Particle sources
Part II:
Ion Source Background

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JYVÄSKYLÄN YLIOPISTO

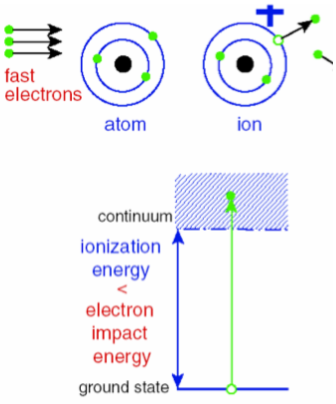
- Ionization and charge exchange
- Cross sections, mean free path and balance equation
- Definition of plasma and some important plasma parameters
- Charge in magnetic field
- Waves in plasma
- Beam formation

Production of ions: how to produce?

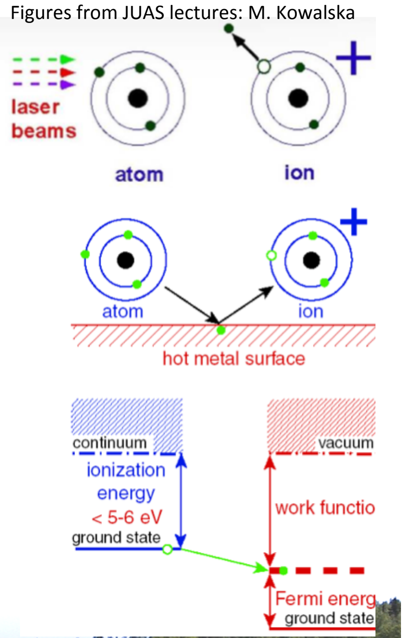
Again: extra energy has to be given to electron in order to get it out from atom!

Positive ions:
- Electron impact
- Photons
- Hot surface

Usually used



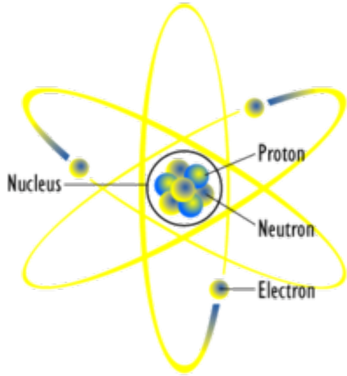
Figures from JUAS lectures: M. Kowalska



Negative ions:
- Electron attachment (rare)
- Molecule dissociation $AB + e^- \Rightarrow AB^{-*} \Rightarrow A^- + B$
- Molecule excitation (has the highest probability)
- Charge exchange (on hot surface)

In order to understand ionization processes we have to know something about atoms

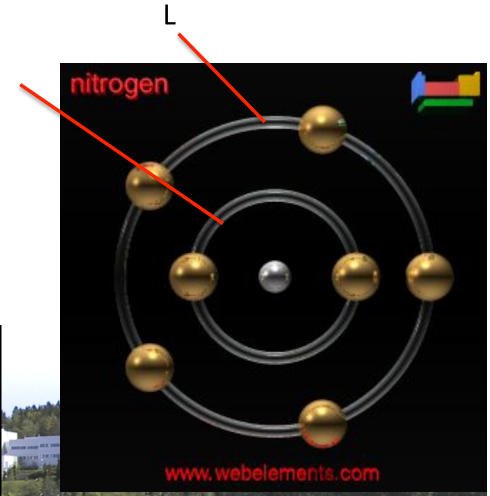
Atoms: Electronic configuration



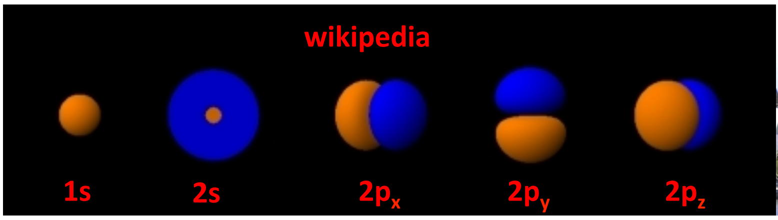
Electron configuration is the distribution of electron in atom. Each atom and its electrons have specific configuration.

Atom is divided to electron shells: principle quantum number *n*: *K* (*n* = 1), *L* (*n* = 2), *M* (*n* = 3),… Each shell can have $2n^2$ electrons, i.e. *K* shell 2 electrons, *L* shell 8 electrons, *M* shell 18 electrons, etc….

2 from spin up (↑), spin down (↓)

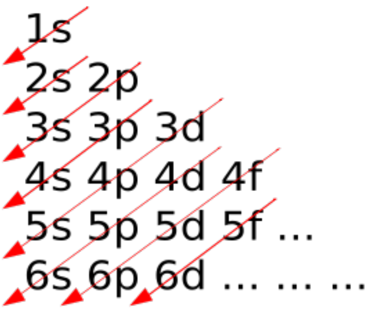


Each shell is divided to subshells *l*: *s*, *p*, *d*, *f* (0, 1, 2, 3)
Maximum number of electrons in the subshell: 2(2*l* + 1), i.e. *s*: 2, *p*: 6, *d*: 10, *f*: 14



Electronic configuration:

How to fill the shells/subshells? Electronic structure follows Madelung rule.



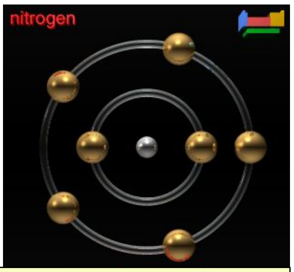
Klechkovski (or Madelung) rule
Wikipedia

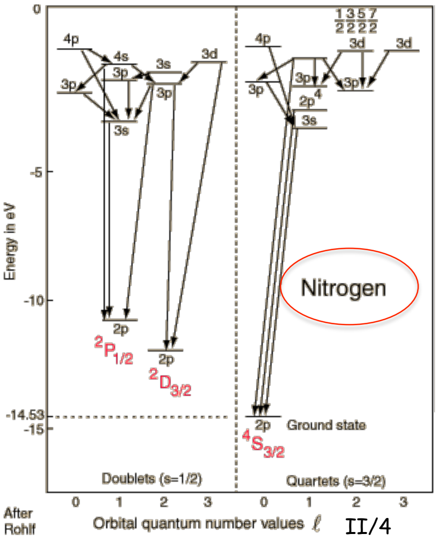
For example

Nitrogen: 7 electrons $1s^2 2s^2 2p^3$

Neon: 10 electrons $1s^2 2s^2 2p^6$

Argon: 18 $1s^2 2s^2 2p^6 3s^2 3p^6$

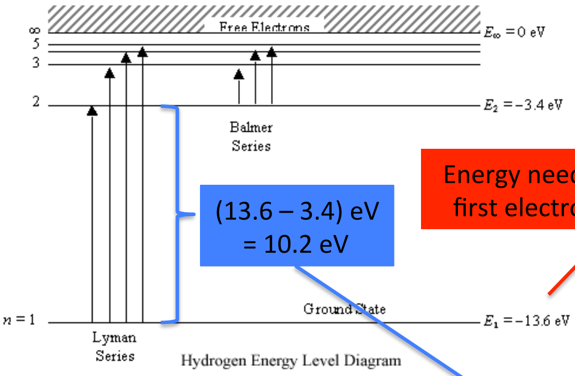




Atom is "filled" following Madelung rule. This corresponds to lowest electronic energy (ground state). The lowest excited state is when the outermost electron moves to next orbital (following Madelung rule). This requires external energy. If enough energy is given the electron can be "removed" from the atom. Consequently an *ion* is created!

Energy levels:

Each element has its own electronic configuration and consequently different energy levels, i.e its own “fingerprint” . This property/selectivity can be used in some applications (for example resonant ionization, Part III)

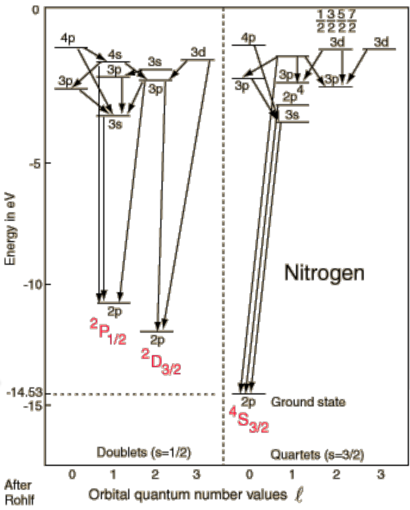


http://web.njit.edu/~gary/321/Lecture5.html

(13.6 – 3.4) eV = 10.2 eV

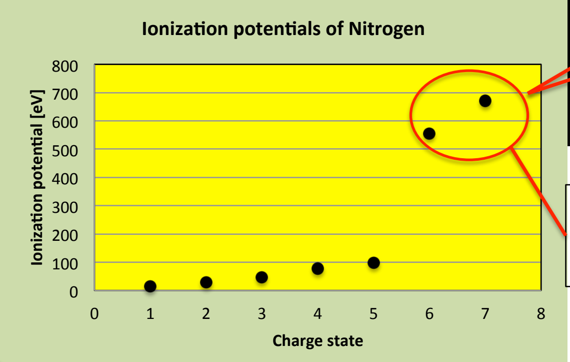
Energy needed to remove the first electron from the atom

Energy needed to excite electron from the ground state to 1st excited state



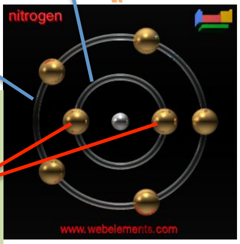
Ionization of atoms and ions:

- Energy is needed in order to remove the electron from the atom/ion.
- The energy depends on the shell structure and increases with charge state.
- First ionization energy: minimum energy to remove an electron from the highest occupied sub-shell
- Second ionization energy: minimum energy needed to remove the second electron from the highest occupied sub-shell of gaseous atom
- Third, fourth,...analogous...



K

L



Inner shell electrons: strongly bound to atom

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

Reaction cross section (σ):

Typically atom is ionized by electron impact. Ionization energies shown in the previous table are the minimum energies making the ionization possible. The ionization occurs also with higher impact energies. Note that ionization probability after the threshold energy is not constant – instead it varies with the energy. This probability can be described by the reaction cross section σ.

The cross section is an effective/specific area (dimension: *m²*) regarding the event of interest. It can be for example:

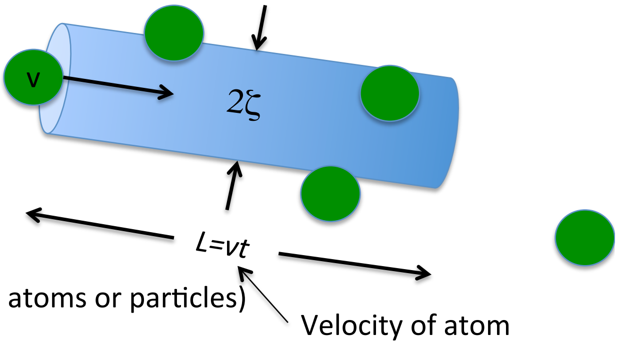
- Absorption/capture
- Scattering
- Fission
- Elastic collision
- Charge exchange
- Ionization
- Etc,….

Reaction cross section is very important parameter for example in the particle and nuclear physics but also in the field of ion sources!

Concept of reaction cross section σ and mean free path λ

Elastic collisions between atoms:
An atom having a diameter of ζ suffers a collision with another atom if anywhere its center is within distance ζ of the center of another atom. Therefore it sweeps out without collision a cylinder of diameter 2ζ. We obtain that ***the cross section*** for the elastic collision is:

$$\sigma = \pi\zeta^2$$



The volume V of the cylinder is:

$$V = \sigma L = \sigma v t$$

The number of collisions the atom experiences during the path L is:

$$N_{coll.} = \sigma v t n_{atoms}$$ (n_{atoms} = density of target atoms or particles)

Distance between the subsequent collisions, i.e. mean free path λ is:

$$\lambda = \frac{\text{Length of cylinder}}{\text{Number of collisions}} = \frac{vt}{\sigma v t n_{atoms}} = \frac{1}{\sigma n}$$

σ [m²]: any cross section
n [1/m³]: density of any targets

Note: In this case the target atom is not moving. If projectile and target atoms have same velocities the equation has to be divided by $2^{1/2}$

Ionization cross section:

Ionization cross section depends on:

- Charge state of atom/ion to be ionized
- Energy of electron
- Atomic number of target atom/ion

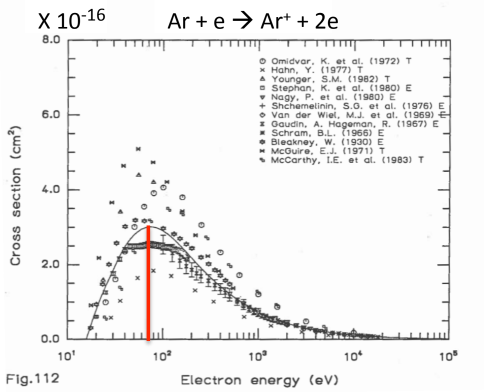


Fig.112

- Cross section is 0 if energy of electron E_e < ionization potential (minimum energy needed for ionization)
- Maximum cross section is reached when $E_e \approx 3$ x ionization potential. After this value cross section start to decrease
- Cross section can be estimated by Lotz formula

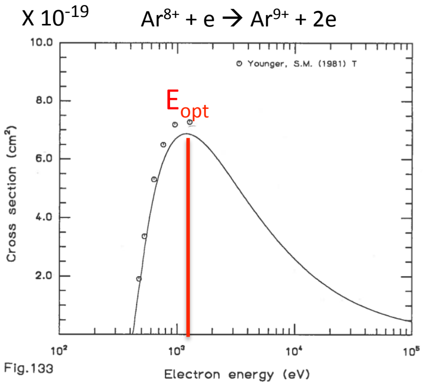


Fig.133

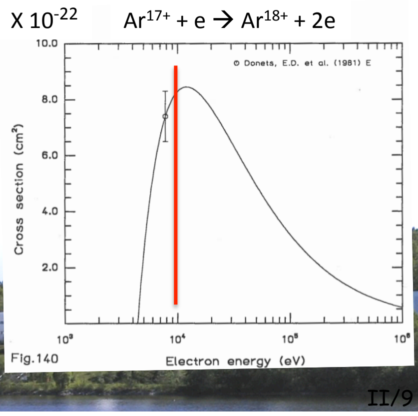
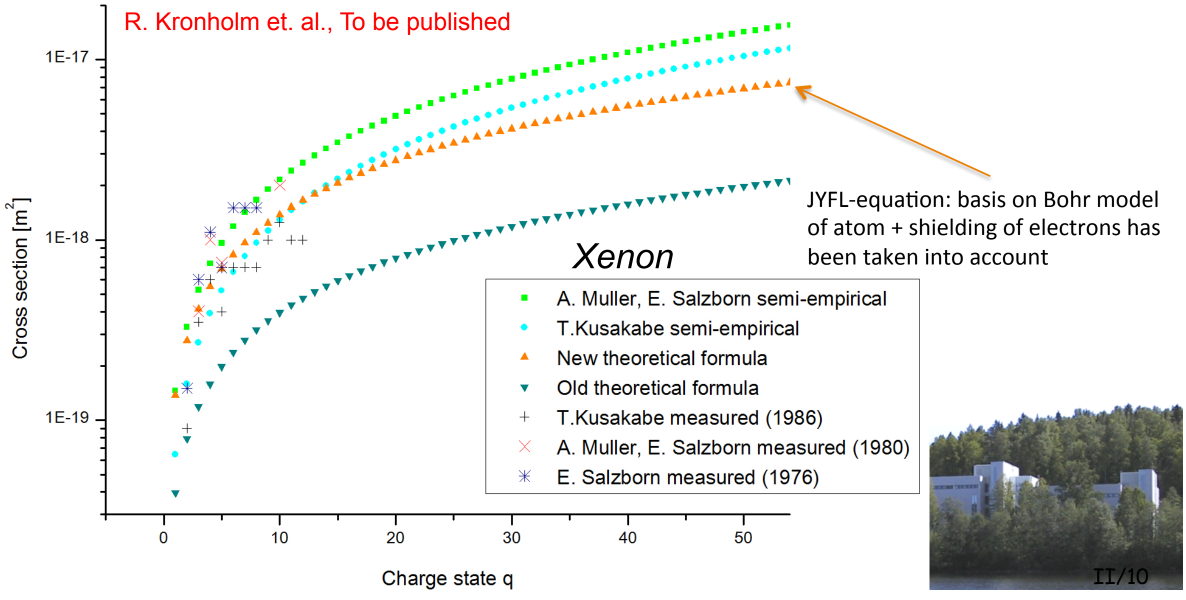


Fig.140

Charge exchange:

- Charge exchange is a destructive process and its meaning increases with the charge state.
- Its cross section can be estimated by different equations (for low energy ions!). For example Kusakabe (semi-empirical), Muller-Salzborn (semi-empirical), H. Knudsen (equation based in Bohr model of atom),…

Cross section for charge exchange between highly charged xenon ions and neutrals:



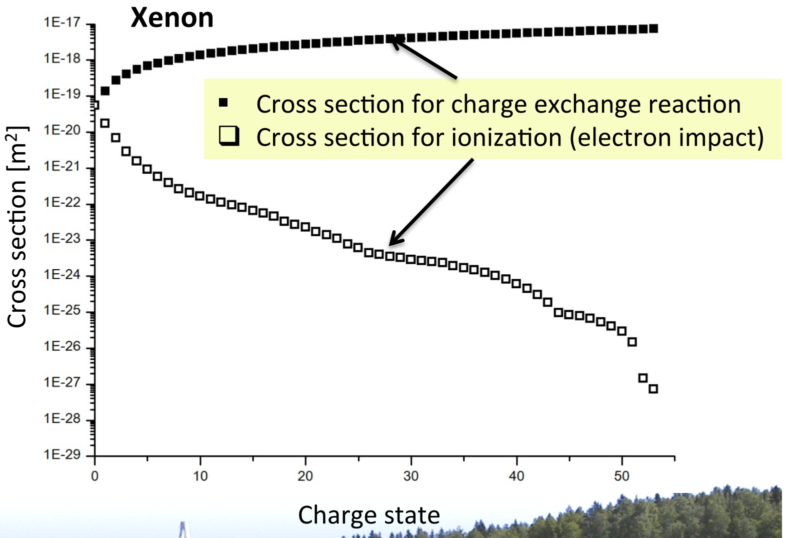
JYFL-equation: basis on Bohr model of atom + shielding of electrons has been taken into account

Ionization versus charge exchange:

In the case of highly charged ions the charge exchange cross section can be several orders of magnitudes higher than the ionization cross section

In steady state condition there is a balance between ionization part and charge exchange part for each charge state (next page: balance equation).

This balance can be changed mainly by changing the densities of electrons (ionizing part: creation) and density of neutrals (charge exchange part: destruction)



$$\lambda_{ionization} = \frac{1}{n_{q-1\to q}\sigma_{ionization}}$$ (creation part)

neutral/ion to be ionized

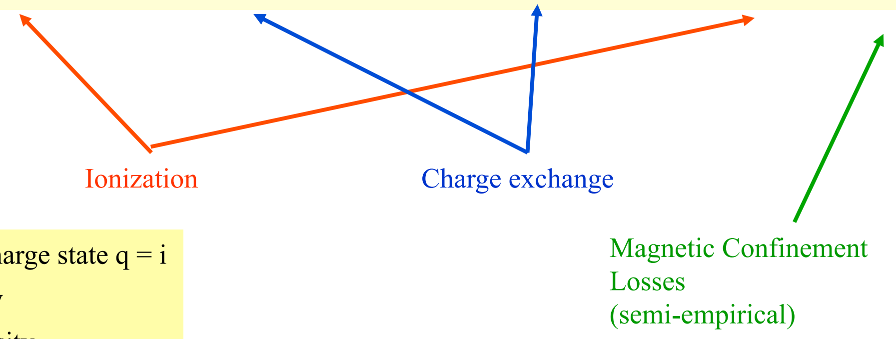
$$\lambda_{\text{charge exchange}} = \frac{1}{n_n\sigma_{\text{charge exchange}}}$$ (destructive part)

Balance equation: plasma of multi-charged ions:

- The processes regarding the each charge state can be described by balance equation:

Creation Destruction

$$\frac{dn_q}{dt} = n_e\left\langle\sigma^{ioniz}_{q-1\to q}v_e\right\rangle n_{q-1} + n_0\left\langle\sigma^{exc}_{q+1\to q}v_i\right\rangle n_{q+1} - n_0\left\langle\sigma^{exc}_{q\to q-1}v_i\right\rangle n_q - n_e\left\langle\sigma^{ioniz}_{q\to q+1}v_e\right\rangle n_q - \frac{n_q}{\tau_i}$$



Ionization

Charge exchange

Magnetic Confinement Losses (semi-empirical)

n_i = ion density, charge state q = i

n_0= neutral density

n_e= electronic density

τ_i= confinement time

Cross section examples:

Example 1: How the intensity of H^+ and Xe^{35+} ion beams decrease (because of charge exchange) when the beam is transported from ion source to the entrance of acceleration?

Lets find out how the intensity decreases when the beam propagates in the beam line towards acceleration:

The probability P for the charge exchange reaction is:

$$P = n_{ce} \sigma dx$$

The intensity I decreases as:

$$dI = -I_0 n_{ce} \sigma dx$$

By the integration we obtain:

$$I = I_0 e^{-\underbrace{n_{ce}\sigma}_{=1/\lambda} x}$$

(slow background, fast beam)

This gives the decay of intensity due to the charge exchange (*ce*) during the beam transport along the beam line. We just have to know the reaction cross section and the pressure inside the beam line. Please notice the *ce* cross section vs beam energy

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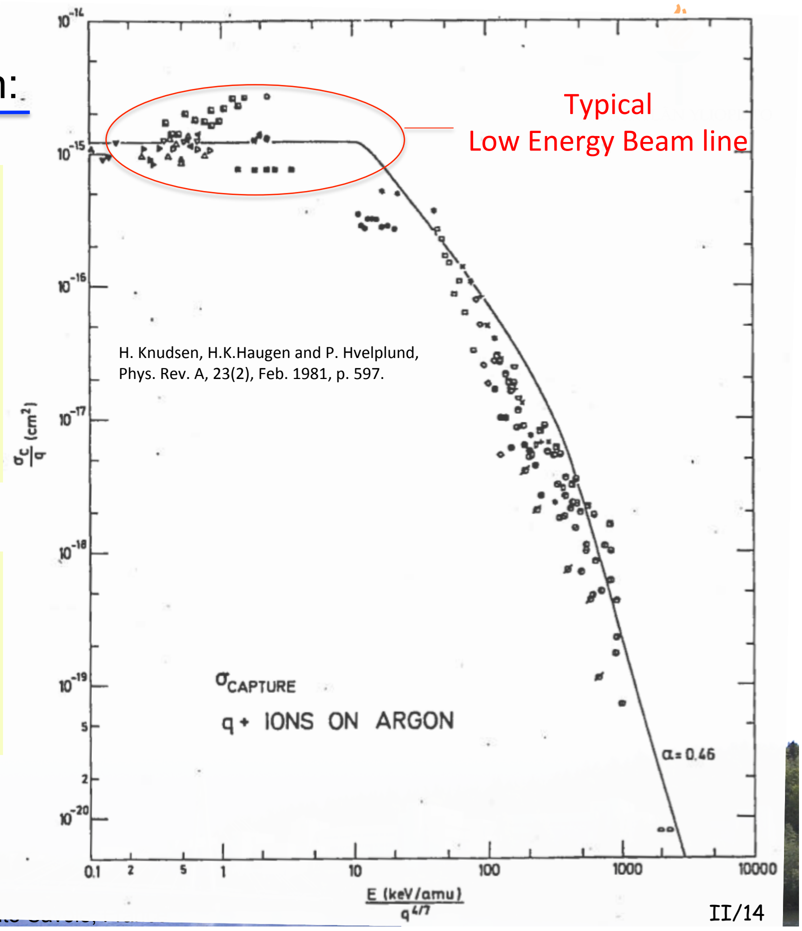
Energy versus charge exchange cross section:

Notice: the charge exchange cross section is more or less constant at low beam energies as is shown by the graph on right. After the threshold energy the cross section start to decrease vigorously. Check if you are beyond this point!

At low energies you can use this graph or afore-mentioned equations/graphs to get “rough” estimation about the cross section.



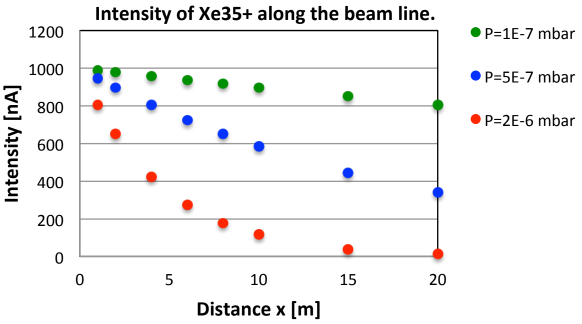
Typical
Low Energy Beam line

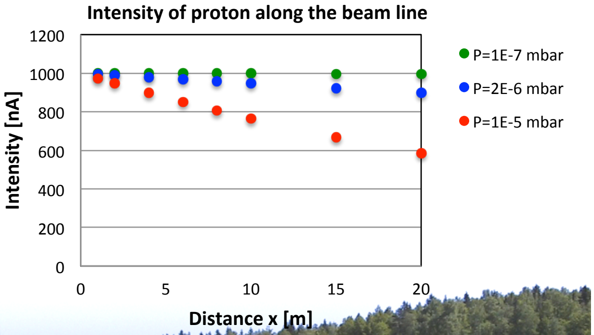
H. Knudsen, H.K.Haugen and P. Hvelplund, Phys. Rev. A, 23(2), Feb. 1981, p. 597.

Charge exchange and intensity decay in Low Energy Beam line:

Examples (for charge exchange):

- Xe^{35+} ($\sigma_{ce} \approx$ 4E-18 m^2)
- proton beam ($\sigma_{ce} \approx$ 1E-19 m^2)
- Intensity after the ion source: 1000 nA
- Length of LEBT: 20 m


Intensity of Xe35+ along the beam line.


Intensity of proton along the beam line

As this example shows the pressure of Low Energy Beam line plays an important role in beam transport in the case of highly charge ion beams. This is due to charge exchange reaction. As can be seen the pressure should not exceed the value of about 1E-7 mbar. In the case of low charge states the pressure requirement is at least one order of magnitude “easier”. Note: do not forget elastic collisions! This reaction has the cross section corresponding to physical size of atom.

Example 2: Penetration of neutral into the plasma vs electron impact ionization

Mean free path of electron before the ionization is defined as

$$\boxed{\lambda = \frac{1}{n_n \sigma_{ion}}}$$

Remember: $t = \lambda / v$ (time to travel the length of 1 mean free path)

It can be assumed that an average collision (=ionization) frequency is

$$\boxed{f = v_e n_n \sigma_{ion}}$$

(calculate the time between subsequent collision)

and the total volumetric ionization rate is

$$\boxed{f_{tot} = v_e n_n \sigma_{ion} n_e}$$

(this can be used for any volumetric reaction rate if cross section and density are known)

An average ionization frequency the neutrals experience is

$$\boxed{f = \frac{v_e n_n \sigma_{ion} n_e}{n_n} = v_e \sigma_{ion} n_e}$$

Because $t = \lambda / v_n$ (time before ionization) we get

$$\boxed{\lambda = \frac{v_n}{v_e \sigma_{ion} n_e}}$$

= penetration depth of neutral into the plasma against electron impact ionization

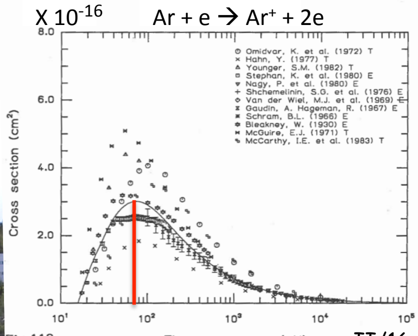


Fig.112

Example 2 continues…

Same way we get

$$\boxed{\lambda = \frac{v_n}{v_q \sigma_{ce} n_q}}$$

= penetration depth of neutral into the plasma against charge exchange reaction

Lets assume: total electron density = 5 · 10^{11} electrons/cm^3 (≈ typical for ECRIS), about 50 % having energy ≈ 20 eV and about 50 % having energy ≈ 50 keV (cold and hot electron population, both ≈ Maxwellian). We get for neutral argon atom (electron impact ionization):

λ (20 eV, T_n = 273 K) = 17 mm (≈ σ_{ion} = 3E-20 m^2)
λ (50 keV, T_n = 273 K) = 34 mm (≈ σ_{ion} = 3E-22 m^2)
λ (20 eV, T_n = 11600 K) = 110 mm (≈ σ_{ion} = 3E-20 m^2)

2nd generation neutral

Notice: Although the ionization cross section is much lower for 50 keV electrons this is compensated by much higher velocity!

Homework: make some assumptions and then estimate:

production rate for Xe^{35+} → Xe^{34+} via charge exchange
production rate for Xe^{35+} → Xe^{36+} via electron impact

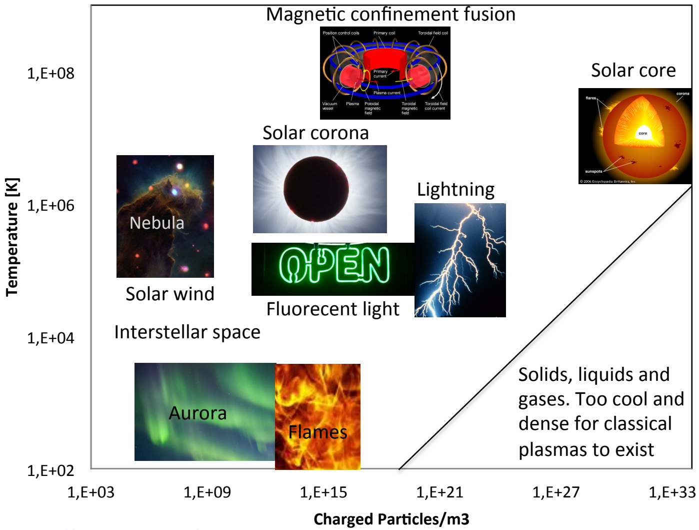
Definition of plasma:

Now we know how to ionize atoms →eventually plasma is generated!

Plasma: quasineutral (macroscopically neutral) substance containing many interacting electrons and ionized atoms or molecules, which exhibit collective behavior due to long range Coulomb forces. Plasma can be considered as fourth state of matter.

Has to fulfill following conditions:

- L>>λ_D, where L is characteristic length of the plasma and is λ_D Debye length
- $$N_D = \frac{4}{3}\pi\lambda_D^3 n_e >> 1$$
- Plasma frequency ω_p is large compared to neutral-electron collision frequency



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Debye length:

Debye length is the length where free charges (of plasma) screen out electric field. The initial amplitude of electric field decreases to the value of E_0/e within the Debye length.

It can be derived starting from Boltzmann constant: $e^{\frac{-E}{kT}}$ where energy E includes both kinetic and potential energy. However, the spatial dependence of distribution depends only on the electric potential, i.e.

$$n \propto e^{\frac{-q\phi}{kT}}$$

Including distribution for ions and electrons and assuming that the potential is zero far from the "disturbance" we will get:

$$\varepsilon_0 \frac{d^2\phi}{dx^2} = e(n_e - Zn_i) = en_{e\infty}\left(e^{\frac{e\phi}{kT_e}} - e^{\frac{-eZ\phi}{kT_i}}\right)$$

Remember Poisson equation:

$$\nabla^2\phi = -\rho/\varepsilon_0$$

density

Assuming that $e\phi/kT$ is small we obtain:

$$\frac{d^2\phi}{dx^2} \approx \frac{e^2 n_{e\infty}(1 + ZT_e/T_i)}{\varepsilon_0 kT_e}\phi$$

Remember:

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ...$$

Remember:

$$\frac{d^2\phi}{dx^2} = \text{constant}\phi \;\Rightarrow\; \text{solution } \phi = \underbrace{Ae^{\sqrt{\text{constant}}x}} + Be^{-\sqrt{\text{constant}}x}$$

Goes to infinity, not a possible solution!

Consequently we obtain: $\phi(x) \propto e^{-\frac{x}{\lambda_D}}$

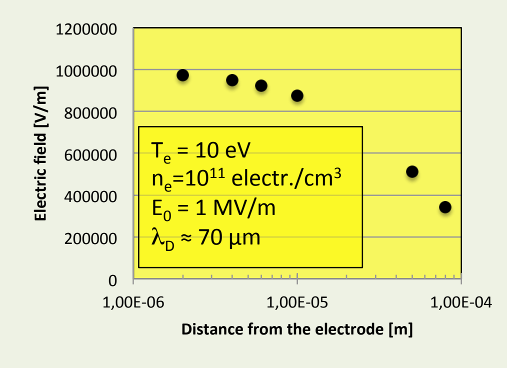
$$\text{where } \lambda_D \equiv \left(\frac{\varepsilon_0 kT_e}{n_e e^2(1 + ZT_e/T_i)}\right)^{1/2} \text{ where } \lambda_D \text{ is Debye length}$$

Note: usually ion part is omitted ($T_e >> T_i$)

$$\boxed{\Rightarrow \lambda_D \equiv \left(\frac{\varepsilon_0 kT_e}{n_e e^2}\right)^{1/2}}$$

Note: 1 eV corresponds to 11600 K

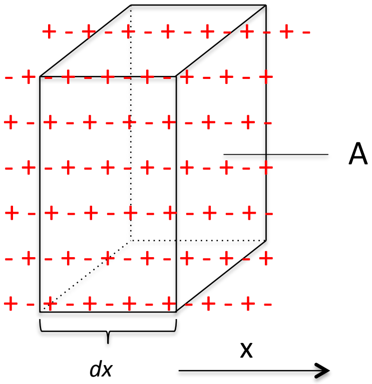
In typical laboratory plasma λ_D is very small!



Plasma	n_e[m^{-3}]	T_e [K]	λ_D [m]
Solar core	10^{32}	10^{7}	10^{-11}
Tokamak	10^{20}	10^{8}	10^{-4}
Gas discharge	10^{16}	10^{4}	10^{-4}
Ionosphere	10^{12}	10^{3}	10^{-3}
Solar wind	10^{6}	10^{5}	10
Interstellar medium	10^{5}	10^{4}	10

Plasma oscillations (ω_p):

- ➢ Lets assume that the completely neutral plasma is initially evenly distributed
- ➢ Then let a small disturbance to the distribution of electrons (shown in figure below)



Lets move the electrons inside the box to right (*x* direction). As a result of this only ions exist inside the box. On the right side of the box negative net charge exists. The charge of these volumes is:

$$dq = \pm en\underbrace{Adx}_{dV}$$

$$\boxed{\begin{aligned}&\text{Gauss:}\\ &\int \bar{E}\cdot\bar{ds} = \frac{\int dq}{\varepsilon_0}\\ &\Rightarrow E_x = -\frac{en_e x}{\varepsilon_0}\end{aligned}} \Rightarrow \boxed{\begin{aligned}&F_x = \frac{e^2 n_e x}{\varepsilon_0}\\ &\Leftrightarrow ma + \frac{e^2 n_e x}{\varepsilon_0} = 0\\ &\Leftrightarrow \frac{d^2x}{dt^2} + \frac{e^2 n_e}{\varepsilon_0 m_e}x = 0\end{aligned}}$$

ω_p^2

← Harmonic oscillator!

The disturbance creates the electric field which tries to restore the quasineutrality. Plasma starts the oscillation at frequency ω_p!

Note: plasma oscillation depends on n_e

Charged particle in magnetic field:

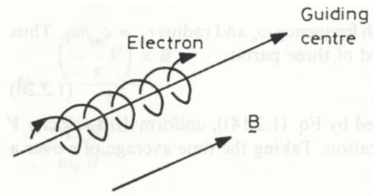
Magnetic field is used for plasma confinement and to guide plasma particles. Behavior of particle is governed by Lorentz force

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

The particle start to circulate around the magnetic field line at the frequency

$$\omega_c = \frac{qB}{m}$$

Gyrofrequency or Larmor frequency



Electron in homogenous B-field

Radius of Larmor motion (gyromotion)

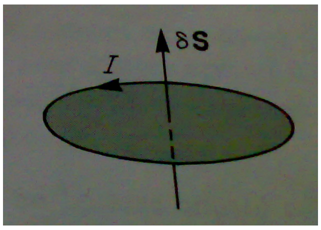
$$r = \frac{v_\perp}{\omega_c}$$

How to arrange the plasma confinement?

Current coil in magnetic field:

Circulating charged particle forms a current loop which can be considered as a magnetic dipole. The magnetic dipole moment is defined as

$$\boxed{\vec m = I\vec S}$$



Magnetic dipole

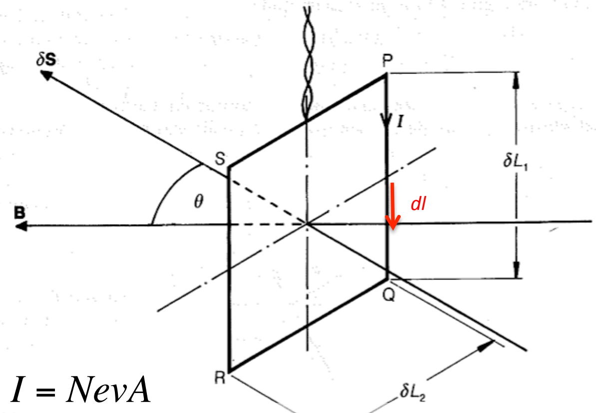
Where S is the area of the loop. The direction of surface vector is defined as is shown by the figure. The concept of magnetic dipole helps us to understand the torque and force affecting on the current loop.

Lets consider the rectangular loop shown on right. The electrons experience the Lorentz force and the force on small *dl* is

$$d\bar F_1 = -e\bar v \times \bar B(ANdl) = Id\bar l \times \bar B$$

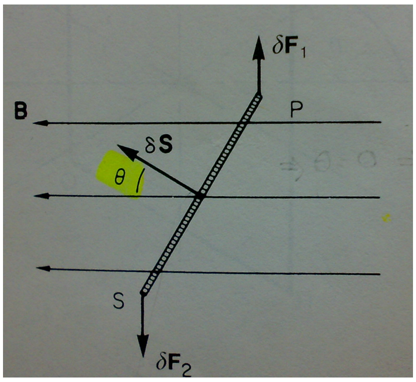
For length δL_1 (side *PQ*) we get

$$\delta F_1 = I\delta L_1 \times \bar B = I\delta L_1 B\sin\theta$$



$$I = NevA$$

A = cross sectional area of wire



Same force in magnitude but in opposite direction to is acting on side RS → total force perpendicular to B-field is zero. However there is torque *T* affecting the current loop which tends to turn **m** parallel to B-field. This torque is:

$$\delta\bar T = I\delta\bar S \times \bar B = \vec m \times \vec B$$

Potential energy U_p changes if θ changes:

$$\partial U_p / \partial\theta = I\delta SB\sin\theta$$

and by the integration we get

$$\partial U_p = -I\delta SB\cos\theta = -\vec m\cdot\vec B$$

$$\Rightarrow \vec F = grad(\vec m\cdot\vec B)$$

Remember: $\vec F = -gradU_p$

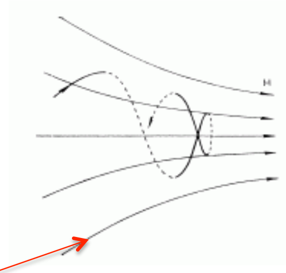
- Tend to twist the coils.
- Causes very strong forces between coils (remarkable problem in the case of SC coils!!) → can cause movement of coil → friction→quenching…

Electron (charged particle) in magnetic field:

The earlier treatment can be applied to electron (electron forms a current loop in B-field).

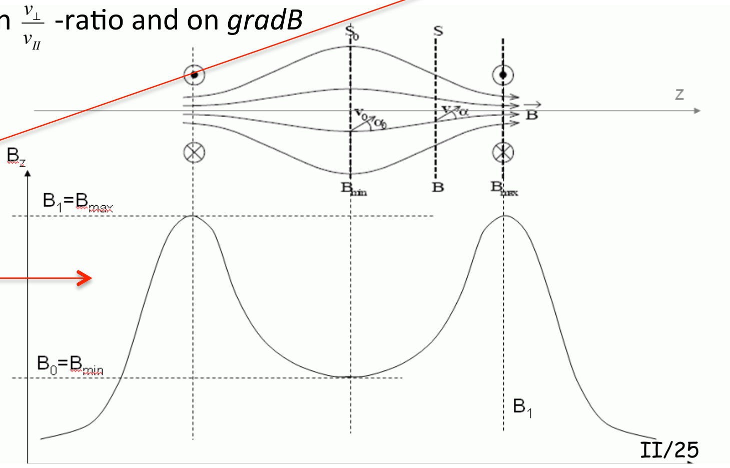
- ➢ The magnetic dipole moment of electron tends to turn so that its direction is parallel to B-field.
- ➢ The electron feels also the force which causes the reflection!

$$F_z = \mu \frac{dB_z}{dz}, \text{ where } \mu = \text{m} = \frac{1}{2}\frac{mv_\perp^2}{B_z} = IS \text{ (=magnetic dipole)}$$



- ➢ µ is time invariant, i.e when B increases → $v_\perp$ increases → v_{II} (parallel with B) decreases → reflection if B increases enough. Reflection depends on $\frac{v_\perp}{v_{II}}$ -ratio and on *gradB* *(no confinement if gradB = 0)*

Magnetic mirror
(confinement in one direction)
Magnetic bottle
(confinement in both directions)



Collisions in plasma:

The trajectory of electron (any charged particle) can be disturbed by collisions. If collision frequency is of the order of the gyrofrequency or higher the particle is not magnetically confined.

$$\langle \nu_{ei} \rangle = \frac{\sqrt{2} n_i z^2 e^4 \ln\Lambda}{12\pi^{3/2}\varepsilon_0^2\sqrt{m_e}(kT_e)^{3/2}}$$ Electron-ion collision frequency

$$\langle \nu_{ee} \rangle \approx \frac{\langle \nu_{ei} \rangle}{n_i z^2 / n_e}$$ Electron-electron collision frequency

$$\langle \nu_{ii} \rangle = \frac{n_i z^4 e^4 \ln\Lambda}{12\pi^{3/2}\varepsilon_0^2\sqrt{M}(kT_{ion})^{3/2}}$$ Ion-ion collision frequency

$$\Lambda = n_e \lambda_D^3$$

ECRIS (typical values): oxygen plasma, average *q = 4, $kT_e \approx$ 20 eV, $kT_i \approx$ 1 eV, $n_e \approx 10^{-17}$ m^{-3}*

$$\langle \nu_{ii} \rangle \approx 600kHz > \langle \nu_{ei} \rangle \approx 150kHz > \langle \nu_{ee} \rangle \approx 30kHz$$

Note: gyrofrequency for:
ions ≈ 200 kHz
electrons≈ 20 GHz

→ Ions are not magnetically confined!

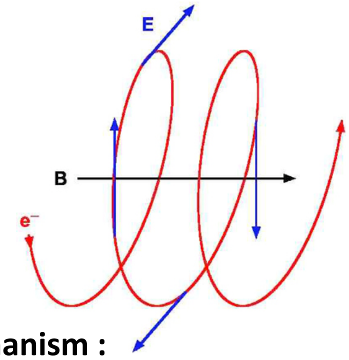
Electron Cyclotron Resonance, Upper Hybrid Resonance

Electron cyclotron resonance occurs when condition

$$\boxed{\omega_{RF} = \omega_c}$$

is fulfilled

Electron in magnetic field B



In addition, the efficient heating requires that gyro-motion of electron has the same phase with the RF

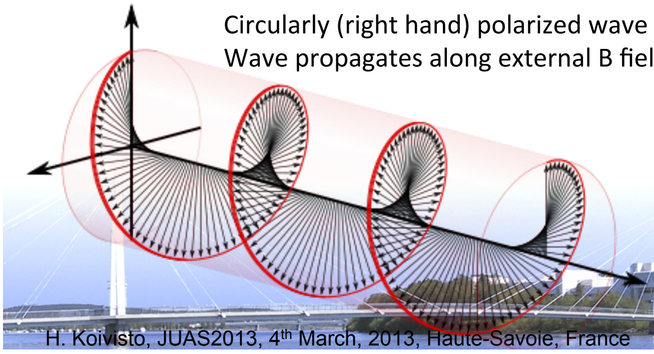
Note: high frequency limit → ions can be considered stationary

Two "main" (resonant) heating mechanism :

ECR heating: $\omega_{RF}=\omega_c= eB/m_e$

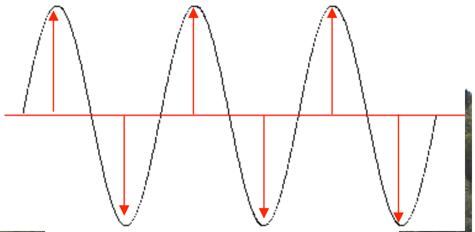
Circularly (right hand) polarized wave

Wave propagates along external B field



UHR heating: $\omega_{RF}^2 = \omega_c^2 + \omega_p^2$

Polarized plane wave. Wave propagation perpendicular to external B field



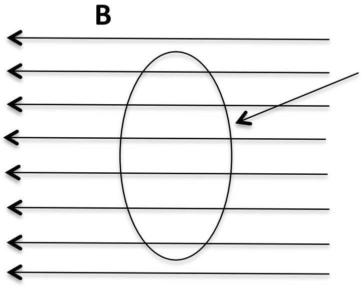
RF E field vs time

Electromagnetic induction:

Electromagnetic induction can be used for plasma heating:

$$\boxed{\oint \vec{E}\cdot\vec{dl} = -\frac{d}{dt}\int_S \vec{B}\cdot\vec{dS}}$$

Faraday law: Magnetic flux through the coil changes → voltage V (=EL) is induced to the coil (electromotive force: e.m.f)



Loop/coil $\boxed{L = \oint dl}$ (Length of the loop)

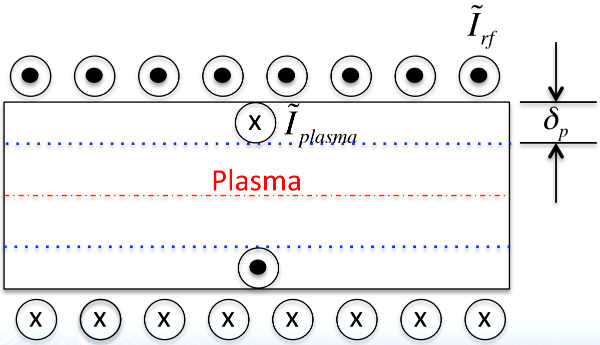
e.m.f increases when *dB/dt* increases

The induced e.m.f tries to keep magnetic flux through the coil constant

What happens in the case of plasma?

Plasma generation by electromagnetic induction:

Lets consider the condition shown below where a vacuum chamber is situated inside a current coil. Lets also assume that the current has a frequency f. Consequently, the B-field generated by the coil oscillates also. As a result of this e.m.f is induced which accelerates the plasma particles in order to produce current which tries to stop the flux falling →the electrons of this current collide with neutrals and cause ionization!



Penetration depth of EM wave (skin depth)

$$\text{skin depth} = \sqrt{\frac{2}{\mu\mu_0\sigma\omega}}$$

permeability

conductivity

Ion beam formation:

Plasma (can) contain(s) different kind of plasma particles: different mass/charge/charge state. We have to have a mean to extract the ions of interest from plasma and form a beam. This is done by extraction designed for this purpose.

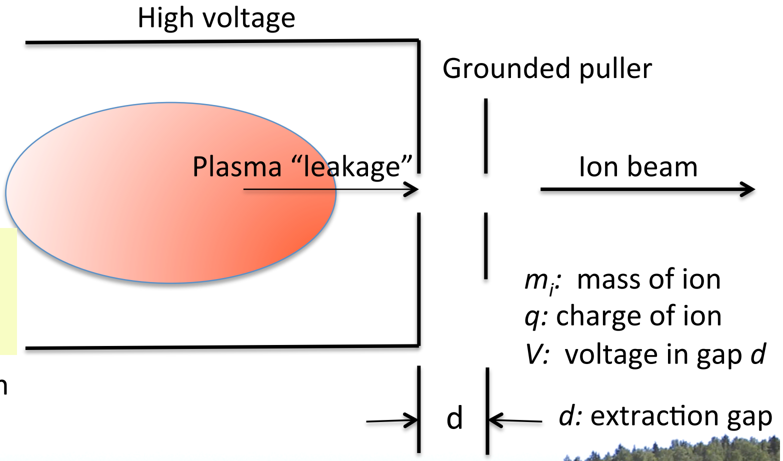
Extraction voltage (between ion source and puller electrode) has very strong impact of beam properties:

$$j = \frac{4}{9}\varepsilon_0 (2q/m_i)^{1/2}\frac{V^{3/2}}{d^2}$$

Gives the maximum current density accelerated by electric field (Child-Lanqmuir law)

Note: beam quality decreases when
- temperature of ion increases
- Acceleration voltage decreases
- Extraction aperture increases
- Magnetic field in gap d increases

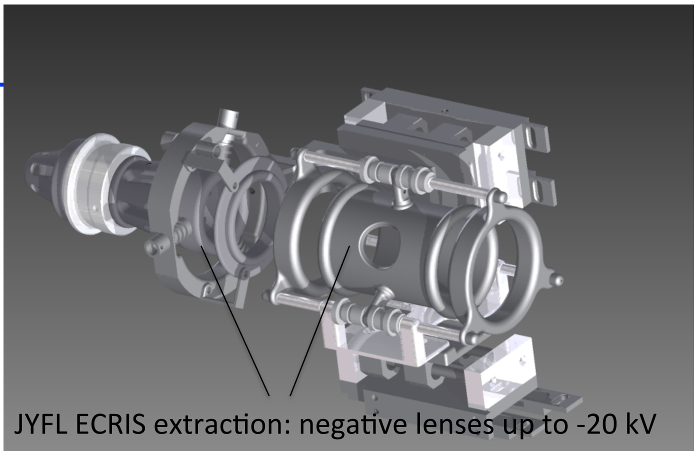
Extraction: Very simple and generic approach!



m_i: mass of ion
q: charge of ion
V: voltage in gap d
d: extraction gap

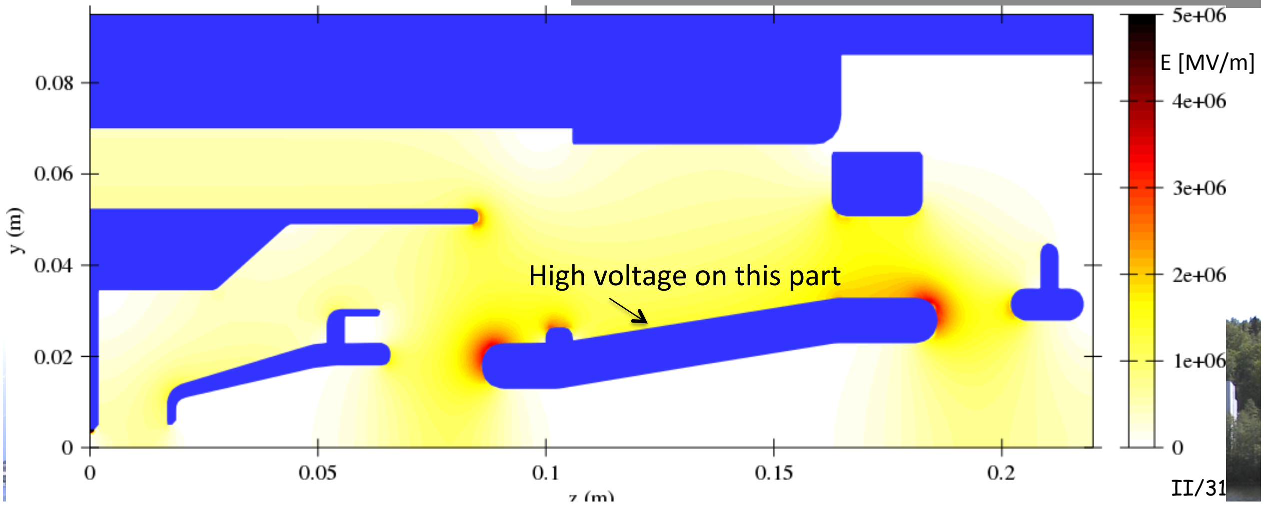
Designing HV-structures:

- Avoid sharp tips and corners (remember these are potential places initiate the discharge; field emission)
- Try to keep *E < 5 MV/m* (*d* at the level of 10^{-2} m). Negative HV is always more challenging!



JYFL ECRIS extraction: negative lenses up to -20 kV

JYFL extraction design by V. Toivanen

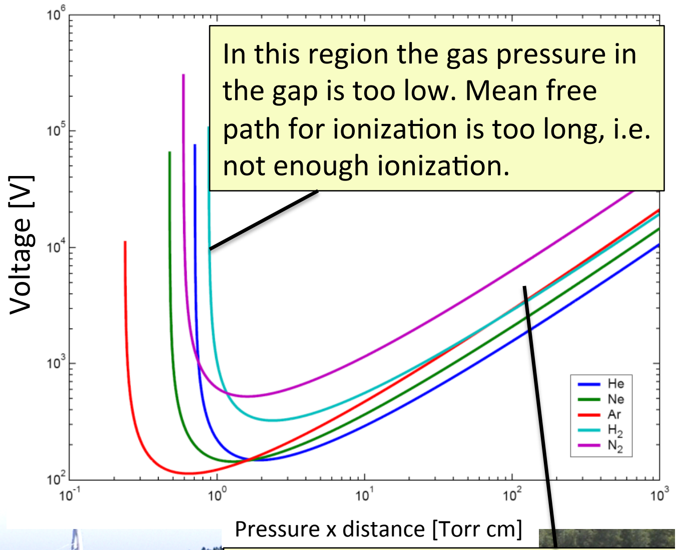


High voltage on this part

The Paschen Law:

The probability for the breakdown between the electrodes (or generally between the surfaces having different potentials) is not constant. It depends on the pressure in the gap!! This tendency is described by the Paschen Law!

- This behavior is dictated by the mean free path (with respect to voltage gap) and ionization cross section
- It was found for example that at 0.001 atmosphere the distance for minimum breakdown voltage is 7.5 mm. The possibility decreases if gap is decreased or increased. This voltage is as low as 327 V.
- The estimation for different geometries and pressure can be done using the Paschen curves shown right



In this region the gas pressure in the gap is too low. Mean free path for ionization is too long, i.e. not enough ionization.

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