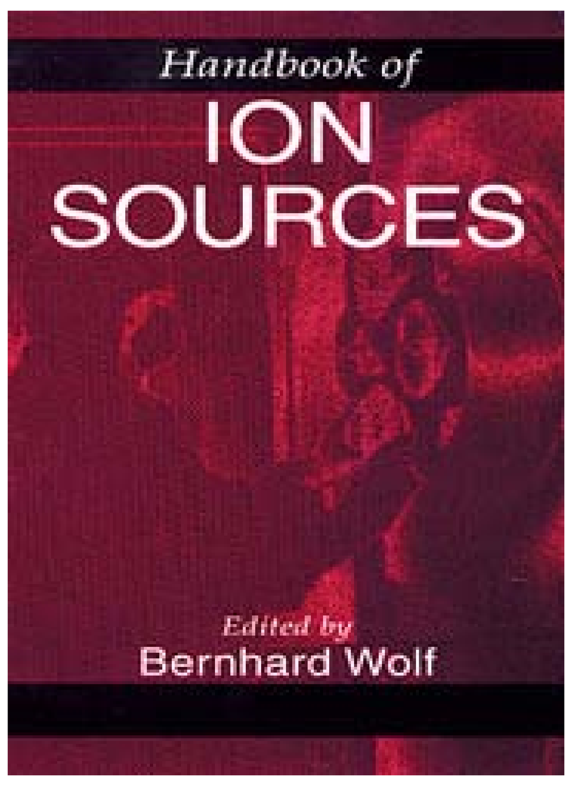
Definitions of Ion Sources



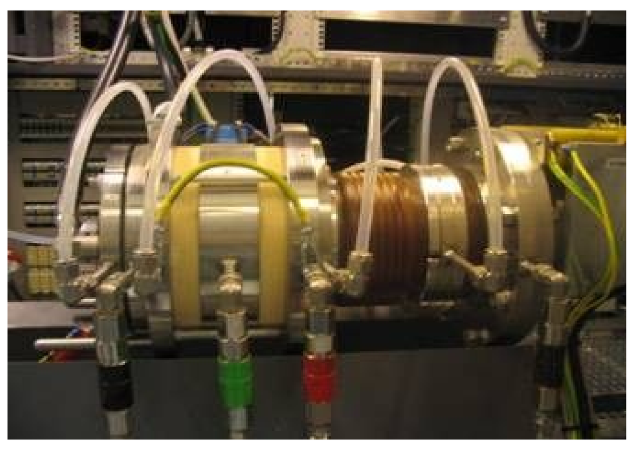
A day out at the zoo…

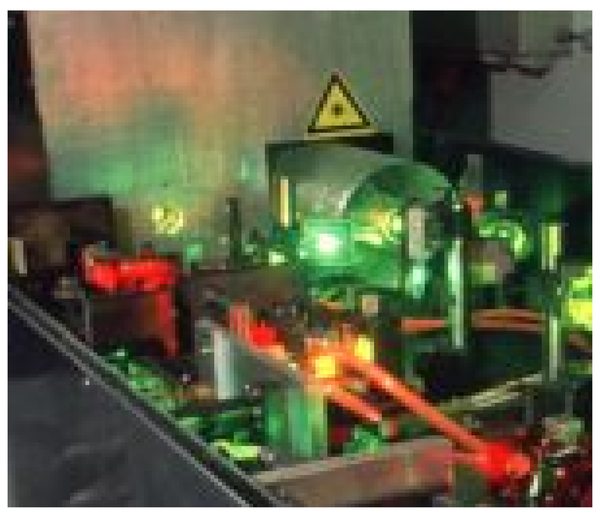
Richard Scrivens
CERN

CAS on Ion Sources, May 2012







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An Approximate Classification System

Try to break down ion sources into a few groups:

- Electron bombardment
- Plasma Discharge
- RF discharge
- Microwave and ECR
- Laser Ion Sources
- Surface
- High Charge State Sources
- Charge Exchange Ion Sources

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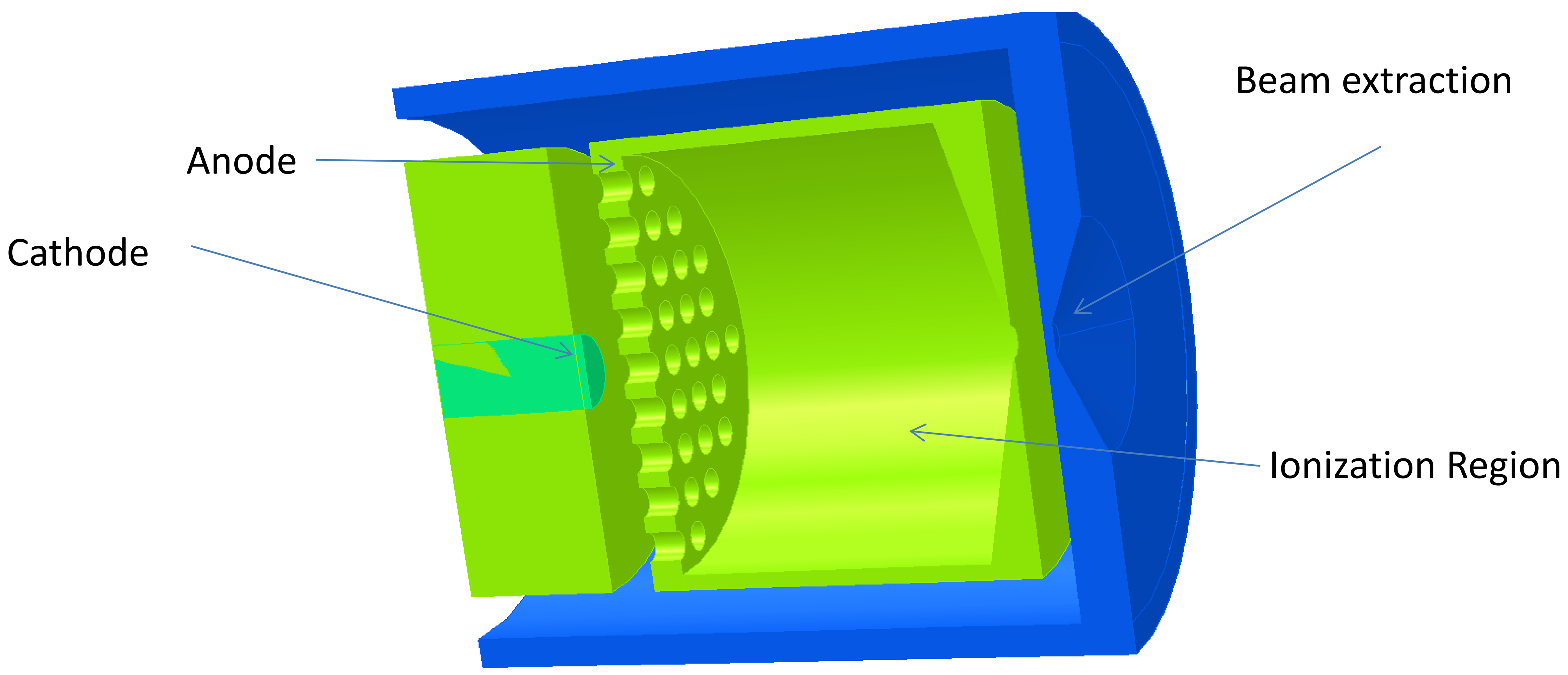
Electron Bombardment Ion Source

- Generate electrons with a cathode.
- Accelerate them with a cathode – anode potential difference.
- The ions impact on neutral atoms and molecules to ionize them.
- Electrons can be confined (path length increased) by magnetic fields.



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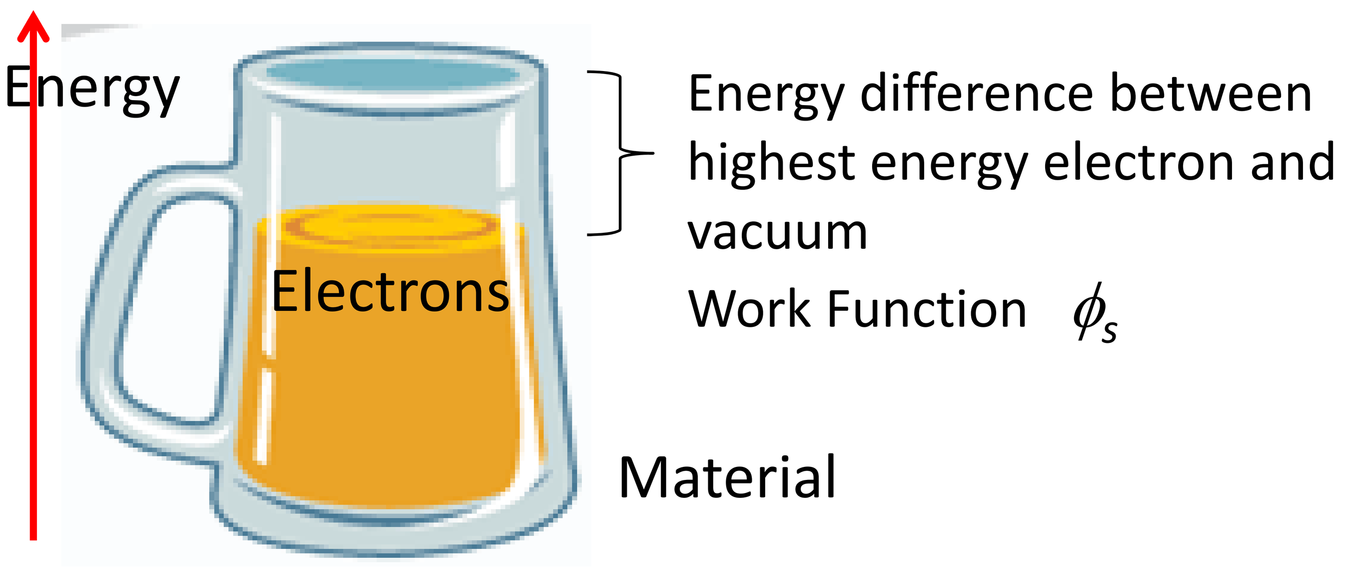
Electron Bombardment Ion Source

Electrons within a material are heated to energies above that needed to escape the material.

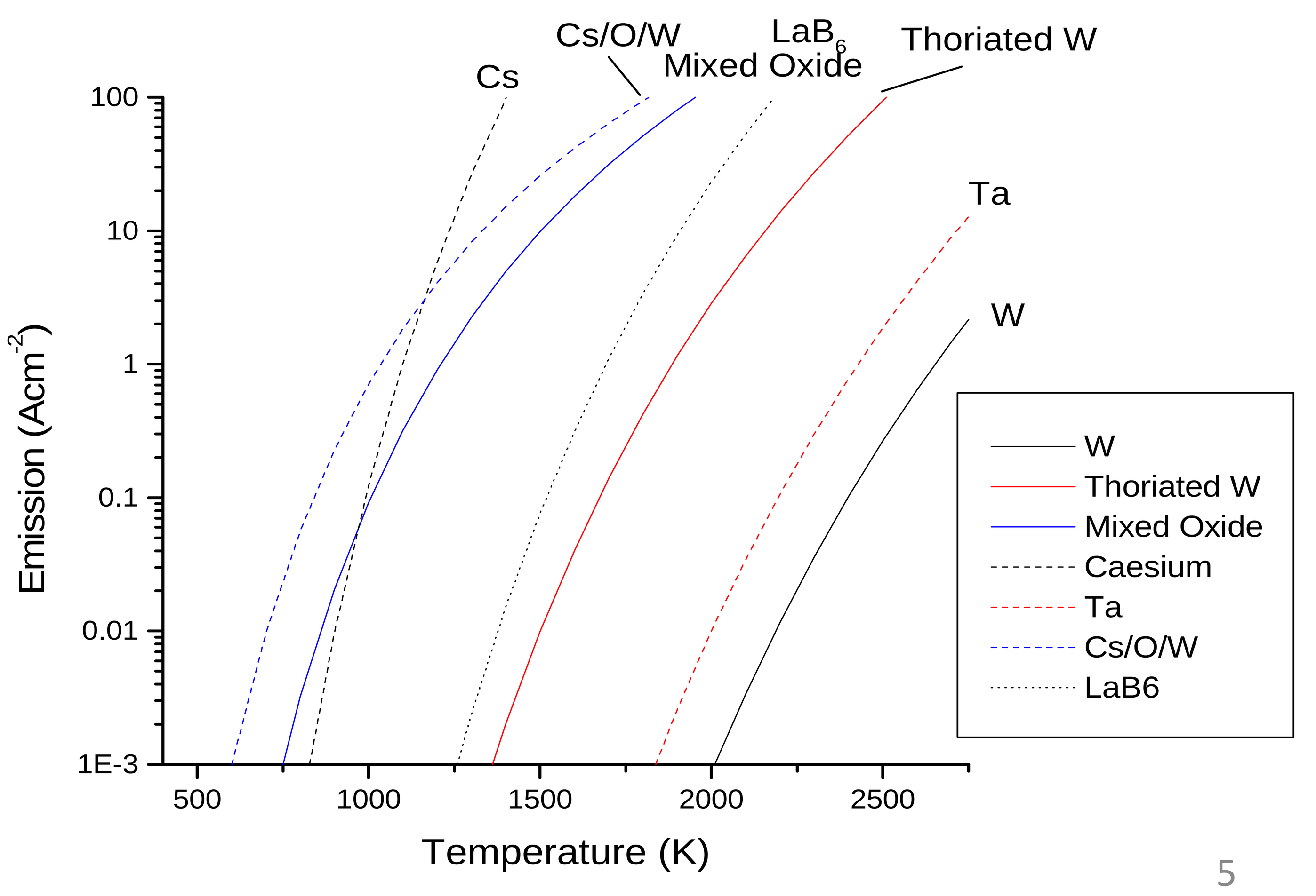
Cathode emission is dominated by the Richardson Dushmann equation.



$$J = A \cdot T^2 \exp\left(\frac{-e\phi_s}{kT}\right)$$

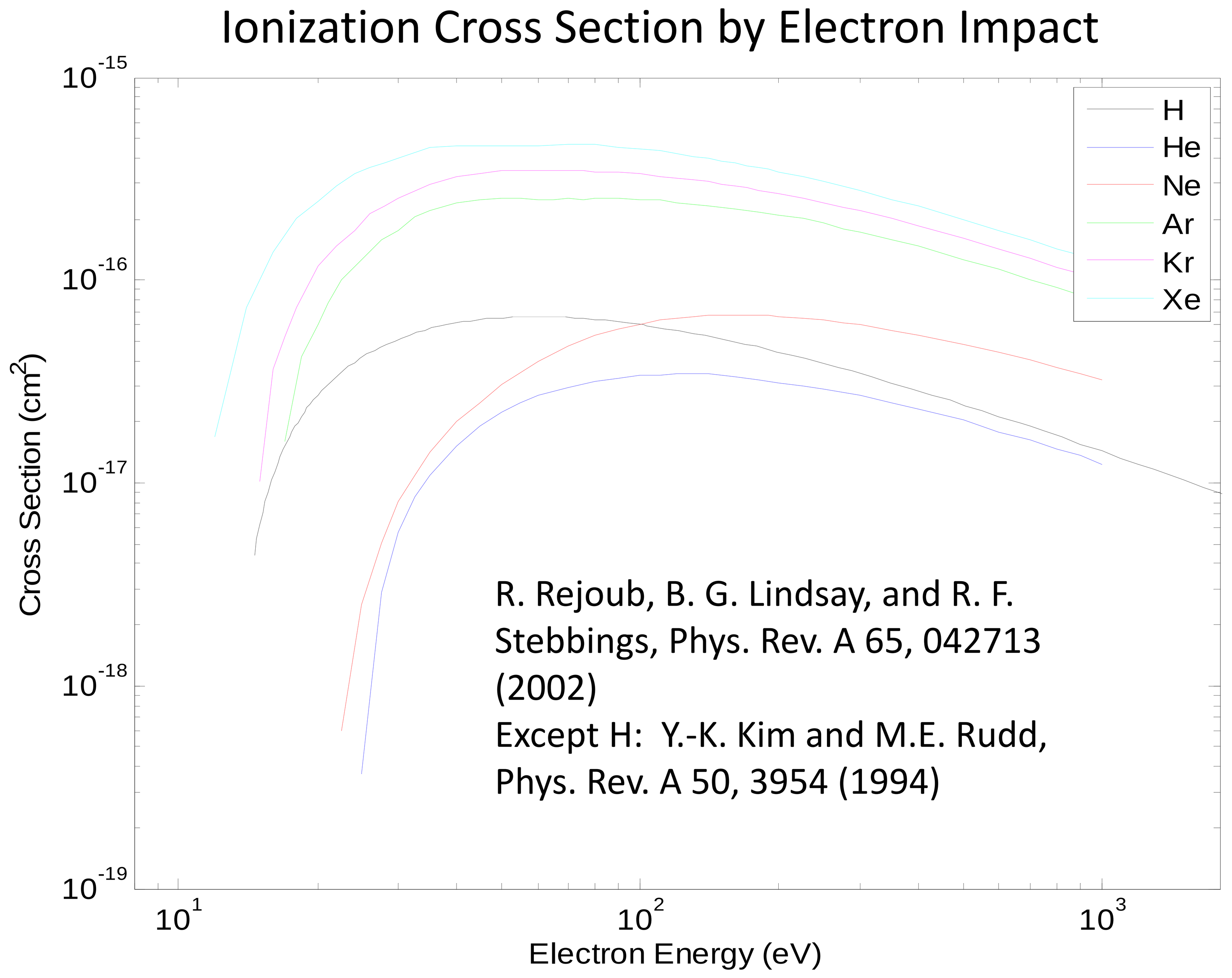
$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2\times10^6\,\mathrm{Am}^{-2}K^{-2}$$

In practice, A is a (temperature independent) value, that is material dependent.



Electron Bombardment Ion Source

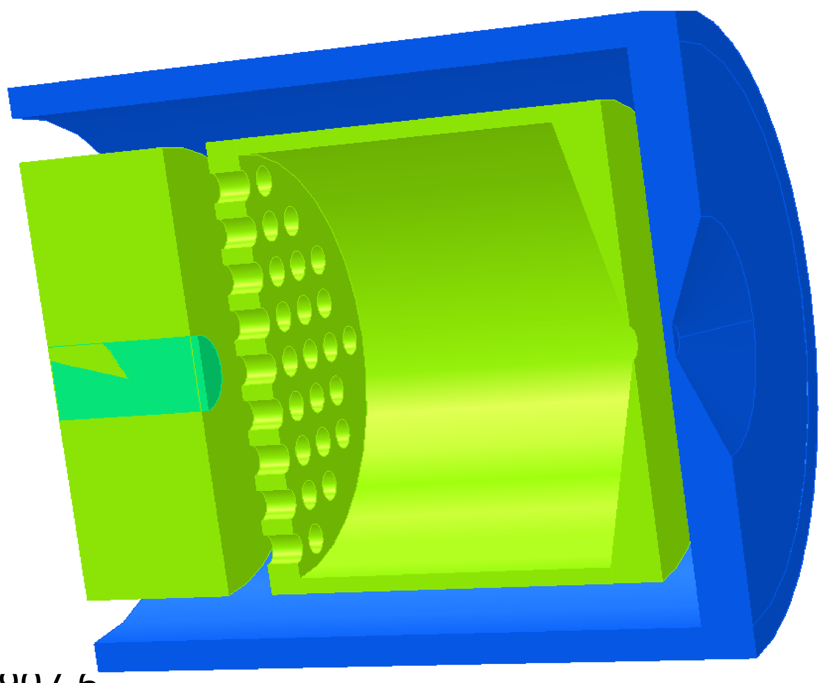
$$\sigma . n_{atom} = \frac{1}{L_{collision}}$$



Some cross section data available in:
http://physics.nist.gov/PhysRefData/Ionization/Xsection.html

Electron Bombardment Ion Source

- The FEBIAD ion source uses a grid near the cathode to provide a electron acceleration followed by a lower E field drift.
- This reduces the electron energy distribution and the ion distribution.
- It also reduces the electric field pulling the ions back towards the cathodes.
- Internal source pressures are usually low (10^{-5} to 10^{-2} mbar).
- Intensity from Electron Bombardment is limited before a strong plasma is formed (where the source becomes a plasmatron).



R.L. Gill, A. Piotrowski, NIM A, Vol 234 (2), p
http://dx.doi.org/10.1016/0168-9002(85)90907-6

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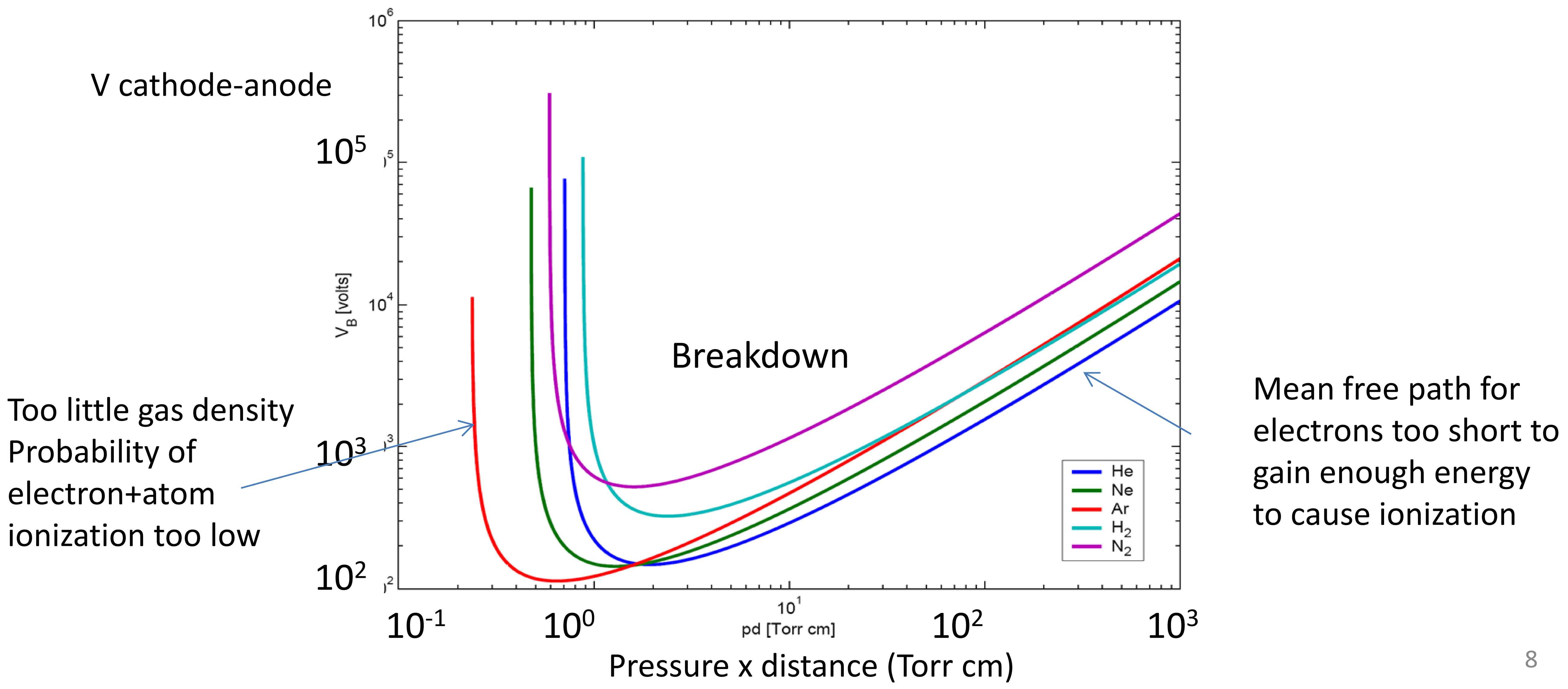
Plasma Discharge Sources

- Van Ardenne pushed the operating regime of the electron bombardment ion sources towards the plasmatron.
- Driven either by a cold cathode, or forced by a hot cathode and thermionic emission.
- A sustained discharge is possible once above the Paschen line for a gas.



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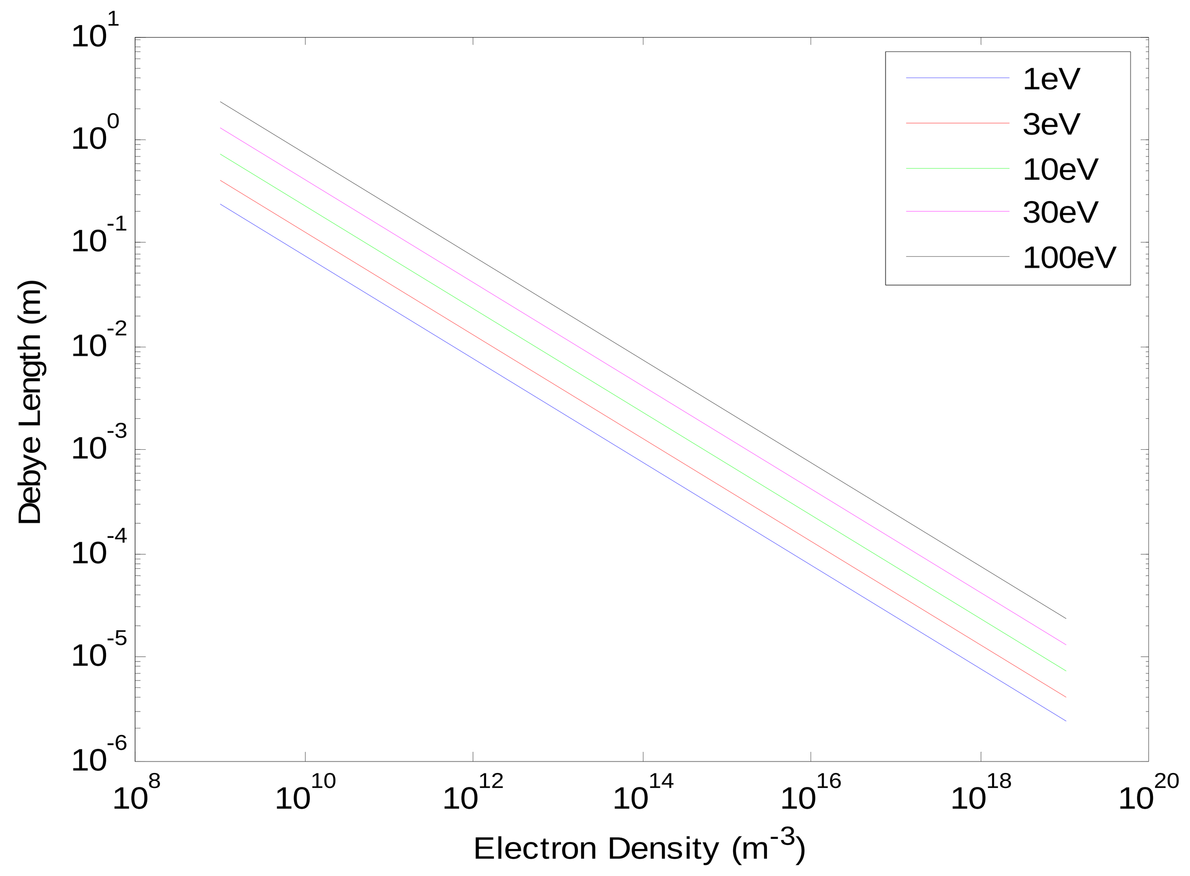
Plasma Discharge Sources

- Von Ardenne pushed the operating regime of the electron bombardment ion sources towards the plasmatron.
- In Plasmatrons and Discharge sources the density of ions (and electrons) is high enough such that a plasma is formed.



Electric fields can permeate a plasma up to the size of the Debye length.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}}$$

- Applied Electric and magnetic fields shape the plasma, but they are also affected by it.
- Electron Bombardment is still the principle route for ionization.

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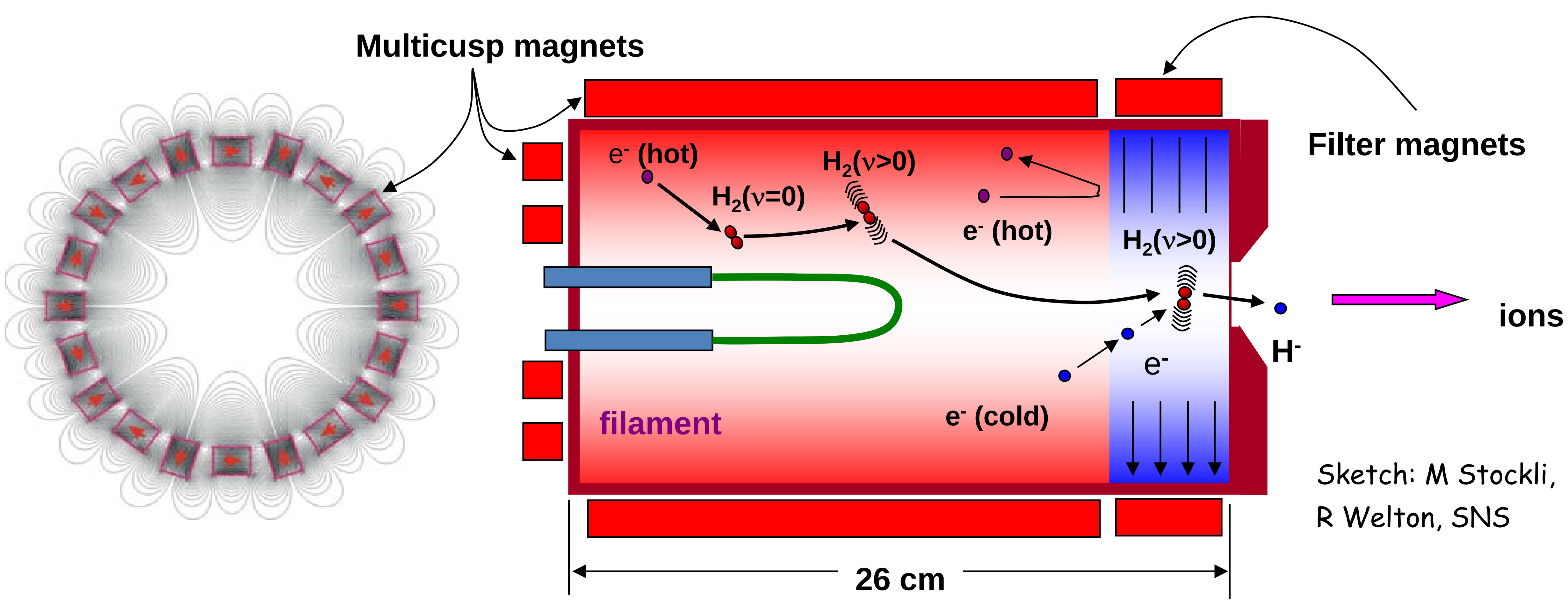
Plasma Discharge Sources



Sketch: M Stockli, R Welton, SNS

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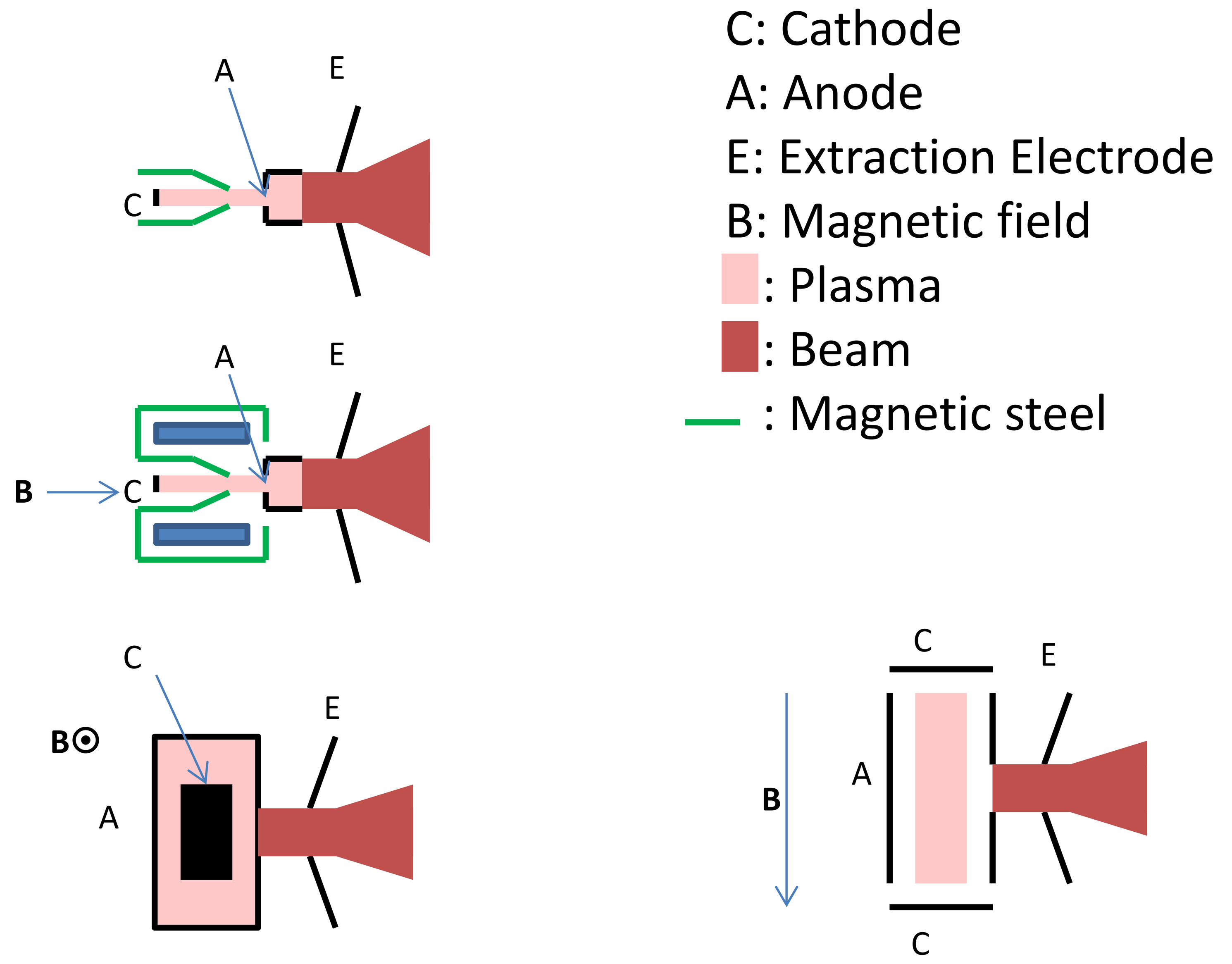
Plasma Discharge Sources
A rich sub-species…

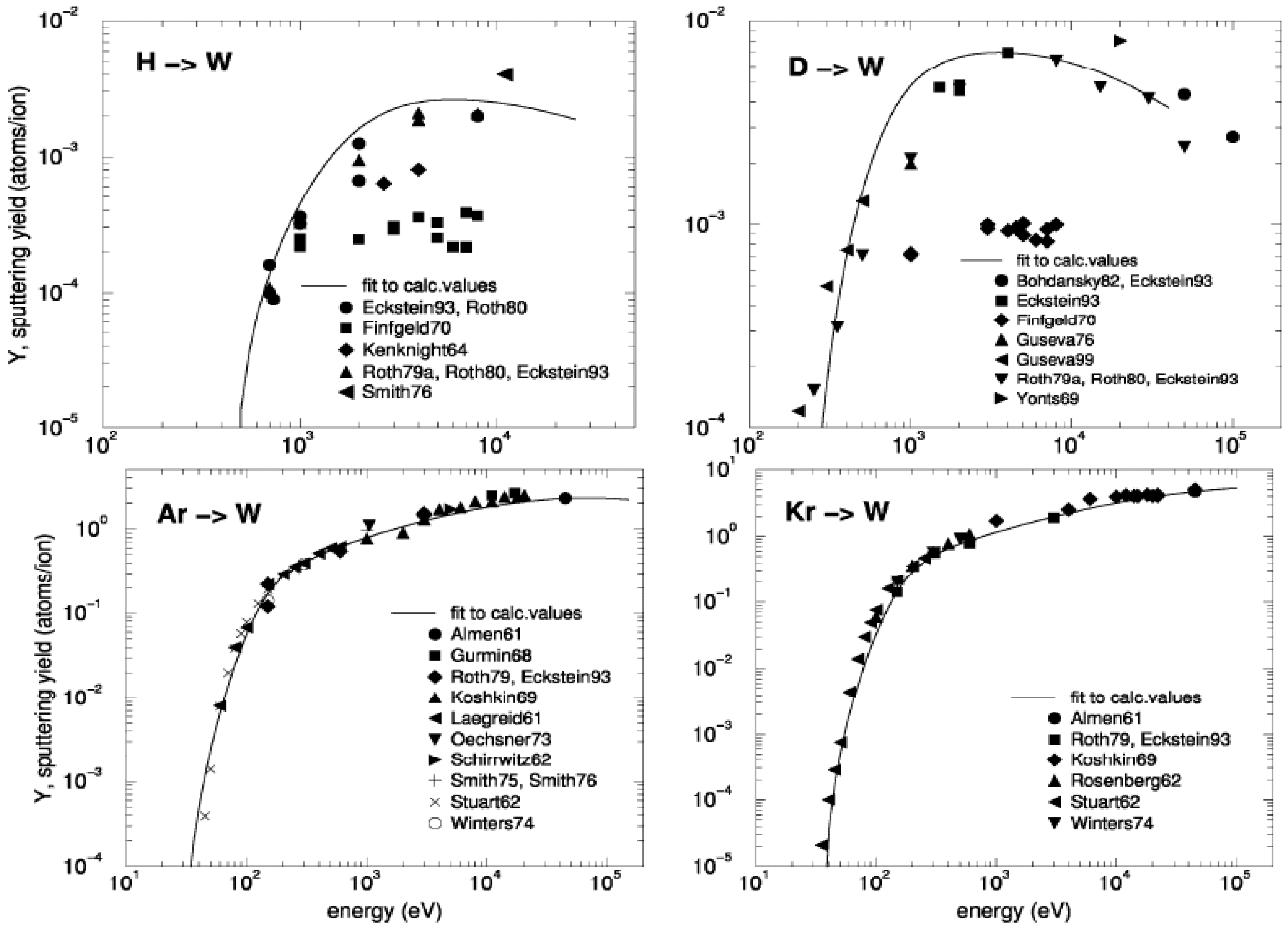
The cathode-anode-B field configuration can be varied to produce different source types:

- Multicusp discharge sources.
- Plasmatron
- Duoplasmatron
- Magnetron
- Penning



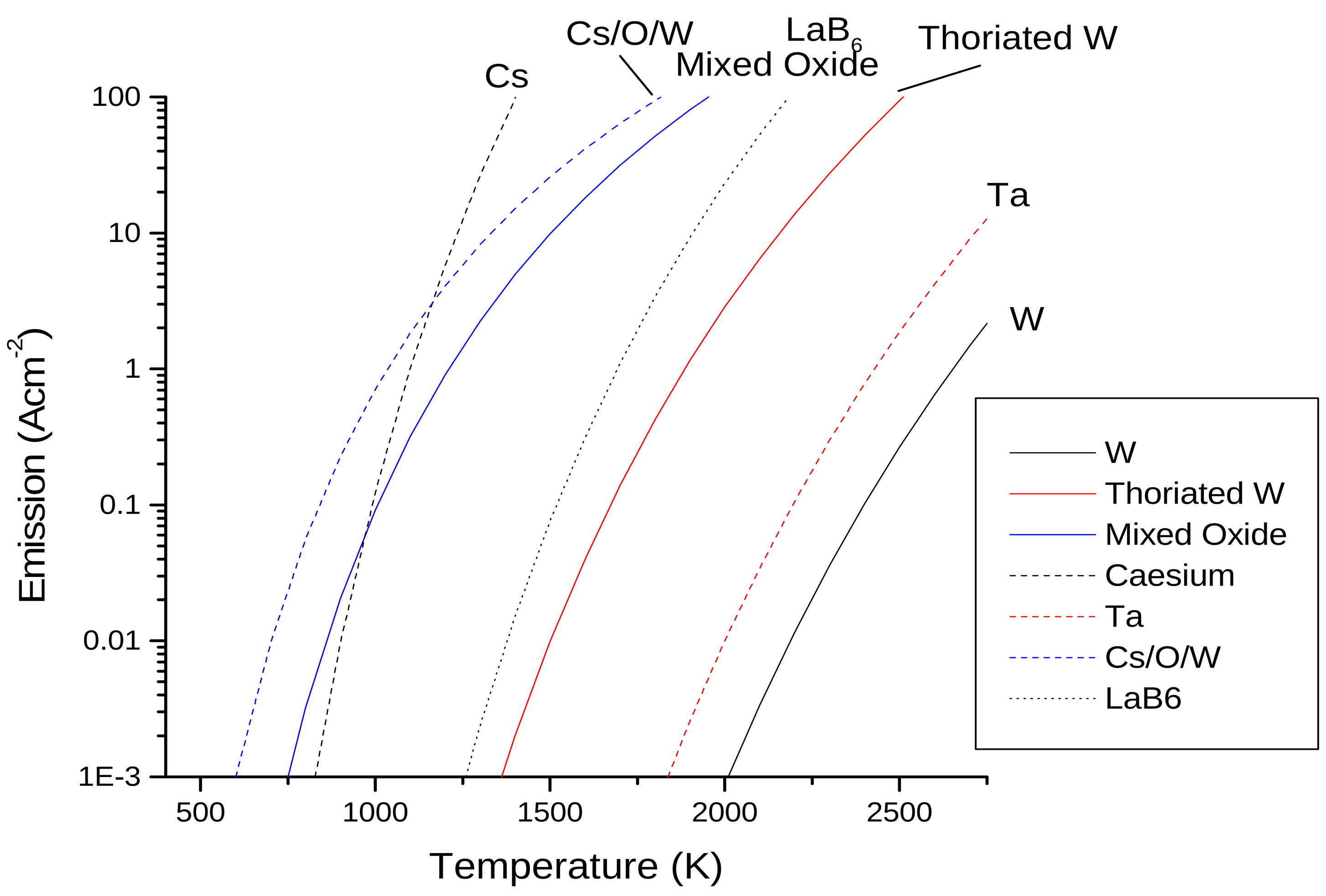
Cathodes – problem 1 – Ion Sputtering

The ions formed in the plasma are attracted to the cathode, and sputter material from it. Heavier atoms sputter much more. Tungsten is one of the hardest materials.



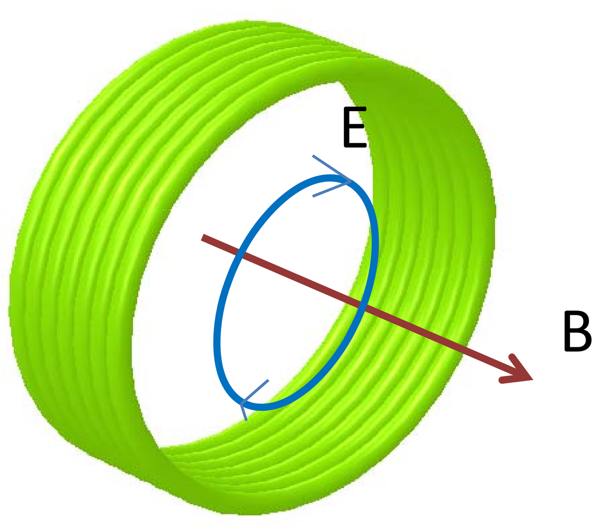
Cathodes – problem 2 – Surface changes

- Gases and other materials in the source can cover the cathode.
- This changes the surface, affecting its emission properties (usually for the worse) .
- Mixed material cathodes – elements sputter and evaporate at different rates.



RF Discharge

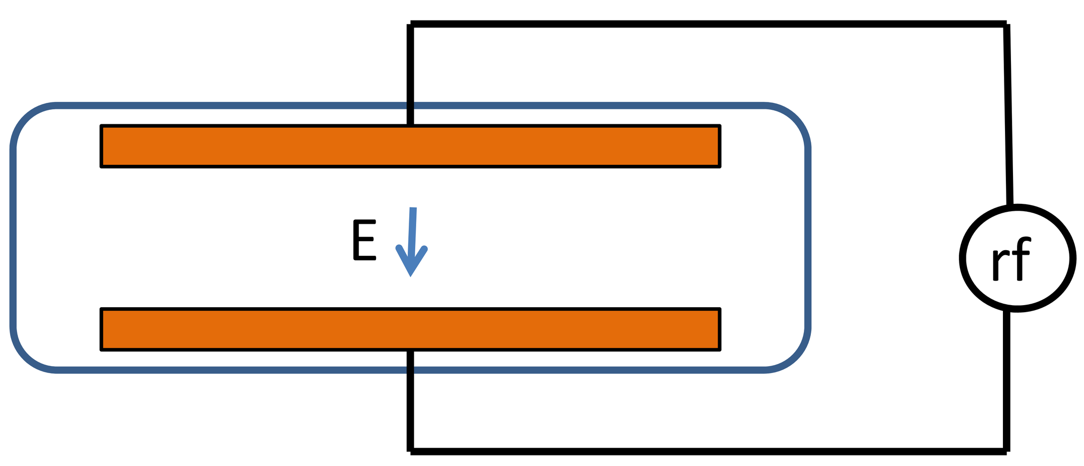
- Instead of using a cathode -> anode potential to create an electric field, the electric field from an RF system can be used.
- Electrons are accelerated by the electric field. Usually there is no wave-plasma resonance…
- Two possibilities
  - Solenoid antenna – a circular electric field is generated around a solenoidal magnetic field (also could be saddle like)



$$E \approx \frac{\mu_0 \pi N_t I r f}{L}$$

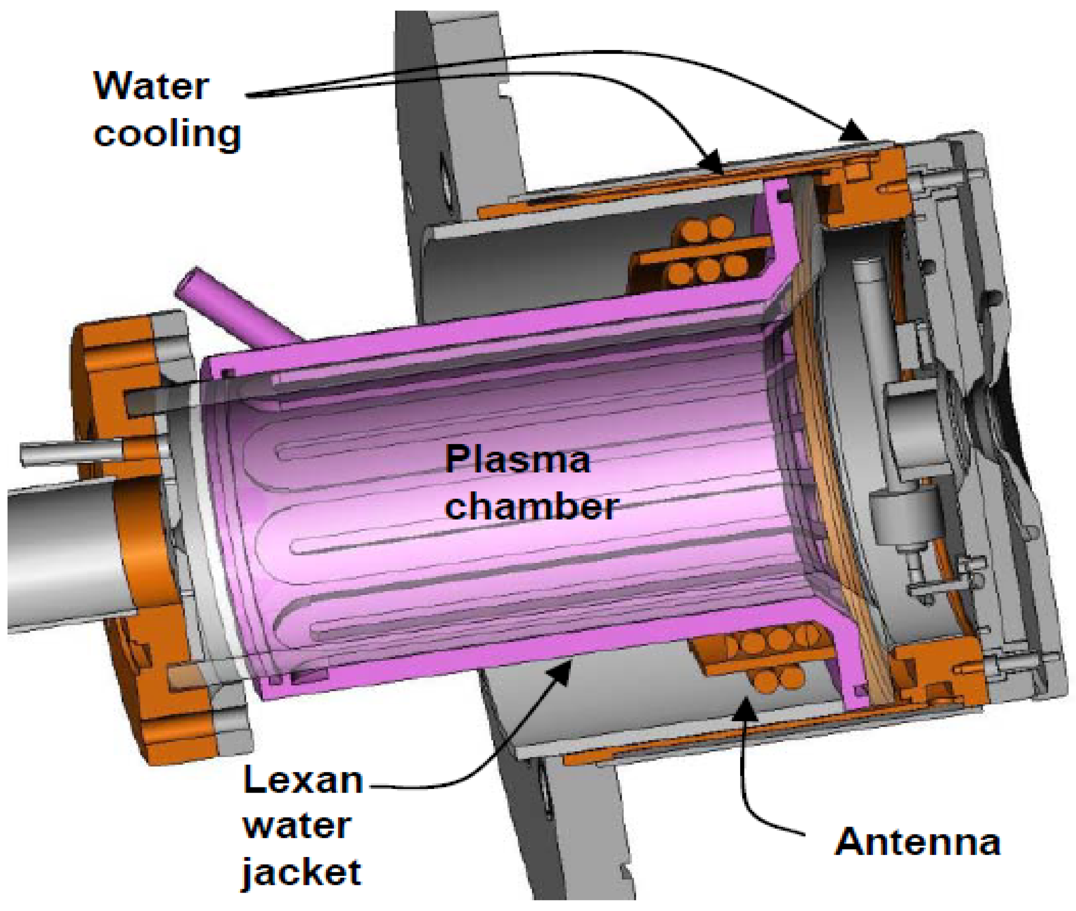
r: solenoid radius
N: solenoid turns
L: solenoid length
I: Peak current

  - Capacitive coupling – the electric field runs between 2 conductors – magnetic field is elsewhere



RF Discharge

- Even the solenoid antenna based systems can produce electric fields of several kV/m.
- As these electric fields do not terminate on a surface, not enhanced by a cathode tip, there is less surface sputtering.
- As there is no resonant heating of electrons, they do not reach too high energies (useful for producing low charge states, or negative ion sources).



SNS External antenna source

ECR ion sources

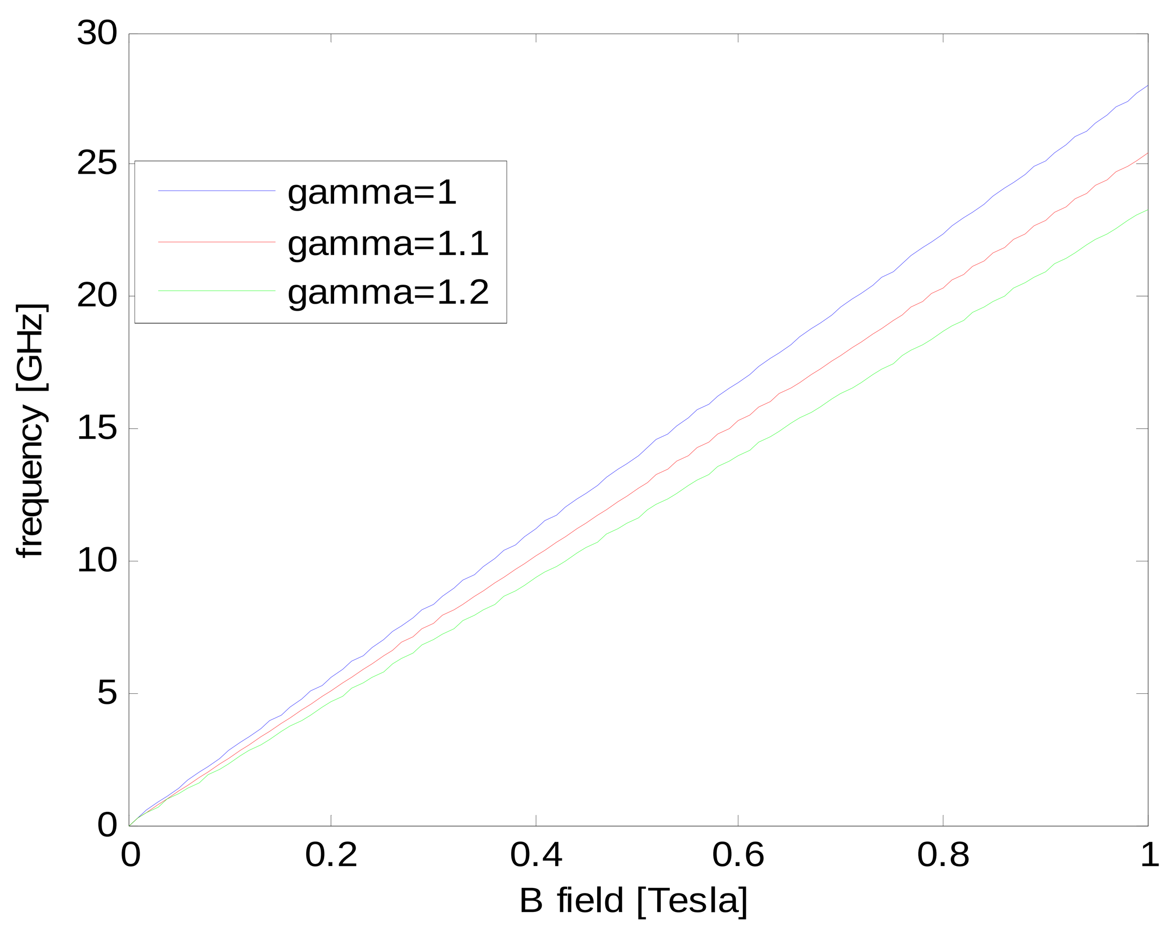
In an Electron Cyclotron Resonance Ion Source (ECR or ECRIS):

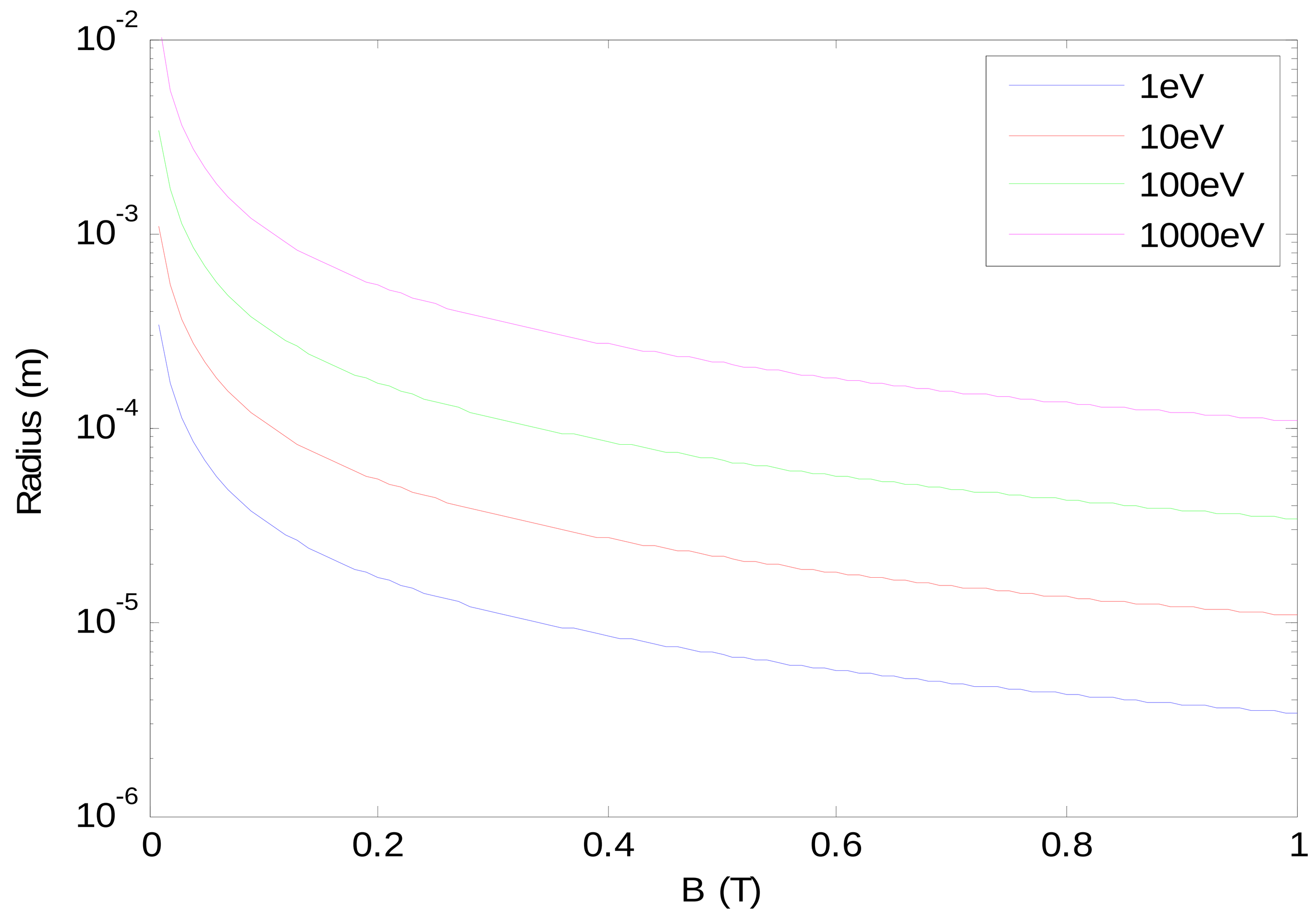
- There is a magnetic field, and the injection of RF or microwaves.
- Wave frequency satisfies the ECR resonance somewhere in the source (f=28 GHz / Tesla)
- The electrons absorb energy from the Right Hand Circular Polarised wave (EM waves can always be decomposed into RHCP and LHCP)
- The electron cycltron radius is small compared to the source volume.

- The ECR ion source has no cathode (overcoming the cathode problems).
- Solenoidal fields are used, in order to place a magnetic field over the whole source chamber.
- Magnets can be permanent, to reduce size and power consumption.

ECR ion sources

$$f_c = \frac{eB}{2\pi\gamma m_e} \qquad \frac{f_c}{B} = 28\,\text{GHz/Tesla} \qquad \rho_c = \frac{\beta\gamma m_e c}{eB}$$





Note: Only energy perpendicular to B field

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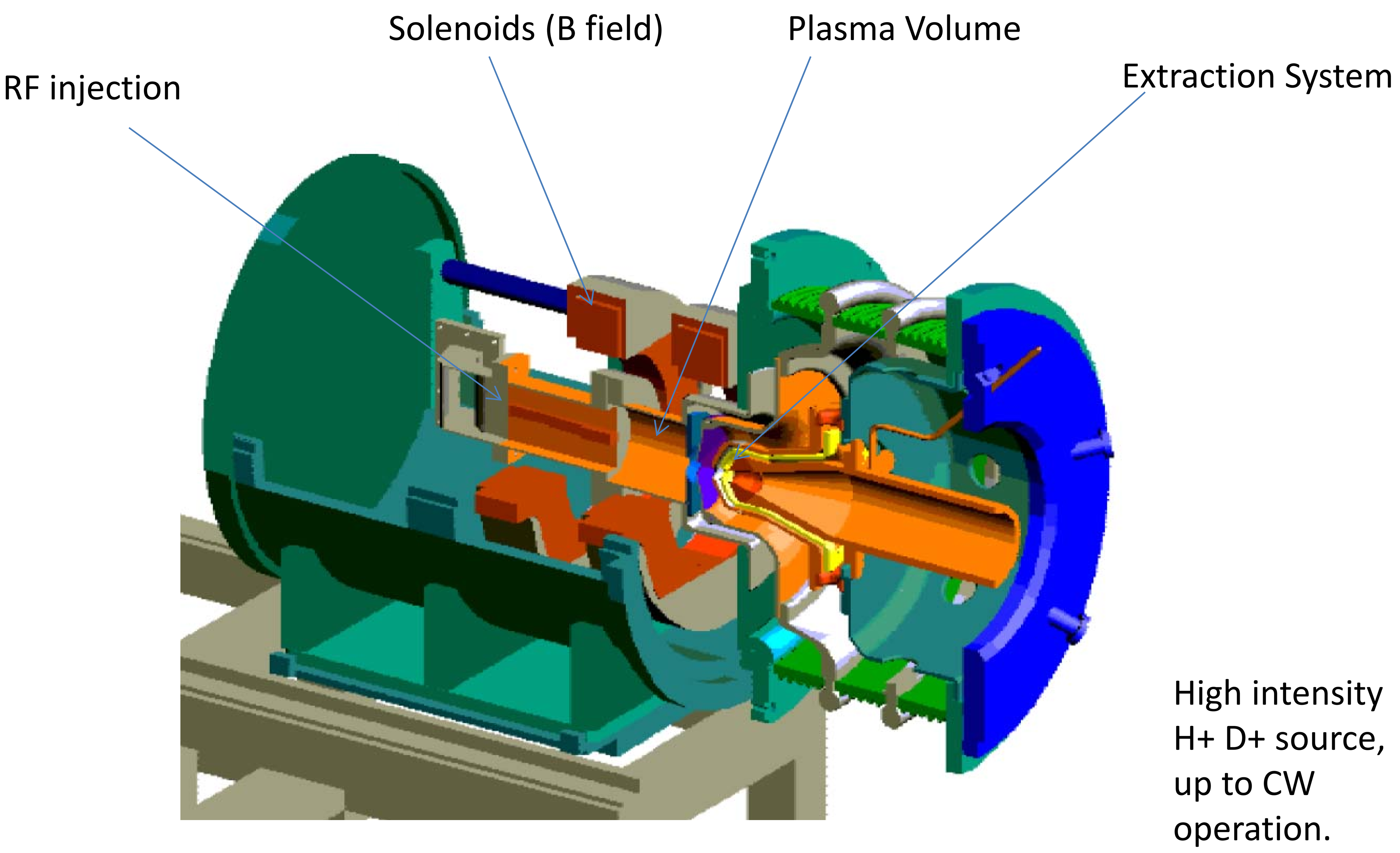
ECR ion sources



High intensity H+ D+ source, up to CW operation.

CEA – SILHI 2.45GHz ECR source for H+, D+

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Laser ion sources

The interaction of light with matter can give rise to two types of ion sources:

Laser *Ionization* Ion Sources

Laser *Plasma* Ion Sources

These two techniques are very different in the way that they produce ions.

Laser *Ionization* ion sources

• It is not easy to ionize atoms directly with a laser.

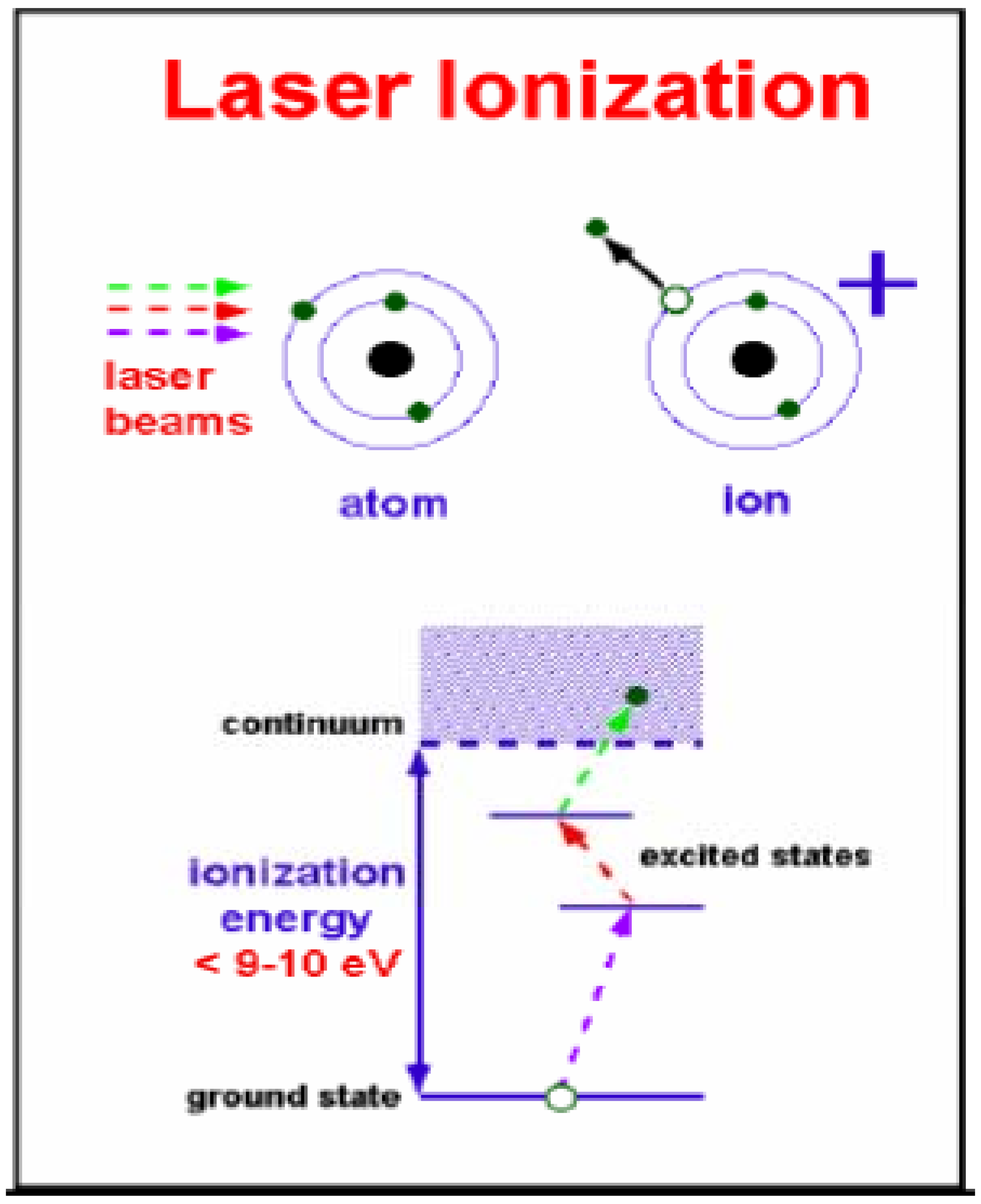
$$\lambda = \frac{hc}{e\Phi_i} = \frac{1.24}{\Phi_i}\mu\text{m}$$

• For the lowest ionization potential (Francium, 3.83eV) this is already UV light.

• Usually necessary to use at least two steps (or more), first to an excited state (requiring a tunable laser) and then to ionize.

• This allows the excitation to be chemically selective.

• Typically the source works continuously with low ion currents (needing a CW laser).



First Ionization Potential (eV) of all elements

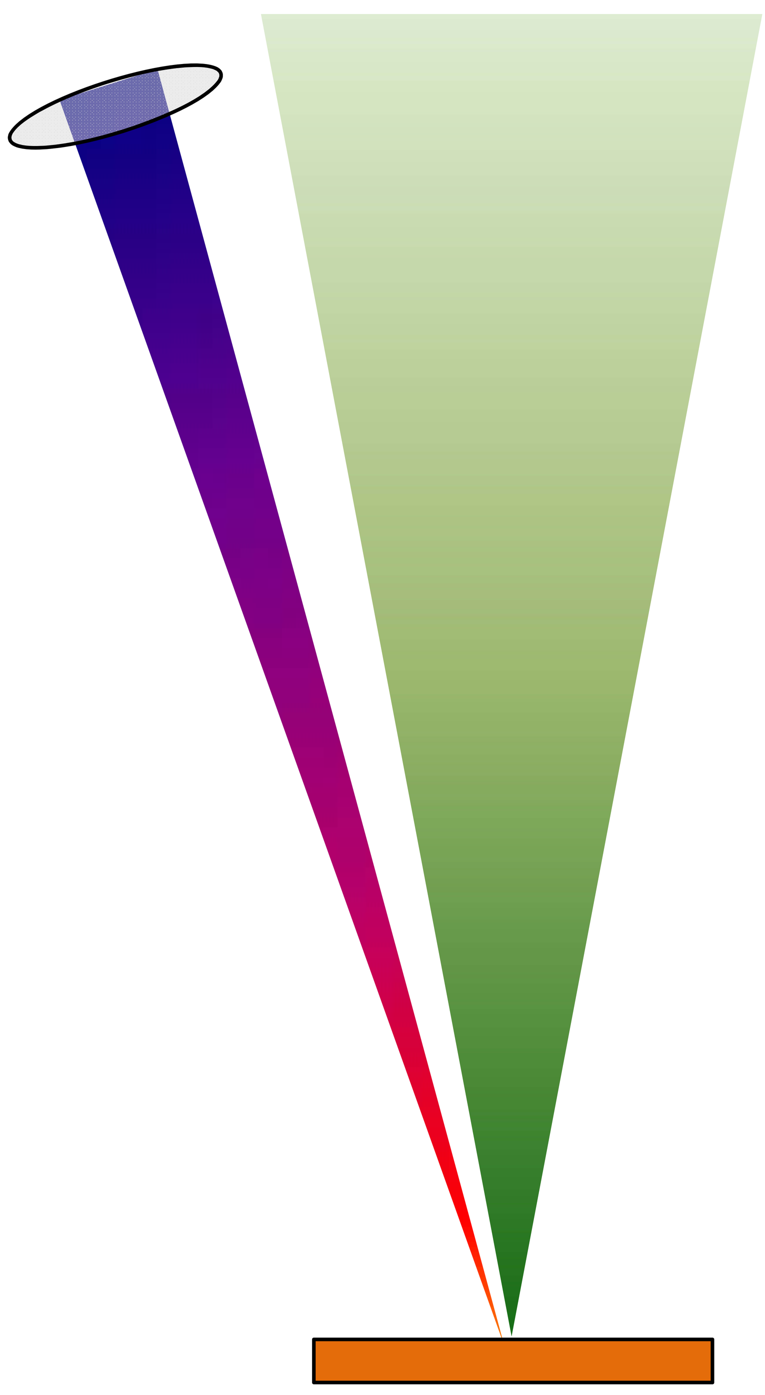
3.83	Francium	6.184	Thulium	7.98	Tungsten
3.894	Cesium	6.19	Neptunium	8.151	Silicon
4.177	Rubidium	6.23	Berkelium	8.298	Boron
4.341	Potassium	6.254	Ytterbium	8.34	Palladium
5.139	Sodium	6.3	Californium	8.42	Polonium
5.17	Actinium	6.38	Yttrium	8.641	Antimony
5.212	Barium	6.42	Einsteinium	8.7	Osmium
5.279	Radium	6.5	Fermium	8.993	Cadmium
5.392	Lithium	6.54	Scandium	9	Platinum
5.4259	Lutetium	6.58	Mendelevium	9.009	Tellurium
5.46	Praseodymium	6.65	Hafnium	9.1	Iridium
5.53	Neodymium	6.65	Nobelium	9.225	Gold
5.54	Cerium	6.74	Vanadium	9.322	Beryllium
5.554	Promethium	6.766	Chromium	9.394	Zinc
5.58	Lanthanum	6.82	Titanium	9.65	Astatine
5.64	Samarium	6.84	Zirconium	9.752	Selenium
5.67	Europium	6.88	Niobium	9.81	Arsenic
5.695	Strontium	7.099	Molybdenum	10.36	Sulfur
5.786	Indium	7.28	Technetium	10.437	Mercury
5.86	Terbium	7.289	Bismuth	10.451	Iodine
5.89	Protactinium	7.344	Tin	10.486	Phosphorus
5.94	Dysprosium	7.37	Ruthenium	10.748	Radon
5.986	Aluminum	7.416	Lead	11.26	Carbon
5.993	Americium	7.435	Manganese	11.814	Bromine
5.999	Gallium	7.46	Rhodium	12.13	Xenon
6.018	Holmium	7.576	Silver	12.967	Chlorine
6.02	Curium	7.635	Nickel	13.598	Hydrogen
6.05	Uranium	7.646	Magnesium	13.618	Oxygen
6.06	Plutonium	7.726	Copper	13.999	Krypton
6.08	Thorium	7.86	Cobalt	14.534	Nitrogen
6.101	Erbium	7.87	Iron	15.759	Argon
6.108	Thallium	7.88	Rhenium	17.422	Fluorine
6.113	Calcium	7.89	Tantalum	21.564	Neon
6.15	Gadolinium	7.899	Germanium	24.587	Helium

Laser *Plasma* ion sources

- A pulsed laser beam is focused onto a target.
- At some position the laser frequency couples to the free electron plasma frequency (either in the material, or the formed plasma).
- In the dense plasma, ions of the target material are formed through electron impact ionization.

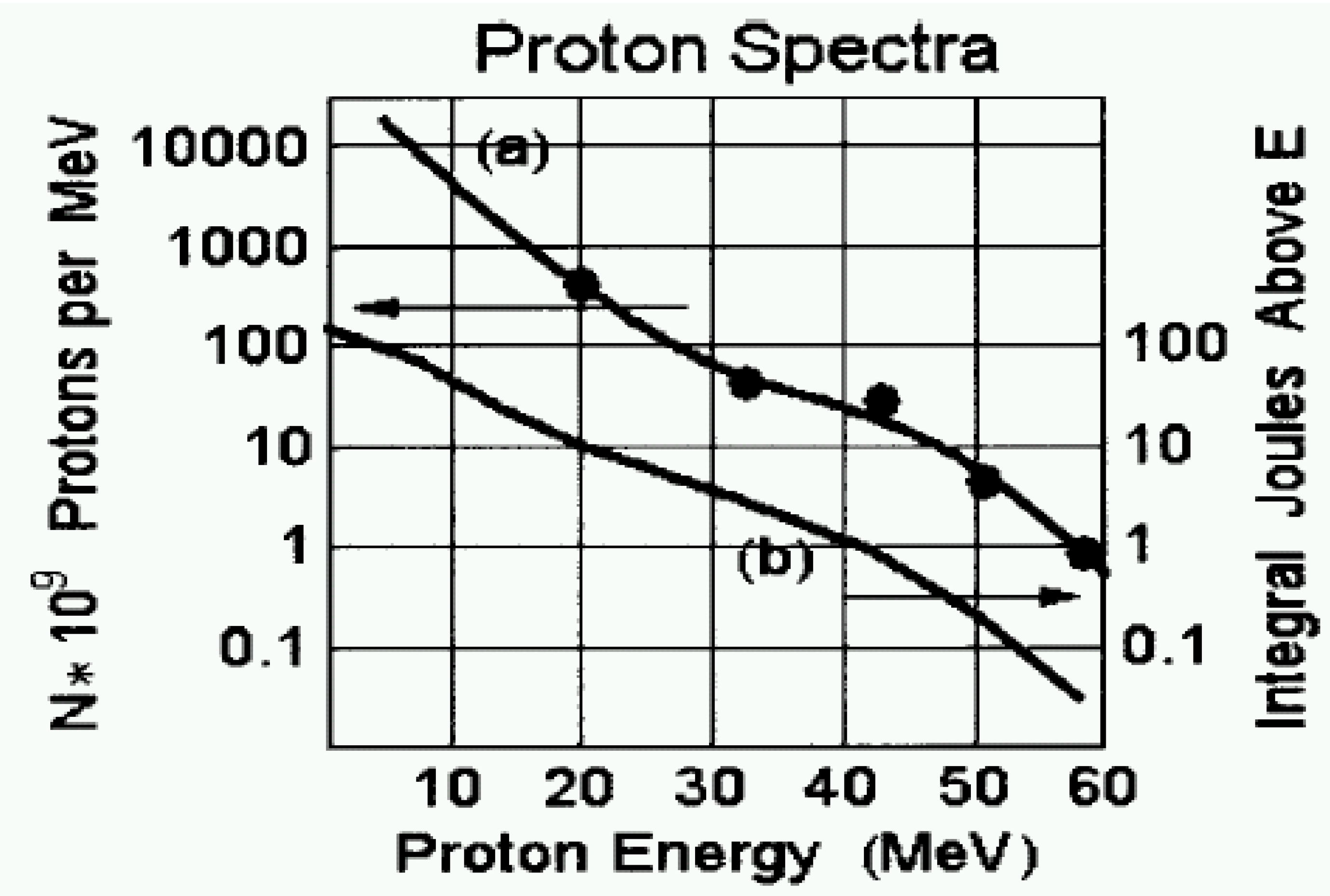
$$\lambda = \frac{2\pi c}{e}\sqrt{\frac{m_e \varepsilon_0}{n_e}}$$

- $n_e = 10^{21}$ cm^{-3} corresponds to 1µm.
- Laser power density needs to be above 10^6 W/cm^2, which is easily available with pulsed lasers.



Laser *Plasma* ion sources

- The future may be PetaWatt lasers (3×10^{20} W/cm^2) focused onto the rear of a thin (CH) target, have produced 58MeV protons – source and accelerator in one!



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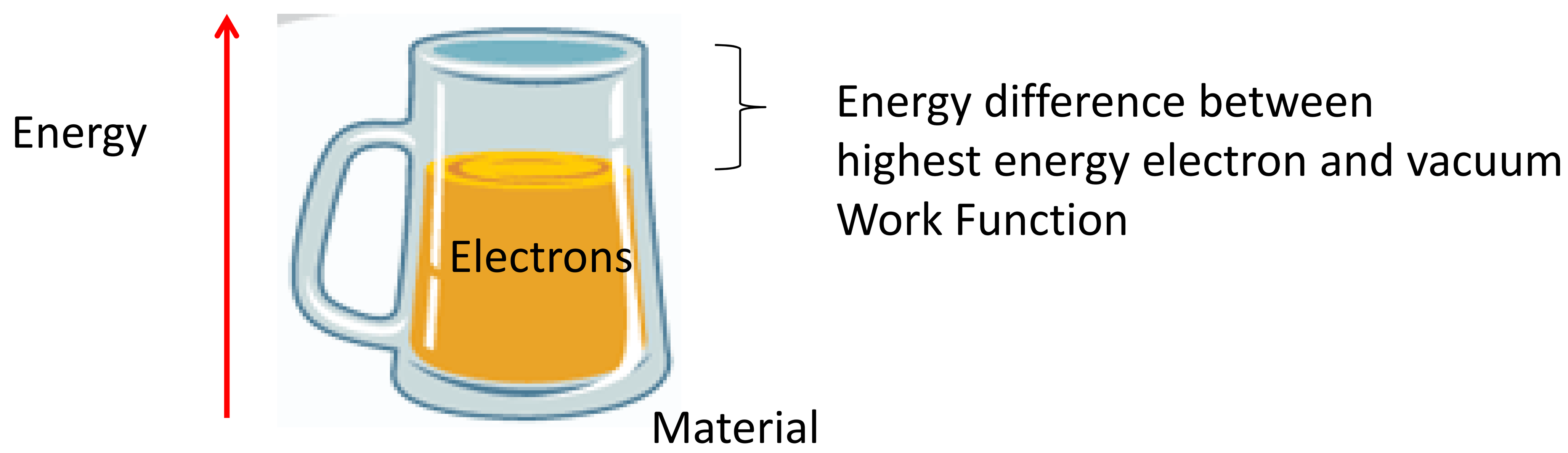
Surface Ion Sources

- Inside a solid state material, conduction electrodes are confined by the charge of the ions of the material.
- They are confined within the material by a binding energy (called the Fermi Energy).
- Energy in excess of the Fermi Energy must be applied in order to liberate an electron (e.g. through the photo-electric effect, or by heating).



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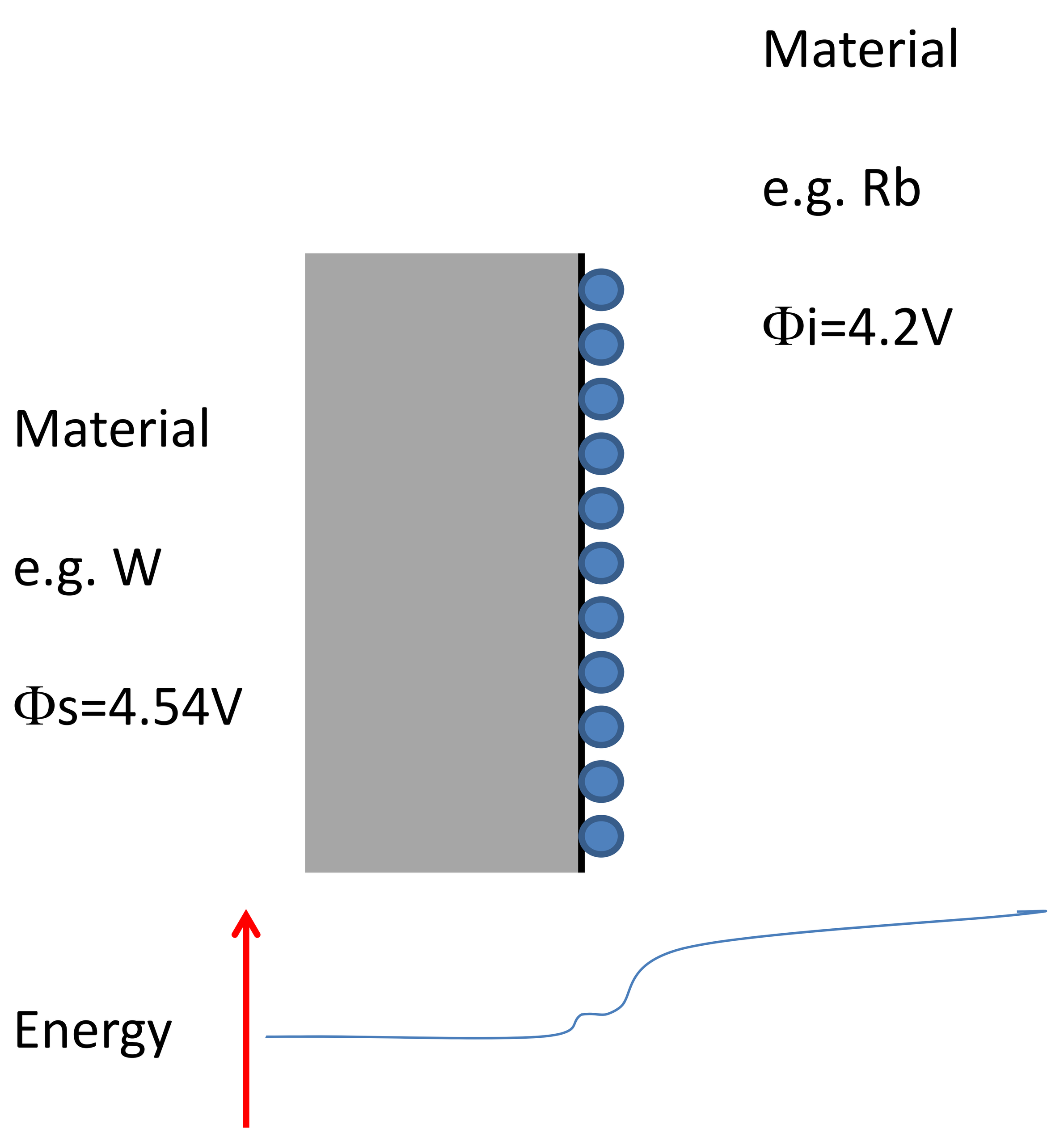
Surface Ion Sources



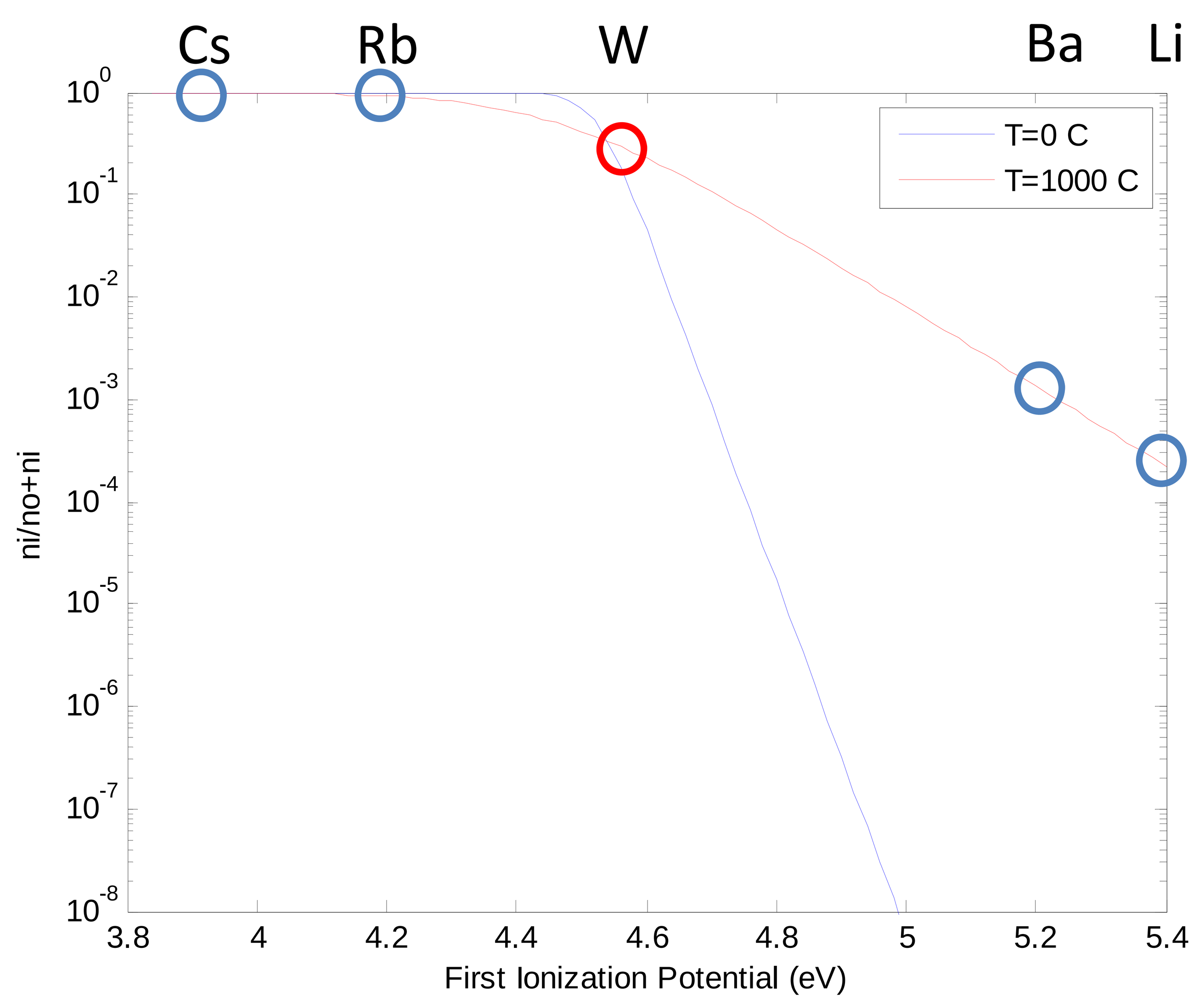
- Similarly the electron is trapped on the atom.
- But if a low ionization potential atom is in contact with a high work-function material, the electrons energetic preference is to be in the material.
- The material needs to be hot enough to evaporate the ions.
- The Saha-Langmuir equation predicts the ratio of ions to neutrals from the surface.

$$\frac{n_i}{n_0 + n_i} = \left(1 + \frac{g_0}{g_i} e^{(\phi_i - \phi_s)/kT}\right)^{-1}$$

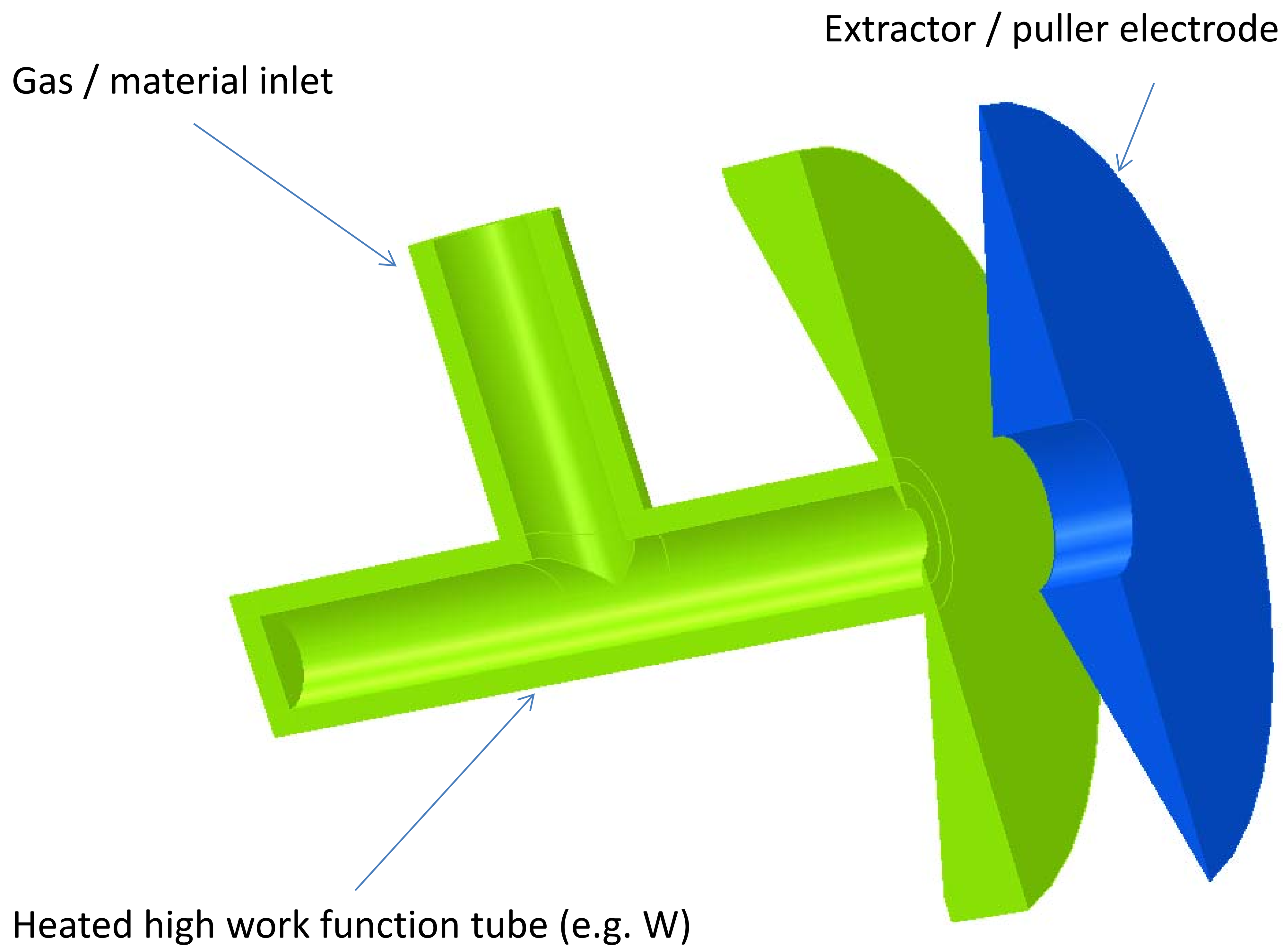
Surface Ion Sources

$$\frac{n_i}{n_0 + n_i} = \left(1 + \frac{g_0}{g_i} e^{(\phi_i - \phi_s)/kT}\right)^{-1}$$

Example ion fraction for Φs=4.54eV
Points are marked at 1000 C



Surface Ion Sources



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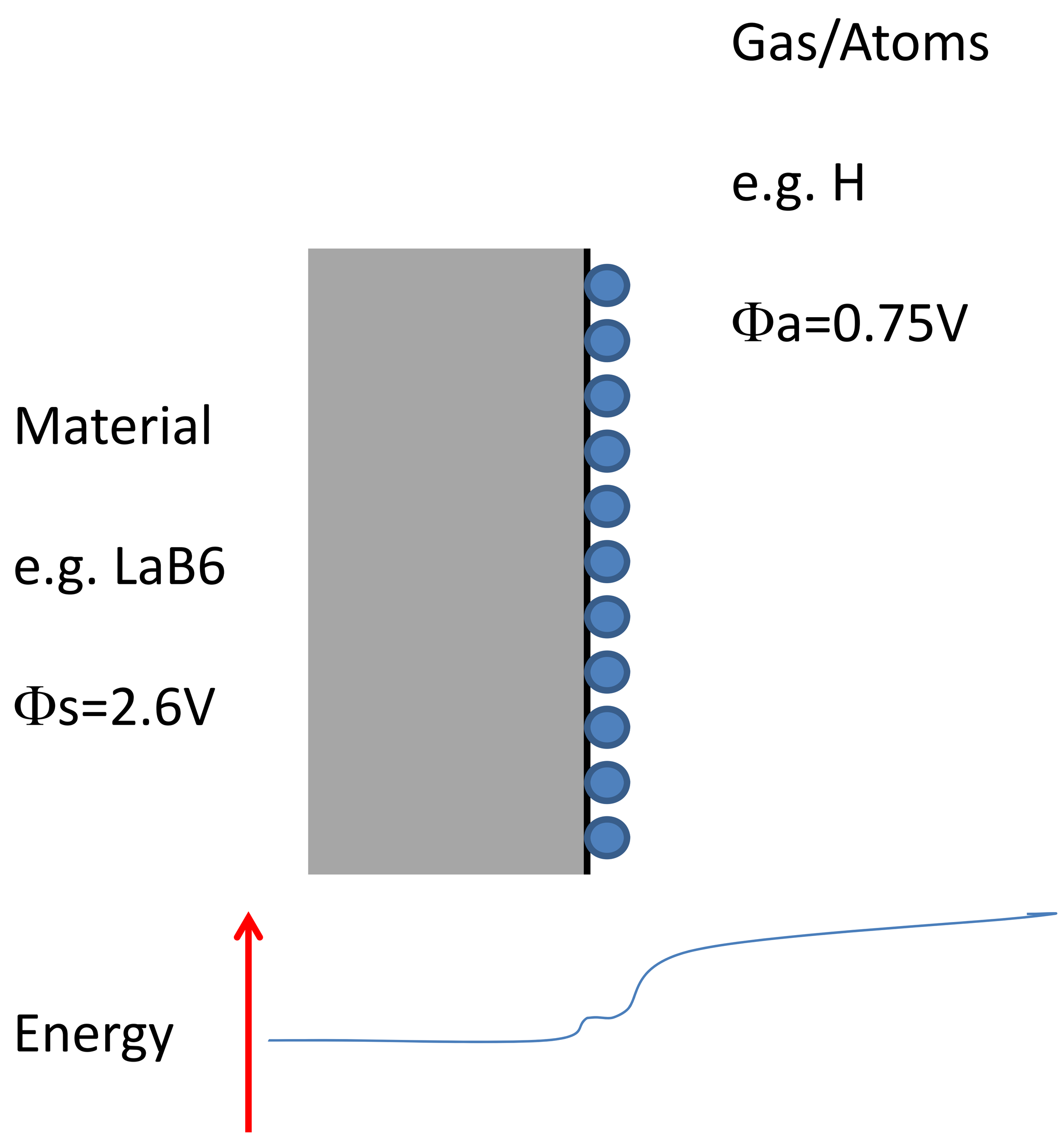
Surface Ion Sources – negative ions



- If the base material has a low work-function, and the atoms a high electron affinity-
- The electrons have a finite probability of being present on the electron.
- Use plasma bombardment to liberate the atoms from the surface.
- Use an alkali metal coating deposited on the surfaces inside a plasma discharge source, to produce the ions.
- The Saha-Langmuir equation can also be used for this case.

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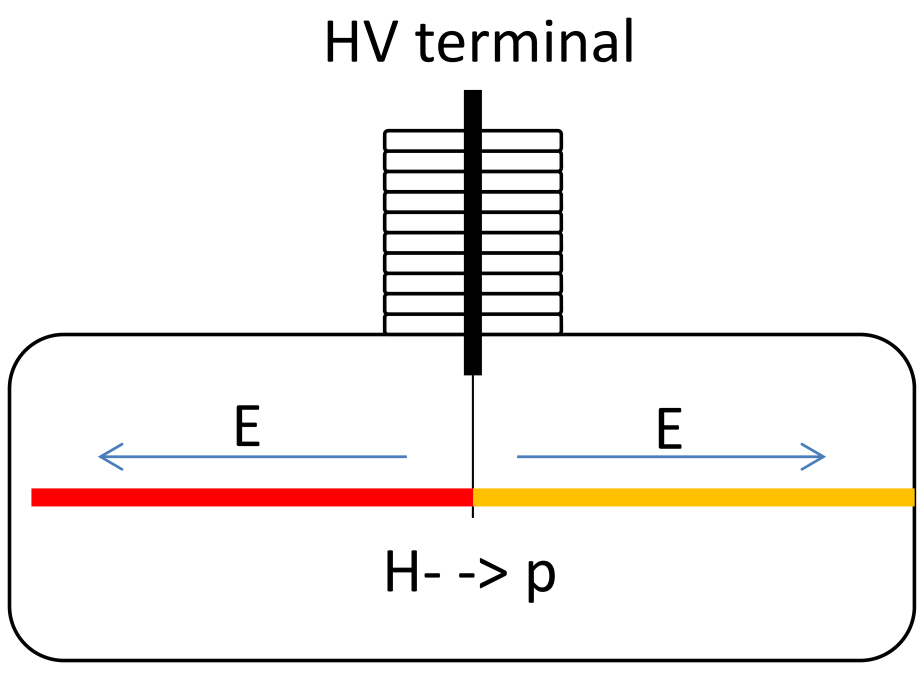
Negative ions – Why?

- Negative ions are (generally) much harder to produce than positive ions.
- Their benefits for the following accelerator are:
  - They have the opposite charge (so are oppositely affected by E and V fields).
  - They are easily stripped to positive ions or neutrals (normally at higher energies).

Tandem

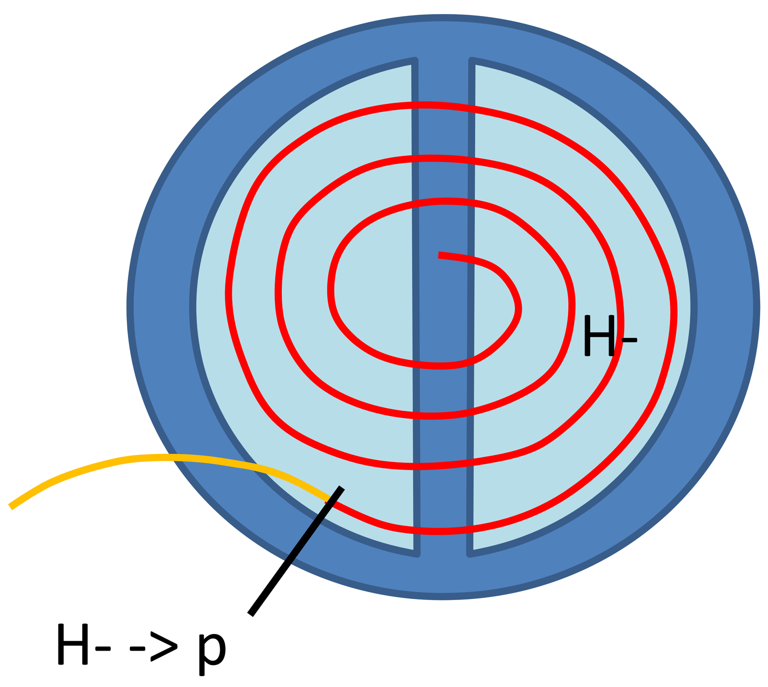
- Negative accelerated to foil, positive ion back to ground.



Negative ions – Why?

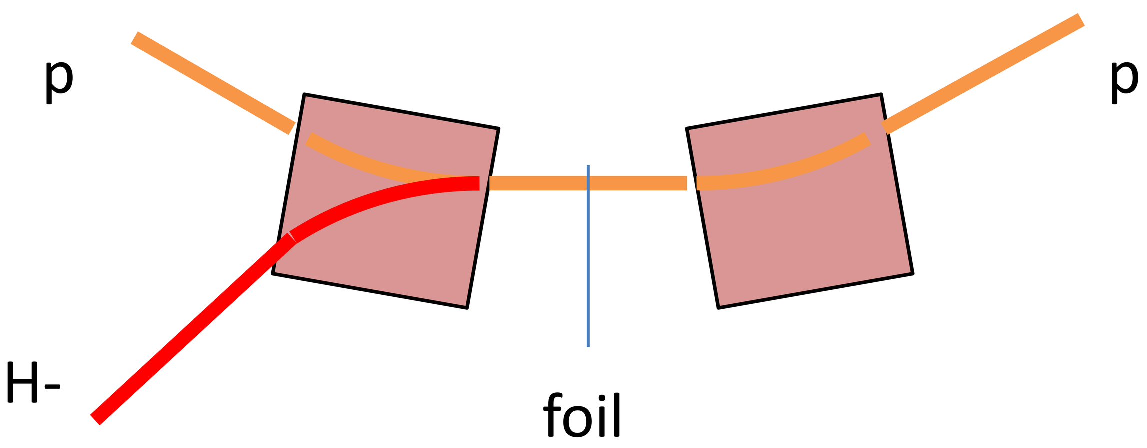
Extraction (from cyclotrons)

- Change the charge in a foil, and the positive ion extracts itself



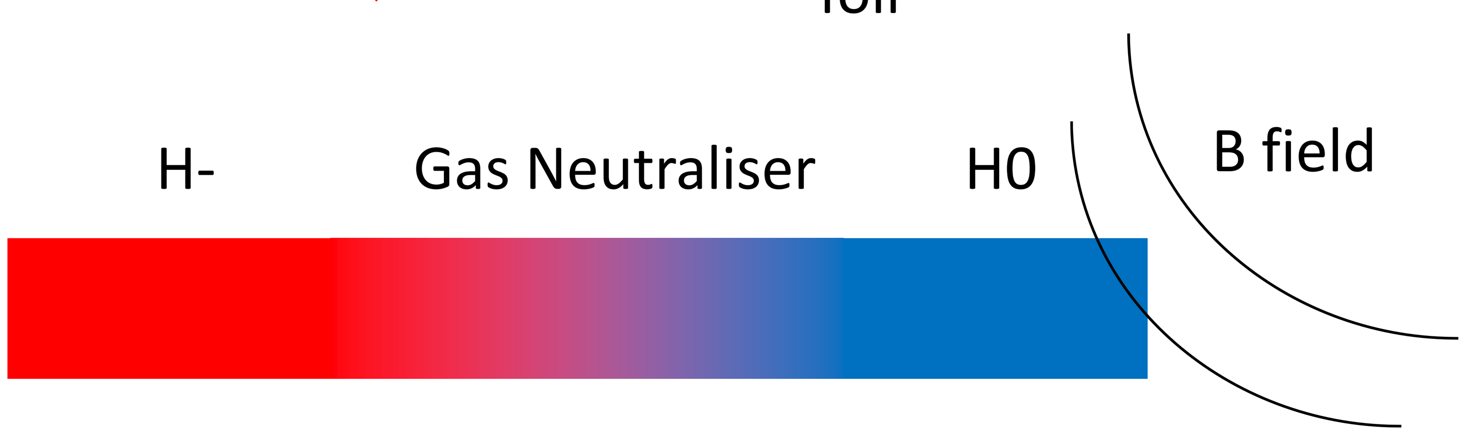
Charge exchange injection (to synchrotron).

- Overlap the negative and (circulating) positive ions – strip to positive – overcome Louiville!



High Energy Neutral Beams (Magnetic Confinement Fusion)

- Efficient stripping to neutrals – to inject through a magnetic field.

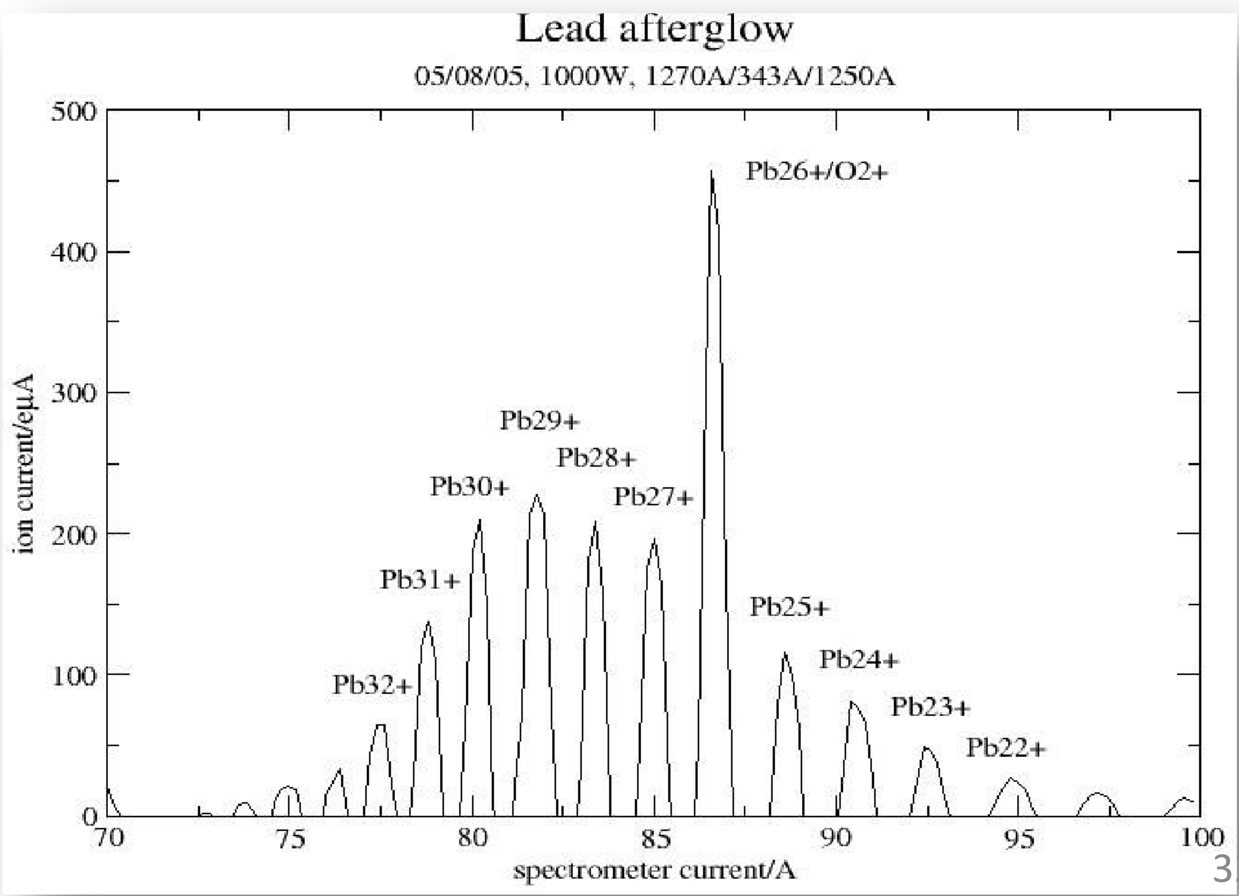


Highly Charged Ions

- For heavy ions it is often necessary to create high charge states.
- The high charge state allows more energy to be gained in the accelerating electric field.
- To create highly charged ions need:
  - Direct ionization with a single electron impact is not feasible ($A \rightarrow A^{n+}$).
  - So multi-step ionization is the only practical solution ($A^{n+} \rightarrow A^{n+1+}$).
  - High Energy electrons – above the ionization potential of the ion charge start required.
  - Ions to remain in the plasma long enough for sufficient ionizing collisions to take place (long time, or dense plasma).
- 3 types of sources are generally used, we have already seen them:

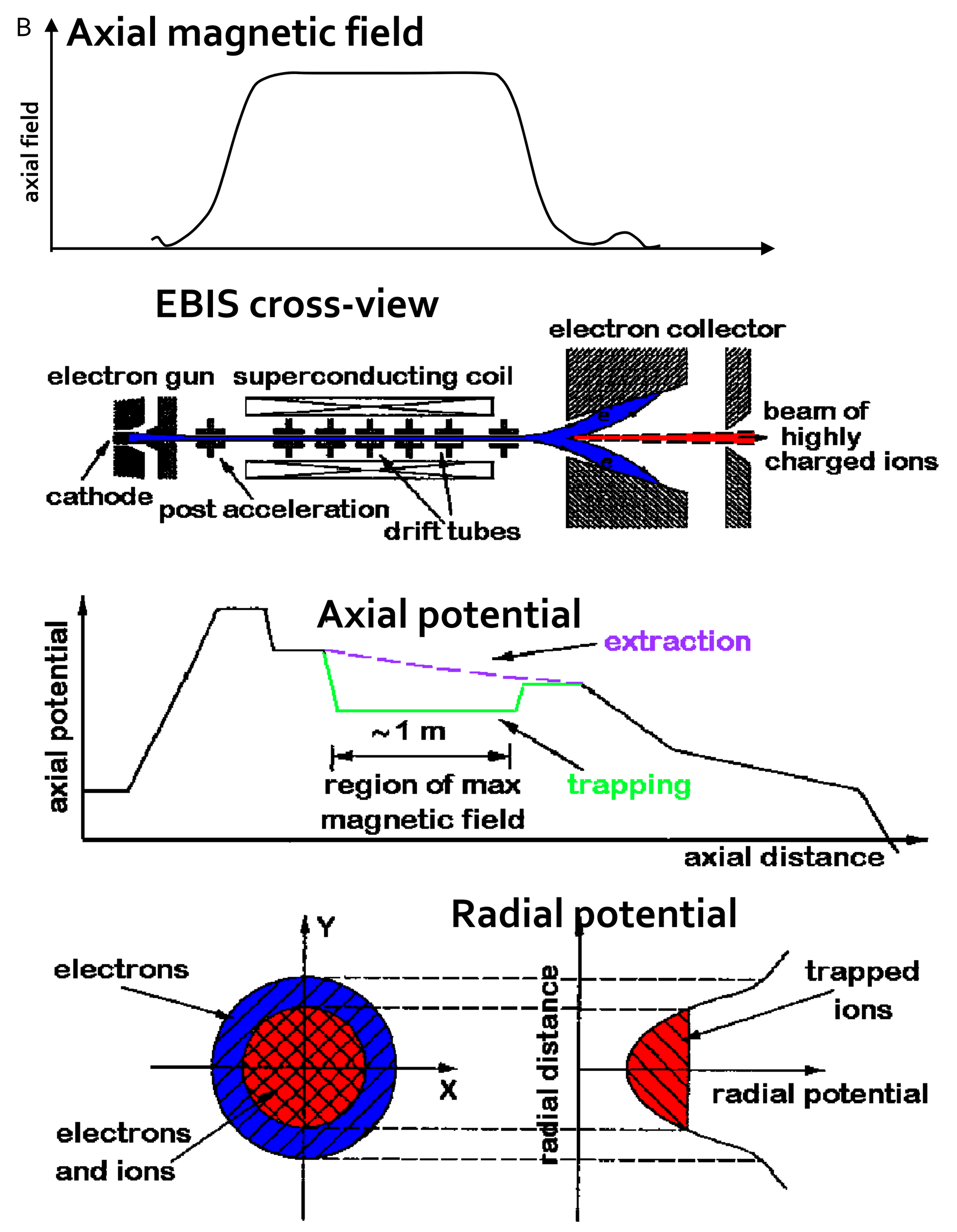
Highly Charged Ions - ECRs

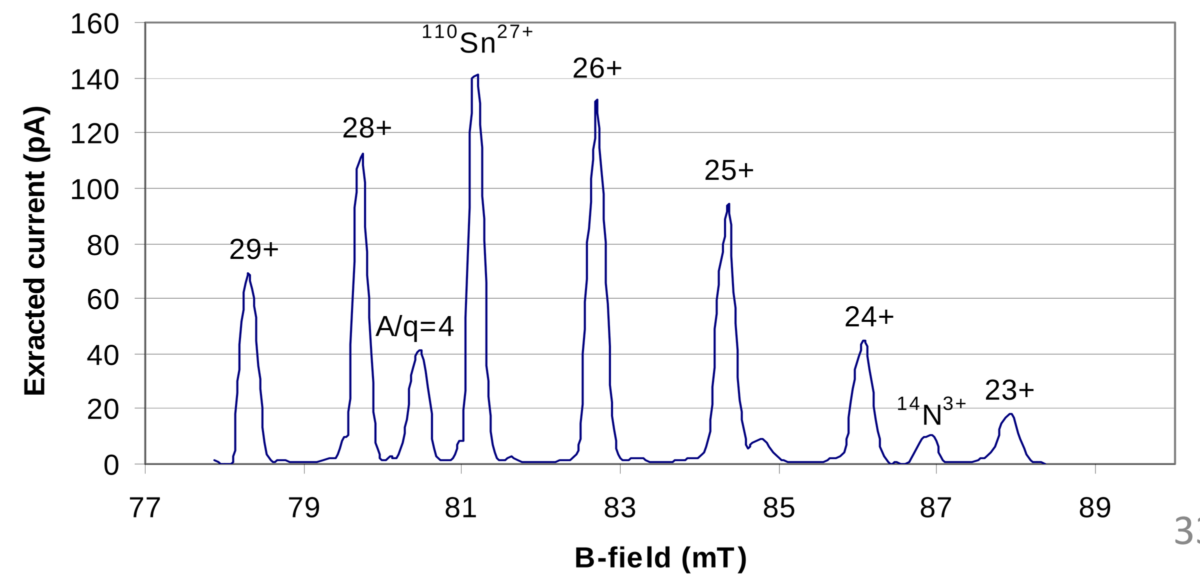
- The electrons are heated using the Electron Cyclotron Resonance.
- The Magnetic field I formed with co-linear solenoids, with a higher magnetic field at the ends, the confine the electrons with a magnetic mirror.
- Radially the confinement is made with a multi-cusp magnet.
- The inverse dynamics of collisional drift means the hot electrons are well confined.
- This leads to a charge density, that traps ions, sufficiently long for mulit-step ionisation to take place.



Highly Charged Ions - EBIS

- The electrons are accelerated from a cathode into a drift region (usually in a solenoid field to increase the current density).
- Ions are trapped radially by the electron beam potential.
- Longitudinal trapping is done with electrodes.
- Neutral gas or 1+ ions are injected, and confined long enough for multi-step ionzation.
- When the ion charge state is reached, one of the electrode barriers is reduced to allow the ions to escape.





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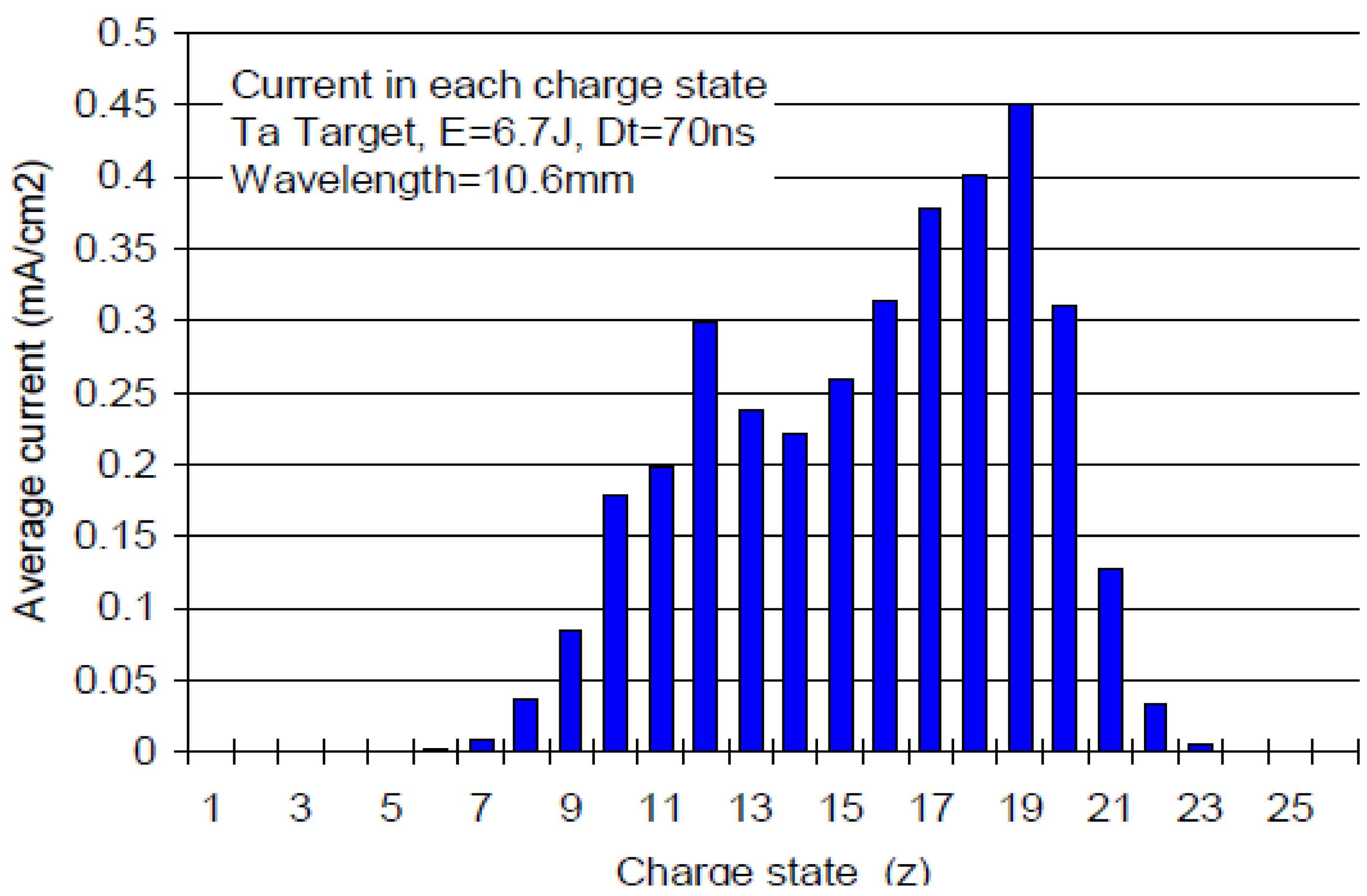
Highly Charged Ions – Laser Ion Sources

- Use the Laser Plasma Ion Source with a high power laser.
- Generate a very dense, hot plasma by coupling to the plasma frequency.
- Ions travel through the plasma, and due to the high density, they still undergo a large number of collisions.
- Spectrum from the Laser Ion Source :



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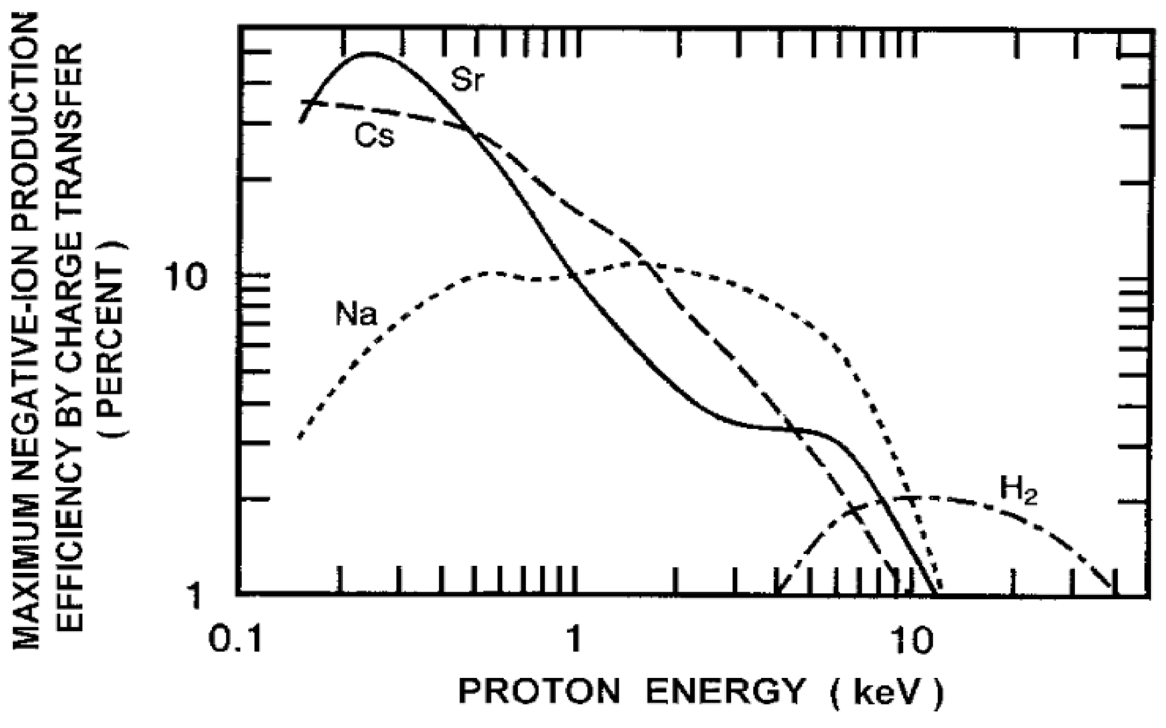
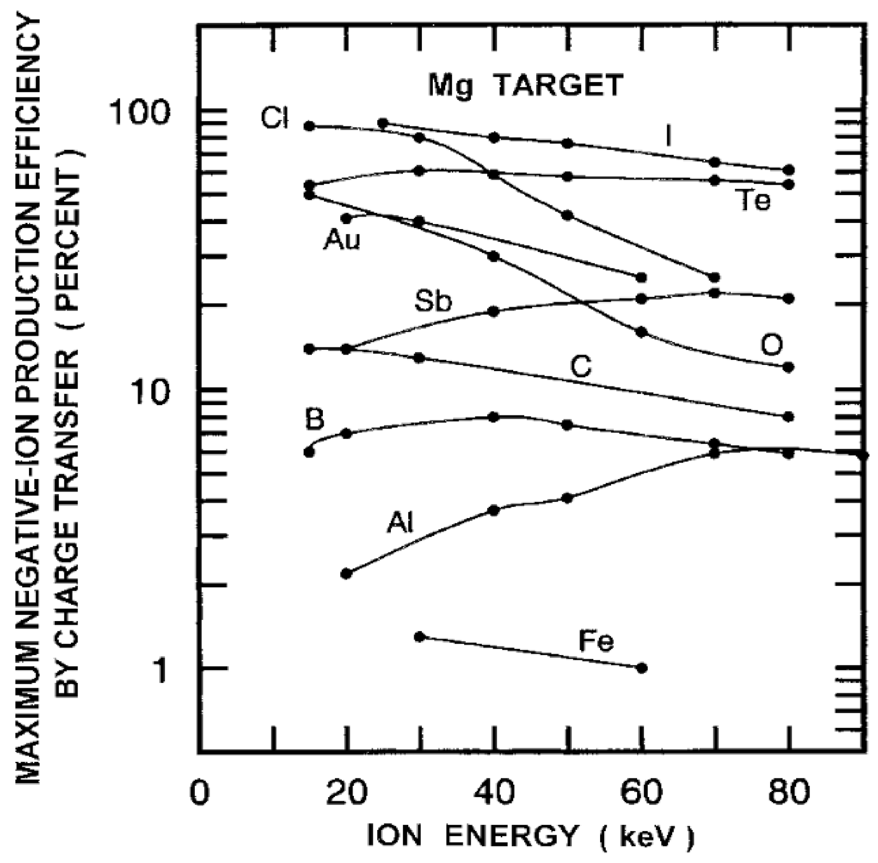
Charge Exchange Ion Sources – Negative Ions

- Ions travelling through a gas can undergo a double charge exchange, to produce negative ions.
- The cross section for the charge exchange is very high for good - electron doner - alkali metals,
- Although there are many sources for H-, not so many are well suited to other negative ion types.

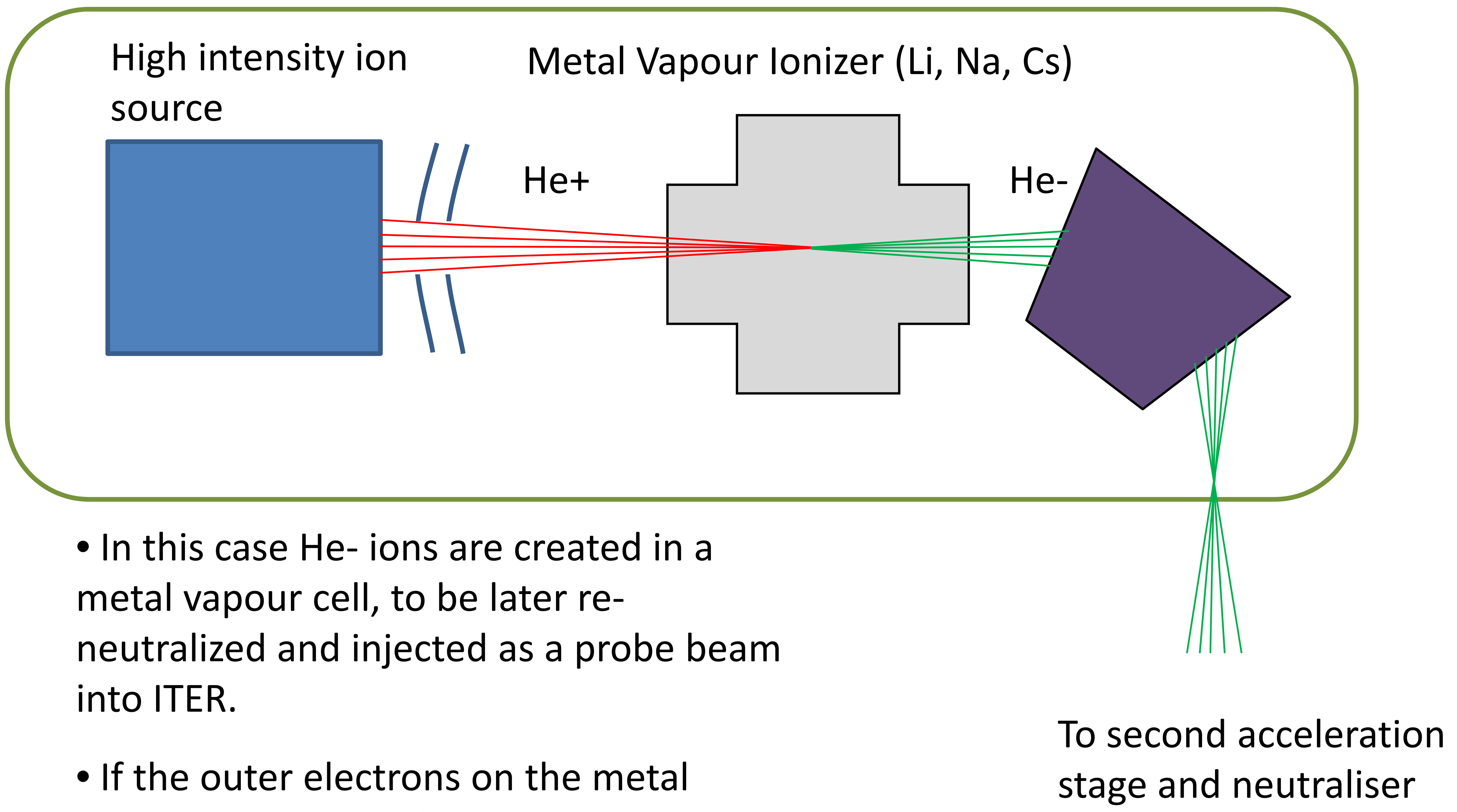


Schlachter and Morgan, AIP Conf. Proc. 111, p149 (1984)



Schlachter, AIP Conf. Proc. 111, p300 (1984)

Charge Exchange Ion Sources – Negative Ions



- In this case He- ions are created in a metal vapour cell, to be later re-neutralized and injected as a probe beam into ITER.
- If the outer electrons on the metal vapour are polarised, this can be transferred to the ion, which can be made to transfer the spin to the nucleus.

Ion Sources – what can we conclude?

- There are a lot of species of ion sources.
- Inside each species, there are sub-species and different implementations.
- Just in this overview, there have been a lot of physical processes shown (if not yet understood), in the next days you will learn even more.
- We are now entering the ***Ion Source Enlightenment*** – we can now start to model the multiple physics processes in our sources on a desktop computer, and understand how our sources are really working…
- Get involved, and become the new Spinoza, Newton, Voltaire…

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Symbols Used

A: Richardson Dushmann constant.
B: Magnetic Field
c: Speed of light.

e: Electron charge
h: Plank Constant
f: Frequency
f_c: Cyclotron Frequency

J: Current density
k: Boltzmann constant

m_e: Electron mass
n_e: Electron density
n_i: Ion Density
n_0: Neutral Atom Density
N_t: Number of turns
T: Temperature

β: Relativistic Beta
ε_o: Free space Permittivity
Φs : Work Function
Φi : Ionization Potential
γ: Relativistic Gamma
λ: Wavelength
ν_c : Collisional frequency
ρ_c: Cyclotron radius

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