Particle sources: Ion sources

Nicolas Delerue

LAL (CNRS and Université de Paris-Sud)

Reminder: electron sources

During the last lecture we saw:

- The three effects used to extract electrons from matter: Thermionic, photoelectric and Schottky.
- How a gun is built.
- The basic dynamics of the particles in the gun.
- Examples of electron guns.
- Today we will do the same for ions.

To do at home: last year's exam

1) What are the 3 physical principles that allow the extraction of electrons from matter ? (3/20)
2) Describe the main elements (at least 5) of a photo-injector. Explaining how the performances of each of these elements contribute to the final performance of the photo-injector. (5/20)
3) Compare the advantages and disadvantages of Copper (Cu ; W=4.7), Cesium (Cs ; W=2.2) and Gold (Au ; W=5.1) as cathode material in the case of a photoinjector and in the case of a thermoionic gun. (6/20)

Today's lecture

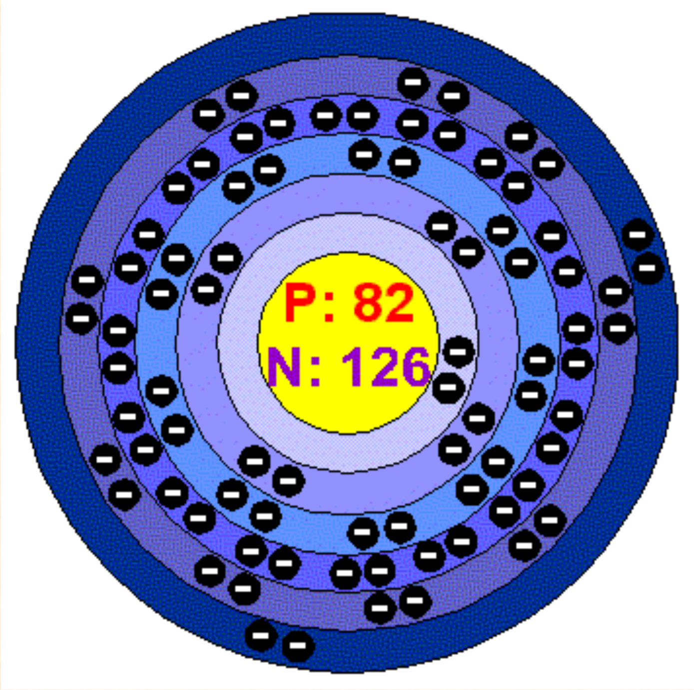
- Ions can be extracted rather easily from gas.
- We will see how to create the necessary conditions for this and how to actually do it.
- We will see that depending on the type of ions different strategies have to be used.
- We will then look at the diversity of ion sources that exists.

Content

- Reminder on atomic physics
- Reminder on plasma physics
- Types of ions sources
- Applications

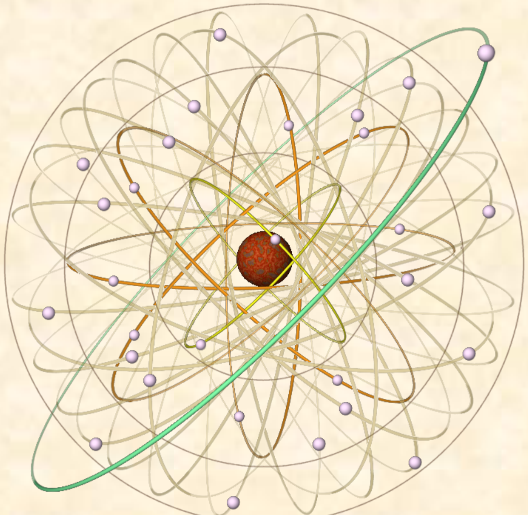
Reminder: atomic physics

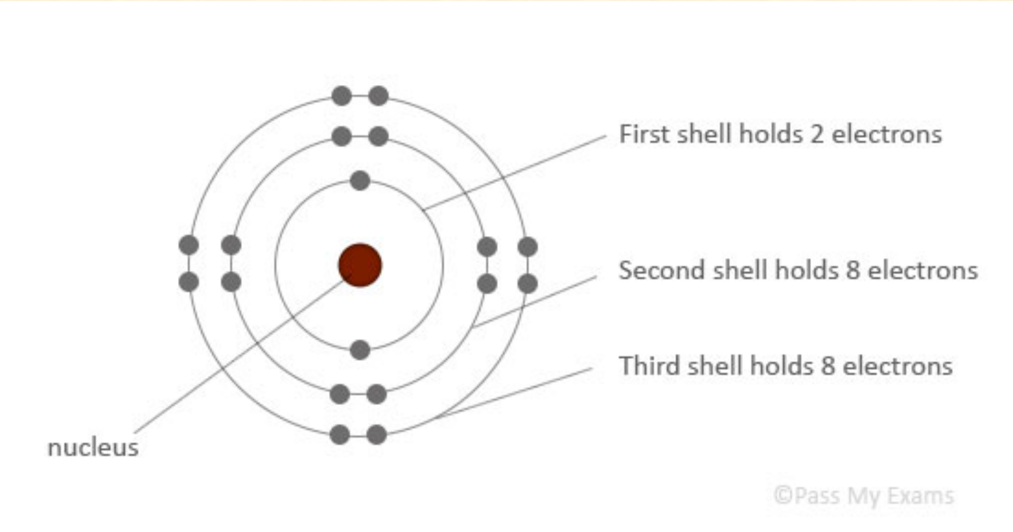
- An atom is made of a nucleus with a cloud of electrons around.
- Atomic physics studies the dynamic of the electrons in this cloud.
- For us, one of the most important question will be: how to remove (or add) the right numbers of electrons to an atom as efficiently as possible.



Electrons in atoms

- Electrons around a nucleus occupy different energy levels.
- The occupancy of each level is limited Pauli’s exclusion principle combined with the degrees of freedom for each level (spin, spin-orbit,…).

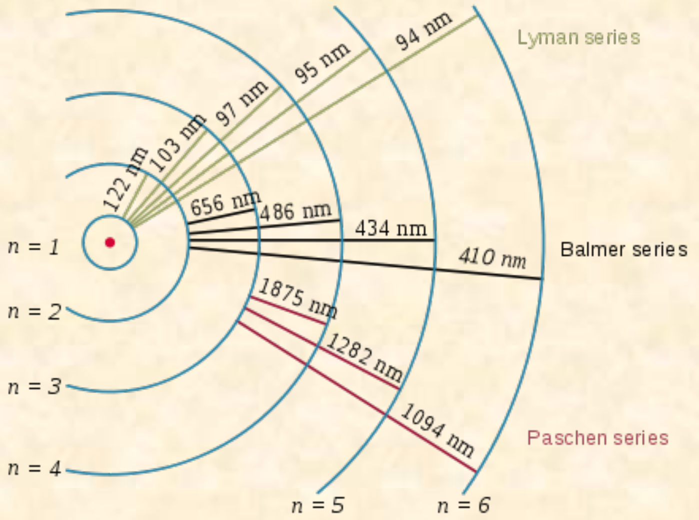




©Pass My Exams

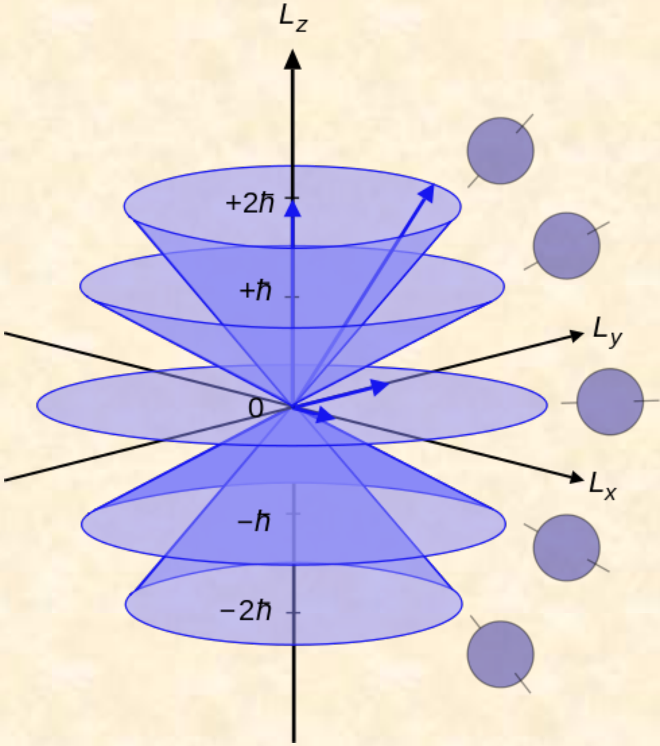
Electron quantum numbers: energy level (n)

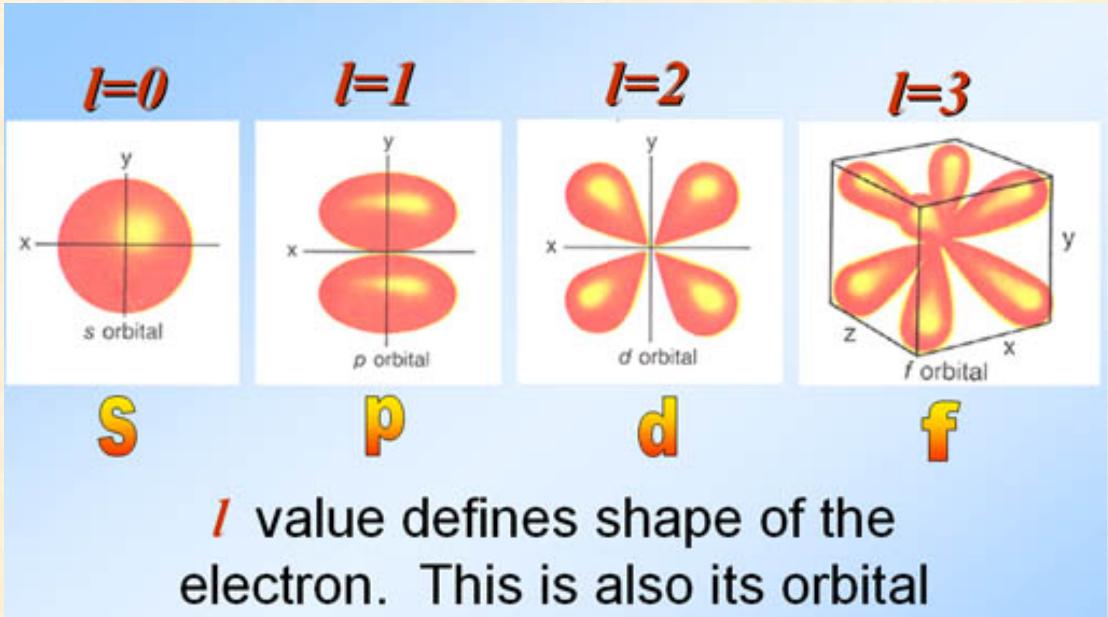
- To satisfy Pauli's exclusion principle, there can not be two electrons around the atom with the same quantum numbers.
- The first of these quantum number is the energy level of the electron. It is written "n".
- It is this quantum level that will normally define the energy of the electrons.
- The energy difference between two levels will define the absorption (or emission) lines of an atom.



Electron quantum numbers: Azimuthal quantum number (l)

- The azimuthal quantum number describes the shape of the orbital.
- l=0, 1,…,n-1

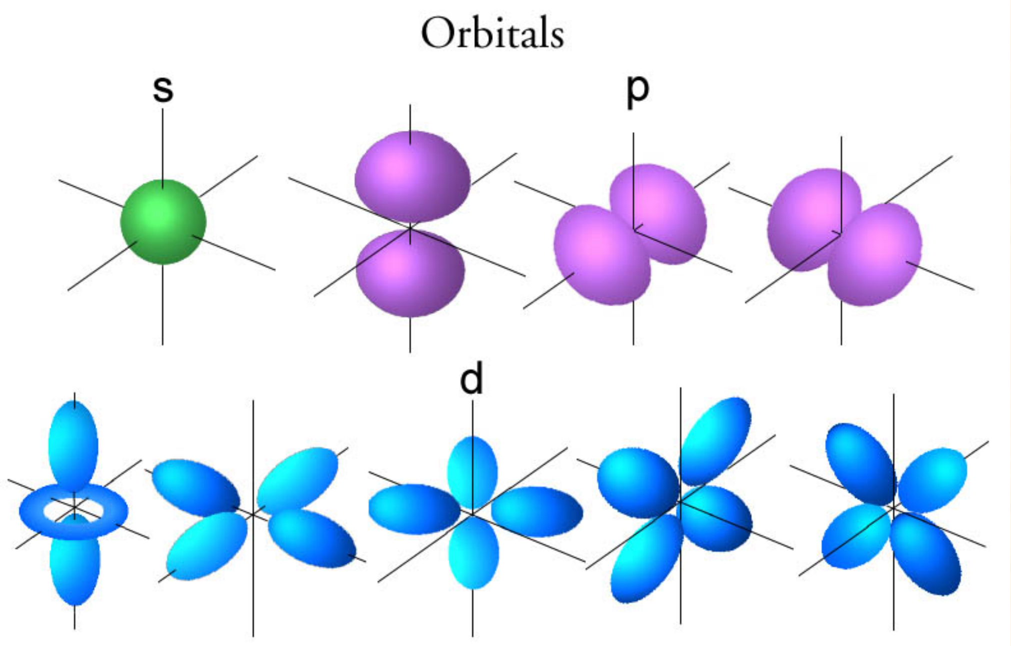




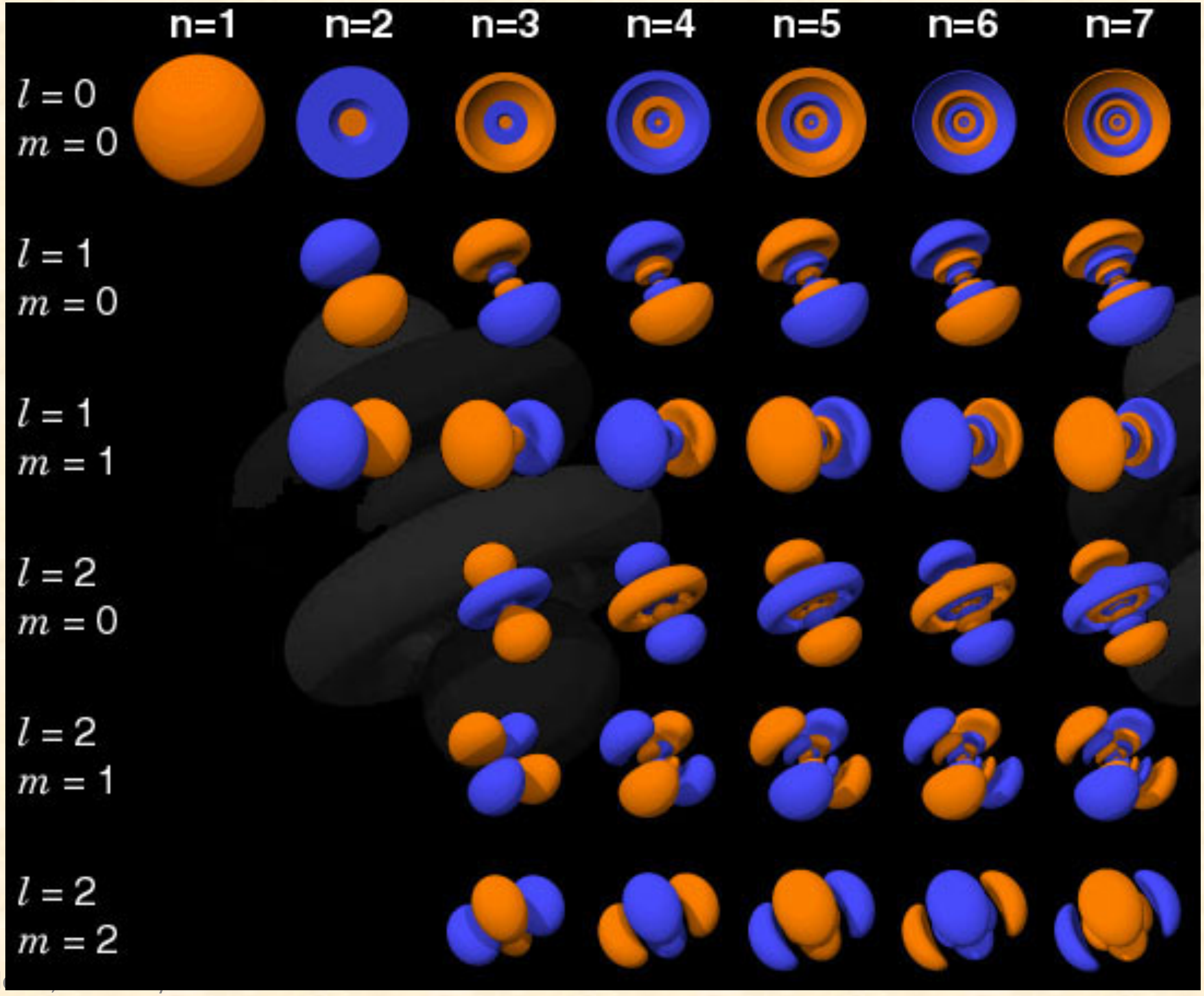
l value defines shape of the electron. This is also its orbital

Electron quantum numbers: Magnetic quantum number (ml)

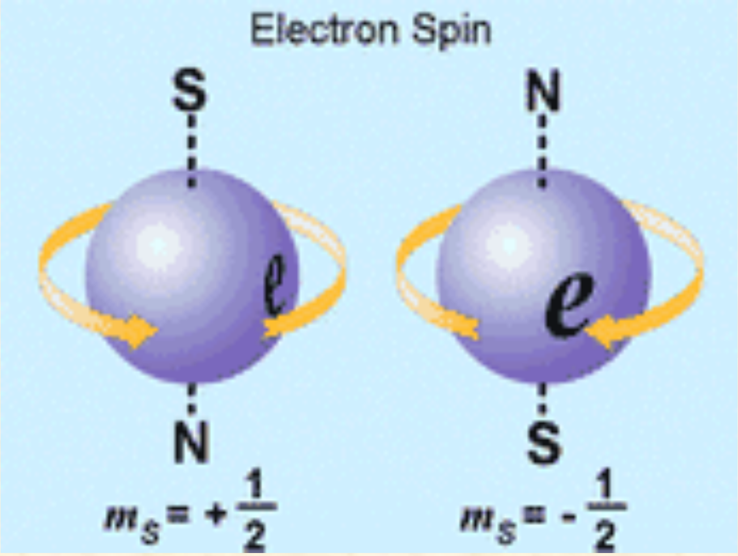
- The magnetic quantum number define on which orbital the electron is (one could say on the "direction" of the orbital).
- $-l \leq m_l \leq l$



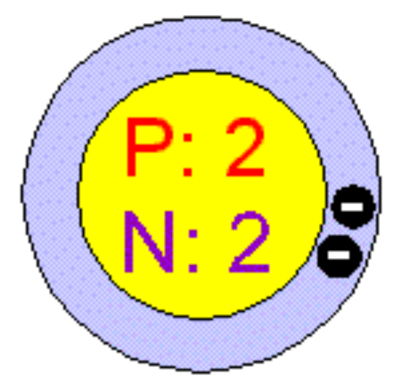
Electron orbitals



Electron quantum numbers: spin projection (ms)

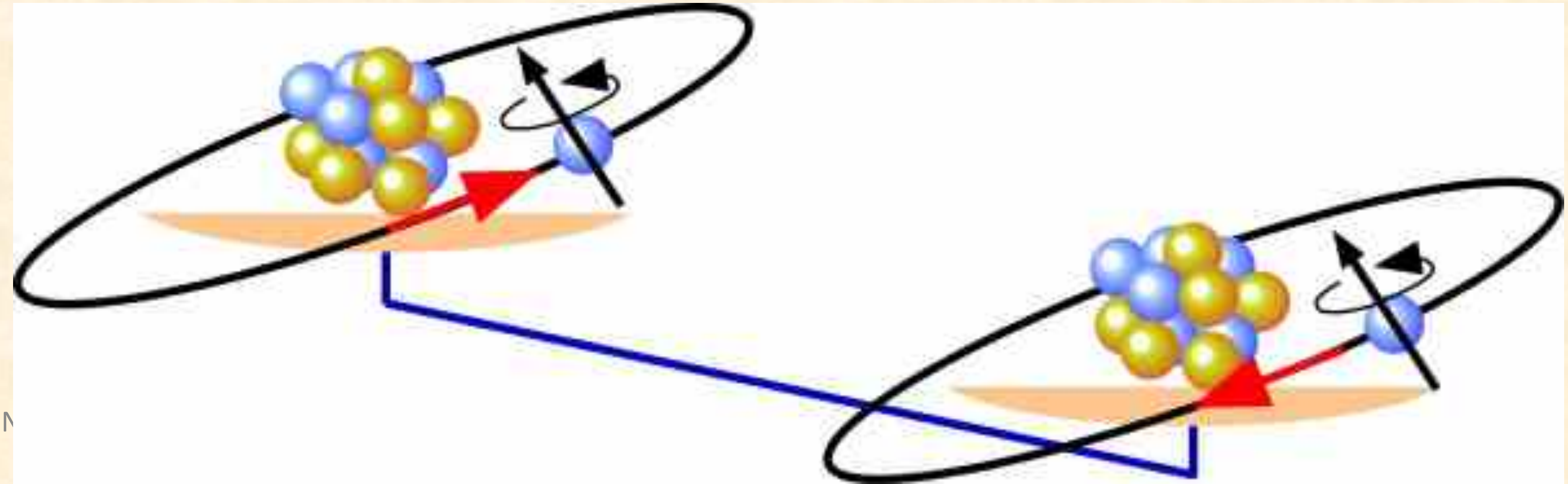


- Electrons can have two different spins: ms=+1/2 or ms=-1/2
- For each energy levels there will therefore be at least space for two electrons.



Electron quantum numbers: Spin-orbit coupling

- The combination of the spin and energy level of the electron in an electromagnetic interaction is called "spin-orbit coupling".
- It leads to a splitting of the spectral lines.
- The L and S operators no longer commute with the Hamiltonian
  => other set of quantum numbers.



Electron quantum numbers: Angular momenta numbers

- Total angular momentum (j):

$$j = |l \pm s|$$

- Angular momentum projection (mj):

$$-j \leq m_j << j$$

$$m_j = m_l + m_s$$

- Parity (P):

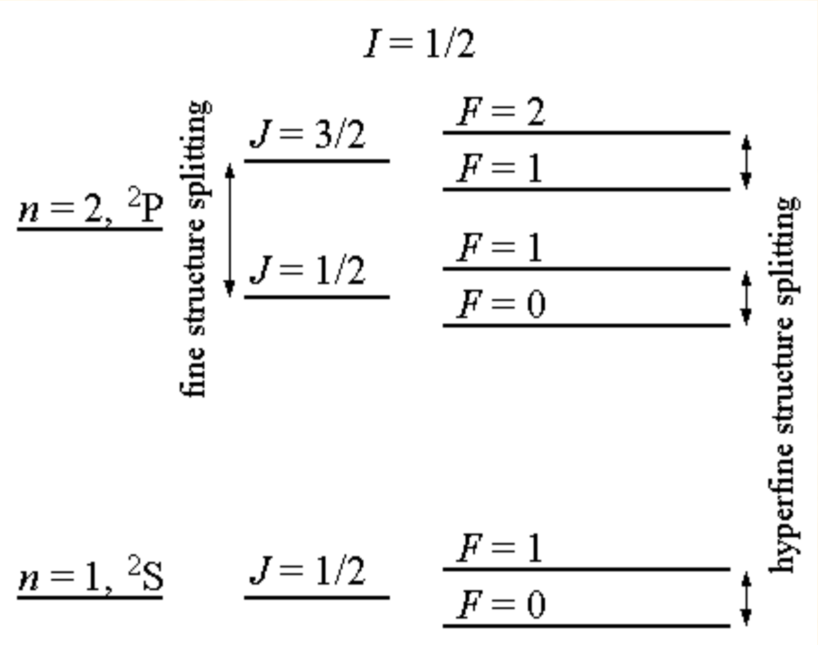
$$P = (-1)^l$$

Electron terms

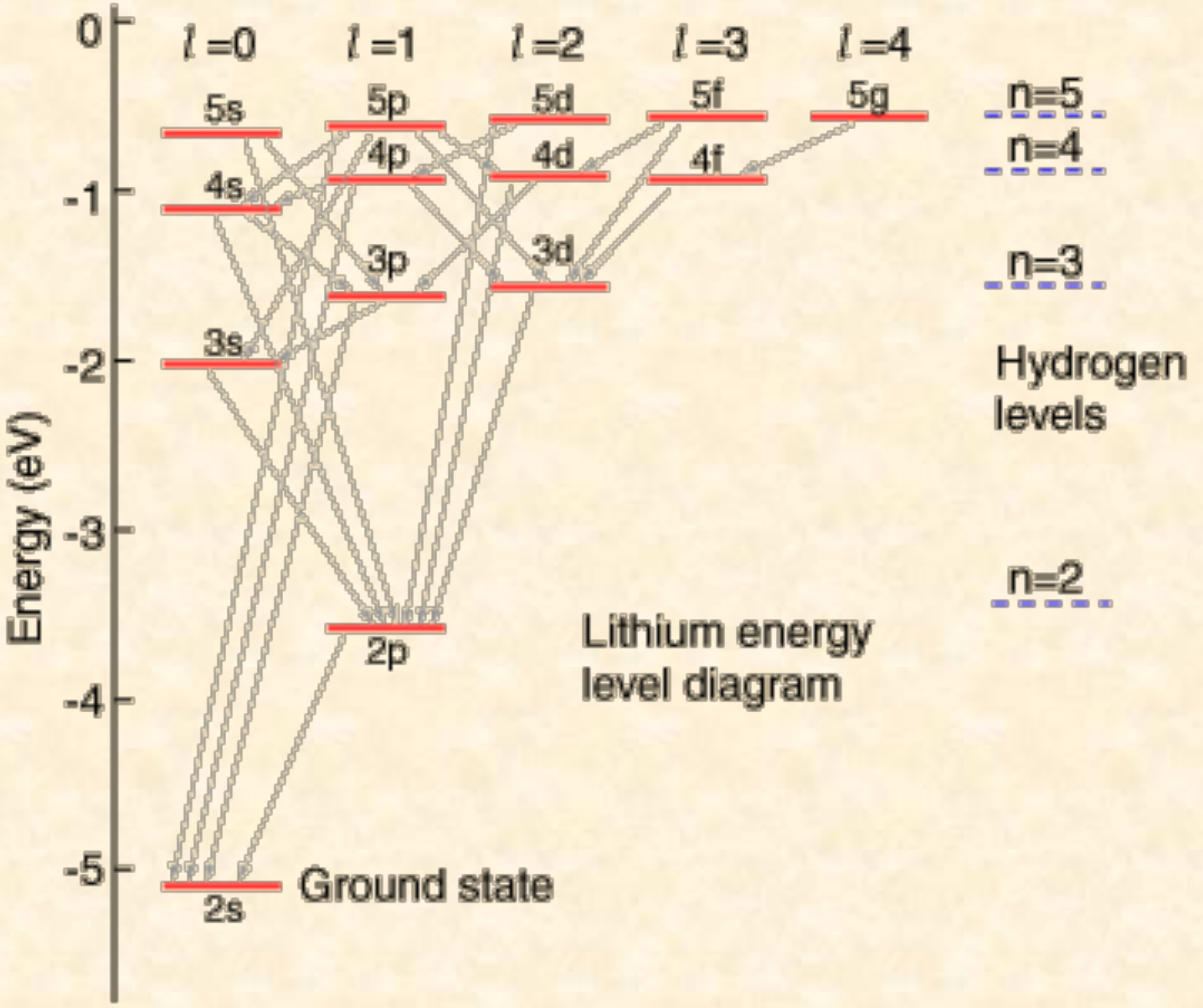
- The following notation can be used:

$$^{2S+1}L_J$$

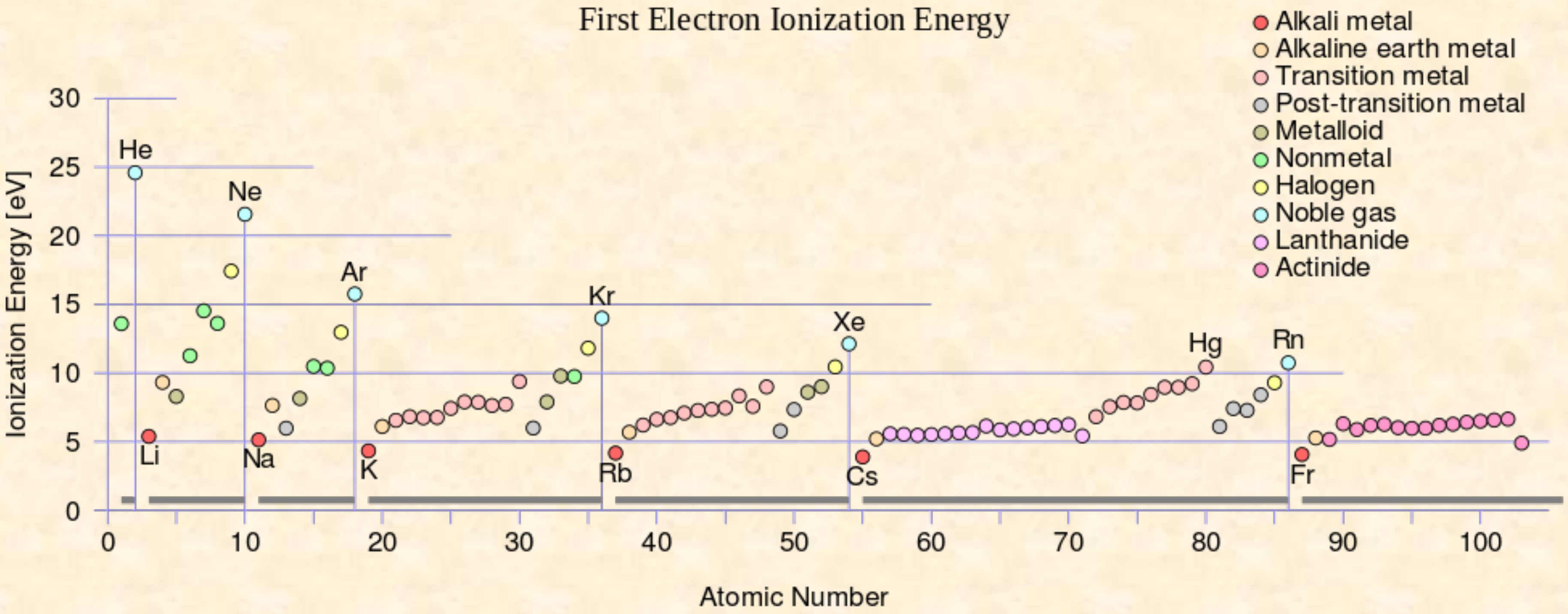
- S: total spin quantum number
- J: total angular momentum quantum number
- L: orbital quantum number (often replaced by a letter:
  L=0 => S
  L=1 => P
  L=2 => D
  L=3 => F
  …



Energy levels: detailed structure



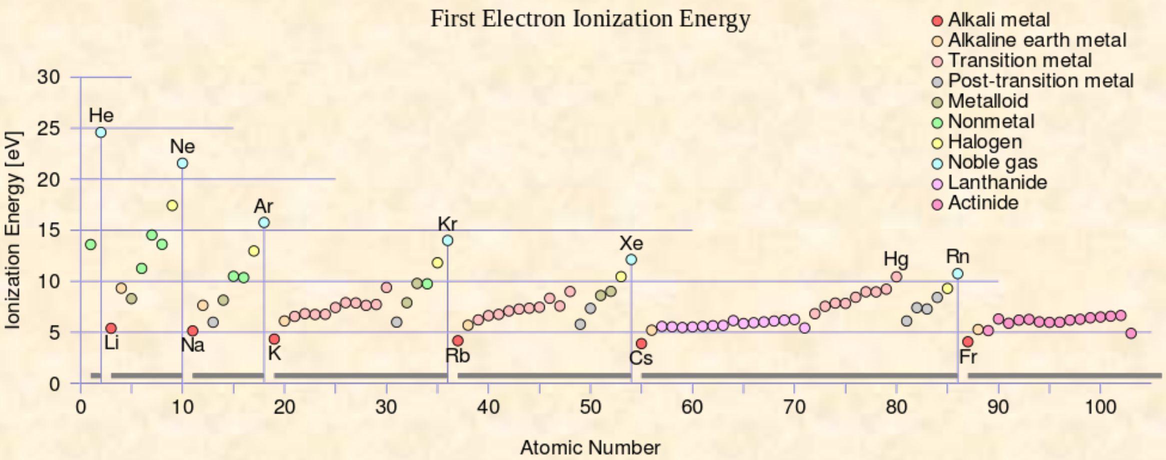
First ionization energy

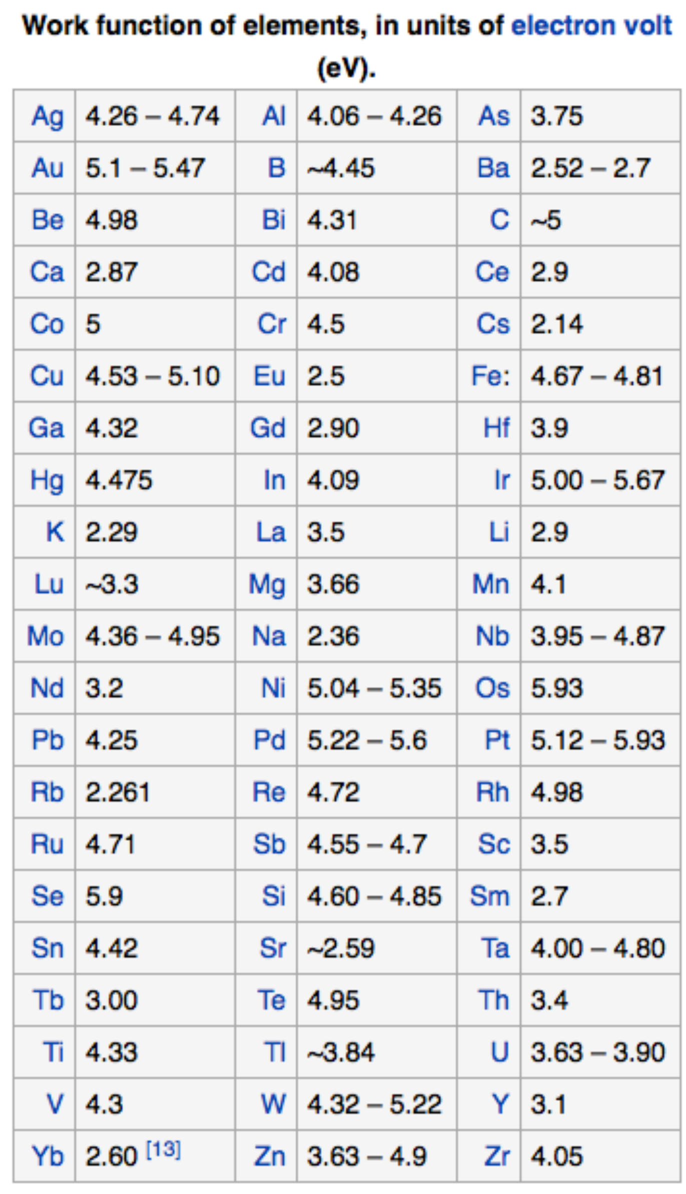


- The first ionization energy is about 5-25 eV.

Quizz

- What is the difference between the “First ionization energy” and the work function seen last week?



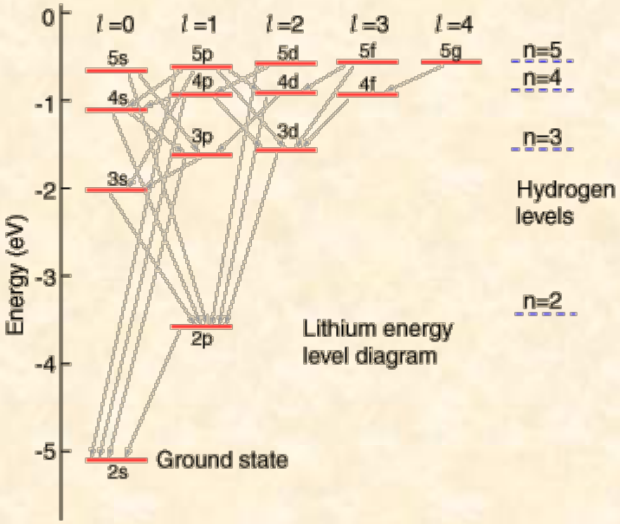


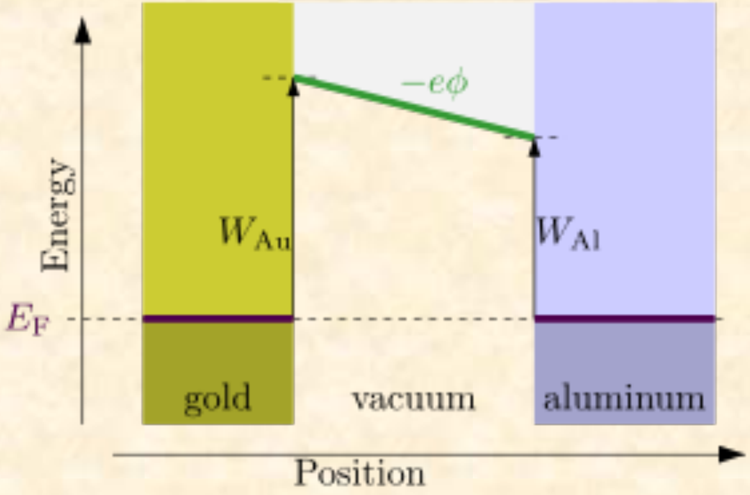
Work function of elements, in units of electron volt (eV).

Ag	4.26 – 4.74	Al	4.06 – 4.26	As	3.75
Au	5.1 – 5.47	B	~4.45	Ba	2.52 – 2.7
Be	4.98	Bi	4.31	C	~5
Ca	2.87	Cd	4.08	Ce	2.9
Co	5	Cr	4.5	Cs	2.14
Cu	4.53 – 5.10	Eu	2.5	Fe:	4.67 – 4.81
Ga	4.32	Gd	2.90	Hf	3.9
Hg	4.475	In	4.09	Ir	5.00 – 5.67
K	2.29	La	3.5	Li	2.9
Lu	~3.3	Mg	3.66	Mn	4.1
Mo	4.36 – 4.95	Na	2.36	Nb	3.95 – 4.87
Nd	3.2	Ni	5.04 – 5.35	Os	5.93
Pb	4.25	Pd	5.22 – 5.6	Pt	5.12 – 5.93
Rb	2.261	Re	4.72	Rh	4.98
Ru	4.71	Sb	4.55 – 4.7	Sc	3.5
Se	5.9	Si	4.60 – 4.85	Sm	2.7
Sn	4.42	Sr	~2.59	Ta	4.00 – 4.80
Tb	3.00	Te	4.95	Th	3.4
Ti	4.33	Tl	~3.84	U	3.63 – 3.90
V	4.3	W	4.32 – 5.22	Y	3.1
Yb	2.60 [13]	Zn	3.63 – 4.9	Zr	4.05

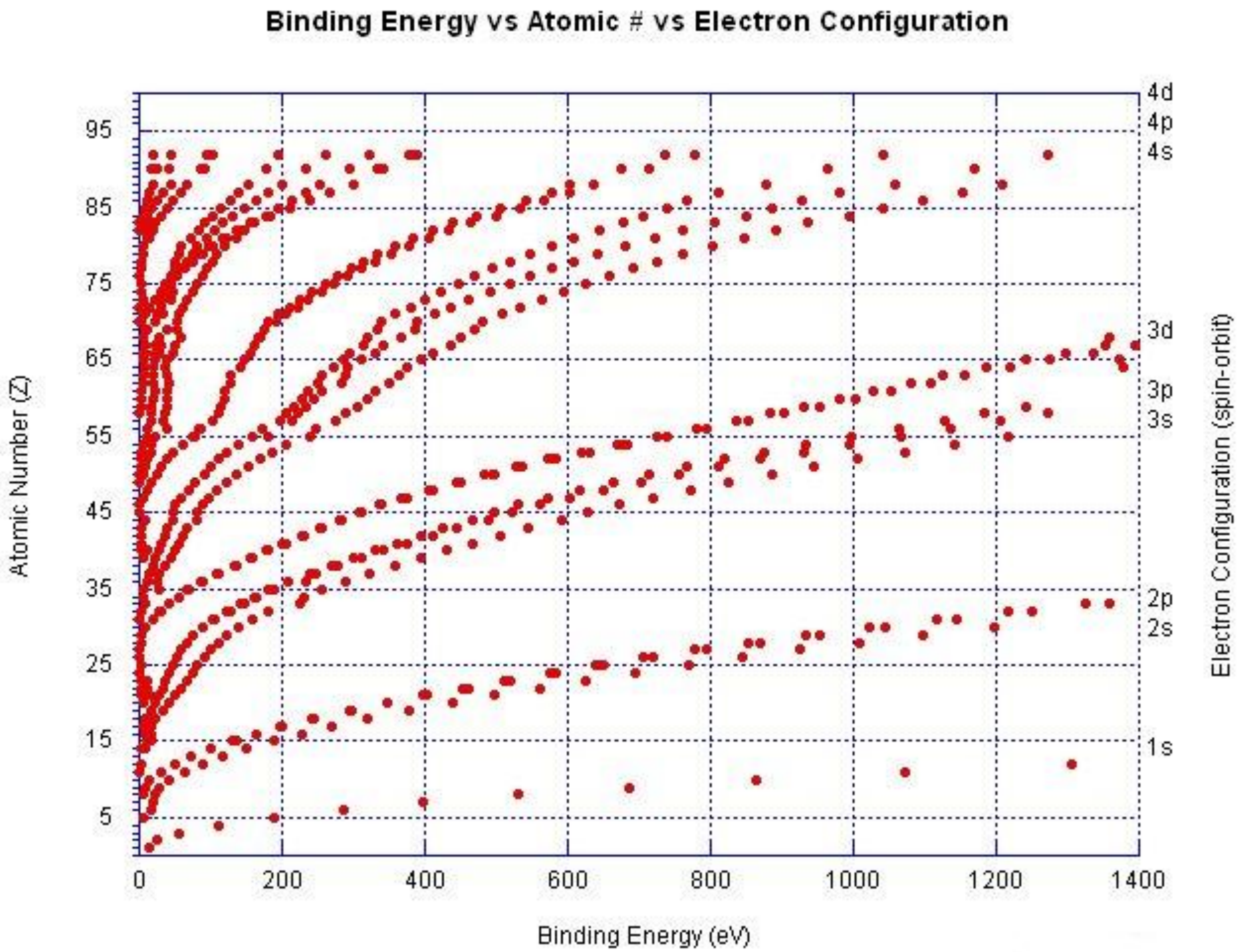
Answer

- Work function is a solid state property whereas ionization is a property of gas.
- However the values of both are close (about 5eV).



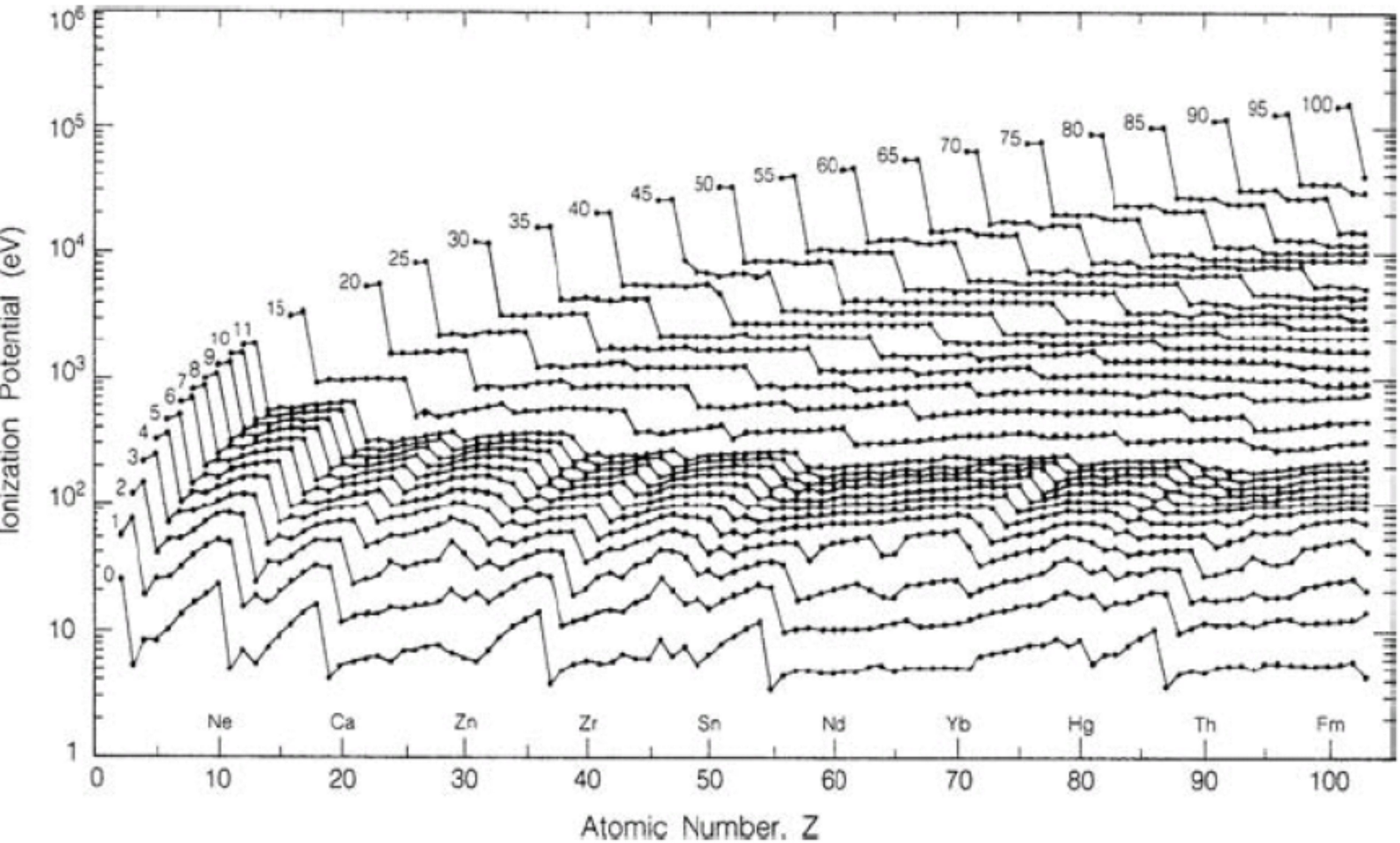


Electron binding energy



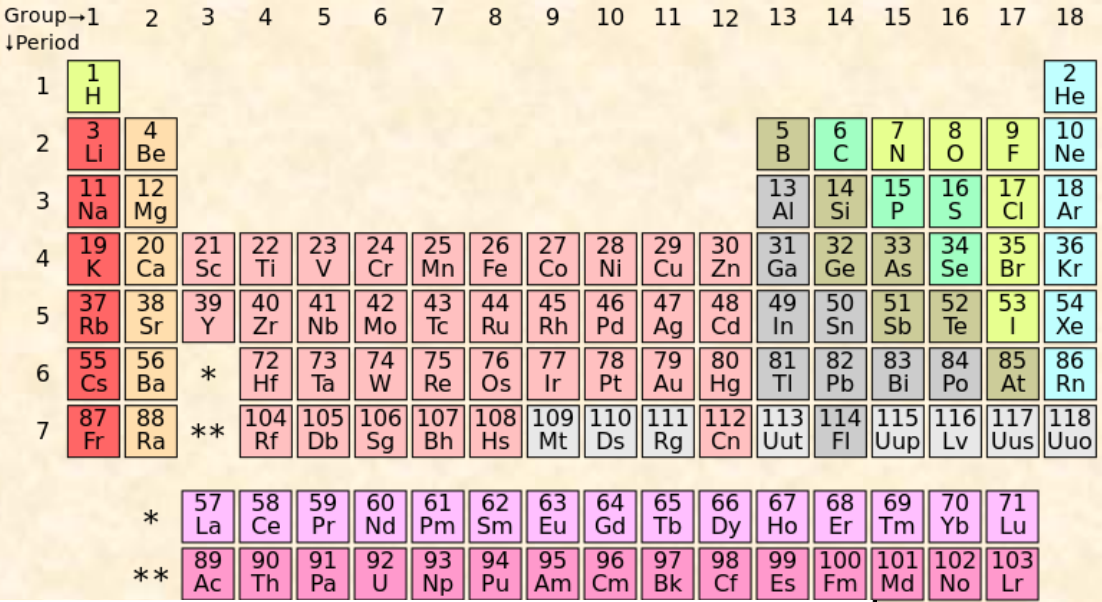
Note the difference 2p-2s

Multiply charged ions

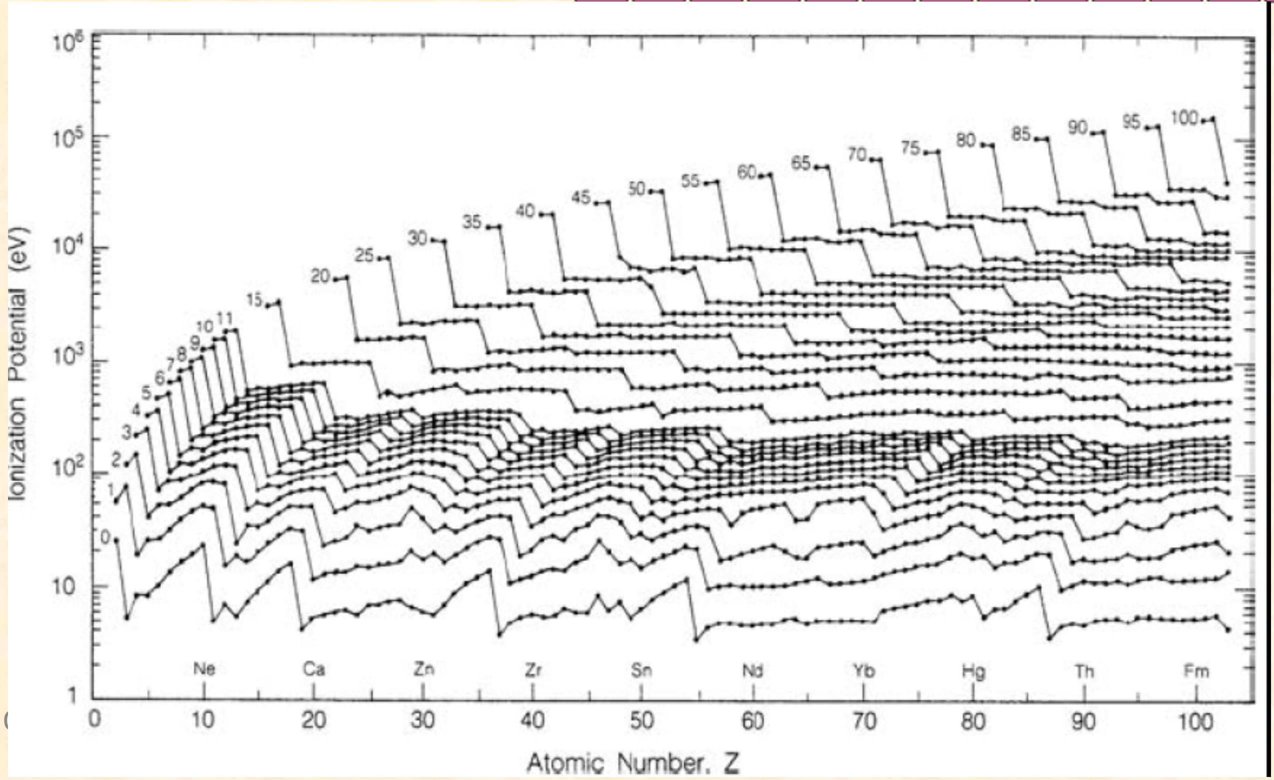


Quizz

- In which column of the periodic table is it easier to ionize?
- In which one is it harder?

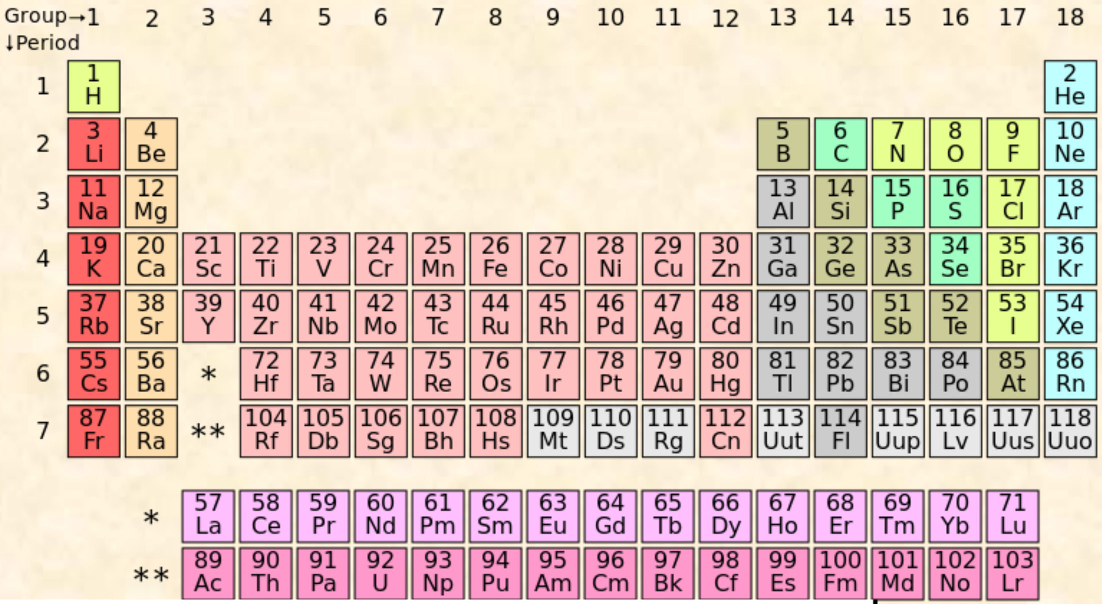


Group→ ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
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	

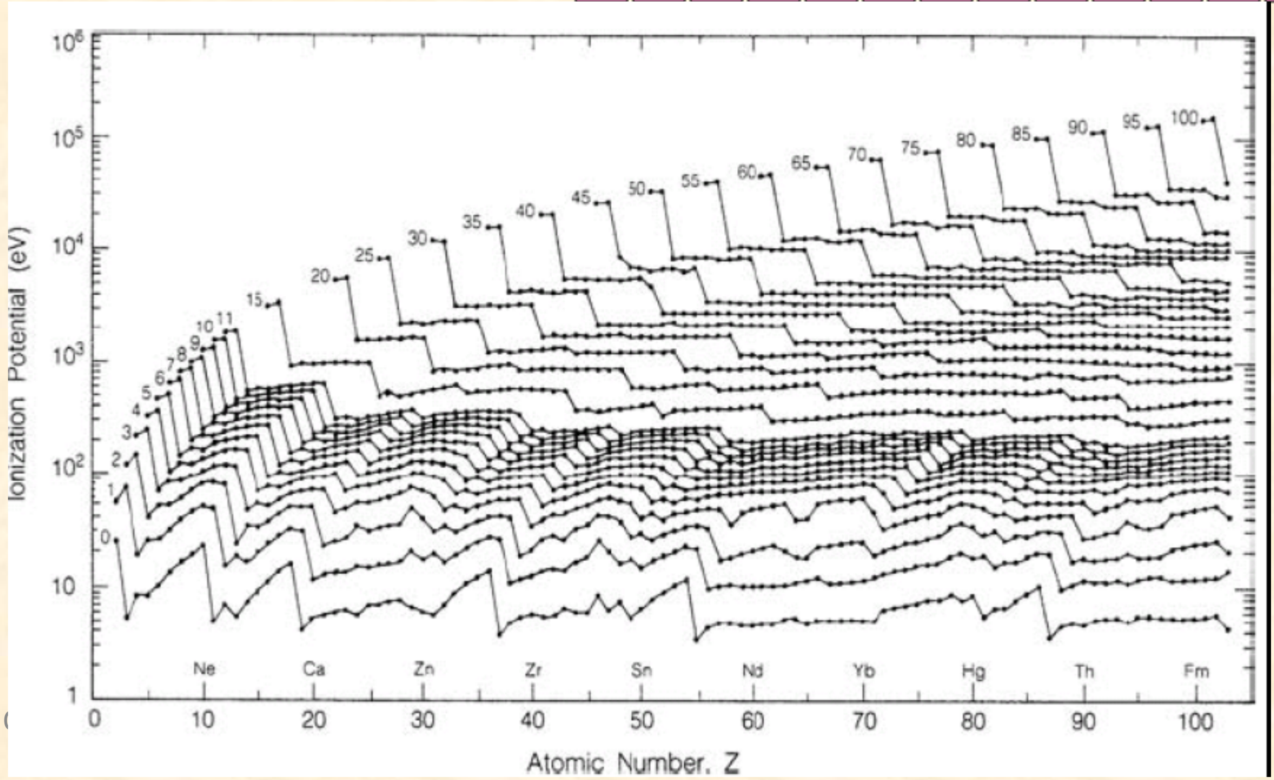


Answer

- In which column of the periodic table is it easier to ionize?
  => the first one.
- In which one is it harder?
  => The last one

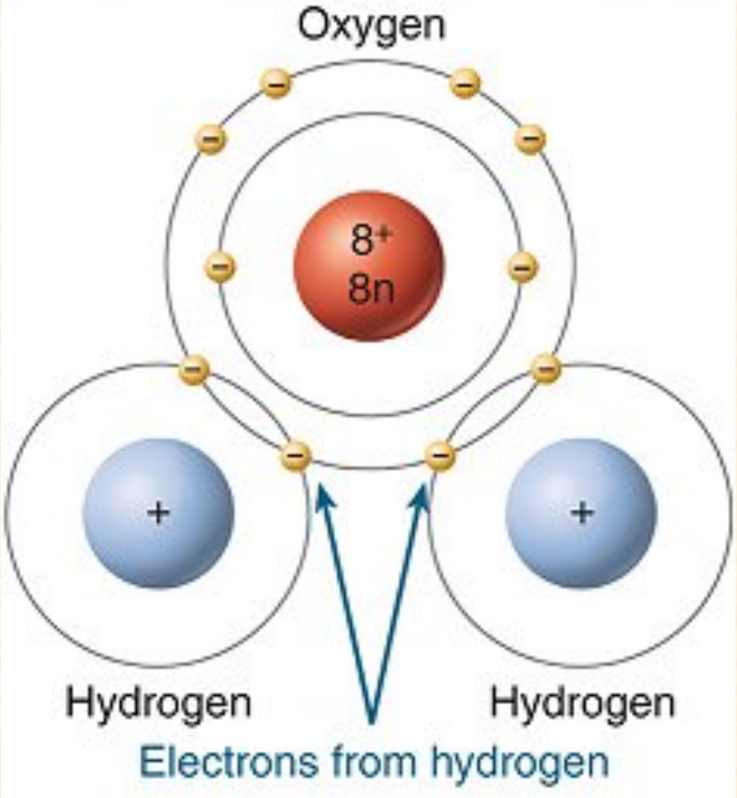


Group→ ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
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	



Valence

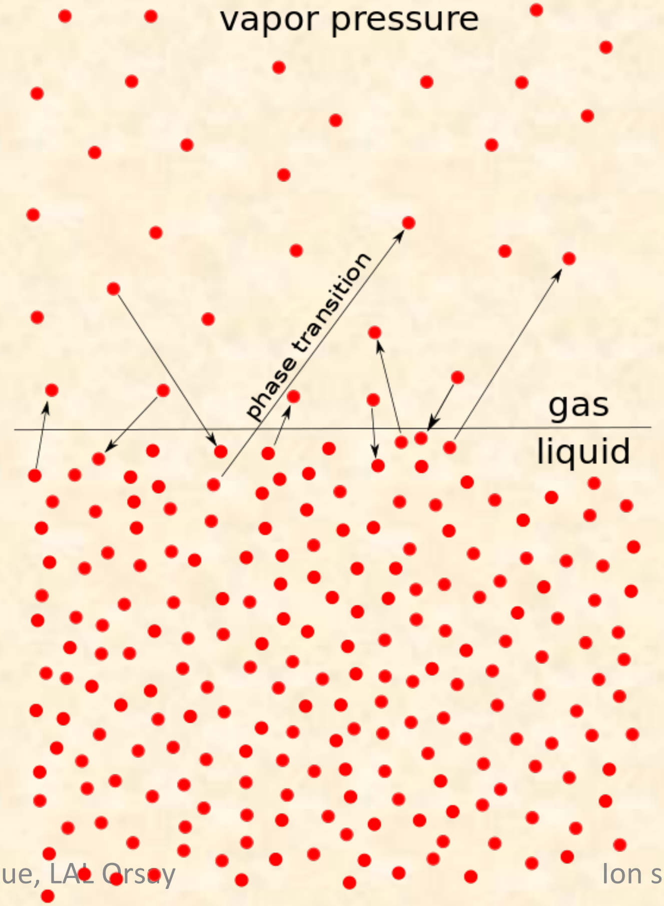
- Only the electrons on the outer shell contribute to the chemical properties of the elements.
- This is called valence.
- The valence is the lower of the number of electron on the outer shell and the number of electrons needed to complete the shell.

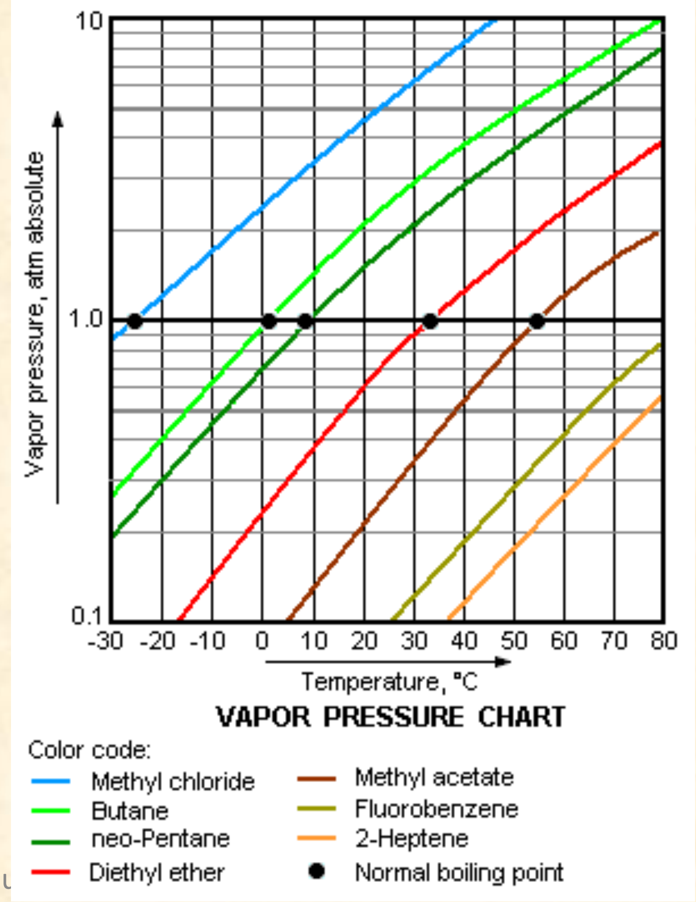


(a) Electron shells in a water molecule

Vapour pressure

- A small fraction of all elements is always in the gaseous (vapour) state.
- There must be an equilibrium between the vapour state and the condensed states.



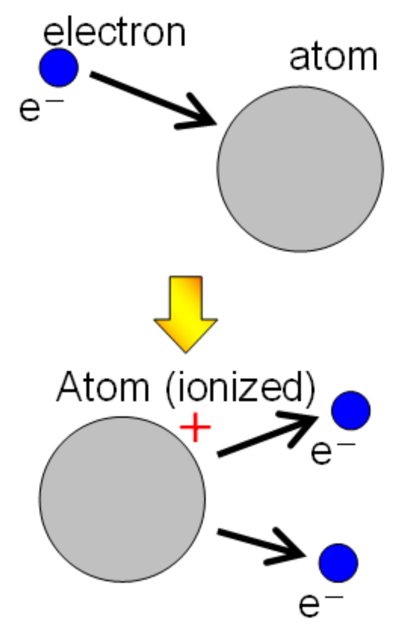


Atomic processes in ions sources: collision with electrons

- Impact ionization/capture

$$A^{Z+} + e \longleftrightarrow A^{(Z+1)+} + e' + e''$$

$$A^{Z+} + e \longleftrightarrow A^{(Z-1)+}$$



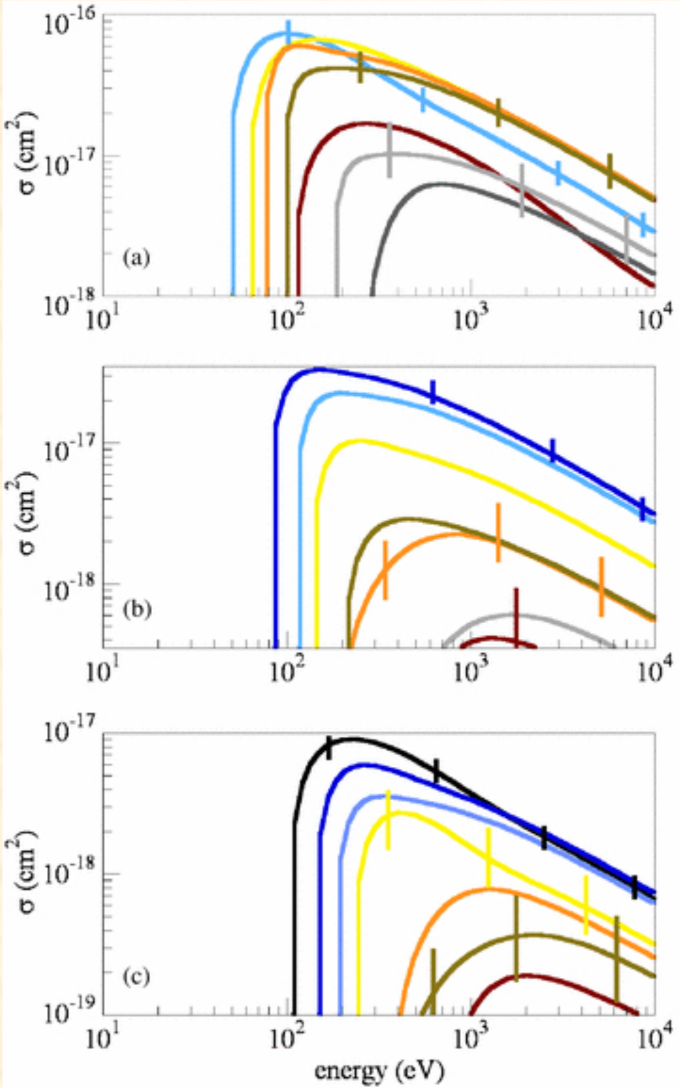
- Impact excitation

$$A^{Z+} + e \longleftrightarrow (A^{Z+})^* + e'$$

(continuous spectrum)

- Note: high cross section!

Collision with electrons



- The energy threshold for ionization increase for higher ionization states.

Cross sections for (e, 2e) (a) and (e, 3e) (b) and (e, 4e) impact ionization (c) for Xe + (black), Xe + 2, (blue), Xe + 3 (light blue), Xe + 4 (yellow), Xe + 5 (orange), Xe + 6 (light brown), Xe + 7 (dark brown), Xe + 8 (light grey) and Xe + 9 (dark grey). Error bars for cross sections yielding Xe + 4, Xe + 7 and Xe + 9 are shown.

Source:
J. Phys. B: At. Mol. Opt. Phys. **38** No 10 (28 May 2005) L183-L190

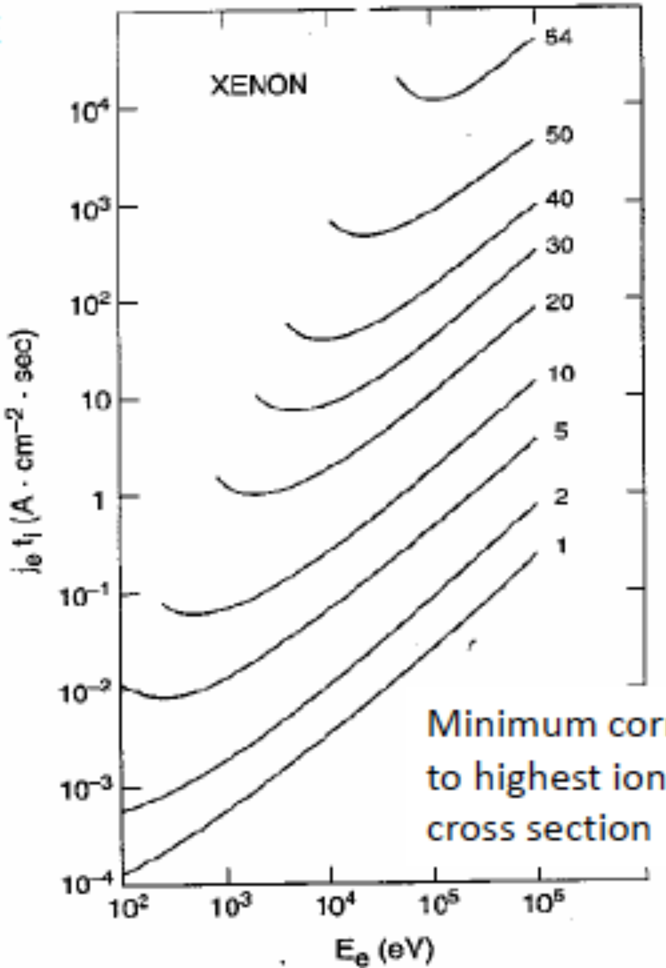
Lotz formula

- Lotz formula: semi-empirical formula for cross-section of multiple ionization

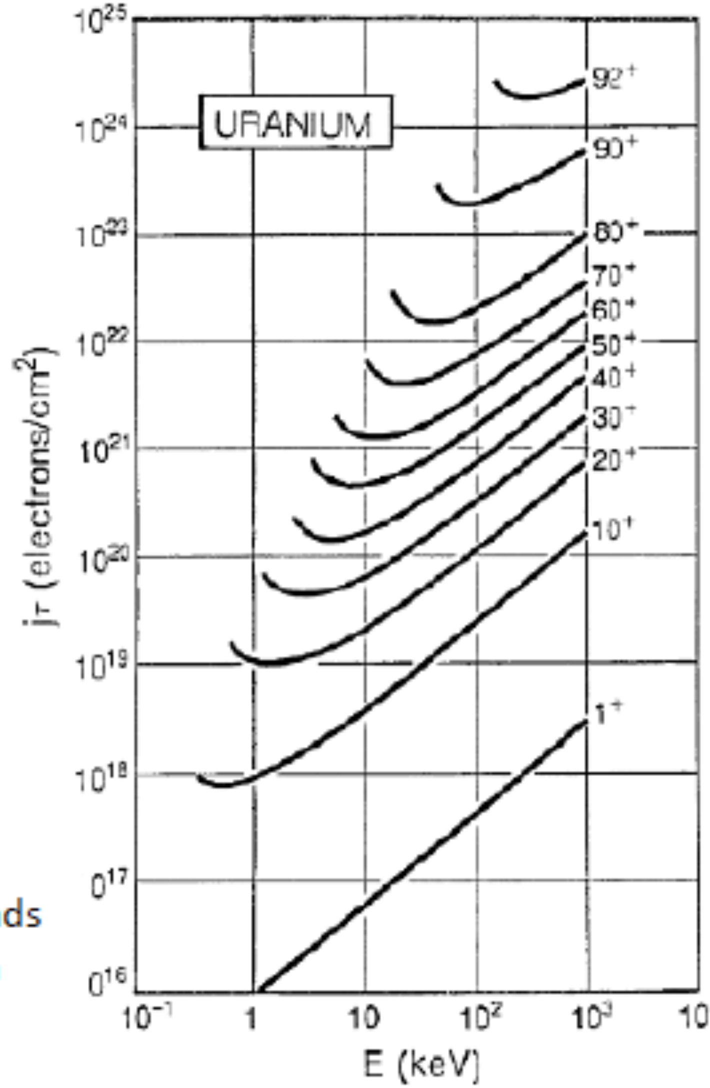
$$\sigma_{q\to q+1} = 4.5\cdot 10^{-14}\cdot\sum_{nl}\frac{\ln\left(E_{kin}/P_i\right)}{E_{kin}\cdot P_i}\quad\left[\mathrm{cm}^2\right]$$

Higher E

Ionization factor $j_e*\tau$ for different charge states of Xe depending on electron energy



Minimum corresponds to highest ionization cross section



W. Lotz, Zeitschrift fuer Physik 206, 205 (1967)

Lotz formula (2)

Lotz formula in detail:

- 3 parameters to represent cross sections for single ionization from ground-state
- Approximates almost all data within 10% and within exp. errors for up to 10keV-electrons
- Empirical formula, but with proper theory basis: (problem for theory: long-range nature of Coulomb potential causing interaction of 2 electrons and ion also at long distances) it follows earlier theoretical work on e-e scattering, uses approximation of starting and final wave functions, gets parameters from fits

Total ionization cross-section

\# of subshell

\# of electrons in subshell

$$\sigma = \sum_{i=1}^{N} a_i q_i \frac{\ln(E/P_i)}{E P_i} \{1 - b_i \exp[-c_i(E/P_i - 1)]\};$$

E<E(max cross section):

$$\sigma = \sum_{i=1}^{N} a_i q_i \frac{\ln(E/P_i)}{E P_i} \{1 - b_i \exp[-c_i(E/P_i - 1)]\};$$

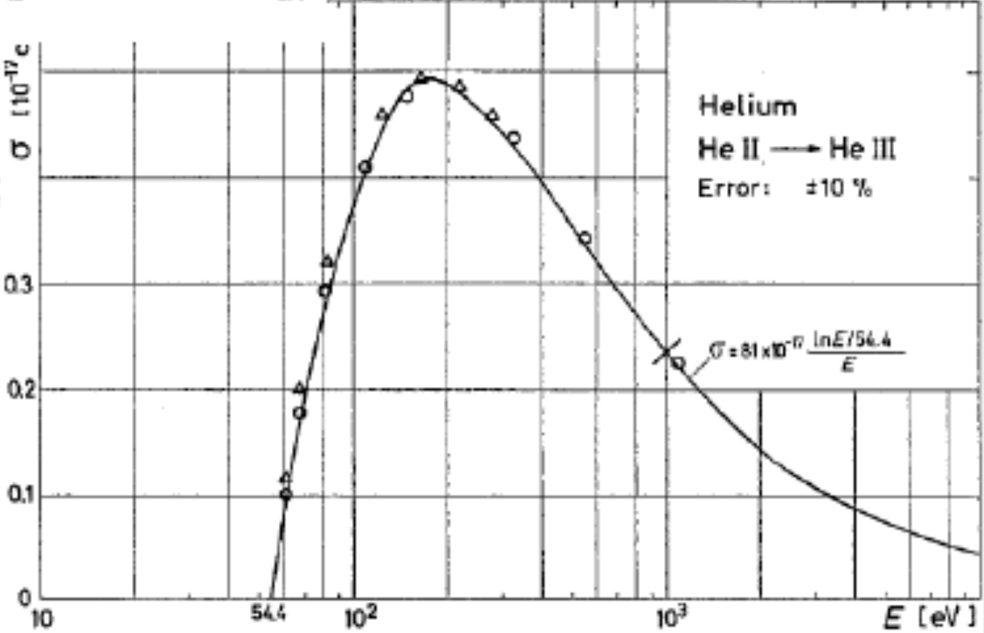
E close to Pi

$$U = E/P_1.$$

$$\sigma \approx a_1 q_1 \frac{(E/P_1 - 1)}{P_1^2} (1 - b_1) \propto U - 1$$

E >>Pi $\sigma_i = a_i q_i \frac{\ln(E/P_i)}{E P_i} \propto \frac{\ln E}{E}.$

a_i= 2.6 – 4.5 e-14 cm2 (empirically)



W. Lotz, Zeitschrift ftir Physik 206, 205 (1967)

Atomic processes in ions sources: collision with photons

- Photo-ionization/Radiative recombination

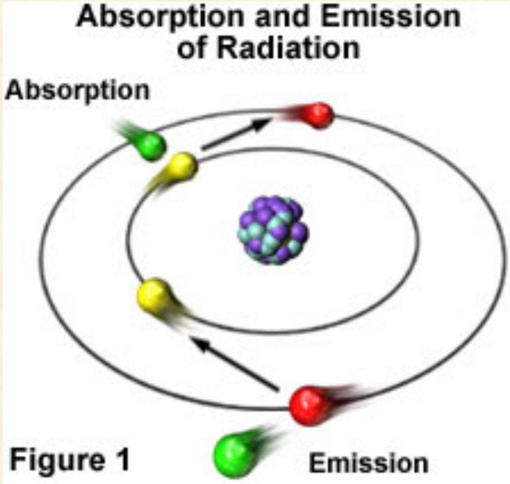
$$A^{Z+} + h\nu \longleftrightarrow A^{(Z+1)+} + e$$

- Excitation

$$A^{Z+} + h\nu \longleftrightarrow (A^{Z+})^*$$

- Photo absorption/Bremstrahlung

$$A^{Z+} + h\nu + e \longleftrightarrow A^{Z+} + e'$$



- Note: cross section lower by several orders of magnitude wrt ionization by collision.

Atomic processes in ions sources: charge exchange

- In the charge exchange process two ions exchange an electrons:

$$A^{Z+} + B^{Z'+} \longleftrightarrow A^{(Z+1)+} + B^{(Z'-1)+}$$

- For this process to take place the right conditions need to be meet.

Ion states equilibrium

- All processes enter in competition!

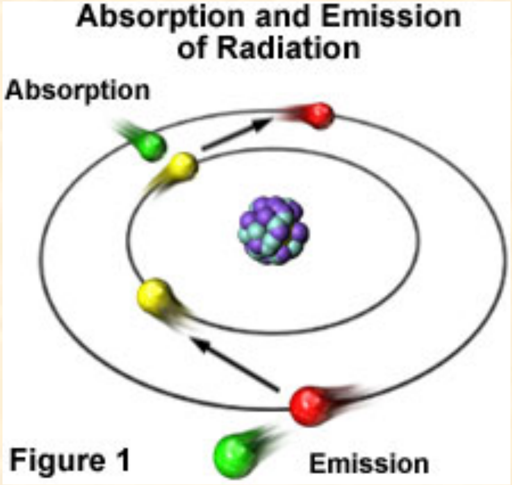
$$\frac{dn}{dt} = source - sink$$

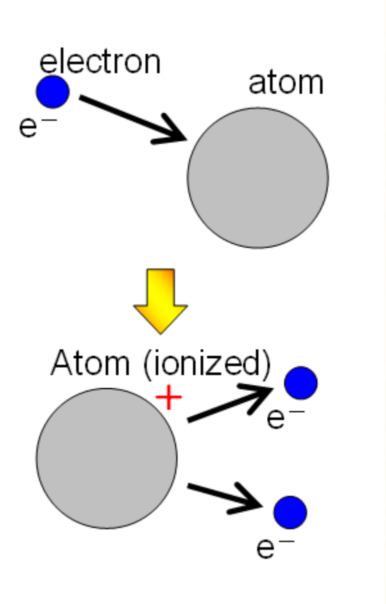
$$A^{Z+} + h\nu \longleftrightarrow A^{(Z+1)+} + e$$

- To get the desired ions one needs to find the parameters that will favour that specie.

Quizz

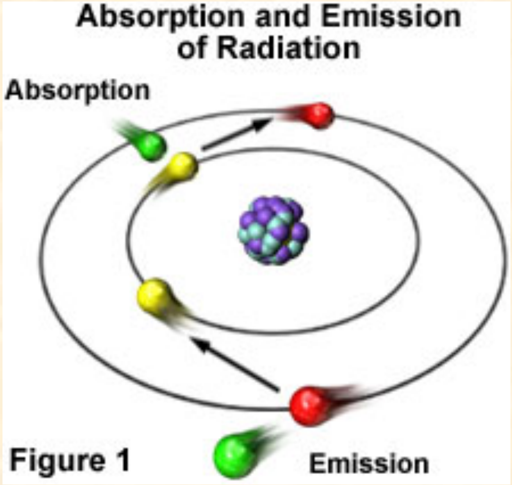
- In which of these cases will photo-ionization be selected over impact ionization?
  (a) A very high current is needed
  (b) To ionize rare gas elements
  (c) A specific charge state has to be selected

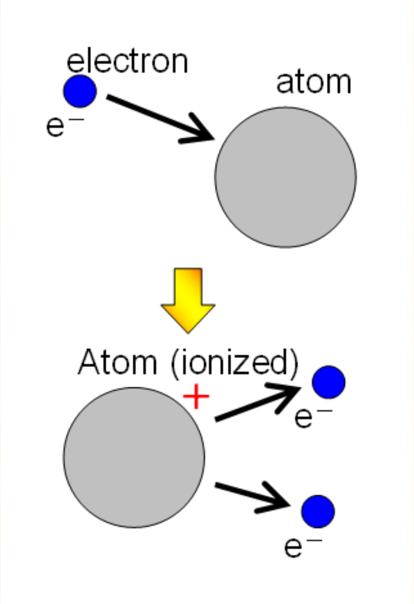




Answer (c)

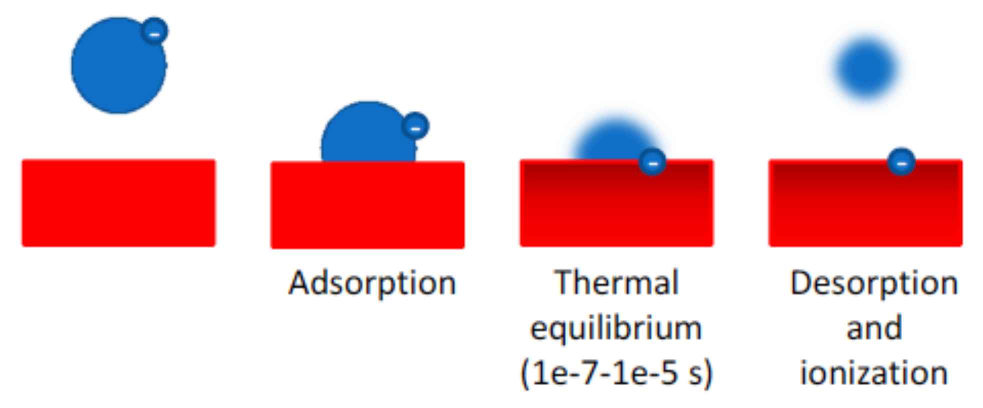
- In which of these cases will photo-ionization be selected over collision ionization?
(a) A very high current is needed
=> Photo-ionization has a lower yield.
(b) To ionize rare gas elements
=> It will be more difficult to ionize such atoms with both methods.
(c) A specific charge state has to be selected
=> By choosing the wavelength one can be more selective.





Surface ionization and desorption

- If the vapor pressure is sufficiently low some atoms will escape from a solid => desorption.
- In some cases the atoms escaping the metal will be charged ions (positively or negatively).
- This process can also take place when ions are first adsorbed by the metal.



Saha-Langmuir equation (1)

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\Lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{\epsilon_{i+1}-\epsilon_i}{k_BT}\right]$$

n_i is the density of atoms in the i-th state of ionization (with i electrons removed).

g_i is the degeneracy of states for the i-ions

ϵ_i is the energy required to remove i electrons from a neutral atom, creating an i-level ion.

n_e is the electron density

Λ is the thermal de Broglie wavelength of an electron

Saha-Langmuir equation (2)

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\Lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{\epsilon_{i+1}-\epsilon_i}{k_BT}\right]$$

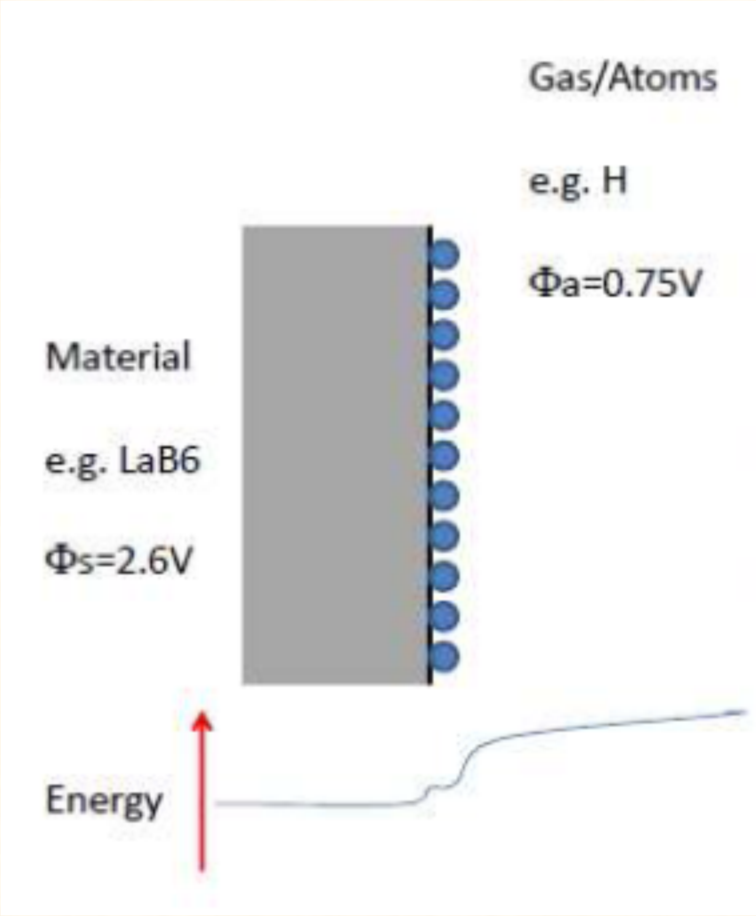
- Notes:
  - final charge state depends on equilibrium values.
  - several ionisation states possible.
  - importance of ionization energy.
  - Favours group 1 elements (lower ionisation energy)
  - Exists also in a form involving the work function.

Surface ionisation

Element	E_1 (eV)	n1/n0 (T=1000K)	n1/n0 (T=1500K)	n1/n0 (T=2000K)
Cs	3.88	790	72	20
K	4.32	6.3	2.2	1.6
Na	5.12	5e-4	5e-3	1.6e-2
Li	5.40	2e-5	6e-4	3e-3

- Lower ionisation energy leads to more ionised emission.
- Higher temperature may reduce ratio of charged ions to neutral atoms (but increase in total emission).

Surface negative ionization



- Principle: deposit a layer of atoms with a high electron affinity.
- The electrons will be transferred to the atom layer.
- Force the emission of the atom layer which takes away part extra electrons at the same time.

Atomic physics summary

- Atomic physics is a key element of understanding ion sources.
- The atomic shell structure determines the energy required to remove (or add) electrons from (to) an atom.
- Several methods of ionization exist (impact ionization, photo ionization, surface ionization…).
- The choice depends on the specie to be ionised and the charge state expected.

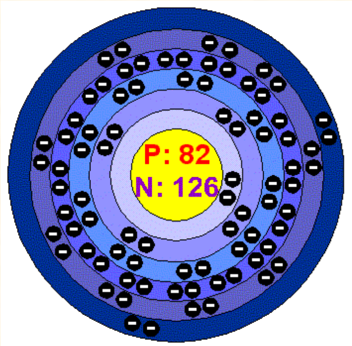
Quizz

- For an ion collider one has the choice between colliding ions A^+ or A^- (A being an unspecified atom).
- Based on the Saha-Langmuir equation which charge state (+1 or -1) would you recommend to use?

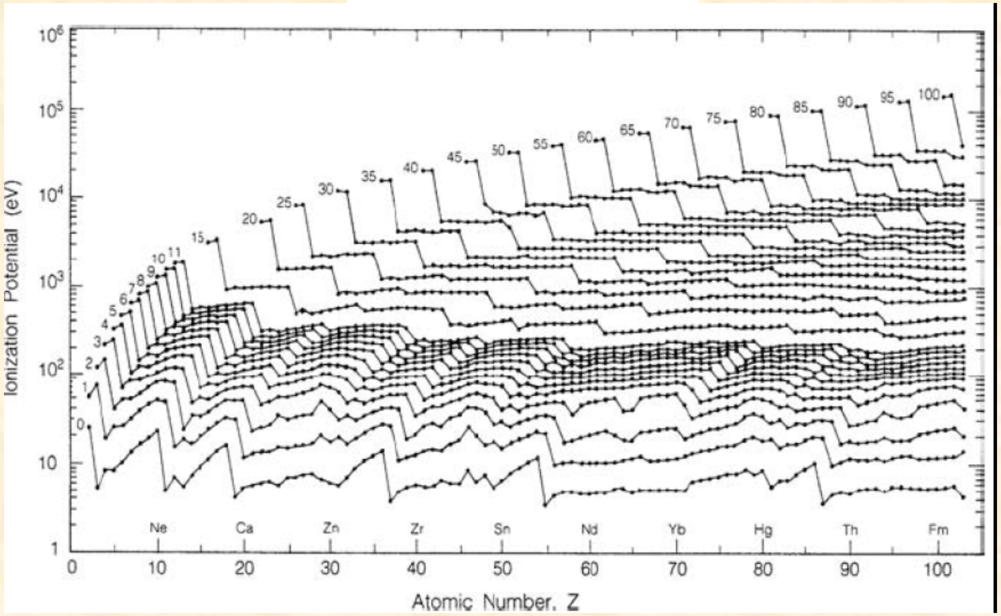
$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\Lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{\epsilon_{i+1}-\epsilon_i}{k_BT}\right]$$

Answer

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\Lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{\epsilon_{i+1}-\epsilon_i}{k_B T}\right]$$

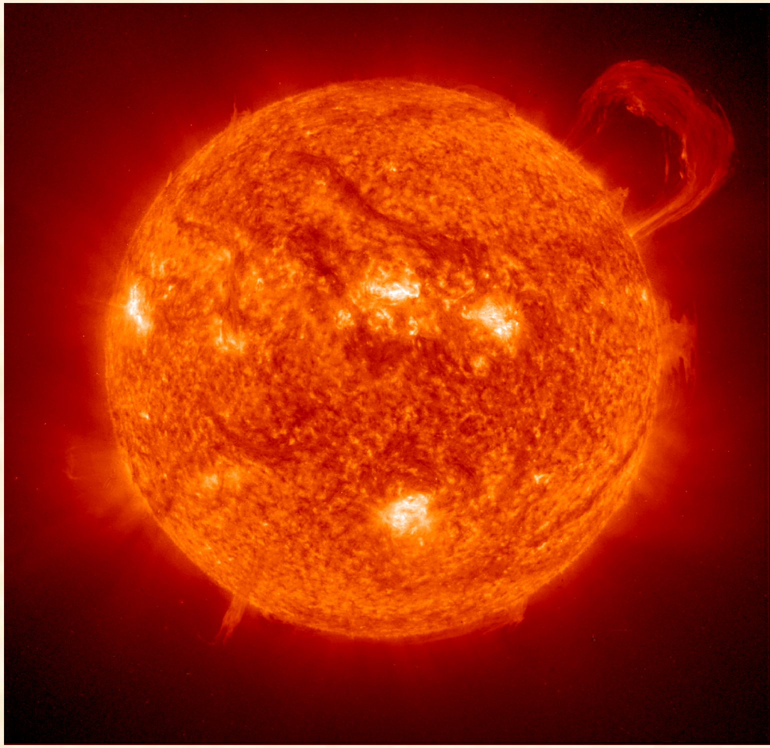


- Electrons further away from the nucleus are always more loosely bound.
- The A^- state will therefore be more difficult to produce and more difficult to transport.
- It is better to use the A^+ state (all other parameters being equal).



Reminder: plasma physics

- In most cases ion sources will involve a “cold” plasma.
- Understanding what happens in the plasma is therefore important.
- A plasma is ionized matter. Eg: The SUN.



Cold vs hot plasma

- A “hot” plasma is a plasma where almost all atoms are ionised.
- In a “cold” plasma only a small fraction (~ 1%) of the atoms are ionised. The temperature of the electrons in a cold plasma can still be several thousand K.

Key elements of a plasma

- 3 constituents:
  - charged ions (positively and negatively)
  - electrons
  - neutrals
- Electric conductivity
- Quasineutrality within bulk
- Sensitivity to electromagnetic fields
- Screening of electric field (sheath formation)
- Collective phenomena (plasma waves,…)

Quantities Characterizing a Plasma

- temperatures of the constituents T
- number densities of the constituents n
- ionization degree η
- Debye length λ_D
- plasma frequency ω_{pl}
- (plasma parameter g)

Temperatures in Plasma

Even in so-called “cold“ plasma electrons have temperatures of the order of 10^4 K and more, while ions and neutrals remain cold (~10^3 K). Thus “cold plasma” is better characterized as “low enthalpy plasma”, because it transfers little heat to its environment.

It has become international usage to use the symbol T not for the thermodynamic temperature measured in Kelvin, but instead for the characteristic energy $k_B T$ (k_B Boltzmann constant) measured in eV. The “speaking” is: “The temperatures are measured in eV”

1 eV corresponds to $1.160*10^4$ K
10^4 K correspond to 0.862 eV

Number Density of Particles Type i

definition $n_i = \dfrac{\text{number of particles}}{\text{volume}},$

units $\left[n_i\right] = 1\,\text{cm}^{-3},$ or $\left[n_i\right] = 1\,\text{m}^{-3}.$

$$10^{-6}\,\text{cm}^{-3} = 1\,\text{m}^{-3} \text{ or } 10^{6}\,\text{m}^{-3} = 1\,\text{cm}^{-3}$$

Quasineutrality

For plasma with singly charged ions only

$$n_\mathrm{i} \approx n_\mathrm{e}$$

For plasma with multiply charged ions

(z charge number of the ions)

$$n_\mathrm{e} \approx \sum_\mathrm{z} \mathrm{z} \cdot n_\mathrm{z}$$

Ionisation degree η or η'

two different definitions are used

$$\eta = \sum_{z} n_z \Big/ \left(n_a + \sum_{z} n_z \right)$$

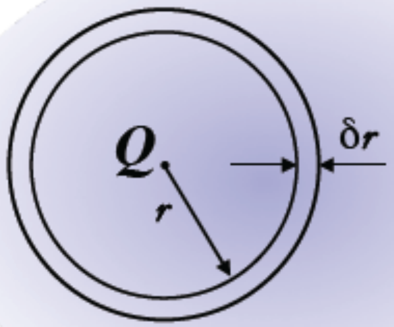
n_a neutral particle density

$$(\eta' = \sum_{z} n_z \Big/ n_a \qquad for\, n_a \rightarrow 0 \; we\; get\; \eta' \rightarrow \infty)$$

$\eta << 1$ "weakly ionised plasma"

$\eta \approx 1$ "strongly" or "fully ionised plasma"

Screening, Debye-Length

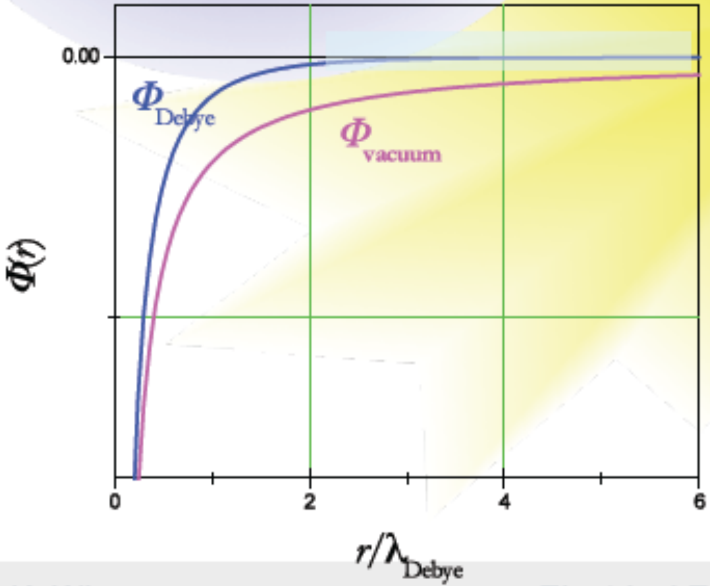


$$\Phi_{vacuum}(r) = Q/\ 4\pi\varepsilon_0\, r$$

$$\delta n = 4\pi n r^2 \delta r \Rightarrow screening$$

$$\Phi_{Debye}(r) = (Q/\ 4\pi\varepsilon_0\, r) * \exp(-r/\lambda_{Debye})$$

„Debye-Hückel-potential“

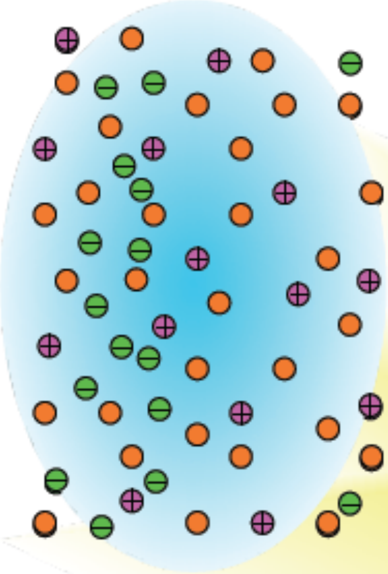


$$\lambda_{Debye} = \left(\frac{\varepsilon_0 k_B T_e}{e^2 n} \right)^{\frac{1}{2}}$$

“Debye length”

P. Debye, E. Hückel 1923

Quasineutrality I



restoring electric field E due to charge separation $$E = \frac{en\Delta x}{\varepsilon_0}$$

Example: fluorescent tube

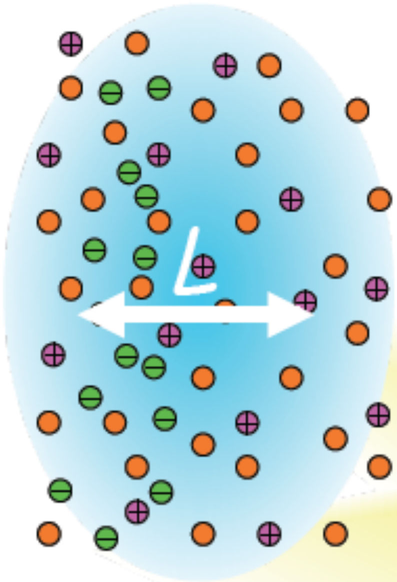
n_e = 10^{16}m^{-3}; Δx = 1mm

E_{max} = 180 kV/m; $U = (E\Delta x)$ = 180V

potential energy of an ion traversing a space charge sheath

$$W_{\mathrm{pot}} = \int_0^{\Delta x} eE\mathrm{d}x = \frac{e^2 n_{\mathrm{e}} (\Delta x)^2}{2\varepsilon_0}; \quad \tfrac{1}{2} k_{\mathrm{B}} T = W_{\mathrm{pot}} \Rightarrow \Delta x = \left(\frac{\varepsilon_0 k_B T}{e^2 n_{\mathrm{e}}} \right)^{\frac{1}{2}} \equiv \lambda_{\mathrm{D}}$$

Quasineutrality II



What amount of deviation from neutrality can exist over a length L?

The increase in potential energy must not surmount $k_B T/2$

$$\tfrac{1}{2} k_{\mathrm{B}} T \approx \tfrac{1}{2} \frac{e^2 \Delta n L^2}{\varepsilon_0}$$

Substituting $k_B T$ by λ_{D} yields

$$\Delta n / n \approx \left(\lambda_{\mathrm{D}} / L\right)^2$$

Ionized gas is plasma only, if its extension is much larger than the Debye-length

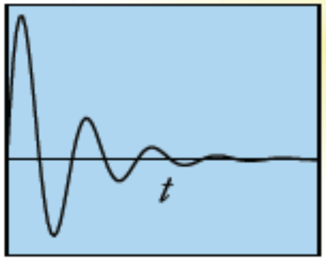
Plasma Oscillations

Equation of motion for electrons moving under the action of the electric field generated by charge separation

$$F = eE = \boxed{e^2 nx/\varepsilon_0 = m_e \mathrm{d}^2 x/\mathrm{d}t^2}$$

This is the equation of a harmonic oscillator with the so-called electron plasma frequency as natural frequency

$$\omega_{pe} = \sqrt{e^2 n/\varepsilon_0 m_e}$$



$$\omega_{pe}/\mathrm{s}^{-1} = 2\pi \cdot 8.98 \cdot \sqrt{n_e/\mathrm{m}^{-3}}$$

Typical value: for $n_e = 10^{17}\mathrm{m}^{-3}$ we have $\omega_{pe} = 2\pi * 2.8$ GHz

Ion Plasma Frequency

If we replace electron charge and mass by the ion charge and mass we obain:

$$\omega_{\mathrm{pi}_z} = \sqrt{(ze)^2 n_z / \varepsilon_0 m_z}$$

This is the characteristic frequency of ion space charges (e.g. ion sheaths at walls).

❖ electromagnetic fields varying with frequencies well above ω_{pi} have almost no effect on the ion motion

❖ Typical values of ω_{pi} are in the MHz range. Thus ionic RF currents are very small when working with frequencies in the 10 MHz range or above. In this case ions follow the (average) DC fields only

Quizz

- Typical value of w_pe are in the GHz whereas w_pi is in the 10s of MHz.
- What happens if I excite a plasma with an RF wave of 100 MHz?

(a) The ions will be excited and not the electrons

(b) The electrons will be excited and not the ions

(c) Both the ions and the electrons will be excited

(d) Neither the ions nor the electrons will be excited.

Do you see an application for this (based on what we discussed earlier today)?

$$\omega_{pe} = \sqrt{\frac{e^2 n}{\varepsilon_0 m_e}}$$

$$\omega_{pi_Z} = \sqrt{\frac{(Ze)^2 n_Z}{\varepsilon_0 m_z}}$$

Answer (b)

- At 100 MHz the frequency is above w_pi
  => ions are not excited.
- The frequency is below w_pe
  => electrons are excited.
- The electrons will gain kinetic energy and not the ions.
  => There will be collisions and this will trigger impact ionization.
  => This phenomena is used in Electron Cyclotron Resonance (ECR) sources.

Plasma Kinetics

if $\lambda_{\mathrm{n}} = 1/n_{\mathrm{e}}^{1/3} >> \lambda_{\text{de Brogli}} = h/m_{\mathrm{e}}v_{\mathrm{th}}$;

$$\left(\tfrac{1}{2}m_{\mathrm{e}}v_{\mathrm{th}}^{2} = k_{\mathrm{B}}T_{\mathrm{e}}\right)$$

plasma can be treated by classical statistics, otherwise it is *degenerate.*

if $k_{\mathrm{B}}T >> e^2/(4\pi\varepsilon_0\lambda_{\mathrm{n}}) \Leftrightarrow \lambda_{\mathrm{D}} >> \lambda_{\mathrm{n}} \Leftrightarrow g \equiv 1/n_{\mathrm{e}}\lambda_{\mathrm{D}}^{3} << 1$

plasma can be treated as an ideal gas. Otherwise it is *strongly coupled* or *non-ideal.*

$$g \propto n_{\mathrm{e}}^{1/2}/(k_{\mathrm{B}}T_e)^{3/2}$$

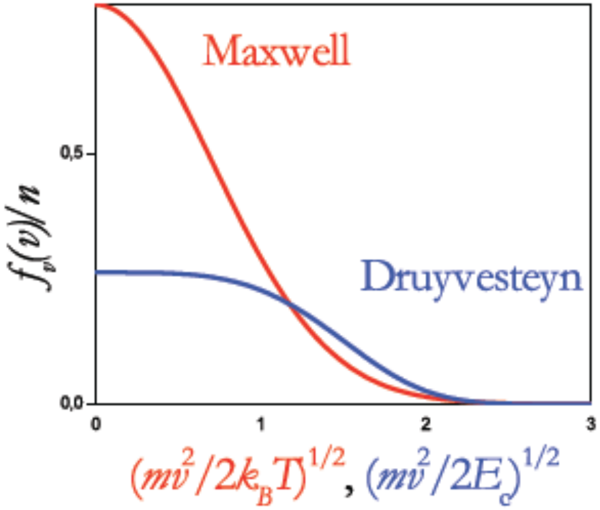
nonideal plasmas are cold and dense

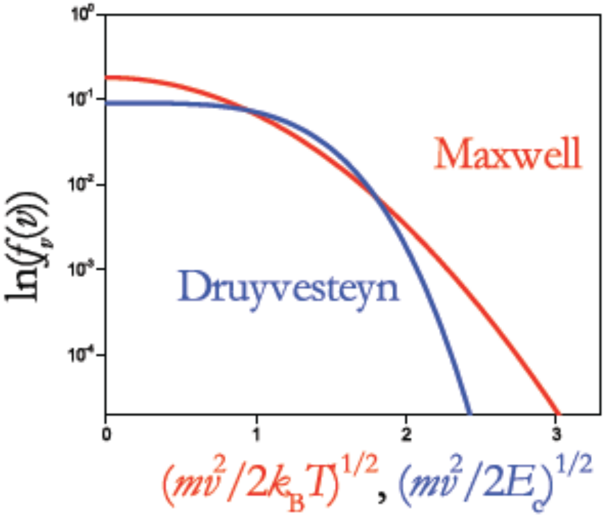
for ion source plasma we have usually g « 1

Electron distribution: Druyvesteyn distribution

- The electron distribution in a plasma does not follow Maxwell's distribution.
- It is better described by Druyvesteyn distribution.

Electron Temperature and Distribution Functions





$$f_v(v) = n\left(\frac{m}{2\pi k_B T}\right)^{3/2}\cdot\exp\left(-\frac{mv^2}{2k_B T}\right)$$

$$\left\langle \frac{1}{2}mv^2\right\rangle = \frac{3}{2}k_B T$$

$$f_v(v) = \frac{n}{\pi\cdot\Gamma(3/4)}\left(\frac{m}{2E_c}\right)^{3/2}\cdot\exp\left(-\left[\frac{mv^2}{2E_c}\right]^2\right)$$

$$\left\langle \frac{1}{2}mv^2\right\rangle = E_c\cdot\Gamma\left(\frac{5}{4}\right)/\Gamma\left(\frac{3}{4}\right)$$

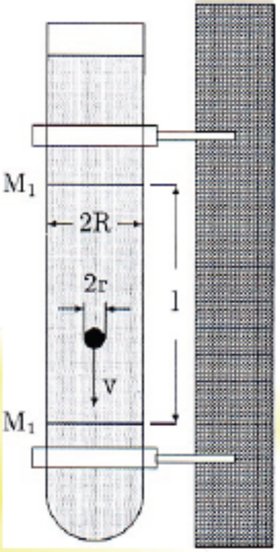
Electron Temperature and Distribution Functions

Jeans' Theorem: If the velocity distribution function can be expressed solely as a function of constants of motion, it is itself a constant of motion.

This theorem applies, for example, if there are no collisions or no transport.

In these cases the velocity distribution function can be written as a function of the **total** energy.

Definition of the mobility *b*



constant velocity of a body moving in a viscous medium under the action of a constant external force (gravitation)

$$\vec{v} \equiv b\vec{F} \quad if \; \vec{F} = q\vec{E} \Rightarrow \boxed{\vec{v} = bq\vec{E}}$$

In weakly ionized plasma friction is due to electron (and ion) collisions with neutrals. For electrons we have:

$$b_{\mathrm{e}} \equiv < 1/m_{\mathrm{e}}\nu_{\mathrm{en}} > = < 1/m_{\mathrm{e}}\sigma_{\mathrm{en}}v_{\mathrm{e}} > \propto 1/\sqrt{m_{\mathrm{e}}}$$

$$< 1/m_{\mathrm{e}}\sigma_{\mathrm{en}}v_{\mathrm{e}} > \equiv \iiint_{\vec{v}_{\mathrm{e}}} (1/m_{\mathrm{e}}\sigma_{\mathrm{en}}v_{\mathrm{e}}) f(\vec{v}_{\mathrm{e}}) d^3v_{\mathrm{e}} \approx \frac{1}{\iiint_{\vec{v}_{\mathrm{e}}} (m_{\mathrm{e}}\sigma_{\mathrm{en}}v_{\mathrm{e}}) f(\vec{v}_{\mathrm{e}}) d^3v_{\mathrm{e}}}$$

Diffusion

Diffusion is a consequence of the Brownian motion of electrons, ions and neutrals.

$$\overrightarrow{\Gamma_{\text{diff}}} = -D\nabla n \qquad \text{I. Fick's law}$$

$$D_{\text{e,i}} = b_{\text{e,i}} k_{\text{B}} T_{\text{e,i}} \quad \text{Einstein relation}$$

$$D_{\text{e,i}} \approx < \nu > \cdot < \lambda >^2 \propto 1/\sqrt{m_{\text{r e,i}}}; \quad < \lambda > = < 1/n\sigma >$$

$$m_{\text{r}} \text{ "reduced mass"}$$

(Collision frequency times square of mean free path between subsequent collisions)

Diffusion

Diffusion is a consequence of the Brownian motion of electrons, ions and neutrals.

$$\overrightarrow{\Gamma_{\text{diff}}} = -D\nabla n \qquad \text{I. Fick's law}$$

$$D_{\text{e,i}} = b_{\text{e,i}} k_{\text{B}} T_{\text{e,i}} \propto 1/\sqrt{m_{\text{r e,i}}}$$

$$\boxed{\frac{D_{\text{e}}}{D_{\text{i}}} = \sqrt{\frac{m_{\text{r i}}}{m_{\text{e}}}}}$$

Sheath Formation in Front of a Wall

walls constitute sinks for charged particles, which are there either discharged (ions) or absorbed (ions and electrons).

As a consequence charged particles are transported from plasma to enclosing walls - generally at different speeds.

Sheath Formation

weakly ionized plasma

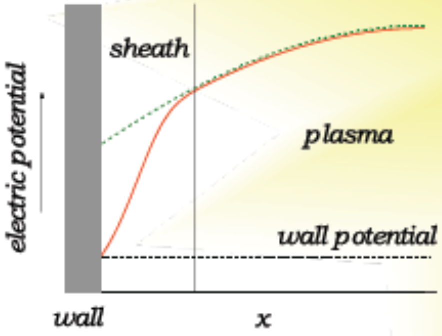
In weakly ionized, nonmagnetized plasma electron transport is fast, ion transport is slow.

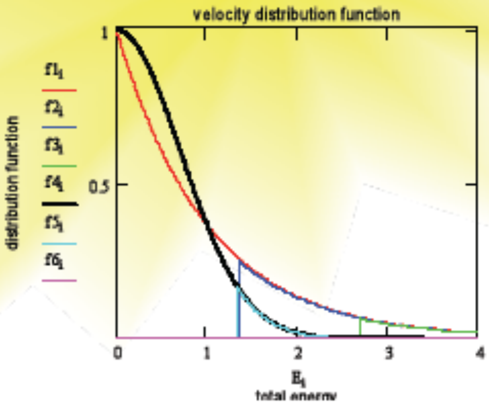
In the presence of a wall a small amount of positive space charge remains in plasma as a consequence. The plasma potential becomes **positive** with respect to enclosing walls, resp. the walls are **negatively charged**.

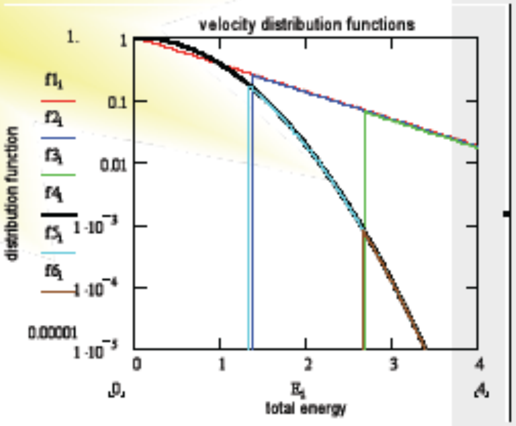
Plasma-Sheath-Transition

application of Jeans' Theorem

In the collisionfree case an isotropic velocity distribution function can be written as a function of the **total** energy, but is defined only for **positive kinetic energy**.

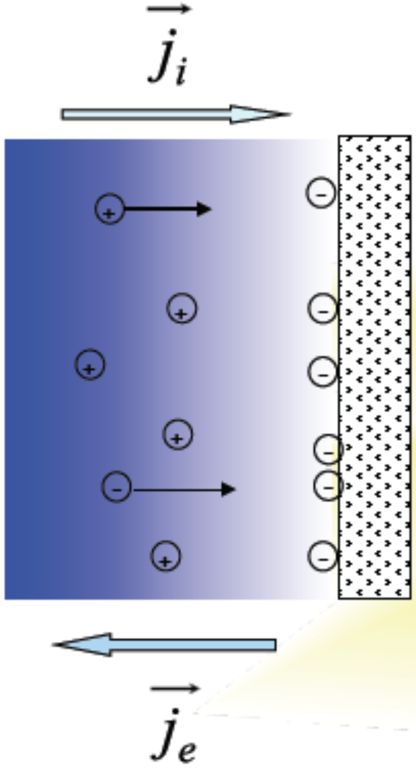






Sheath Formation

in weakly ionized plasma



Charging of a dielectric wall

$$\vec{j} = \vec{j}_e + \vec{j}_i = 0$$

$$\left|\vec{j}_i\right| = \left|\vec{j}_e\right| = \left|\vec{j}_{e0}\right| \exp(-qU_{wall} / kT_e)$$

$$\text{when } U_{plasma} = 0$$

$$U_{wall} = -\frac{kT_e}{e} \ln\left(\frac{\left|\vec{j}_i\right|}{\left|\vec{j}_{e0}\right|}\right)$$

Sheath Formation

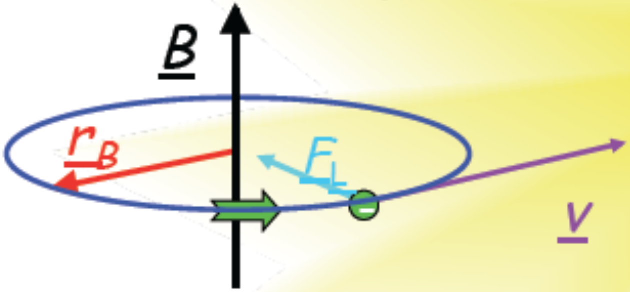
weakly ionized plasma

At insulating walls the negative charge on a wall locally regulates itself in such a way that the ion and electron wall **current densities** become equal.

At metallic walls such a condition may hold for the **total currents** only. This is important in case of microwave discharges with external magnetic field

Gyration of ions and electrons under the action of a static magnetic field

- ❖ A static magnetic field of induction $\underline{B}$ interacts with particles of mass m and charge q by the so-called Lorentz Force $\underline{F_L}$. A circular motion, a gyration is the consequence (non-relativistic case in plasma).



$$\overrightarrow{F_L} = q\vec{v} \times \vec{B}$$

The radius (cyclotron radius) r_B of the circular trajectory is given by $r_B = mv/qB$
The corresponding cyclotron frequency ω_B does not depend on the particle velocity v: $\omega_B = qB/m$

Particle Motion in Magnetized Plasma

$m\dot{\vec{v}} = q\vec{v} \times \vec{B} + \vec{F}$ vector equation of motion

$$\vec{F} \equiv \vec{F}_\perp + \vec{F}_\parallel, \; \vec{v} \equiv \vec{v}_\perp + \vec{v}_\parallel$$

(components $\parallel$ and $\perp$ to $\vec{B}$)

$m\dot{\vec{v}}_\perp = q\vec{v}_\perp \times \vec{B} + \vec{F}_\perp$ $\vec{B}$ - dependent part

$m\dot{\vec{v}}_\perp = q\vec{v}_\perp \times \vec{B}$ homogeneous part (Gyration)

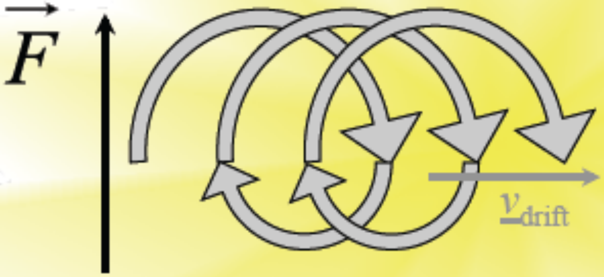
$-q\vec{v}_\perp \times \vec{B} = \vec{F}_\perp$ inhomogeneous part

(no acceleration, drift)

Drift

Solution of the inhomogeneous part

$$qB^2\vec{v}_\perp = \vec{F}_\perp \times \vec{B} \quad \text{or} \quad \vec{v}_\perp = \frac{\vec{F}\times\vec{B}}{qB^2} \equiv \vec{v}_{drift}$$

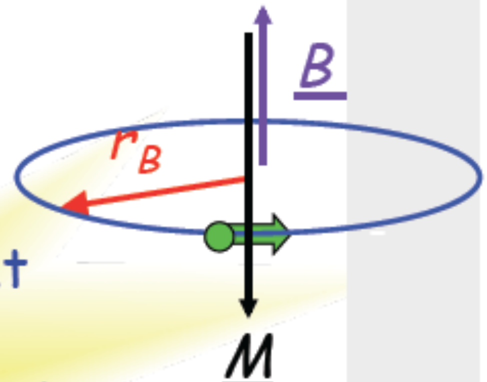


special case: $\vec{F} = q\vec{E} \Rightarrow \vec{v}_{\text{drift}} = \vec{E}\times\vec{B}/B^2$

'EcrossB drift', not dependent on charge and mass

Magnetic Moment

gyrating particle as a pseudo particle with a magnetic moment M:



$$I = q / \tau_B = q\omega_B / 2\pi$$ circular current

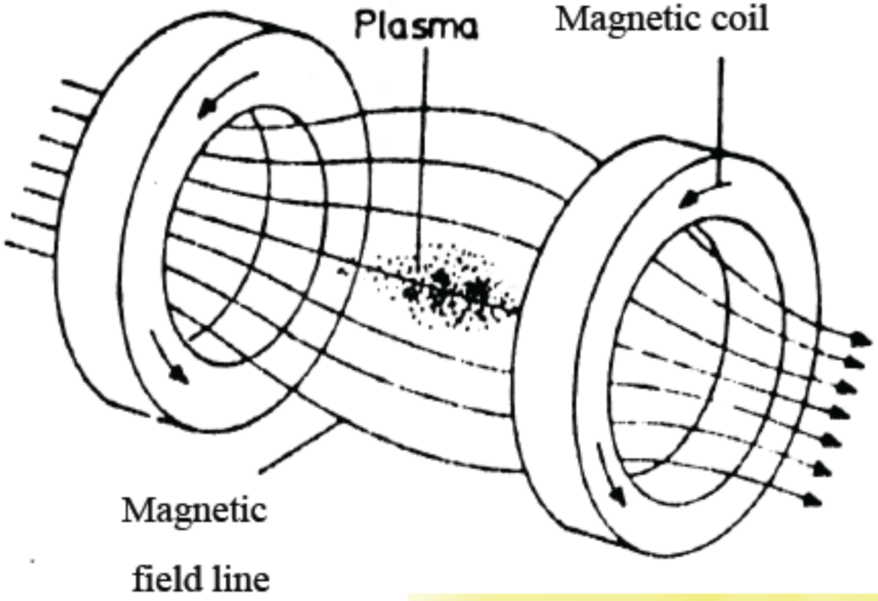
$$A = r_B^2 \pi$$ area of current loop

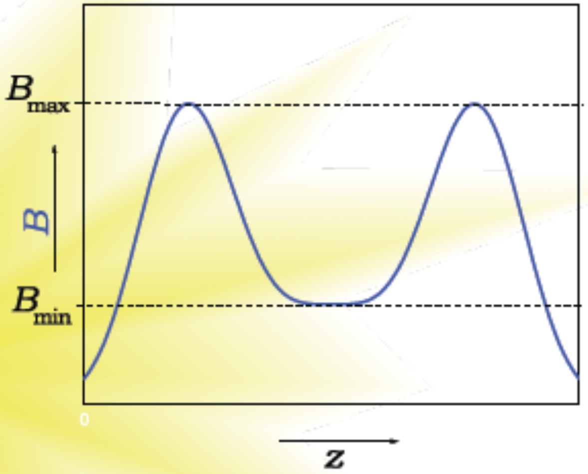
$$M = IA = \frac{q^2 B}{2\pi m} \frac{\pi m^2 v_\perp{}^2}{q^2 B^2} = \frac{\frac{1}{2} m v_\perp{}^2}{B} = \frac{W_\perp}{B}$$

$$M = const \qquad W = W_\perp + W_\parallel = const \quad \Rightarrow W_\parallel = W - MB$$

“adiabatic constant”

Magnetic Mirror Trap

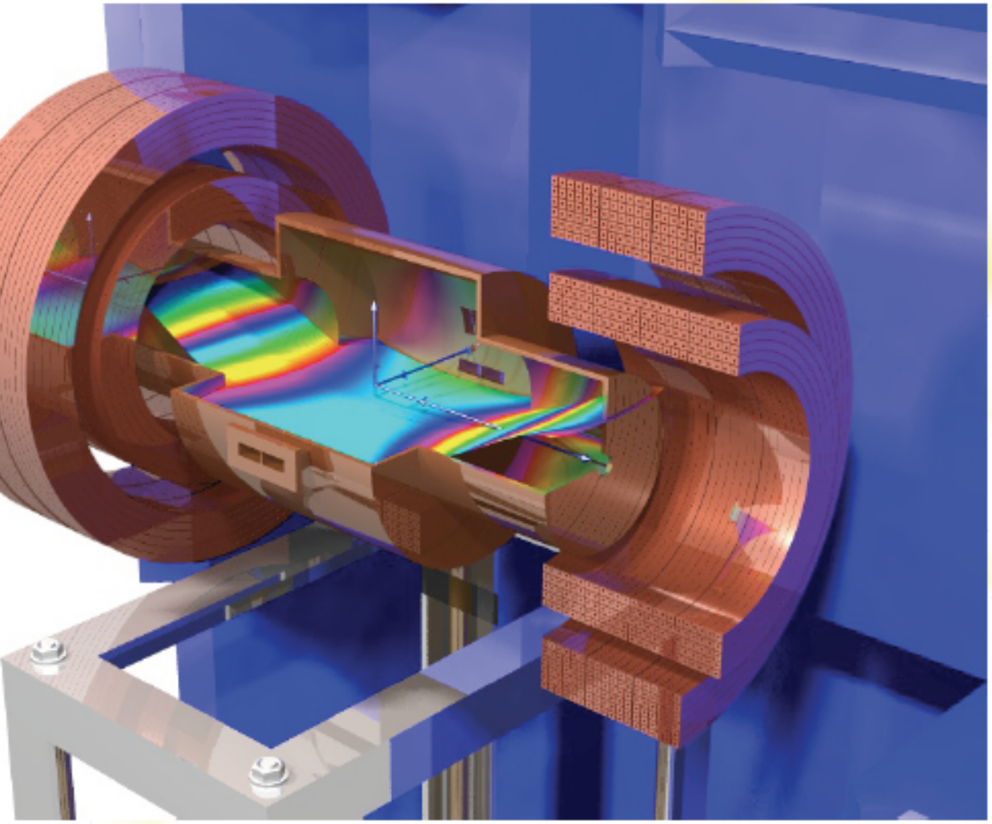




$$M = W_{\perp 0} / B_{\min}; \quad W_{\|mirror} \leq 0, \text{if } W \leq M \cdot B_{\max} = W_{\perp 0} \frac{B_{\max}}{B_{\min}}$$

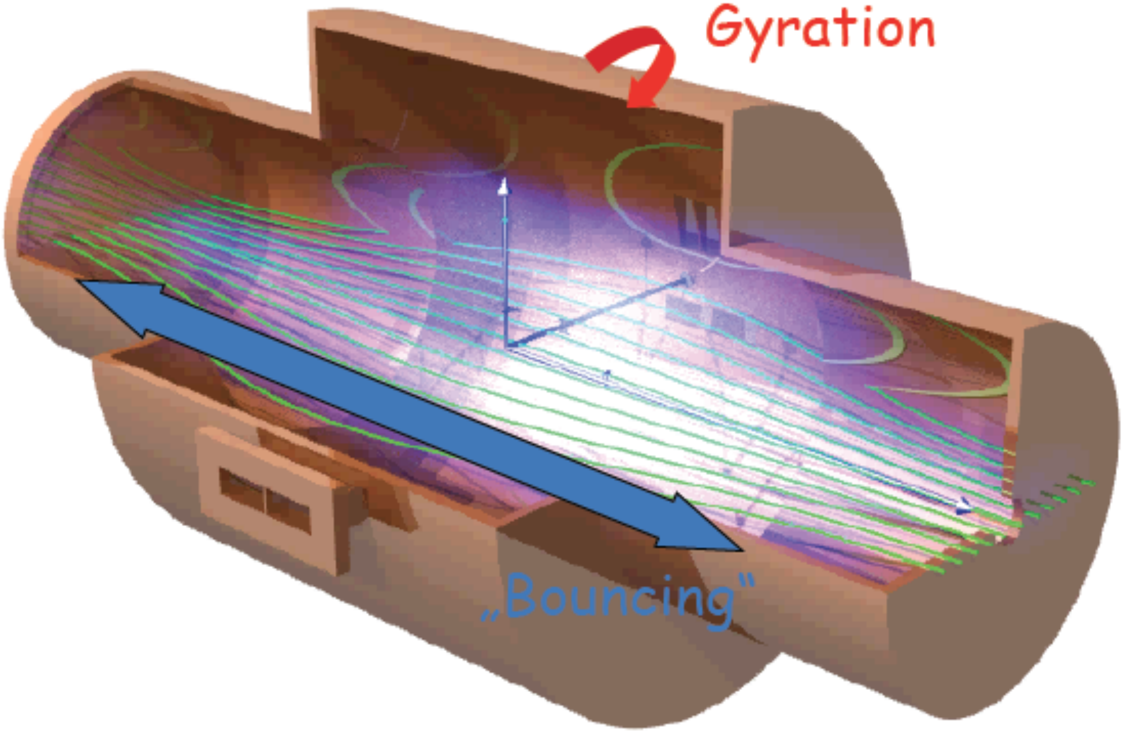
$$\text{condition for containment}: \frac{W_{\perp 0}}{W} \geq \frac{B_{\min}}{B_{\max}} \equiv \frac{1}{R}; \text{R "mirror ratio"}$$

A „Hammock“ for charged particles



© U. Wolters

Charged particle movement between magnetic mirrors



© U. Wolters

Diffusion in an External Magnetic Field

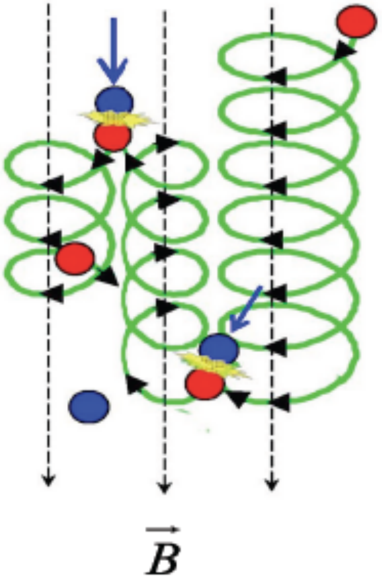
transport **along** the field lines resembles transport in the absence of a magnetic field. Thus:

$$\frac{D_{\|e}}{D_{\|i}} = \sqrt{\frac{m_{ri}}{m_e}}$$

Diffusion in an External Magnetic Field

transport **across** the field lines is a hopping from field line to field line as a consequence of collisions.

Thus the average displacement per collision is the average gyration radius r_B, not the mean free path



$$D_\perp \approx <\nu \cdot r_B^2> \propto \sqrt{m} \Rightarrow \frac{D_{\perp e}}{D_{\perp i}} = \sqrt{\frac{m_e}{m_{ri}}}$$

AC Conductivity

$\vec{v} = bq\vec{E}$ definition of the mobility

per analogy for nonresonant oscillatory motion

$$\mathrm{i} = \sqrt{-1}$$

$$m\dot{\vec{v}} = q\vec{E}(t) = q\vec{E_0} \cdot \exp(-\mathrm{i}\omega t), \Rightarrow$$

$$\vec{v} = \frac{\mathrm{i}}{\omega m} q\vec{E} \equiv bq\vec{E} \Rightarrow \boxed{b = \frac{\mathrm{i}}{\omega m} \text{ ac mobility}}$$

AC Conductivity

Density of electric current induced by an electric field $\underline{E}$ in a plasma with different kinds of charged particles (index k)

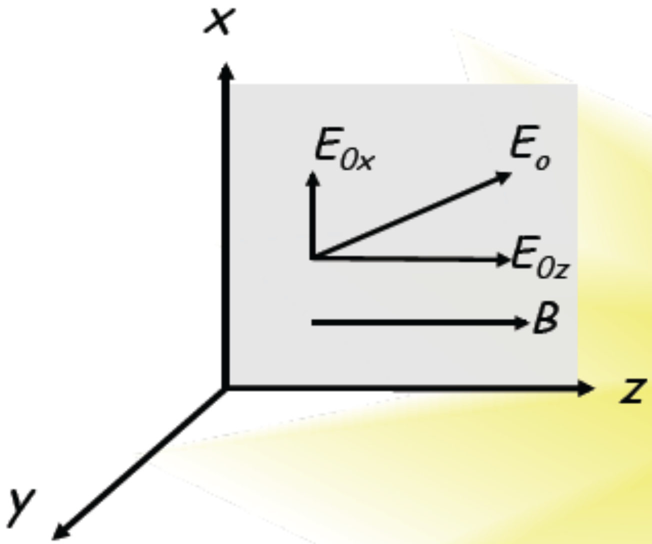
$$\vec{j} = \sum_{\mathrm{k}} q_{\mathrm{k}} n_{\mathrm{k}} \vec{v}_{\mathrm{k}} = (\sum_{\mathrm{k}} q_{\mathrm{k}} n_{\mathrm{k}} b_{\mathrm{k}} q_{\mathrm{k}})\vec{E} \equiv \sigma \vec{E}$$

$$\text{thus} \quad \sigma = \sum_{\mathrm{k}} q_{\mathrm{k}} n_{\mathrm{k}} b_{\mathrm{k}} = \mathrm{i} \sum_{\mathrm{k}} q_{\mathrm{k}}^2 n_{\mathrm{k}} / \omega m_{\mathrm{k}}$$

AC Conductivity of a nonmagnetized plasma

(not dependent on charge sign !!)

AC Conductivity of Magnetized Plasma



$$m\dot{\vec{v}} - q\vec{v} \times \vec{B} - q\vec{E} = 0$$

Ansatz

$$\vec{B} = (0,0,B)$$

$$\vec{E} = (E_x,0,E_z)$$

$$\vec{v} = \left\{ a_x(t)\vec{E}_{0x} + a_y(t)\vec{E}_{0x} \times \underline{B} + a_z(t)\vec{E}_{0z} \right\} \exp(-\mathrm{i}\omega t)$$

AC Conductivity of Magnetized Plasma

$$\frac{\partial a_z}{\partial t} - \mathrm{i}\omega a_z - \frac{q}{m} = 0$$

$$\frac{\partial a_x}{\partial t} - \mathrm{i}\omega a_x - \frac{q}{m} + \frac{qB^2 a_y}{m} = 0$$

$$\frac{\partial a_y}{\partial t} - \mathrm{i}\omega a_y - \frac{q a_x}{m} = 0 \;\Big|\; \frac{\partial}{\partial t}\cdot$$

$$\frac{\partial^2 a_y}{\partial t^2} - 2\mathrm{i}\omega \frac{\partial a_y}{\partial t} + \left(\omega_{\mathrm{B}}^2 - \omega^2\right) a_y = \frac{q^2}{m^2}$$

$$a_z = \frac{\mathrm{i}q}{\omega m} \Rightarrow v_z = \frac{\mathrm{i}qE_z}{\omega m}$$

inhomogeneous solution;
homogeneous solution
yields a constant velocity

homogenous solution
describes gyration

For calculating electric currents we need to consider the drift velocities obtained from the inhomogeneous parts of the equations

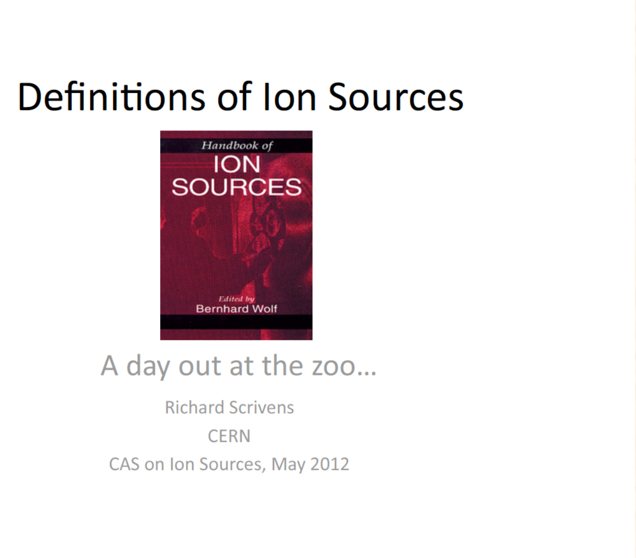
EM Waves propagation in plasma

- The propagation of an EM wave in plasma will depend on its frequency.
- Some wave will be cut-off by the plasma and will not propagate.
- Some will be transmitted.
- Some wave with the right frequency may even resonate in the plasma.
  => Cf plasma physics lecture,

TYPES OF IONS SOURCES

Types of ions sources

- Now that we have seen the basic physics used in ion sources we will se the different types of ion sources.
- *Most of the following slides come from Richard Scrivens' lecture at the CAS in 2012 but some are taken from other lectures at CAS.*



Definitions of Ion Sources

A day out at the zoo…

Richard Scrivens
CERN
CAS on Ion Sources, May 2012

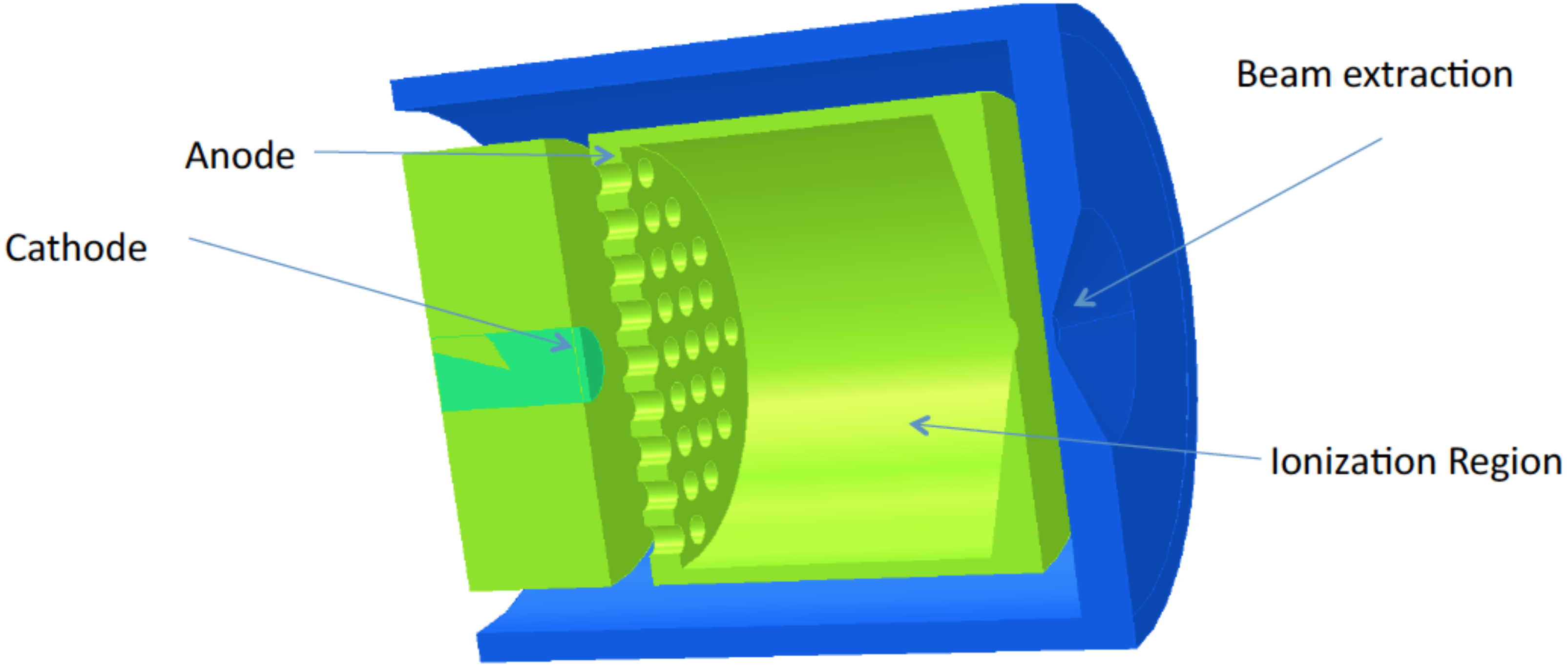
An Approximate Classification System

Try to break down ion sources into a few groups:

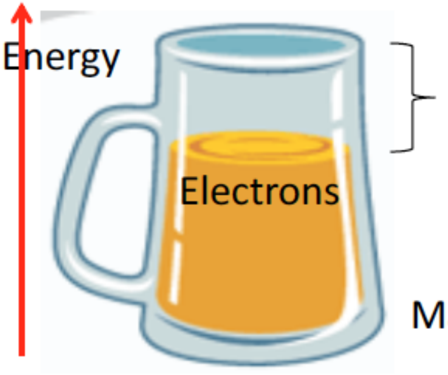
- Electron bombardment
- Plasma Discharge
- RF discharge
- Microwave and ECR
- Laser Ion Sources
- Surface
- High Charge State Sources
- Charge Exchange Ion Sources

Electron Bombardment Ion Source

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



Electron Bombardment Ion Source



Energy difference between highest energy electron and vacuum

Work Function ϕ_s

Material

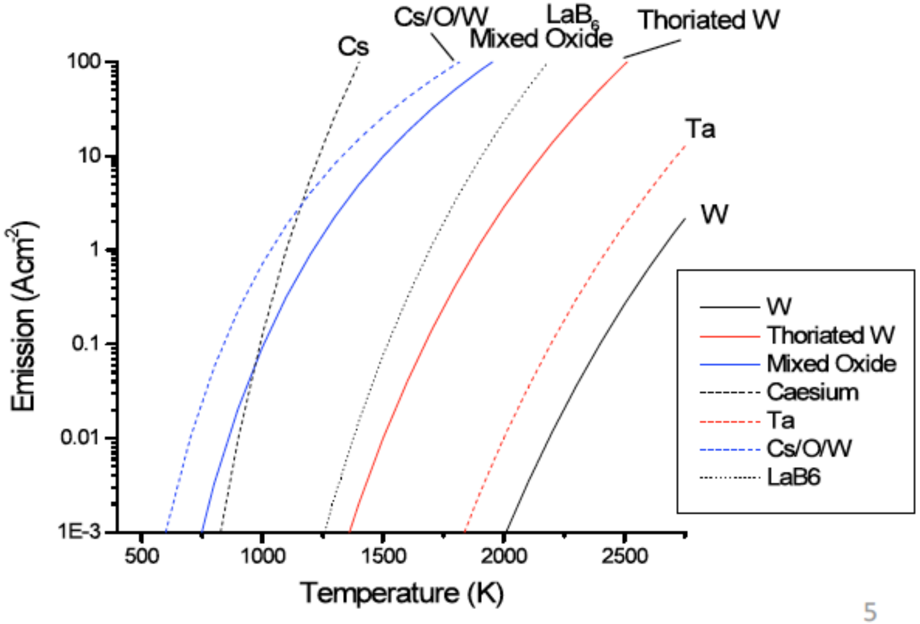
Electrons within a material are heated to energies above that needed to escape the material.

Cathode emission is dominated by the Richardson Dushmann equation.

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

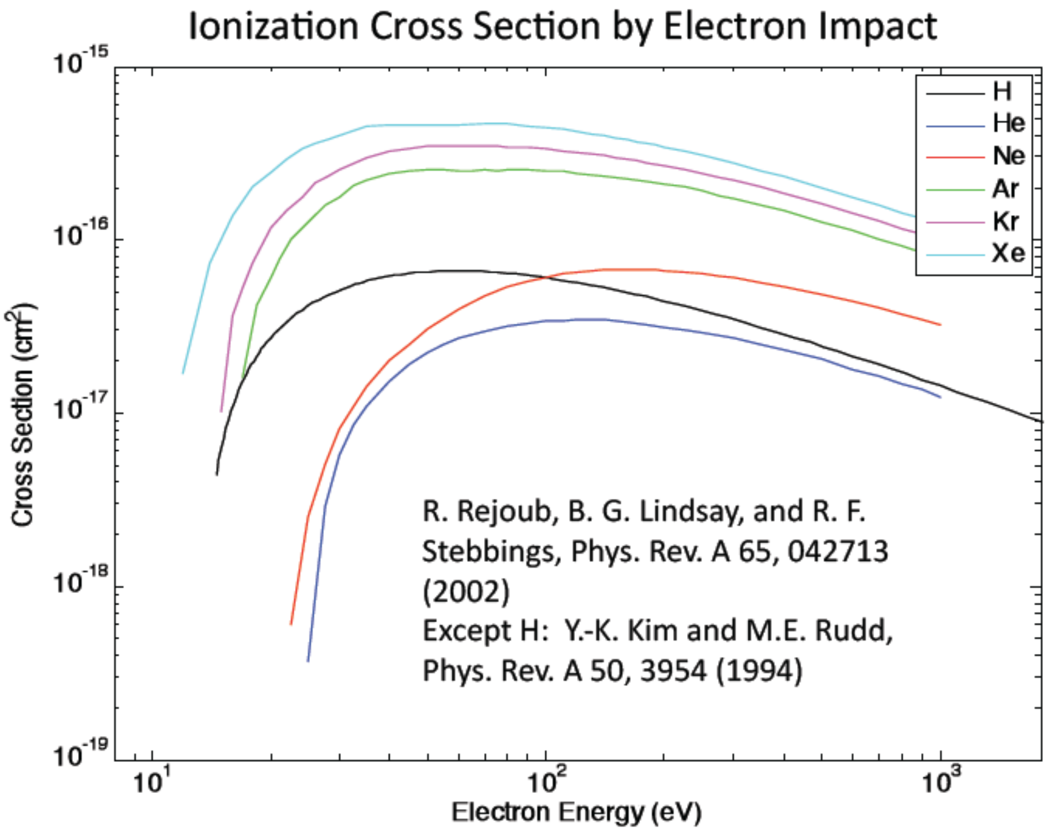
$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2 \times 10^6 \,\mathrm{Am}^{-2} K^{-2}$$

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



Electron Bombardment Ion Source

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

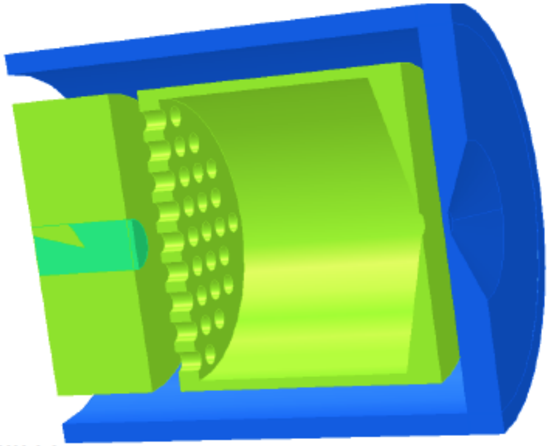

Ionization Cross Section by Electron Impact

R. Rejoub, B. G. Lindsay, and R. F. Stebbings, Phys. Rev. A 65, 042713 (2002)
Except H: Y.-K. Kim and M.E. Rudd, Phys. Rev. A 50, 3954 (1994)

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

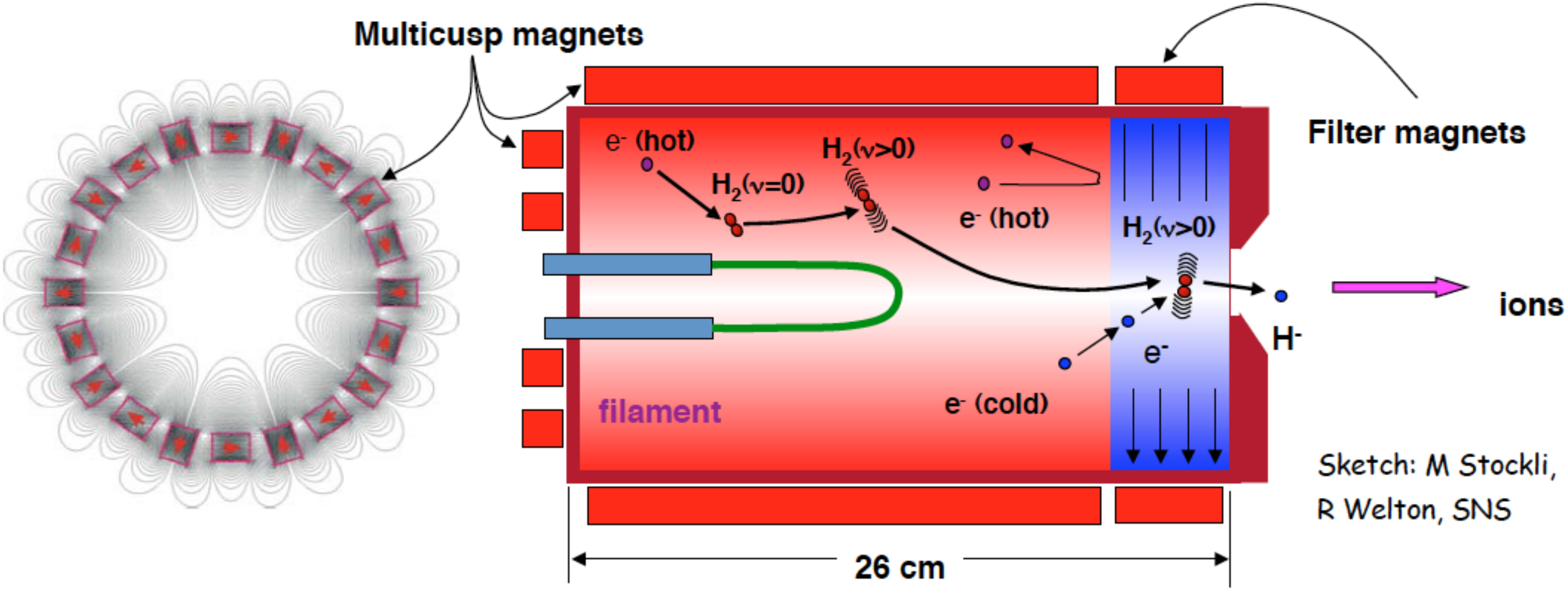
Electron Bombardment Ion Source

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



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

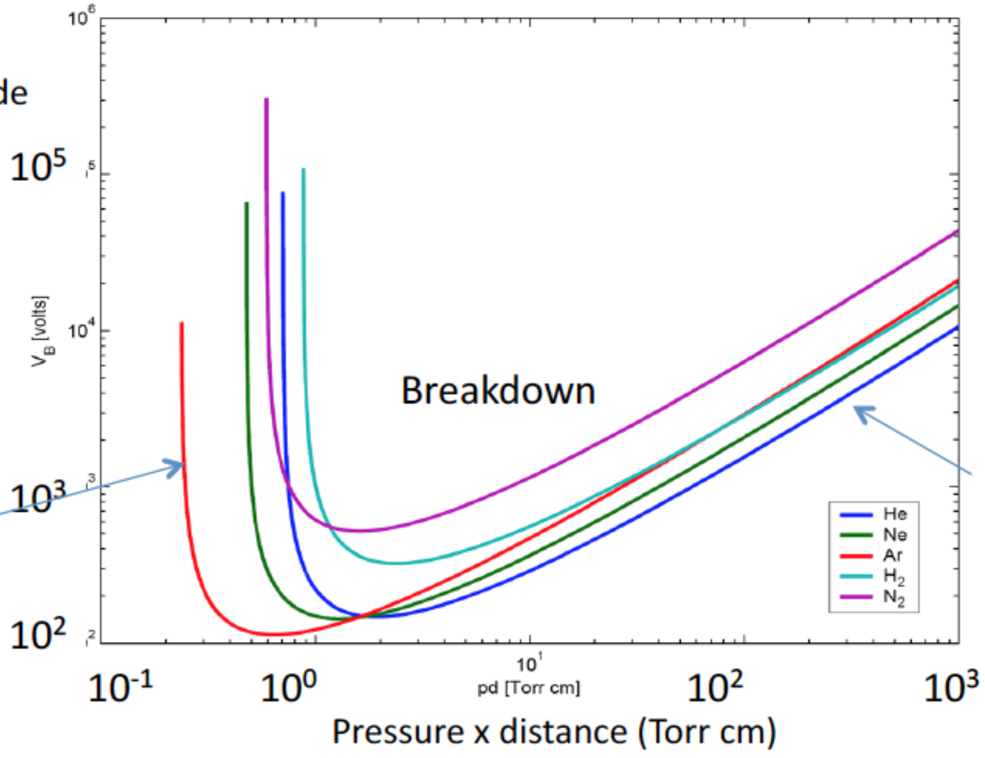
Plasma Discharge Sources



Sketch: M Stockli, R Welton, SNS

Plasma Discharge Sources

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



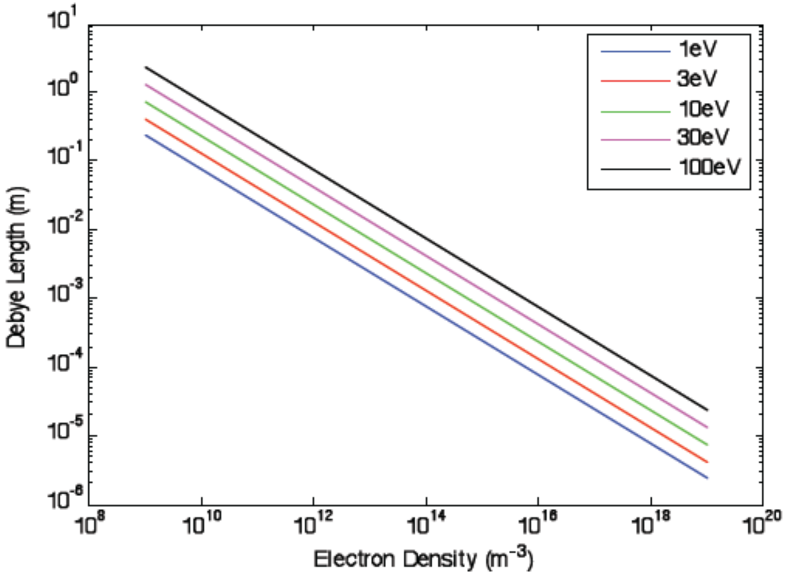
V cathode-anode

Too little gas density
Probability of electrc
+atom ionization too
low

Mean free path for
electrons too short to
gain enough energy to
cause ionization

Plasma Discharge Sources

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



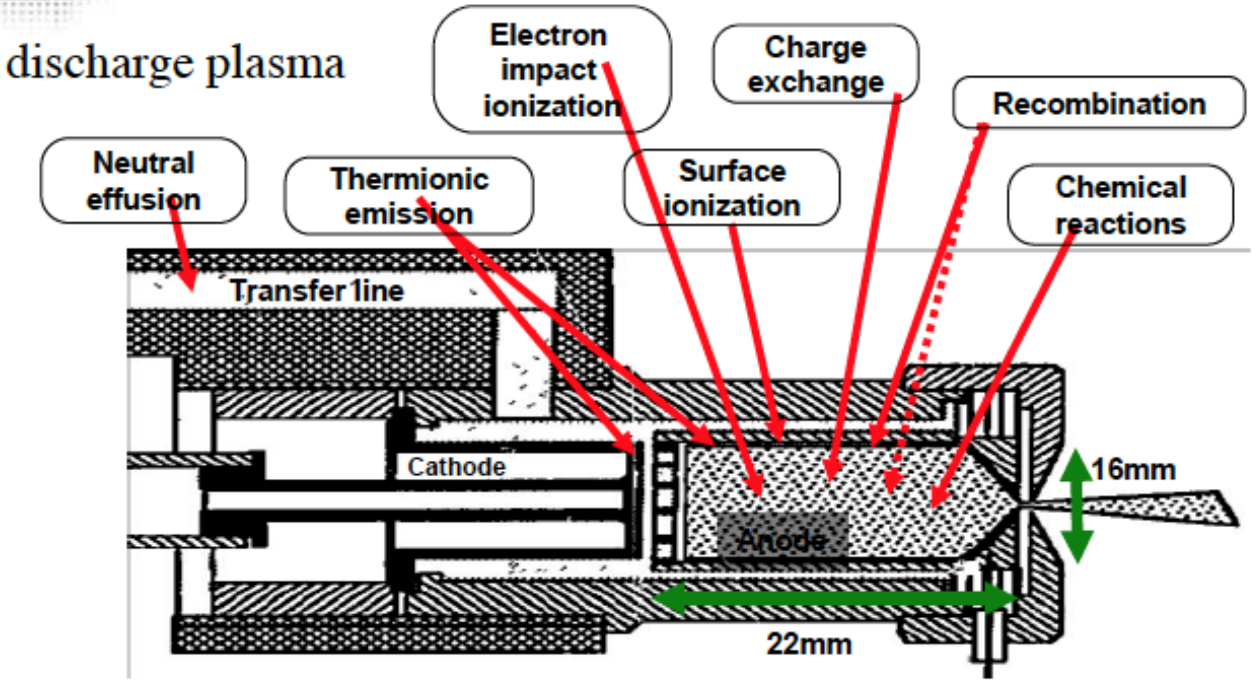
Electric fields can permeate a plasma up to the size of the Debye length.

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

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

Modeling of “relevant phenomena”

Modeling of the arc discharge plasma

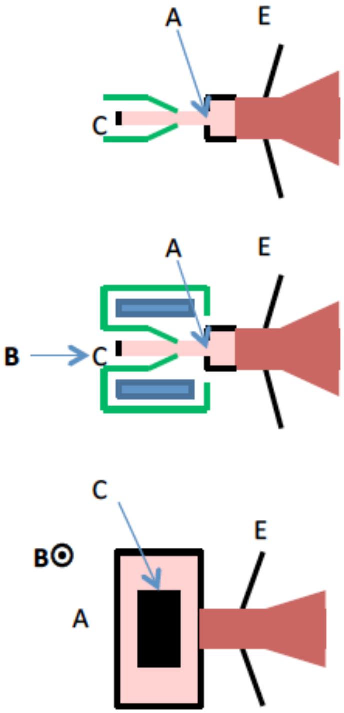


- ➢ Full cocktail of possible phenomena.
- ➢ Not all appearing all over the variation range of the operation parameters.
- ➢ Some of them can be neglected at the nominal parameters.
- ➢ Application range has been investigated (experiment vs. theory).
- ➢ Performance limitations could be pointed out, justified and removed

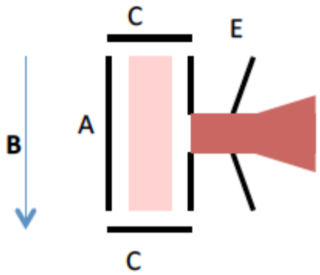
Plasma Discharge Sources
A rich sub-species…

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

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

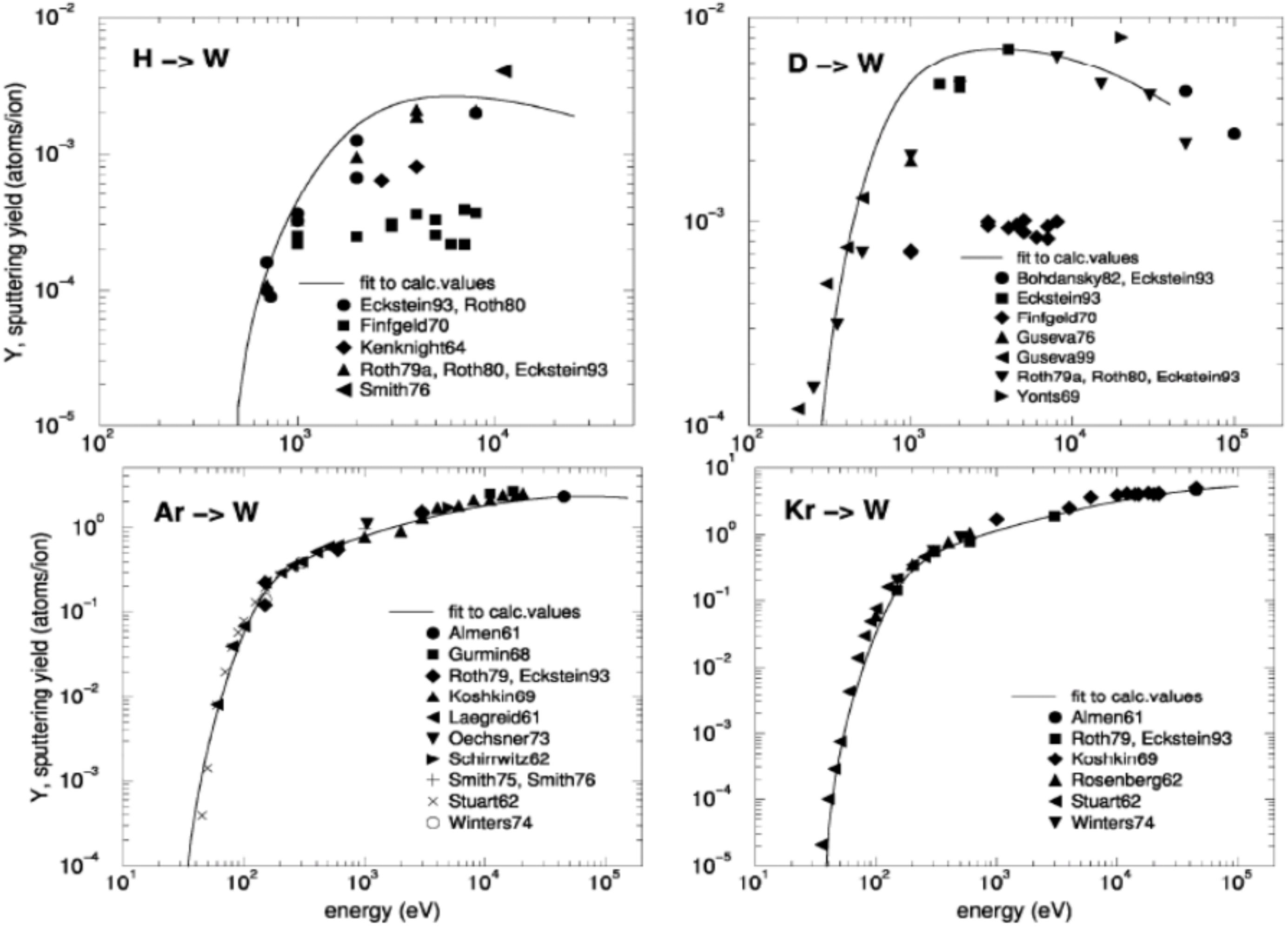


C: Cathode
A: Anode
E: Extraction Electrode
B: Magnetic field
□ : Plasma
■ : Beam
— : Magnetic steel



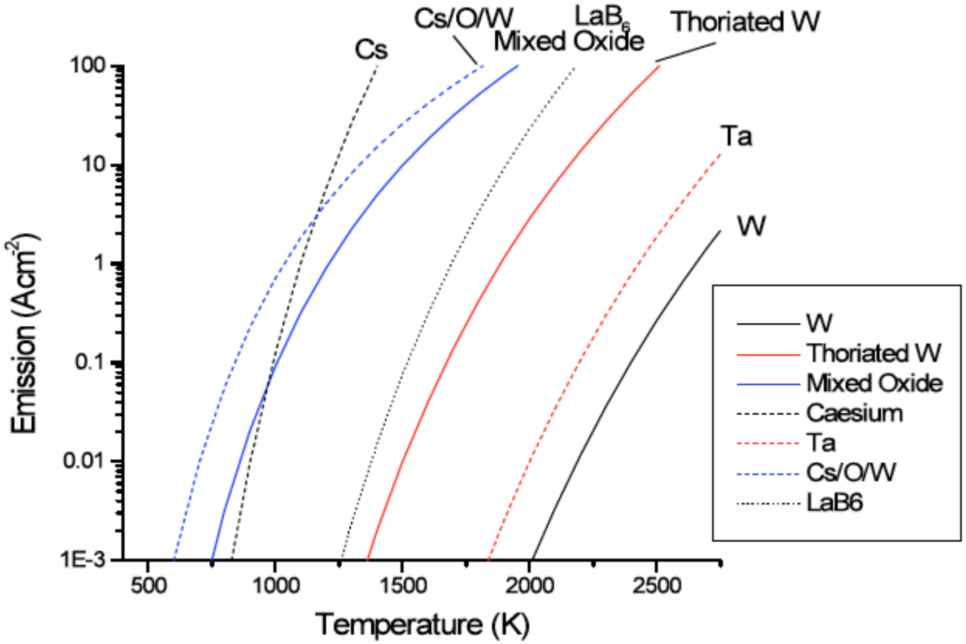
Cathodes – problem 1 – Ion Sputtering

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



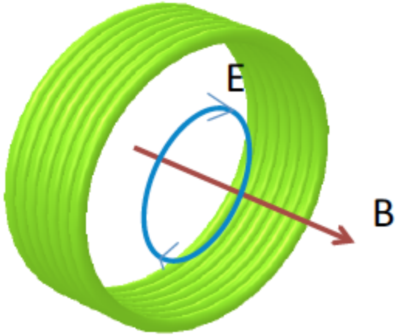
Cathodes – problem 2 – Surface changes

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



RF Discharge

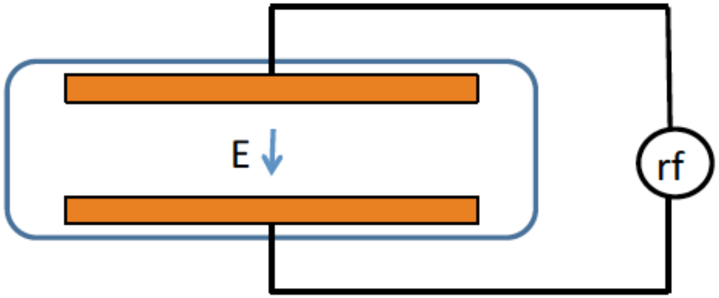
- Instead of using a cathode -> anode potential to create an electric field, the electric field from an RF system can be used.
- Electrons are accelerated by the electric field. Usually there is no wave-plasma resonance…
- Two possibilities
  - Solenoid antenna – a circular electric field is generated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



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

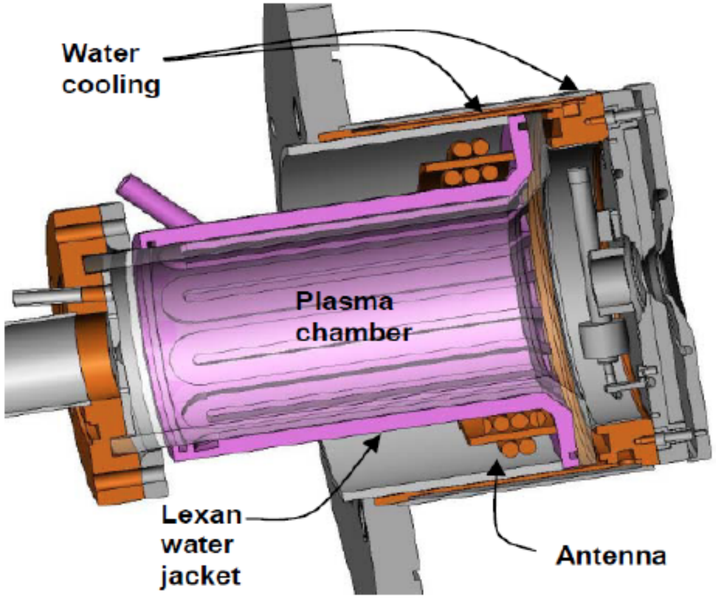
r: solenoid radius
N: solenoid turns
L: solenoid length
I: Peak current

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



RF Discharge

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



SNS External antenna source

ECR ion sources

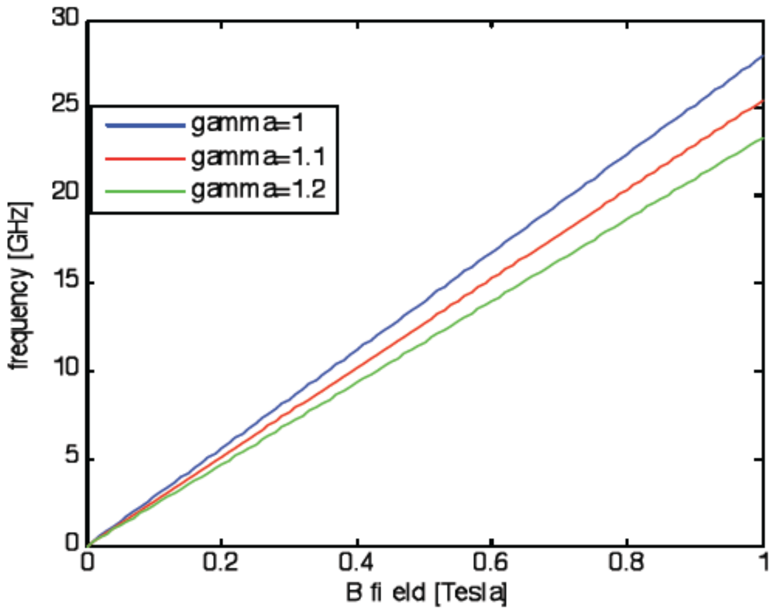
In an Electron Cyclotron Resonance Ion Source (ECR or ECRIS):

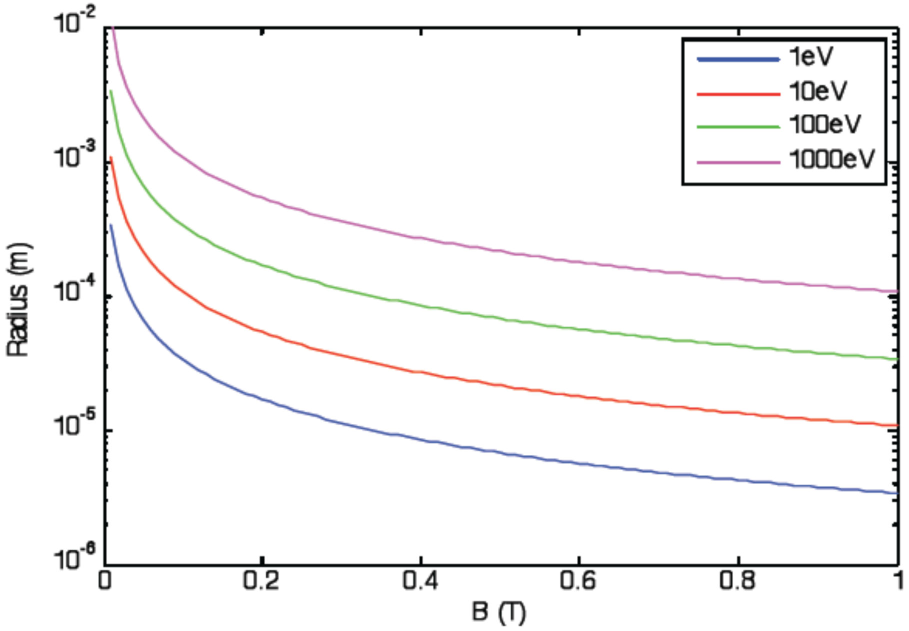
- There is a magnetic field, and the injection of RF or microwaves.
- Wave frequency satisfies the ECR resonance somewhere in the source (f=28 GHz / Tesla)
- The electrons absorb energy from the Right Hand Circular Polarised wave (EM waves can always be decomposed into RHCP and LHCP)
- The electron cycltron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

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

ECR ion sources

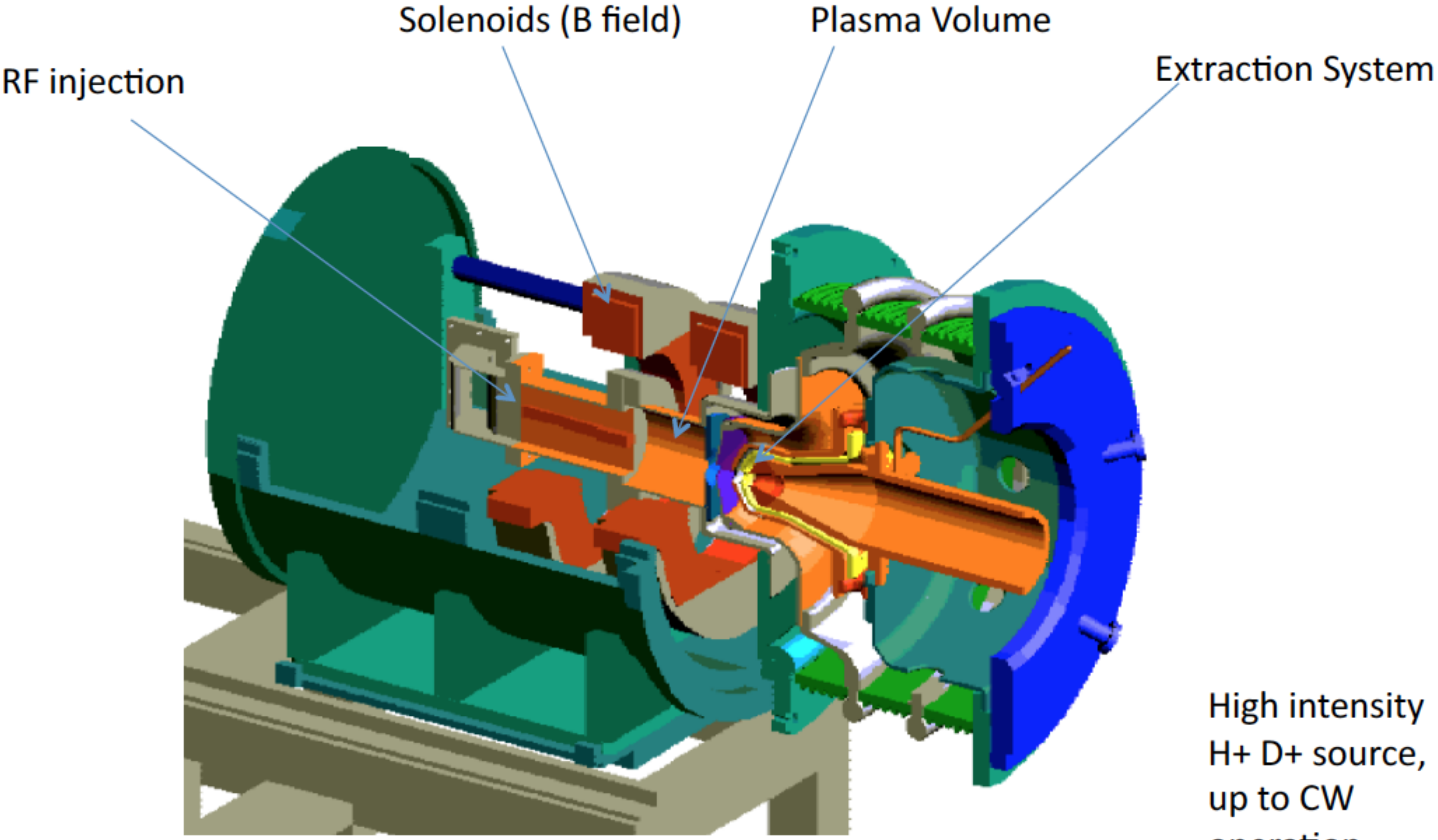
$$f_L = \frac{eB}{2\pi\gamma m_e} \qquad \frac{f_L}{B} = 28\text{GHz/Tesla} \qquad \rho_L = \frac{\beta\gamma m_e c}{eB}$$





Note: Only energy perpendicular to B field

ECR ion sources

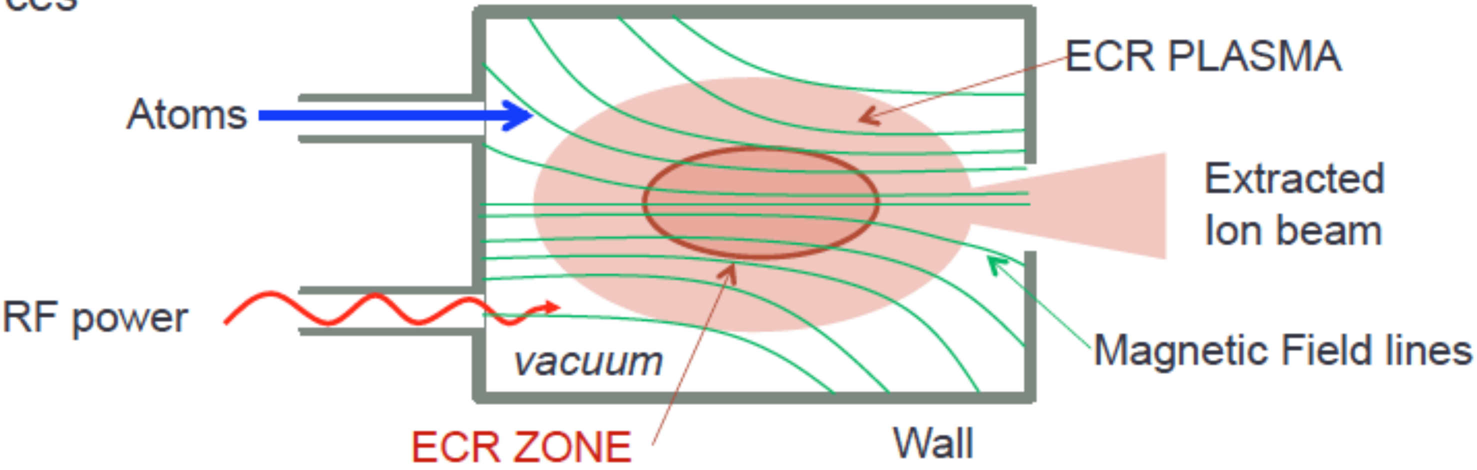


CEA – SILHI 2.45GHz ECR source for H+, D+

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

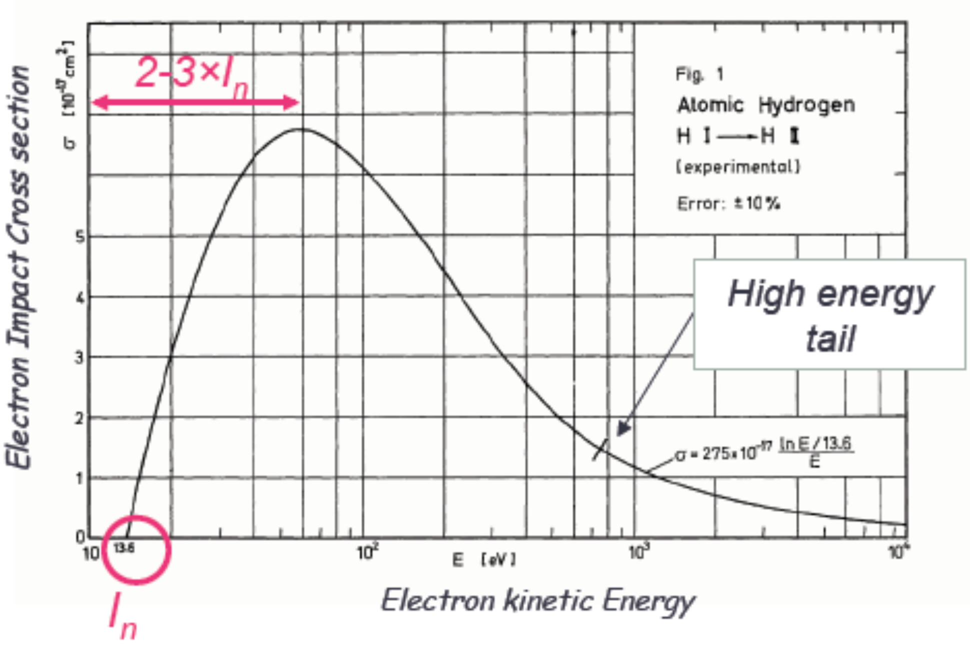
Ingredients of Electron Cyclotron Resonance Ion Source

- An ECR ion source requires:
  - A secondary vacuum level to allow multicharged ion production
  - A RF injection in a metallic cavity (usually multimode)
  - A sophisticated magnetic Field structure that enables to:
    - Transfer RF power to electrons through the ECR mechanism
    - Confine long enough the (hot) electrons to ionize atoms
    - Confine long enough ions to allow multi-ionization ions
    - Generate a stable CW plasma
  - An atom injection system (gas or condensables) to sustain the plasma density
  - An extraction system to accelerate ions from the plasma
- In the following, we will try to detail these points to provide an overview of ECR ion sources



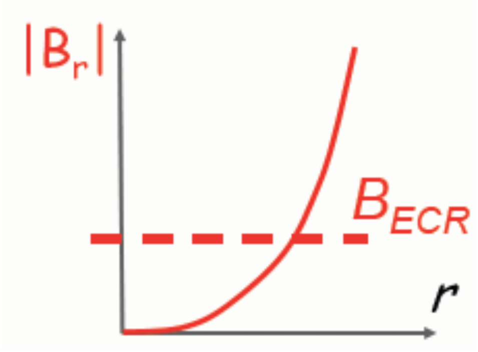
Ion creation through Electron Impact Ionization (in gas or plasma)

- Ions are produced through a direct collision between an atom and a free energetic electron
  - $e^- + A^{n+} \rightarrow A^{(n+1)+} + e^- + e^-$
  - 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 $E_e \sim 2 - 3 \times I_n$
  - Higher energy electron can contribute significantly
  - Double charge electron impact ionization may also occur…

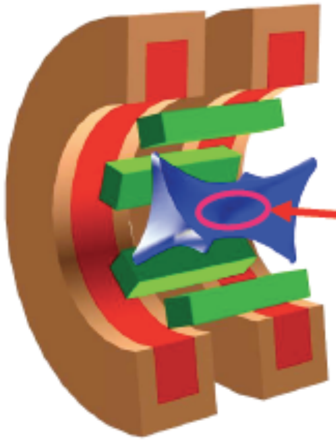


ECR Magnetic confinement: Minimum |B| structure

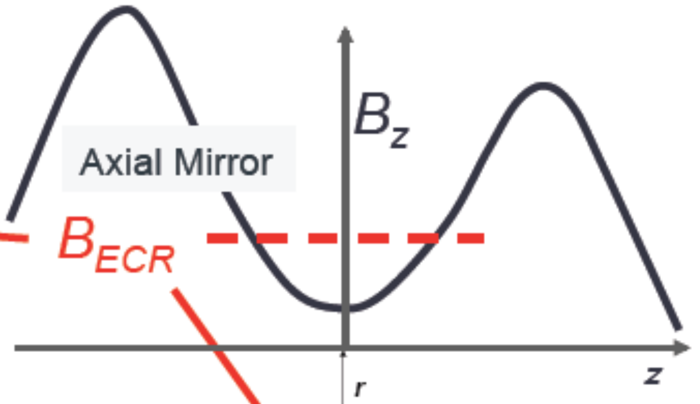
- ECR ion sources features a sophisticated magnetic field structure to optimize charged particle trapping
  - Superimposition of axial coils and hexapole coils
  - The ECR surface ($|B|=B_{ECR}$) is closed

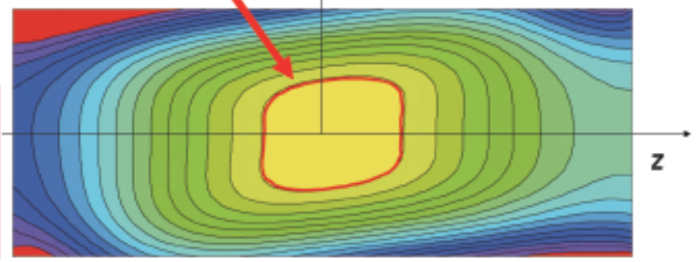


Hexapolar Field



Source LBNL

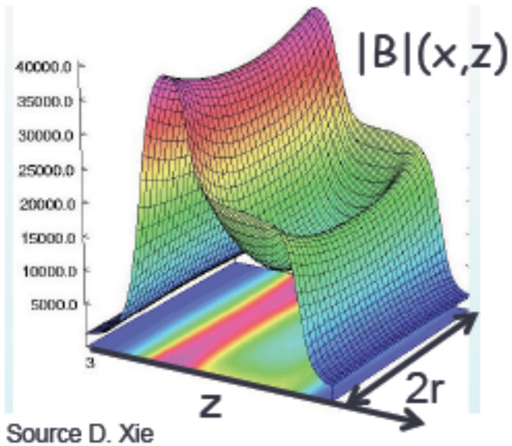




Iso B lines

Source RIKEN, Nakagawa

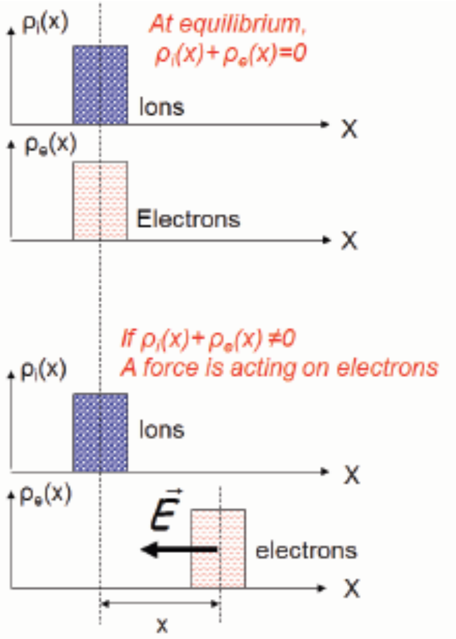
$$\boxed{\omega = \omega_{ce} = \frac{qB_{ECR}}{m}}$$



Source D. Xie

Plasma Oscillations – ECR cut off density

- The plasma Frequency ω_p is the natural oscillation frequency of a plasma, as a response to a perturbation
  - Oscillations driven by electrons
  - $\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$
- The simplest dispersion relation of an EM wave in a plasma is:
  - $\omega^2 = {\omega_p}^2 + k^2 c^2$
  - EM wave propagates if $\omega > \omega_p$
- ECR Cut-off density:
  - $\omega > \omega_p \Rightarrow n_e < \frac{m_e \varepsilon_0 \omega^2}{e^2}$
  - At a given ECR frequency, the plasma density is limited
    - $n_e \propto \omega^2{}_{ECR}$

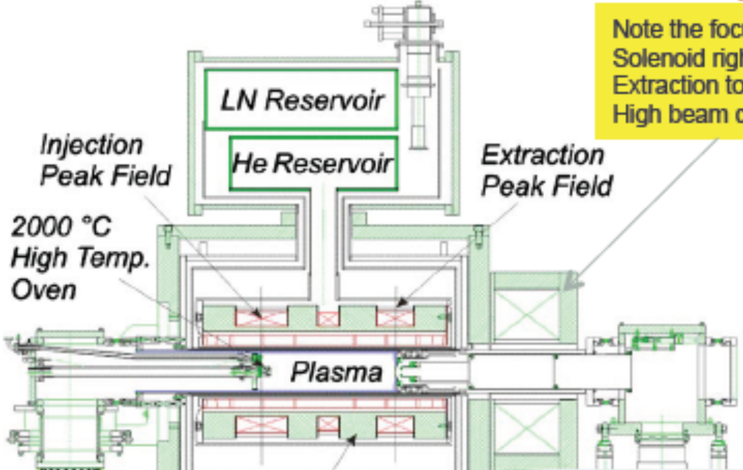


=> Oscillations at the plasma frequency

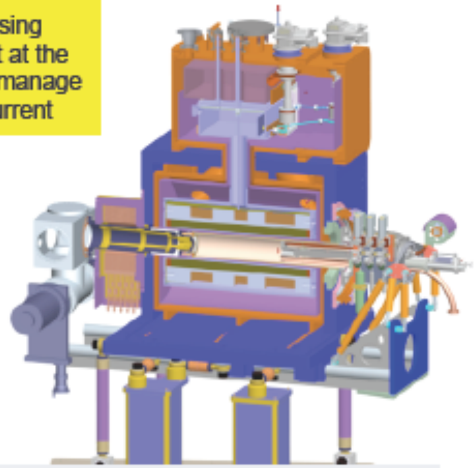
Above cut off:
RF is reflected
=> no more ECR heating!

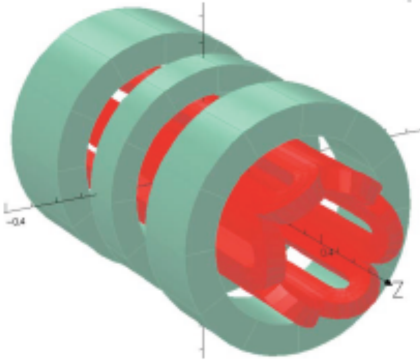
the first 28 GHz ECRIS VENUS, LBNL (2002)

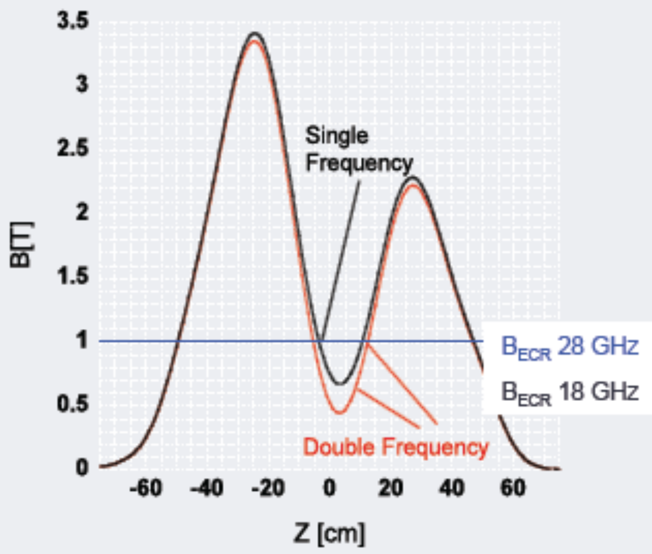
- f=18+28 GHz - (2+6) kW
- B_{ECR}=1 T
- Fully superconducting ECRIS
  - NbTi:Cu wire technology
  - 4K LHe + thermal 40 K shield
  - 4x1.4 W cryocooling
- Axial profile 3.5-0.35-2.2 T
- Radial hexapole at wall Br=2.2 T
- Dedicated to very high intensity, very high charge state applied to cyclotron acceleration
- 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

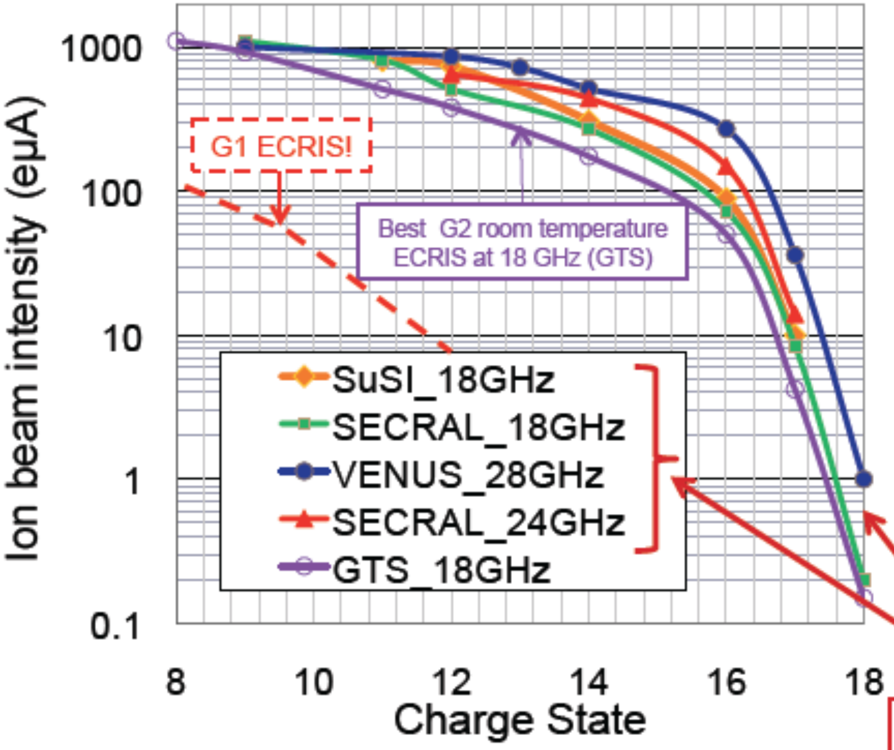






Example of Today High Charge state production

- Today ECRIS Argon beam performance

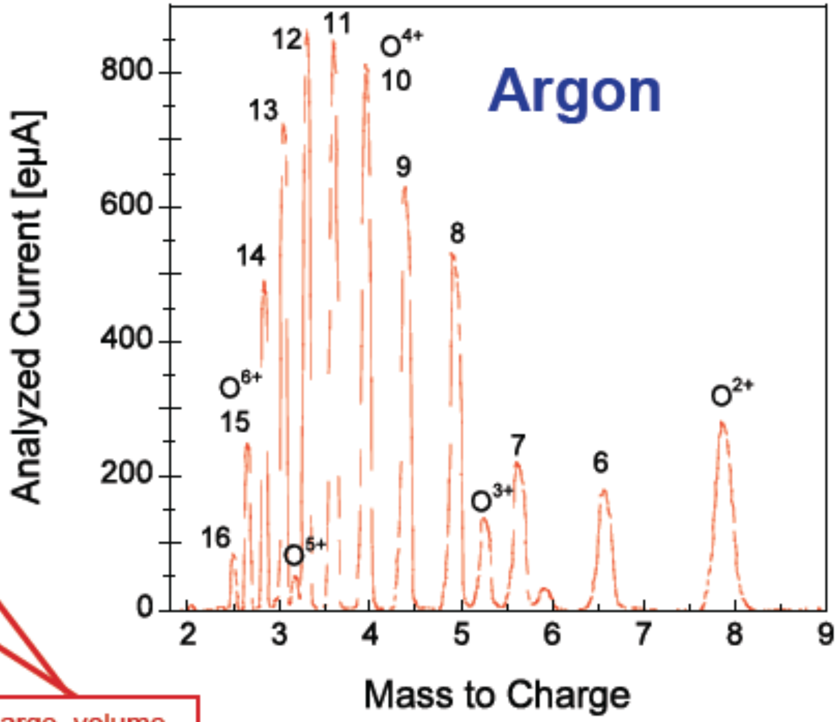


G1 ECRIS!

Best G2 room temperature ECRIS at 18 GHz (GTS)

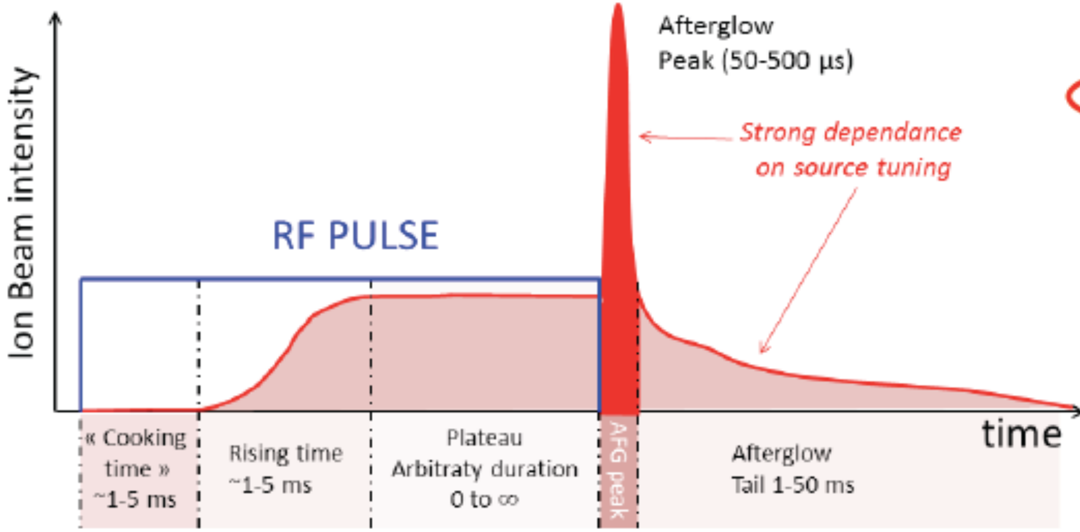
Source: G.Machicoane, MSU/NSCL,ICIS'11, modified

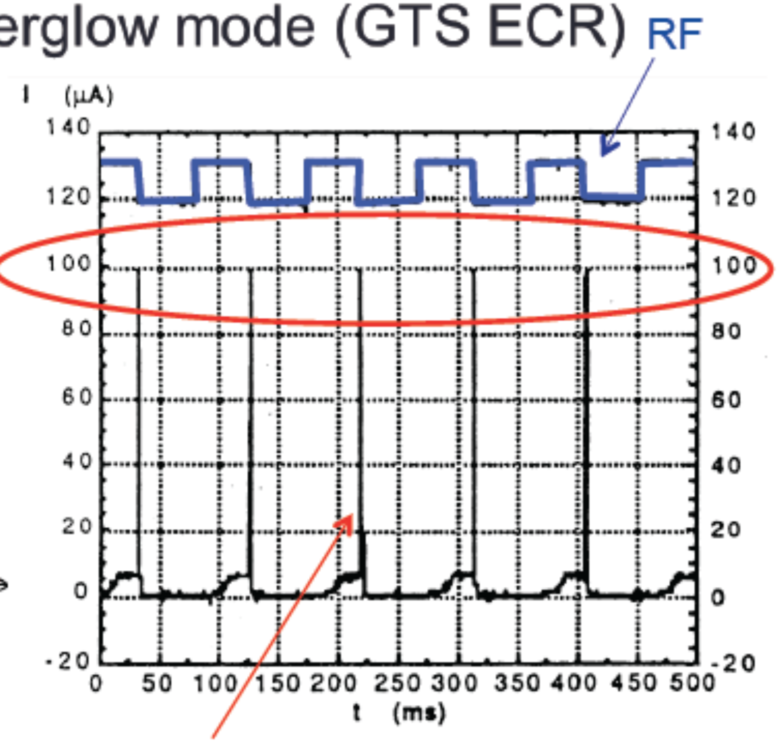
Large volume superconducting ECRIS G3



Pulse Mode operation for Synchrotrons: The Afterglow

- 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)

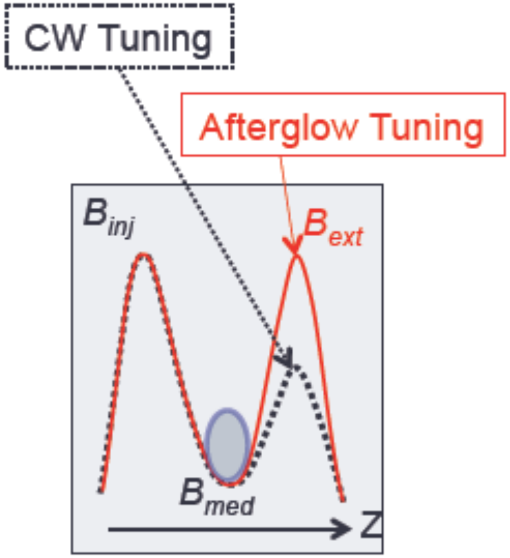




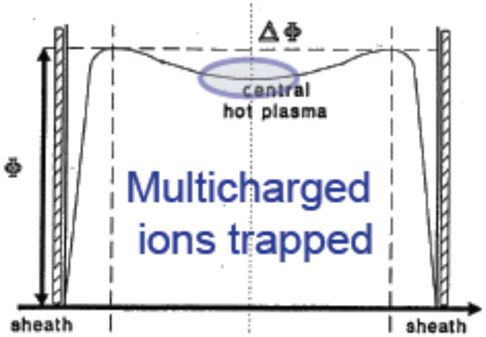
Pb^{28+} pulses (ECR4 GANIL)

The Afterglow mechanism

- The ECR is tuned to provide High plasma confinement
  - Bext~Binj ⇒ very small loss cone
  - ⇔ Very low extracted current in CW mode
- The hot confined electrons population, maintained by the RF, build a large potential dip ΔΦ around the axis
  - Pastukov, 1974
  - ⇒ Accumulation of ions trapped at the center of the source
- At RF stop: the electron heating stops brutally:
  - ⇒ Fast destruction of the potential dip $\Delta\Phi \rightarrow 0$
  - ⇒ Deconfinement of multicharged ions
  - ⇒ High intensity peak of multicharged ions

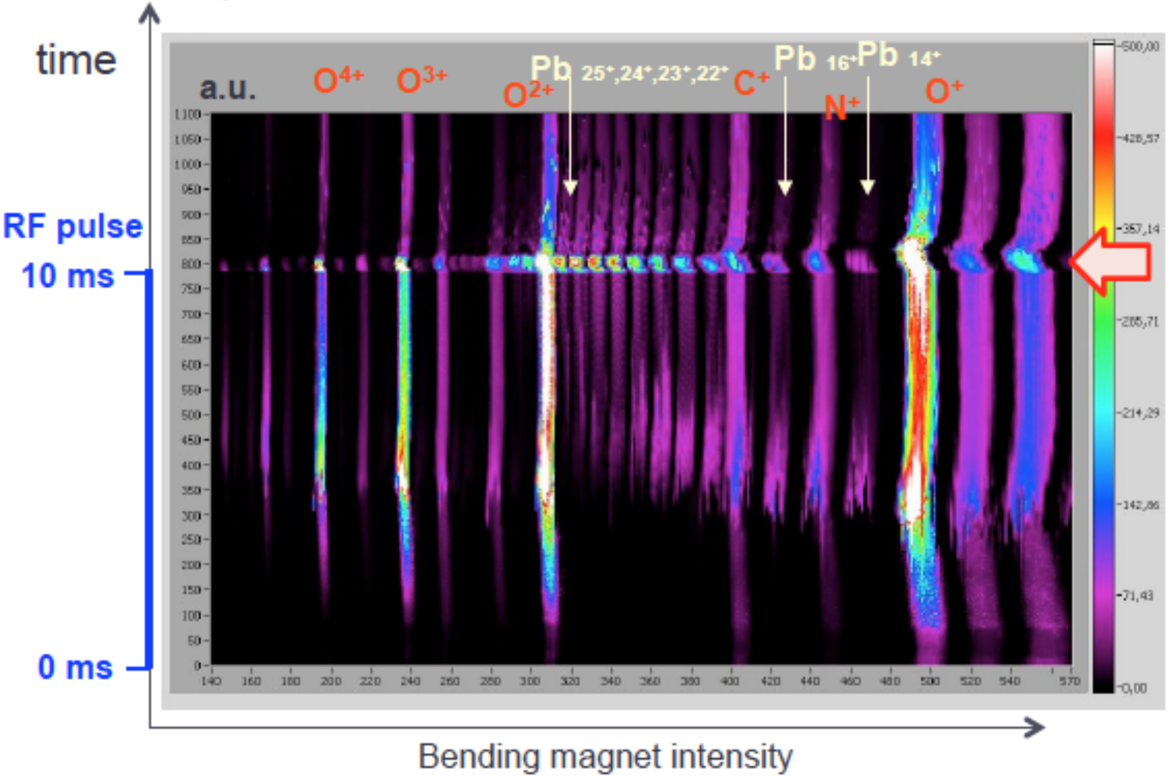


Axial Magnetic Mirror



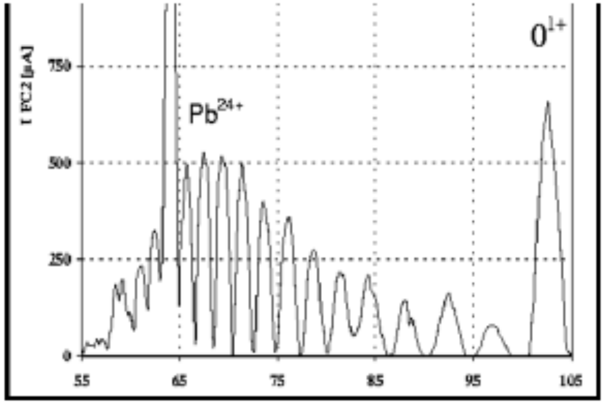
Lead Afterglow Spectrum

- 650 µA Pb25+ - 28 GHz- PHOENIX V1 SOURCE (LPSC) - 10 ms/10 Hz



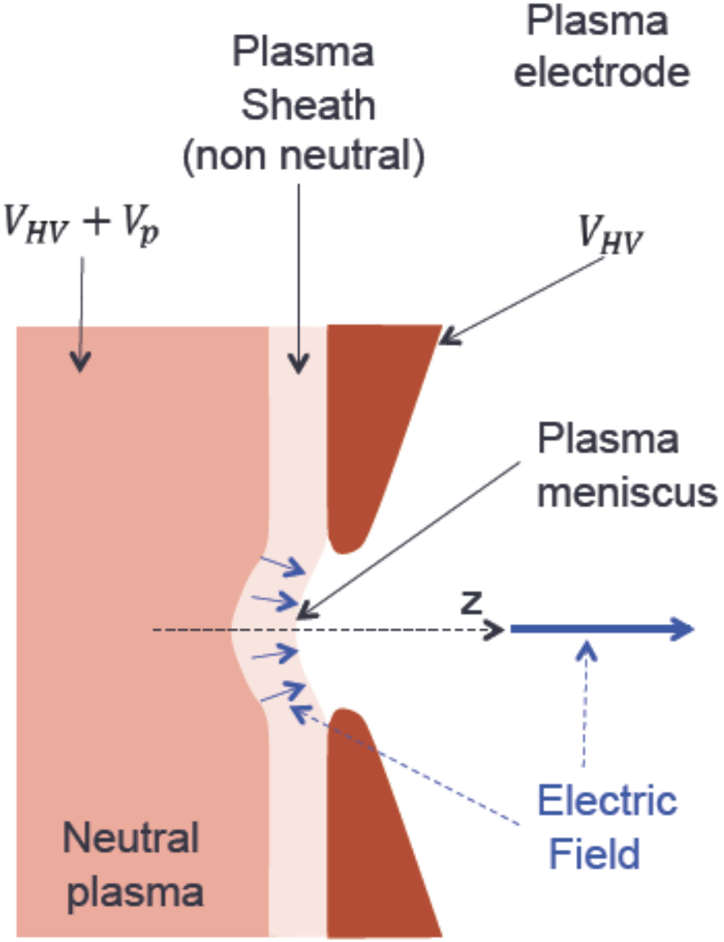
AFTERGLOW

Very stable tuning at 500 µA



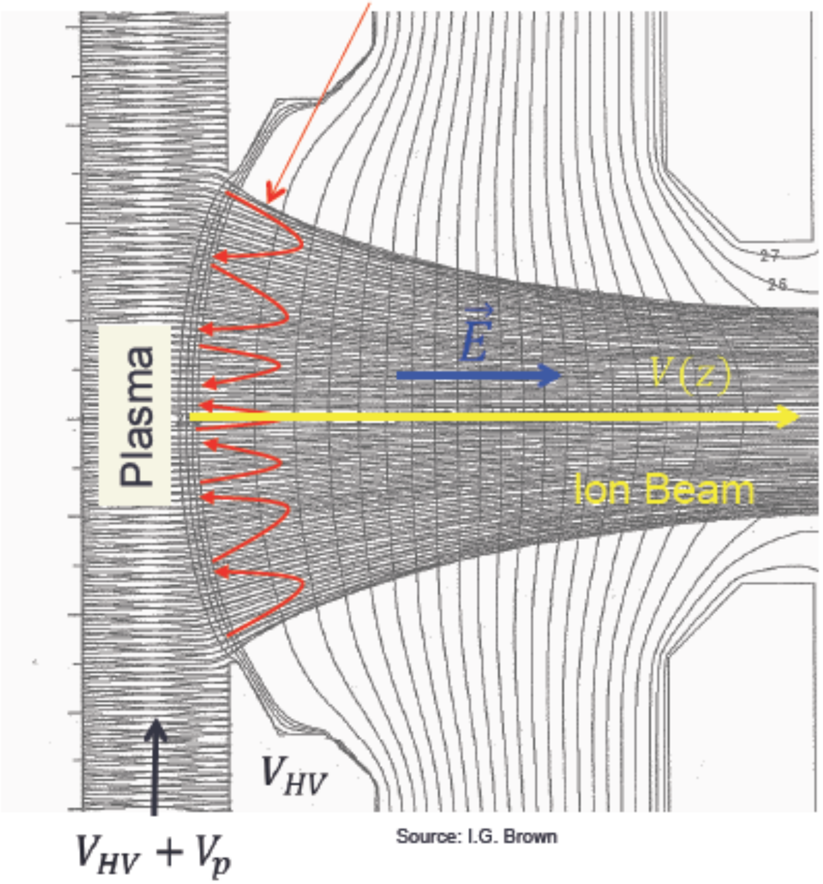
Ion Extraction from the plasma

- The plasma potential is $V_p > 0$ (usually ~5-50 eV)
- The plasma meniscus is the natural curvature of the plasma in front of the circular electrode hole
- The plasma meniscus shape is not predictible. A concave meniscus is optimum for ion extraction.
- The ions are extracted from the plasma sheath (non neutral area, see appendix).
- The ions incident velocity in the early sheath can be modelized by the Bohm criterion:
  - $v_{\text{i}} = \sqrt{kT_e/m_i}$
- Ions extracted have escaped the magnetic mirror, so their initial velocity angle θ with respect to $\vec{B}$ are distributed in the loss cone ruled by the Axial Mirror ratio $R = \sqrt{B_{max}/B_{min}}$:
  - $v_{\|} = v \cos\theta$
  - $\sin\theta \leq \frac{1}{\sqrt{R}}$



Hot Electrons contribution to the emittance

- The hot electrons of ECRIS play an important role in the early beam formation, when the ions have very low energy
- Hot electrons (k$T_e \sim 1 - 5\ keV$) penetrate into the extraction gap and neutralize partially the space charge induced by the ions, until a point where they are reflected back to the source
- The electron density in the ECR plasma sheath is usually approximated by the Boltzmann distribution function, assuming a gaussian electron distribution function:
- $n_e = n_{e0} e^{\frac{e(V(z)-V_{HV}-V_p)}{kT_e}}$
  - n_{e0} is the electron density in the neutral plasma
  - $V(z)$ is the local potential at position z in the extraction area
  - Vp is the plasma potential, V_{HV} the High Voltage



Hot electrons repelled by the Electric field

Source: I.G. Brown

Laser ion sources

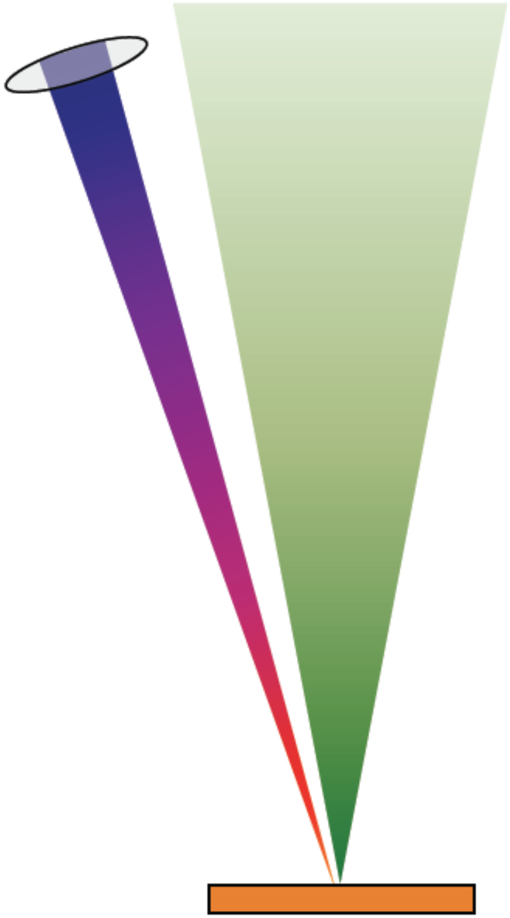
The interaction of light with matter can give rise to two types of ion sources:

Laser *Ionization* Ion Sources

Laser *Plasma* Ion Sources

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

Laser *Plasma* ion sources



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

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

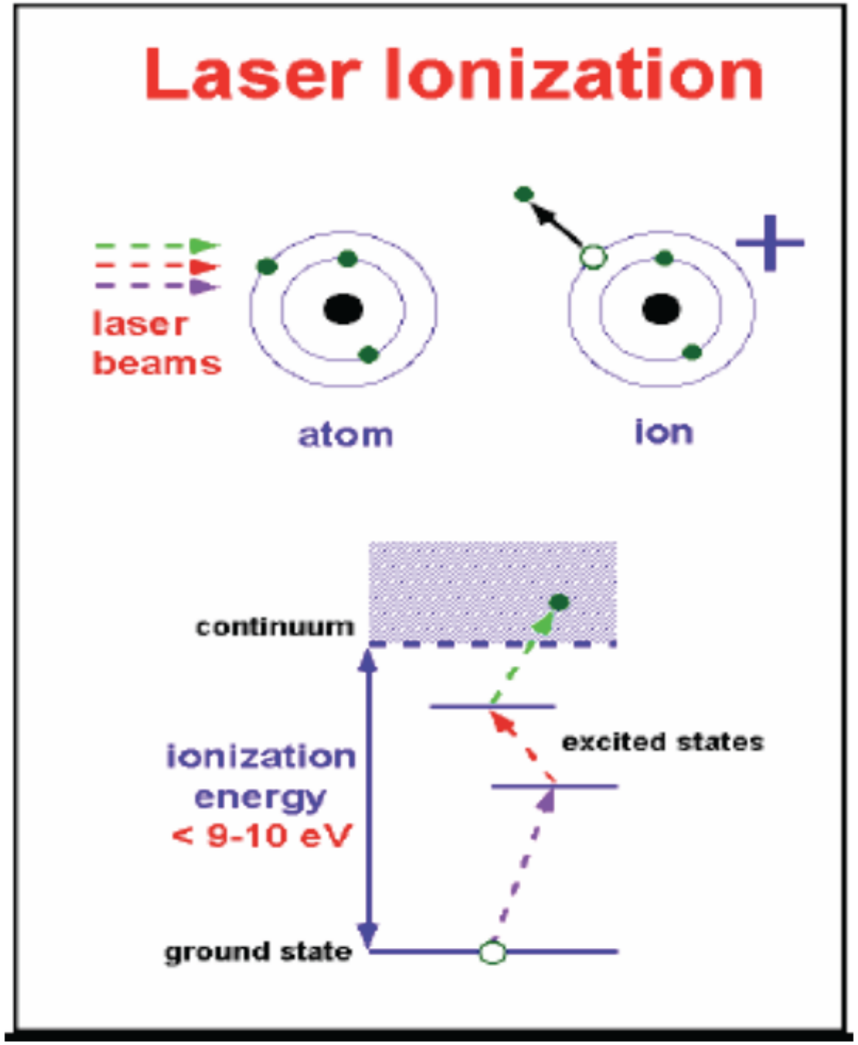
- $n_e = 10^{21}$ cm^{-3} corresponds to 1µm.
- Laser power density needs to be above 10^6 W/cm^2, which is easily available with pulsed lasers.

Laser *Ionization* ion sources

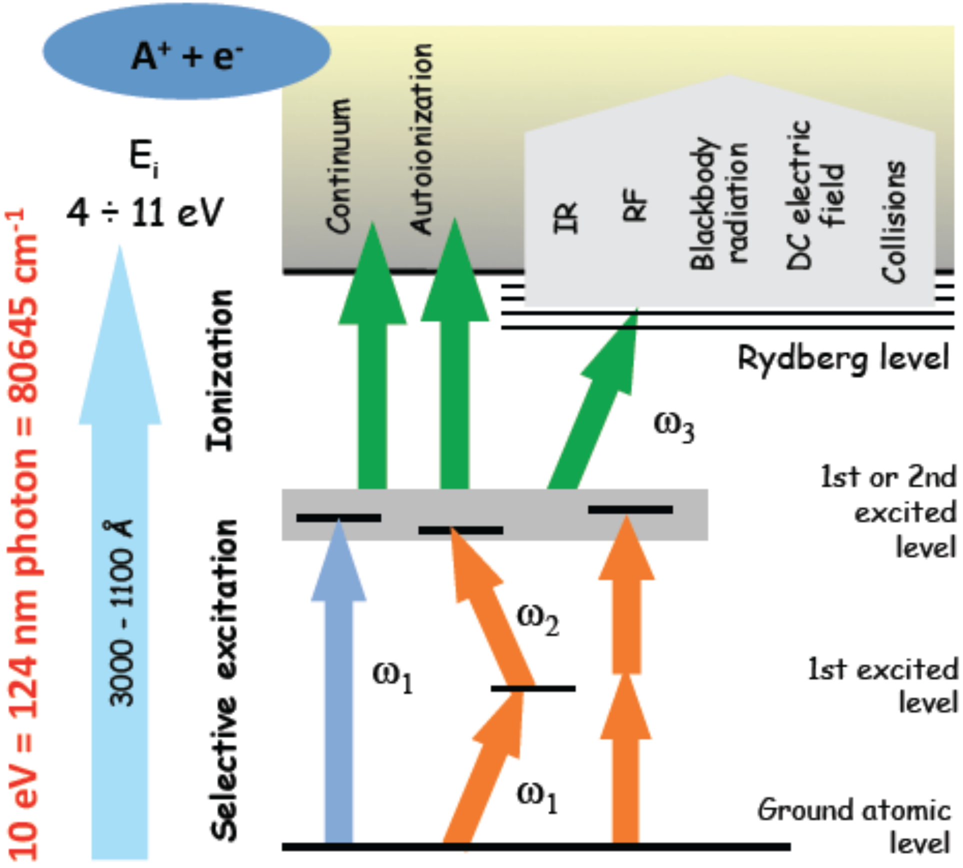
- It is not easy to ionize atoms directly with a laser.

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

- For the lowest ionization potential (Francium, 3.83eV) this is already UV light.
- Usually necessary to use at least two steps (or more), first to an excited state (requiring a tunable laser) and then to ionize.
- This allows the excitation to be chemically selective.
- Typically the source works continuously with low ion currents (needing a CW laser).



Laser ion source – using this fingerprint for selective ionization

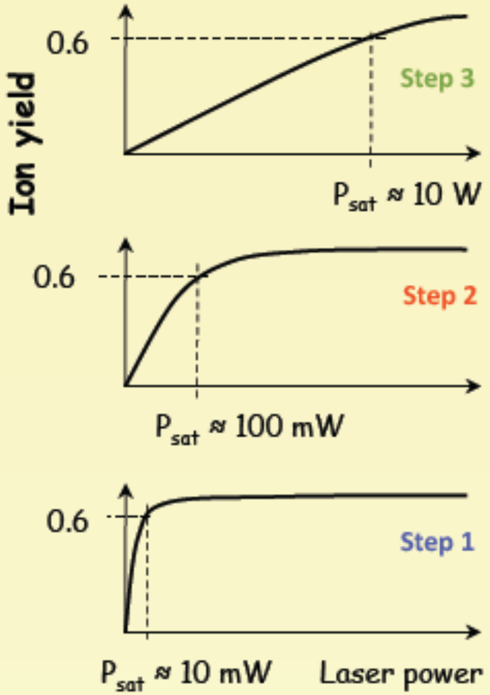


$$\omega_i(\text{laser}) = \omega_i(\text{atom}); \quad P_i(\text{laser}) \geq P_i(\text{saturation})$$

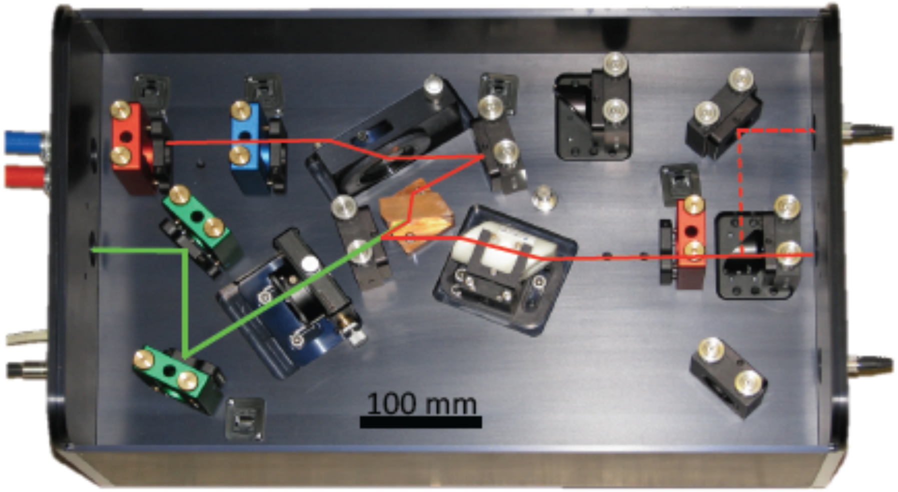
$P_{sat.} = \boxed{\bar{\Lambda}}_{sat.} \times f_{laser} \times S_{laser\ beam}$

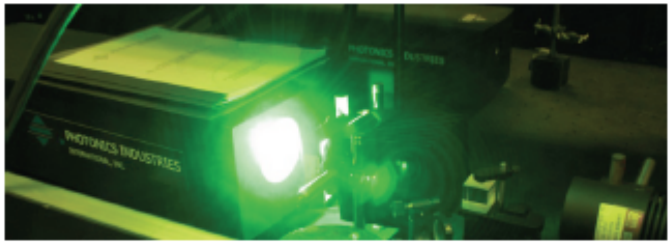
$\boxed{\bar{\Lambda}}_{sat.} = \hbar\omega_i/2\sigma_i$

$f_{laser} = 10$ kHz $\text{Ø}_{laser} = 3$ mm



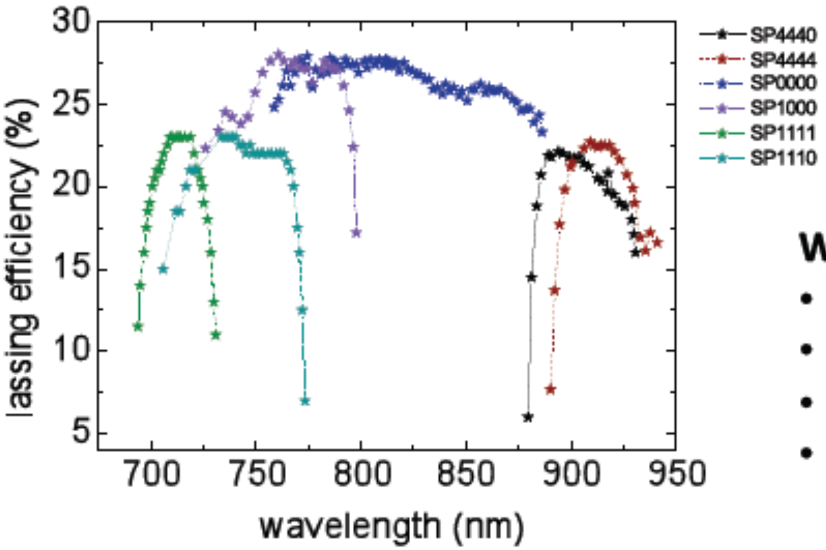
The RILIS Ti:Sa lasers





Pump laser: Nd:YAG (532 nm),
Photonics
Repetition rate: 10 kHz
Pulse length: 180 ns
Power: 60 W

Ti:Sa lasers:
Line width: 5 GHz
Pulse length: 30-50 ns



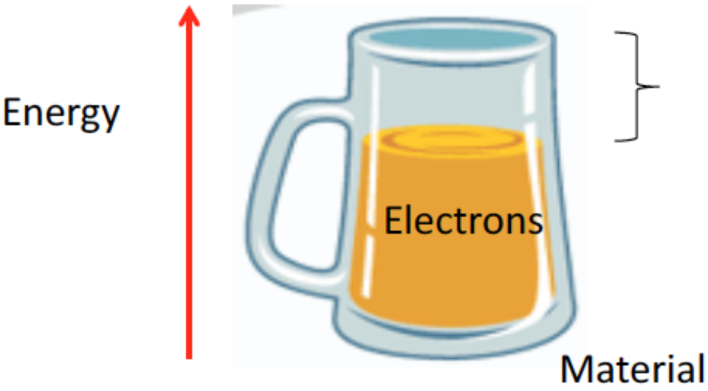
Wavelength tuning range (6 mirror sets):
- Fundamental (ω) **690** - **940** nm (5 W)
- 2nd harmonic (2ω) **345** - **470** nm (1 W)
- 3rd harmonic (3ω) **230** - **310** nm (150 mW)
- 4th harmonic (4ω) **205** - **235** nm (50 mW)

"A complementary laser system for ISOLDE RILIS"

S Rothe et al: Journal of Physics: Conference Series 312 (2011) 052020

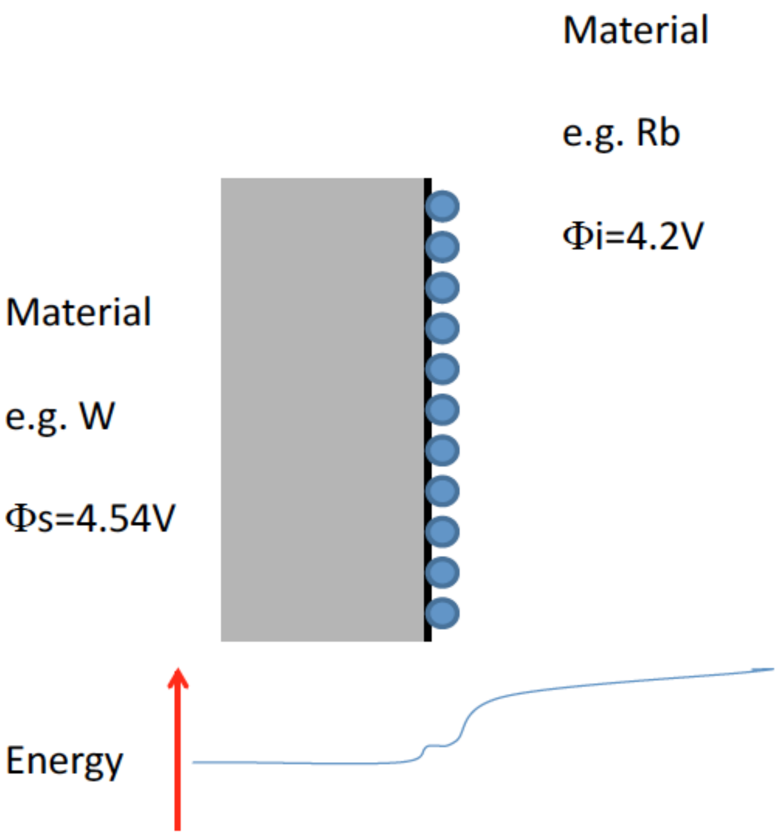
Surface Ion Sources

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



Energy difference between
highest energy electron and vacuum
Work Function

Surface Ion Sources



Material

e.g. Rb

Φi=4.2V

Material

e.g. W

Φs=4.54V

Energy

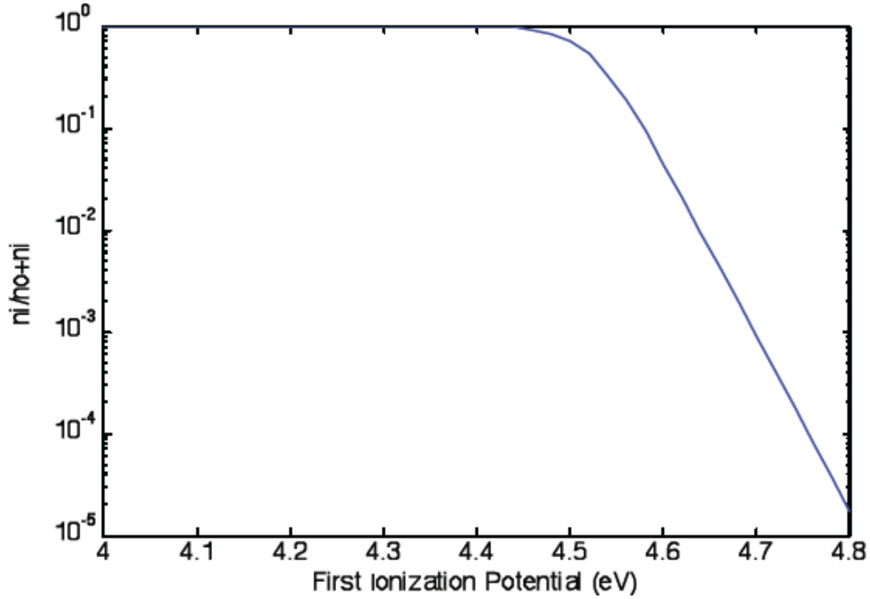
- Similarly the electron is trapped on the atom.
- But if a low ionization potential atom is in contact with a high work-function material, the electrons energetic preference is to be in the material.
- The material needs to be hot enough to evaporate the ions.
- The Saha-Langmuir equation predicts the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

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

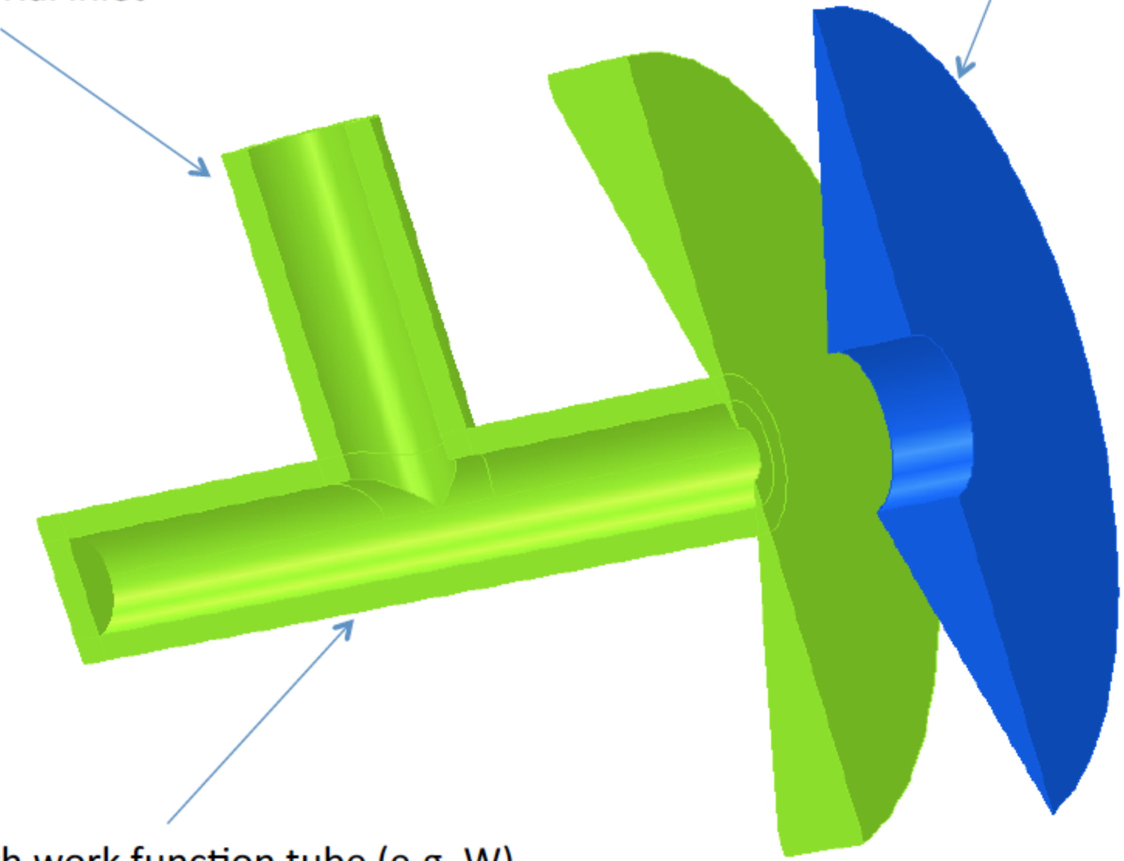
Surface Ion Sources

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

Example ion fraction for Φs=4.54eV
At room temperature



Surface Ion Sources



Extractor / puller electrode

Gas / material inlet

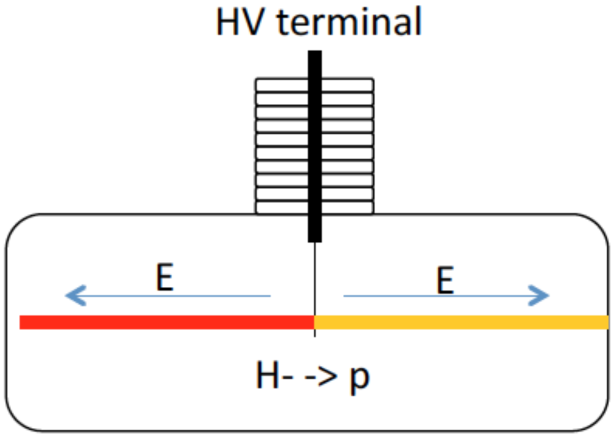
Heated high work function tube (e.g. W)

Negative ions – Why?

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

Tandem

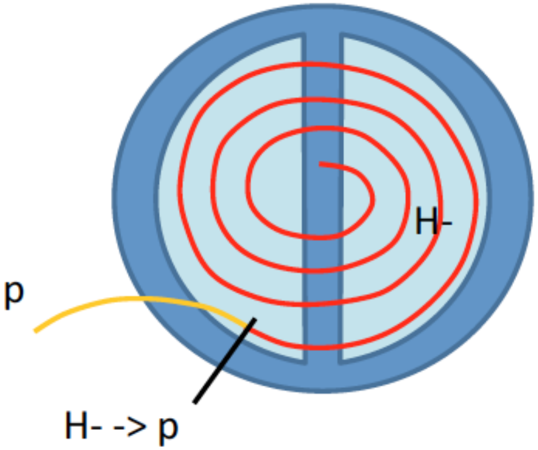
- Negative accelerated to foil, positive ion back to ground.



Negative ions – Why?

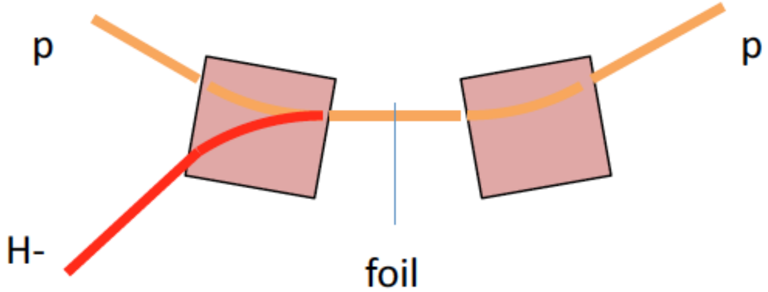
Extraction (from cyclotrons)

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



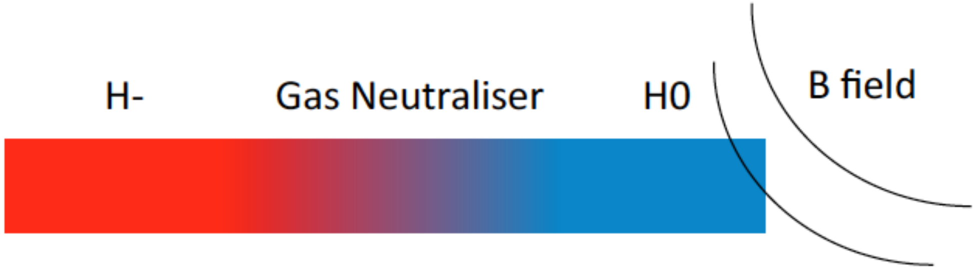
Charge exchange injection (to synchrotron).

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



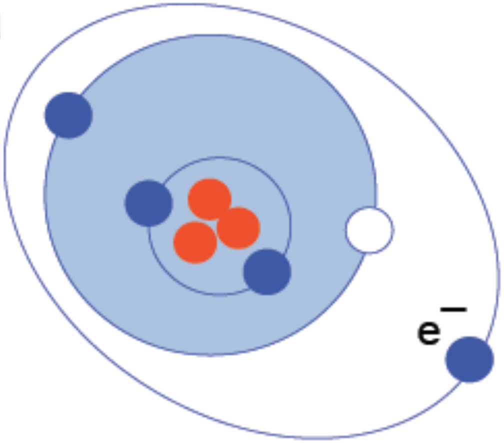
High Energy Neutral Beams (Magnetic Confinement Fusion)

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



Negative Ions – There is one too many!

- Especially atoms with an open shell attract an extra electron and can form a stable ion with a net charge of –e.

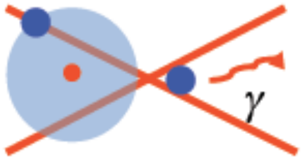


- The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.
- The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for Ti$^-$ and 3.6 eV for Cl$^-$, e.g. 0.75 eV for H$^-$.
- For electron energies above 10 eV, the H$^-$ ionization cross section is ~30·10^{-16} cm^2, ~30 times larger than for a typical neutral atom!!
- For H$^+$ energies below 1 keV, the recombination cross section is larger than 100·10^{-16} cm^2.

Negative ions are fragile !

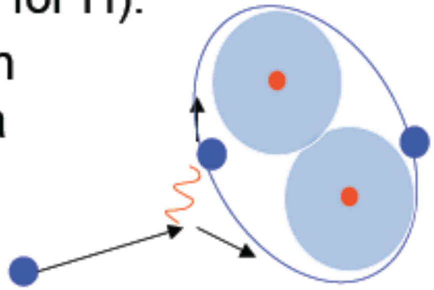
Charged particle collisions destroy negative ions easily!!

So how are H^- ions produced?



- Conserving energy and momentum when forming a negative ion through direct electron attachment, the excess energy has to be dissipated through a photon. $H + e = H^- + \gamma$

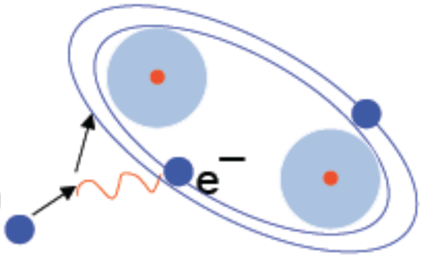
  But Radiative Capture is rare ($5 \cdot 10^{-22}$ cm^2 for H).



- More likely are processes where the excess energy can be transferred to a third particle, e.g. when dissociating a molecule (4.5 eV for H_2): $H_2 + e = H + H + e$

  and sometimes $= H + H^-$

  ($\sim 10^{-20}$ cm^2 for H_2 and $E_e > 10$ eV)



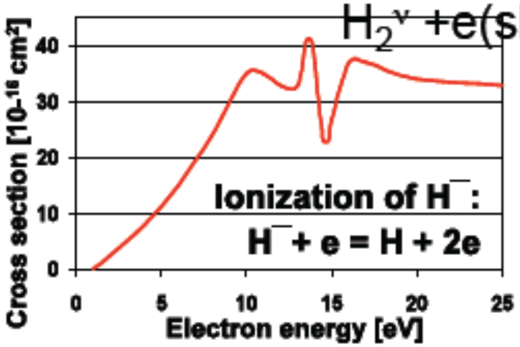
- Most likely are processes which excite a molecule to the edge of breakup (rovibrationally excited $4 < \nu < 12$)

  $H_2 + e(\text{fast}) = H_2^\nu + e$

  ($\sim 5 \cdot 10^{-18} cm^2$ for $4 \leq \nu \leq 9$ and $E_e > 15$ eV)

  and then dissociated by a slow electron

  $H_2^\nu + e(\text{slow}) = H + H^-$ ($\sim 3 \cdot 10^{-20}$ cm^2 for $4 \leq \nu \leq 9$ & $E_e < 1$eV)

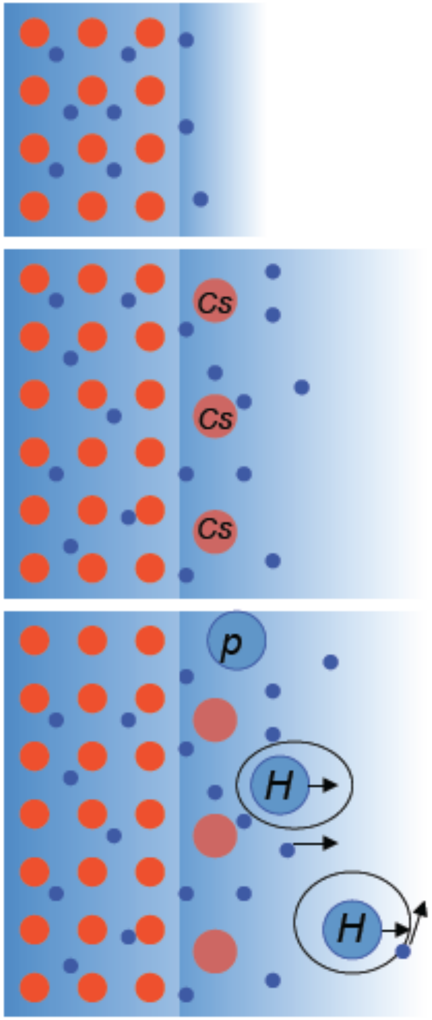


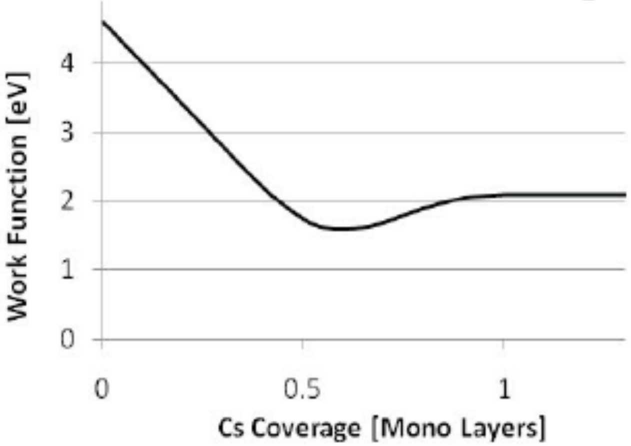
- However, the fast electron needed to excite the molecules, destroy ($\sim 3 \cdot 10^{-15} cm^2$) the H^- faster than they are produced!

A catch 22!

Surface Production of H^- Ions

- *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 to values even below their bulk work function, e.g. ~1.6 eV for Cs on Mo.*
- *Lowering the work function increases the probability that hydrogen atoms leaving the surface capture a second electron.*
- *The dominant process is protons capturing an electron when hitting the surface, and capturing a 2nd electron when bouncing back into the plasma.*

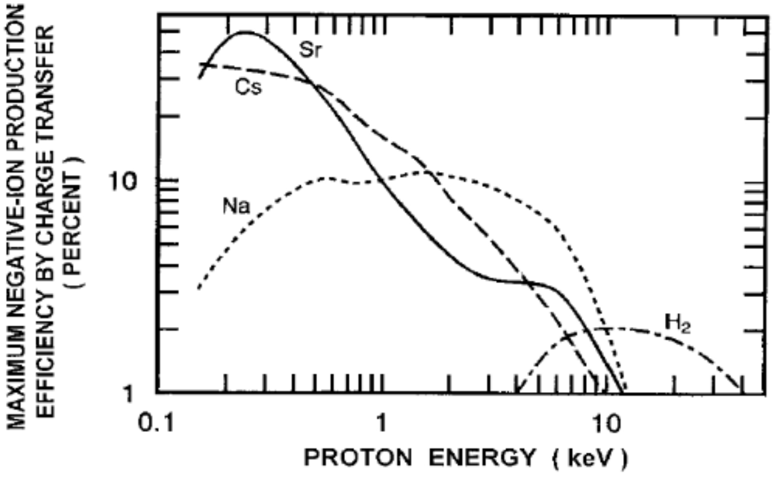




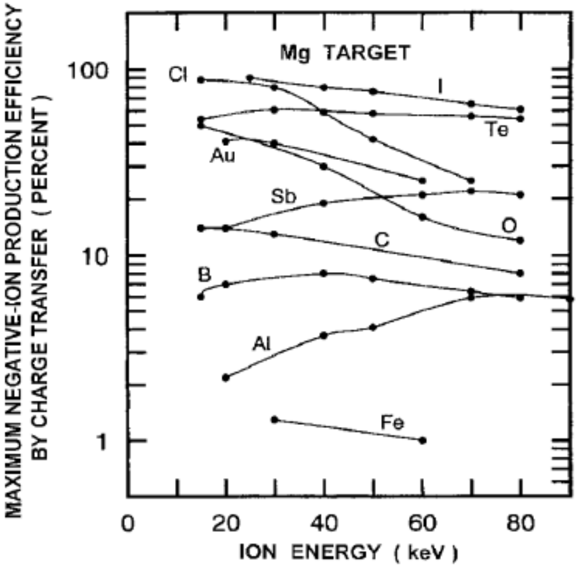
In the absence of Cs, residues on the surface (H_2O) and/or sputtered atoms (especially alkali from ceramics) can also lower the work function!

Charge Exchange Ion Sources – Negative Ions

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

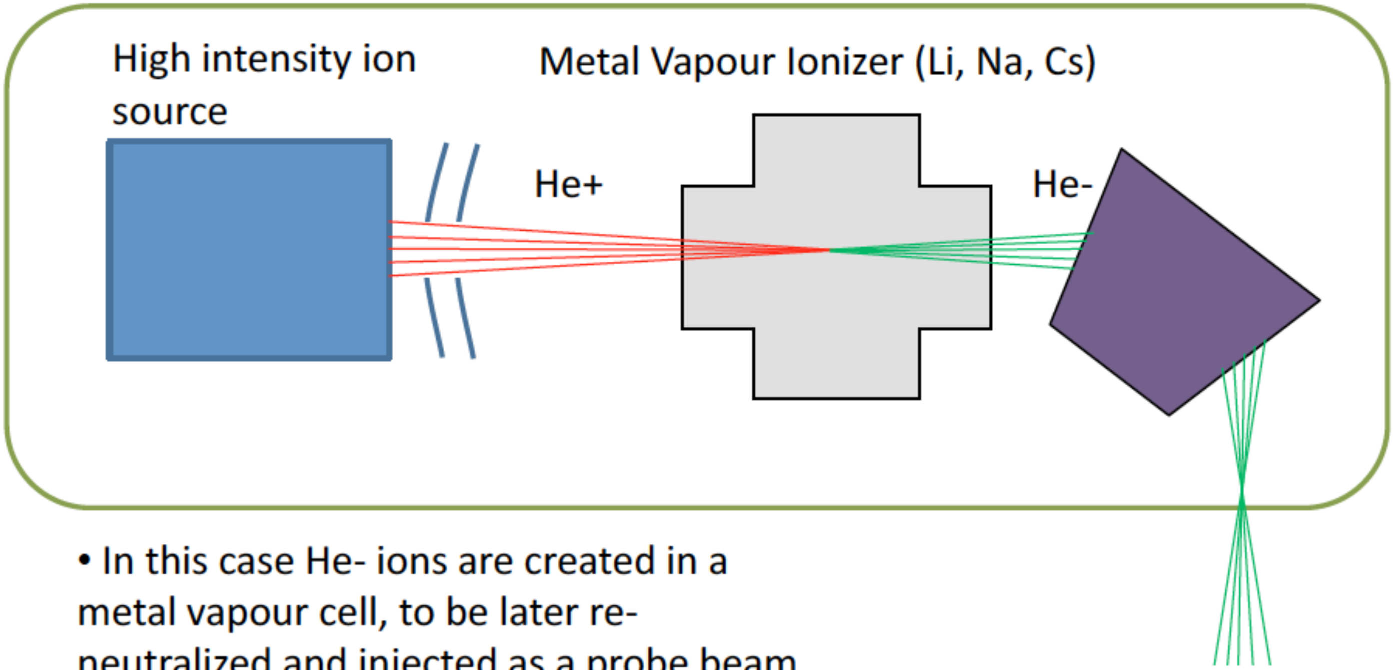


Schlachter and Morgan, AIP Conf. Proc. 111, p149 (1984)



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

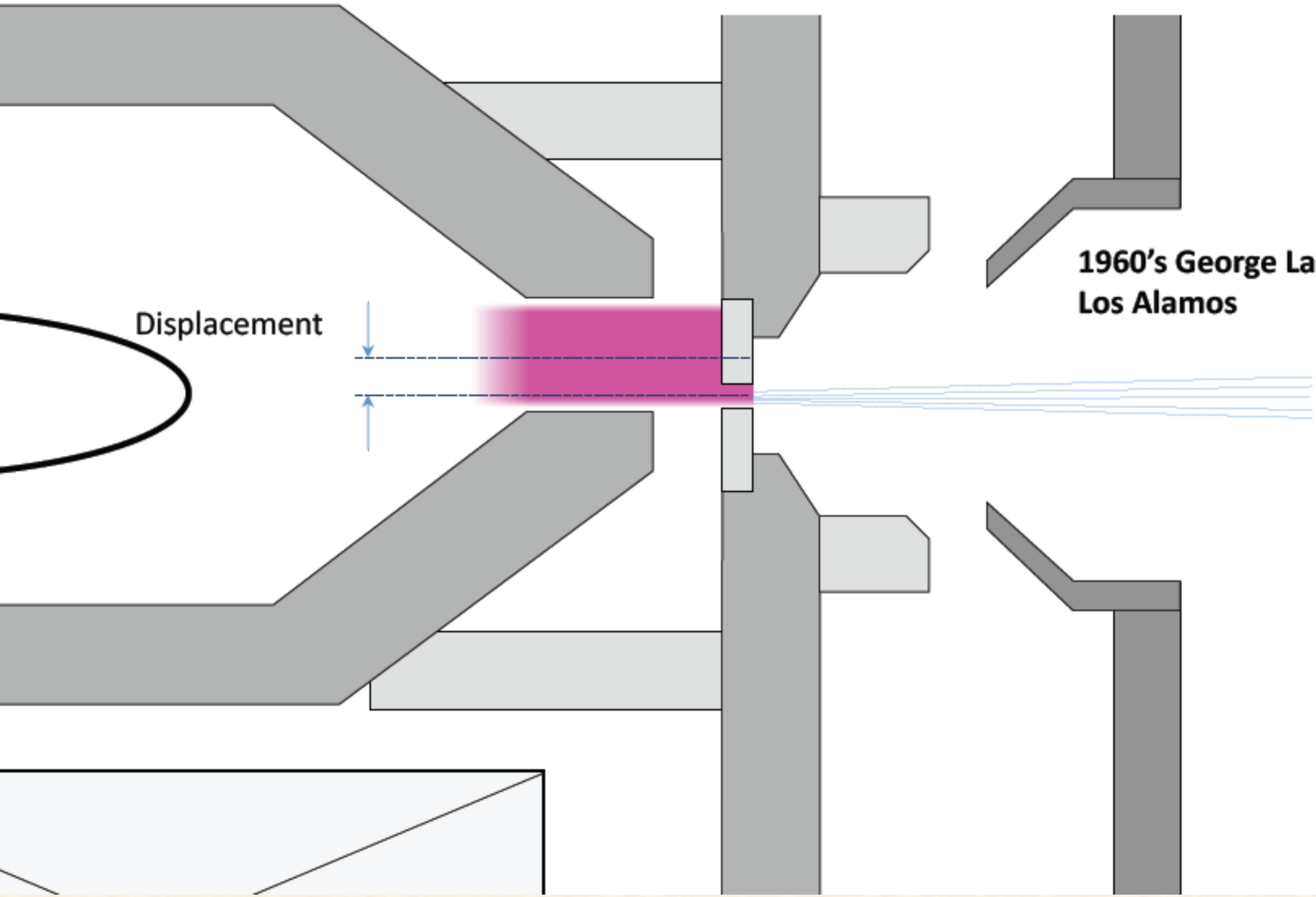
Charge Exchange Ion Sources – Negative Ions



- In this case He- ions are created in a metal vapour cell, to be later re-neutralized and injected as a probe beam into ITER.

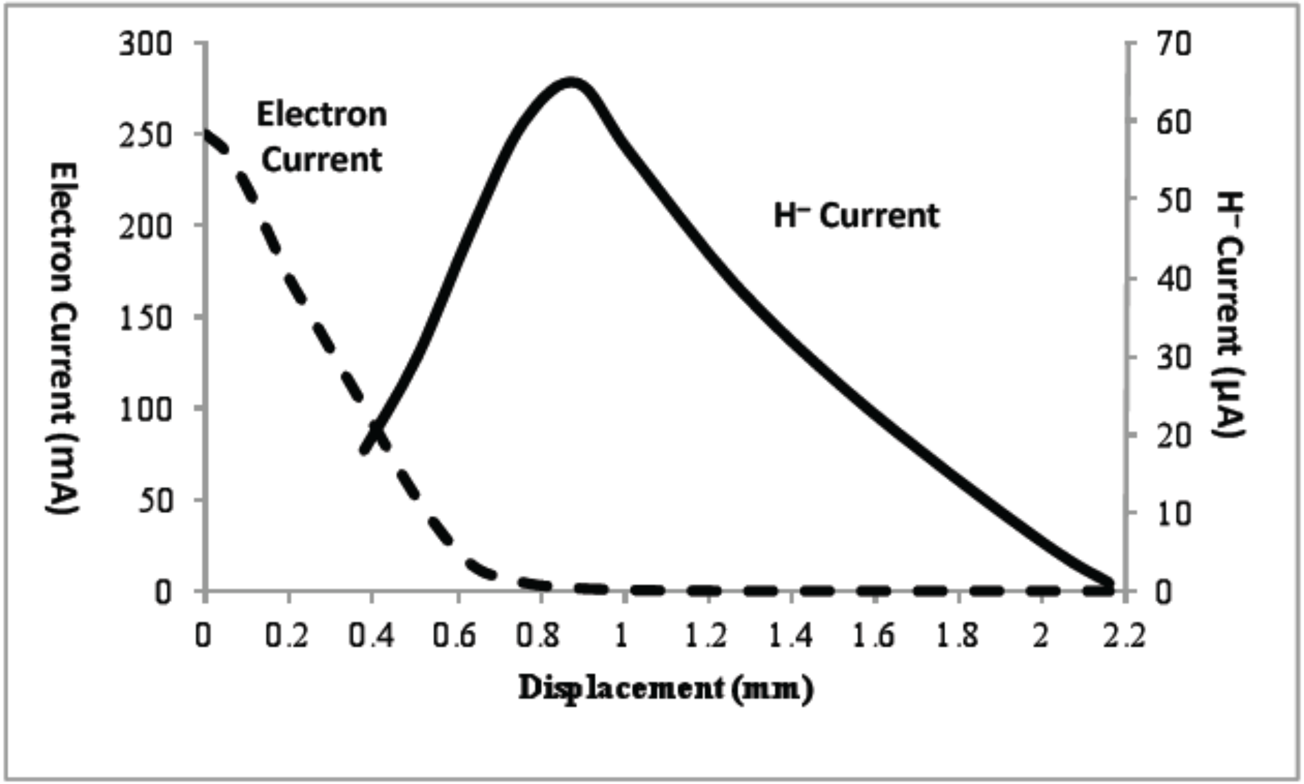
- If the outer electrons on the metal vapour are polarised, this can be transferred to the ion, which can be made to transfer the spin to the nucleus.

Off Axis Duoplasmatron Extraction

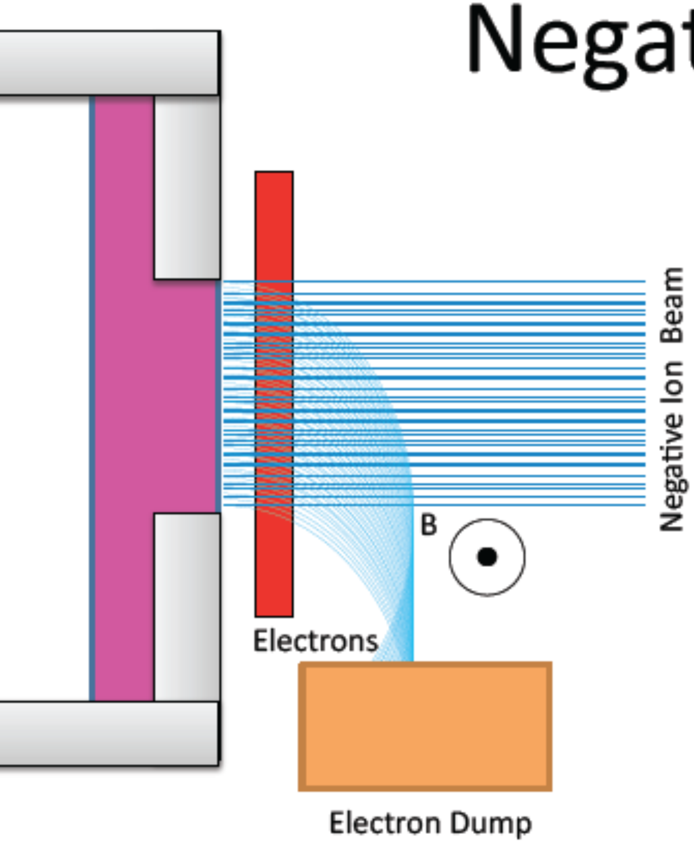


1960's George Lawrence Los Alamos

Off Axis Duoplasmatron Extraction



Negative Ion Extraction



Electrons will also be extracted

Up to 1000 times the H^- current!

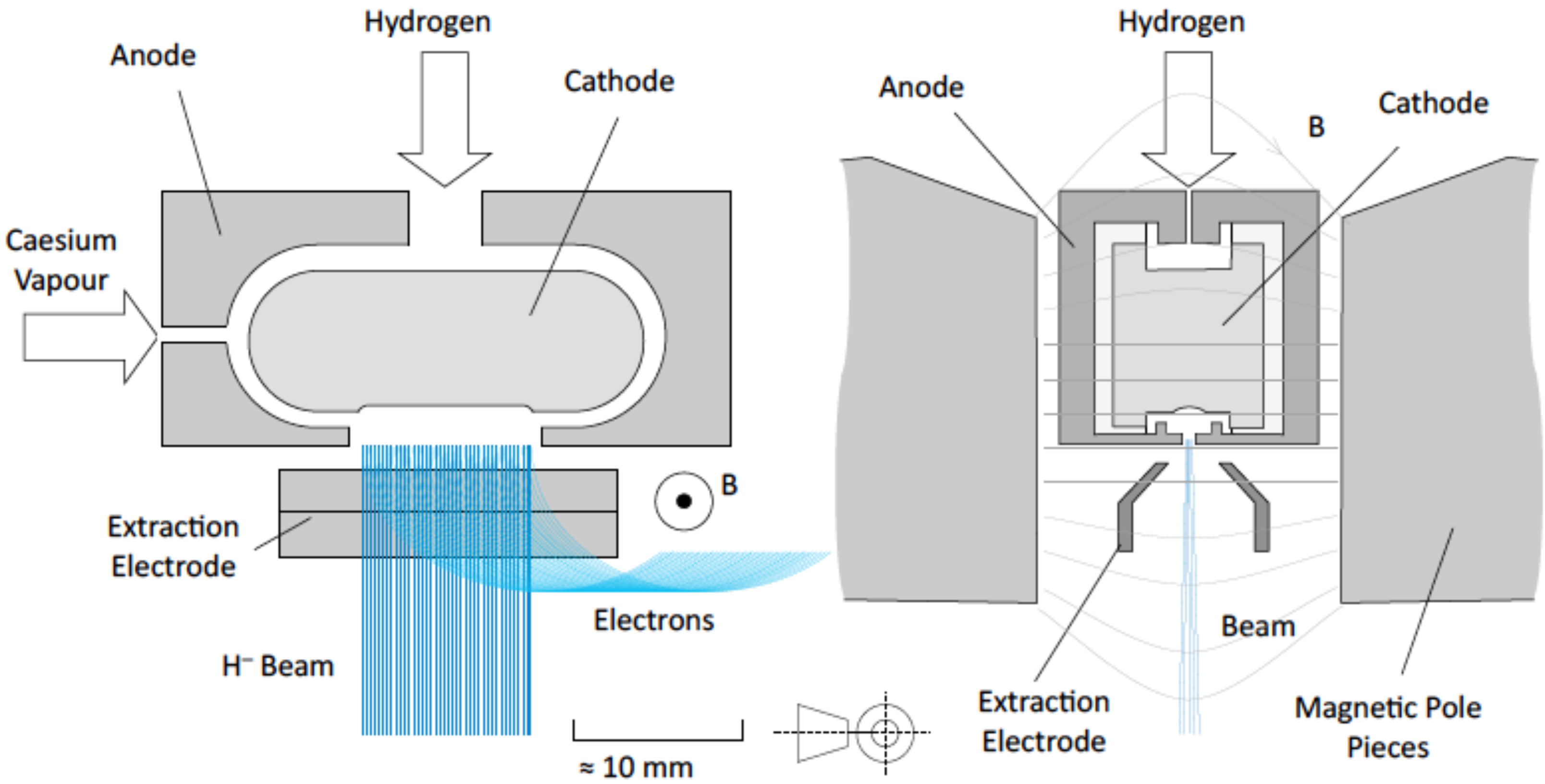
Use a magnetic field

Dump must be properly designed

SPS sources:

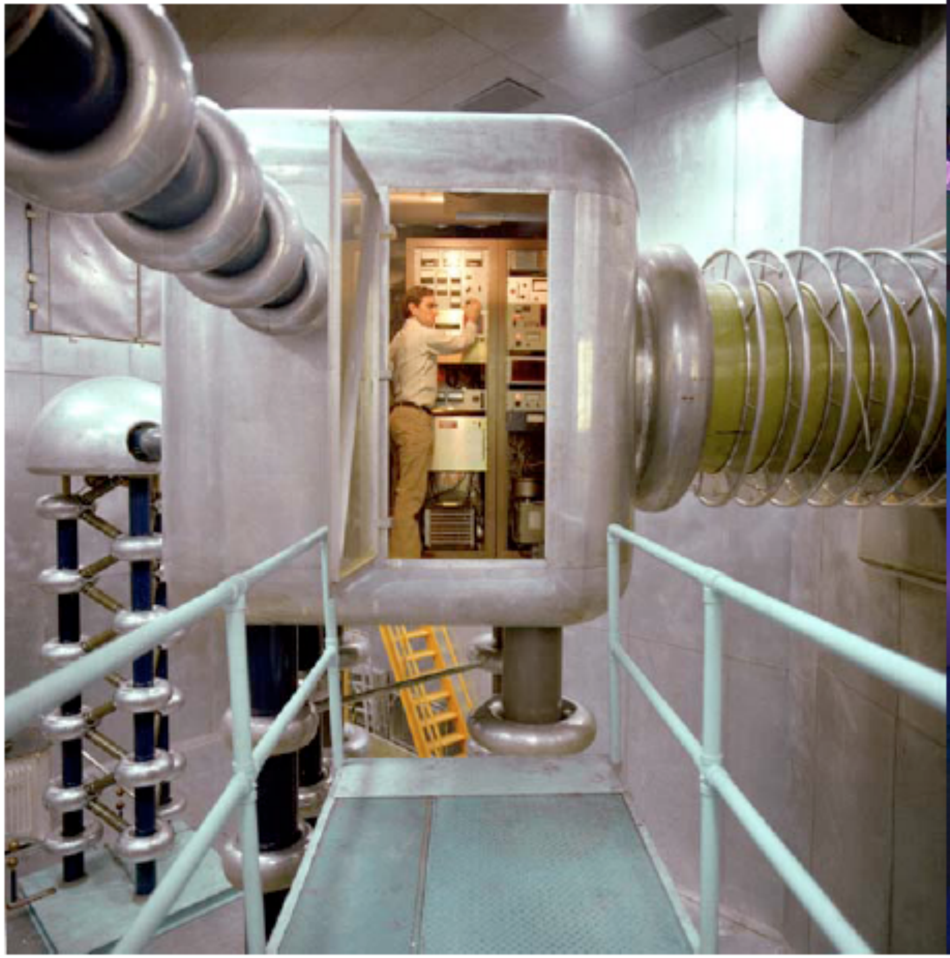
only 0.5 to 10 times H^- current

Magnetron Source



Fermilab Magnetron

750 kV Acceleration Column



Highly Charged Ions

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

Highly Charged Ions - ECRs

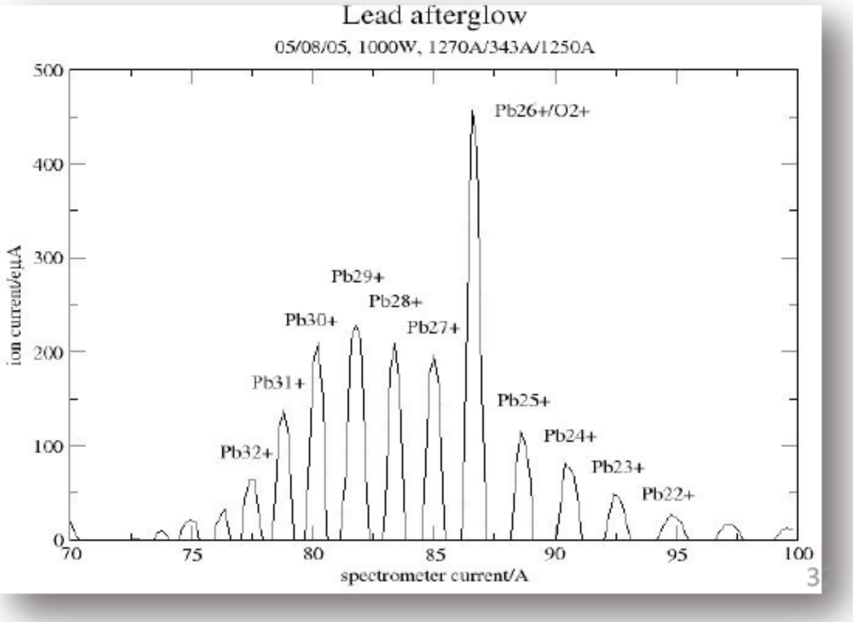
- The electrons are heated using the Electron Cyclotron Resonance.

- The Magnetic field I formed with co-linear solenoids, with a higher magnetic field at the ends, the confine the electrons with a magnetic mirror.

- Radially the confinement is made with a multi-cusp magnet.

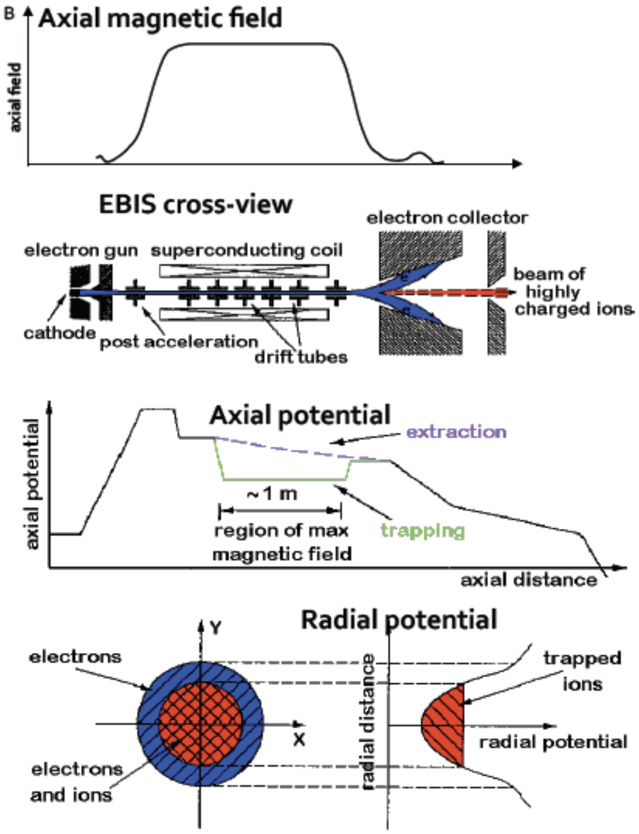
- The inverse dynamics of collisional drift means the hot electrons are well confined.

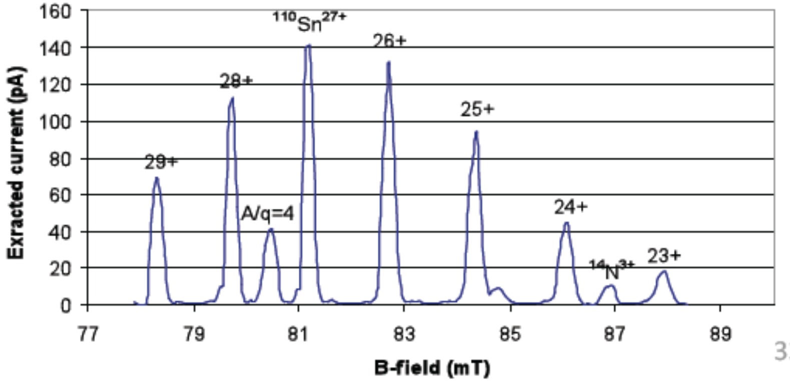
- This leads to a charge density, that traps ions, sufficiently long for mulit-step ionisation to take place.



Highly Charged Ions - EBIS

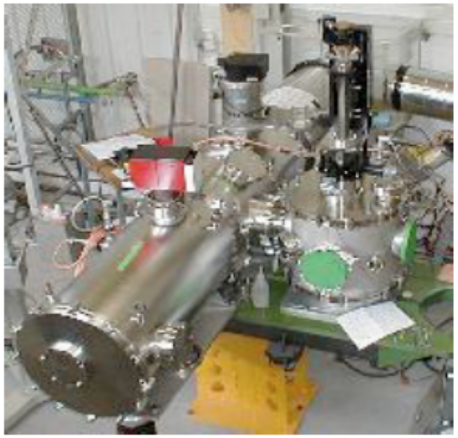
- The electrons are accelerated from a cathode into a drift region (usually in a solenoid field to increase the current density).
- Ions are trapped radially by the electron beam potential.
- Longitudinal trapping is done with electrodes.
- Neutral gas or 1+ ions are injected, and confined long enough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

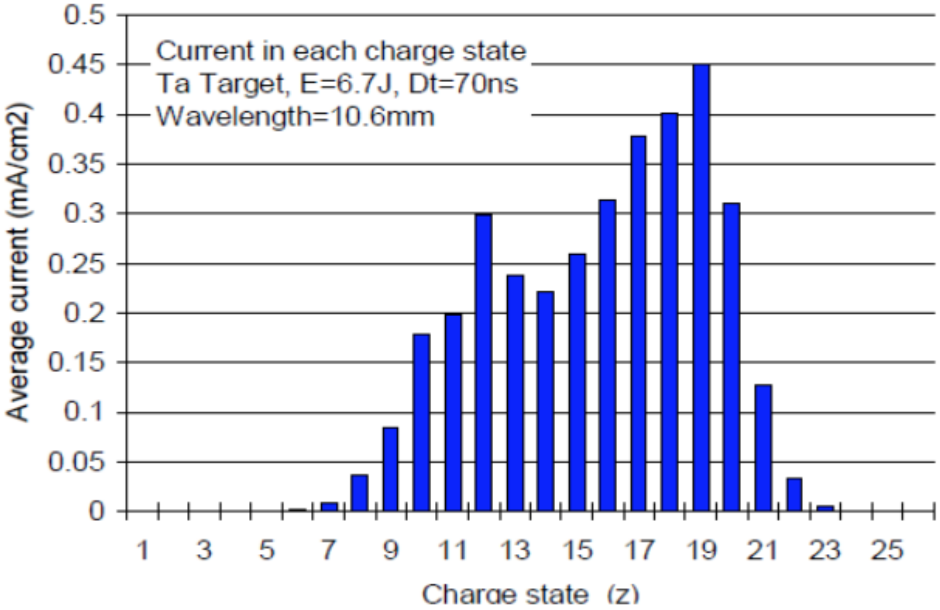




Highly Charged Ions – Laser Ion Sources

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





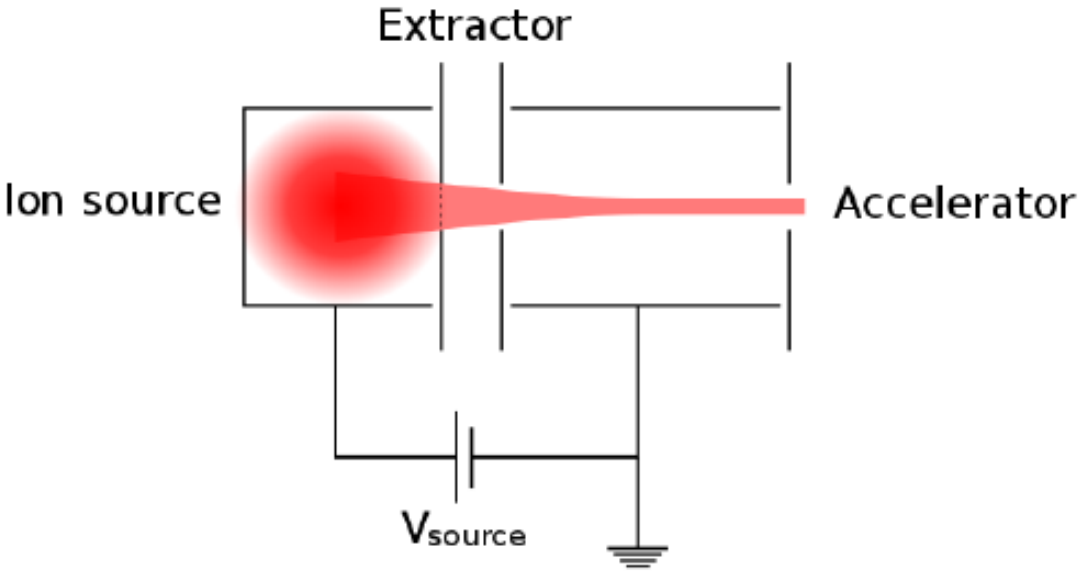
Ion source conclusion

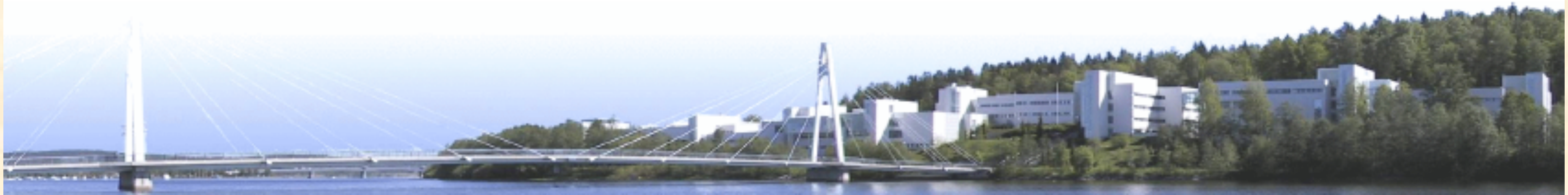
- Accelerators require many different types of ion sources.
- This can be achieved by relying on different physical processes.
- There are different technical implementation to achieve these processes.
  => Ion sources are a very complex topic and there is still a lot of R&D happening.

BEAM TRANSPORT

Basic beam extraction and transport

The extractor takes the plasma flux $J = \frac{1}{4}qn\bar{v}$ and forms a beam with energy $E = q(V_{\text{source}} - V_{\text{gnd}})$ transporting it to the following application.



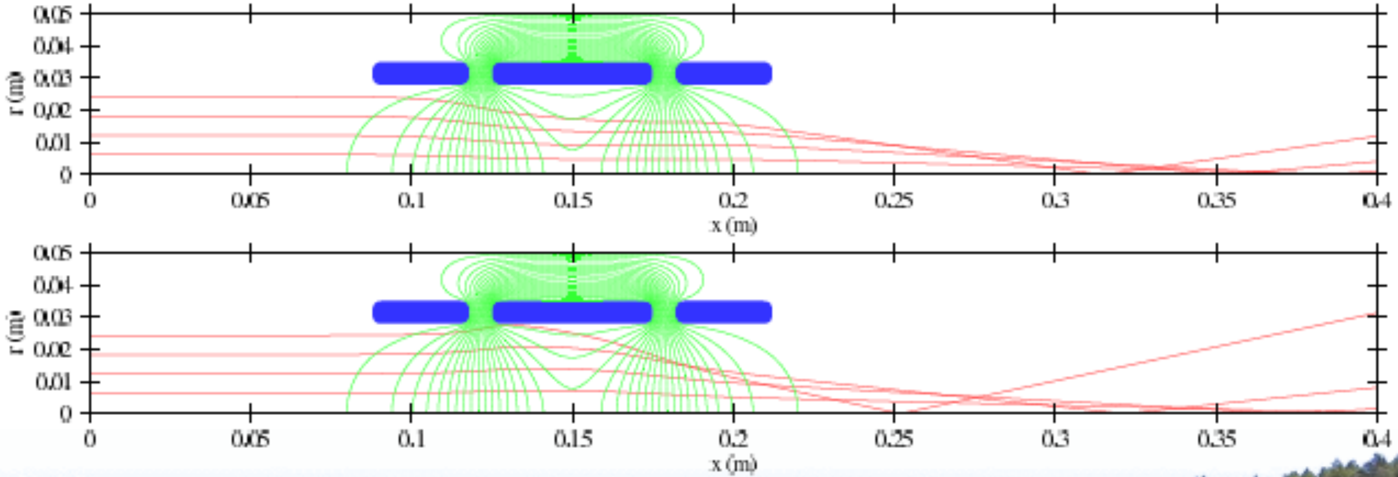


Einzel focusing

Einzel is a cylindrically symmetric focusing lens, which is characterized by voltage ratio

$$R = \frac{V_{\mathrm{einzel}} - V_{\mathrm{tube}}}{V_{\mathrm{tube}} - V_0},$$

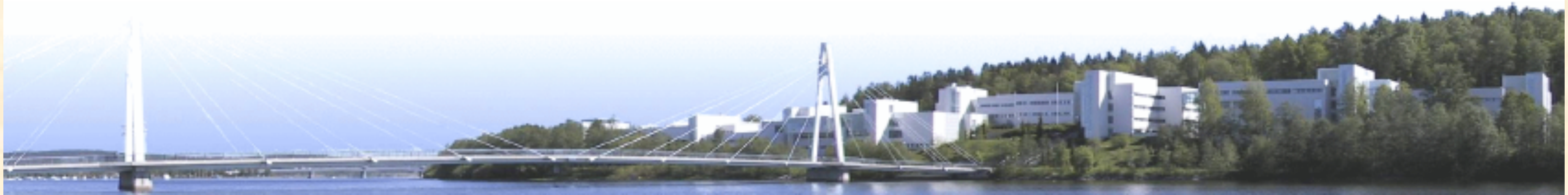
where V_{einzel} is the center electrode potential, V_{tube} is the beam tube potential and V_0 is the potential where particle kinetic enrgy is zero. The einzel lens can be accelerating ($R > 0$) or decelerating ($R < 0$).



Beam space charge compensation

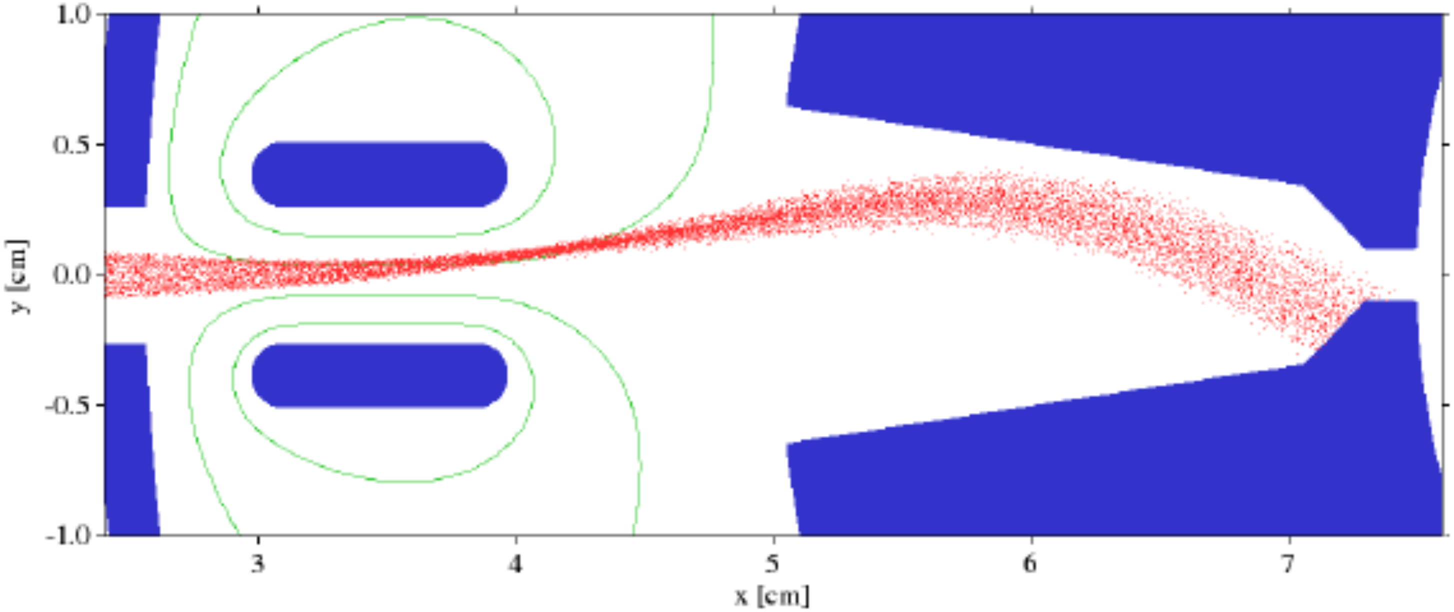
Transport of high-intensity, low-energy beams can be difficult due to space charge blow-up. Beam compensation helps in low E-field areas.

- Background gas ionization: e^- and X^+ created within the beam.
- Opposite sign to beam trapped in beam potential, while same sign particles accelerated out $\Rightarrow$ decreasing beam potential.
- Secondary electron emission from beam halo hitting beam tube providing compensating particles for positive beams.
- Also methods for active compensation: running electron beam in opposite direction of the main beam.
- Usually increased by feeding background gas into the beamline.



Parallel plates for beam chopping

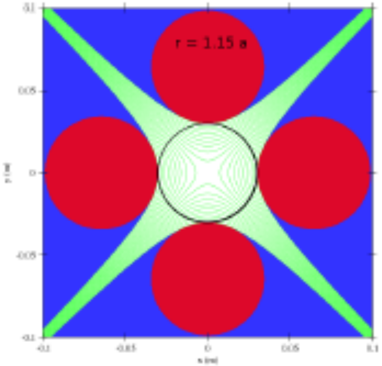
Fast beam chopping can be done with parallel plates: LBNL built neutron generator using 15 ns rise-time ±1500 V switches for generating 5 ns beam pulses.

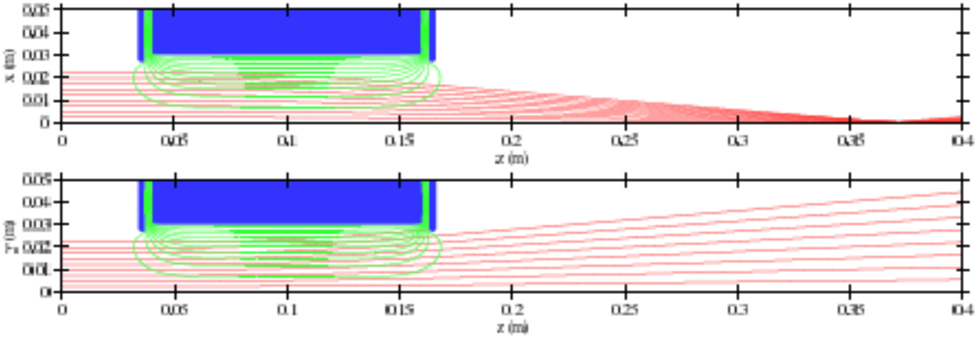


PIC simulation with IBSIMU.

Electrostatic quadrupole focusing

Electrostatic quadrupole: ideally hyperbolic electrodes, cylindrical ok





$$
\begin{aligned}
1/f_x &= k\tan(kw) \\
1/f_y &= -k\tanh(kw) \text{ ,where } k^2 = \frac{V_{\text{quad}}}{G_0 V_{\text{acc}}}
\end{aligned}
$$

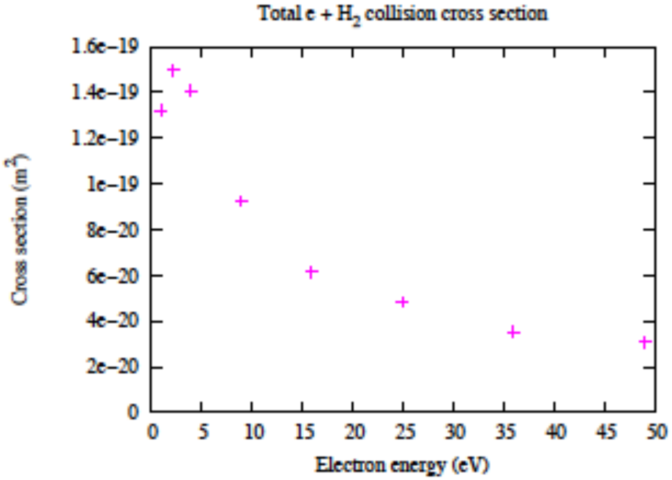
- Used as doublets or triplets for focusing in both directions.
- Can also provide beam steering if electrodes independently controlled.

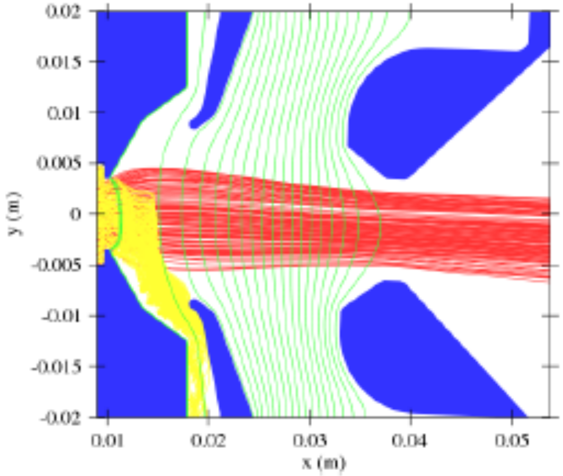
UNIVERSITY OF JYVÄSKYLÄ

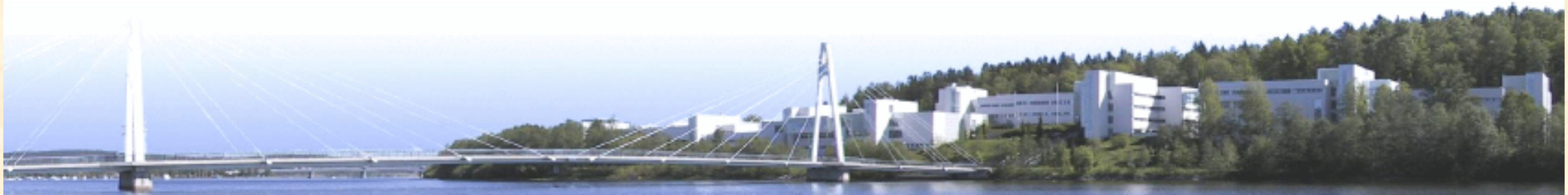
Negative ion plasma extraction model

Magnetic field suppression for electrons inside plasma

- Electrons highly collisional until velocity large enough
- Magnetic field suppression for electrons inside plasma

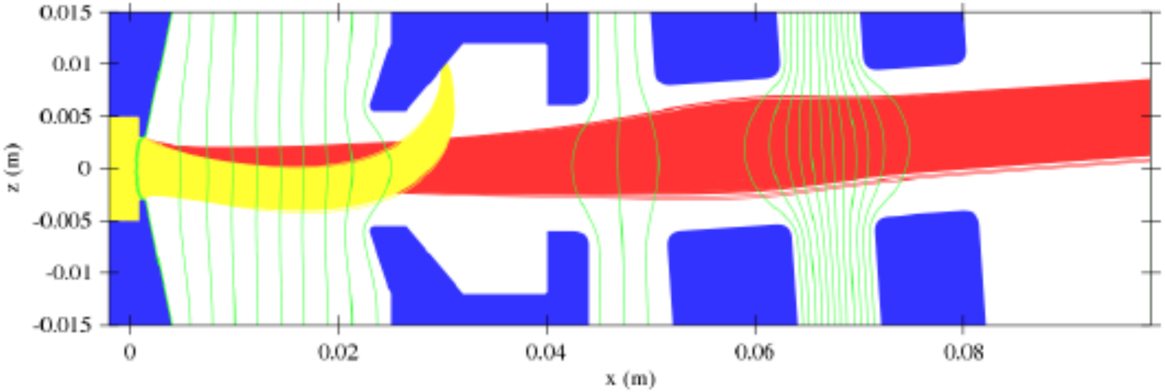


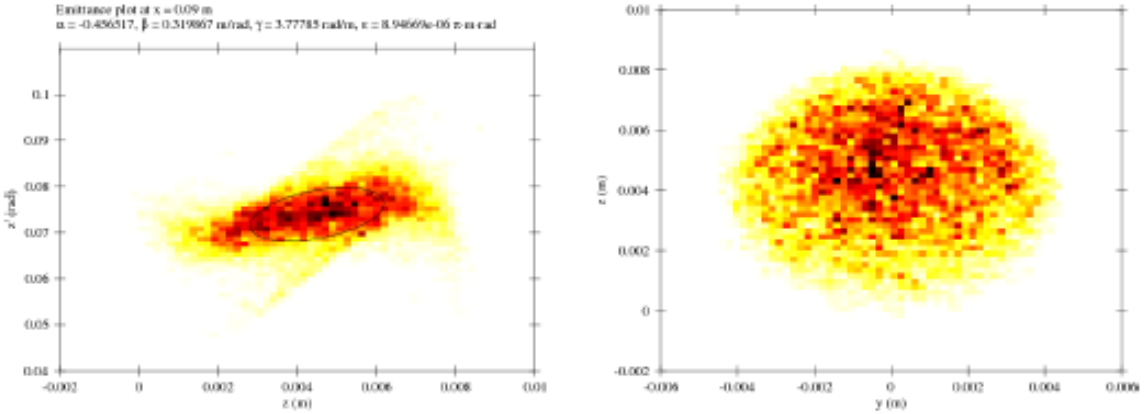


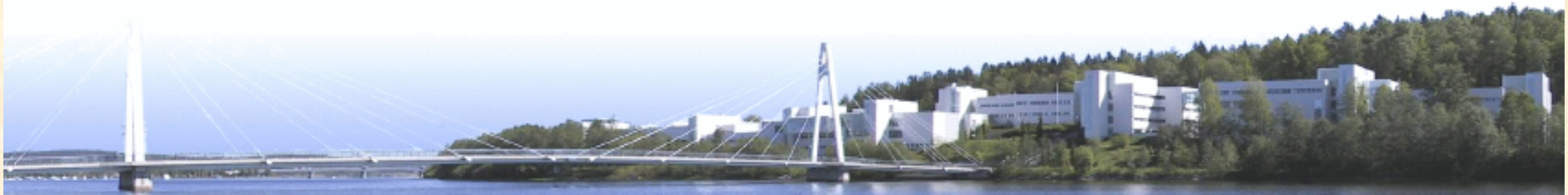


Texas A&M: 3D geometry design

Geometry was optimized for low-aberration emittance and centered beam







OTHER APPLICATIONS

Ion thrusters for spacecraft propulsion

Tsiolkovsky rocket equation:

$$v_e = v_T \ln \frac{m_0}{m_e}$$

Maximum speed = exhaust velocity x ln(Initial mass/final mass)

Chemical thrusters		small	large
Electrical thrusters	up to 25 x larger	large	small

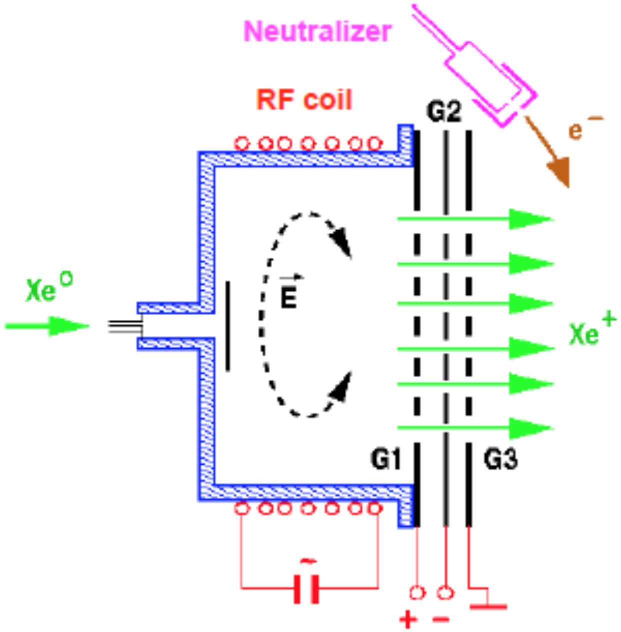
- Small thrust (0.1 - 1 N) but
- Very reliable
- High propellant capacity
- propulsion energy provided by an electric source
- exact control of the thrust

=> used for

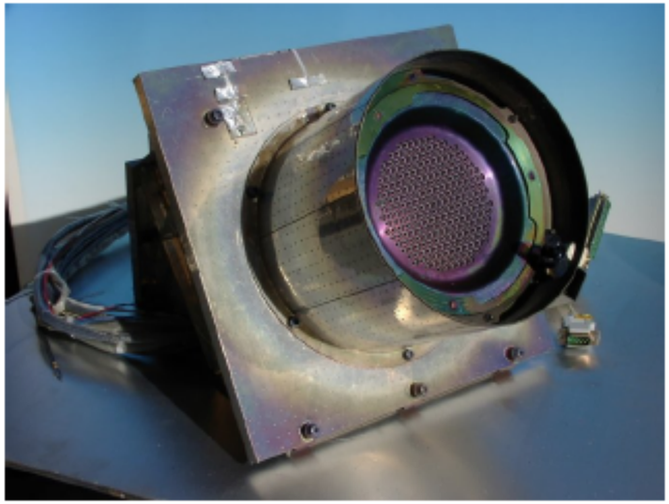
space missions, space probes

orbit control of satellites

RF ion thrusters



RIT 10
Giessen university



Propellant: **Xenon**
(high mass => high momentum => high thrust)
10 cm diameter,
Thrust: 0.01 – 1 N

Acceleration voltage: ca 2 kV
Power supply: solar
4 MHz, few 100 W,

Summary

- Ions for accelerators can be produced through 3 different phenomenon:
  - impact ionization
  - photo-ionization
  - charge exchange
- There is a large variety of ion sources design, suited to different ion requirements.

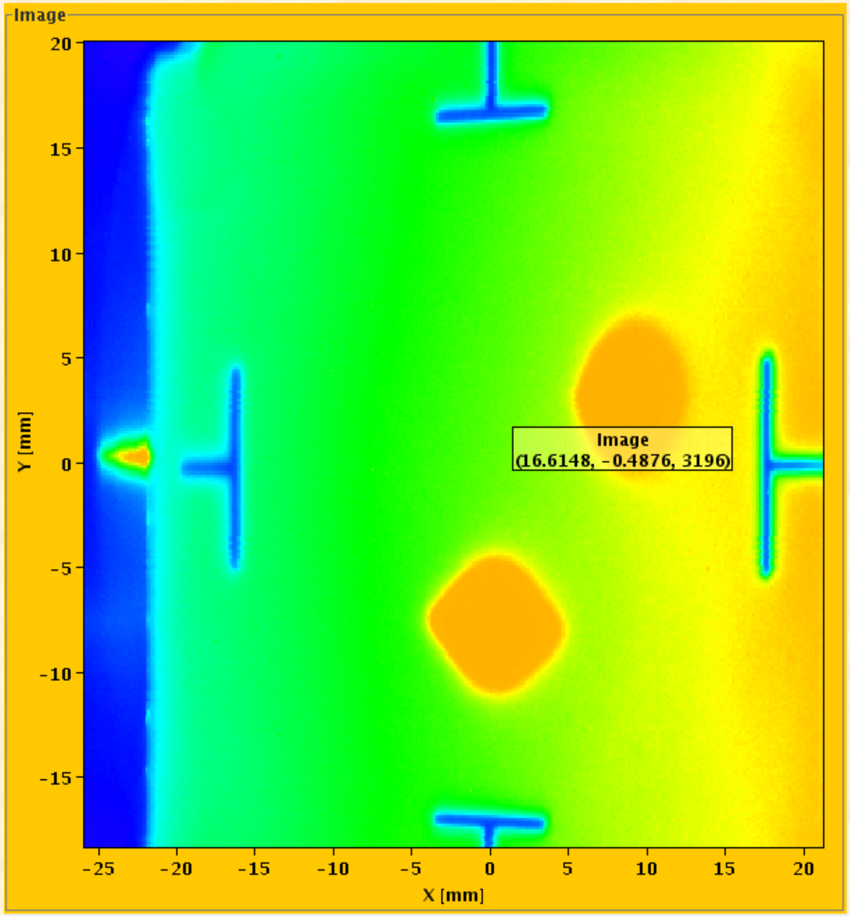
Diagnostics

What do **we** want to know about the beam?

?

What do you want to know about the beam?

- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses



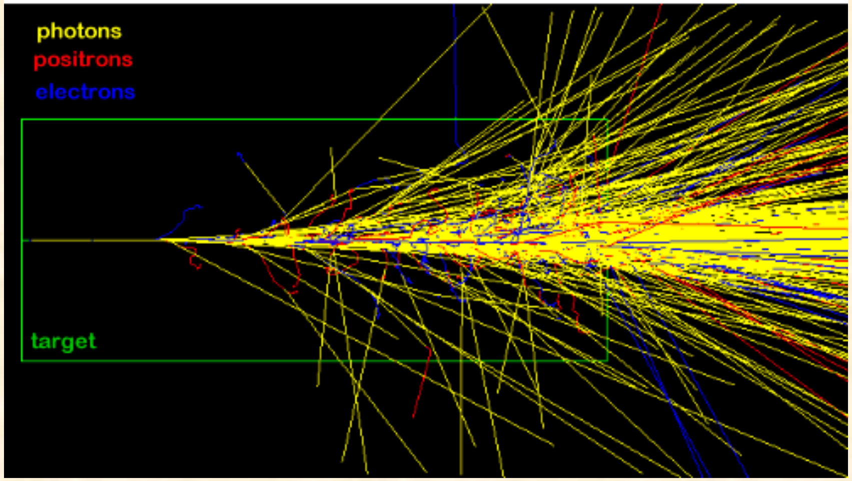
Beam properties measurements

- Almost all accelerators accelerate ***charged particles***
- There are mainly 2 types of beam diagnostics:

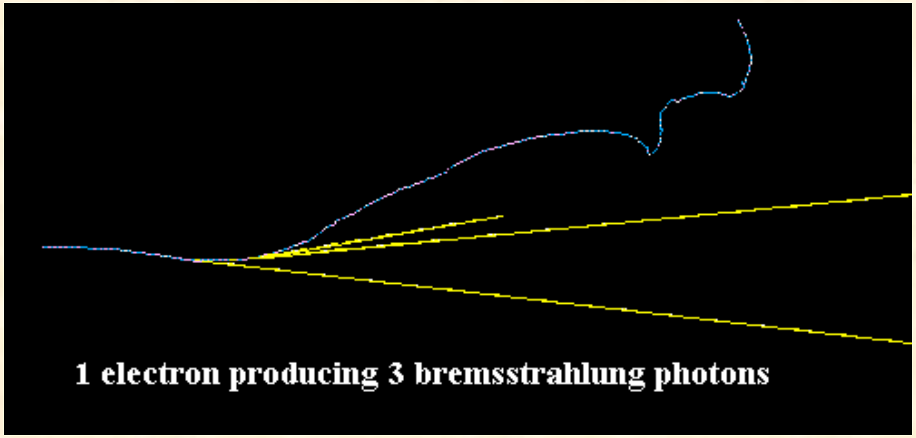
  - Diagnostics that use the interaction of the beam with matter

  - Diagnostics that use radiations emitted by the beam to measure its properties.
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

Particles interactions with matter



Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

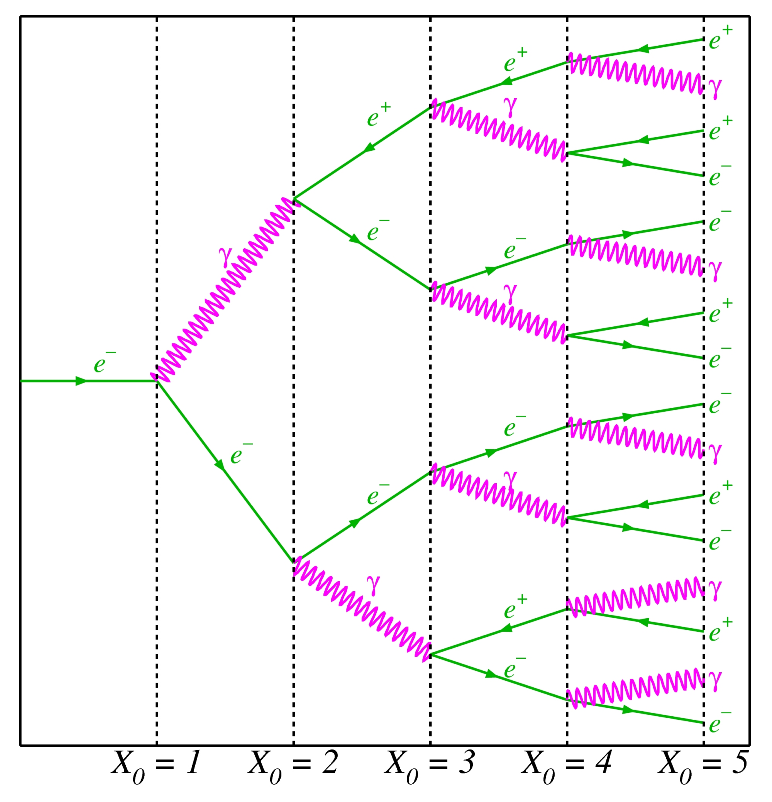


1 electron producing 3 bremsstrahlung photons

- High energy particles interact with matter in several ways.
- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produced when such scattering occur will

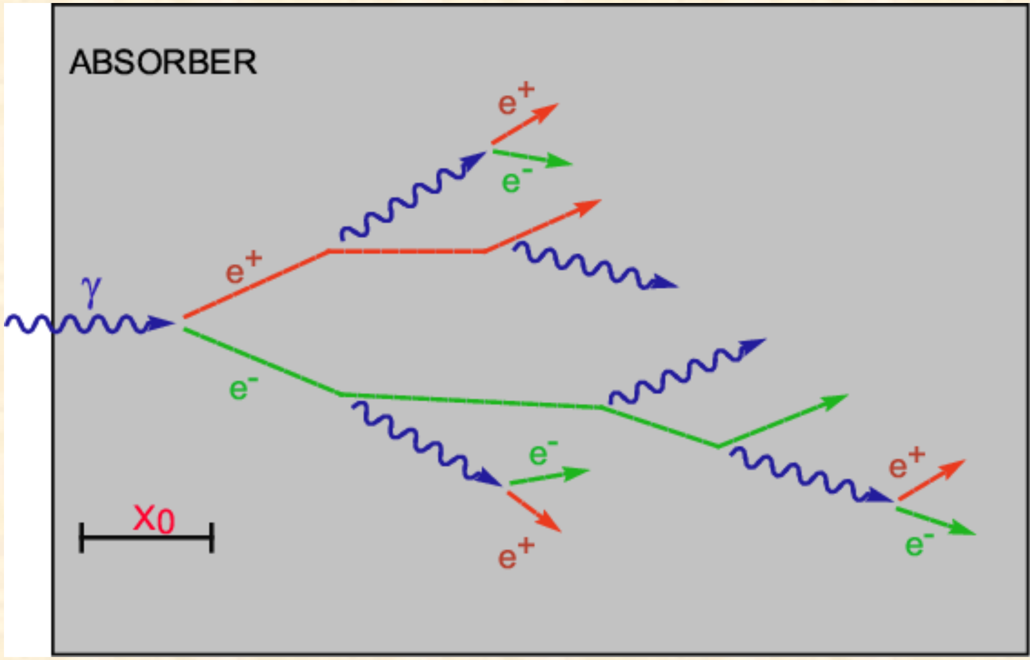
Example: Electron shower

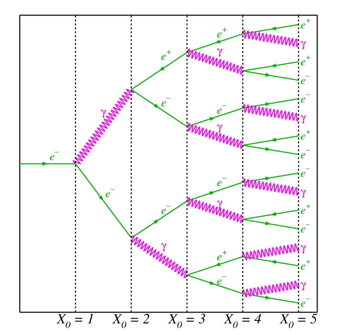
- The distance after which an electron or a photon interacts is called the "radiation length"
- Radiation length vary from material to material and can be found in tables.
- X_0(Pb)= 0.56cm
  X_0(Ta)= 0.41cm
  X_0(Cu)= 1.44cm
  X_0(Fe)= 1.76cm
  X_0(C graphite)= 19.32cm



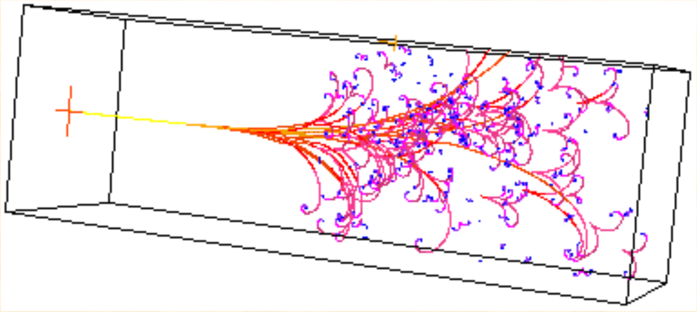
Particle absorption

- Particles loose 1/e of their energy after each radiation length.
- The reality is a bit more complex but statistically this picture is true...
- Heavy particles such as protons will loose some energy as they travel in matter and suddenly stop when their energy slow enough.





Faraday cup (1)



- Let's send the beam on a piece of copper.
- What information can be measured after the beam has hit the copper?

Faraday cup (2)

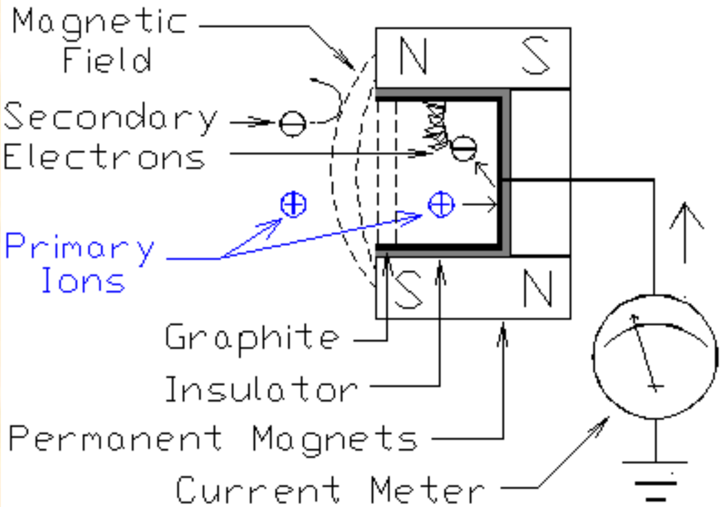


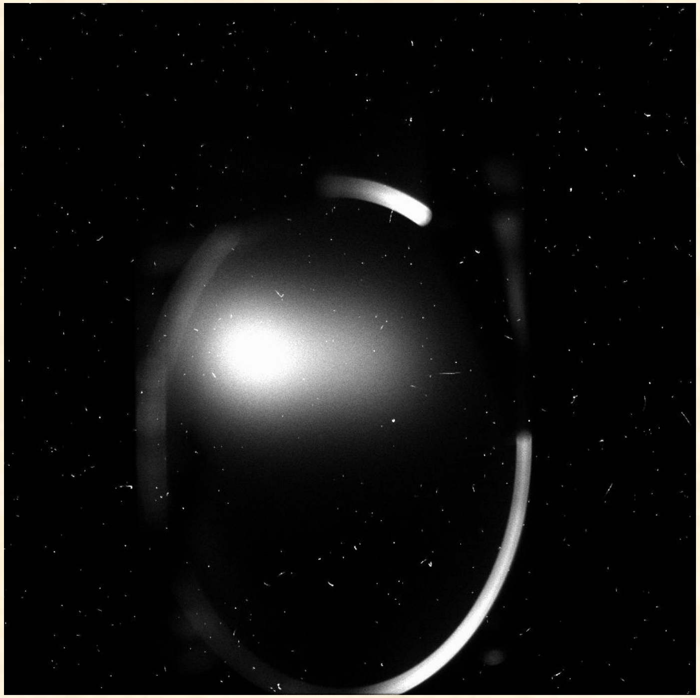
Image source: Pelletron.com

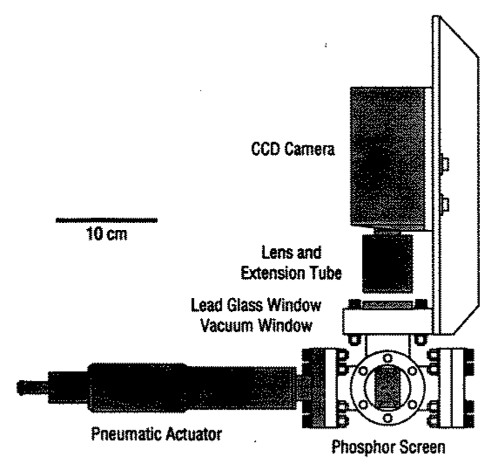
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- The total energy of the beam could also be measured by using the cup as a calorimeter, but usually knowing the charge is enough as most beam are almost monochromatic.
- At high energy Faraday cups can be large:
  More than 1m at SOLEIL for a
  3 GeV electron beam.

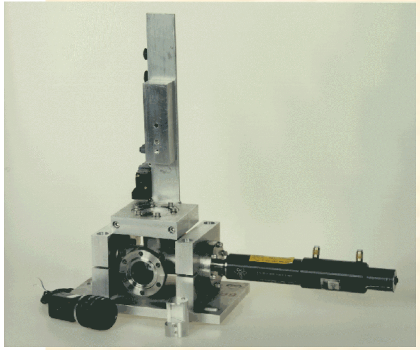
Screen (1)

- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

Screen (2)

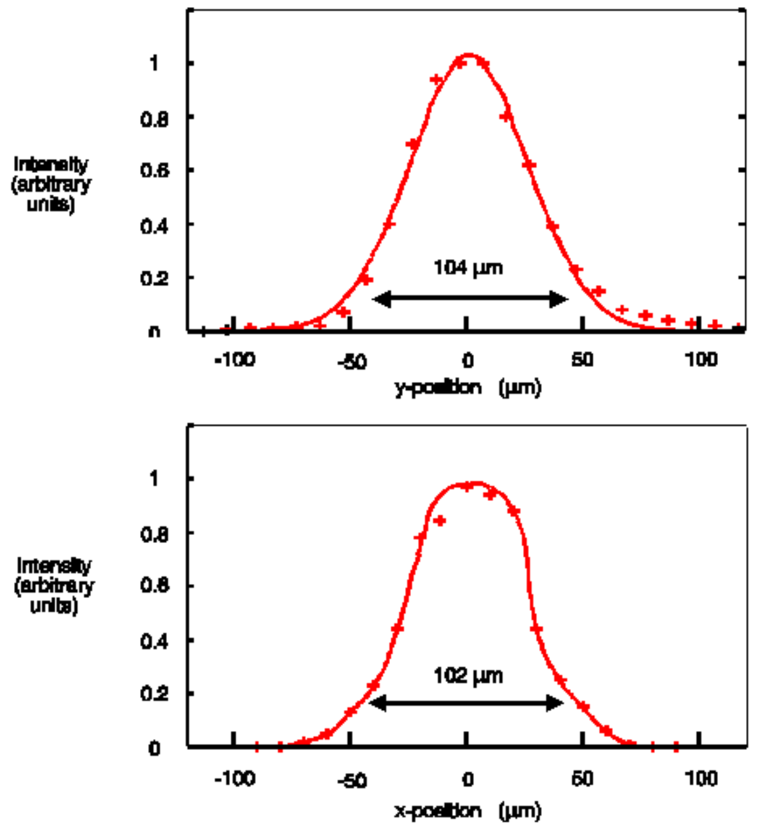






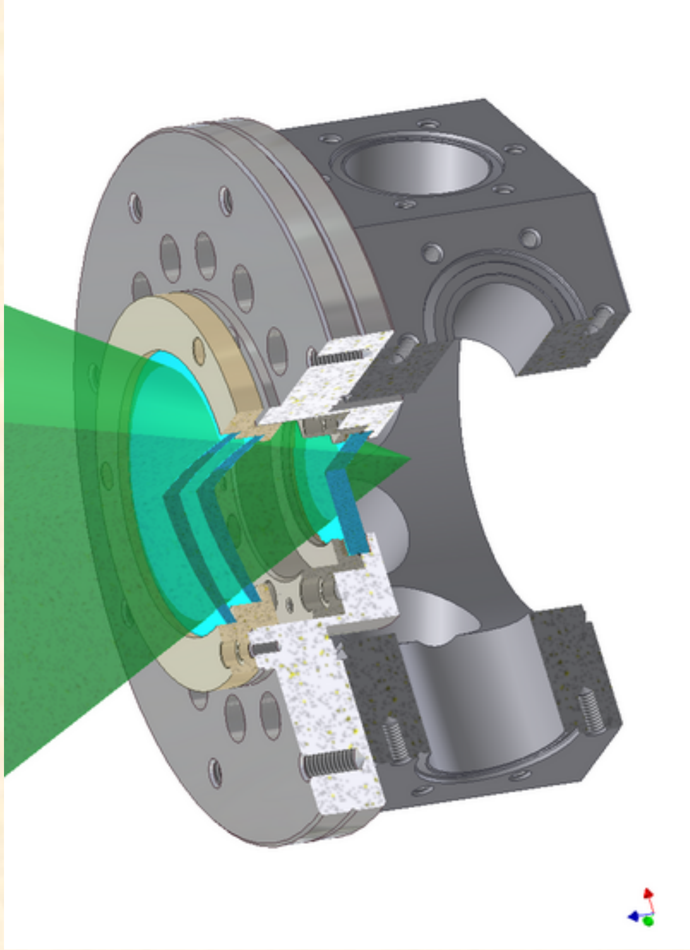
- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at
  45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

Wire-scanner



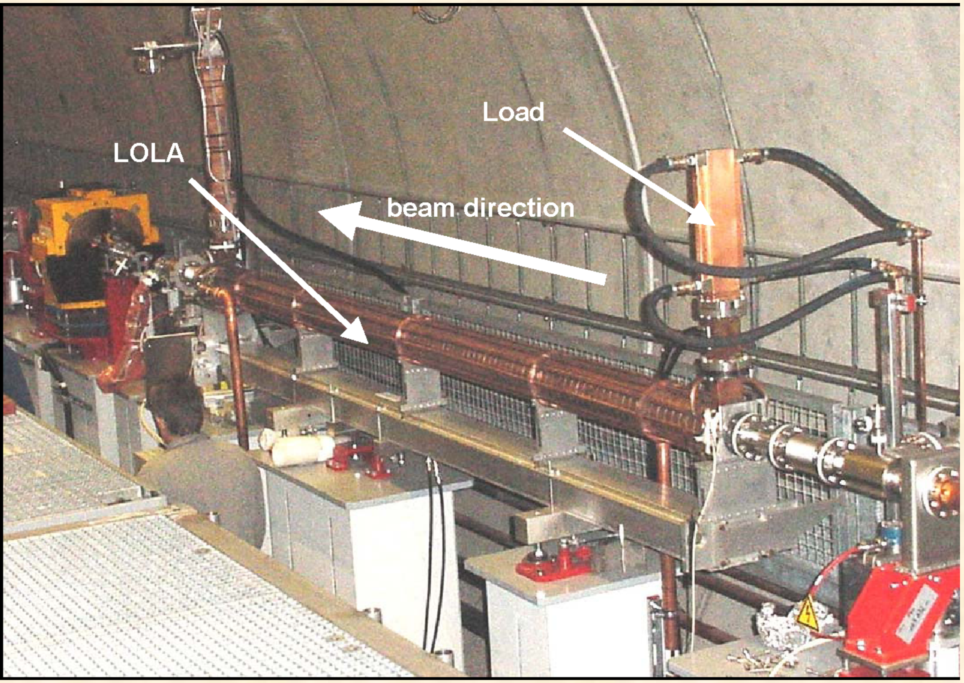
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
  => better resolution than with screens & less disruptive
- However, a too strong beam current can lead to damages to the wire (requiring replacement of the wire).

Laser-wire

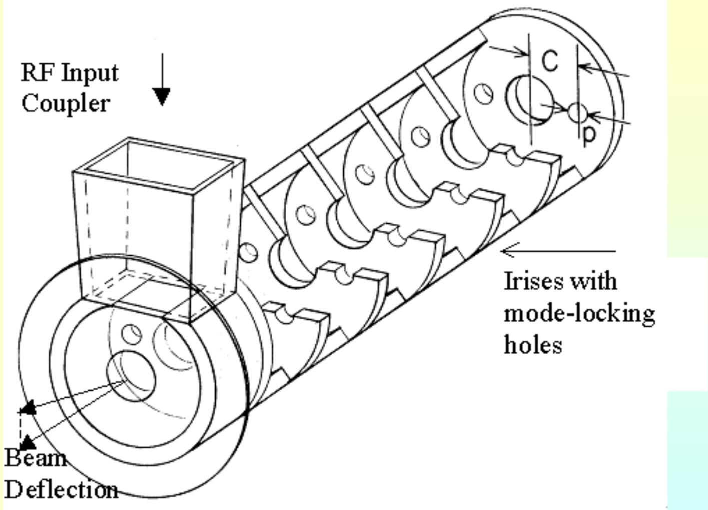


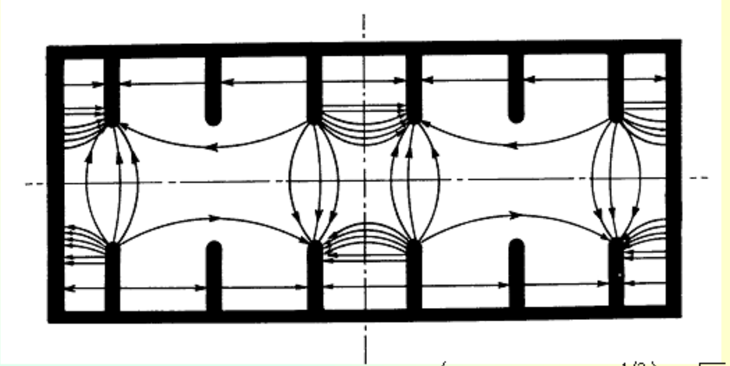
- To mitigate the problem of broken wires in wire-scanners it is possible to replace the wire by a laser.
- This technique called “laser-wire” also allow to reach better resolutions.
- High power lasers (or long integration times) are needed.

Longitudinal properties



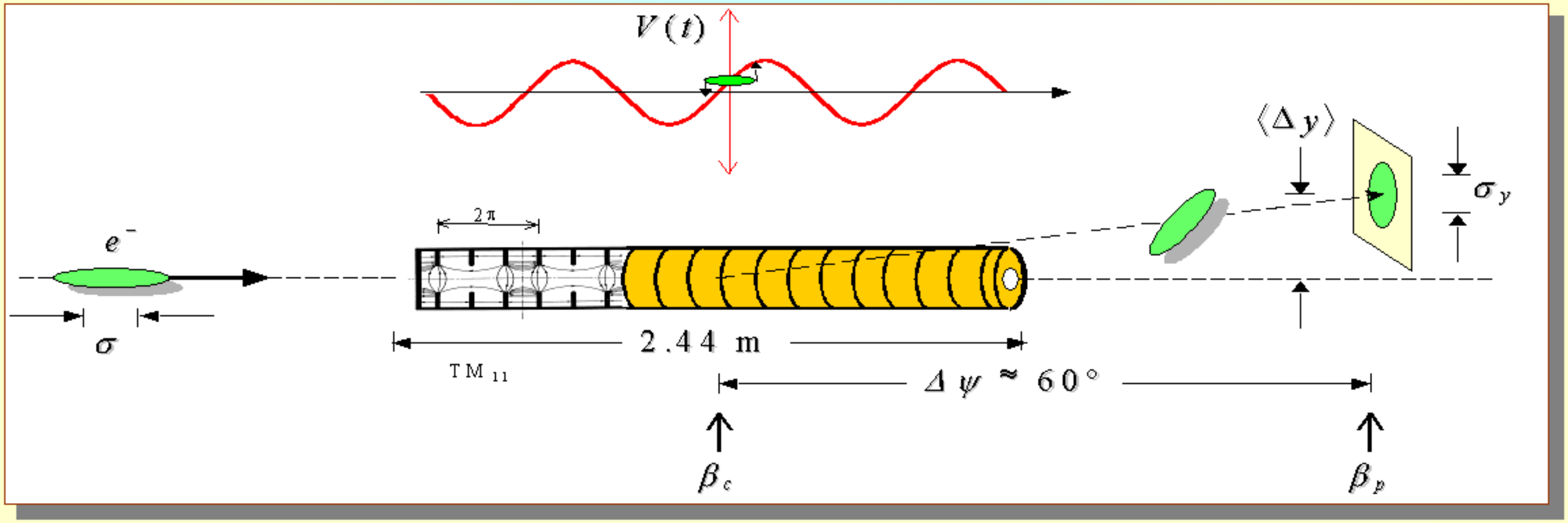
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



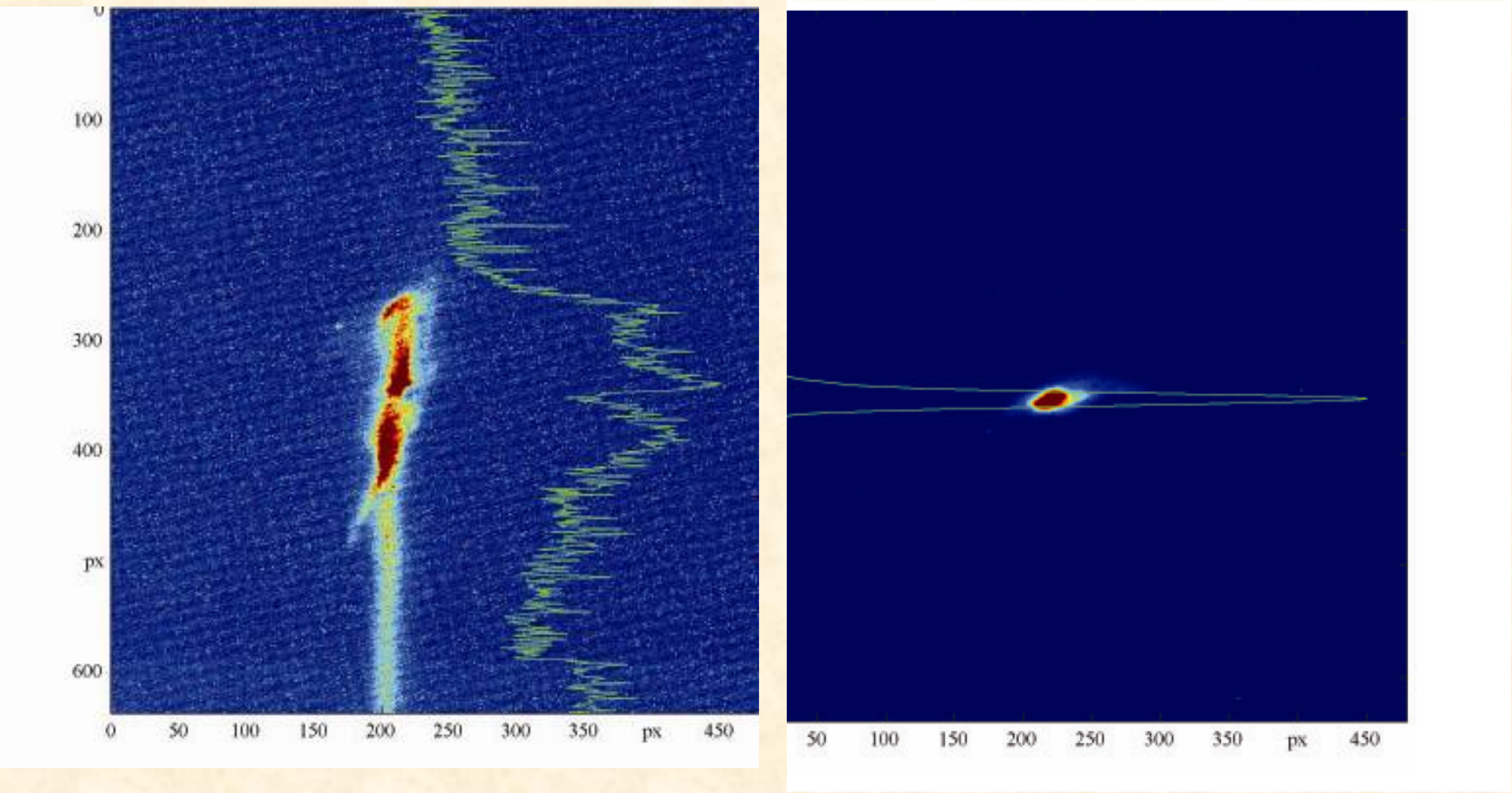


$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L\sqrt{P_0}$$

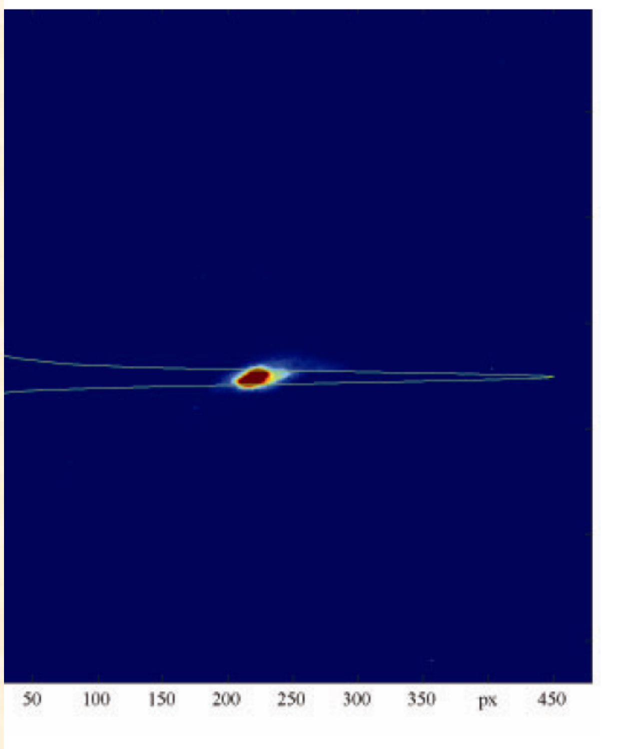
$$bunchlenght, \sigma_z \approx \frac{\lambda_{\mathrm{rf}}}{2\pi}\frac{E_S}{|eV_0 \sin\Delta\psi \cos\varphi|}\sqrt{\frac{\left(\sigma_y^2 - \sigma_{y0}^2\right)}{\beta_d \beta_s}}$$



RF deflector off and on



Deflection calculations



- The transverse quick given by the cavity is

$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{pc}\left[\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right]$$

- This leads to an offset

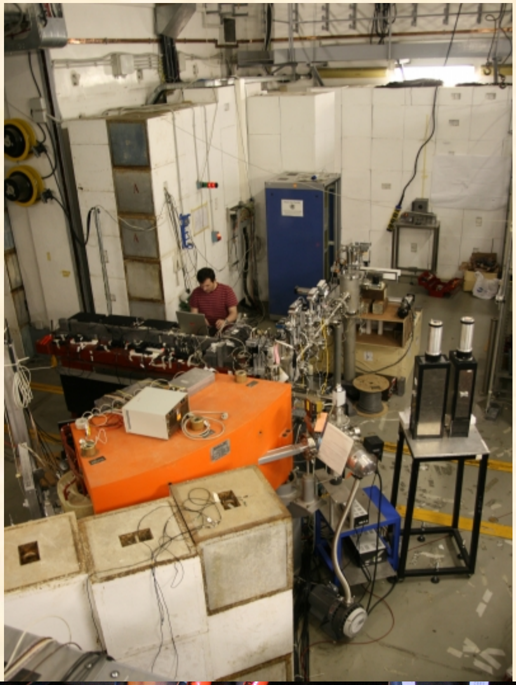
$$\Delta x = \sqrt{\beta_1\beta_2}\,\sin\Delta\psi\cdot\Delta\theta$$

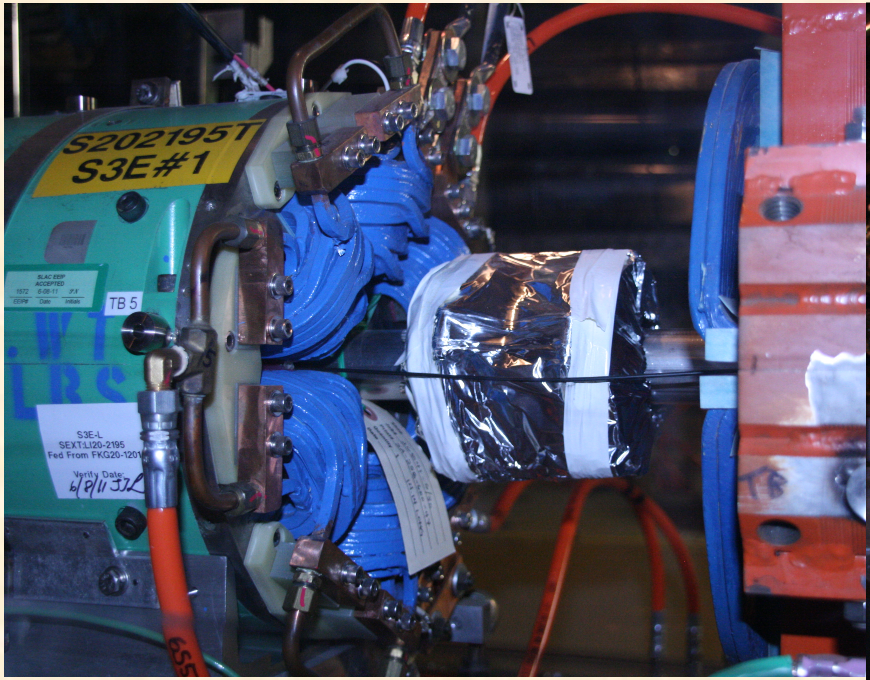
- And a resulting beam size

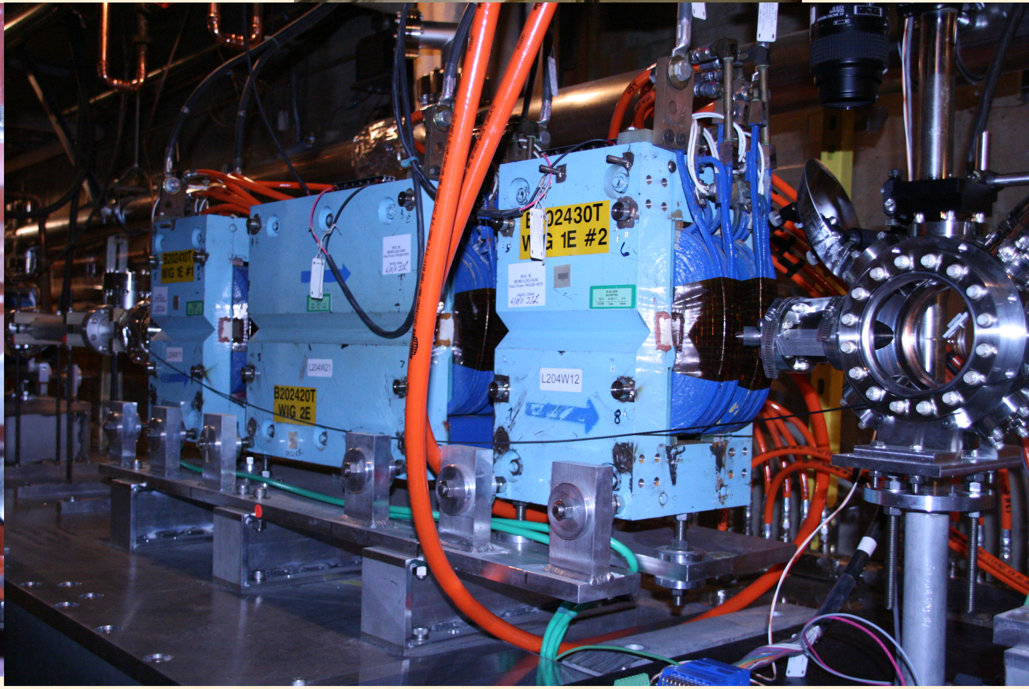
$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda\gamma m_e}\sin\Delta\psi\cos\varphi\right)^2}$$

Beam losses

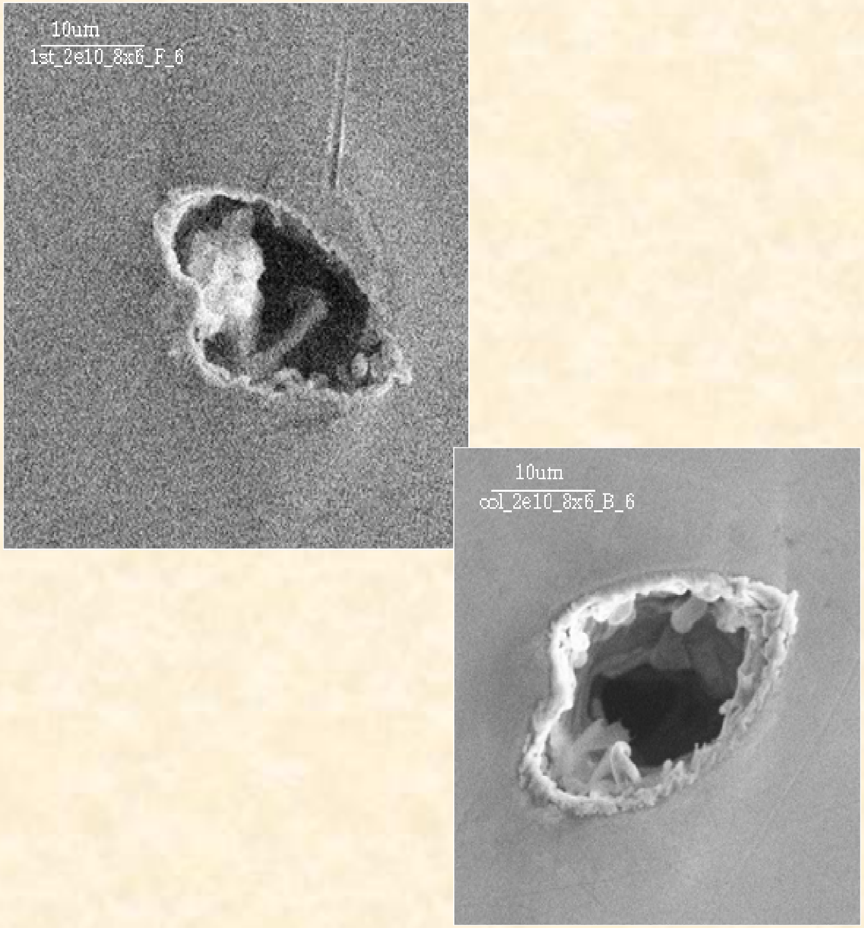
- It is important to monitor the beam losses directly:
- Small beam losses may not be detected by other systems
- Beam losses are a source of radiation and activation
- Most beam losses indicate that there is a problem somewhere.
- In some accelerators on optical fibre is used to track the losses (by induced Cerenkov light).
- Beam loss monitoring is often compulsory to minimize health risks.







Limitation of these monitors



- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

Summary
(particles interaction with matter)

	Interaction with matter
Charge	Faraday cup
Position	Screen
Size or shape (transv.)	Screen or wire-scanner/LW
Size or shape (longit)	RF cavity + screen
Energy	???
Losses	Scintillator

- We have seen that it is possible to build monitors which use the interactions of particles with matter.
- These monitors tend to be destructive: they significantly damage/modify the beam.
- These monitors tend to be simple but can be damaged by high energy and/or high intensity beams.

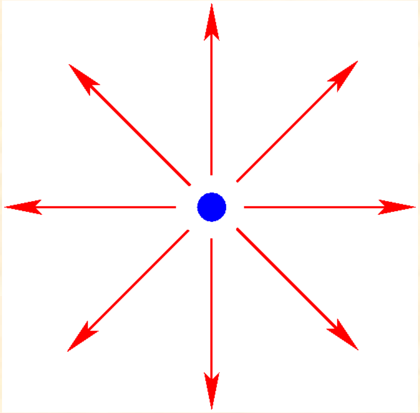
Quizz

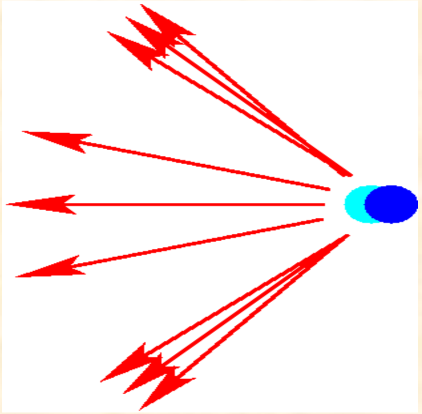
- Which diagnostic would you use to measure the quantum efficiency of an RF-gun?
  (a) A wire-scanner
  (b) A faraday cup
  (c) A screen
  (d) A deflecting cavity

Answer (b) [or (c)]

- The quantum efficiency is a measure of the charge (with respect to the laser energy) so the most appropriate diagnostic is the Faraday cup.
- However for relative measurements a screen can also be used.

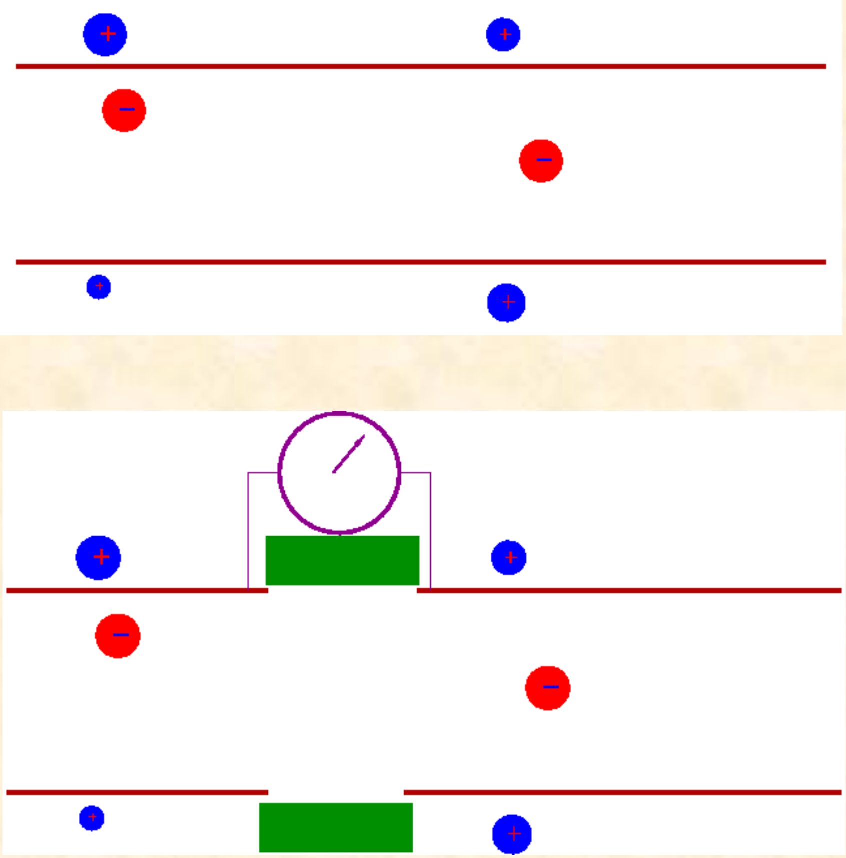
Charged particle





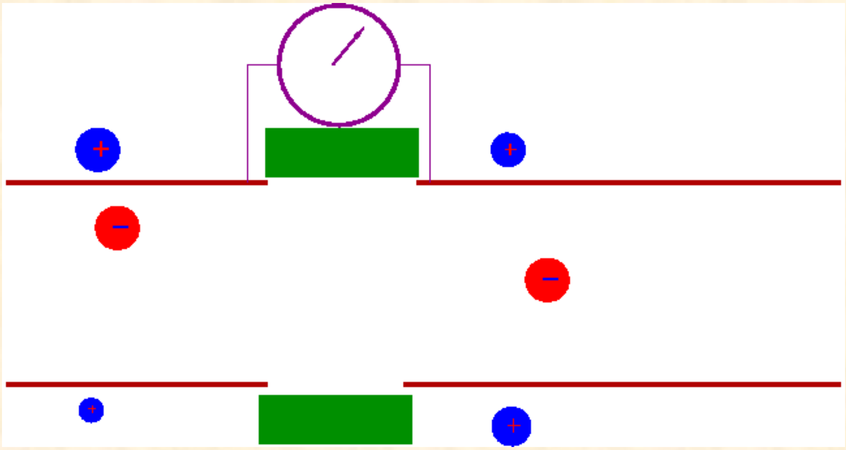
- Any charged particle "radiates"
- These electromagnetic radiations can be detected without disrupting the beam.
- One needs to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

Beam current monitor



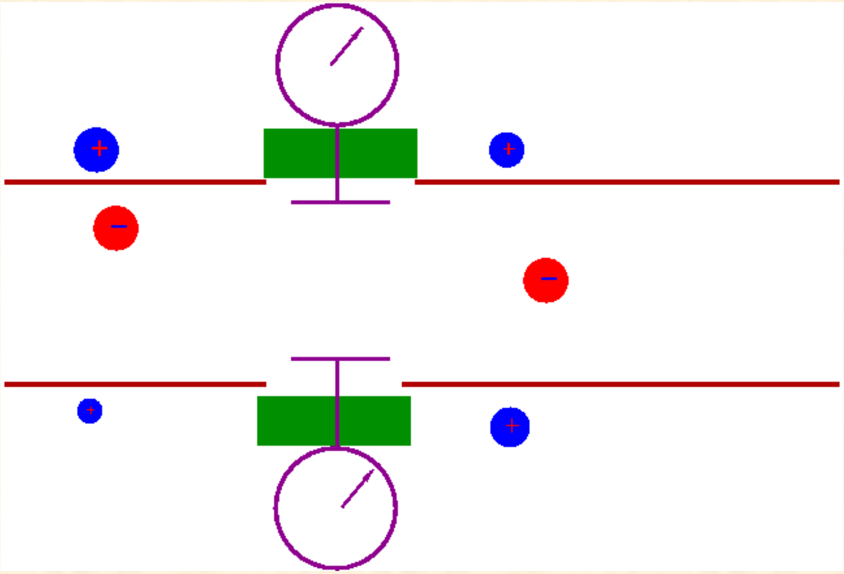
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

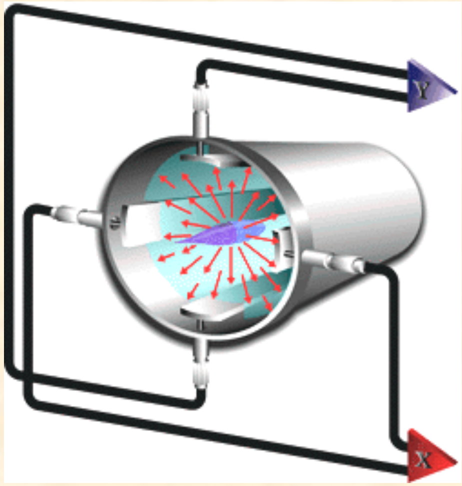
Beam current monitor vs Faraday cup



- Both devices have pros and cons.
- A Faraday cup destroys the beam but it gives a very accurate charge measurements
- A Beam current monitor does not affect the beam but must be calibrated.
- Both tend to be used but at different locations along the accelerator.

Beam position monitor

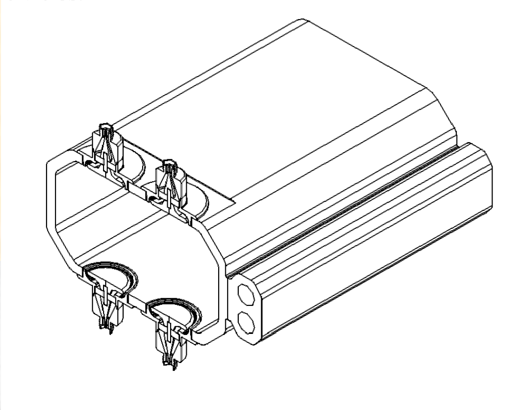


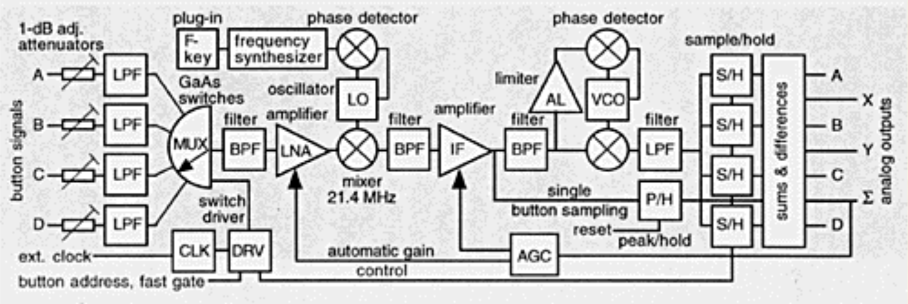


- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

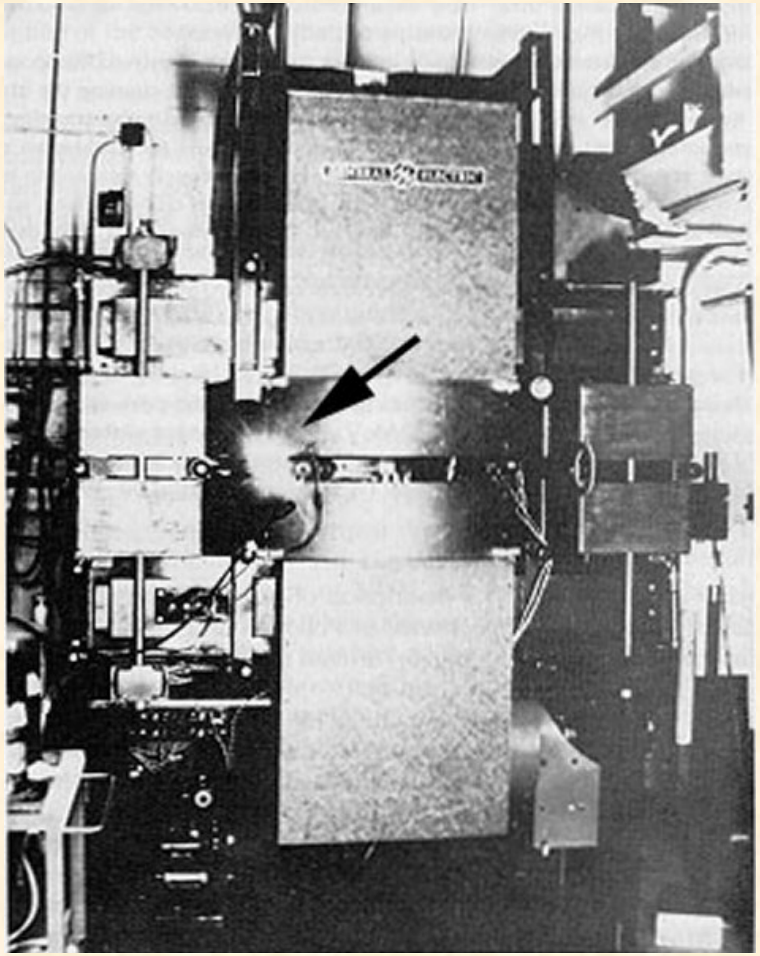
Beam Position Monitor (2)

- BPM are one of the most common diagnostic at an accelerator.
- They exist on many different configurations.
- At synchrotrons it is not possible to have electrodes in the horizontal plane so the electrodes have to be above or below the beam.
- Although the basic principle is simple, very advanced electronics are used to get he best possible precision.
- In typical synchrotrons there is a large number of BPMs, about 1 every 4 meters in the ring!

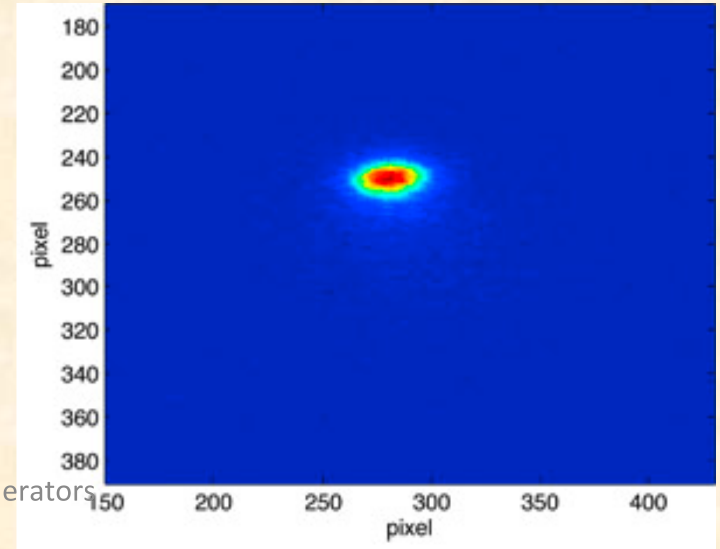




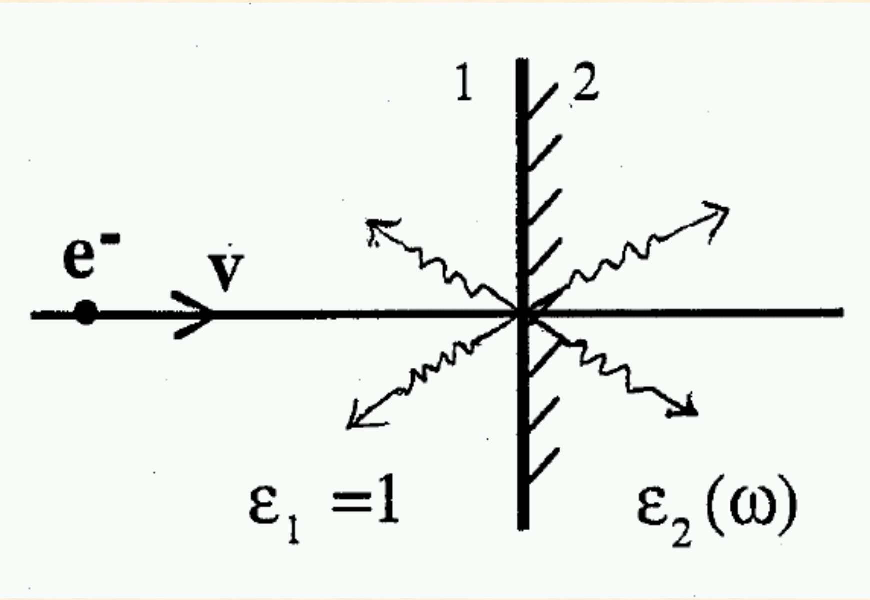
Synchrotron radiation

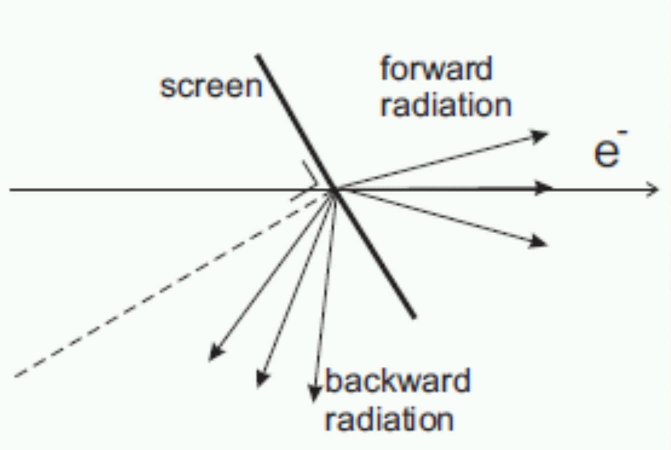


- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



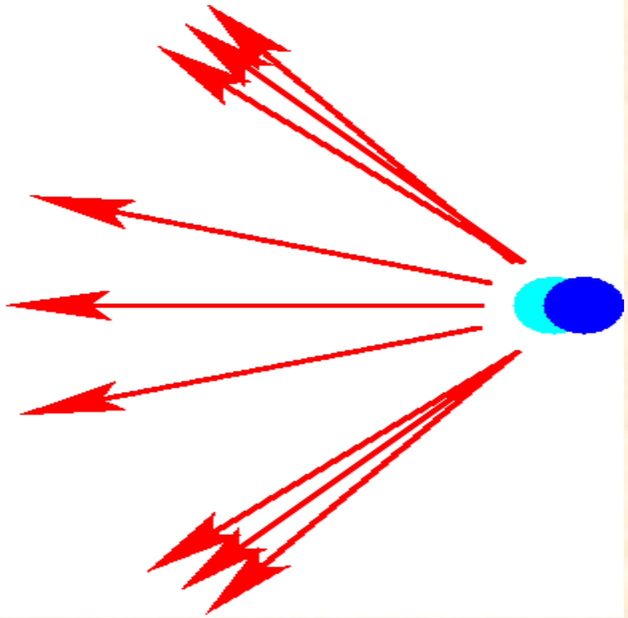
Optical Transition Radiation





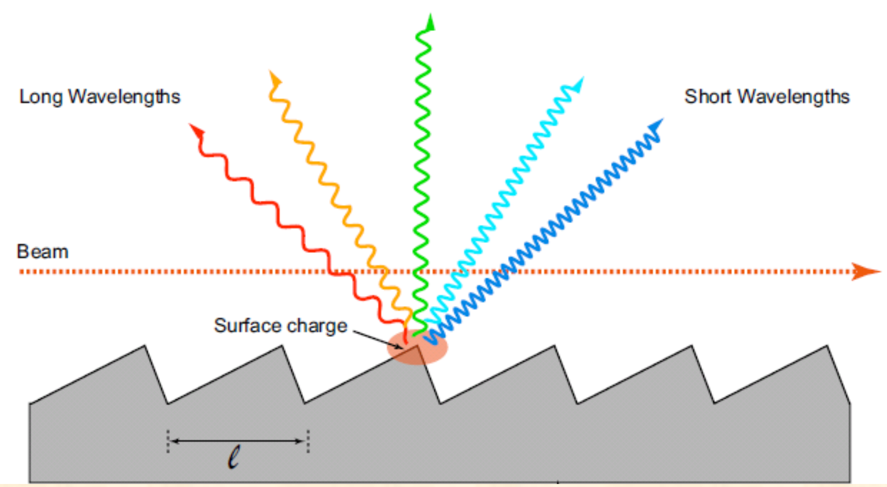
- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape (and possibly other things).
- As this is a surface effect, very thin (non disruptive) screens can be used.

Optical Diffraction Radiation



- It is also possible to use a screen to reflect the wake created by the charged particles bunch.
- This technique is called ODR.
- It is even less disruptive than OTR.

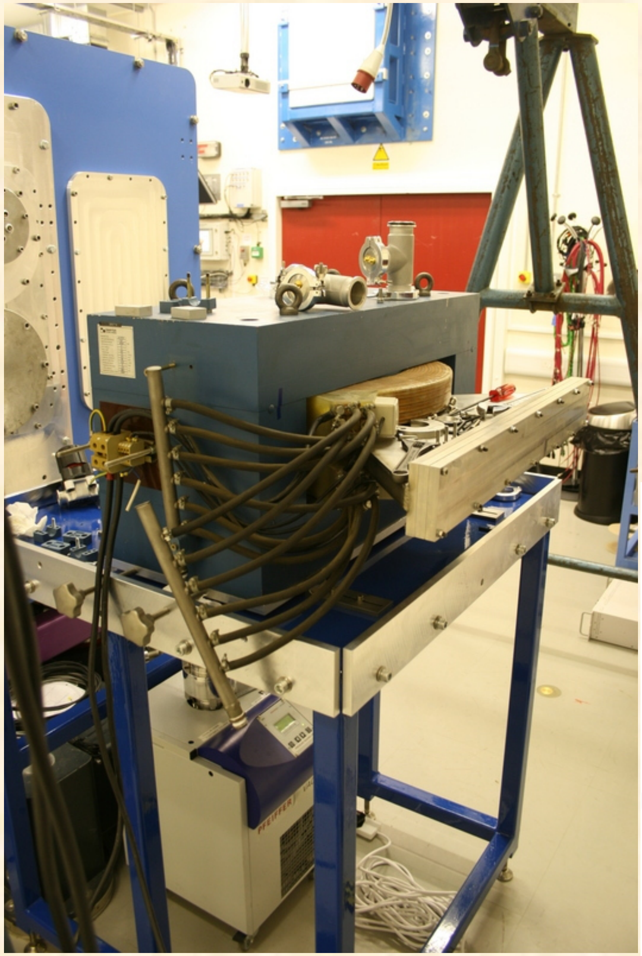
Longitudinal profiles



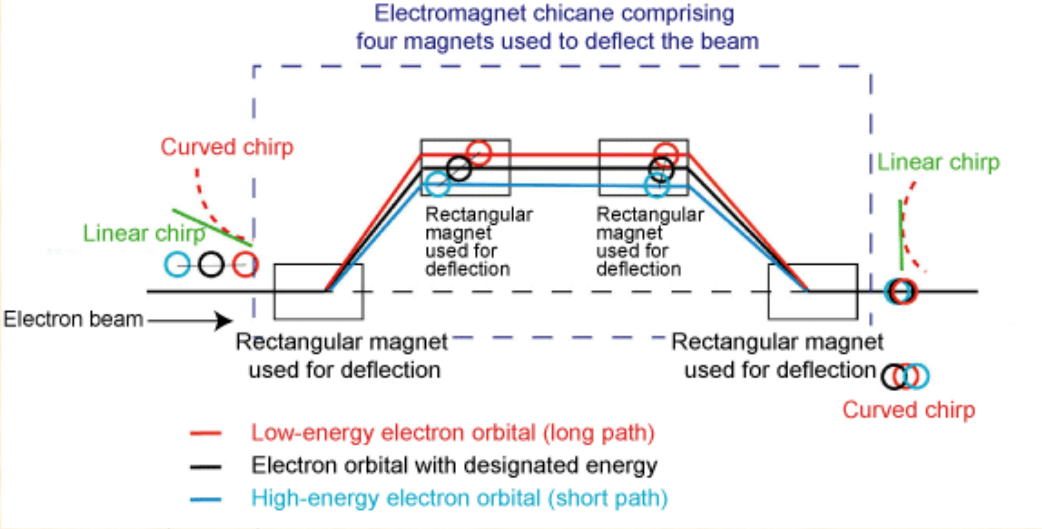
- Longitudinal profiles of short beams are one of the most difficult measurement.
- Several techniques use radiation induced by the beam.
- In the Smith-Purcell method a grating is used.
- The beam interacts coherently with the grating and emits radiation.
- The intensity and wavelength of this radiation depends on the longitudinal profile of the beam.
- Most longitudinal profile measurement techniques actually measure the Fourier transform of the beam => reconstruction needed!

$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)|F(\omega)|^2]$$

Energy measurements



- To measure (or select) the energy of the particles a bending magnet is often the best solution.
- This can be done in an “energy chicane”.



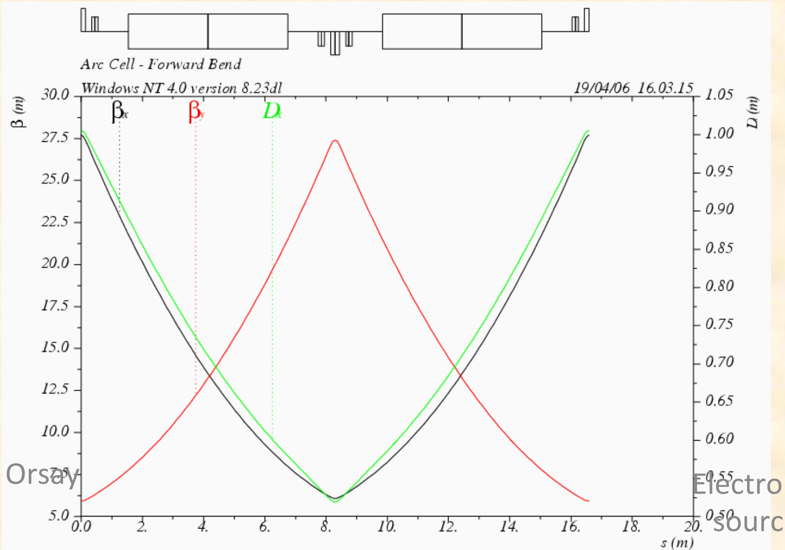
Diagnostics overview

	Interaction with matter	**Radiation**
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transverse)	Screen or wire-scanner	Synchrotron radiation or optical transition radiation
Size or shape (longitudinal)	RF cavity + screen	Radiation detectors (eg: Smith-Purcell)
Energy		Bending magnet
Losses	Scintillator	

Emittance measurement: Multi screen/wire method

- The emittance is not directly an observable.
- The beam size is an observable.
- By measuring the beam size at several locations it is possible to fit the best emittance.
- The beam size can be measured by using screens or wires (beam size measurements will be discussed next week during the diagnostics lecture).

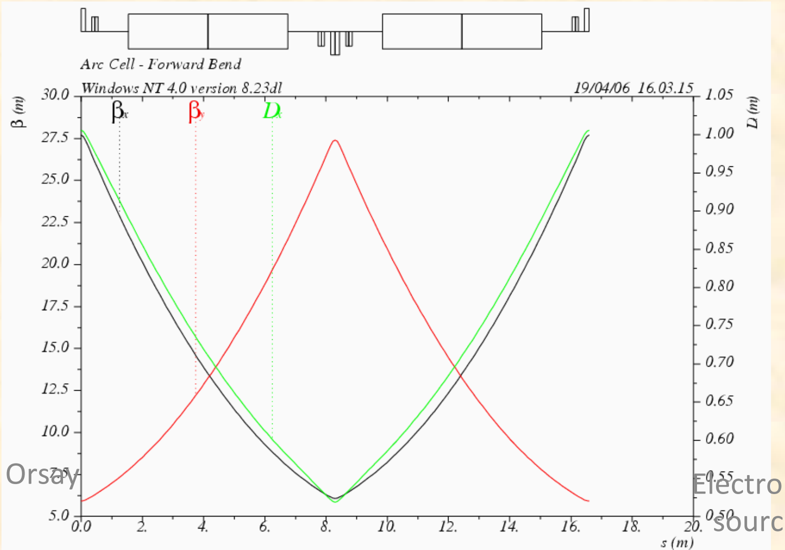
$$\sigma = \sqrt{\in(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$



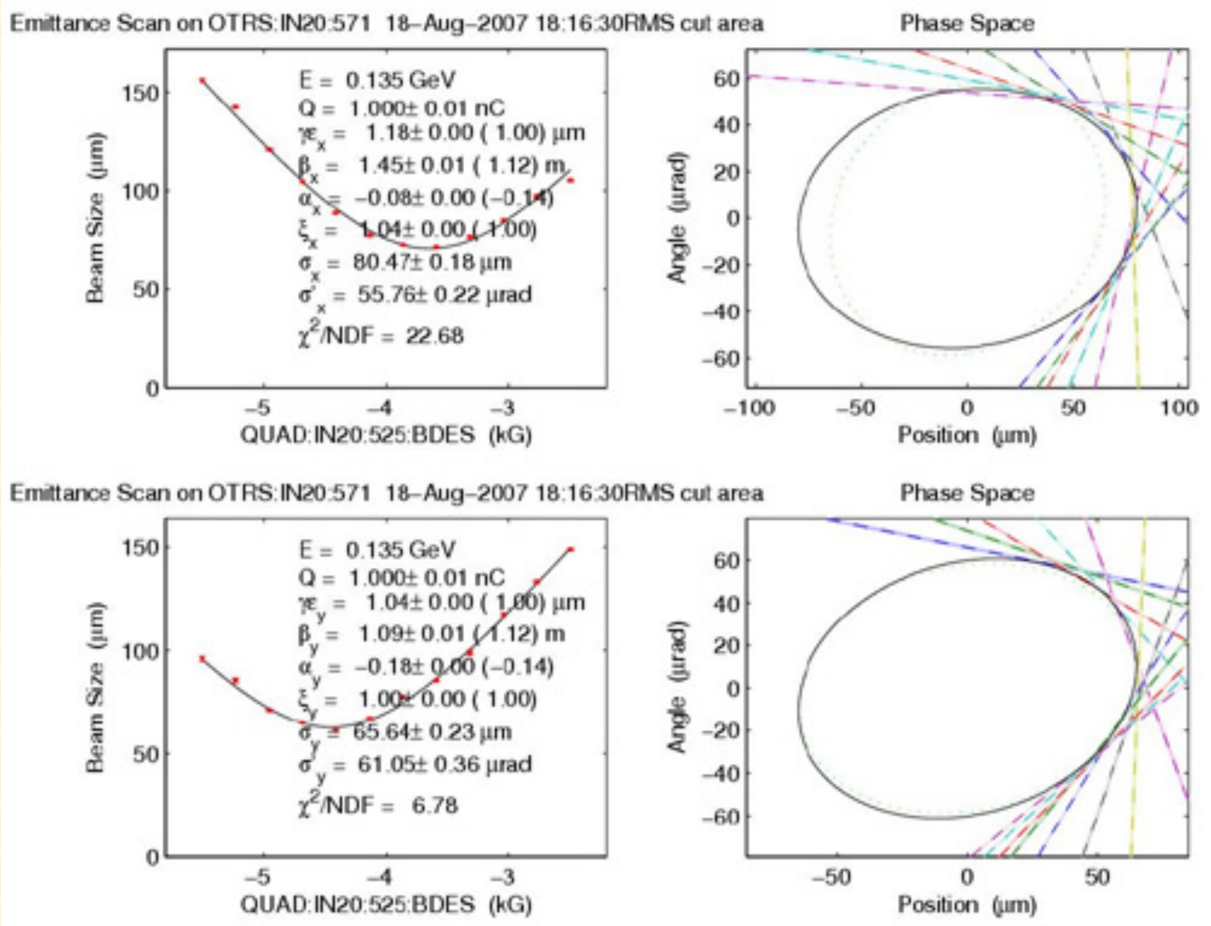
Quad scan

- The emittance can also be measured by changing the strength of a quadrupole and measuring the location at a fixed position.
- This modifies the beta function of the beam and once again this can be fitted to find the best emittance value.

$$\sigma = \sqrt{\in(\beta_0 - 2\alpha_0 s + \gamma_0 s^2)}$$



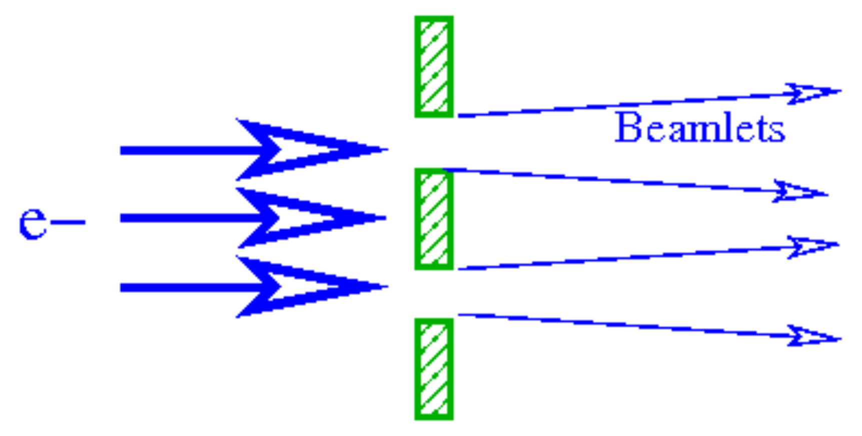
Quad scan emittance measurement

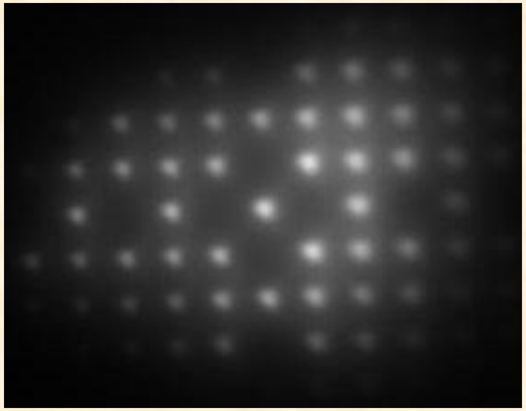


Source: LCLS

Pepper-pot (1)

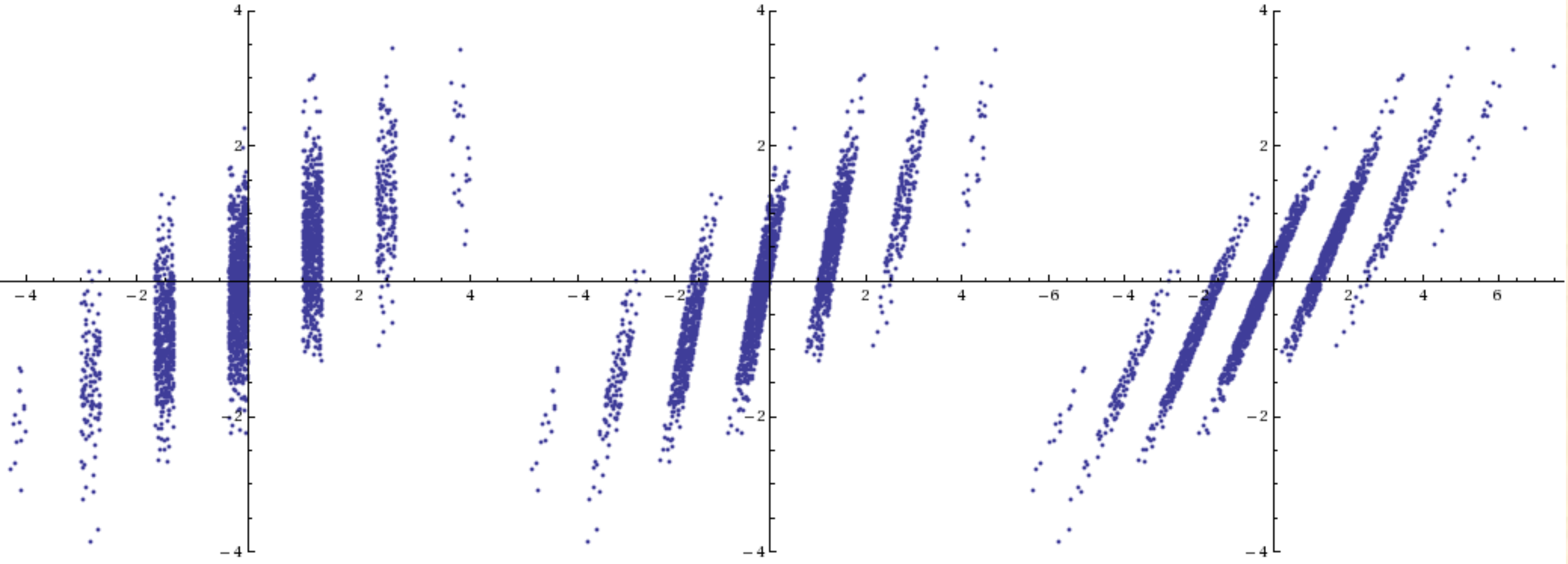
- A grid of dense material inserted in the beam path will split the beam in several beamlets.
- The transverse position at which these beamlets were created is know (it is the position of the grid).
- A measurement of the size of the beamlets downstream gives access to the beam divergence.
- The beam size plus the beam divergence can be combined to give the value of the emittance.





Pepper-pot measurement of the transverse emittance of a van de graaff

Pepper-pot (2)



- In the phase space, the effect of pepper-pot is shown above:
  - The beam is sampled at given x positions
  - After the pepper-pot, the beam drifts
- The measurement must be made close enough so that the beamlets do not overlap.
- The Pepper-pot method is a destructive single-shot technique (the beam is destroyed after the measurement but a single pulse is enough to make the measurement).
- It is used a low energy, for example for the study of particle gun properties.

Quizz

- If you want to study the effect of space charge in your photo-injector which diagnostic will you use?
  (a) Faraday cup
  (b) Beam position monitor
  (c) Screen
  (d) Spectrometer magnet
  (e) Pepper-pot

Answer (e) [or (c)]

- Space charge will affect the emittance and the size of the beam.
- The most appropriate diagnostic would be a pepper-pot that accurately measure the change in emittance (e).
- However a screen located at the correct location would also be suitable (c).

Beam diagnostics specific to ion sources

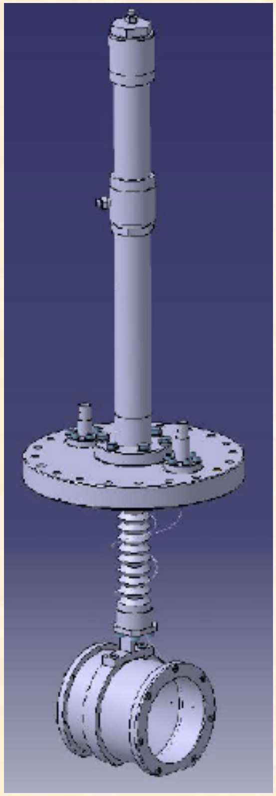
- Some diagnostics are specific to ion sources.

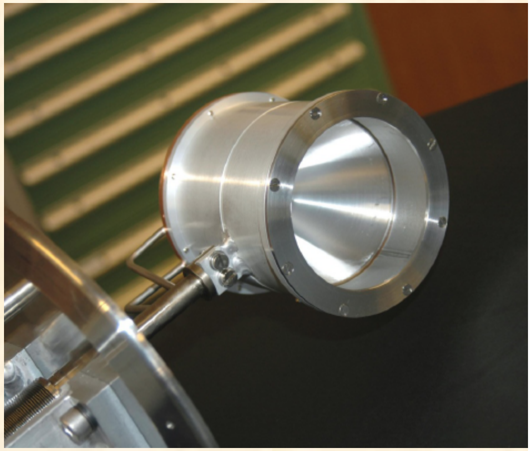
Quizz

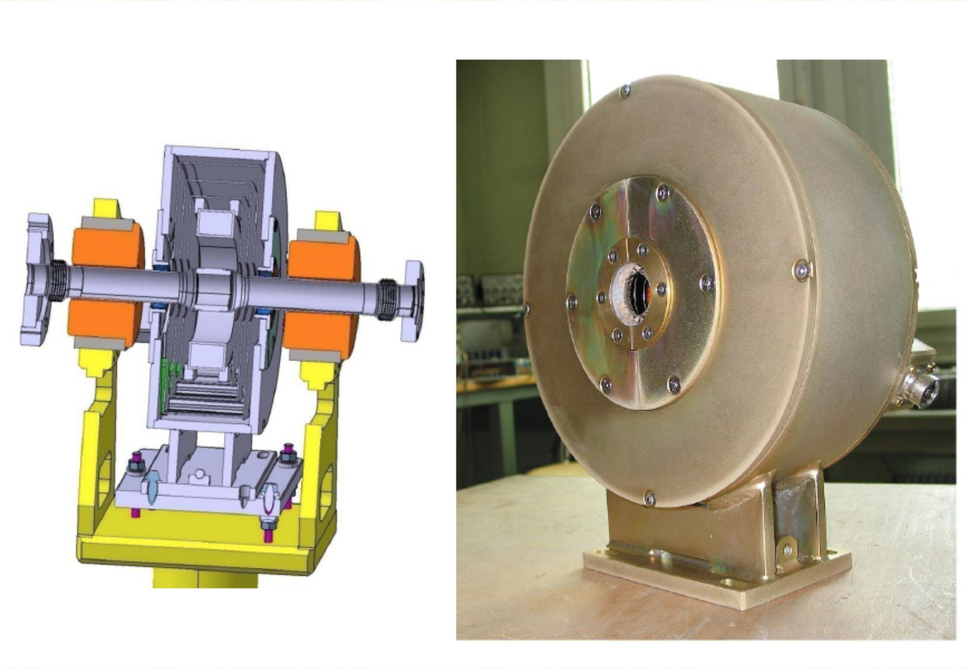
- How to measure the charge of a beam? (2 answers)

Answer

- Faraday cup (intercepting).
- Beam current monitor (non intercepting).

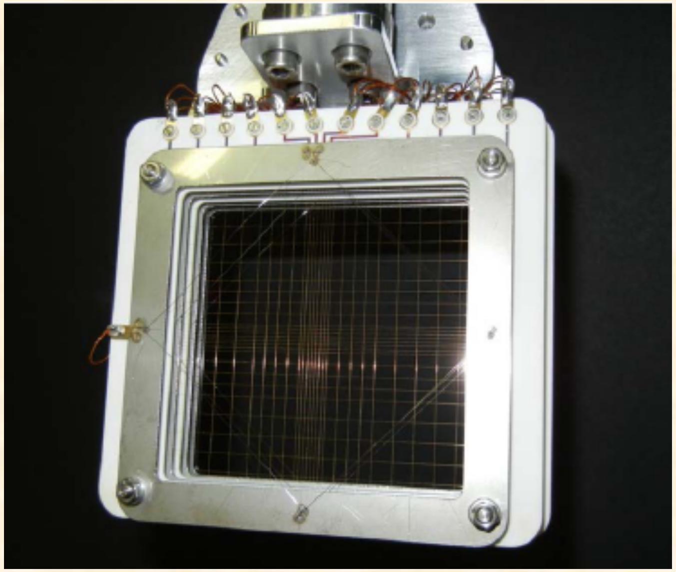


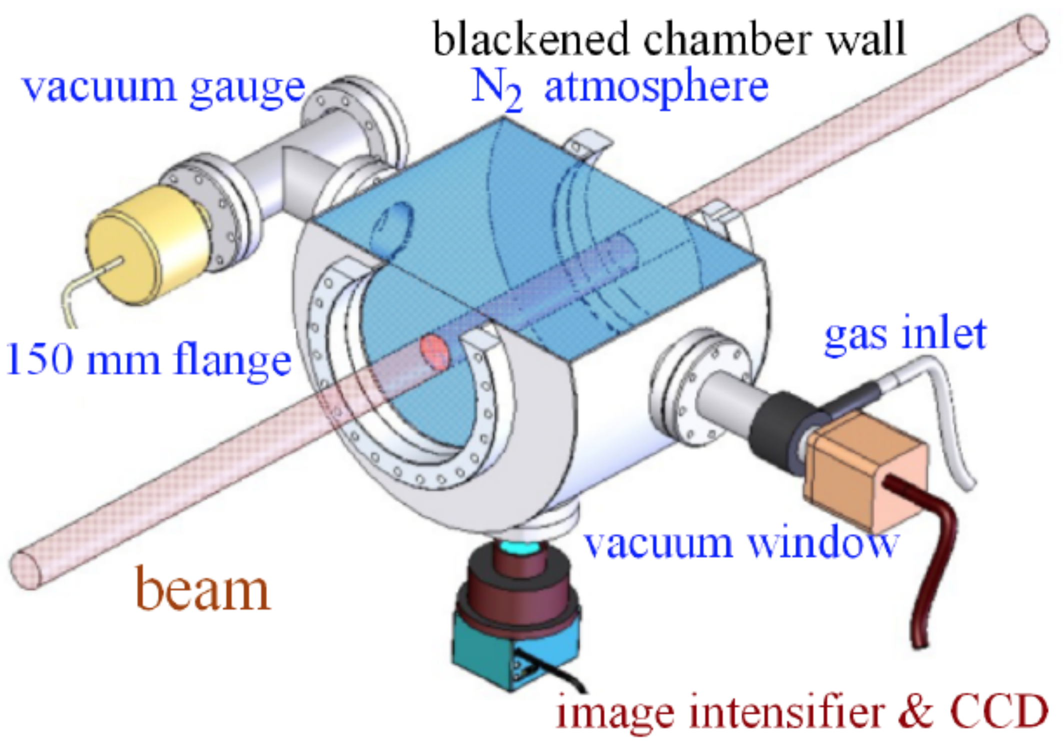




Profile measurements

- Screens are more difficult to use with low energy ions because they have very little kinetic energy.
- Grids of wires can be used instead.
- Gas fluorescence monitors can also be used.





Diagnostics summary

- The properties of a particle beam can be measured, either:
  - through its interactions with matter (destructive measurement)
  - or by detecting the radiation measurements (almost non perturbative measurement)
- The more accurate the measurement has to be the more precise/expensive the measuring equipment will be.
- Diagnostics for particle accelerators are an active research area with conferences dedicated to the topic every year.

Last year's exam

4) Describe in detail one physical process that allows to ionize atoms in an ion source (2/20).

5) Discuss on the relative difficulty of producing ions using Fluor (Z=9), Neon (Z=10) and Sodium (Z=11). The atomic configuration of sodium is 1s2 2s2 2p6 3s1. (2/20)

Homework

- Which source is used for the LHC on Linac 2, on Linac 3 and on Linac 4? Why?
- Which source is used at Synchrotron SOLEIL? (You will be able to answer why after the beam dynamics courses)
- Which source will be used at the European XFEL? Why?

The answers to these questions will be assumed as known for the exam.

Recommended readings

(and credits for some of the material used in this lecture)

- CERN Accelerator School (CAS) on Ion source, June 2012:
  http://cas.web.cern.ch/cas/Slovakia-2012/Senec-advert.html

Lectures slides are at

http://lal.delerue.org/teaching/2018_GI