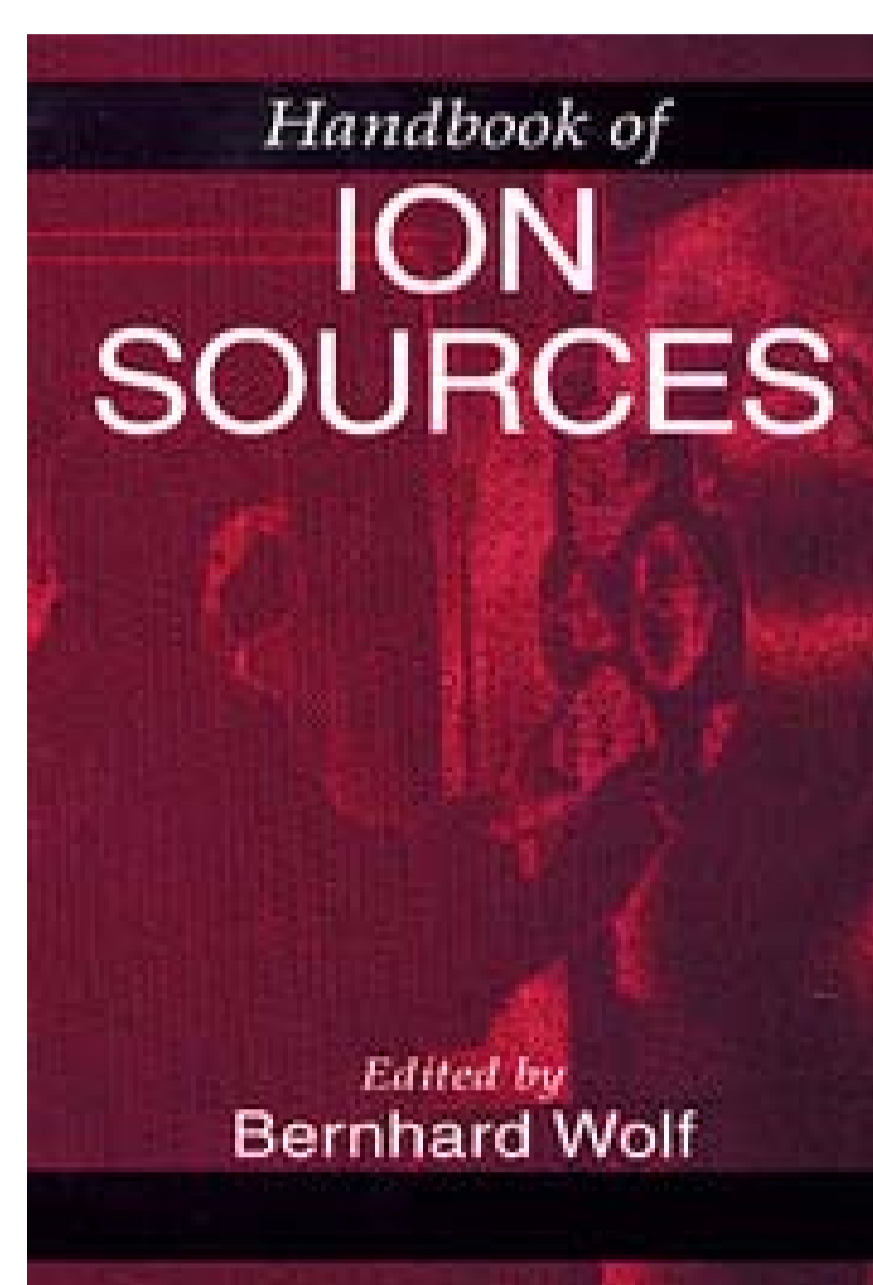


Definitions of Ion Sources



A day out at the zoo...

Richard Scrivens

CERN

CAS on Ion Sources, May 2011



An Approximate Classification System

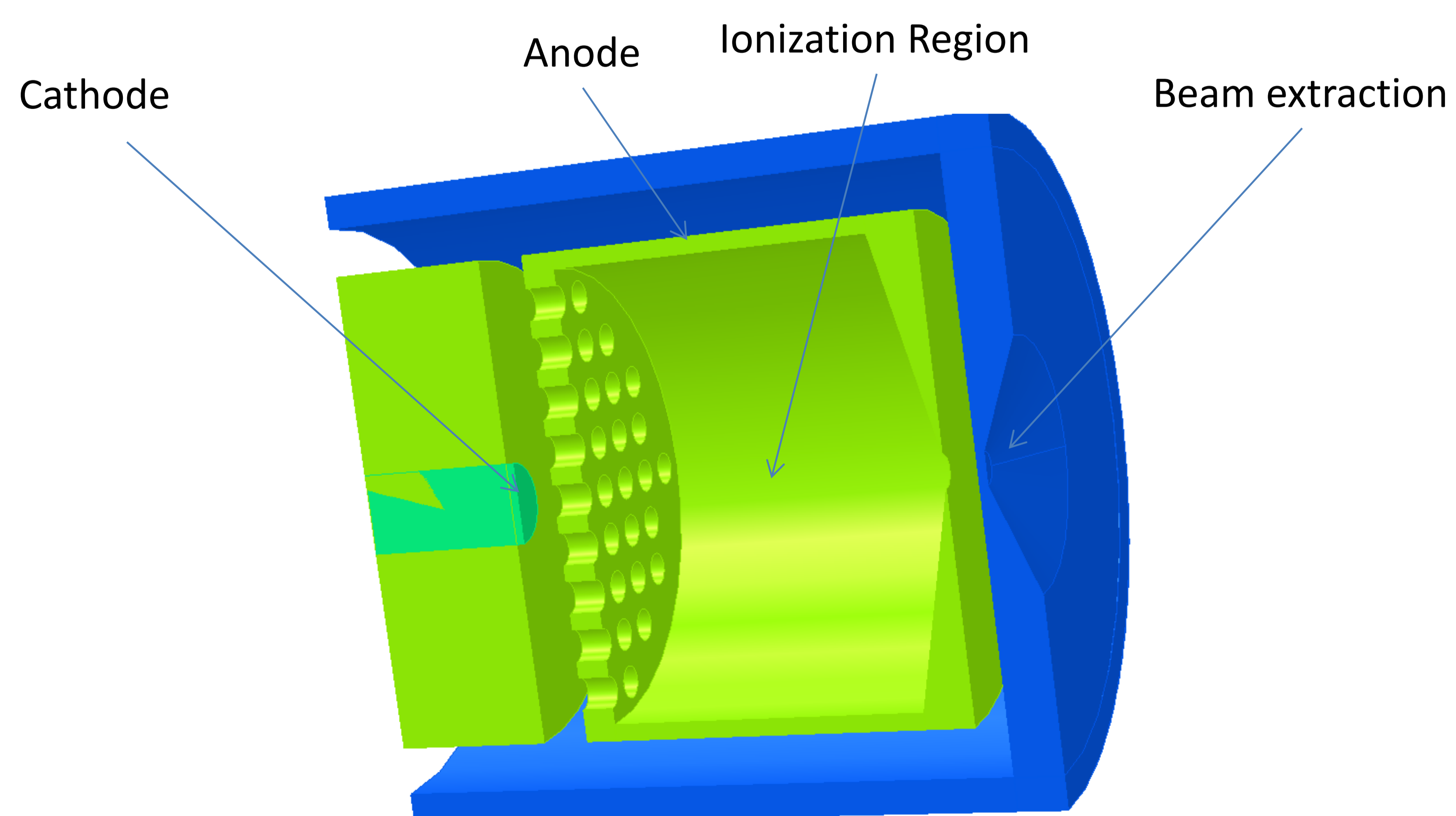
Try to break down ion sources into a few groups:

- 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

- A simplified FEBIAD ion source
- The ions are created in a field free region.
- Can lead to a low energy spread on the ions.



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Electron Bombardment Ion Source

Electrons emitted from a cathode.

Collide with residual gas ions to cause ionization.

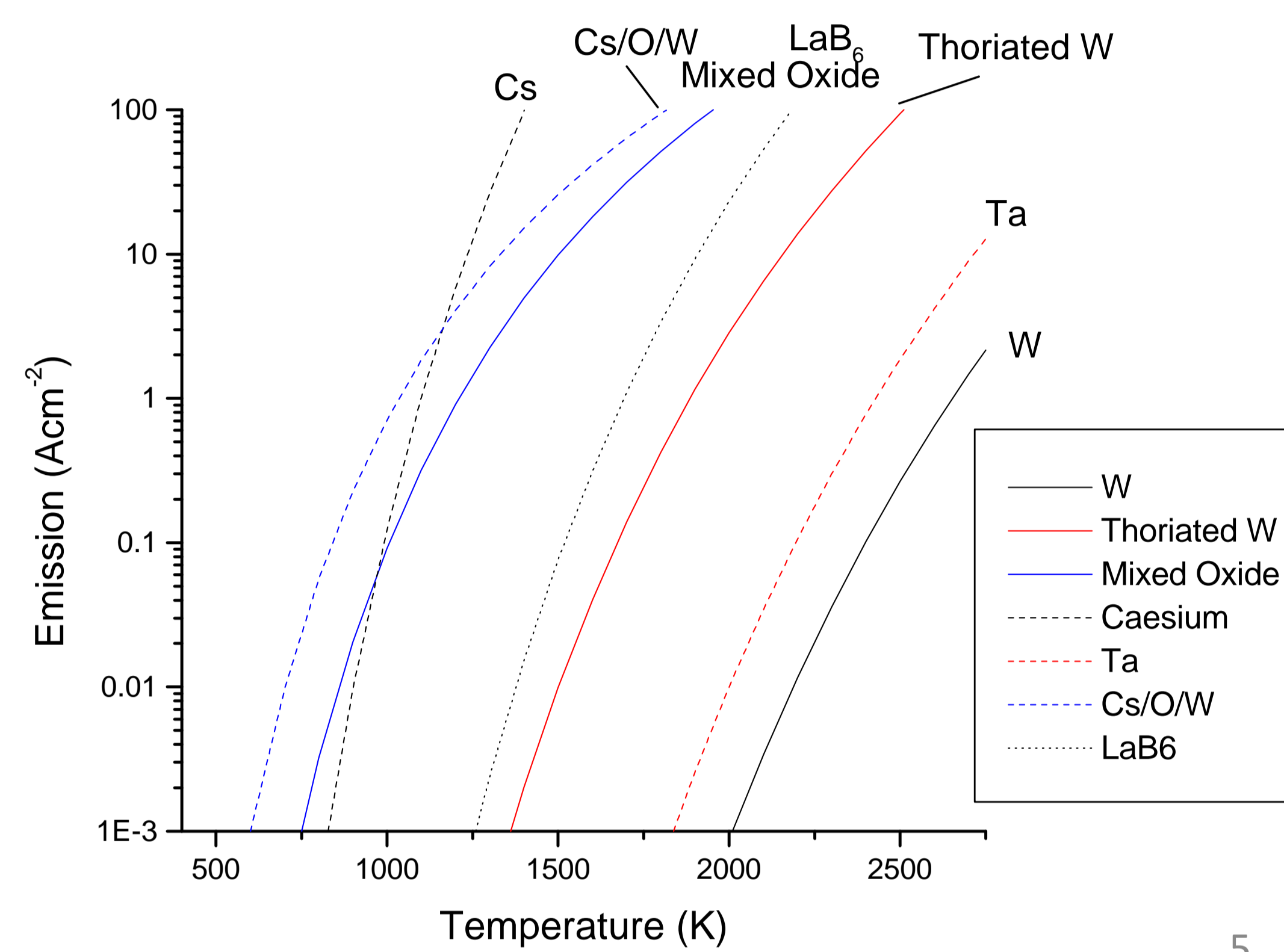
The plasma density remains low enough that the cathode to anode voltage distribution is quite linear.

Cathode emission is dominated by the Richardson Dushman equation.

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

$$A = \frac{4\pi m_e k^2}{h^3} \approx 1.2 \times 10^6 \text{ Am}^{-2} \text{ K}^{-2}$$

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



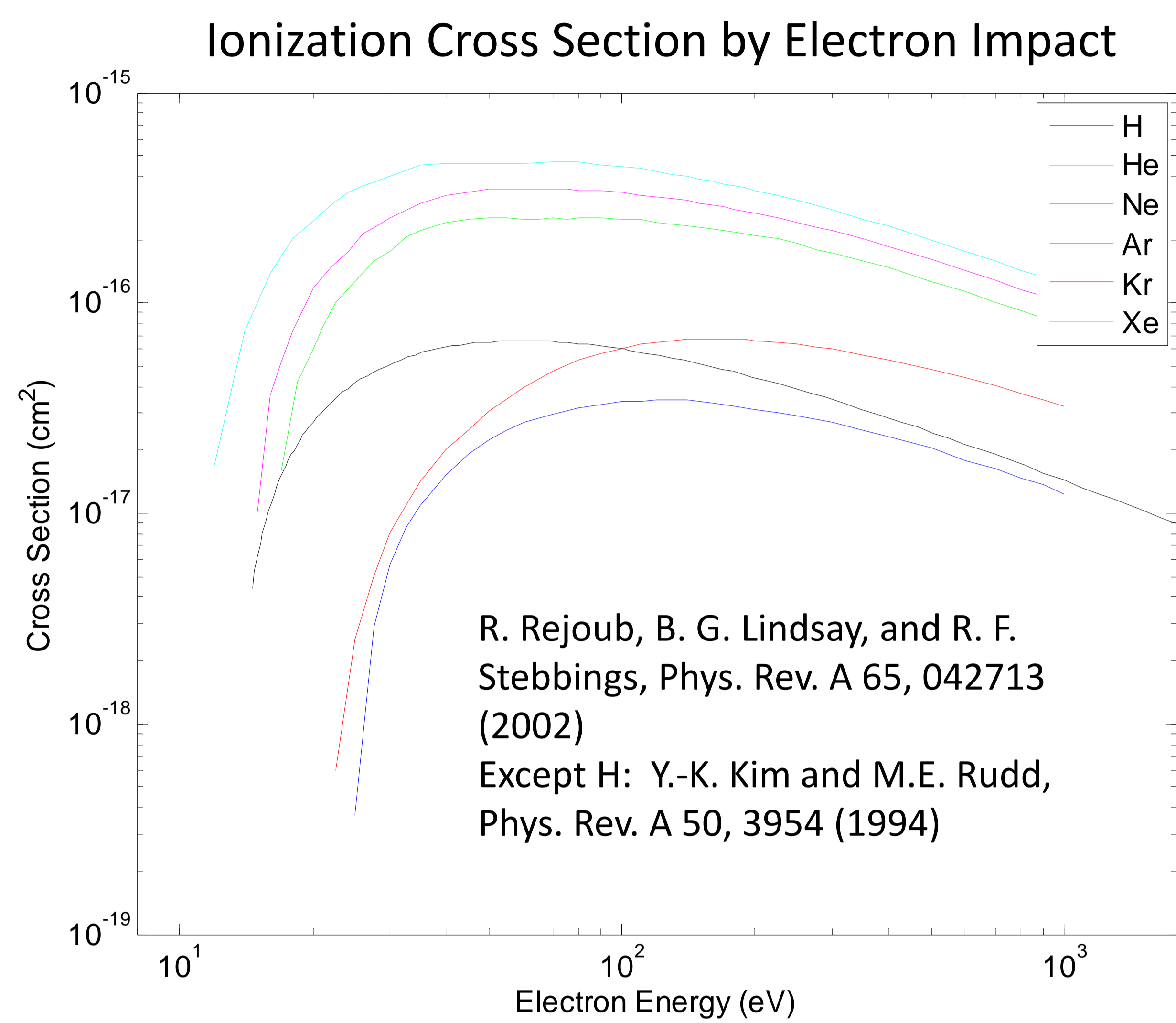
5

Electron Bombardment Ion Source

- The FEBIAD ion source uses a grid near the cathode to provide an 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).

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Electron Bombardment Ion Source

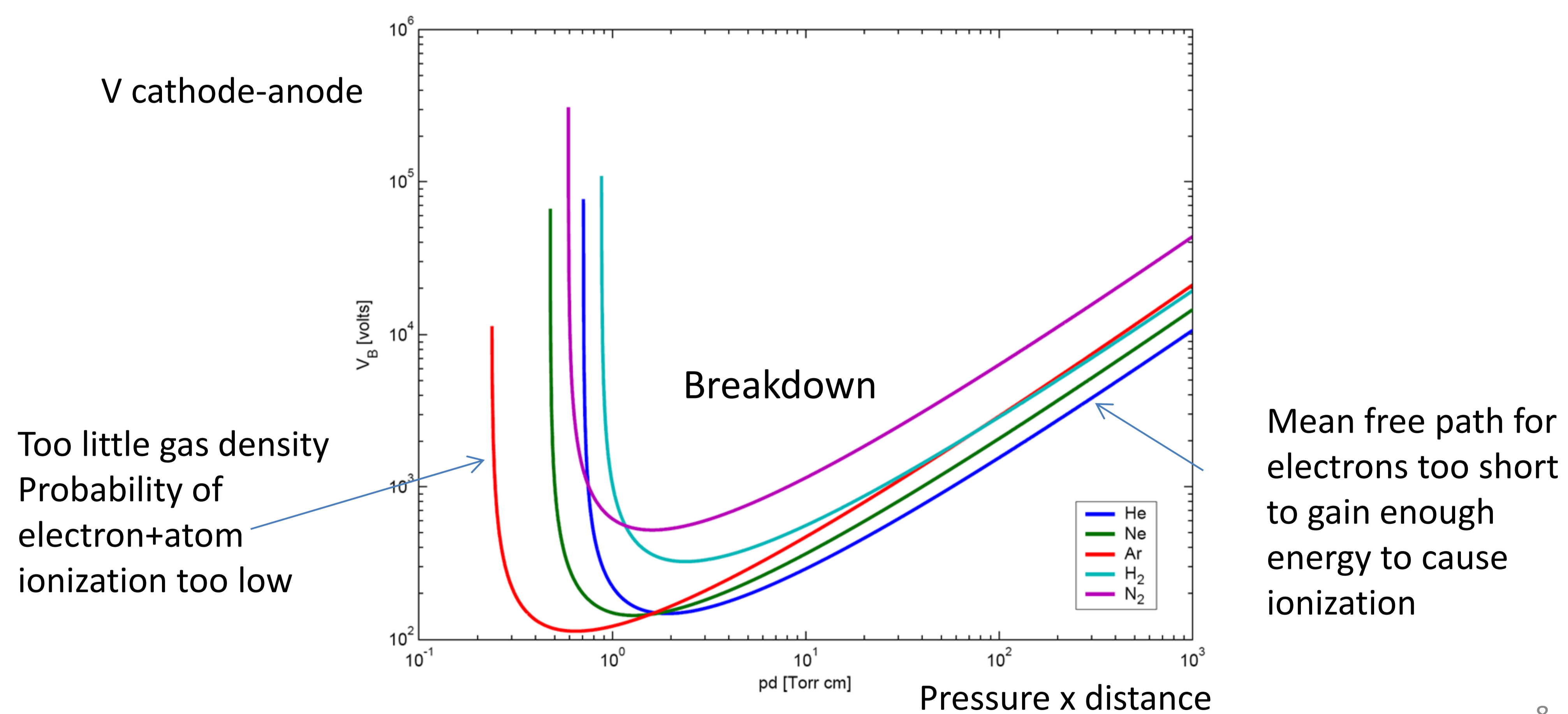


Some cross section data available in:
<http://physics.nist.gov/PhysRefData/Ionization/Xsection.html>

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Plasma Discharge Sources

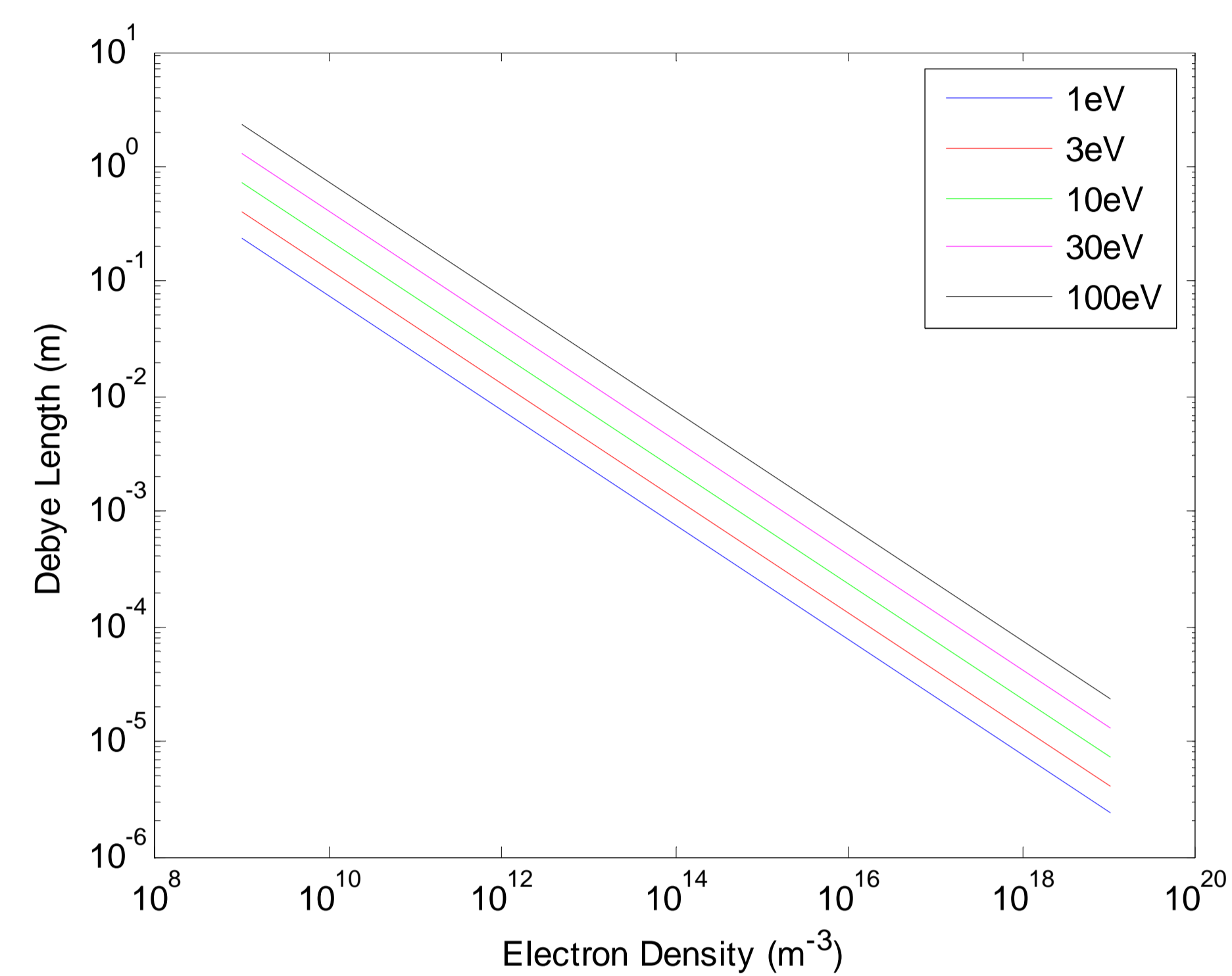
- Van Ardenne pushed the operating regime of the electron bombardment ion sources towards the plasmatron.
- Driven either by a cold cathode, or forced by a hot cathode and thermionic emission.
- A sustained discharge is possible once above the Paschen line for a gas.



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Plasma Discharge Sources

- Van 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.



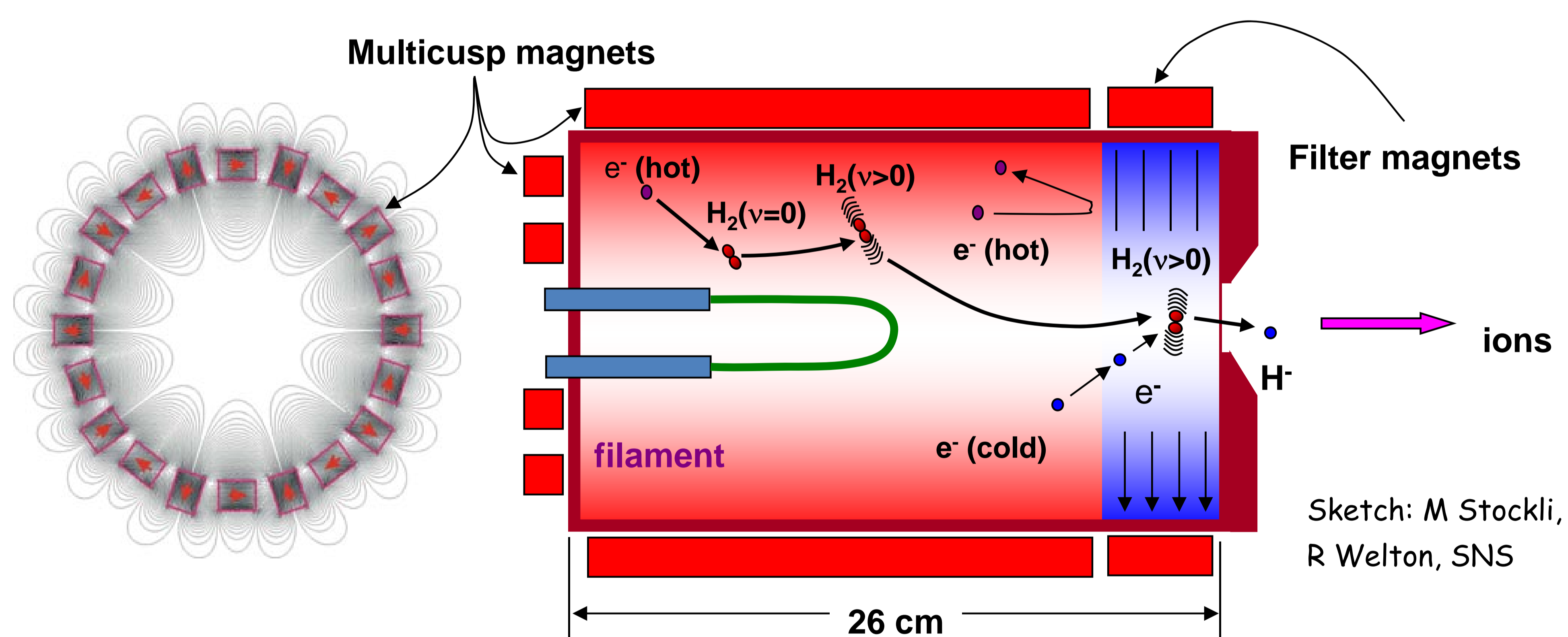
Electric fields can permeate a plasma up to the size of the Debye length.

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}$$

- 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



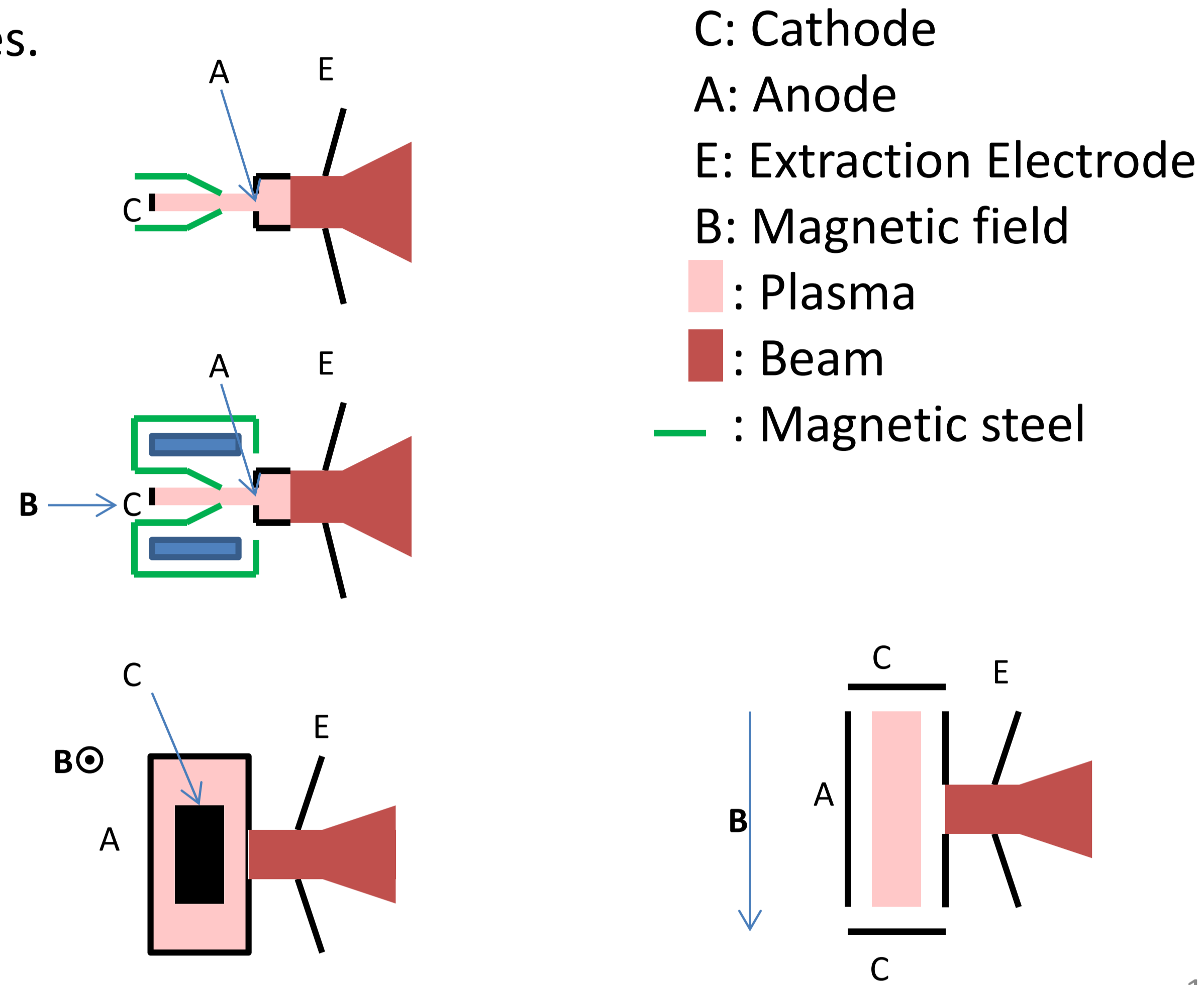
10

Plasma Discharge Sources

A rich sub-species...

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

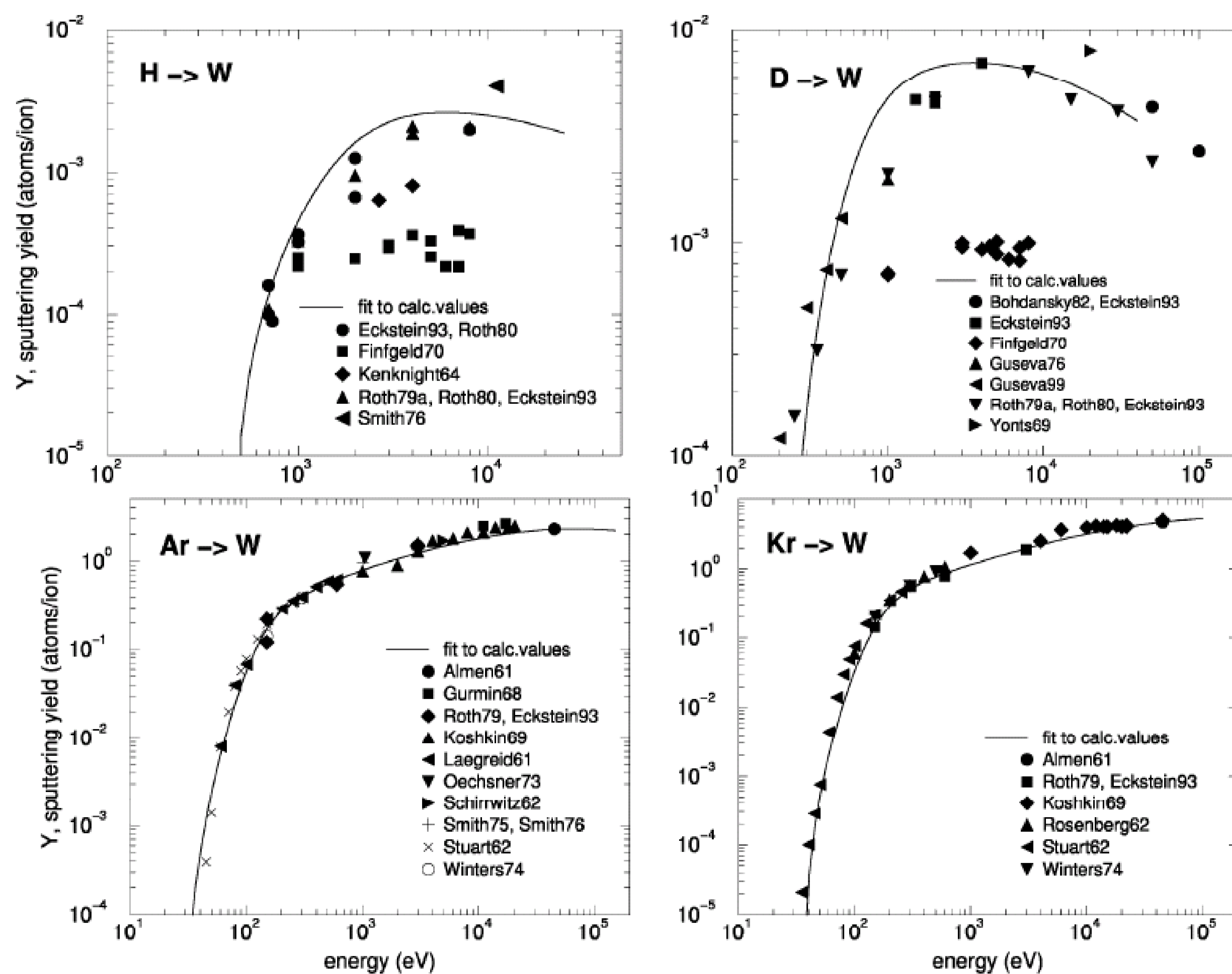
- Multicusp discharge sources.
- Plasmatron
- Duoplasmatron
- Magnetron
- Penning



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Cathodes – problem 1 – Ion Sputtering

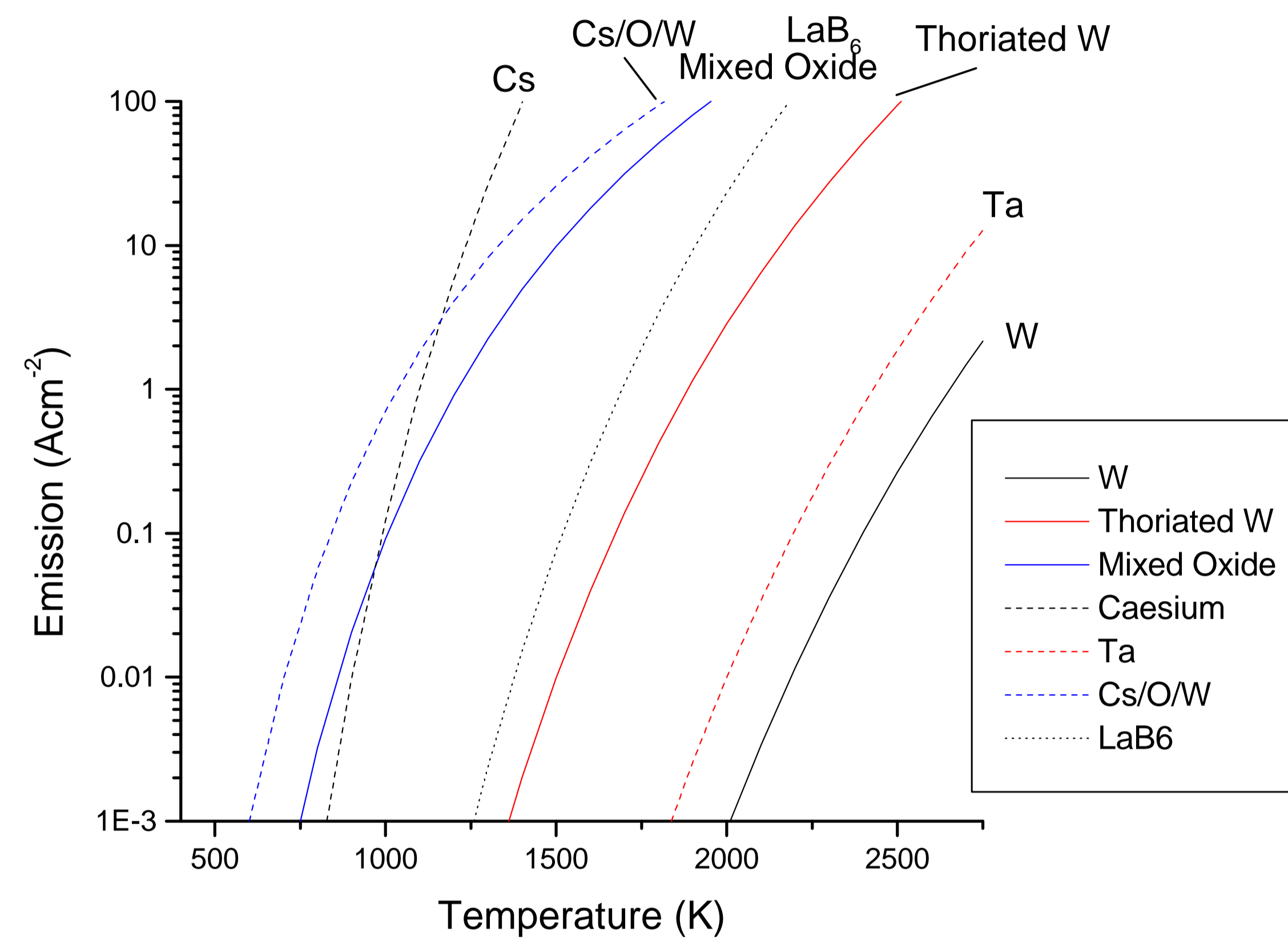
The ions formed in the plasma are attracted to the cathode, and sputter material from it.



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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.



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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

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

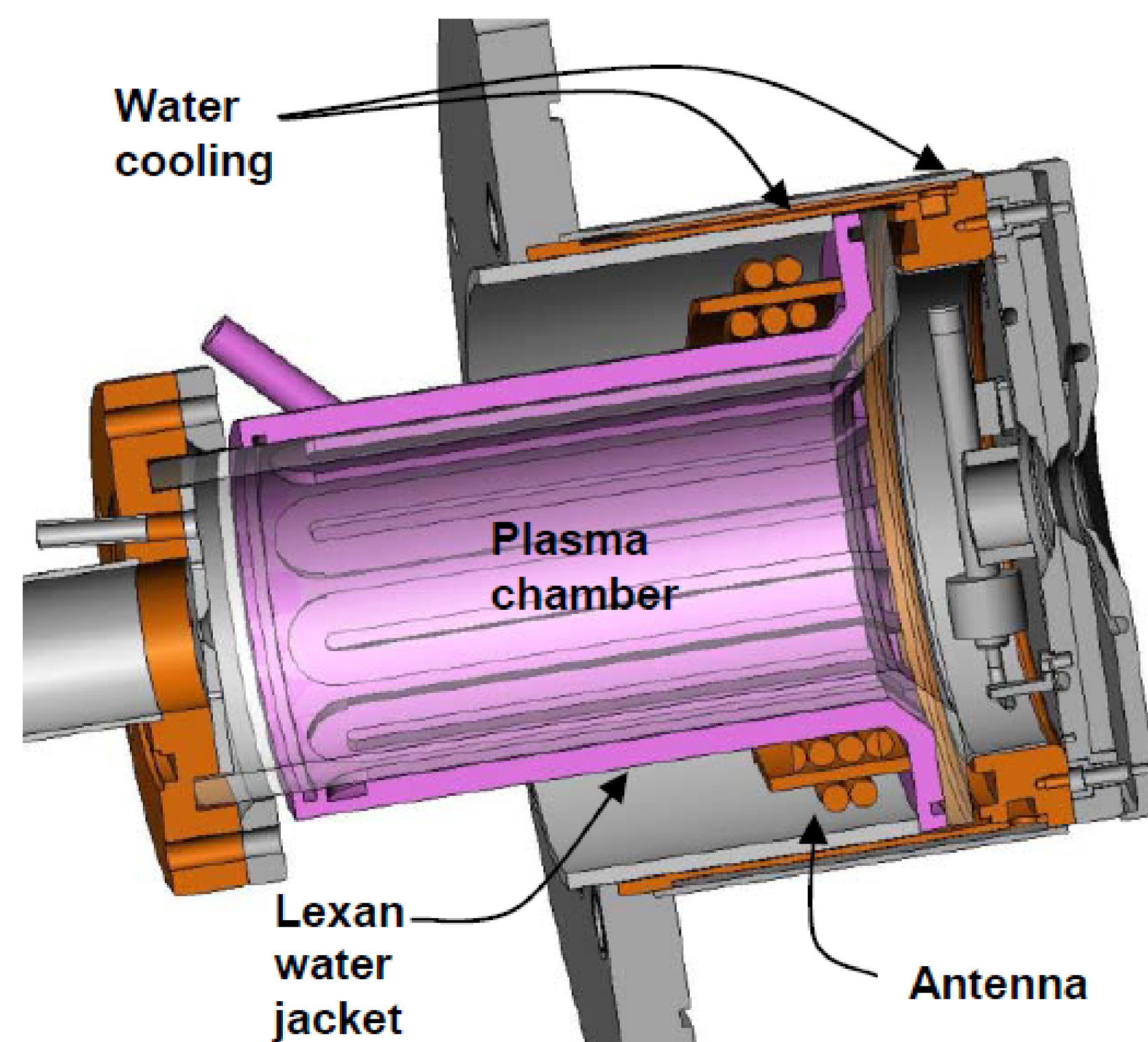
r : solenoid radius
 N : solenoid turns
 L : solenoid length
 I : Peak current

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

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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

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ECR ion sources

In an ECR ion source:

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

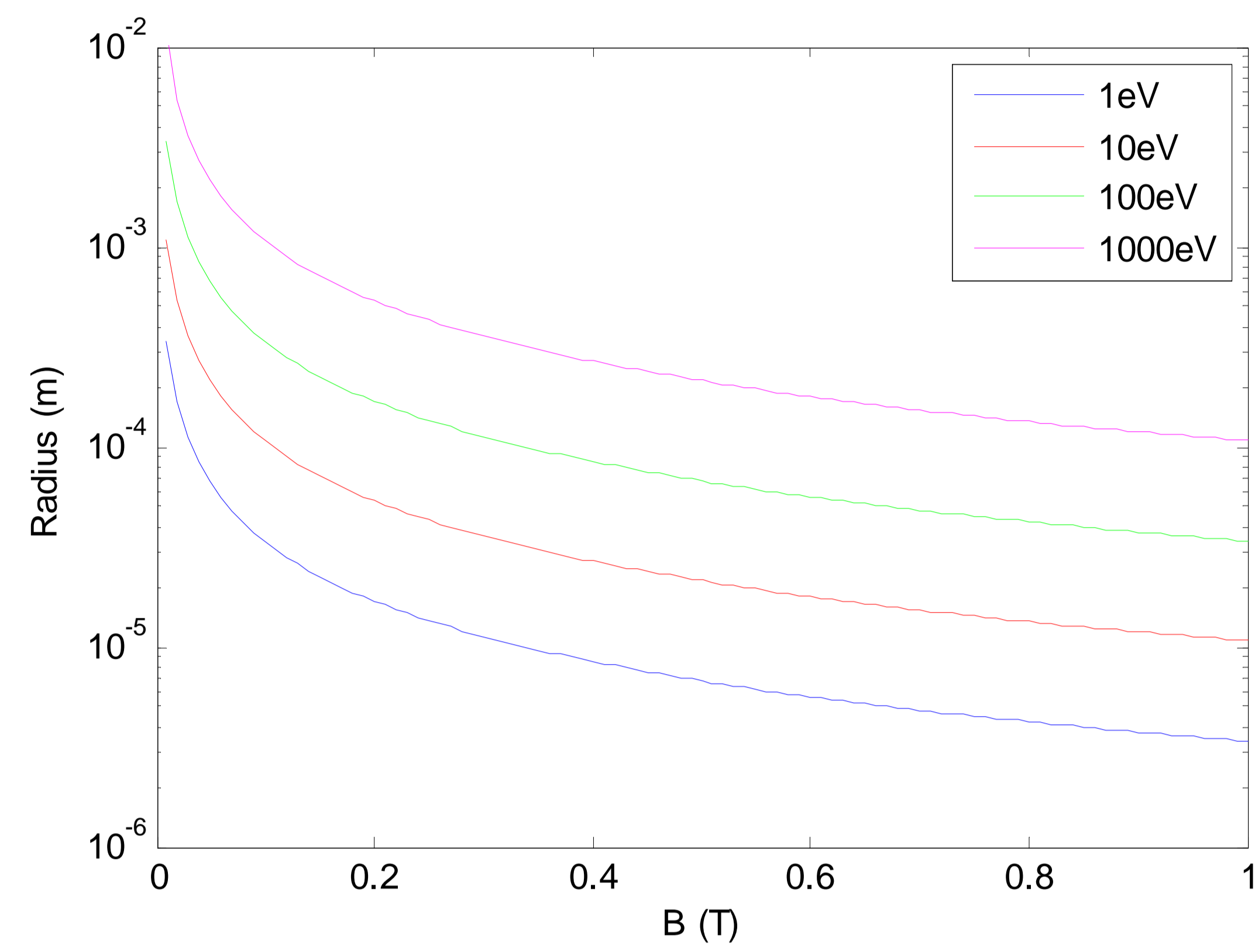
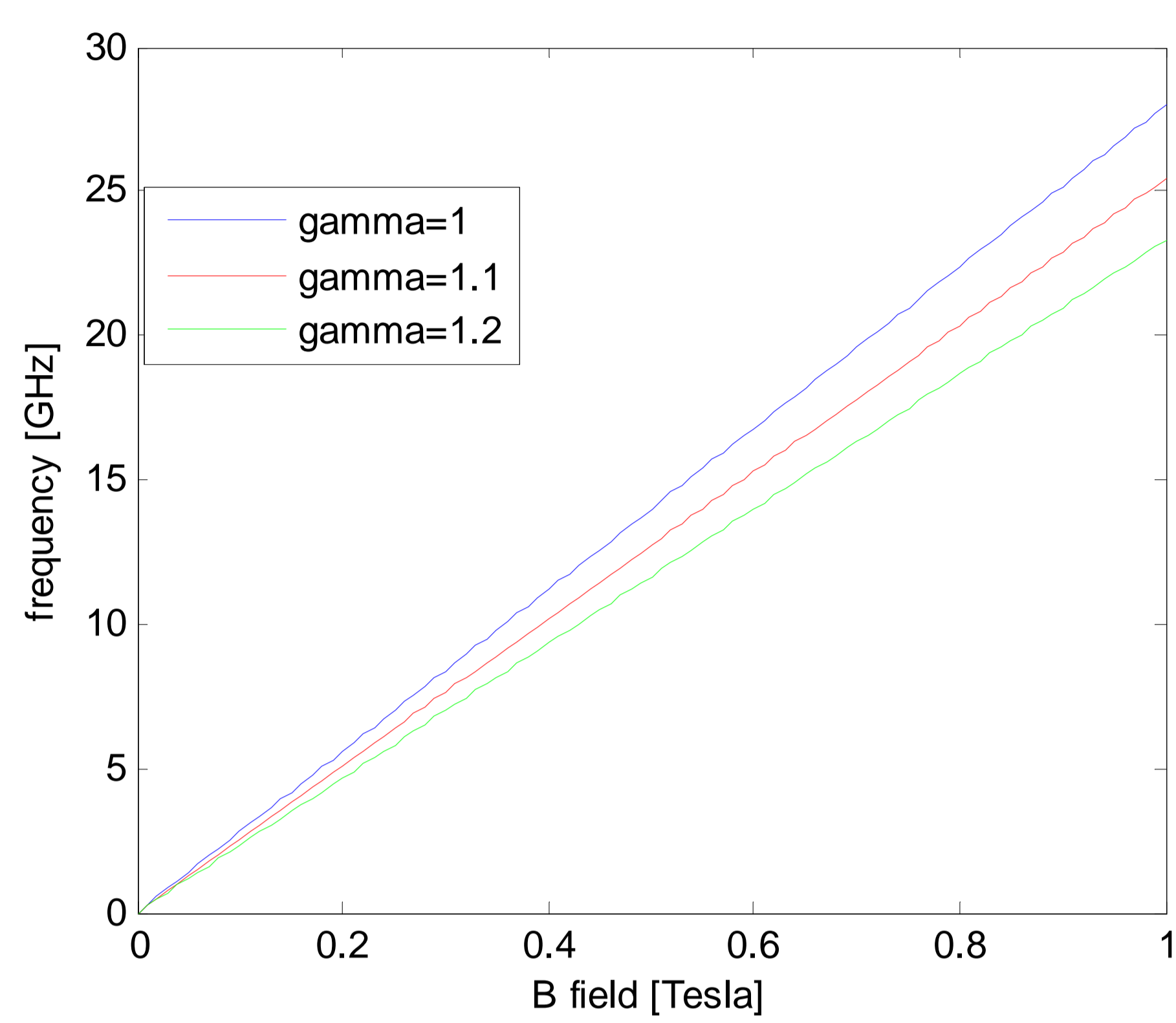
16

ECR ion sources

$$f_L = \frac{eB}{2\pi\gamma m_e}$$

$$\frac{f_L}{B} = 28\text{GHz/Tesla}$$

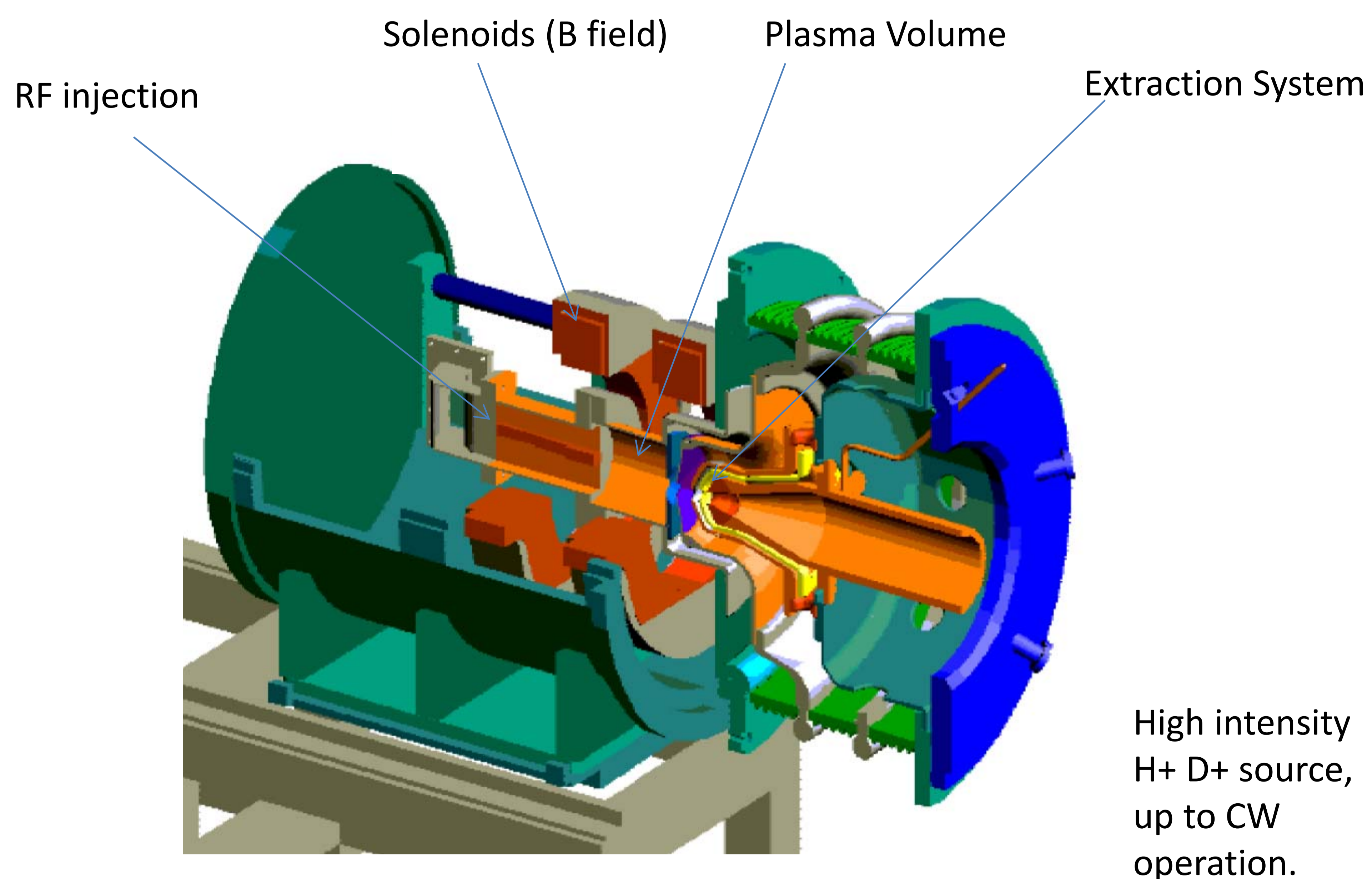
$$\rho_L = \frac{\beta\gamma m_e c}{eB}$$



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.

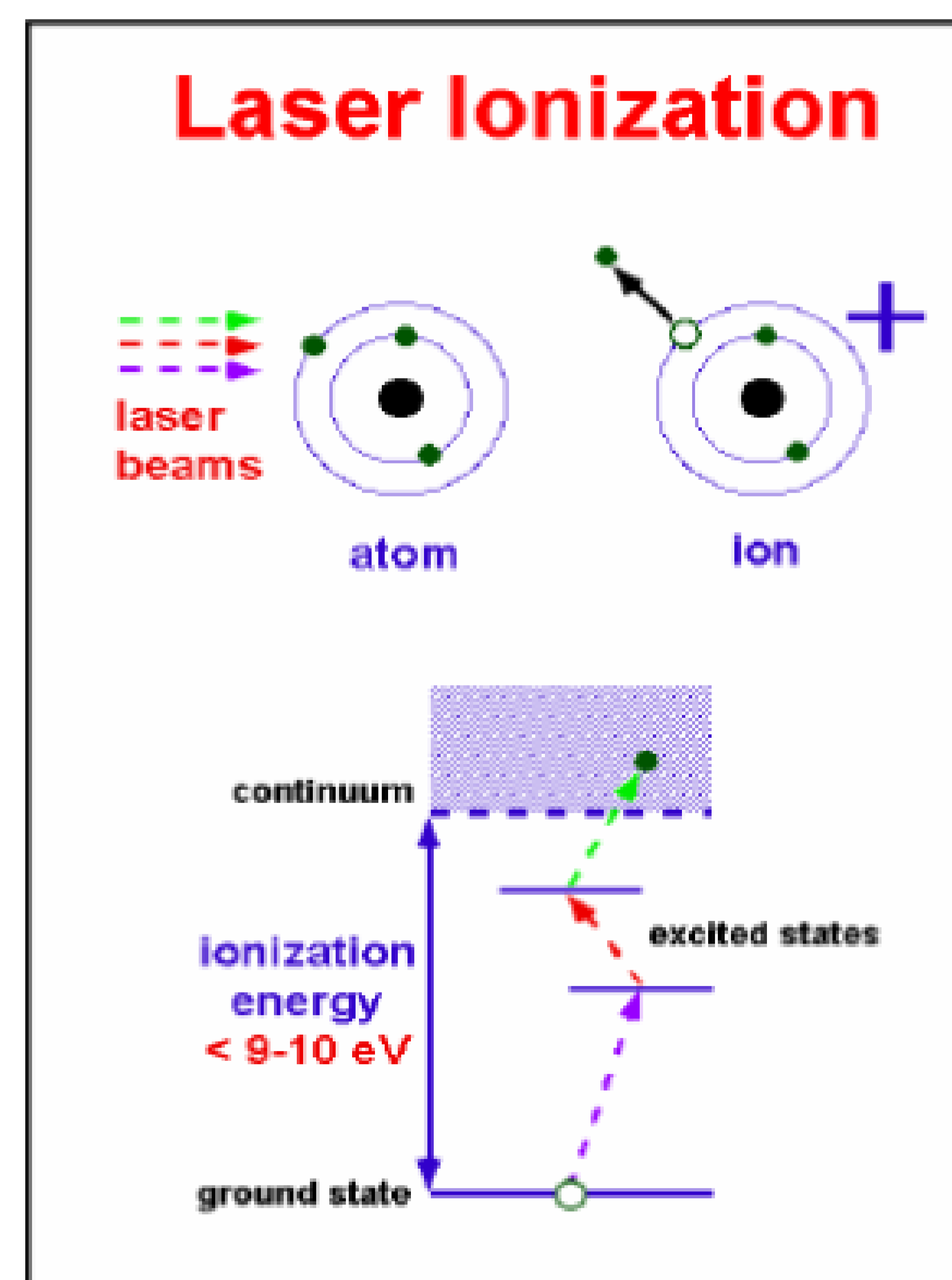
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Laser *Ionization* ion sources

- 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).



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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

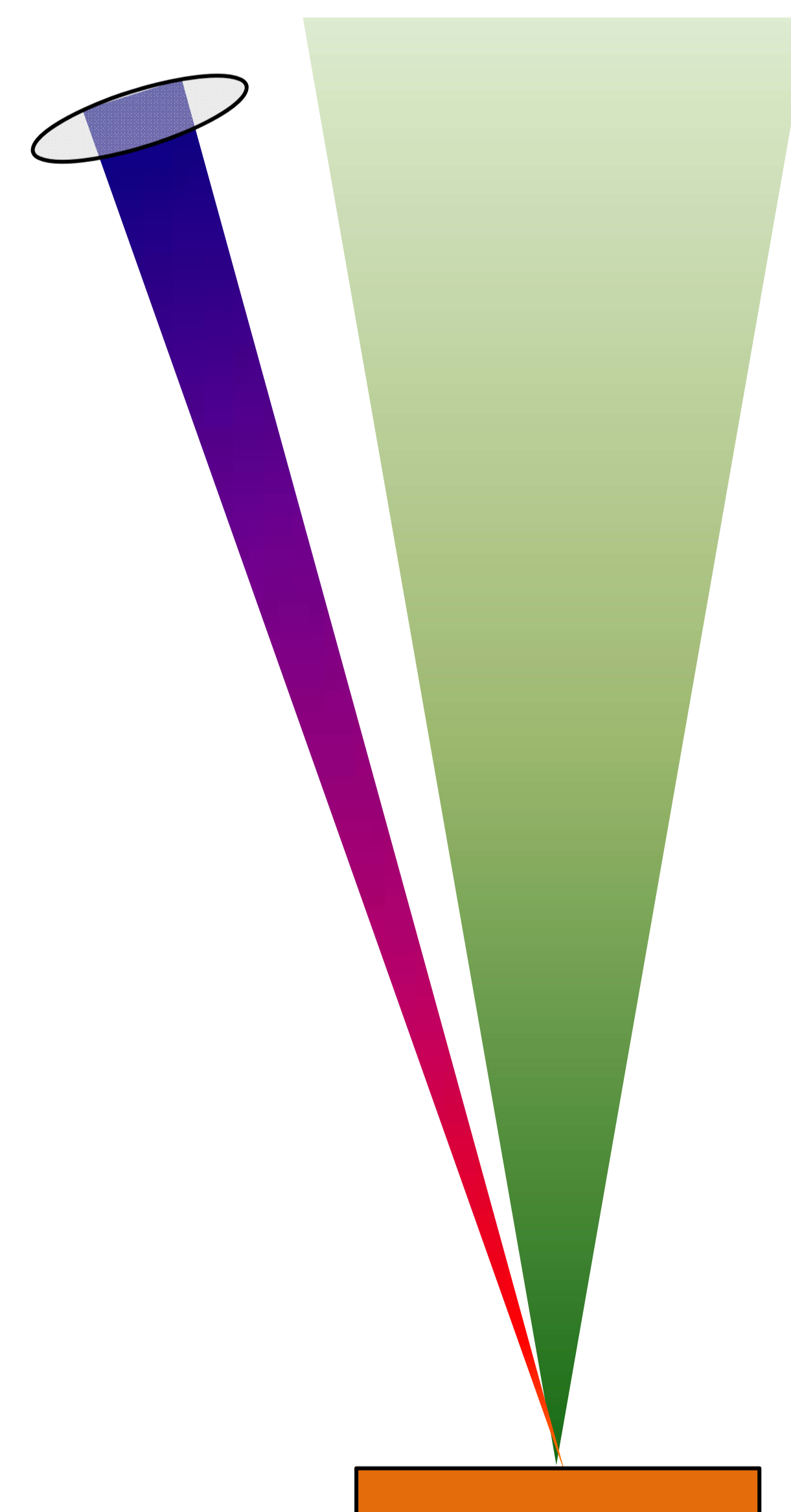
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Laser Plasma ion sources

- 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.

$$\lambda = \frac{2\pi c}{e} \sqrt{\frac{m_e \epsilon_0}{n_e}}$$

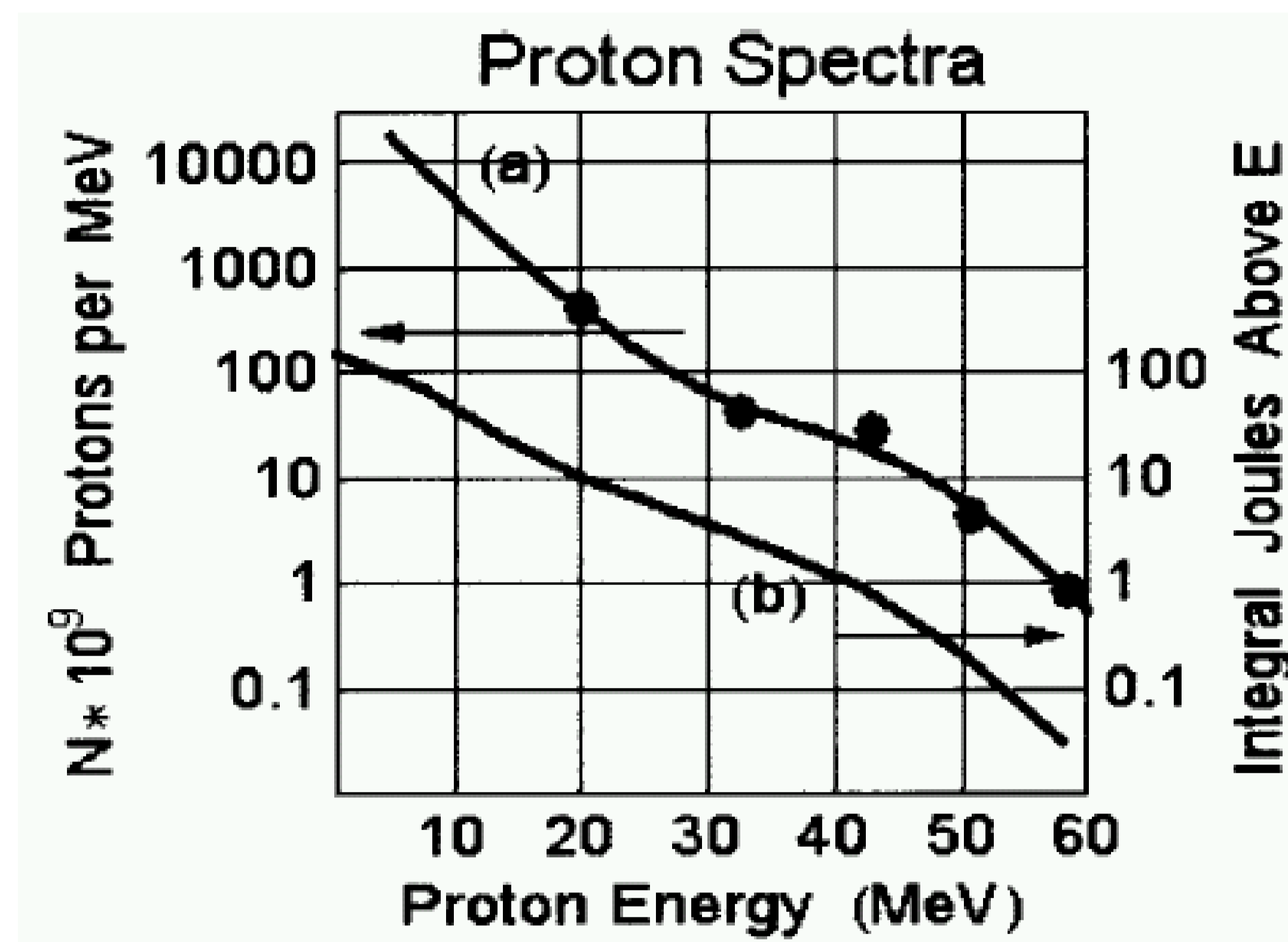
- $n_e = 10^{21} \text{ cm}^{-3}$ corresponds to $1 \mu\text{m}$.
- Laser power density needs to be above 10^6 W/cm^2 , which is easily available with pulsed lasers.



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Laser Plasma ion sources

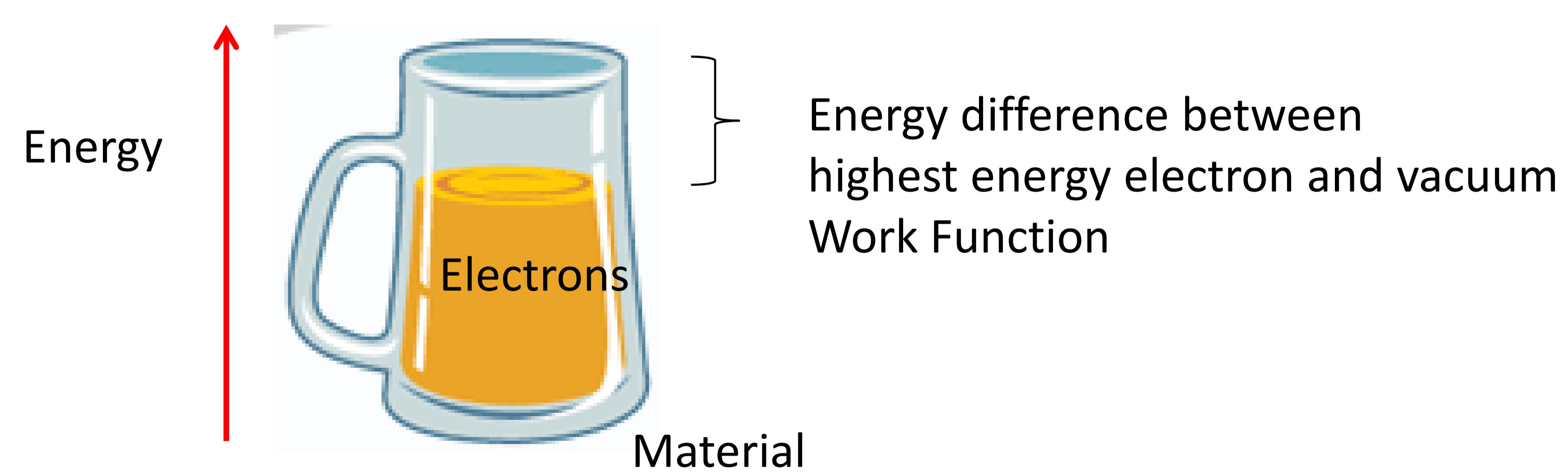
- PetaWatt laser (3×10^{20} W/cm²) focused onto the rear of a thin (CH) target, have produced 58MeV protons – source and accelerator in one!



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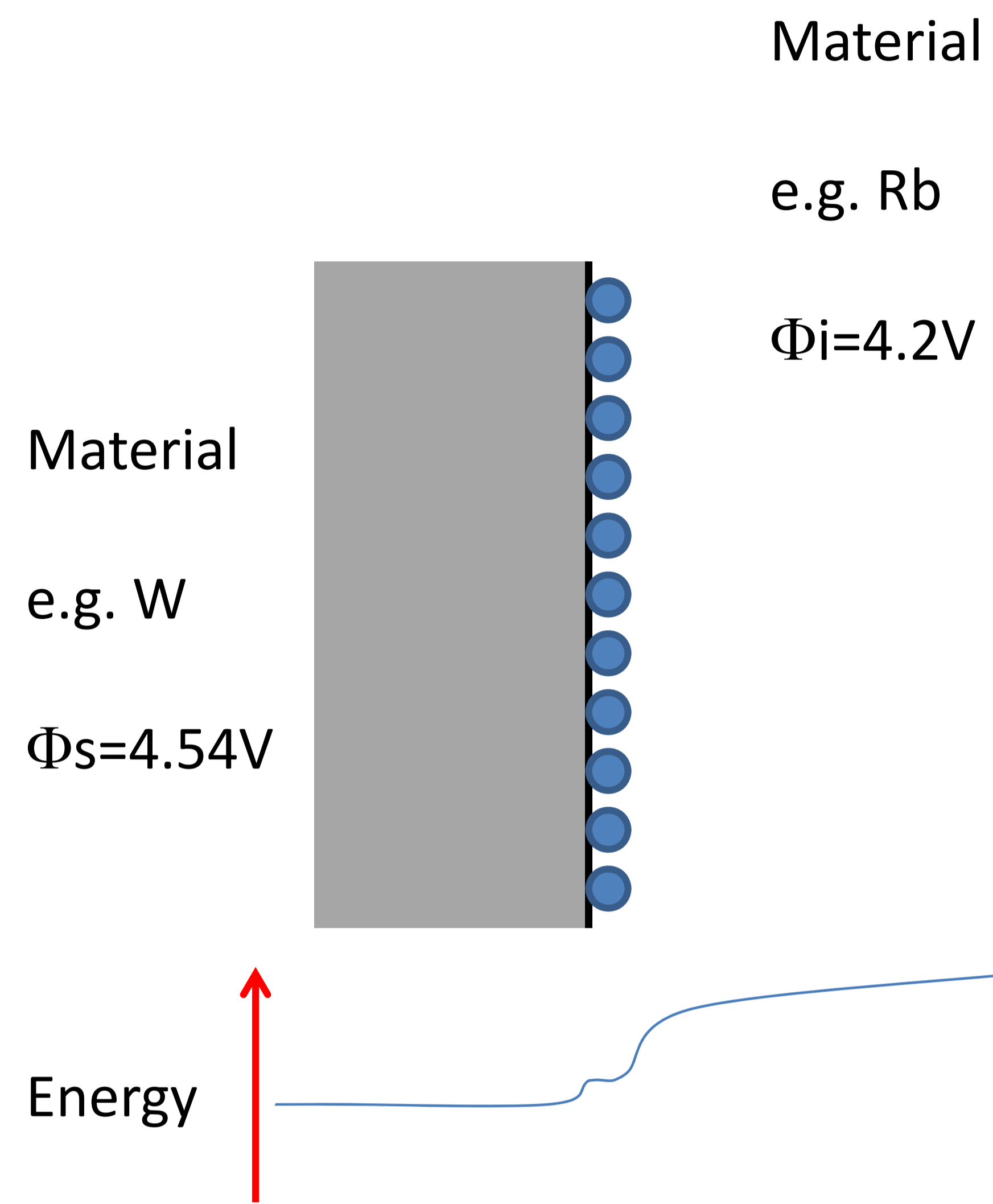
Surface Ion Sources

- Inside a solid state material, conduction electrons 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.

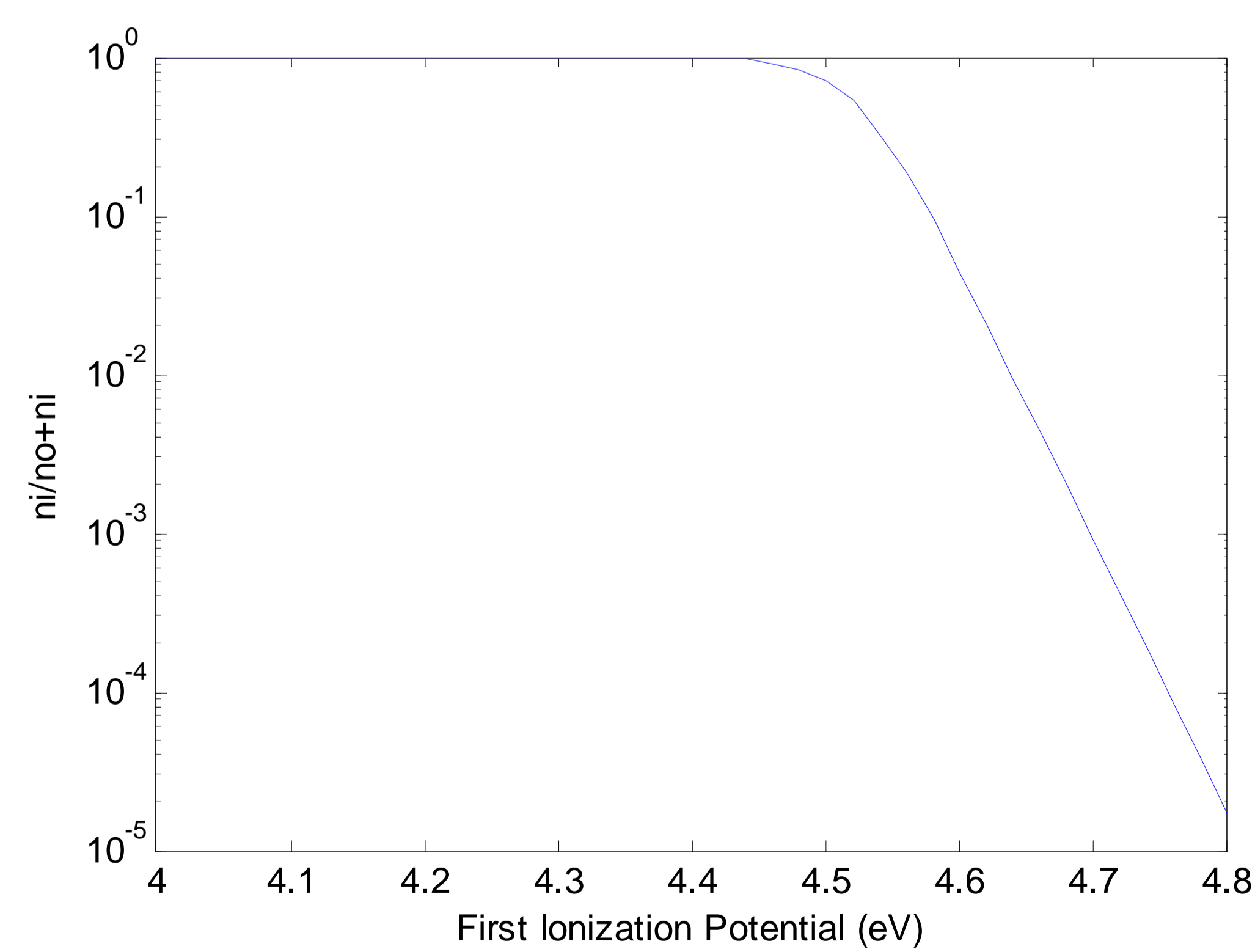
$$\frac{n_i}{n_0 + n_i} = \left(1 + \frac{g_0}{g_i} e^{(\phi_i - \phi_s)/kT} \right)^{-1}$$

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Surface Ion Sources

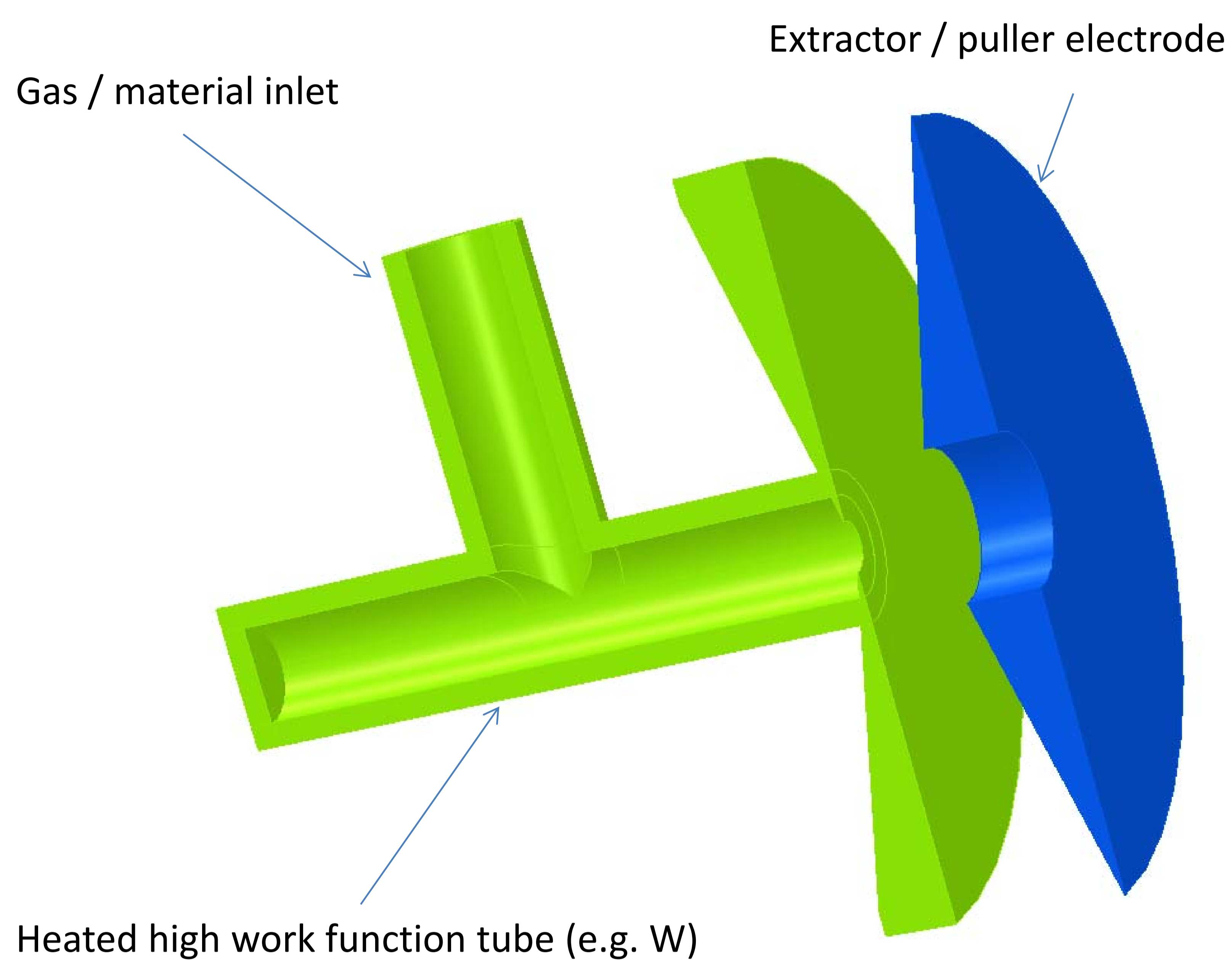
$$\frac{n_i}{n_0 + n_i} = \left(1 + \frac{g_0}{g_i} e^{(\phi_i - \phi_s)/kT} \right)^{-1}$$

Example ion fraction for $\Phi_s=4.54\text{eV}$
At room temperature



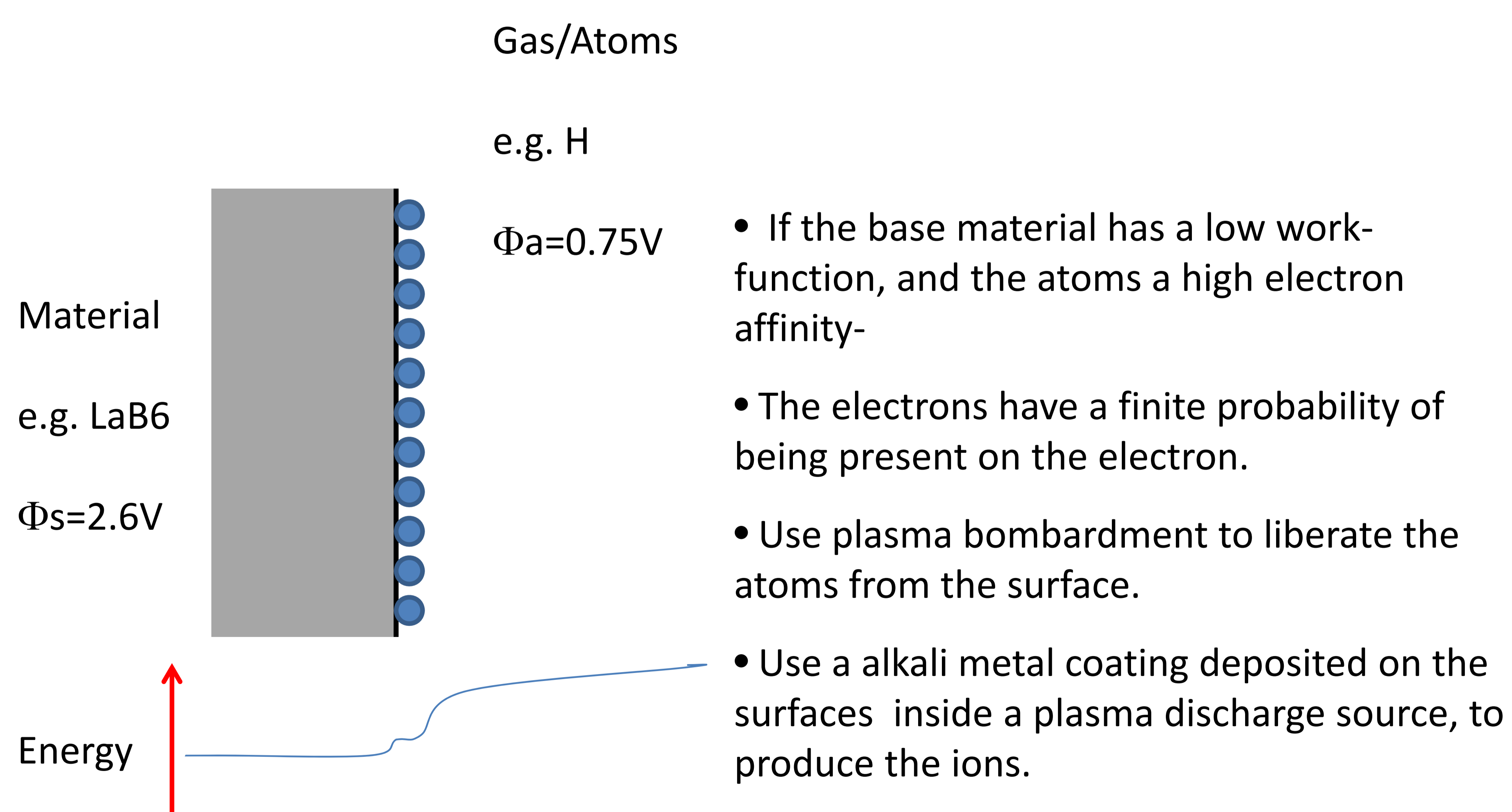
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Surface Ion Sources



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Surface Ion Sources – negative ions



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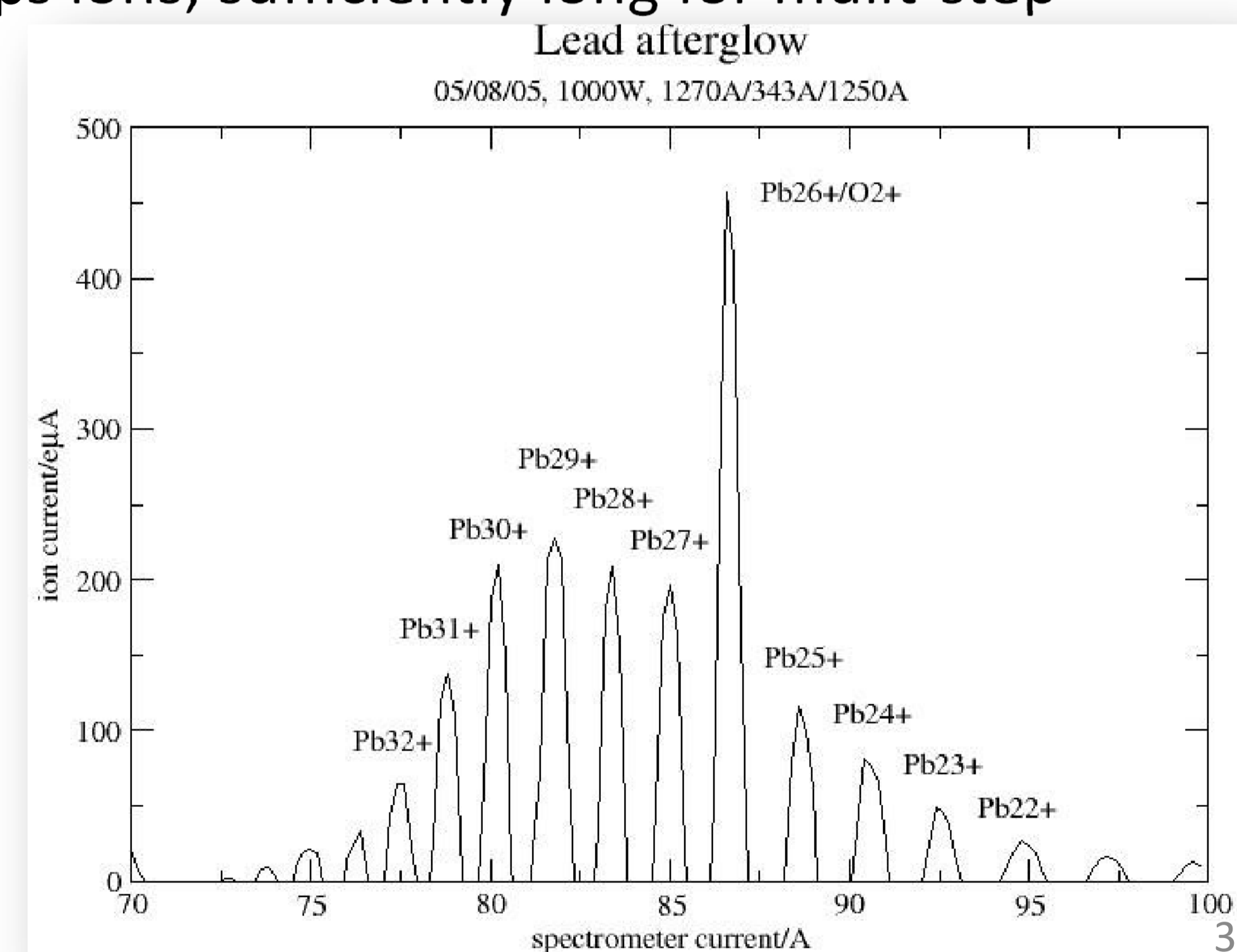
Highly Charged Ions

- 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 state 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:

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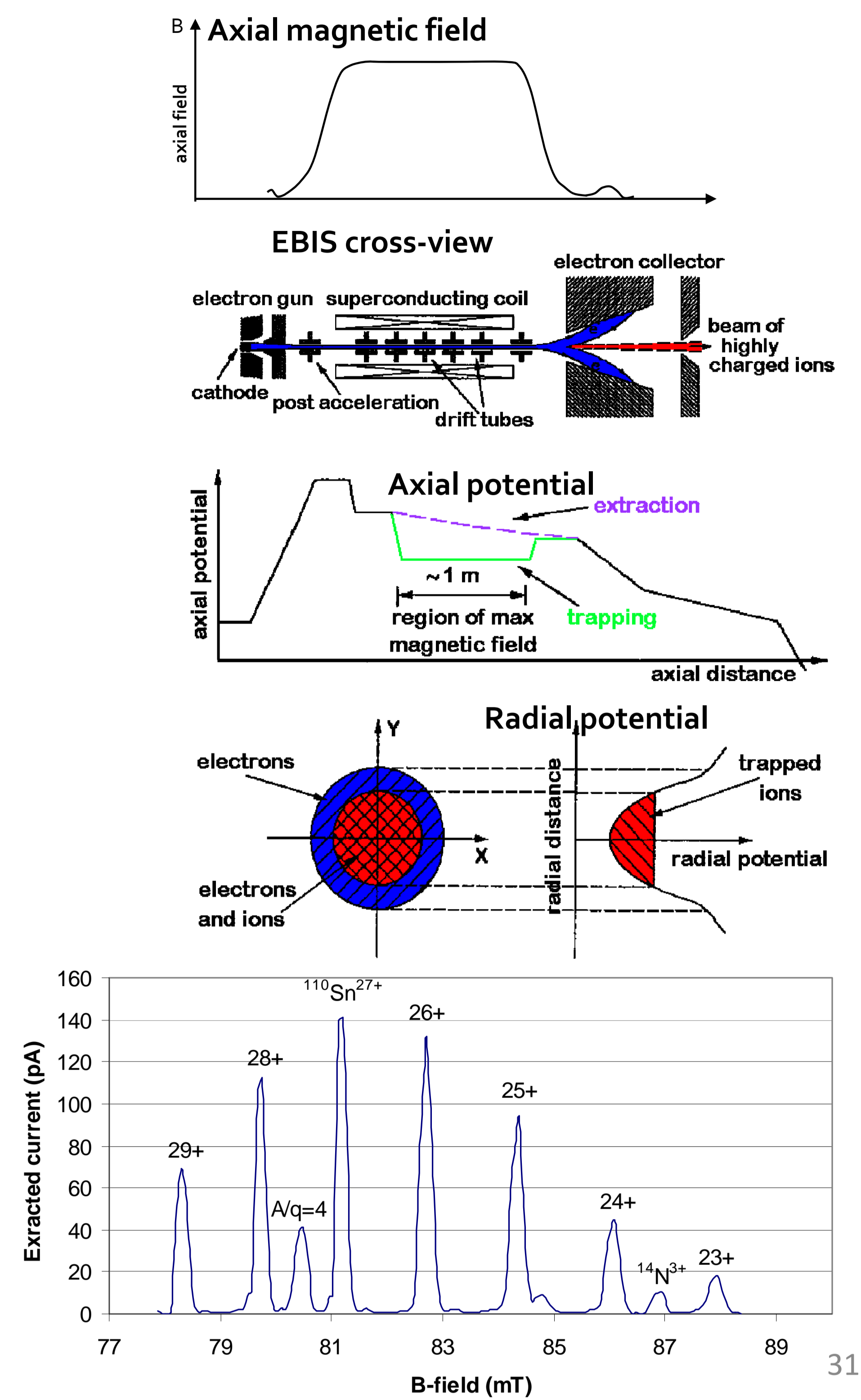
Highly Charged Ions - ECRs

- The electrons are heated using the Electron Cyclotron Resonance.
- The Magnetic field is formed with co-linear solenoids, with a higher magnetic field at the ends, to 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 multi-step ionisation to take place.



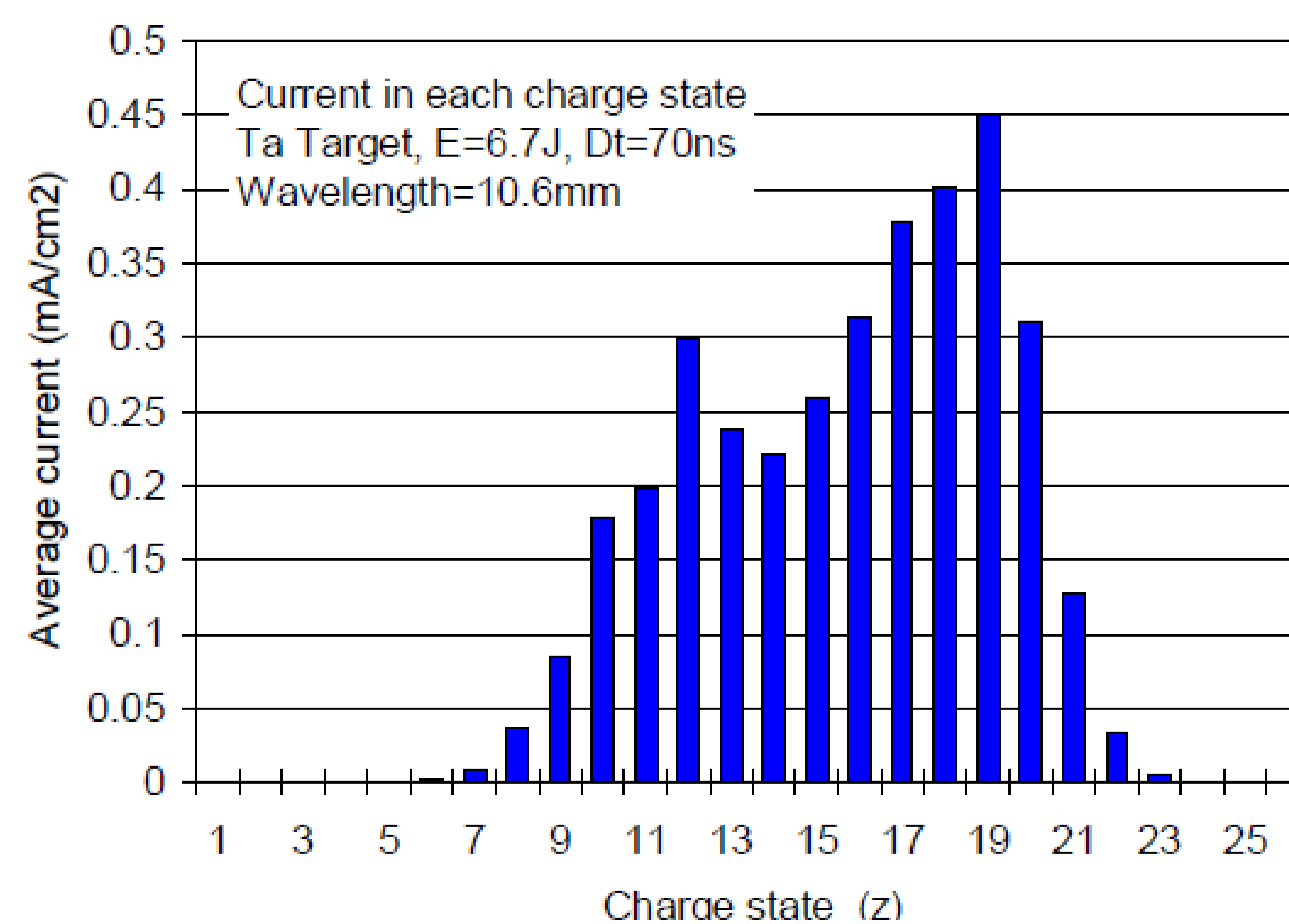
Highly Charged Ions - EBIS

- 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 ionization.
- When the ion charge state is reached, one of the electrode barriers is reduced to allow the ions to escape.



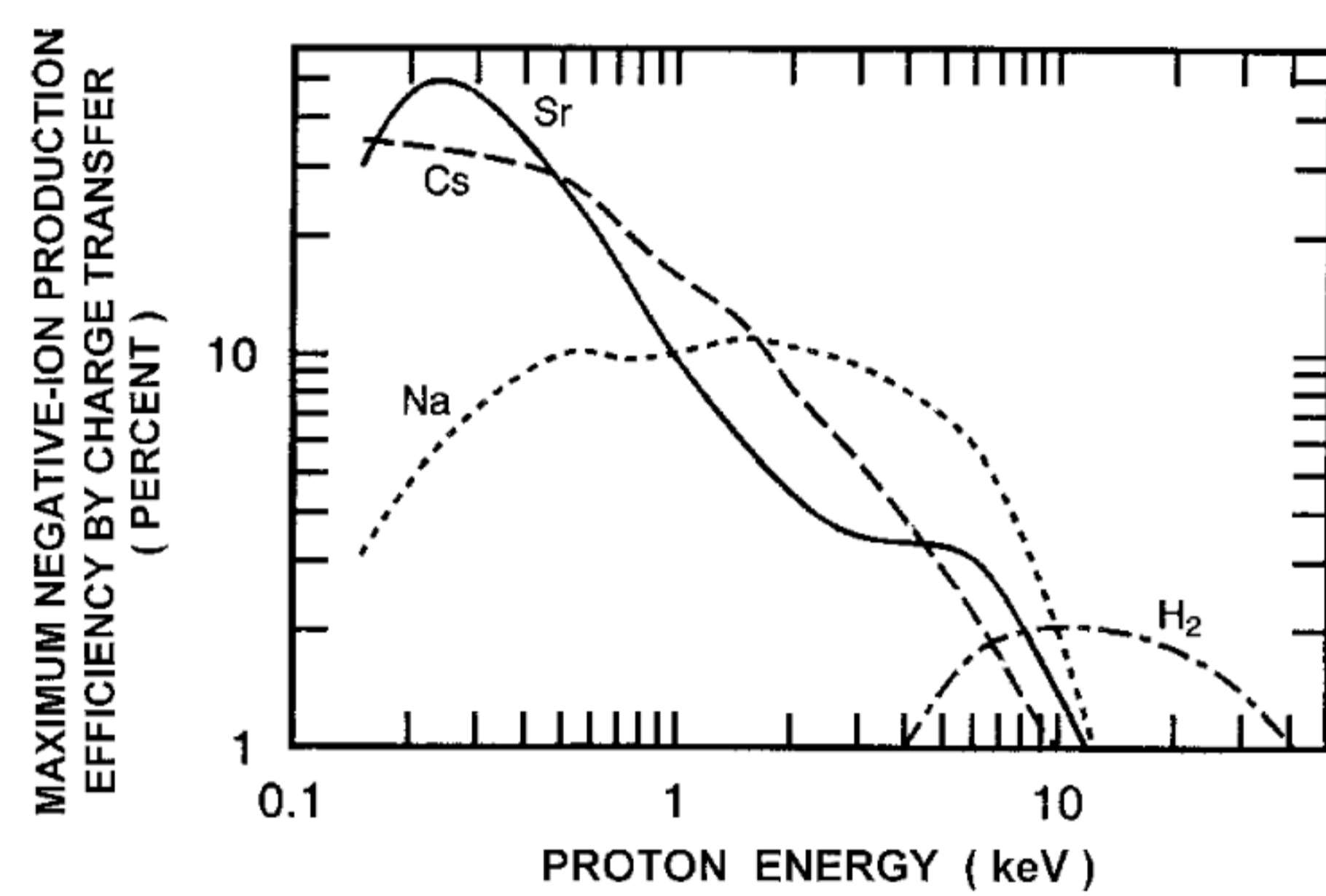
Highly Charged Ions – Laser Ion Sources

- 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 :

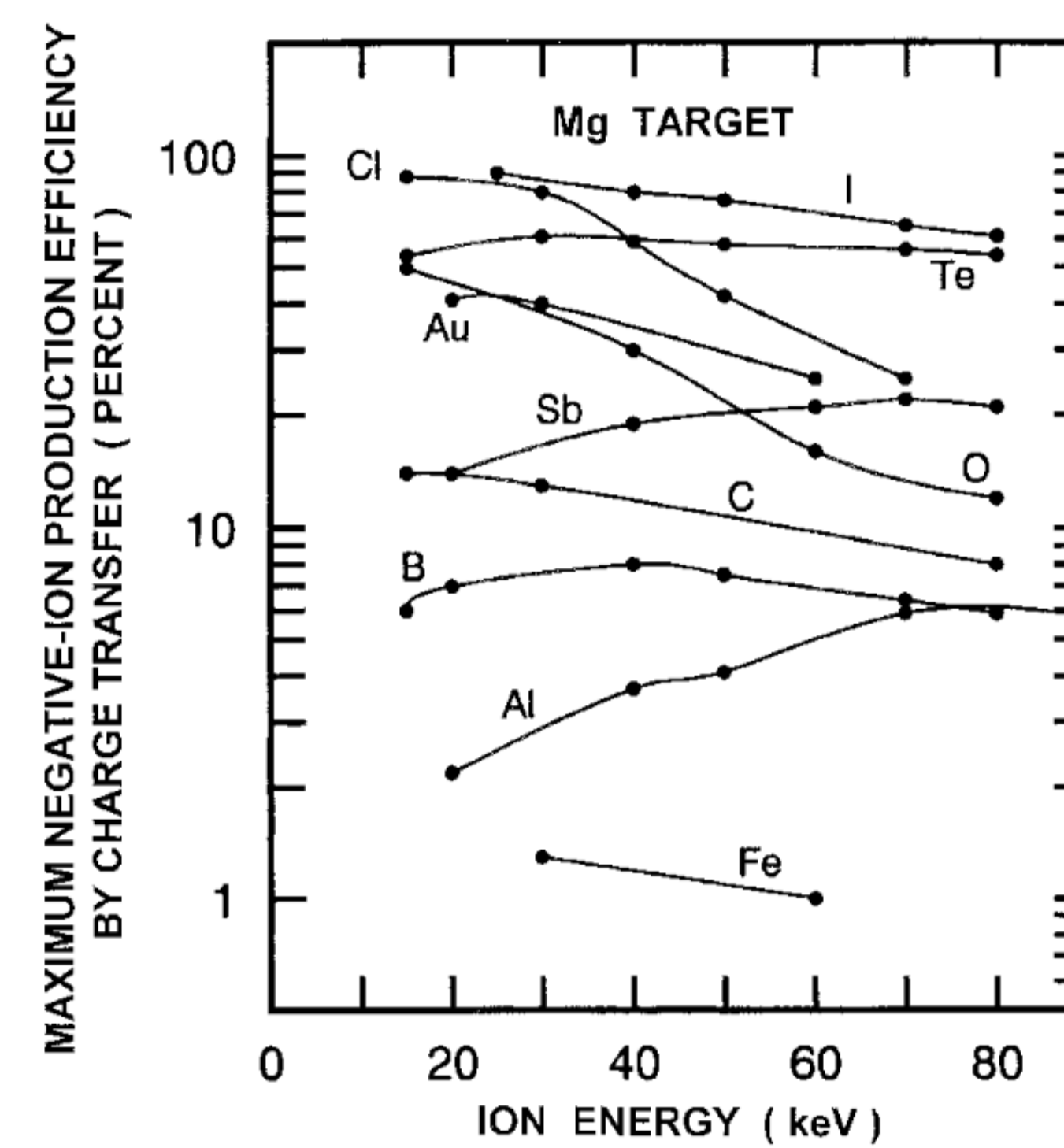


Charge Exchange Ion Sources – Negative Ions

- 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 donor 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)

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Charge Exchange Ion Sources – Negative Ions

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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 Dushman constant.	β : Relativistic Beta
B: Magnetic Field	Φ_s : Work Function
c: Speed of light.	Φ_i : Ionization Potential
e: Electron charge	γ : Relativistic Gamma
h: Plank Constant	ν_c : Collisional frequency
f: Frequency	ρ_L : Lamour radius
f_L : Lamour Frequency	
J: Current density	
k: Boltzmann constant	
m_e : Electron mass	
n_e : Electron density	
n_i : Ion Density	
n_0 : Neutral Atom Density	
T: Temperature	

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