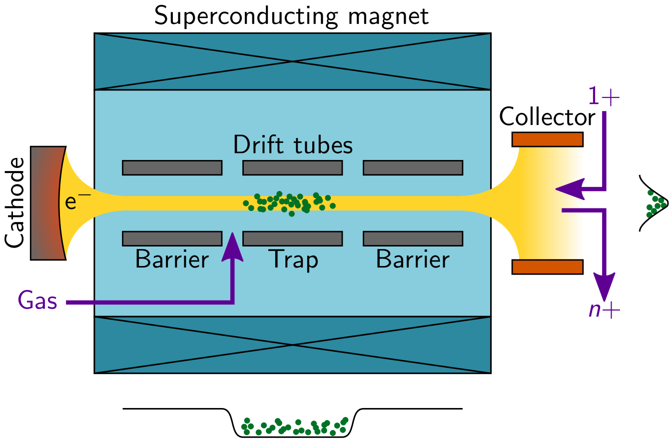
Simulating the charge breeding process in an electron beam ion source

ABP Group Information Meeting

Hannes Pahl, ABP-HSL

Electron Beam Ion Sources (EBIS)

Magnetically compressed e^{-}-beam used to trap and successively ionise particles to high charge states.

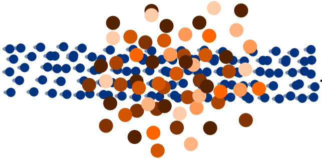


In-trap measurements are hard
— need simulations to understand charge breeding dynamics.

Simplified rate equations

- Charge breeding is stochastic process driven by electron beam
- Inelastic collision can either increase or decrease charge state

$$\frac{\mathrm{d}N_q}{\mathrm{d}t} = \frac{j_e}{q_e} \left(N_{q-1}\sigma^{\mathrm{EI}}_{q-1} + N_{q+1}\sigma^{\mathrm{RR}}_{q+1} - N_q \sigma^{\mathrm{EI}}_{q} - N_q \sigma^{\mathrm{RR}}_{q} \right)$$



$$j_e = \frac{I}{\pi r_e^2}$$

j_e Beam current density

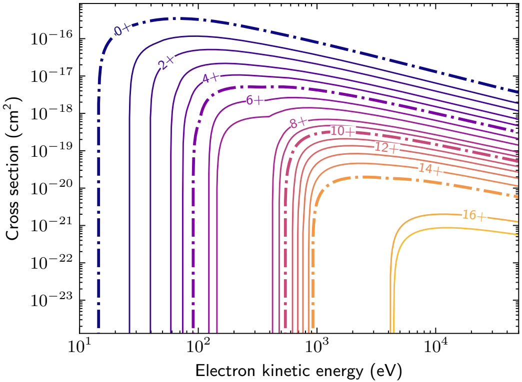
σ_q^X Cross section

N_q # ions in charge state q

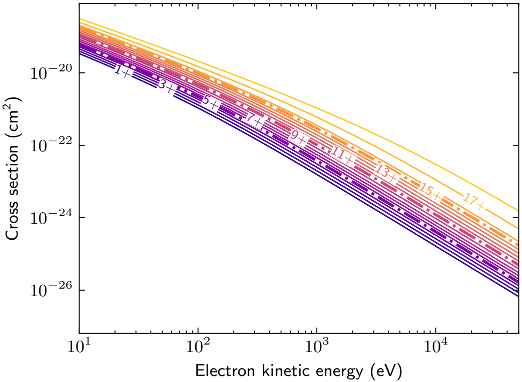
EI Electron impact ionisation

RR Radiative recombination

Electron ionisation (EI) / Radiative recombination (RR)

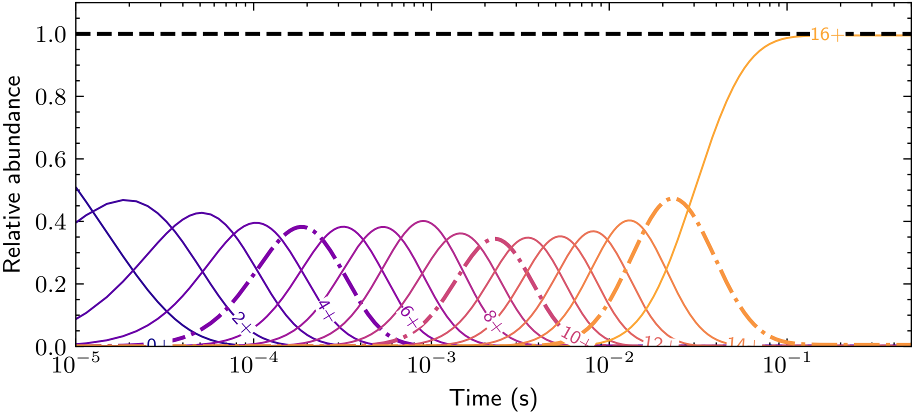


EI cross sections of argon (Lotz)



RR cross sections of argon (Kim & Pratt)

Argon charge state evolution



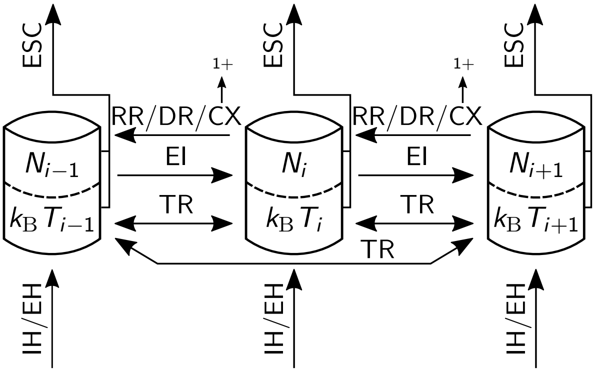
Ar^{1+} ions, $j = 500\,\mathrm{A/cm^2}$, $E_e = 2100\,\mathrm{eV}$.

Temperature effects

- Axial and radial traps are finite
- Electron beam heats ion cloud through elastic collisions
- Ions spread out in radial trap
  $\Rightarrow$ reduced overlap with electron beam
- Hot ions can escape from the trap entirely

Need to take ion temperature into account!

Rate flow chart



EI	Electron ionisation
RR	Radiative recomb.
DR	Dielectronic recomb.
CX	Charge exchange
EH	Electron beam heating
IH	Ionisation heating
TR	Thermal relaxation
ESC	Escape / losses

Rate equations for ion density and temperature NB: This description assumes that the kinetic distribution has a defined temperature at any given time!

Temperature driving effects

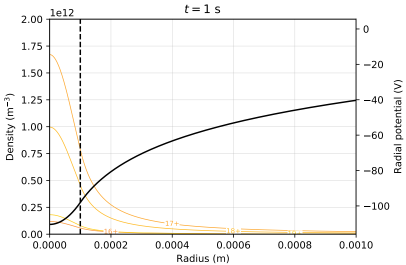
EH Elastic collisions transfer energy from beam to ion cloud.

IH Sudden increase of charge state provides excess radial potential energy, which subsequently thermalises.

TR Collisions between different ions even out temperature. (Heating rates are charge state sensitive.)

ESC High energy tail of thermal ion distribution escapes from trap, resulting in net cooling effect.

Radial space charge trap



Electron beam induces negative radial trapping potential

$$\Phi_{\mathrm{SC}}(r) = \begin{cases} \Phi_0 \left[\left(\frac{r}{r_e} \right)^2 + 2 \ln \frac{r_e}{r_{\mathrm{DT}}} - 1 \right] & \text{if } r \leq r_e \\ \Phi_0 2 \ln \frac{r}{r_{\mathrm{DT}}} & \text{if } r > r_e \end{cases}$$

Ions spread out in radial potential $n_i(r) \propto \exp\left(\frac{-q_i e \Phi(r)}{k_{\mathrm{B}} T_i}\right)$

Determines overlap factors f_{ei} (electron ion) and f_{ij} (ion ion) ≤ 1 reducing effective collision / interaction rates

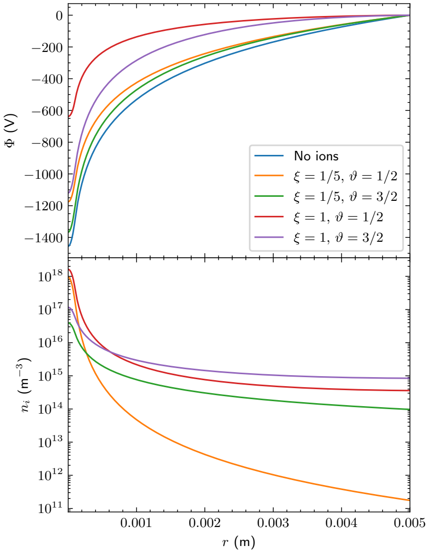
Space charge compensation

- Positive ion charge accumulates and compensates electron space charge.
- Net potential is defined by self consistent solution of Boltzmann-Poisson equation
- $\Rightarrow$ Trap gets shallower
- $\Rightarrow$ Electron beam energy increases

Example

$I = 1\,\mathrm{A},\ E_e = 10\,\mathrm{keV},\ r_e = 0.1\,\mathrm{mm},\ r_{\mathrm{DT}} = 5\,\mathrm{mm}$

$\xi = N_{1+}/N_e,\ \vartheta = k_{\mathrm{B}} T_i/(q_i \Phi_0)$

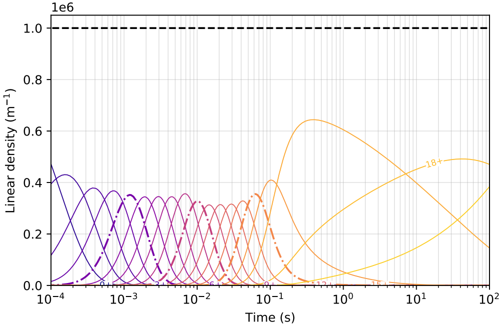


Example: Evaporative cooling

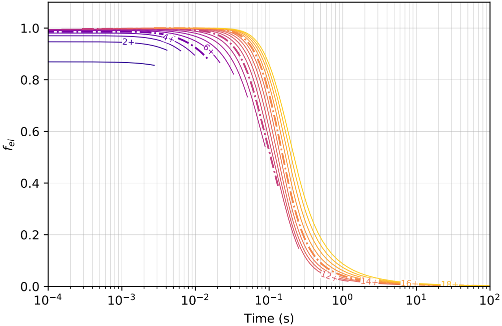
Light ions can be boiled off from the trap to cool heavier ions

- 1st Charge breeding of potassium
  - Deep axial trap (500 V)
- 2nd Charge breeding of potassium with cooling gas
  - Shallow axial trap (50 V)
  - 1×10^{-11} mbar nitrogen background pressure

Charge breeding of potassium



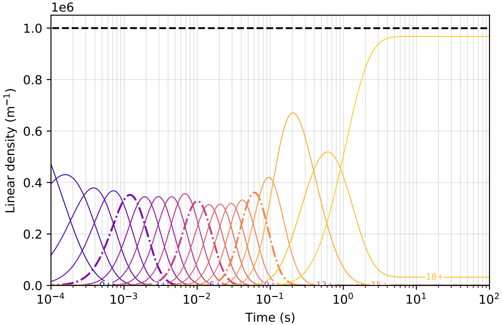
Charge state evolution



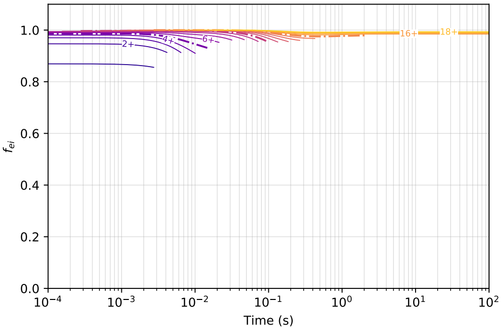
Electron ion overlap factors

$$I = 0.1 \text{ A},\ r_e = 100\ \mu\text{m},\ E_e = 15 \text{ keV},\ V_{ax} = 500 \text{ V}$$

Injection of nitrogen as cooling gas



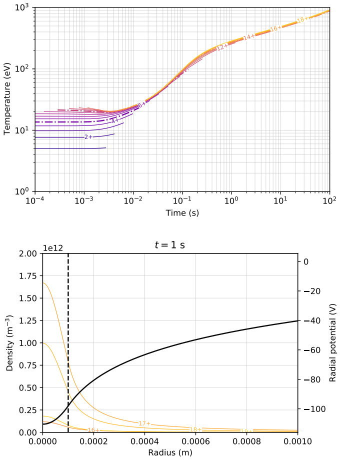
Charge state evolution



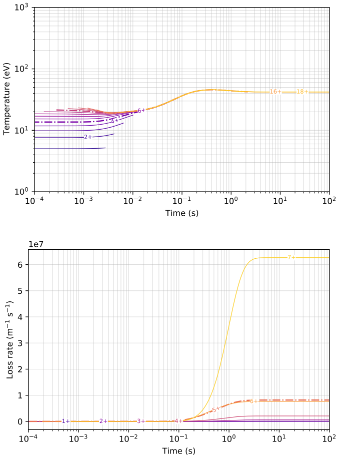
Electron ion overlap factors

$I = 0.1$ A, $r_e = 100\ \mu$m, $E_e = 15$ keV, $V_{ax} = 50$ V, $p_{\mathrm{N}} = 10^{-11}$ mbar

Cooling through nitrogen escape



Uncooled potassium temperature and radial distribution at 1 s.



Cooled potassium temperature and nitrogen escape rate.

EBISIM

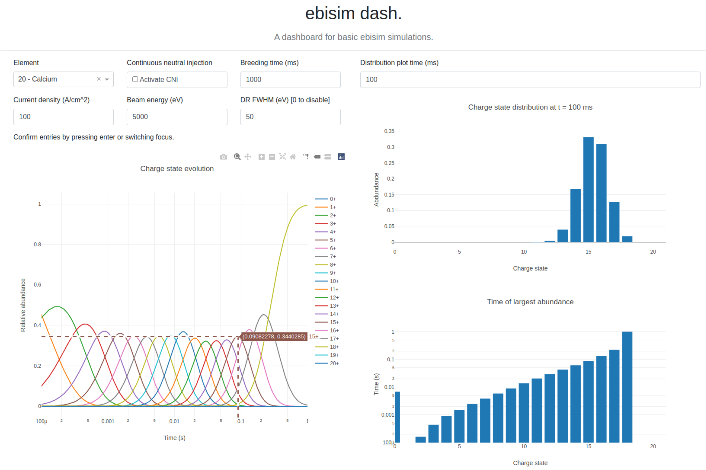
EBISIM - A Python package for EBIS/T simulations

- Cross sections
- Plasma parameters
- Radial Boltzmann Poisson solver
- Basic / full simulation model
- Atomic data $Z \leq 105$
- Result visualisation and analysis

- Built on standard scientific Python stack
- Fully written in Python, no extension modules
- Low level functions accelerated by “numba” through JIT compilation
- Continuous integration (docs, tests, linting)

`https://ebisim.readthedocs.io/en/latest/`

EBISIM Webinterface



`http://ebis.web.cern.ch/ebisim`

Open questions / ideas

- Understand conflicting models for axial / radial escape rates
- Radial motion under influence of magnetic field
- Loss rates in shallow / inverted traps
- Future: Spatially / kinetically resolved? (e.g. PIC, Vlasov)
- Linking simulation results to beam formation

Summary

- Overview of effects contributing to charge breeding
  - Ionisation / recombination
  - Temperature and overlap
  - Radial space charge compensation
- EBISIM
  - Free and modern Python toolbox for charge breeding simulations
  - Integrates well into existing scientific Python stack
  - Web interface for interactive simplified simulations

BACKUP

Extended rate equations

$$
\begin{aligned}
\frac{dN_i}{dt} = &- \left(R_i^{\mathrm{EI}} + R_i^{\mathrm{RR}} + R_i^{\mathrm{DR}} + R_i^{\mathrm{CX}}\right) \\
&+ R_{i-1}^{\mathrm{EI}} + R_{i+1}^{\mathrm{RR}} + R_{i+1}^{\mathrm{DR}} + R_{i+1}^{\mathrm{CX}} - R_i^{\mathrm{ESC}} \\
\frac{d(k_{\mathrm{B}} T_i)}{dt} = &\left(S_i^{\mathrm{EI}} + S_i^{\mathrm{RR}} + S_i^{\mathrm{DR}} + S_i^{\mathrm{CX}}\right) \\
&+ S_i^{\mathrm{EH}} + S_i^{\mathrm{IH}} - S_i^{\mathrm{ESC}} + S_i^{\mathrm{TR}}
\end{aligned}
$$

- Each ion species and charge state may have individual temperature.
- NB: This description assumes that the kinetic distribution has a defined temperature at any given time!

Electron and ionisation heating

EH **Electron heating / Spitzer heating**
Elastic collisions transfer energy from beam to ion cloud.

$$S_i^{\mathrm{EH}} \propto \frac{j_e q_i^2}{m_i E_e}$$

IH **Ionisation heating**
Sudden increase of charge state provides excess radial potential energy, which subsequently thermalises.

Heat transfer and losses

TR Ion - ion heat transfer

Collisions between different ions even out temperature.

$$S_i^{\mathrm{TR}} = \sum_j C_{ij}(\dots)(k_{\mathrm{B}} T_j - k_{\mathrm{B}} T_i)$$

ESC Ion losses and evaporative cooling

High energy tail of thermal distribution escapes from trap, reducing temperature after rethermalisation.

$$R_i^{\mathrm{ESC}} \propto \exp(-\omega_i)/\omega_i, \text{ where } \omega_i = q_i \Phi_{trap}/(k_{\mathrm{B}} T_i) \gg 1$$