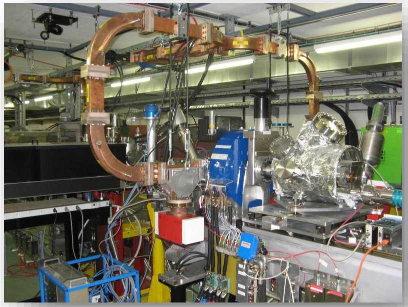

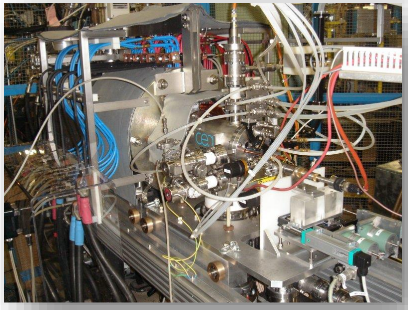

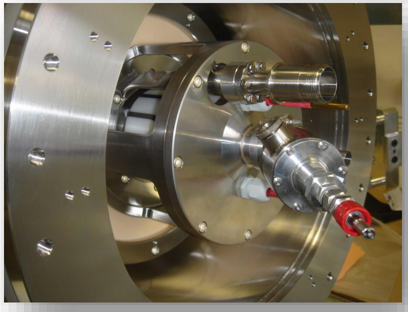

Particle sources for pedestrians

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The CERN Accelerator School

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Outline

- Introduction
  - What is a particle source?
- Electron sources
  - Basic principles
  - Examples
- Ion sources
  - Generalized model
  - Examples
- Engineering
- Conclusions

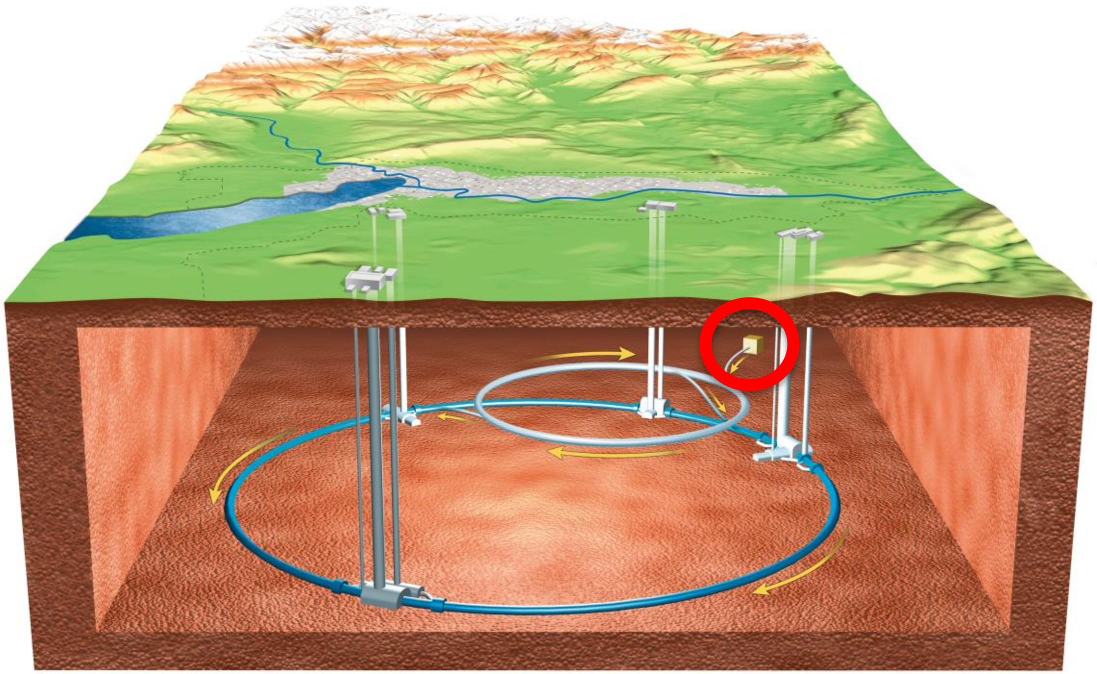
INTRODUCTION

- 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 textbook
- What can this lecture not provide?
  - the complete theory of particle production
  - the complete overview of all particle sources (e.g. radioactive ion sources, antiproton sources, positron sources are not included)
  - in-depth explanations
- for more information see the books listed in the bibliography

What is a particle source?

For an accelerator physicist a particle source is somewhere far away.

It is a black box with three buttons:



- On/Off
- Particle type
- Intensity

What is a particle source?

Definition (for primary beams)

A particle source is a device to create a charged particle beam.

This definition is not perfect but covers most of the cases.
Particles in this context are electrons, ions, molecules and clusters.

Why we have to create a <u>charged</u> particle beam?

Ordinary matter is neutral.

In an accelerator electric and magnetic fields are used to manipulate the beam (acceleration and transport).

What does it mean "to create a particle beam"?

The particle source

- ionizes the particles or create free electrons
- shapes a beam

The main beam properties are defined at the source

- charge state
- beam intensity
- beam energy
- beam shape and emittance
- time structure (continuous or pulsed)

Why do we have to speak about sources?

- The particle source is an essential part of an accelerator.
- It is important to understand the limitations of the source (beam properties, reliability, lifetime).
- Accelerator experts tend to forget these limitations 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 (to find compromises between wishes and reality).
- It is always good to know where the source is located and who the specialists are.

ELECTRON SOURCES

Basic principles

- 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)

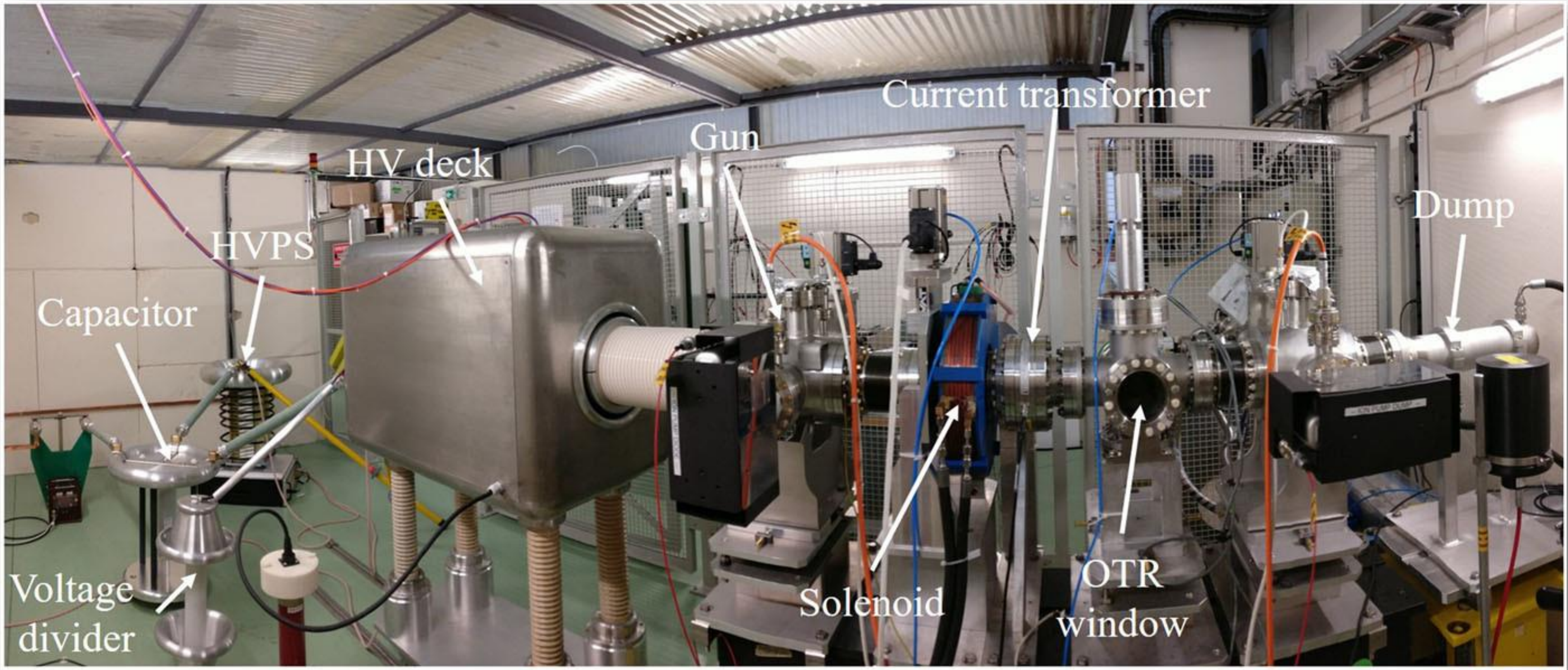
- the **brightness** $B \propto \frac{I}{\varepsilon_x \varepsilon_y}$

  is a value to describe the *quality of the beam*
  (I — peak current, ε — transverse normalised emittance)

Basic principles II

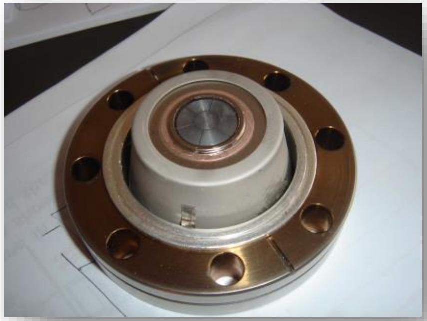
- there are different mechanism to ”produce“ the electrons
  ⇒ thermionic emission, photoemission, field emission
- there exist a big variety of cathodes in terms of the shape and in terms of material
- the electric field can be DC or RF
  ⇒ fast acceleration needed to overcome space charge, RF fields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

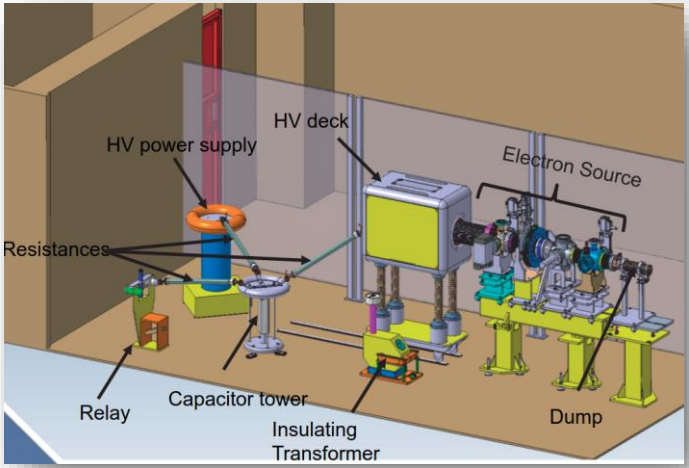
High voltage DC gun with thermionic cathode

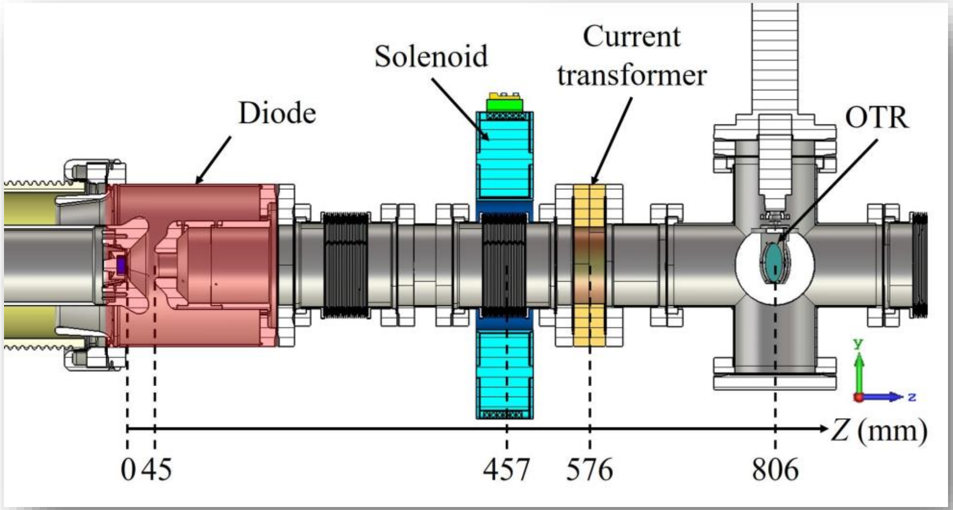


Location: CLIC Drive Beam Electron Gun

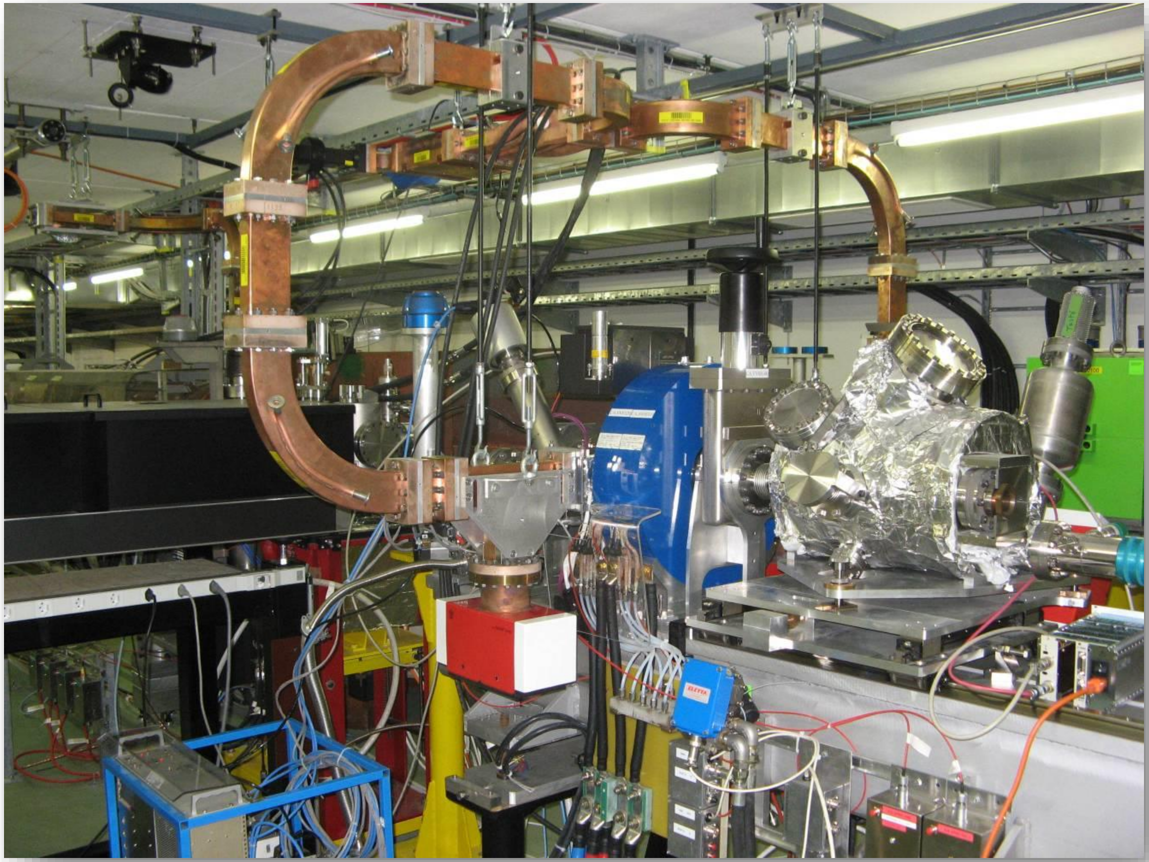
- simple structure, robust, long lifetime
- grid in front of the cathode to switch the current
- good stability (pulse to pulse and long term)
- limited brilliance (”slow“ acceleration)
- main mode of failure: external
  (e.g. power supplies)





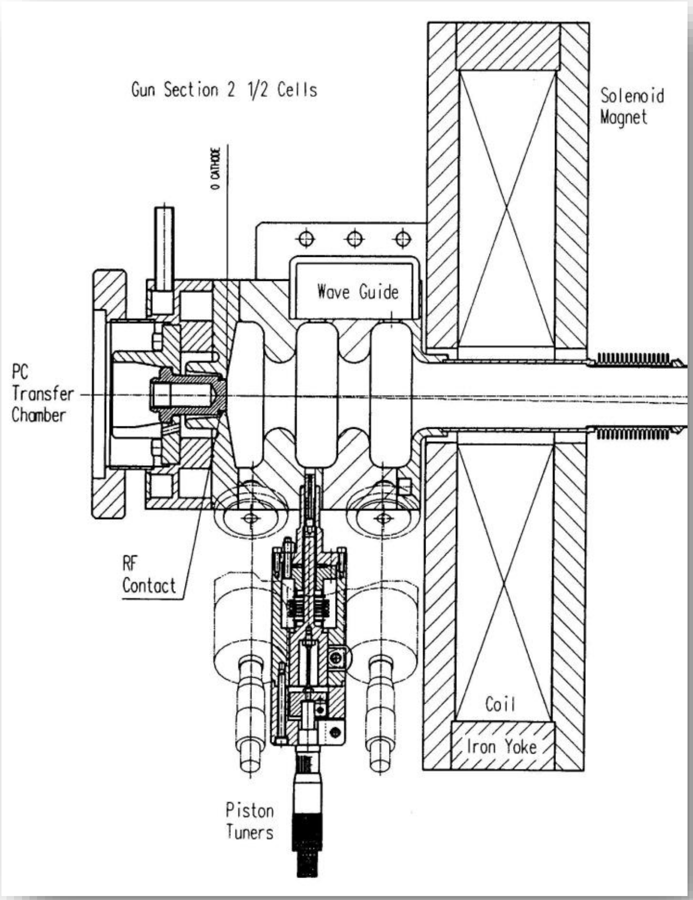


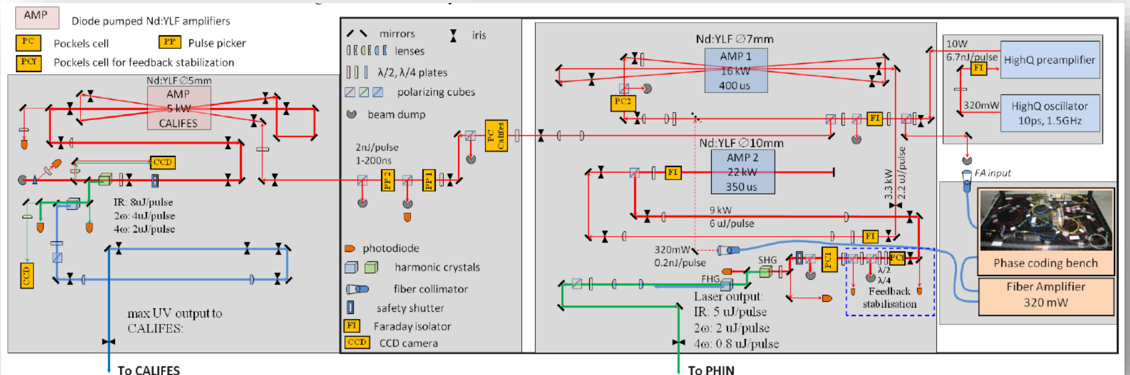
RF gun with photocathode



Location: CTF3 photo injector

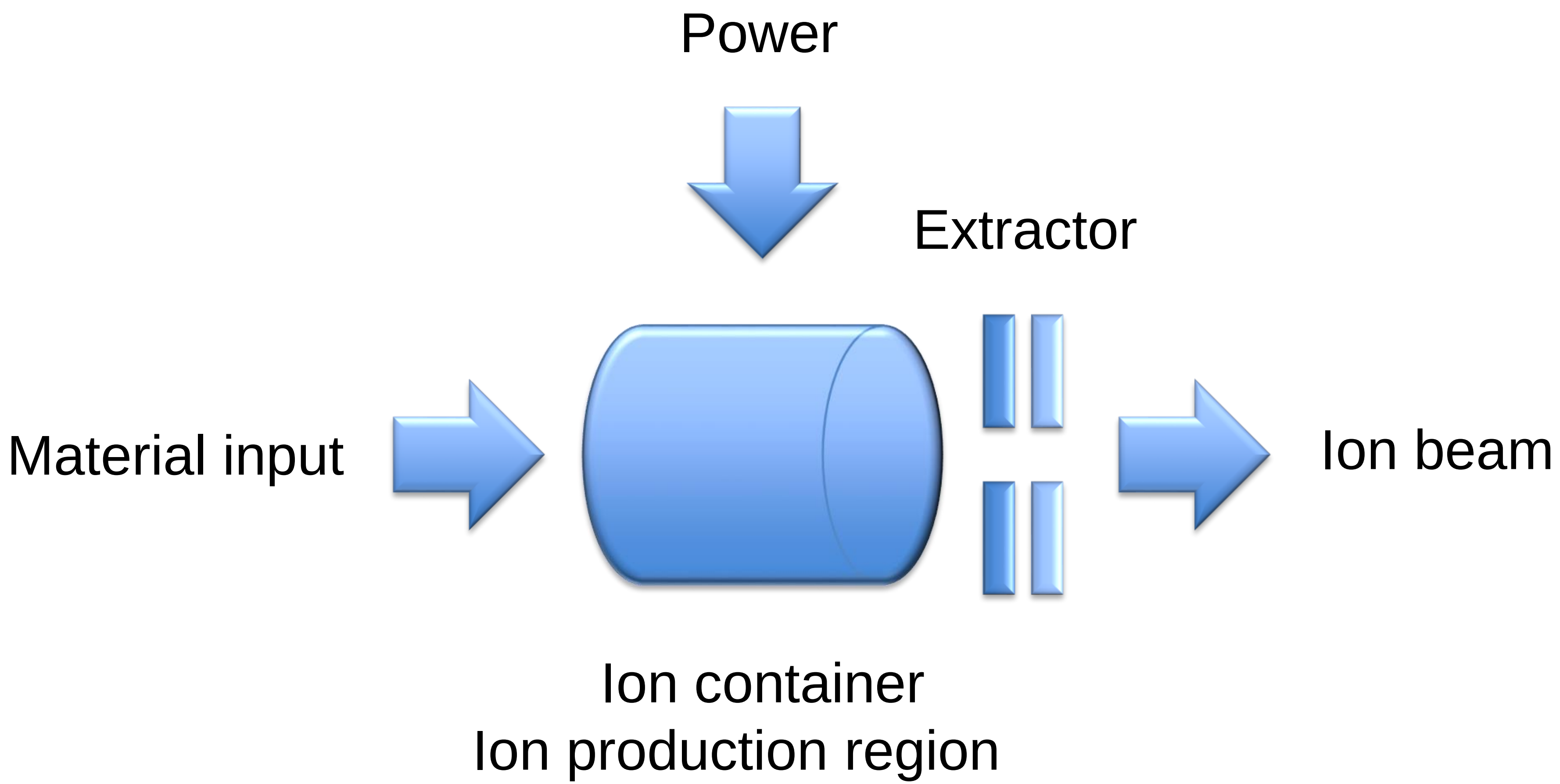
- the concept of the photo injector was first proposed and tested in the mid-1980s by J.S. Fraser and R.L. Sheffield
- a photocathode is enclosed in a 2½ cell RF cavity
- the beam pulse structure is defined by the laser pulse
- the pulse-to-pulse stability depends on the laser (limited)
- high brilliance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





ION SOURCES

Generalized source model

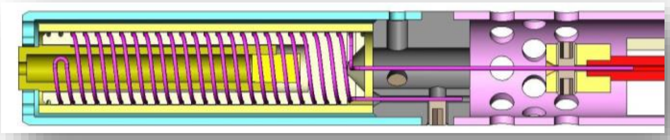


Generalized source model
Ion container and production region

- The container is the main body of the source
- It has an interfaces to the whole source infrastructure (vacuum, cooling, injection, extraction, …)
- It should have a very good base vacuum
  - Impurities have effects on the ion production, the ion life time and can also disturb the source stability and the beam extraction
- In most (but not all) of the sources the ions are created inside a plasma
- The plasma is confined by a magnetic field (big variety of magnetic field structures: cusp, magnetic mirror, …)

Generalized source model
Power and particle input

- Input of power
  - Electrical discharges (filament sustained)
  - Radio frequency (internal or external antenna)
  - Microwave
  - Laser
  - Electron beam
- Input of (neutral) particles
  - Media: gas, liquid, solid, ions
  - Feeding methods: high vapour pressure materials, volatile chemical compounds (MIVOC method), sputtering, oven, laser evaporation, singly charged ion source



These lists are not exhaustive.

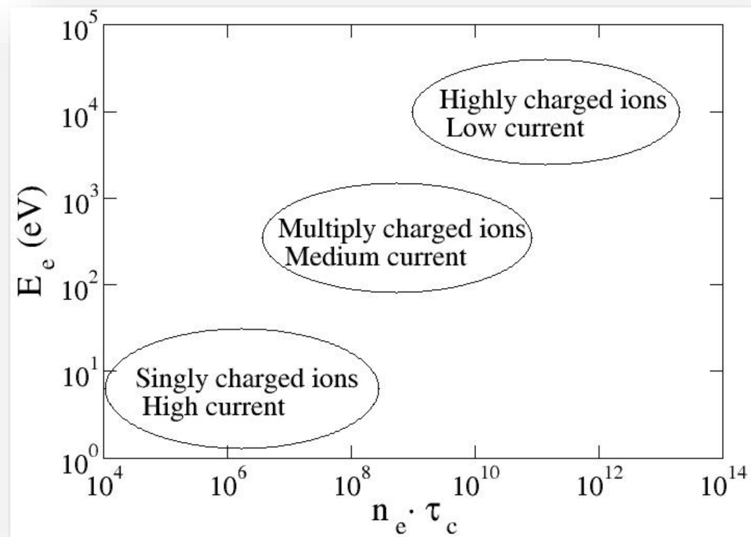
Ion production I

Basic differential equation concerning the ion production process (simplified)

$$\frac{dn_i}{dt} = n_{i-1}\sigma_{i-1,i}j_e - n_i\sigma_{i,i+1}j_e - \frac{n_i}{\tau_c(i)}$$

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

- Terms of ion production
- Terms of ion losses
- The ion confinement time τ_c 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)



Golovanivski plot

Ion production II

Processes increasing the charge state $q^{n+} \rightarrow q^{(n+1)+}$

- Ionization
  - Single ionization
  - Double ionization
  - Creating of higher charge states is a step-by-step process
  - The ionization process has an energy threshold
=> the production of higher charge states needs a higher electron energy
- Charge exchange (for low n)

Processes decreasing the charge state $q^{n+} \rightarrow q^{(n-1)+}$

- 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

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

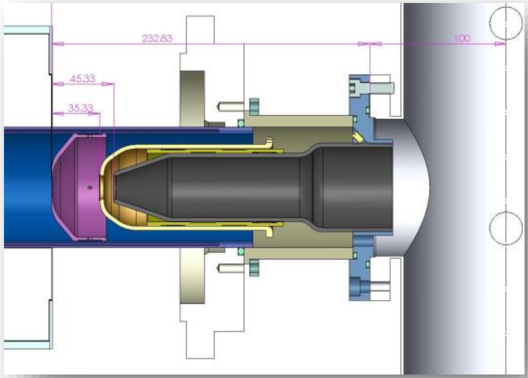
$$\mathrm{H_2}(\nu^{''}) + \mathrm{e}^- \rightarrow \mathrm{H}^- + \mathrm{H}$$

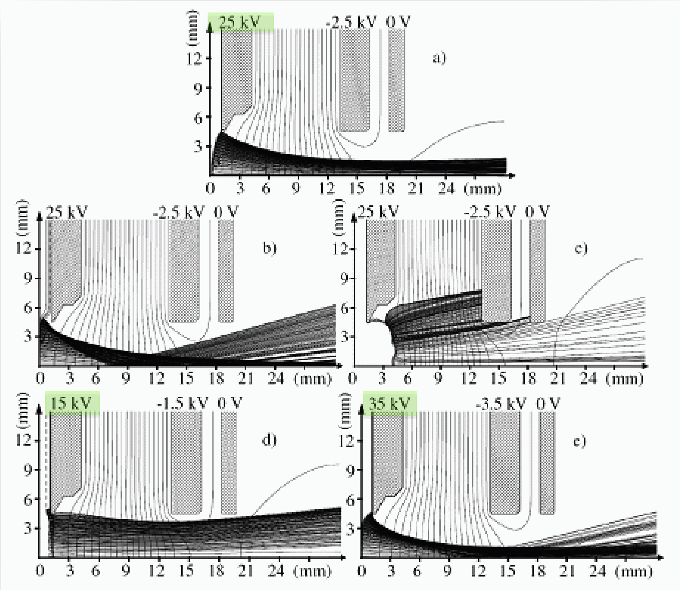
- H^- ions are very sensitive to particle collisions and strong fields (Lorentz stripping)
  => only H^- ions created near to the extraction hole can be extracted

Beam extraction and transport

- The extraction system consists of several electrodes
- In general, the source body is on high voltage and the beam line on ground potential
- The dynamic equilibrium between the plasma and the extracted particles creates a so-called *plasma meniscus*
- Based on the extraction geometry, the extraction voltage and the plasma density the extracted beam can be overfocussed, parallel or divergent
- In the extraction the initial emittance of the beam is created
- The maximum current density *j* in the case of the space charge limit for a gap of the length *d* and an extraction voltage *U* (Child-Langmuir equation)

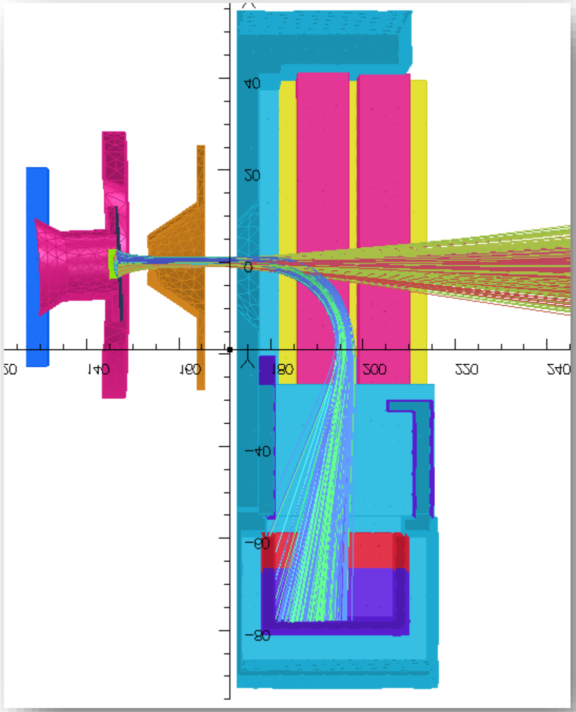
$$j = \frac{4\epsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{U^{3/2}}{d^2}$$

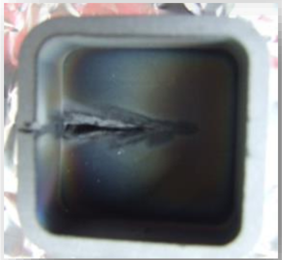


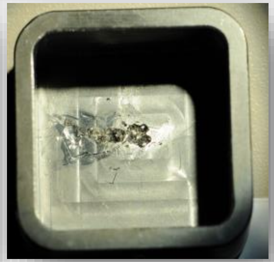


H^- extraction

- In the case of H^- (or other negative ions) electrons are co-extracted
- Ratio e^-/H^- depends on the source type and the production mechanism
- The electrons are influencing the ion beam (space charge)
- Have to be removed from the beam as early as possible
- At full extraction voltage the electron beam can be quite destructive







DESCRIPTION OF SOME SELECTED SOURCE TYPES

Ion source applications

- Primary beam
  - Accelerators (scientific, medical)
  - Neutral beam injector for fusion devices
  - Ion beam lithography for nanostructures
  - Implanter for semiconductor production
- Secondary beam
  - Target ion sources of ISOL facilities
  - Charge breeders

Ion source types

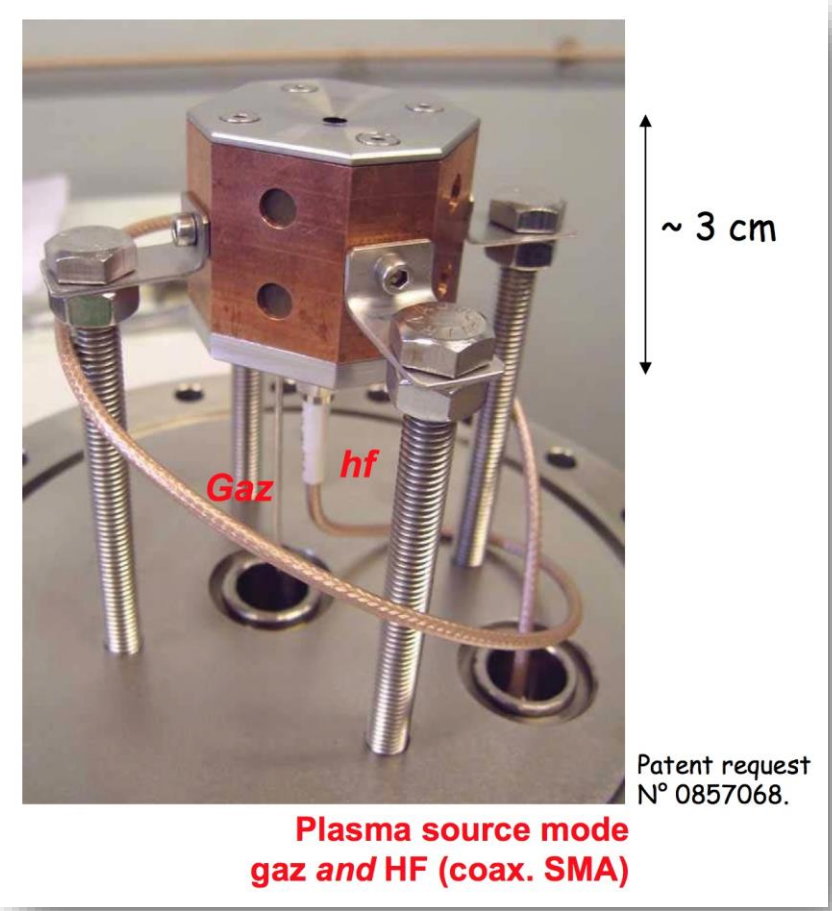
- Duoplasmatron
- Electron cyclotron resonance ion source (ECRIS)
- Electron beam ion source (EBIS)
- Laser ion source (LIS)
- Penning ion source
- RF ion sources
- Metal vapor vacuum arc ion source (MEVVA)
- Liquid metal ion sources

- Sources for negative ions
- Sources for polarized beams

There are small sources

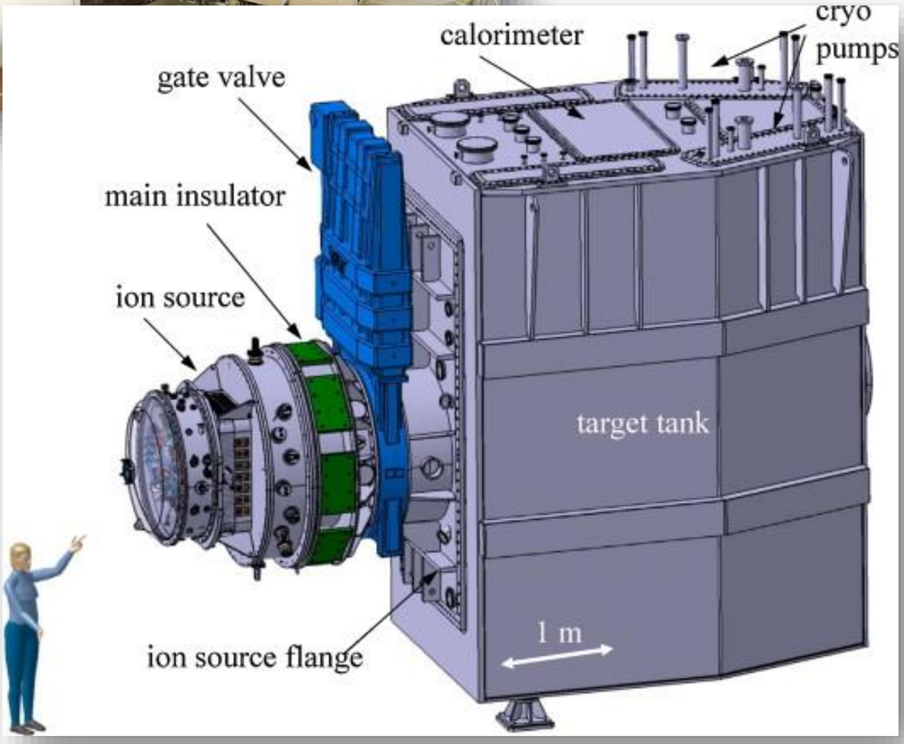
COMIC source

(COmpact MIcrowave and Coaxial)

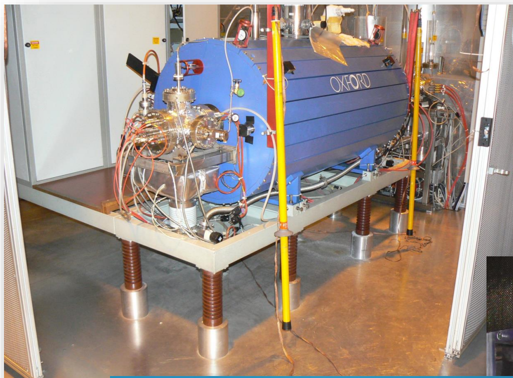


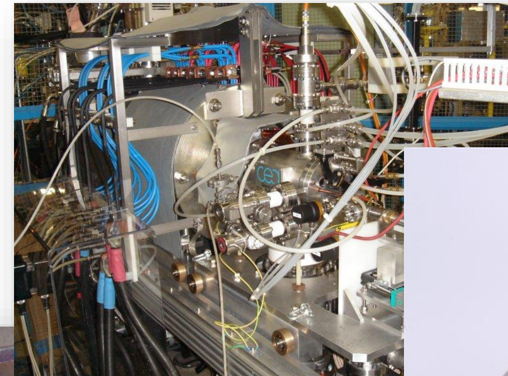
There are big sources

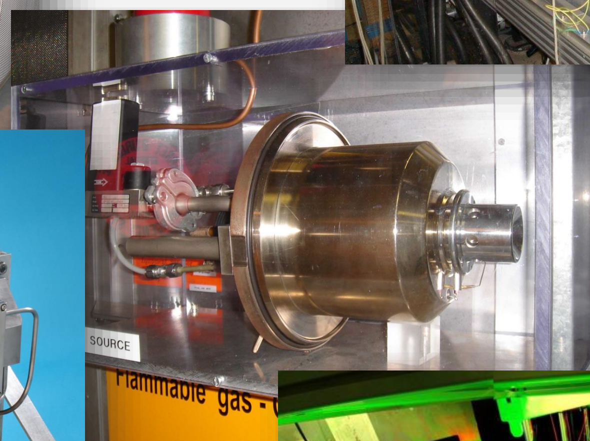
negative ion sources for the neutral beam injector

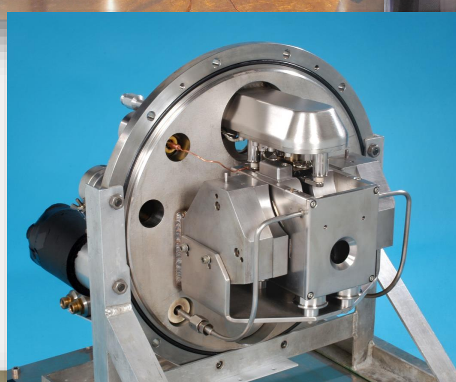


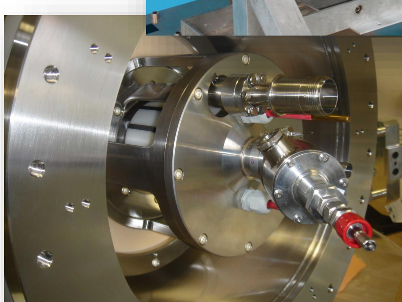
There are sources for any purpose



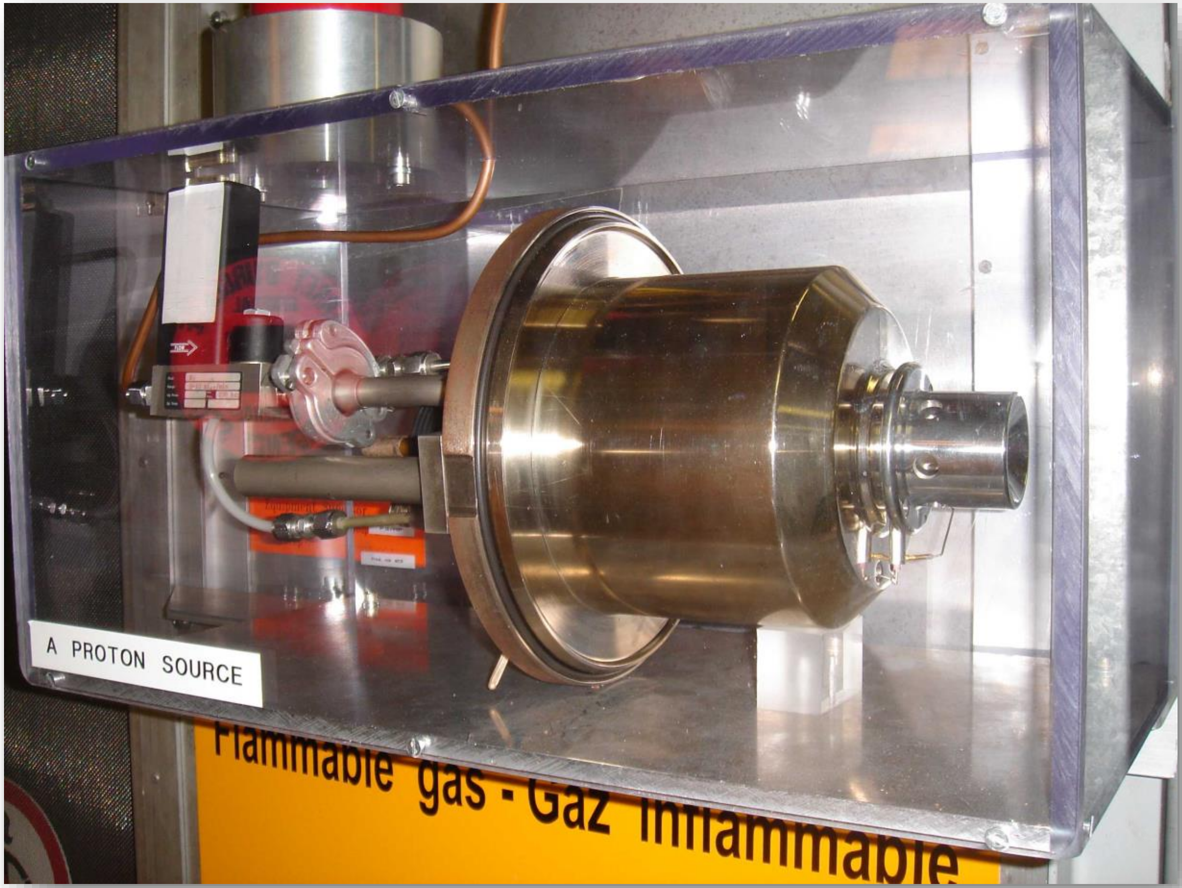








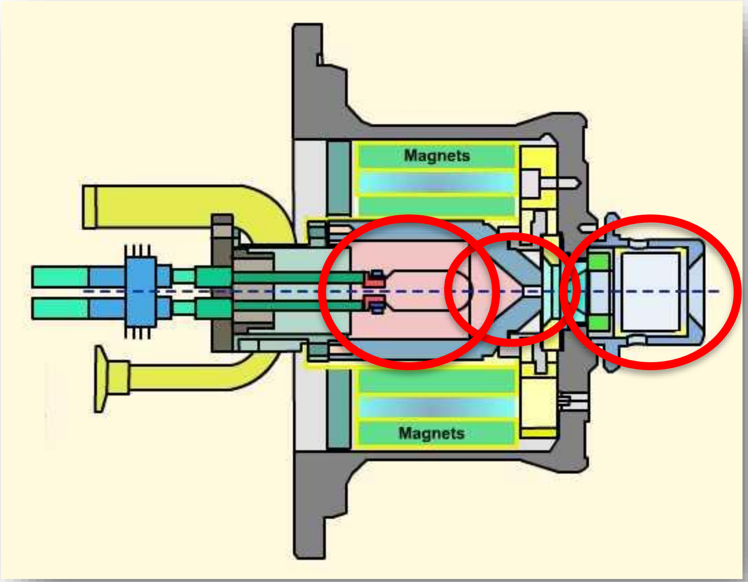
The Duoplasmatron



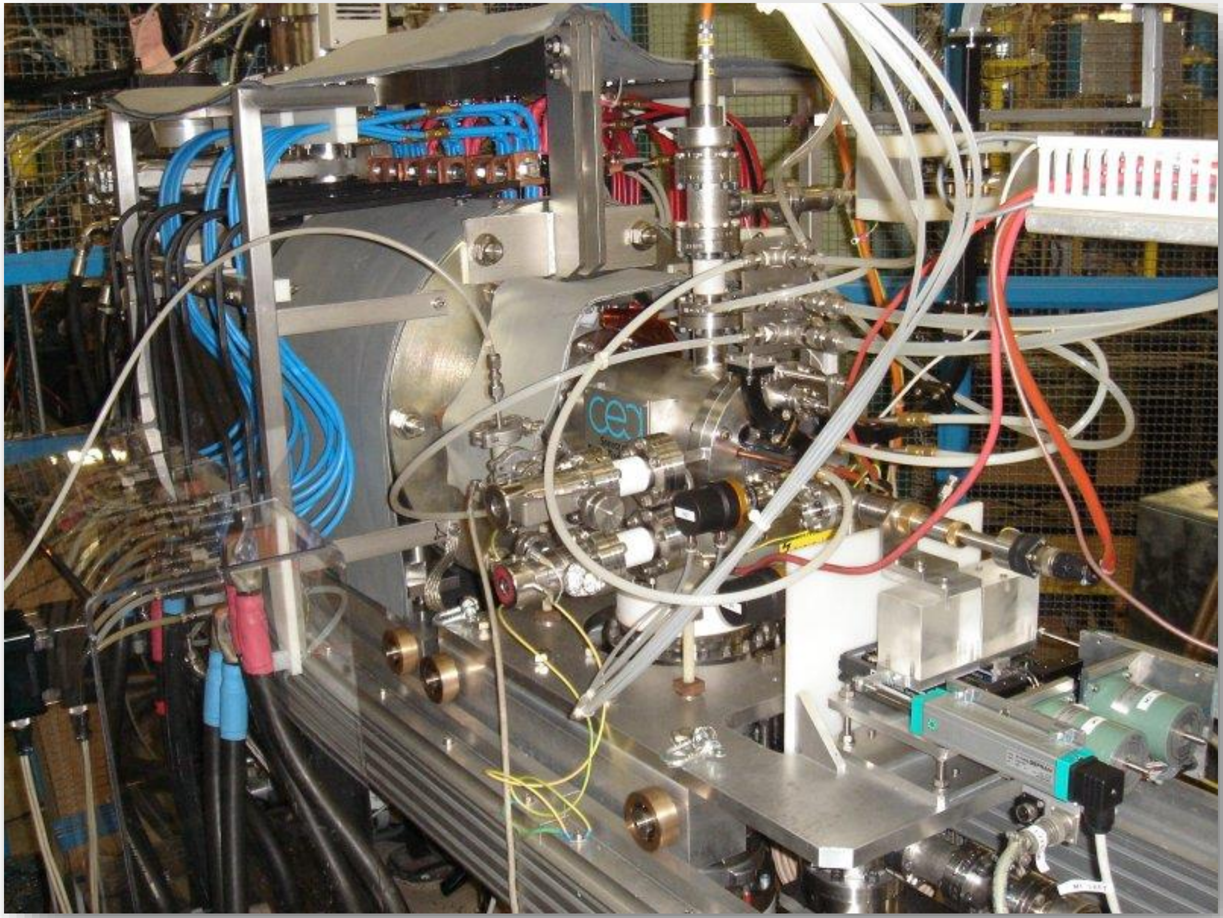
Location: Linac2

The Duoplasmatron II

- Developed 1956 by Manfred von Ardenne (Germany)
- Driven by an arc discharge sustained by a heated filament
- A strong magnetic field in the discharge region increases the plasma density (compared to the cathode region)
- 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
- Hydrogen gas is used as input medium at Linac2 (80-85% H^{+}, the rest are H^{2+}, H^{3+})



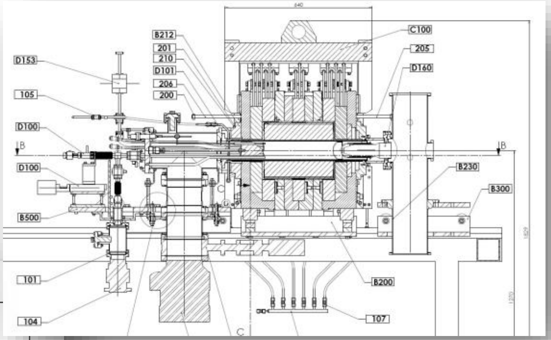
The Electron Cyclotron Resonance Ion Source (ECRIS)

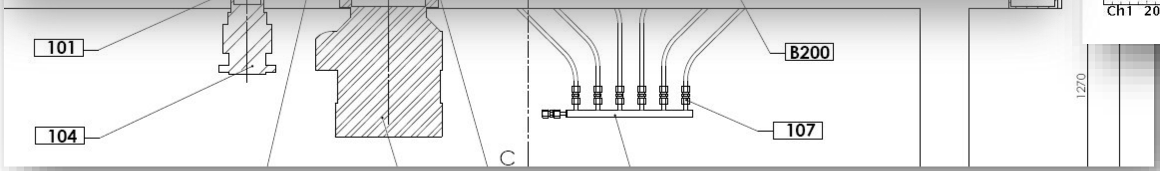


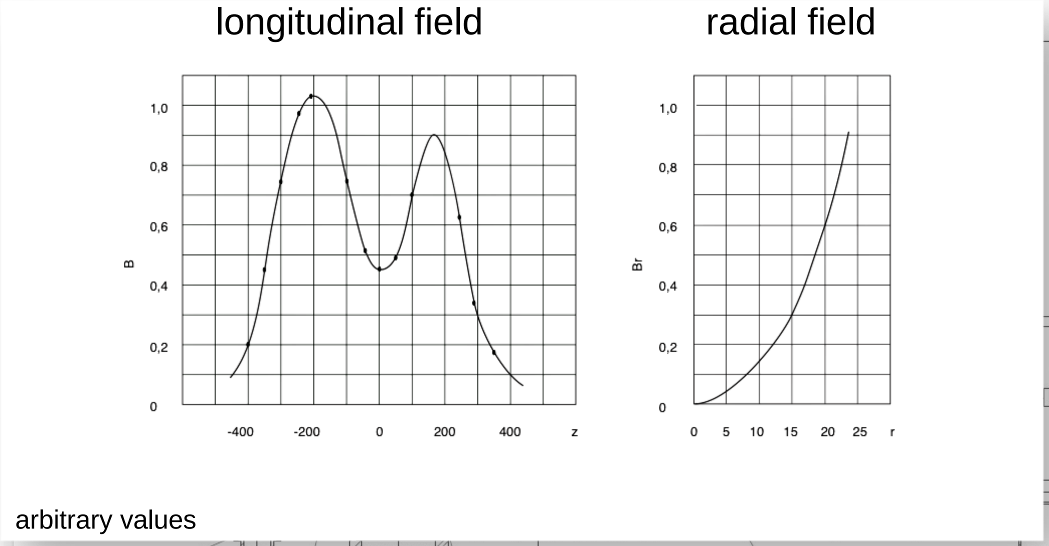
Location: Linac3 (GTS-LHC)

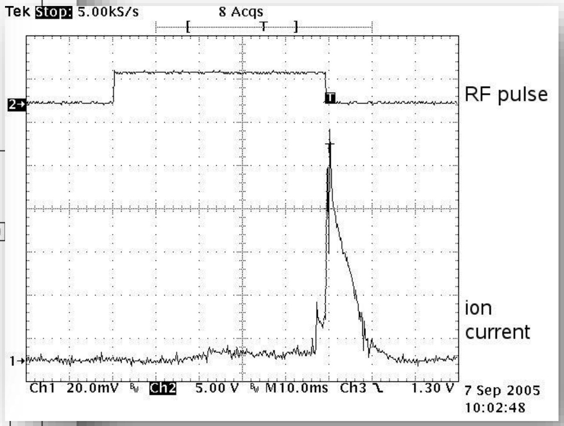
The ECRIS II

- Developed 1965 by Richard Geller (France)
- 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

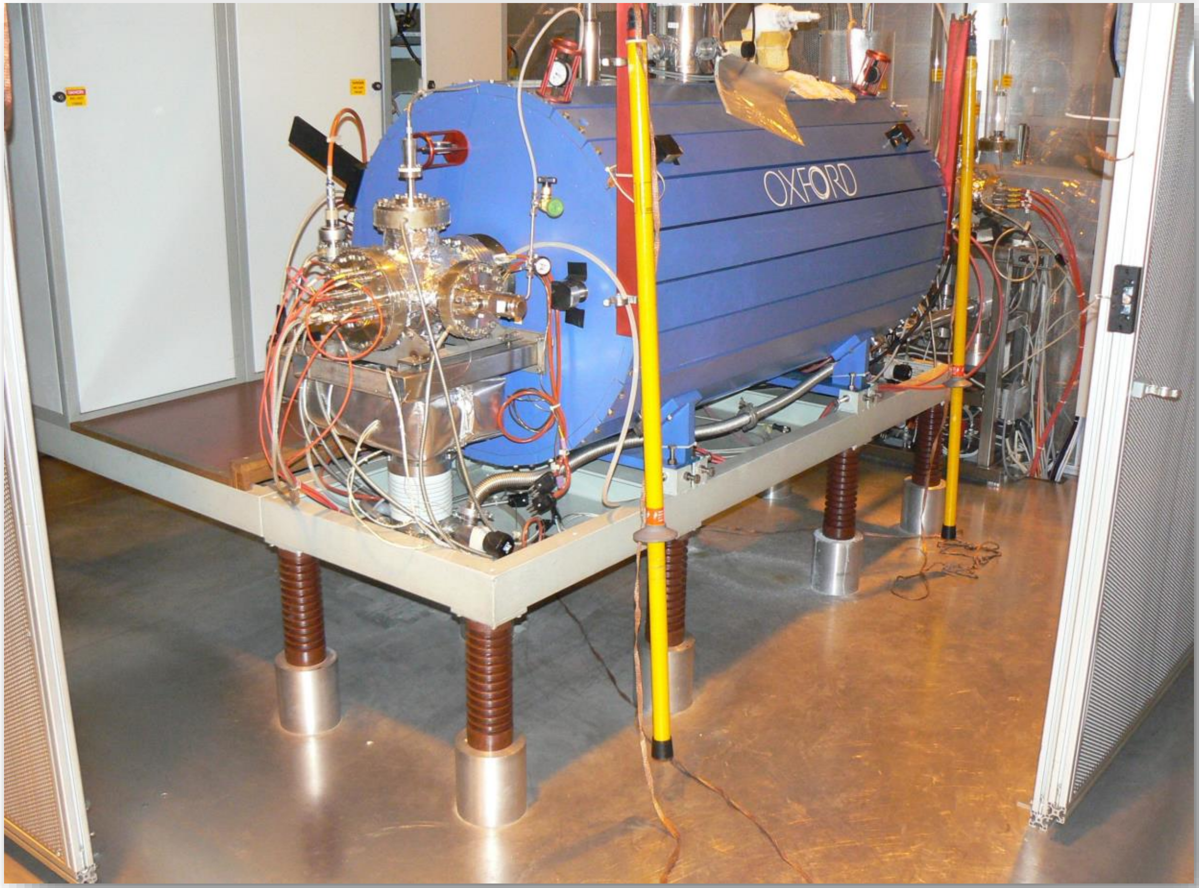








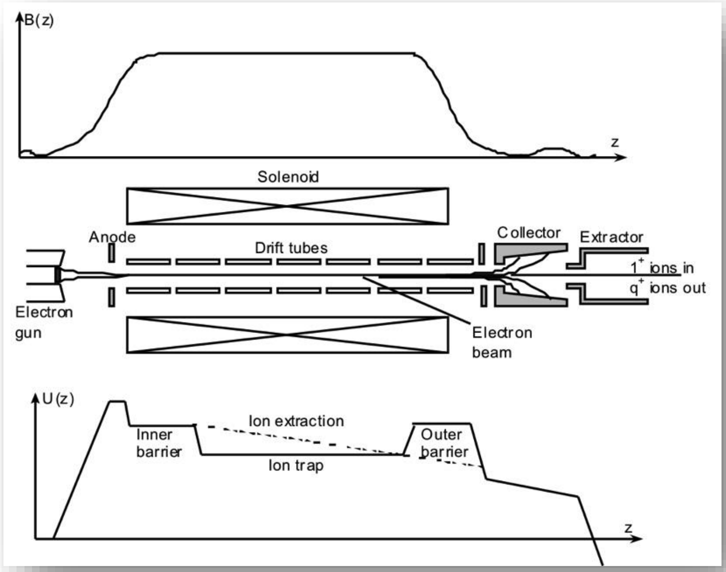
The Electron Beam Ion Source (EBIS)



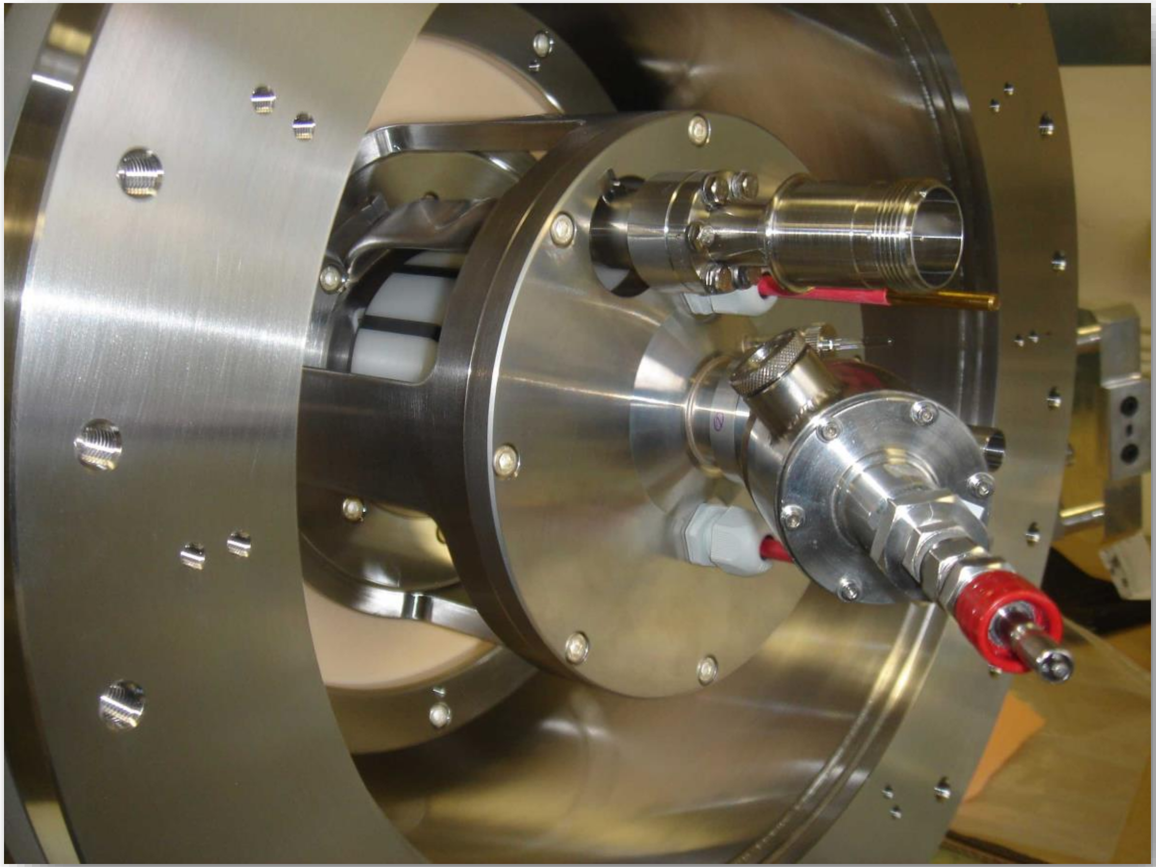
Location: REX ISOLDE

The EBIS II

- Developed 1965 by Evgeni D. Donets (Russia)
- The longitudinal confinement is given by electrostatic fields
- The radial confinement is given by the electron beam, which is compressed by a solenoidal field
- The ionsation takes place inside the high energetic, high density electron beam
- The extraction process is controlled by the voltage level of the trap electrodes
- The ion injection is also controlled by the trap electrodes (monocharged ion injection)
- The total ion current depends on the trap charge capacity
- Low transverse emittance
- Delivers short pulses of high charge states
- The life time and the reliability is mainly defined by the electron gun



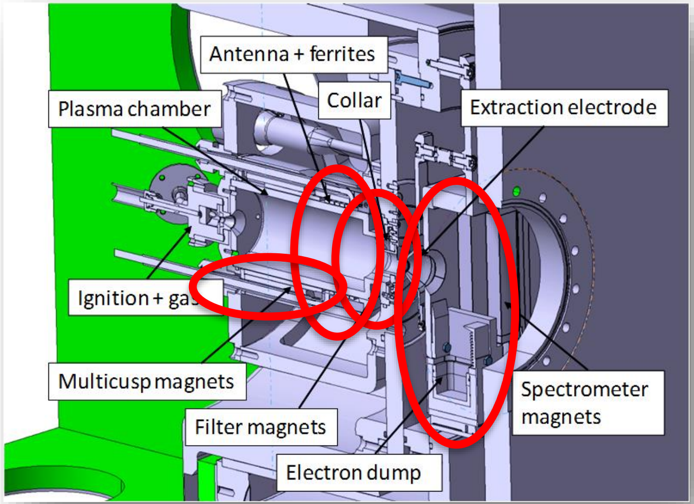
The RF driven H^- source

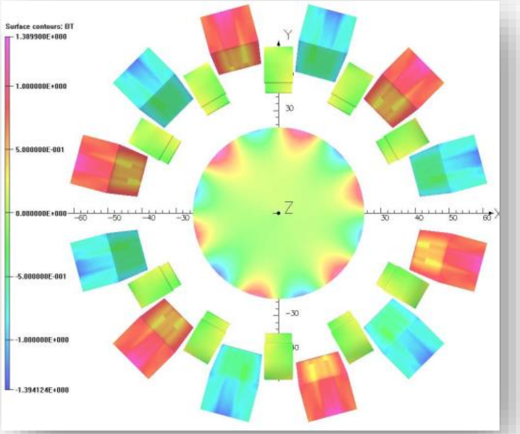


Location: Linac4

The H^- source II

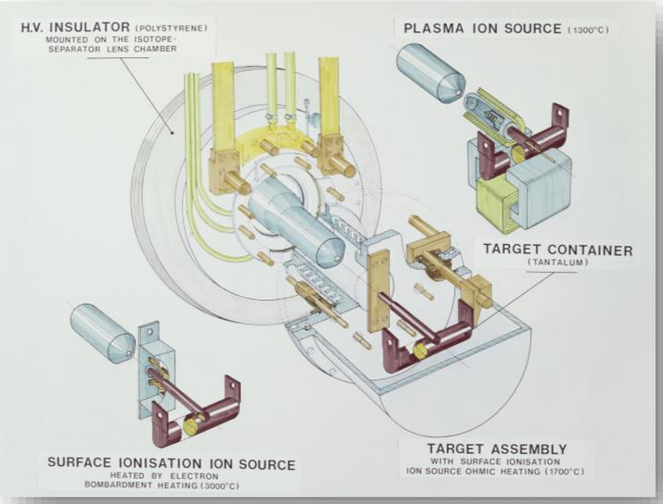
- RF driven ion sources were developed in the late 1940s, negative ion sources were developed according to requirements
- The use of caesium makes the surface process the dominant H^- production mechanism, reduces the number of co-extracted electrons and increases the ion current
- The RF power is coupled inductively into the plasma
- The plasma region separated by a magnetic filter into two regions of different electron temperature
- The plasma could be confined by a magnetic cusp structure
- The co-extracted electrons are removed in an spectrometer
- Delivers pulsed high currents of H^-
- No antenna or filament in the plasma
  ➔ high reliability





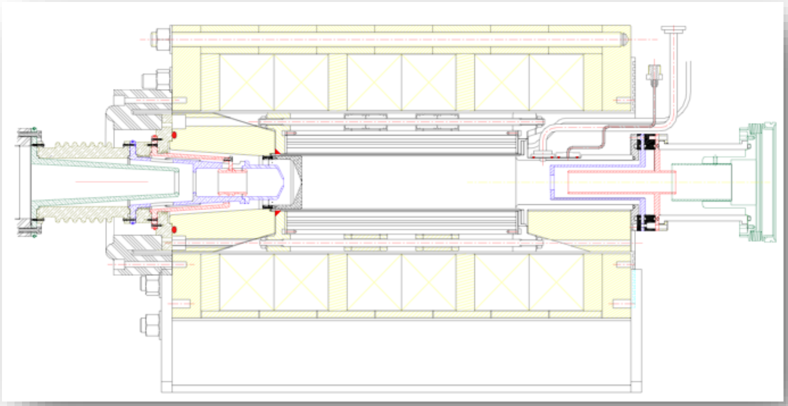
Secondary beams
Target ion sources

- Part of isotope online separators (e.g. ISOLDE)
- Ionizing the material coming from the target (creating a singly charged ion beam)
- Ionization done by different methods, adapted to the isotope (surface ionization, plasma ionization, laser ionization…)
- Special design needed due to high radiation environment

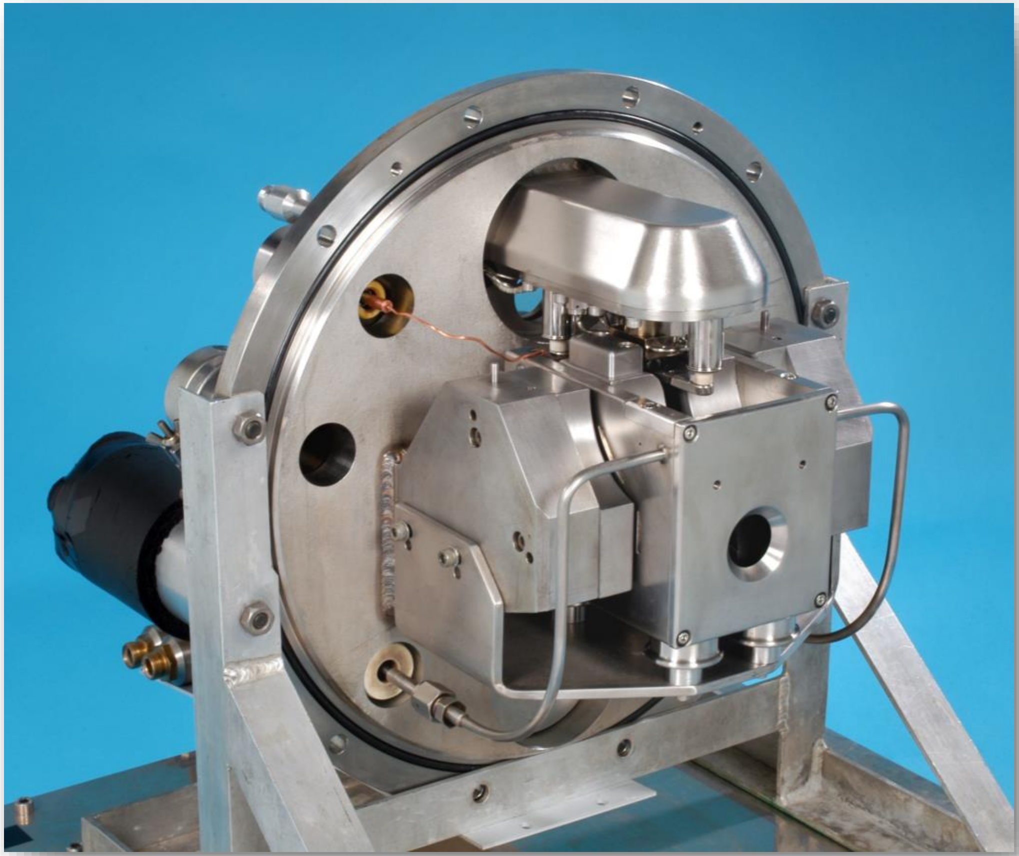


Secondary beams
Charge breeder

- Breed singly charged (radioactive) ions to higher charge states (1+ -> n+)
- Post-accelerator can be more compact and efficient for n+ ions
- Source has to accumulate a (continuous) current of singly charged ions, breed it to higher charge states and and release them in a pulse
- For radioactive beams the breeding efficiency is very important (ionization time, ionization efficiency)
- Source types used: ECRIS, EBIS
- Source needs to be adapted for the injection of singly charged ions



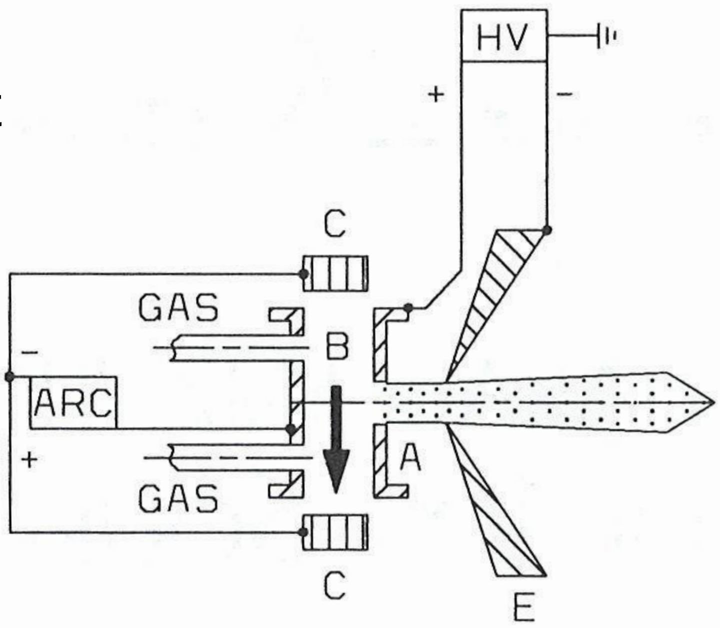
The Penning ion source



Location: ISIS/Rutherford Appleton Laboratory near Oxford

Penning source II

- Penning discharge investigated by L.R. Maxwell in 1931
- Penning source first used as internal sources in cyclotrons in the 1940's
- hollow anode cylinder with a cathode on each end
- strong axial field confines the electrons
- cathode could be cold, hot or a filament with cold anticathode
- radial extraction through a slit in the anode
- used for singly charged, multiply charged or negative ions
- short life time due to erosion
- limited beam quality (beam noise and distorted emittance due to extraction from a slit)



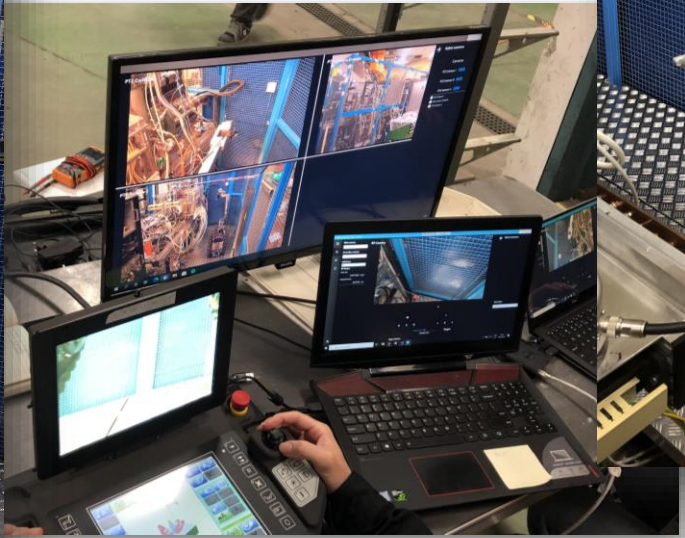
ENGINEERING

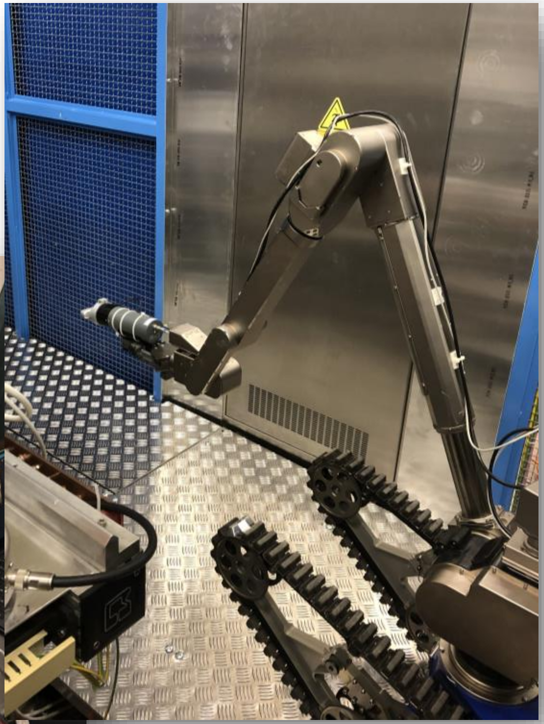
Not to forget …

- Vacuum
- High voltage
- Microwaves
- Cooling
- Control system
- Interlocks
- Safety

… and sometimes one can have real fun

Radiation measurements at an unshielded source with a robot





CONCLUSION

Summary

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

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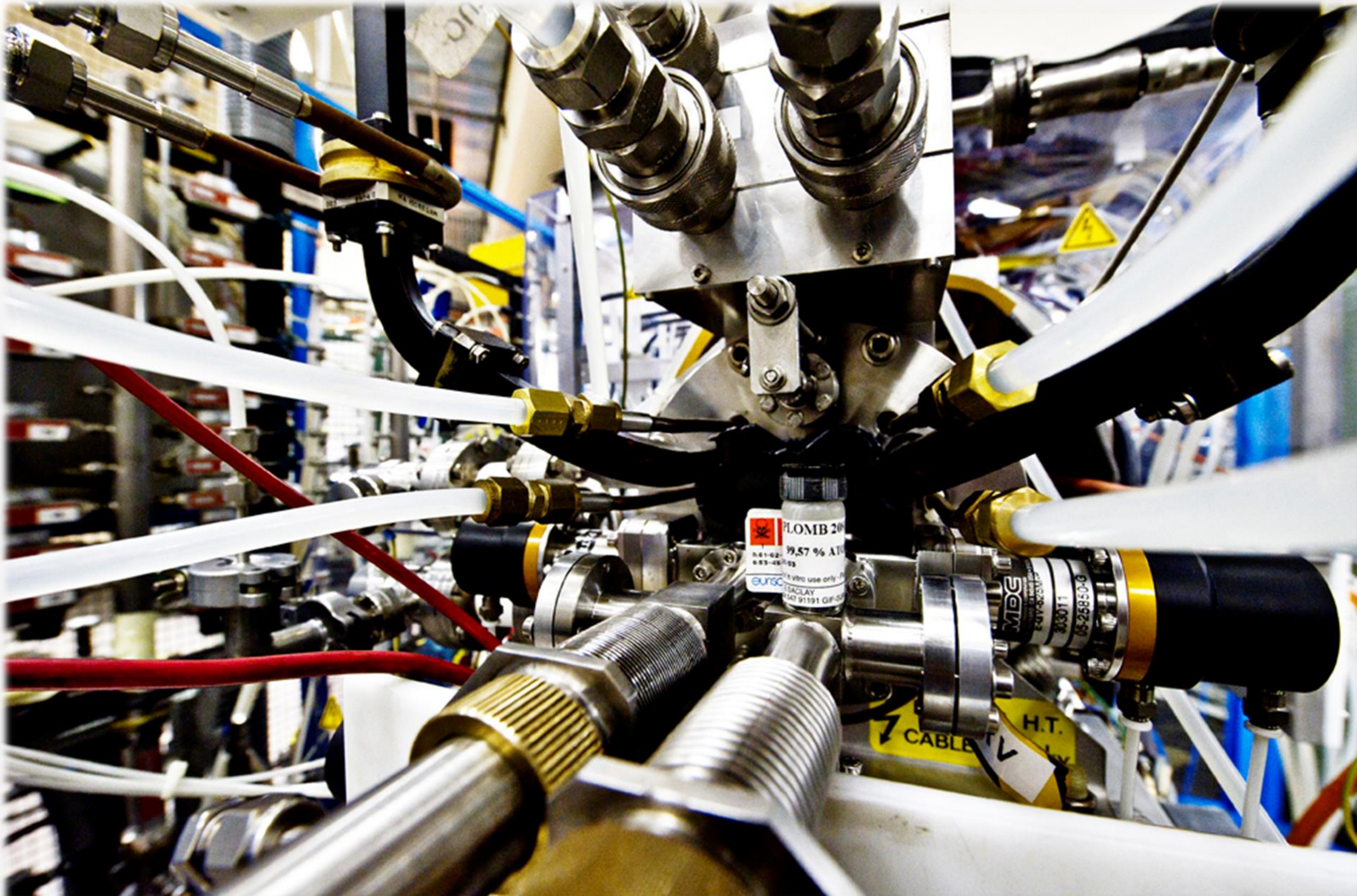

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