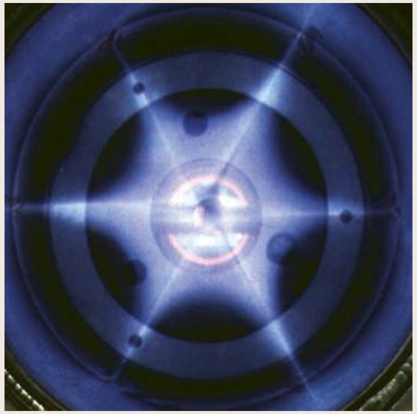
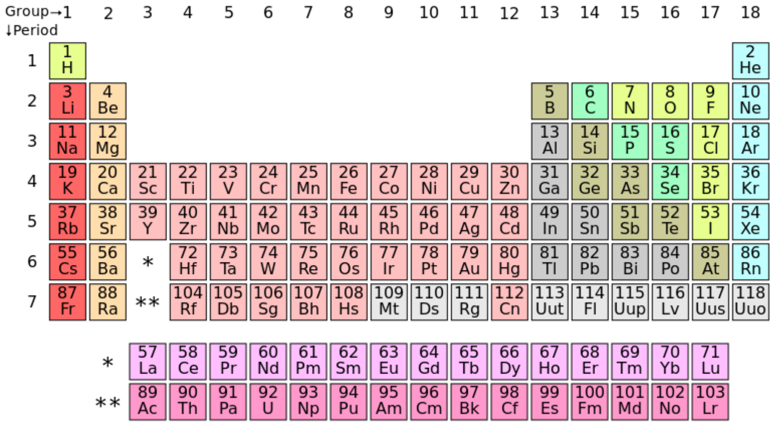


ION SOURCES

An introduction to ion sources

Introduction to ion sources (1/2)

- The need for ion beam covers the whole Periodic table
- The process to ionize a specific atom depends on the group (column) to which it belongs
  - The atom chemical properties are of great importance to decide how to ionize it
- There are several ways to ionize atoms in ion sources:
  - **With a low density plasma** under vacuum (very common)
    - Works great for any gas and also condensable like metals, provided the metal can evaporate at high temperature
  - **On a surface** (specific technique)
    - Works great with the first group: Alcaline
  - **Directly from solid** (specific technique)
    - Via sputtering (uncommon technique used for negative ion production, discussed later)



Group→1 ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Introduction to ion sources (2/2)

- Another complication specific to ion beams comes from the fact that ions are very heavy with respect to electrons and that the acceleration process is proportional to Q/M ratio.
- To save money, you want to shorten your linear accelerator and accelerate the highest Q/M ratio to reduce the total length
- Multicharged ion sources have been developped for this purpose
  - They are much more complicated and expensive
  - But finally, they can save several M€ on an accelerator budget by shortening the acceleration section
- The lecture will review a large number of ion sources…
  It's impossible to go into detail !
- Prior to presenting an ion source, the lecture will start with some background physics

Electronic configuration of atoms

- Each atom has a specific electronic cloud configuration
- Each electron has a spin number $\boldsymbol{s}$ up (↑) or down (↓)
- The electrons are splitted into shells defined by quantum numbers:
- principle quantum number $\boldsymbol{n}$:
  - *K* $(n = 1)$, *L* $(n = 2)$, *M* $(n = 3)$,…
  - Each shell can host $2n^2$ electrons, i.e. *K* shell 2 electrons, *L* shell 8 electrons, *M* shell 18 electrons, etc.…
- Quantum orbital number $\boldsymbol{l}$:
  - $\boldsymbol{0 < l < n}$
  - Each shell is divided into orbital subshells l: *s*, *p*, *d*, *f* (l=0, 1, 2, 3)
  - Maximum number of electrons in the subshell: $2(2l + 1)$, i.e. *s*: 2, *p*: 6, *d*: 10, *f*: 14
- Third quantum number $\boldsymbol{m_l}$:
  - m_l is the projection of the orbital number l along the z-axis.
  - In each orbital subshell, $-l < m_l < l$
- So on each shell, individual electron is specified by its unique quantum numbers: $\boldsymbol{n, l, m, s}$

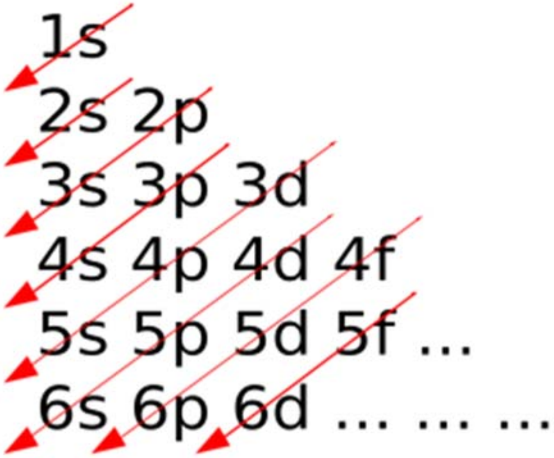
Kshell: $n = 1 \to l = 0 \to m = 0 \to s = \begin{cases} \uparrow \\ \downarrow \end{cases}$

Lshell: $$n = 2 \to l = \begin{cases} 1 \to m = \begin{cases} -1 \to s = \begin{cases} \uparrow \\ \downarrow \end{cases} \\ 0 \to \quad s = \begin{cases} \uparrow \\ \downarrow \end{cases} \\ 1 \to s = \begin{cases} \uparrow \\ \downarrow \end{cases} \end{cases} \\ 0 \to m = 0 \to s = \begin{cases} \uparrow \\ \downarrow \end{cases} \end{cases}$$

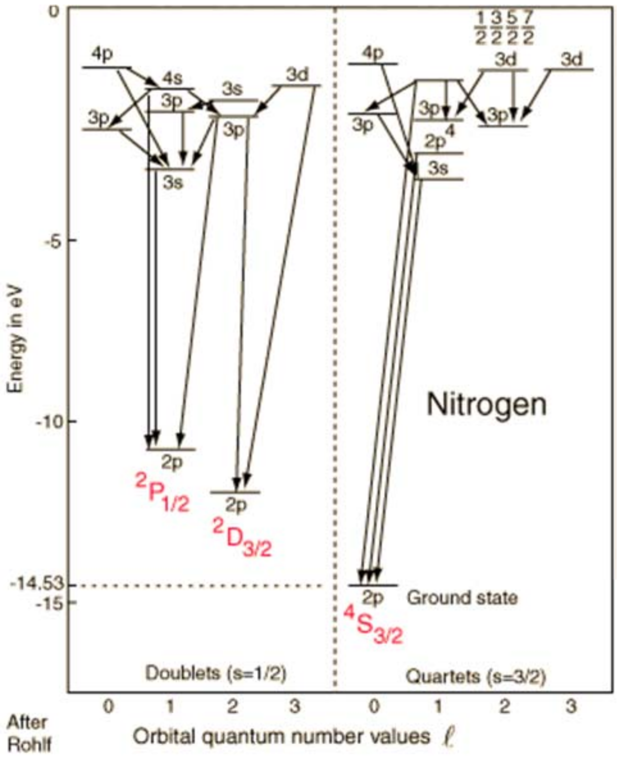
Material compiled from H. koivisto, JUAS12 lecture

Electronic configuration of atoms

- The shells/subshells are filled up following the Klechkovski (Madelung) rule:
  - With $n + l$ increasing
  - In case of equality, the first shell filled is the one with the lowest n
    - Nitrogen (Z=7): $1s^2 2s^2 2p^3$
    - Neon (Z=10): $1s^2 2s^2 2p^6$
    - Argon (Z=18): $1s^2 2s^2 2p^6 3s^2 3p^6$
  - Electrons are bound to the deepest layers with the maximum bound energy
- The rule is not absolute: some exception exists
    - Ex.: Cr, Cu, Mo, Pd, Ag, La, Ce, Gd…


1s
2s 2p
3s 3p 3d
4s 4p 4d 4f
5s 5p 5d 5f …
6s 6p 6d … … …

Klechkovski (Madelung) rule



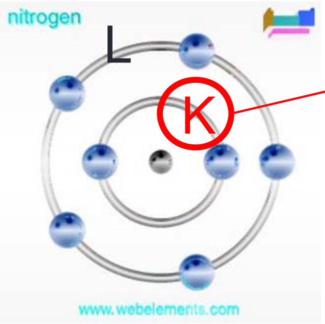
After Rohlf

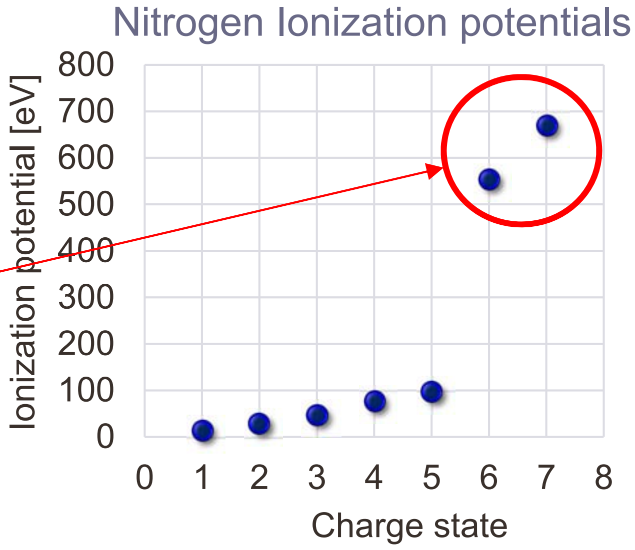
Material compiled from H. koivisto, JUAS12 lecture

Electrons binding energy in atoms

- Electrons are bound to the atom nucleus with and energy depending on the atom number Z, and the quantum numbers n, l, m
  - The deeper the electron shell (lower n), the higher the binding energy
  - For a given subshell, The higher the Z, the higher the binding energy
- The first ionization energy (or « ionization potential ») is the minimum energy that must be brought to the atom to expell a first electron
- The second ionization energy is the minimum energy required to remove a second electron from the highest occupied subshell
- Etc…

See T. Carlson, CALCULATED IONIZATION POTENTIALS FOR MULTIPLY CHARGED IONS , ATOMIC DATA, 2, 63-99 (1970)





Ion charge state →

	1+	2+	3+	4+	5+	6+	7+	8+	9+
H	13,6	-	-	-	-	-	-	-	-
He	24,6	54,4	-	-	-	-	-	-	-
N	14,5	29,8	47,7	77,9	98,4	554	670		
Ne	21,6	41,0	63,5	97,1	126	157	207	239	1195
Ar	15,8	27,6	40,7	59,8	75,0	91,0	124	144	422
Kr	14,0	24,4	36,9	52,5	64,7	78,5	111	126	231
Xe	12,1	21,2	32,1	44,6	57,0	68,4	96,4	109	205

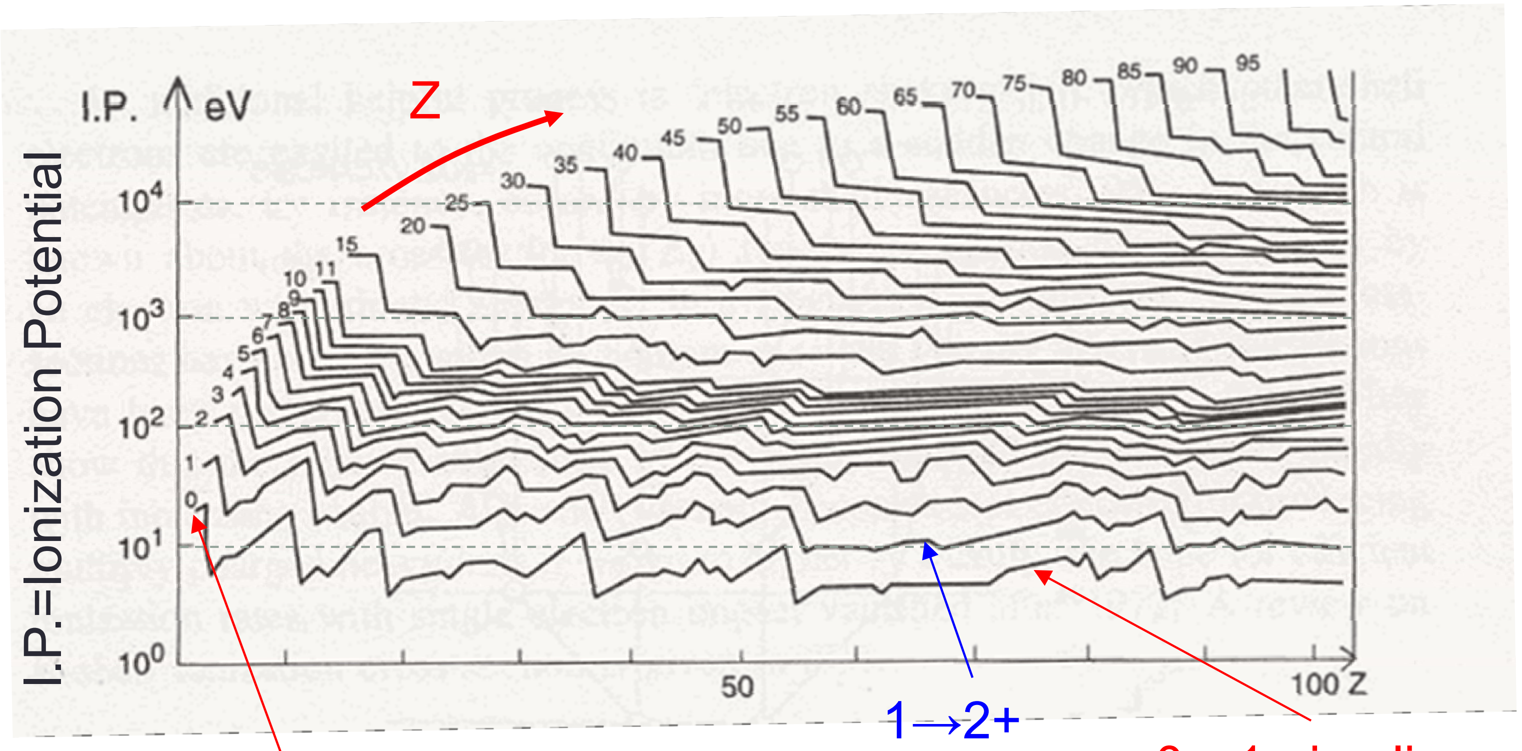
Electron bounding energy (eV) of some gas vs ion charge stat

Material compiled from H. koivisto, JUAS13 lecture

Electrons binding energy in atoms

- This plot represents the *(n+1)th* ionization potential lines of ion with initial charge state *n* as a function of the atom number *Z*
- The deepest shell electron binding energy increases drastically with *Z :*

- $Z = 2 \rightarrow \sim 10^2\ eV$
- $Z = 8 \rightarrow \sim 10^3\ eV$
- $Z = 25 \rightarrow \sim 10^4\ eV$



I.P.=Ionization Potential

Z

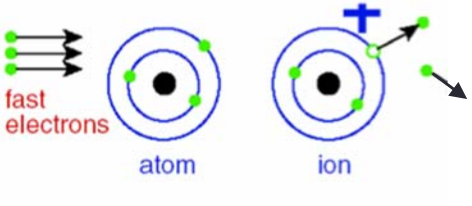
Initial ion charge state

1→2+ ion line

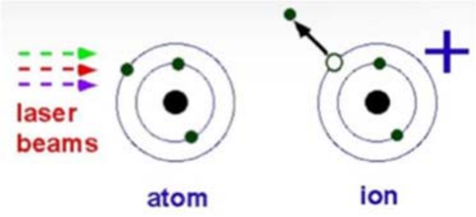
0→1+ ion line

How to Ionize an atom

- **Electron Impact**: an energetic electron collide with an atom (ion) and expells one shell electron
  - $e^- + A^{n+} \overset{I_n}{\rightarrow} A^{(n+1)+} + 2e^-$
  - Threshold energy: the nth Ionization potential I_n
  - The electron impact is the most convenient method used in ion sources. It is developped later

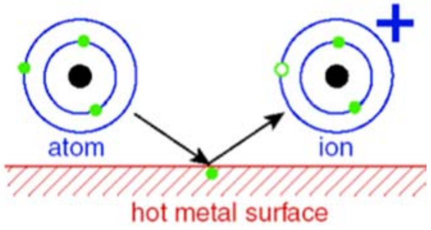


- **Photon ionization**: a photon with an energy close to the nth Ionization potential I_n gives its energy to the atom and frees one electron
  - $h\nu + A^{n+} \overset{I_n}{\rightarrow} A^{(n+1)+} + e^-$
  - The photon disappears
  - The photon ionization process is of interest for specific applications like ionizing atoms in a Radioactive Ion Beam facility.
    - In this case, a set of lasers are used to guide an electron from shell to shell until it is freed.



Figures from JUAS lectures: M. Kowalska

- **Surface Ionization:** an atom is directly ionized by a hot surface
  - $A + X \rightarrow A^+ + e^- + X$
  - Tunnel effect (quantum mechanics), discussed later in the lecture
  - Very efficient method to ionize Alcaline atoms



How to recombine an ion

- Very easily!
- Ions are surrounded by an electric field which attracts back electrons

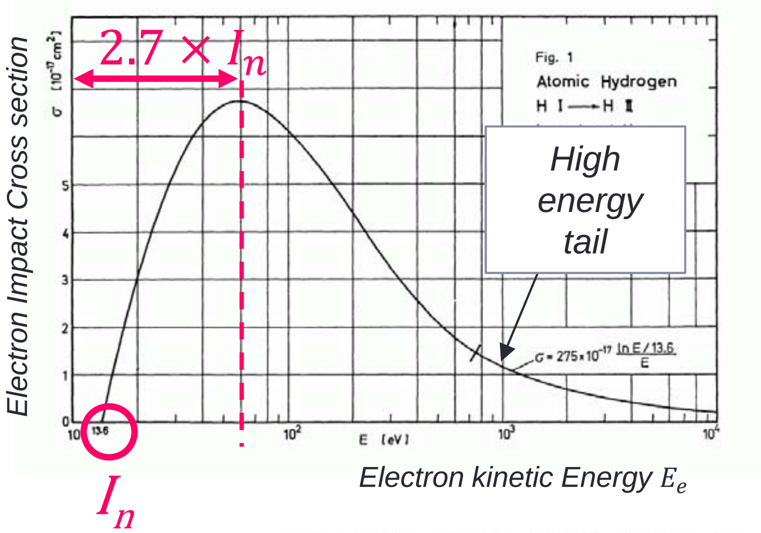
- The main channels for an ion to lose a charge state are:
  - **Charge exchange**: an ion and an atom cross one each other, the ion electric field sucks up an electron from the atom
    - $\overset{\boldsymbol{e^-}}{\curvearrowleft}$ $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+} + radiative\ processes$
      - Dominant process
    - $A^{n+} + B^{m+} \rightarrow A^{(n-1)+} + B^{(m+1)+} + radiative\ processes$
    - Any ion grazing a surface will suck up electron from it
    - Worst case: any ion **touching a surface** is immediately **neutralized**
  - **Radiative recombination:** a slow electron is re-captured by an ion
    - $e^- + A^{n+} \rightarrow A^{(n-1)+} + h\nu$
    - This term is usually neglected in ion source field, because electrons are too fast to recombine

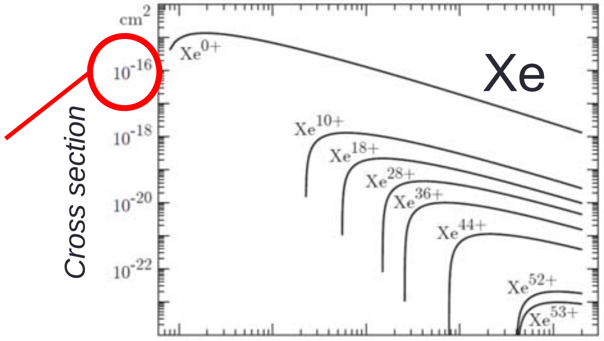
Cross-section and other microsopic processes

- Cross-section: σ *(cm^{2}or barn)*
  - The cross section σ is the effective area which governs the probability of a specific physical interaction between two particles. Its unit is usually cm^2 or *barn* (10^{-24} cm^2)
- Collision rate: $n\sigma v$ *(Hz or s^{-1})*
  - The number of collision $N_{col.}$ between a single particle with a velocity v and a set of gaseous atoms targets with a density n during a time t is given by:
  - $N_{col.} = n\sigma v t$
  - σ is the cross section associated to this particular collision
  - $\sigma v t$ is the volume swept by the electron during a time t
  - The collision rate is $\frac{N_{collision}}{t} = n\sigma v$ in Hertz (s^{-1})
- Mean Free Path: $\lambda = \frac{1}{\sigma n}$ *(cm or m)*
  - The MFP is the mean distance λ covered by a particle between two interactions with a target of the same type.
    - The probability to have an interaction is proportional to the target density n (in cm^{-3}) and the cross-section σ. The probability to have a collision along a distance l is $P(l) = n\sigma l$. The MFP is such that $P(\lambda) = 1$. So $\lambda = \frac{1}{\sigma n}$

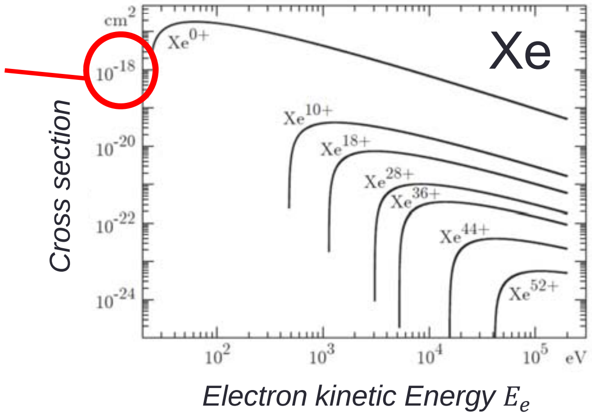
Electron Impact Ionization

- Ions are produced through a direct collision between an atom and a free energetic electron
  - $e^- + A^{n+} \rightarrow A^{(n+1)+} + e^- + e^-$
    - single impact, most probable
  - $e^- + A^{n+} \rightarrow A^{(n+2)+} + 2e^- + e^-$
    - double impact, much less probable
  - Kinetic energy threshold E_e of the impinging electron is the binding energy I_n of the shell electron: $E_e > I_n$
  - Optimum of cross-section for $E_e \sim 2.7 \times I_n$
  - Higher energy electron can contribute significantly





Electron impact
Single ionization
$\sigma \sim 10^{-16}\ cm^2$

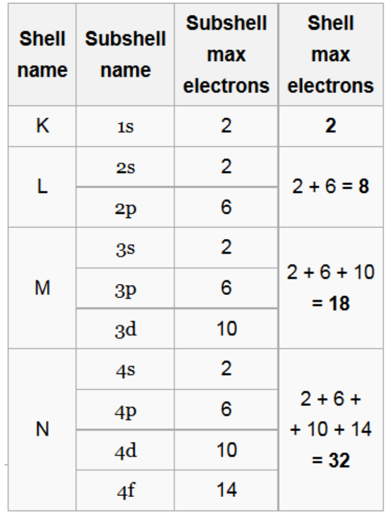


Electron impact
Double ionization
$\sigma \sim 10^{-18}\ cm^2$

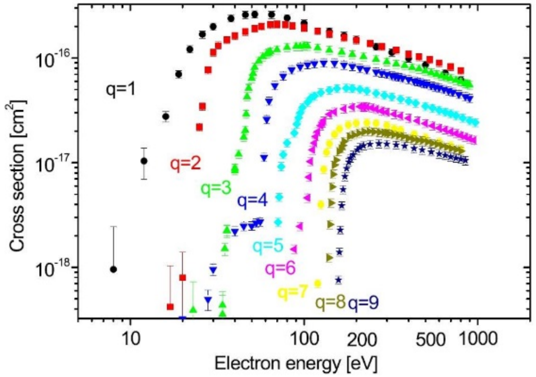
Xe plots from F. Wenanders, CAS2012

Electron Impact Ionization

- Electron impact ionization cross section can be estimated by the semi-empirical Lotz Formula (valid for $E >> P_i$):
  - $\sigma_{q \to q+1} \sim 4.5 \times 10^{-14} \sum_{i=1}^{N} q_i \frac{\ln(\frac{E}{P_i})}{E P_i}\ (cm^2)$
  - E *incident electron kinetic energy*
  - Sum on the N atom/ion electrons subshells : (n,l fixed = 1 subshell)
  - q_i number of electrons on the subshell i
  - P_i binding energy of electrons on the subshell i: $P_i = E_{n,l}$
  - Each remaining electron on an ion contributes individually to the global cross section of ionization $\sigma_{q \to q+1}$
  - High charge state production requires hot electrons as P_i increases dramatically for deep subshells
  - The higher the charge state, the lower the cross section intensity



Shell name	Subshell name	Subshell max electrons	Shell max electrons
K	1s	2	**2**
L	2s	2	2 + 6 = **8**
	2p	6	
M	3s	2	2 + 6 + 10 = **18**
	3p	6	
	3d	10	
N	4s	2	2 + 6 + 10 + 14 = **32**
	4p	6	
	4d	10	
	4f	14	

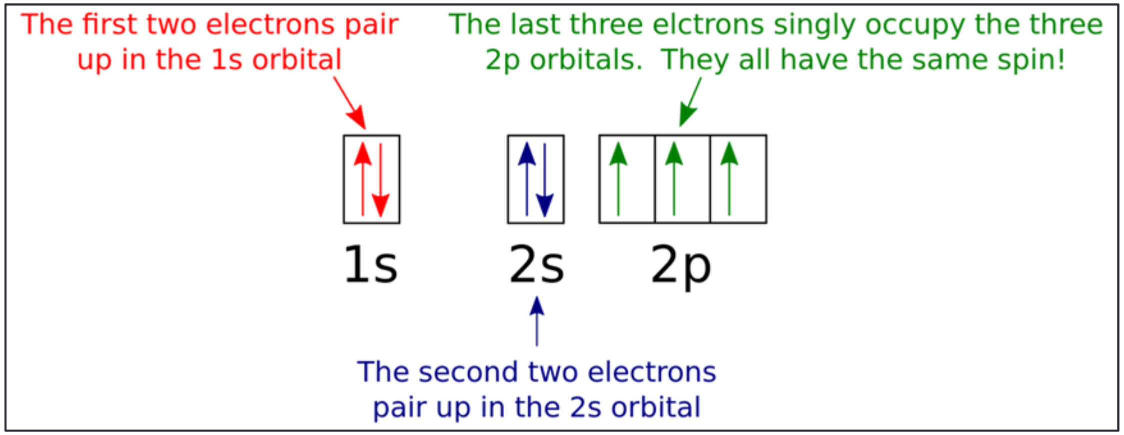


Example for Bismuth

Z	I_n (eV)	$\sigma_{max}\ (cm^2)$
1+	7.2	$\sim 2.4 \times 10^{-16}$
22+	159	$\sim 4.9 \times 10^{-19}$
54+	939	$\sim 1.4 \times 10^{-20}$
72+	3999	$\sim 7.8 \times 10^{-22}$
82+	90526	$\sim 1.5 \times 10^{-24}$

Electron Impact Ionization

- Example with Nitrogen: $1s^2 2s^2 2p^3$
- $\sigma_{0\rightarrow 1} \sim 4.5 \times 10^{-14} \sum_{i=1}^{3} q_i \frac{\ln(\frac{E}{P_i})}{EP_i}$
- $\sigma_{0\rightarrow 1} \sim 4.5 \times 10^{-14} \left(q_{1s} \frac{\ln(\frac{E}{P_{1s}})}{EP_{1s}} + q_{2s} \frac{\ln(\frac{E}{P_{2s}})}{EP_{2s}} + q_{2p} \frac{\ln(\frac{E}{P_{2p}})}{EP_{2p}} \right)$
- $q_{1s} = 2\ ;\ q_{2s} = 2\ ;\ q_{2p} = 3$
- $P_{1s}\ ,\ P_{2s}\ ,\ P_{2p}$ are tabulated



The first two electrons pair up in the 1s orbital

The last three elctrons singly occupy the three 2p orbitals. They all have the same spin!

The second two electrons pair up in the 2s orbital

https://commons.wikimedia.org/wiki/File:Orbital_diagram_nitrogen.svg

Charge Exchange

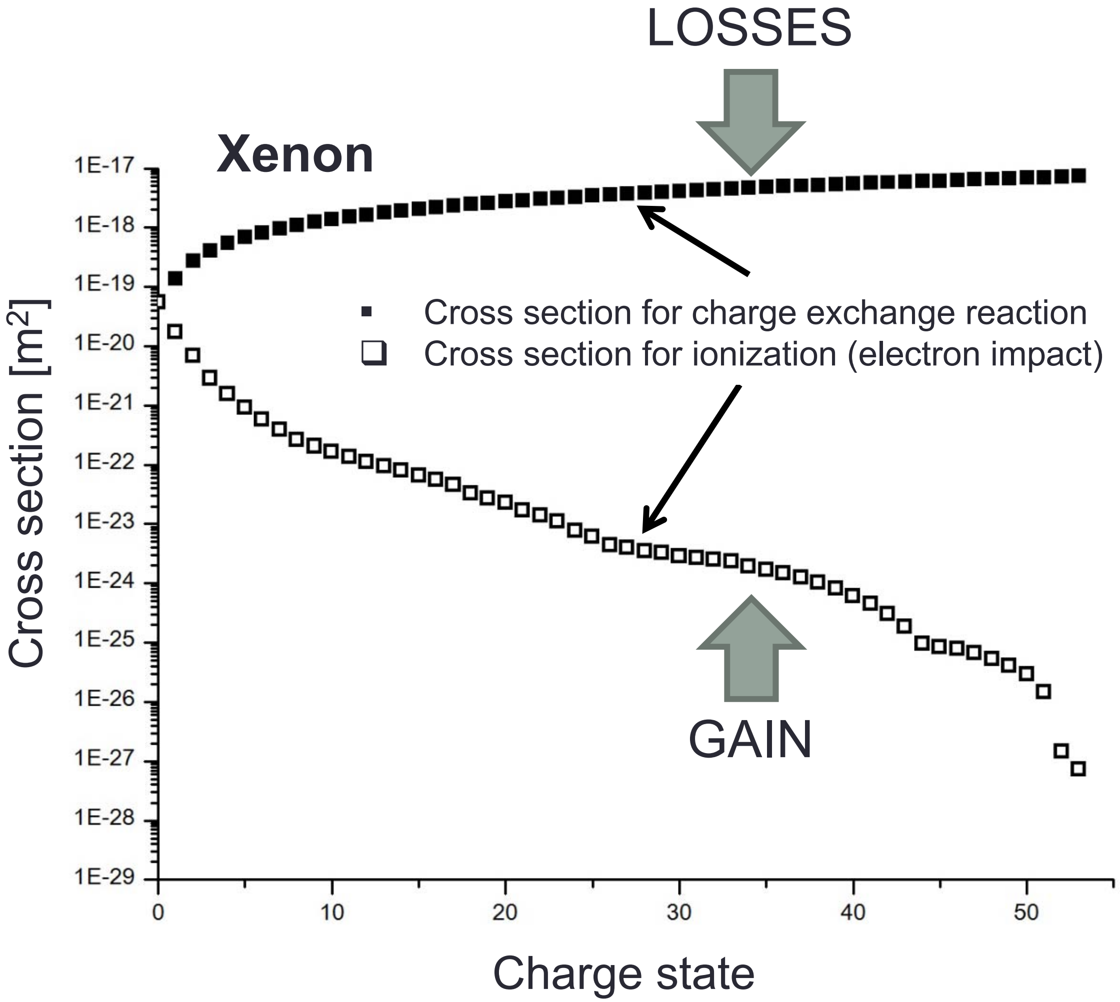
- The main process to reduce an ion charge state is through atom-ion collision
  - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+}$ (+radiative transitions)
    - Long distance interaction: the electric field of the ion sucks up an electron from the atom electron cloud
    - Any ion surface grazing signs the death warrant of a high charge Ion
  - semi-empirical formula :
    - $\sigma_{CE}(n \rightarrow n-1) \sim 1.43 \times 10^{-12} q^{1.17} I_0{}^{-2.76}\ (cm^2)$ (A. Müller, 1977)
    - I_0 1st ionization potential in eV, q ion charge state

Example :
Bismuth with O_2

Z	1+	22+	54+	72+	82+
σ_{CE} (cm2)	1.5×10^{-15}	5.6×10^{-14}	1.6×10^{-13}	2.2×10^{-13}	2.6×10^{-13}

Electron Impact vs Charge Exchange

- The charge exchange cross section is always above the electron impact one…
  - Loss > creation!
- How to reduce the net ion loss through charge exchange?
  - By reducing the pressure in the source to minimize the neutral atom population
  - By having a large population of fast electrons to produce more ionization!



A simple Charge state balance model

- The ion charge state distribution in an ECRIS can be reproduced with a 0 Dimension model including a set of balance equations:

creation

destruction

$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma^{EI}_{j\to i} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma^{CE}_{i+1\to i} v_{i+1} \right\rangle}_{} \underbrace{- n_0 n_i \left\langle \sigma^{CE}_{i\to i-1} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma^{EI}_{i\to j} v_e \right\rangle}_{} \underbrace{- \frac{n_i}{\tau_i}}_{}$$

Losses
(ion extraction,
wall…)

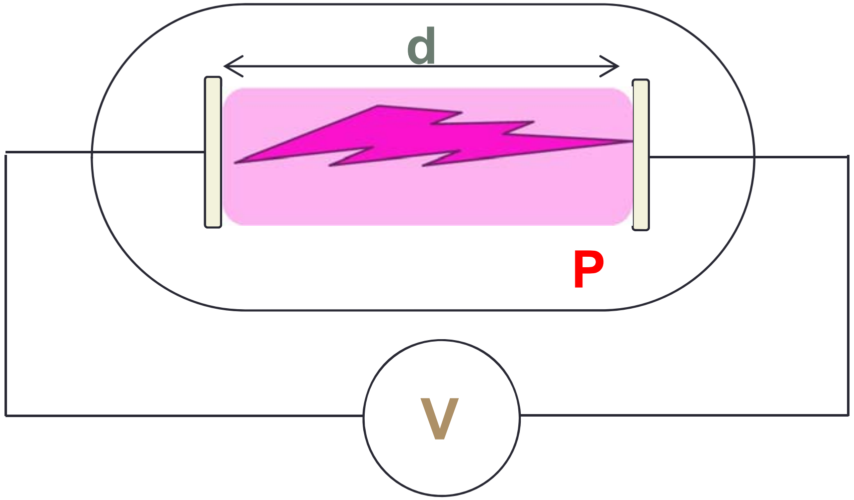
  - n_i : ion density with charge state i
  - n_e, v_e : electron density, velocity
  - σ , cross section of microscopic process
    - Electron impact or charge exchange here only
  - $\langle \sigma v_e \rangle = \frac{\int \sigma v_e f(v_e) dv_e}{\int f(v_e) dv_e}$
  - τ_i is the confinement time of ion in the source
  - $-\frac{n_i}{\tau_i}$ represents the ion losses for species i (to the wall, or extracted current intensity)
  - Free Parameters: n_e, $f(v_e)$, τ_i
- Model can be used to investigate ion source physics
- Model can be refined using second order effect: radiative recombination, dielectric recombination

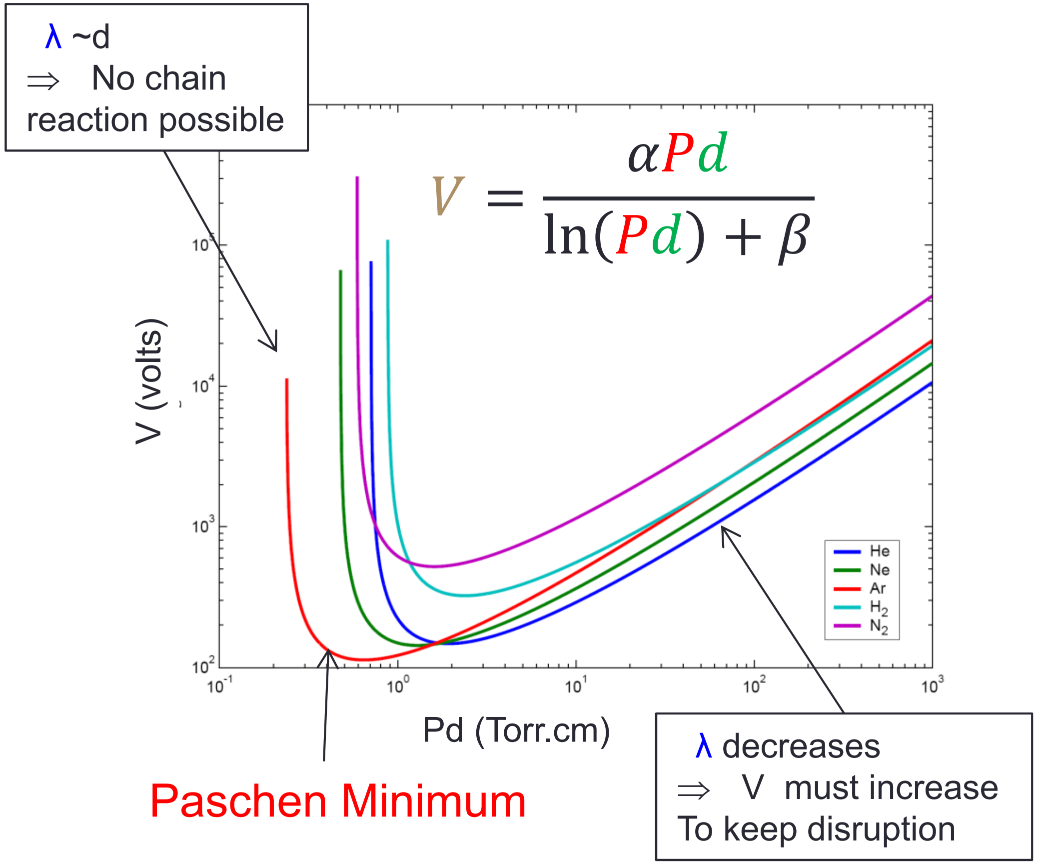
The Paschen Law

- The Paschen Law describes the condition to initiate a (violent) breakdown in a gas tube (equipped with an anode and a cathode at each end) as a function of:
  - The pressure ***P*** (*P*=*nkT*, *n* gas density)
  - The voltage ***V*** between 2 electrodes
  - The distance ***d*** between 2 electrodes
  - α, β constants for one gas

- Why is there a disruption?
  - A single free electron is accelerated by the electric field E=V/d
  - The distance between 2 collisions with gas molecule is the mean free path λ.
  - If the energy gained between 2 collisions is greater than the 1st ionization potential of the gas, a second electron is created via **electron impact** => avalanche=> breakdown of a plasma

- Asymptotic behaviour
  - The higher the pressure (density), the lower λ and the higher the necessary voltage V to make a disruption (more atoms to ionize on a shorter distance). The curve increases.
  - At low pressure, λ ~d and no more chain reaction is possible, the avalanche breakdown is no more possible.





$$V = \frac{\alpha P d}{\ln(Pd) + \beta}$$

λ ~d
⇒ No chain reaction possible

λ decreases
⇒ V must increase
To keep disruption

Paschen Minimum

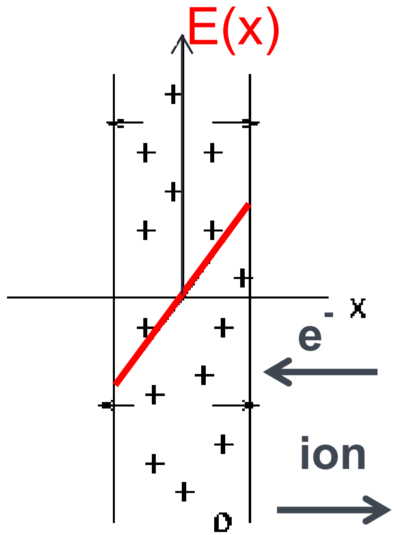
Basics of plasma physics - generalities

- Plasma is considered as the 4th state of matter
- It can be considered as a ionized gas, composed of ions and electrons and possibly of neutral atoms.
  - The degree of ionization of a plasma is $\alpha = \frac{n_i}{n_i+n}$, n is the density of neutral, and n_i is the ion density
- A plasma is always neutral taken as a whole
  - $n_i \times e + n_e \times (-e) = 0$ (n_i= ion density of single charge state, n_e= electron density)
- Plasma exists on a wide range of density, pressure and temperatures
  - a Hot (Thermal) Plasma is such that it approaches a state of local thermodynamic equilibrium where Ti=Te (Ti ion temperature, Te electron temperature).
  - a Cold Plasma is such that the move of ions can be neglected with respect to electrons, so Te>>Ti. A cold plasma is out of local thermodynamic equilibrium.
- Usual laboratory plasmas are created under vacuum and sustained by injecting electromagnetic power.

- Plasma applied to particle source are mainly **cold plasmas**, since their goal is to create low emittance beam, and the lower the ion temperature, the smaller the beam emittance

Basics of plasma physics – Quasi neutrality – Debye Length

- Any local difference between n_i and n_e gives rise to a huge electromagnetic force that tends to reduce it, to tend back to neutrality. One talks about collective behaviour of a plasma.
  - If $n_i \neq n_e$, then a local space charge appears: $\rho = e(n_i - n_e)$
  - A local electric field appears: $div(\vec{E}) = \frac{\rho}{\varepsilon_0}$
  - Let's consider a one dimension slab of plasma with a n_i excess
  - $\frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$ => $\mathrm{E(x)} = \frac{\rho}{\varepsilon_0}\mathrm{x}$
  - The resulting force $\boldsymbol{F_x}(\mathbf{x}) = (\pm\mathbf{e})\frac{\boldsymbol{\rho}}{\boldsymbol{\varepsilon_0}}\mathbf{x}$ expells ions and attracts nearby electrons, tending eventually to reduce the space charge $$\rho = e(n_i - n_e) \rightarrow 0$$



- So plasma are also **locally neutral**
- The smallest dimension scale at which the plasma is quasi−neutral is called the Debye Length
  - $\lambda_D \sim \sqrt{\frac{\epsilon_0 k T_e}{n e^2}}$, k is the Boltzmann constant, n plasma density (cold plasma)

Basics of plasma physics – electron and ion mobility

- The mean velocity of a particle in a plasma at temperature T is expressed as:

$$\frac{1}{2}\mathrm{m}v^2 = \frac{3}{2}kT$$

- For a plasma with $T_i=T_e=T$, the electrons are moving faster than ions:

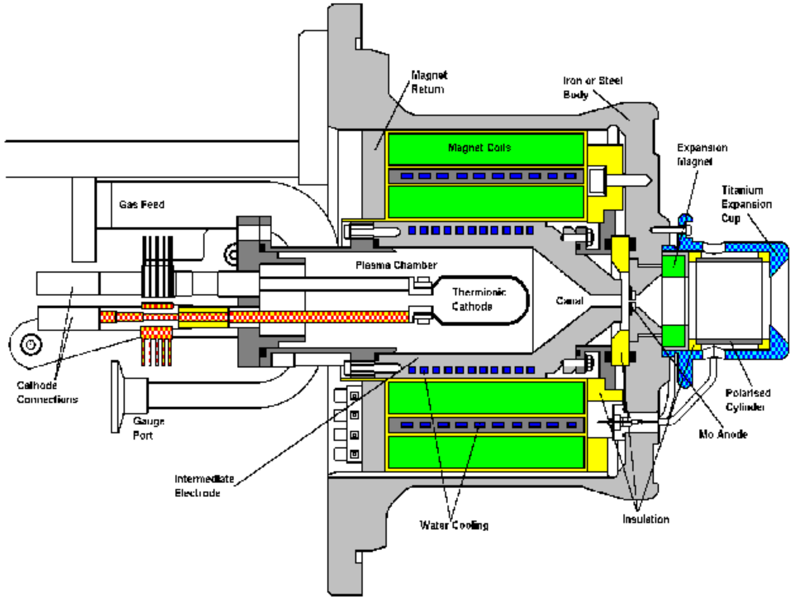
$$\frac{v_i}{v_e} = \sqrt{\frac{m_e}{m_i}} \ll 1$$

- Electrons are also more sensitive than ions to any electric field E:

$$F_x = m\frac{dv}{dx} = qE \Rightarrow \left|\frac{dv_i}{dv_e}\right| = \frac{m_e}{m_i} \ll 1$$

- In a cold plasma with $T_e>>T_i$, it is assumed that the motion of ions is negligible with respect to the one of electrons.
  - Simplification of theory and calculations
  - Case of Many Ion Sources

The Duo-plasmatron Ion source

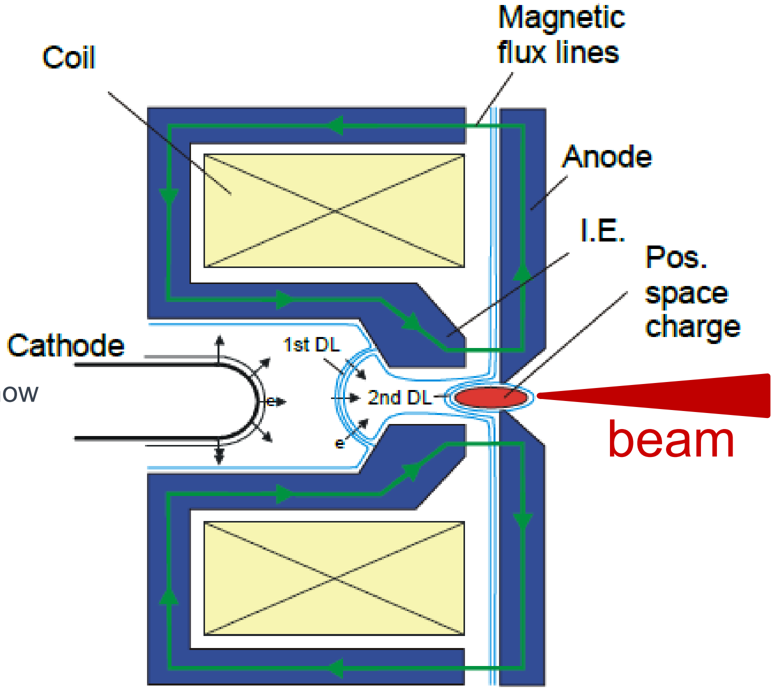


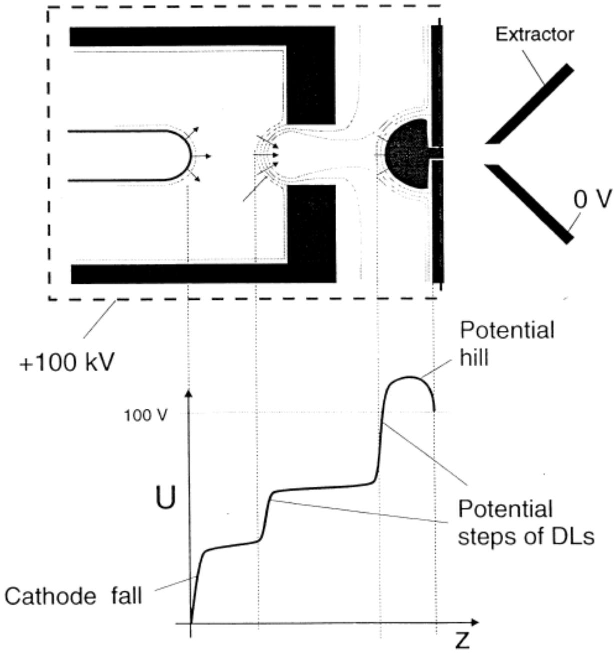
- The duo-plasmatron is a 1+ ion source able to produce beam from any gas
- A gas is injected at ~0.1-1 mbar in the plasma chamber
- A hot cathode is emitting thermionic electrons which are accelerated two times toward the anode located right at the extraction of the source
- The second place of electron acceleration coincides with a **magnetic compression** induced by the solenoid iron yoke
- In this area, the pressure is optimum to breakdown a 1+ ion plasma which drifts naturally toward the extraction hole

- The Duoplasmatron produces up to 300 mA of H+ beam in pulsed mode (1 Hz - 20-100 μs) at CERN

- Gas Ionization Efficiency <1%

- PRO:
  - Very High current, short pulses
  - Small source
- CONS:
  - Fast Cathode aging by ion sputtering in CW
  - Delicate Cathode formation, requires a specific know-how

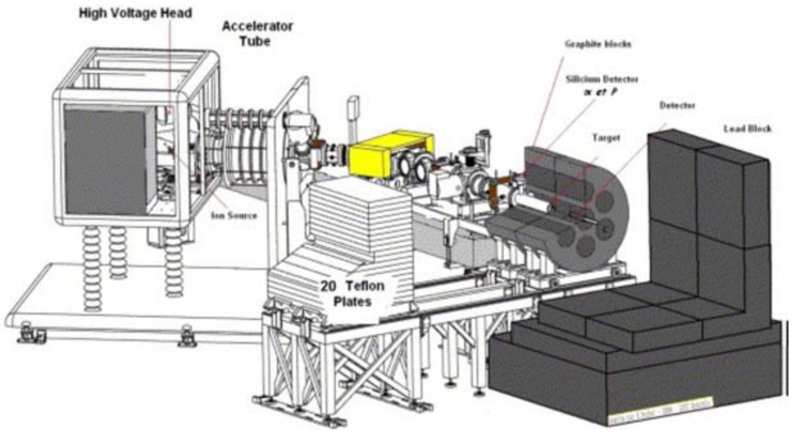


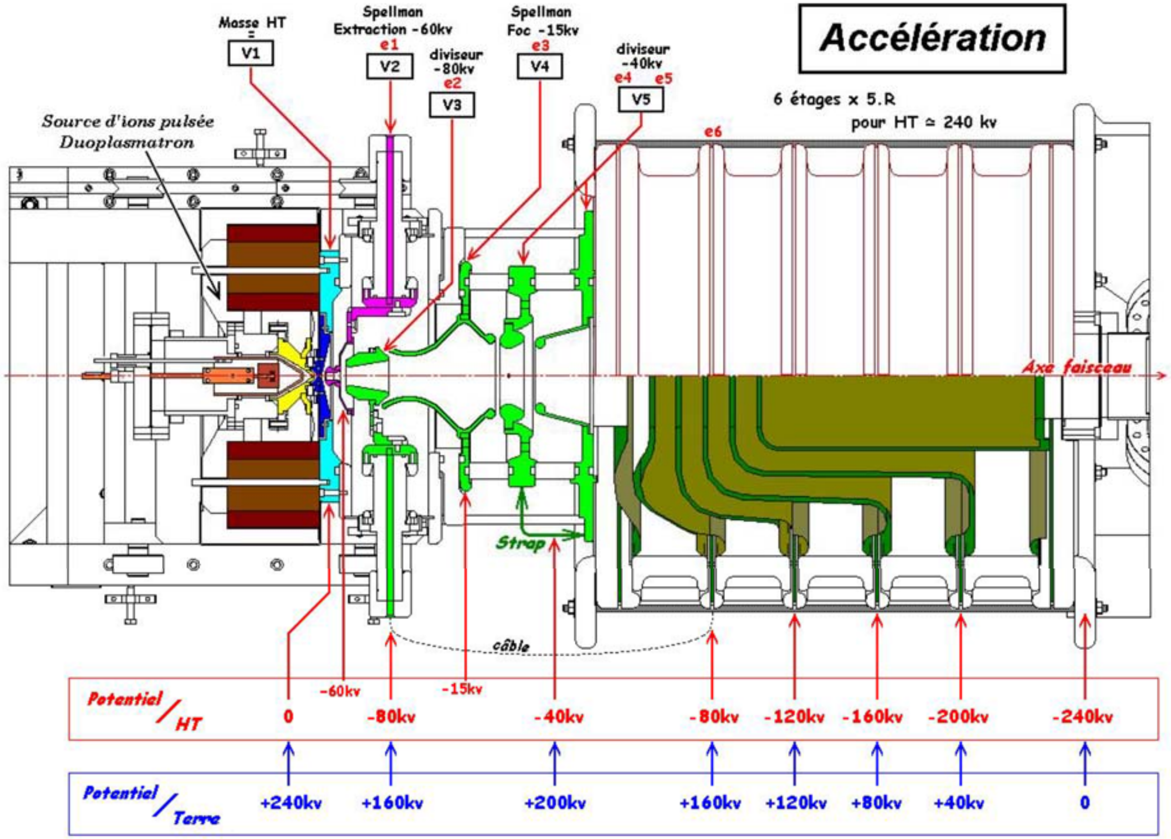


Extracted from, P. Sortais, JUAS 2006

GENEPI Duoplasmatron (LPSC)

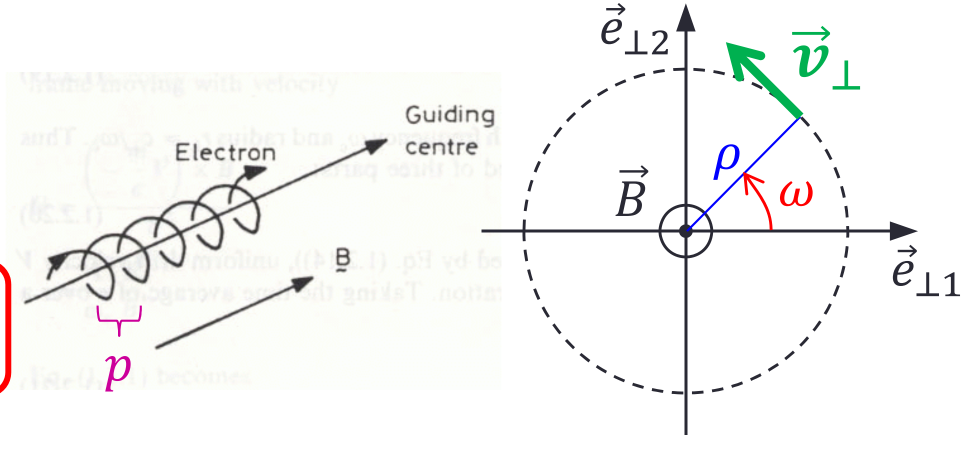
- High intensity pulsed ion beams are produced with a very low space charge compensation in the accelerator
- A short pre-acceleration is mandatory to prevent the beam to blow up before reaching the area of experiment or the next accelerator stage
- Example of the GENEPI accelerator where the source is set on high voltage platform at 180 kV
- The ion source is set at +60 kV with respect to the platform
- Electrostatic lenses focused and accelerate the beam toward the acceleration tube





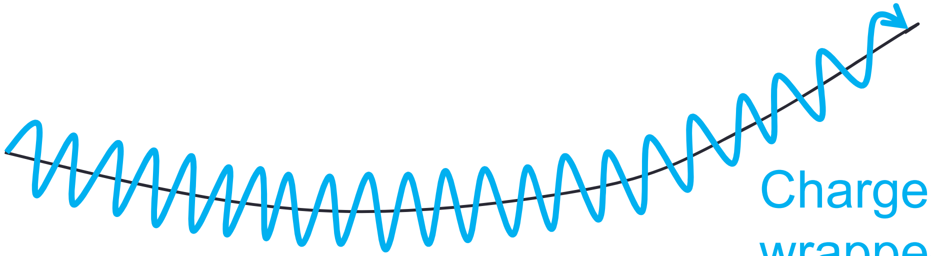
Motion of a charged particle in a constant magnetic field

- The Individual motion of a charged particle in a magnetic field is ruled by:
- $m\dfrac{d\vec{v}}{dt} = q\vec{v} \times \vec{B}$
- Velocity is decomposed as $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$ with $\vec{v}_{\perp} . \vec{B} = 0$ and $\vec{v}_{\parallel} \parallel \vec{B}$
  - We define the space vectors $\vec{e}_{\parallel} = \dfrac{\vec{B}}{B}$, $\vec{e}_{\perp 1} = \dfrac{\vec{v}_{\perp}}{v_{\perp}}$ and $\vec{e}_{\perp 2} = \vec{e}_{\parallel} \times \vec{e}_{\perp 1}$
- General solution for the velocity is:
- $\begin{cases} v_{\parallel} = const \\ \vec{v}_{\perp} = \rho\omega(\sin \omega t . \vec{e}_{\perp 1} + \cos \omega t . \vec{e}_{\perp 2}) \end{cases}$
- $\omega = \dfrac{qB}{m}$ is the cyclotronic frequency
- ρ is the Larmor radius (constant)
- The particle trajectory is an helix with radius ρ and pitch $p = \dfrac{2\pi v_{\parallel}}{\omega}$

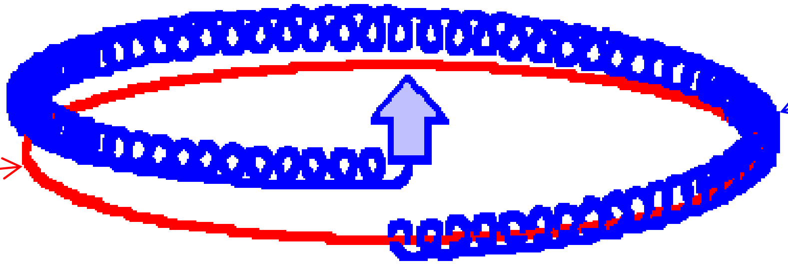


Motion of a particle in a non-uniform magnetic field

- If the spacial variation of B is much larger than the larmor radius ($\frac{1}{\left|\frac{\overrightarrow{\nabla B}}{\vec{B}}\right|} \gg \rho$), then the particle follows the curved field line:



- If $\frac{1}{\left|\frac{\overrightarrow{\nabla B}}{\vec{B}}\right|} \sim \rho$, then a slow drift of the particle with respect to the actual field line occurs

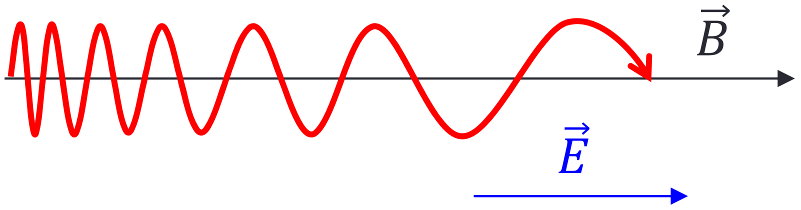


http://www-fusion-magnetique.cea.fr

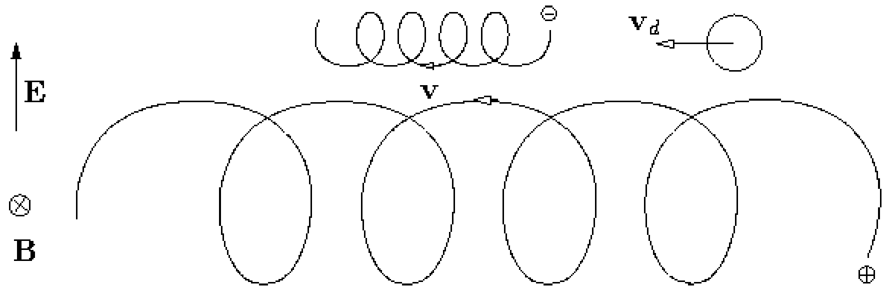
Motion of particles in a $\vec{E}+\vec{B}$ Field

$$m\frac{d\vec{v}}{dt}=q\vec{E}+q\vec{v}\times\vec{B}$$

- Motion of a charged particle with $\vec{E}||\vec{B}$
  - $v_{||}$ increases linearly with time
  - Helical trajectory with an increasing thread pitch

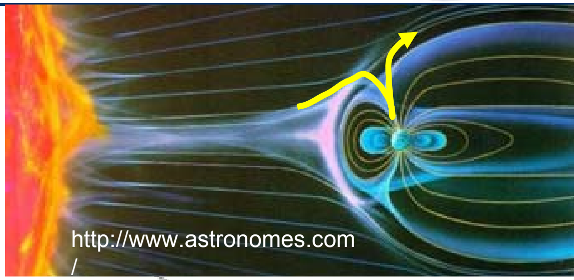


- Motion of a charged particle with $\vec{E}\perp\vec{D}$
  - Cycloidal trajectory
  - No Mean acceleration due to E !
  - Drift velocity : $\overrightarrow{v_D}=\frac{\vec{E}\times\vec{B}}{B^2}$



The Magnetic Mirror Effect

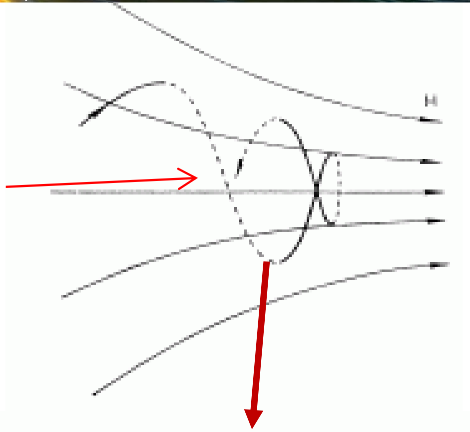
Solar wind reflection by the Earth magnetosphere

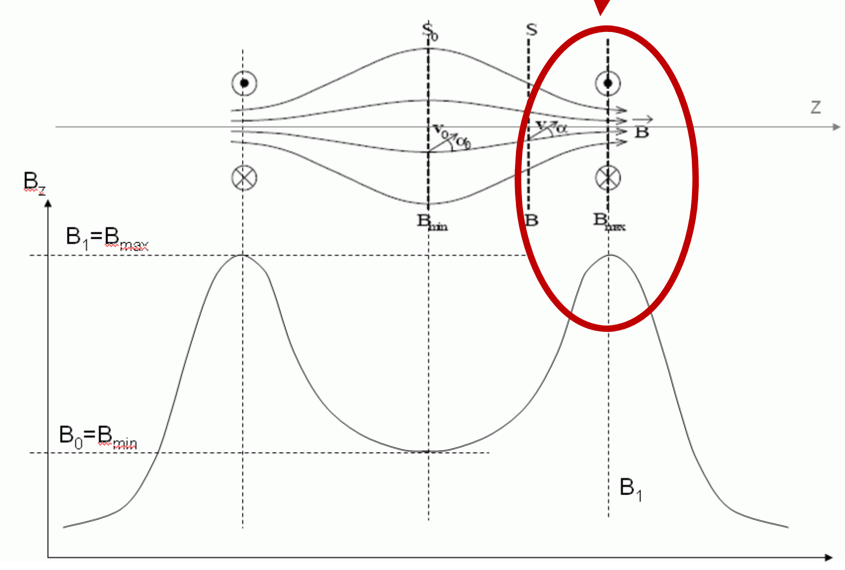


http://www.astronomes.com/

- When a charged particle propagates along z toward a higher magnetic field region, it may be reflected back
  - $T_{kin} = W_{\parallel} + W_{\perp} = \frac{1}{2}m{v_{\parallel}}^2 + \frac{1}{2}m{v_{\perp}}^2 = const$
  - $\mu = \frac{m{v_{\perp}}^2}{2B} = \frac{W_{\perp}}{B} \sim const$ (magnetic moment)
- $T_{kin}(z) = \frac{1}{2}m{v_{\parallel}}^2(z) + \mu B(z) = const$
  - When B increases, then the velocity is adiabatically transferred from $v_{\parallel}$ to $v_{\perp}$
- The particle is stopped at $z = z_1$ where$(v_{\parallel} = 0)$ and $B(z_1) = \frac{T_{kin}}{\mu}$
  - $T_{kin}(z_1) = \frac{1}{2}m{v_{\perp}}^2$
  - The particule is forced to go backward

A particle can be reflected By a high magnetic field intensity

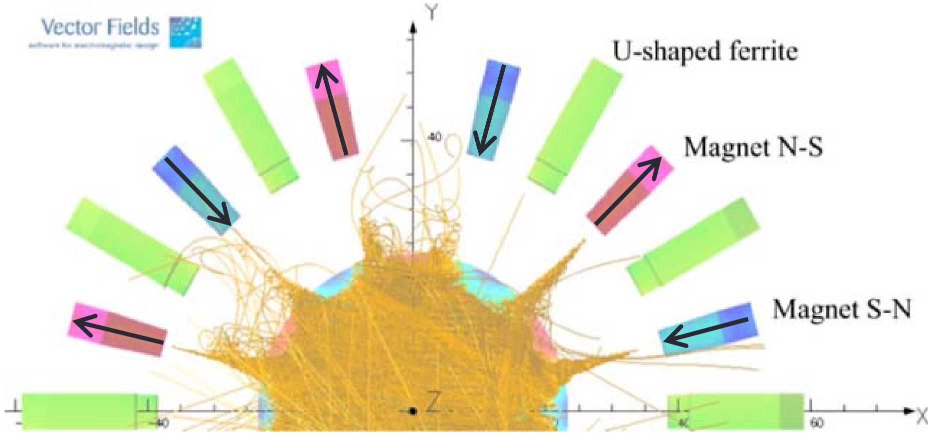




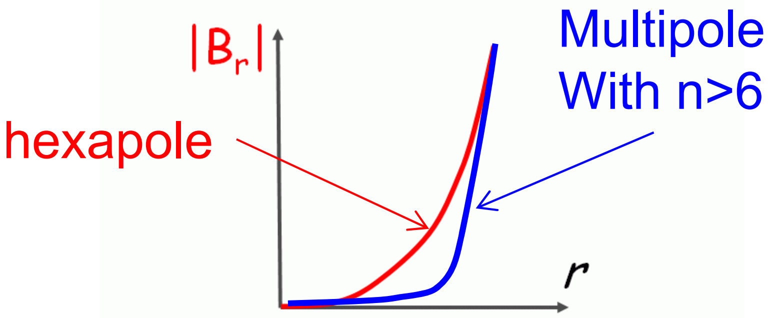
Axial magnetic mirror done with a set of 2 coils

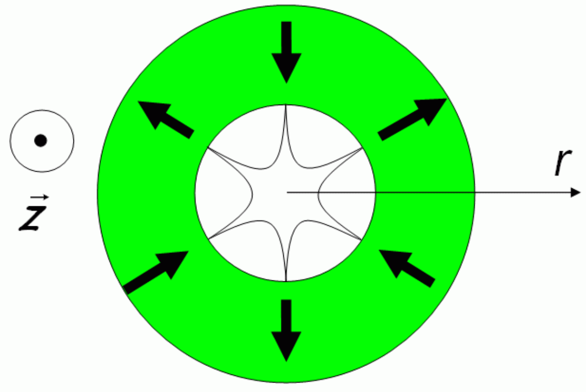
Radial magnetic mirror

- An axial magnetic mirror is done with a set of solenoids
  - See former slide
- A radial confinement can be achieved with a so-called « multipole structure »
  - A set of radial magnets are placed along a circular path with an alternated direction of magnetization
  - The magnetic intensity in the center is zero
  - The magnetic intensity increases with the radius and is maximum near to the magnets
  - The lower the multipole order, the higher the magnetic field at an intermediate radius



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

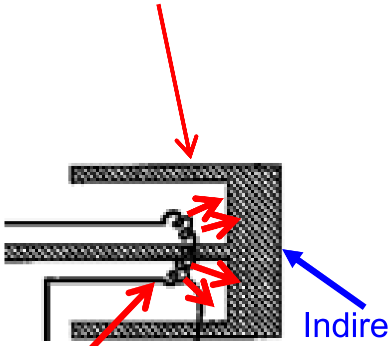


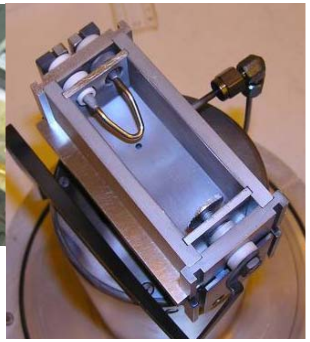


Radial Mirror
(Permanent magnet hexapole)

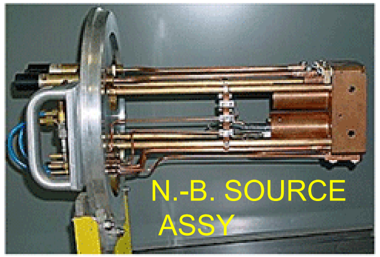
The Indirectly Heated Cathode (IHC) Ion Source

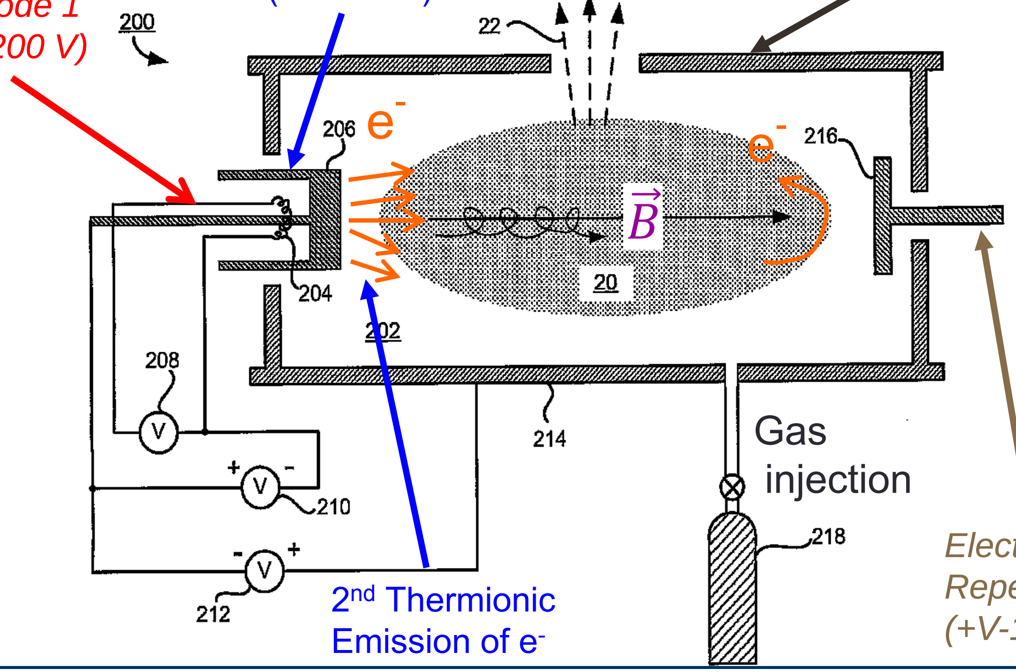
- An upgraded Niel-Bernas filament Ion Source
- Used in industrial implanters to produce intense 1+ ion beams up to **~40 mA**
- The ion source contains two cathodes:
  - A first classical thermionic cathode
  - A second massive **indirectly heated thermionic cathode** which protects the first one from the intense ion sputtering from the plasma
  - Filament lifetime 200-800h, depending on condition of operation
  - The anode is the source body itself
  - A uniform magnetic field $\vec{B}$ forces the electrons to spiral along the ion source length
  - An electron repeller located at the other end is added to produce an electrostatic electron confinement
    - Secondary electrons created by an electron impact in the plasma are created at a potential lower than the repeller one
      => electrons reflected back to the plasma
  - Extraction through a slit (1mm x20~40 mm)
  - Pressure in the source ~10^{-3}-10^{-5} mbar
  - Ionization efficiency ~1%





Niels-Bernas (not IHC!)



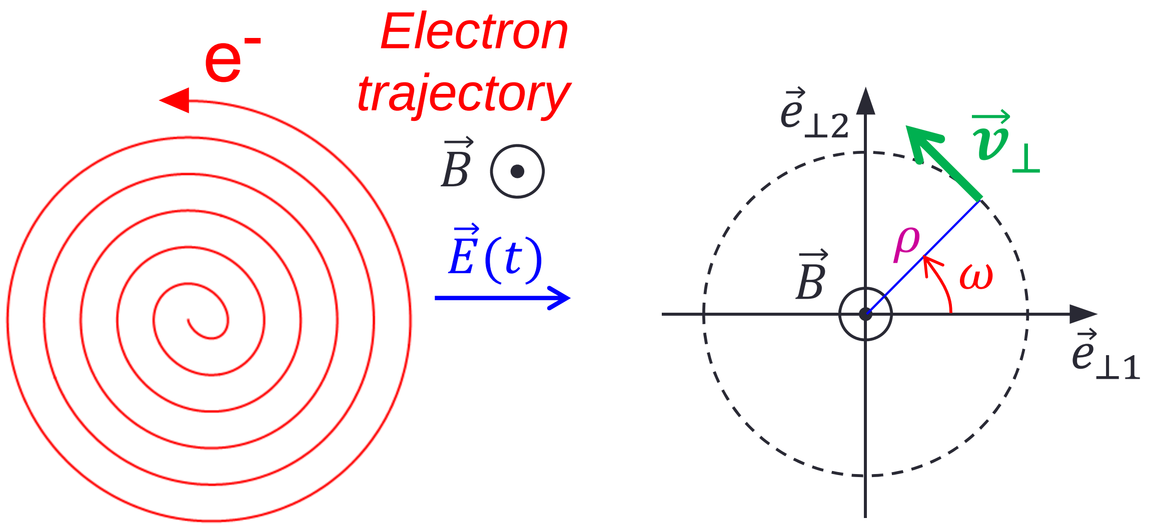


(introduction to) the Electron Cyclotron Resonance (ECR)

- When a particle is baking in a magnetic field $\vec{B}$ and a transverse time varying electric field $\vec{E}(t)$, a resonant transfer of energy from the electric field to the particle can occur, provided the particule cyclotronic frequency equals the electric field frequency

  - $\vec{B} = B\vec{z}$
  - $\omega = \frac{qB}{m}$ cyclotronic frequency
  - $\vec{E}(t) = E\cos(\omega_{HF}t)\,\vec{x}$
  - ECR resonance condition:

$$\boxed{\omega_{HF} = \omega = \frac{eB}{m}}$$

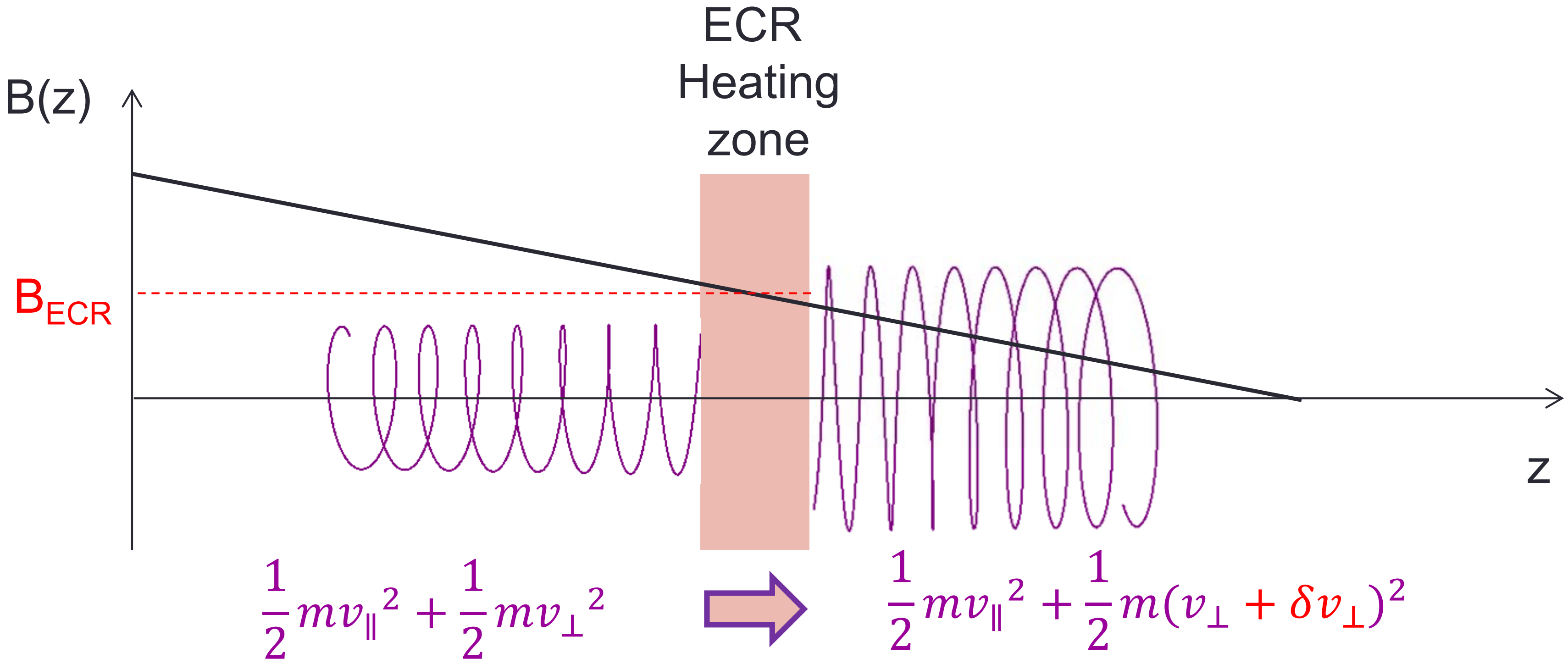


- Since the electric field turns at the same velocity as the particle (an electron here), the particule sees a constant electric field in its own framework => **constant acceleration**
- The particle describes a spiral and gains transverse energy:
  - $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
  - $\vec{v}_{\parallel} = const$ and $\vec{v}_{\perp} = \rho(t)\omega$
- That’s a very convenient way to accelerate electrons!

PS: the ECR heating mechanism is More complicated than Presented.

ECR Heating in a Magnetic Gradient

- In ECR Ion Sources, the ECR zone is usually reduced to a surface, inside a volume, where B is such that $\omega_{HF} = \omega = \frac{eB}{m}$
  - When electrons pass through the ECR surface they are slightly accelerated (in mean) and may gain a few eV of kinetic energy
  - The parallel velocity $v_{\parallel}$ is unchanged, while $v_{\perp}$ increases
  - The ECR zone thickness is correlated to the local magnetic field slope

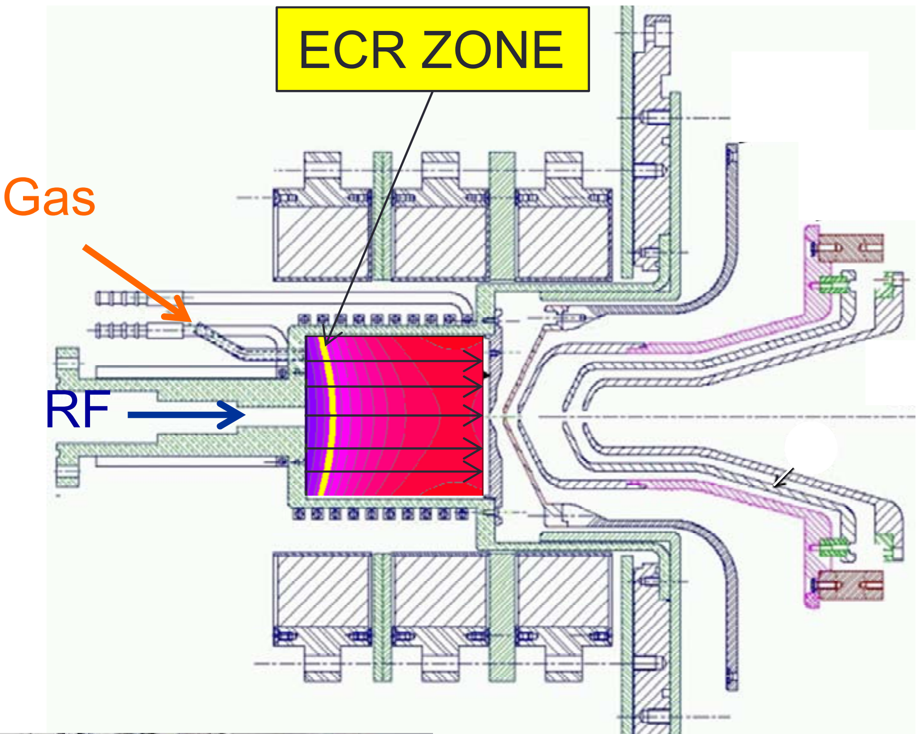


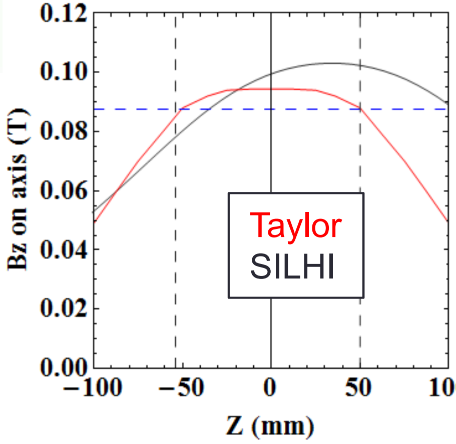
$$\frac{1}{2}mv_{\parallel}^2 + \frac{1}{2}mv_{\perp}^2 \Rightarrow \frac{1}{2}mv_{\parallel}^2 + \frac{1}{2}m(v_{\perp} + \delta v_{\perp})^2$$

1+ Electron Cyclotron Resonance Ion Source

Known as « microwave source »

- SILHI source with permanent magnets (CEA/IRFU)
  - Suitable for any gas
  - RF frequency: 2.45 GHz ($\lambda \sim 12\ cm$)
- The plasma chamber is filled with a flat axial magnetic field generated by permanent magnets
- A single ECR surface is located in the chamber
    - ECR located at the maximum of RF electric field, near to the RF input.
    - A second resonance is located out of the chamber in the extraction system (when the magnetic field decreases)
  - The plasma electrons are heated when passing through the ECR zone to ~10-20 eV which allows creating 1+ ions
  - Secondary electron emission from the chamber wall helps keeping the ion production balance to equilibrium
  - The source can produce ~100 mA of H+
    - 80% of proton fraction H^+, 20% of H_2^+ and H_3^+
  - High voltage extraction : 40-100 kV
- Main advantage of ECR Ion source: NO FILAMENT!
  - The source can stay for long term operation without any maintenance



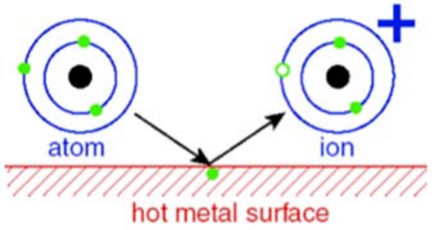


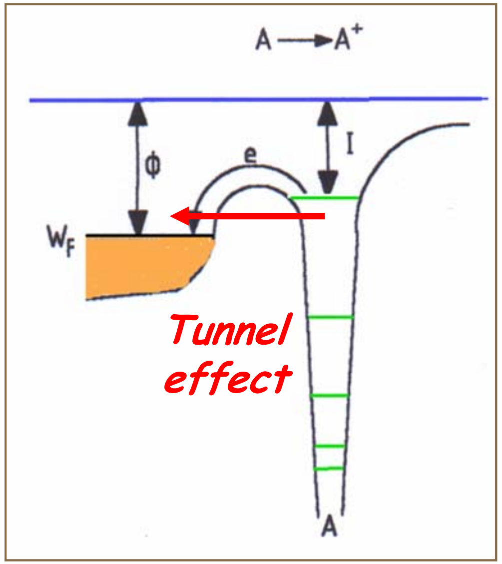
Axial magnetic field on axis

Ionization of atoms on surfaces

- A metal with a High Work Function can steal an electron to an adsorbed atom through Tunnel Effect
  - The ion production efficiency is given

    by the **SAHA relation**: $\frac{N^+}{N_0} = C^+ e^{\frac{\varphi - I}{kT}}$, provided $\varphi > I$
    - I First Ionisation Potential of adsorbed atom
    - φ metal work function
    - T metal temperature

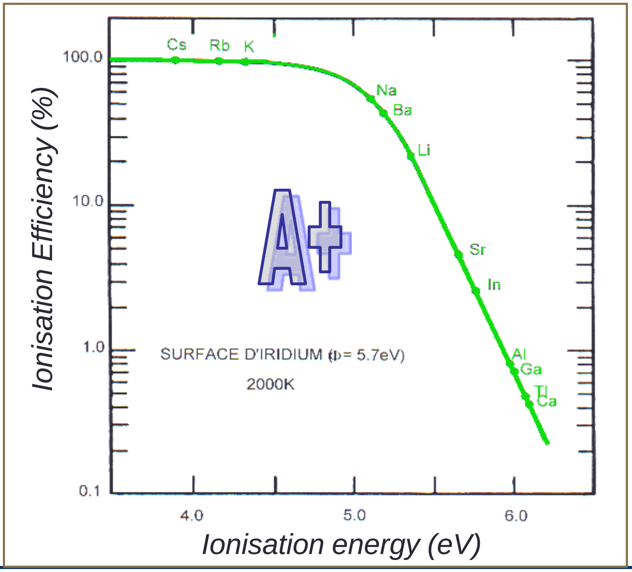




Works with High φ metals and low *I* atoms

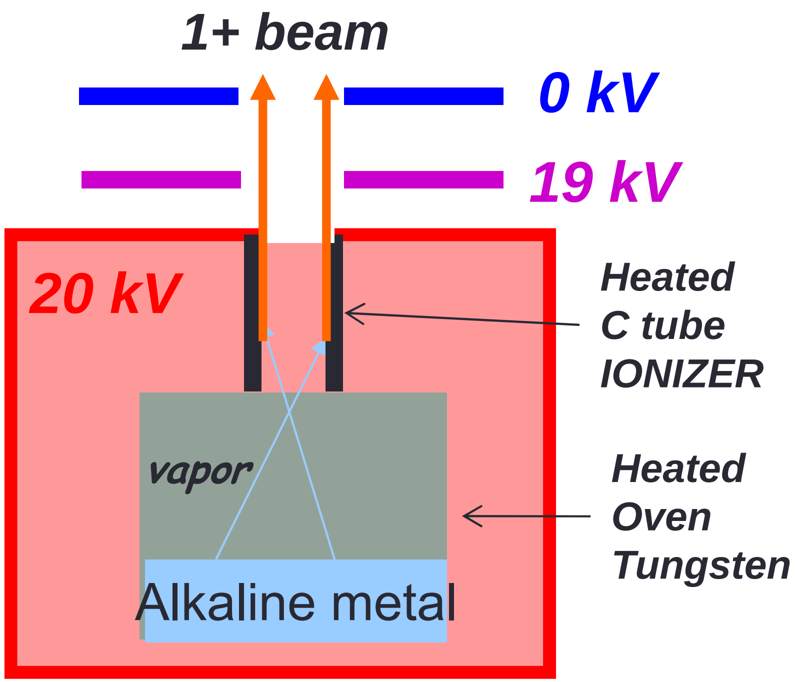
- Metals used : W-Ox, Ir, Pt, C, Re , W
- Atoms ionized : Alkalines, Alkaline earths

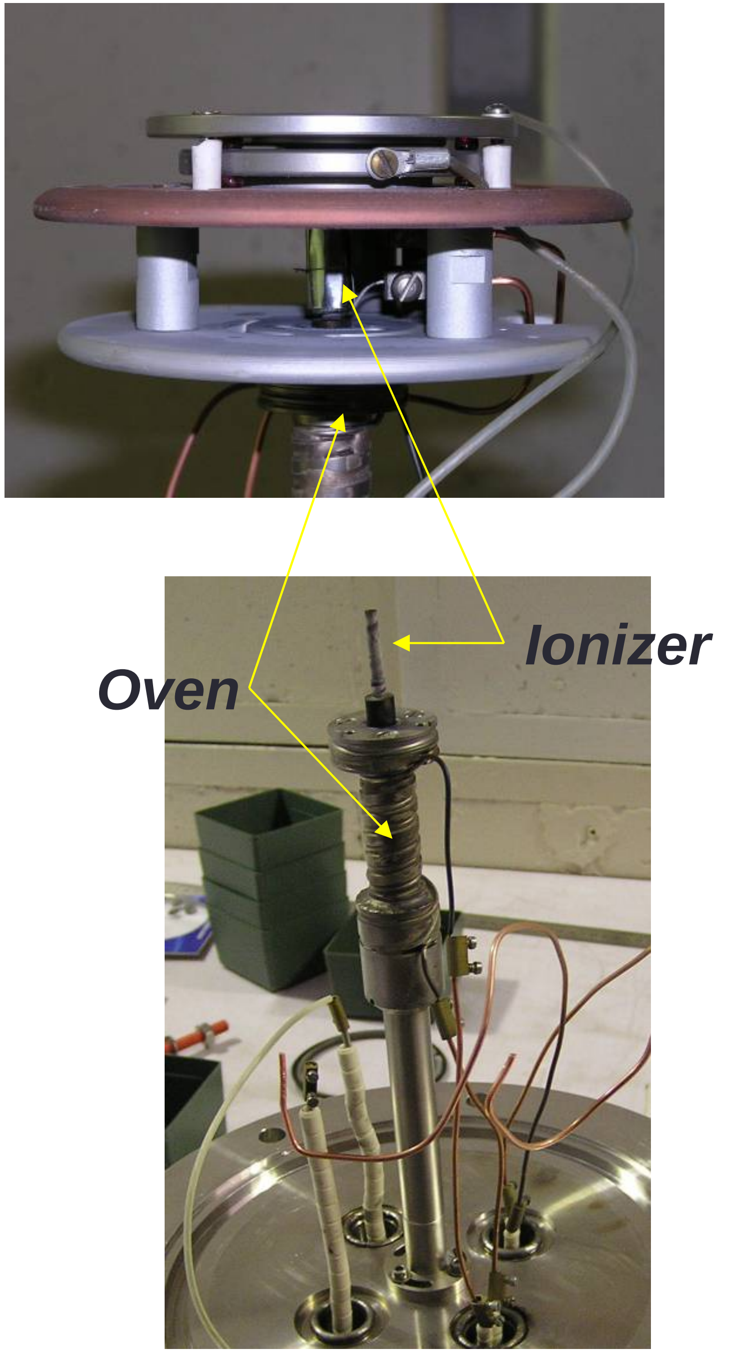
- High Temperature helps to desorb atoms
- Very efficient method, very selective technique



1+ Surface Ionization Source

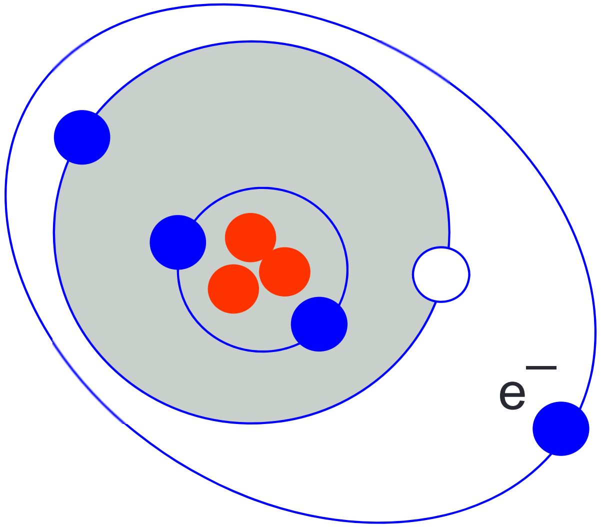
- An alkaline metal (or alkaline earth) is heated in an oven
- Atoms evaporates toward a heated ionizer tube made up with a high work function metal
- Atoms are adsorbed to the wall
- Atom desorbs at high Temperature with one e^- stolen by the metal => ionization



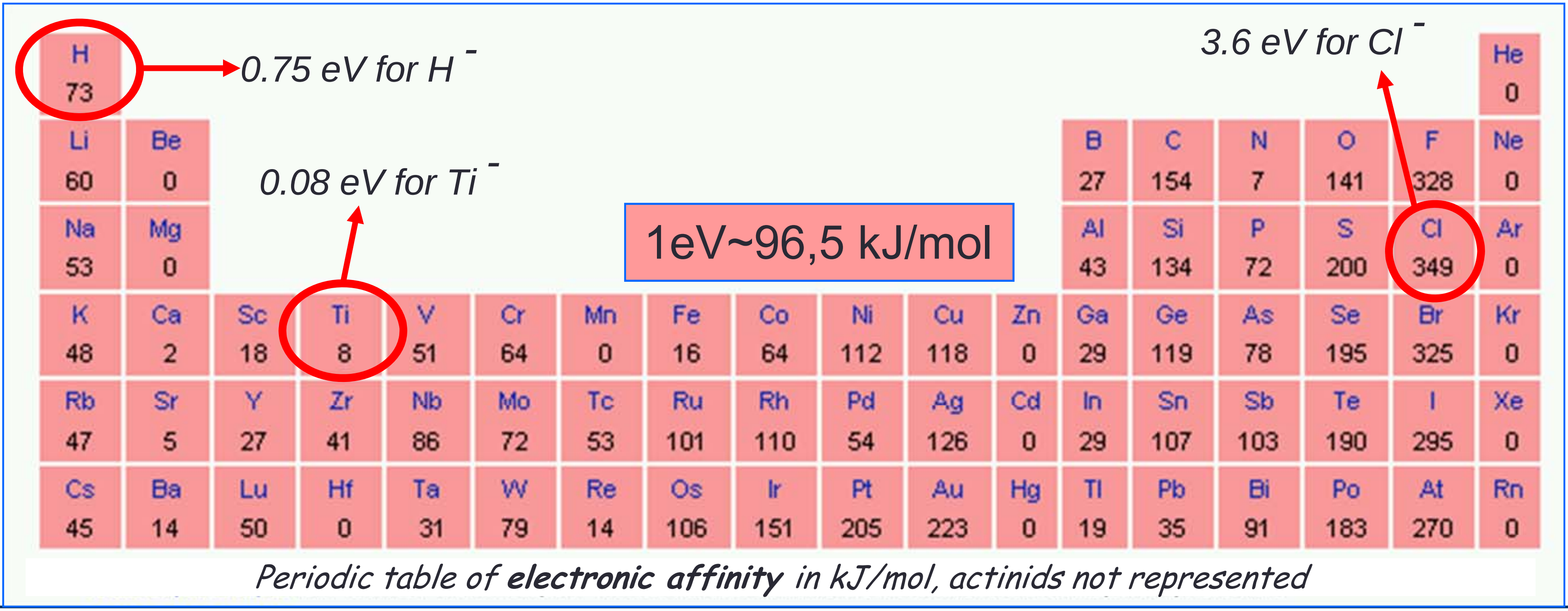


Negative Ions- Electron Affinity

Negative ION Materials from M. Stockli, ORNL, J. Arianer, IPNO,H. Koivisto, JYFL



- What is a Negative Ion?
  - Atoms with unclosed shells can accept an extra electron and form a stable ion with a 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).



0.75 eV for H^-

3.6 eV for Cl^-

0.08 eV for Ti^-

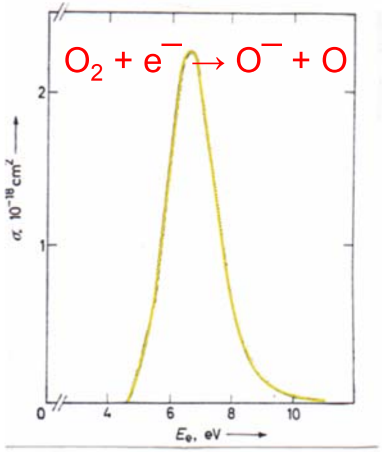
1eV~96,5 kJ/mol

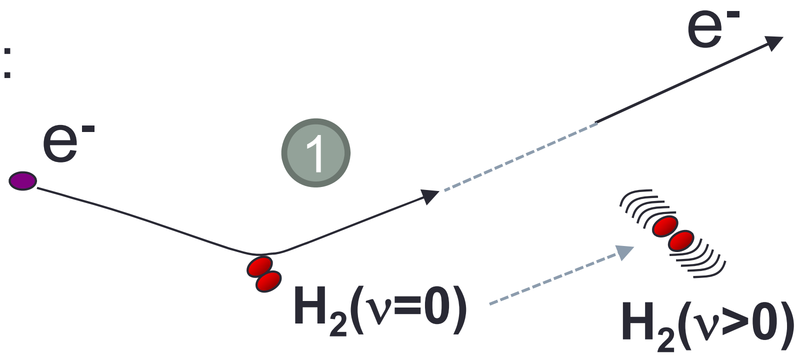
H 73																	He 0
Li 60	Be 0											B 27	C 154	N 7	O 141	F 328	Ne 0
Na 53	Mg 0											Al 43	Si 134	P 72	S 200	Cl 349	Ar 0
K 48	Ca 2	Sc 18	Ti 8	V 51	Cr 64	Mn 0	Fe 16	Co 64	Ni 112	Cu 118	Zn 0	Ga 29	Ge 119	As 78	Se 195	Br 325	Kr 0
Rb 47	Sr 5	Y 27	Zr 41	Nb 86	Mo 72	Tc 53	Ru 101	Rh 110	Pd 54	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

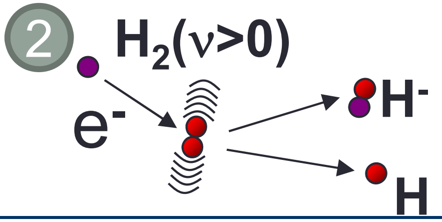
*Periodic table of **electronic affinity** in kJ/mol, actinids not represented*

How to create a negative ion? (1/2)

- The creation of negative ions is exothermic. Excess energy should be dumped to a third particle. Negative ions can be produced on surfaces and in a plasma (« volume ionization »).
- Volume ionization:
  - Dissociative attachement:
    - the excess of energy is transferred to a third particle when dissociating a molecule
    - $AB + e^- \rightarrow A^- + B$ (rare event)
  - 3 body collision:
    - $A + B + e^- \rightarrow A^- + B$ (rare event)
- Example of H^- production which requires 2 steps:
    - Step 1: H_2 excitation by electron impact
    - $e^-(fast) + H_2 \rightarrow H_2^\nu + e^-$,
      (ν=molecule **high vibrational state**)
    - Step 2: Dissociative attachement
    - $H_2^\nu + e^- \rightarrow H^- + H$

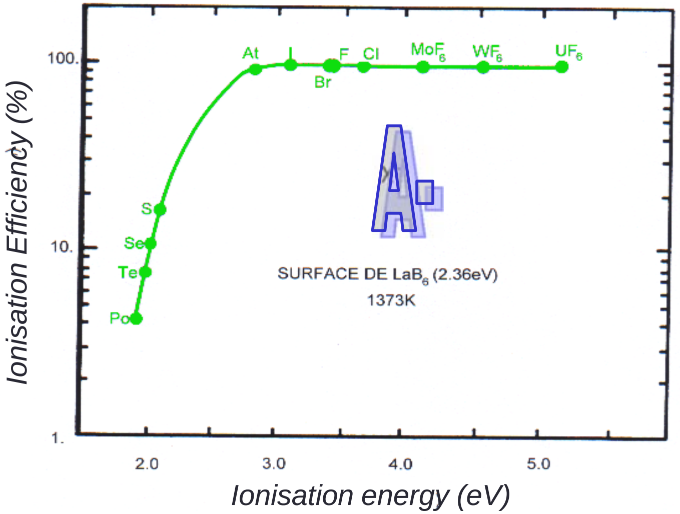


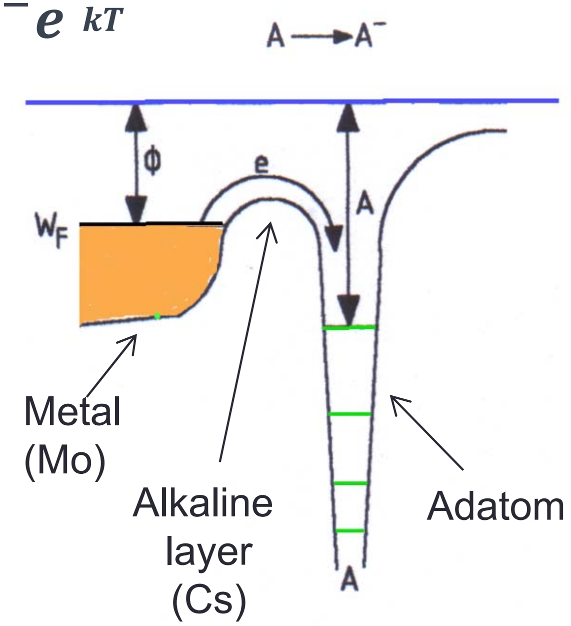


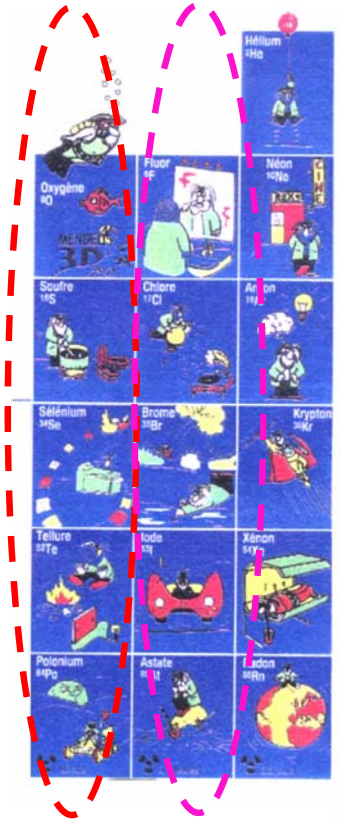


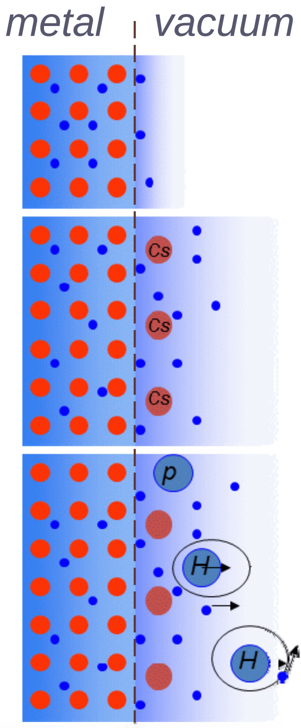
How to create a negative ion? (2/2)

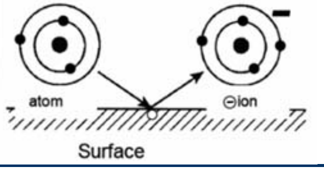
- **Surface production:**
  - As seen in the Electron source part, Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface.
  - Alkaline metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, **alkaline 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 $A > \varphi$
  - Surface ionization works efficiently with Halogens and Chalcogens
  - Langmuir-Saha Formula: $\frac{N^-}{N_0} = C^- e^{\frac{A-\varphi}{kT}}$
  - High kT helps to desorb A^-





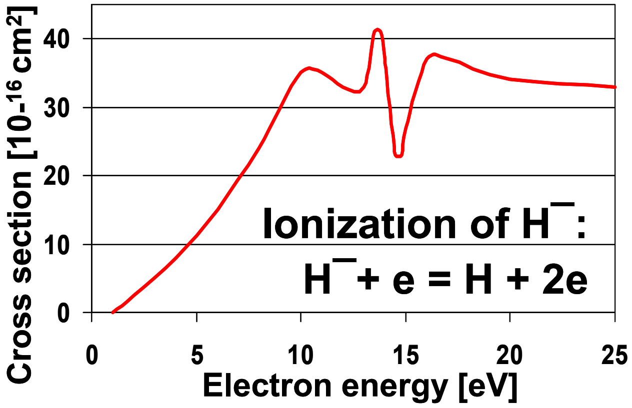


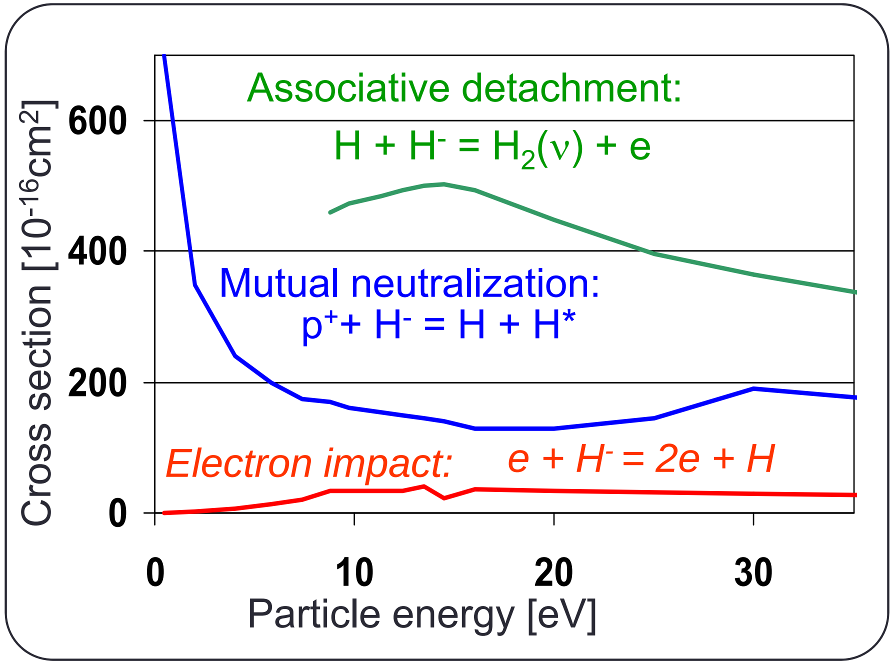




How to lose a negative ion?

- Very very easily!
  - Electron impact ionization:
    $A^- + e^- \rightarrow A + 2\,e^-$
  - Mutual neutralisation (Recombination)
    $A^- + H^+ \rightarrow A + H$
  - Collisional Detachment:
    $A^- + B \rightarrow A + B + e^-$
  - 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
  - **Negative ions must be extracted close to their place of birth**

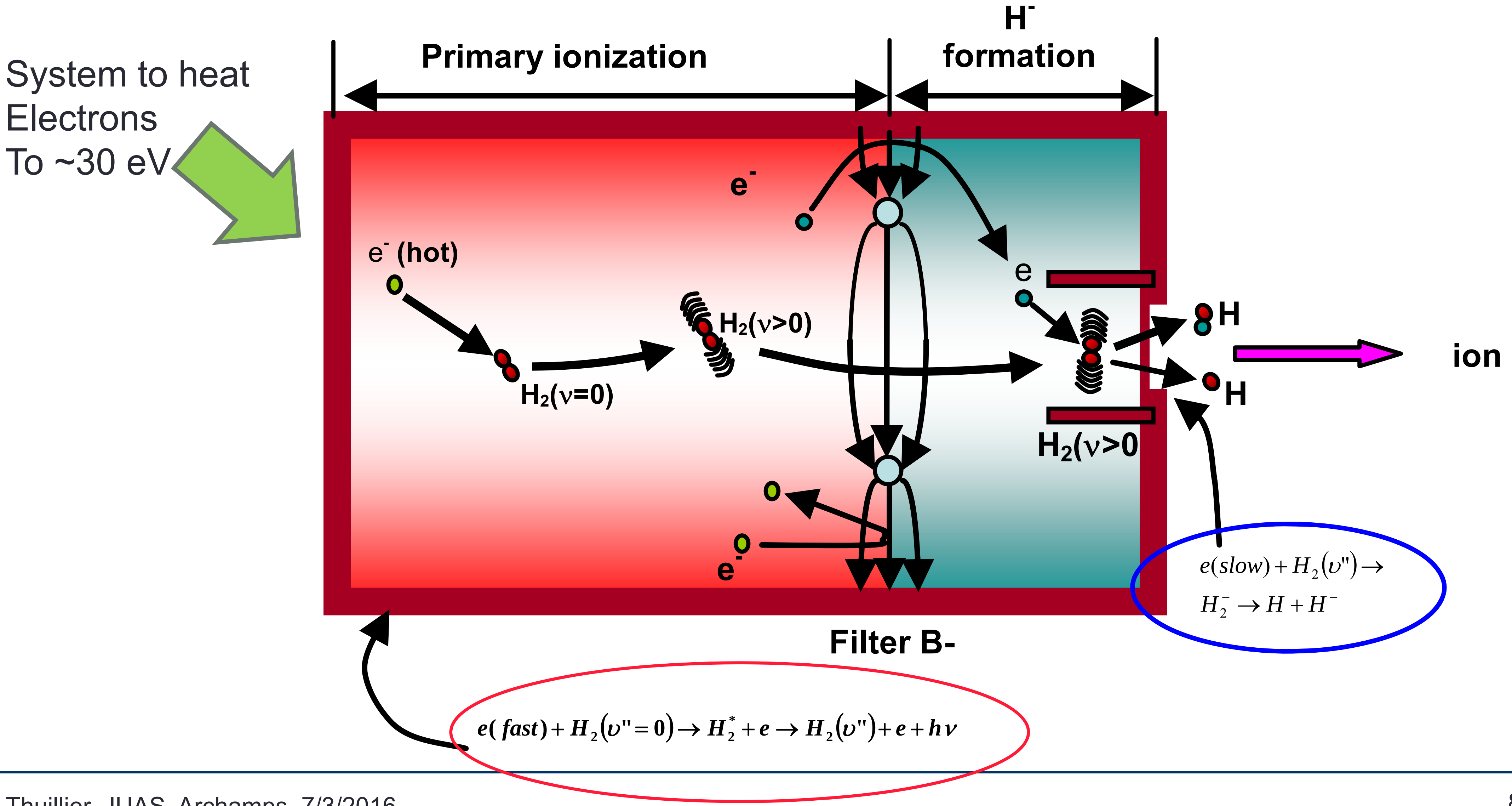




Example of H^- destruction process

Volume production of H^-

- “Hot” electrons are reflected back by a filter B-field.
- Cold electrons are highly collisional and are not magnetically confined



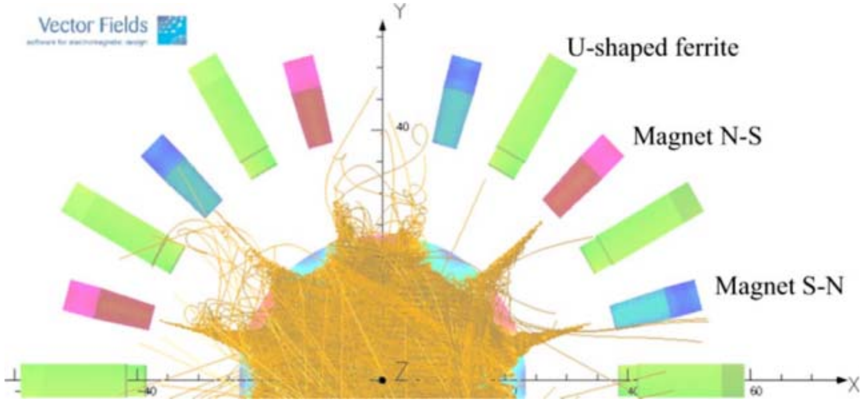
$$e(slow) + H_2(\upsilon'') \rightarrow H_2^- \rightarrow H + H^-$$

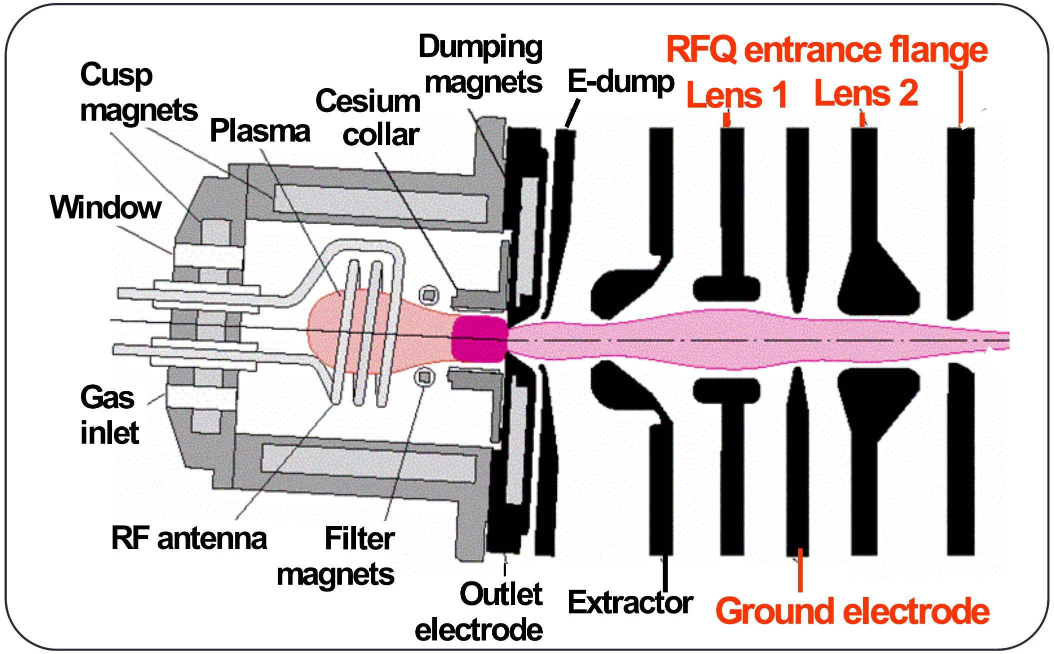
$$e(fast) + H_2(\upsilon''=0) \rightarrow H_2^* + e \rightarrow H_2(\upsilon'') + e + h\nu$$

Radio-Frequency Negative Ion Source

- Example of the ORNL H¯ Ion Source
  - A multicusp magnetic structure provides a radial plasma confinement
  - H_2 gas is injected on the rear part
  - A pulsed 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).
  - A Cs collar is present near to the source extraction to boost H¯ production (by ~200%)
  - Source is pulsed with 6% Duty Cycle to produce 50 mA of H¯
  - Advantage: no filament! But the use of Cs collar is tricky and maintenance is required every 6 weeks

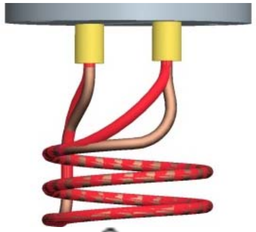
Trajectories of e^- in a CUSP magnetic structure (CERN), Rev. Sci. Instrum. 81, 02A723 (2010))

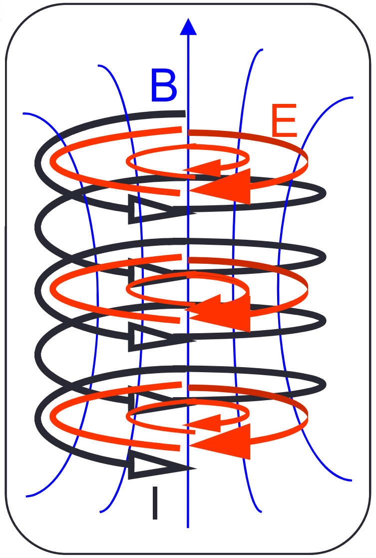




Radio-Frequency Negative Ion Source – Plasma Generation

- The plasma is inductively driven by a RF antenna making 3 turns around the plasma
    - The axial time varying magnetic field B(t) generated by the antenna induces a circular electric field in the plasma. This electric field accelerate electrons up to ~30 eV.
- A multicusp magnetic field confines the plasma towards the center
- A CW low power plasma is maintained by a 13 MHz amplifier (~300 W)
- The "Main" plasma is pulsed by a 2 MHz amplifier (50-60 kW), with a pulse length 1 ms @ 60 Hz



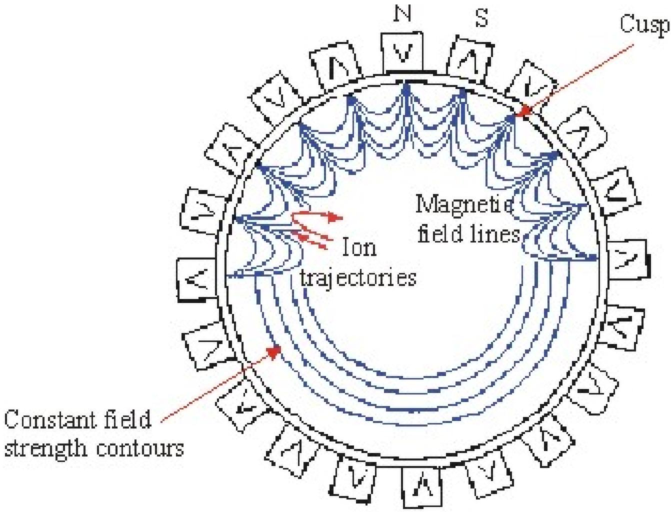


$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

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

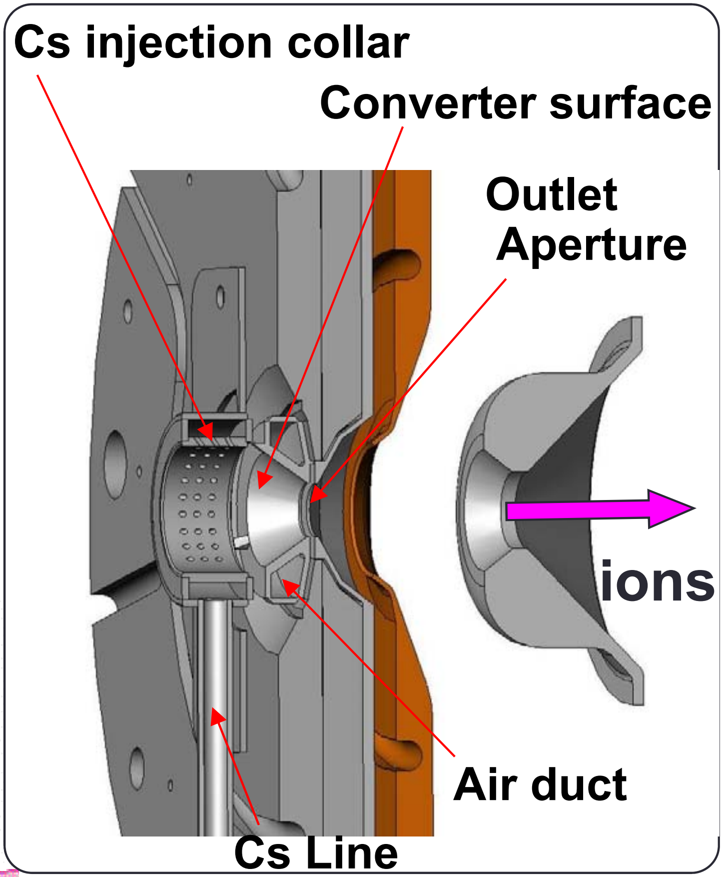
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

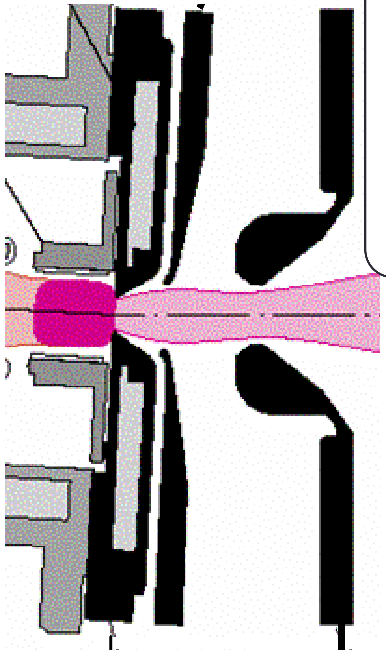
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

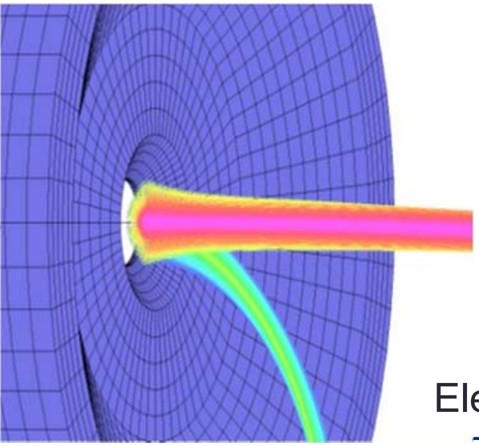


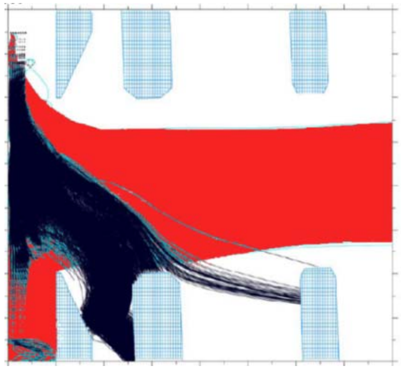
RF Negative Ion Source – Cesiation System and Beam Extraction

- Cesium system:
  - The Cs flux is controlled by an external oven
    - Cs manipulation is tricky (pyrophoric, unuasable once oxydised)
- Gain of H^- current:
  - 10 mA (no Cs) -> 50 mA (Cs)
- H^- extraction
  - A dumping magnet is located in the extraction area to deviate the co-extracted electrons off-axis
  - The co-extracted electron beam is dumped on the intermediate electrodes
  - The source is tilted to have the H^- on the accelerator axis







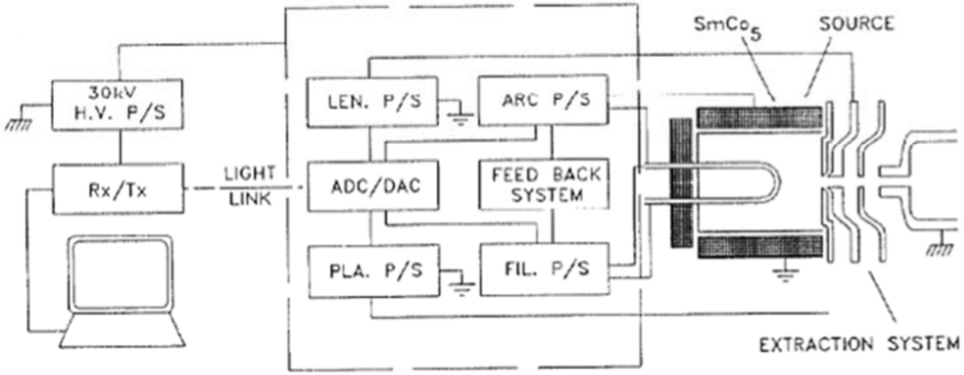


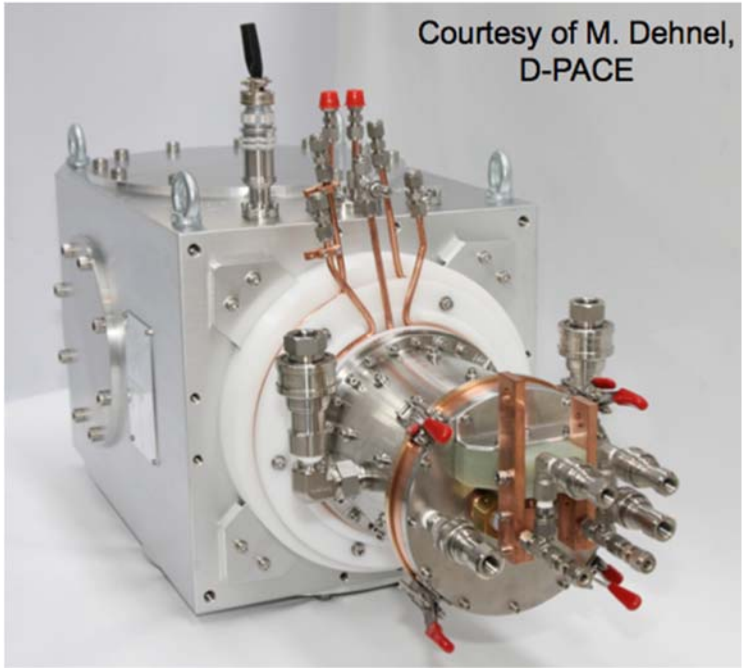
Electron deviation in the Extraction gap

Filament driven Triumf H- ion source: Volume production

- The TRIUMF H- source was developed ~1990 to inject H- into the TRIUMF Cyclotron
- A filament driven plasma is confined by a multicusp field
- Filter field generated by two inverted cusp magnets near the outlet.
- Licensed to and sold by D- PACE at www.d-pace.com
  - Beam current: 15 mA continuous
  - Ion energy: 20-30 kV
  - Efficiency: 3 mA/kW
  - Filament lifetime: 2 weeks at peak current
  - Cesium free

K. Jayamanna, M. McDonald, D.H. Yuan, P.W. Schmor, EPAC (1990) 647

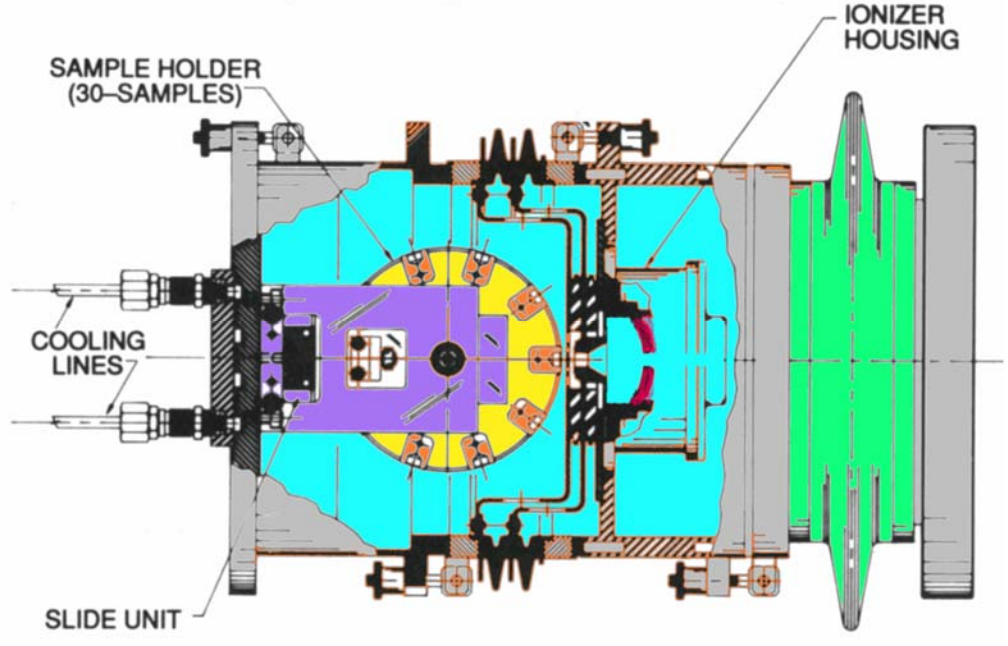


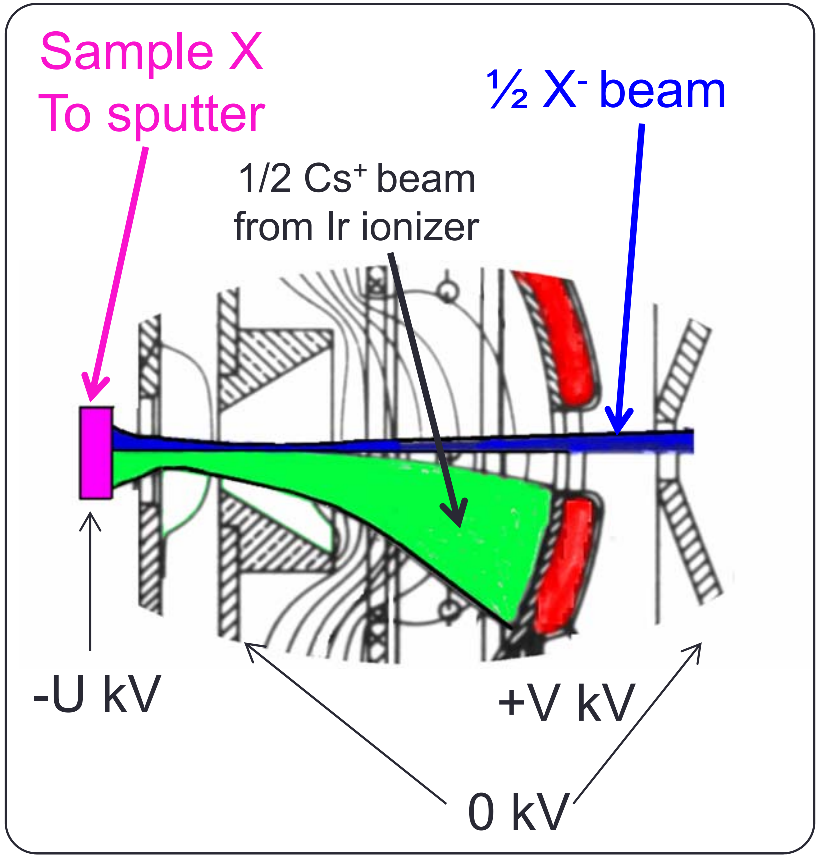


Courtesy of M. Dehnel, D-PACE

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

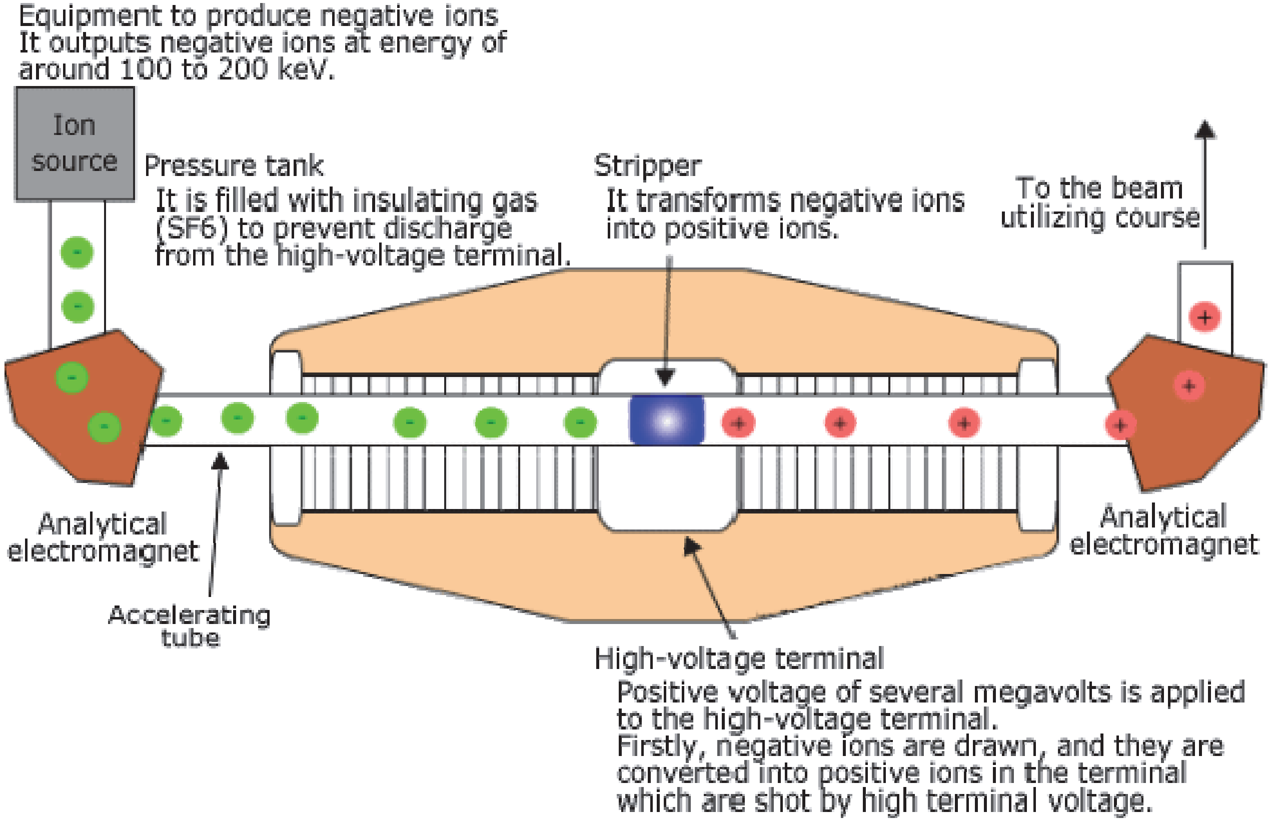




- Negative Metal Ions are produced (helped with high kT)
- Automatic Rotation of Sample to sputter to increase the beam time

Negative Ion Source Applications for TANDEM

- TANDEM Accelerator http://www.werc.or.jp/english/reseadeve/activities/accelerator/accelerator/tandem/index.htm
  - The negative ion beam is accelerated up to the tandem center set at at high positive voltage
  - The negative ions are then stripped in a target transforming them into positive ions
  - The ions undergo a new acceleration toward the tandem exit.



Equipment to produce negative ions
It outputs negative ions at energy of around 100 to 200 keV.

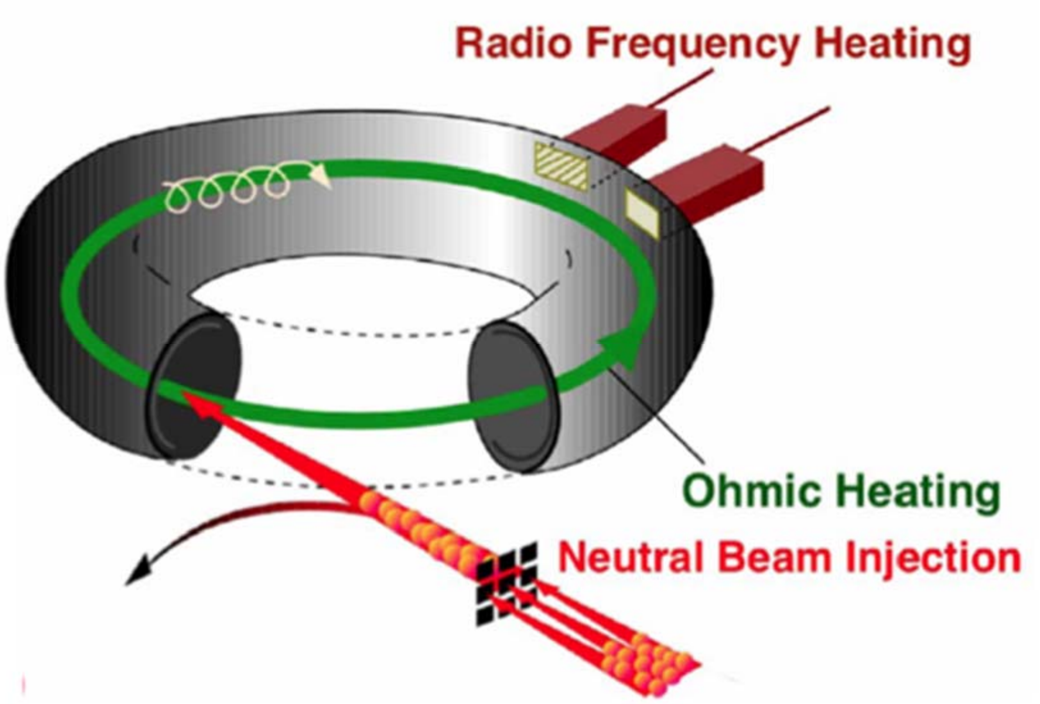
Pressure tank
It is filled with insulating gas (SF6) to prevent discharge from the high-voltage terminal.

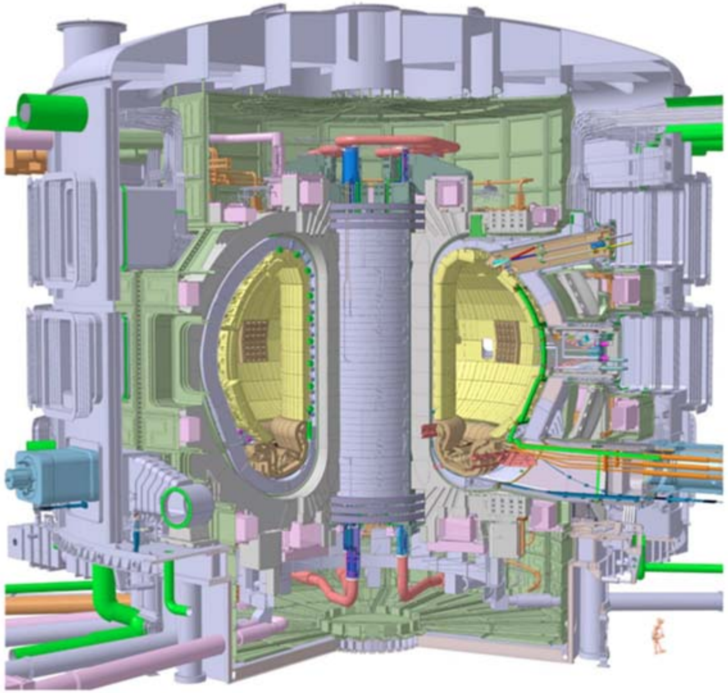
Stripper
It transforms negative ions into positive ions.

High-voltage terminal
Positive voltage of several megavolts is applied to the high-voltage terminal.
Firstly, negative ions are drawn, and they are converted into positive ions in the terminal which are shot by high terminal voltage.

Negative Ion Application for TOKAMAK

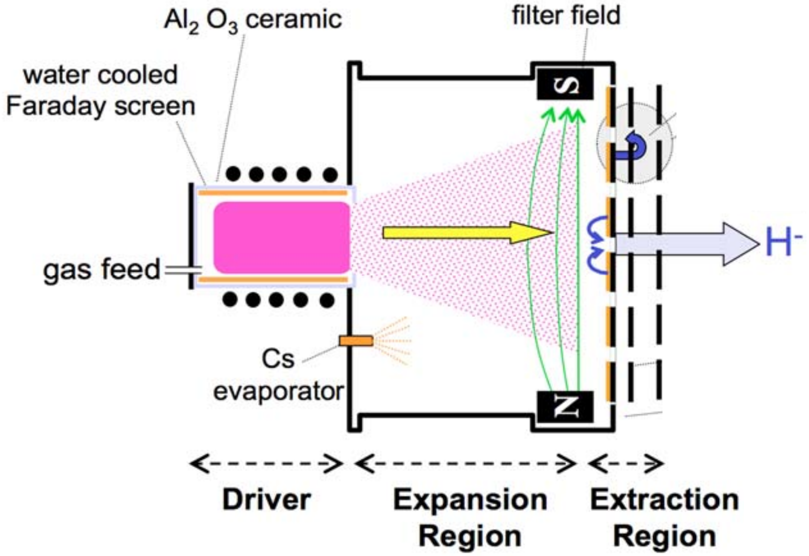
- ITER: Neutral beam injection:
  - Heating power requirement > 50 MW
  - Neutral Beam Injection ≈ 33 MW
  - Ion Cyclotron Heating ≈ 20 MW, ECR Heating ≈ 20 MW
  - A D^- beam is produced and accelerated; it is then neutralized before being injected into the plasma

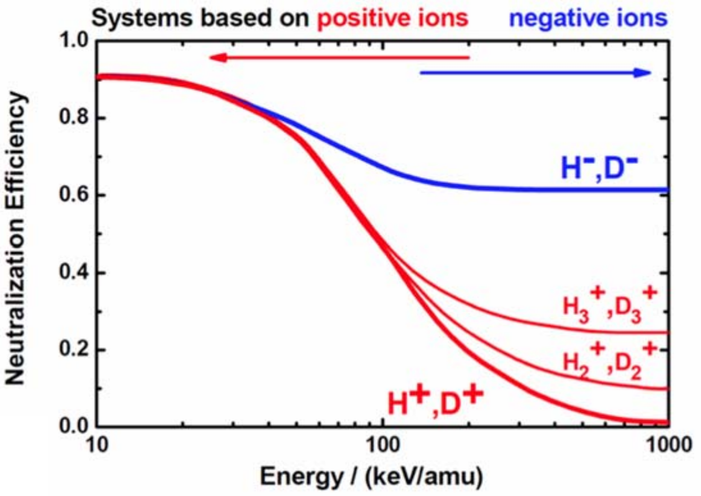




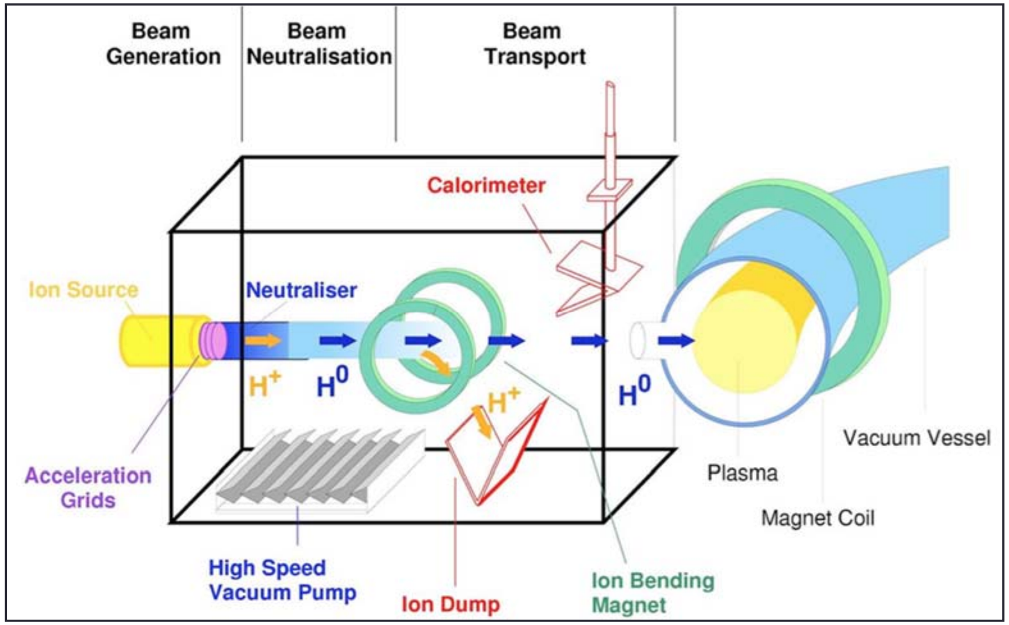
D^- Ion source for ITER

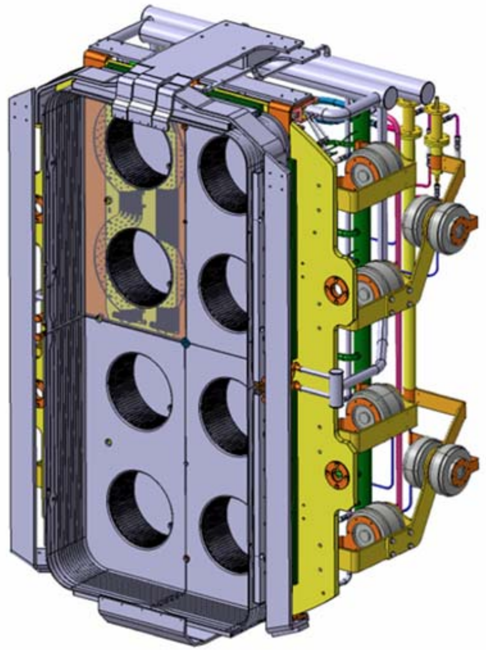
- Beam Requirement: 40 A (D^-) @1 MeV
  - D^- is used because of its much higher neutralisation efficiency at 1 MeV
- The D^- beam is neutralized before its injection in the Tokamak





ITER source 1.9 x 0.9 m^2

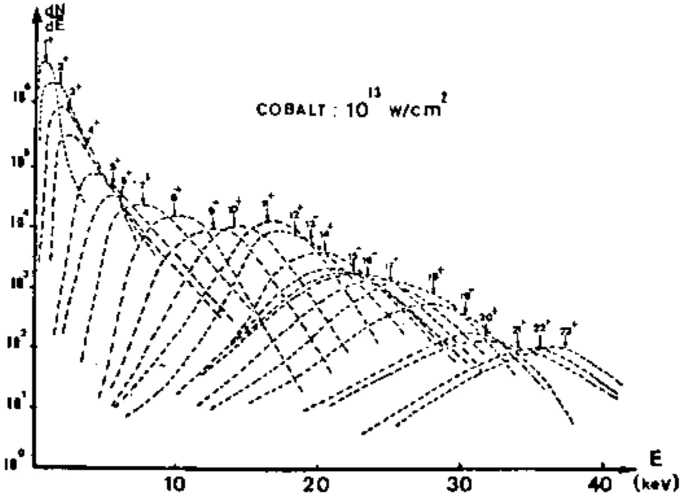


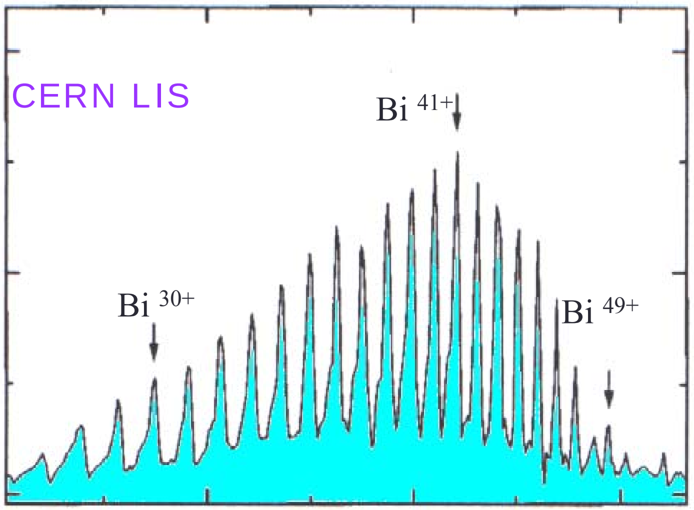


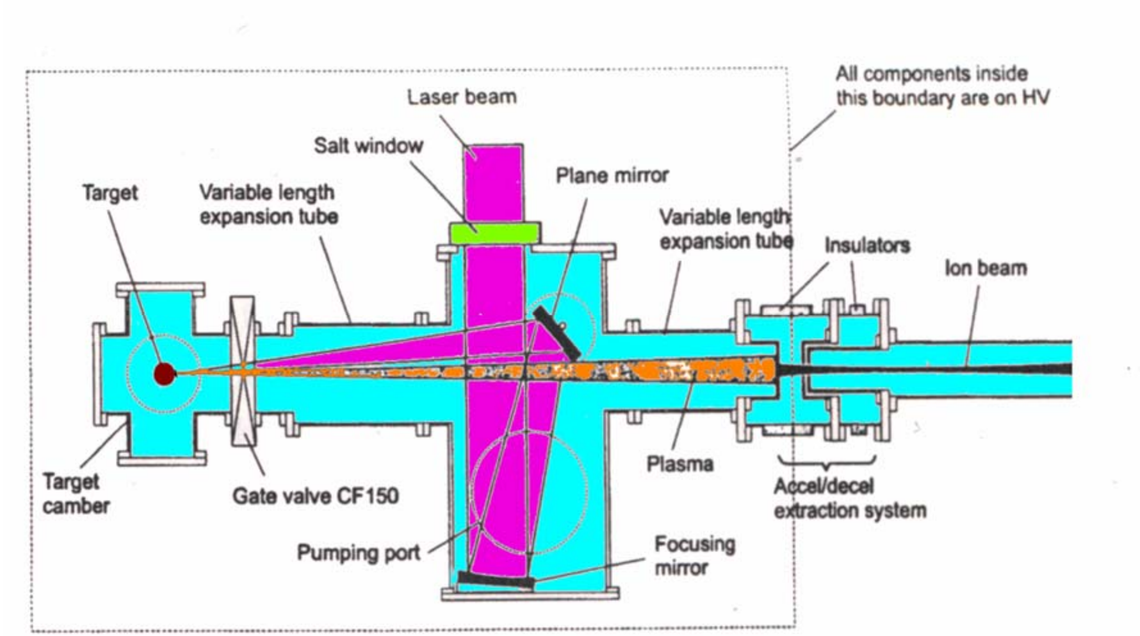
Material from CAS2012: W. Kraus

Laser Ion Source

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

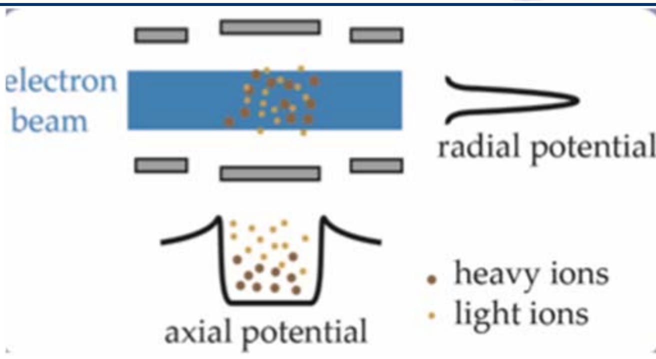






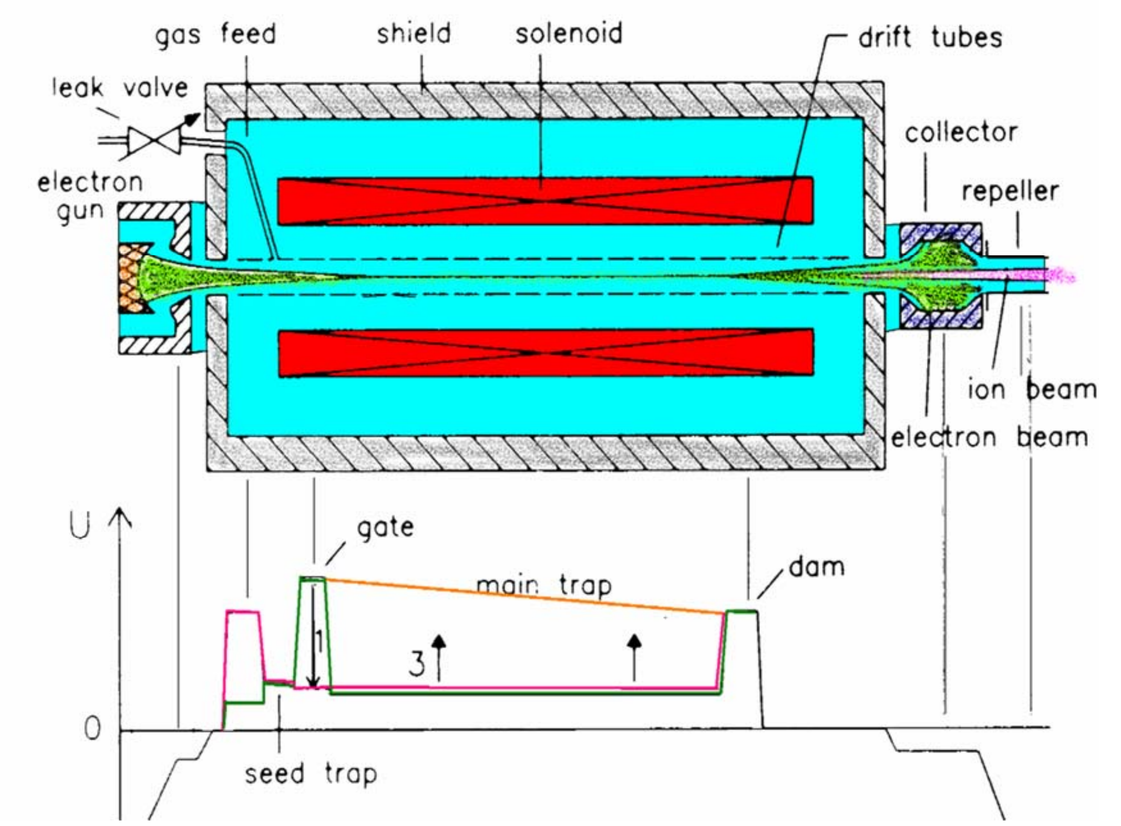
Specifications :
CO_2-N_2-He laser 100J-10^{13}W.cm^{-2}
pulses of 50ns at 1Hz
1.4 10^{10} Pb^{25+} per pulse

Electron Beam Ion Source (EBIS)



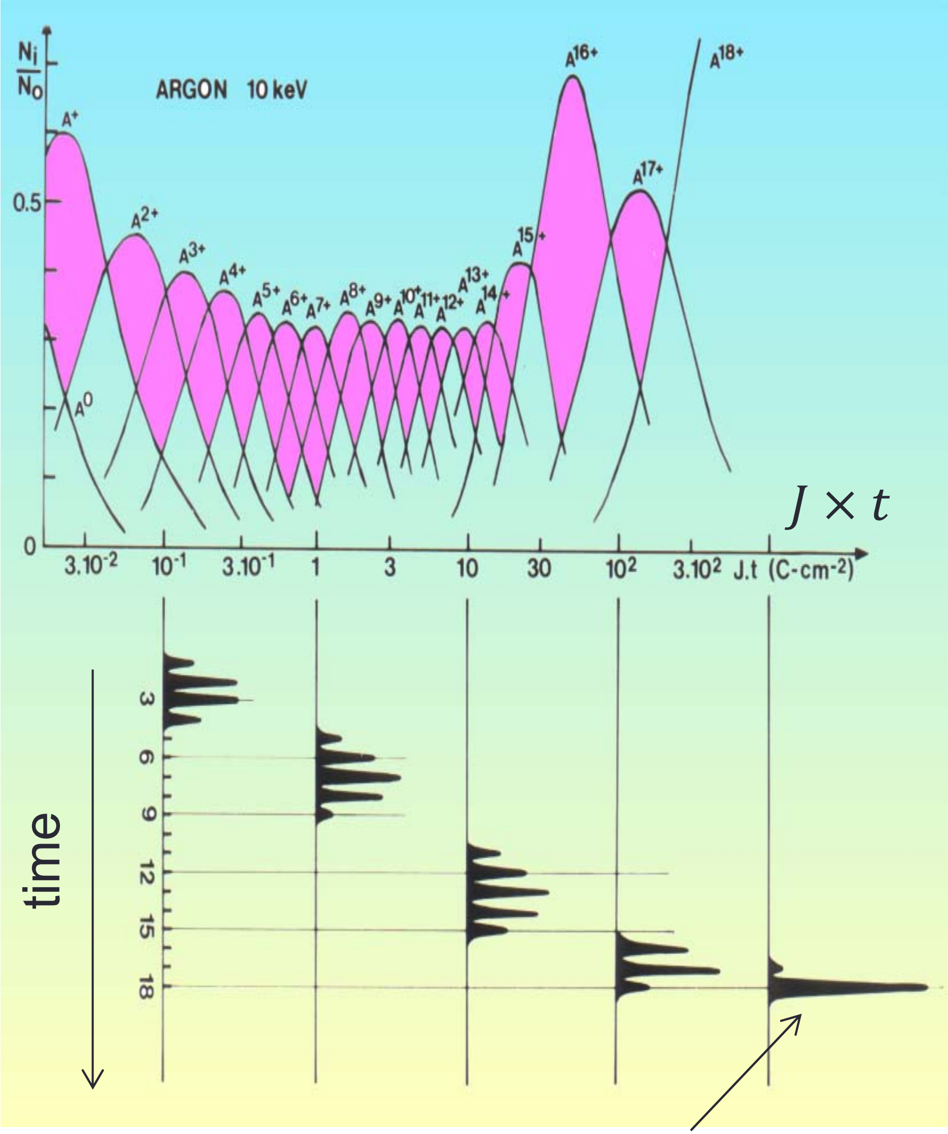
Zschornack, CAS2012 lectures

- Electron beam issued from a thermionic gun (V up to 200 kV, 1 A)
  - injected as a Brillouin flow on the axis of a long 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 confinement
  - due to the combination of the radial space charge e^- potential well and a longitudinal voltage distribution applied on a series of tubes.
- The source is cyclic (pulsed operation)
  - 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.
- Low Pressure requirement: P< 10^{-9} mbar



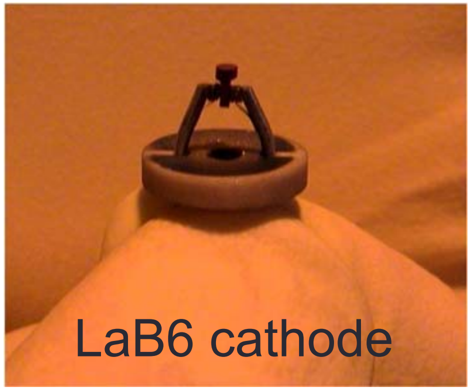
EBIS Performance

- Production of Very High Charge state
  - The Ions charge state distribution increase with the “cooking time”
  - Charge state distribution is narrow
  - Ultra high charge state achievable
- Limited pulse repetition rate
  - Long Cooking time (10-100 ms)
  - Suitable for LINAC & synchrotrons
- Limited beam intensity
  - Max. space charge in the trap:
  - $Q \leq 3.36 \times 10^{11} \frac{IL}{\sqrt{E}}$
    - I, E electron beam intensity, energy
    - L trap length
    - Q max ion charge trapped

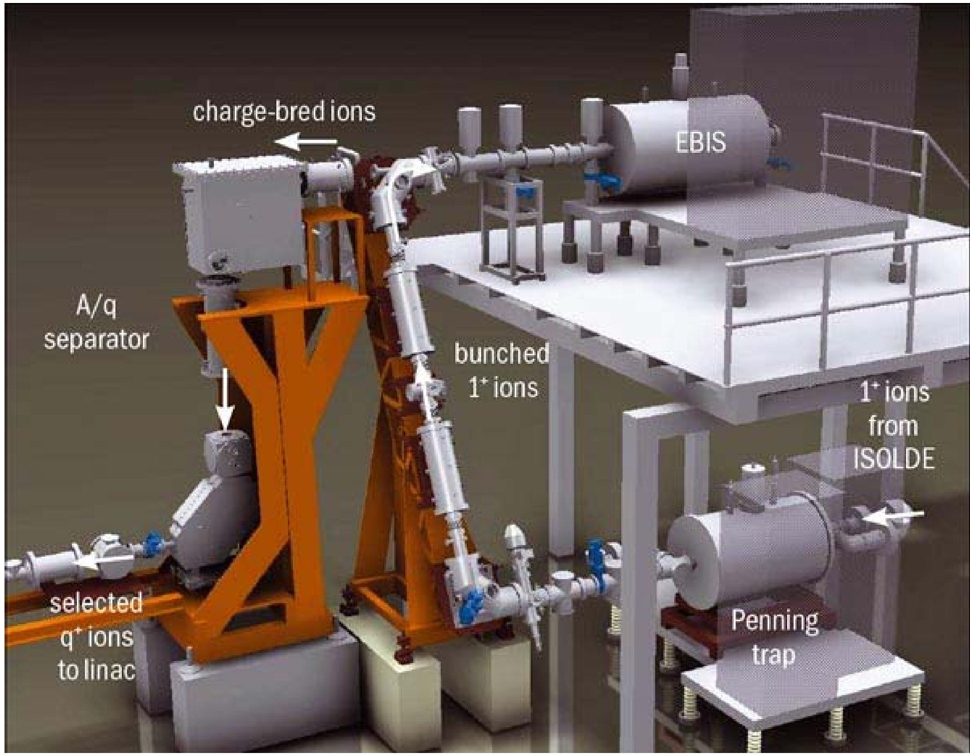


Fully stripped Argon!

The REX-EBIS setup



- REX-EBIS specifications (CERN)
  - LaB6 cathode (thermal electron gun)
  - jcathode<20A/cm2
  - je=jtrap<200A/cm2
  - Ie=460mA (normal operation 200mA)
  - E=3.5-6keV
  - 3 drift tubes L=200 to 800 mm
  - Theoretical capacity 5·10^{10} positive charges
  - Ultra-high vacuum 10^{-10}-10^{-11} mbar

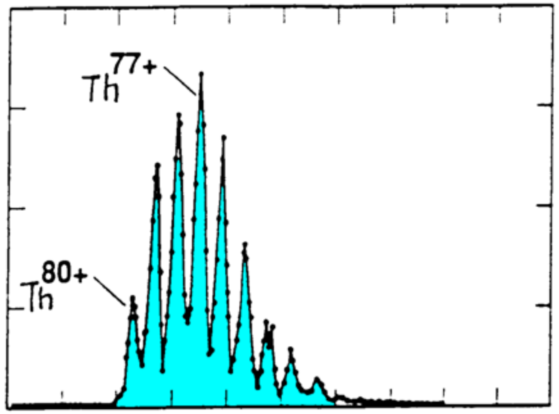


The charge state is selected with a mass separator of Nier-Spectrometer type

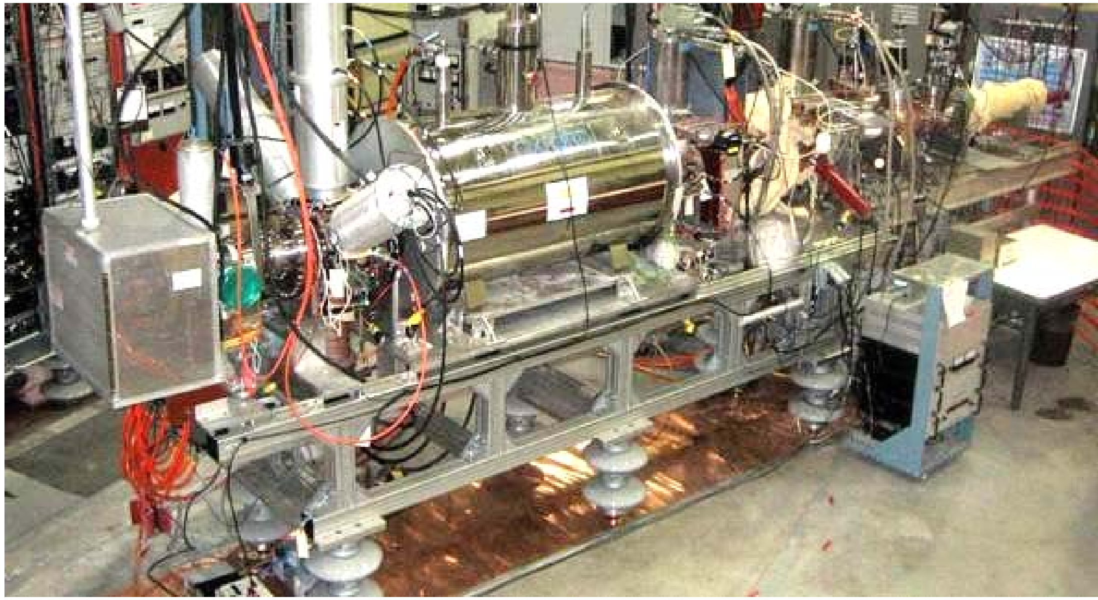
Performances: F. Wenander et al.,
Rev. Sci. Instrum. 77, 03B104 (2006)
ICIS 05 Proceedings

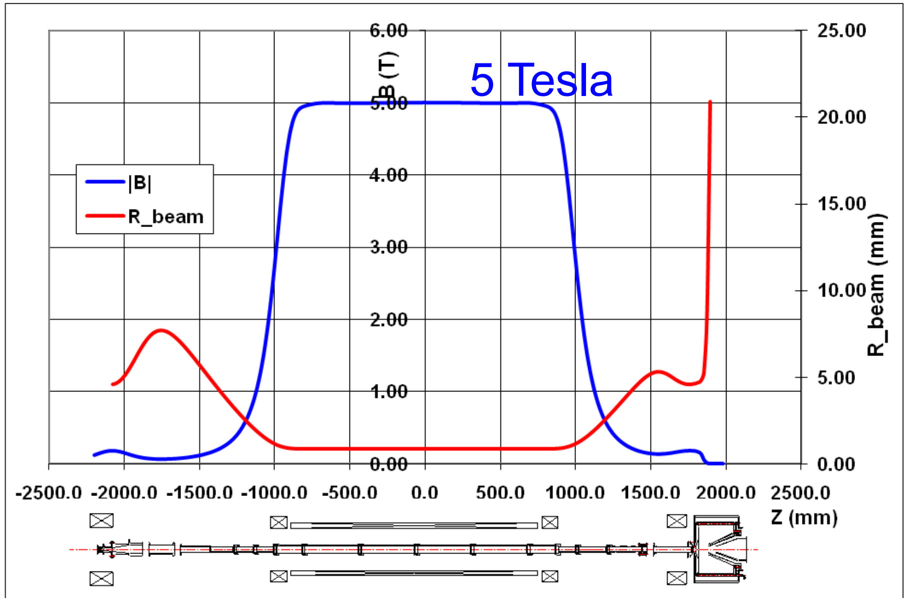
High Intensity EBIS at RHIC

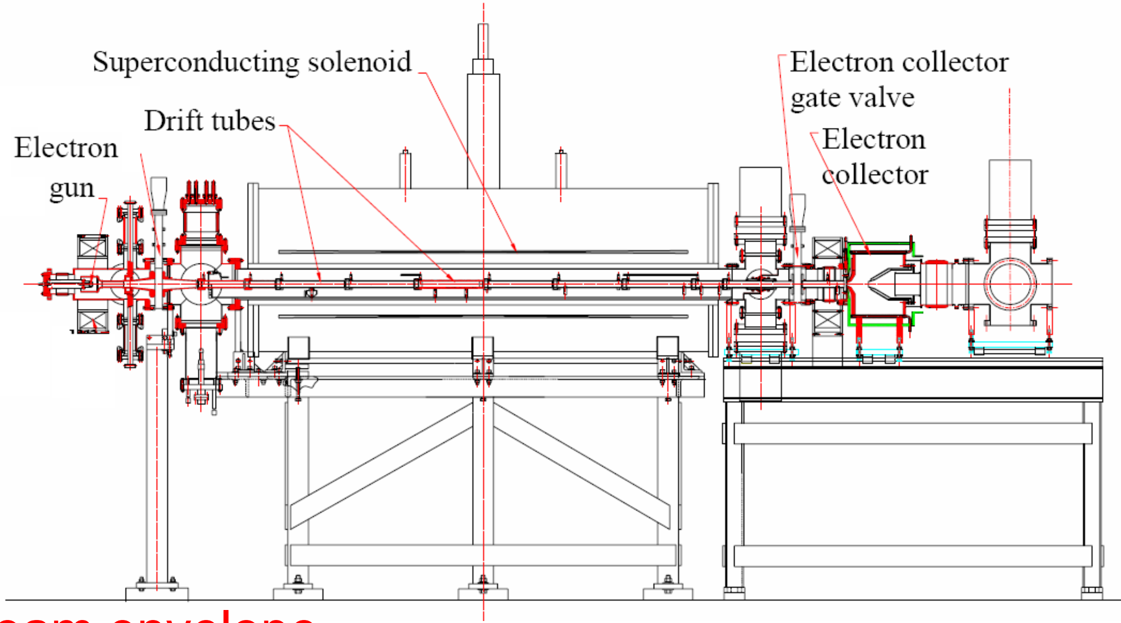
- 1.7 mA – 10 µs – 5 Hz



Narrow charge state distribution for Th beam

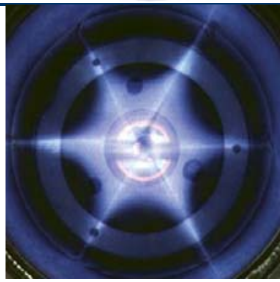




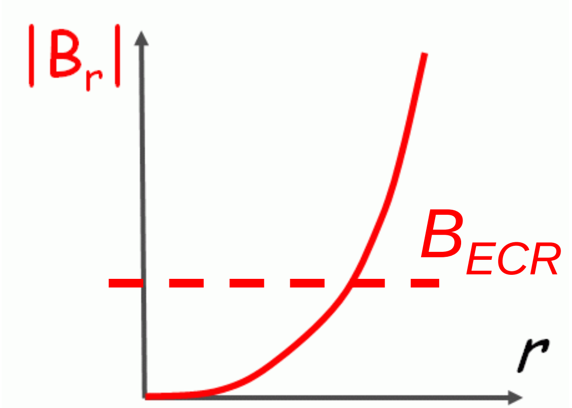


Magnetic field profile along the trap – Electron beam envelope

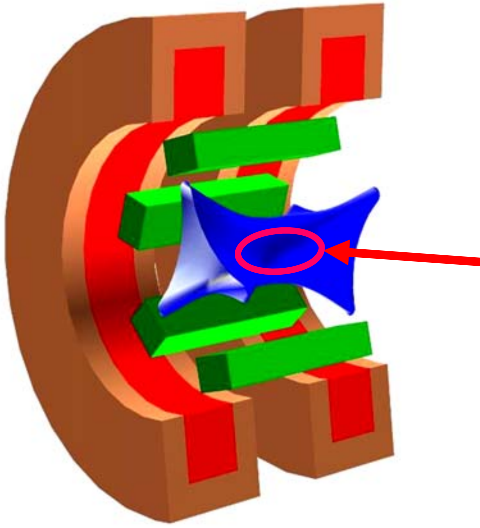
Electron Cyclotron Resonance Ion Source



- ECR ion sources features a sophisticated magnetic field structure to optimize charged particle trapping
  - Superimposition of axial coils and hexapole coils
  - The ECR surface (place where $|B|=B_{ECR}$)is closed
  - ECR surface =place where the electrons are heated by a microwave

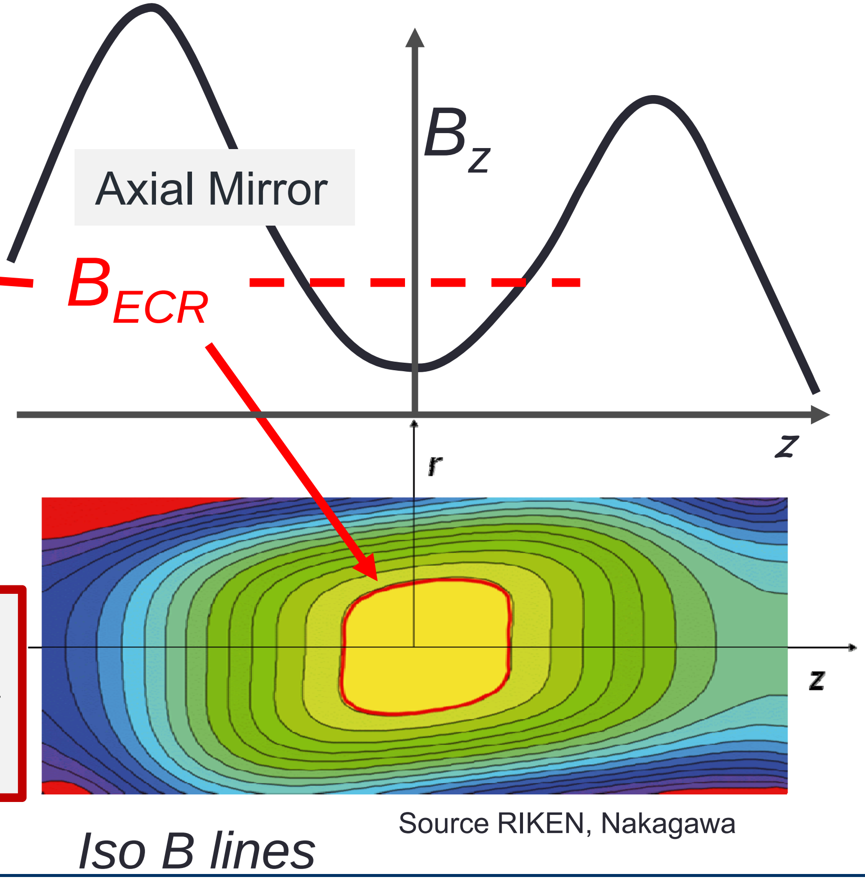


Hexapolar Field



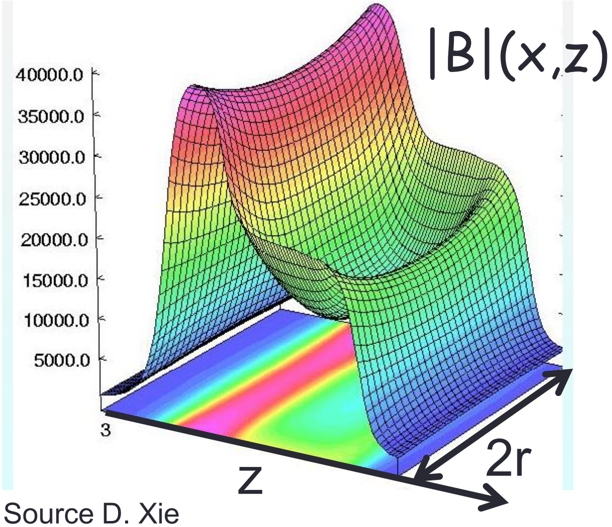
Source LBNL

$$\omega = \omega_{ce} = \frac{qB_{ECR}}{m}$$



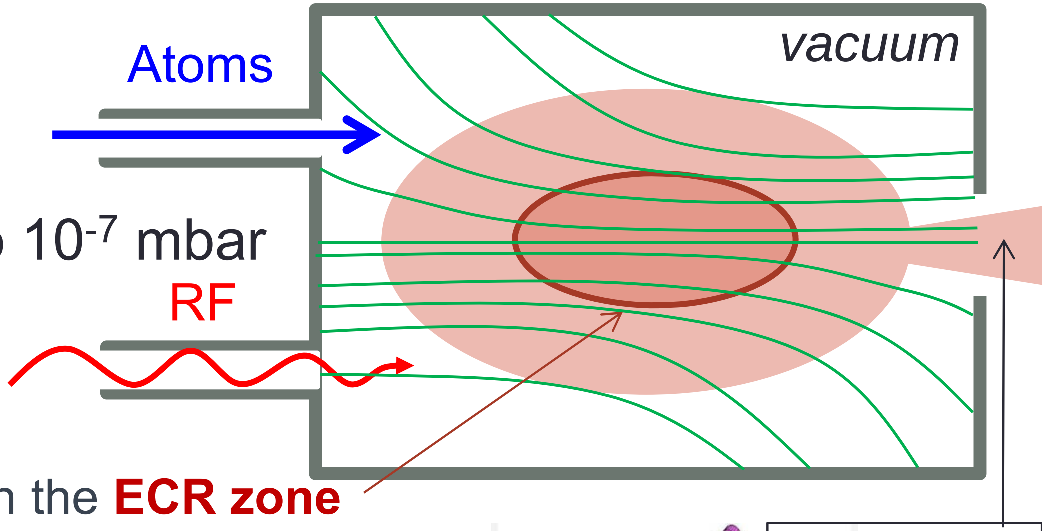
Iso B lines

Source RIKEN, Nakagawa

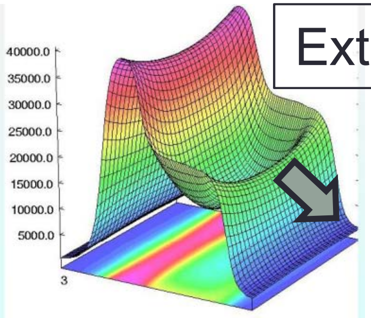


Source D. Xie

ECR Plasma build up



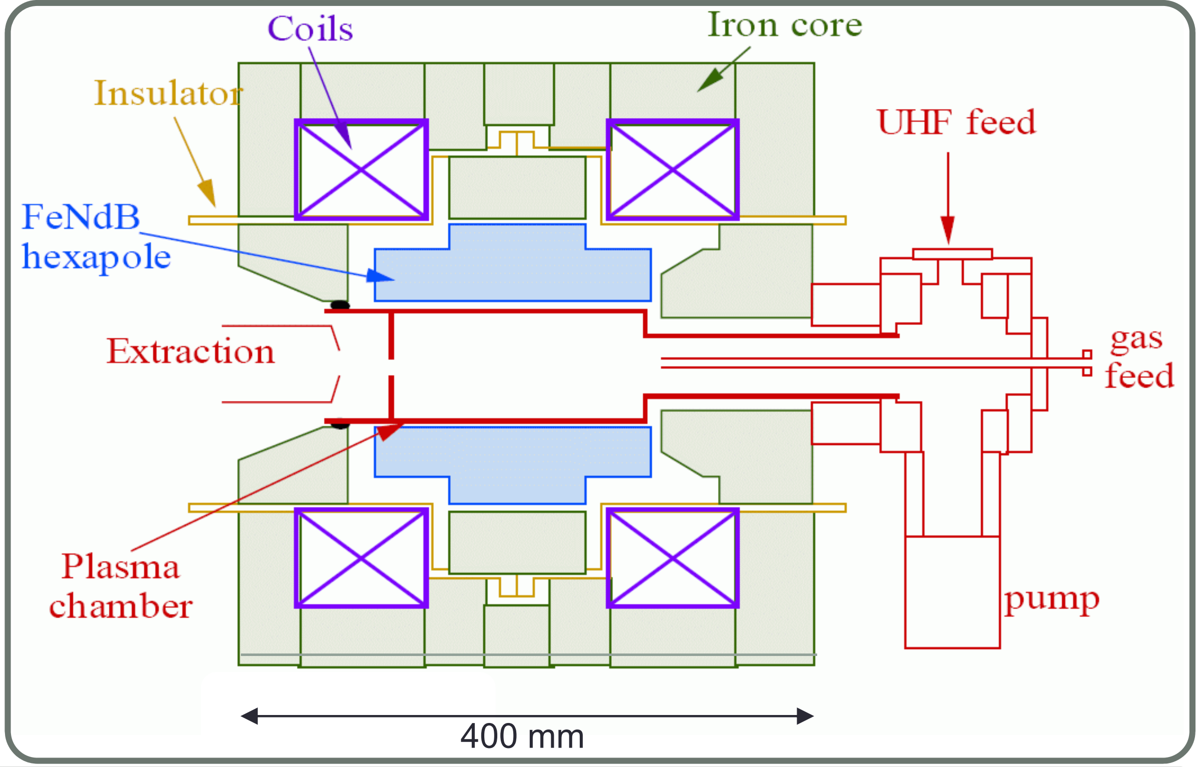
- Pumping & Gas Injection to reach P~10^{-6} to 10^{-7} mbar in the source
- Microwave injection from a waveguide
- Plasma breakdown
  - 1 single electron is heated by a passage through the **ECR zone**
  - The electron bounces thousands of time in the trap and kT_e increases
  - When $kTe>I_1^+$, a first ion is created and a new electron is available
  - Fast Amplification of electron and ion population (~100 µs)
  - =>plasma breakdown

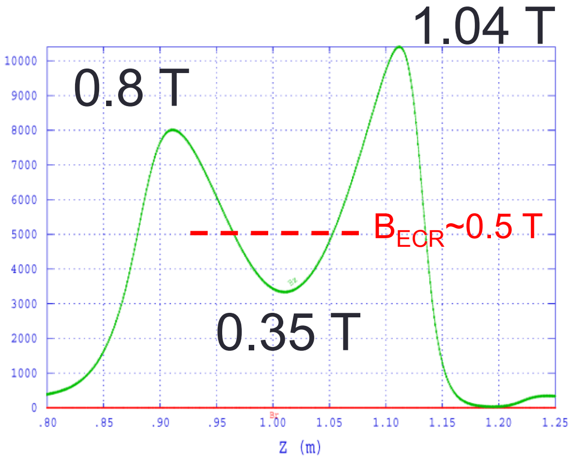


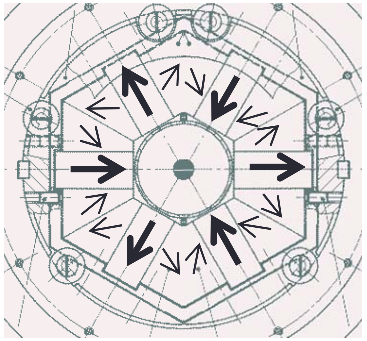
- Multicharged ion build up
  - When Te is established (kT_e~1-5 keV), multicharged ions are continuously produced and trapped in the magnetic bottle
  - Ions remain cold in an ECR: kT_i~1/40 eV, (m_e<<m_i)
- Population of the loss cone through particle diffusion (coulombian interaction)=> constant change in the particle trajectory=> random redistribution of $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
- => ion extraction through the magnetic **loss cone** on the side of the source presenting the minimum magnetic field intensity

Example of ECR4 (GANIL)

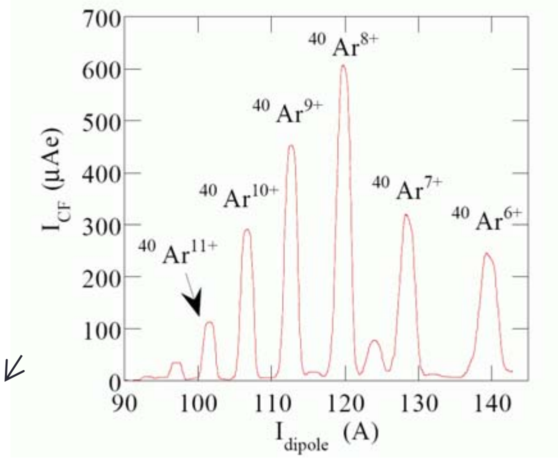
- Microwave: f=14.5 GHz-1.5 kW (B_{ECR}=0.64 T)
- Coaxial RF coupling from a cube located outside the source, equipped with a movable rod (not shown) able to adapt RF impedance to the ECR cavity.
- Axial Mirror: 1.04 T – 0.35 T – 0.8 T
- Hexapole: 1 T FeNdB magnets
- Typical Ion Beam: ~650 µA Ar^{8+} CW
- Chamber volume (Ø64 mm×L200 mm) V~0.5 liter
- Can produce any gas and many condensable beams

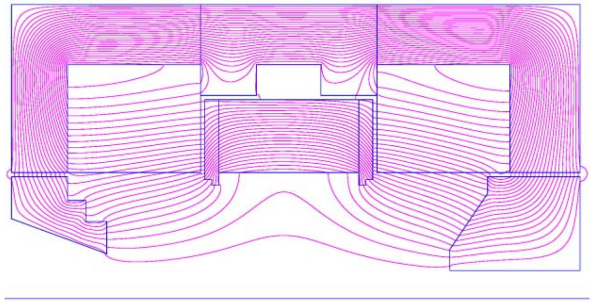






FeNdB hexapole

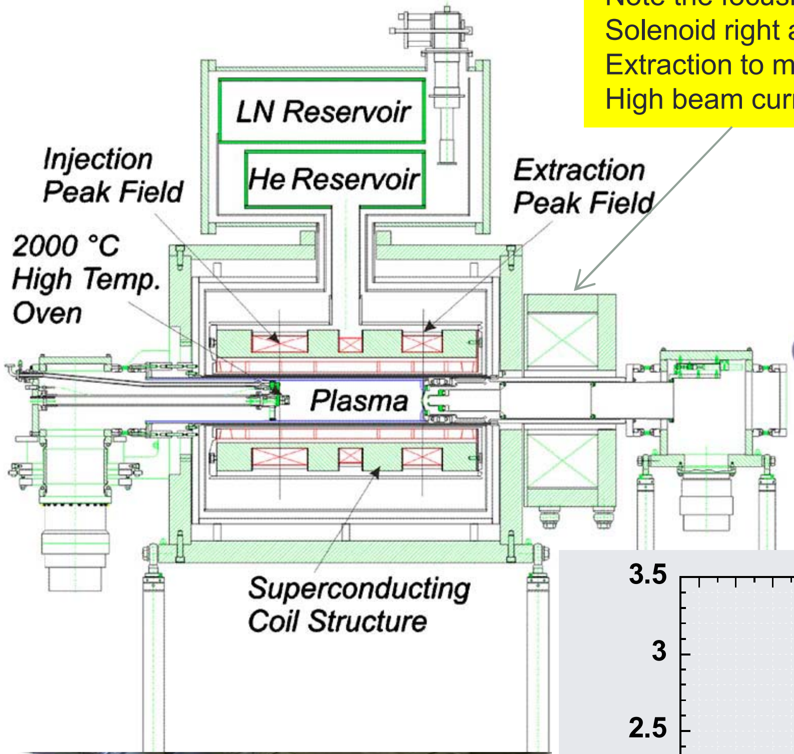




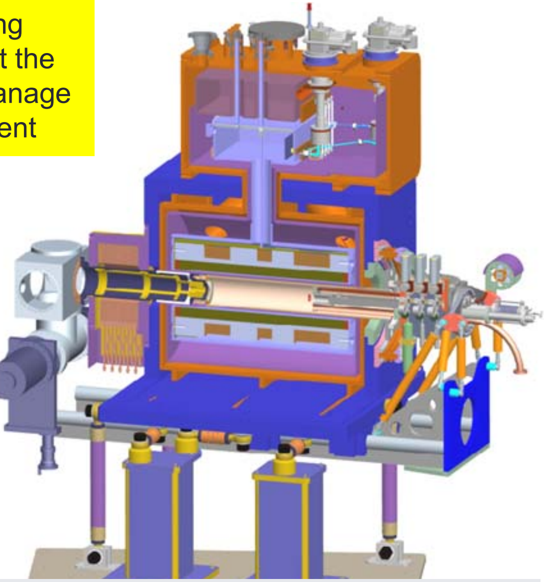
Axial Magnetic field lines (ECR4M)

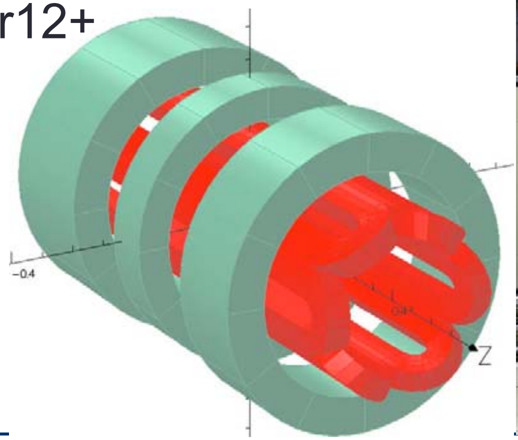
VENUS ECR Ion Source (LBNL)

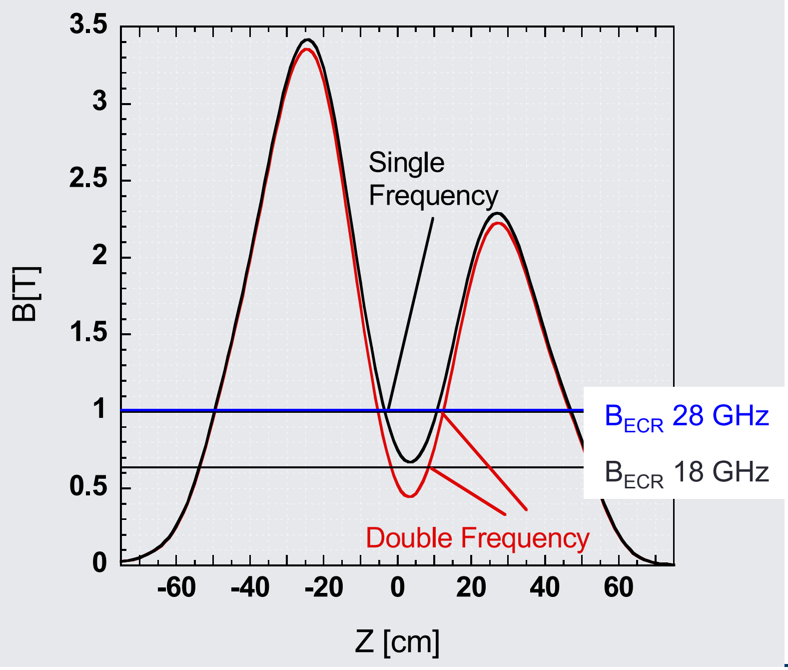
- f=18+28 GHz - (2+6) kW
- B_{ECR}=1 T
- Fully superconducting ECRIS
  - NbTi:Cu wire technology
  - 4K LHe + thermal 40 K shield
  - 4×1.4 W cryocooling
- Axial profile 3.5-0.35-2.2 T
- Radial hexapole at wall Br=2.2 T
- Dedicated to very high intensity, very high charge state applied to cyclotron acceleration
- Plasma Chamber volume V~8.5 liter
  - Ø~15 cm , L~50 cm
- V~25 kV
- Typical beams: 3 mA O^{6+}, 0.86 mA Ar12+



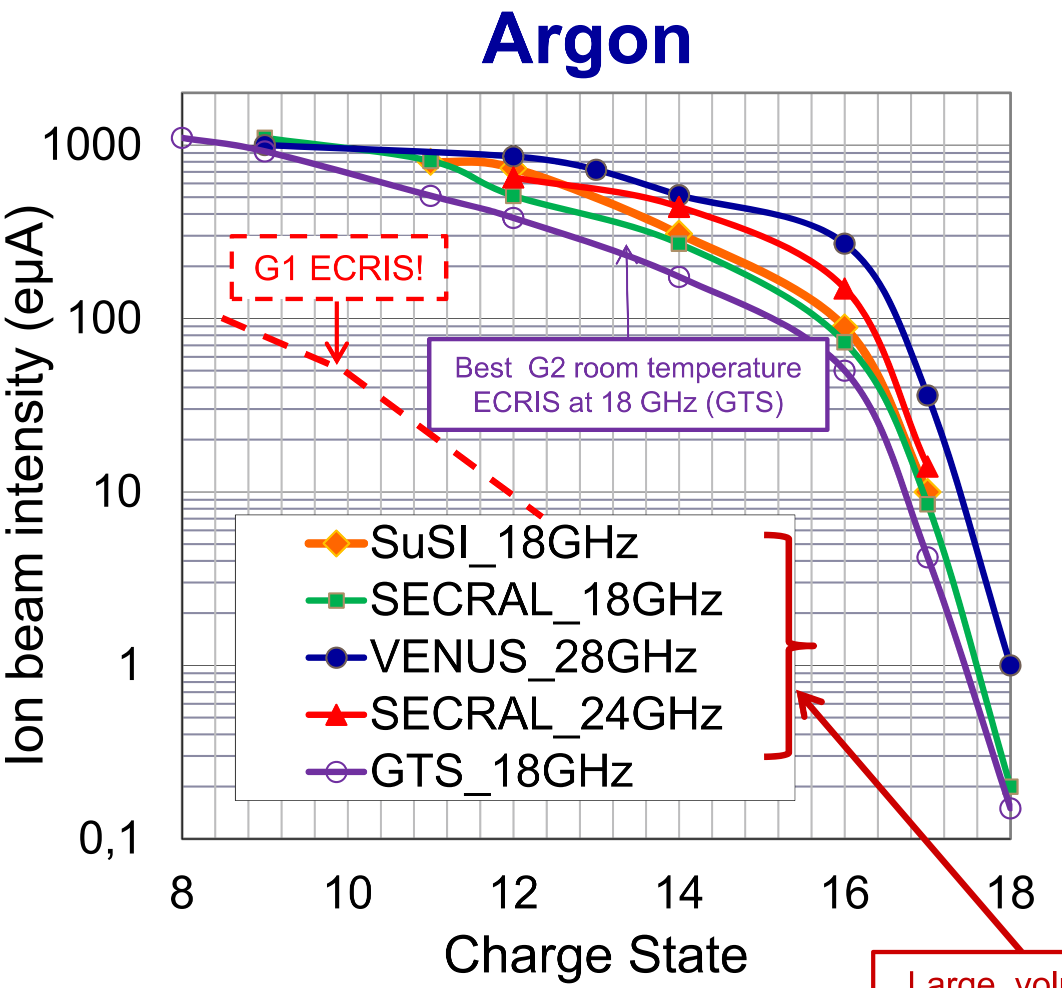
Note the focusing Solenoid right at the Extraction to manage High beam current





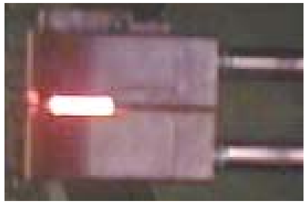


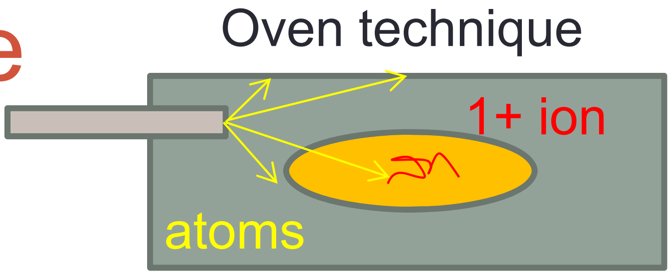
Example of Today ECR performance

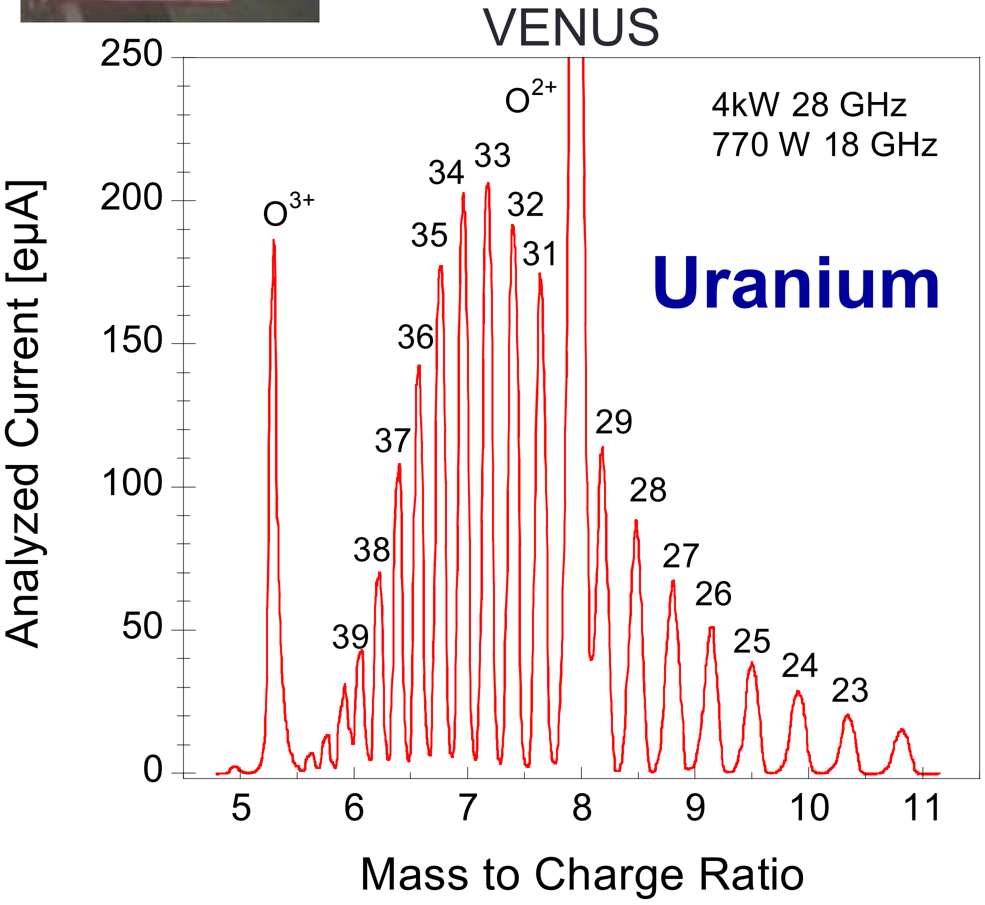


Large volume superconducting ECRIS G3

Source: G.Machicoane, MSU/NSCL,ICIS'11, modified



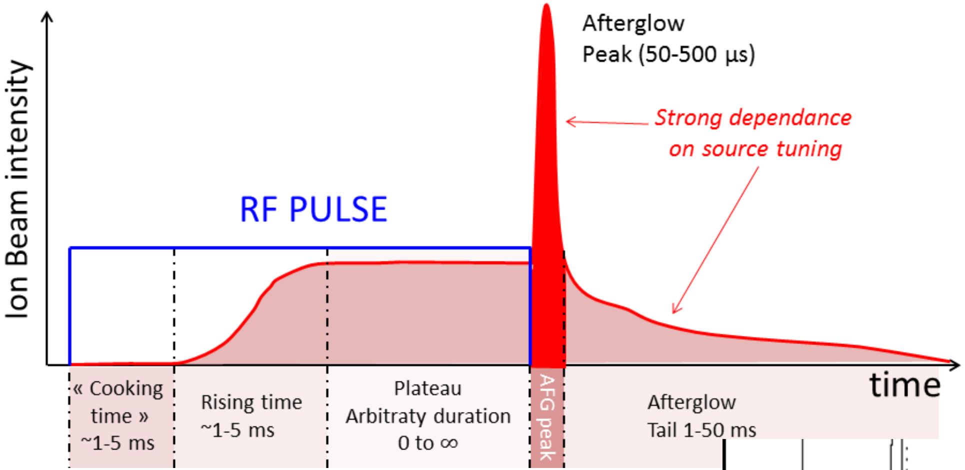


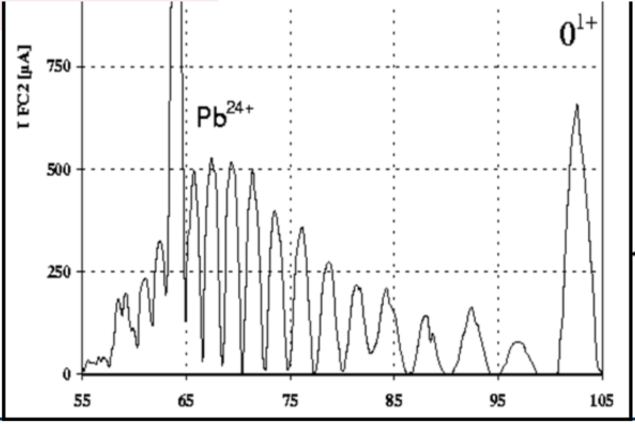


Metallic vapors (from an oven)
Injected in an oxygen plasma

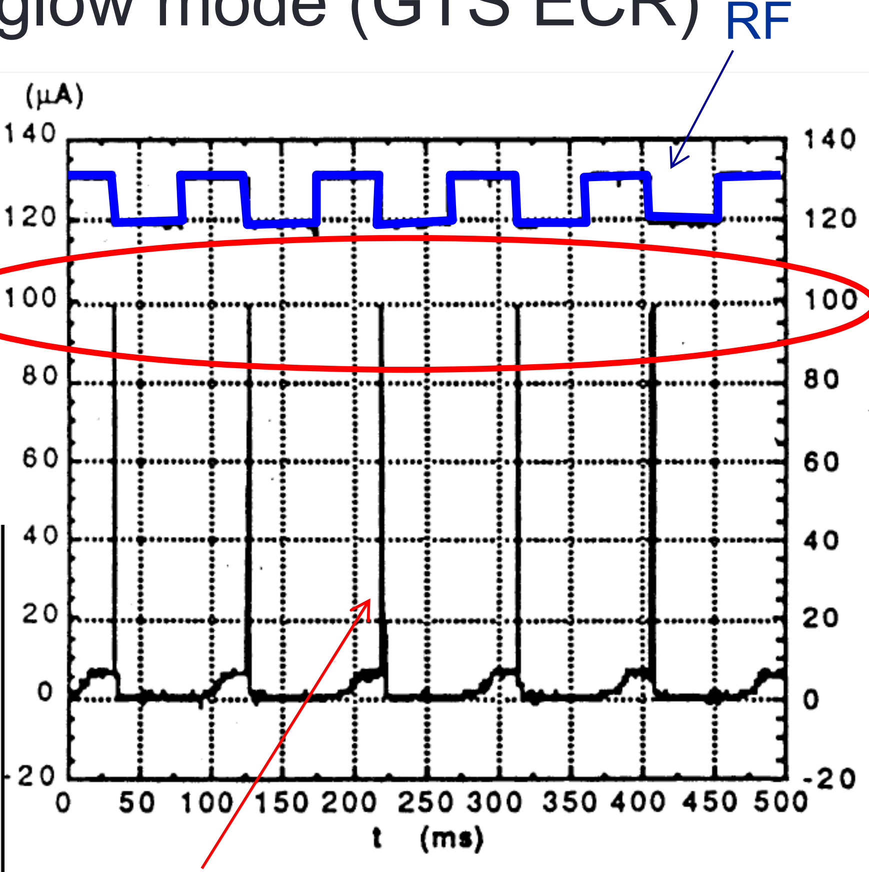
ECR Pulse Mode operation for Synchrotrons

- When the RF is pulsed, ECRIS can be tuned to produce a high intensity peak with a duration $\delta t \sim 50 - 400\ \mu s$, suitable for multi-turn Synchrotron injection
- LHC Lead beams are produced in Afterglow mode (GTS ECR)





500 µA Pb^{24+} with the PHOENIX source

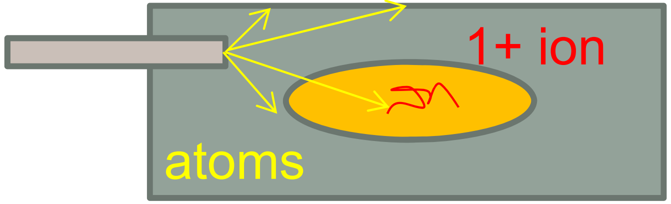


Pb^{28+} pulses (ECR4 GANIL)

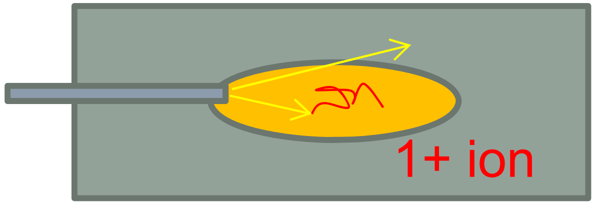
Condensable Ion Beam production in ECR Ion Sources

- The high plasma density of ECR ion Sources features a short mean free path for 1st ionization of atoms: $\lambda_{0\rightarrow 1+} \sim 1-10\ cm$
- On flight ionization of condensable or refractory atom can be performed by severa techniques in ECRIS
  - **Oven technique**: An miniature oven is inserted in front of the ECR plasma and heated up to the temperature at which a condensable atom evaporates under vacuum
  - **Sputtering technique**: when the evaporation temperature is unreachable, a sample of condensable is introduced inside the plasma which sputters the material. The sample can be biased to negative voltage to increase sputtering yield.
  - **MIVOC technique** (Metal Ions from VOlatile Compounds): condensable atoms are chemically inserted in an organic molecule that is gaseous under vacuum. The gas diffuses to the plasma.
  - **Wall heating**: It is complementary of oven or sputtering technique. A refractory cylindrical metallic liner (Mo, Ta, W) is placed around the plasma chamber with a weak thermal interaction with the water cooled wall. The liner temperature increases due to RF and plasma heating. The sticking time of condensable is reduced, which allows wall recycling and improve the global ionization efficiency.

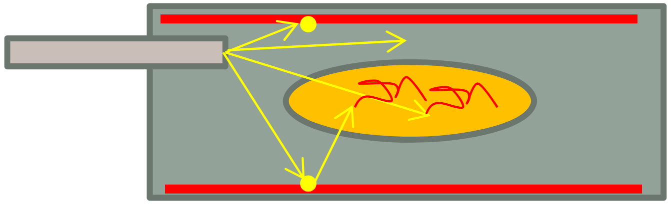
Oven technique



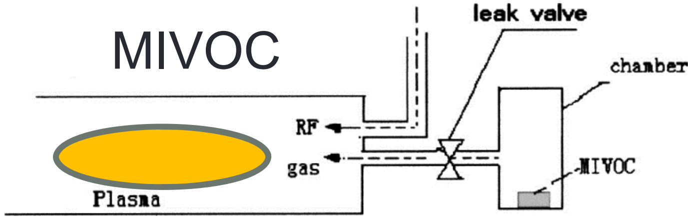
Sputtering technique



Hot Wall liner



MIVOC



Lanzhou, IMP, china