2\rho^2}}_{focusing}}^{dipole} + \overbrace{\frac{k_1}{2}(x^2 - y^2)}^{quadrupole} + \overbrace{\frac{k_2}{6}(x^3 - 3xy^2)}^{sextupole}$$

$$\left(\text{using (MAD convention)}: \quad k_n = \frac{1}{B\rho}\frac{\partial^n B_y}{\partial x^n} \right)$$

- **The Hamiltonian describes exactly the motion of a particle through a magnet**
- **Basis to extend the linear to a non-linear formalism**
- **Can be used as a whole or separate terms**

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

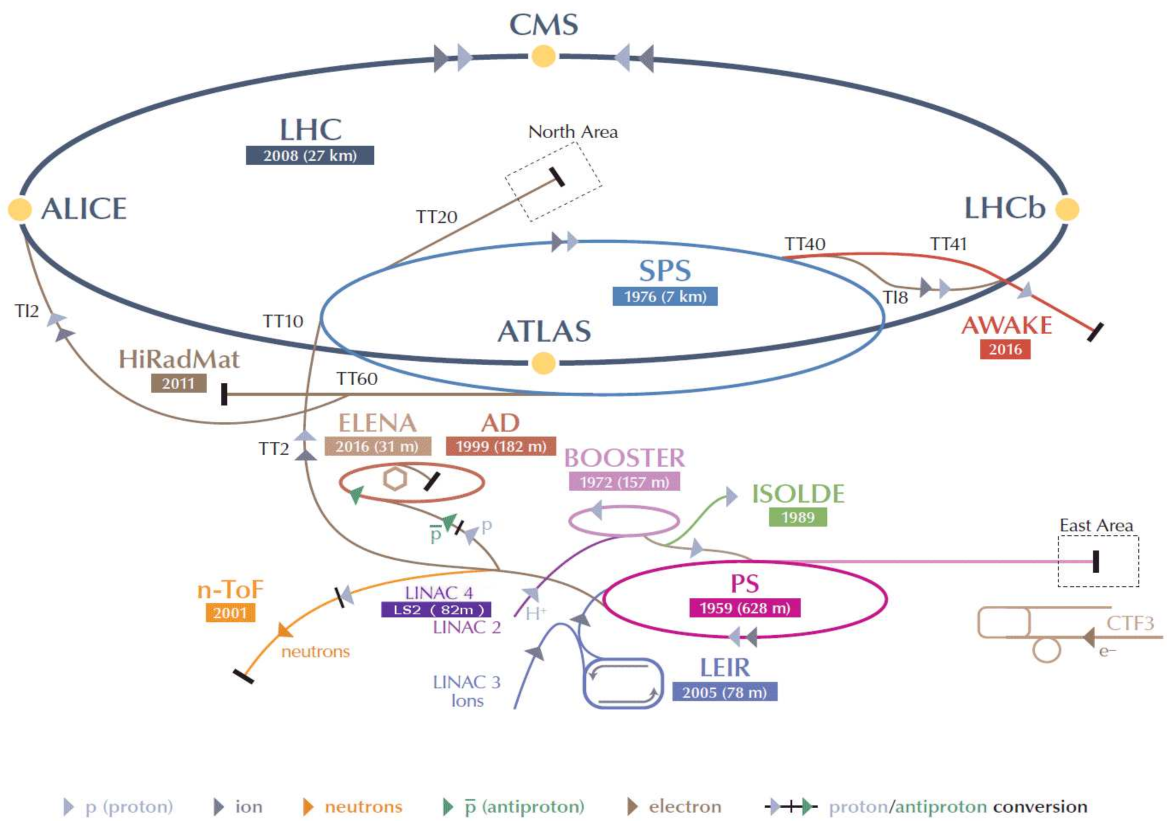
The purpose of the machine

- 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

CERN accelerator complex (2016)



(active machines only !)

Why so many accelerators ?

- **Accelerators have a limited range, several stages needed. "Injector Complex"**
- **We cannot accelerate a particle from zero to large momentum in a single machine**
- **Injector complex uses sources, linacs and synchrotrons**

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, ..)**

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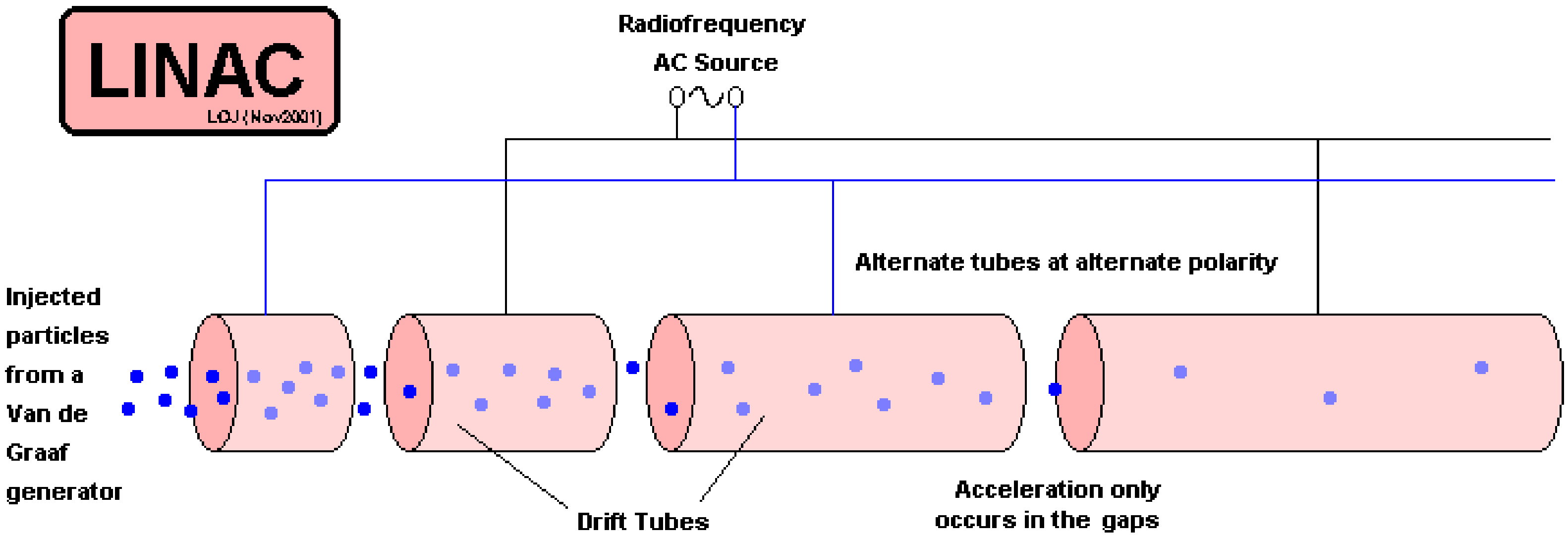
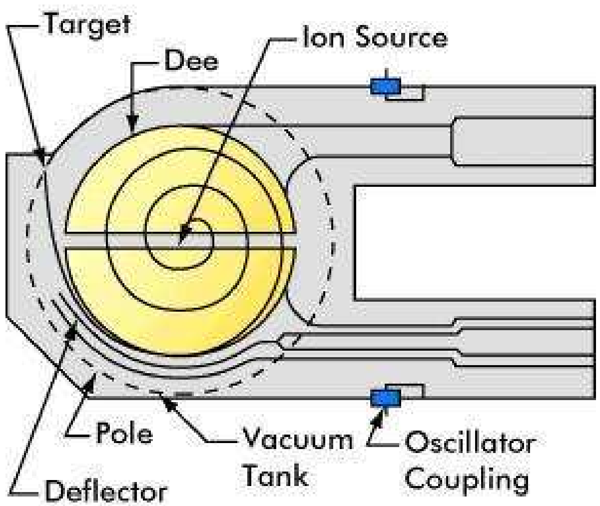
  - **HEP experiments:** $p, \bar{p}, e^-, e^+, ions, \nu, \mu^\pm, ..$
- **Sources are important: some particles are hard to get ($\bar{p}, \nu, \mu^\pm$, ions, ..)**
- **Resources are important too: usually determine the type (and size) of your machine**

Different types - linear accelerators

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

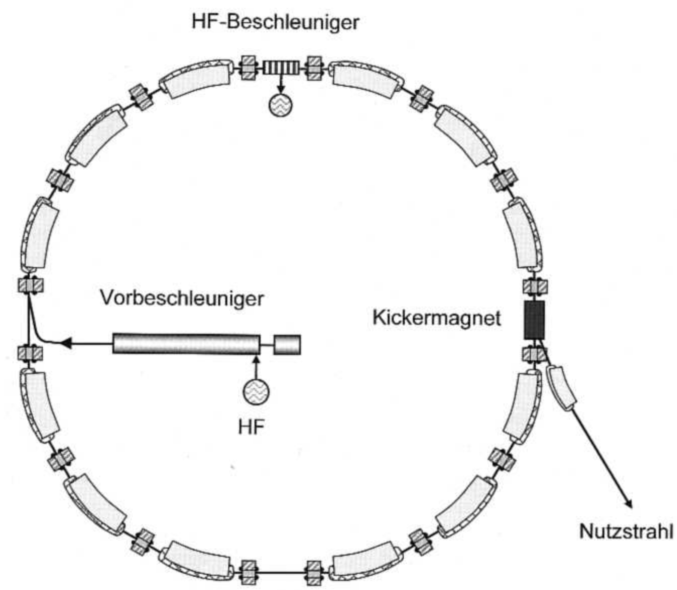


Different types - cyclotrons



- 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:

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

- **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 applications
- For example: 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 ? (remember relativity)

- **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** → $E_{cm} = \sqrt{2m^2 + 2E_1 m}$

  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 !!**

(Circular) Colliders:

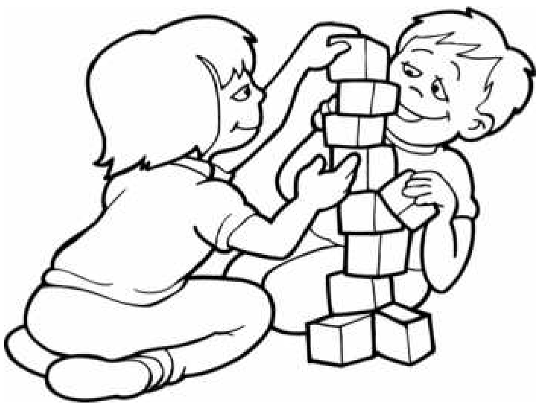
- For collider, additional advantages:
  - Particles are "re-used" until they interact
- For collider, additional difficulties:
  - Special lattices, insertions
  - Maximize (optimize) luminosity
  - Additional collective effects, e.g. beam-beam
  - → Advanced course on accelerator physics (next year)

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, contraction, time dilation ...
- Personal recommendation: always do the calculation, in particular for lower energy machines

The required systems

Often deserve dedicated (special) schools:



- **Magnets: (2009)**
- **Superconductivity: (2013)**
- **RF Systems: (1991, 1993, 2000, 2010, 2017)**
- **Diagnostics: (2008, 2018)**
- **Vacuum, cryogenics, metrology: (1992, 1997, 1999, 2002, 2006, 2017)**
- **Power Converters, Control system: (1990, 2004, 2007, 2014)**
- **Ion Sources: (2012)**
- **Collective effects: (1983, 2015)**

The required systems

- **Beam dynamics is the basics to define (and understand) the requirements for all systems**
- **All systems must work reliably**
- **Failure of one system can ruin the project**
- **Communication all important**

Stages of a machine design

1. **Define purpose of the machine and basic parameters**
2. **Magnet configuration (lattice)**
3. **Diagnostics system**
4. **Beam dynamics (single and multi particle effects, radiation,**
5. **Acceleration (RF) system**
6. **Auxiliaries and systems: injection, extraction, vacuum, power converters,....**

Consider a synchrotron (Why ??)

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)

Consider the design of a synchrotron

Go through and 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**

Look first at the linear transverse dynamics:

The choice of the (linear) 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 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 2π/480 = 0.01309 rad**

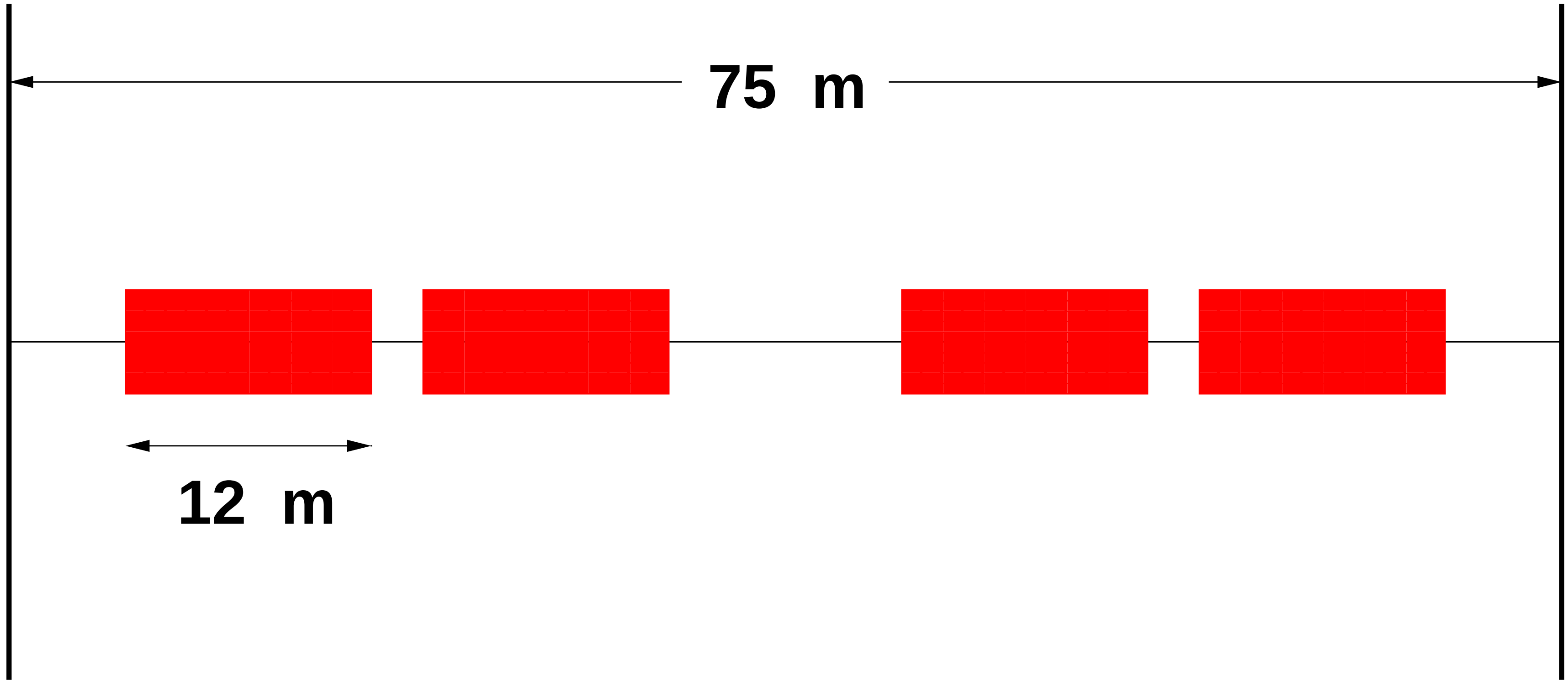
$$B \cdot L = 0.01309 \ rad \ \cdot \ 3.3356 \ \cdot \ 500 \ GeV$$

- **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



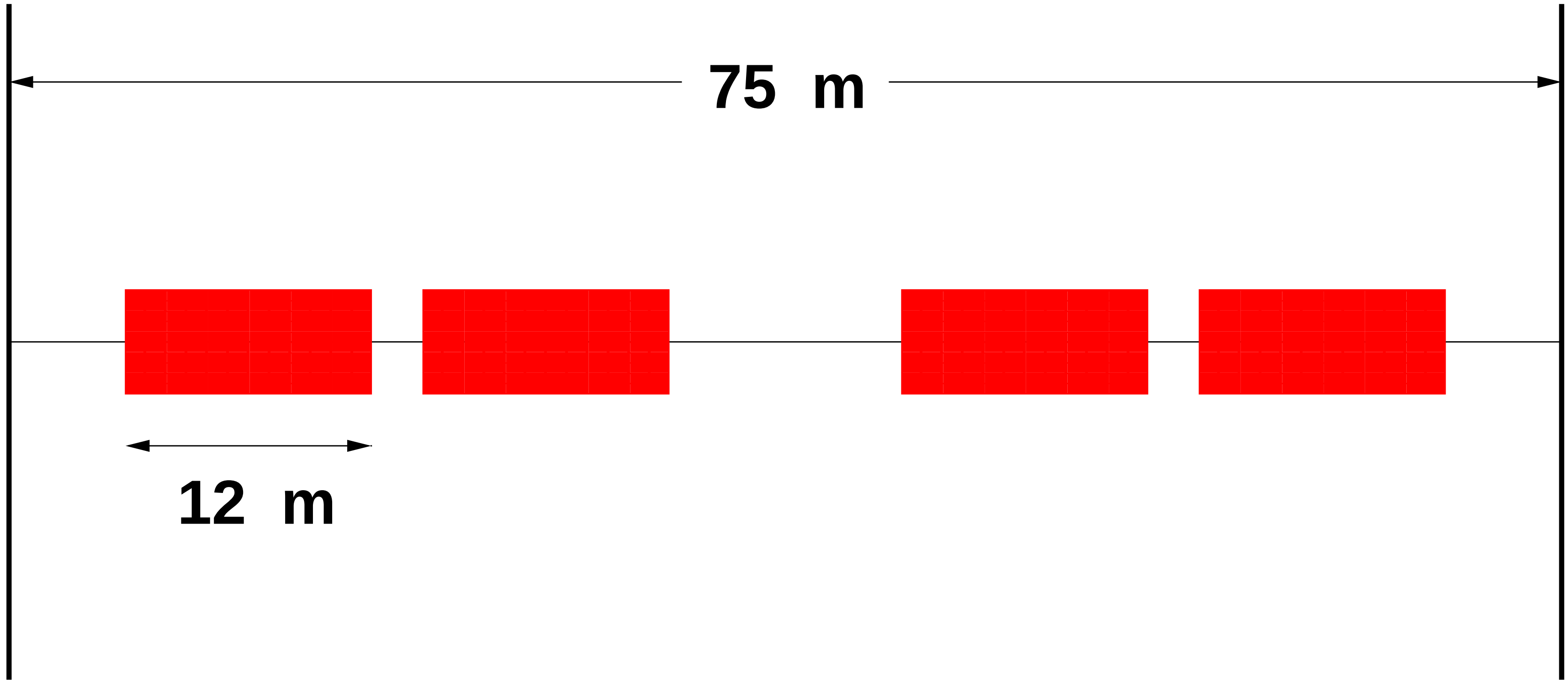
Complete the cell (see "Transverse Dynamics")

- 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)

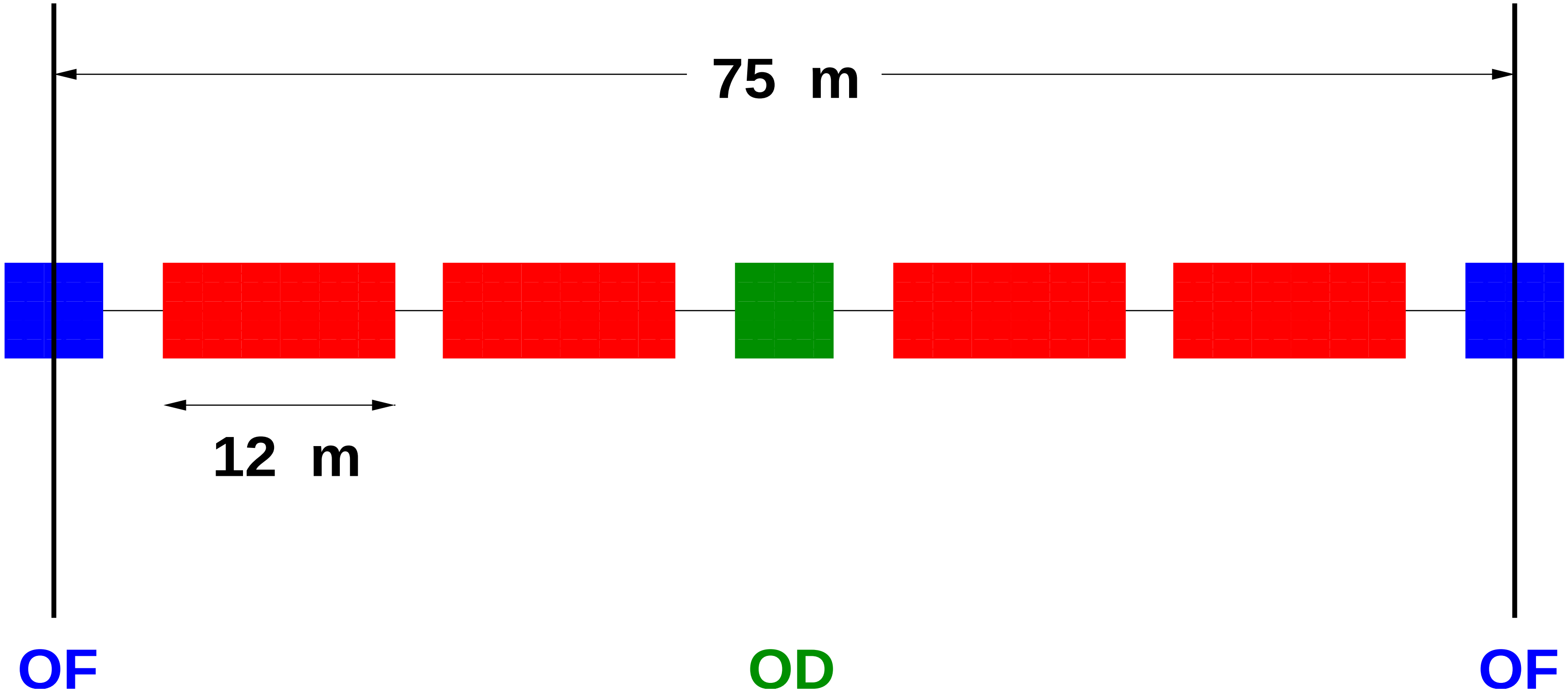
⚠ Careful: all these concept were developed for (proton) synchrotrons only.

- For leptons, other machines, beam lines: press reset

First part of the 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

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

Basic relations for the cell

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

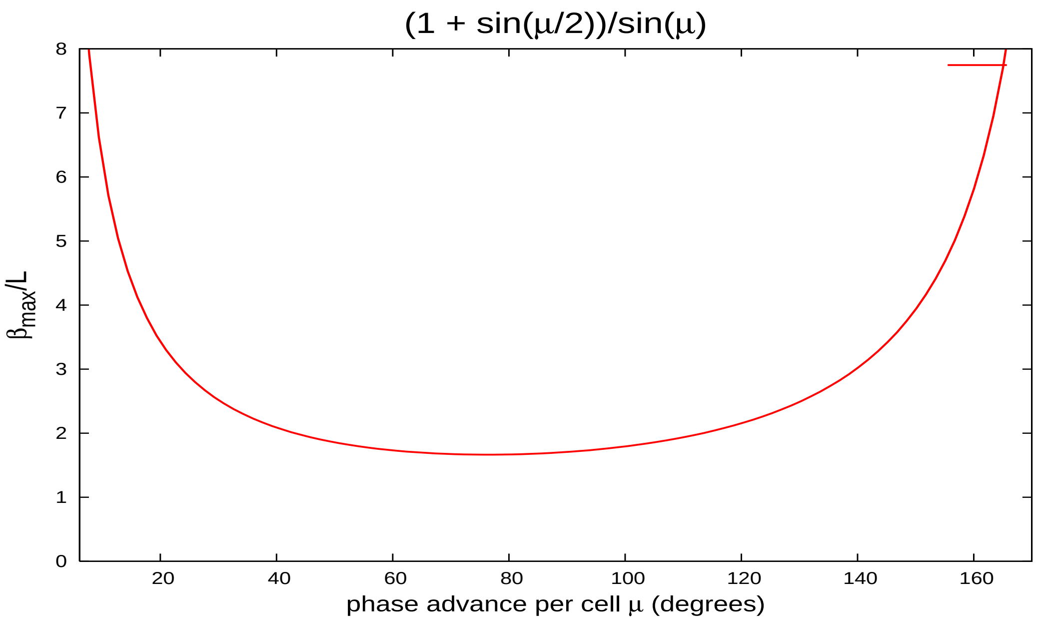
$$\hat{\beta} = \frac{L_{cell}(1+sin(\mu/2))}{sin(\mu)}$$

- **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** $\hat{\beta}$

→ **You can never get a** $\hat{\beta}$ **smaller than the cell length**

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**

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

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

How to get a (stable) circular machine ?

1. **Write down maps (matrices in the simplified, linear case) for every element (should be in 2 or 3 D)**
2. **Multiply all maps together to get the one-turn-map (one-turn-matrix)** M
3. **Analyse the one-turn-matrix:**
   - **Tunes are the "eigenvalues" of the matrix**
   - **If all eigenvalues are real: machine is stable (in the simple 1D case, this boils down to the highly simplified** $Tr(M) < 2$ **formulation)**
   - **Eigenvectors give** α, β, γ
   - **Allows study of coupling and other effects**

Interlude: the emittance saga

- Definition of emittances seems confusing ...
- Different for synchrotrons, linacs and sources ?
- Popular to mix:
  - Phase space invariants ↔ phase space volume ↔ beam emittances !
  - Hadrons vs leptons (concepts are very different) ?
  - Linear or non-linear dynamics ? (some definitions may become total nonsense)
  - For definition: (x, x') or (x, p_x) ?

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

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

Interlude: the emittance saga

- **How do these compare ?**

1.0 μm

1.0 mm mrad

1.0 π mm mrad

3.14 mm mrad

Basic relations for the machine

Basic relationships for global parameters are available:

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

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

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

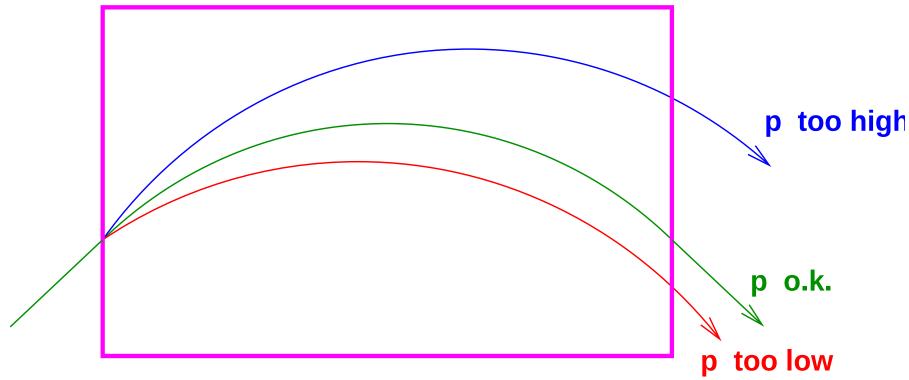
$< D > \quad \approx \quad \alpha \cdot R/Q \quad [\approx 1.6m]$

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

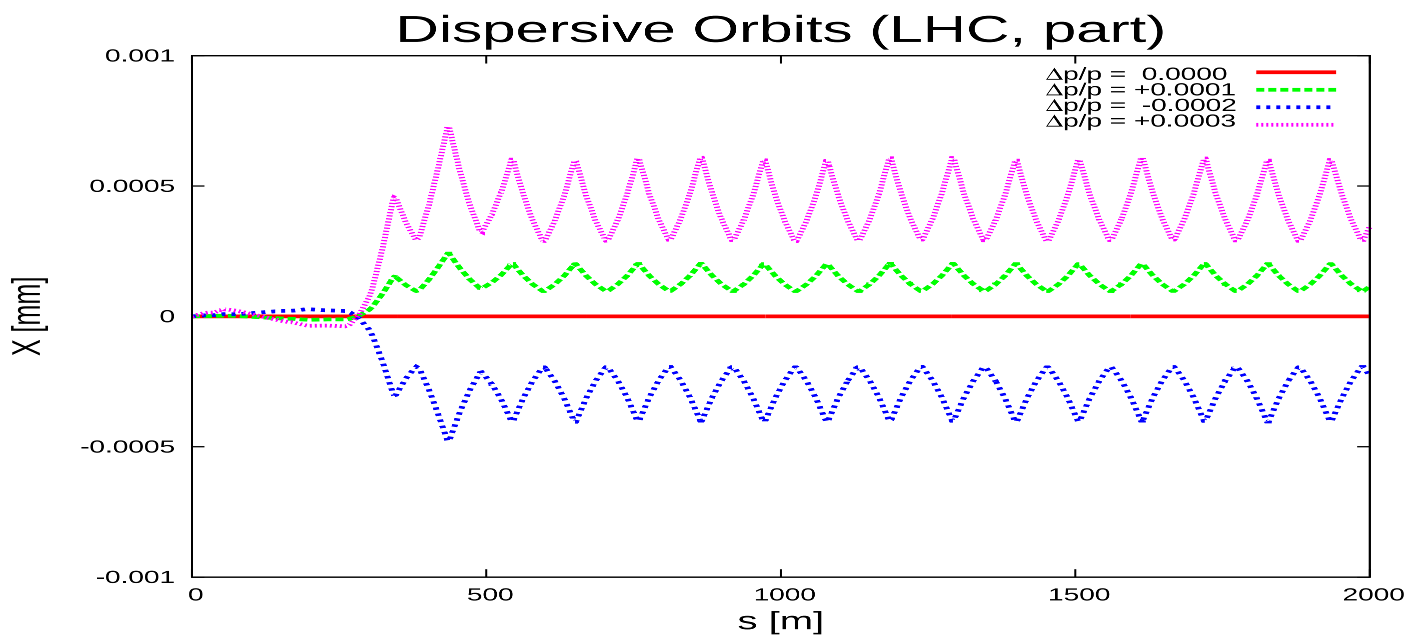
Detailed lattice design

- 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**



- **Higher and lower momentum particles on different orbits along part of the LHC ring**

Some problems with dispersion

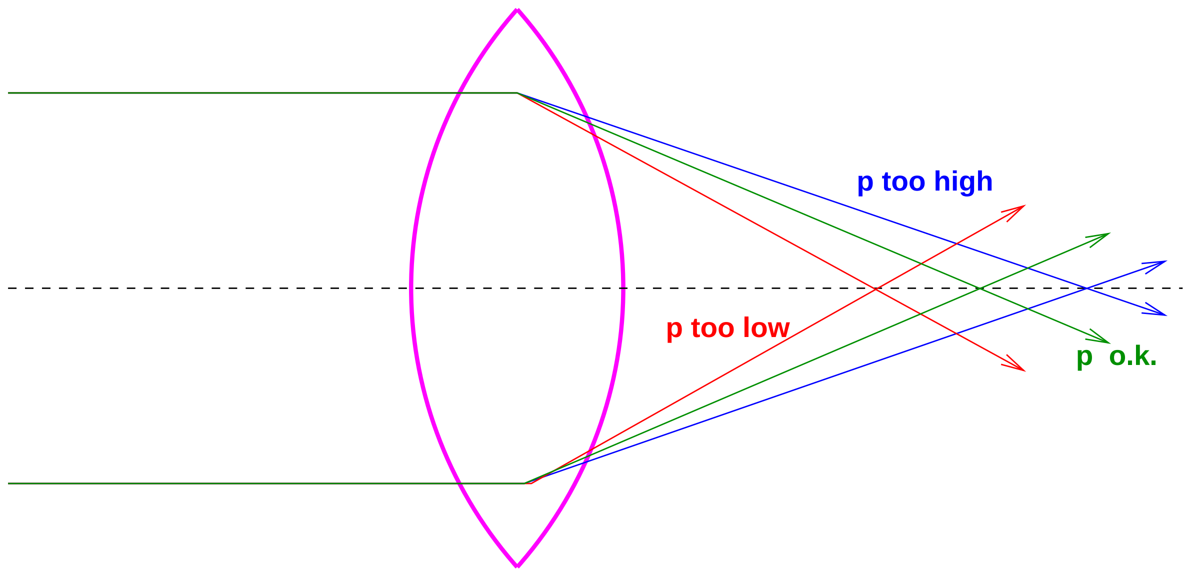
- **With momentum error: more aperture required**
- **With momentum spread: more aperture required**

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

Example LHC: $D_x \approx$ **2 m → effect for momentum offset can be several times the beam size, at interaction point should be smaller than 2 cm !**

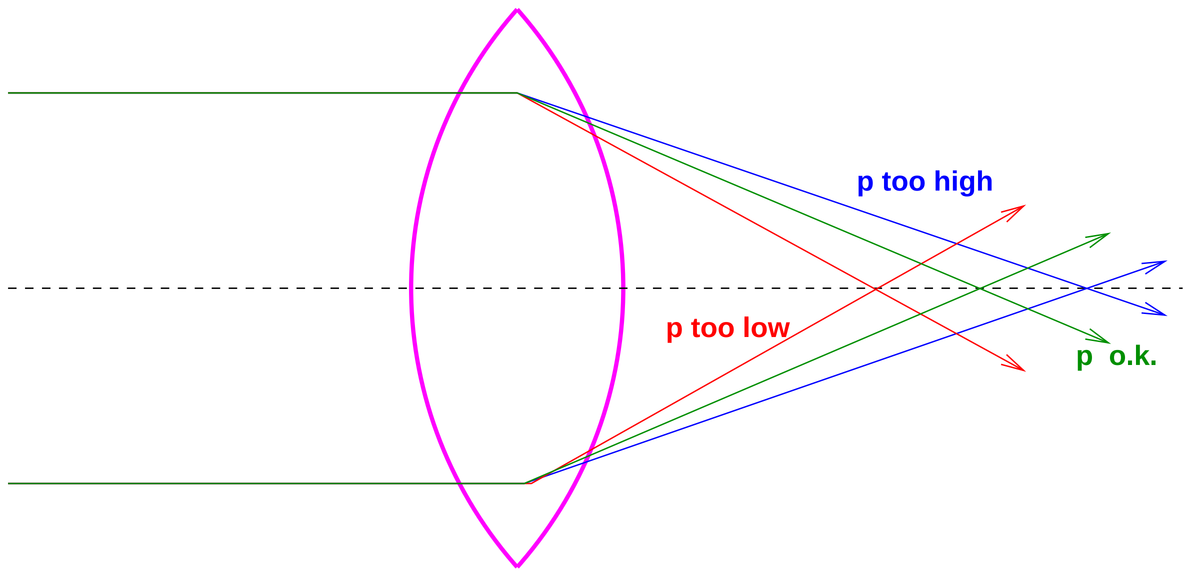
- **Emittance increase with radiation**
- **Can excite synchro-betatron resonances**

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**

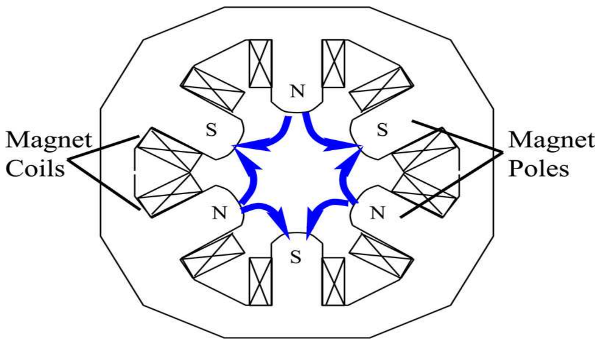
Problems with chromaticity

- **Tune spread due to momentum spread (non-linear resonances): should not be too large**
- **Collective instabilities, for damping might need:**
  - **Positive chromaticity**
  - **Negative chromaticity**

Q' needs to be controlled !

LHC runs at a very high positive chromaticity ..

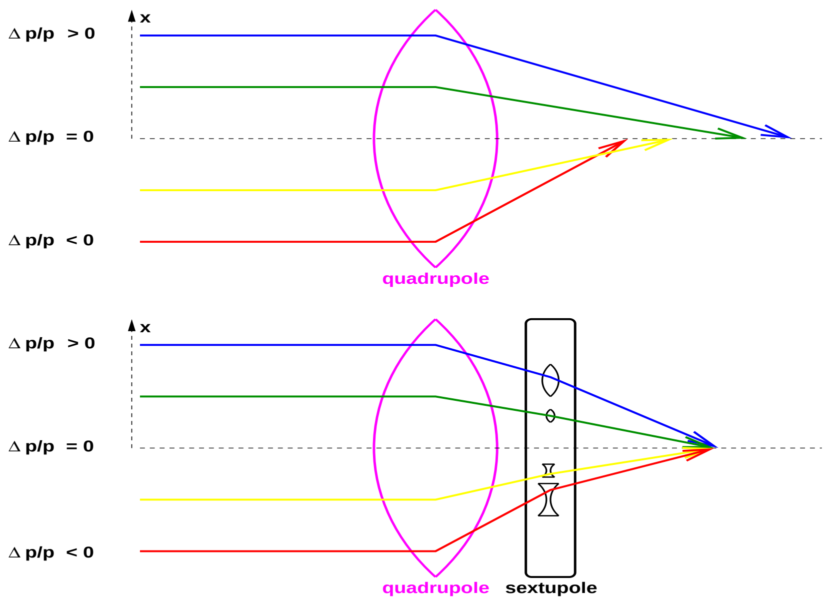
Correction of chromaticity



- **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** $x < 0$

Note: focusing effect is (always) the <u>derivative</u> of the force at the orbit:

$$\frac{\partial x^2}{\partial x} \ = \ 2x$$ **, focusing is linear with the amplitude !**

➡ **Correction can be computed by hand, better: use a computer program like MAD**

Problems with 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**
  - **Special lattice design**
- **Maybe unexpected: zero chromaticity is bad !**

Non-linear effects ... (the real^2 world, lectures by A. Wolski)

Non-linear (wanted and unwanted) fields change the picture completely (see [3, 4]). Main sources are:

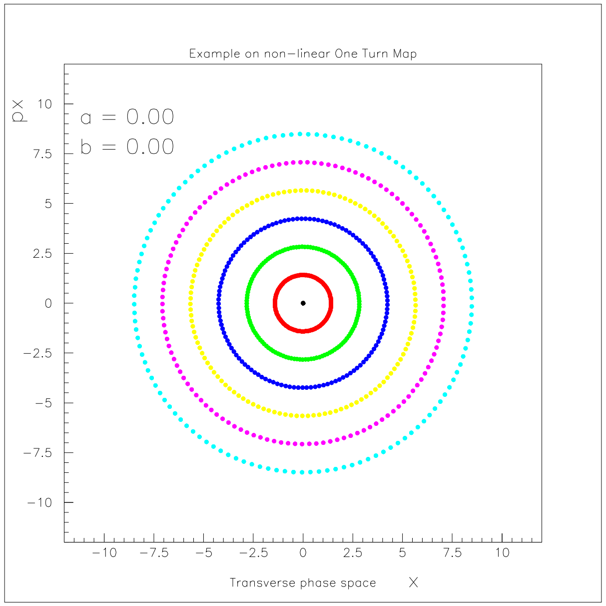
- **Unwanted but Needed:**
  - Sextupoles (chromaticity correction and resonant extraction)
  - Octupoles (e.g. Landau damping, see Advanced Course)
  - Beam-beam effects, ..
  - Others ..
- **Unwanted:**
  - Multipolar fields in magnets, non-linear RF buckets
  - Space charge, ..
  - Rigorous treatment of "linear" elements
  - ...

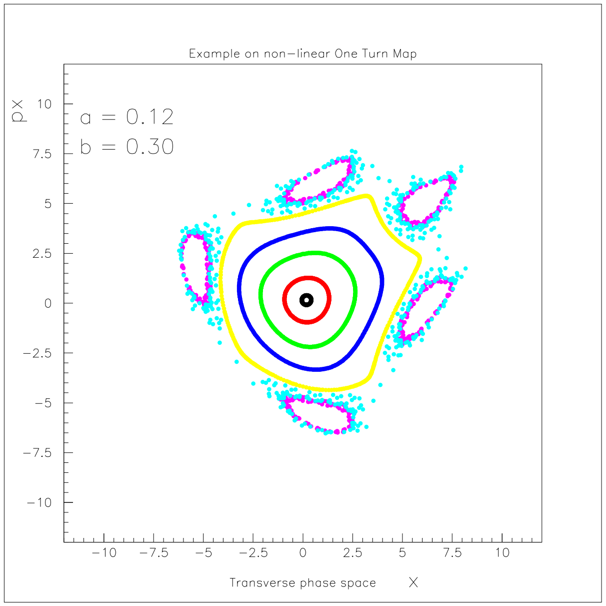
Observable effects:

- **Non-linear effects are the origin of "chaotic behaviour" (of the beam)**
- **Excitation of resonances and amplitude dependent tunes of the particles**
- **Phase space becomes heavily distorted and have nothing in common with ellipses**
- **Shrinking of the stable area, i.e. dynamic aperture (can go as low as zero !)**

Is it time to wave the white flag ?

Ideal world - Real world

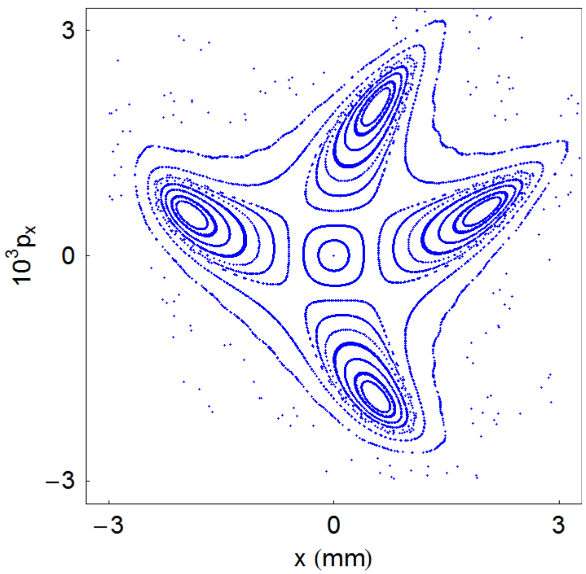




In ideal world: phase space diagrams show ellipses (normalised become circles, was not introduced, but inevitable for beam dynamics calculations)

In real world: largely distorted phase space, one nonlinear element, driving a 5th order resonance

Fixpoints:



FIXPOINTS !

Not mentioned in Transverse Dynamics, but vital for beam dynamics

Particle returns to the same point in phase space

What is the significance ? (resonances, closed orbit, ...)

How many fixpoints do we see ???

Tools available (some mentioned by A. Wolski):

Note: many tools have been developped and elaborated rather recently (1985 -)

- **Say "good bye" to matrices and "hello" to non-linear maps ..**
  - **Not all maps are possible and appropriate**
  - **A machine description can be very complex**
  - **Formalisms needed to compute maps and analyse the behaviour (stability etc.)**
- **Advanced Course will treat these aspects extensively**

  Some teaser: (Taylor maps, symplectic integrators, Lie transforms, Normal Form analysis, Truncated Power Series Algebra, ...)

It is still a very active area of reseach

Beam instrumentation and diagnostics

The key to a good control of the machine (it is the ONLY way to see the beam, without enough diagnostics you are doomed):

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

→ advanced level course, special schools

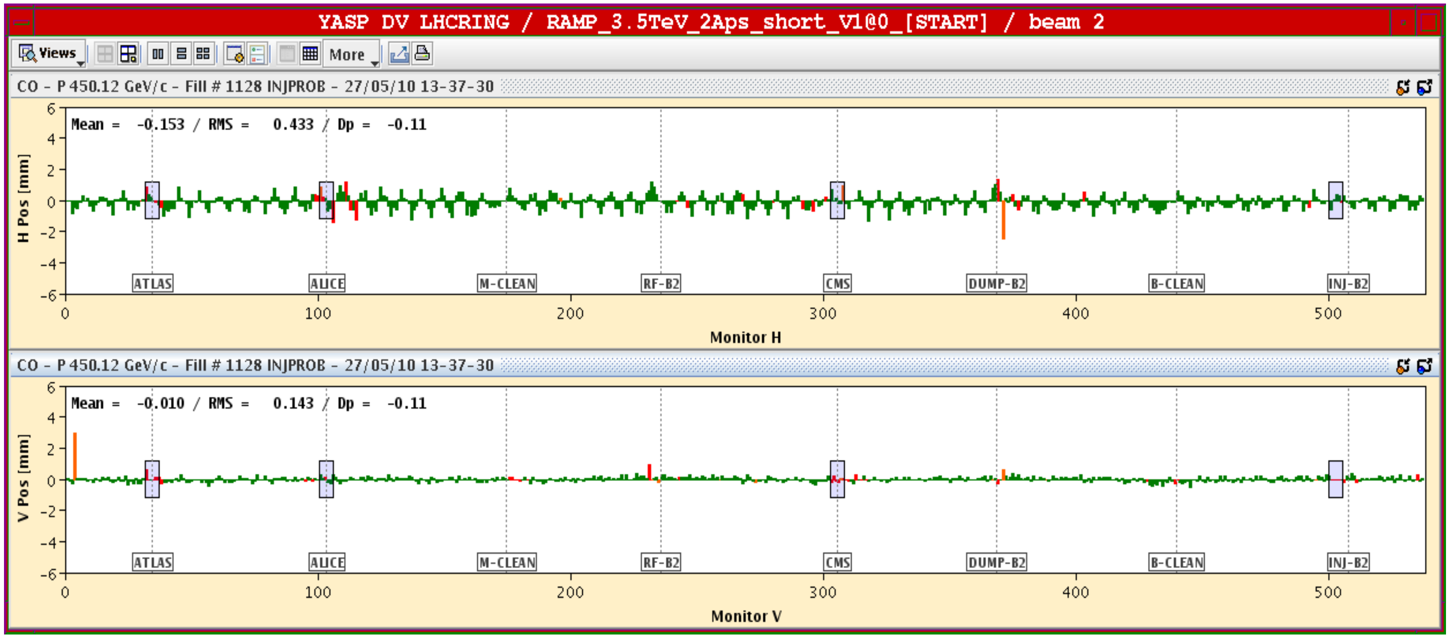
As an example: Orbit and trajectory correction

- 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
  - Large deviations cause change of beam parameters and optics
- 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 (see lecture on "Linear Imperfections")
- Most important: good and reliable orbit measurement

  Excellent: LHC   Not so good: LEP

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)

- **Emittance can be easily changed by changing the optics:**
  - **Controlling dispersion**
  - **Phase advance (tune)**
- **Additional devices (selection):**
  - **Wigglers (emittance increase or decrease easily possible, ditto undulators)**
  - **Combined function elements (e.g. dipole/quadrupole) can manipulate damping partition**

Beam transfer

- Accelerators have a limited range.
- Beams must be transfered between accelerators or storage rings and to the clients (experiments, patients, ...)
- Beam lines must conserve the desired properties
  - Beam size increase must be avoided
  - Losses or filamentation must be avoided
  - Precise control required (e.g. therapy)
- 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	$\|Z/n\|\ \Omega$
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

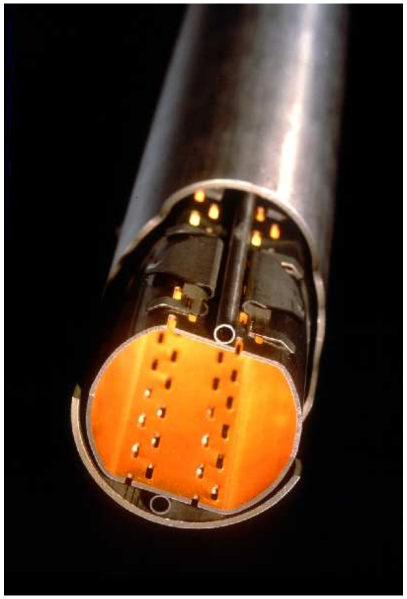
Hardware systems: magnets

- **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, comparable to interstellar vacuum**
- **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, colder than outer space !)**
  - **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.**

Protection of the machine and people:

- **Beam dump (you have to stop a Boing 767 at take-off speed)**
- **An elaborate collimation scheme and loss detection necessary**

The "Introductory" course in a nutshell

- Different types of accelerators
- Relativity and e.m. theory
- Longitudinal and transverse dynamics
- Imperfections and resonances, get flavour of non-linear effects
- Transferlines and injection/extraction
- Multi-particle effects
- Synchrotron radiation and damping
- Beam diagnostics
- Magnets and power systems
- 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:
  1. Optics design
  2. RF measurements
  3. Beam diagnostics
- New lectures on detailed topics

New issues at the next school - a selection

- **Special lattices and insertions (low emittance, ..)**
- **RF cavities and LINAC structures**
- **Magnet design**
- **Various types of accelerators**
- **More Beam Dynamics (the "real world"):**
  - **Non-linear beam dynamics (a new core topic !)**
  - **Instabilities, impedances, feedback, space charge**
  - **Landau damping**
  - **Beam-beam effects**
  - **Machine protection**
  - **...**

CAS in 2017

- **Specialized courses:**

  Beam Injection, Extraction and Transfer
  10.3. - 19.3. 2017, Erice, Italy
  Vacuum for Particle Acceleratos
  6.6. - 16.6. 2017, Lund, Sweden
  RF Systems (Joint Accelerator School)
  October 2017, Japan

- **General course:**

  Advanced Level Course
  somewhere in United Kingdom (ex-EU)