PE Mini Lectures
„How to produce a particle beam?“
19.06.2019
Recap: How to describe a particle beam?

- Particle behaviour is described using concept of **phase space**.
  - 6d phase space: \((x, y, z, p_x, p_y, p_z)\)
  - Transverse (4d) phase space: \((x, x', y, y')\)
- Linear forces \(\rightarrow\) point moves on an ellipse in phase space.

- **Liouville’s theorem**: The (6d) phase space volume is conserved (assuming *no interactions between the particles, no binary collisions, no dissipative forces and no particle losses or charge exchanges*). For uncoupled motion in the perpendicular planes, also the 2d phase space area is conserved.

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**Linear harmonic oscillator**


![Trajectory in phase space \((x, v_x)\)](https://www.acs.psu.edu/drussell/Demos/phase-diagram/phase-diagram.html)

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**Conservation of phase-space volume**
Recap: Emittance as phase-space area

Area in the transverse 2d phase-space projections:

\[
A_x = \int \int dx \, dx' = \varepsilon_x \pi \\
A_y = \int \int dy \, dy' = \varepsilon_y \pi
\]

The quantity \( \varepsilon = \frac{A}{\pi} \) is called \textbf{emittance}.

Typical units for the transverse emittance: [mm*mrad] or [\(\mu\)m].

- The \textbf{emittance} quantifies the occupied \textbf{area in phase space}.
- It is an important figure of merit for the \textbf{beam quality}.
- Challenge: not all phase-space distributions can be (easily) described by a limiting contour (ellipse) \( \rightarrow \) Use instead a statistical definition of the emittance.

How to produce a particle beam?

**RMS Emittance**

Based on a statistical approach, the RMS (root mean square) emittance is defined as:

$$\epsilon_{\text{rms}} = \sqrt{\frac{\overline{x^2}}{\overline{x'^2}} - \frac{\overline{xx'}}{\overline{x'^2}}}$$

The RMS emittance depends not only on the occupied phase space area, but also on the shape of the particle density distribution.

Example:

See: N. Chauvin, CAS, Prague 2014.
Recap: How to describe a particle beam?

- In an accelerator, the restoring force $k(s)$ is $s$-dependent.
  $\rightarrow$ Solve Hill’s equation.
- Shape and orientation of the phase ellipse are given by the Courant-Snyder or Twiss parameters $\alpha$, $\beta$, $\gamma$. They are used to describe the beam dynamics along the lattice.
- The beta function $\beta(s)$ is determined by the focusing properties of the lattice (optics).
- Beam size is given by: $\hat{x}(s) = \sqrt{\varepsilon} \sqrt{\beta(s)}$

$$x(s) = \sqrt{\varepsilon} \sqrt{\beta(s)} \cdot \cos(\psi(s) + \phi)$$

B. Holzer, *Introduction to Transverse Beam Dynamics*, CAS 2016
Outline: Beam and Accelerator Physics

1) Basics: How to describe a particle beam?
   • Concept of phase space
   • Conservation of phase-space volume (Liouville theorem)
   • Emittance
   • Beta function and Twiss parameters

2) How to produce a particle beam?
   • Ion sources
   • Space charge

3) How to transport a particle beam?
   • How to deflect a beam?
   • How to focus a beam?
   • Magnet types and their beam-dynamics functions

4) How to accelerate a particle beam?
   • RF accelerators (LINACS and RF cavities)
   • Ring accelerators: cyclotron, synchrotrons
   • Colliders
A large (hadron) accelerator complex typically comprises:

- Ion sources, beam transport and transfer lines, linear accelerators (linacs), synchrotrons, storage rings, (cyclotrons).

Source: GSI

Video
How to produce a particle beam?

1) **Ion generation**: ionize atoms/molecules (ignite plasma) and confine them

2) **Beam formation**: extract and pre-accelerate ions (typically to 10...100 keV)

*This includes protons (positive hydrogen ions), but not e⁻/e⁺, which are not treated here.*
Ionisation and plasma generation

Idea: generate a quasi-neutral plasma via (impact) ionisation

\[ \sum q_i n_i = n_e \]

Provide free atoms/molecules in the plasma chamber:

- Gas insertion
- Melting and evaporating
- Sputtering

→ **Confine plasma** using electric and magnetic fields (solenoid, dipole, multicusp fields).

Provide free electrons:

- Thermionic emission
- Photoionisation
- Arc discharge

Provide required ionisation energy:

- Electrostatic acceleration of electrons
- RF heating
- Electron cyclotron resonance

Acknowledgement: O. Meusel
Beam Extraction and Plasma Meniscus

\[ E_{int} > E_{ext} \]

Convex

\[ E_{int} = E_{ext} \]

Flat

\[ E_{int} < E_{ext} \]

Concave

Assuming no space-charge effects.

Pictures: D. Faircloth, CAS, Prague 2014
How to produce a particle beam?

Beam Extraction: phase space

\[ E_{\text{int}} > E_{\text{ext}} \]
\[ E_{\text{int}} = E_{\text{ext}} \]
\[ E_{\text{int}} < E_{\text{ext}} \]

Assuming no space-charge effects.

Pictures: D. Faircloth, CAS, Prague 2014
How to produce a particle beam?

Initial ‘thermal’ emittance

Assuming
• Ions at plasma temperature $T$
• Maxwell momentum distribution of the ions $\langle p_x^2 \rangle = mkT$
• Beam size of $R = 2 \sqrt{\langle x^2 \rangle}$
• No influence of external fields

$\varepsilon = 2R \sqrt{\frac{kT}{mc^2}}$

Additional sources contributing to beam emittance:
• irregularities in the plasma meniscus extraction surface
• aberrations due to ion-source extraction optics
• optical aberrations of the focusing elements of the LEBT
• non-linearity of the electric field created by the beam space charge
• beam fluctuations due to ion-source instability or power regulation

See Batygin, USPAS 2014
Vacuum diode

What limits the electron current in a vacuum tube?

I-V Characteristics of Vacuum Diode under forward bias

Even assuming an infinite reservoir of charged particles, the maximum emitted current is limited by space charge.

**Child-Langmuir law:**

\[
J_0 = \frac{4}{9} \epsilon_0 \left( \frac{2q}{m_0} \right)^{1/2} \frac{V_0^{3/2}}{d^2}
\]

How fast can a particle be?

Velocity according to Newton’s law (classical mechanics):

\[ v = \sqrt{\frac{2E}{m}} \]

Velocity according to Einstein’s theory of special relativity:

\[ v = c \sqrt{1 - \frac{1}{\gamma^2}} \]

Particles move as if their mass increased:

\[ m = \gamma m_0 \]

Total energy:

\[ E = mc^2 = \gamma m_0 c^2 \]

Kinetic energy:

\[ E_k = E - E_0 = (\gamma - 1)m_0 c^2 \]

Thanks to D. Noll
Space charge and self-fields

Moving charges produces:
- Repulsive electric field
- Attractive magnetic field

Using the Maxwell equations and modelling the beam as a uniformly charged cylinder...

\[
\text{div } \vec{E} = \frac{\rho}{\varepsilon_0} \quad \text{rot } \vec{B} = \mu_0 j
\]

...the resulting force is:

\[
\vec{F}_{sc}(r) = q\left(\vec{E} + \vec{v} \times \vec{B}\right) = q\left(E_r - \beta c B_\phi\right) \vec{e}_r = \frac{q I_b}{2 \pi \varepsilon_0 \beta c} \left(1 - \beta^2\right) \frac{r}{r_b^2} \vec{e}_r
\]

\(v \ll c\) : Repulsive electric force dominates.
\(v \to c\) : Repulsive electric and attractive magn. forces compensate each other.

Derivation: Struckmeier 2005, Chap. 6.1
Space charge: some remarks

- Low energy and high intensity beams $\rightarrow$ Large space charge forces.
- High energy beams: Space charge forces small/negligible.

$\rightarrow$ For “all [high-current] machines the major challenge is in the low-energy part, where the beam quality is defined”. [Ferdinand, PAC’07, 2564]

LHC Injectors Upgrade (LIU) project includes
- Increase of PSB injection energy from 50 MeV (LINAC2) to 160 MeV (LINAC4)
- Increase of PS injection energy from 1.4 GeV to 2 GeV
...to reduce space charge constraints.
How to produce a particle beam?

Space-charge compensation (neutralization) 1

Compensation build-up time:

\[ \tau_{\text{comp}} = \frac{1}{n_{\text{gas}} \sigma_i v_p} \]

Typically \( \sim \mathcal{O}(100) \) of \( \mu s \)

- External electric fields destroy the space-charge compensation
- Sometimes it is also called space-charge neutralization

D. Faircloth, CAS, Prague 2014; O. Meusel et al., 2007.
Space-charge compensation (neutralization) II

Example: Effect of space-charge compensation on beam size

Space-charge compensation degree (and distribution of compensation particles) has a significant effect on the initial beam properties! They have to be well controlled/understood, to achieve good beam quality and reproducibility.

→ Use of a chopper at e.g. LINAC4 to remove first ~150 µs of beam pulse.
How to produce a particle beam?

Ion sources: extraction systems

D. Faircloth, CAS, Prague 2014.
Example: Filament-Driven Ion Source

Filament-driven volume-type ion source @ IAP, Frankfurt

Advantage: low plasma temperature → low emittance beam; high current.
Plasmatron (late 1940s)

Manfred von Ardenne

Faircloth, CAS 2016
Duoplasmatron (1956)

- Filament Power Supply 2-100 A
- Cathode Filament
- Gas Feed
- Solenoid Field Iron
- Return Yoke
- Anode
- Conical Iron Funnel
- Intermediate Electrode
- Expansion Cup
- Extraction Electrode
- Extraction Voltage Supply 5-50 kV
- Beam
- Defocusing Solenoid

Manfred von Ardenne

Faircloth, CAS 2016
Example: CERN Duoplasmatron

300 mA protons
150 μs pulses at 1 Hz

Used for LINAC2

Faircloth, CAS 2016
“All protons accelerated at CERN are obtained from standard hydrogen. Although proton beams at the LHC are very intense, only 2 nanograms of hydrogen*) are accelerated each day. Therefore, it would take the LHC about 1 million years to accelerate 1 gram of hydrogen.”

*) the total mass of protons is calculated at rest


1.2 x 10^20 protons were accelerated in the accelerator complex in 2016. This might sound like a huge number, but in reality it corresponds to a minuscule quantity of matter, roughly equivalent to the number of protons in a grain of sand. In fact, protons are so small that this amount is enough to supply all the experiments. The LHC uses only a tiny portion of these protons, less than 0.1%, as shown in the diagram.

CERN Annual Report 2016
Example: ECR Source

- Based on Electron Cyclotron Resonance (ECR)
- High current, low maintenance (no filament...)
- LINAC3 uses an ECR source to provide the lead ions

\[ \omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m} \]
How to produce a particle beam?

Example: LINAC4 $\text{H}^-$ ion source

- $\text{H}^-$ ions required for charge-exchange injection into the PSB
- Will be operated with Caesium

Caesium reservoir


5 g Caesium Ampoule

Faircloth, CAS 2016
Conclusions

- **Ion source** = Plasma generator (ion generation) + extraction system (beam formation)
  - 1) Provide free atoms, provide free electrons, provide required ionization energy, and confine plasma. 2) Extract beam.
- Shape of **plasma meniscus** depends on plasma density and electric extraction field. It has to be matched for optimum beam extraction.
- **Initial emittance** of the extracted particle beam is linked to the plasma temperature.
- Maximum emitted source current is limited (not only) by space charge (Child-Langmuir law).
- Moving charges produces **electric and magnetic self-fields**
  - Low energy and high intensity beams → Large space charge forces.
  - High energy beams: Space charge forces small/negligible.
- **Space-charge compensation** affects initial beam properties.
- There exist a variety of **different ion source types**:
  - Filament-driven IS: low emittance...
  - Duoplasmatron: high current
  - ECR: low maintenance...
  - (EBIS: highly charged ions... see backup slides)
- For LINAC4, an H⁻ ion source is required.
Next Mini Lectures:
• **Wednesday, 03.07.2019, 15.00h**, Room 30-6-19
• **Wednesday, 17.07.2019, ?h**
Questions?
Comments?

“Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a much higher level.” (Enrico Fermi)
How to produce a particle beam?

H- beams: motivation

Tandem accelerators

Cyclotron extraction

Neutral Beams

Multi-turn injection into rings

Stripping foil

Protons

H- from Linac

D. Faircloth, CAS, Prague 2014.
Example: Electron Beam Ion Sources

- Electron Gun
- Electron Beam
- Drift Tubes
- Superconducting Solenoid
- Magnetic Shielding
- Electron Dump
- Extraction Electrode
- Ionisation Chamber
- ≈ 100 mm
- Stepwise ionisation
- Drift Tube V
- Trapping and Ionisation Phase

Faircloth, CAS 2016
Example: Electron Beam Ion Sources

EBIS are excellent to provide highly charged ions.

Faircloth, CAS 2016
How to produce a particle beam?

Ion Source

- Arc-discharge driven ion source
- Proton current: 50 mA (240 mA)
- Current density: 480 mA/cm²
- DC operation
- Proton fraction > 90%
- Beam energy: 120 keV
- $\varepsilon_{\text{rms, norm}} < 0.08 \text{ mm} \cdot \text{mrad}$ (low ion temperature)
Normalized Emittance

- Emittance: Intrinsic beam parameter that cannot be changed by the focusing properties.
- Not constant during acceleration → Normalization
- The beam emittance shrinks during acceleration $\varepsilon \sim 1/\gamma$
- $\rightarrow$ beam size shrinks with $\gamma^{-1/2}$
- **Highest aperture required at low (injection) energy**

$$x' = \frac{dx}{ds} = \frac{dx}{dt} \frac{dt}{ds} = \beta \frac{p_x}{p}$$

$$\varepsilon = \int x' dx = \int \frac{p_x dx}{p} \propto \text{const} \frac{1}{m_0 c \cdot \gamma \beta}$$

$\Rightarrow \varepsilon = \int x' dx \propto \frac{1}{\beta \gamma}$

**the beam emittance shrinks during acceleration $\varepsilon \sim 1/\gamma$**

Holzer, Introduction to Transverse Beam Optics II, CAS Budapest, 2016