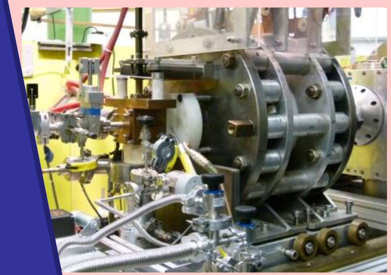
Ion sources

K. Knie / GSI

MUCIS



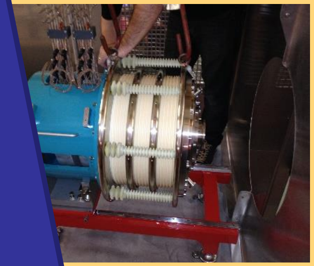
ECR

Thank you very much
for providing me lots of information
and letting me steal your illustrations:

Dan Faircloth (RAL)
(read his script!!!!!)

Oliver Kester (GSI/TRIUMF)
Rustam Berezov (GSI)
Ralph Hollinger (GSI)
Alexey Adonin (GSI)

MEVVA

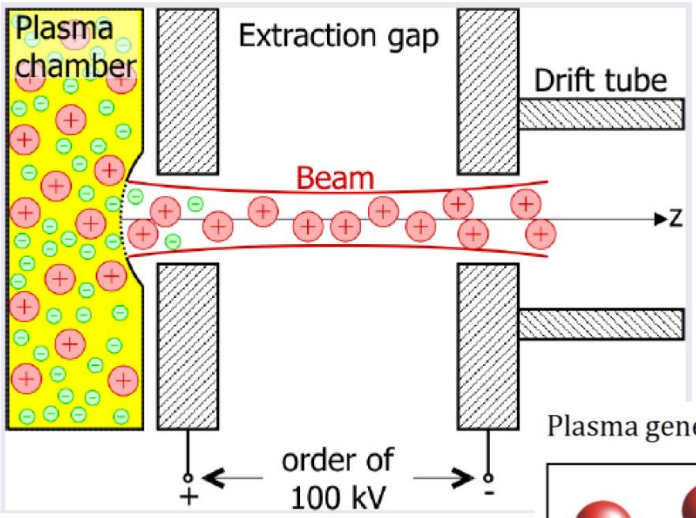


…c source

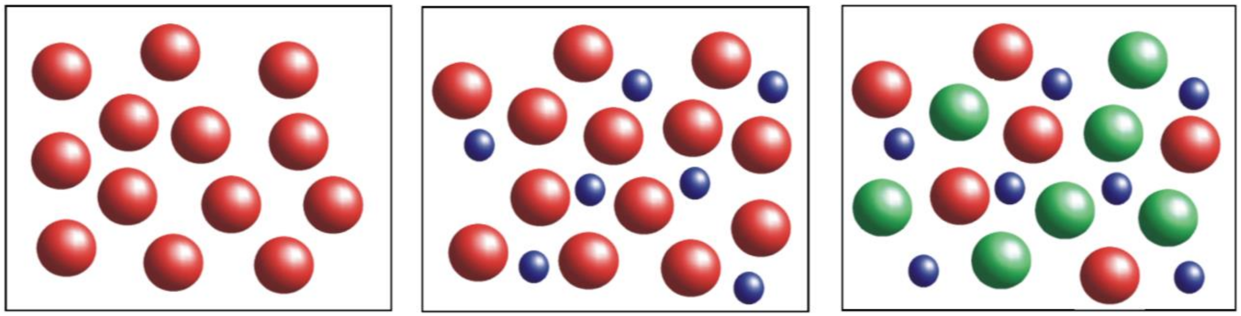
Sources used at GSI (a…

FAIR

Introduction: Ions



Plasma generation:



Make atoms available in the plasma generator via:

- Gas injection
- Vapour, melting of solids
- Sputtering

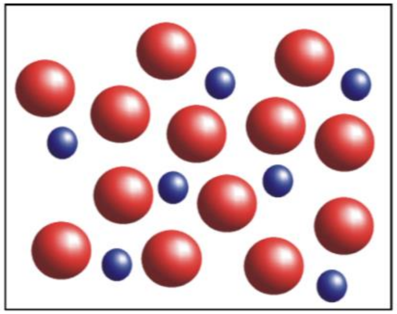
Generate free electrons:

- Thermionic emission
- Photo ionisation
- Discharge

Supply the ionisation energy:

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

Introduction: Electrons



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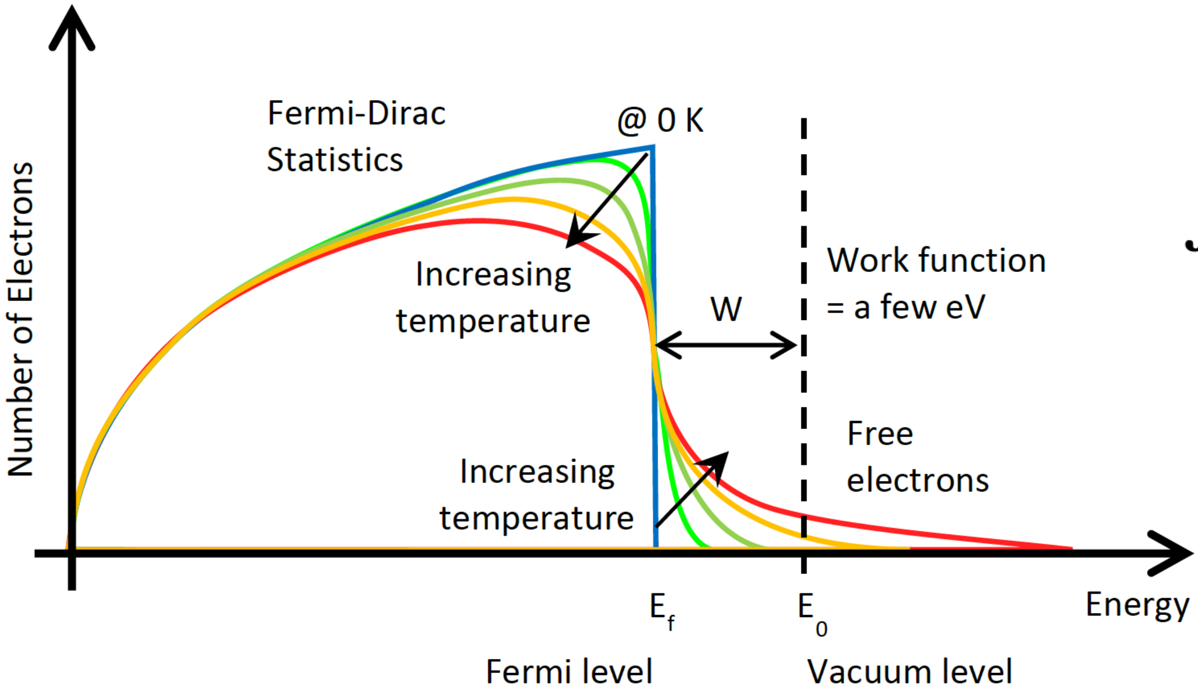
Generation of Free Electrons

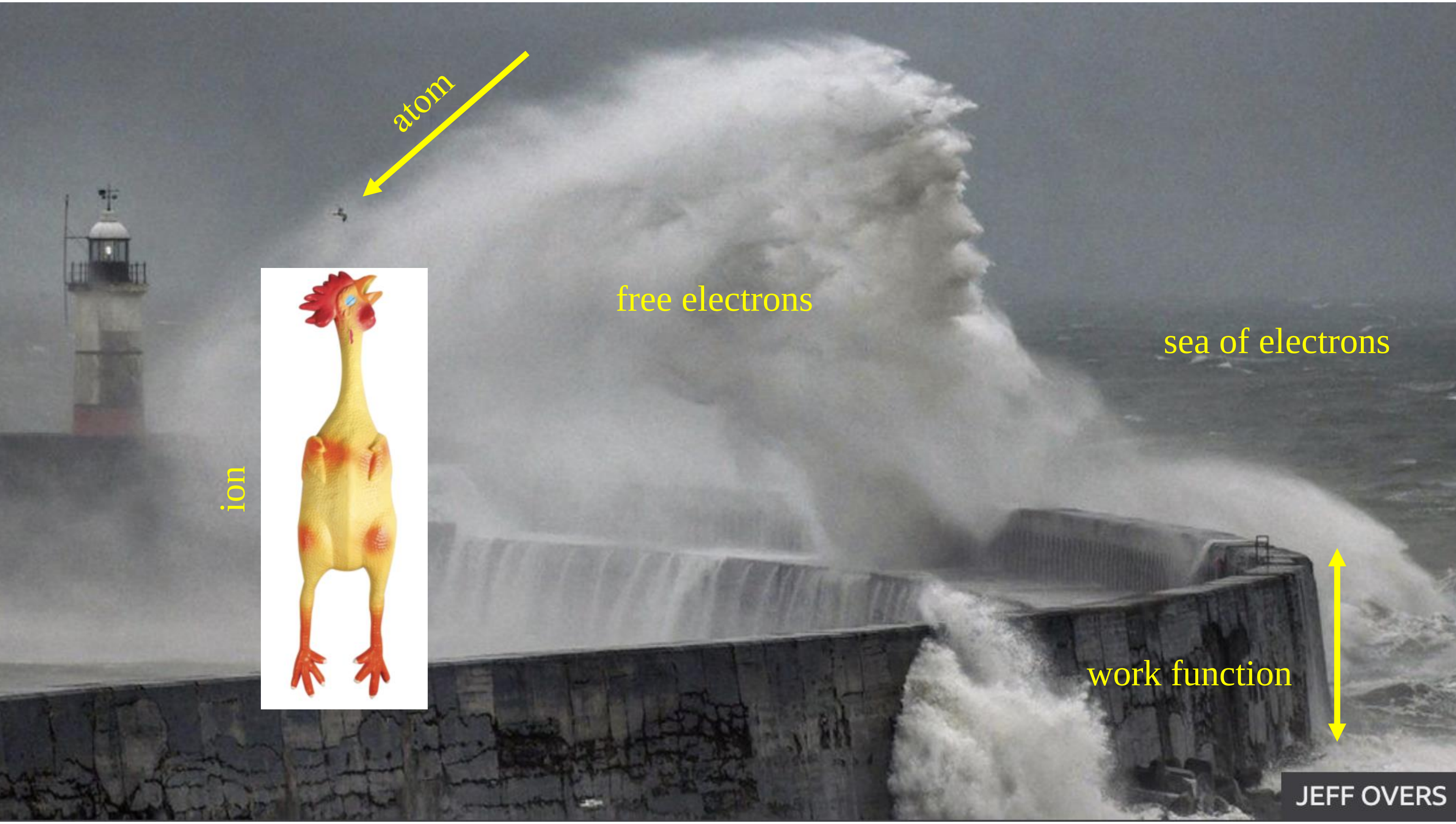


$$J = A_G T^2 e^{\frac{-W}{kT}}$$

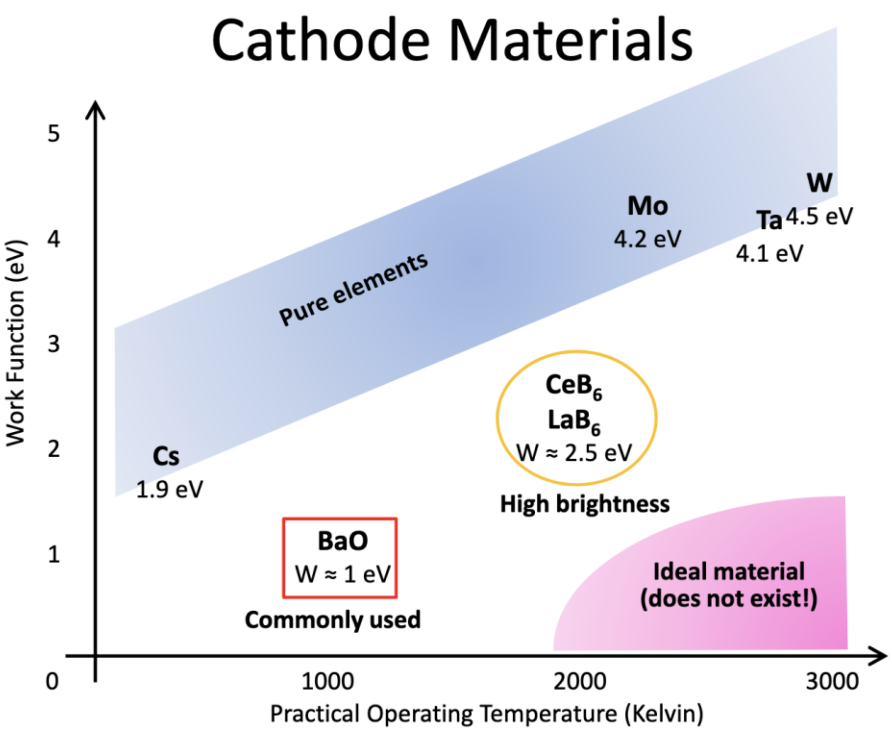
Richardson's Law

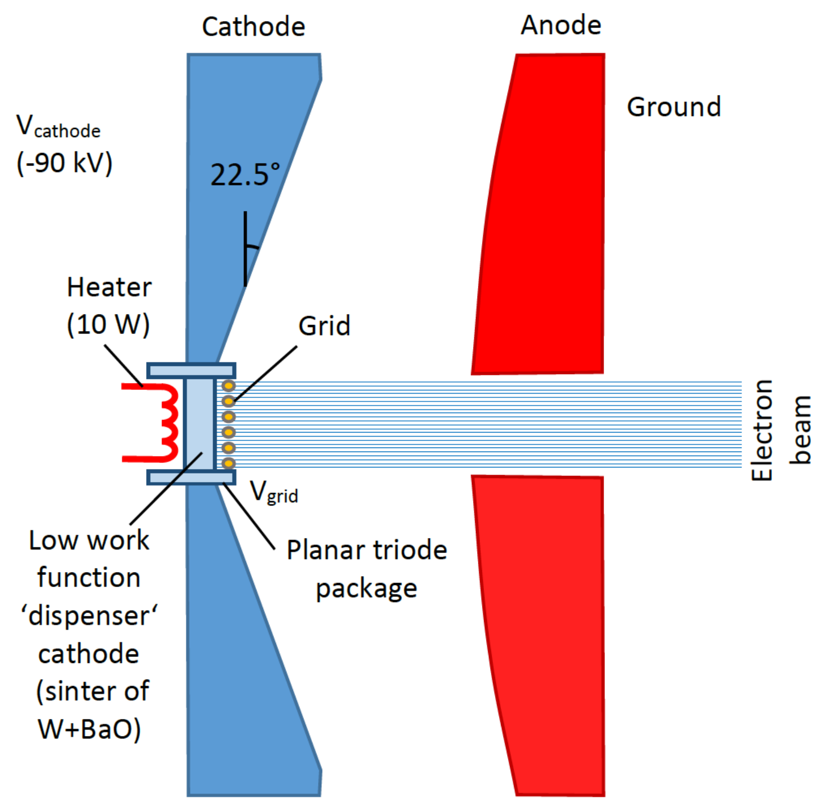
- Work function: Amount of energy required for an electron to exit the metal
- Field enhanced thermionic emission:
  An electrical field can reduce the effective work function (i.e. pull out electrons)
- Field emission:
  At even higher electrical field the electrons can tunnel through the barrier

Generation of Free Electrons



Thermionic Emission





Lowest possible work function
Highest possible temperature

Photo Emission

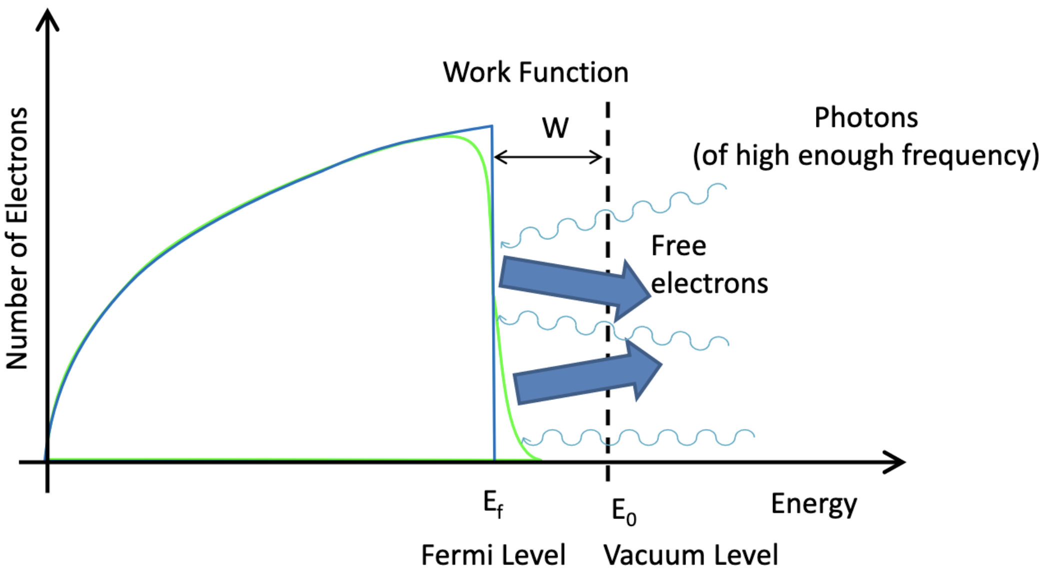
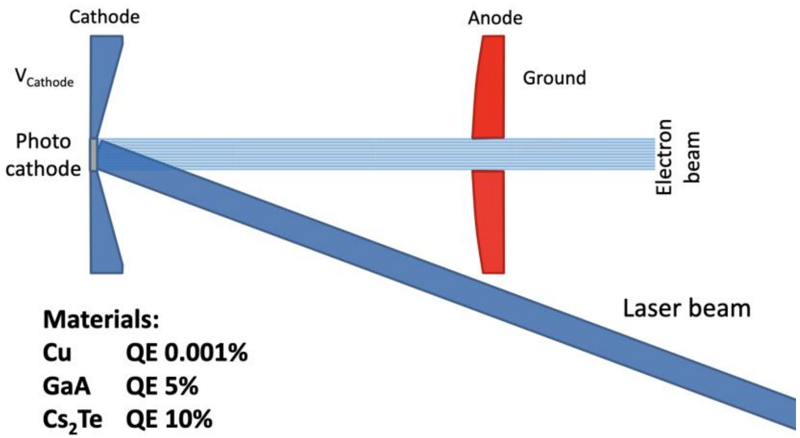


Photo Emission Gun

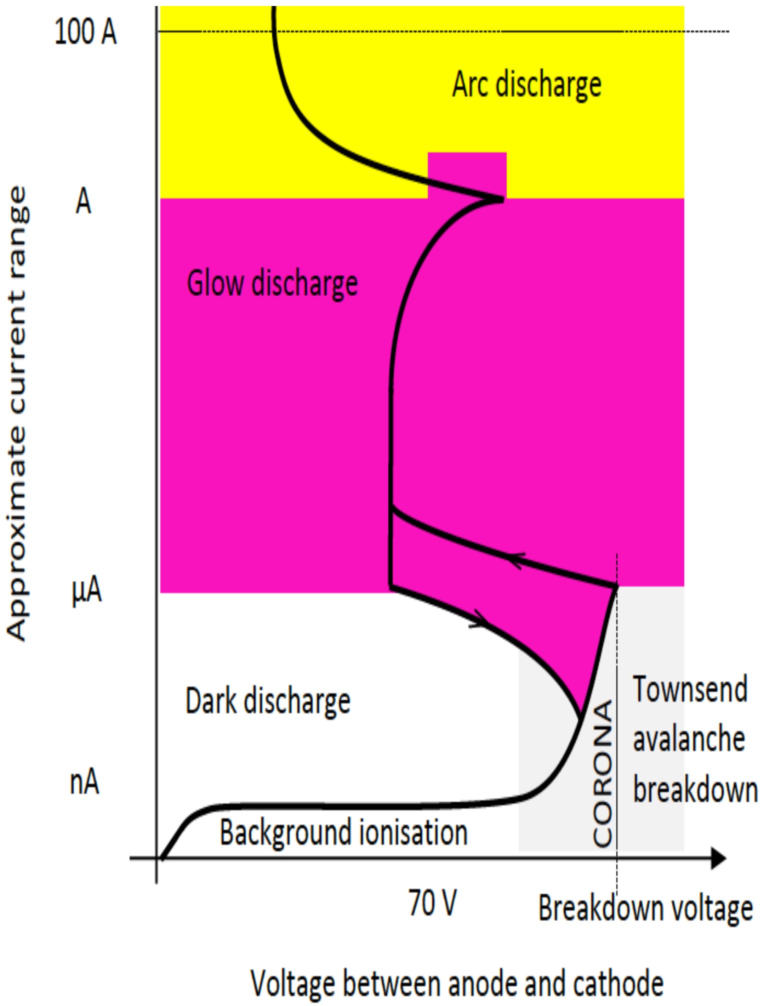


Materials:

Cu	**QE 0.001%**
GaA	**QE 5%**
Cs_2Te	**QE 10%**

$$\text{Quantum efficiency (QE)} = \frac{\text{Number of electrons produced}}{\text{Number of incident photons}}$$

Discharges



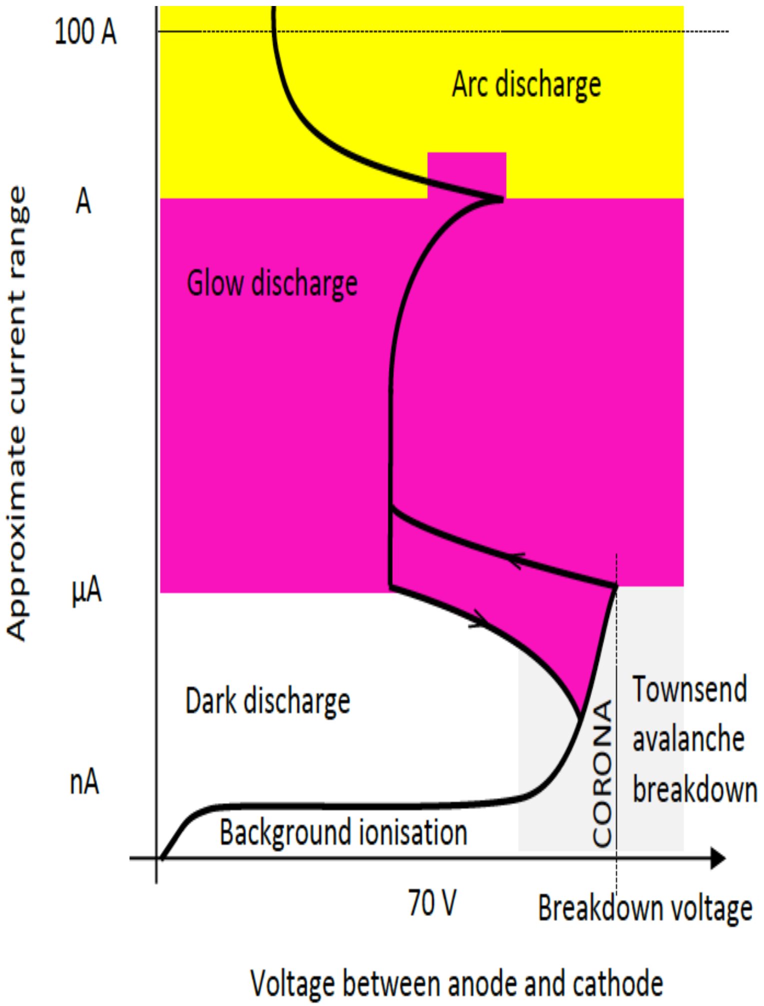
Cathode reaches a temperature sufficient for thermionic electron emission

Pos. ions impact cathode and produce electrons

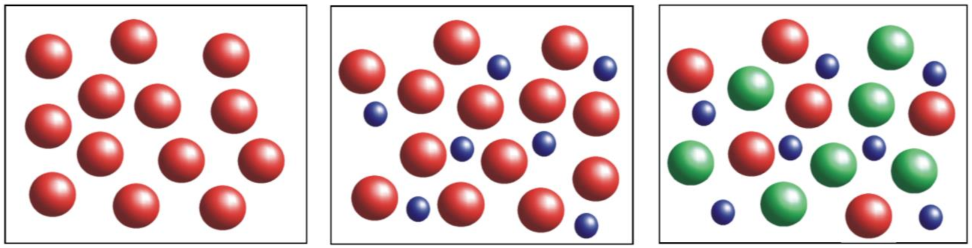
Electron energy sufficient to ionize gas atoms

Electrons produced by cosmic rays, radioactivity…

Discharges



Plasma generation:



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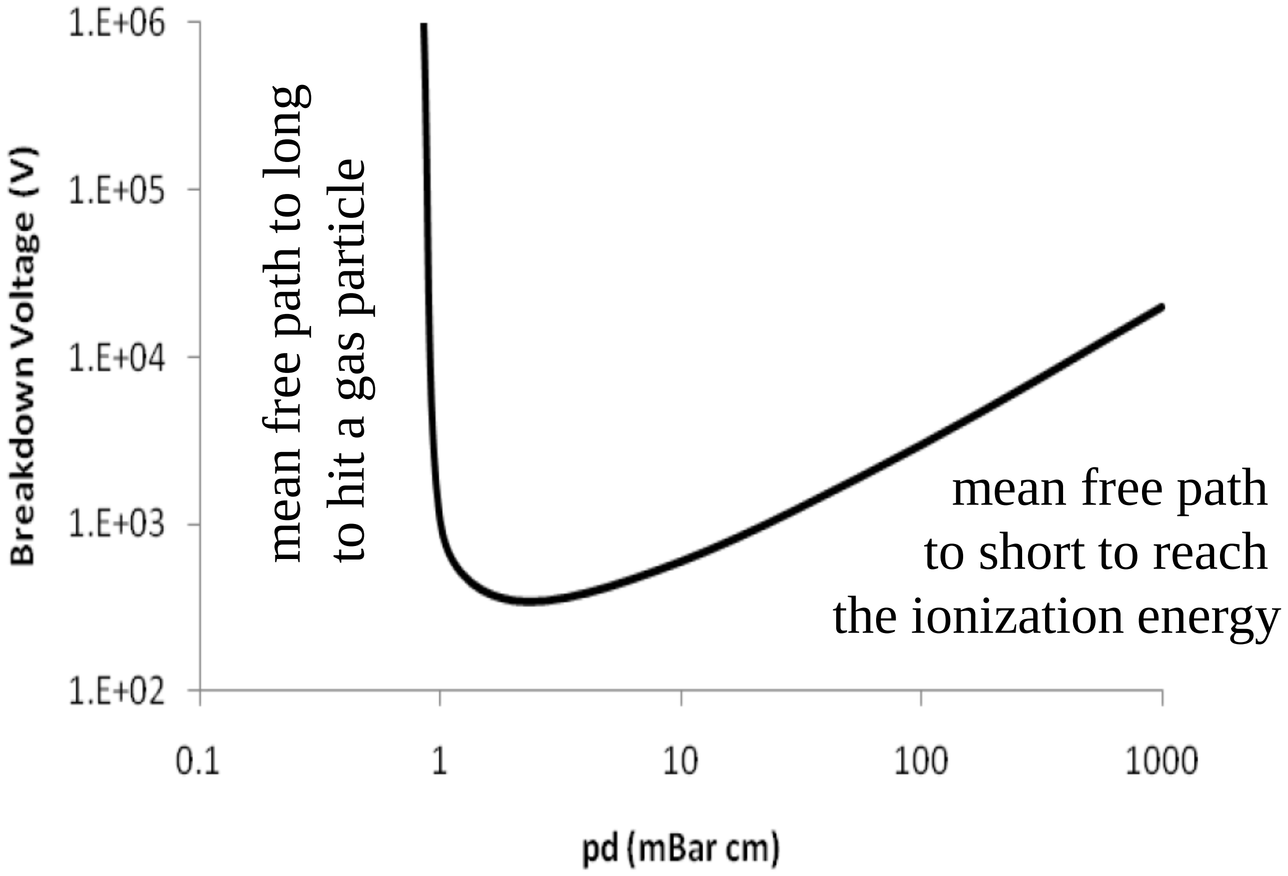
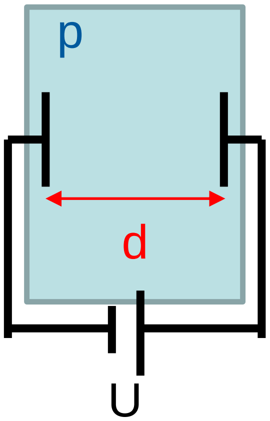
Discharges generate free electrons AND can supply the ionization energy

Discharges: The Paschen Curve





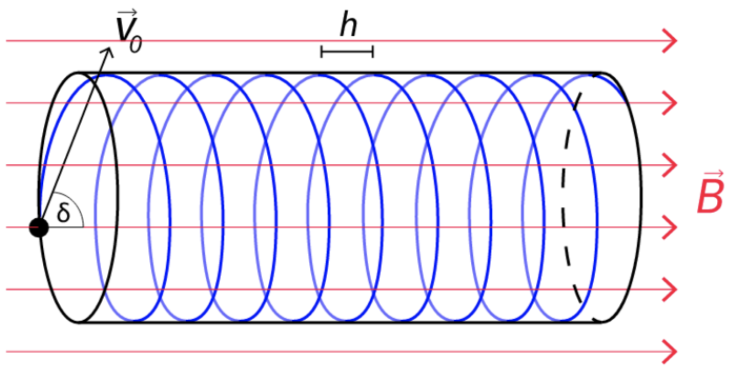
Basic Plasma Properties

- solid ➞ liquid ➞ gaseous ⇢ plasma
  ➞ distinct ⇢ continuous transition

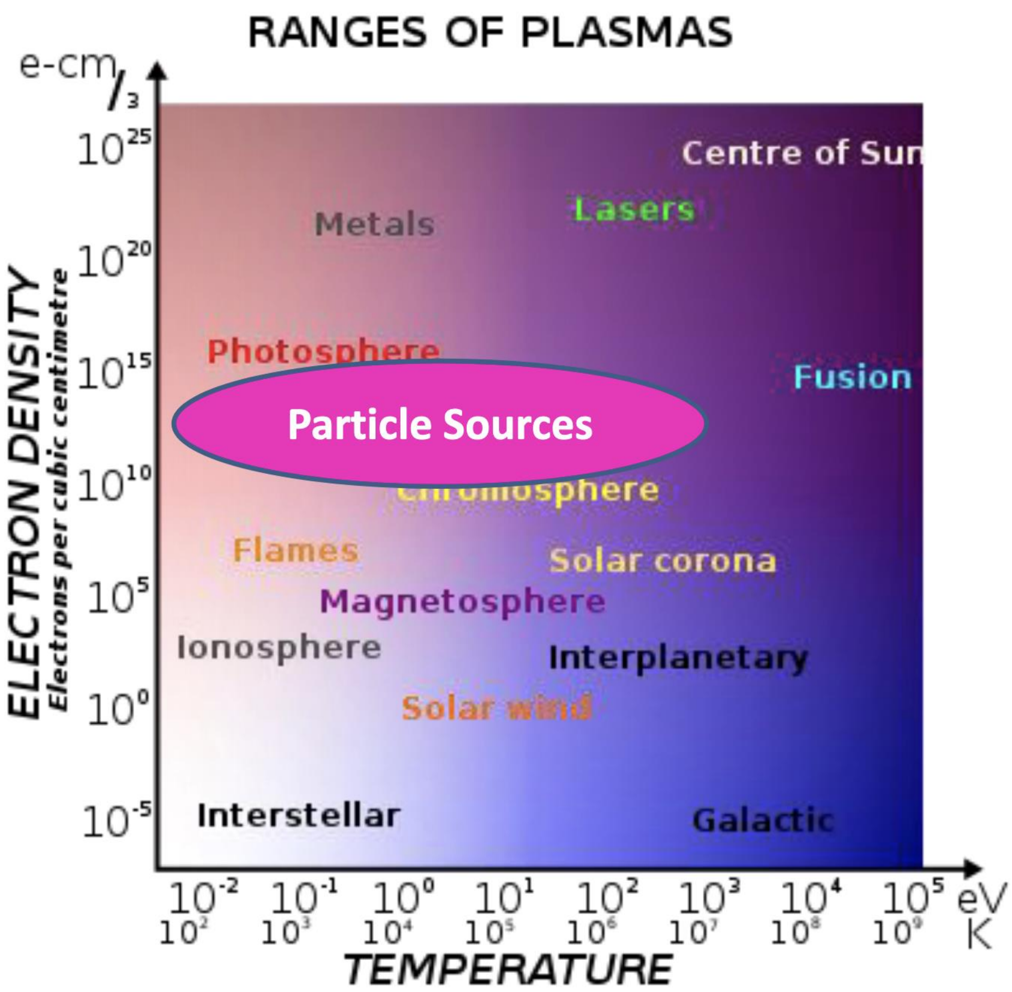
- Charged particles see electromagnetic force, move and collide: excitation, ionisation, neutralisation, recombination…

- Ionisation mainly depends on:
  - Number densities: $\boldsymbol{n_e}$ for electrons, $\boldsymbol{n_i}$ for ions, $\boldsymbol{n_n}$ for neutral particles
  - Temperatures: $\boldsymbol{T_e}$, $\boldsymbol{T_i}$, $\boldsymbol{T_n}$

- $\boldsymbol{T_e \neq T_i \neq T_n}$
  - $T_e \approx 1$ keV and $T_i \approx 1$ eV in an ECR source (1 eV ≙ 11600 K)
  - In magnetic fields T can be different for diffe



Basic Plasma Properties



Ionization

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

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

collisions with **photons**

Photo ionization — Radiative Recombination (RR)

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

Excitation — Spontaneous emission

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

Photo absorption — Bremsstrahlung

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

$$\frac{dn_{z+1}}{dt} = n_e \cdot n_z \cdot v_e \sigma_{z\to z+1} - n_e \cdot n_{z+1} \cdot \beta_{z+1,TBR}$$

Single-ionisation: He + e → He^{+} + 2e

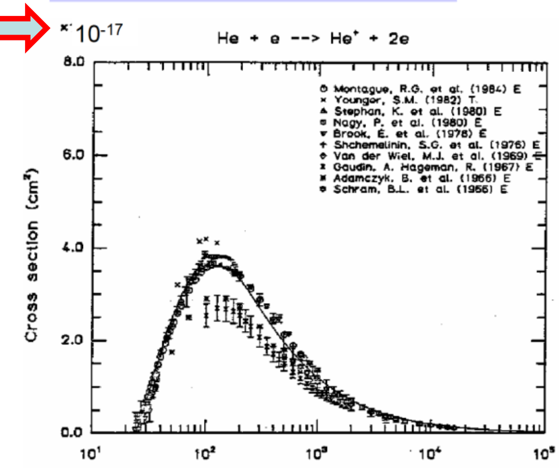


Fig.9

He^{+} + e → He^{2+} + 2e

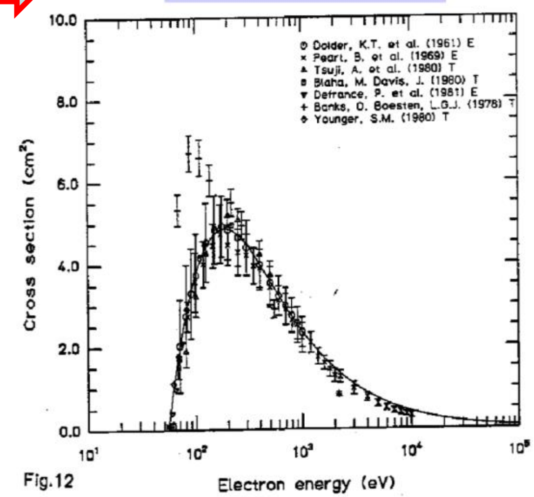
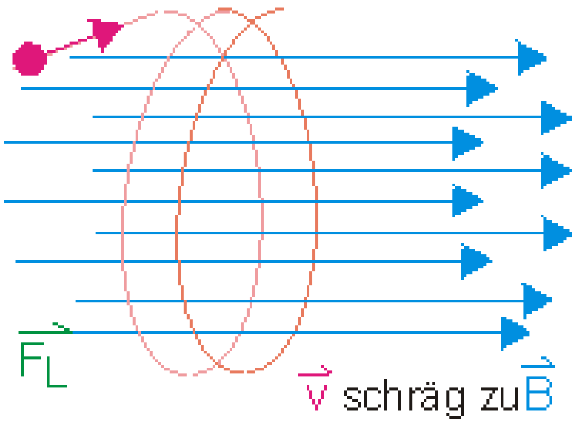
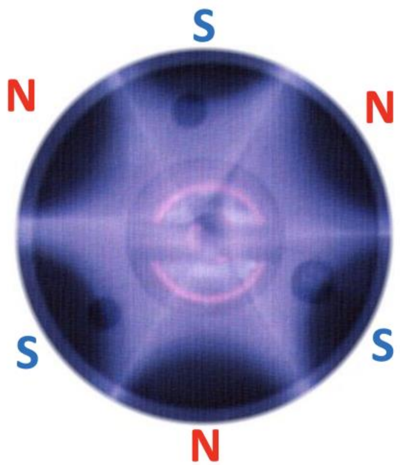


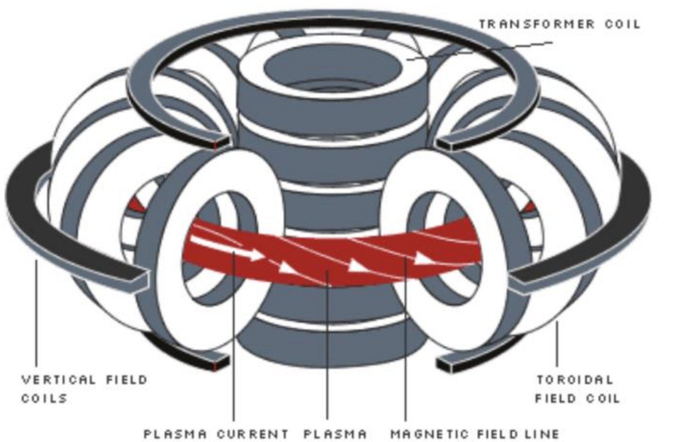
Fig.12

Magnetic Confinement

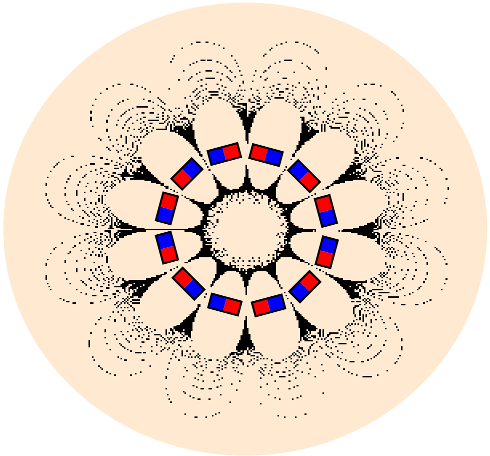




Hexapole



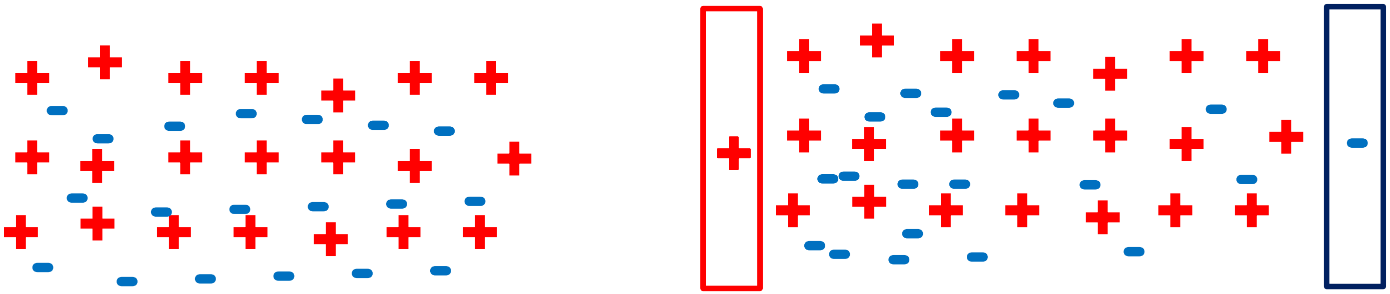
Solenoid (here you see a fusion reactor, ion sources use straight solenoids)



Multicusp (permanent magnets)

Debye Length

In a plasma free electrons redistribute themselves and screen out electric fields

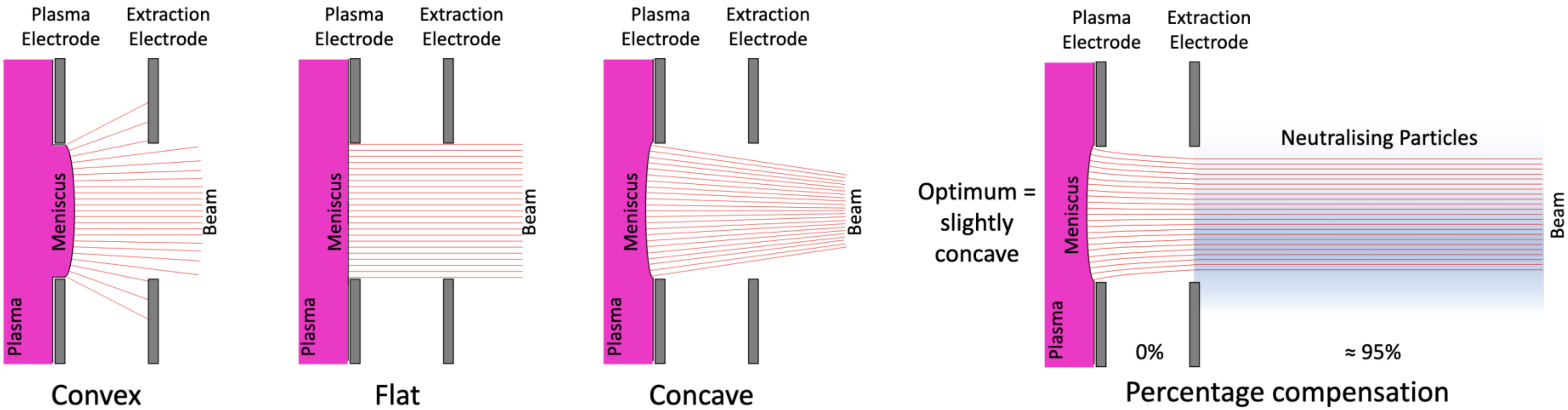


$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e {q_e}^2}}$$

In one Debye length the field is reduced to 1/e (typically 0.1 – 1 mm in sources)

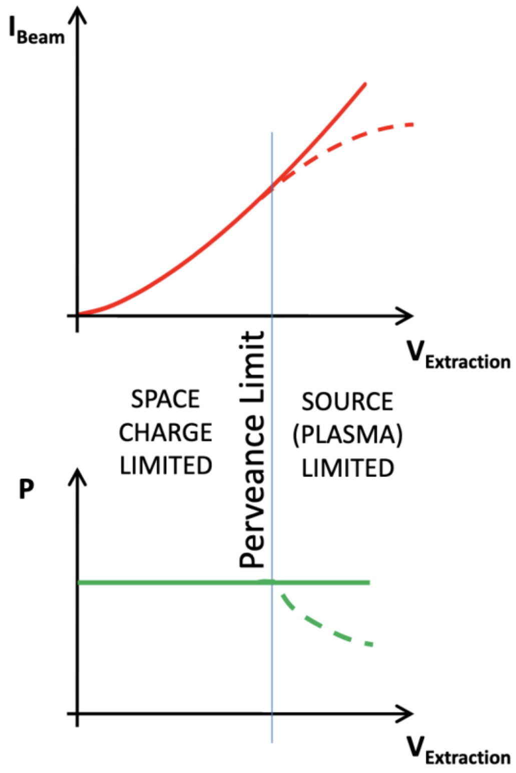
Extraction

- Ions can only be extracted from the edge of the plasma.
  This layer called meniscus is only few Debye lengths thick.
- The parameters of the source has to be carefully chosen in order to obtain the right geometry of the meniscus.
- High current sources should be space charge compensated:
  A low pressure gas right behind the source is ionized by the beam.
  Electrons are attracted by the beam, positive ions repelled.
  Space charge and beam blow-up is reduced.

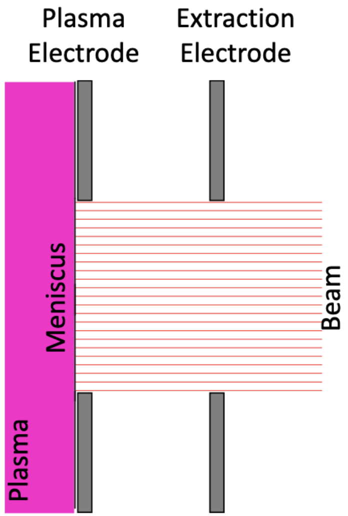


with space charge compensation

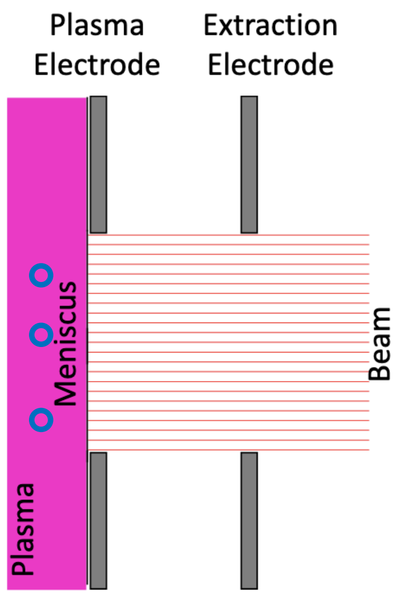
Child-Langmuir Law and Perveance

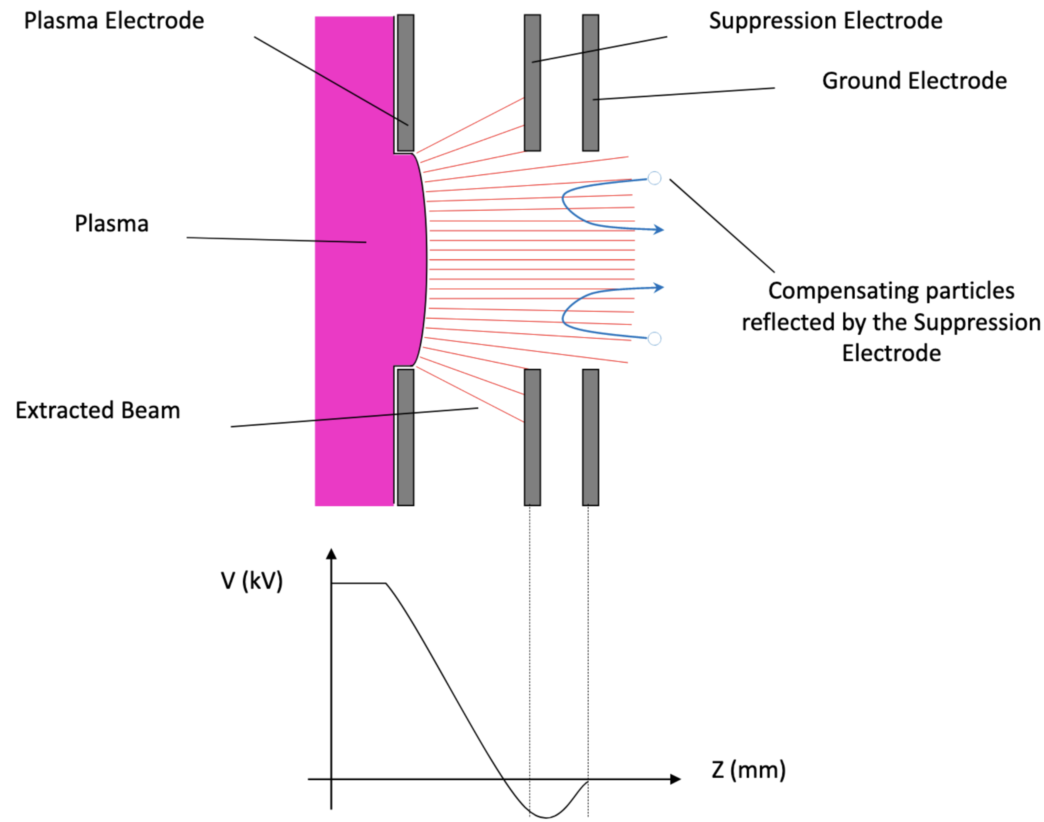


- There is an absolute limit for the current density which can be extracted from a plasma.
- The electric field originating from the space charge of the beam cancels out the extraction field.
- Child-Langmuir: $j \sim V_{extr.}^{3/2}$
- Perveance: the beam intensity is limited by the capability of the plasma to supply fresh ions.



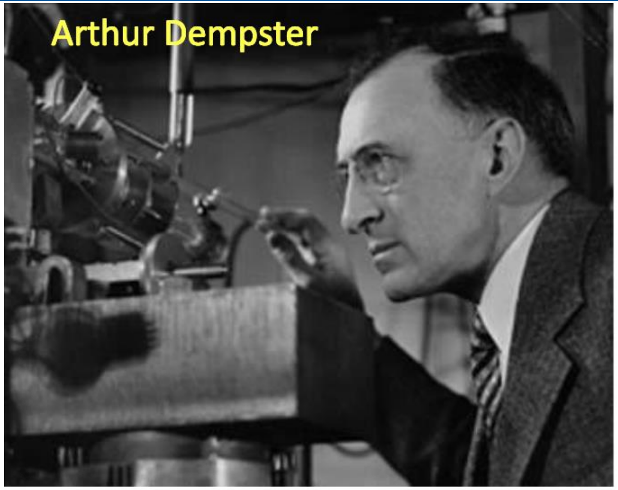
Suppressor Electrode





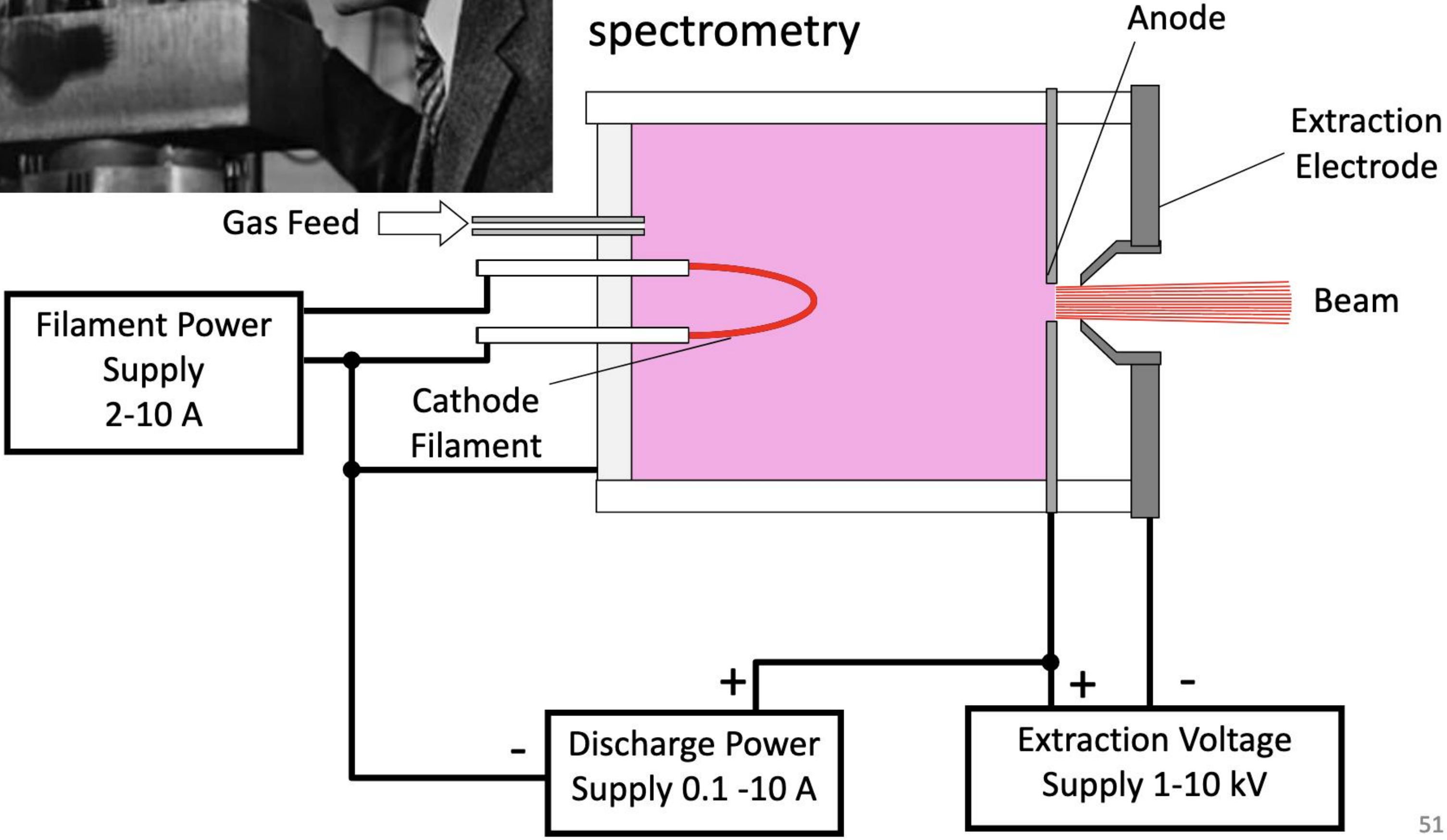
Pos. ion source:
Electrons e.g. from rest gas ionization are sucked into the plasma region!

Hot Cathode Ion Sources



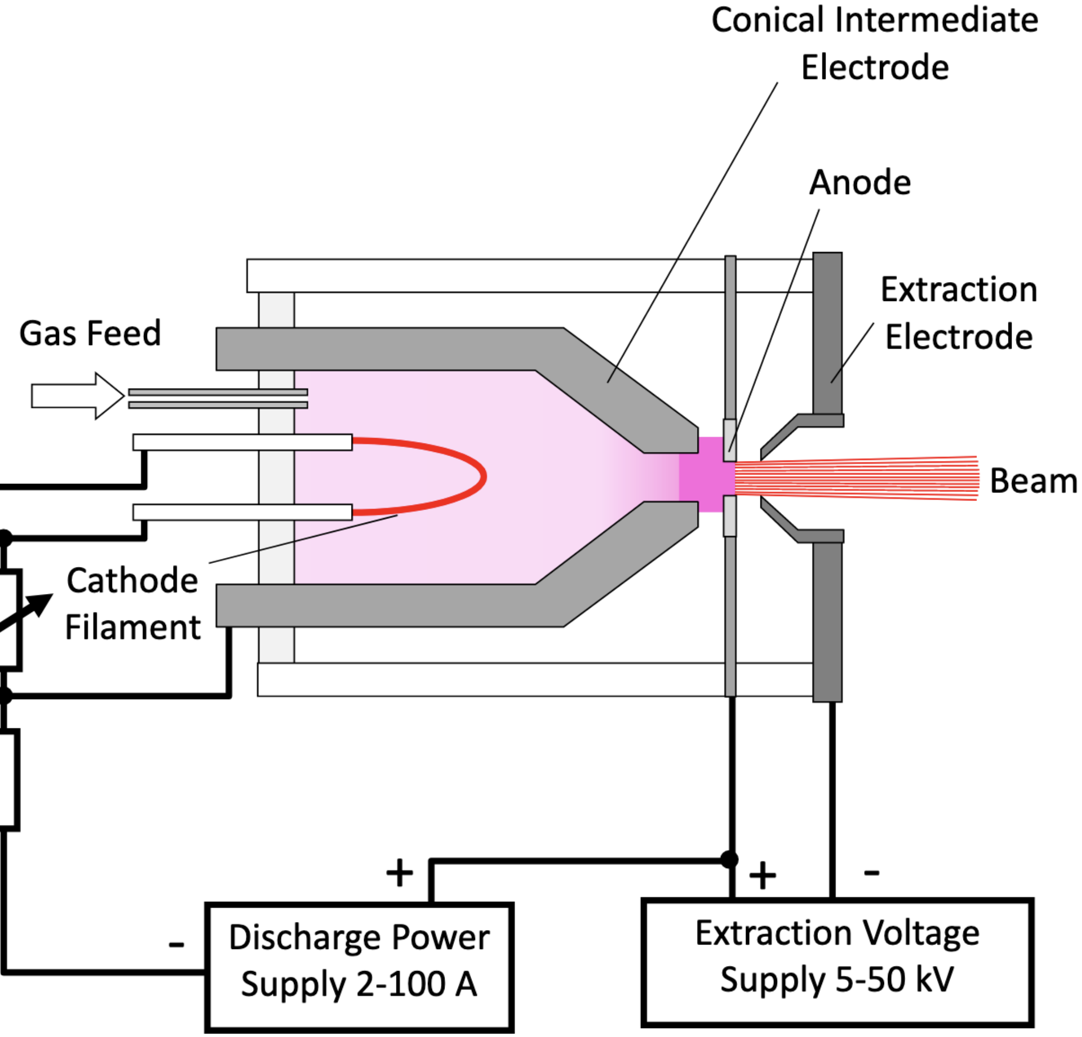
Electron Bombardment Source (1916)

Early mass spectrometry

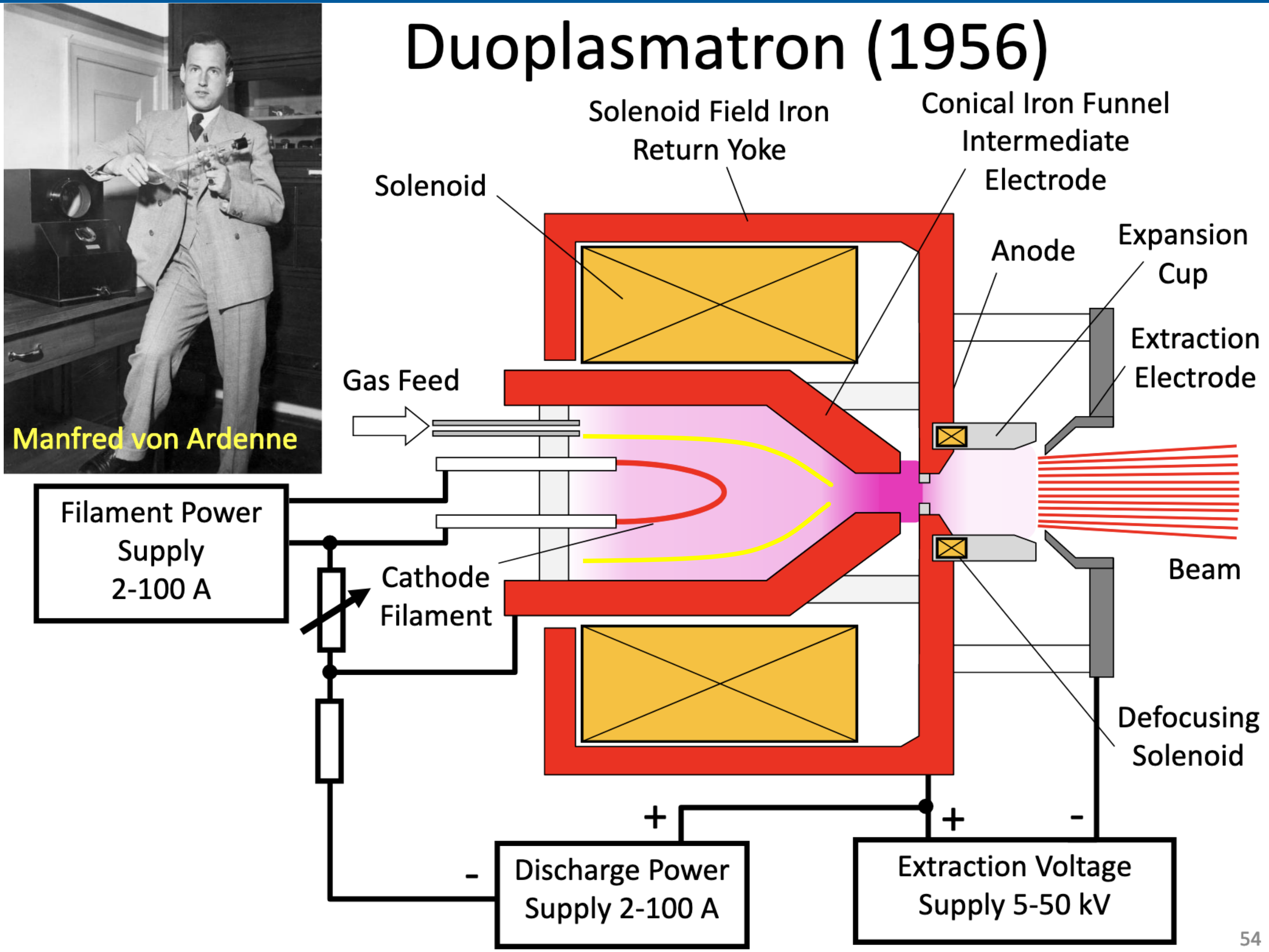


Hot Cathode Ion Sources

Plasmatron (late 1940s)



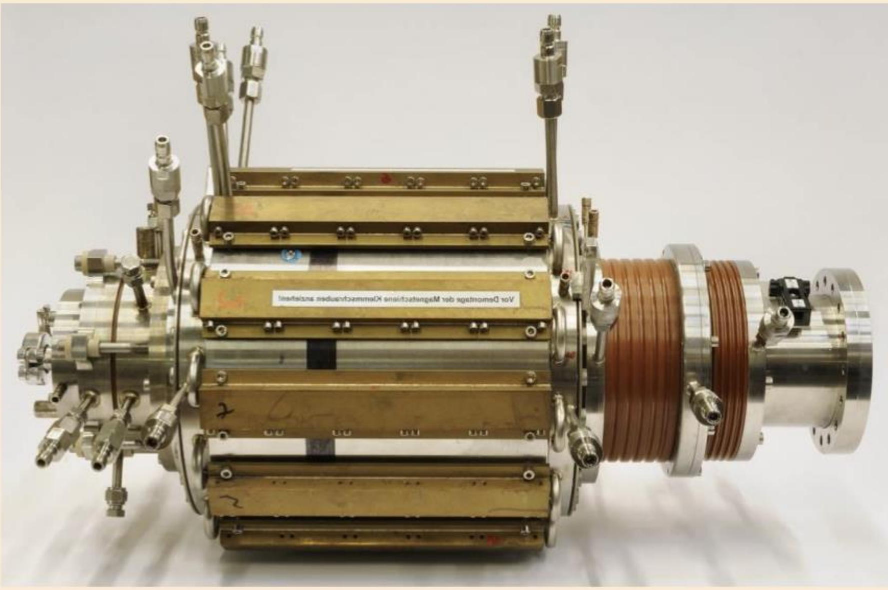
Hot Cathode Ion Sources

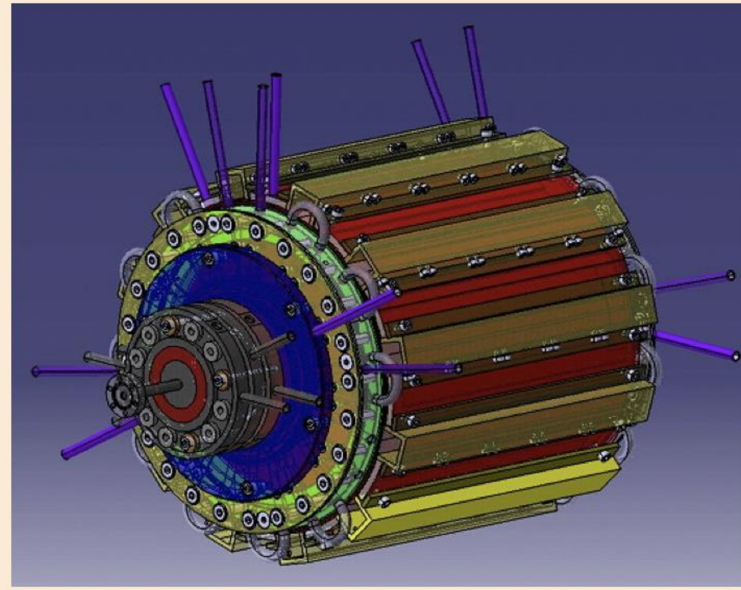


Hot Cathode Ion Sources

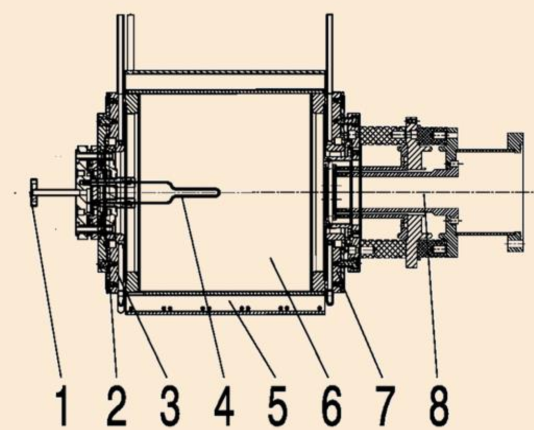
MUCIS New

R. Hollinger



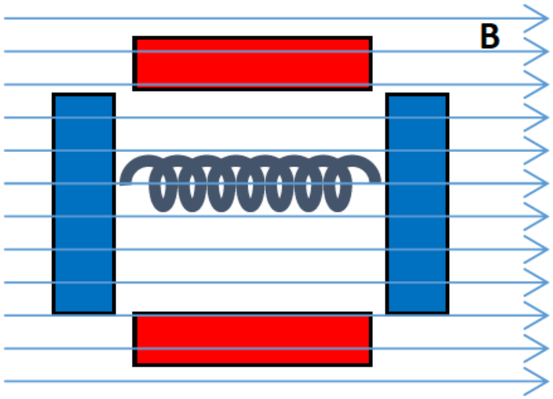


- **Bigger Plasma chamber**
- **Improved Cooling (I_{arc} = 200A)**
- **Symmetrical Magnet alignment at the ends**
- **Halbach-alignment of the Magnets**
- **Optimized for highly-charged ions (Kr^{2+}, Xe^{3+})**



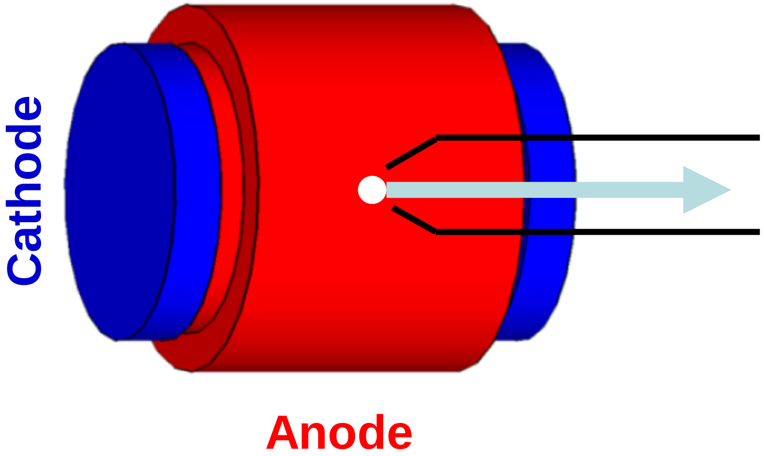
1 - Gas inlet
2 - Cooling system
3 - Cathode flange
4 - Filament
5 - Magnets
6 - Anode
7 - PE flange
8 - Triode system

Penning Sources (PIG: Penning Ion Gauge)



Discharge current depends on pressure:
Pressure measuring device (vacuum techniques)

Conversion to a DIY ion source
(extremely simplified)



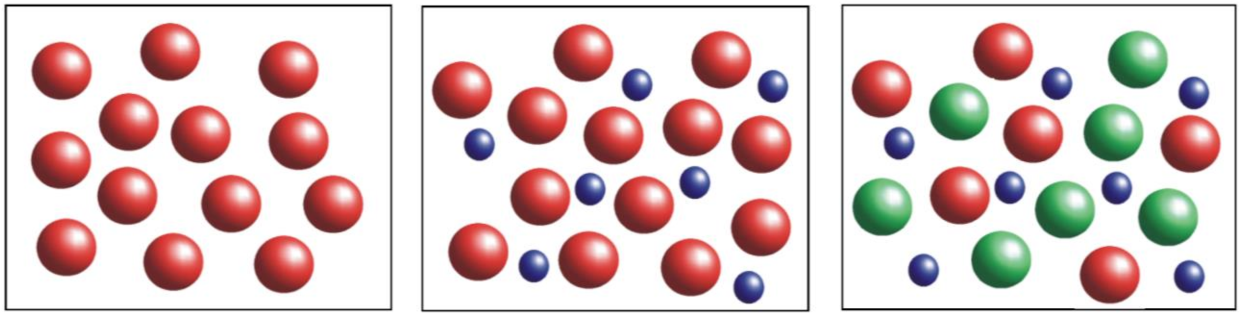
Drill a hole

Add and extration electrode

Done!

Vacuum Arc Driven Sources

Plasma generation:



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- Photo ionisation
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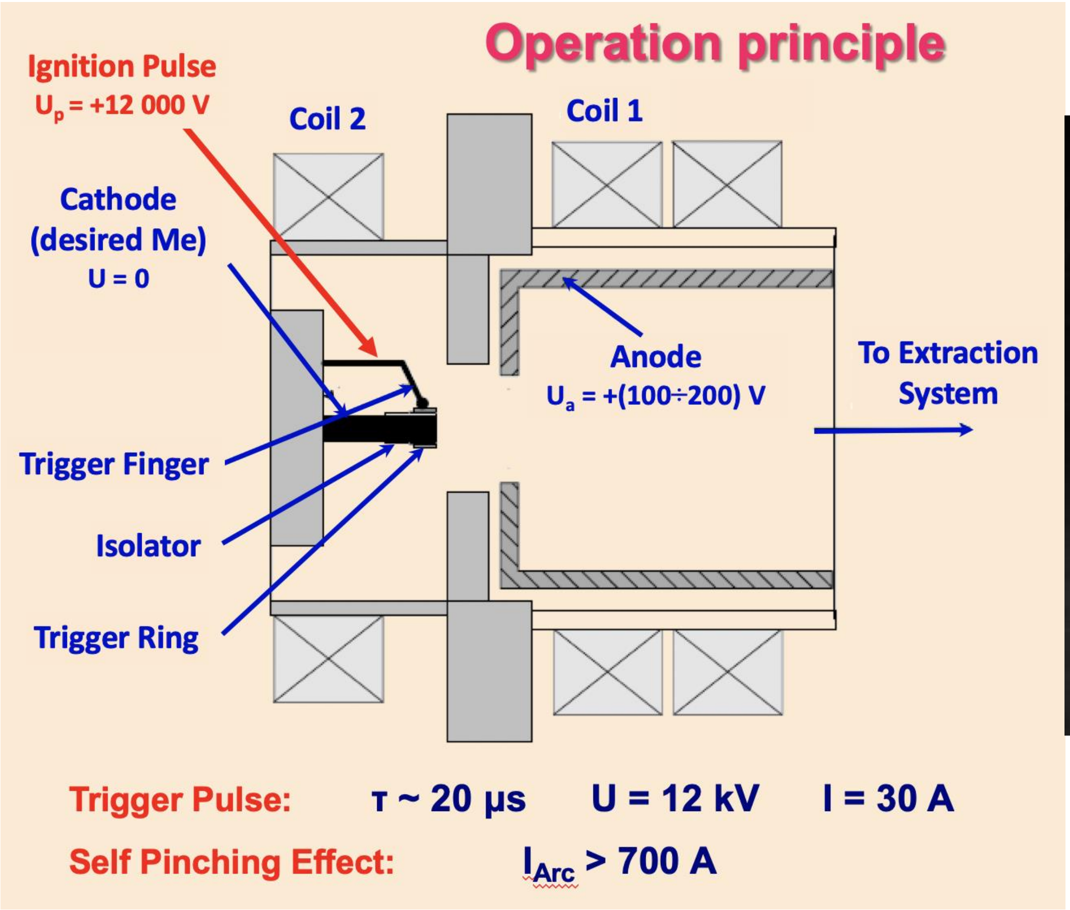
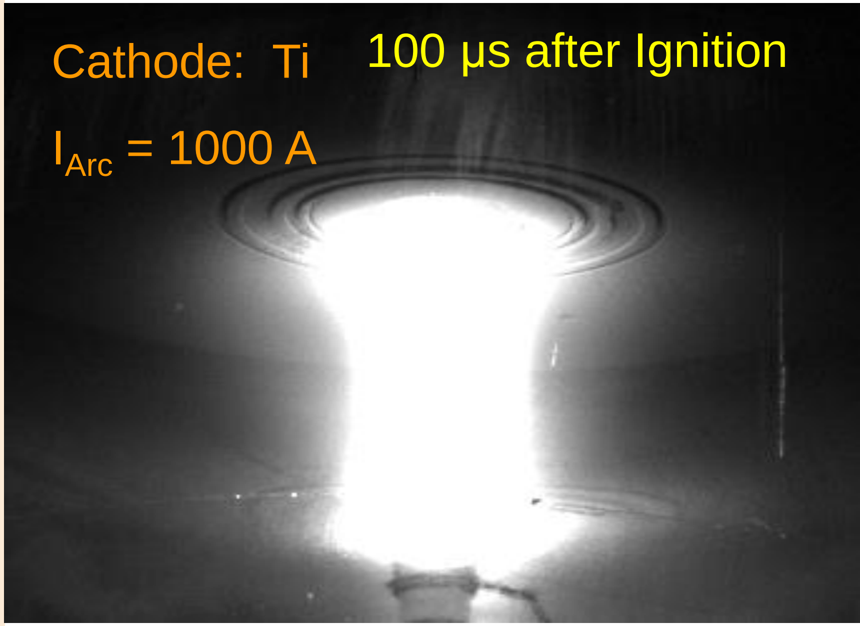
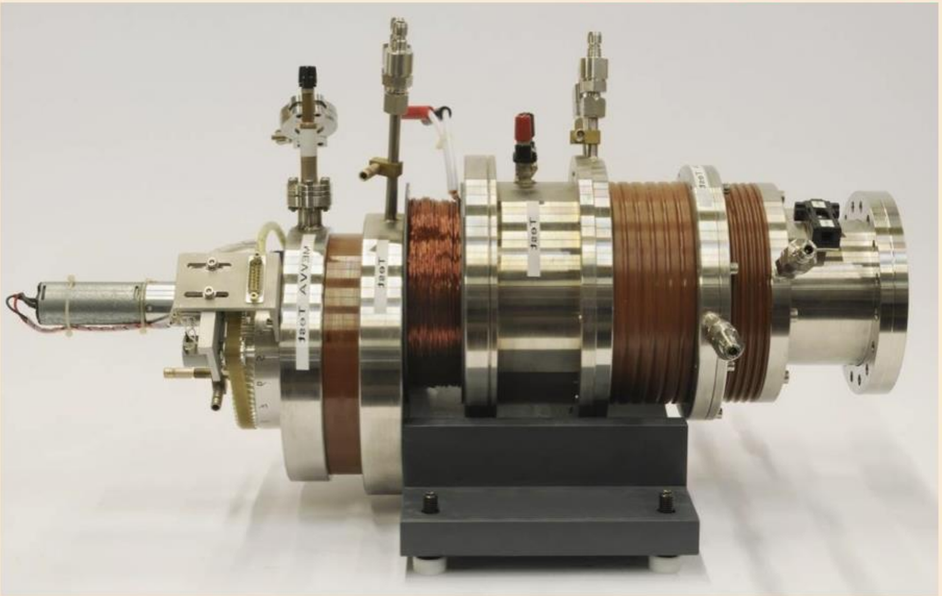
Vacuum Arc Driven Sources

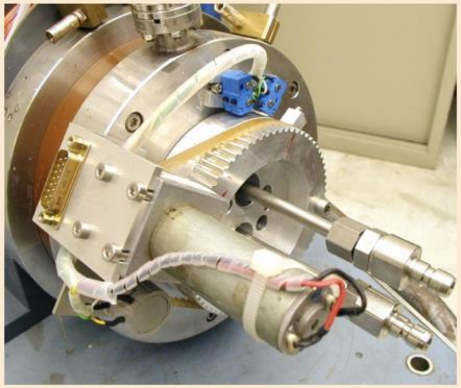


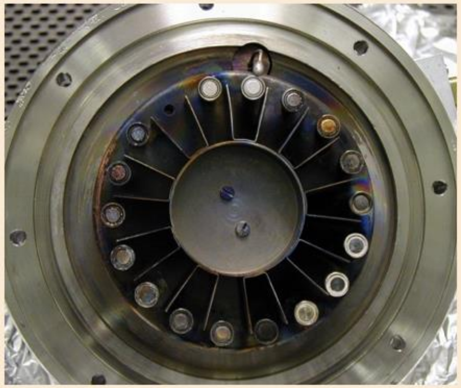


Vacuum Arc Driven Sources

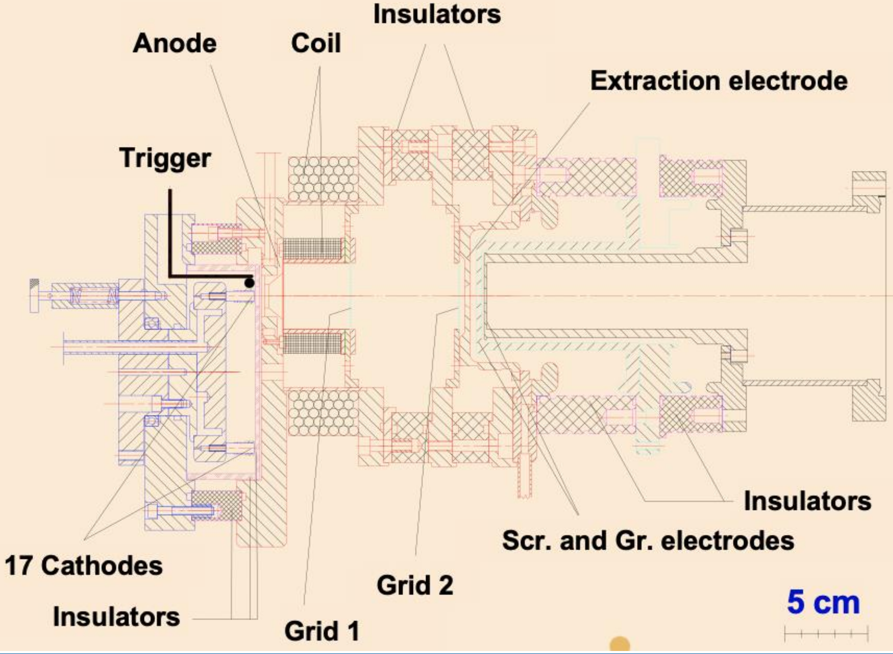
MEVVA (Metal Vapor Vacuum Arc Ion Source)





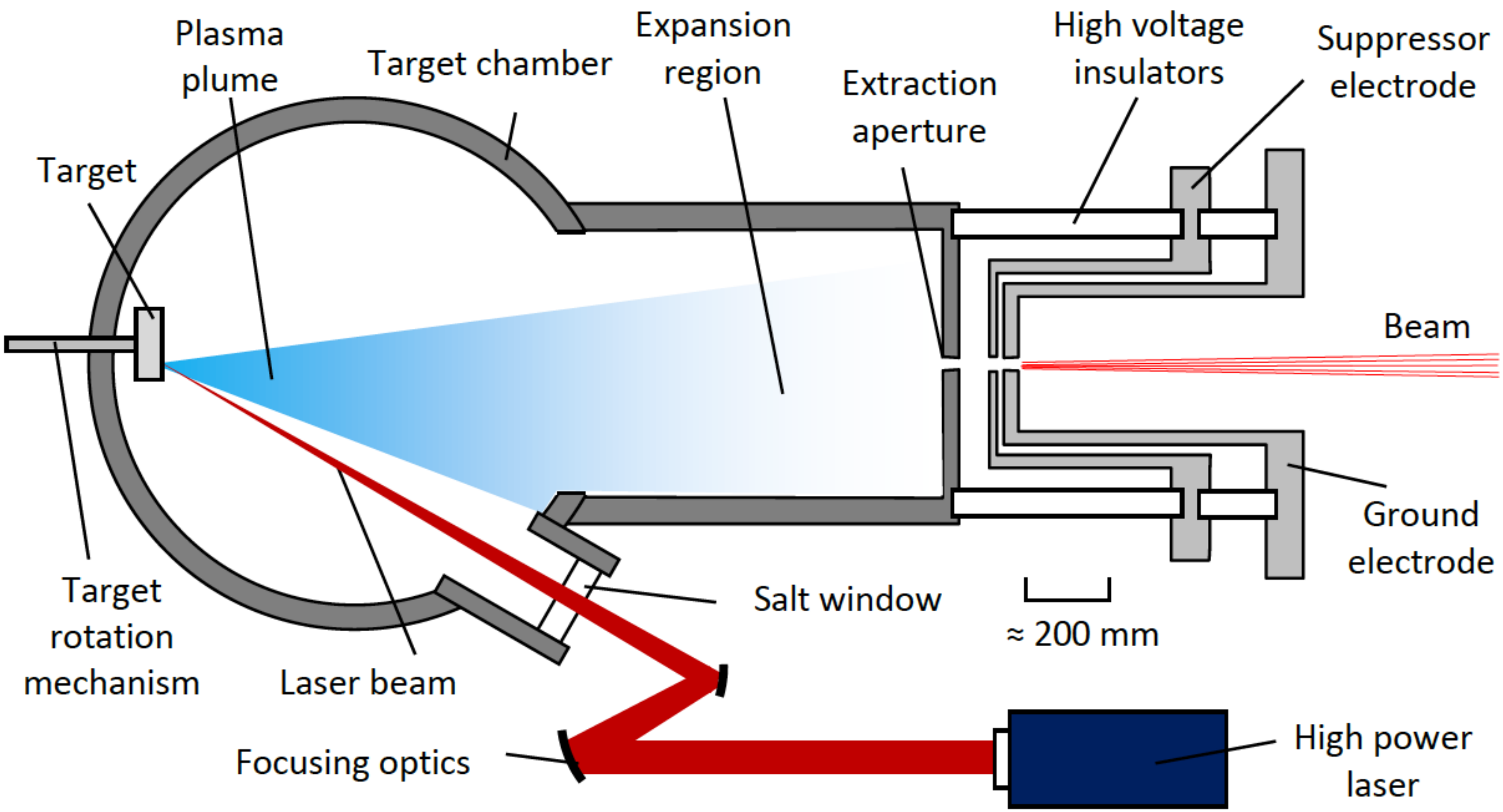


- Revolver with 17 Cathodes
- 2 Solenoids: 0.1 and 0.2 Tesla
- Arc Power: 50 kW (13.3 MW/cm²)
- Arc Current: ~1 kA
- Duty Cycle: typical 1 Hz, 1 ms
- Working Material: ductile Metalls
- Life time: ~1 Week (Uranium)



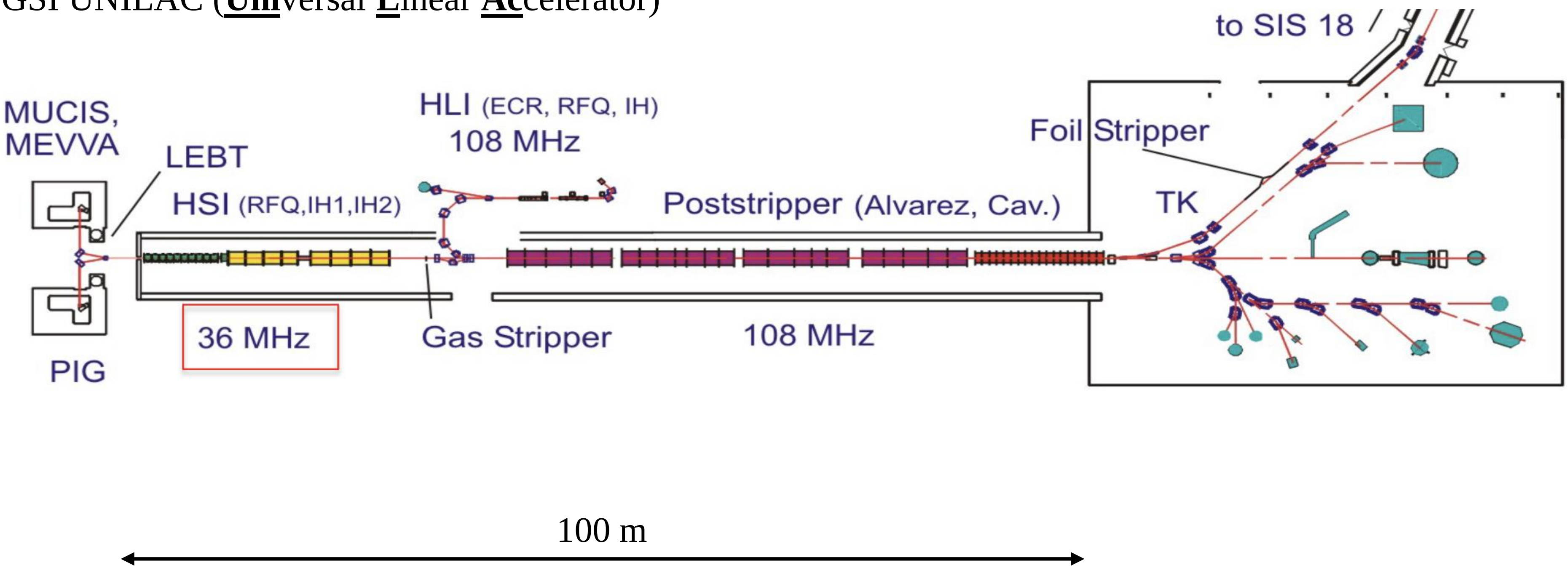
I. Brown

Laser Sources



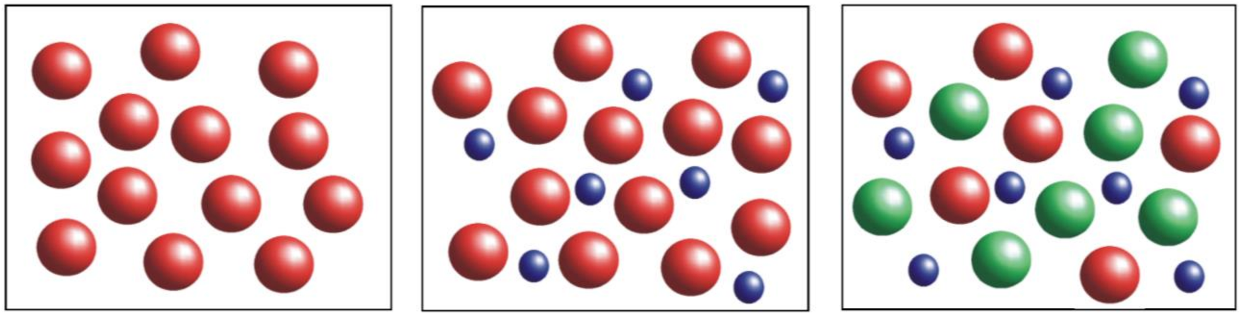
High Charge State Sources

GSI UNILAC (**Uni**versal **L**inear **Ac**celerator)



RF Sources

Plasma generation:



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- Discharge

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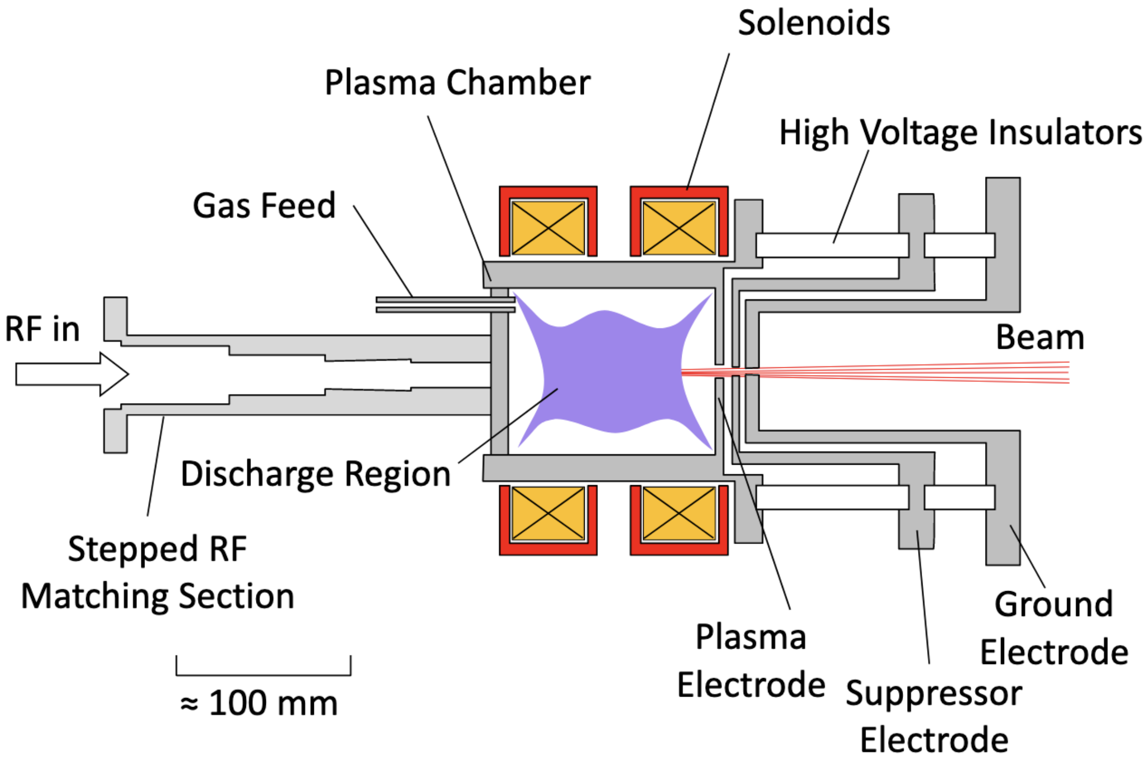
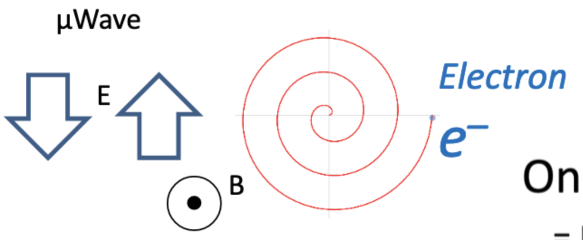
- E x B-drift

RF Sources: Microwave Discharge and ECR





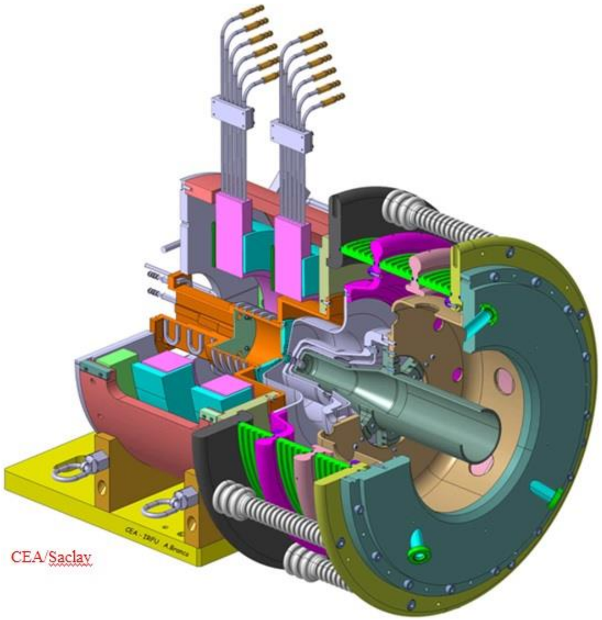
Off resonance (or high pressure)

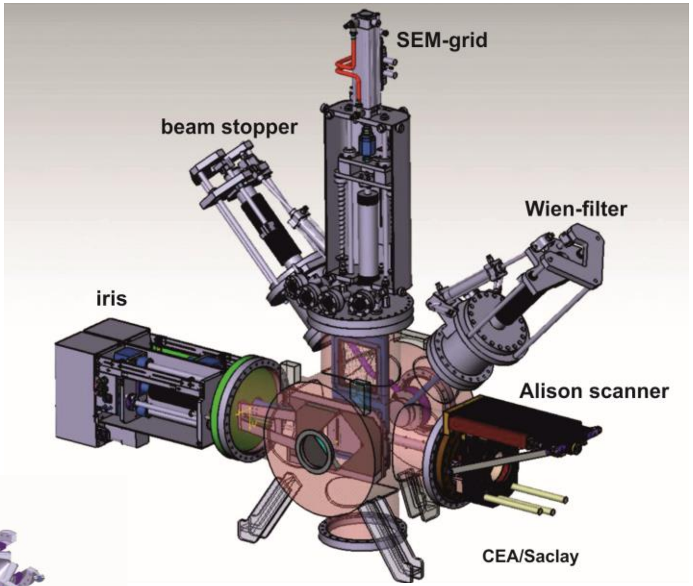
= Microwave discharge ion sources

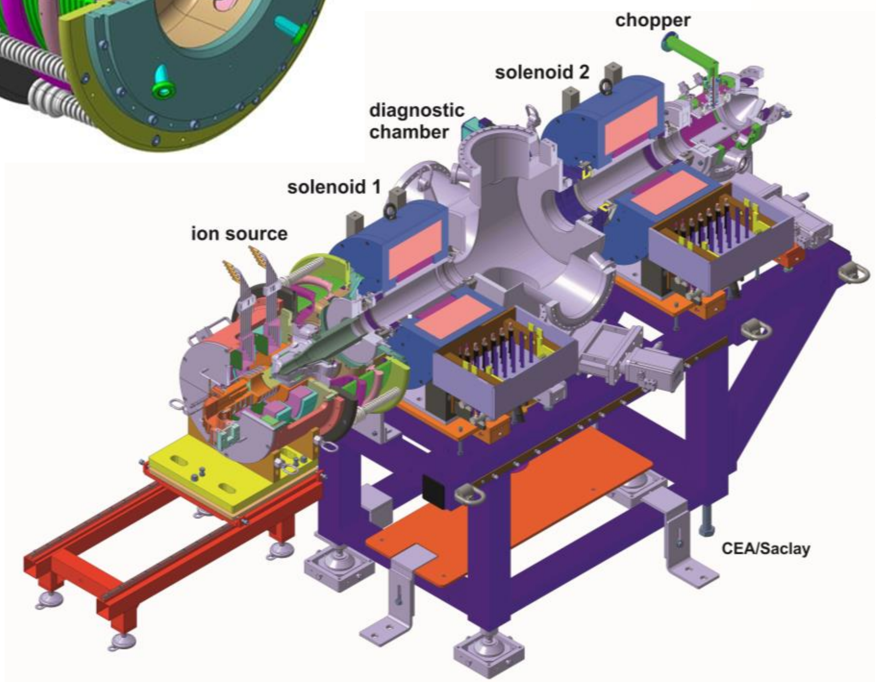
On resonance

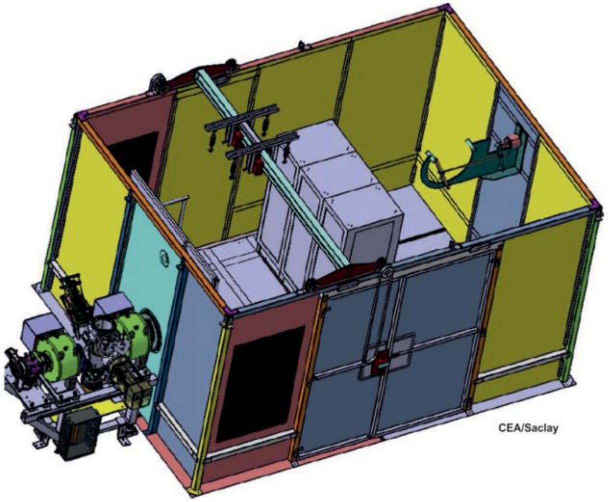
= Electron Cyclotron Resonance (ECR) sources

RF Sources: FAIR pLinac source from CEA





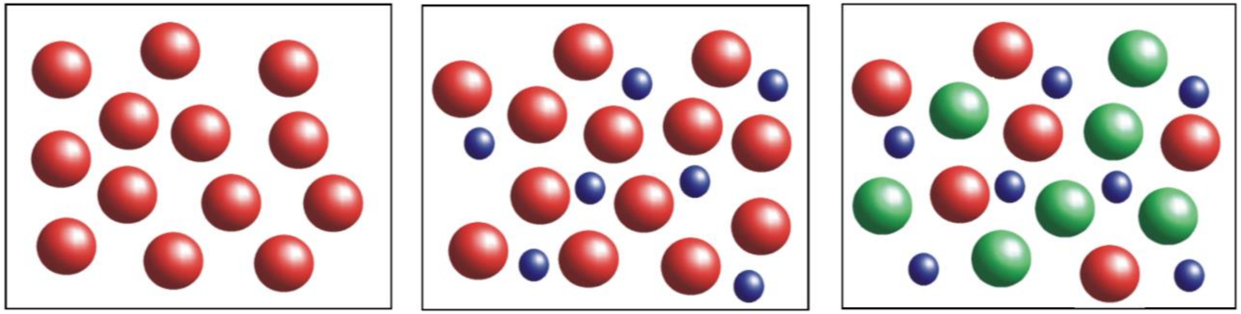




RF Sources: FAIR pLinac source from CEA

Electron Beam Ion Sources (EBIS)

Plasma generation:



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- Sputtering

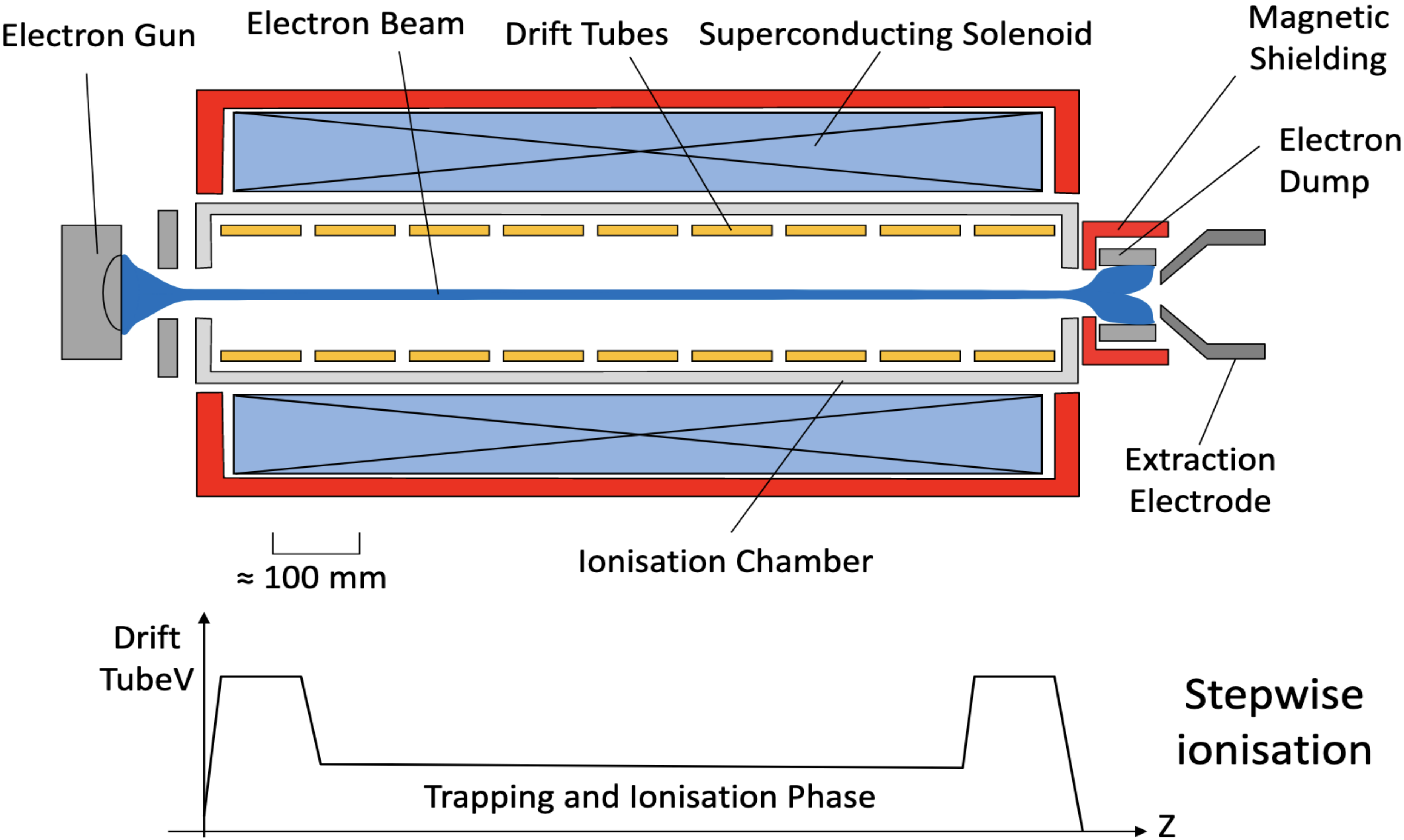
Generate free electrons:

- Thermionic emission
- Photo ionisation
- Discharge

Supply the ionisation energy:

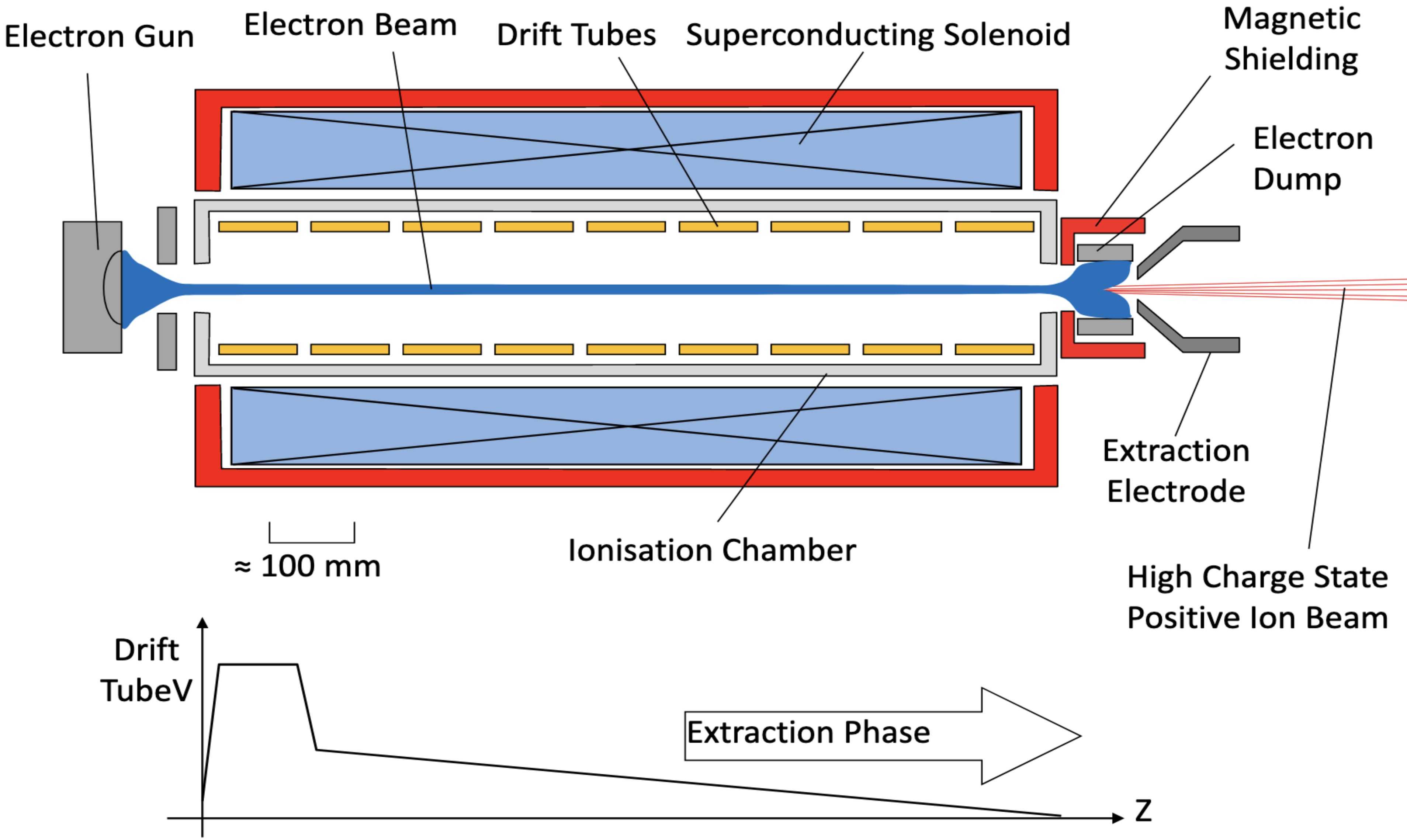
- Electron acceleration (electrostatic → e-gun)
- rf-heating
- E x B-drift

Electron Beam Ion Sources (EBIS)



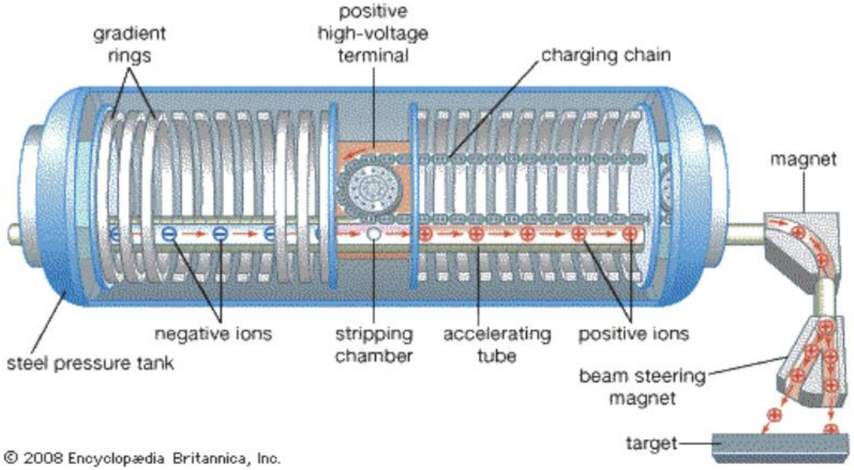
Stepwise ionisation

Electron Beam Ion Sources (EBIS)

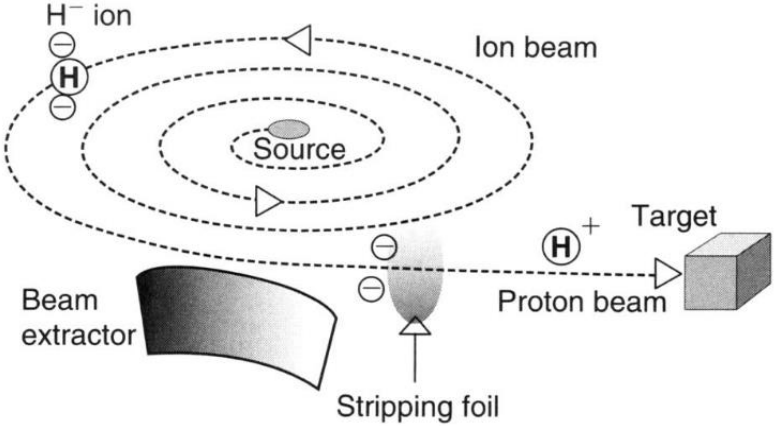


Negative Ion Sources: Applications

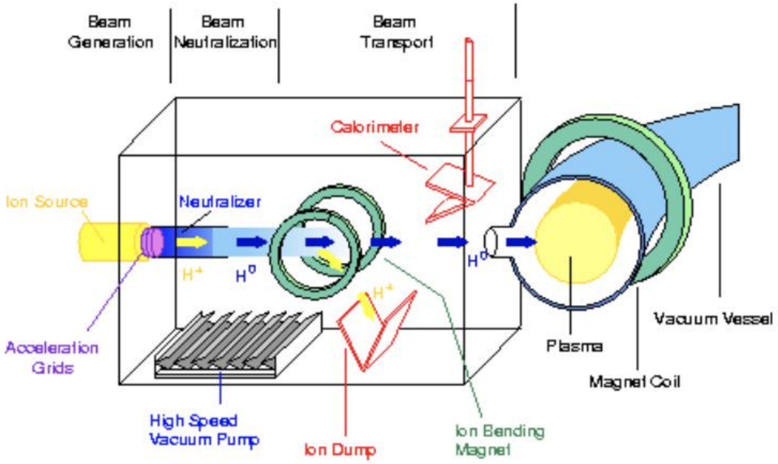
Tandem accelerators



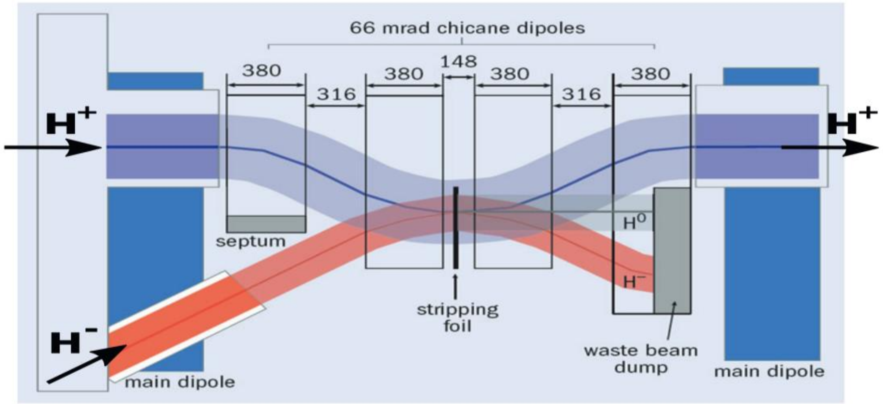
Cyclotron extraction



Neutral Beams



Multi-turn injection into rings

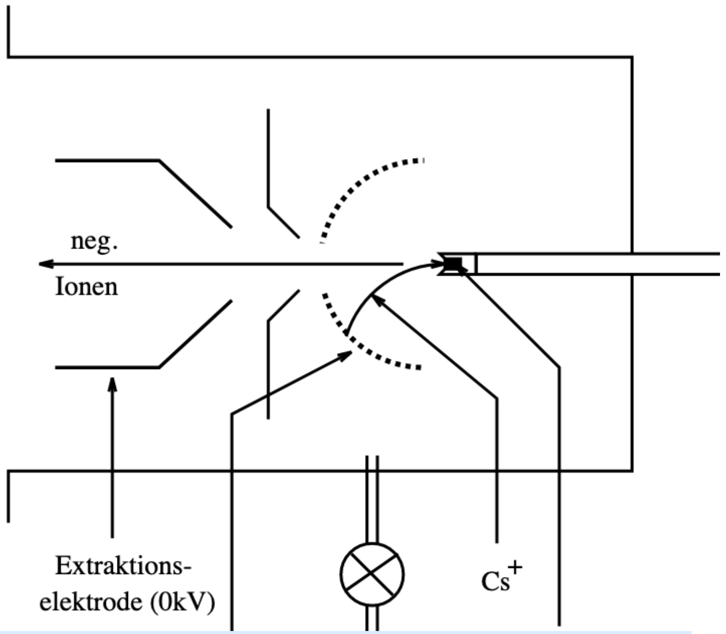


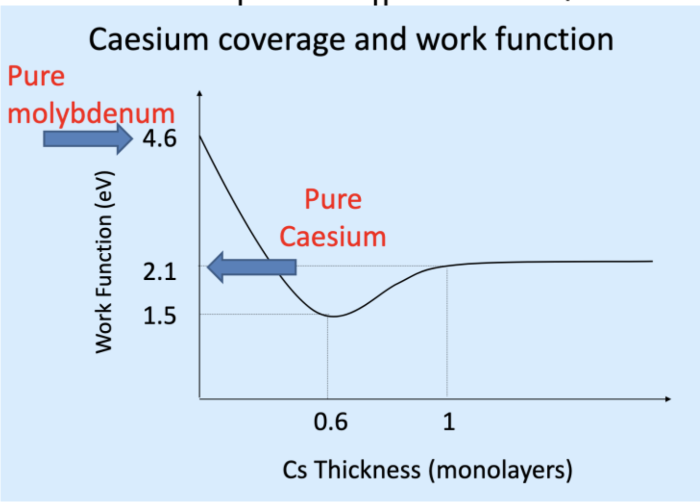
Cesium Sputter Source (Middleton Source)

- Cesium is ionized on a hot Ta-surface
- Cs^+ ions are accelerated to a sputter target
- Negative to neutral ratio: Langmuir-Saha-Equation

$$N^- / N^0 \sim e^{\frac{EA-W}{kT_e}}$$

- Electron affinity *EA* should be high:
  high currents e.g. from halogens possible
- Work function should be low:
  Substantial reduction by a Cs layer on the target
- Atoms with negative *EA* form no stable neg. ions:
  No noble gas beams from sputter sources,
  but also no Mn^-, Mg^- or $^{14}N^-$





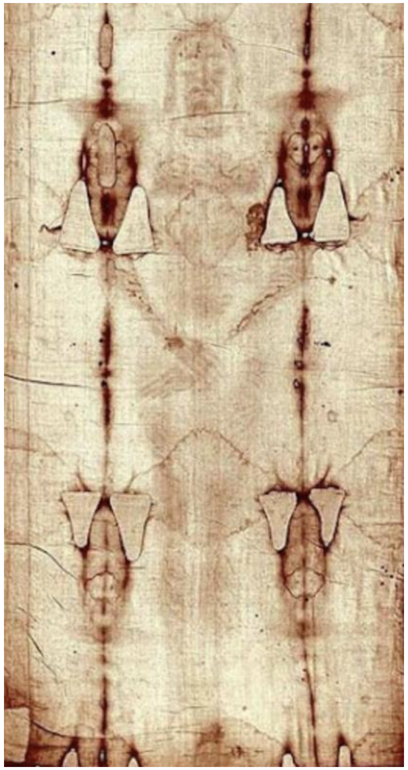
Excursion: Accelerator Mass Spectrometry
or Utilizing the Disadvantages of Negative Sputter Ion Sources

- Cosmic rays are permanently producing ^{14}C in the atmosphere via $^{14}N(p,n)^{14}C$
- The whole biosphere has an equilibrium ratio $^{14}C/C = 10^{-12}$
- After the dead of an organism, this $^{14}C/C$ ratio decreases with an half life of 5730 yr
- Measuring the ^{14}C content allows dating of this organism

$$A = \lambda N = \ln(2) / T_{1/2} \times N$$

- Short half life: measure decays
- long half life: count particles

Ötzi: about 5300 yrs old



Shroud of Turin: about 800 yrs old

Excursion: Accelerator Mass Spectrometry
or Utilizing the Disadvantages of Negative Sputter Ion Sources

$^{12}C^-$, $^{13}C^-$

$^{14}C^-$, $^{12}CH_2^-$, $^{13}CH^-$

$^{14}C^- \rightarrow {}^{14}C^{x+}$

$^{12}CH_2^- \rightarrow {}^{13}C^{x+} + H^+$

Coulomb explosion

$^{14}C^{n+}$

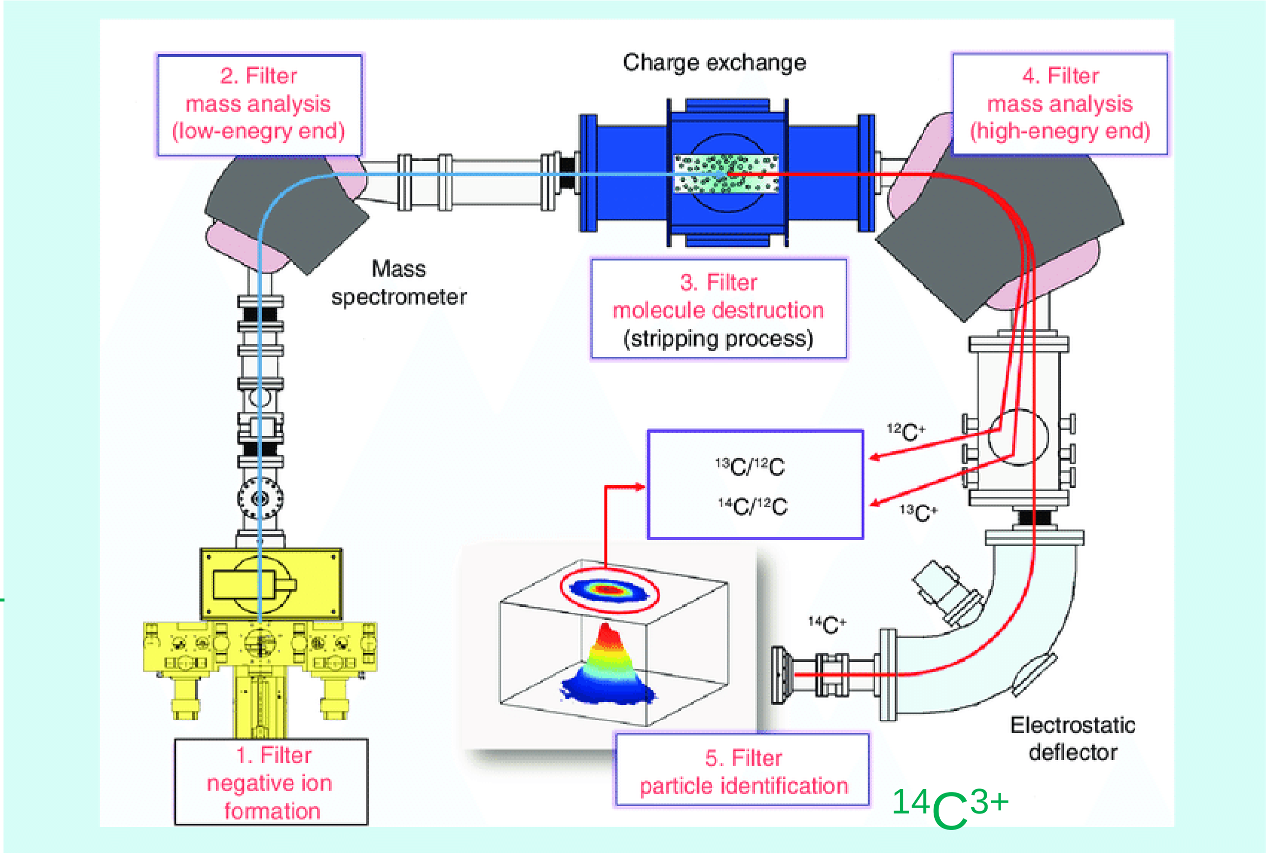
$^{12}C^{x+}$ $^{13}C^{x+}$

$^{14}N^-$, $^{28}Si^{2-}$…

$^{12}C^-$, $^{13}C^-$, $^{14}C^-$

$^{12}CH_2^-$, $^{13}CH^-$

…

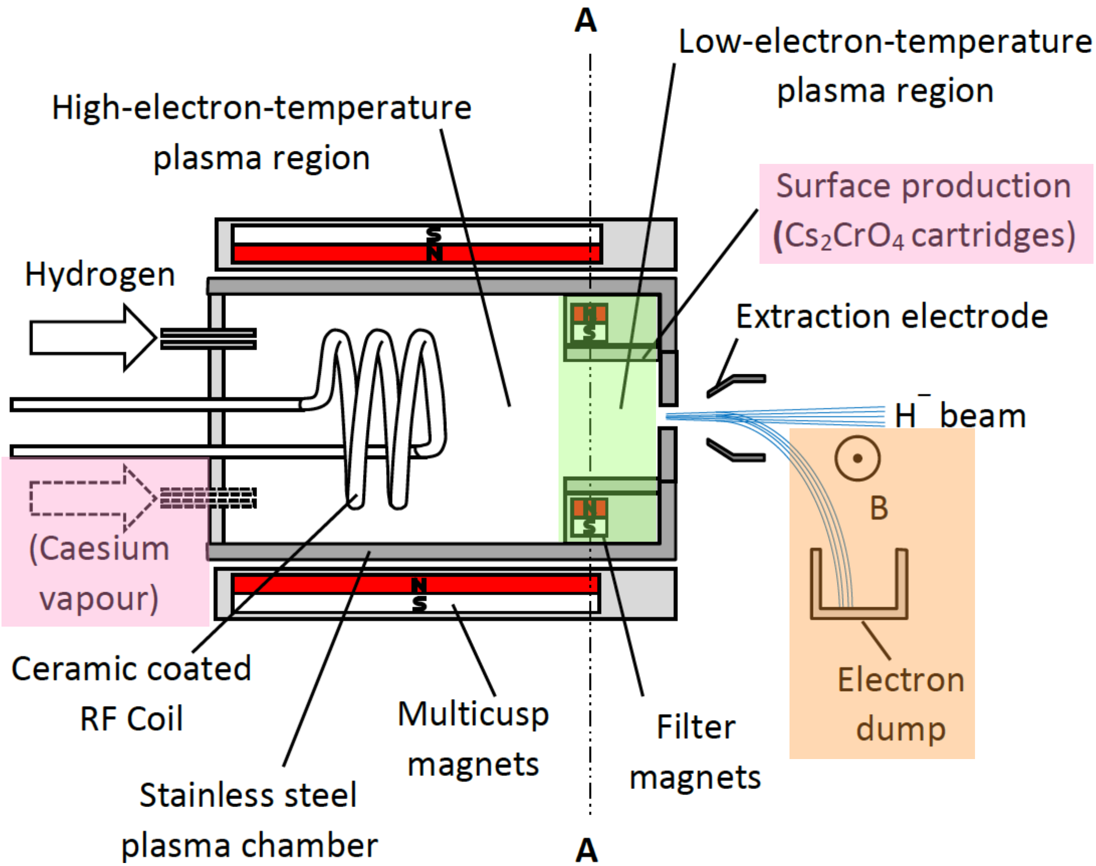


$^{14}C^{3+}$

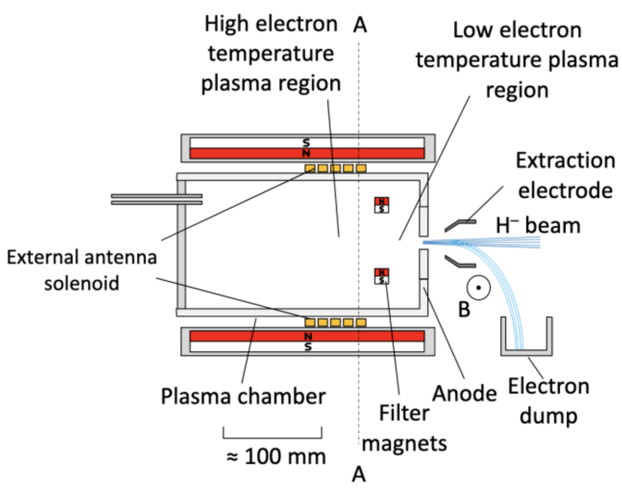
remaining background

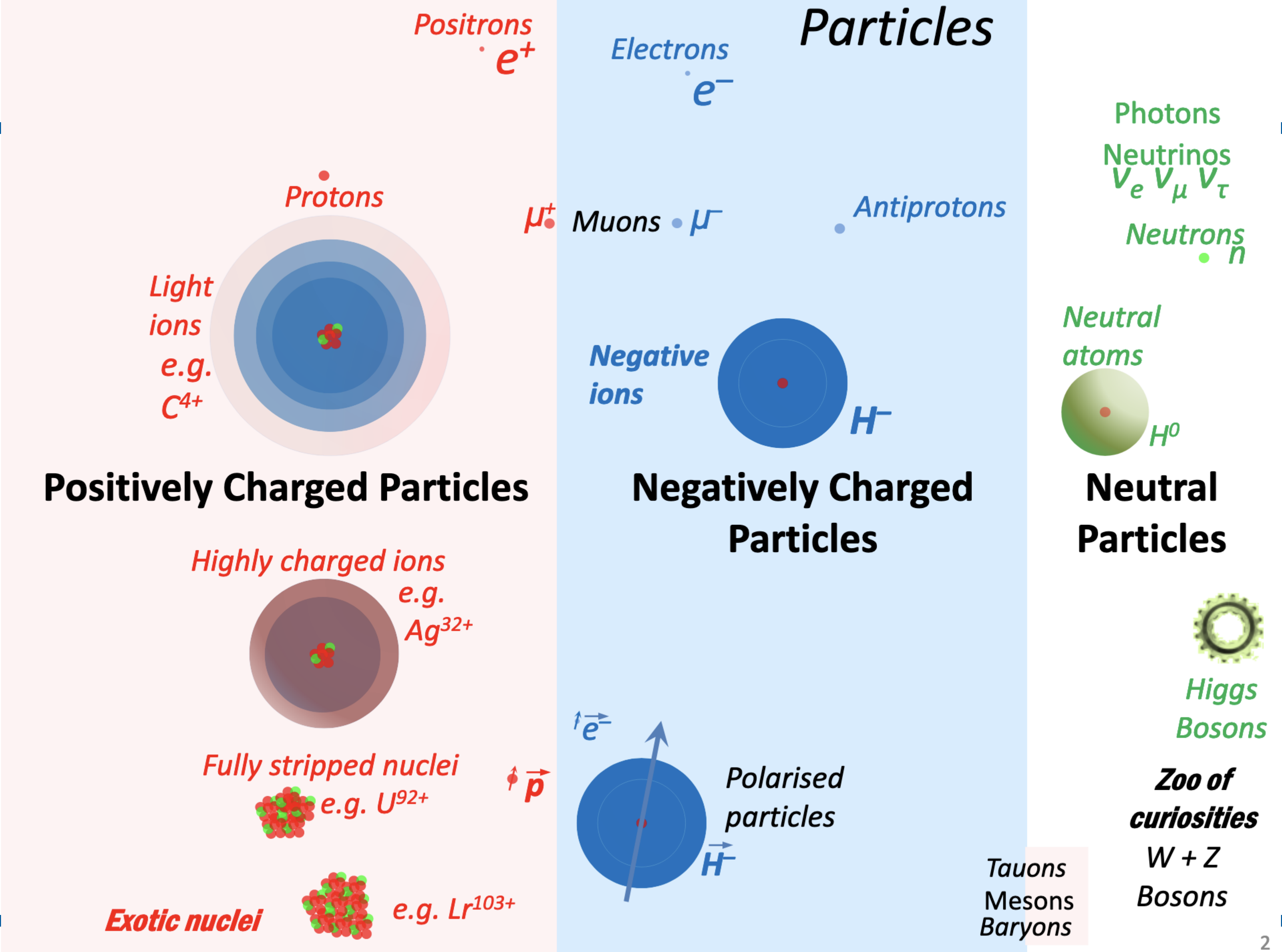
Vuong, Le er al. (2015). Opportunities in low-level radiocarbon microtracing: applications and new technology. Future Science OA. 2. 10.4155/fso.15.74.

Negative RF Sources



- Filter magnets to avoid fast electrons in the extraction region
- Electron dump
- Possibility to add Cs




Particles
Positrons
e+
Electrons
e−
Photons
Neutrinos
νe νμ ντ
Protons
μ+
Muons
μ−
Antiprotons
Neutrons
n
Light ions e.g. C4+
Negative ions
H−
Neutral atoms
H0
Positively Charged Particles
Negatively Charged Particles
Neutral Particles
Highly charged ions e.g. Ag32+
Higgs Bosons
e−
Fully stripped nuclei
e.g. U92+
p
Polarised particles
H−
Zoo of curiosities
W + Z Bosons
Tauons
Mesons
Baryons
Exotic nuclei
e.g. Lr103+

Particles and **Sources**