Sources of intense beams of heavy ions

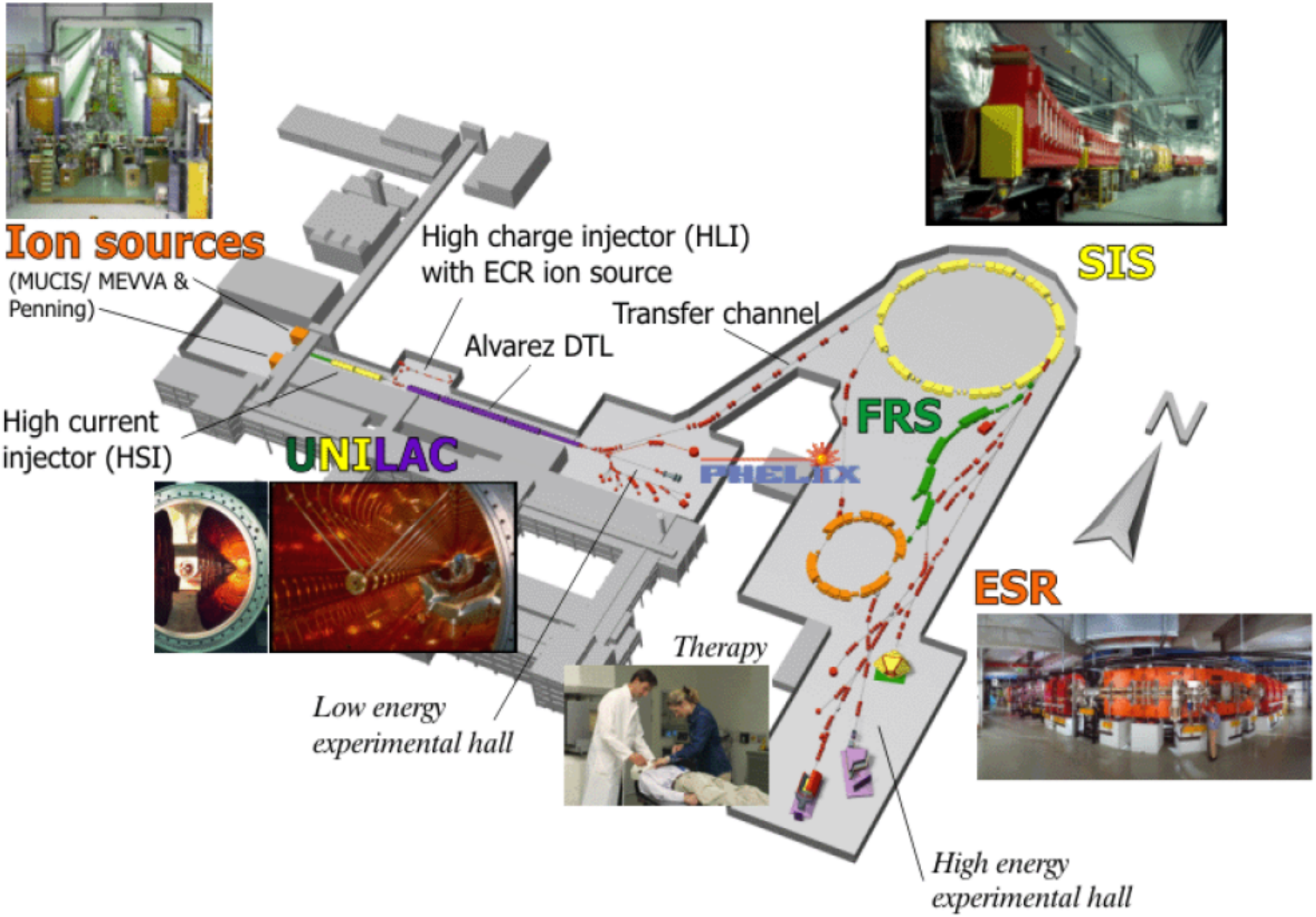
Wilhelm und Else Heraeus Stiftung

517. WE-Heraeus-Seminar
Accelerator physics for intense ion beams

Oliver Kester

Institut für Angewandte Physik,
Goethe-Universität Frankfurt
and
GSI Helmholtzzentrum für Schwerionenforschung

Heavy ion accelerator facility



Outline

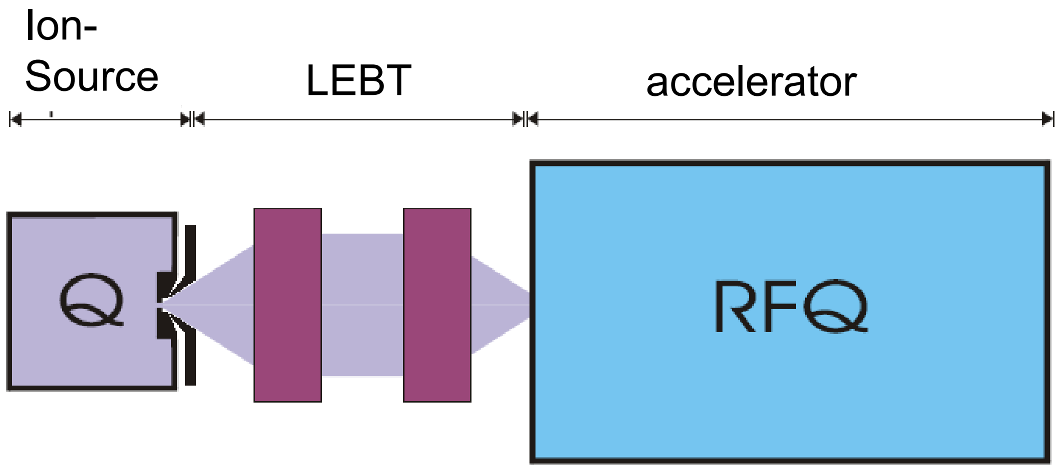
- Introduction and Basics

  Ionisation, plasma generation
  confinement and extraction of ions

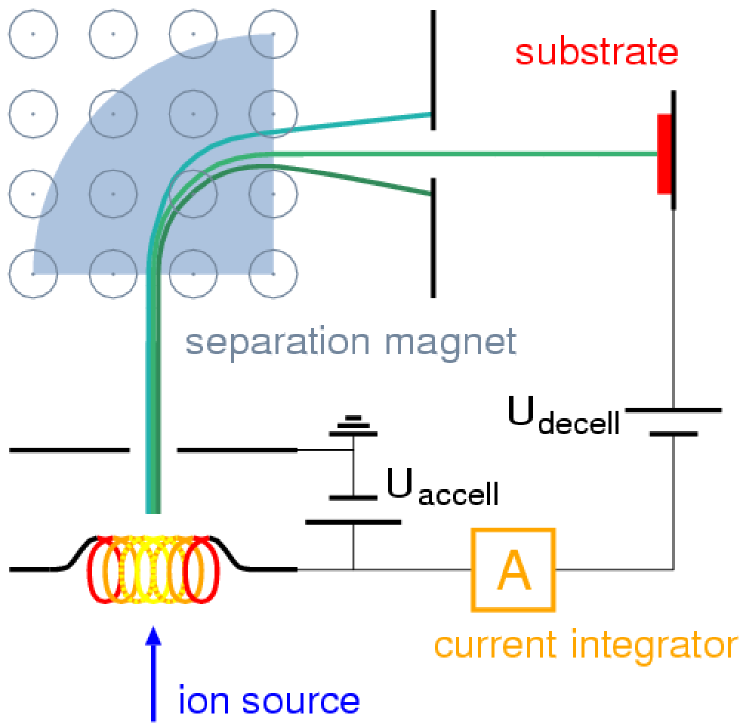
- High current ions sources
  - Multi-cups ion sources
  - rf-driven ion sources
  - Metal vapor vacuum arc sources (MeVVA)

- High charge state ion sources
  - The Electron Cyclotron Resonance Ion Sources (ECRIS)
  - The Electron Beam Ion Source (EBIS)

Ion sources – accelerator application



Typical structure
of an injection line:



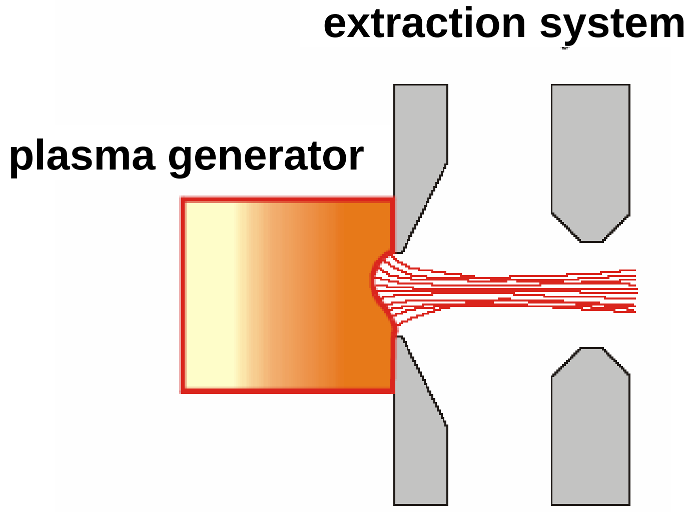
Ion implanter

Penetration depth → beam energy
Intense ion source → volume ion sources

For semiconductor production

Introduction and Basics

Physics of ion sources?

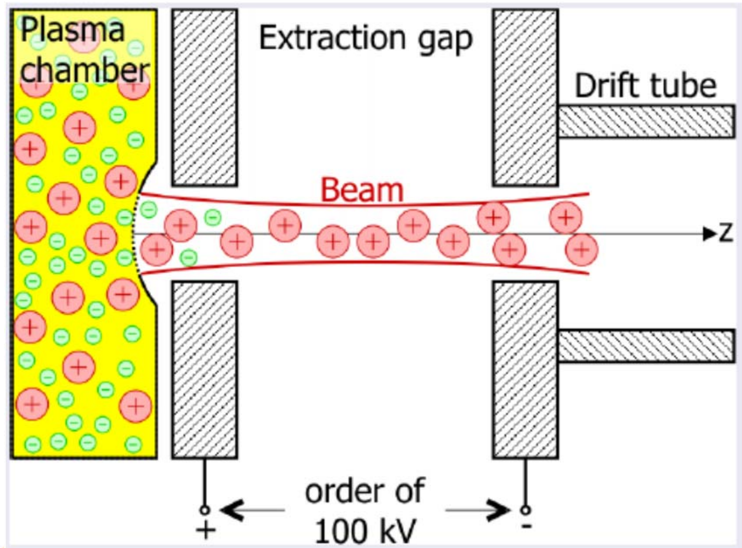


The physics of ion sources:

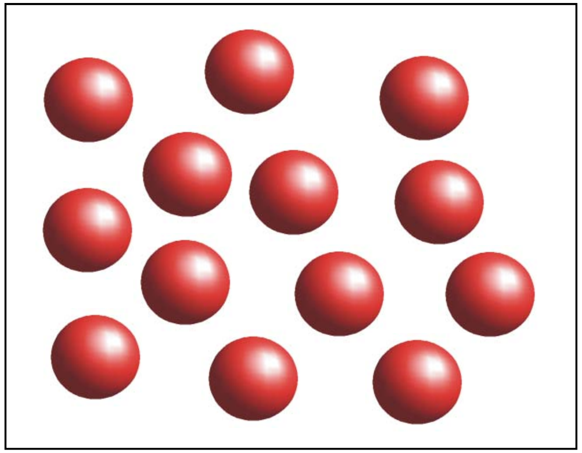
- Ionisation of atoms (Electron impact ionisation, photoionization)
- Production of charged particles (Electrons, ions) → Production of plasma
- Plasma physics
- Beam shaping and charged particle transport
- Electromagnetic fields (electric, magnetic, rf)

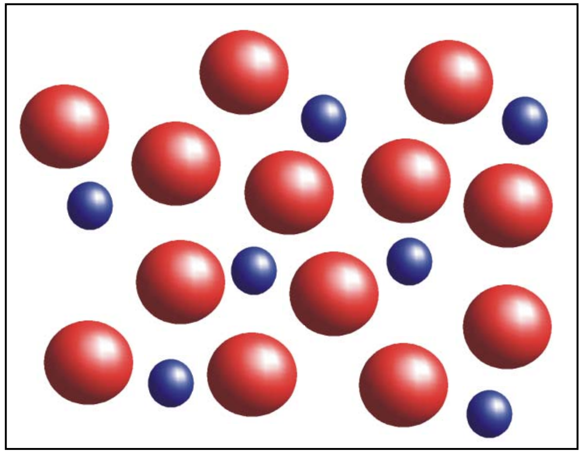
Principle of a plasma ion source:

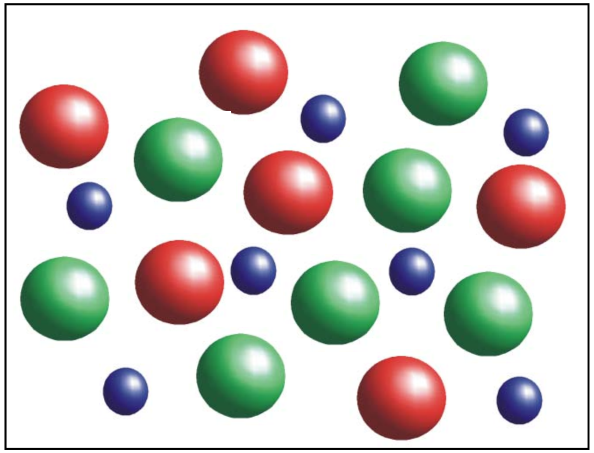
- plasma generation
- extraction



Plasma generation







Make atoms available in the plasma generator via:

- Gas injection
- Vapour, melting of solids
- Sputtering

Generate free electrons:

- Thermionic emission
- Photo ionisation
- Discharge

Supply the ionisation energy:

- Electron acceleration (electrostatic → e-gun)
- rf-heating
- E x B-drift

Atomic processs in a Plasma

collisions with **electrons**

Impact Ionization | Three-Body-Recombination (TBR)

$$A^{Z+} + e \leftrightarrow A^{(Z+1)+} + e' + e''$$

A^{Z+}: Atom of species A with charge state Z
e' : electron changed energy

Impact excitation | Impact de-excitation

$$A^{Z+} + e \leftrightarrow \left(A^{Z+}\right)^{*} + e' \Rightarrow$$ Non-radiative transition

collisions with **photons**

Photo ionization | Radiative Recombination (RR)

$$A^{Z+} + h\upsilon \leftrightarrow A^{(Z+1)+} + e \Rightarrow$$ Line spectrum

Excitation | Spontaneous emission

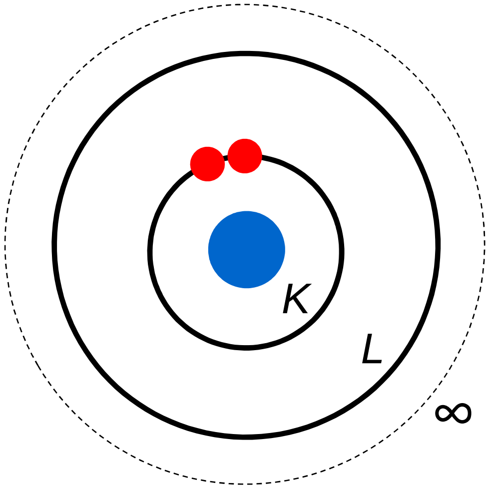
$$A^{Z+} + h\upsilon \leftrightarrow \left(A^{Z+}\right)^{*}$$

Photo absorption | Bremsstrahlung

$$A^{Z+} + h\upsilon + e \leftrightarrow A^{Z+} + e' \Rightarrow$$ Continuous spectrum

Electron impact Ionisation

The electron impact ionization is the most fundamental ionization process for the operation of ion sources.



electron impact ionisation

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

The probability for removing one electron (q → q+1) is determined by the cross section $\sigma_{q \rightarrow q+1}$ [cm^2].

$$\bar{\tau}_{q\rightarrow q+1} = \frac{n_q}{\nu_{q\rightarrow q+1}} = \frac{1}{n_e v_e \sigma_{q\rightarrow q+1}} = \frac{e}{j_e \sigma_{q\rightarrow q+1}}$$

The average ionization time in the charge state *q* depends only on the cross section and the current density of the electrons.

e-impact ionisation cross section

Approximation of the cross section in quantum-mechanical calculations done by Bethe (1930) using the Born Approximation:

Scattering of a matter wave at a central potential V(r) for $E_{kin} >> E_{ion}$ (perturbation).

$$\sigma_i^{nl} = const \cdot Z_{nl} \frac{1}{E_{kin} E_{nl}} \ln\left(\frac{E_{kin}}{E_{nl}}\right)$$

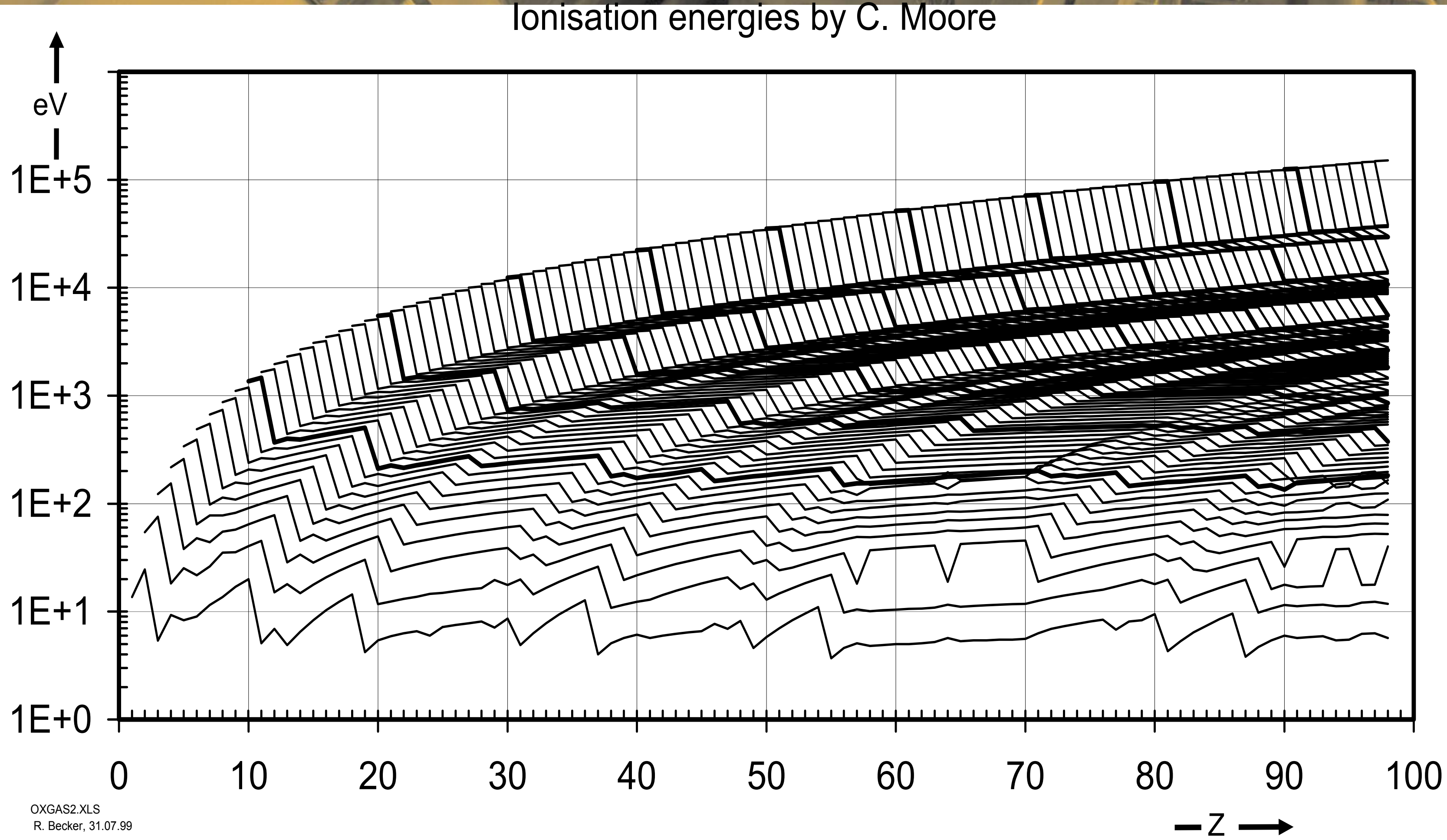
All electrons in an atom or ion contribute with their individual σ_{ei} to the total cross section σ, as long as the kinetic energy E_{kin} of the projectile is larger then the ionization energy E_{nl} of these electrons.

$$\sigma_{q \to q+1} = \sum_{i=1}^{N} \sigma_i = \sum_{i=1}^{N} q_i \sigma_{ei}$$

Semi-empirical formula developed by **Lotz 1967** for the energy dependence of the cross sections for the elements from H to Ca and for energies < 10 keV is commonly used.

$$\sigma_{q \to q+1} = 4.5 \cdot 10^{-14} \cdot \sum_{i=1}^{N} \frac{\ln\left(E_{kin} / P_i \right)}{E_{kin} \cdot P_i} \quad \left[\mathrm{cm}^2\right]$$

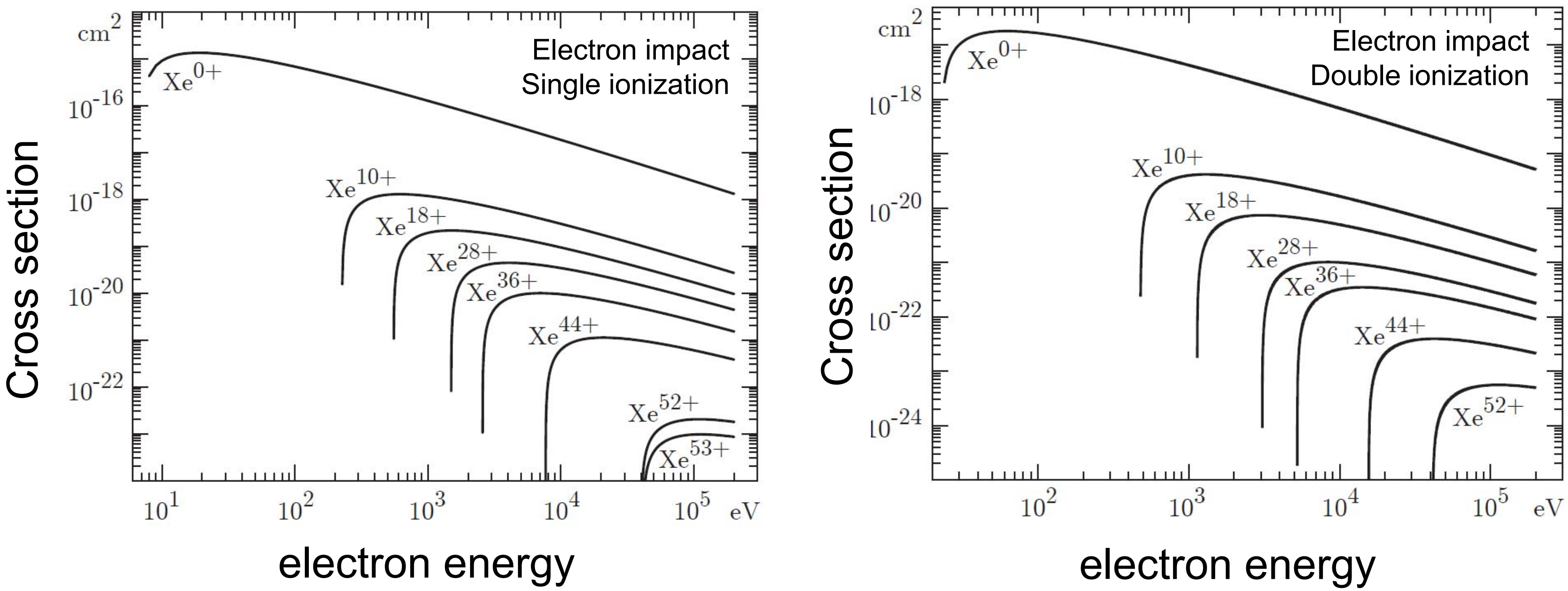
Ionisation potential



- Ionization energies up to 100 keV ($U^{91+} \rightarrow U^{92+}$) required
- Shell structure of the atomic shells is visible

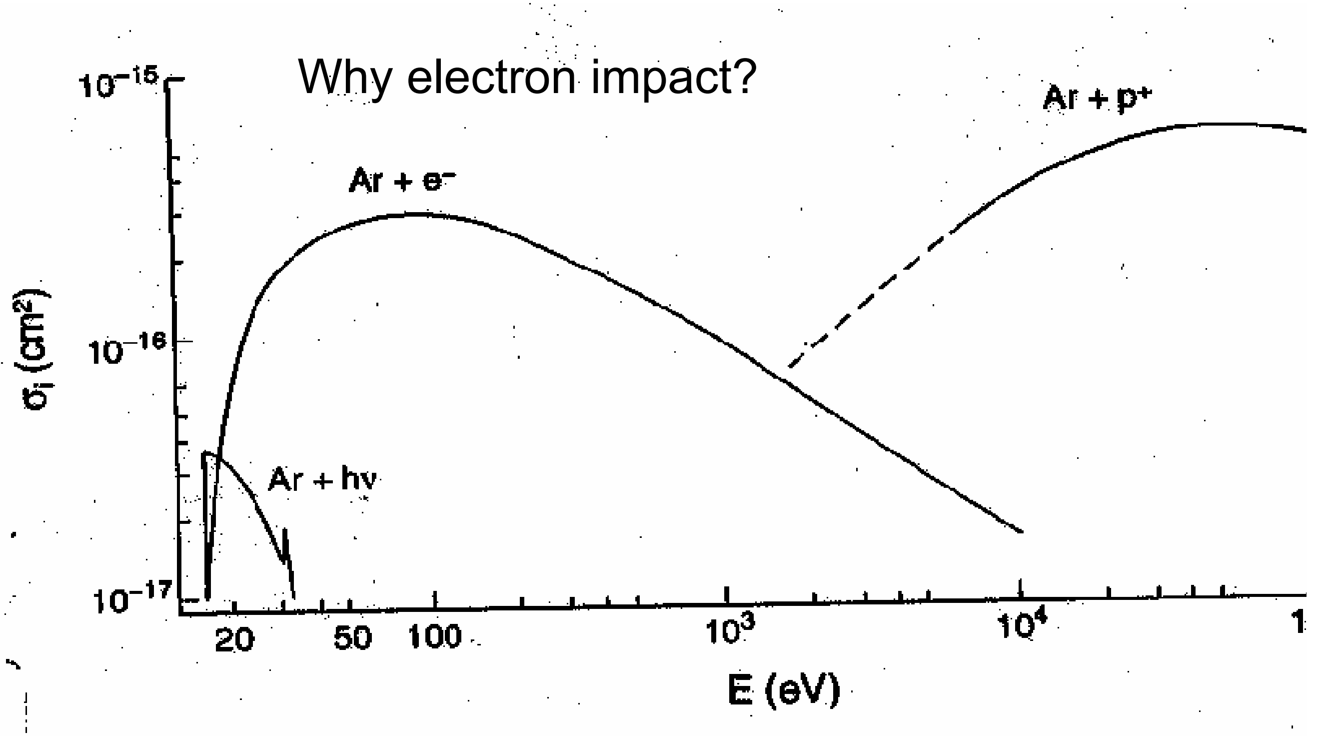
Successive e-impact ionisation

Multi electron removal or single electron **successive** ionization?



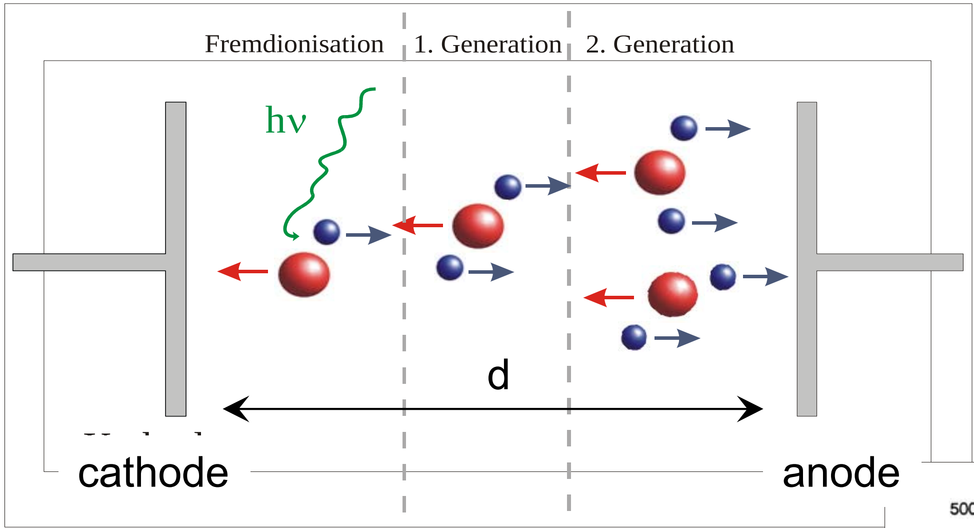
Single step → much higher cross section

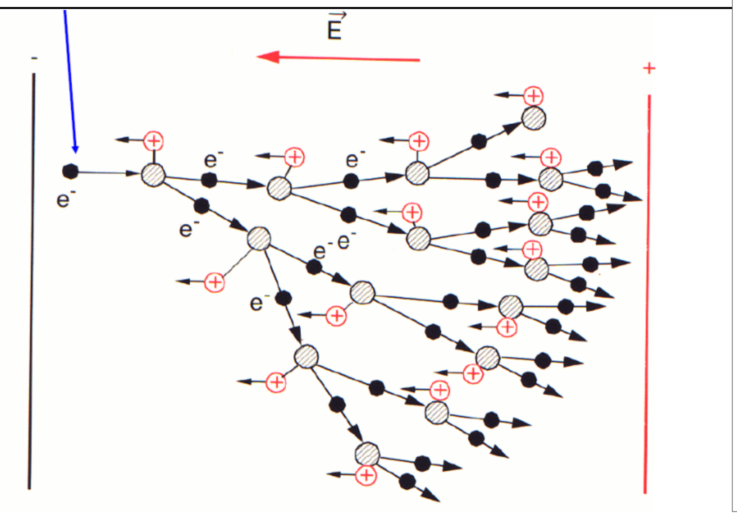
Successive e-impact ionisation



The cross section for the impact ionization is orders of magnitudes higher than the cross section for photo ionization.
The cross section depends on the mass of the colliding particle, since the energy transfer from a heavy projectile is reduced.

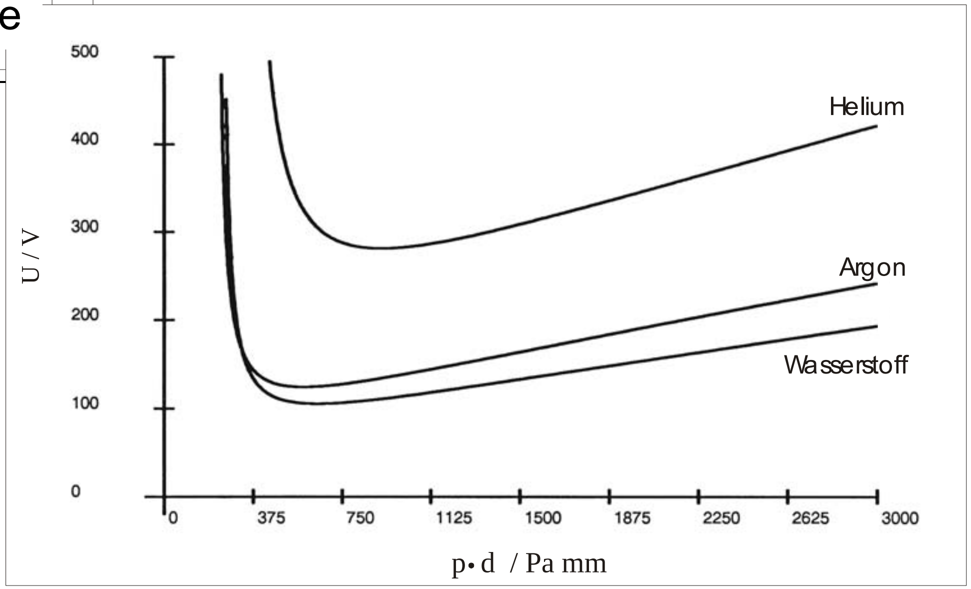
Plasma generation - discharge



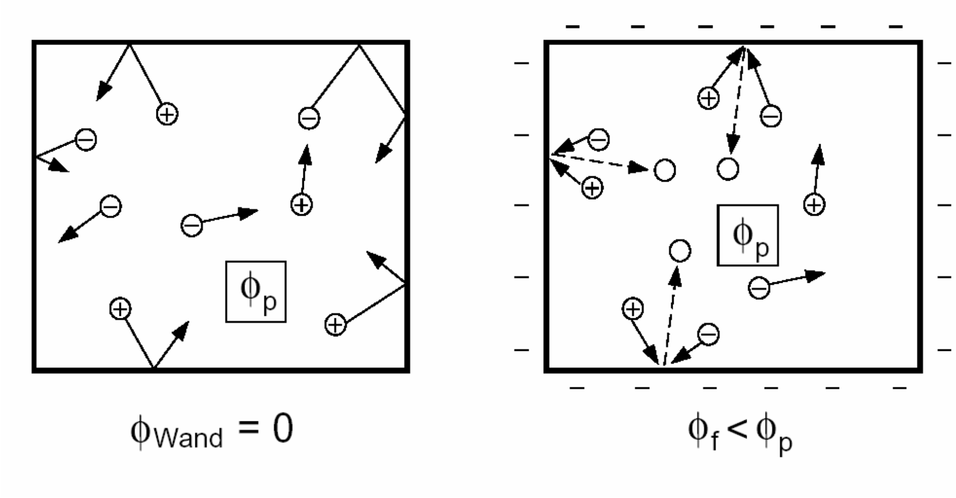


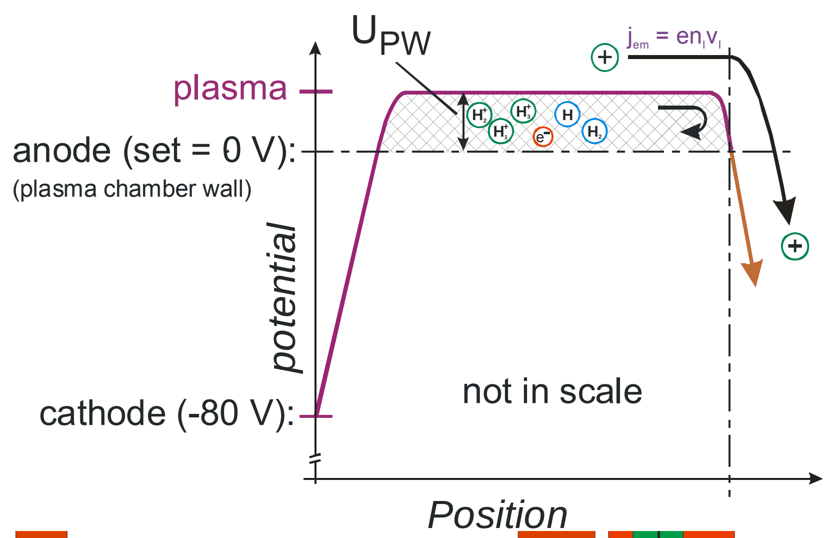
The discharge depends on the gas pressure and the electric field strength

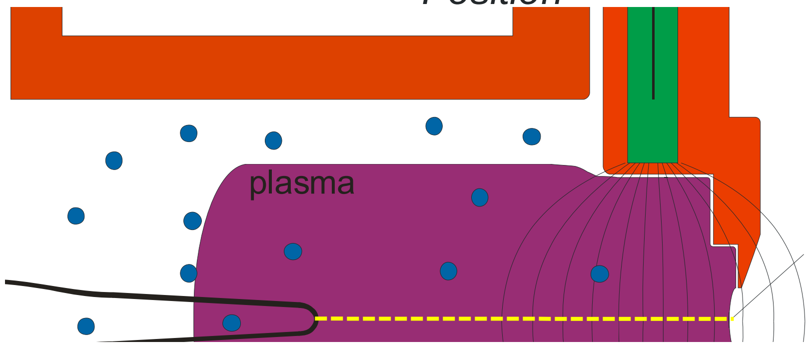
→ Paschen curve



Plasma potential and potential distribution







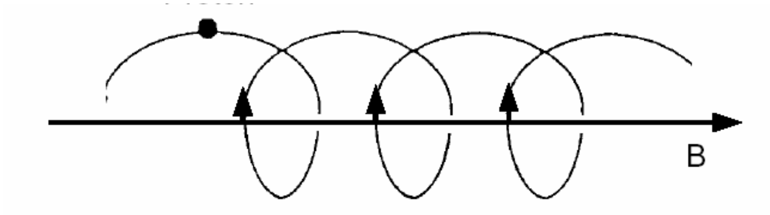
Plasma-wall interface:

a) ideally reflected

b) complete wall recombination

→ different mobilities of electrons and ions lead to a positive potential of the plasma towards the wall

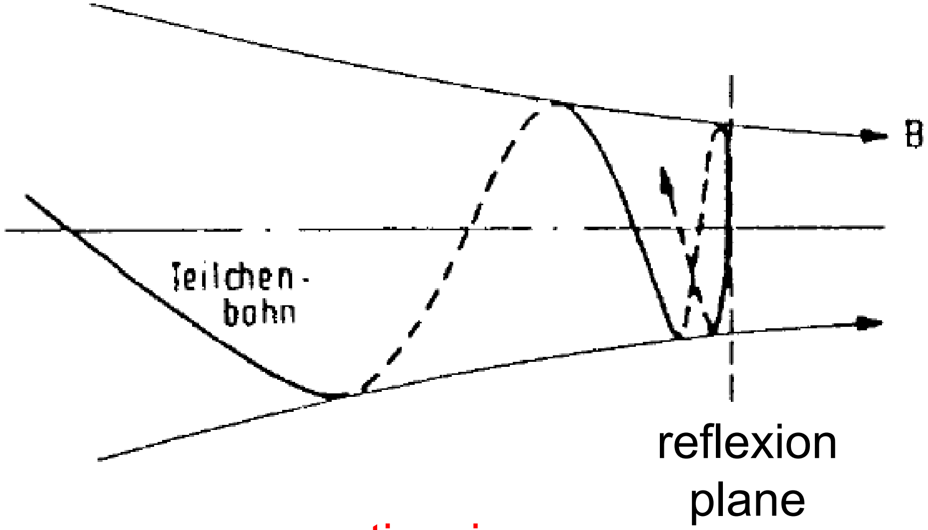
Magnetic confinement

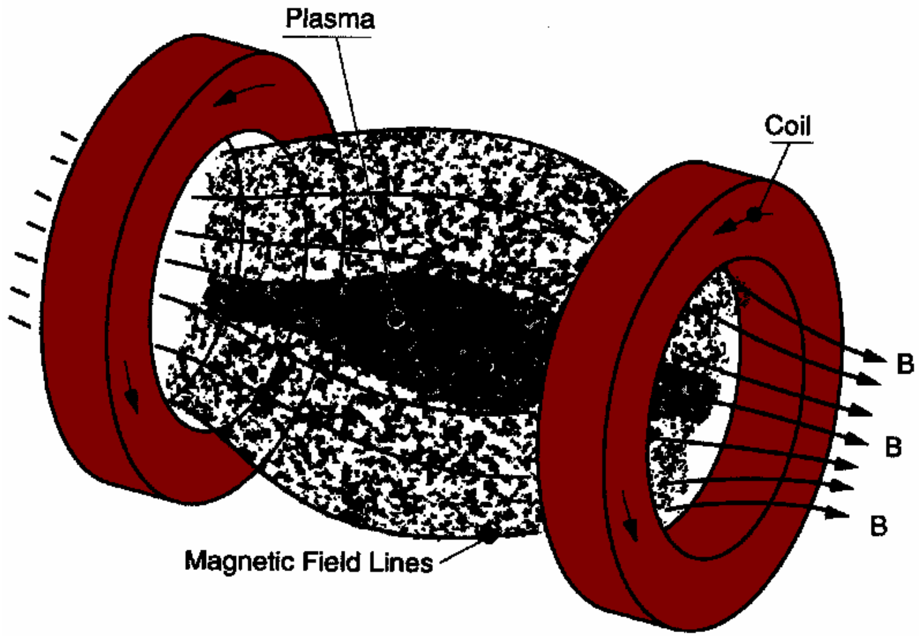


$$\omega_c = \frac{q}{m} B$$ cyclotron frequency

$$r = \frac{m \cdot v_\perp}{q \cdot B}$$ gyration radius

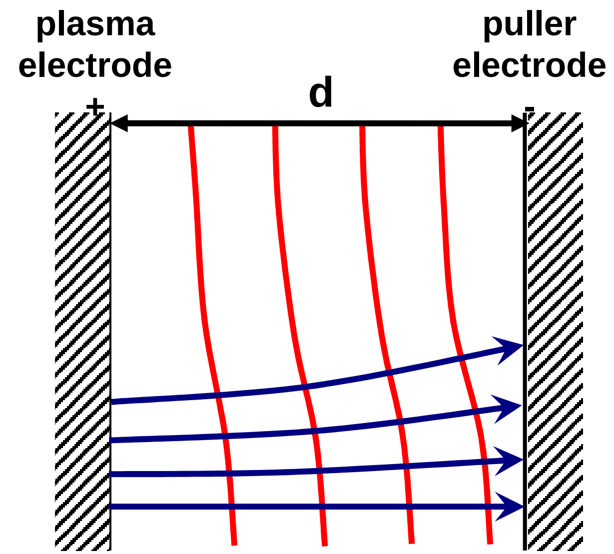
If a charged particle moves into a zone with stronger magnetic field, the kinetic energy of the gyration increases!
→ total kinetic energy is constant, therefore the particle is decelerated in B-field direction

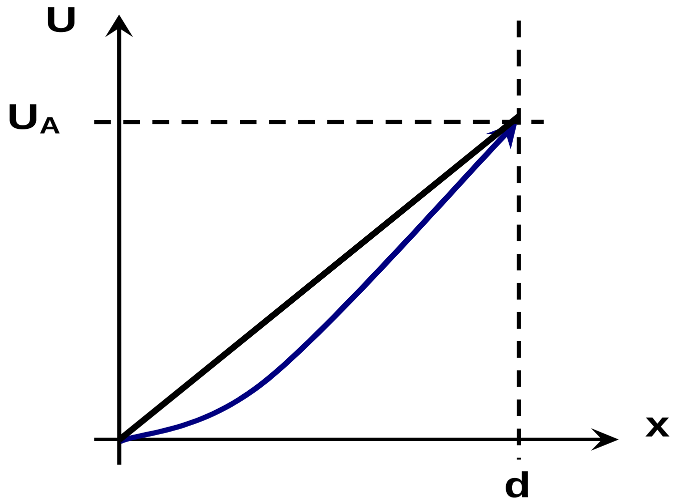


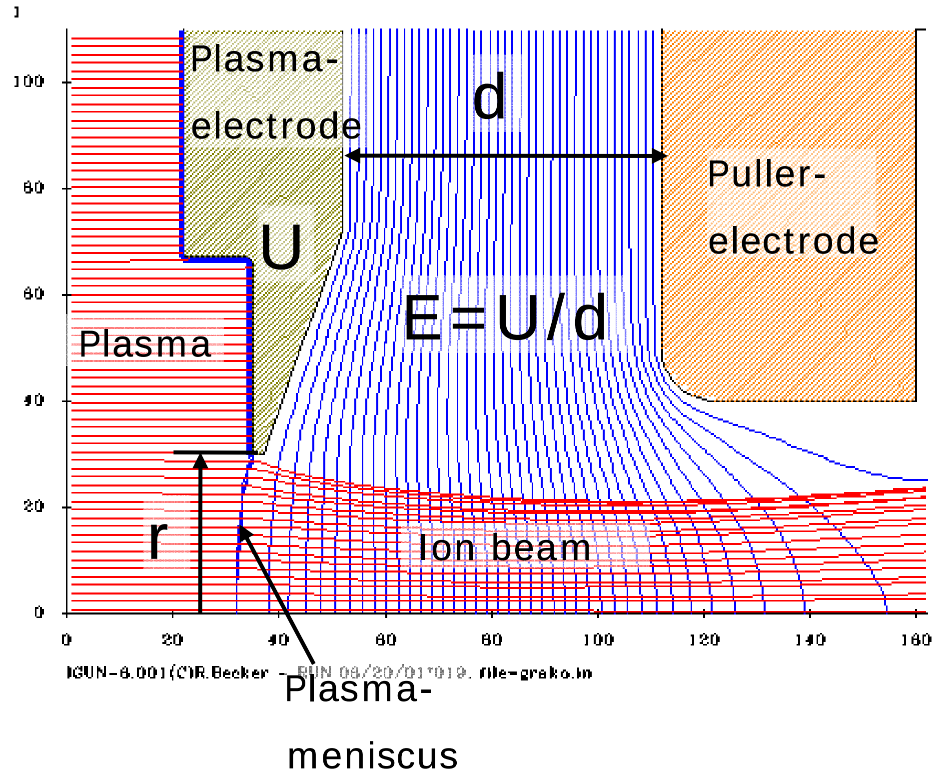


magnetic mirror

Child-Langmuir-Law





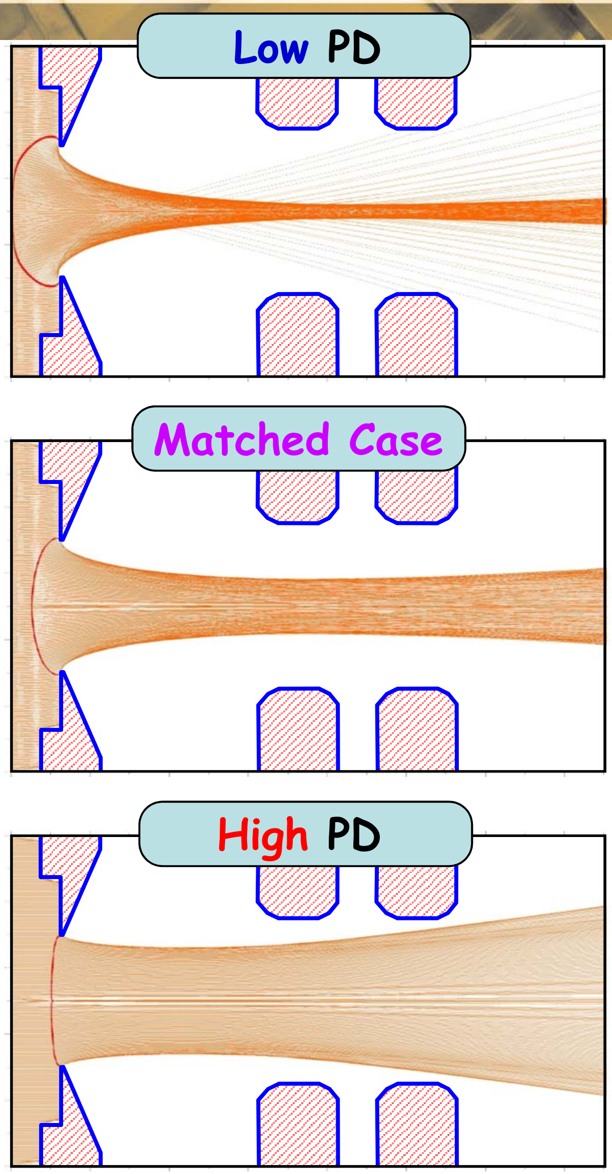


$$I = \frac{4\pi}{9}\varepsilon_0 \sqrt{\frac{2qe}{A \cdot m_u}} \cdot r^2 \frac{U^{3/2}}{d^2}$$

$$I = P \cdot U^{3/2}$$

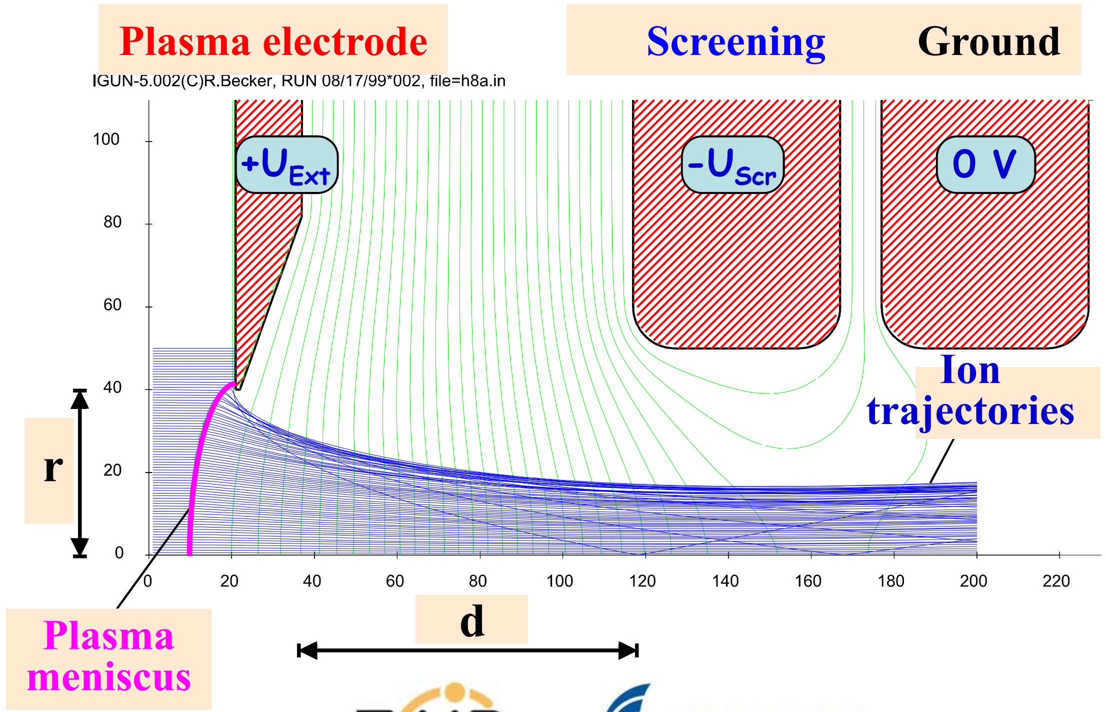
P = Perveance

Ion extraction

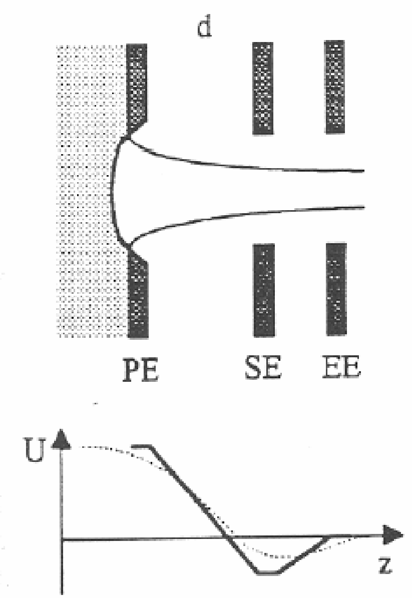


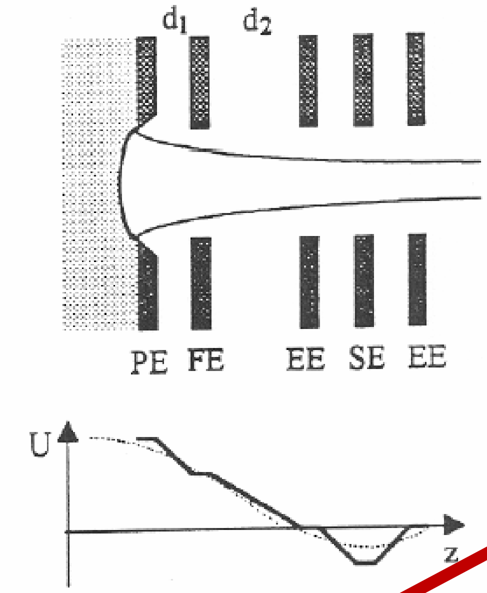
$$S = r/d$$ aspect ratio

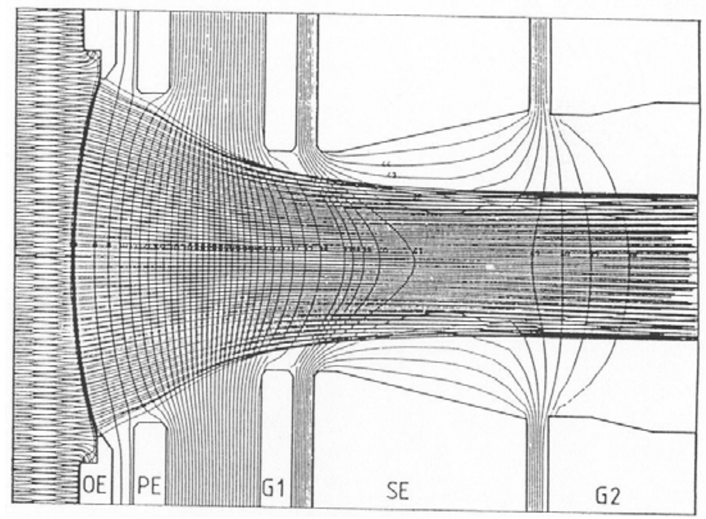
$$I = \frac{4\pi}{9}\varepsilon_0\sqrt{\frac{2eq}{m_i}}\cdot U^{3/2}S^2 = 1.7\cdot 10^{-7}\sqrt{\frac{q}{A}}\sqrt{S}\cdot r^{3/2}E^{3/2}$$



Extraction Systems



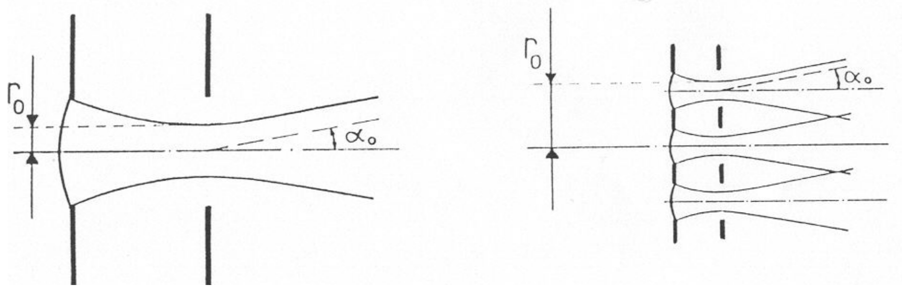




Triode extraction system → most simple system for preservation of space charge compensation.

Pentode extraction system
→ Formation electrode (FE) + Einzellens set-up

single and multi-aperture extraction
→ to overcome the current limit for a single-aperture extraction system

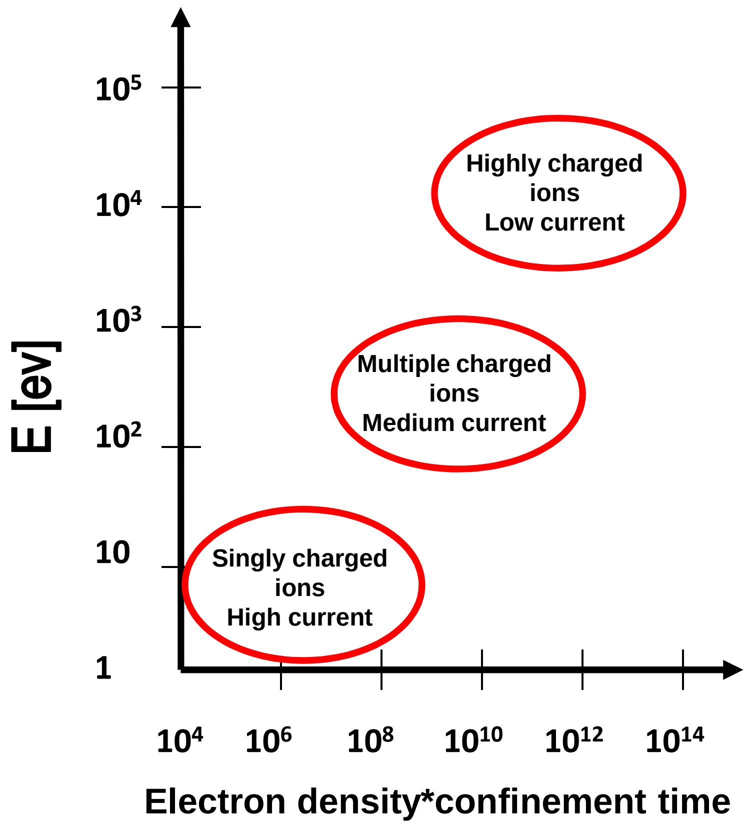


Classification of ion sources

➤ The electron energy determines the maximum charge state that can be reached by electron impact ionisation.

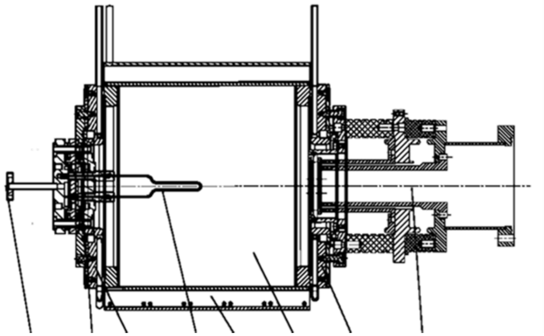
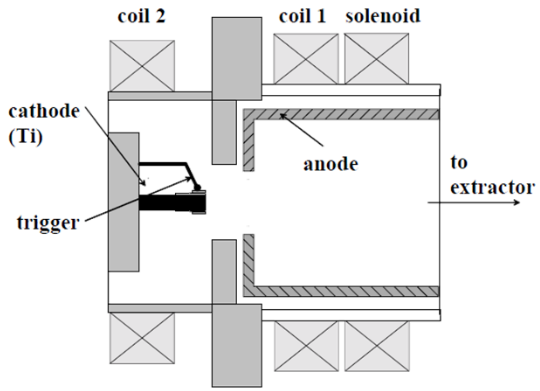
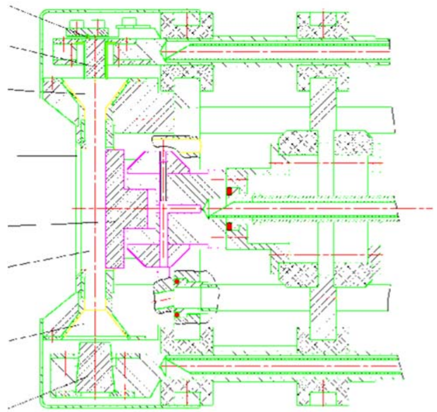
➤ The density*confinement time determines the time required to reach a certain charge state

If the confinement time is too low, the ion species gets lost before reaching the required charge state!

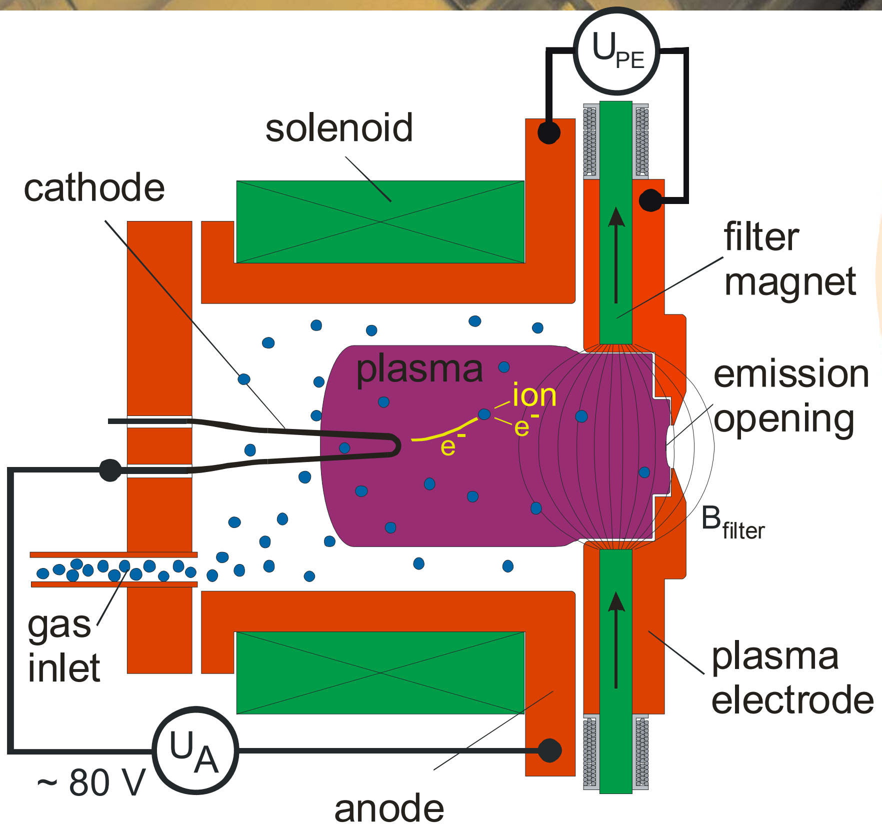


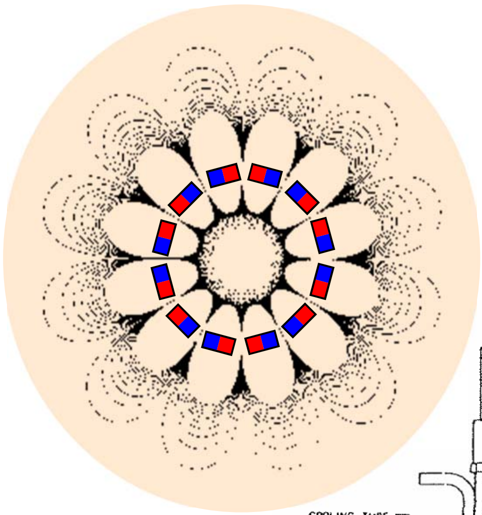
High current ion sources

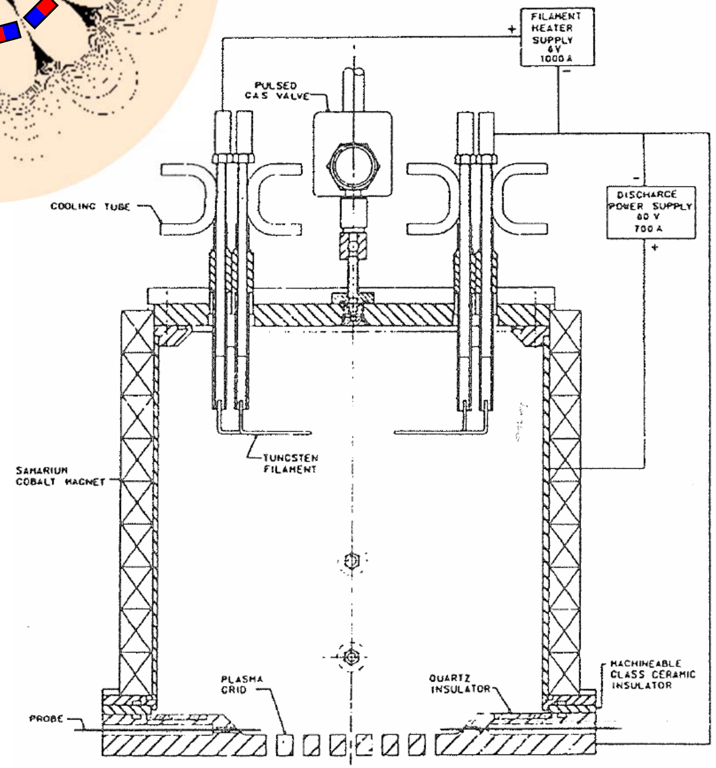
Overview - high current sources

Filament driven	Vacuum Arc driven	High Duty factor
		
MUCIS, MUCIS New, CHORDIS	**MEVVA, VARIS**	**PIG**
Working material:		
Gases	**Metalls and Gases**	**Metalls and Gases**

Volume source – multicusp source



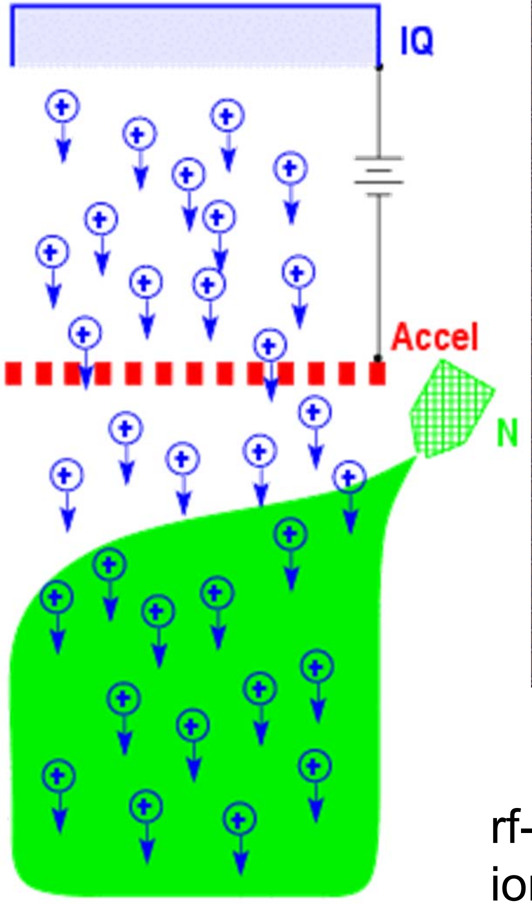


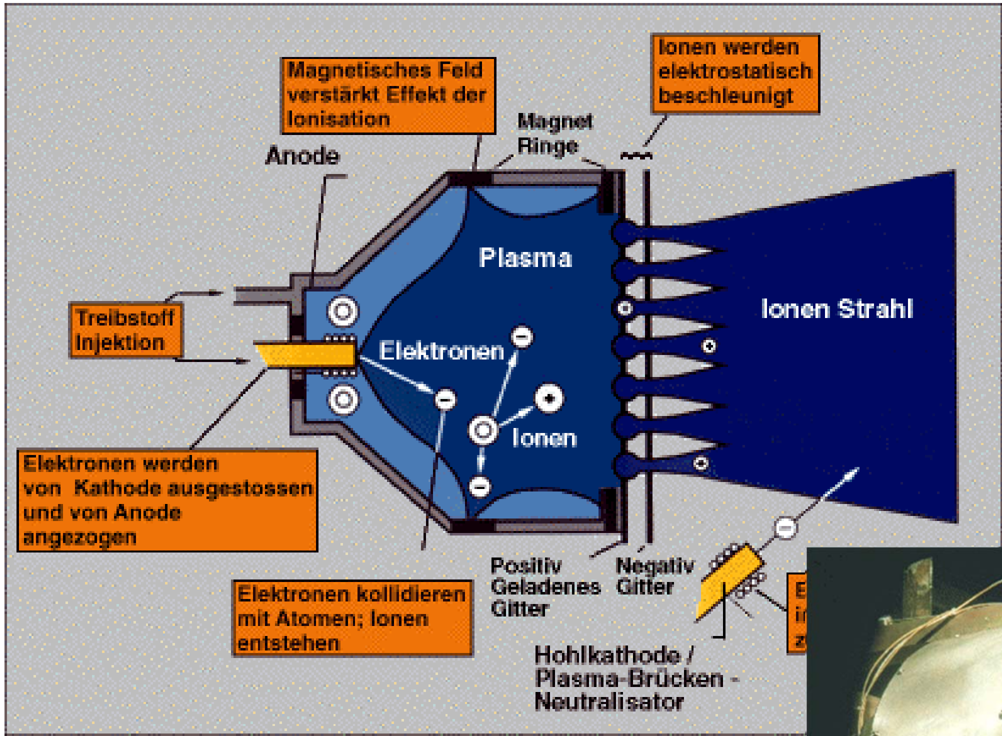


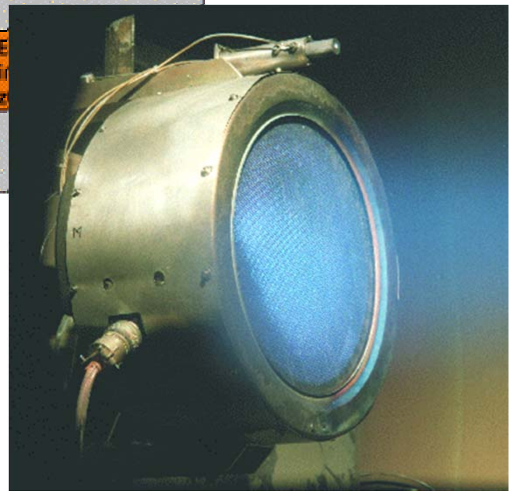
<u>typical operation parameters (hydrogen):</u>

U_A: ~ 80 V, I_A: < 80 A
U_{PE}: < -150 V, I_{PE}: < 25 A
P_{arc}: < 10 kW, p_s: 10 – 75 Pa
B_{sol}: ~ 25 mT

Special type of volume sources







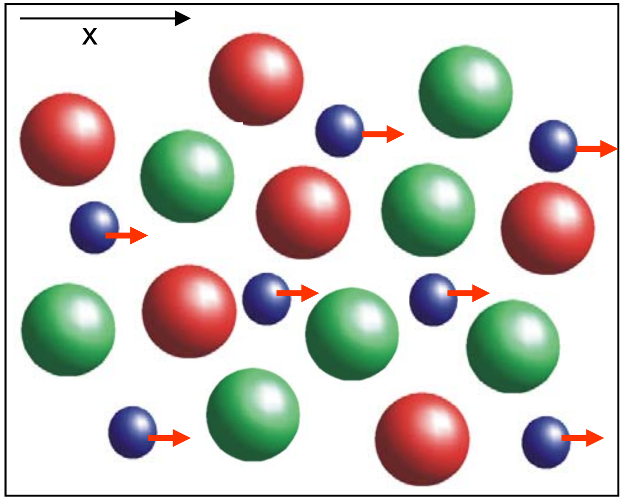
rf-volume sources as
ion propulsion device
(ion thruster)

Plasmageneration via rf - injection

- Pressure region: 10^{-2} - 10^{-3} hPa
- $f \leq \nu_{e,n}$
- $\lambda_e < L$
- rf-power ~ kW
- f = 1-100 MHz

$$E = E_p \sin(\omega t)$$

HF

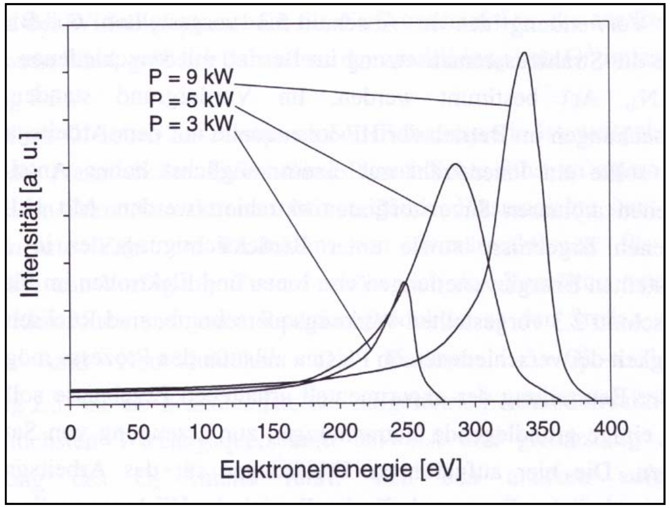


$$m_e \frac{dv}{dt} = eE_p \sin(\omega t + \phi)$$

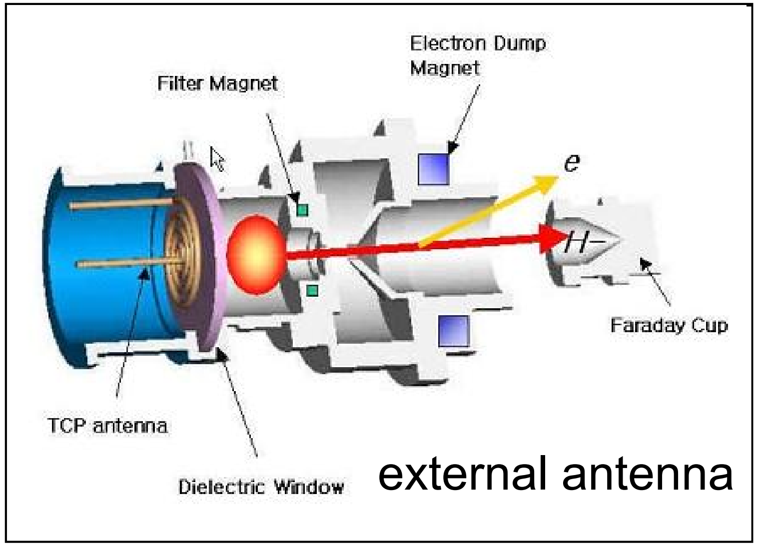
$$v = v_0 + \frac{eE_p}{m_e \omega}\left[\cos\phi - \cos(\omega t + \phi)\right]$$

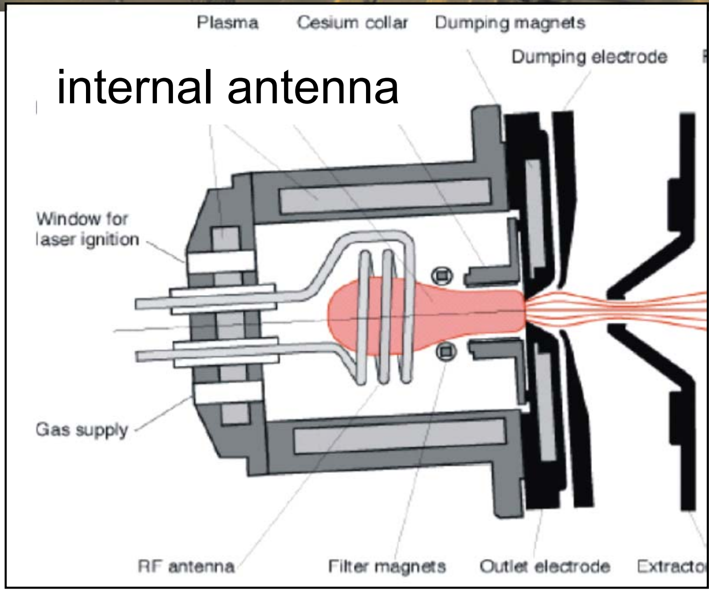
Without collisions, the electrons do not take energy out of the rf-field!

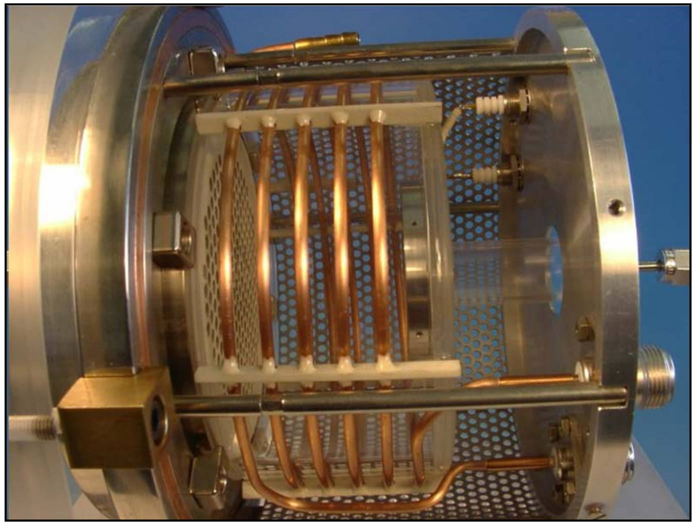
The phase of the electron movement can be changed by collisions. New electrons are generated by ionization processes. If the production rate is bigger than the loss rate, a stable rf-discharge follows.



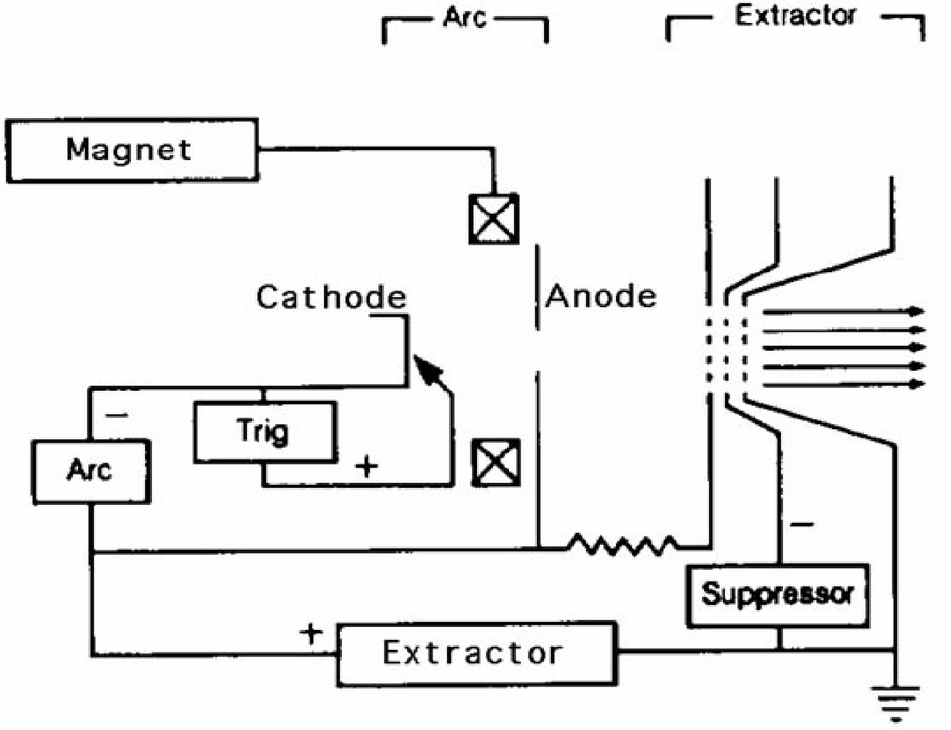
rf – ion sources



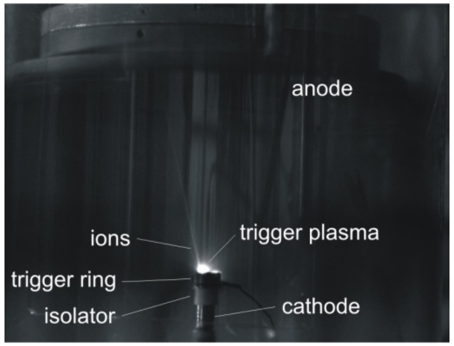


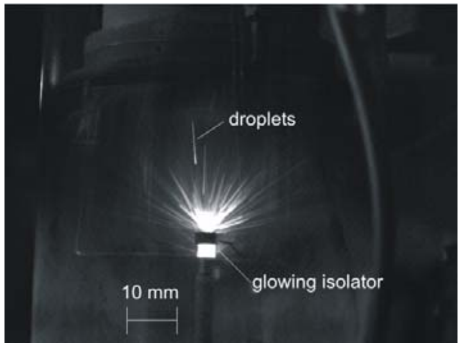


Vacuum arc driven sources



R. Hollinger





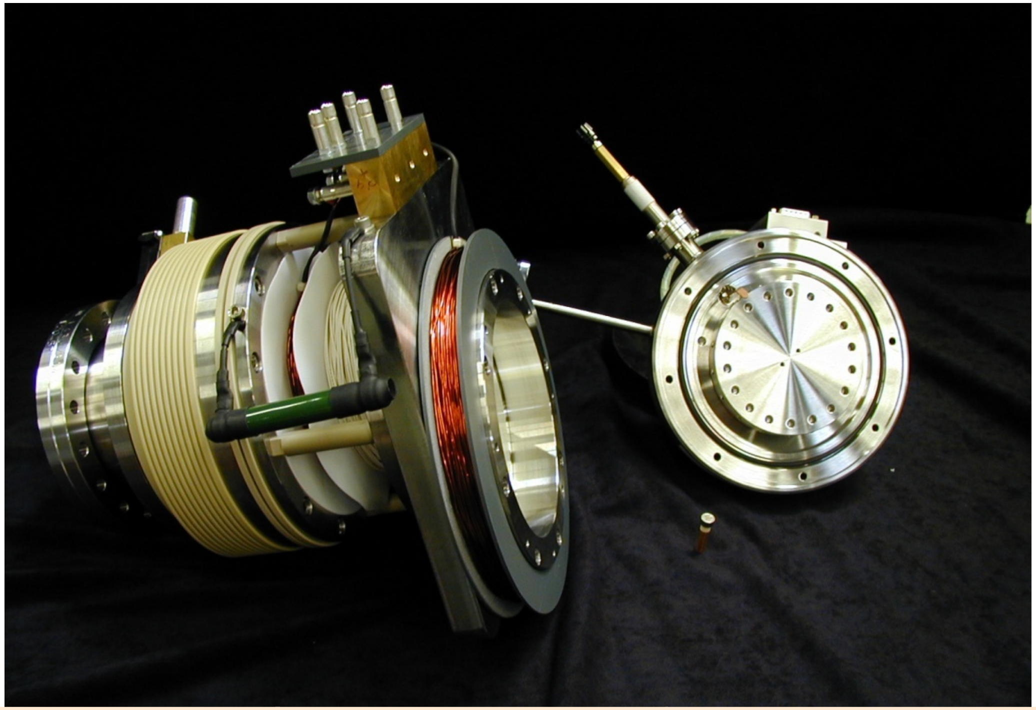
The MeVVa-ion source (**M**etal **V**apor **V**acuum **A**rc) produces intense current of multi-charges metallic ions.

- Discharge between the hot cathode and the cold trigger generates the „Metal Vapor".
- The discharge between the cathode and the anode generates the plasma.

GSI MeVVA source in operation

R. Hollinger

VARIS (Vacuum Arc Ion Source)



17 cathodes
2 solenoids (0,1 and 0,2 Tesla)
Arc power: 50 kW (13,3 MW/cm^2)
Arc current: ~1 kA
Duty cycle: usually 1 Hz, 1 ms

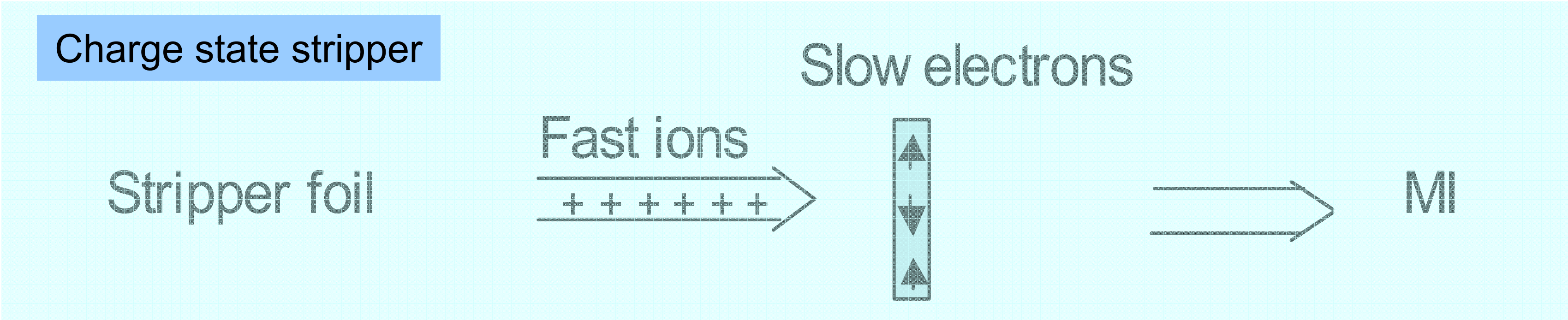
- **Optimized for Uranium (67% of $^{238}U^{4+}$)**
- **Emission current density 170 mA/cm^2**

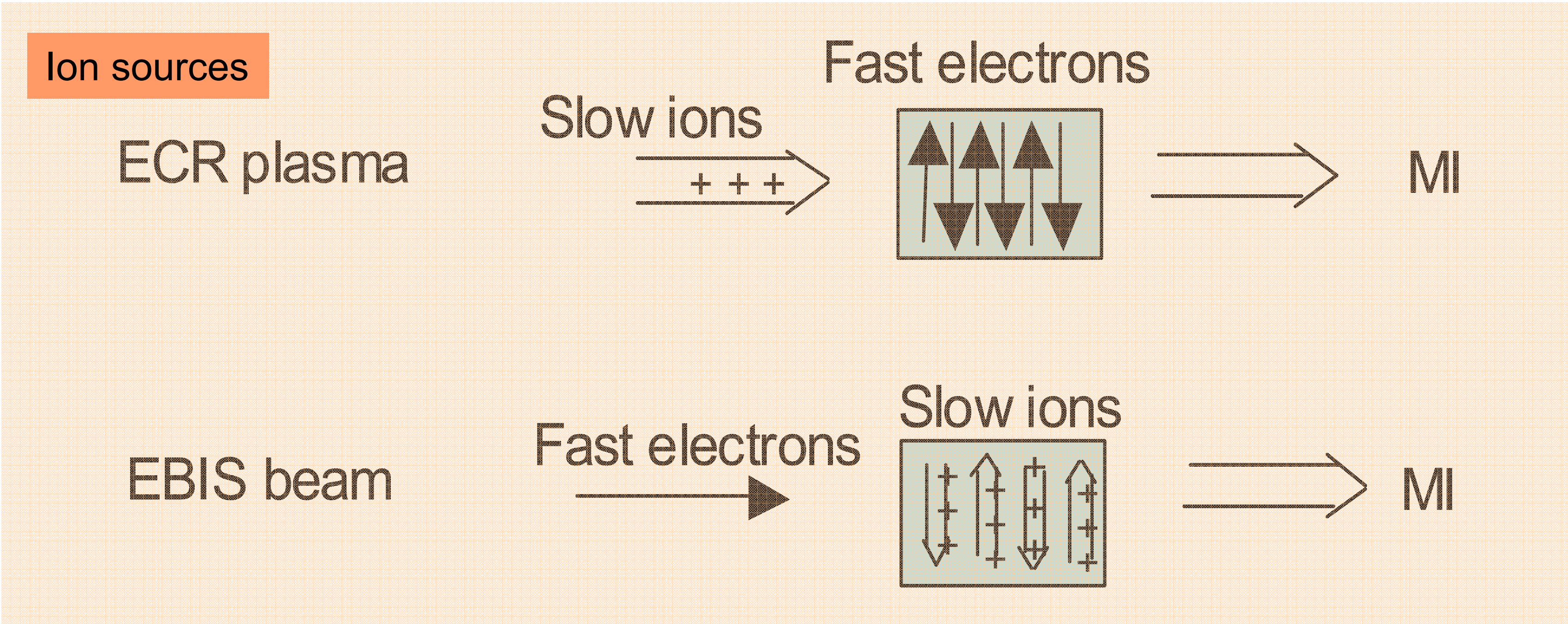
  → 156 mA @ 32 kV
  55 mA @ 131 kV
  20 mA in front of the RFQ

Challenges:
- Improving the beam quality at plasma extraction
- Lifetime of cathodes
- 3 Hz operation

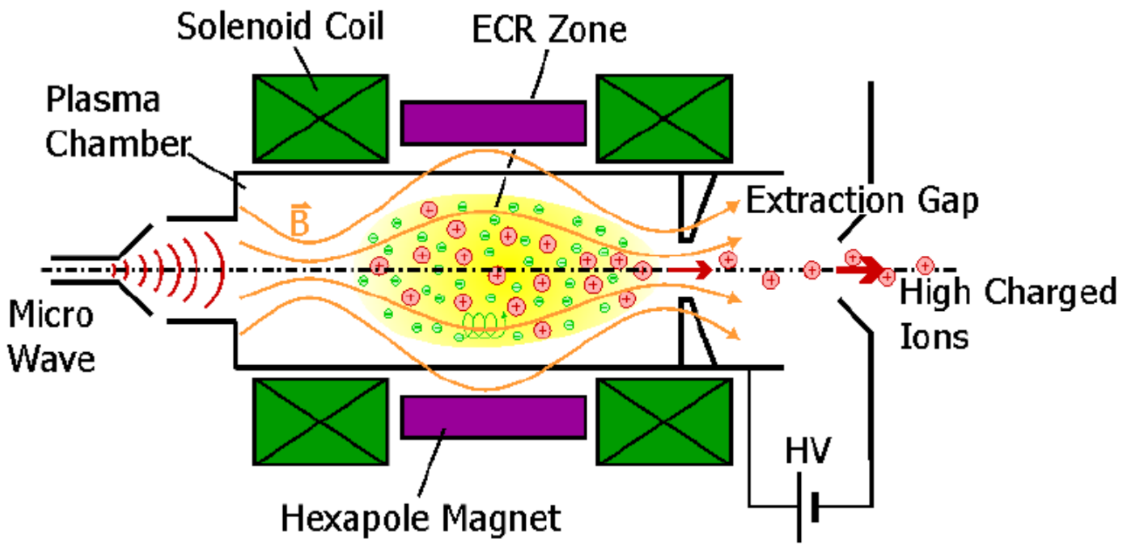
High charge state ion sources

Production of multi-charged ions



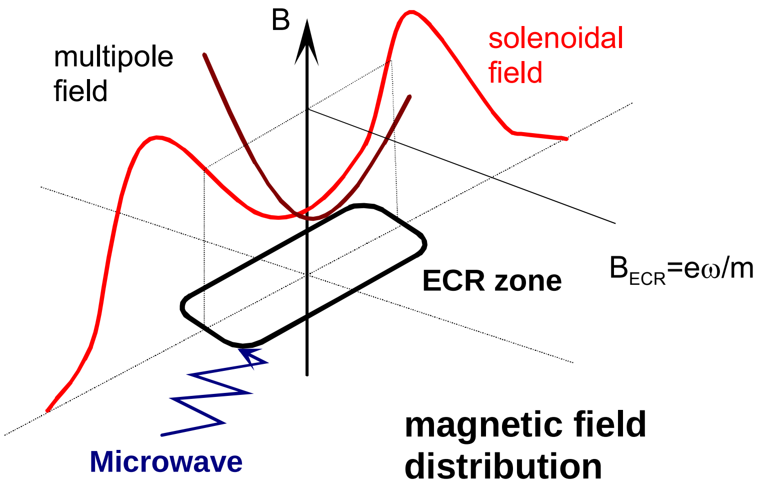


Electron Cyclotron Resonance ion source (ECRIS)



- Resonant microwave plasma heating
- Magnetic confinement
- Higher frequency (28 GHz) higher Becr ~ f

Challenges:
→ Magnetic field
→Ion extraction and beam transport

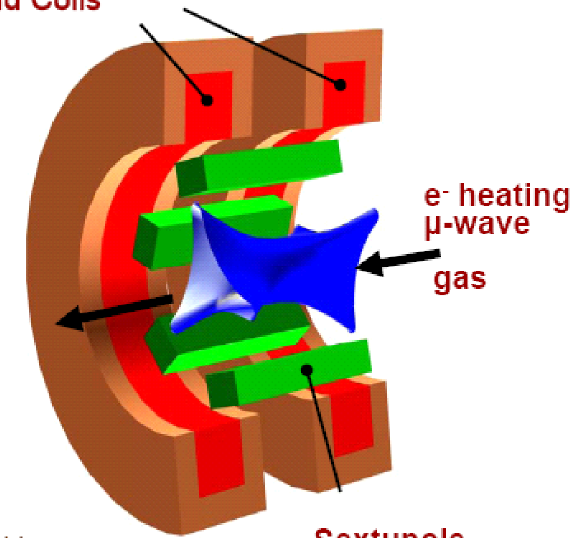


magnetic field distribution

$$\omega_c = \frac{e}{m_e} B \quad \Rightarrow$$

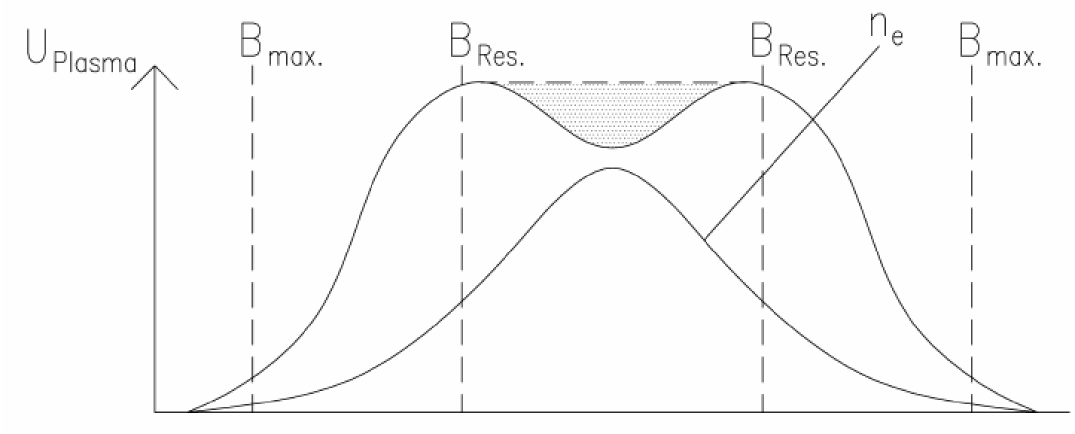
$$f = \frac{eB}{2\pi \cdot m_e} = 2.796 * 10^{10} \cdot B[T]$$

ECRIS basics

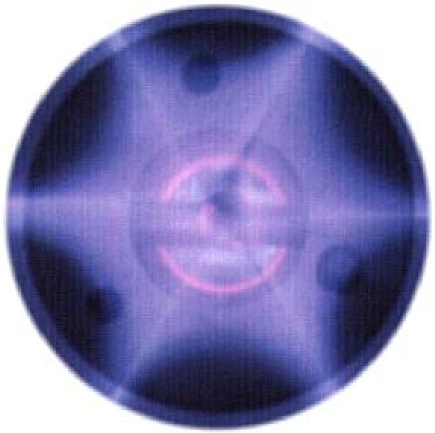


f=28 GHz

$B_{resonance}$= 1T



- Variation of the plasma potential
- Intense heating of electrons → MeV energies



The following magnetic-field relations are valid for high power ECRs:

B_{inj}/B_{ecr} ~ 4, B_{ext}/B_{ecr} ~ 2, B_{min}/B_{ecr} ~ 0.8,
$B_{rad}/B_{ecr} \geq 2$, $B_{ext}/B_{rad} \leq 0.9$

ECRIS scaling laws and ion intensities

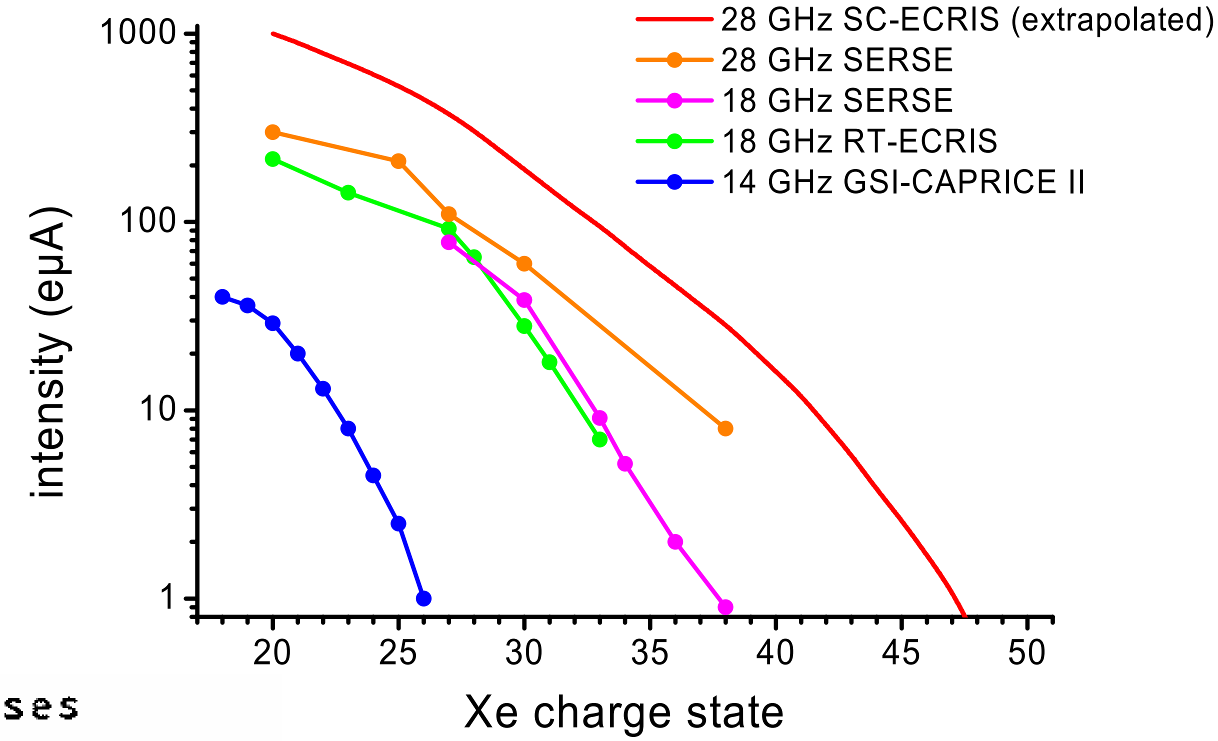
$n_e \propto \omega_{rf}^2$

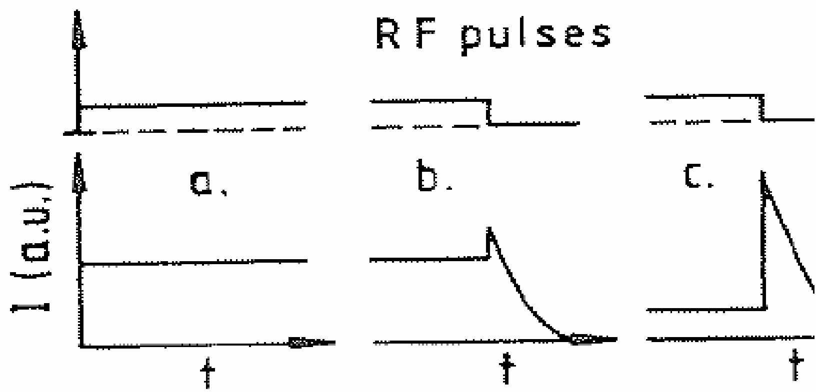
$\tau_{ion} \propto B_{max}/B_{min}$

$I \propto \omega_{rf}^2/M$

$I \propto n_{ion} / \tau_{ion}$

$I \propto P_{rf}^{1/3}$

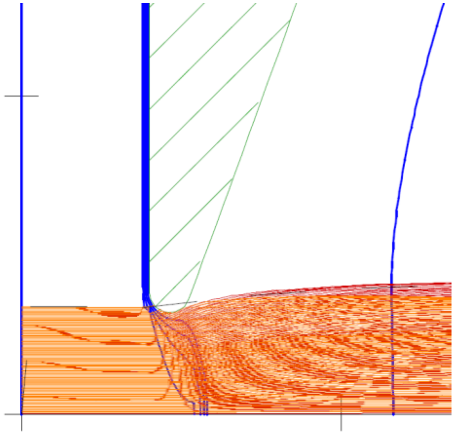




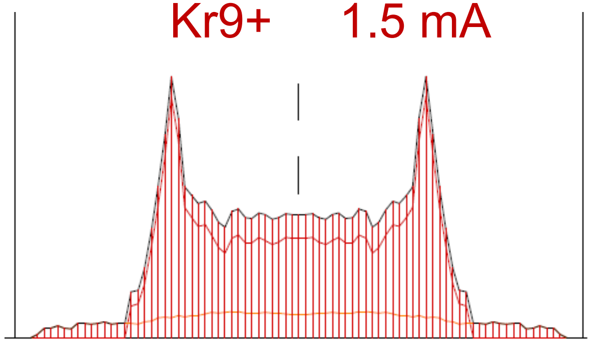
ECRIS is usually running cw
→ pulse operation in "afterglow mode"

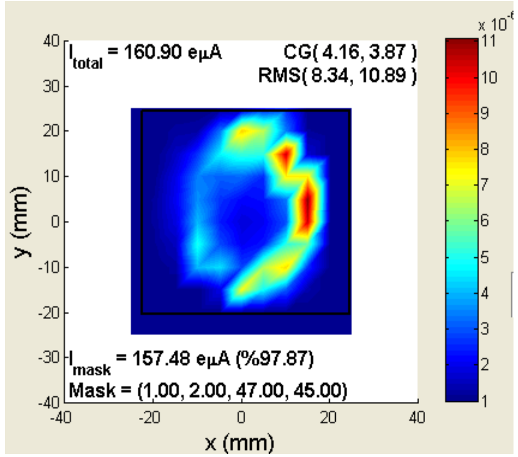
Plasma boundary and profile

Mismatched extraction

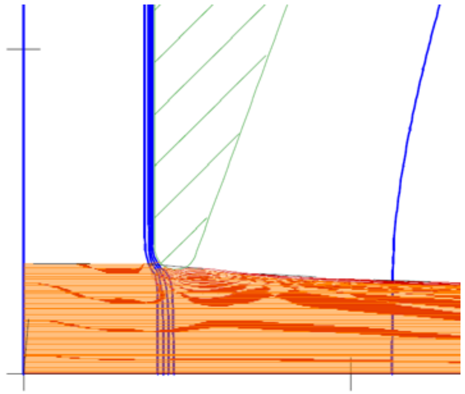


Kr17+ 0.5 mA
Kr9+ 1.5 mA

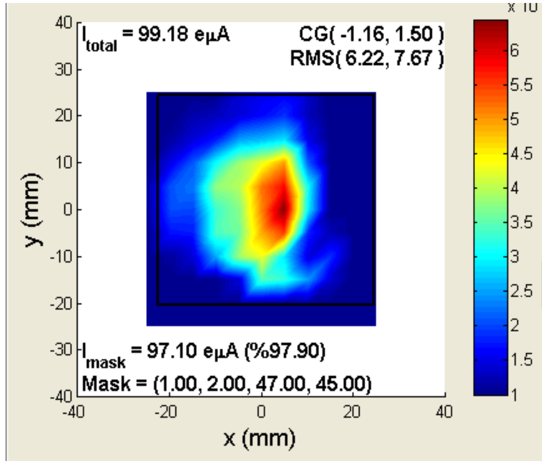




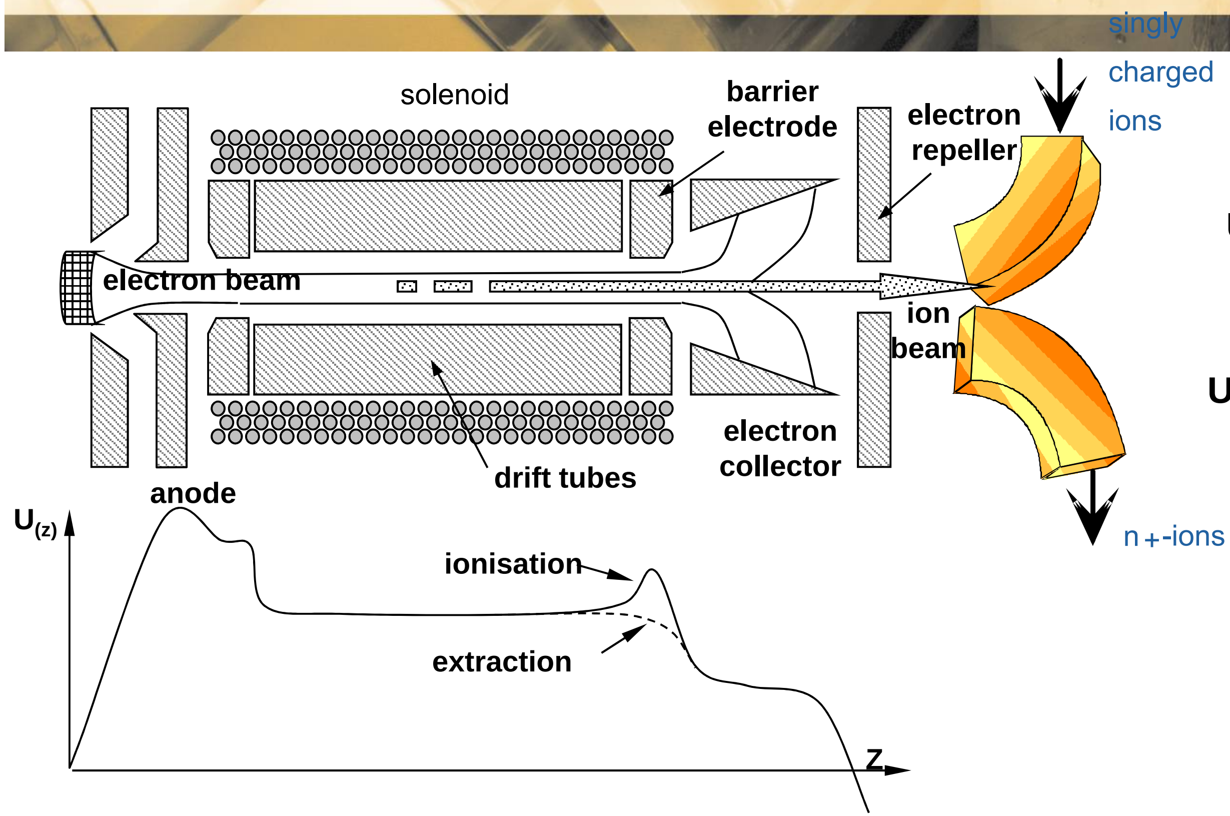
Matched extraction



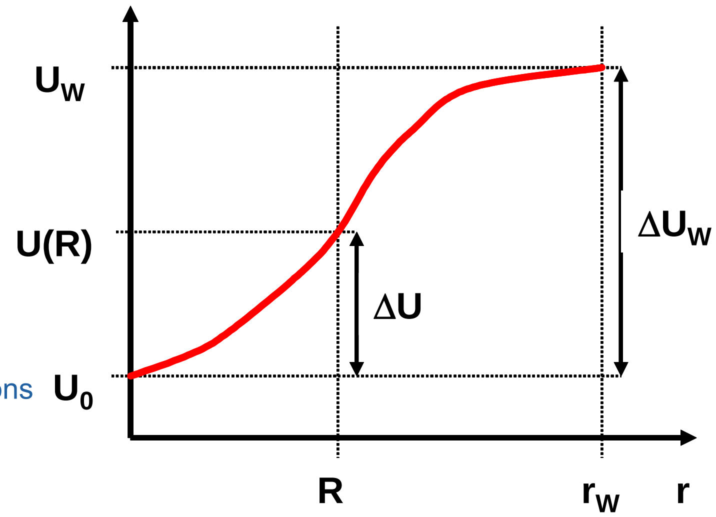
Kr17+ 0.25 mA
Kr9+ 0.75 mA



Electron Beam Ion



space charge potential

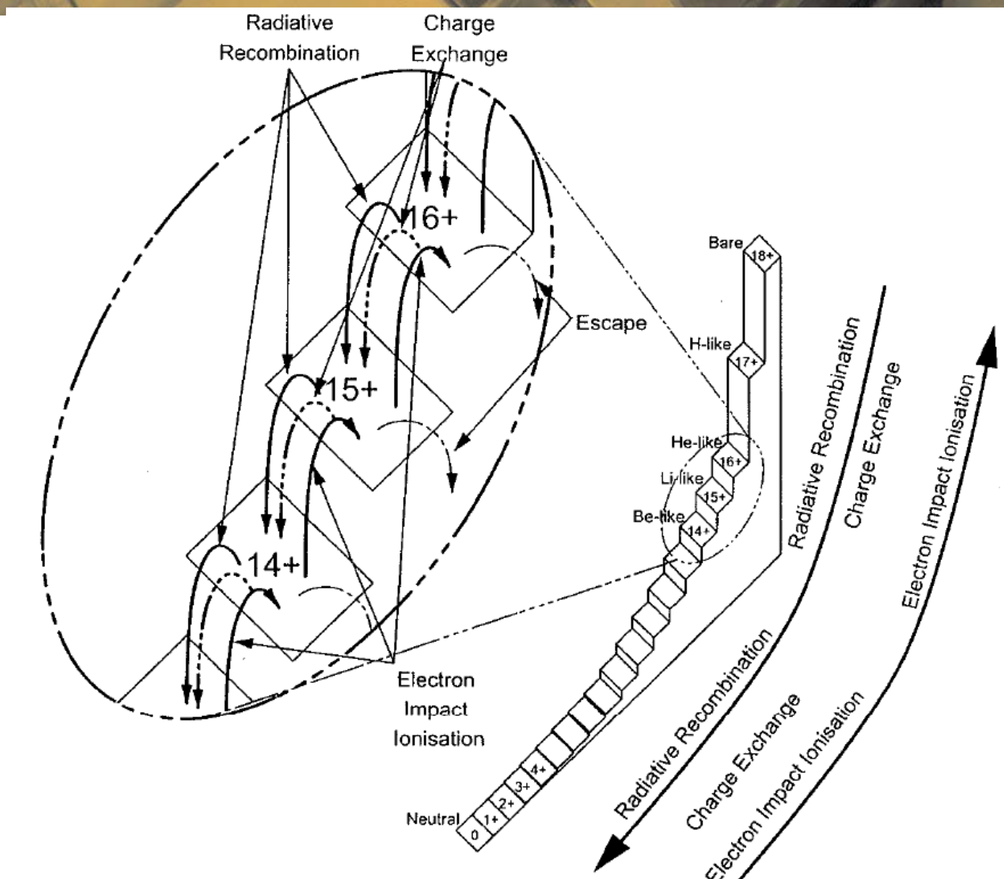


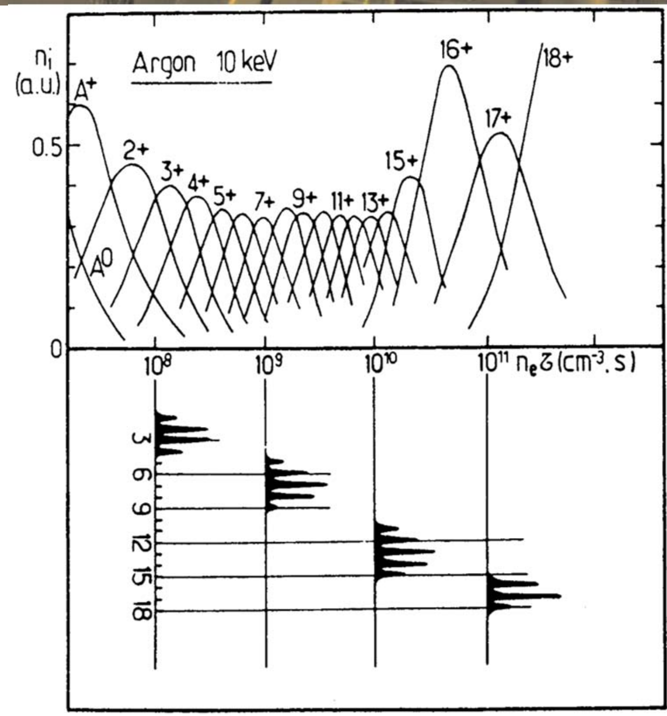
$$N^{-} = \sqrt{\frac{m_e}{2e^3}} \cdot l \cdot \frac{I_e}{\sqrt{U_e}}$$

- Electrostatic confinement
- Intense electron beam (current density, up to 10^4 A/cm^2)
- Tunable electron beam energy
- Storage capacity ~ trap length, electron current

Ie = electron beam current
Ue= electron beam energy
l = length of confinement region

Charge state development in an EBIS/T





Charge development for stepwise ionisation

$$\boxed{\frac{dn}{dt} = Sources - Drains}$$

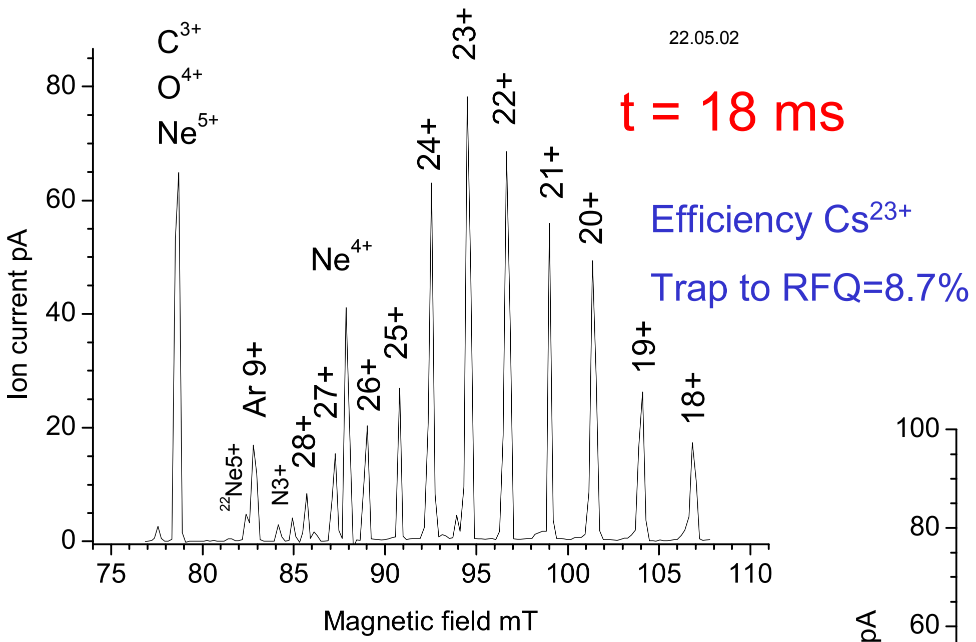
example →

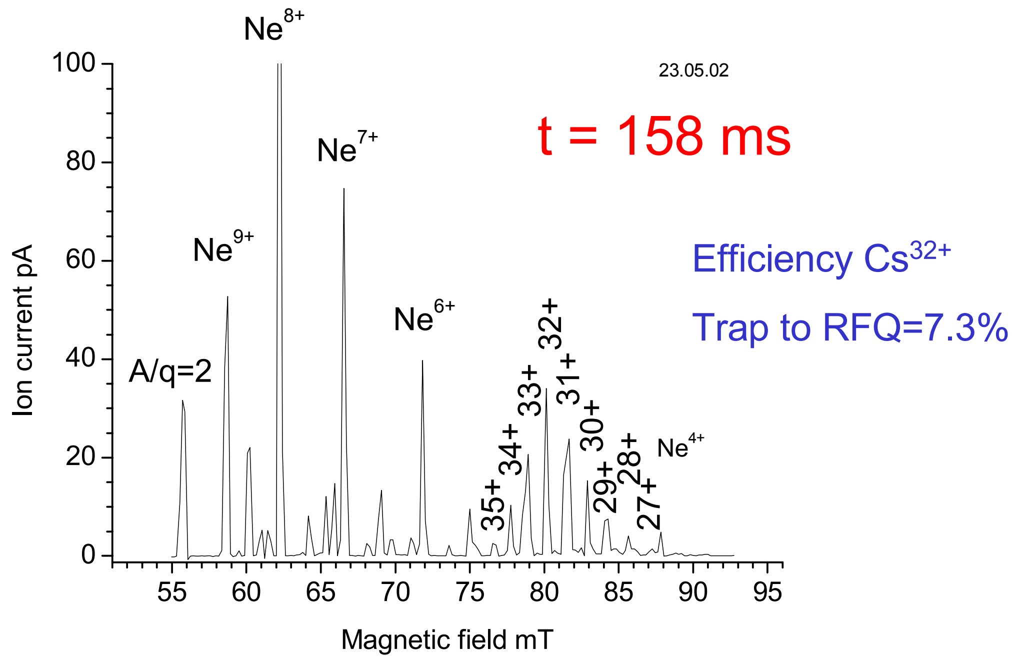
Electron impact ionisation

Radiative recombination (RR)

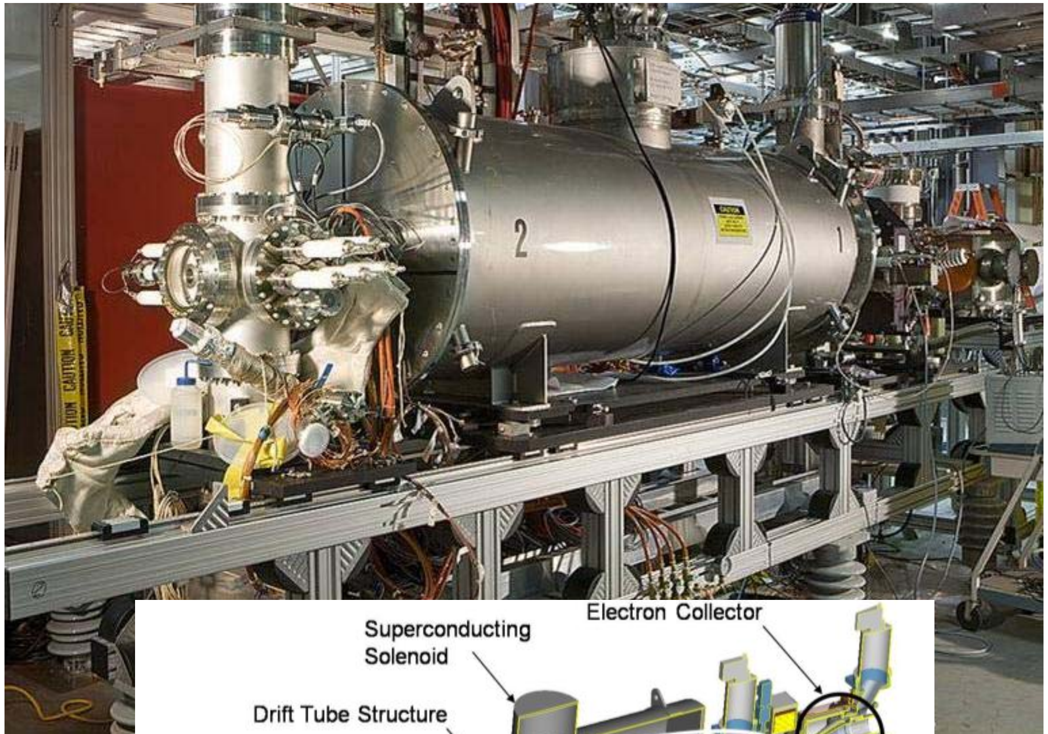
$$\frac{dn_{z+1}}{dt} = n_e \cdot n_z \cdot v_e \sigma_{z \rightarrow z+1} - n_e \cdot n_{z+1} \cdot \sigma_{z+1,RR}$$

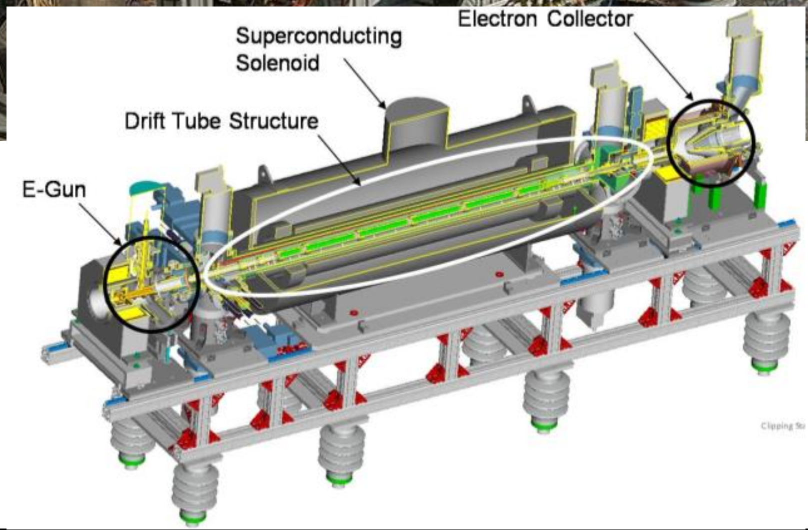
Extracted ion beams - example

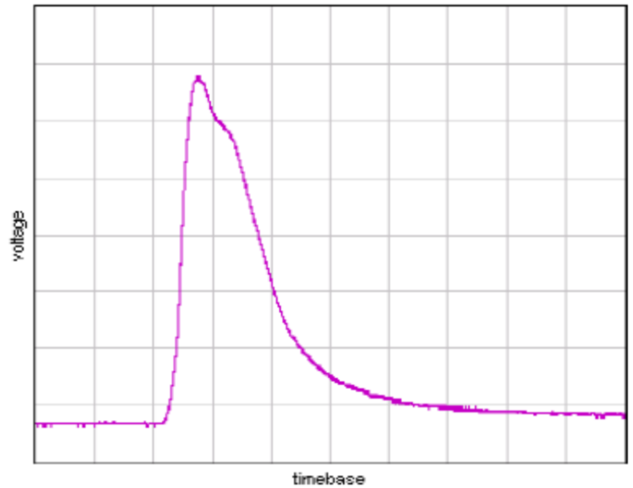




RHIC EBIS / BNL – Intense pulses of HCIs







6 mA Au pulse;

~2.6 x 10^9 Au32+ / pulse

Maximum B-field	5.0 T
"Warm" ID	204 mm
Length of solenoid	1900 mm
He refilling period	30 days

Top-ten reasons for „why it‘s great to be an ion source physicist“

10. Spouses never need to worry about what their ion source physicist husband or wife is up to when they still aren't home by midnight...they know with great confidence that they're just at the lab changing a source!

9. Between

   - the International Conference on Ion Sources,
   - the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source,
   - the ECR Ion Source Workshop,
   - The International Conference on Negative Ions, Beams and Sources,
   - the International Symposium on the Production and Neutralization of Negative Ions and Beams,
   - the Workshop on Negative Ion Formation and Beam Handling,
   - the International Conference on Sources of Highly Charged Ions,

   the ion source community has the greatest number of conferences and workshops of any scientific discipline measured per linear inch of subject matter

8. Endless hours can be devoted to the important philosophical meaning of "pi" as in "the output emittance is 0.2 pi-mm-mrad"

7. Believe it or not, sometimes the rf-ion source antenna picks up free Satellite Television!

6. High-voltage, hydrogen gas, antennas and power supplies: it's every little kids dream!

5. In what other field can you acquire a Ph.D., and then spend your professional life practicing the occult?

4. When the phone rings during dinner time, you always know who it is: no its not a tele-marketer, it just the lab...the ion source went down!

3. In what other field could you advertise a workshop on "RF-driven, multicusp, Cesium-enhanced H-sources", and have 50 people actually show up?

2. Job security...when was the last time you heard a manager say, "the ion source is running so well, we're going to let the entire group go."

1. It's a subject in which anyone can make a contribution, and everyone has an opinion!

Courtesy of Stuart Stuart Henderson/ORNL