Ion beam extraction from magnetized plasma

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outline

- some basic equations, describing the plasma
- experimental experiences, showing the plasma
- simulation of an ion beam, extracted from the plasma

Conservation laws

energy

$const = aq\Phi + \frac{1}{2} mv^2$

the sum of kinetic and potential energy is constant

m mass
v velocity
Φ potential
a charge state
q charge

momentum

$\mu = 1/B * \frac{1}{2} mv^2_{\perp}$

magnetic moment is constant

μ magnetic moment
B magnetic flux density
$v_{\perp}$ transverse velocity

Larmor radius

$$r_L = mv_\perp / qB$$

Some examples, with the assumption of a certain transverse energy (here 5 eV) and a given magnetic flux density (here 1Tesla) are given in the following table:

mass	charge	velocity [m/s]	r_L@B=1T [m]
electron	-1	1327075	$7.5\ 10^{-6}$
p	1	30971	$0.32\ 10^{-3}$
Ar	10	9793	$0.41\ 10^{-3}$
Xe	10	8525	$1.17\ 10^{-3}$
U	1	2000	$4.97\ 10^{-3}$
U	28	10620	$0.94\ 10^{-3}$

Larmor radii for ions (and of course for electrons) are small compared with the plasma chamber dimension!

$\leftrightarrow$

Plasma is fully magnetized!

Not only the electrons as for example in a Penning or Duoplasmatron ion source

Shielding

Debye length λ_D

$$\lambda_D = \sqrt{\varepsilon_0 k T_e / (n_e\, e^2)}$$

$$\lambda_D = 7.43\ 10^3 \sqrt{T_e[\mathrm{eV}] / n_e[\mathrm{m}^{-3}]}$$

n_e number of electrons

ε_0 dielectric constant

k Boltzman constant

e electron charge

T_e electron temperature

But, if magnetic field is present, this definition is not valid any more!

This definition of the Debye length might be correct in the direction of the magnetic field line, perpendicular to the field line the Debye length sometimes is replaced by the Larmor radius.

Dynamic shielding

plasma frequency (electrons)

$$\omega_{pe} = \sqrt{n_e\, e^2 / m_e \varepsilon_0} \approx 56.4 \sqrt{n_e[m^{-3}]}$$

ω_{pe} plasma frequency for electrons

m_e electron mass

plasma frequency (ions)

$$\omega_{pi} = \sqrt{n_i\, e^2 / m_i \varepsilon_0}$$

ω_{pi} plasma frequency for ions

m_i ion mass

Because $\omega_{pe} > \omega_{pi} \rightarrow \omega_p = \omega_{pe}$

Bohm's sheath criterion defines the difference between plasma chamber potential and plasma potential.

$\Phi = -T_e \ln \sqrt{m_i/(2\pi m_e)}$ But what is T_e? $\ln(\sqrt{m_i/(2\pi m_e)})$ is between 2.8 and 5.5

The plasma potential in the order of several Volts to several 10 Volts. From that, the temperature of all electrons can be calculated. Of course, this does not exclude the presence of high energy electrons.

Self's theory for the description of the plasma boundary is valid along each magnetic field line, with the assumption that 'enough' electrons are available on any magnetic field line.

$n_e = n_{e0} \exp((\Phi-\Phi_{pl})/kT_e)$ **S.A. Self, Phys. Fluids 6, p.1762, 1963.**

The available electron density does not only depend on plasma characteristics, but also on the magnetic field direction:

$n_{e0}(\text{plasma},B)$.

$\mathbf{n_e}$	electron density
$\mathbf{n_{e0}}$	electron density within the undisturbed plasma
$\mathbf{\Phi_{pl}}$	plasma potential
$\mathbf{\Phi}$	potential at (x,y,z)
K	Boltzmann's constant
$\mathbf{T_e}$	electron temperature

Just for completeness: electron cyclotron resonance frequency

$$\omega_{ce} = 1.76 * 10^{11} * B[T]$$

For ions, this frequency is lower by the factor of m_e/m_i

Collisions and diffusion

It is possible to estimate the time necessary for the momentum transfer between different particles[Zohm]:

$\tau_{ee} = 2\pi 3^{1.5}\, \varepsilon_0^2 \sqrt{m_e} (kT_e)^{1.5} / (e^4 \ln\Lambda\, n_e)$

$\tau_{ei} \approx \tau_{ee} \quad \tau_{ie} \approx m_i/m_e\, \tau_{ee}$

$\tau_{ii} \approx \tau_{ee} \sqrt{m_i/m_e}\, (T_i/T_e)^{1.5}$

already with the assumption that $T_e = T_i = T$ λ_c becomes larger than the plasma chamber.

$\lambda_c[m] \approx 2 * 10^{16}\, T[eV]^2 / n[m^{-3}]$

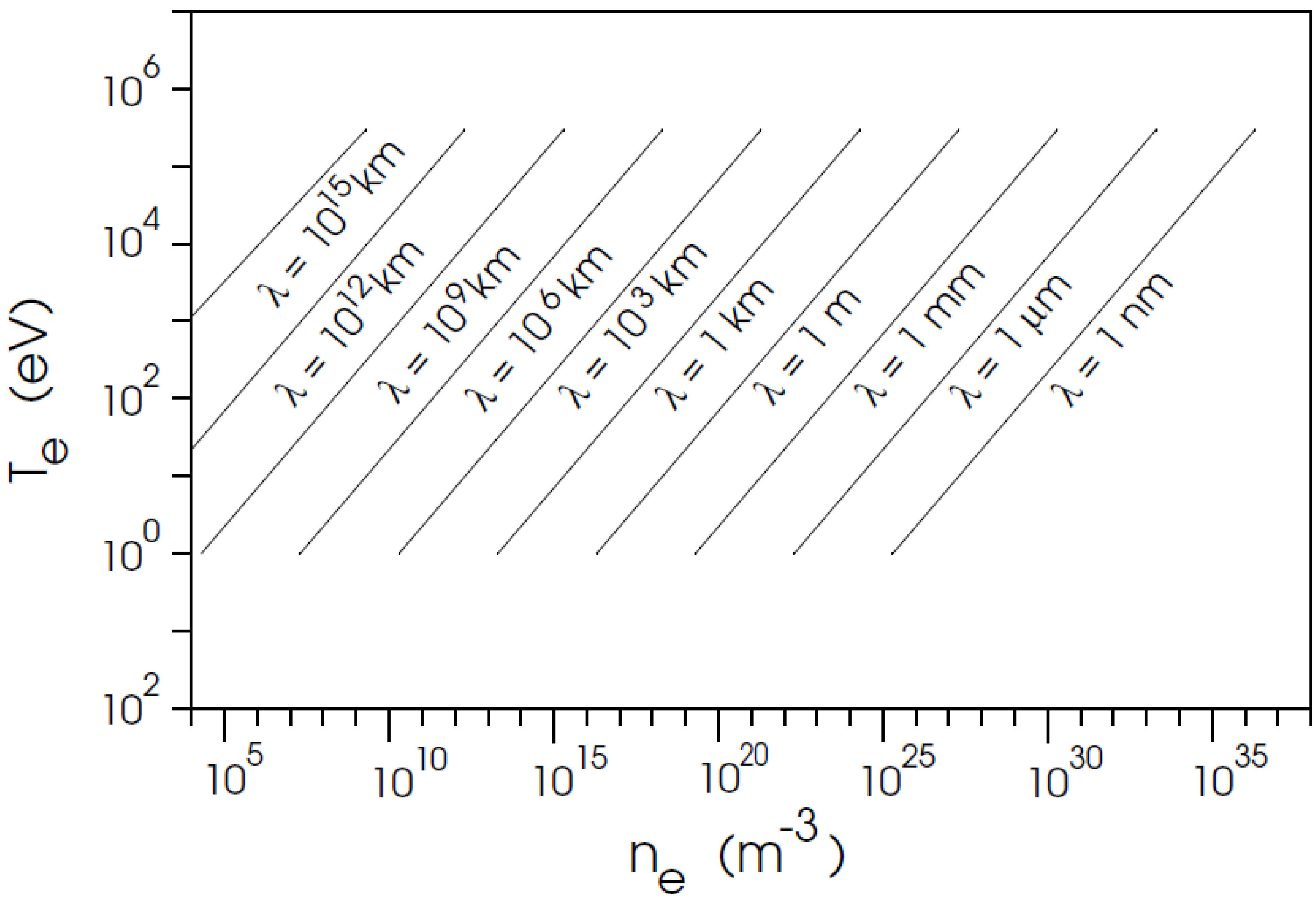
λ_c mean distance between collisions

T temperature

n_e electron density

The average length between two collisions λ_c is larger than the dimension of the plasma chamber.

If λ_c is large, diffusion effects are small. This fact is confirmed by pictures from the plasma.



Mean free path length between collisions within a thermal plasma[Zohm], shown in a n-T diagram.

Collisions and diffusion

$$\partial n/\partial t - D\,\Delta^2 n = 0$$

However, diffusion coefficients for electrons $\parallel$ to B, and $\perp$ to B are different, of course for ions as well! Only the neutrals will behave differently.

$$D_{\parallel e} = 1.2\ 10^{22}\ T_e^{2.5}/n$$

$$D_{\perp e} = 4.0\ 10^{-22}\ n\ /\ (\sqrt{T_e} B^2)$$

Diffusion is effective in the direction of the magnetic field line, but becomes less important perpendicular to the magnetic field line.

Experimental results: diffusion?

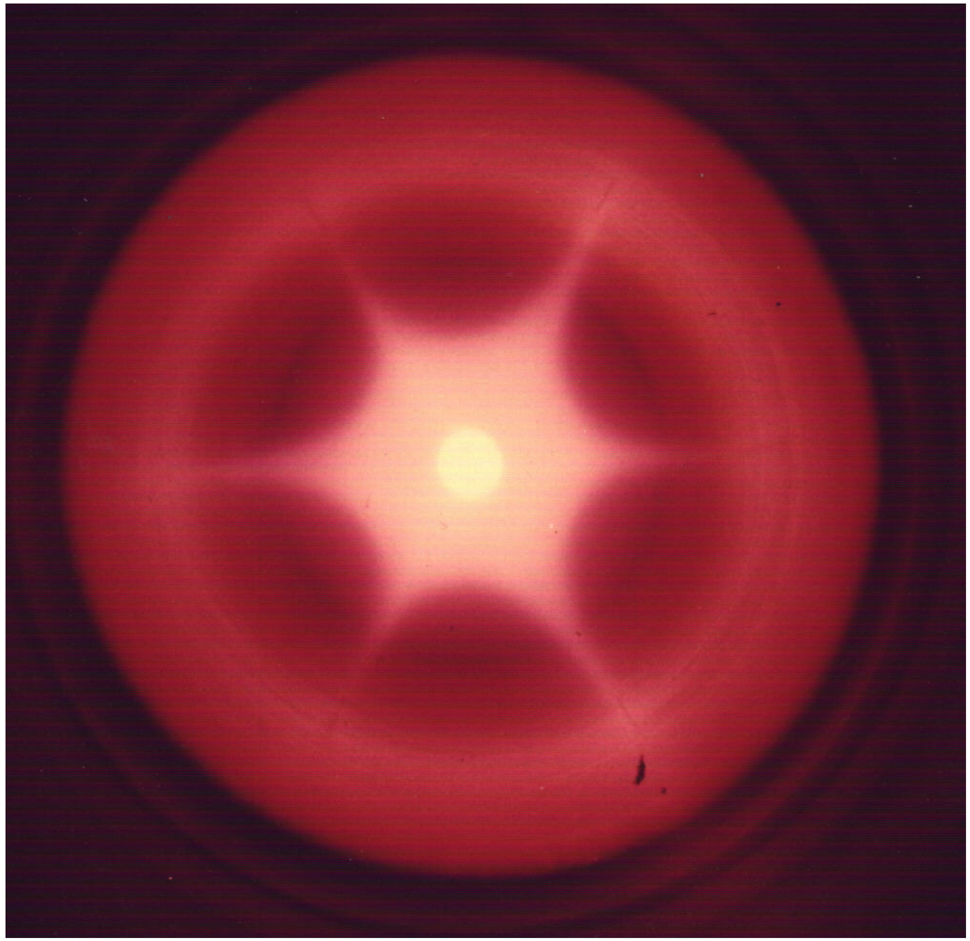


Photo by Meyer, Oak Ridge, TN

Experimental results: diffusion?

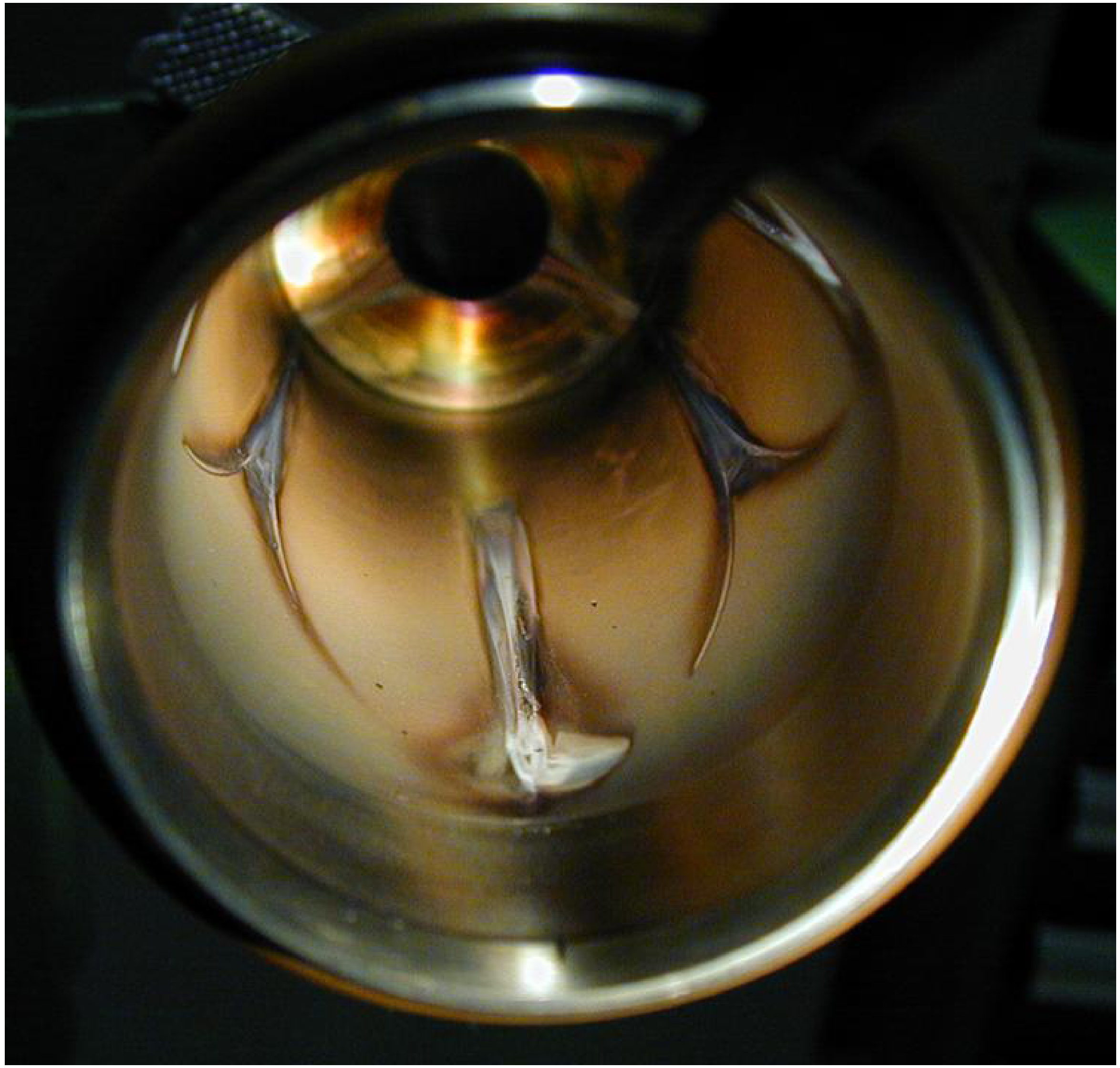


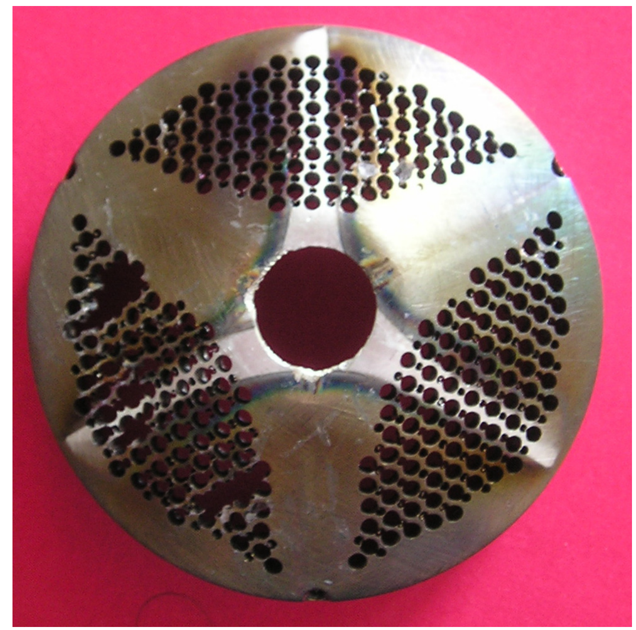
Photo from the CAPRICE plasma chamber, GSI

Experimental results: diffusion?

Drilling holes into the extraction electrode (plasma electrode), to improve the vacuum conditions within the plasma chamber.

The electrode has to be aligned with respect to the magnetic field distribution, otherwise it will not work!

ok



Something went wrong …

Photo by Geller, Grenoble, France

Motion of charged particles within the plasma is mainly determined by the Lorentz force. In addition a E×B-drift can be identified on the end plates of the plasma chamber.

The B-field is assumed to be mainly in longitudinal direction. The E-field should be mainly in radial direction; may be with a nonlinear dependency from the radius.

Therefore, the E×B-drift has to be in azimuthal direction.

Experimental results: ExB drift?

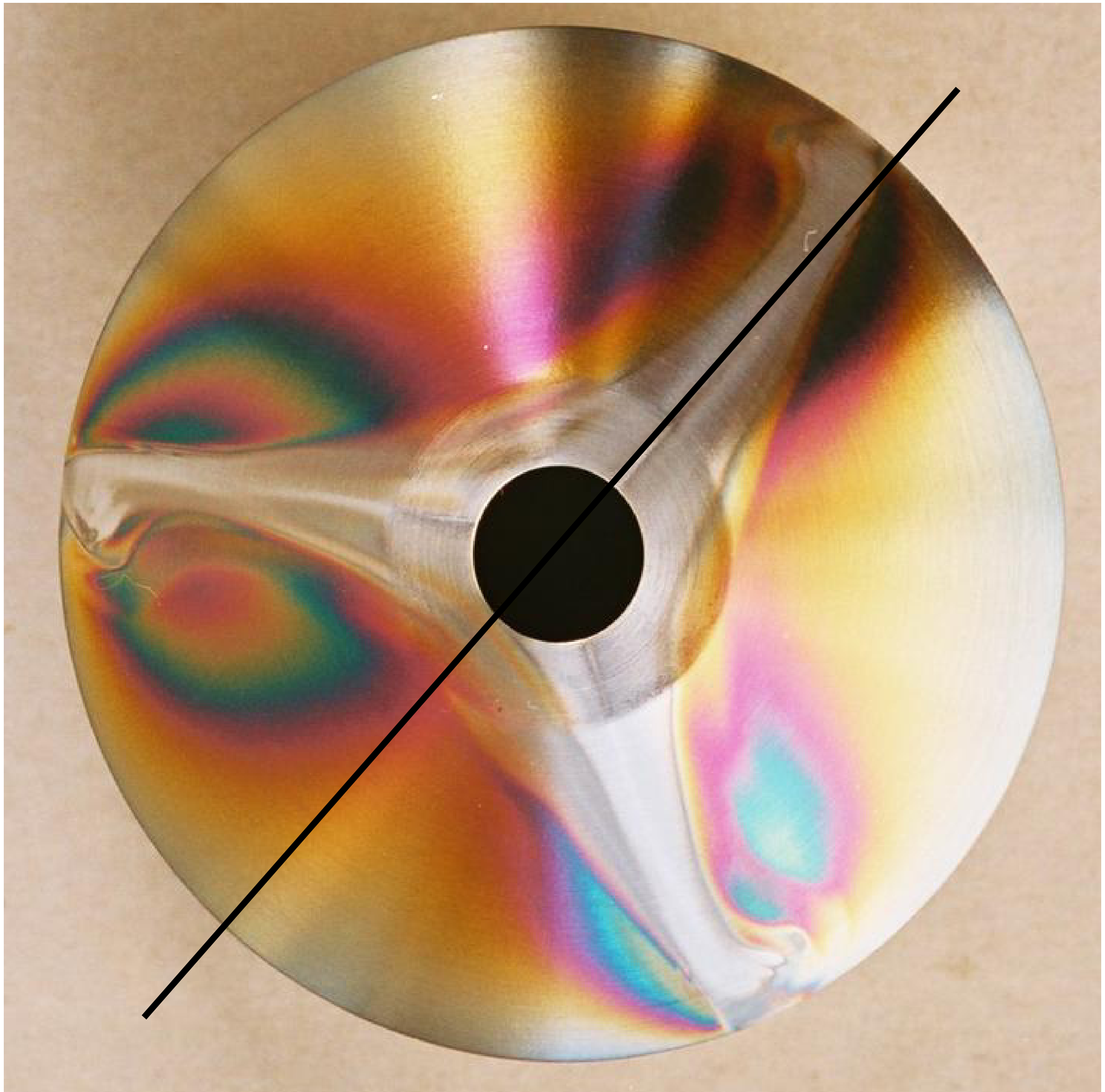


Photo from the CAPRICE extraction electrode, GSI

Experimental results: ExB drift?

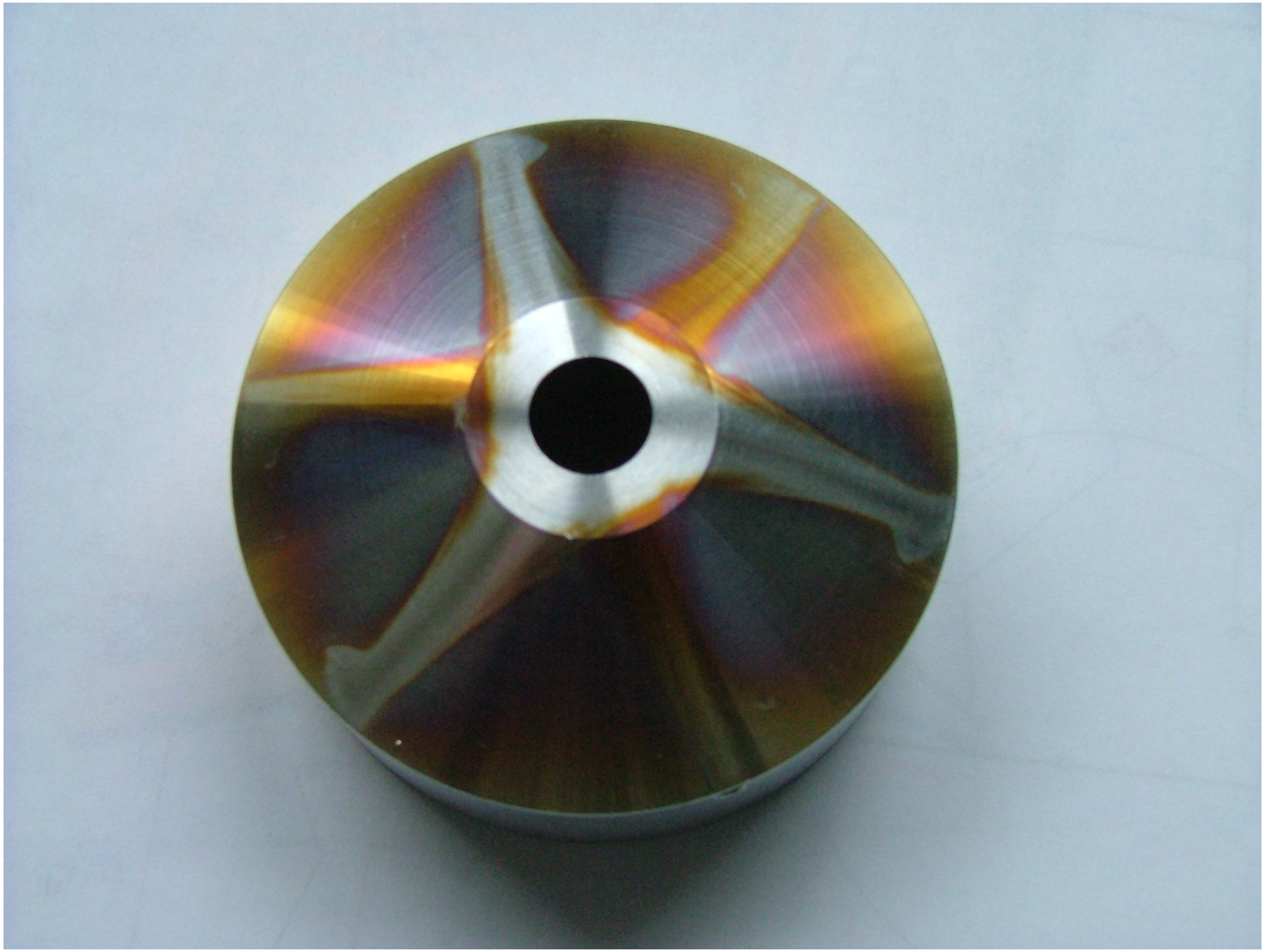


Photo from the CAPRICE extraction electrode, GSI

preparation for the simulation process made with KOBRA3-INP

- All analytic dependencies should be used to perform the simulation!
- compute nodal information given by geometry
- compute magnetic flux density components on each node (3D necessary!)

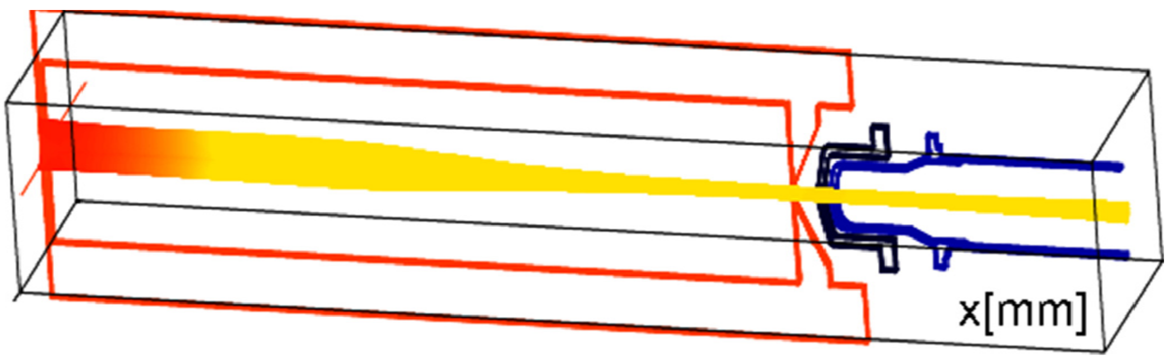
  use the correct coil settings

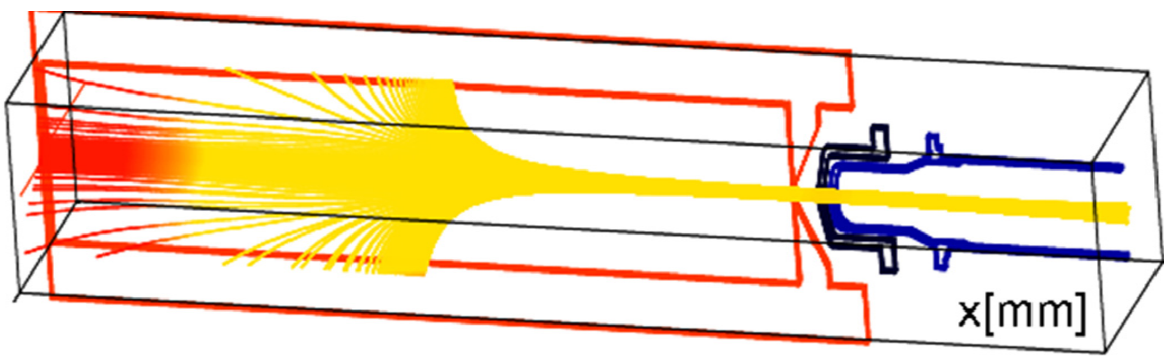
- compute electric potential given by the electrodes; space charge 0
- compute starting conditions for particles

  use the correct starting conditions!
  compute magnetic field lines going through the extraction aperture.
  generate starting coordinates for ions when the local magnetic flux density is above the flux density at the extraction aperture

- ray tracing and generation of space charge
- solve Poisson equation and do ray tracing, creating new space charge iteratively
- Self's model to compensate space charge forces of positive ions close to the plasma potential can be used.

Geometry and magnetic flux density for the MS-ECRIS





Strong magnetic fields for the plasma confinement (magnetic flux density has been calculated with Tosca®):

- magnetic field lines going through the extraction aperture indicate the possible paths of ions to be extracted.
- the color of the field line changes from yellow to red, when the flux density is equal the flux density at the extraction aperture.
- but the field lines depend on specific coil settings.

If the azimuth is increased, the field line might come from different longitudinal positions (lower picture). That means that the $\oint Bds$ changes with azimuth!

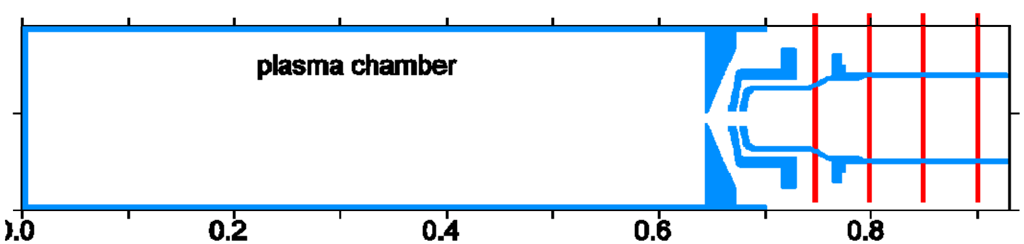
If $\oint Bds \neq 0$ the trajectory will become twisted.

A PIC (particle in cell) code is required, if time dependant processes are to be studied. For the simulation of the cw beam a trajectory code is absolutely sufficient.

- Using the coordinates and the local magnetic flux density of the magnetic filed lines going through the extraction electrode aperture provide starting coordinates for the ions.

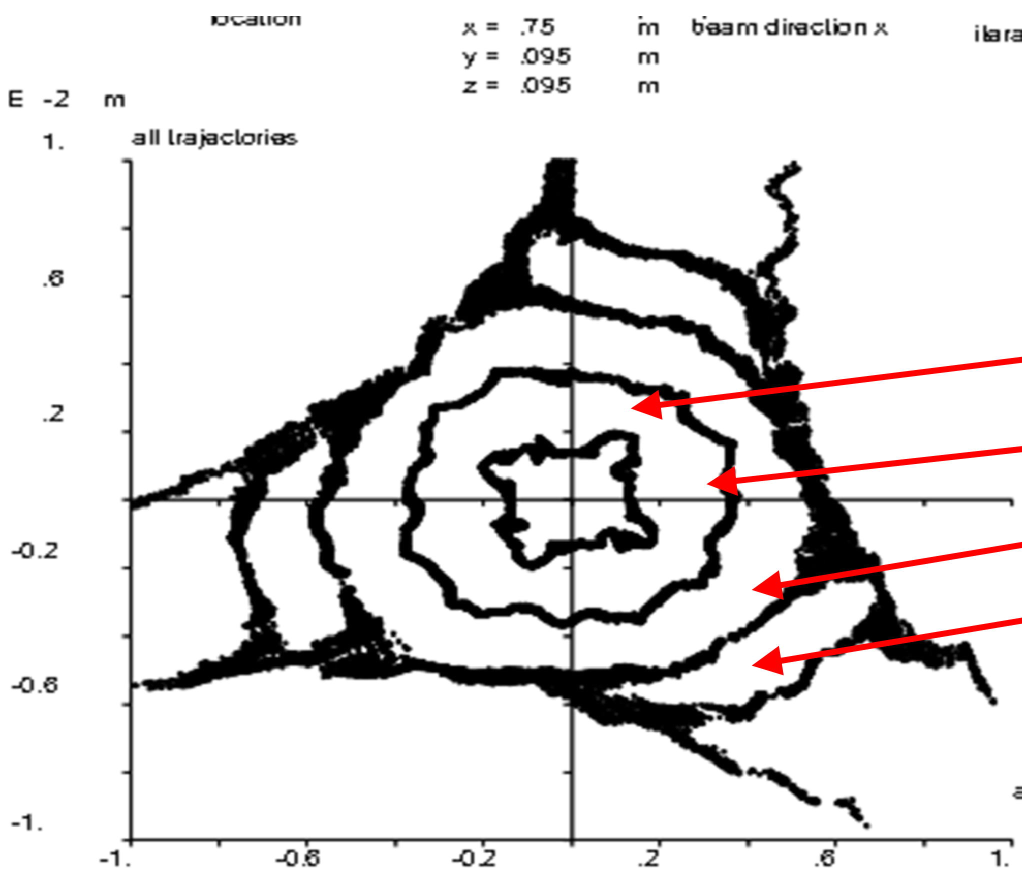
- The ‘structure’ of the extracted beam (shown on the next slight) is because magnetic field lines have been traced for discrete coordinates only (r_i, x_0, θ): r_i=1,2,3,4mm, x_0=0.64m, θ = 0,360°. This structure is of course artificial, but interpretation is convinient.

4 different planes where profiles, emittances, and momentum space are shown on the next slights.



Note: all computed particle presentations are projections of the 6-dimensional phase space into the 2-dimensional plotting space.

extracted ions (here only Ar^{3+} is shown)

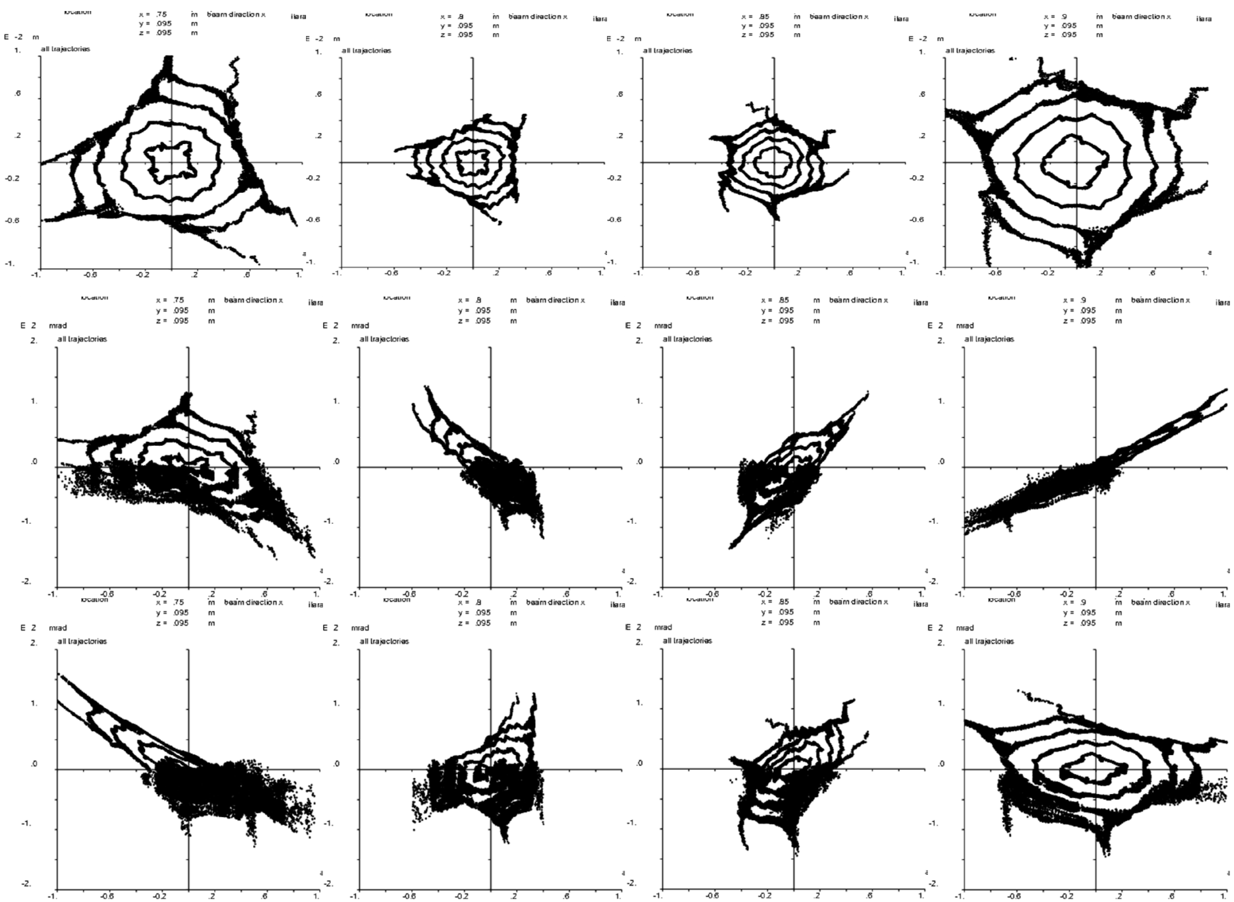


Profile at X = 0.75m

starting conditions from field lines with different radius at the extraction aperture

- r=1 mm
- r=2 mm
- r=3 mm
- r=4 mm

Scale +/- 1cm for both axis

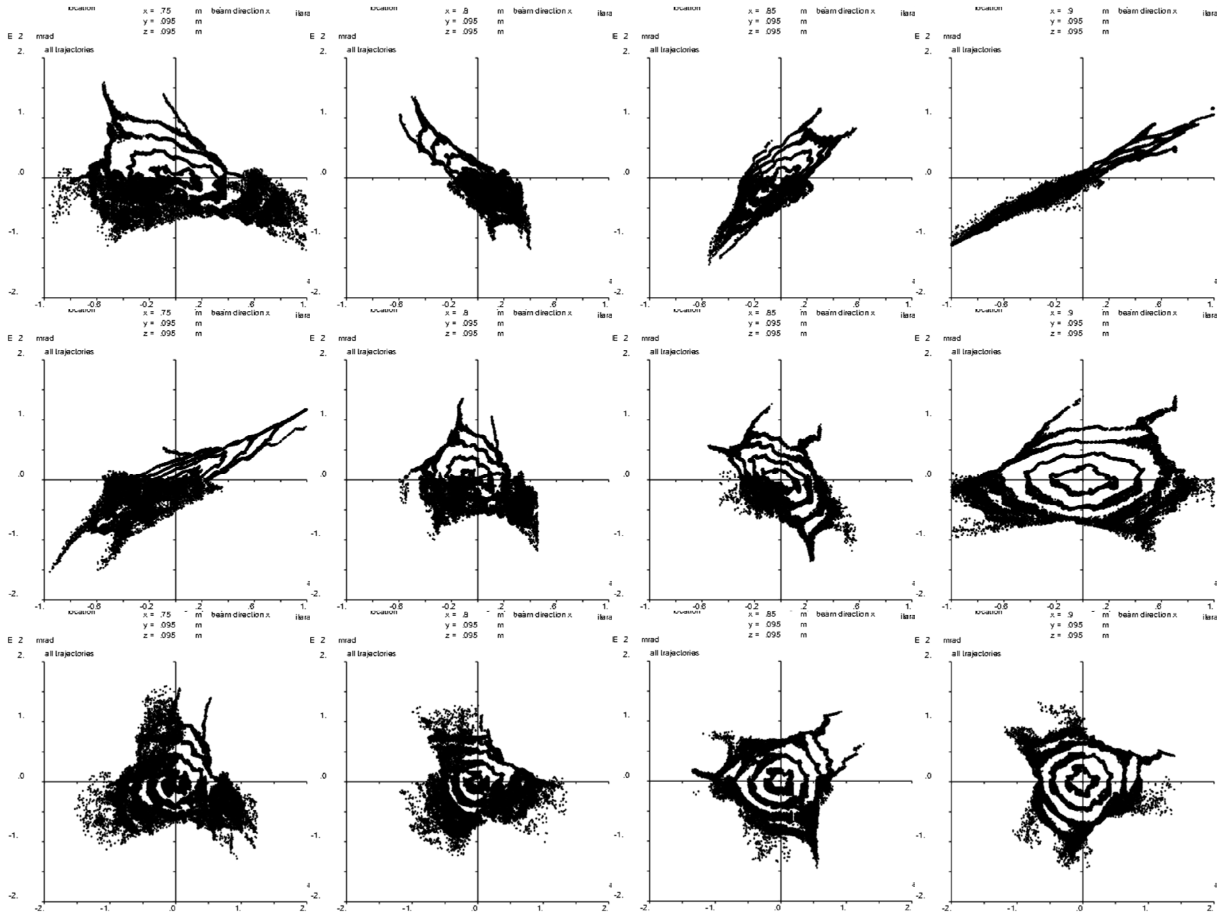


real space y-z

emittance y-y’

mixed phase space y-z’

x=0.75 m x=0.80 m x=0.85 m x=0.90 m



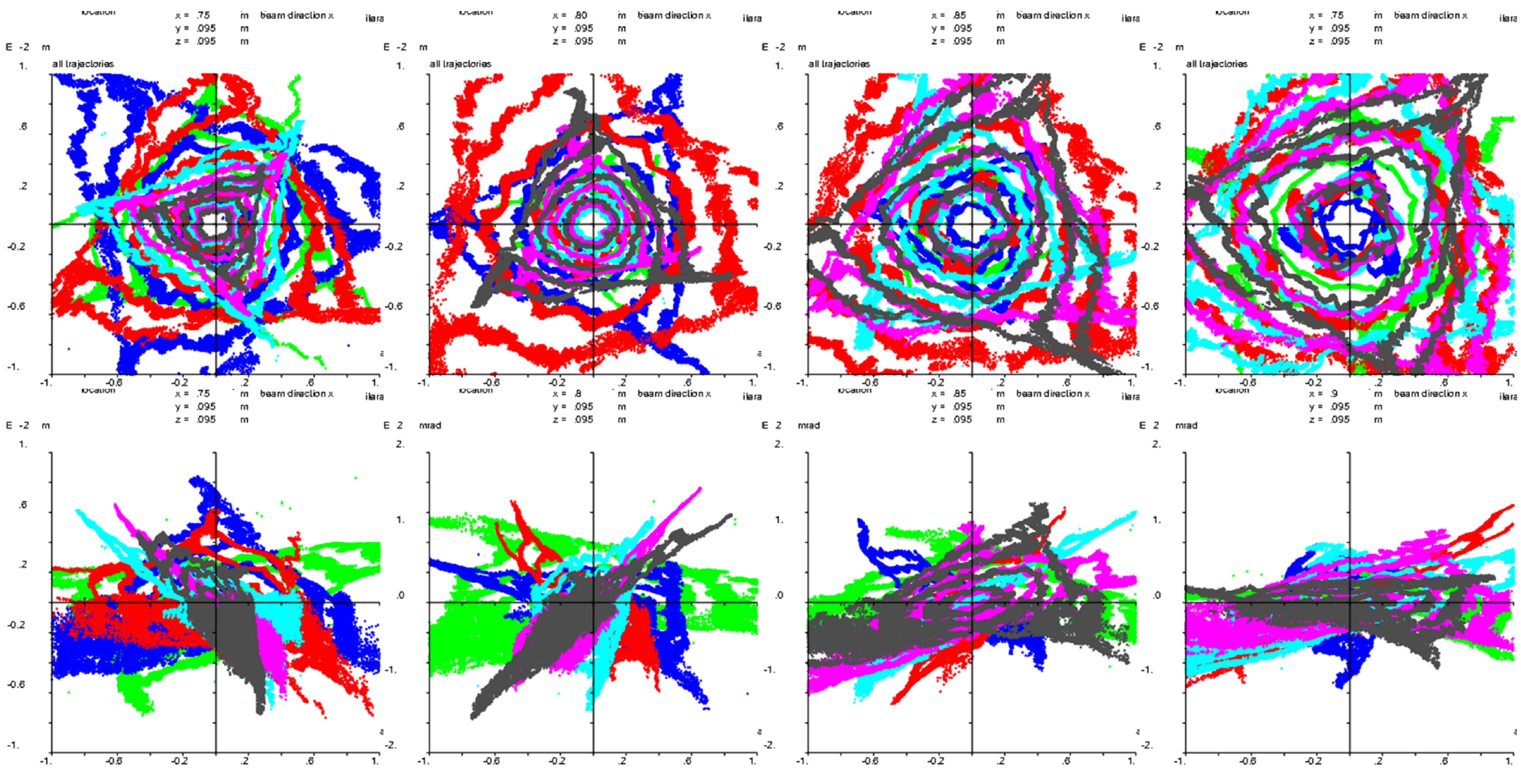
emittance z-z’

mixed phase space z-y’

momentum space y’-z’

x=0.75 m | x=0.80 m | x=0.85 m | x=0.90 m

extracted ions (here different charge states of Ar are shown)



profile y-z

scale +/- 1cm

emittance y-y'

scale +/- 1cm

+/- 200 mrad

X = 0.75 0.8 0.85 0.9 m

Ar^{6+} Ar^{5+} Ar^{4+} Ar^{3+} Ar^{2+} Ar^{+}

Conclusions:

The stray field of the solenoid from the source already focus the extracted beam. Overfocusing might occur at low m/q or at high B.

Different charge states are treated differently.

Extracted ions have their origin at different longitudinal positions inside the plasma.

Ions extracted on one radius are generated at different longitudinal positions, depending on the azimuth, having therefore different $\int B\,ds \neq 0$!!

The structure of the extracted beam is already formed inside the plasma chamber.

The current of each trajectory will depend on the plasma density at the individual starting coordinate. This part of the simulation is still not included. An interface to another program could be made here [e.g. to TrapCad, S.Biri].

Child's law should be valid, but only locally along each magnetic field line. At some starting coordinates the plasma might be also emission limited, depending where the magnetic field line has its origin.

Thank you for your attention!