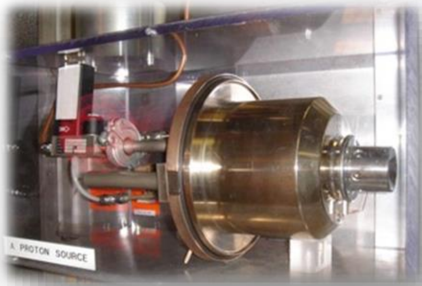
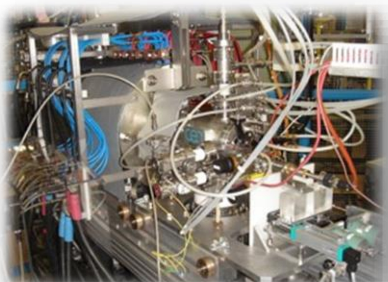
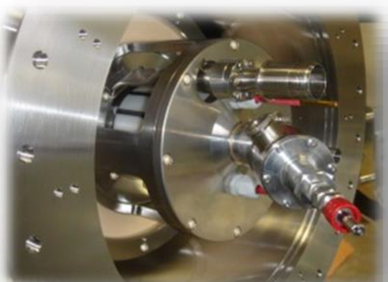






Ion source physics and technology

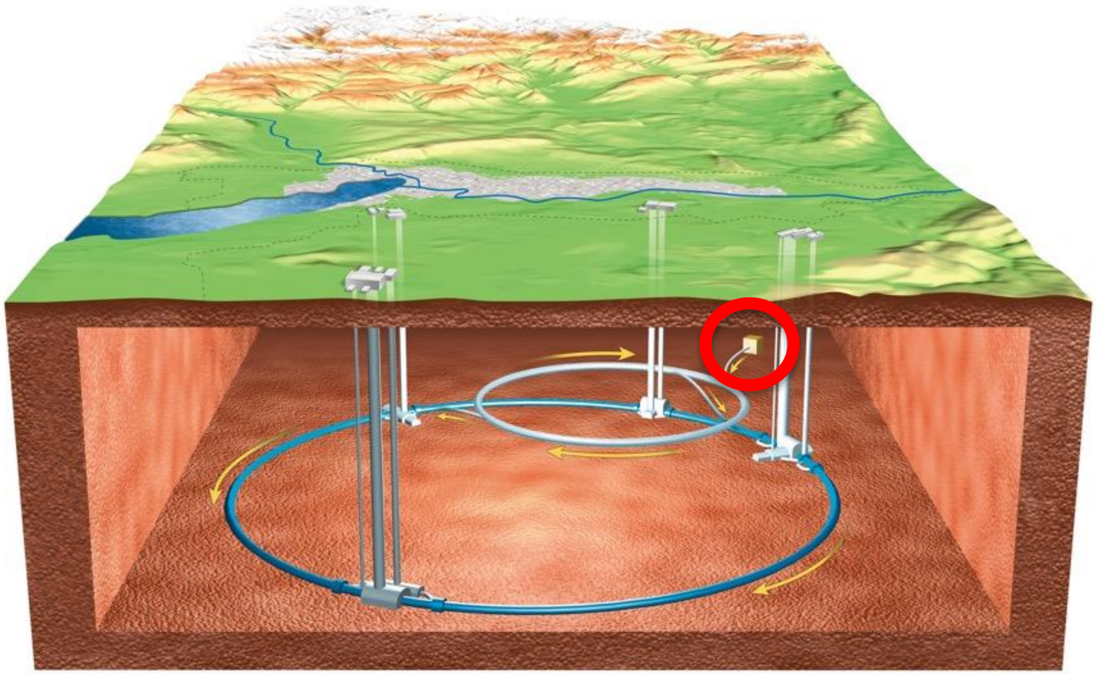
Detlef Küchler
CERN/BE/ABP/HSL

INTRODUCTION

What is an ion source?

For an accelerator physicist an ion source is somewhere far away.

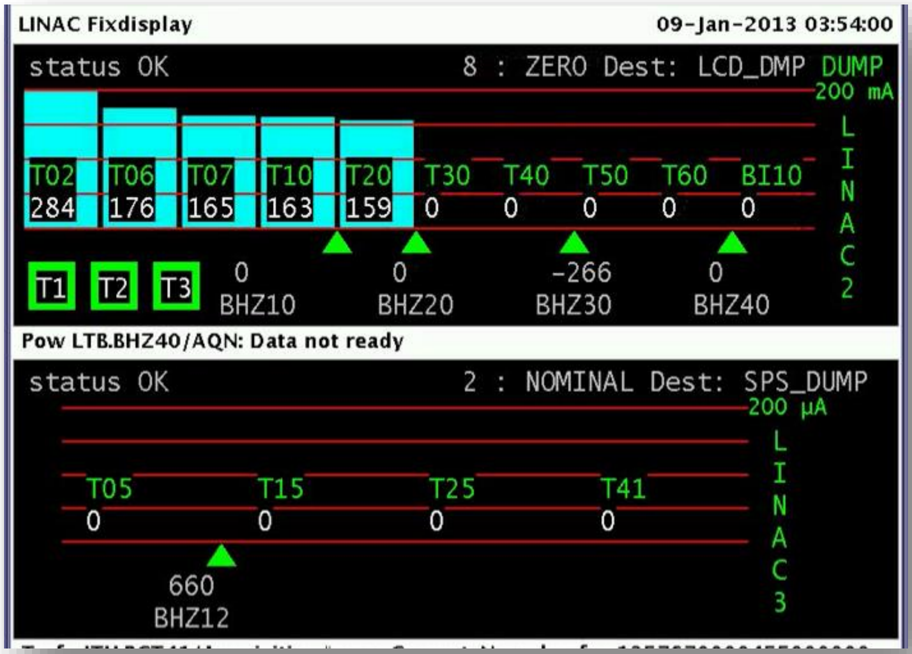
It is a black box with three buttons:



- On/Off
- Particle type
- Intensity

What is an ion source?

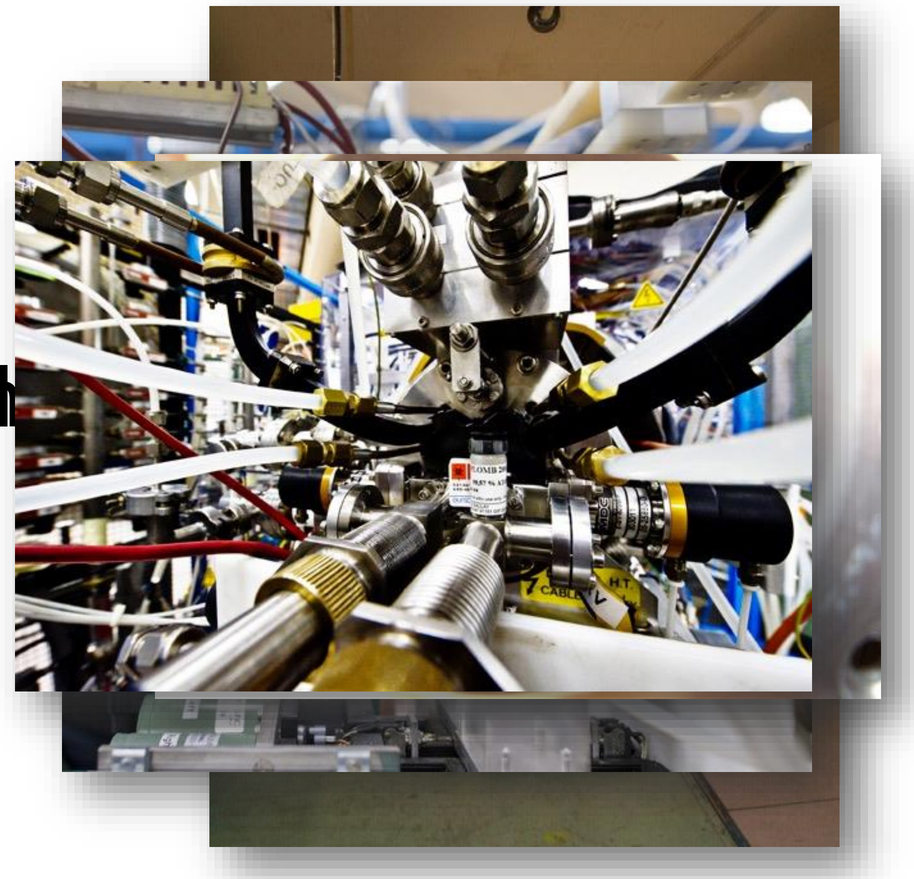
For an operator, if there is a problem, it must be the ion source!



What is an ion source?

For an ion source physicist an ion source is

… [illegible]



What is an ion source?

Definition (for primary beams)

An ion 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 ions, molecules and clusters.

Why we have to create a charged particle beam?

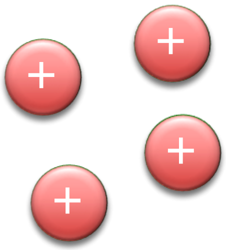
Ordinary matter is neutral.

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 ion source

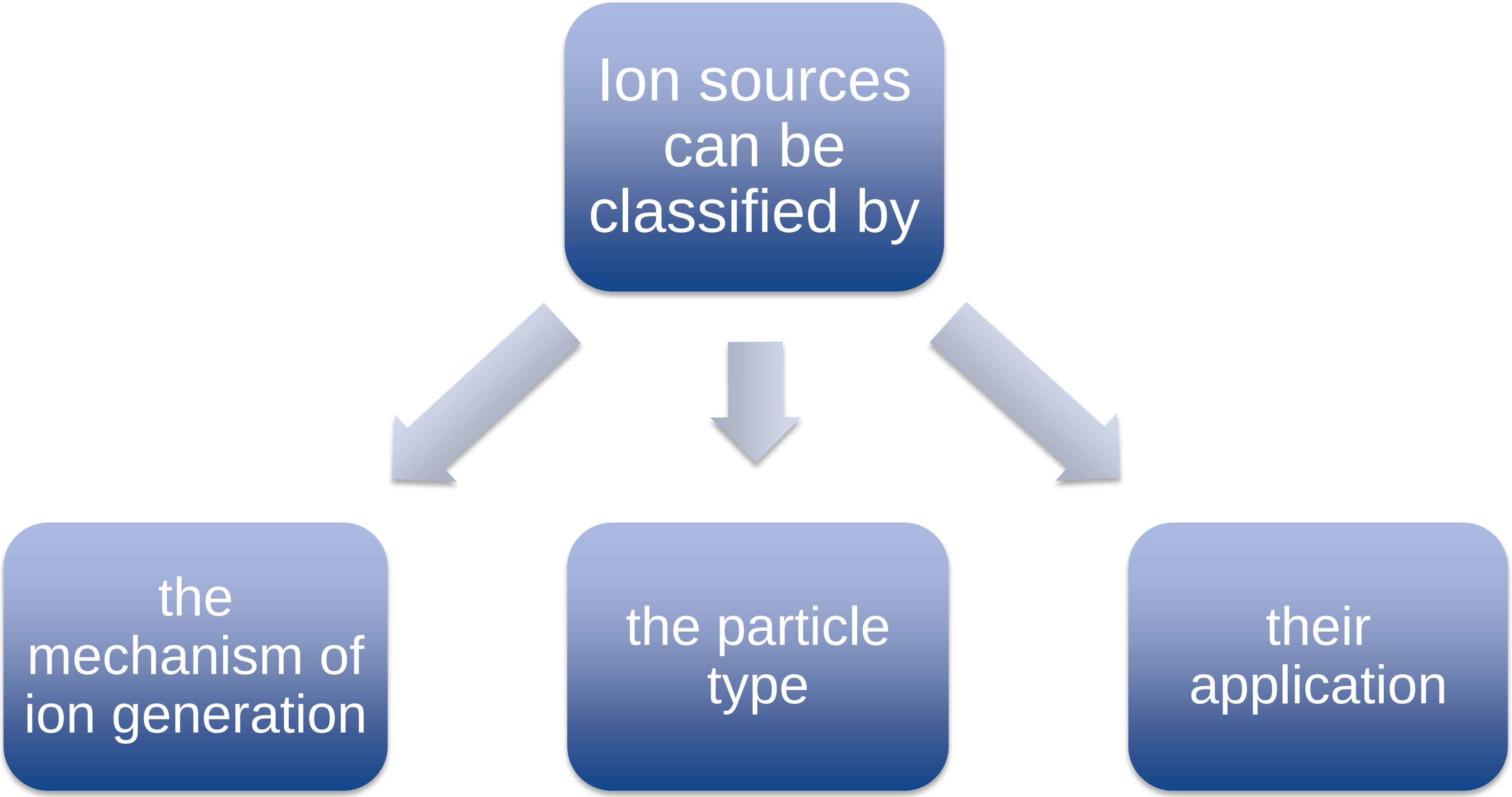
- ionizes the particles
- shapes a beam



The main beam properties are defined at the source

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

Classification of ion sources



Classification by ion generation mechanism

The ionization takes place

- in a plasma
- by electron bombardment
- due to field ionization
- on a surface
- due to laser irradiation
- due to charge transfer

The list is not complete.

Classification by particle type

Ion sources for

- positive ions
- molecular ions
- polarized ions
- negative ions
- cluster

The list is not complete.

Classification by application

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

The list is not complete.

Some ion source types

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

Why do we have to speak about ion sources?

- The ion source is an essential part of an accelerator.
- It is important to understand the limitations of the source (beam properties, reliability, life time).
- 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.

What will this lecture provide?

- some basic principles of ion production and beam extraction
- some examples of ion 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 plasmas,
  ion production and beam extraction
- the complete overview of all types of ion sources and their technical background
- in-depth explanations

For more information see the books listed in the bibliography.

Structure of this lecture

Atomic physics

- Rate equation
- Atomic processes

Plasma physics

- Plasma parameters
- Particle processes

Source physics

- Source principle
- Source operation
- Beam extraction

Engineering

- Technical infrastruc-ture to operate an ion source

ATOMIC PHYSICS

Basic differential equation concerning the ion production process - Rate equation

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

- n_i – ion density of the charge state i
- $\sigma_{i,i-1}$ – cross section going from the charge state i to the charge state i-1
- j_e – electron current density ($j_e = n_e \times v_e$)
- $\tau_c(i)$ – ion confinement time

Basic differential equation concerning the ion production process - Rate equation

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

Terms of ion production

Terms of ion losses

- The equation is simplified. Some source and loss terms are missing.
- The creation of higher charge states is a stepwise process.
- A similar equation describes the evolution of the energy density.

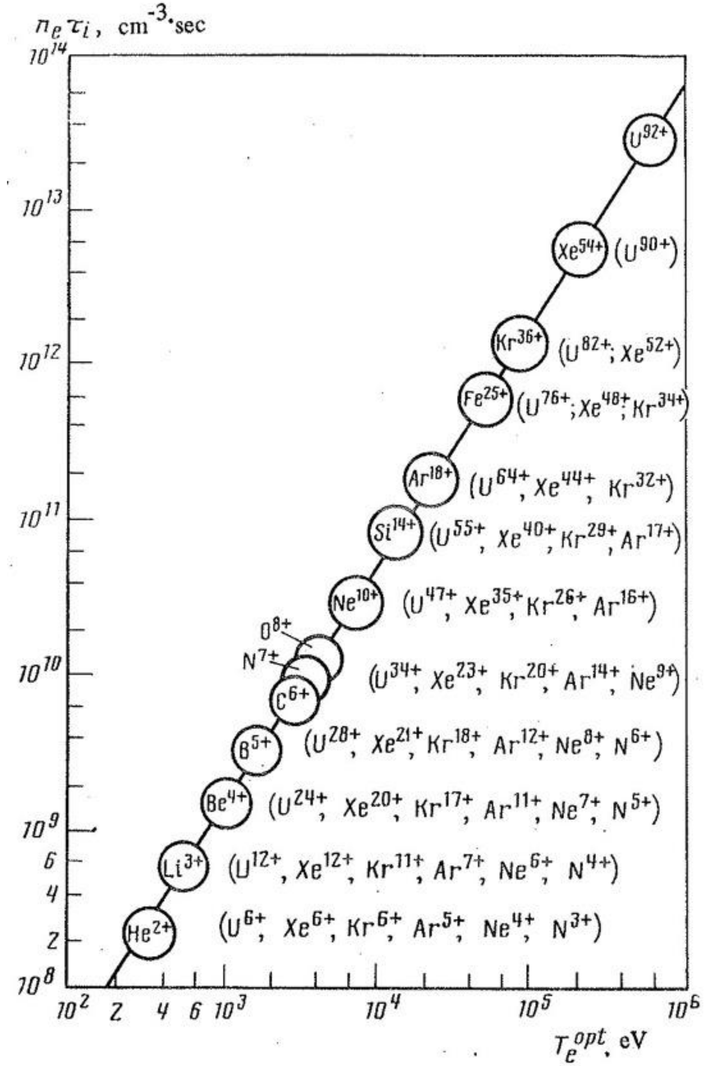
More precise example

$$
\begin{aligned}
\frac{dN_q^k}{dt} = \; & N_{q-2}^k j_e \sigma^k_{I2:q-2\to q} + N_{q-1}^k \Bigg[j_e \sigma^k_{I:q-1\to q} + N_{q-1}^k v^{kk}_{q-1,q-1} \sigma^{kk}_{EX:q-1\to q,q-1\to q-2} \\
& + 2N_{q+1}^k v^{kk}_{q-1,q+1} \sigma^{kk}_{EX:q-1\to q,q+1\to q} + \sum_{i=q+2}^{Z^k} N_i^k v^{kk}_{q-1,i} \sigma^{kk}_{EX:q-1\to q,i\to i-1} \\
& + \sum_{\forall j\neq k} \sum_{i=q-1}^{Z^j} N_i^j v^{kj}_{q-1,i} \sigma^{kj}_{EX:q-1\to q,i\to i-1} \Bigg] \\
& - N_q^k \Bigg[j_e \left(\sigma^k_{I:q\to q+1} + \sigma^k_{I2:q\to q+2} + \sigma^k_{RR:q\to q-1} \right) + N_0^k v^{kk}_{q,0} \sigma^{kk}_{EX2:q\to q-2,0\to 2} \\
& + \sum_{i=0}^{q-2} N_i^k v^{kk}_{q,i} \sigma^{kk}_{EX:q\to q-1,i\to i+1} + 2N_q^k v^{kk}_{q,q} \sigma^{kk}_{EX:q\to q-1,q\to q+1} \\
& + \sum_{i=q+2}^{Z^k} N_i^k v^{kk}_{q,i} \sigma^{kk}_{EX:q\to q+1,i\to i-1} + \sum_{\forall j\neq k} \Bigg(N_0^j v^{kj}_{q,0} \sigma^{kj}_{EX2:q\to q-2,0\to 2} \\
& + \sum_{i=0}^{q} N_i^j v^{kj}_{q,i} \sigma^{kj}_{EX:q\to q-1,i\to i+1} + \sum_{i=q}^{Z^j} N_i^j v^{kj}_{q,i} \sigma^{kj}_{EX:q\to q+1,i\to i-1} \Bigg) \Bigg] \\
& + N_{q+1}^k \Bigg[j_e \sigma^k_{RR:q+1\to q} + \sum_{i=0}^{q-2} N_i^k v^{kk}_{q+1,i} \sigma^{kk}_{EX:q+1\to q,i\to i+1} \\
& + N_{q+1}^k v^{kk}_{q+1,q+1} \sigma^{kk}_{EX:q+1\to q,q+1\to q+2} + \sum_{\forall j\neq k} \sum_{i=0}^{q+1} N_i^j v^{kj}_{q+1,i} \sigma^{kj}_{EX:q+1\to q,i\to i+1} \Bigg] \\
& + N_{q+2}^k \Bigg[N_0^k v^{kk}_{q+2,0} \sigma^{kk}_{EX2:q+2\to q,0\to 2} + \sum_{\forall j\neq k} N_0^j v^{kj}_{q+2,0} \sigma^{kj}_{EX2:q+2\to q,0\to 2} \Bigg] - \left[\frac{dN_q^k}{dt} \right]^{\mathrm{esc}}
\end{aligned}
$$

… but this is still only one equation of the complete differential equation system!

Golovanivskii plot

- The ion confinement time τ_c and the electron density n_e are influencing the maximum charge state that could be reached.
- The confinement time influences the losses from the plasma and in this way the ion current that can be extracted (high confinement time => low ion current).



K.S. Golovanivskii, Magnetic mirror trap with electron-cyclotron plasma heating as a source of multiply charged ions, Instrum Exp Tech; (1986) p. 989.

Main atomic processes

Charge state increasing reactions

- Electron impact ionization
- Charge exchange
- Surface ionization
- Photoionization
- Field ionization

Charge state lowering reactions

- Radiative recombination
- Dielectronic recombination
- Charge exchange

Electron impact ionization

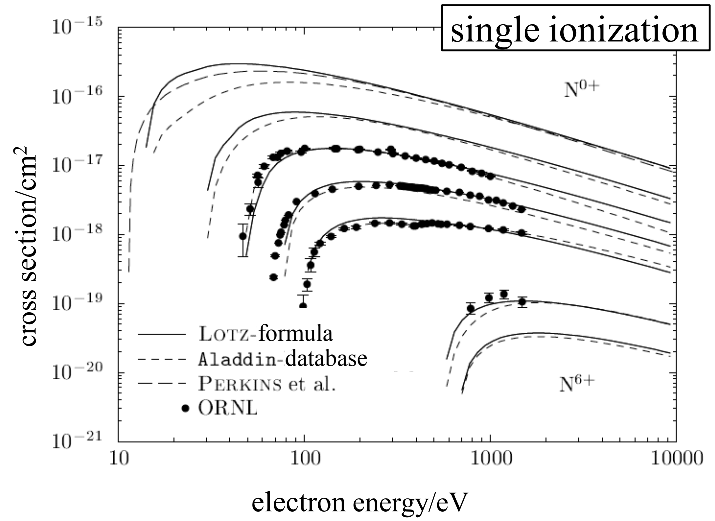
- dominant ionization process in plasmas
- single ionization

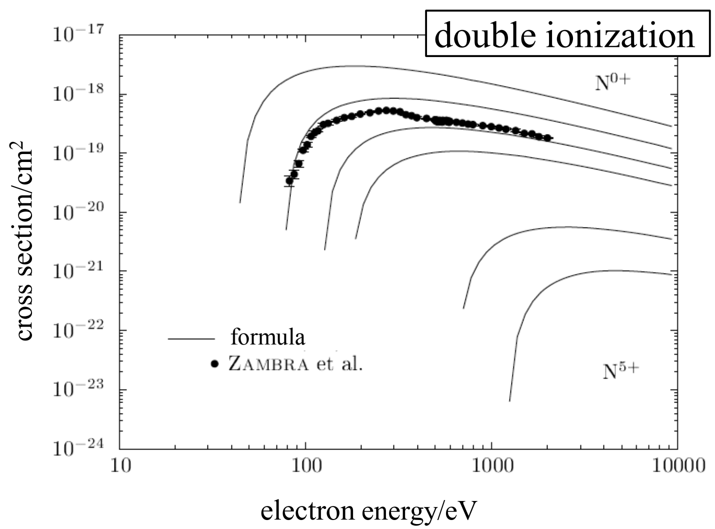
$$A^{q+} + e^{-} \rightarrow A^{(q+1)+} + 2e^{-}$$

- double ionization

$$A^{q+} + e^{-} \rightarrow A^{(q+2)+} + 3e^{-}$$

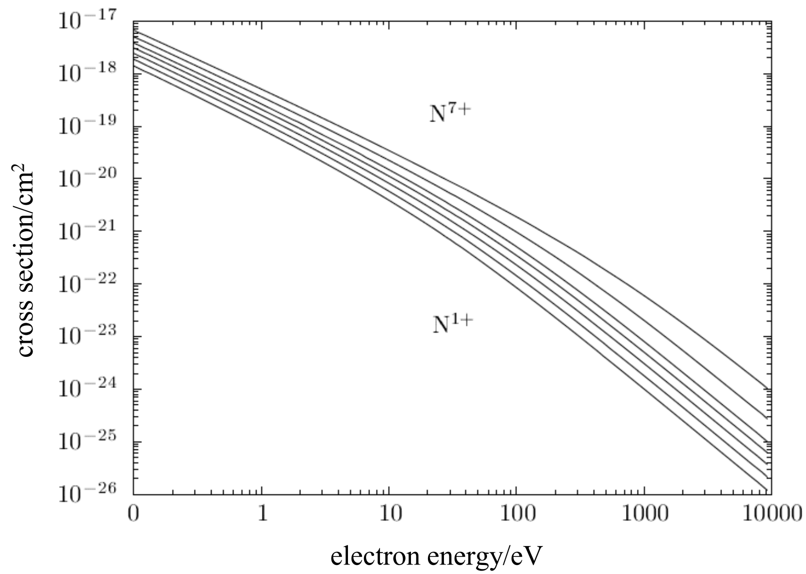
- energy threshold (ionization energy) => the production of higher charge states needs a higher electron energy
- the cross section has its maximum at around two to three times the ionization energy
- the ionization rate has its maximum at around five times the ionization energy





Radiative recombination

- $A^{q+} + e^{-} \rightarrow A^{(q-1)+} + hn$
- Limiting process towards higher charge states
- The cross sections are bigger for lower electron temperatures and higher charge states



Charge exchange

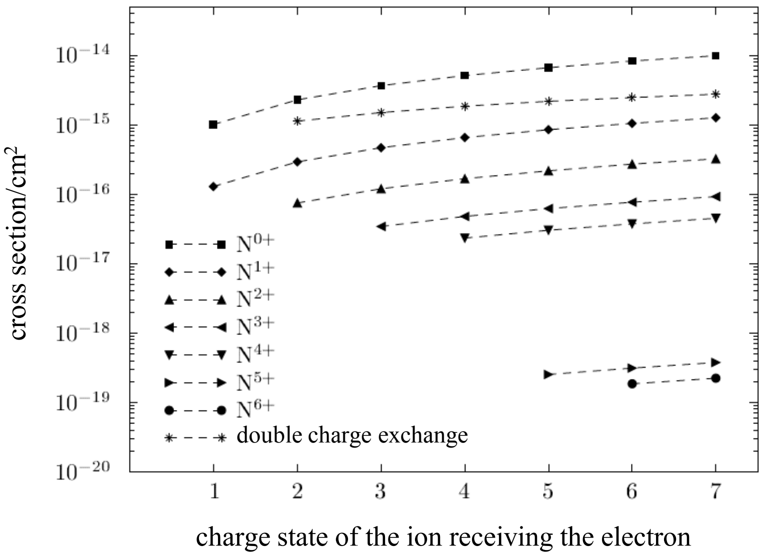
- the charge exchange acts in both directions
  - increases the charge state for low q
  - lower the charge state for high q
  - it is also possible between different ion charge states
- depends on the neutral particle density (rest gas)
- cross sections are bigger for higher charge states

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+}$$

$$A^{q+} + B \rightarrow A^{(q-2)+} + B^{2+}$$

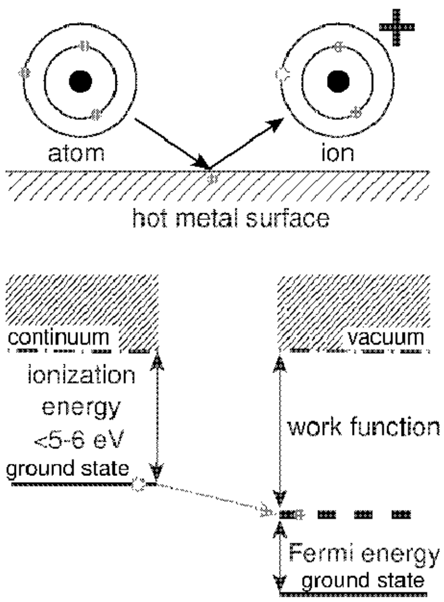
$$A^{q+} + B^{p+} \rightarrow A^{(q-1)+} + B^{(p+1)+} \quad q \geq p$$

also possible with $B \neq A$



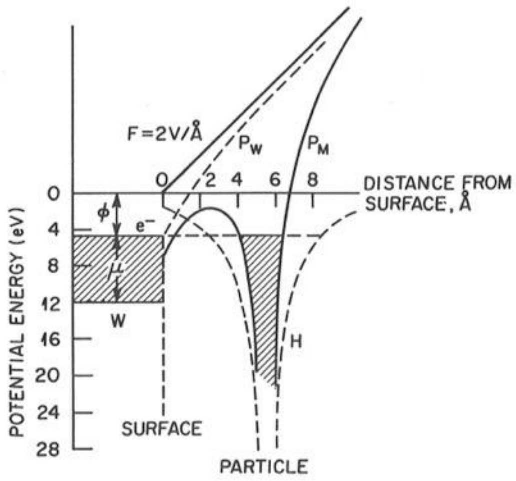
Other processes I

- Surface ionization
  - positive ionization of atoms with low ionization potential on heated metal surfaces with a high work function (e.g. tungsten)
  - the surface has to be heated to increase the desorption
  - works only for a limited number of elements (alkalines)
  - negative ions can be created for elements with high electron affinity



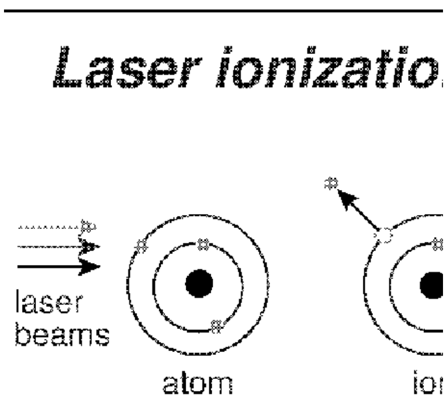
Other processes II

- Field ionization
  - high electric field gradient modifies atom potential so that an electron can tunnel into the metal surface
  - dominant process in liquid metal ion sources



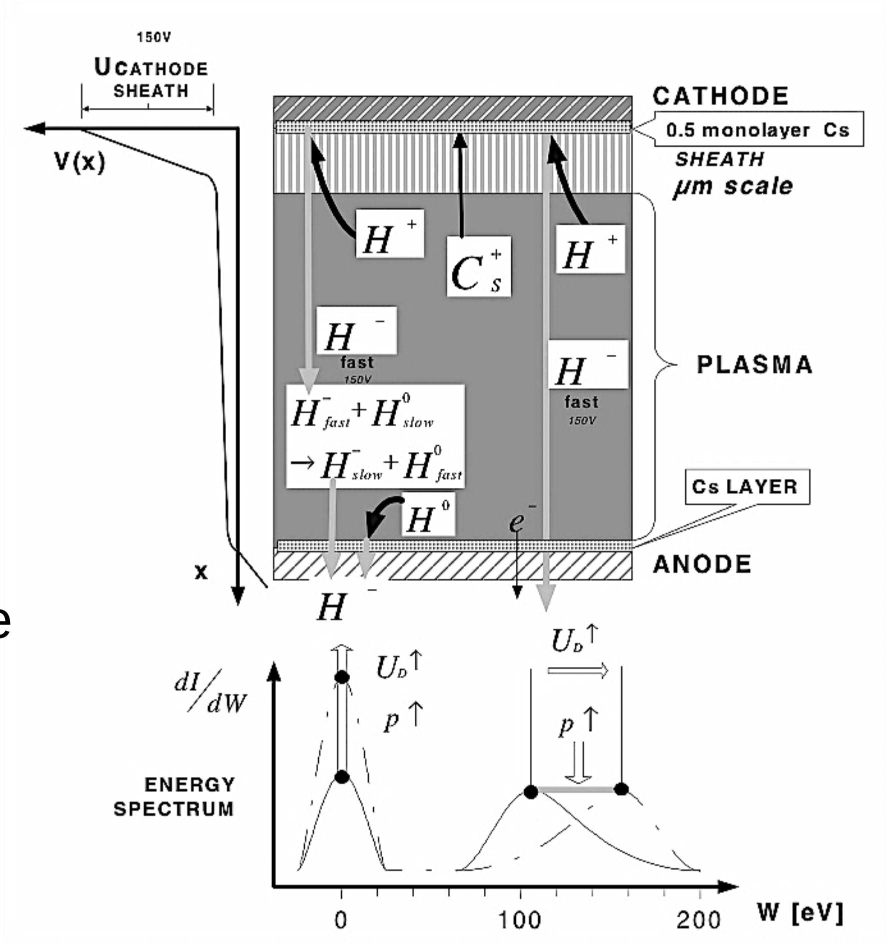
Other processes III

- Photoionization
  - $A^{q+} + hn \rightarrow A^{(q+1)+} + e^{-}$
  - the photon energy has to exceed the ionization energy
  - dominant process in resonant laser ion sources
    (combined steps of excitation and ionization, chemically selective)
- Dielectronic recombination
  - $A^{q+} + e^{-} \rightarrow A^{(q-1)+*} \rightarrow A^{(q-1)+} + hn$
  - resonant process
  - could play a role for higher charge states depending on electron energy and density



H$^-$ production I

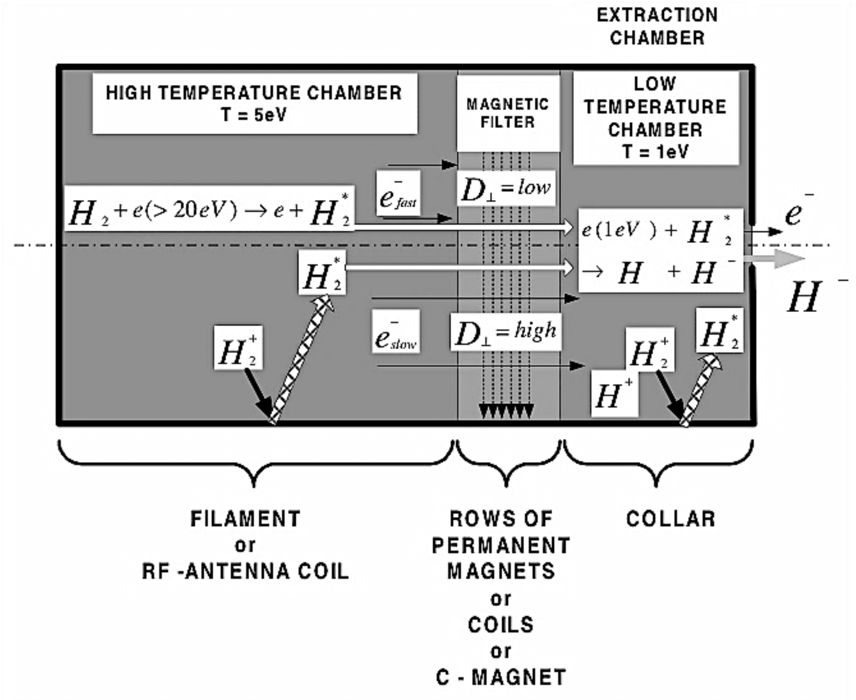
- charge transfer
  - the simplest method is the conversion of a primary proton beam in a converter target (e.g. a cesiated surface, cesium vapor or hydrogen gas)
  - used e.g. for polarized beams
- surface effect
  - protons from a plasma hitting the wall can pick up electrons, the walls are covered with low work function material (e.g. cesium)



H^- production II

- volume effect
  - H^- is created from vibrational excited hydrogen molecules through dissociative electron attachment
- 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

$$H_2(n'') + e^- \rightarrow H^- + H$$

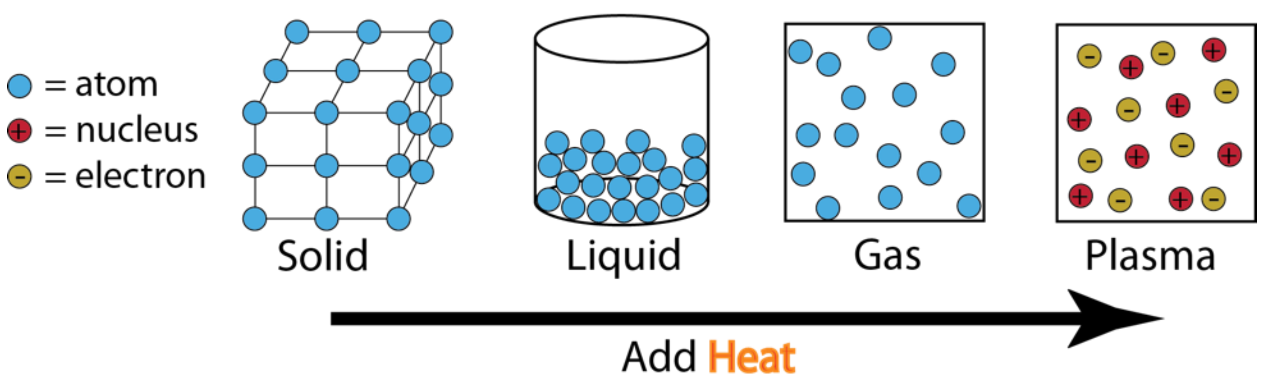


PLASMA PHYSICS

What is a plasma?

A plasma is a quasi neutral gas of charged and neutral particles which exhibits collective behavior. (F.F. Chen "Plasma physics")

It is often also called the 4th state of matter.



What is quasi neutrality?

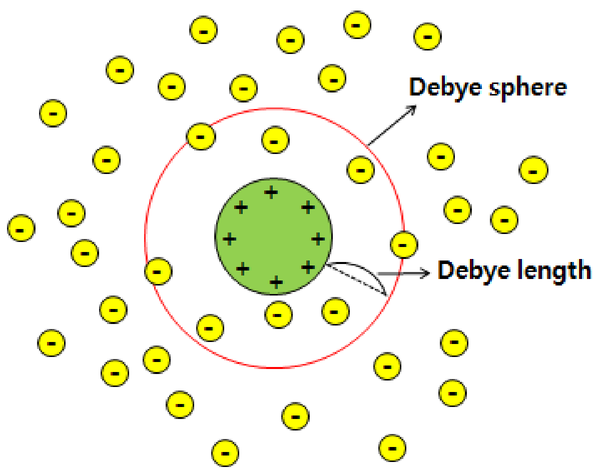
- overall charge neutrality is preserved

$$\sum_i q_i n_i = n_e$$

- due to the electron movement local deviations are possible
- departure from neutrality gives rise to electric fields limiting the charge build-up
- the system is quasi neutral if the dimensions are much larger than the Debye length λ_D

$$\lambda_D = \left(\frac{\varepsilon_0 k T_e}{n_e e^2} \right)^{1/2}$$

$$\lambda_D[\mathrm{cm}] = 743\left(T_e[\mathrm{eV}] / n_e[\mathrm{cm}^{-3}]\right)^{1/2}$$



What is collective behavior?

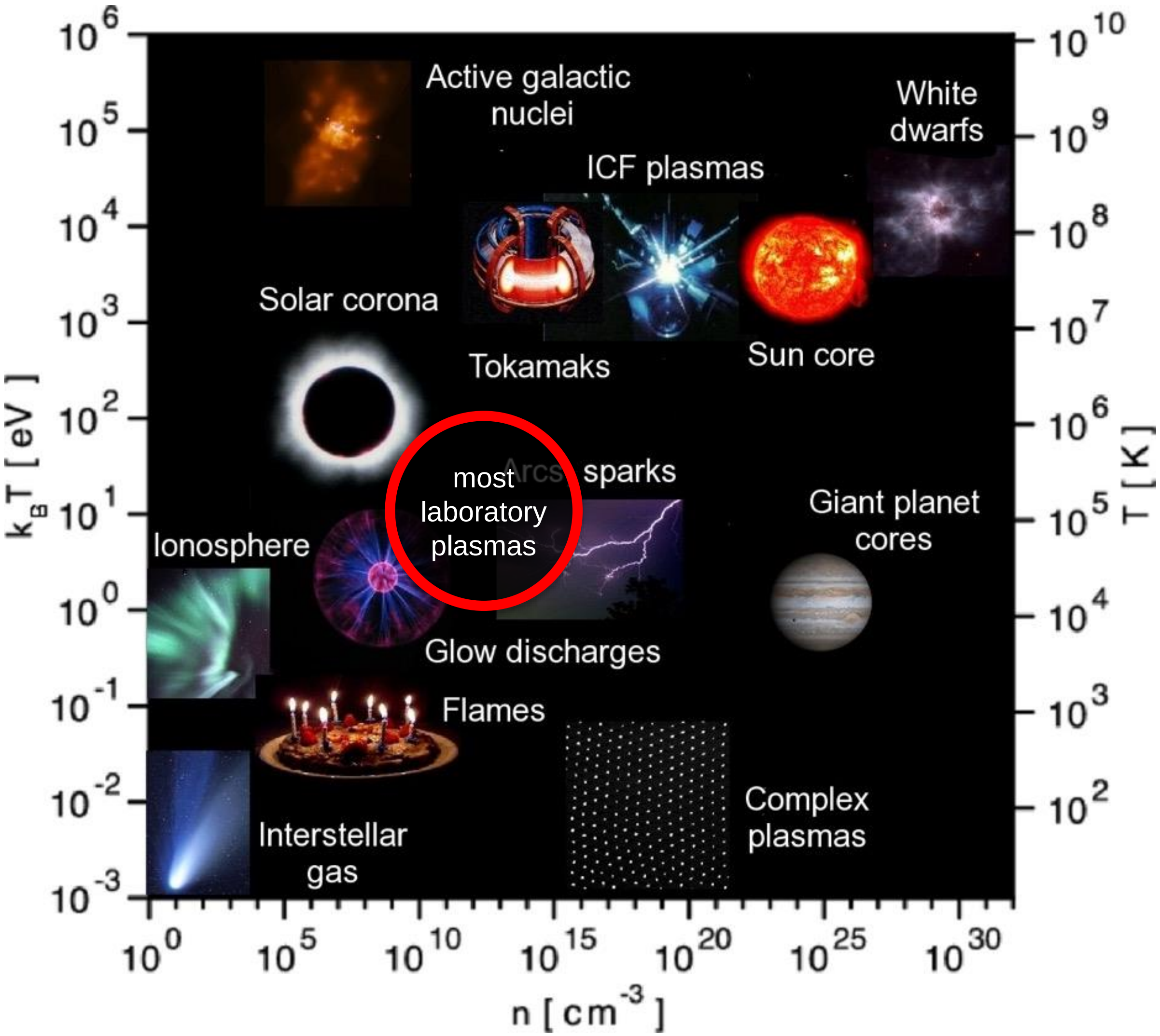
- the plasma consists of charged particles
- the moving charges can create local concentrations of charges
  -> electric fields
- the moving charges can generate currents
  -> magnetic fields
- the fields affect motion of other charged particles far away
- coupling of local conditions with remote plasma regions -> collective behavior

“Because of collective behaviour, a plasma does not tend to conform to external influences; rather, it often behaves as if it had a mind of its own.”

F.F. Chen

Plasma map

plasmas exist in a wide range of densities and temperatures



Basic plasma parameters

- particle density
  - electron density n_e, ion density n_i, neutral density n_0
  - units: cm^{-3} or m^{-3}
  - in ion sources in the vicinity of $n_e \sim 10^{12}$ cm^{-3}
  - Attention! the term “plasma density” is not very well defined

Basic plasma parameters II

- particle temperature
  - electron temperature T_e, ion temperature T_i, neutral temperature T_0
  - units: eV or K (1 eV ≅ 11600 K)
  - in the presence of a magnetic field the temperatures can be anisotropic (parallel and perpendicular to the field: $T_{\parallel}$ and $T_{\perp}$)
  - the term "temperature" is defined only for a Maxwellian energy distribution (thermal equilibrium)
  - Attention! the term "plasma temperature" makes only sense if all temperatures are the same

Basic plasma parameters III

- ionization fraction
  - ratio of the ion density to the total density of ions and neutrals $\frac{n_i}{n_i + n_0}$
  - if there are no neutrals left the plasma is fully ionized
  - Attention! the term “highly ionized” is used for plasma with high ionization fraction or for ions with a high charge state

Basic plasma parameters IV

- plasma frequency
  - small deviations from charge neutrality causing a restoring force -> plasma oscillation
  - for electrons for ions

$$\omega_{pe} = \left(\frac{e^2 n_e}{\varepsilon_0 m_e} \right)^{1/2} \qquad \omega_{pi} = \left(\frac{q^2 e^2 n_i}{\varepsilon_0 m_i} \right)^{1/2}$$

n – density, *m* – mass, *q* – charge state

$$f_{pe}\left[\mathrm{Hz}\right] = 8980\sqrt{n_e\left[\mathrm{cm}^{-3}\right]} \qquad f_{pi}\left[\mathrm{Hz}\right] = 210q\sqrt{\frac{n_i\left[\mathrm{cm}^{-3}\right]}{A\left[\mathrm{amu}\right]}}$$

Single particle motion

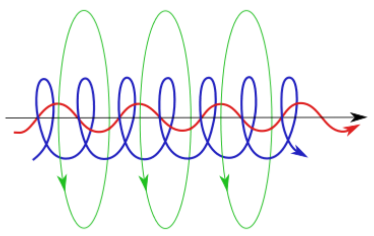
- the Lorentz force is determining the motion of charged particles in electrical and magnetic fields

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

- due to the orientation of the fields to each other, the field structures (field inhomogeneities) and temporal variations different kinds of particle motion are possible
(ExB drift, gradient drift, …)

Single particle motion II

- charged particles in a magnetic field are gyrating around the field lines



- cyclotron frequency

$$\omega_c = \frac{qeB}{m} \qquad f_{ce}[\mathrm{GHz}] = 28 \times B[\mathrm{T}] \qquad f_{ci}[\mathrm{MHz}] = 15.2\,\frac{qB[\mathrm{T}]}{A}$$

- Larmor radius

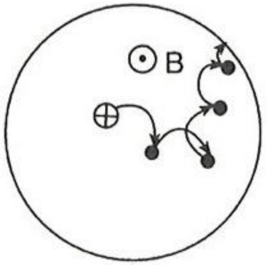
$$r_L = \frac{v_\perp}{\omega_c} = \frac{m v_\perp}{qeB}$$

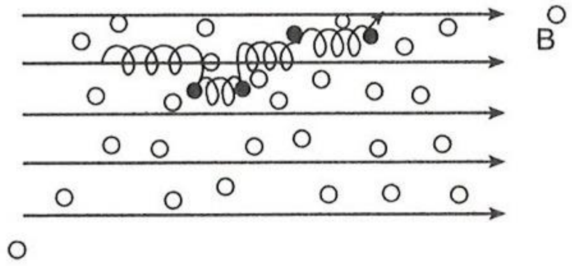
$$r_{Le}[\mathrm{cm}] = 0.00033\,\frac{\sqrt{T_e[\mathrm{eV}]}}{B[\mathrm{T}]}$$

$$r_{Li}[\mathrm{cm}] = 0.0014\,\frac{\sqrt{A T_i[\mathrm{eV}]}}{qB[\mathrm{T}]}$$

Diffusion

- particle transport due to density gradient
- in neutral gases the diffusion is reduced due to collisions
- in magnetized plasmas collisions cause diffusion (restore particle freedom to cross the magnetic field)





Diffusion II

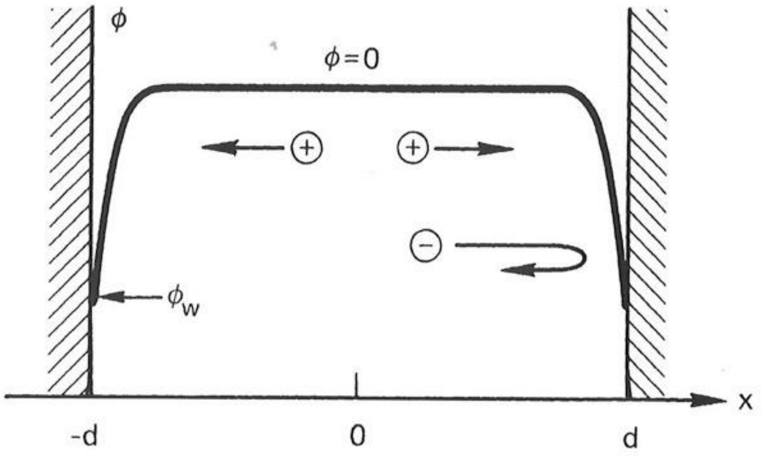
- diffusive motion in a neutral gas (flux Φ)
  -> definition of the diffusion coefficient D_i
  $$\Gamma_i = -D_i \nabla n_i$$
- D_i is not a constant, depends on densities, temperatures, …
- diffusion is ambipolar, particles of each sign diffuse with same velocity (role of the slow particles)
- many different approaches to describe the diffusion coefficient for the different plasma types

Multi particle model

- for a self-consistent description with varying time one can describe a plasma as a fluid (Magnetohydrodynamics MHD)
- periodic motions can be described with waves
- in a fully ionized plasma the collisions are Coulomb collisions
- there are elastic (energy transfer) and inelastic collisions (atomic processes)
- collisions are described by collision frequency (typical time scale) and mean free path (typical length scale)

Plasma-wall interaction

- between a plasma and a wall a boundary layer is formed -> the plasma sheath
- the sheath has in the undisturbed case a thickness of around one Debye length
- due to the different mobility of ions and electrons a plasma potential builds up
- it decelerates the electrons and accelerates the ions to balance the flows and to keep the plasma neutrality
- the sheath screens external fields



Plasma heating

- to trigger and sustain atomic and plasma physical processes one has to introduce energy into the plasma
- this can be done in may different ways
  - Electrical discharges (filament sustained)
    - → Duoplasmatron, MEVVA
  - Radio frequency (internal or external antenna)
    - → RF driven ion sources, H^- sources, Multicusp sources
  - Laser
    - → Laser Ion Sources
  - Microwave
    - → ECRIS

Microwave plasma heating

- the plasma is heated resonantly if the injected microwave has the same frequency as the electron cyclotron frequency

$$W_{RF} = W_c$$

- stochastical process
- only frequencies higher than the electron plasma frequency can penetrate the plasma, the others are reflected -> critical density for the energy transfer

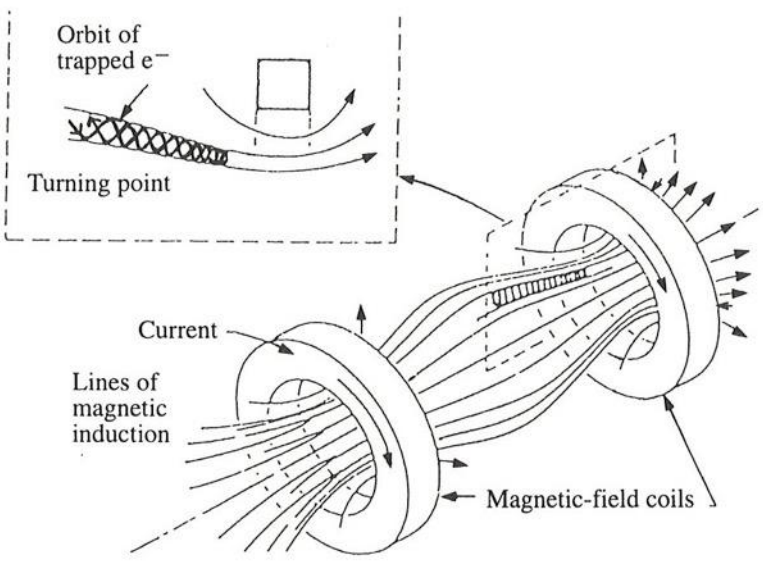
$$n < n_{\mathrm{crit}}\left[\mathrm{cm}^{-3}\right] = 1.25 \cdot 10^{12} f^2 \left[\mathrm{GHz}\right]$$

- due to mode conversion, non-linear and other effects overdense plasmas are possible

Plasma confinement

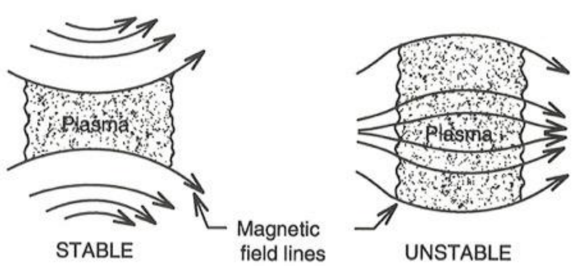
- magnetic fields are used to confine the plasma
- many different types: multicusp, magnetic mirror, magnetic bottle (minimum-B mirror)
- the magnetic moment is an invariant -> magnetic mirror effect
- if B goes up, $v_{\perp}$ goes up and $v_{\parallel}$ goes down (conservation of total energy), reflection where $v_{\parallel}$ becomes zero

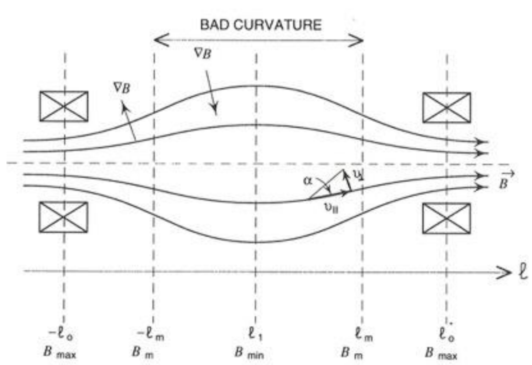
$$\mu = \frac{E_{\text{kin}}}{B} = \frac{\frac{1}{2}mv_{\perp}^{2}}{B} = \text{inv.}$$

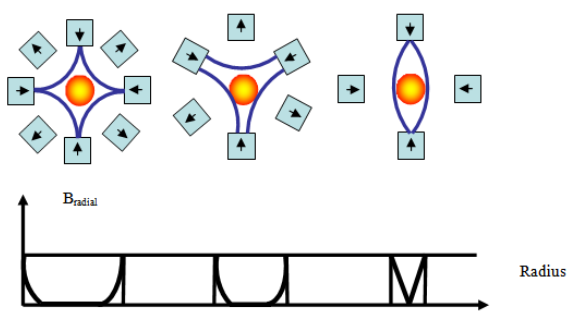


Plasma confinement II

- the simple magnetic mirror is MHD unstable
- due to the curvature of the field lines there is a gravitational-like force outwards driving the plasma radially
- adding a magnetic multipole creates a field with convex field lines -> MHD stable (minimum-B mirror)
- disadvantage: the multipole forces a non-rotational symmetric plasma distribution



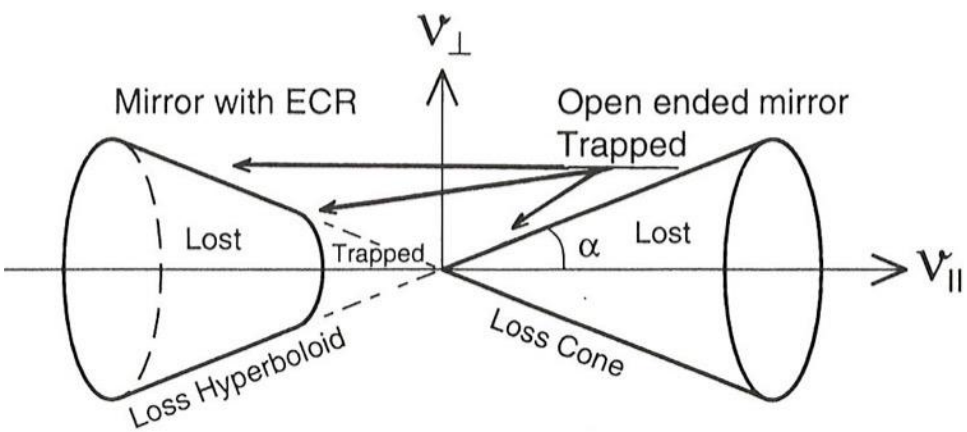




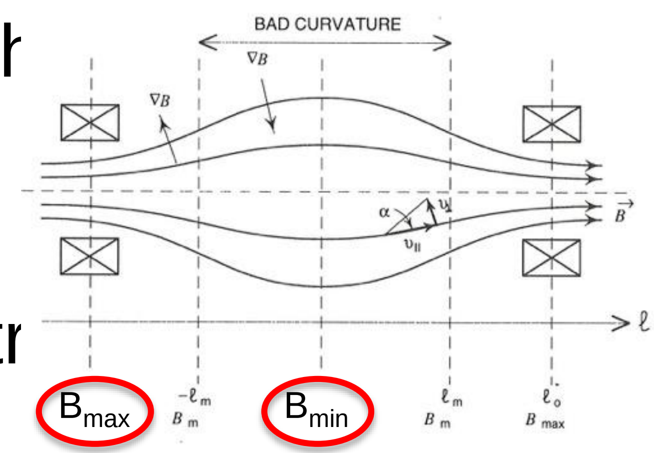
Plasma losses

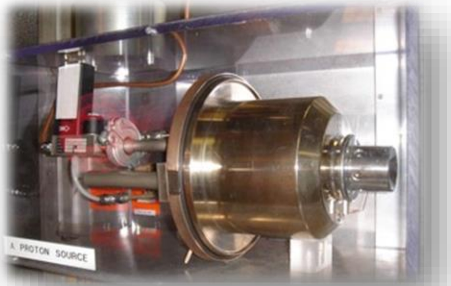
- for the magnetic mirror a trapping condition in the velocity space can be formulated -> mirror ratio

$$\sin^2 a = \frac{B_{min}}{B_{max}}$$



- the volume defined by th ed the loss cone
- particles inside the loss ne plasma (and can be extr







Ion source physics and technology part II

Detlef Küchler
CERN/BE/ABP/HSL

Structure of this lecture

Atomic physics

- Rate equation
- Atomic processes

Plasma physics

- Plasma parameters
- Particle processes

Source physics

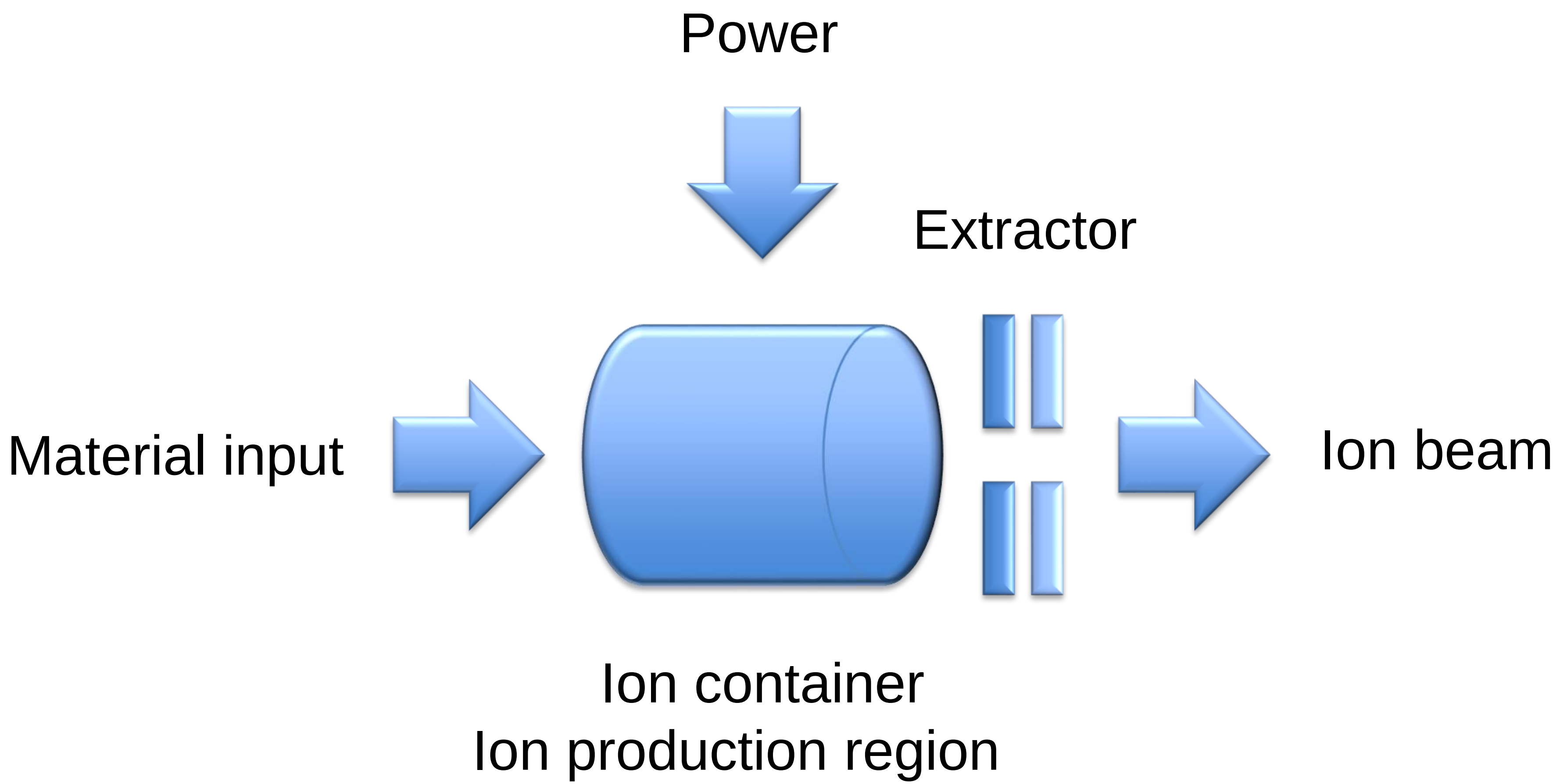
- Source principle
- Source operation
- Beam extraction

Engineering

- Technical infrastruc-ture to operate an ion source

SOURCE PHYSICS

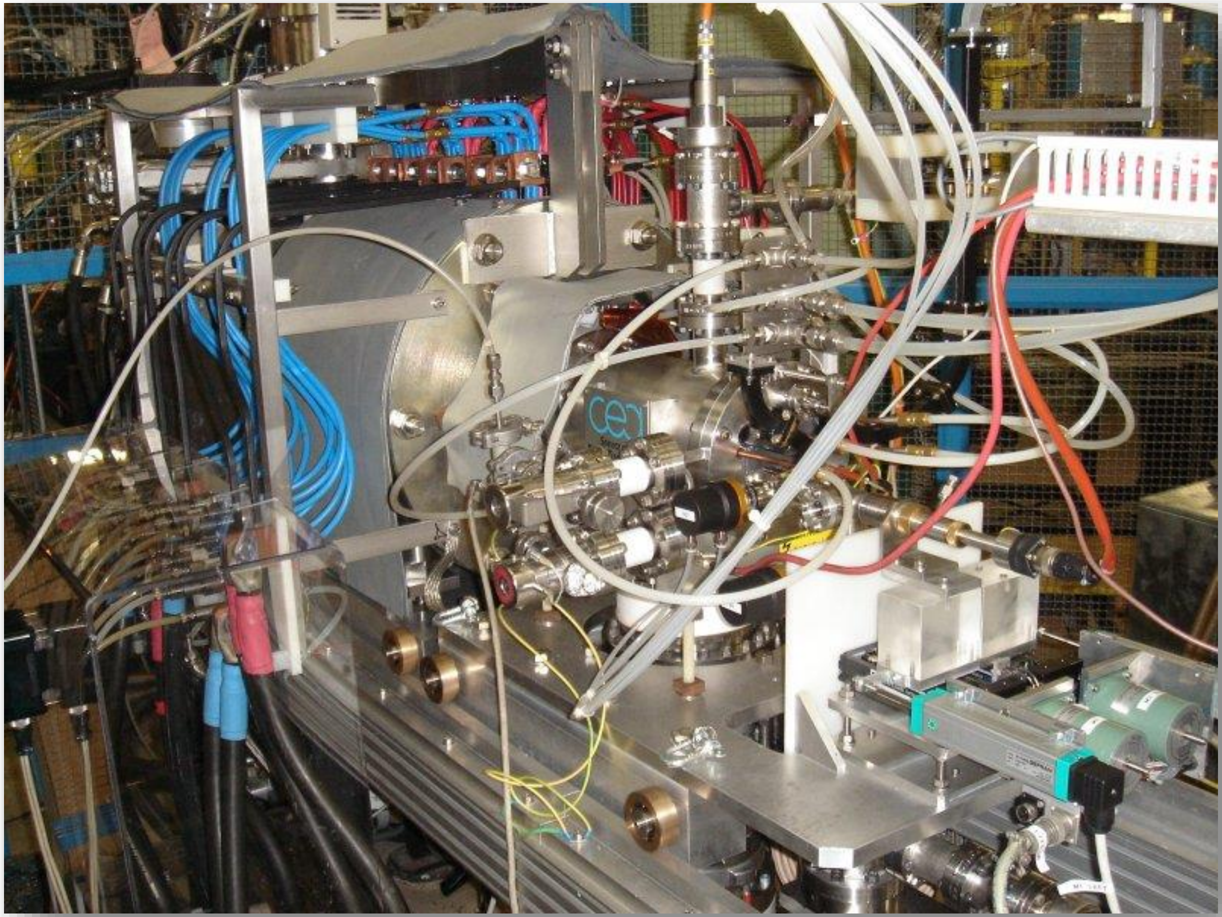
Generalized source model



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, …)

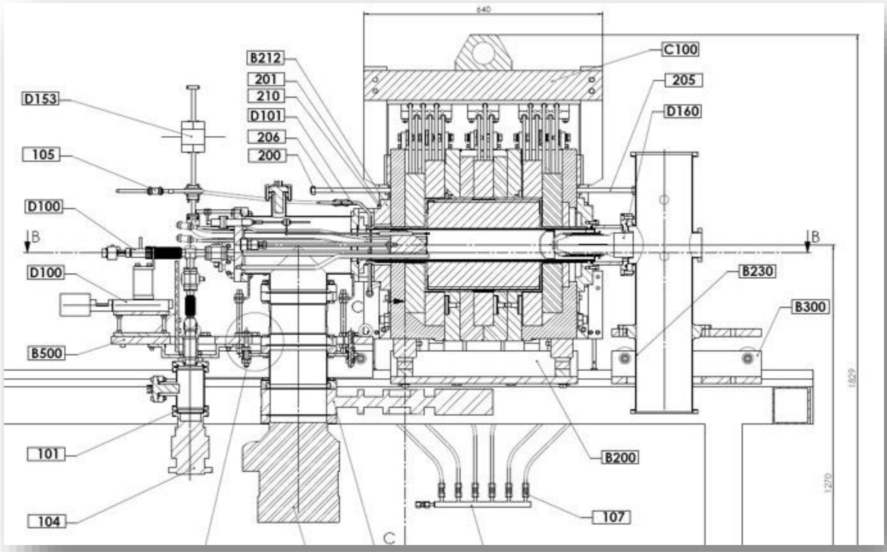
The Electron Cyclotron Resonance Ion Source (ECRIS)



Location: CERN Linac3 (GTS-LHC)

The ECRIS II

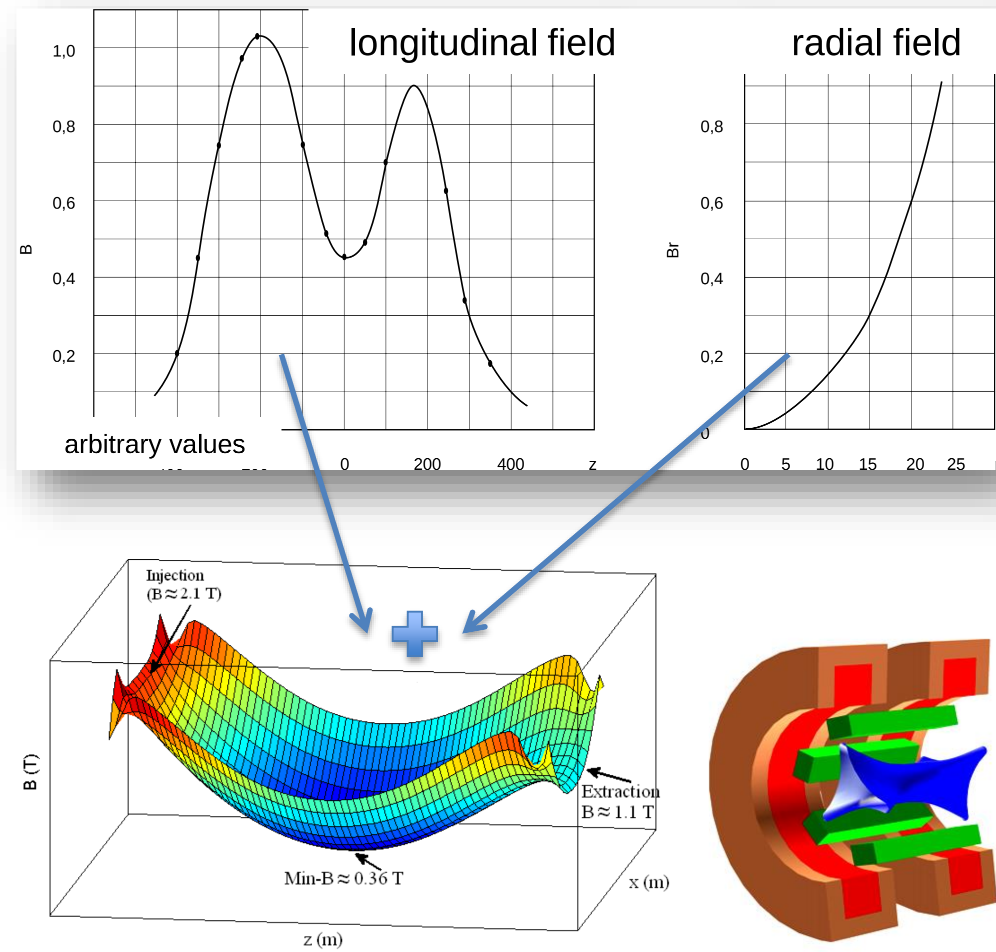
- Developed 1965 by Richard Geller (France)
- The plasma is confined in a “magnetic bottle”, the longitudinal field is created with solenoids, the radial field is created with a permanent magnet hexapole



The ECRIS III

magnetic field structure

- radial field ~ r^2
- extraction field lower to balance ion creation and ion extraction
- scaling laws for optimal source operation
- 3rd generation sources with superconducting coils



The ECRIS IV

- the plasma is heated due to the resonance of the injected microwave with the electron cyclotron frequency

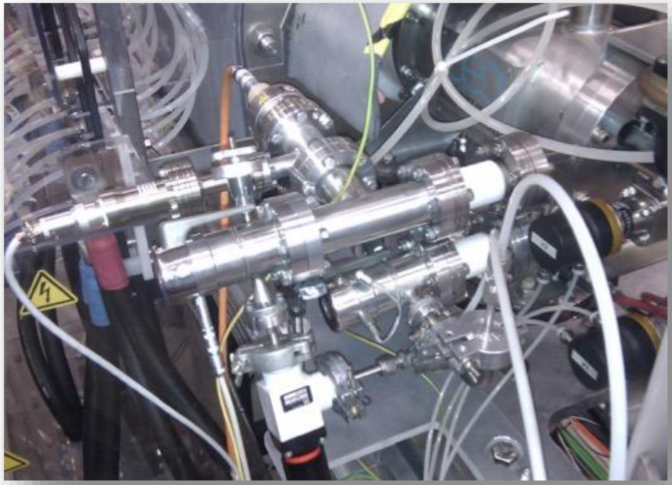
$$w_{RF} = w_c = \frac{eB}{m_e}$$

(actual used frequencies 6.4 GHz, 14.5 GHz, 18 GHz or 28 GHz)

- delivers high currents for medium charge states
- no antennas or filaments in the ion production region ➔ high reliability

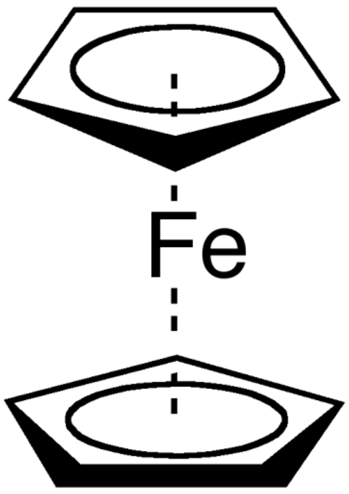
Material input

- the source can be operated with gas, liquids, solids or ions
- gas: direct connection with flow control
- liquids: direct connection with flow control, depending on the vapor pressure some heating may be necessary
- ions: single charged ions into charge breeders



Material input - solids

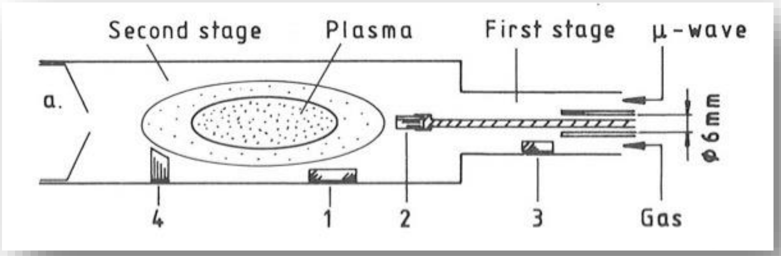
- high vapor pressure materials
- volatile chemical compounds (MIVOC method – Metal Ions from VOlatile Compounds)
- for both methods the feeding could be similar to gas input or oven operation
- laser evaporation

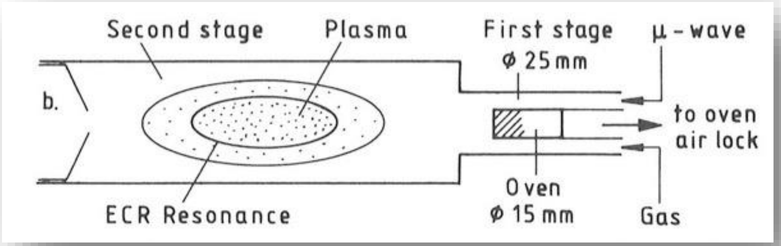


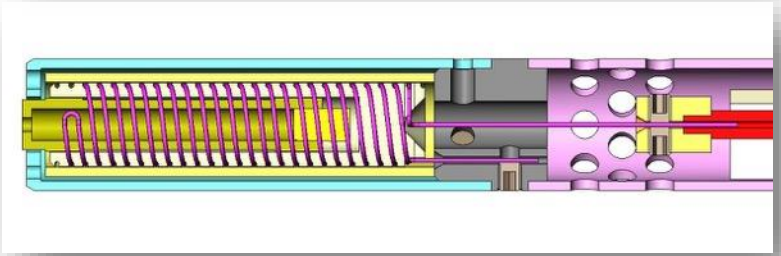
Ferrocene

Material input – solids II

- sputtering
  - simple
  - sample can be biased
  - good for refractive materials
  - difficult to control beam stability
- oven
  - different oven designs exist (up to 2000ºC)
  - good control of beam stability
  - problems with “hot chemistry”



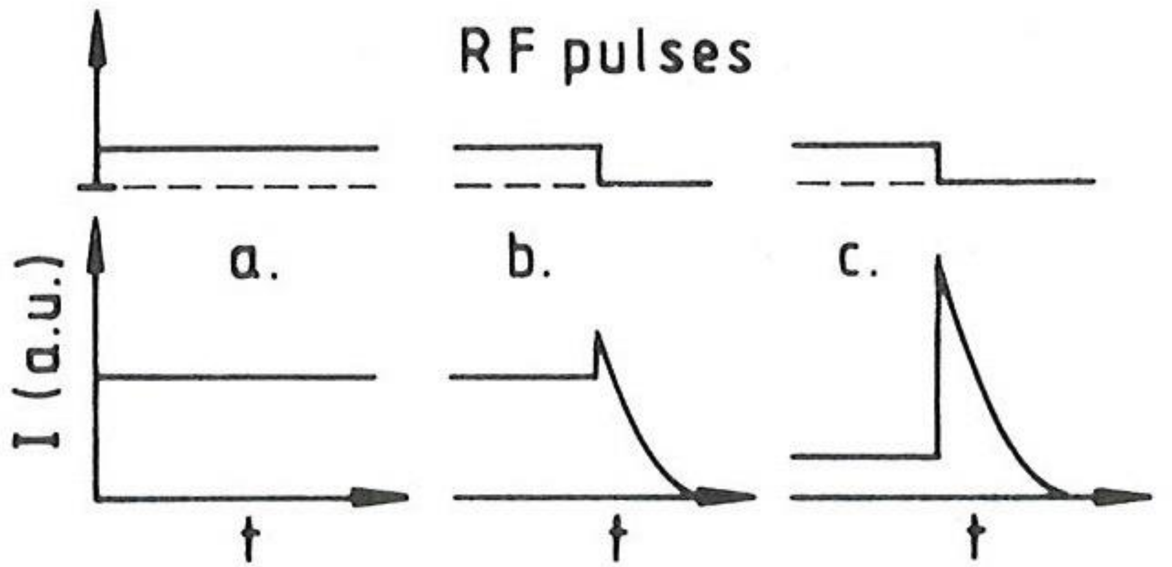




Operation modes

- not every user needs continuous beam
  - synchrotrons are filled with pulsed beam
  - cyclotrons take continuous beam
- the microwave can be injected continuous or pulsed into the source
  - different timing -> different source behavior
  - special source tuning for every mode
  - different confinement -> different charge state distribution

Operation modes II



a) continuous wave (cw)
b) pulsed
c) afterglow

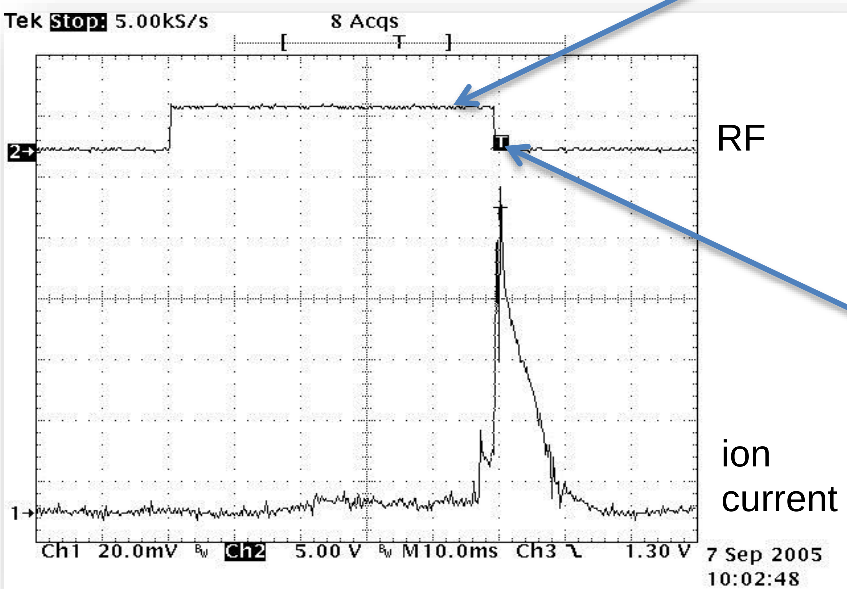
Afterglow

- special mode of operation
- short pulses (some ms) of high charge states after the end of the RF pulse

ain pulse.

Analysis of decay times

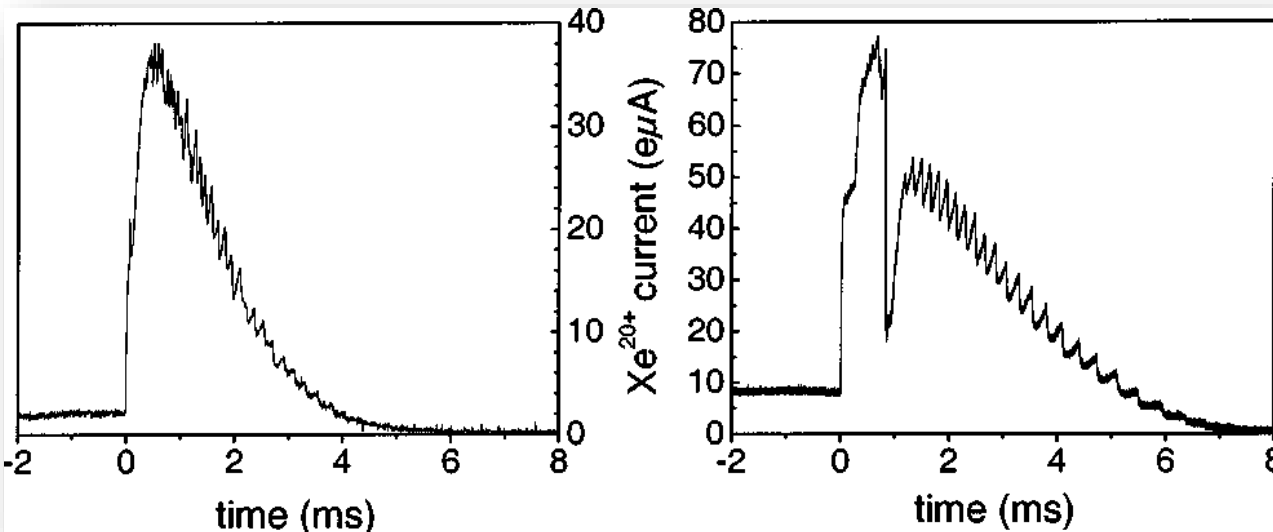
g. 3 shows the afterglow for the charge ates of lead ranging from 21 to 31, normal- ed to the same height, to allow a comparison the shape (the maximum currents corre- ond to the distribution on fig 1a). One sees



The followin measurements mad t a constant source etting which was opti ized for this stable mode. The RF power wa kW, the pulse duration was 50 ms at th sual repetition rate of 10 Hz. The current i e source coils was 860 A for the rear an 20 A for the front (extraction).

Afterglow II

different tunings result in different time behaviors, intensities and pulse-to-pulse stabilities



Extraction

- only particles lost from the plasma can be extracted
  - high confinement -> high charge states but low current
  - low confinement -> low charge states but high current
- one cannot “pull” the particles out of the source
- the plasma screens any external field (plasma sheath)
- plasma is locally reshaped and redistributed due to the external field

Extraction II

- the extraction can be
  - space charge limited (space charge cloud in front of the extraction system)
  - emission limited (plasma cannot deliver enough particles)
- the emissive surface of the plasma is often referred to as plasma meniscus
- the dynamic equilibrium between the plasma and the extracted particles creates the meniscus

Child-Langmuir law

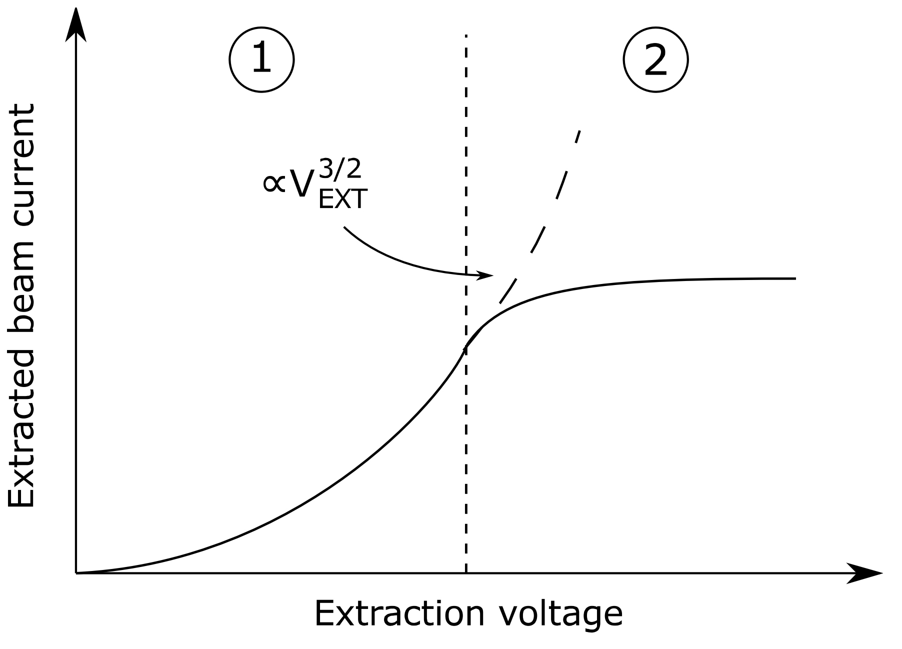
- defines the maximal extractable emission current density *j*

$$j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{U^{3/2}}{d^2}$$

q – ion charge state, *m* – ion mass,
U – extraction voltage, *d* – extraction gap

- conditions
  - – planar and indefinite emission area
  - – particles have zero initial longitudinal energy

Child-Langmuir law II

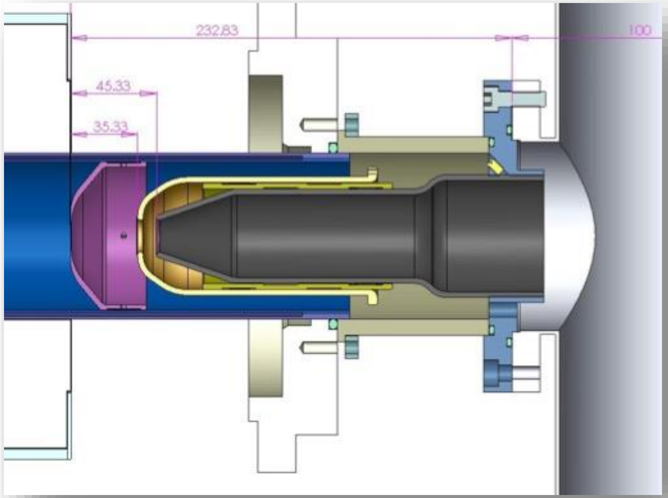


① space charge limited

② emission limited

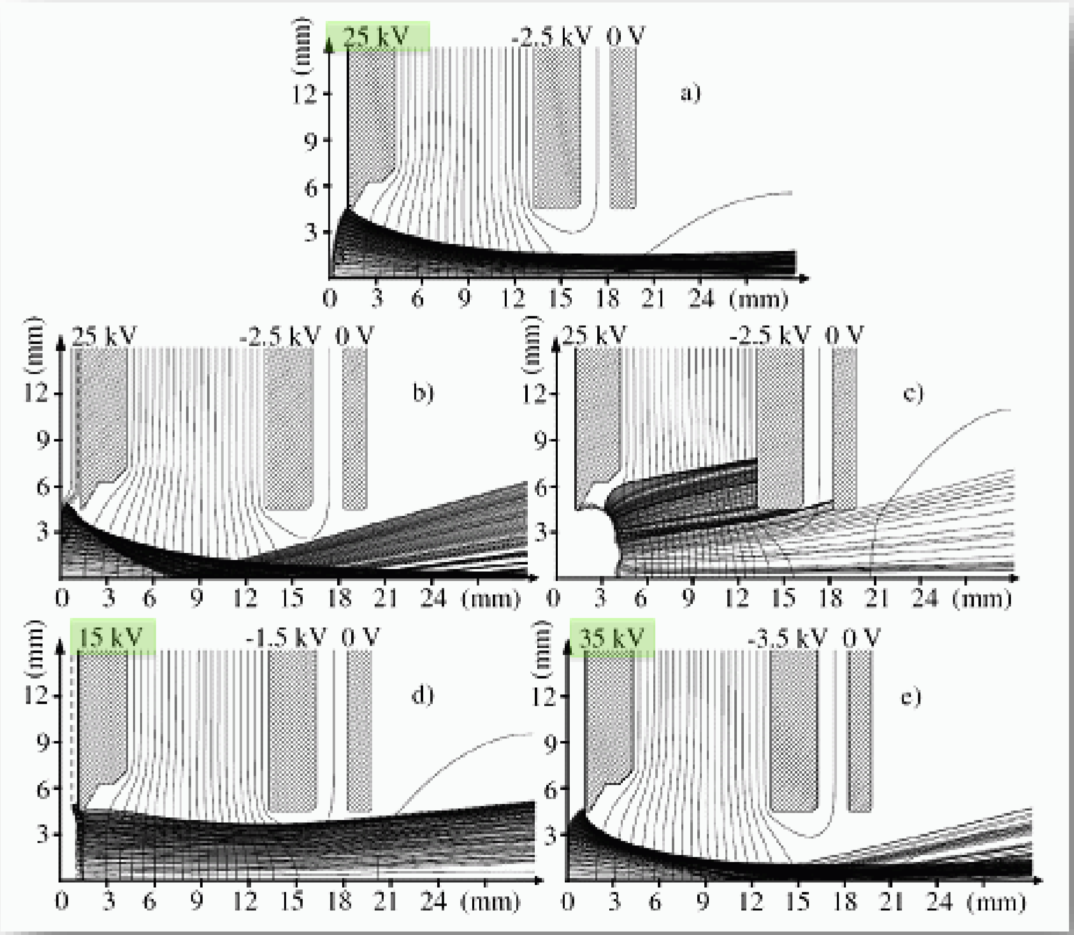
Extraction system

- the extraction system consists of several electrodes
- in general the source body is on high voltage and the beam line on ground potential
- additional electrodes can serve for electron suppression or beam shaping



Extraction system II

Based on the extraction geometry, the extraction voltage and the plasma density the extracted beam can be overfocussed, parallel or divergent



Emittance

- in the extraction system the initial emittance of the beam is created
- emittance for the “hot” ion limit

$$e^{\text{temp}}_{x,\,\text{rms, n}} = 0.0164 r \sqrt{\frac{kT_i}{M_i}}$$

ε – temperature dependent normalized rms emittance ,
r – radius of the extraction aperture (in mm), kT_i – ion temperature (in eV),
M_i – ion mass (in amu)

- conditions
  - isotropic emission in the solid angle 2π
  - homogeneous electric field

Emittance II

- emittance for the transport of a beam to a field free region ("cold" ion limit)

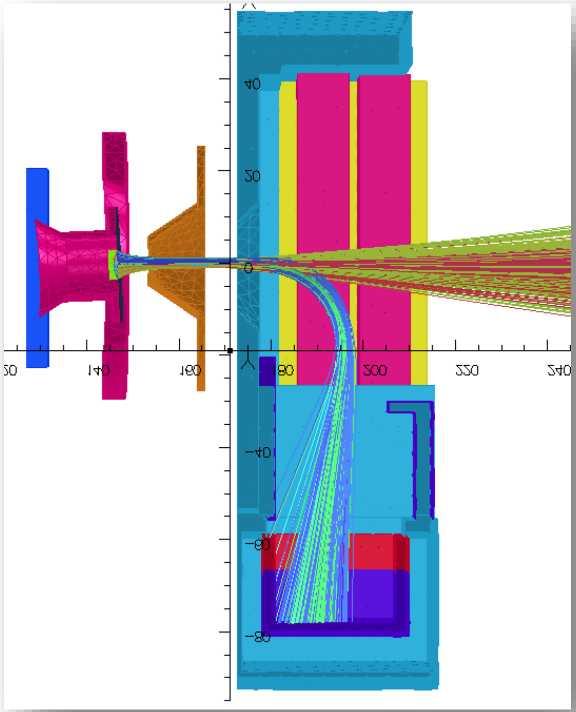
$$\varepsilon_{x,\,\mathrm{rms,\,n}}^{\mathrm{mag}} = 0.0402 r^2 \frac{qB}{M_i}$$

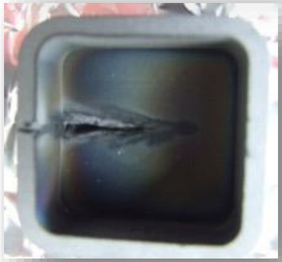
ε – magnetic field dependent normalized rms emittance,
r – radius of the extraction aperture (in mm), q – ion charge state,
B – magnetic field at the extraction where the ions originate from,
M_i – ion mass (in amu)

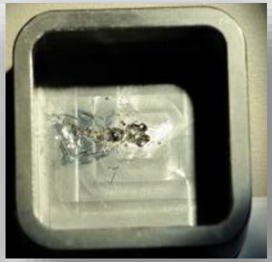
- for the real source emittance one has to take into account field inhomogeneities and the plasma distribution

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 due to the space charge (emittance)
- have to be removed from the beam as early as possible
- at full extraction voltage the electron beam can be quite destructive

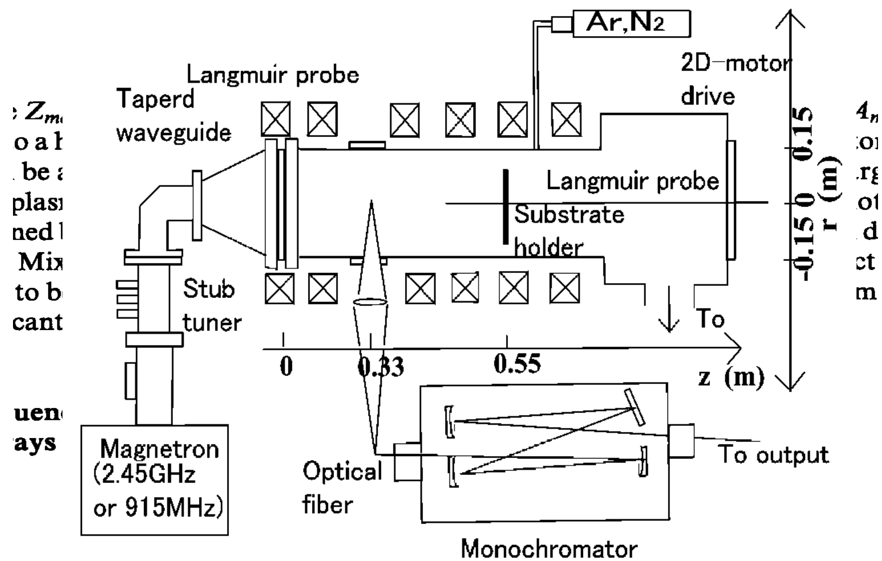


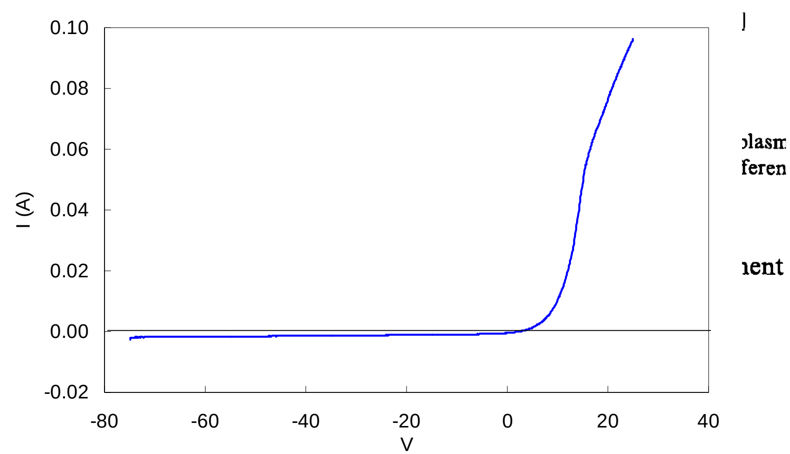




Plasma diagnostics

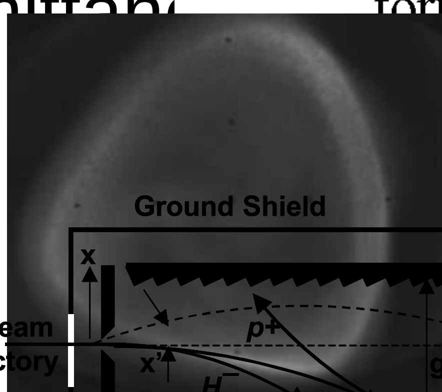
- direct and indirect measurement of plasma properties
  → density, temperature, charge state distribution
- radiation
  - light
  - x-rays
    - characteristic x-rays
    - bremsstrahlung
  - microwave radiation
- Langmuir probe

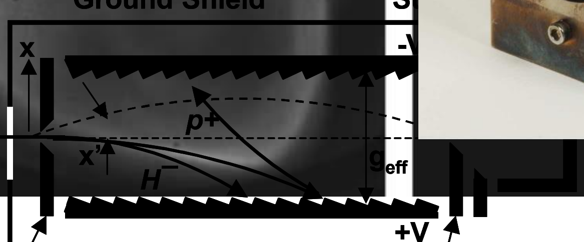


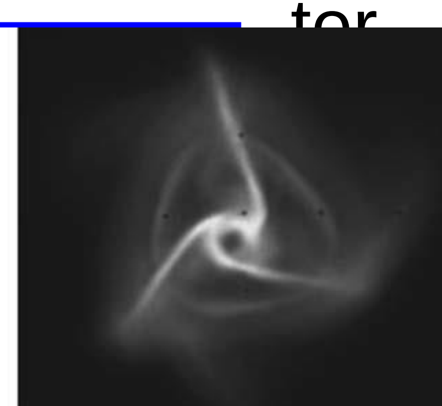


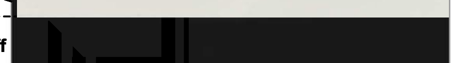
Beam diagnostics

- measurement of beam properties
  → intensity, emittance, charge state distribution
- Faraday cup
- beam current transformer
- beam profile mea… creens, grids)
- emittan… torus … tor
  All









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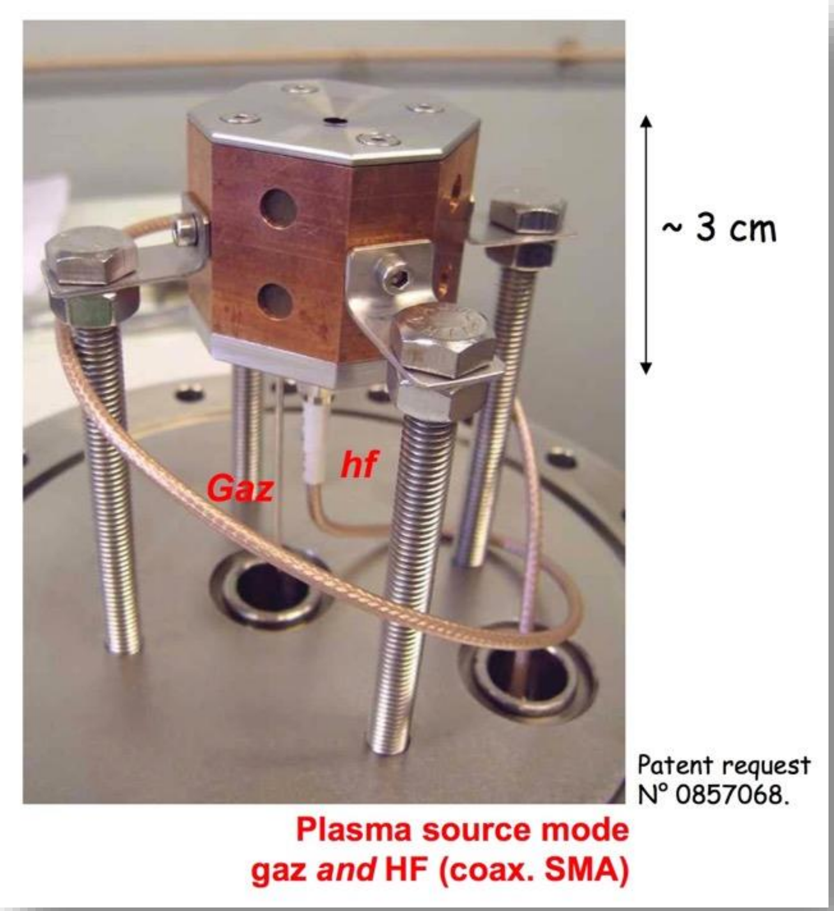
OTHER SOURCE TYPES

There are small sources

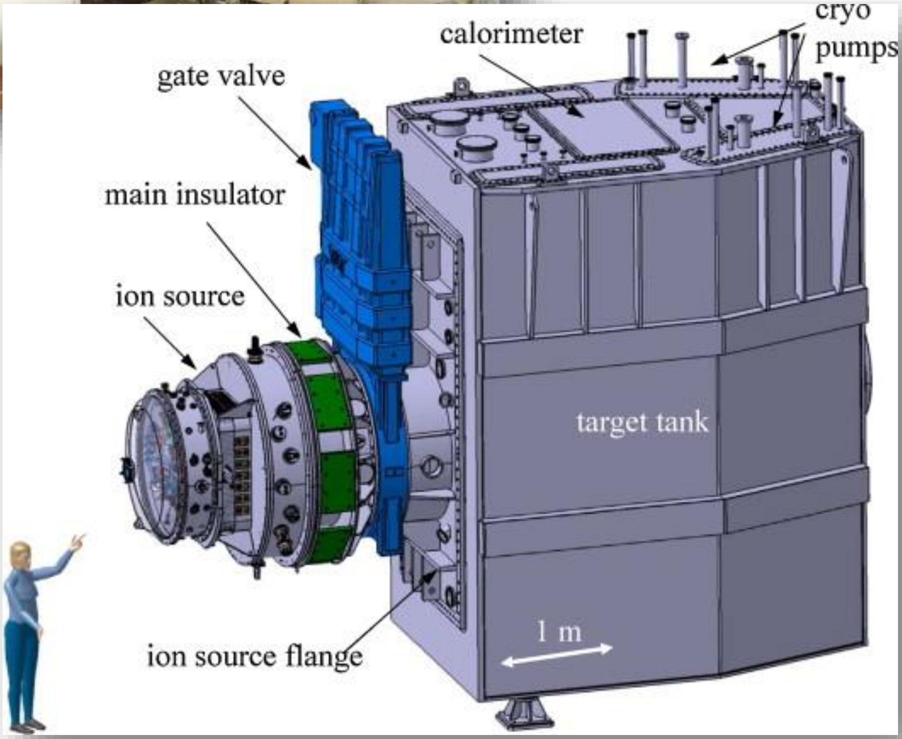
COMIC source

(COmpact MIcrowave and Coaxial)

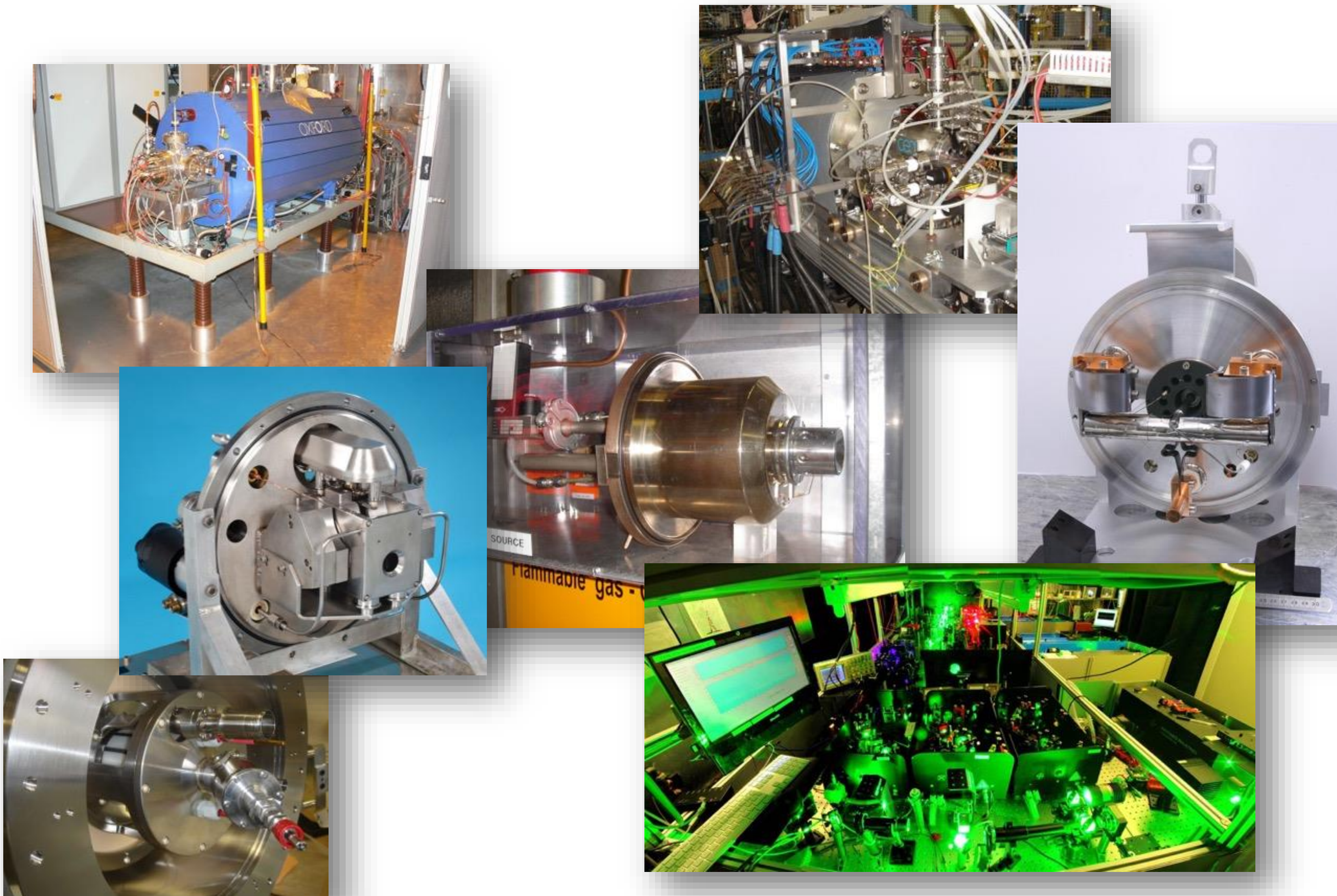


There are big sources

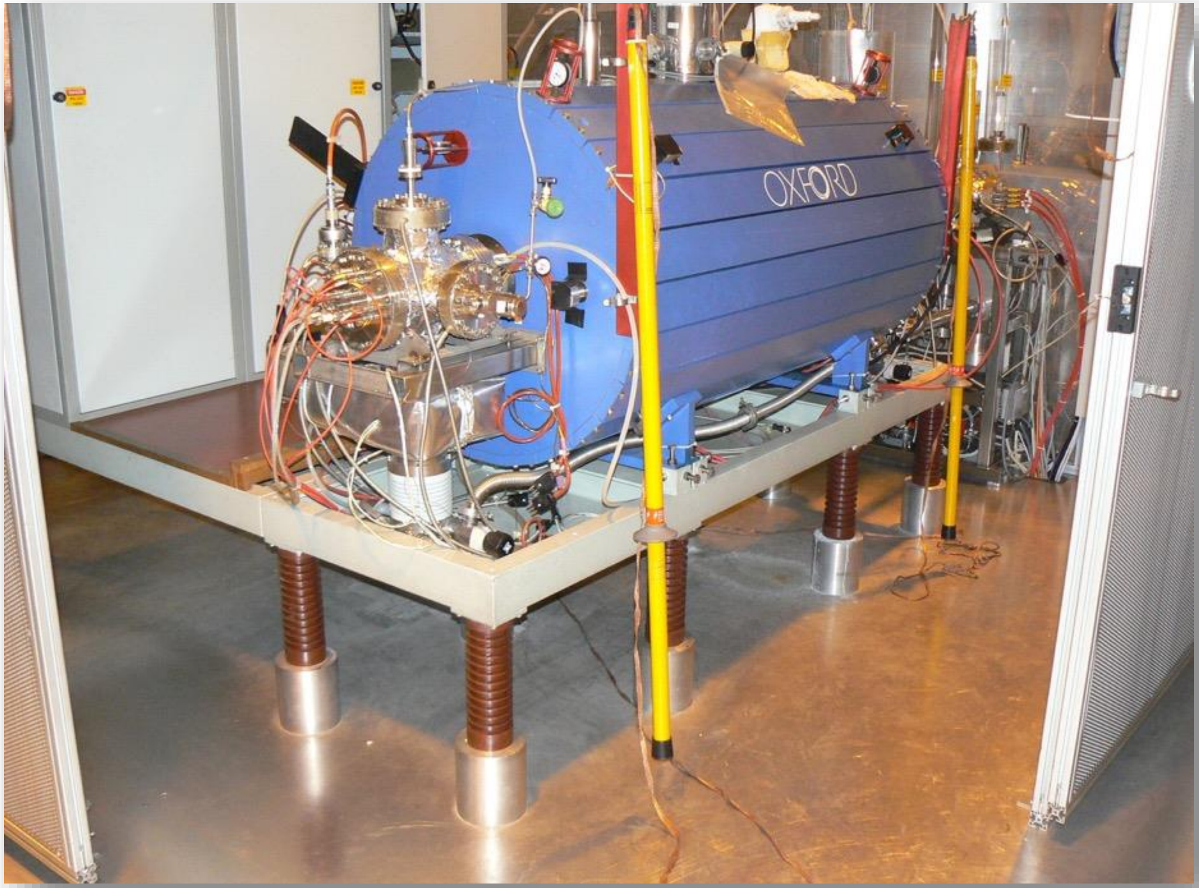
negative ion sources for the neutral beam injector



There are sources for any purpose



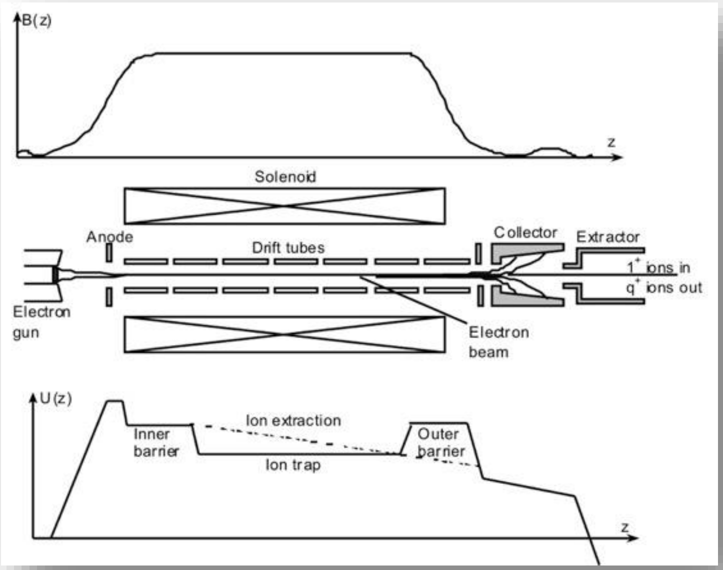
The Electron Beam Ion Source (EBIS)



Location: CERN REX ISOLDE

The EBIS II

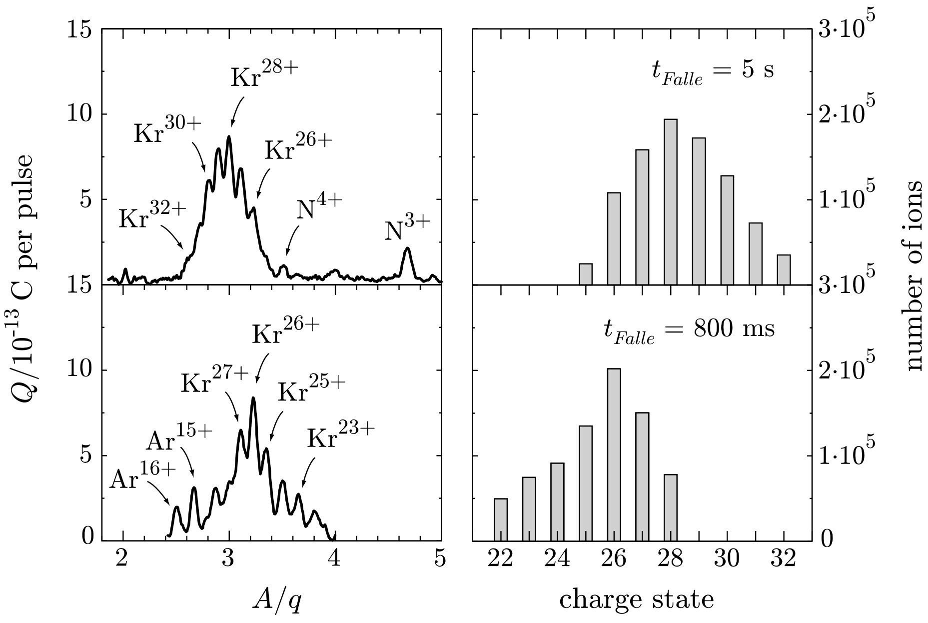
- Developed 1965 by Evgeni D. Donets (Russia)
- The longitudinal confinement is given by electrostatic fields
- The radial confinement is given by the electron beam, which is compressed by a solenoidal field



- The extraction process is controlled by the voltage level of the trap electrodes
- The ion injection is also controlled by the trap electrodes (singly charged ion injection)

The EBIS III

- The ionization takes place inside a highly energetic, high density electron beam
- The total ion current depends on the trap charge capacity
- Low transverse emittance
- Delivers short pulses of high charge states (charge breeding)
- The life time and the reliability is mainly defined by the electron gun

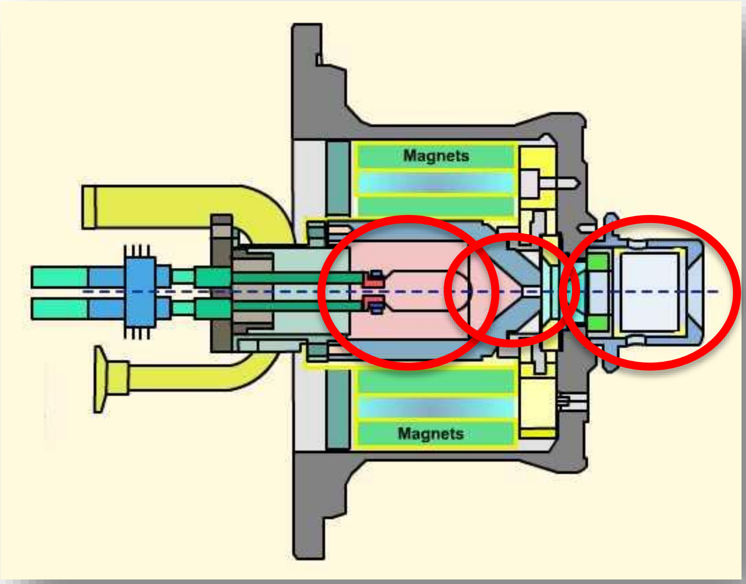


The Duoplasmatron

Location: CERN 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



The Duoplasmatron III

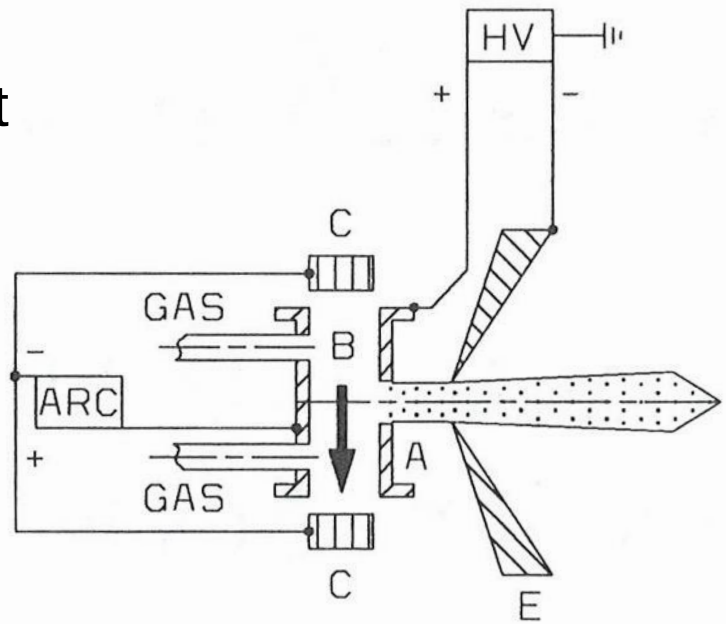
- Duoplasmatron: there are two plasma regions
  - low density plasma between cathode and intermediate electrode
  - high density plasma between intermediate electrode and anode
- Delivers short pulses with a very high intensity of mostly singly charged ions (mA)
- Hydrogen gas is used as input medium at Linac2 (80-85% H^+, the rest are H_2^+, H_3^+)

The Penning ion source

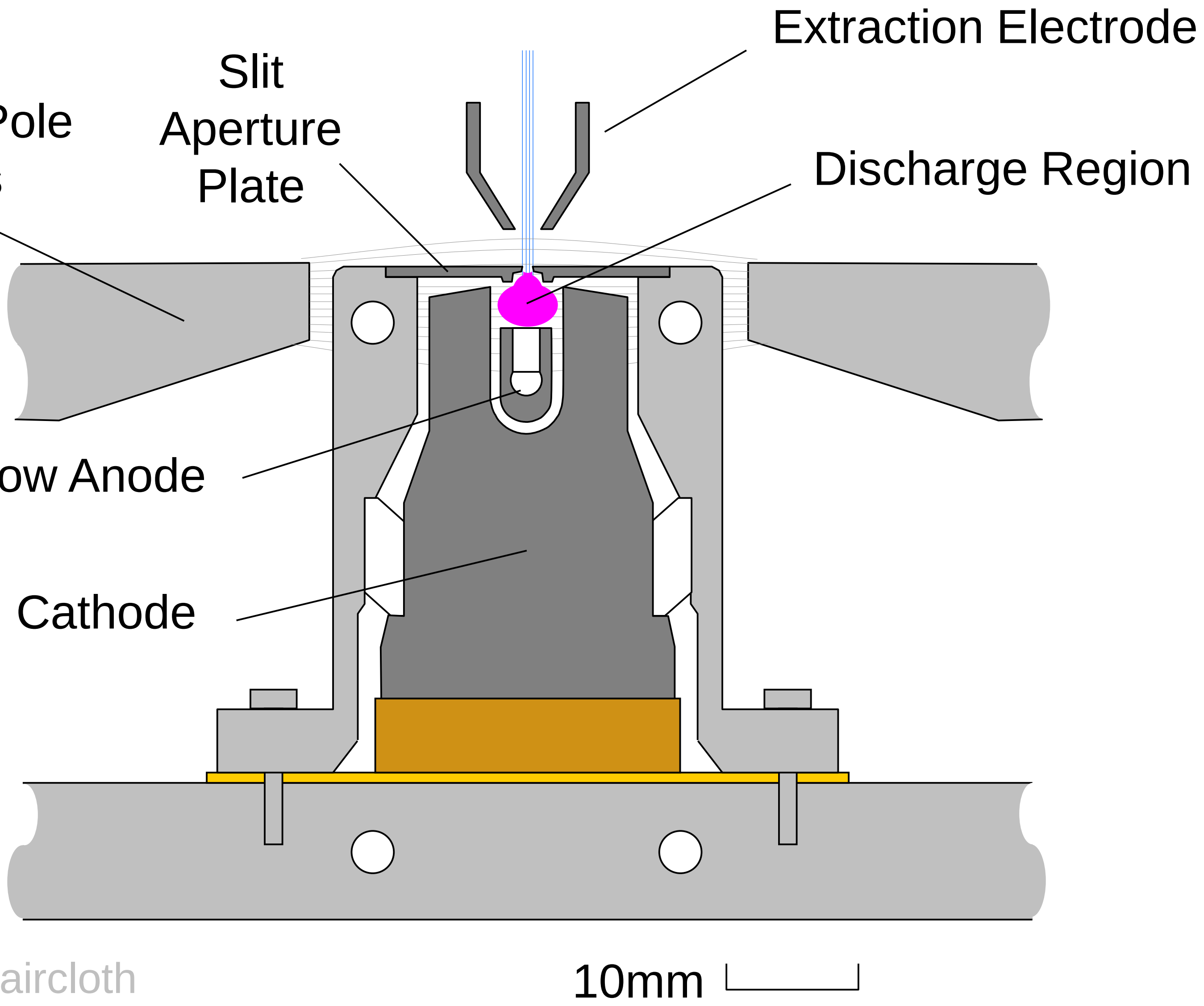
Location: ISIS/Rutherford Appleton Laboratory near Oxford

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)

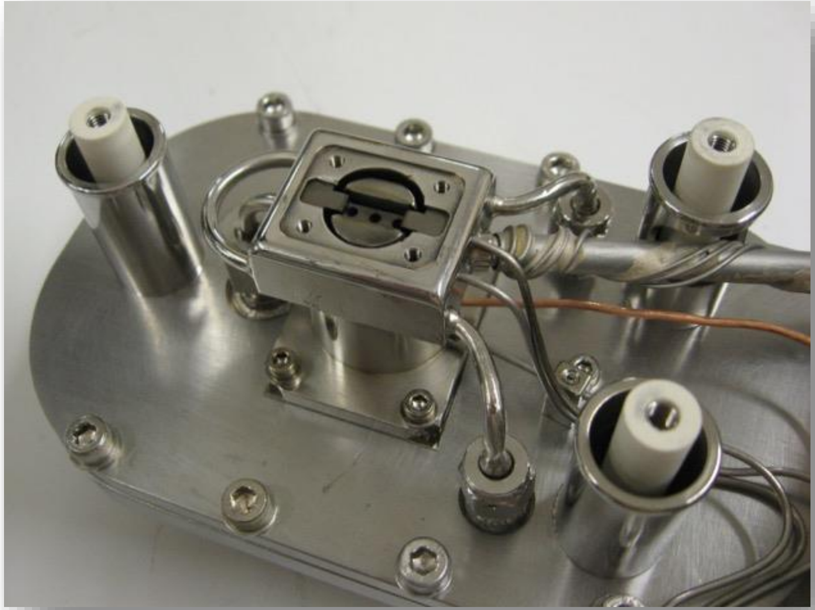


Penning source III



Courtesy of D. Faircloth

Penning source IV

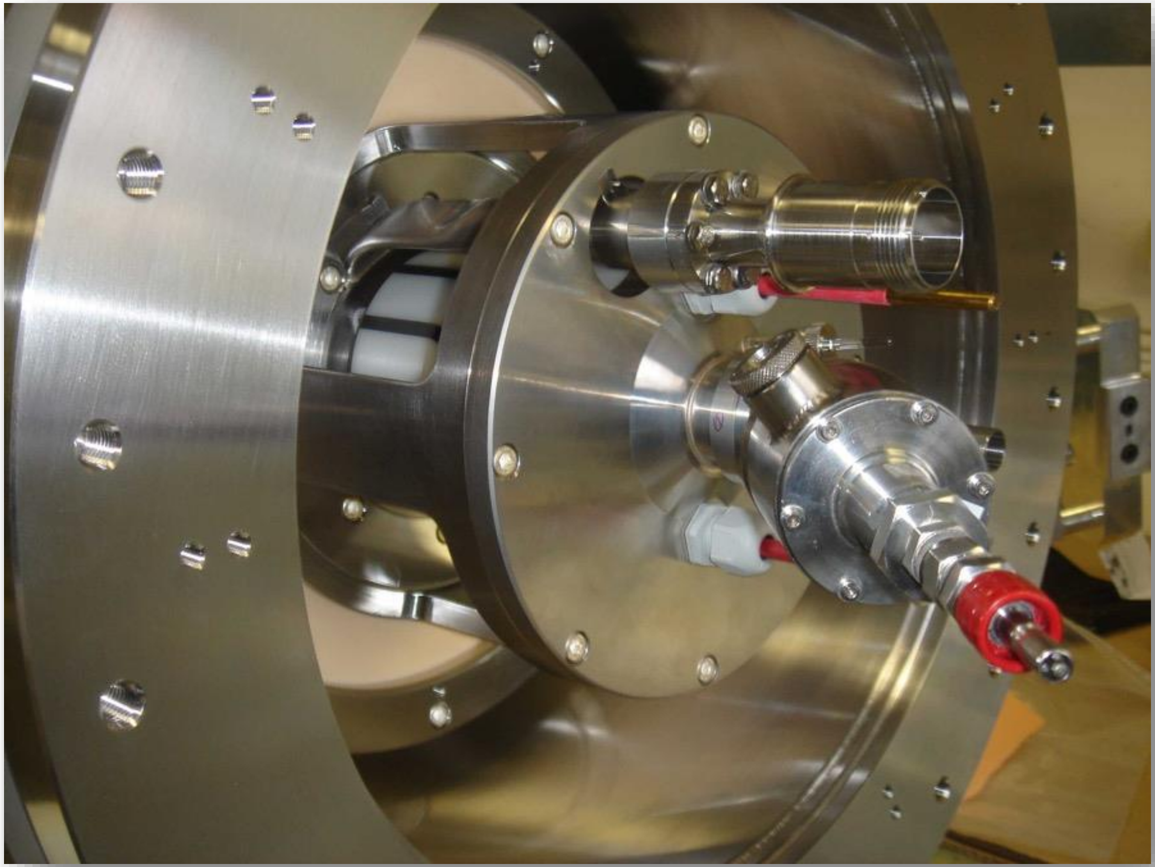


source open

extraction installed

Courtesy of D. Faircloth

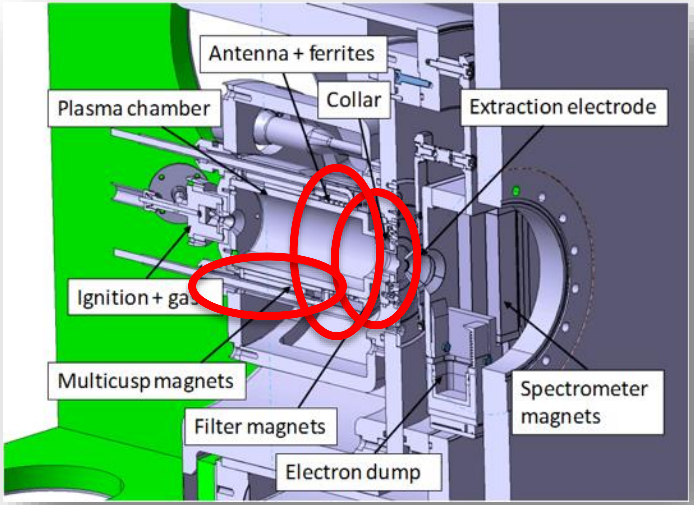
The RF driven H^- source

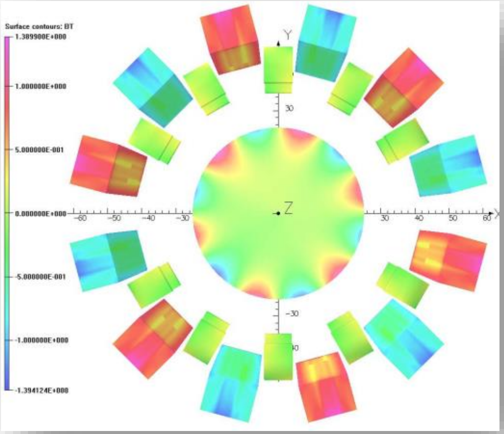


Location: CERN Linac4

The H^- source II

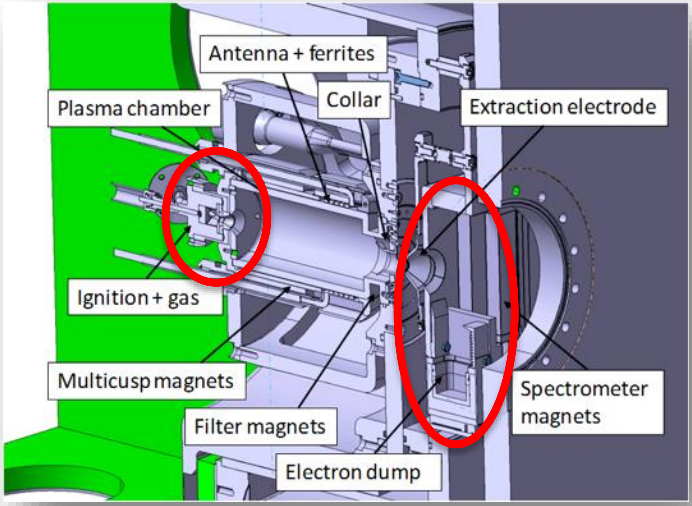
- RF driven ion sources were developed in the late 1940s, negative ion sources were developed according to requirements
- H^- is created in the volume process
- The RF power is coupled inductively into the plasma
- The plasma region separated by a magnetic filter into two regions of different electron temperature
- The plasma is confined by a magnetic cusp structure





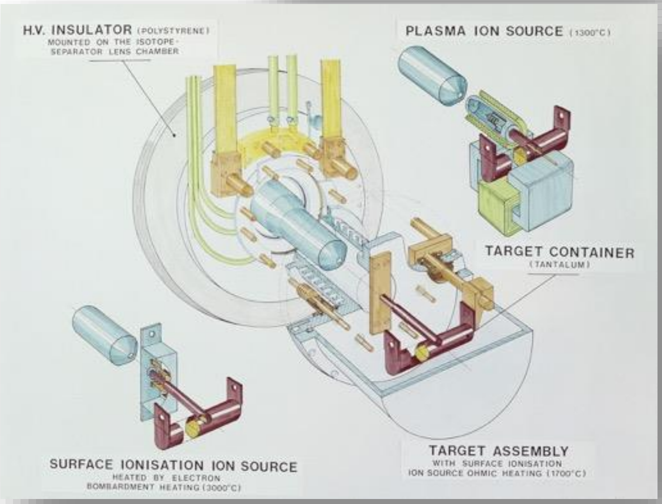
The H^- source III

- 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^-
- Cesium free and no antenna or filament in the plasma
  ➔ high reliability
- The use of cesium does reduce the number of co-extracted electrons and increase the ion current



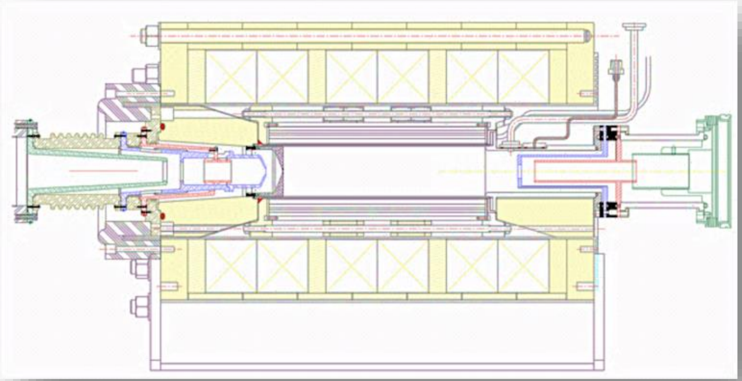
Secondary beams
Target ion sources

- Part of isotope online separators (e.g. CERN 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

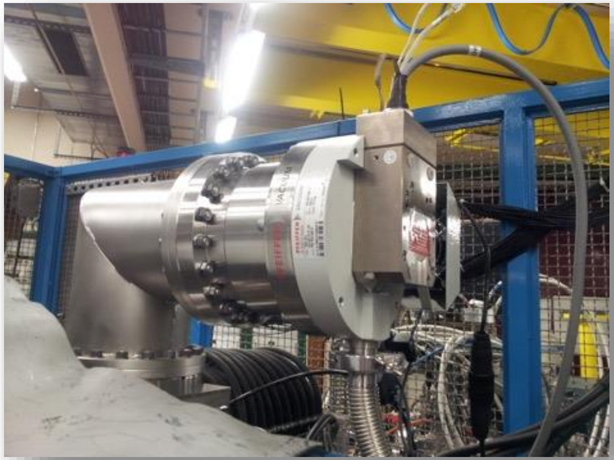
- Breed singly charged (radioactive) ions to higher charge states (1+ -> n+)
- Post-accelerator can be more compact and efficient for n+ ions
- Source has to accumulate a (continuous) current of singly charged ions, breed it to higher charge states and and release them in a pulse
- For radioactive beams 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



ENGINEERING

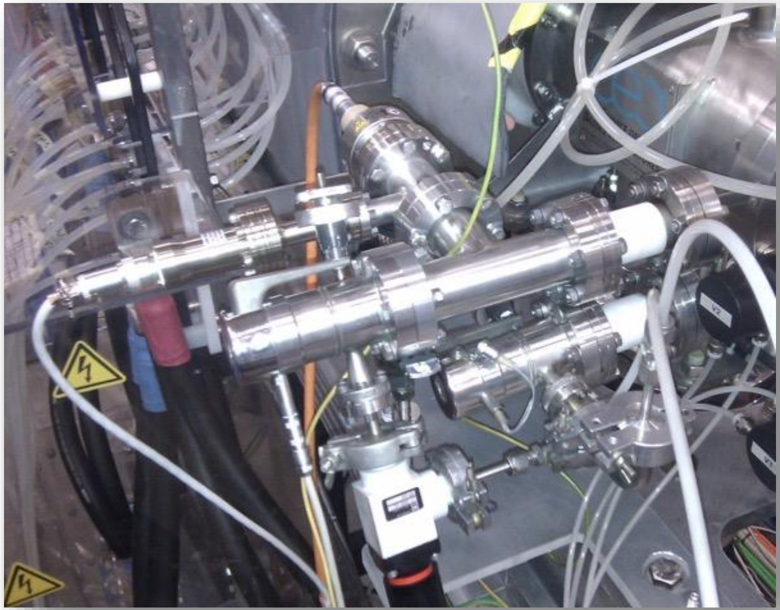
Vacuum I

- the source is pumped by several pumping groups each consisting of a roughing pump and a turbo molecular pump
(+ some valves and vacuum controls)
- the pumps should be oil free
(risk of vacuum contamination with carbon hydrides)



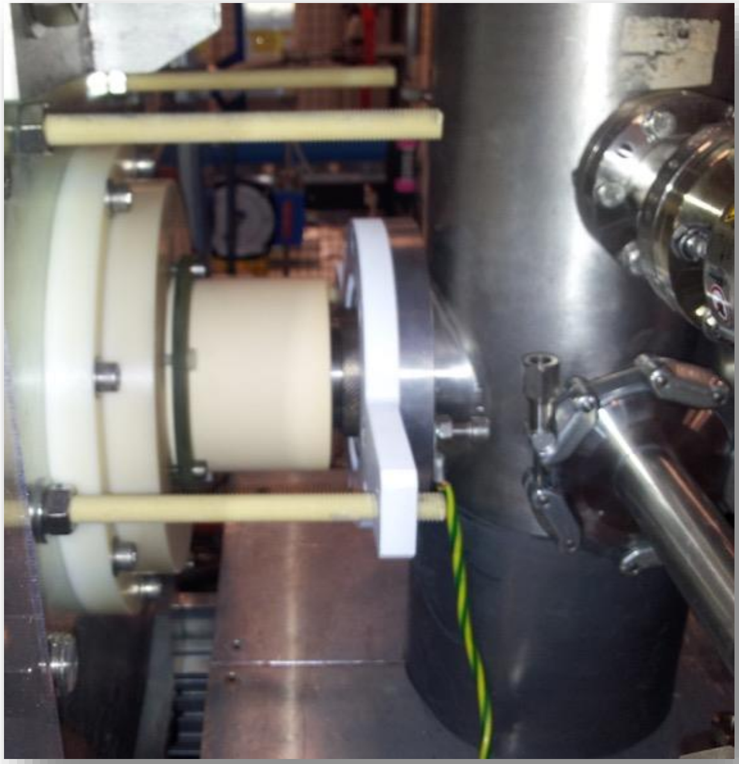
Vacuum II

- the vacuum levels are measured at several different positions
- one of these values can be used for the gas feedback loop



Vacuum III

- wherever possible the connections are metal sealed (CF flanges), otherwise o-rings are used (Viton, e.g. at the main insulator)
- after any manipulation on the vacuum system one should make a leak detection



low base pressure => less impurities and higher possible charge states

Vacuum IV

the ionization processes in a plasma reduce the neutral particle density n_0 in the plasma chamber and in the plasma itself

=> the plasma acts as a vacuum pump

High voltage I

- high voltage can be found at different locations: source extraction, vacuum gauges, ion getter pumps, microwave generator, …
- insulation: ceramics, plastic, air, vacuum, …
  - rule of thumb: 3-5 kV/cm in air, 1 kV/mm in vacuum (but in the presence of electric and magnetic fields the situation is different)
  - keep insulators clean, avoid dust
- good electric connections important
- centralized earth connection on ground and on the high voltage platform (star like topology, avoid earth loops)

High voltage II

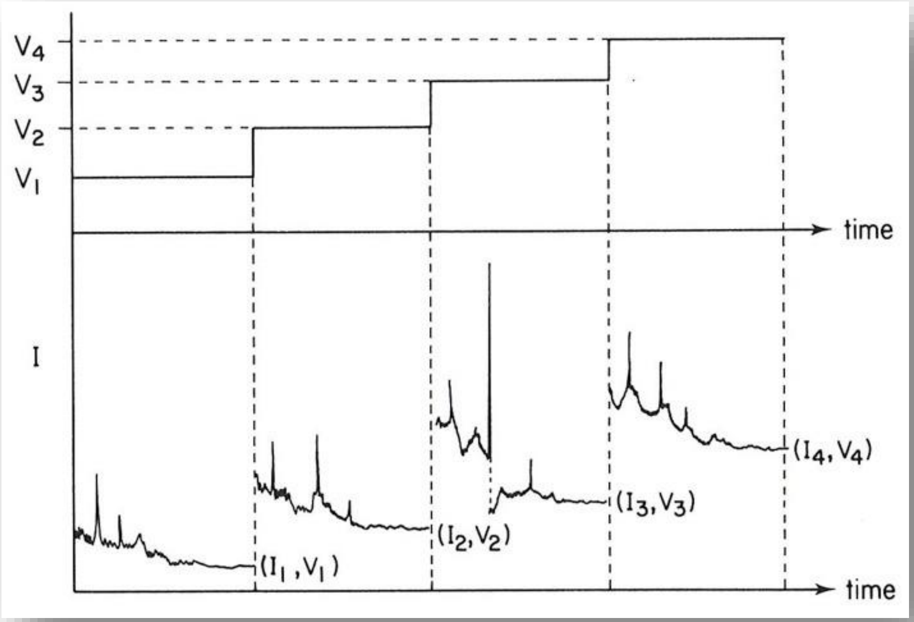
- if there are power consumers on the high voltage platform one needs a separation transformer
- communication with devices on the high voltage platform (e.g. via glass fiber)

High voltage III

- cooling on the HT platform (local system or with demineralized water and long tubes)
- active or passive beam load compensation => stored energy in the capacitors, issue during break downs

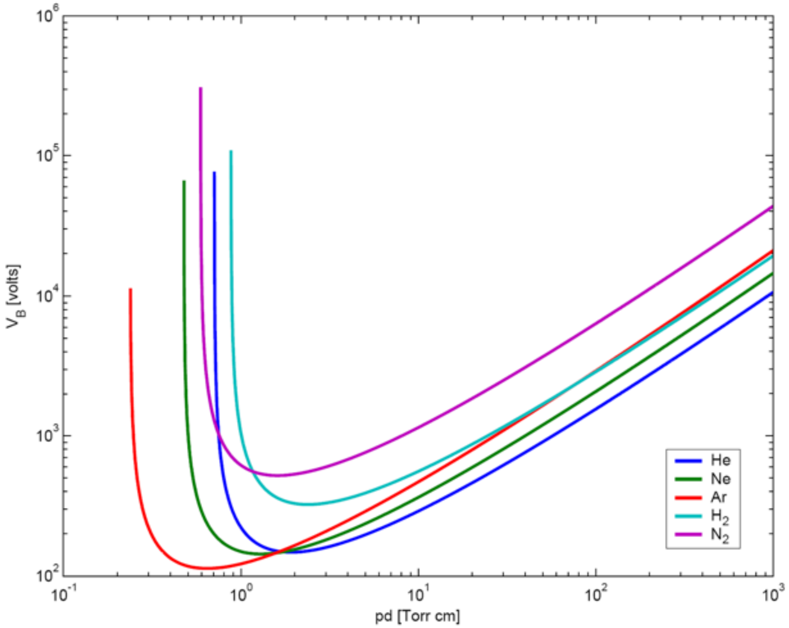
High voltage IV

high voltage systems need to be conditioned to minimized the drain current



High voltage V

- high voltage breakdown at low pressures (discharge, arc)
  -> Paschen's curve
- crossed electric and magnetic fields
  -> Penning discharges (desired in Penning gauges, undesired in extraction systems)

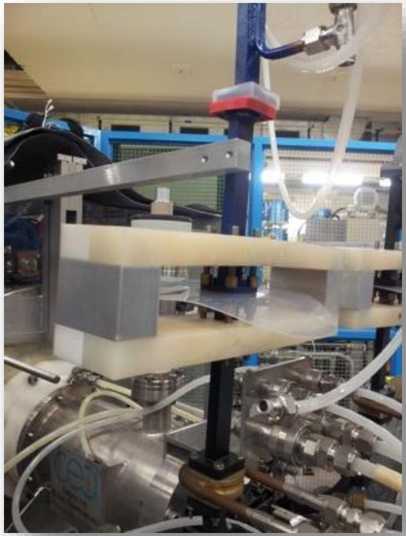


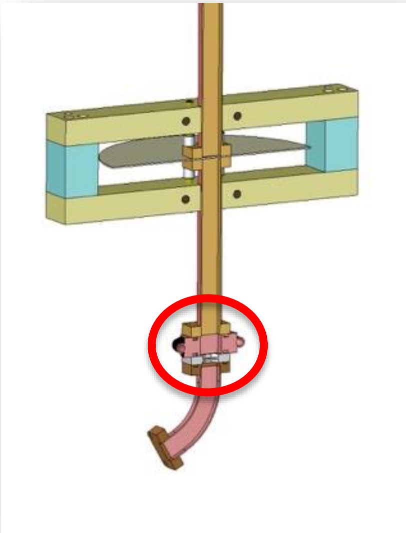
Microwaves I

the source is driven by a klystron-based generator
(2^{nd} generator is available as backup)

Microwaves II

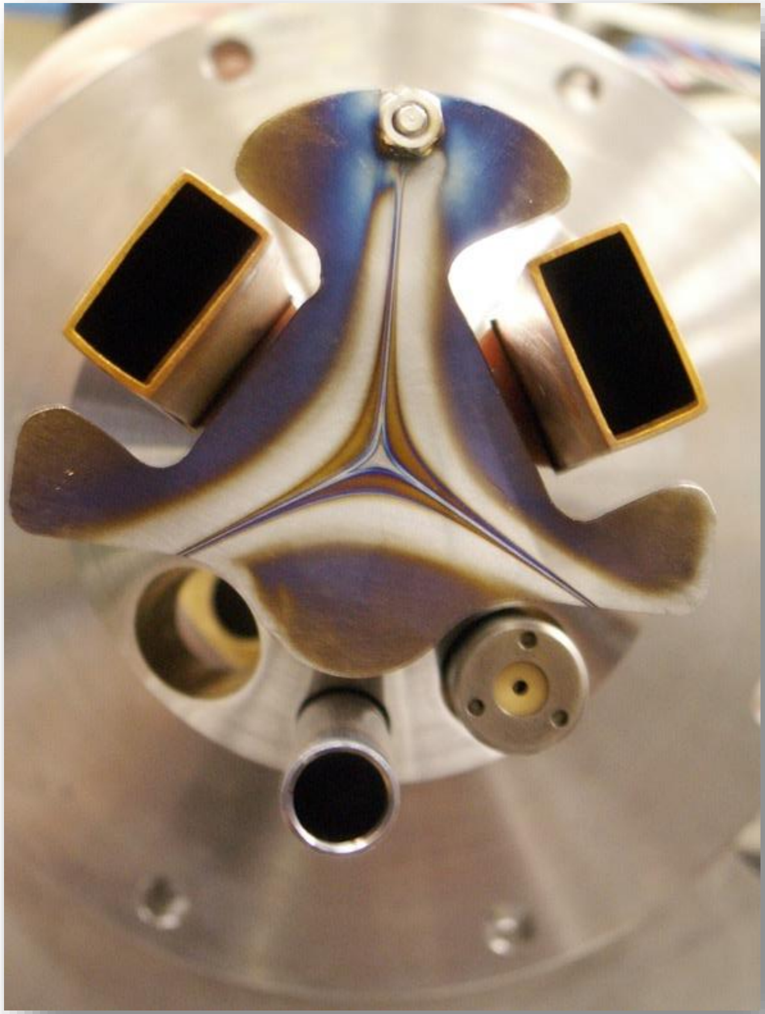
- the waveguides are water cooled (to reduce the change of the length due to heating)
- the high voltage break separates the ground from the high voltage part of the waveguide
- the microwave window separates the source vacuum from the outside (quartz window inside the waveguide)





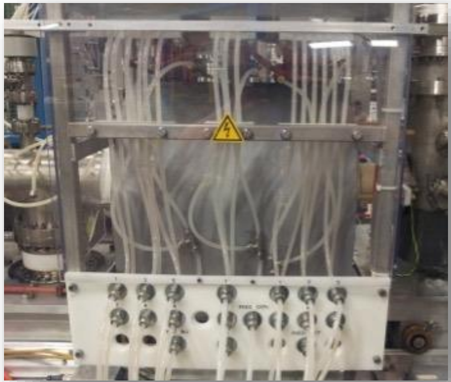
Microwaves III

- there are different ways to inject the microwave into the plasma chamber (open waveguide, coaxial waveguide, …)
- waveguide tuning may reduce losses in the waveguide and improve the microwave injection into the source



Cooling I

- many systems need to be cooled or temperature stabilized
- cooling with air
  - convection, ventilator, …
  - air conditioning (with temperature and humidity control)
- cooling with water
  - tap water (but not for magnets!)
  - demineralized water
  - chilled water



Cooling II

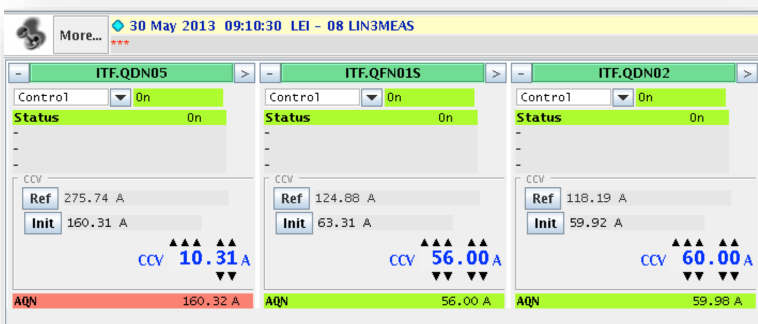
- cooling power is controlled by the flow (influenced by the pressure difference and the mechanical design)
- temperature and flow need to be controlled and interlocked (temperature sensitive equipment e.g. permanent magnetic hexapole)
- a heat exchanger may be needed if the output temperature reaches critical values (to lower the input temperature)

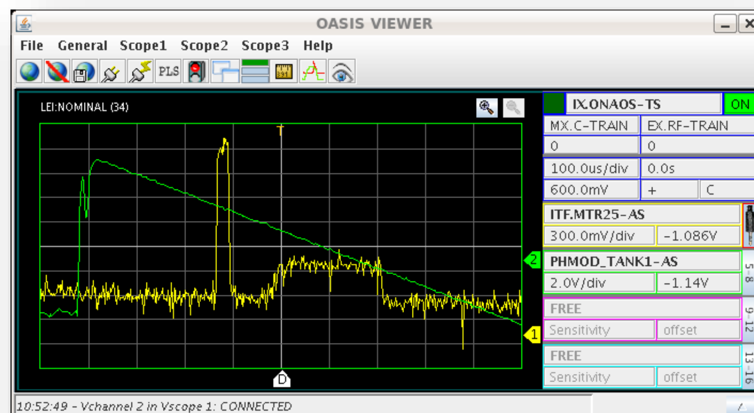
Cooling III

- water quality and the mechanical design of the cooling circuits are important
- the system could be blocked or leaks could be created due to
  - electrochemical corrosion (water conductivity and combination of insulators and metals)
  - cavitation (diameter changes in the cooling channels)
- condensation may be a problem if there is no power load; especially on high voltage platforms (corrosion, short circuits)

Control system I

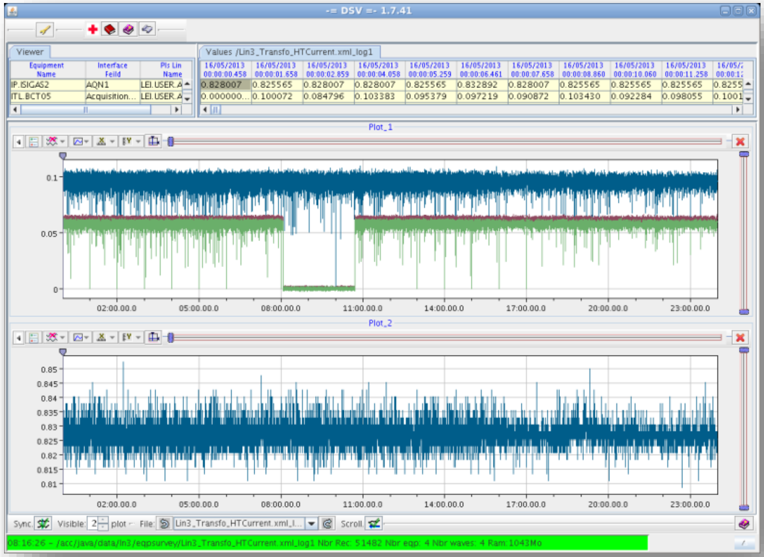
control and measure device settings (voltages, currents, timing, …)

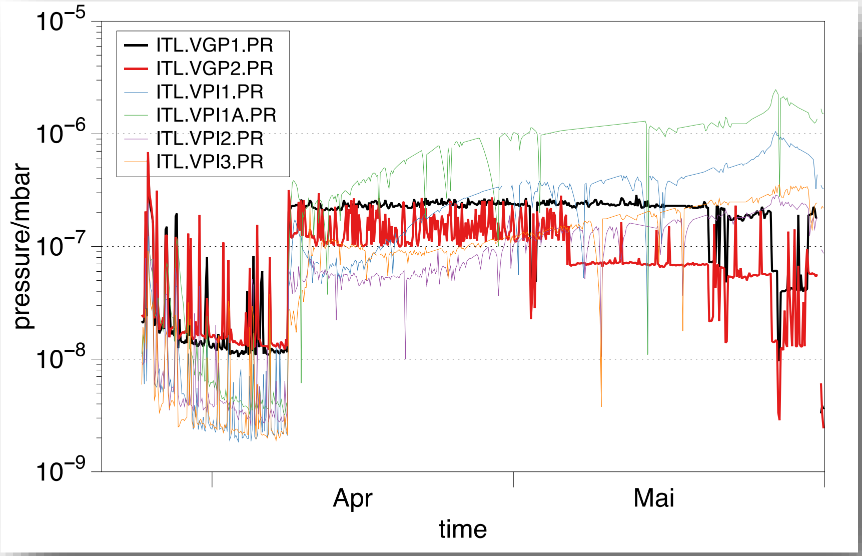




Control system II

data logging (short and long term)





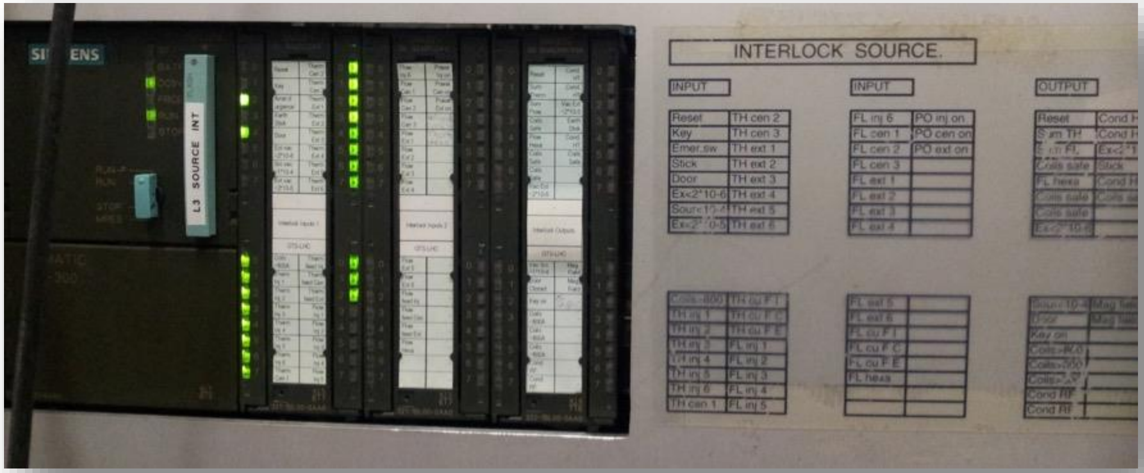
Control system III

- local and remote systems
- can be distributed (connection via Ethernet or dedicated bus systems)
- hardware
  - industrial computers
  - PLC's
  - dedicated hardware
- software
  - EPICS
  - LabVIEW
  - WinCC
  - "home made" (e.g. CERN FESA)
  - databases for data storage (e.g. Oracle)



Interlock system

- part of the control system
- machine and personal protection
- can be hierarchical
- can have many input channels
- has to prevent to start the device or stop it in case of problems
- if possible use hardware interlocks, especially for the personal protection



Safety issues I

Working on an ion source one has to take into account different safety risks:

- noise from racks, pumps, …
- heavy weights (e.g. during source manipulation)
- water in the presence of electricity
- water at high pressures
- systems operating with compressed air
- explosive gases (e.g. hydrogen)
- toxic and/or carcinogenic materials (cesium, lead, many of the substances used with MIVOC, …)

Safety issues II

- High voltage
  - high voltage cage to enclose the biased elements
  - usage of active and passive earthing devices
- strong magnetic fields
  - permanent magnets cannot be switched off
  - careful handling of tools and metals pieces in the vicinity of the magnets

Safety issues III

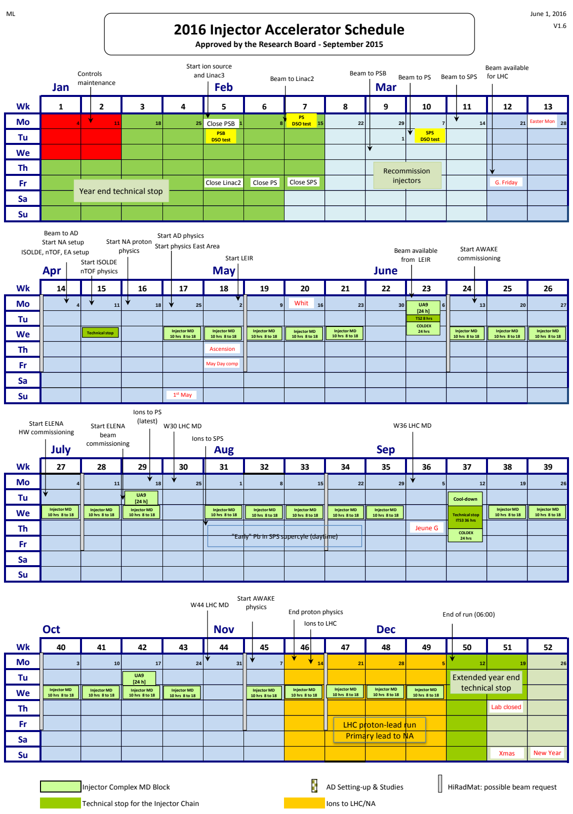
- x-rays
  - shielding
  - dosimetry
  - monitoring
- microwave radiation/ radiofrequency
  - dosimetry
  - monitoring

Safety issues IV

- access restrictions/limitations
- protective equipment
- working procedures
- safety rules
- ALARA principle
  (As Low As Reasonable Achievable)

Schedule

- coordination in relation with other machines and adaptation to changing schedules is important
- the source is the first part to start-up
- sequence for a start-up
  - hardware preparation, setup
  - hardware test
  - commissioning without and with beam
  - physics run
- sometimes switch over time from one element or setting to an other is needed
- periods for dedicated machine development time have to be requested (as the source delivers beam to all other machines)
- always foresee time for repairs and maintenance



CONCLUSION

Summary

- Ion sources are an essential part of an accelerator chain
- Ion sources have a wide range of application in industry and research
- All ion 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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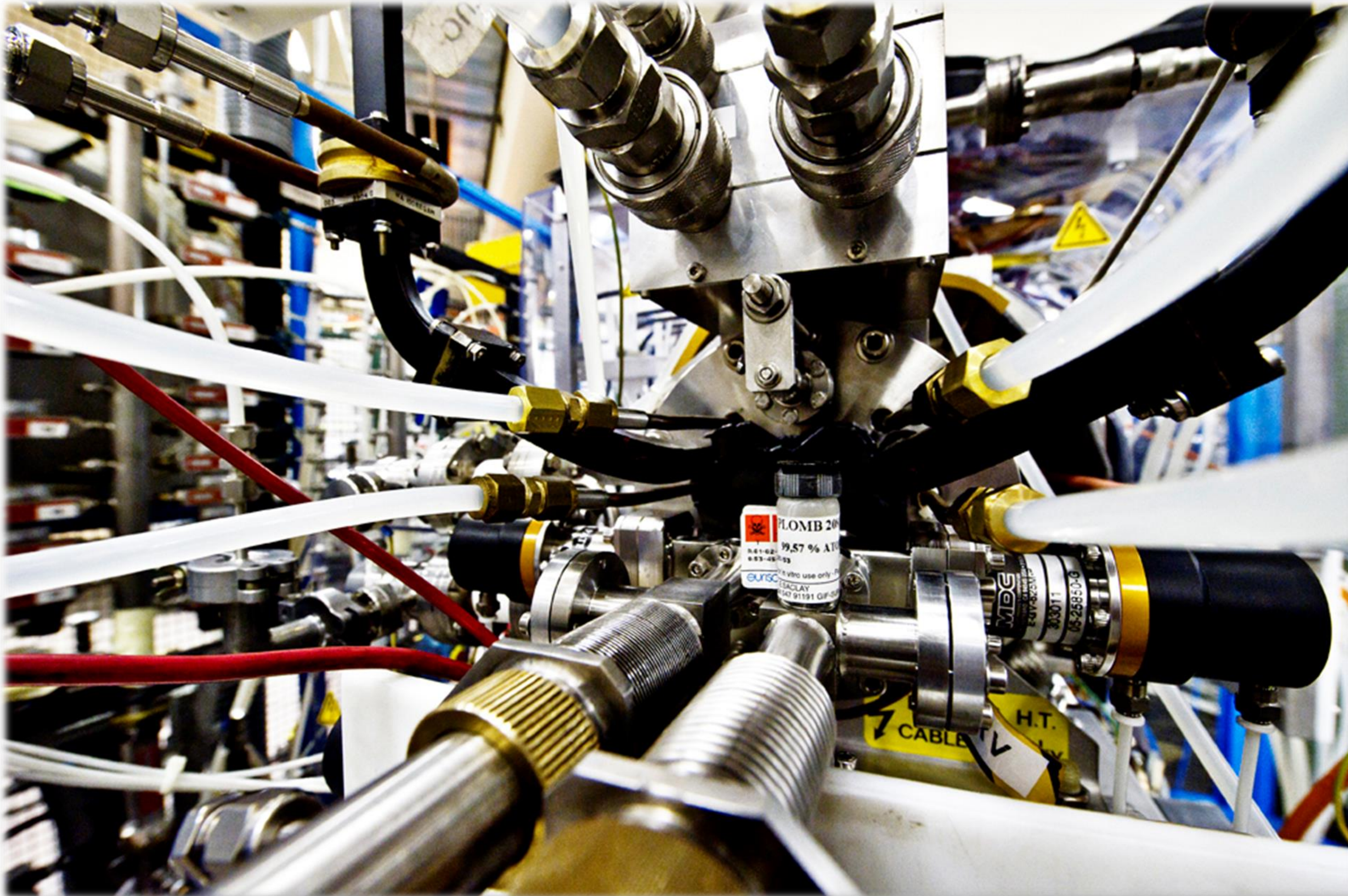
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