Part II

Ion Sources

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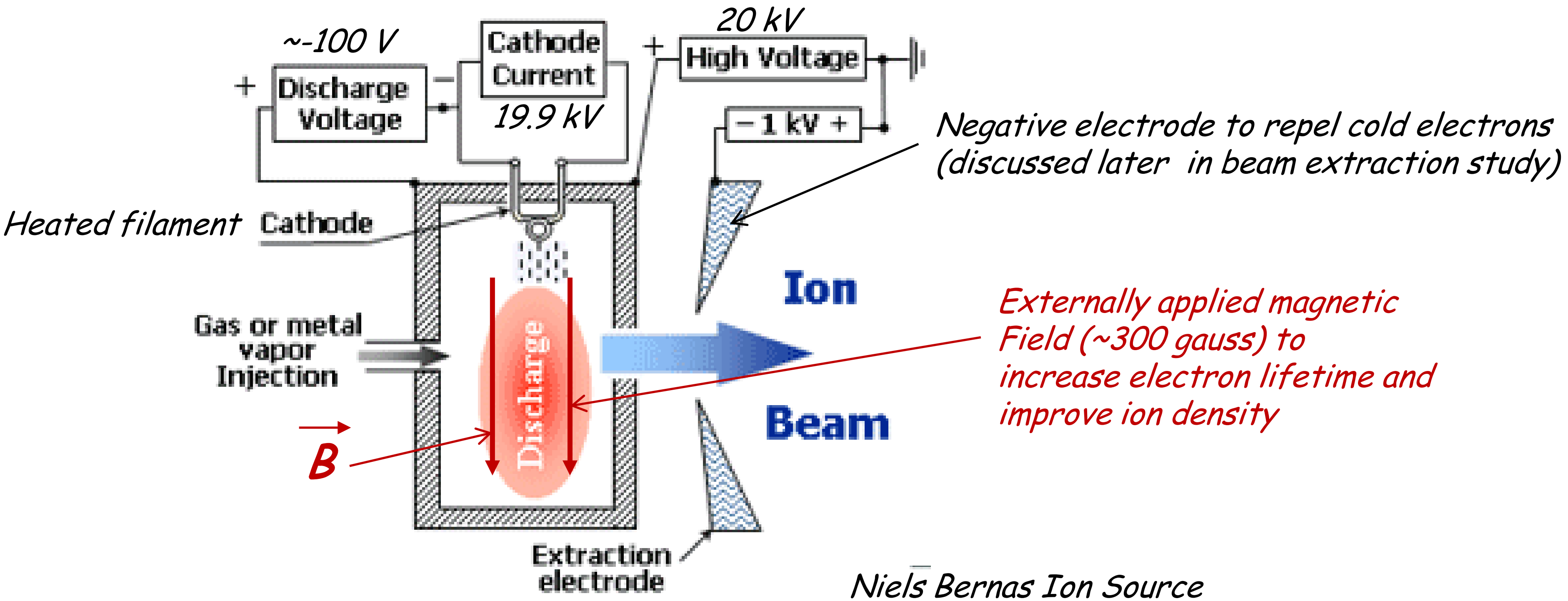
A selection of ion sources is presented. Many other exists…

- Filament Ion Source
- Surface Ionization Ion Source
- Negative Ion Sources
- Electron Beam Ion Source
- Laser Ion Source
- Electron Cyclotron Ion Sources

Annex: Beam Extraction and beam selection

Filament Ion Source

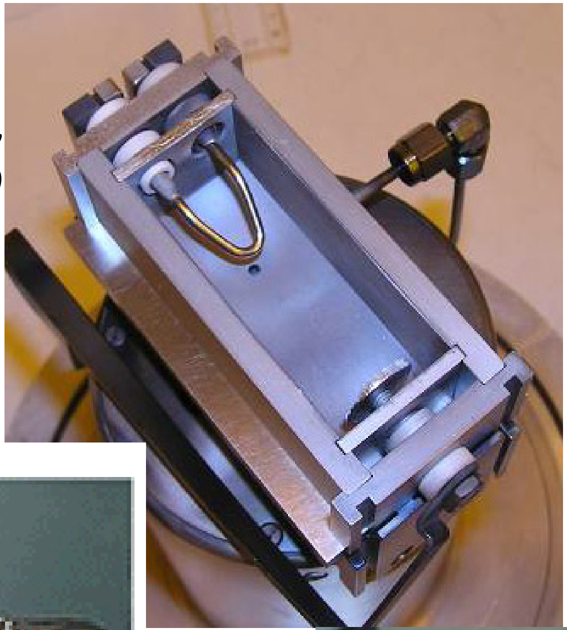
- Filament ion sources use a primary themionic GUN to generate electrons with energy E~100 eV
- Atom ionization is done by direct electron impact
- Very simple and robust design, used in industrial implanters
- 1+ beams are generated, with few % of 2+ & 3+ charge states
- Example here is the **Niels-Bernas Ion Source**
- Drawback: aging of filament by Sputtering
- 20 mA beam => some 10 hours / 2 mA beam => some 100 hours

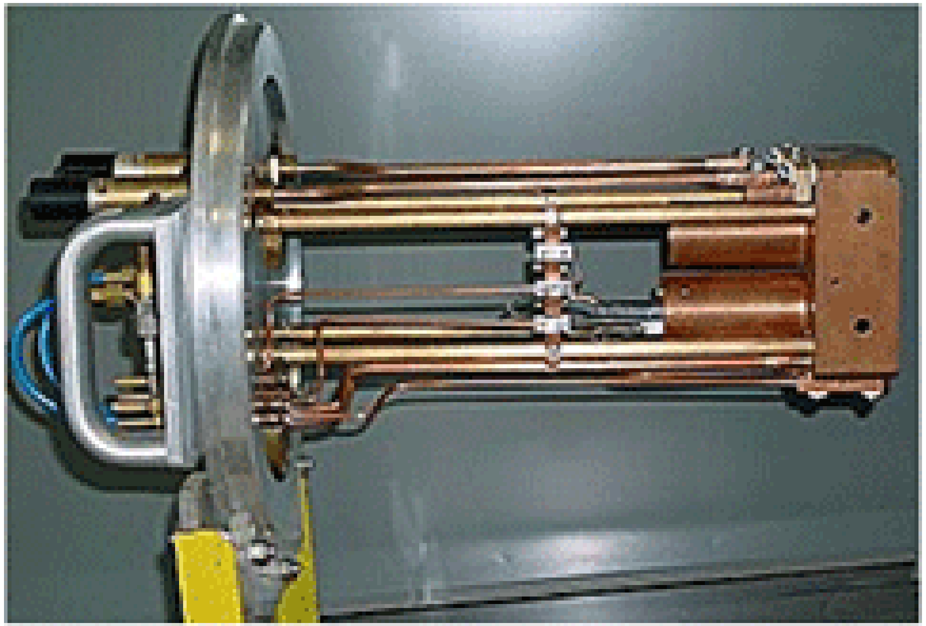


Niels Bernas Ion Source

Filament Ion Source

View of the plasma Chamber equipped with an electron repeller (see next slide)



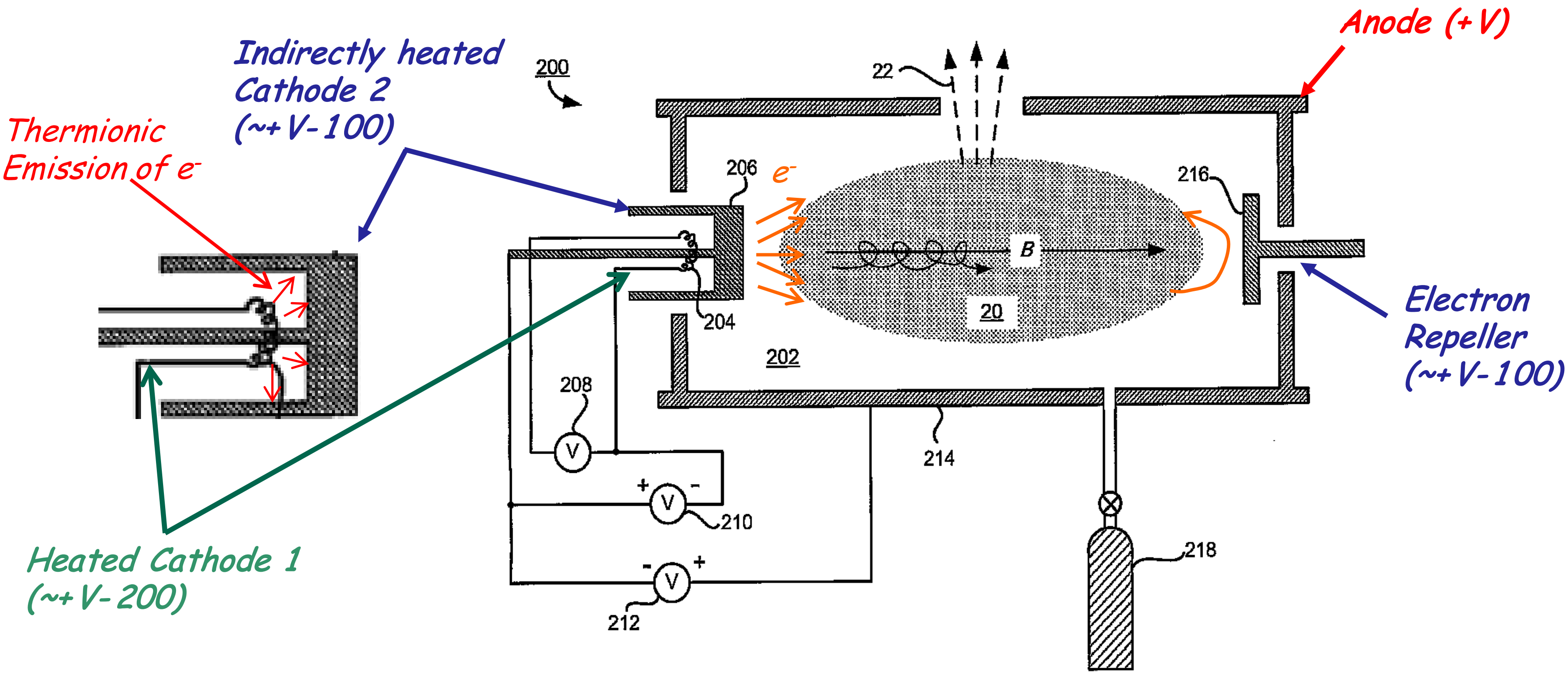


View of the source and its mechanics, ready to be plugged in ionic implanter

View of the beam extraction slit

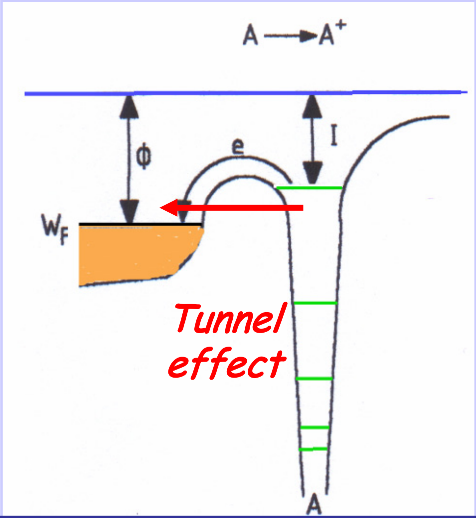
Up to date filament Ion source

- Indirectly Heated Cathod (IHC) Ion Source
  - Modified Niel-Bernas Source
  - Enhanced filament lifetime at high current thanks to the bulk cathode # 2
  - At 20 mA => lifetime is 200-800 h, depending on ions to produce
  - electron repeller added to improve electron confinement
  - Dipole Magnetic field confinement



Surface Ionization Source

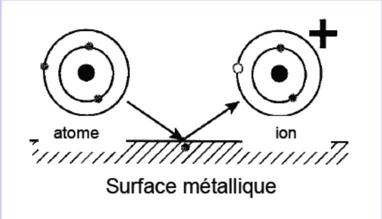
A metal with High Work Function can steal an electron to an adsorbed atom through Tunnel Effect



SAHA formula :

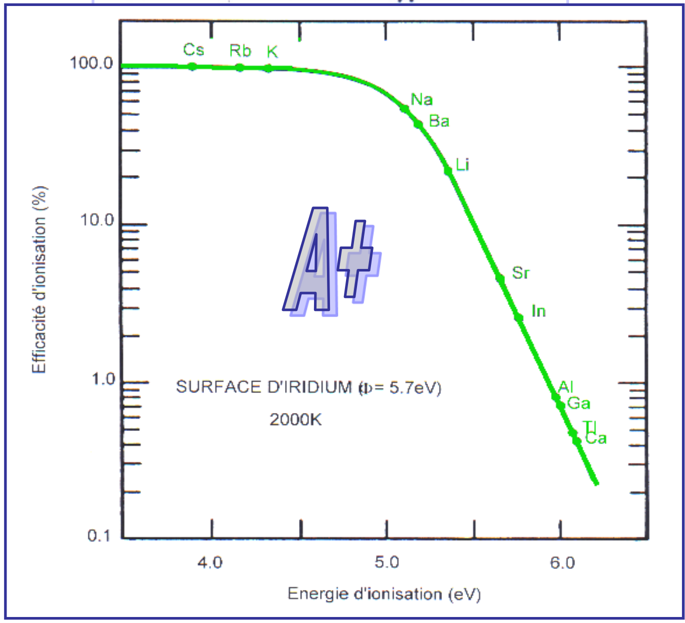
$$\frac{N^+}{N_0} = C^+ e^{((\Phi - I)/kT)}$$

- *First Ionisation Potential I of adsorbed atom*
- *Work function Φ of metal*
- *kT Temperature of metal*
- *Provided Φ > I*



Works with High Φ metals and low I atoms

- *Metals used : W-Ox,Ir,Pt,C,Re,W*
- *Atoms ionized : Alkalines, Alkaline earths*

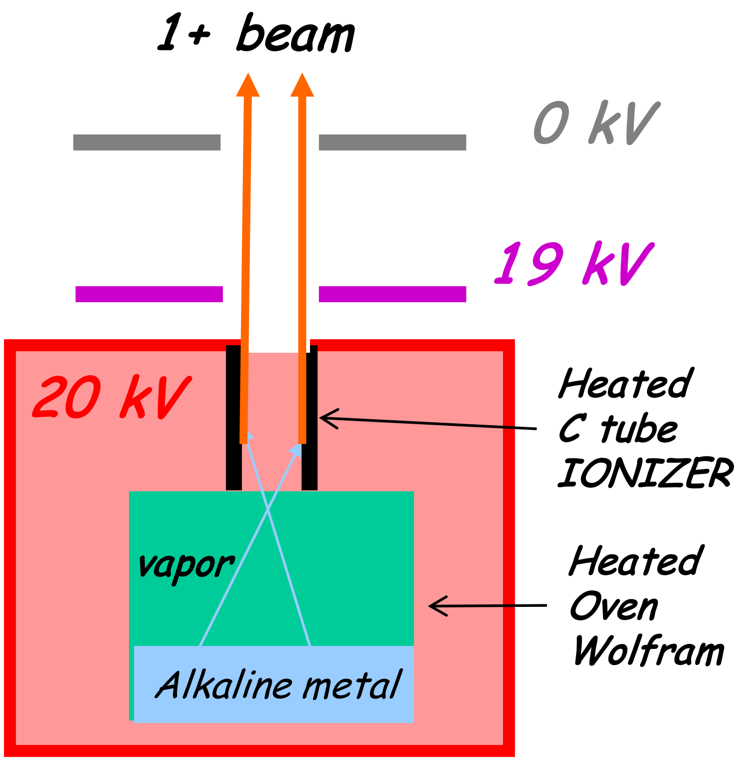


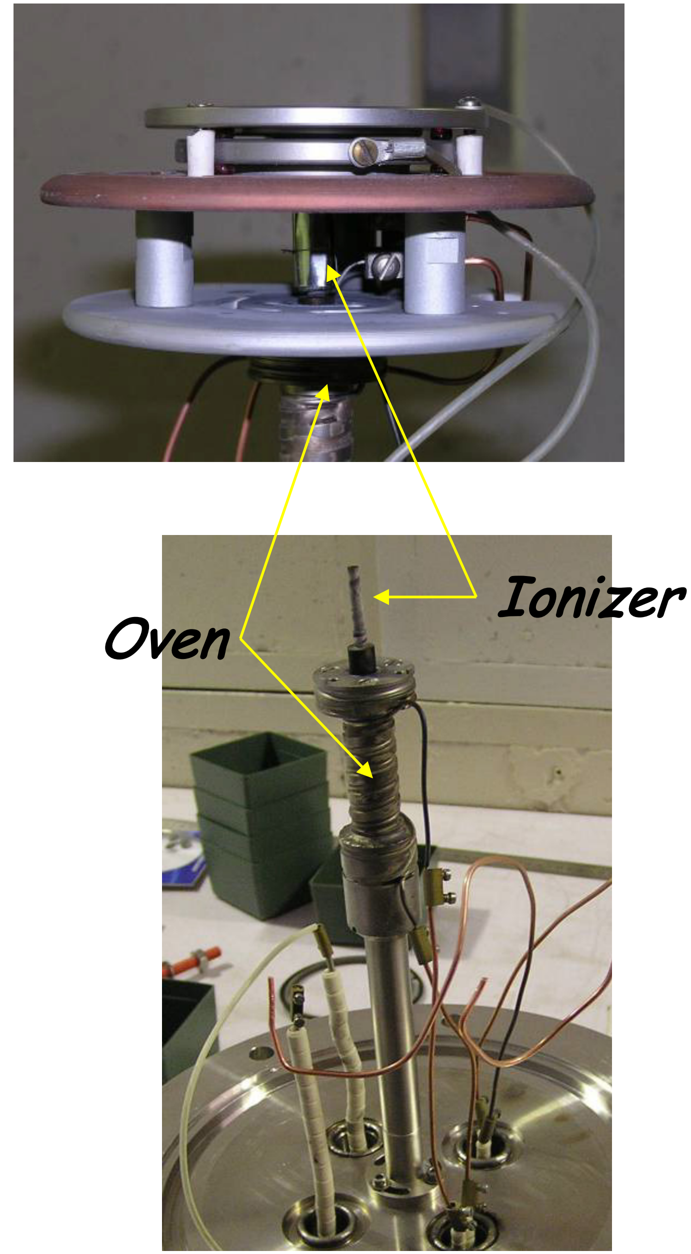
High Temperature helps to desorb atoms

Very efficient method, very selective technique

Surface Ionization Source

- An alkaline metal is heated in an oven
- Atoms evaporates toward a heated ionizer tube made up with a high work function metal
- Atoms are adsorbed to the wall
- Atom desorbed by high kT with one e^- stolen by the metal => ionization

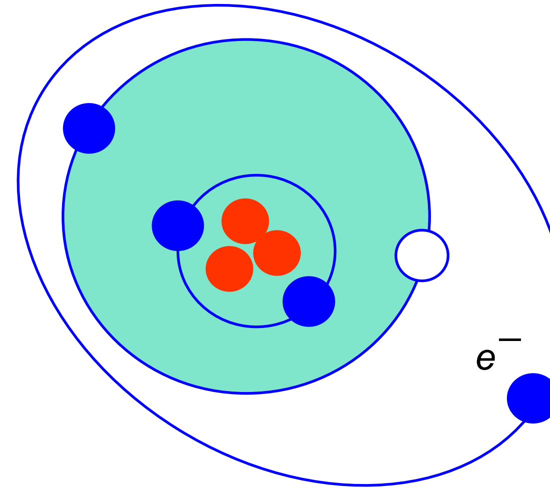




Negative Ion Sources

Next Slides Materials from M. Stockli, ORNL, USA and J. Arianer, IPNO, France

- **What is a Negative Ion?**
  - Atoms with unclosed shells can accept and extra electron and form a stable ion with net charge of -e
  - The stability is quantified by the Electron Affinity, the minimum energy required to remove the extra electron.
  - The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for Ti^{-} and 3.6 eV for Cl^{-}.



- **Negative ions are very fragile!**
  - (M)any Collision can break the binding (see next slides).

H 73																	He 0
Li 60	Be 0											B 27	C 154	N 7	O 141	F 328	Ne 0
Na 53	Mg 0											Al 43	Si 134	P 72	S 200	Cl 349	Ar 0
K 48	Ca 2	Sc 18	Ti 8	V 51	Cr 64	Mn 0	Fe 16	Co 64	Ni 112	Cu 118	Zn 0	Ga 29	Ge 119	As 78	Se 195	Br 325	Kr 0
Rb 47	Sr 5	Y 27	Zr 41	Nb 86	Mo 72	Tc 53	Ru 101	Rh 110	Pd 54	Ag 126	Cd 0	In 29	Sn 107	Sb 103	Te 190	I 295	Xe 0
Cs 45	Ba 14	Lu 50	Hf 0	Ta 31	W 79	Re 14	Os 106	Ir 151	Pt 205	Au 223	Hg 0	Tl 19	Pb 35	Bi 91	Po 183	At 270	Rn 0

0.75 eV for H^{-}

0.08 eV for Ti^{-}

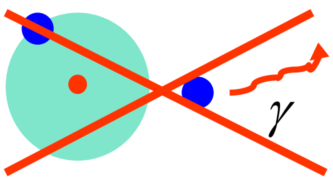
3.6 eV for Cl^{-}

1eV~96,5 kJ/mol

*Periodic table of **electronic affinity** in kJ/mol, actinids not represented*

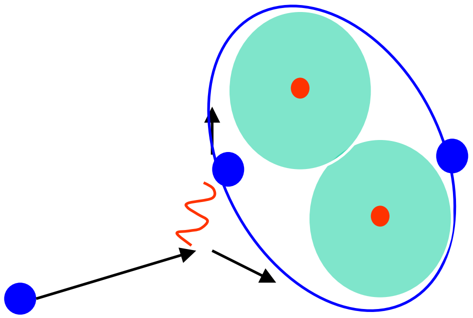
Negative Ion Production in a plasma (Volume ionization)

- The creation of negative ions is exothermic. Excess energy should be dumped to a third particle
  - **Radiative Capture** = direct electron attachment
    e.g. $H + e^- \rightarrow H^- + \gamma$
    → Very low probability (eg $\sigma \sim 5 \cdot 10^{-22}$ cm² for H), rare event

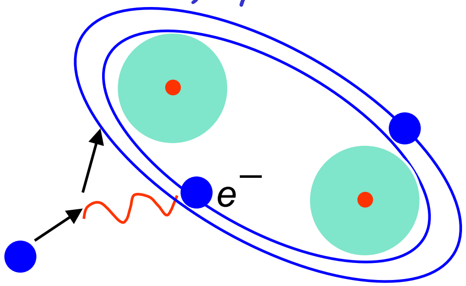


Unlikely radiative capture

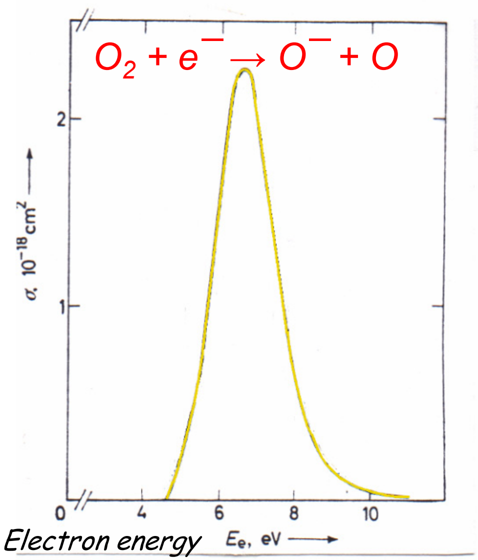
  - **Dissociative Attachment** = the excess energy in the collision can be transferred to a third particle when dissociating a molecule:
    $AB + e^- \rightarrow A + B + e^-$
    $AB + e^- \rightarrow A^- + B$ (sometimes)
    → Higher probability to occur (e.g. $\sigma \sim 10^{-20}$ cm² for H_2 and E_e >10 eV)
    → Requires low energy electrons (~1-100 eV)
    → The dissociative attachment is enhanced if the molecule is first excited to a high vibrational state (near breakdown) by a fast electron
    → e.g. $H_2 + e^-(\text{fast}) = H_2^{v} + e^-$
    ($\sigma \sim 5 \cdot 10^{-18}$cm² for $4 \le v \le 9$ and E_e >15 eV)
    → Then $H2^{v} + e^-(\text{slow}) = H + H^-$
    ($\sigma \sim 3 \cdot 10^{-20}$ cm2 for $4 \le v \le 9$ & Ee<1eV)



Likely dissossiative attachement



Very likely Dissociative attachement on an excited molecule

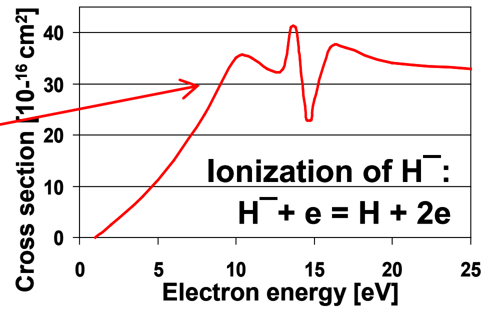


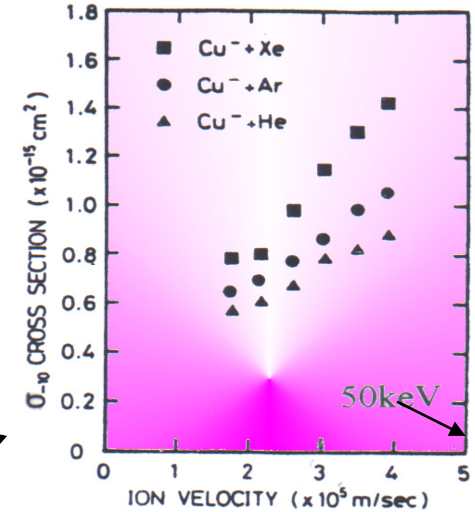
Electron energy

  - **3 Body Collision:**
    $A+B + e^- \rightarrow A^- + B$

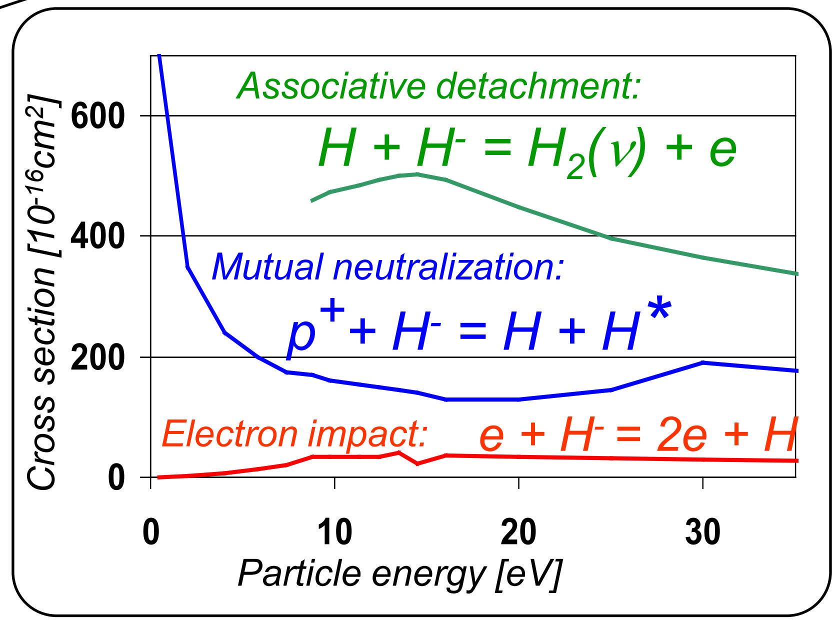
Negative Ion Losses in a plasma (Volume ionization)

- Negative ions are very easy to loose in a plasma
  - o **Electron impact ionization:**
    $A^- + e^- \rightarrow A + 2e^-$
    - → For H^-: $\sigma \sim 30 \cdot 10^{-16}$ cm²
    - → So σ 30 times larger than for a typical neutral atom!!





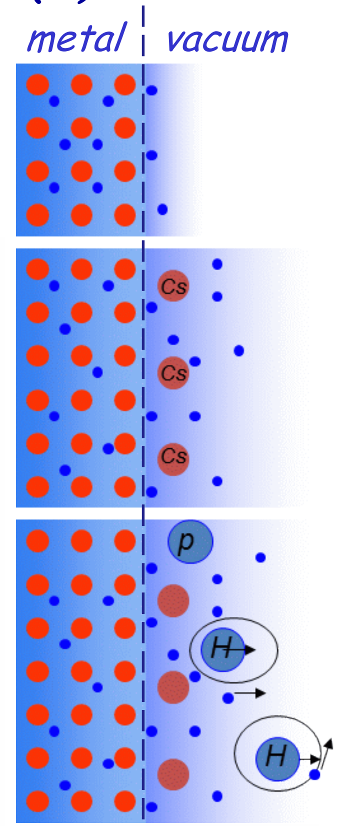
  - o **Mutual neutralisation** (Recombination)
    $A^- + H^+ \rightarrow A + H$
    - → *Dominant process for $E_{p+} \sim eV$*
    - → *For H^-, $\sigma = 7 \cdot 10^{-14}$ cm² for $E_{p+} \approx 0.5eV$*
  - o **Collisional Detachment:**
    $A^- + B \rightarrow A + B + e^-$
  - o **Associative Detachment:**
    $A^- + B \rightarrow AB + e^-$
- Negative ions are totally destroyed a few cm away from their place of birth in a $n \sim 10^{13}$ cm^{-3} plasma
- They must be extracted close to their place of birth



Exemple of H^- destruction process

Surface Production of Negative Ions

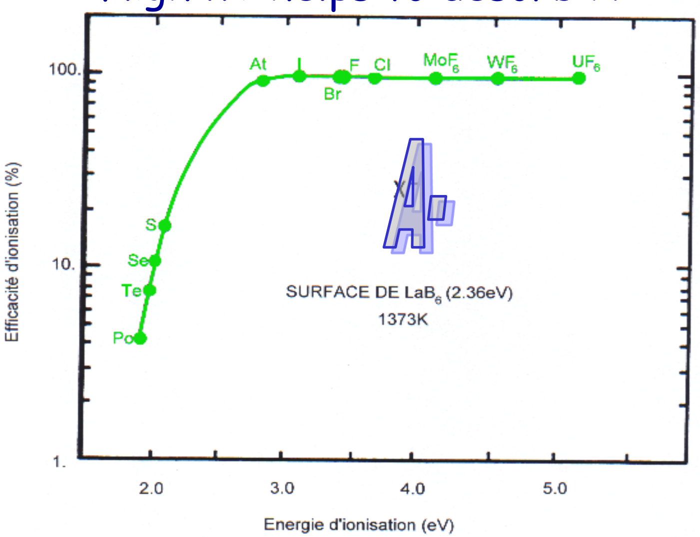
- As seen in the Electron source part, Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface.
- Alkali metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, **alkali atoms** can **lower the surface work function** *(Φ)* to values even below their bulk work function, e.g. ~1.6 eV for Cs on Mo.

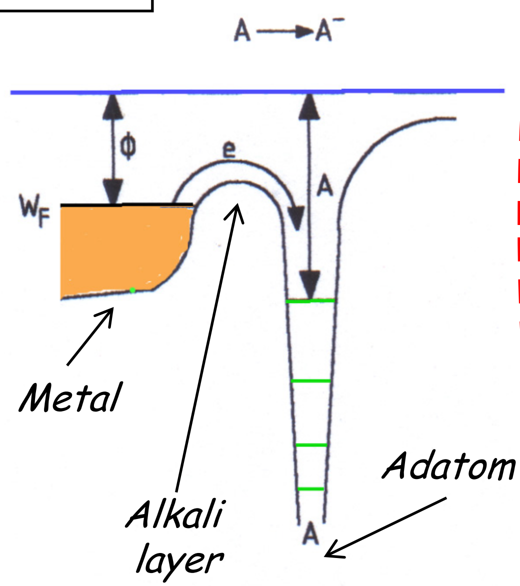


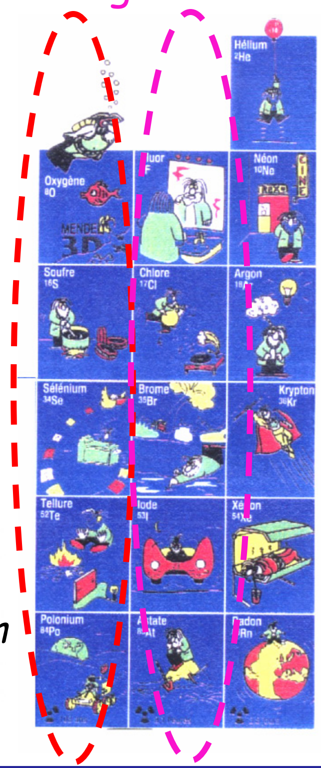
- Electrons from metal can be captured by atoms stuck on surface (adatoms) through **tunnel effect**, provided ***A*> Φ**
- Surface ionization works efficiently with Halogens and Chalcogens
- Saha Formula:

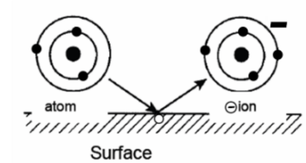
$$\frac{N^-}{N_0} = C^- e^{((A-\Phi)/kT)}$$

- High kT helps to desorb A^-





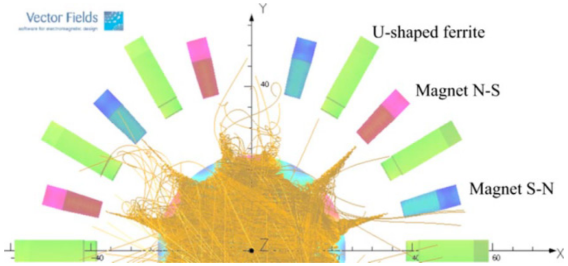


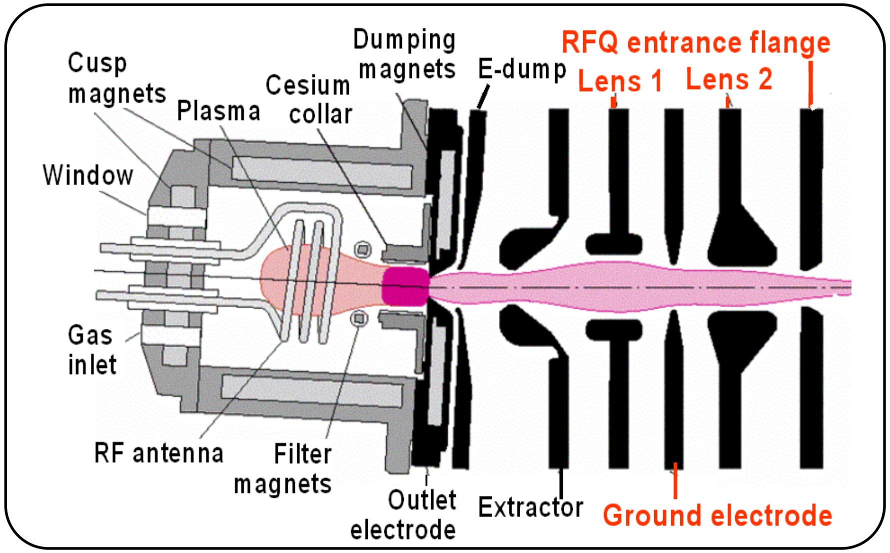


Radio Frequency Negative Ion Source - ORNL

- Example of the ORNL H^- Ion Source
  - A multicusp magnetic structure increase plasma confinement
    - → Permanent magnets

Trajectories of e⁻ in a CUSP magnetic structure (CERN), Rev. Sci. Instrum. 81, 02A723 (2010))

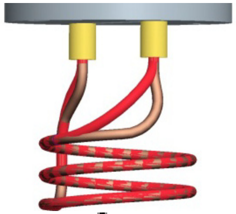




  - H_2 gas is injected on the rear
  - A RF antenna under vacuum generates the plasma (see next slide) and ionizes hydrogen to produce H^+, H_2^ν, e^-
  - Two filter magnets (SmCo 200 Gauss) repel hot electrons generated by the RF. (e.g. a 35 eV electron turns around on a 1 mm radius).
    - → Cold electrons and cold ions undergo very many collisions with other particles, resulting in a diffusion process which favors the cold charged particles ($v_{diff} \sim T^{-\frac{1}{2}}$). Therefore the electron temperature decreases exponentially through the filter and extraction region.
    - → Excited neutral molecules migrate freely to the extraction region.
    - → The cold electron colliding with exited molecules near the outlet produce the extractable H^- ions => **~10 mA achievable in the volume**
  - A Cs collar is present near to the source extraction to boost H^- production Source is pulsed with 6% Duty Cycle to produce 50 mA of H^-

Radio Frequency Negative Ion Source – Plasma Generation

- The 3rd Maxwell Equation, $\nabla \times E = -\partial B/\partial t$ describes a curling E field generated by a changing magnetic field in absence of any charge.
- A changing magnetic field B can be produced with an alternating current $i = i_o \cdot \cos(\omega t)$ in N windings with radius r_o:
  → $B = \frac{1}{2} \cdot \mu_o \cdot N \cdot i / r_o$ *(Biot-Savart)*
- Now integrate Maxwell's 3rd equation for Faraday's law:
  → $\int E \cdot ds = -d\Phi_B/dt = -d/dt \int B \cdot dA$
- and solve for E: $E(r,t) = \frac{1}{4} \cdot r/r_o \cdot \mu_o \cdot \omega \cdot N \cdot i_o \cdot \sin(\omega t)$
- The **electric field** accelerate electrons and ions and favors electron impact ionization => PLASMA

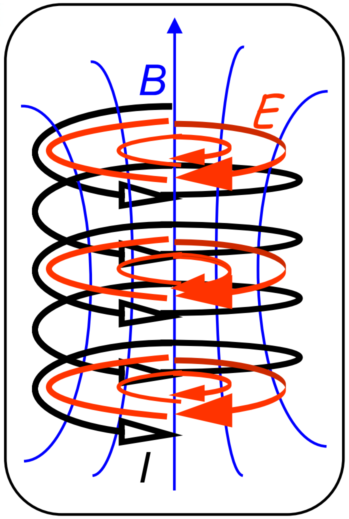


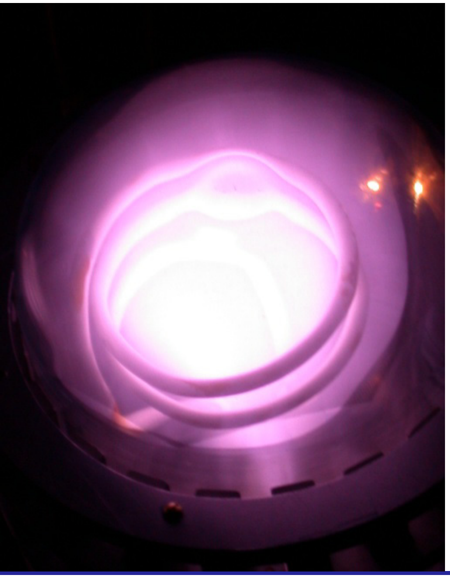
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

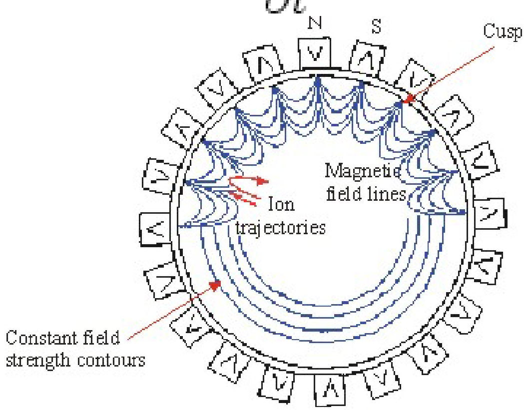
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$





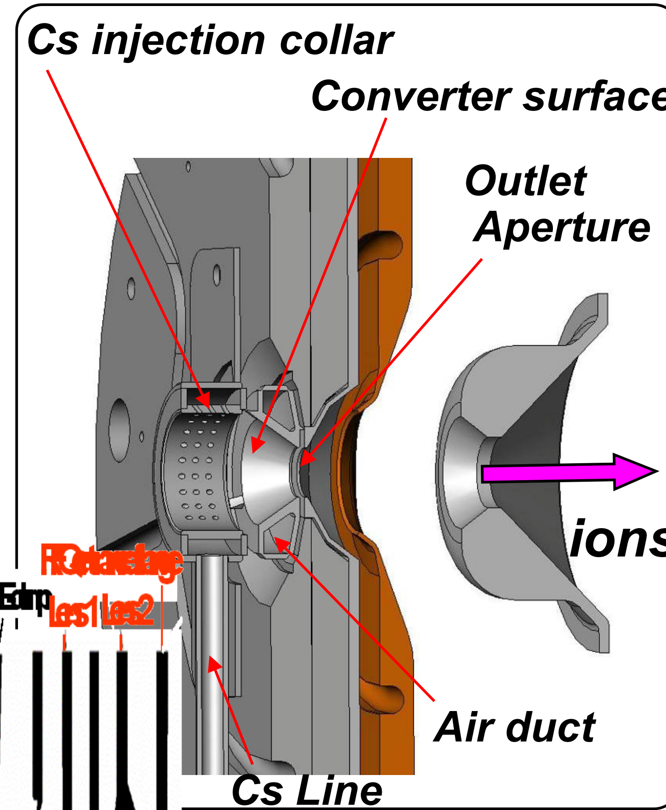
→ The E field in the center is ~zero
→ The E field outside the winding is ~zero
→ The E field is most intense on the inside of the coils and parallel to the windings

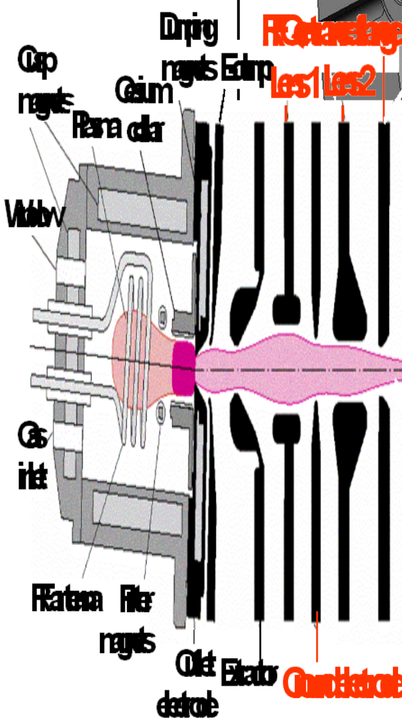


- The plasma is mostly generated near the inside of the windings.
- The RF causes the plasma to drift in circular direction.
- The multicups field guides the drifting plasma towards the center.

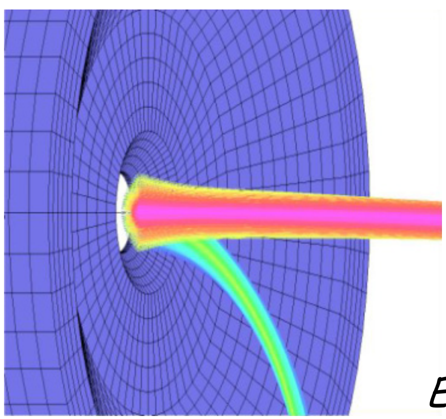
RF Negative Ion Source – Cesiation System and Beam Extraction

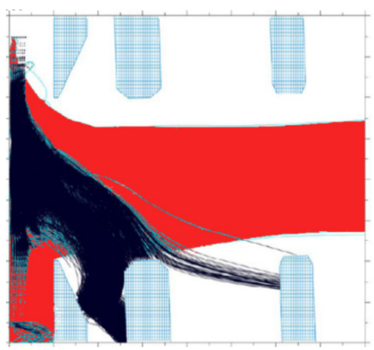
- **Cesium system:**
  - Cs flux controlled by an external oven temperature (ORNL/Fermilab design)
- **Gain of H^- current:**
  - 10 mA (no Cs) -> 50 mA (Cs)
  - pulsed operation (6% Duty Factor)
- **H^- extraction**
  - Dumping magnet in the extraction area to deviate electrons extracted
  - Special Electrode to dump co-extracted electron beam





- *Tilt of the source to have H^- extraction on axis*



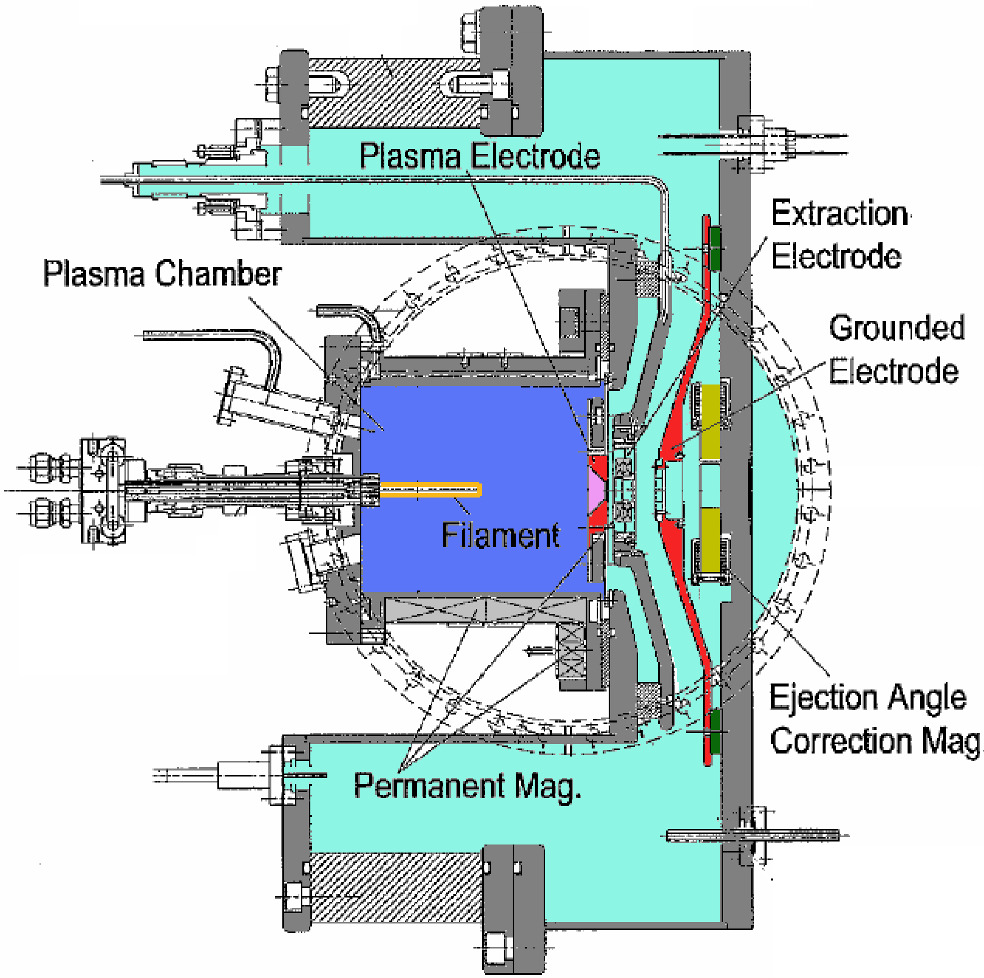


Electron deviation in the Extraction gap

Hot Cathode Negative Ion Source

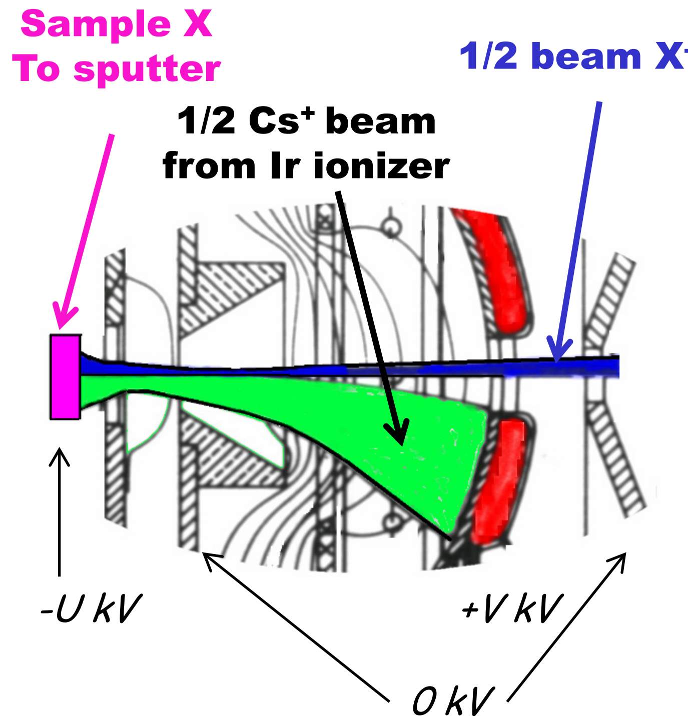
- J-PARC, Japan
  - Slow Electrons created by a heated cathod filament
  - Multicusp magnetic field (permanent magnets)
  - Cs Free
  - 0.5ms pulses, 25Hz, 50kW
  - Intensities → 30mA H^-
  - Extraction in a dipolar magnetic field to dump electrons

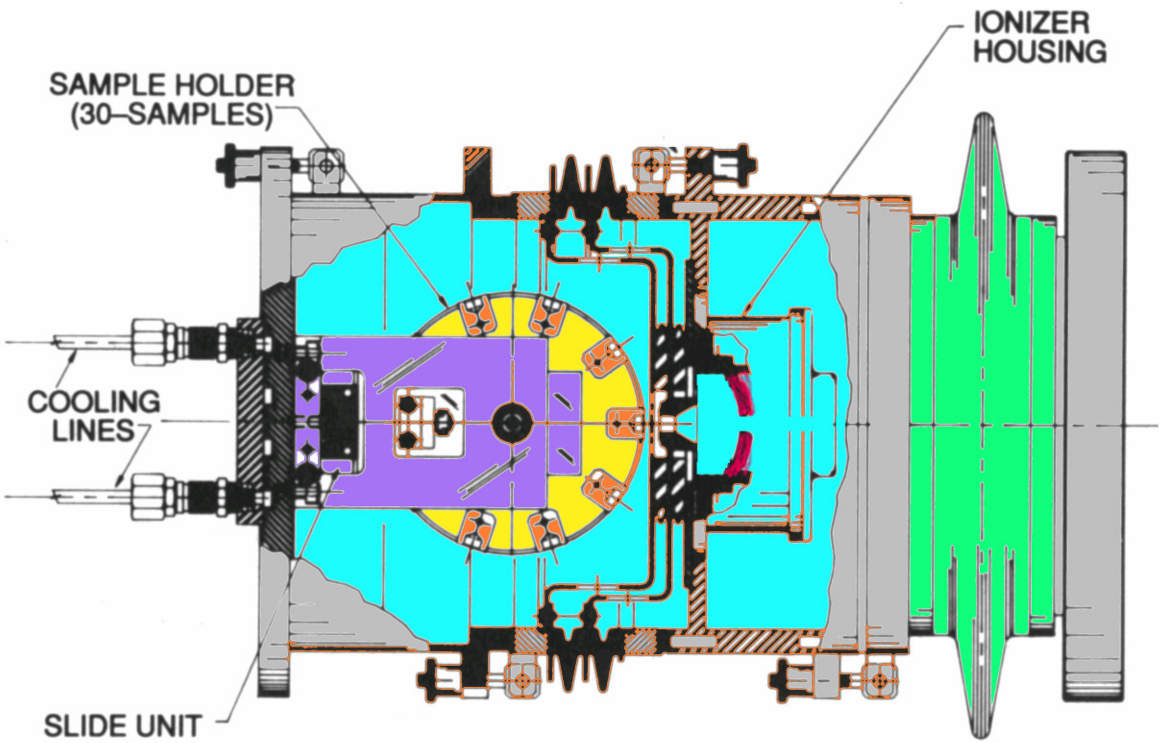
Many other types exist…



Negative Metallic Ion Source

- **Inversed Middleton Source**
  - A Surface Ionization Source produces Cs^+ beam around the extraction aperture of the source
  - Cs^+ Ions are accelerated toward a metallic sample holder set to a negative voltage
  - The Cs induces sputtering AND reduces the work function of the metal target

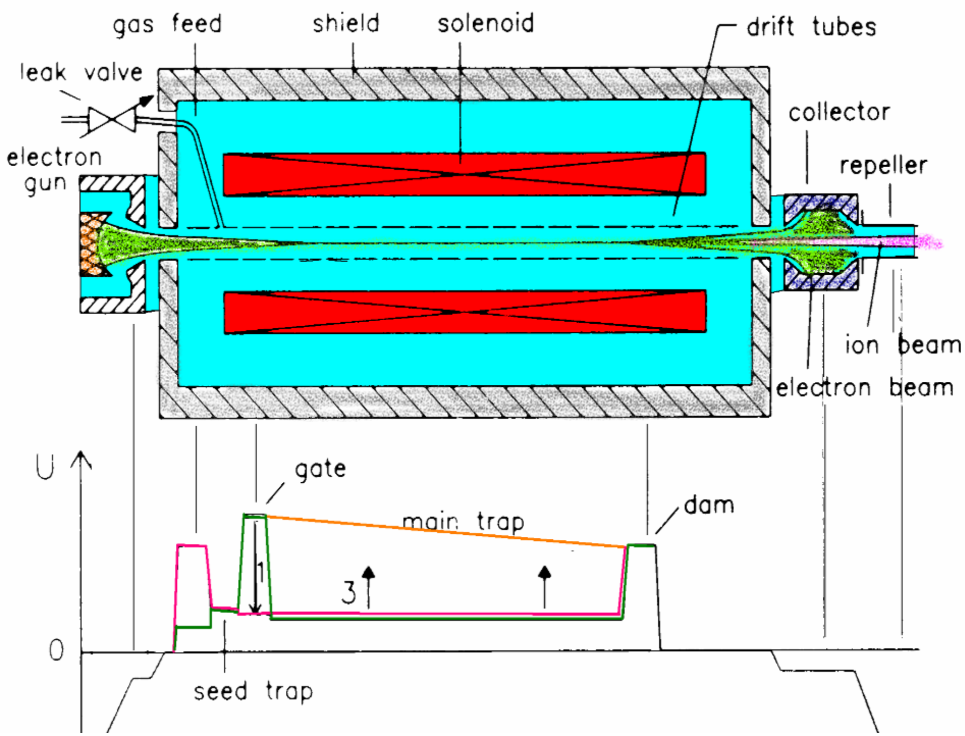




- *Negative Metal Ions are produced (helped with high kT)*
- *Rotation of Sample to sputter to increase beam time*

Electron Beam Ion Source (EBIS)

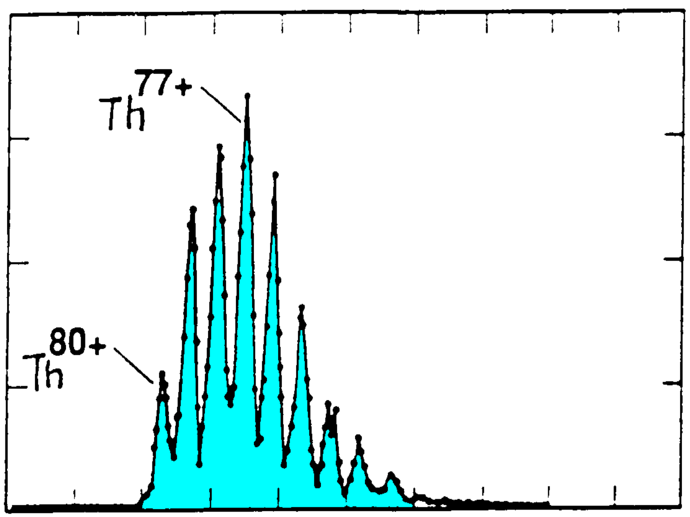
- Electron beam issued from a gun
  - injected as a Brillouin flow on the axis of a solenoid, to get very high current densities. Close to the collector, it is generally slowed down to save power.
- Stepwise ionization by e- impact.
  - The charge exchange is avoided owing to a pulsed neutral injection.
- Ion containment
  - due to the combination of the radial space charge e- potential well and a longitudinal voltage distribution applied on a series of tubes. The maximum charge number which may be trapped is **$Q+ \leq 10^{13}\ I\ V^{-1/2}\ L$**
- The source is cyclic
  - 3 phases : neutral injection, containment and expulsion,
  - obtained by programming the tube potentials. The source output is then limited. The variation of the containment time allows to adjust the CSD.
- EBIS can be used as a charge breeder
  - 1+ injection, cooking, n+ bunch extraction
- Low Pressure requirement: P< 10-9 mbar

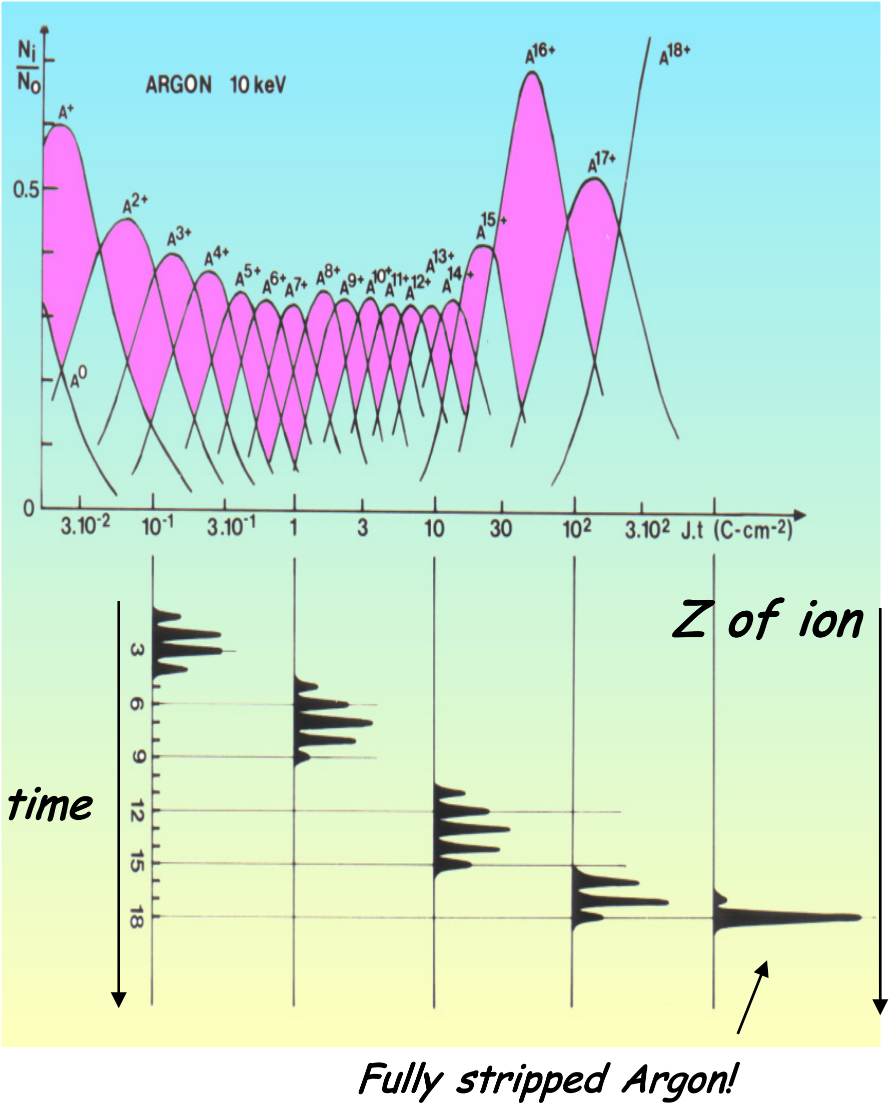


Electron Beam Ion Source (EBIS)

Production of Very High Charge state

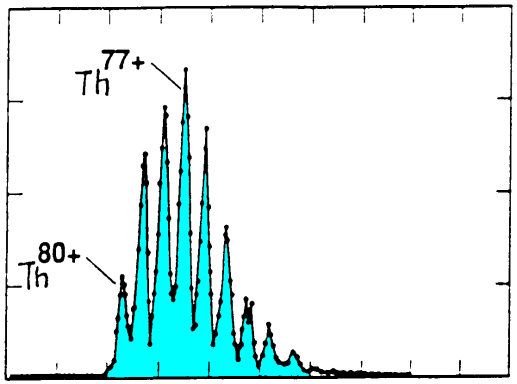
- The Ions charge state distribution increase with time
- Charge state distribution is narrow
- Ultra high charge state achievable
- Limited pulse repetition rate and beam intensity
  - → space charge in the trap
  - → Long Cooking time (10-100 ms)

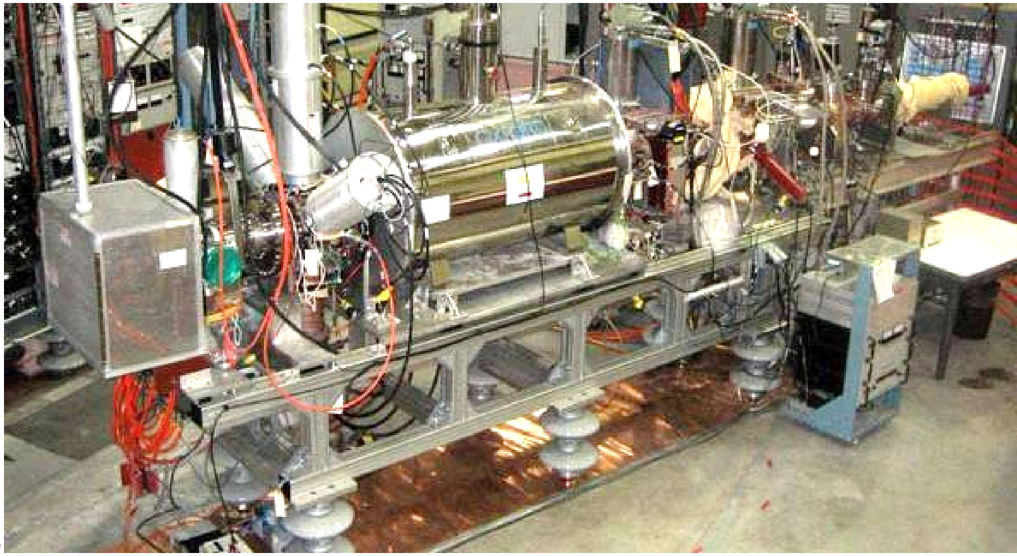




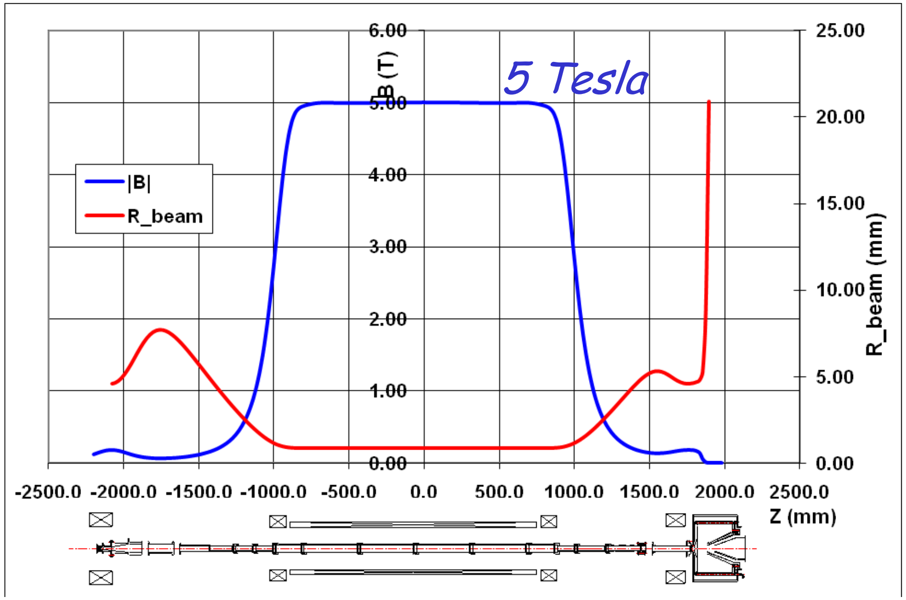
RHIC EBIS, BNL, USA

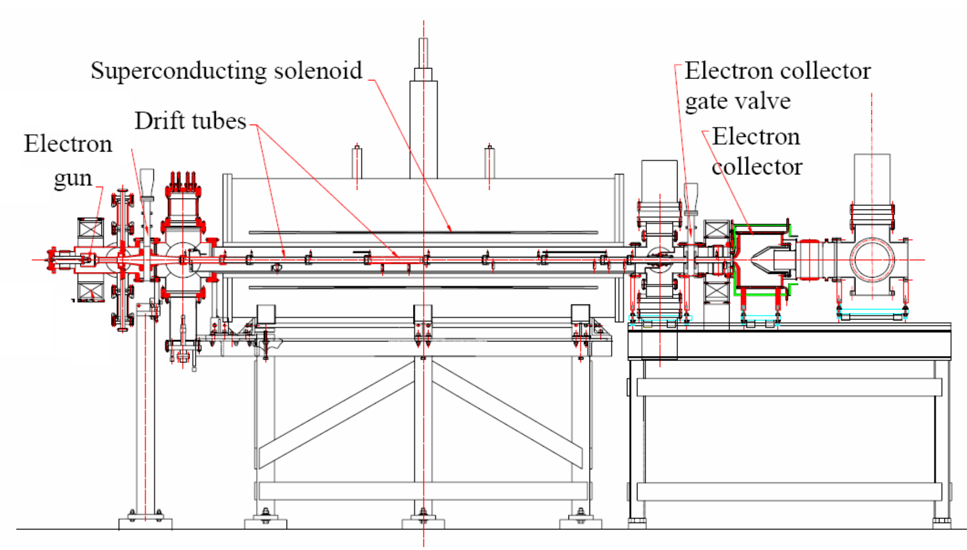
- High Intensity EBIS at RHIC
  - 1.7 mA – 10 μs – 5 Hz





Narrow charge state distribution for Th beam

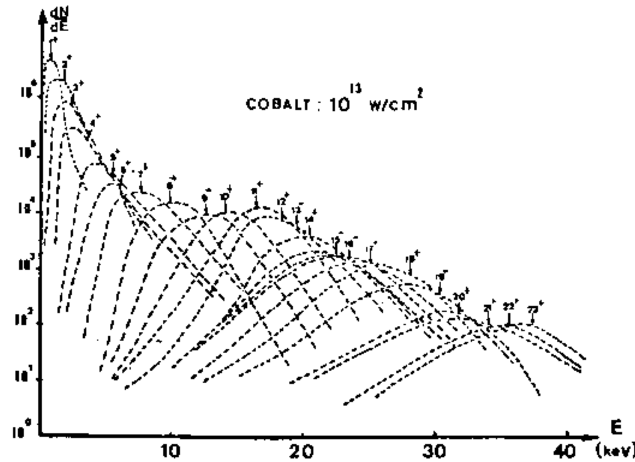


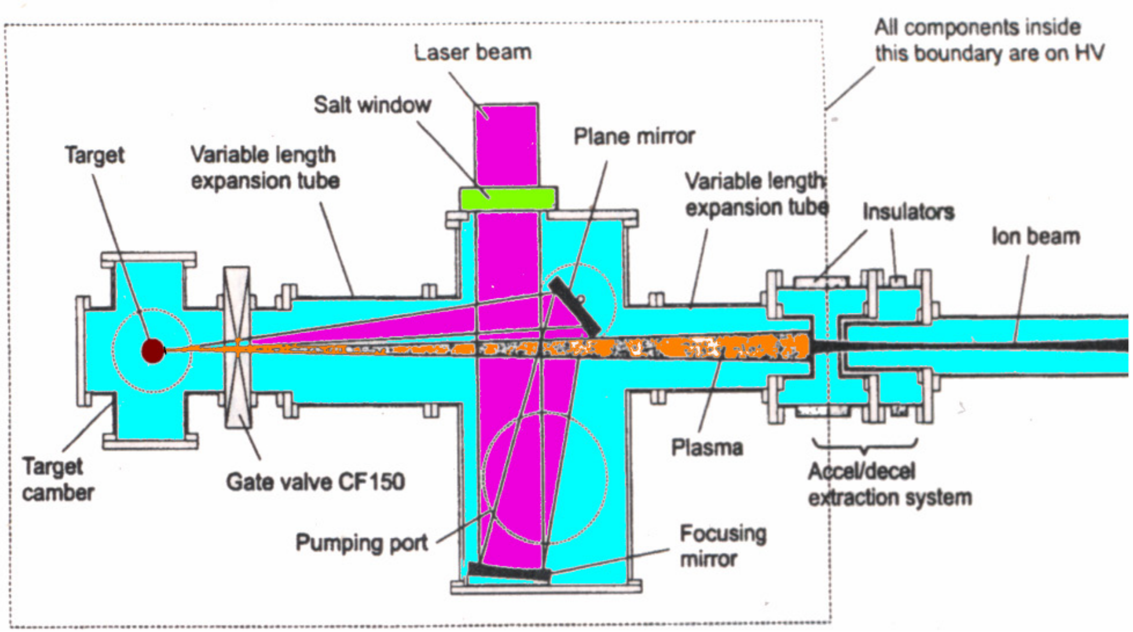


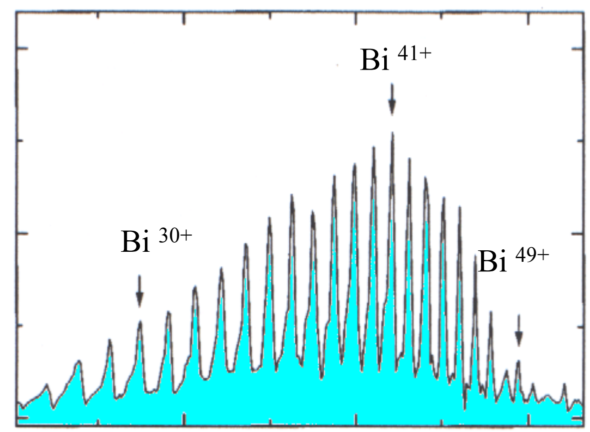
Magnetic field profile along the trap – *Electron beam envelope*

Laser Ion Source

- *A very strong power laser pulse evaporates matter and generates a medium to high charge state hot plasma*
  - *Very High density plasma*
  - *Complicated plasma physics*
  - *High charge state ions created*
  - *High currents*
  - *Very Hot ions (KeV to MeV)*
  - *Complicated extraction and process*
  - *Pulsed beams (~1 Hz)*





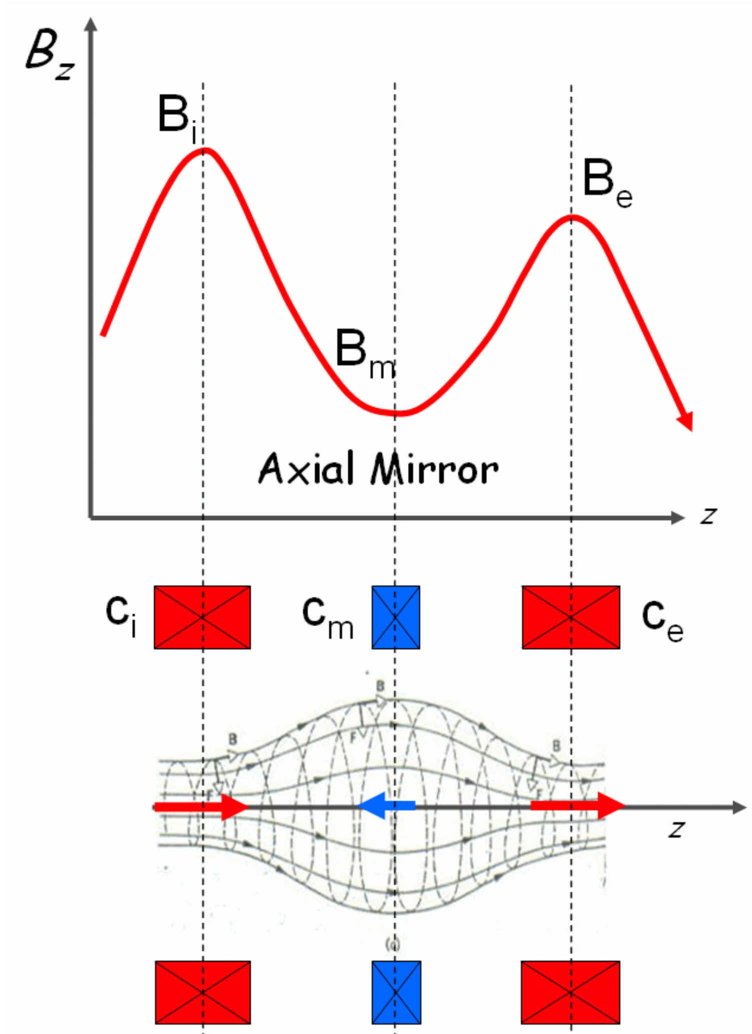


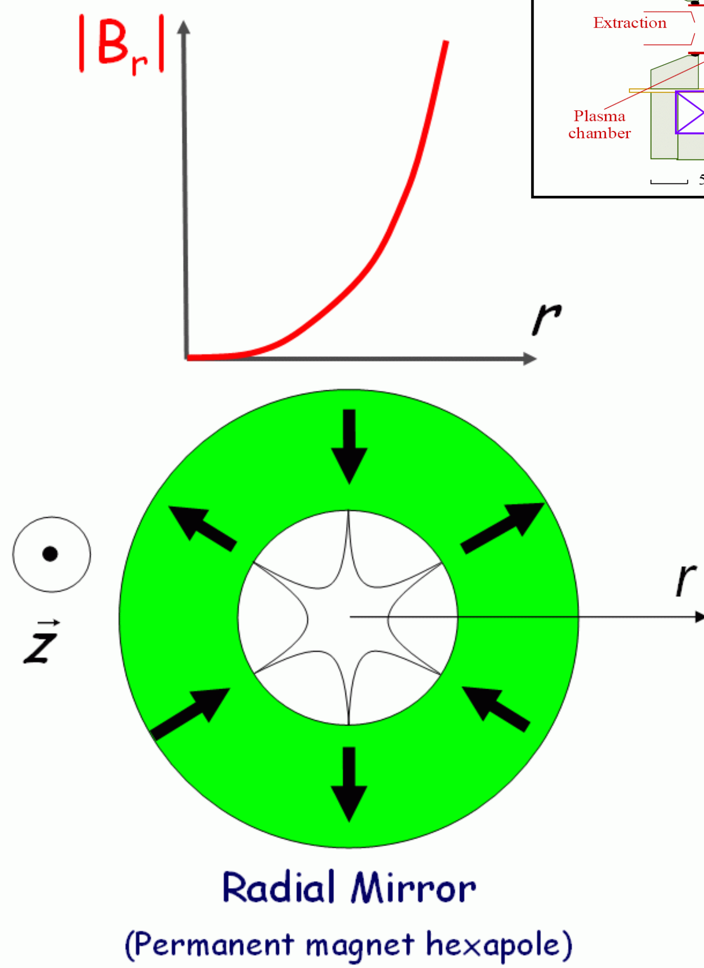
CERN LIS

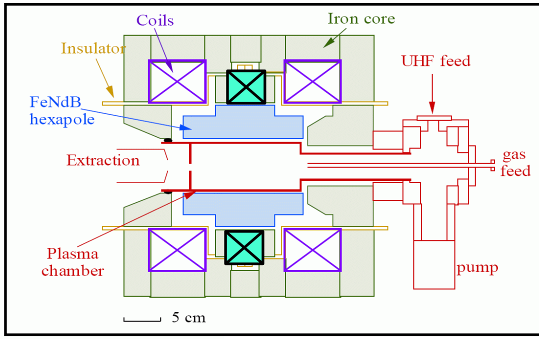
Specifications :
CO_2-N_2-He laser 100J-10^{13}W.cm^{-2}
pulses of 50ns at 1Hz
1.4 10^{10} Pb^{25+} per pulse

The Magnetic Bottle or min-|B| structure

A multicharged ECR ion source contains a complicated magnetic field to confine ions

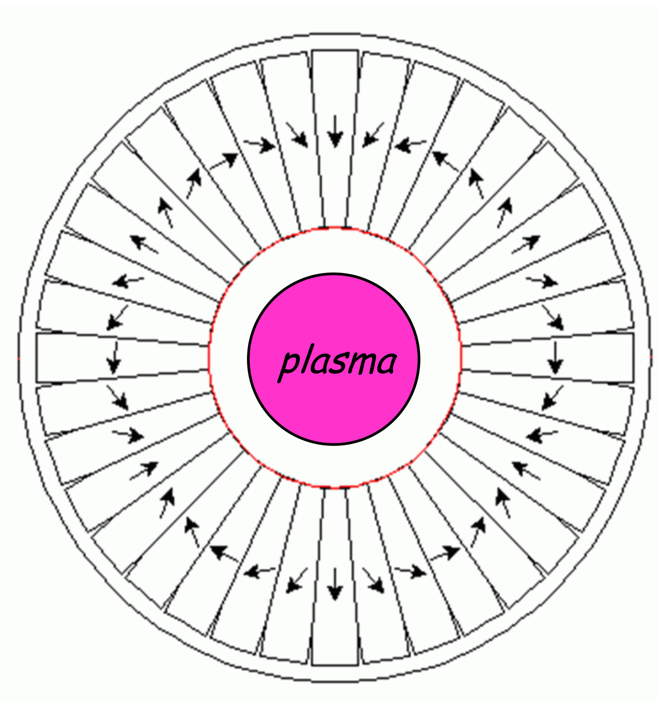






3 coils to tune the mirror ratio

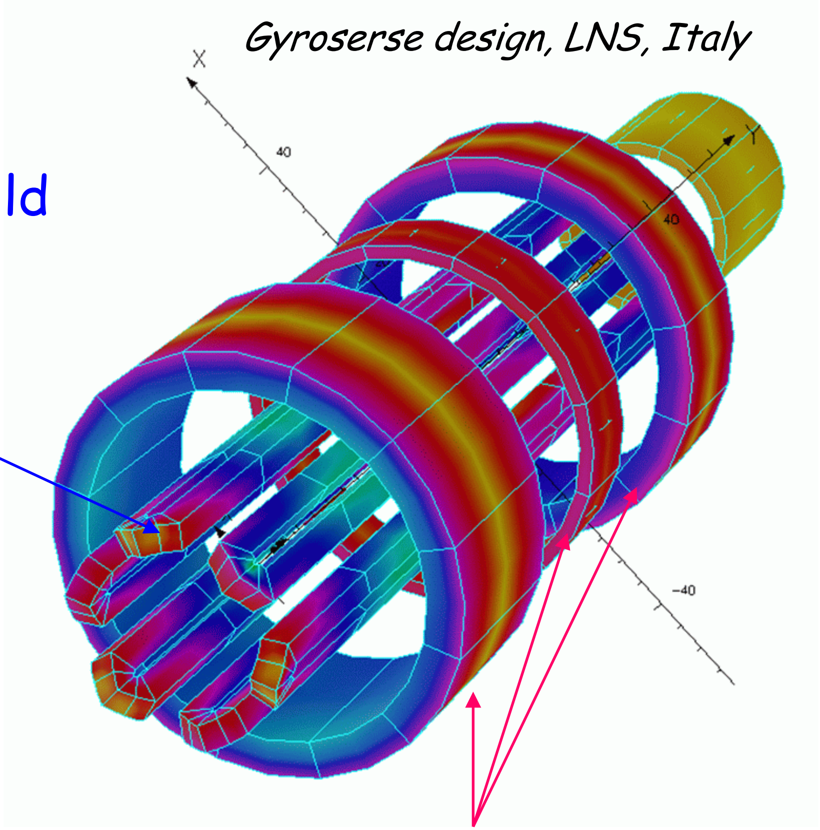
Permanent magnet hexapole



- HallBach Type structure :
  - eg : 36 magnets
  - 30° of magnetization angle between magnets
  - FeNdB magnets
  - SmCo magnets

- Typical magnetic intensity available in the plasma :
  - 1,2 to 1,6 Tesla
  - 2 Tesla max at magnet surface possible

Superconducting hexapole



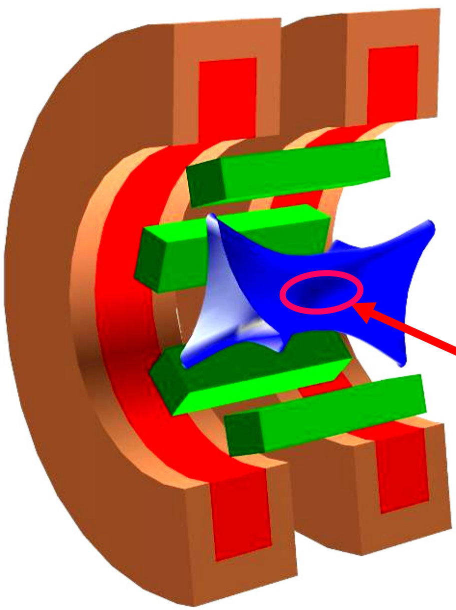
Advantages :

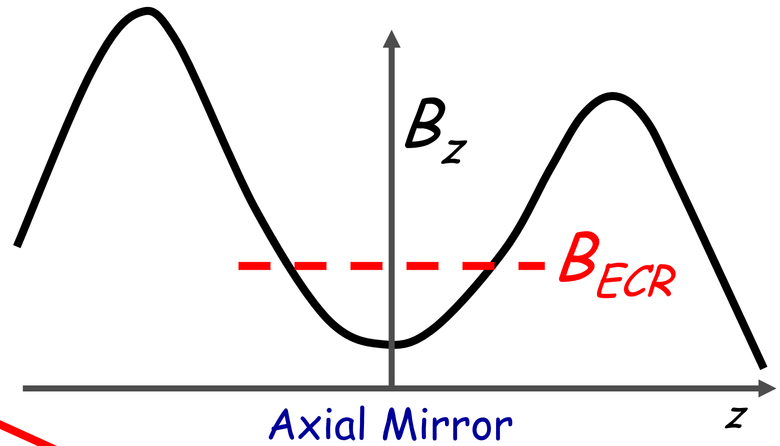
- High radial magnetic field (>2 T)
- Tunable radial field
- Large plasma volume

Inconvenients:

- Strong forces induced in the coils=> high risk @ building
- Expensive

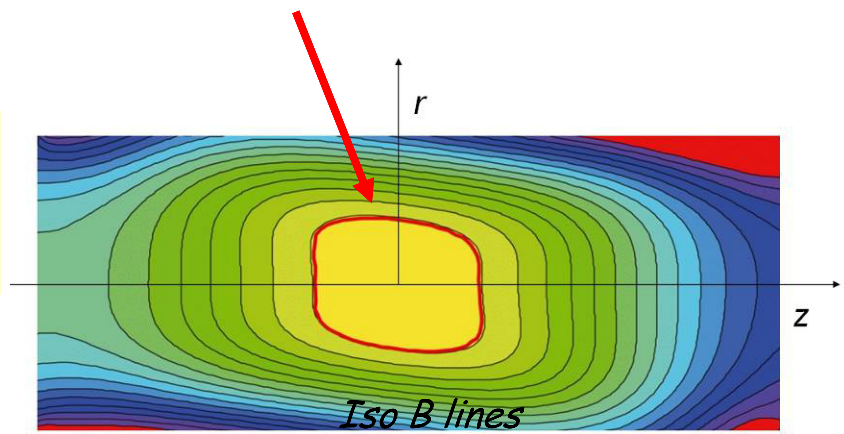
- The ECR Zone in an ECRIS: place where microwave frequency = electron cyclotron frequency

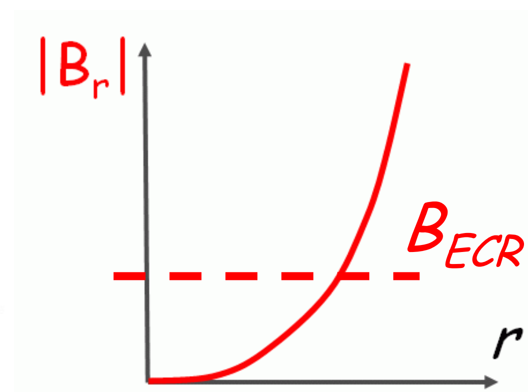




Electron Cyclotron Resonance	
Frequency	Magnetic Field
2.45 GHz	876 Gauss
18 GHz	0.64 T
28 GHz	1 T
60 GHz	2,1 T

$$\omega = \omega_c = \frac{qB_{ECR}}{m}$$



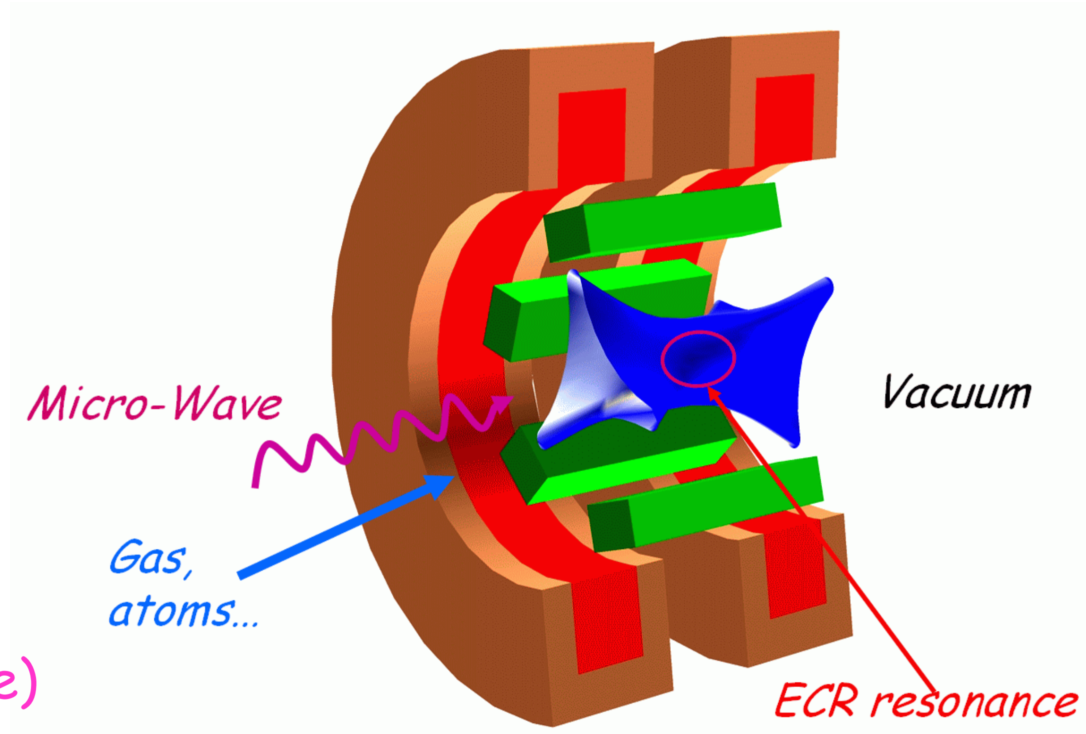


The ECR zone is usually a closed surface that do not touch walls

Plasma Generation :

- Gas, or metallic vapor injection

- Secondary vacuum
(=> ~~charge exchange~~)

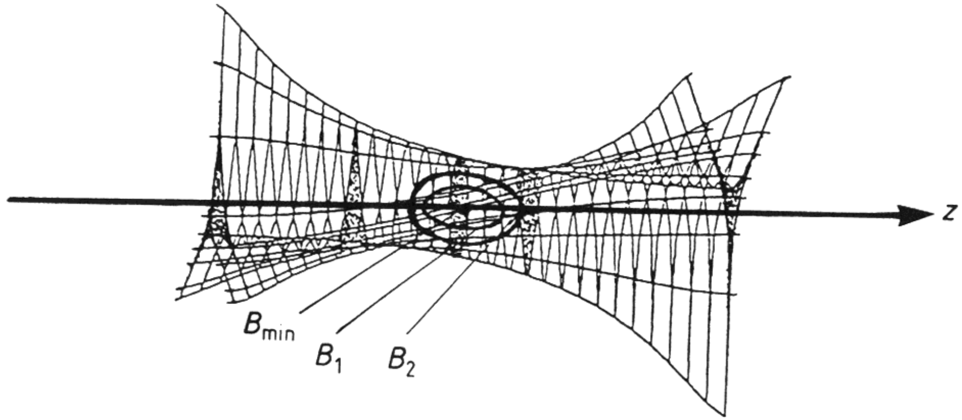


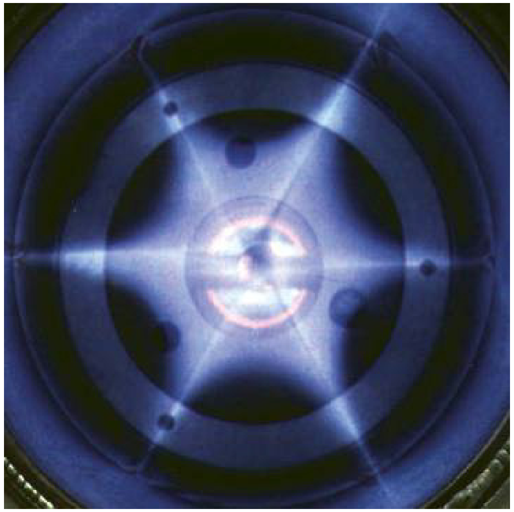
- Metallic cavity
(multimode : L>>λwave)

- Microwave injection

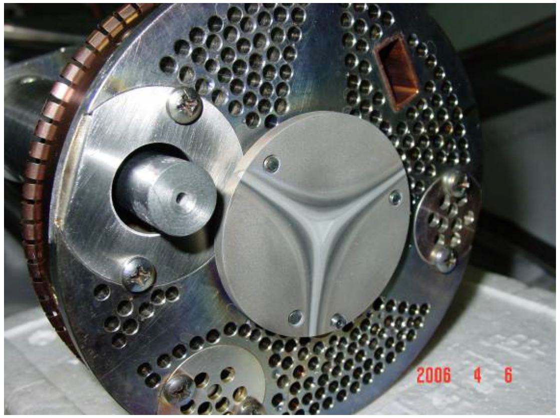
ECR PLASMA

➢ Plasma Shape :





3+3=6



Lanzou, China

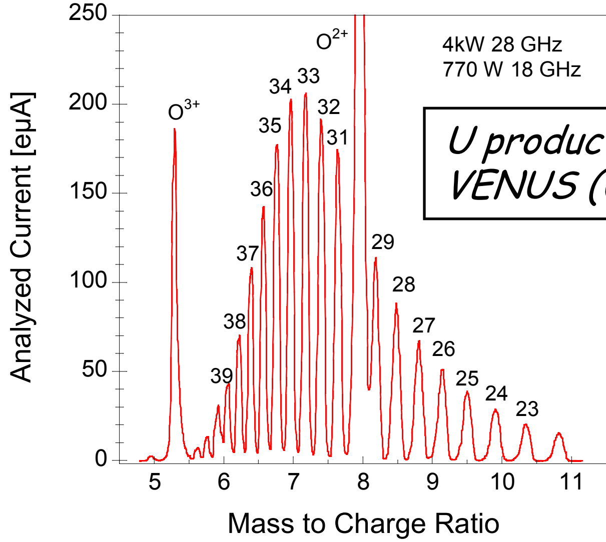
A star with 3 wings

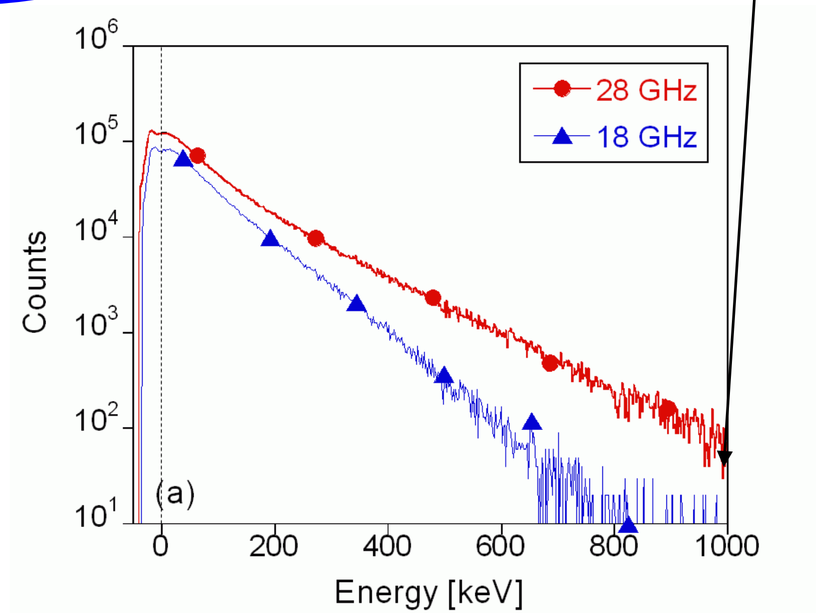
ECR Plasma characteristics :

- Microwave frequency f~2.45 -> 28 GHz
- B_{ECR} B~0.08 -> 1 Tesla
- Plasma density n~10^{11} ->10^{13} cm^{-3}
- Ion Temperature T_i~eV (cold plasma)
- Electron Temperature Te~ few keV (non-maxwellian)

Te_{max}-> MeV

⇒Multi-charged ions Production





Bremsstrahlung X-Rays Induced by electrons in VENUS Source (Berkely, USA)

->The frequency Scaling Laws

- Ions Current :

$$I \sim n_e$$ *Current extracted*

- Plasma Density :

$$n_e \sim f^2{}_{ECR}$$

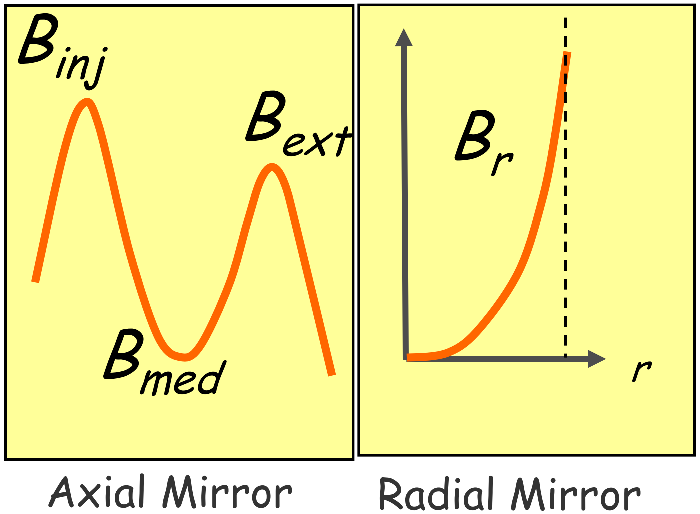
$$B_{ECR} = \frac{f_{ECR}}{28\ GHz}\ Tesla$$

f_{ECR} [GHz]	Λ [cm]	n_e [cm^{-3}]	$\Lambda_{0->1+}$ [cm]	$\tau_{0->1+}$ [µs]	B_{ECR} [T]
2.45	~12	7.4×10^{10}	~7	~10	0.09
14	~2	2.5×10^{12}	0.2	3	0.5
28	~1	$\sim 10^{13}$	0.05	0.7	1
60	~ 0.5	4.4×10^{13}	0.01	0.17	2

- Magnetic Confinement Optimum for the High Charge State Ion Production :

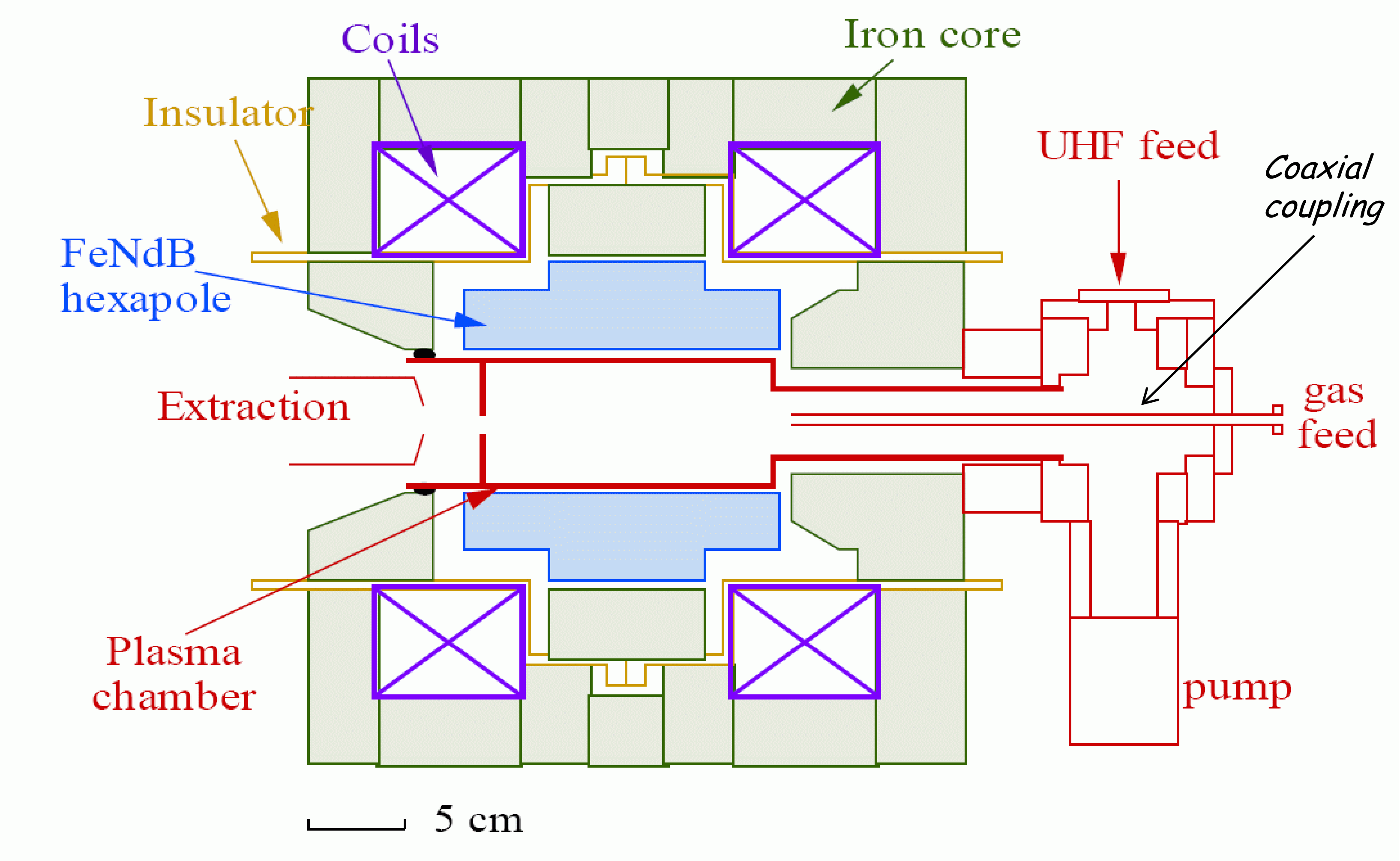
$$B_{ECR} = \frac{f_{ECR}}{28\ GHz}\ Tesla$$

Magnetic Confinement parameters



1990	2003	?	
14	28	60	f_{ECR} [GHz]
0.5	1	2	B_{ECR} [Tesla]
2	4	8	$B_{INJ} \sim 3-4\ B_{ECR}$
1	2	4	$B_{rad} \sim 2\ B_{ECR}$
0.2	0.5	1	$B_{med} \sim 0.5-0.8\ B_{ECR}$
1	2	4	$B_{ext} \leq B_{rad}$

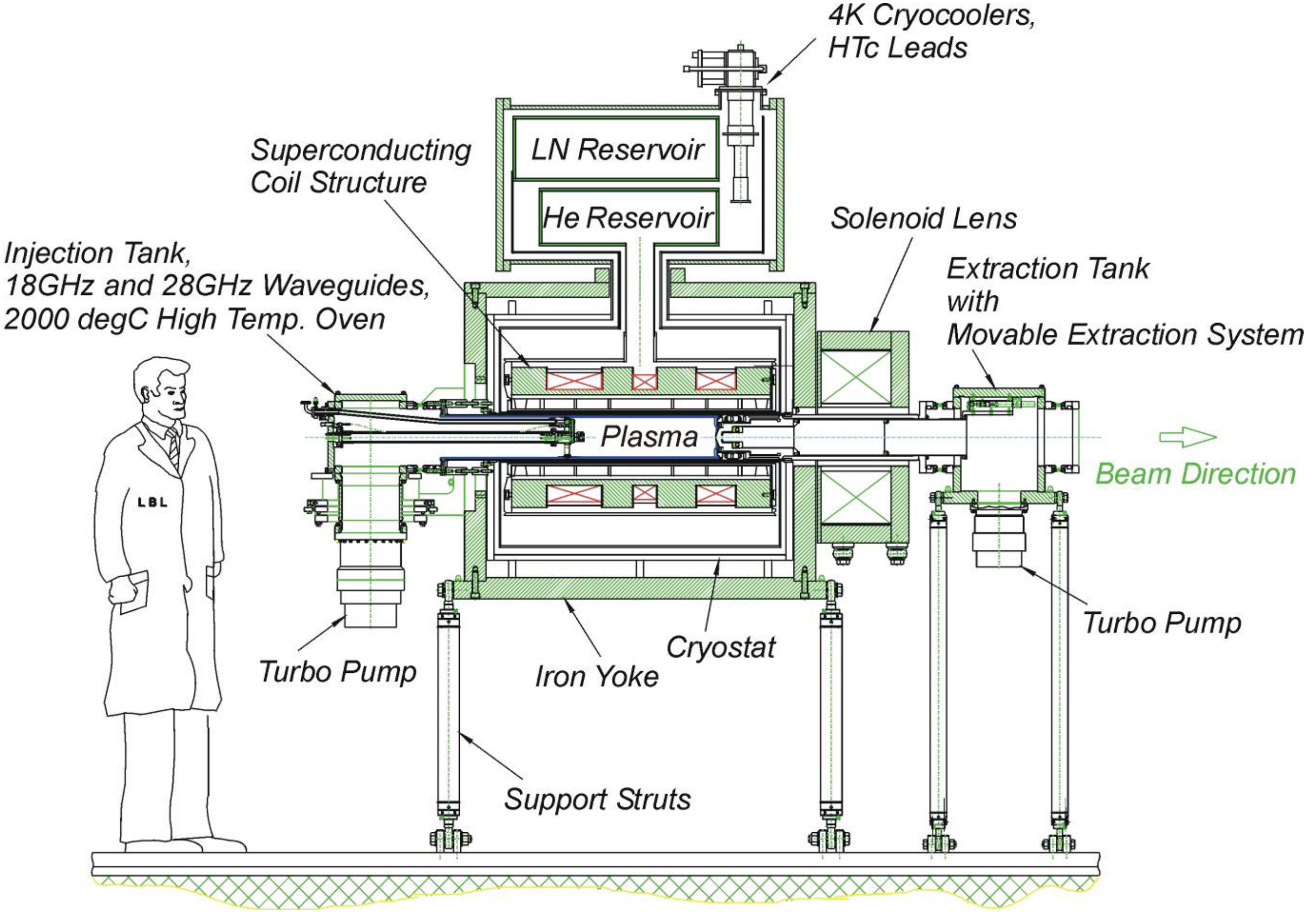
- Example of ECR4 GANIL (France) : 14 GHz



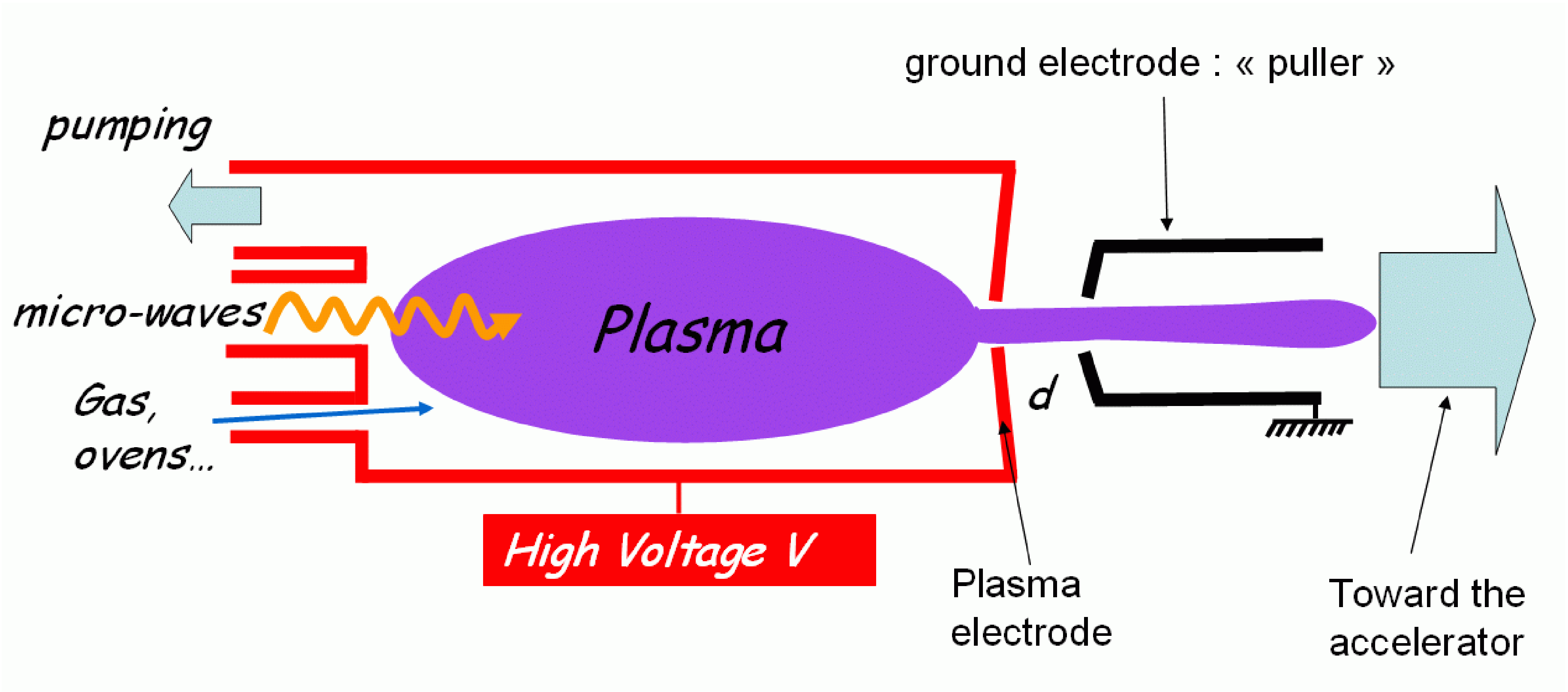
Electron Cyclotron Resonance Ion Source

- Example of the VENUS source Berkekey (USA) : 28 GHz

Achieved magnetic fields
Binj ≤4 T, Bext ≤ 3 T, Brad≤2.2 T



Simple example of beam extraction from an ECR ion source



Extracted current *I=J.A*

J=current density
A=area of the circular hole in the plasma electrode

The Child Langmuir Law (1/2)

- Beam extraction with space charge limitation
- For electrons beam :
- For ions beam :

$$J \le \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\,\frac{V^{3/2}}{d^2}$$

$$J \le \frac{4\varepsilon_0}{9}\sqrt{\frac{2Ze}{Am_A}}\,\frac{V^{3/2}}{d^2}$$

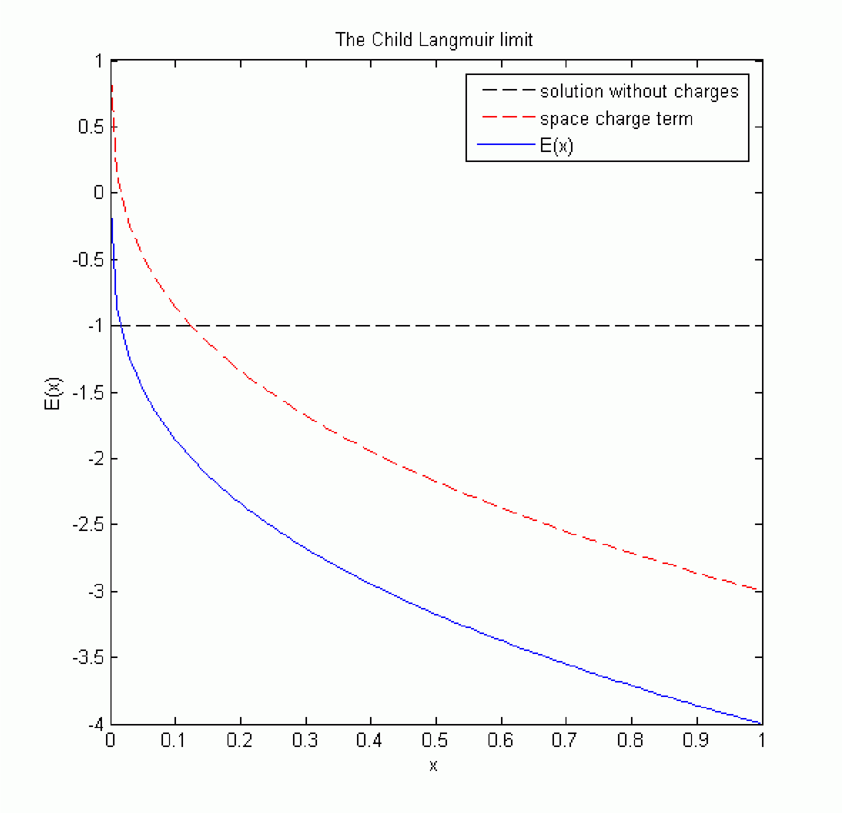
J=current density extracted from the source

V=acceleration voltage

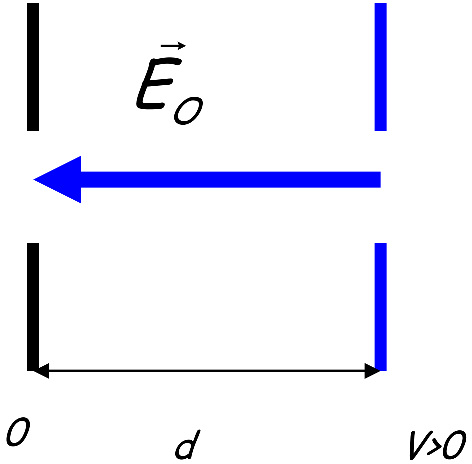
d= gap between electrodes

Z,A charge and atomic ion numbers

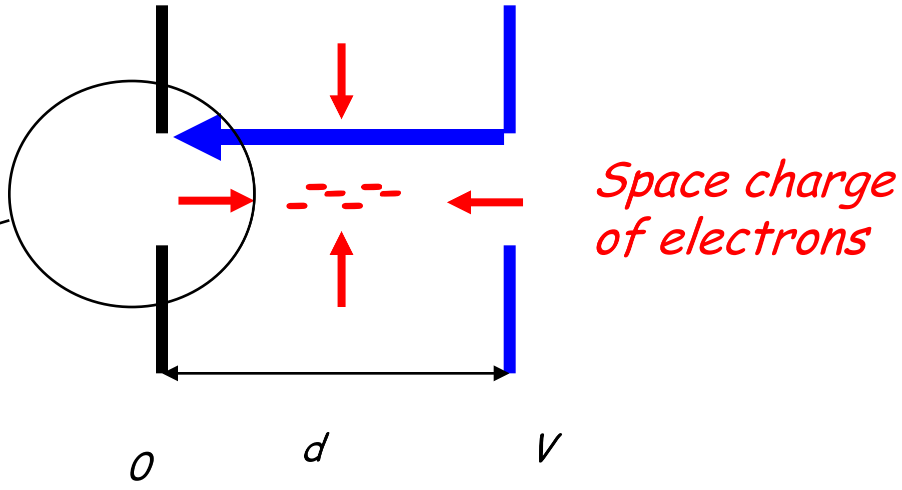
The Child Langmuir Law (2/2)



Without charges



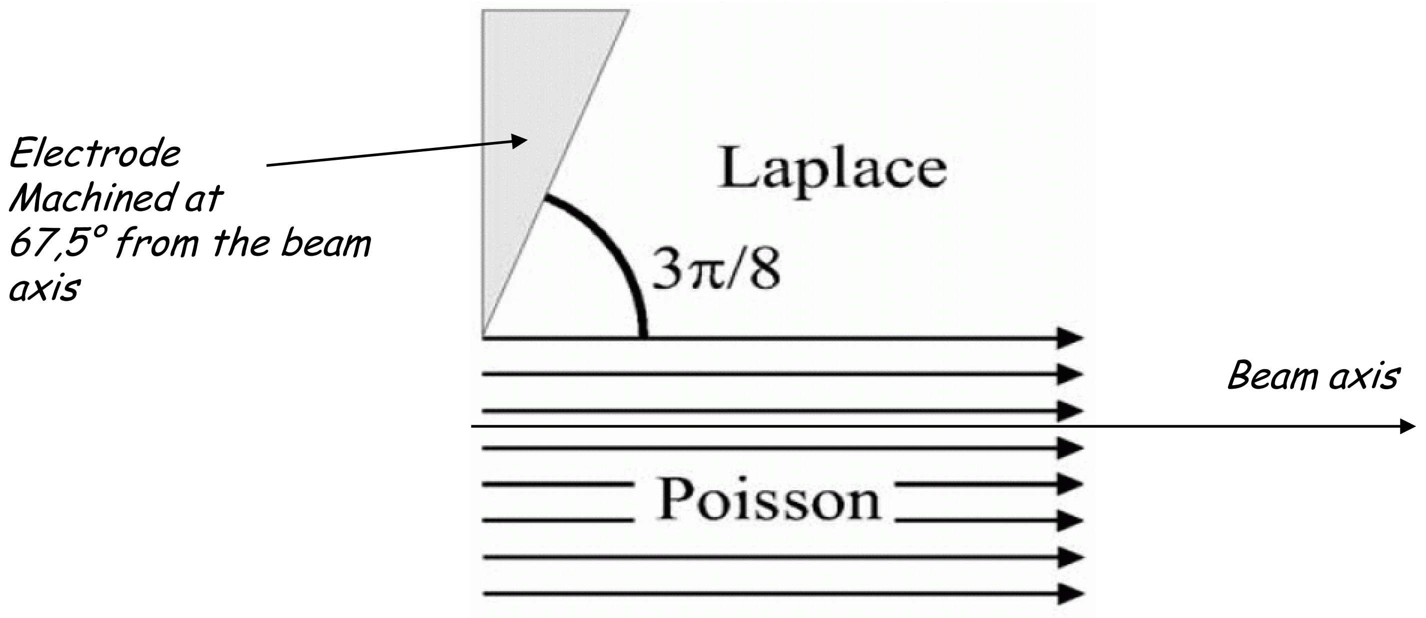
Without charges



$$\vec{E}(0) = \vec{E}_0 + \vec{E}_{space charge}$$

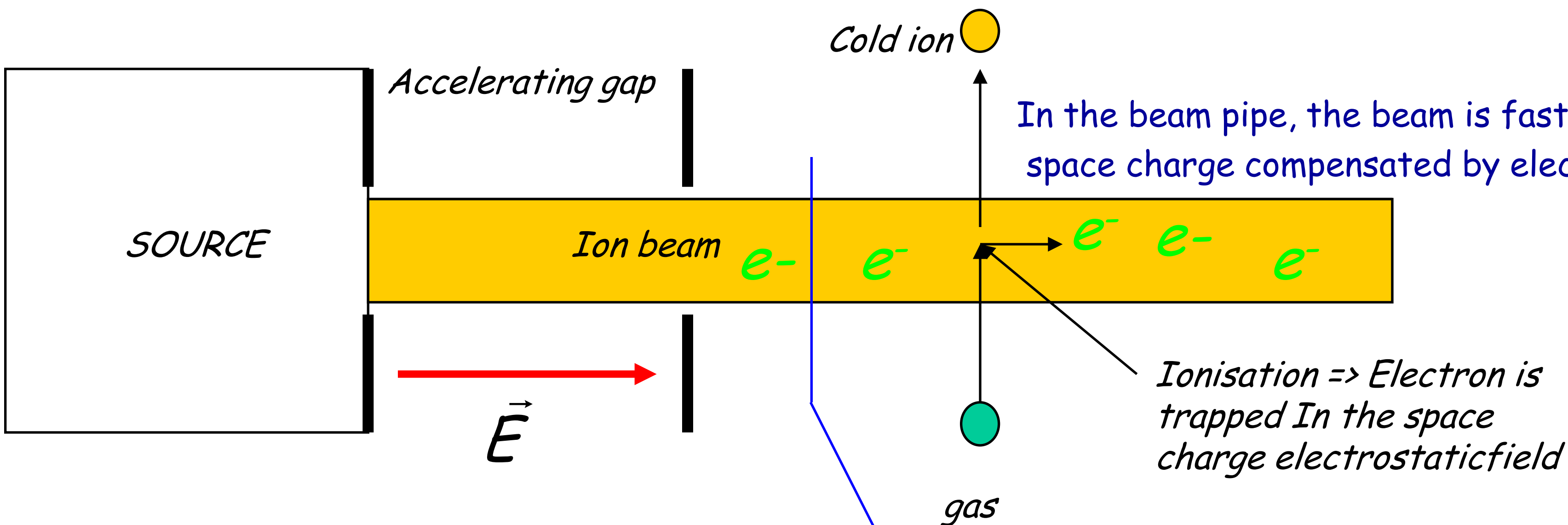
Limit case when E(0)=0 => Child Langmuir law

➢ Extraction Geometry : The Pierce angle (for electrons)



- Angle calculated such that the static accelerating electric field compensates exactly the radial space charge component created by the presence of the beam.
- => a parallel beam with reduced aberrations is created

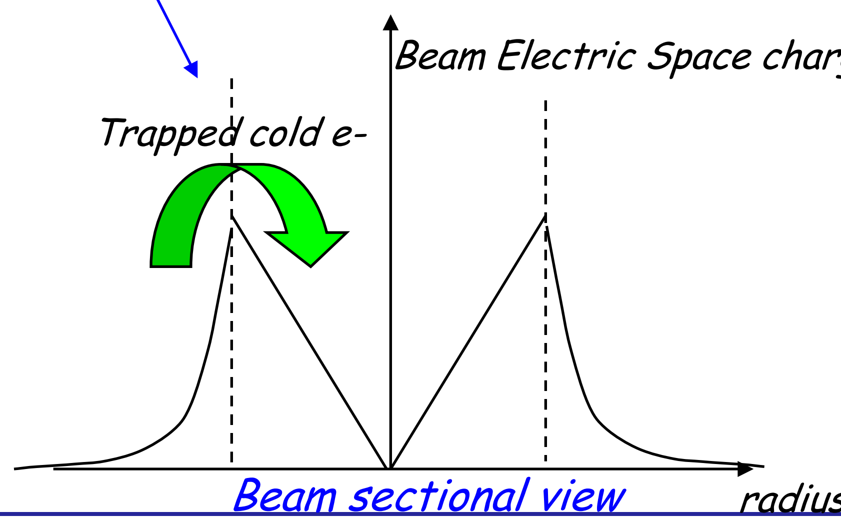
➢ The space charge compensation for ions beams



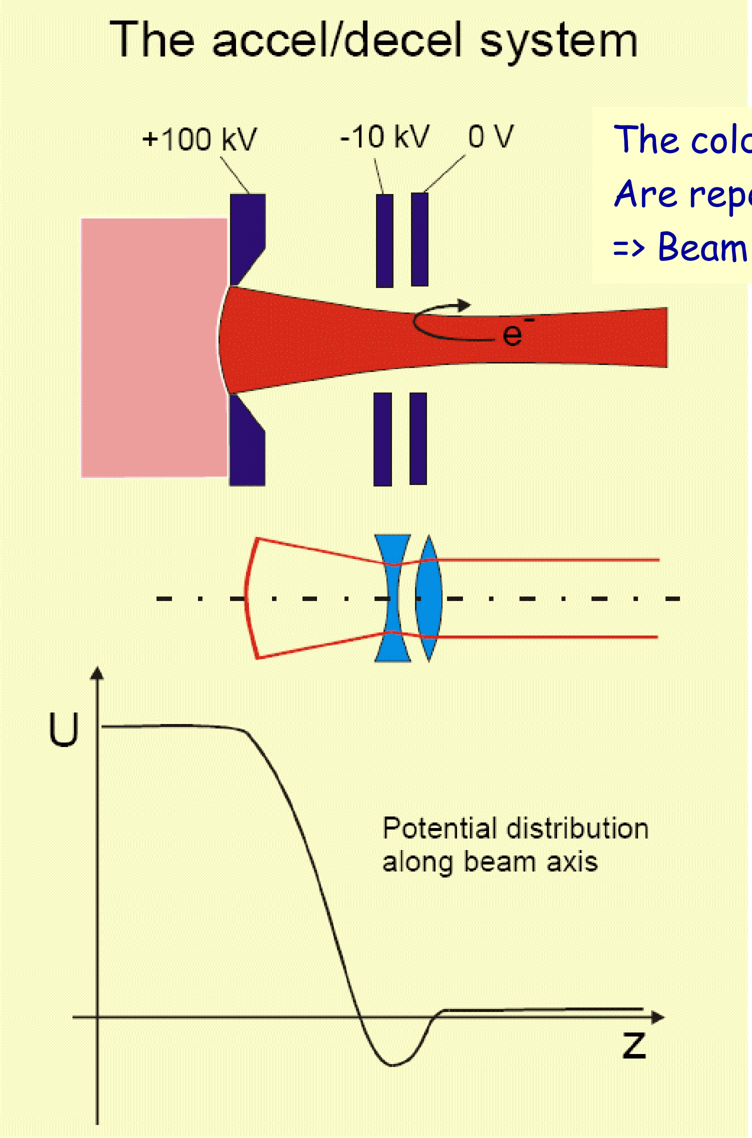
In the beam pipe, the beam is fastly space charge compensated by electrons

In the accelerating gap, the electric field accelerates the cold electrons toward the source => no space charge compensation here

Morever, cold electrons scattering from The beam to the accelerating gap will be sucked toward the source => <u>loss of space charge compensation in the beam line</u>



➢ The Triode System (or « accel-decel »)



The cold electrons from the beam line
Are repelled by the negative voltage
=> Beam is space charge compensated

Ions Beam composition

- Ions of interest
- Buffer gas (to optimize ion of interest and sustain plasma density)
- Gas contaminant (C,N,O,H,H20,N2,O2…)
- Metallic contaminant (elements from the plasma chamber)
- And SEVERAL charge states mixed together for each element produced.

A selection to keep only the ion of interest is required

6. Low energy ions beam separation

➢ Selection Through a magnetic dipole

ρ is the radius of curvature

B magnetic field in the dipole

U high voltage of the source

M mass of the ion

Z charge state of the ion

$$B\rho = \sqrt{\frac{2}{e}}\sqrt{\frac{M}{Z}U}$$