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U.S. DEPARTMENT OF ENERGY

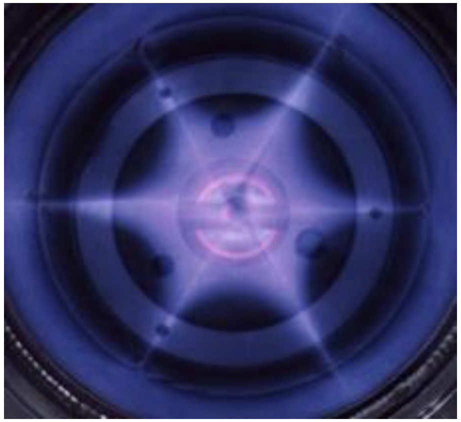
3. Plasma Physics Fundamentals for Ion Sources

Daniela Leitner (LBNL, MSU),

Damon Todd (LBNL),

Daniel Winklehner (MIT)

What is a plasma?



- Plasma is the fourth **fundamental states of matter**.
- Partially or fully ionized gas consisting of **free electrons and free ions** as well as neutral atoms and molecules (ratio between neutrals and ions, important factor for the plasma)

- Need to be **constantly heated to be sustained** (fusion in stars, on earth energy must be added in form of energetic electrons, rf fields, microwave)
- **Must be confined** if it should be sustained for some time (gravity in stars, on earth with magnetic fields)
- The particle transport and dynamics is determined through collective processes

Key Plasma Properties

- Particle Density
- Ionization Degree – Quasi Neutrality
- Plasma Temperature
- Plasma as a Gas
- Debye Length – Plasma Sheath
- Plasma Oscillation

Readings and materials for the lecture

- **Brown, I.G.**, *The Physics and Technology of Ion Sources*. 2nd ed. The Physics and Technology of Ion Sources. 2005: Wiley-VCH Verlag GmbH & Co. KGaA, chapter 2
- **Stangeby, P.C. and G.M. McCracken**, *Plasma boundary phenomena in tokamaks*. Nuclear Fusion, 1990. 30(7): p. 1225.
- **Wiesemann, K.**, *A Short Introduction to Plasma Physics*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.
- **Geller**, *Electron Cyclotron Resonance Ion Sources, IOP Pub, 1996*

Particle Density, Quasi Neutrality and Degree of Neutralization

- Plasma contains positive and (negative) ions, electrons, and neutrals
- P**lasma densities** = number of electrons/ions per volume: **10^8 – 10^{15}/ cm^3** for ion sources
- **Macroscopic overall neutral !**

$$n_e = \sum_{j=1}^{Z} q_j n_q$$

- Otherwise there would be big electric fields : for example for 10^{12}/cm^3 plasma density, if 1% is non neutralized in a sphere of radius 1 cm 6000V/cm electrostatic field near the sphere!)

$$E = \frac{Q}{(4\pi\epsilon_0)r^2}, \quad Q = (\frac{4\pi r^3}{3})n_e e$$

$$E_{1\%} = 6 \cdot 10^3 \frac{1}{cm}, \; r = 1cm, n_e = \frac{10^{12}}{cm^2})$$

- Microscopic: deviations due to thermal motions → plasma oscillations

Degree of Neutralization

- The degree of ionization describes the

$$\eta_i = \frac{\sum_{j=1}^{Z} q_j n_q}{n_{atoms} + \sum_{j=1}^{Z} q_j n_q}$$

- Typically the degree of ionization is low for standard ion source and in the order of 10^{-3} to 10^{-5}. These are weakly ionized plasma with poor confinement
- Plasma properties prevail in when η_i >10% (ECR ion sources > 50-80%)
- Ionization degree is directly related to ionization efficiency !
- The higher the ionization degree (plasma confinement) the lower the pressure required to sustain the discharge

Plasma temperature [1]

- Plasma particles can be described with a Maxwellian distribution in equilibrium state (like an ideal gas)

$$f(v_x) = n\left(\frac{m}{2\pi kT}\right)^{\frac{1}{2}} e^{-\frac{mv_x^2}{2kT}} \longrightarrow \overline{v} = \sqrt{\frac{8kT}{\pi m}}$$

$$\overline{v}_e = 67\cdot 10^4\sqrt{T_e[eV]}\,\frac{m}{s}$$

$$\overline{v}_i = 1.57\cdot 10^4\sqrt{\frac{T_i[eV]}{A}}\,\frac{m}{s}$$

- T…Plasma Temperature: Typically described as energy of the particles and expressed in eV

$$1eV = kT = 1.38\cdot 10^{-23}\frac{J}{K}11600K$$

$$1eV \propto 11600K$$

- With the velocity distribution one can calculate the Energy distribution and the mean energy

$$f(E) = n\left(\frac{4E}{\pi(kT)^3}\right)^{\frac{1}{2}} e^{-\frac{E}{kT}} \longrightarrow \overline{E} = \frac{3kT}{2}$$

Plasma temperature [2]

- **Ions and electrons** have often **very different temperatures** Te>>Ti in plasma sources
- The ion temperature is directly related to the beam quality, the larger the transverse temperature – the larger the emittance of the beam (the intrinsic transverse momentum) – the larger will be the final focusing spot that can be achieved with the beam (Daniel's lecture) !

$$\epsilon_{n-rms}^{th} = 0.016 \cdot r \sqrt{\frac{k_B T_i}{A}}$$

- Therefore for ion source plasmas the electrons are heated not the ions (unlike fusion plasmas)
- In the **extraction regions ions and electrons temperatures equalize through collisions**, a good assumption for plasma simulation close to the extraction region is Te=Ti (0.5 to a few eV)
- **If there is a magnetic field present, the transverse and the longitudinal plasma temperatures can vary widely!**

Debye Length

- Neutrality is intrinsic to plasma - the electric field that would arise drives the plasma back to neutrality, but local fields can arise that lead to
  - Fluctuations, noise, oscillations (harmonic oscillator)
- The local volume in which the plasma can be non neutral is called: **Debye Length = shielding or screening distance**

$$E = \frac{n_e e \delta x_i}{\epsilon_0}$$

Field created between the two charge separated regions

$$W_{pot} = \int_0^{\delta x} e E_x dx = \frac{e^2 n_e (\delta x)^2}{2\epsilon_0} \qquad W_{pot} = \tfrac{1}{2} k_B T_e$$

The temperature describes the mobility of the plasma particles !

$$\tfrac{1}{2} k_B T_e = \frac{e^2 n_e (\delta x)^2}{2\epsilon_0} \rightarrow \delta x = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = \lambda_D$$

Debye Lengths!!

- The Debye lengths defines the sphere in which the electric fields have an influence. Outside this sphere the electric charges are shielded !

$$\lambda_D = 743 \sqrt{\frac{T_e}{n_e}}$$

mm to 0.01 mm

Plasma in connection with the wall will builds a plasma sheath

Qualitatively explanation of the plasma sheath

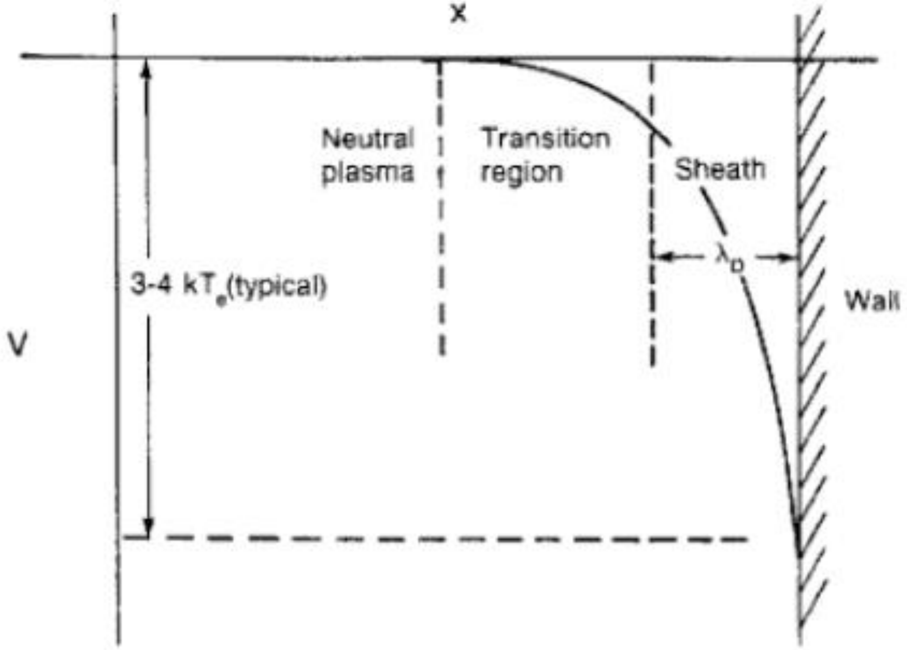
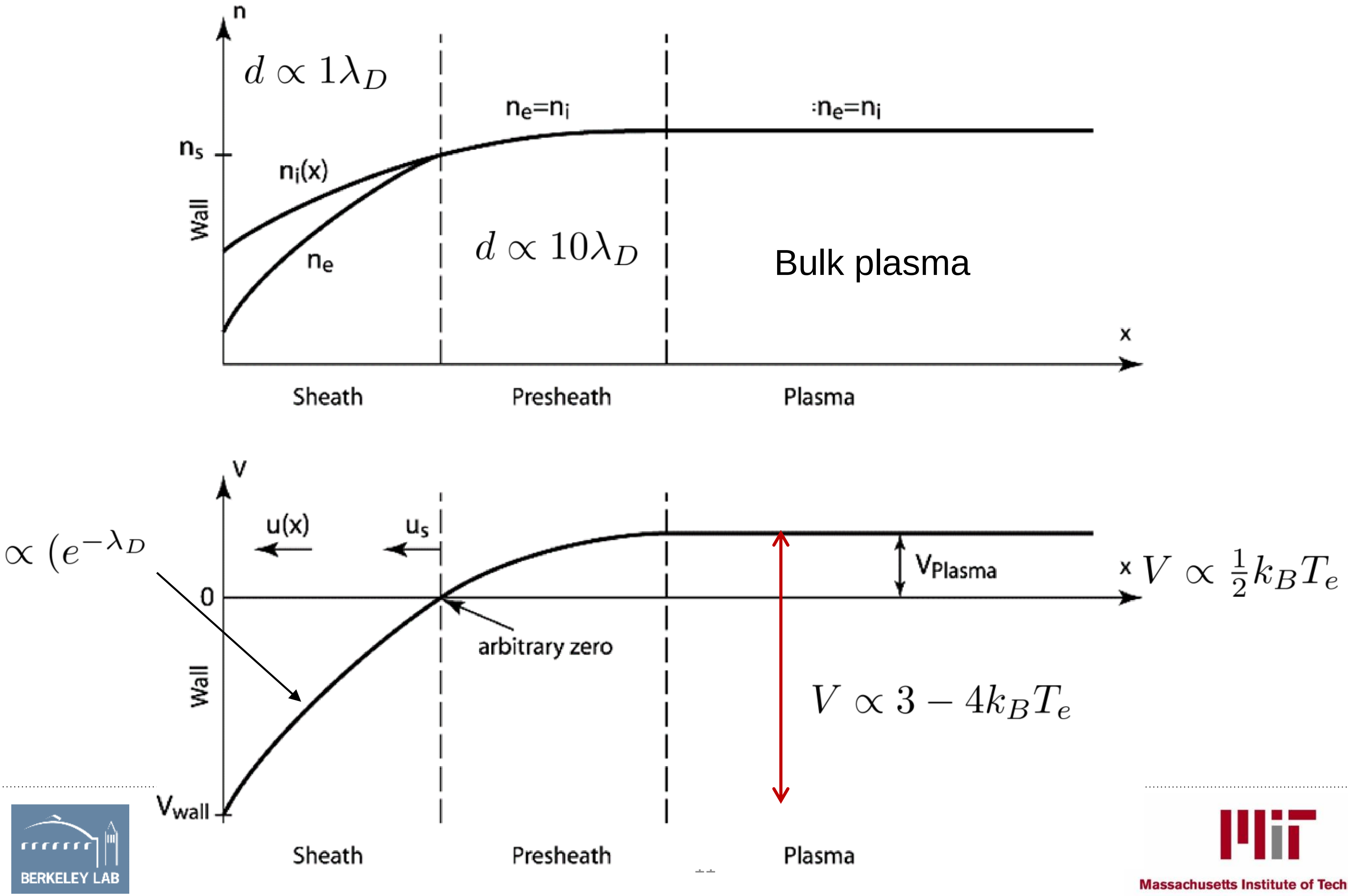


Figure 2.2 The plasma sheath: plasma potential vs. distance from within the plasma volume to the wall.

- If the plasma faces a wall, electrons within the Debye radius will be lost to the wall faster than ions (lower mass-higher mobility)
- Consequently the plasma charges up positively against the wall potential (plasma potential) to maintain neutrality
- The bulk plasma stays neutral, but a sheath is created with a thickness of λ_D and a potential difference of $\Phi_p - \Phi_w$ (roughly 3-4 kTe)

Stangeby, P.C. and G.M. McCracken, *Plasma boundary phenomena in tokamaks.* Nuclear Fusion, 1990. **30**(7): p. 1225.

Plasma sheath



Plasma Potential

Derived from electron and ion flux to the wall (multiple ion species):

$$\Phi_p = \Phi_w + \frac{kT_e}{e}\left[\ln\sum_{j=1}^{k} q_j n_{i,j} - \ln\left(\sum_{j=1}^{k} q_j n_{i,j}\sqrt{2\pi\frac{m_e}{m_{i,j}}\left(1+\frac{T_{i,j}}{T_e}\right)}\right)\right]$$

- Since this is a diffusion process: it depends on the electron temperature and ion temperature!
- Expression above is used for typical plasma extraction codes (e.g. IGUN, PB-gun, …)

Plasma sheath and beam transport

- The plasma potential is one cause of the energy spread of ions extracted from sources
- Ions are accelerated through the sheath (to the extraction system, also increases sputtering energy beyond the T_i
- If the confinement is enhanced or electrons are replaced through external injection into the plasma, the energy spread of the ions will be reduced!

Plasma sheath and beam transport

- Extraction systems: Sheath thickness with an external voltage is in the order of

$$d_{sheath} = \lambda_D \sqrt{\frac{e \cdot V_{ext}}{k_B T}}$$

for 10kV, $T_e = 5eV$, $\frac{10^{10}}{cm^3}$

44 Debye lengths !

- Ions are accelerated through the sheath (to the extraction system)
- The velocity of the ions entering the sheath is determined through the Bohm criteria

$$C_s = \frac{k(T_e + T_i)}{m_i}$$

- The current density available for extraction (ions into the sheath to the extraction system)

$$j_{plasma} = \frac{e n_e}{\sqrt{2}} \sqrt{\frac{T_e}{m_i}} \text{ with } T_e = T_i$$

The extractable current is proportional to T_e and inverse proportional to m_i!!!

Plasma Oscillations –Plasma Frequency

- Macroscopic the plasma is charge neutral, microscopic the imbalance of charges leads to micro instabilities, fluctuations and oscillations

$$E = \frac{e}{\epsilon_0} n x$$

- Electric field by a local charge separation along distance x
- The charge unbalance leads to a restoring force !

$$F = eE = \frac{e^2}{\epsilon_0} n x = m_e \frac{d^2 x}{dt^2}$$

- Equation of and harmonic oscillator with eigenfrequency ω!

$$\boxed{\omega_e = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}}$$

$$\boxed{\omega_i = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_i}}}$$

Plasma frequency GHz range !

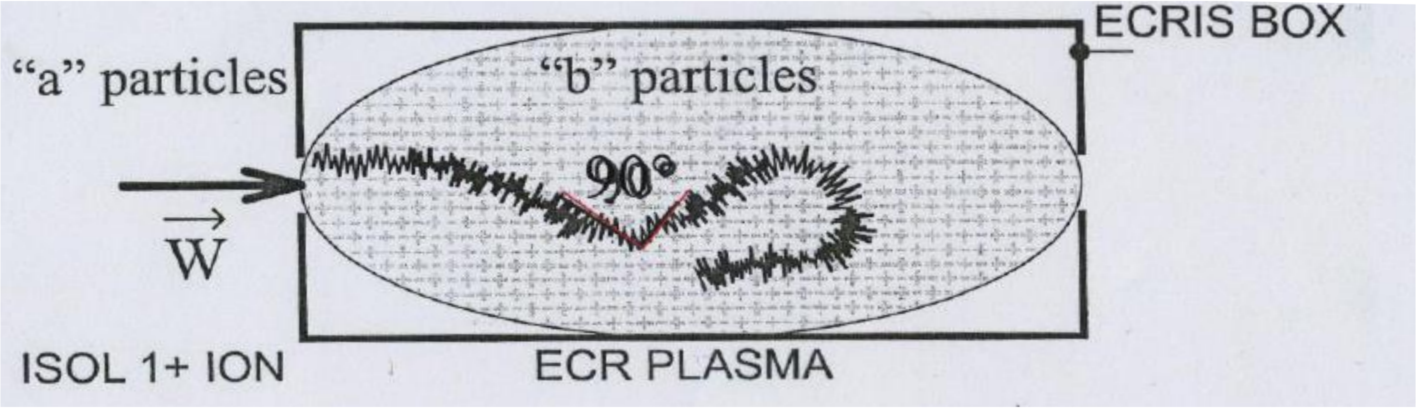
Plasma frequency MHz range !

Collisions in Plasma

- Collision are fundamentally different between charge particles in the plasma – they are governed through collective effects
- Collisions in plasma are governed through long range interactions (coulomb collisions between charged particles – takes several interactions to deflect an ion- usually the characteristic time is calculated for a collective 90˚ scattering (Spitzer collisions)
- Mean time for a deflection: “relaxation time’

$$\nu_{ee}^{90} > \nu_{ii}^{90}$$

- Thermalization will take several cm in the plasma for injected ions



Diffusion processes in magnetized plasmas

- In the direction of the fields there is no force, transverse the particles are bend into the circular motion

$$F = q\vec{v} \times \vec{B} \qquad r_c = \frac{mv}{eQB} \longrightarrow$$

$f_{ce} = 28 \cdot GHz \cdot B(T)$

$f_{ci} = 15.2 \cdot MHz \cdot \frac{Q}{A} B(T)$

A....atomic mass number

Q....Charge state

- Therefore the transport // to the field is different than ⊥ !
- // to the field the transport dominated by 90˚ collisions

$$f_e^{90} > f_i^{90} \longrightarrow \frac{D_{\parallel e}}{D_{\parallel i}} \propto \sqrt{\frac{m_i}{m_e}}$$

Electron loss dominantly // to the field

- ⊥ to the field the transport is dominated by the gyrotron motion.

$$f_c >> f_{coul} \qquad r_{ci} >> r_{ce} \longrightarrow \frac{D_{\perp e}}{D_{\perp i}} \propto \sqrt{\frac{m_e}{m_i}}$$

Loss is dominated by hoping from one field line to the next

Ion loss dominantly ⊥ to the field

Magnetic Pressure And Plasma Pressure

- Pressure by the gas is given by the ideal gas equation

$$P = nk_BT$$

- Pressure by the plasma is given by

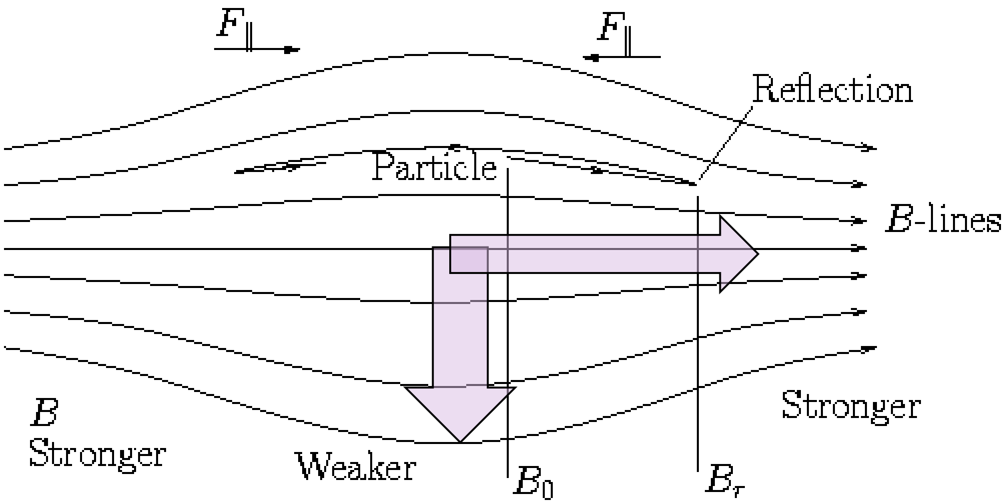
$$P = nk_BT_e + nk_BT_i$$

- An external magnetic field gradient asserts a force on the plasma (magnetic pressure)

$$P = \frac{B^2}{\mu}$$

- For stable plasma conditions the external magnetic pressure (confinement field) must be equal to the internal pressure
- The plasma pressure is equal to the external magnetic pressure
- Plasma confinement is stable when the magnetic field increases (pressure will drive the plasma fluid back). If the magnetic field decreases the plasma can escape.

Mirror picture



Magnetic pressure gets stronger

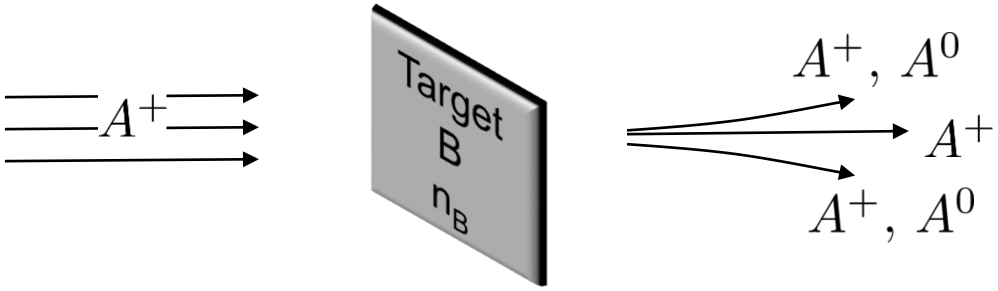
Magnetic pressure gets weaker

Atomic Physics in Ion Sources

Cross sections [cm^2], [barn]

$$N_{events} = N_{incident} \cdot \underbrace{n_{target} d_{target}}_{\frac{atoms}{cm^2}} \cdot \sigma$$

σ .. Effective area quantifying the probability of the event



Particles can either have an interaction with the target (scattered, charge exchange) or continue to move without interaction

Attenuation of a beam through a target

$$dI_{A^+} = -\sigma n_B I_{A^+}(x) dx$$

$$\frac{dI_{A^+}}{I_{A^+}(x)} = -\sigma n_B dx$$

$$I(x) = I_0 e^{-\sigma n_B x} = I_0 e^{-\frac{x}{\lambda}}$$

$$\lambda = (\sigma n_B)^{-1} \text{ (mean free path)}$$

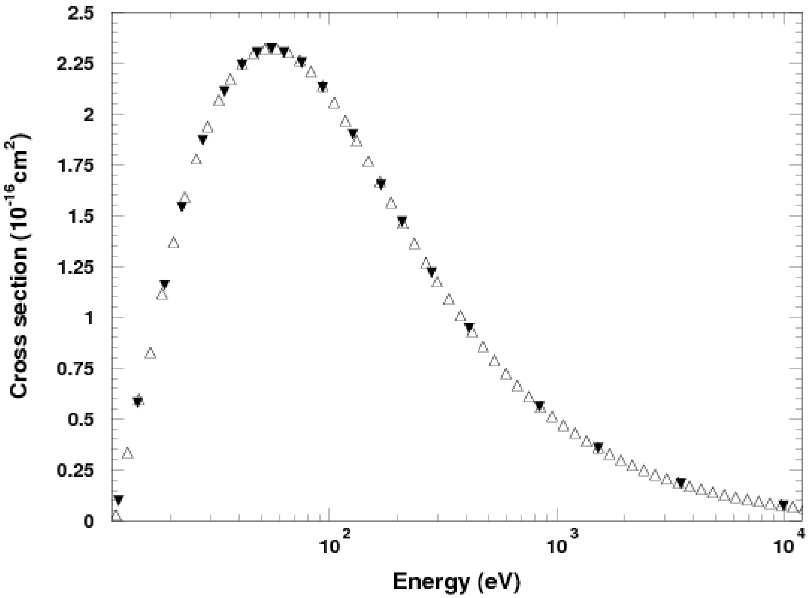
$$\nu = \frac{v}{\lambda} = \sigma v n_B \text{ (Collission Frequency)}$$

$$R = n_B \int_0^\infty \sigma(v) v f(v) dv = n_B < \sigma v >$$

(Reaction Rate)

n_B .... target density
v .... relative velocity
$\sigma(v)$ .... cross section as a function of velocity

Characteristics of Cross Section Values



- Cross sections are dependent on the energy and impact angle
- Total cross sections often take more than one process into account
- Good resource: http://www.nist.gov/pml/data/atom_molec.cfm

- Cross sections depend on the atomic model used for the calculations (few are measured), so different approximations for different energy ranges are used!!
- ± %20 percent is already a very good value!

Figure from: Ionization cross sections for low energy electron transport Hee Seo, Maria Grazia Pia, Paolo Saracco and Chan Hyeong Kim, http://arxiv.org/pdf/1110.2357.pdf

Atomic Processes in Ion Source

- Plasma is formed from neutrals through ionization processes
  - **Electron Impact Ionization**
  - Multiple Ionization
  - Photoionization
  - Ion impact ionization
  - Field Ionization
  - Resonance Laser Ionization
  - Laser Ionization

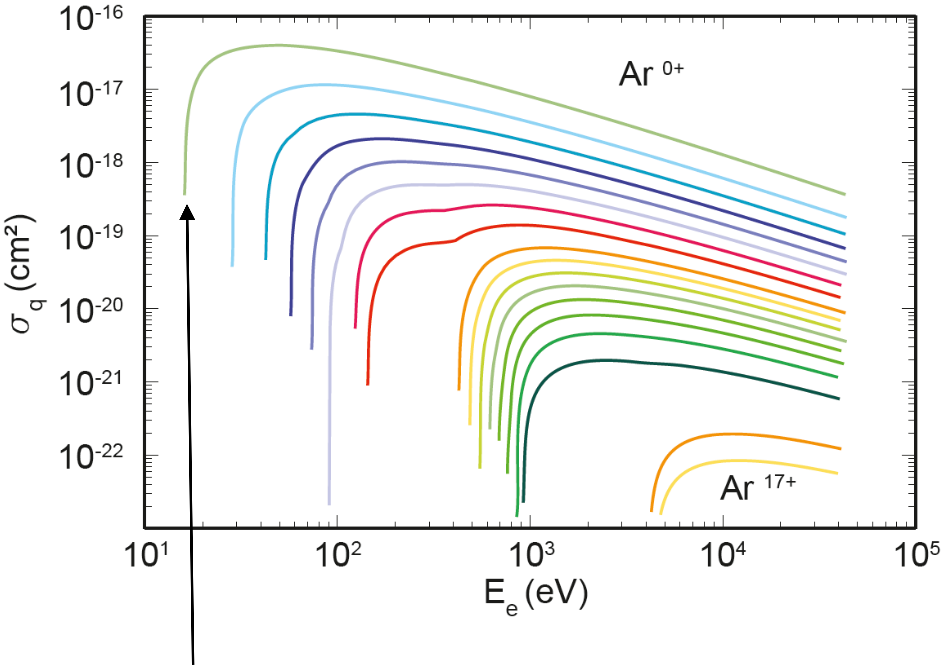
Threshold Energy

(Ionization Potential)

- Processes that drive ions back to neutral states or lower charge states:
  - Recombination and charge exchange processes
- Negative Ions (Tuesday)
  - Double charge exchange
  - Dissociative detachment

Electron impact ionization most important cross section!

$$X^{q+} + e^- \rightarrow X^{(q+1)+} + 2e^-$$



Strongly decreases with Charge State

$$\sigma_{single} >> \sigma_{multiple}$$

Ions need to be confined long enough to get ionized by step by step ionization

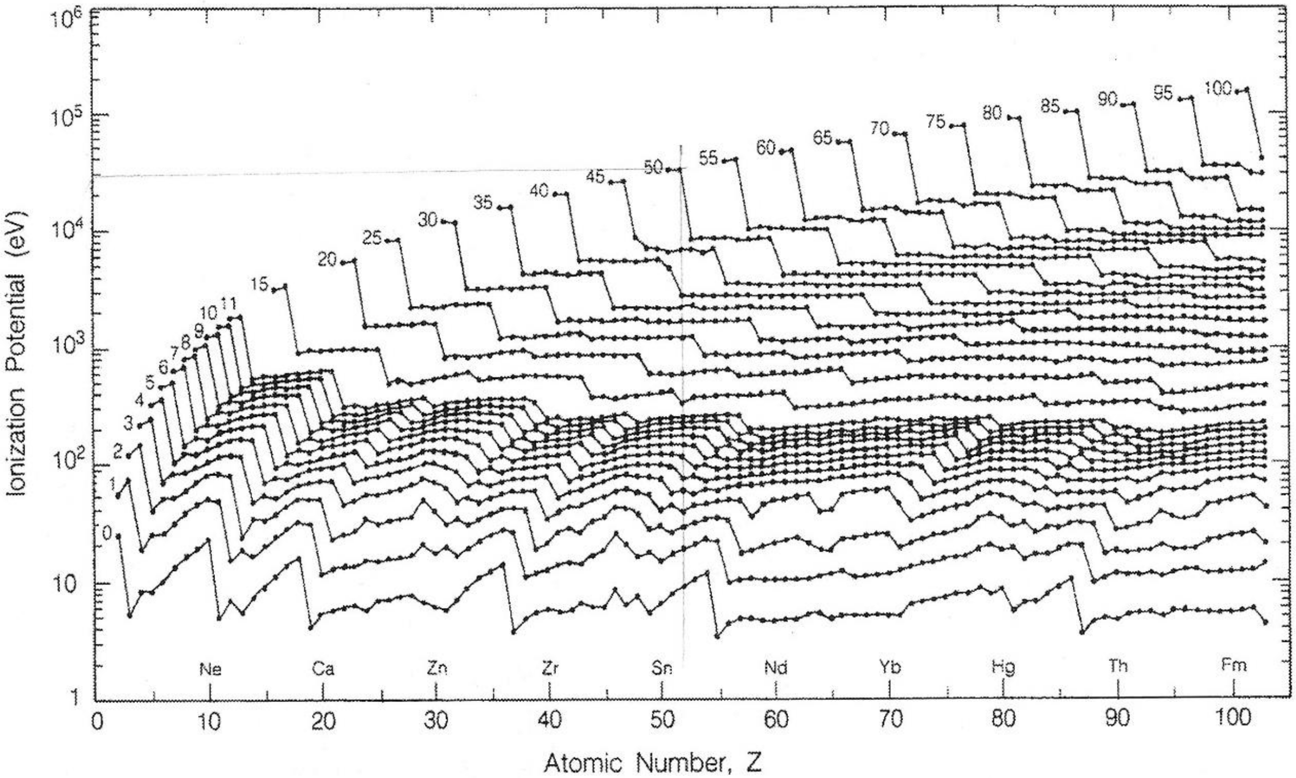
Threshold Energy
Cross section peaks at 2-3 times the ionization energy

$$\sigma_{i,i+1} = 1.4 \cdot 10^{-13} \frac{ln \frac{E_e}{E_i}}{E_e E_i} (eV)^2 cm^2$$

E_e: E-beam energy

E_i: Ionization potential

Ionization Potentials



NIST ionization Potentials

Homework: explain the ionization potential as a function of atomic mass. Why are there sharp drops in the ionization potential?

Hint: Use your knowledge about the periodic system

Homework for day one related to this part

- Calculate the cyclotron frequency for electrons and ions, calculate the Debye length for your ion source system or assume a reasonable temperature and density, estimate the penetration depth of extraction voltage typically used at you ion source into the plasma
- Derive a simple formula for the magnet rigidity Broh for ions in a magnetic field.
- Homework: explain the ionization potential as a function of atomic mass. Why are there sharp drops in the ionization potential?
  NIST ionization Potentials
  Hint: Use your knowledge about the periodic system