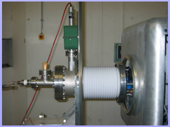
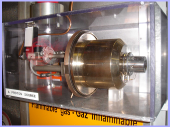
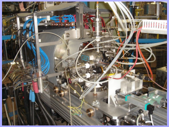
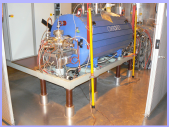
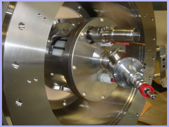
Particle sources for pedestrians

D. Küchler

CERN/BE/ABP/HSL

27 February 2009

Outline

You are here

1. Introduction
2. Electron sources
3. Ion sources
4. Final remarks

Introduction

- What provides this lecture?
  - some basic principles of particle production
  - some examples of particle sources
  - only a limited number of formulas and values, because this could be easily found in any text book

Introduction

- What provides this lecture?
  - some basic principles of particle production
  - some examples of particle sources
  - only a limited number of formulas and values, because this could be easily found in any text book
- What can this lecture not provide?
  - the complete theory of particle production
  - the complete overview of all particle sources (e.g. radioactive ion sources, anti-proton sources, positron sources are not included)
  - in-depth explanations

Introduction

- What provides this lecture?
  - some basic principles of particle production
  - some examples of particle sources
  - only a limited number of formulas and values, because this could be easily found in any text book
- What can this lecture not provide?
  - the complete theory of particle production
  - the complete overview of all particle sources (e.g. radioactive ion sources, anti-proton sources, positron sources are not included)
  - in-depth explanations
- for more informations see the books listed in the bibliography

Why we need to speak about particle sources?

- one cannot start the acceleration from ordinary matter
  $\Rightarrow$ it has to be “charged” and a primary beam has to be “shaped“
- it is important to understand the limitations of the source
  (beam intensity, emittance, charge state, beam structure, reliability and life time),
  accelerator people tend to ”forget“ them and try to shift their problems towards the source
- a basic knowledge of the source can help during the operation and is essential for designing an accelerator
- it is always good to know where the source is and who the specialists are

You are here

Basic principles I

- the **perveance** $P = \frac{I}{U^{3/2}}$ is a gun parameter, that is based on the space charge limit of the beam and depends only on the electrode geometry and not on the electron emitter
  (I — beam current, U — voltage between anode and cathode)
- the **brightness** $B \propto \frac{I}{\varepsilon_x \varepsilon_y}$ is a value to describe the quality of the beam
  (I — peak current, ε — transverse normalised emittance)

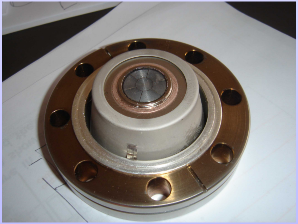
Basic principles II

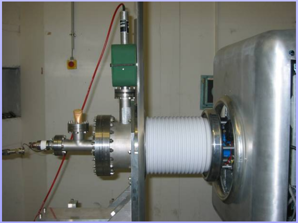
- there are different mechanism to "produce" the electrons
  ⇒ thermionic emission, photoemission, field emission
- there exist a big variety of cathodes in terms of the shape and in terms of material
- the electric field can be DC or RF
  ⇒ fast acceleration needed to overcome space charge, RF fields allow a higher voltage to get a more brilliant beam
- the focussing can be pure electrostatic or including magnetic fields
- unpolarised or polarised beams

Electron guns I

High voltage DC gun with thermionic cathode

- simple structure, robust, long lifetime
- grid in front of the cathode to switch the current
- good stability (pulse to pulse and long term)
- limited brilliance ("slow" acceleration)
- main mode of failure: external (e.g. power supplies)

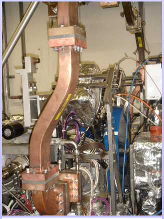


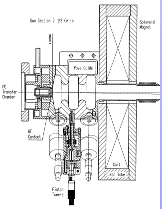


Electron guns II

RF gun with photocathode

- the concept of the photo injector was first proposed and tested in the mid-1980s by J.S. Fraser and R.L. Sheffield
- a photocathode is enclosed in a 2½ cell RF cavity
- the beam pulse structure is defined by the laser pulse
- the pulse to pulse stability depends on the laser (limited)
- high brilliance (due to the high RF field)
- short lifetime of the cathode (weeks)
- very good vacuum needed (problem of recoil ions)





You are here

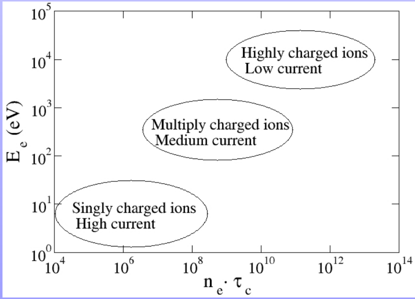
The ion production

Basic differential equation concerning the ion production process (simplified)

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = n_{i-1}\sigma_{i-1,i}j_e - n_i\sigma_{i,i+1}j_e - \frac{n_i}{\tau_c(i)}$$

n_i ion density
σ cross section
j_e electron current density
$\tau_c(i)$ ion confinement time

- terms of ion production and ion losses
- the ion confinement time $\tau_c(i)$ influences the charge state that could be reached but also the ion current that can be extracted
- a complete model needs to include also the single particle transport (diffusion), the macroscopic behaviour (waves, MHD), the plasma–wall interaction, the energy balance (electron heating)



The ion production II

Processes increasing the charge state $q^{n+} \longrightarrow q^{(n+i)+}$

- ionisation
  - single ionisation
  - double ionisation
  - creating of higher charge states is a step-by-step process
  - ionisation process has a energy threshold
    $\Rightarrow$ the production of higher charge states needs a higher electron energy
- charge exchange (for low n)

Processes decreasing the charge state $q^{n+} \longrightarrow q^{(n-i)+}$

- recombination
  - radiative recombination
  - the cross sections are bigger for lower electron temperatures
  - dielectronic recombination (resonant process)
- charge exchange (for high n)
  - depending on the neutral particle density (rest gas)
  - cross sections are bigger for higher charge states

The H^- production

- **charge transfer:** the simplest method is the conversion of a primary proton beam in a converter target (e.g. a caesiated surface, caesium vapour or hydrogen gas)
- **surface effect:** protons from a plasma hitting the wall can pick up electrons, the walls are covered with low work function material (e.g. caesium)
- **volume effect:** H^- is created from vibrational excited hydrogen molecules through dissociative electron attachment

$$\mathrm{H_2}(\nu^{''}) + \mathrm{e}^- \rightarrow \mathrm{H}^- + \mathrm{H}$$

- H^- ions are very sensitive to particle collisions

Source input and output

Particle input media

- gas
- liquids
- solids

N.B. These lists are not exhaustive.

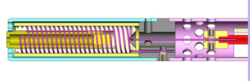
Source input and output

Particle input media

- gas
- liquids
- solids

Particle feeding methods

- low vapour pressure agents
- volatile chemical compounds
- sputtering
- oven
- laser evaporation
- single charge ion source



N.B. These lists are not exhaustive.

Source input and output

Particle input media

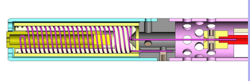
- gas
- liquids
- solids

Energy feeding

- electrical discharges (filament sustained)
- radio frequency (internal or external antenna)
- microwave
- laser
- electron beam

Particle feeding methods

- low vapour pressure agents
- volatile chemical compounds
- sputtering
- oven
- laser evaporation
- single charge ion source



N.B. These lists are not exhaustive.

Source input and output

Particle input media

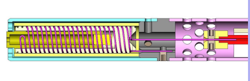
- gas
- liquids
- solids

Energy feeding

- electrical discharges (filament sustained)
- radio frequency (internal or external antenna)
- microwave
- laser
- electron beam

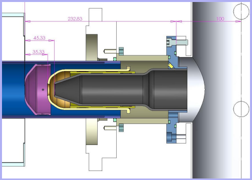
Particle feeding methods

- low vapour pressure agents
- volatile chemical compounds
- sputtering
- oven
- laser evaporation
- single charge ion source



Extraction

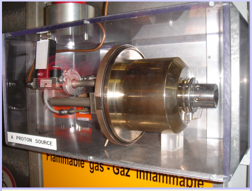
- system of several electrodes
- source body on high voltage
- beam extraction and shaping
- initial emittance creation

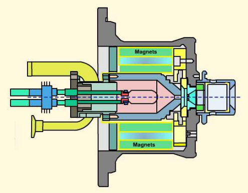


N.B. These lists are not exhaustive.

The Duoplasmatron

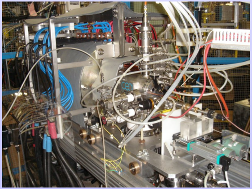
- developed 1956 by Manfred von Ardenne
- driven by an arc discharge sustained by a heated filament
- a strong magnetic field in the discharge region increases the plasma density
- hydrogen gas is used as input medium
- in the expansion cup the plasma density is reduced to decrease the beam divergence
- delivers short pulses with a very high intensity of mostly mono charged ions

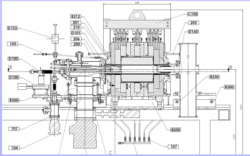


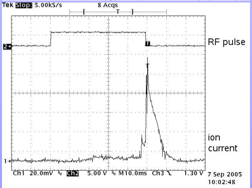


The Electron Cyclotron Resonance Ion Source (ECRIS)

- developed 1965 by Richard Geller
- the plasma is confined in a "magnetic bottle", the longitudinal field is created with solenoids, the radial field is created with a magnetic hexapole
- the plasma is heated due to the resonance of the injected microwave with the electron cyclotron frequency $\omega_c = \frac{eB}{m_e}$
  (actual used frequencies 14.5 GHz, 18 GHz or 28 GHz)
- "afterglow" mode of operation: pulsing the microwave power results in a peak current of the higher charge states after the end of the microwave pulse
- delivers high currents for medium charge states
- no antennas or filaments in the ion production region ⇒ high reliability

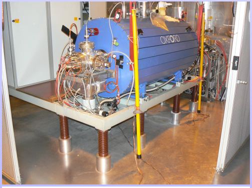


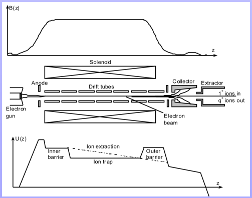




The Electron Beam Ion Source (EBIS)

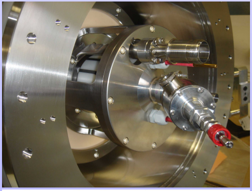
- developed 1965 by Evgeni D. Donets
- the longitudinal confinement is given by electrostatic fields, the radial confinement is given by the electron beam, which is compressed by a solenoidal field
- ionsation takes place inside the high energetic, high density electron beam
- delivers short pulses of high charge states
- the extraction process is controlled by the voltage level of the trap electrodes
- the total current depends on the trap charge capacity
- low emittance
- the life time and the reliability is mainly defined by the electron gun

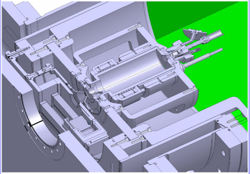




The RF driven H^- source

- RF driven ion sources were developed in the late 1940s, negative ion sources were developed according to requirements
- the H^- is created in the volume process
- the RF power is coupled inductively into the plasma
- the plasma region separated by a magnetic filter into two regions of different electron temperature
- the plasma is confined by a magnetic cusp structure
- the ignition of the plasma is supported by an electron gun
- the co-extracted electrons are removed in an spectrometer
- delivers pulsed high currents of H^-
- caesium free and no antenna or filament in the plasma $\Rightarrow$ high reliability



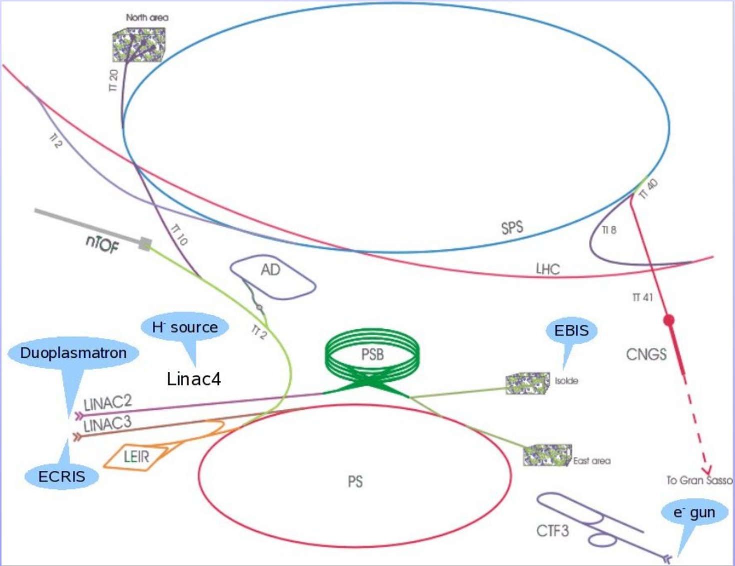


You are here

Final remarks

- particle sources are an essential part of the accelerator chain
- all particle sources have certain limitations that define their field of application, there is no universal source
- the reliability of the source contributes to the availability of a beam from the accelerator
- ion sources can create primary or secondary beams in a wide range of charge states and current

Sources at CERN



Bibliography

- A. Wu Chao, M. Tigner (Ed.), Handbook of Accelerator Physics and Engineering, World Scientific, 2002.
- M. Sedlaček, Electron physics of vacuum and gaseous devices, Wiley, 1996.
- I.G. Brown (Ed.), The Physics and Technology of Ion Sources, Wiley, 2004.
- B. Wolf (Ed.), Handbook of Ion Sources, CRC Press, 1995.
- H. Zhang, Ion Sources, Springer, 1999.
- CERN Accelerator School, Fifth General Accelerator Physics Course, CERN 94-01, 1994.