Putting it all together

Werner Herr, CERN

Review of the course ...

- What did we learn?
- What can we do with that?
- How can you contribute to an accelerator project?
Review of the course...

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

The TAKEAWAY
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*):

<table>
<thead>
<tr>
<th>Application</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-energy physics research</td>
<td>120</td>
</tr>
<tr>
<td>Synchrotron light sources</td>
<td>50</td>
</tr>
<tr>
<td>Ion beam analysis</td>
<td>200</td>
</tr>
<tr>
<td>Photon or electron therapy</td>
<td>9100</td>
</tr>
<tr>
<td>Hadron therapy</td>
<td>30</td>
</tr>
<tr>
<td>Radioisotope production</td>
<td>550</td>
</tr>
<tr>
<td>Ion implantation</td>
<td>9500</td>
</tr>
<tr>
<td>Neutrons for industry or security</td>
<td>1000</td>
</tr>
<tr>
<td>Radiation processing</td>
<td>2000</td>
</tr>
<tr>
<td>Electron cutting and welding</td>
<td>4500</td>
</tr>
<tr>
<td>Non-destructive testing</td>
<td>650</td>
</tr>
</tbody>
</table>

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
- 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:
\[ B\rho = p/e = m_0v\gamma/e \]

Synchrotron radiation losses:
\[ eU_0 = A\gamma^4/\rho \]

Numerical examples:
The choice of the type of particles

Two machines in the same tunnel:

<table>
<thead>
<tr>
<th>Machine</th>
<th>Magnetic Field (T)</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC (7000 GeV)</td>
<td>8.3</td>
<td>0.00001</td>
</tr>
<tr>
<td>LEP (100 GeV)</td>
<td>0.12</td>
<td>3</td>
</tr>
</tbody>
</table>

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

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

LHC (pp): 14000 GeV versus $\approx 115$ GeV

LEP ($e^+e^-$): 210 GeV versus $\approx 330$ MeV!!
Colliders:

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

- For collider, additional **difficulties**:
  - Special lattices
  - Insertions
  - Additional collective effects

- Advanced course on accelerator physics (next year)
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 (2009)
- Diagnostics: measure the beams (2008)
- Sources, beam transfer, injection, extraction! (2012)
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
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
- 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:

\[ p = m_0 c \beta \gamma \]

\[ B \rho = m v / e = p / e \]

A handy formula:

\[ B[T] \cdot \rho[m] = 3.3356 \ E[GeV] \]
The choice of fundamental parameters

- If you have $B$: choose $E$, $\rho$
  (e.g. SPS $\rightarrow$ B-field limited to 1.9 T)

- If you have $E$: choose $B$, $\rho$
  (e.g. LEP $\rightarrow$ energy fixed by $Z_0$ mass)

- If you have $\rho$: choose $E$, $B$
  (e.g. LHC $\rightarrow$ 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 $B[T] \cdot \rho[m] = 3.3356 \cdot E[GeV]$
  - $\rho = 833.9 \text{ m}$
  - $C = 2\pi \rho = 5239.5 \text{ m}$

- 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
- $480 \cdot 12$ m = 5760 m = 0.649000 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

75 m

12 m
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)
First part of the cell

75 m

12 m
Second part of the cell

75 m

12 m

QF  QD  QF
A FODO cell matrix

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

$L, f \rightarrow$ cell length and focusing length of Quadrupole

*) from your exercises ...

⚠️ In literature: $L$ is sometimes half-length of cell
Basic relations for the cell

\[ \sin\left(\frac{\mu}{2}\right) = \frac{L_{\text{cell}}}{4f} \]

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

Phase advance \( \mu \) determined by focusing \( f \) (i.e. quadrupole strength) and cell length \( L_{\text{cell}} \)

Maximum \( \hat{\beta} \) depends on cell length \( L_{\text{cell}} \), larger cells also mean larger \( \hat{\beta} \)
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 ($\mu$): usually between 60 and 90 degrees, important for closed orbit and chromaticity correction, insertion design
- Maximum $\beta$-function ($\hat{\beta}$): important for aperture

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

⚠️ Careful: all these concepts are developed for synchrotrons
Definition of emittances seems confusing ...
Different for beam dynamics and sources ?
Mixing particle and beam emittances !
Hadrons vs leptons ?
Linear or non-linear dynamics ?
For definition: \((x, x')\) or \((x, p_x)\) ?
Check what people use for definition ...
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 $\mu$m
1.0 mm mrad
1.0 $\pi$ mm mrad
3.14 mm mrad
Basic relations for the machine

Basic relationships for global parameters are available:

**Tune:** \( Q = n_{cell} \cdot \mu / 2\pi \) \( \approx 30 \)

\( < \beta > \approx R/Q \) \( \approx 50m \)

\( \alpha \approx 1/Q^2 \) \( \approx 0.0011 \)

\( < D > \approx \alpha \cdot R/Q \) \( \approx 1.6m \)

\( \gamma_{tr} \approx Q \) \( \approx 30 \)
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 the ring

Described by the lattice function dispersion $D$
Problems with dispersion

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

\[ A(s) = \sqrt{\epsilon \cdot \beta(s)} + D(s) \cdot \frac{\Delta p}{p} \]

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

- Emittance increase with radiation
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 $(\epsilon, \beta)$!
- 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!
Focusing $1/f$ of a quadrupole depends on momentum

Different focusing leads to different tune

$$\left( \frac{1}{f} \propto \sin(\mu/2) \right)$$
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

\[ Q' = \frac{\Delta Q}{\Delta \frac{p}{p}} \]

for \( \Delta \frac{p}{p} < 0 \) \( \Delta Q > 0 \) \( \rightarrow \) \( Q' < 0 \)

for \( \Delta \frac{p}{p} > 0 \) \( \Delta Q < 0 \) \( \rightarrow \) \( Q' < 0 \)

\( Q' \) 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
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 too 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
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
The RF system has three (main) tasks:

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

Must consider:

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

We know from

\[ B\rho = \frac{mv}{e} = \frac{p}{e} \]

that the energy gain per turn is:

\[ \Delta E_{\text{turn}} = e\rho (\Delta B/\Delta t)C \]

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:

\[ V_{\text{min}} = \frac{\Delta E_{\text{turn}}}{(e \sin(\Phi_s))} \]
During the acceleration the particles get faster (for $\gamma$ not too large) and the RF frequency has to change. For $\beta$ 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 ($\gamma_{tr}$)
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 $\sigma_s$, 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.
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 ($\beta$-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
  - ...

![Image of LHC beam screen](image-url)
**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 $\rightarrow 10^{-4} - 10^{-5}$)
- 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 transverse dynamics
- Imperfections and resonances
- 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

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 measurements
  3 Beam diagnostics
- New lectures on detailed topics
New issues at the next school

- Optics design: lattices and insertions
- Non-linear beam dynamics
- Instabilities, space charge effects
- Landau damping
- Beam-beam effects
- Special lattices (low emittance, ..)
- RF cavities and LINAC structures
- Magnet design
- ...

...
Specialized course:
Superconductivity for Accelerators
25.4. - 4.5. 2013, Erice, Italy

General course:
Advanced Level Course
August 2013, Trondheim, Norway