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Low **E**nergy **B**eam **T**ransport

Space Charge Compensation

Space Charge Lenses

*** Introduction**

*** Production of compensation particles**

***Particle distributions & redistributions**

*** Compensation within lenses**

*** Decompensation at RFQ entrance**

***Temporal effects**

*** Space charge lenses**

*** Beam - "Plasma" interactions**

*** Examples**

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Space charge compensation

Envelopequation

$$\frac{d^2X}{dz^2} = \frac{\langle \varepsilon_{rms,x} \rangle^2}{X^3} + \frac{K}{2(X+Y)} - k_x^2 X$$

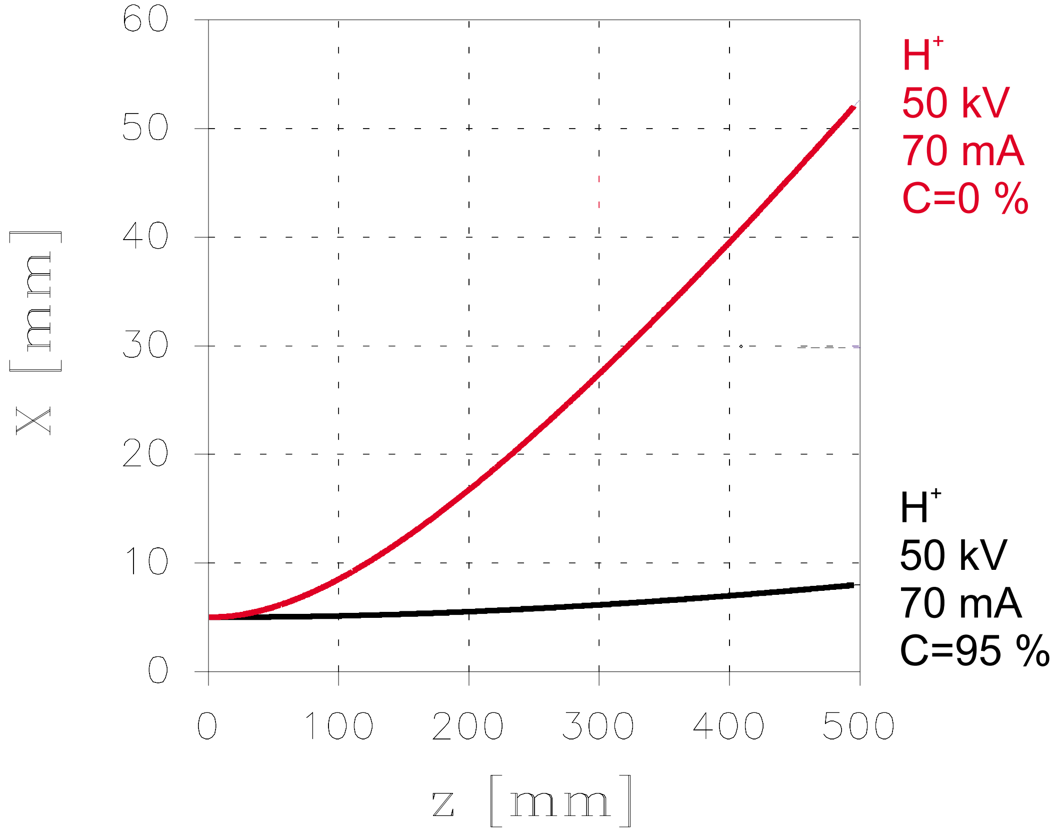
emittance

lenses

gen. perveance (space charge)

$$K = \frac{\Delta U}{U} = \left(\frac{1}{4\pi\varepsilon_0} \sqrt{\frac{Am}{2e\zeta}} \right) \frac{I}{U^{3/2}}$$

"For LEBT-systems space charge compensation can drastically enhance beam current limit and reduce strength of focussing fields."



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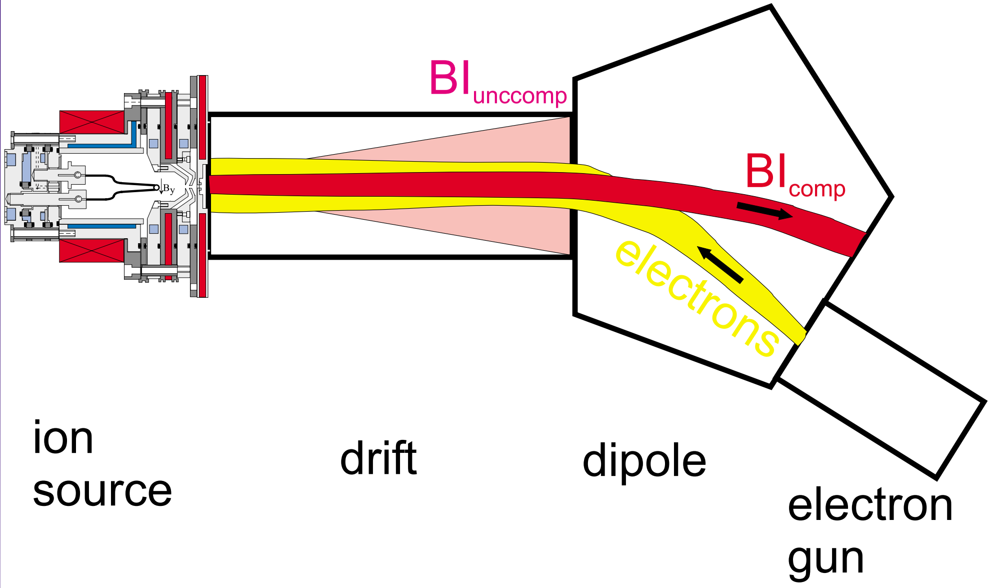
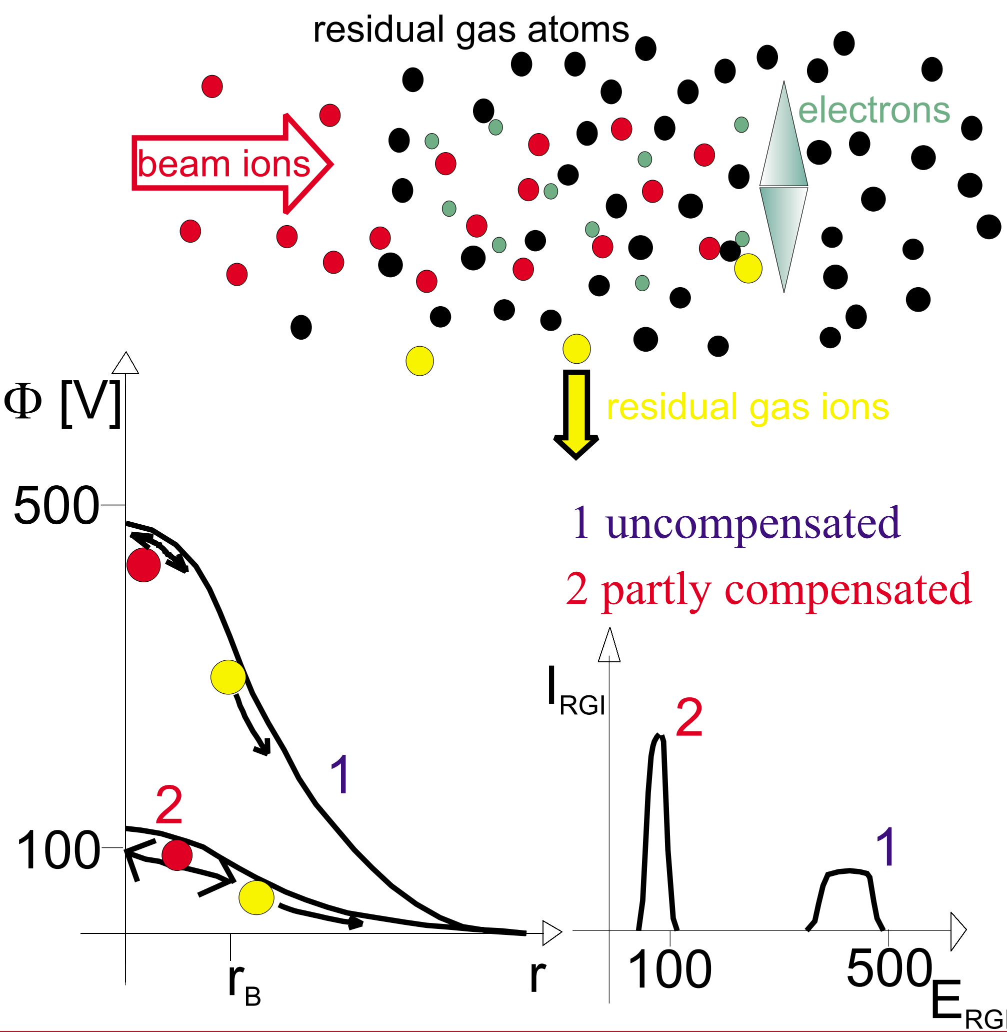
Space charge compensation by :

externally generated compensation particles



* plasma channel
* z-pinch plasma lenses
* space charge lenses

beam generated compensation particles



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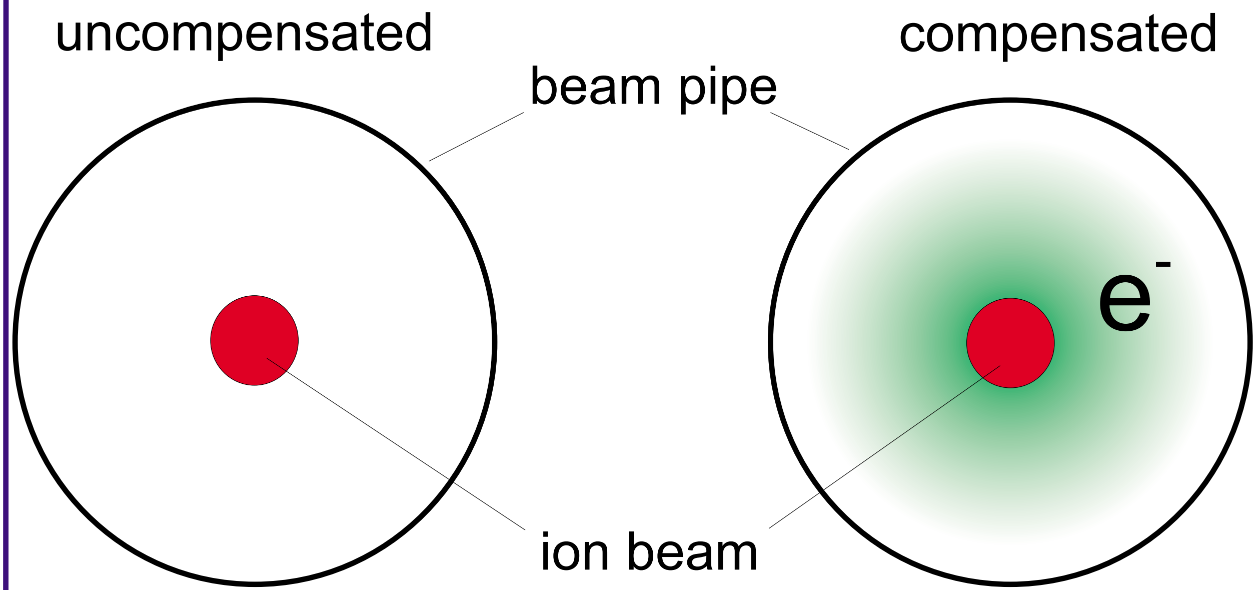
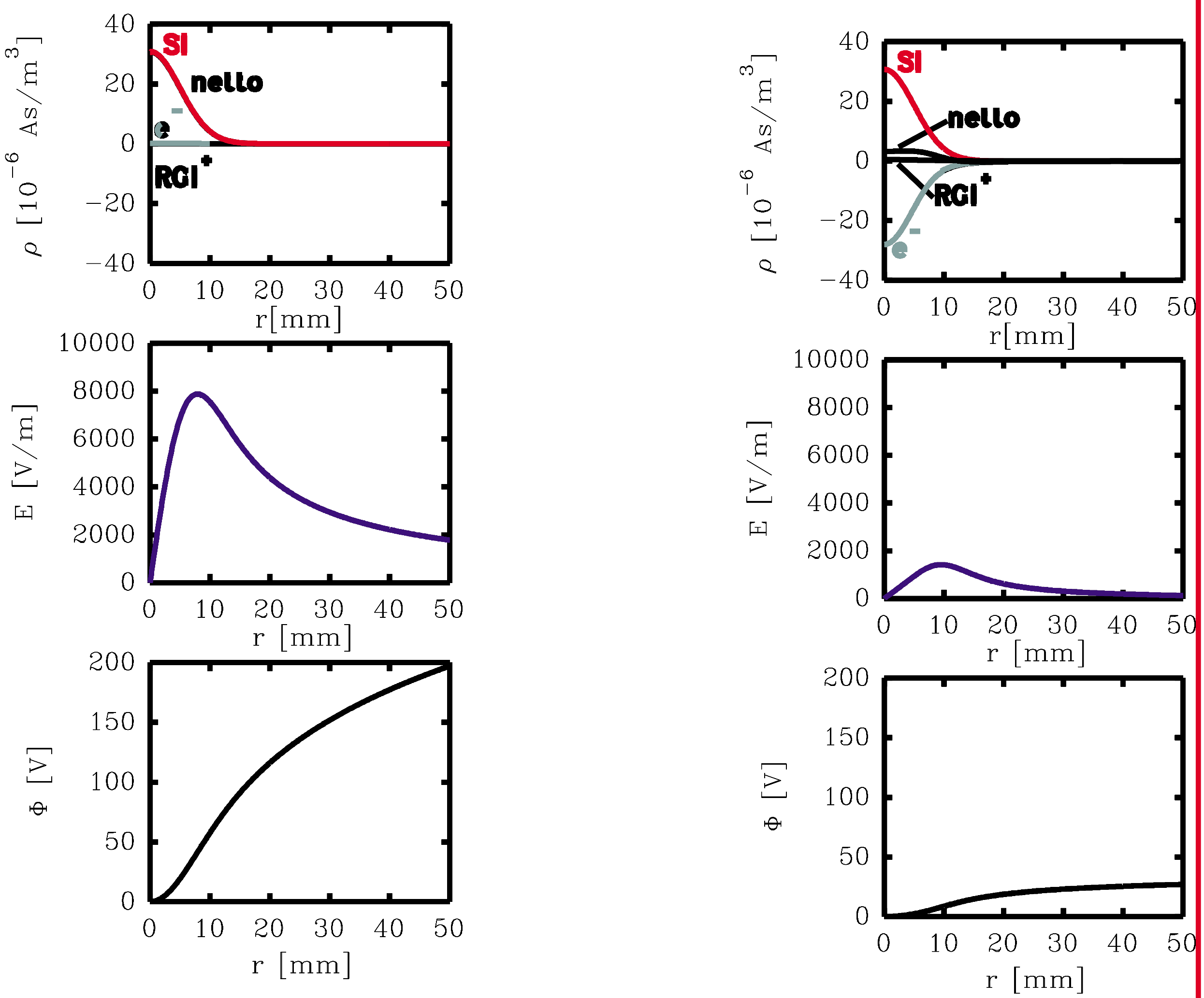
Space charge compensation reduces net charge density, electric field and beampotential





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Theory of space charge compensation and particle distribution

The net charge density is given by :

$$\rho_{net}(r) = \rho_{SI}(r) + \rho_{KE}(r) + \rho_{RGI}(r)$$

- production of compensation electrons and residual gas ions

$$\dot{\rho}_{[RGI,KE]}(r) = \rho_{SI}(r) \cdot v_{SI} \cdot n_{RGA} \cdot \sigma_{[RGI;KE]}$$

- "extraction" of residual gas ions by self field of the ion beam

$$\rho_{RGI}(r) = \frac{1}{r} \int_0^r \frac{\dot{\rho}_{RGI}(r^*) r'}{v_{RGI}(r', r^*)} dr'$$

$$v_{RGI}(r) = \sqrt{\frac{2 q_{RGI} \left[\Phi(r^*) - \Phi(r) \right]}{m_{RGI}}}$$

- thermalisation of the enclosed electrons (CE)

$$\rho_{KE}(r,z) = \rho_{KE}(\Phi_{\max}) \cdot e^{\left[-\frac{e(\Phi \max - \Phi(r))}{k T_{KE}} \right]}$$

Therefrom for a determination of the "beamplasma" state
it is neccesary to know :

- the radial beam ion density profile
- the residual gas pressure
- cross sections
- electron density on axis
- electrontemperature

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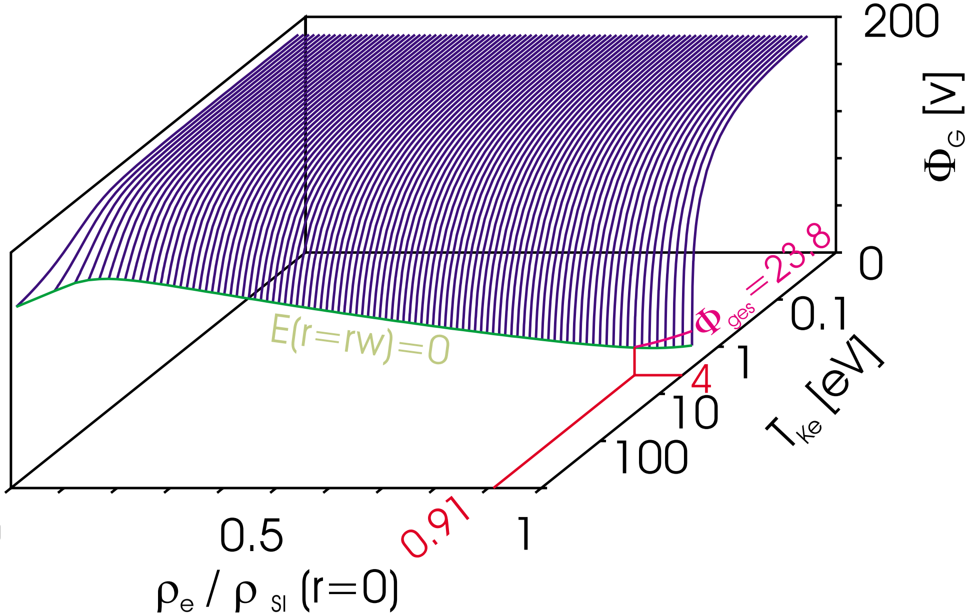
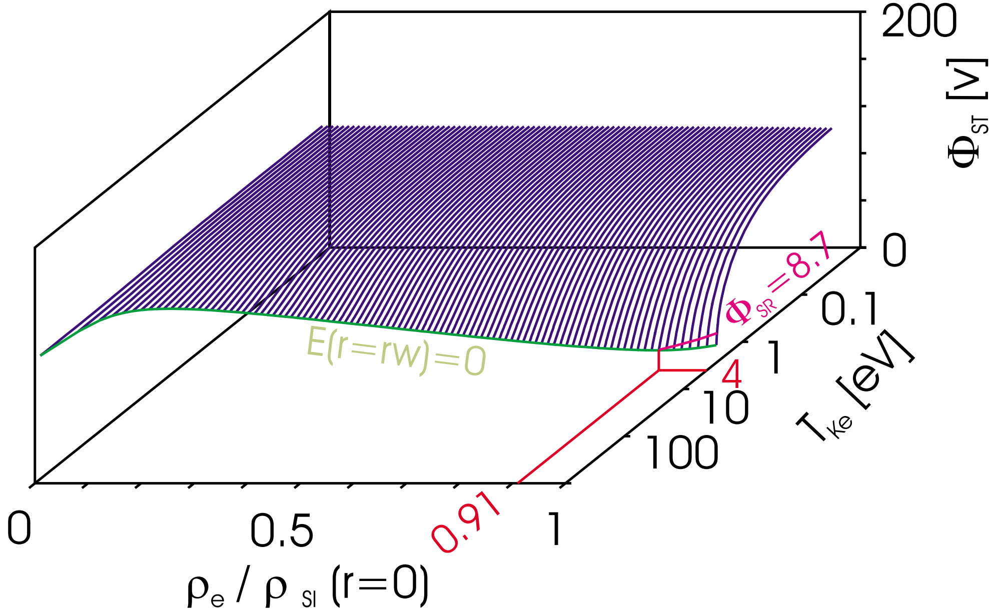
Determination of state of "beamplasma" by selfconsistent numerical simulations

$$\Phi(r) = \frac{1}{\varepsilon_0}\int_0^{r'}\frac{1}{r''}\cdot\int_0^{r''} r\cdot\Bigg[\overbrace{\underbrace{\rho_{SI}(r)}_{\rho_{SI}(r)} + \underbrace{\rho_{KE,SA}\cdot\exp\left[-\frac{e\cdot\Phi(r)}{kT_{KE}}\right]}_{\rho_{KE}(r)} + \underbrace{\frac{1}{r'''}\int_0^{r'''}\frac{\rho_{SI}(r_{Erz})\cdot v_{SI}\cdot n_{RGA}\cdot\sigma_{RGI}}{\sqrt{\frac{2}{m_{RGI}}\cdot q_{RGI}\cdot\left(\Phi(r)-\Phi(r_{Erz})\right)}}\cdot r\;dr}_{\rho_{RGI}(r)}}^{\rho_{netto}(r)}\Bigg]\,dr\;dr$$

total beam potential

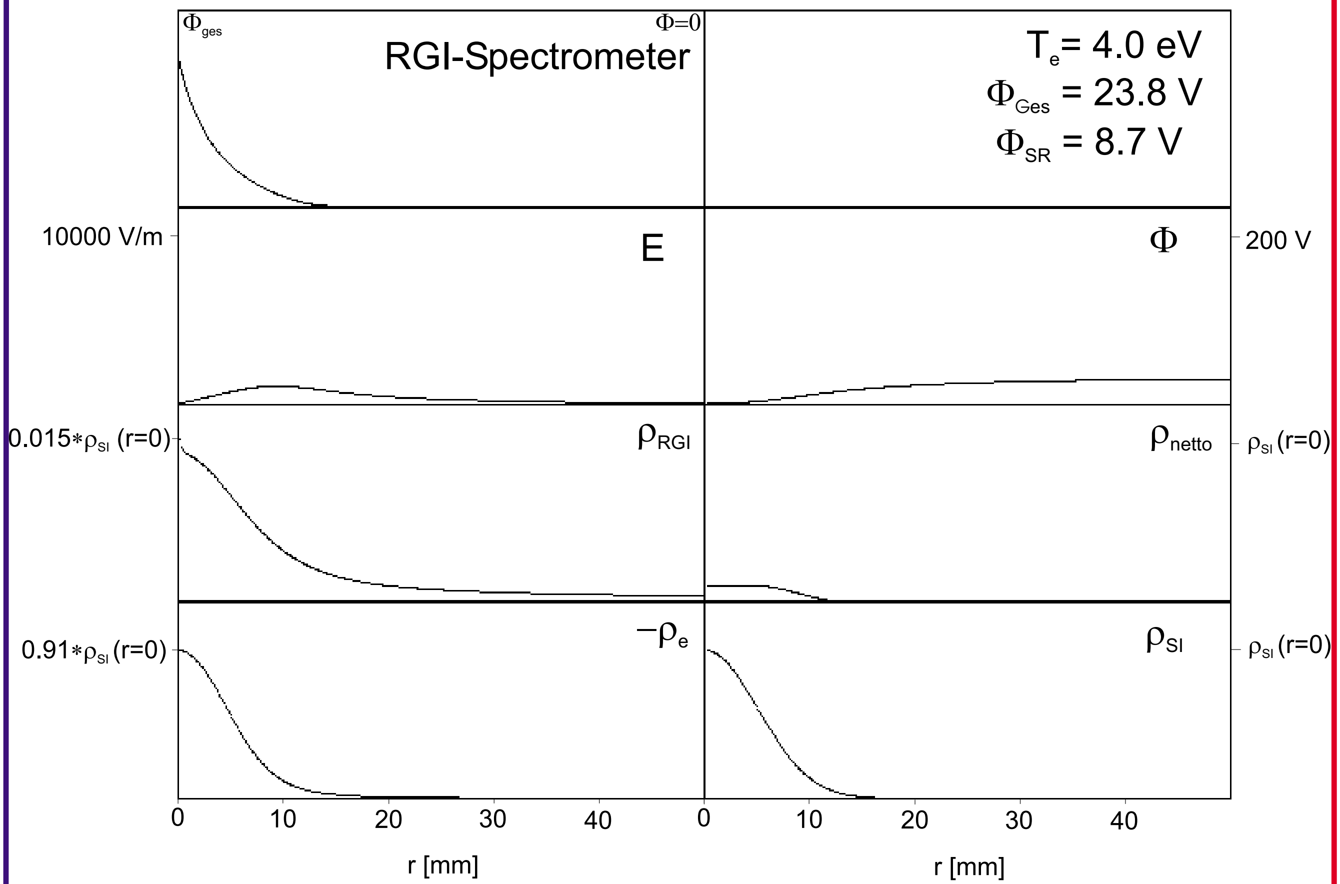


beam potential drop inside beam

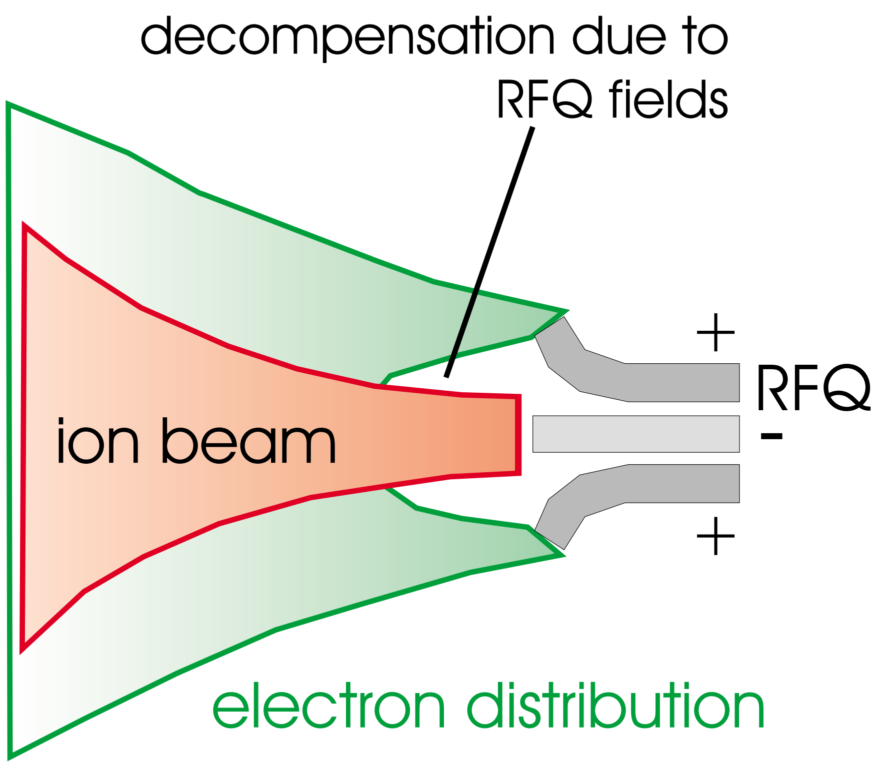


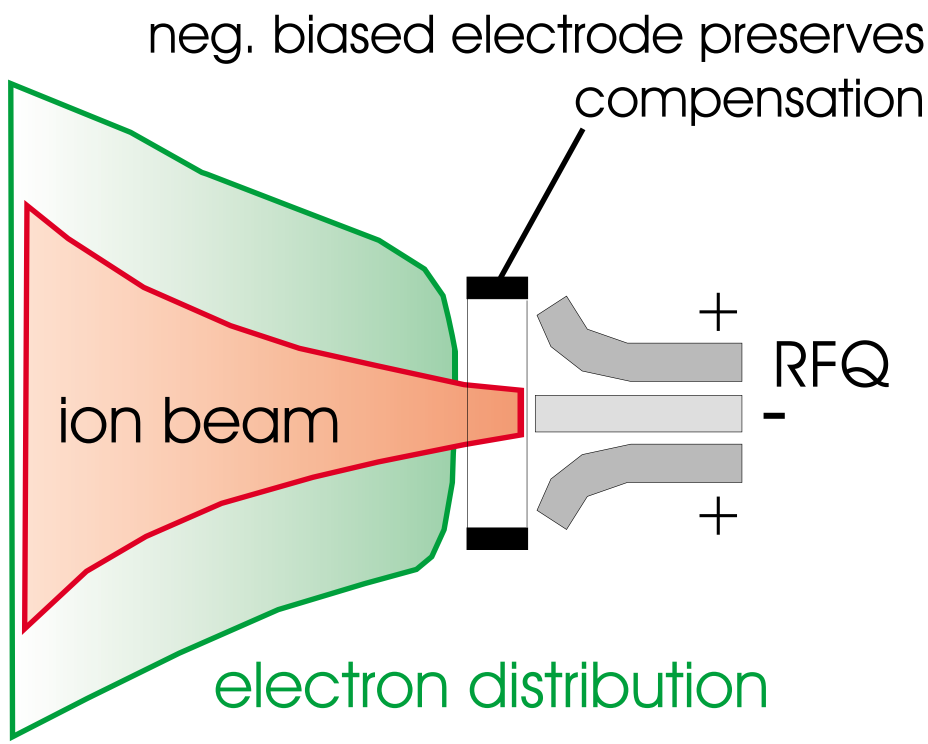
By comparison between
calculated and measured
beam potentials the state of the "beam plasma"
can be determined unequivocal

Example
For an He^+, 3.35 mA, 10 keV
the beampotentials have been measured to be
Φ_{total} = 23.8 V and Φ_{beam} = 8.7 V
therefrom the "free" parameters are :
T_e=4.0 eV und ρ_e/ρ_{SI} = 0.91



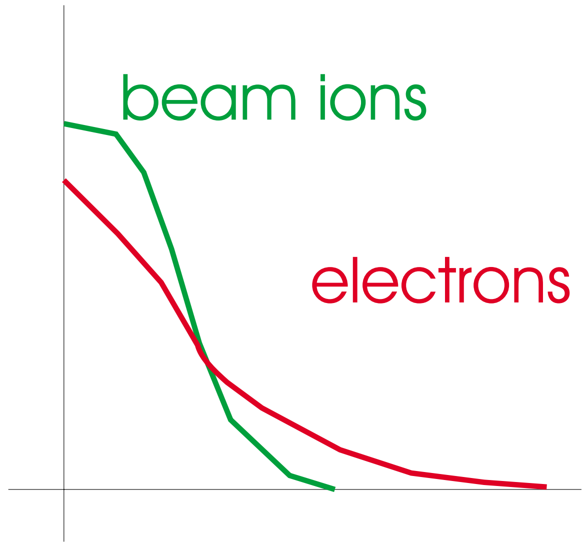
Injection electrode for suppression of RFQ - decompensation effect





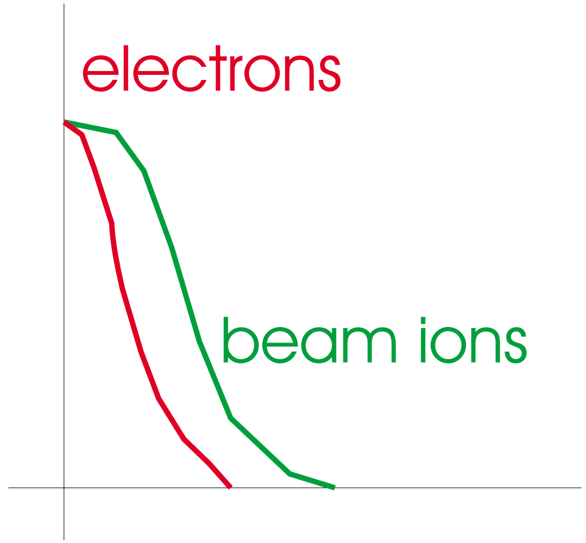
Radial electron density distribution in compensated ion beams

in drift region



dominated by radial losses
"good" global degree of compensation
"bad" degree of compensation on axis

in solenoid



dominated by longitudinal losses
"bad" global degree of compensation
"good" degree of compensation on axis

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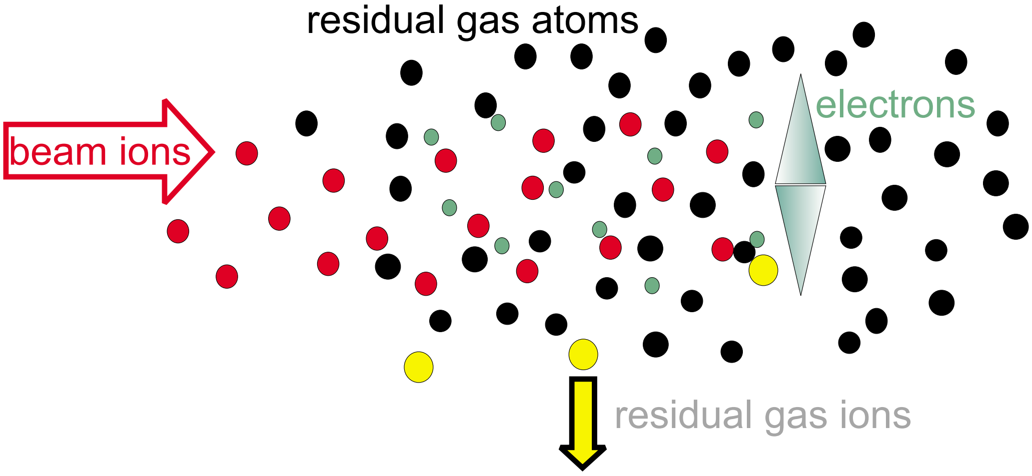
Temporal effects & rise time of space charge compensation



Production rate of compensation particles is given by:

$$\dot{n}_{CP} = \sigma_{CP} n_{RGA} v_{BI} n_{SI}$$

neglecting losses and assuming equal number of particles

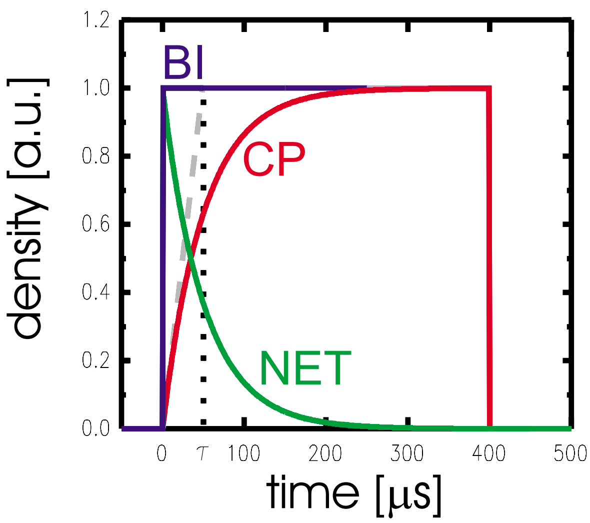
$$N_{SI} = N_{CP}$$

the rise time is given by

$$\tau_{SSC} = \frac{1}{\sigma_{RGI} n_{RGA} v_{BI}}$$

summarizing losses in an exponential term :

$$N_{CP} = \int_{t=0}^{t} \frac{dI_{BI}}{dt} \left(1 - e^{-\frac{t}{\tau_{ssc}}} \right) dt$$



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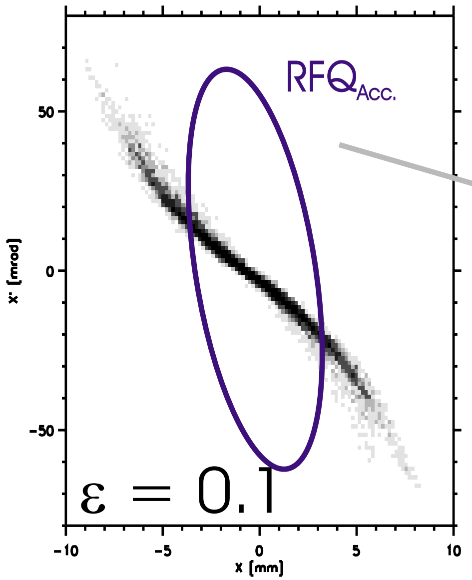
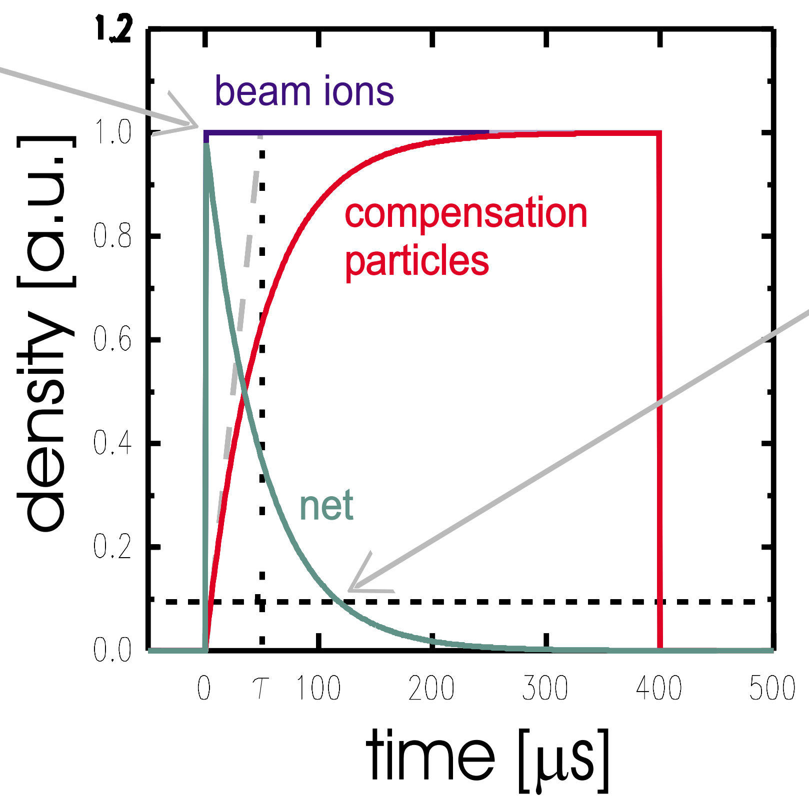
Influence of space charge compensation on injection into the RFQ. Mismatch due to rise time of compensation

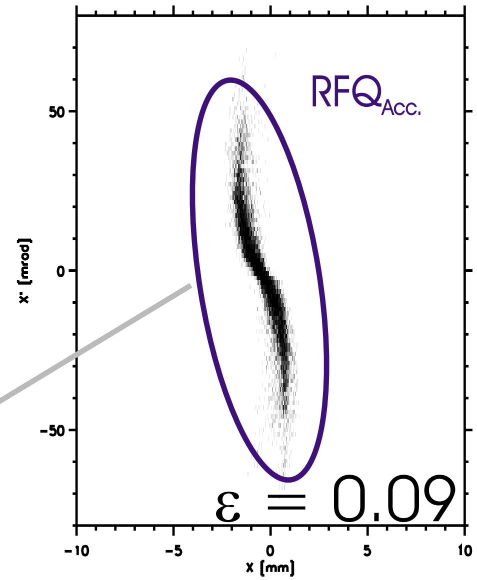
(calculation for D^+ , 100 keV , 140 mA)

Space $charge_{net}$ =100 %
0% compensated





Space $charge_{net}$ =10 %
90% compensated



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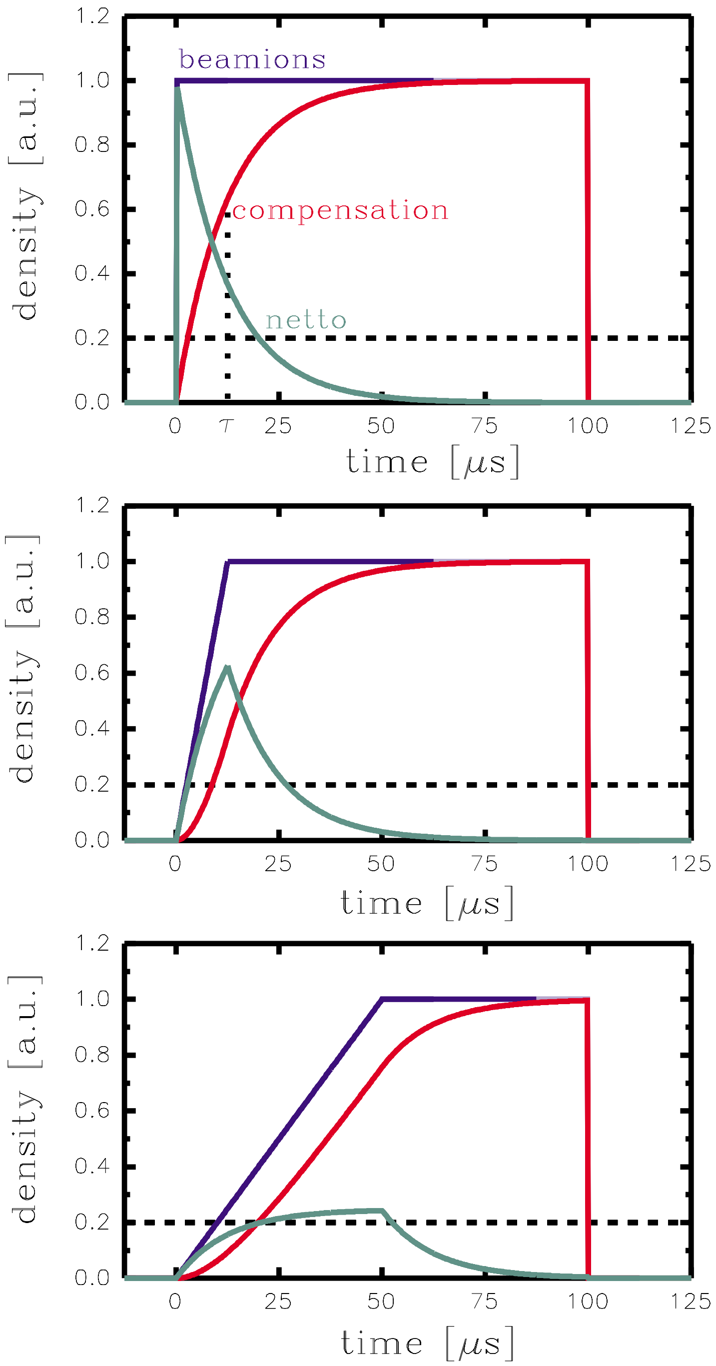
Comparison between the influence of the rise time of the ion source (τ_{source}) and space charge compensation (τ_{SCC}) on beam transport.



$50 * \tau_{source} = \tau_{SCC}$
dominated by
rise time
of compensation

$\tau_{source} = 4 * \tau_{SCC}$
dominated by
rise time
of ion source

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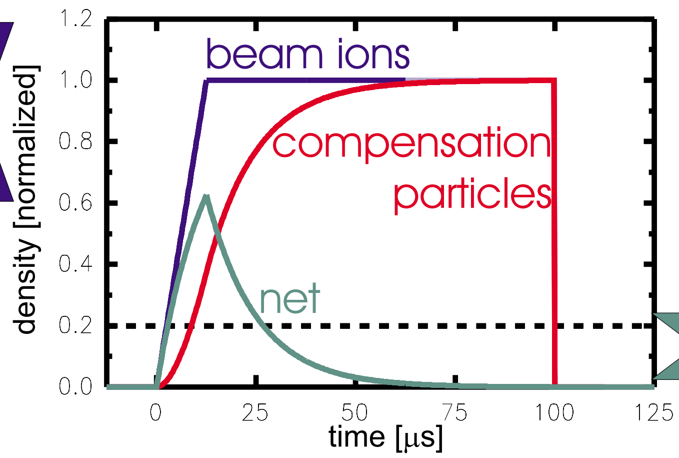
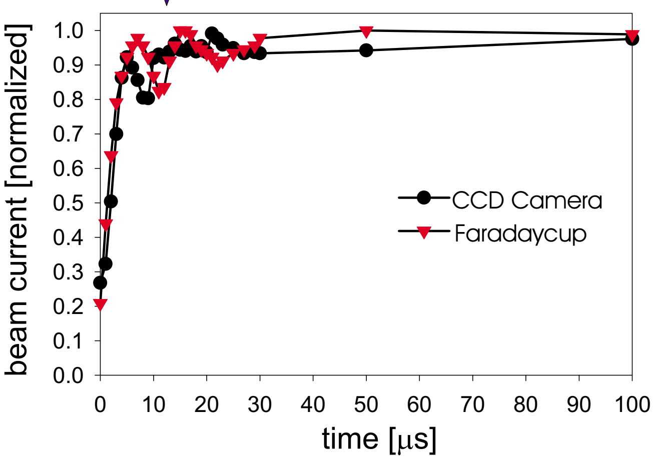
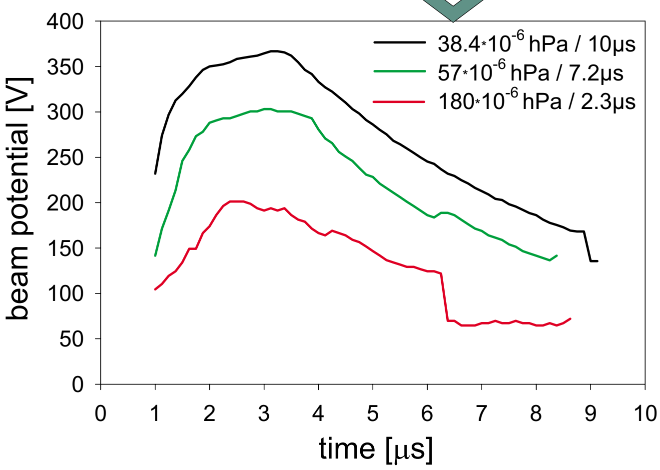
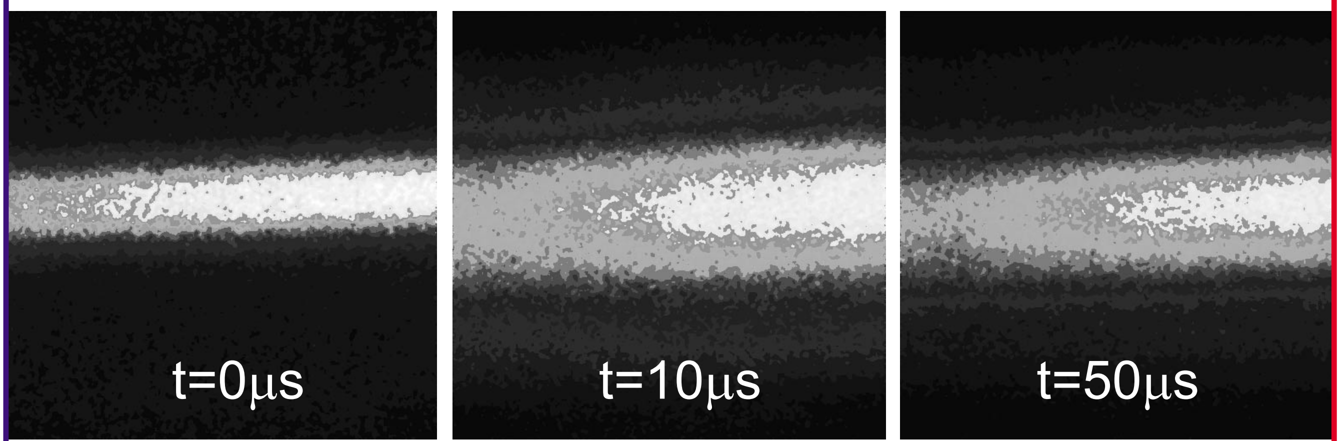
Measurements on the rise time of compensation at the SILHI-LEBT (CEA Saclay) (H^+ / 92 keV / 62 mA) (Dr. A. Jakob)







Transversal beam dimensions (by CCD)



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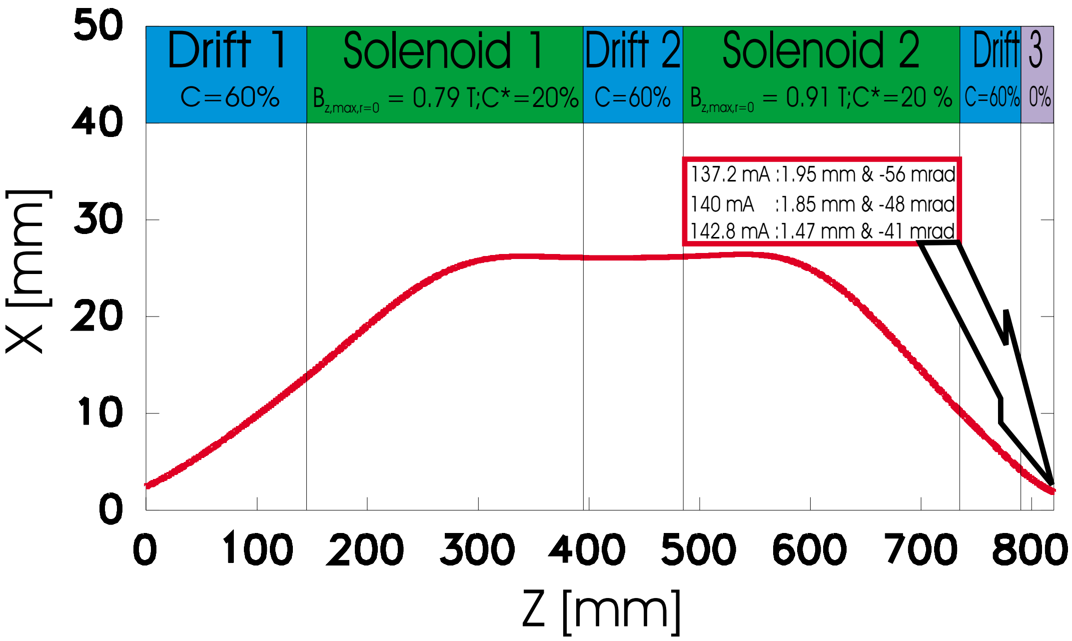
Numerical simulation of compensated beam transport in an solenoid LEBT including

fringe fields, CP distributions, RFQ decomp. and source noise

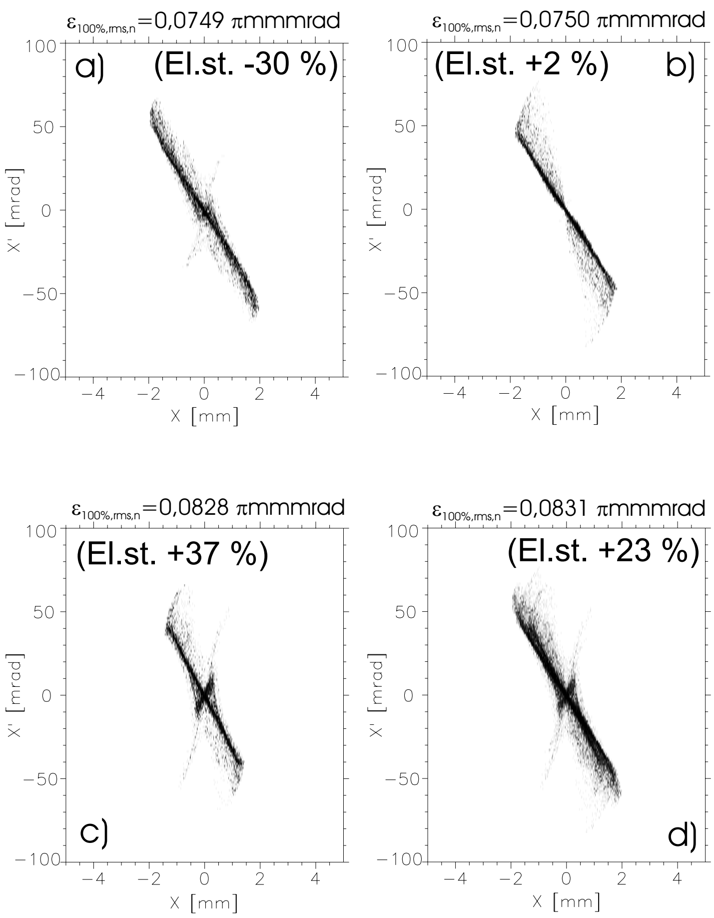


137.2 mA

140 mA

142.8 mA

140 mA +-2%



Summary :

For an future light ion injector
space charge compensated LEBT
using solenoids
is in favor compared with
electrostatic einzellenses:

* reduction of space charge forces
leads to:

- higher transmission due to lower radial losses
- lower emittance growth for DC beam
(incl. +- 2 % source noise)
- reduced technical efforts (money)
- longer MTBF
-space for beam diagnostics

but depending on residual gas pressure:

- particle losses due to interaction
between residual gas & beam ions
- rise time of compensation for the
(compare with rise time of ion source !)

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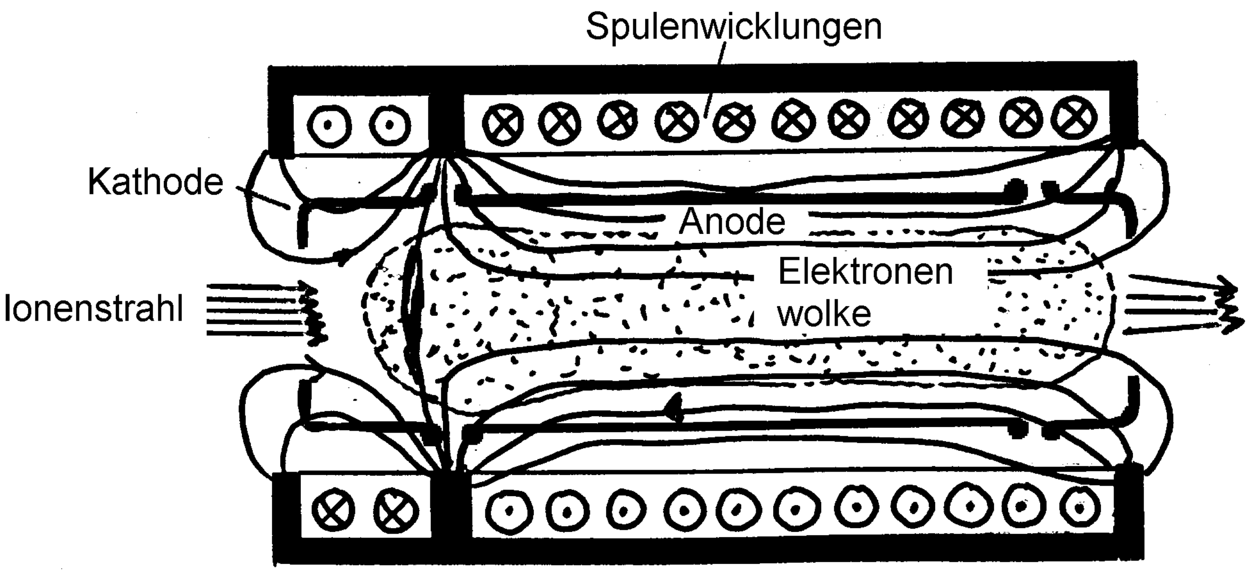
Gabor lens :
A space charge cloud of electrons foccusing ion beams



"D. Gabor described 1947 (Nature 160) theoretically the acciveable electron density in the above illustrated set up as a function of the magnetic field"

The electrons in the lens are longitudinally captured by the potential walls of the electric field, they can not reach the anode if the magnetic field is strong enough. The attainable electron density is given by:

$$\rho_{e,\max.,rad.} = \frac{e \cdot \varepsilon_0 \cdot B_z^2}{2 \cdot m_e}$$

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The first Frankfurt Gabor lens

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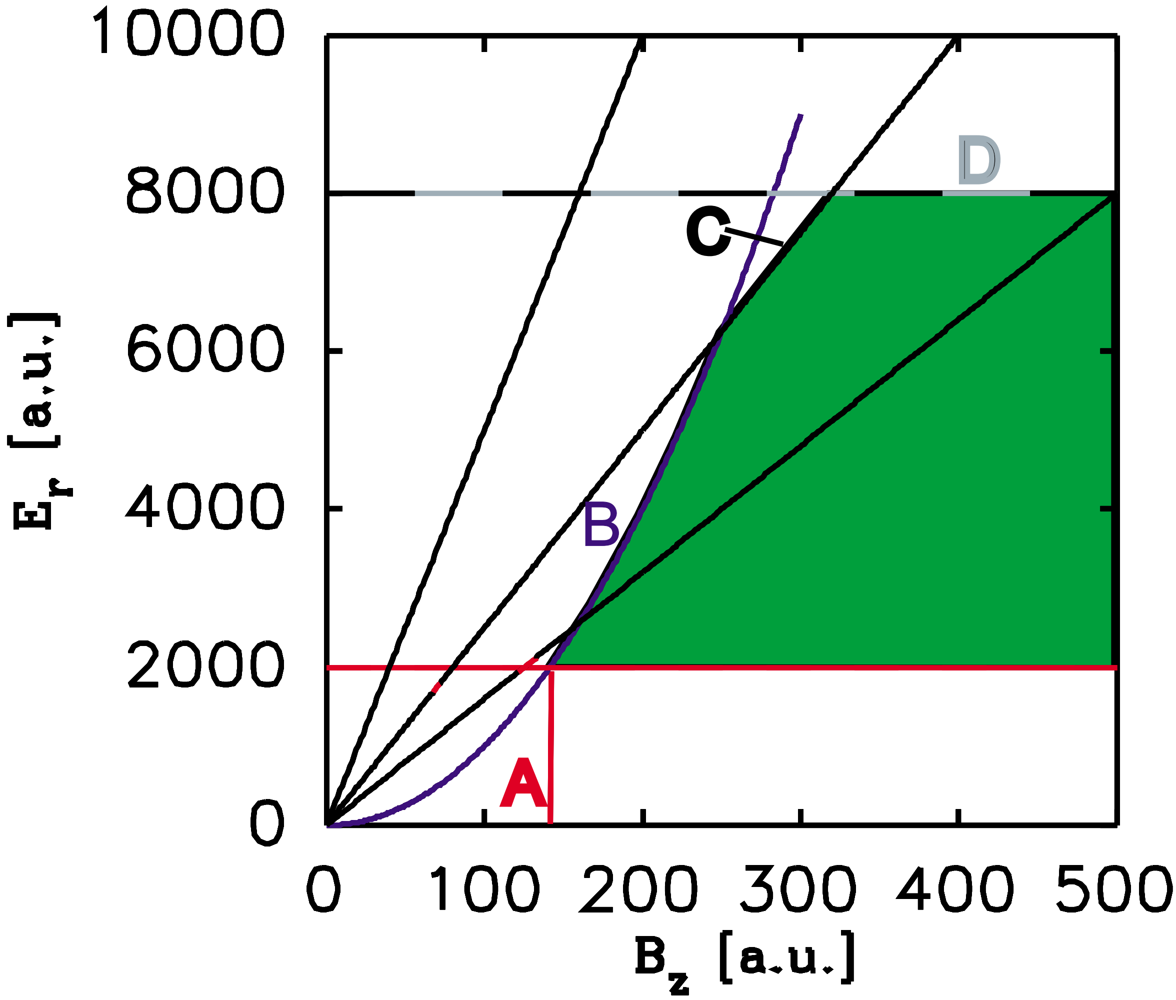
Theory on Gabor lens workfunction



A) minimal magnetic field for enclosure (depending on electrode geometry)

B) radial enclosure criteria (Briollionflow / Gabor: $n_e \propto B^2$)

C) radial losses by diffusion across fieldlines

D) maximum longitudinal enclosure (anodepotential)

Workflowdiagram for simulation of electron density distribution in a Gabor lens

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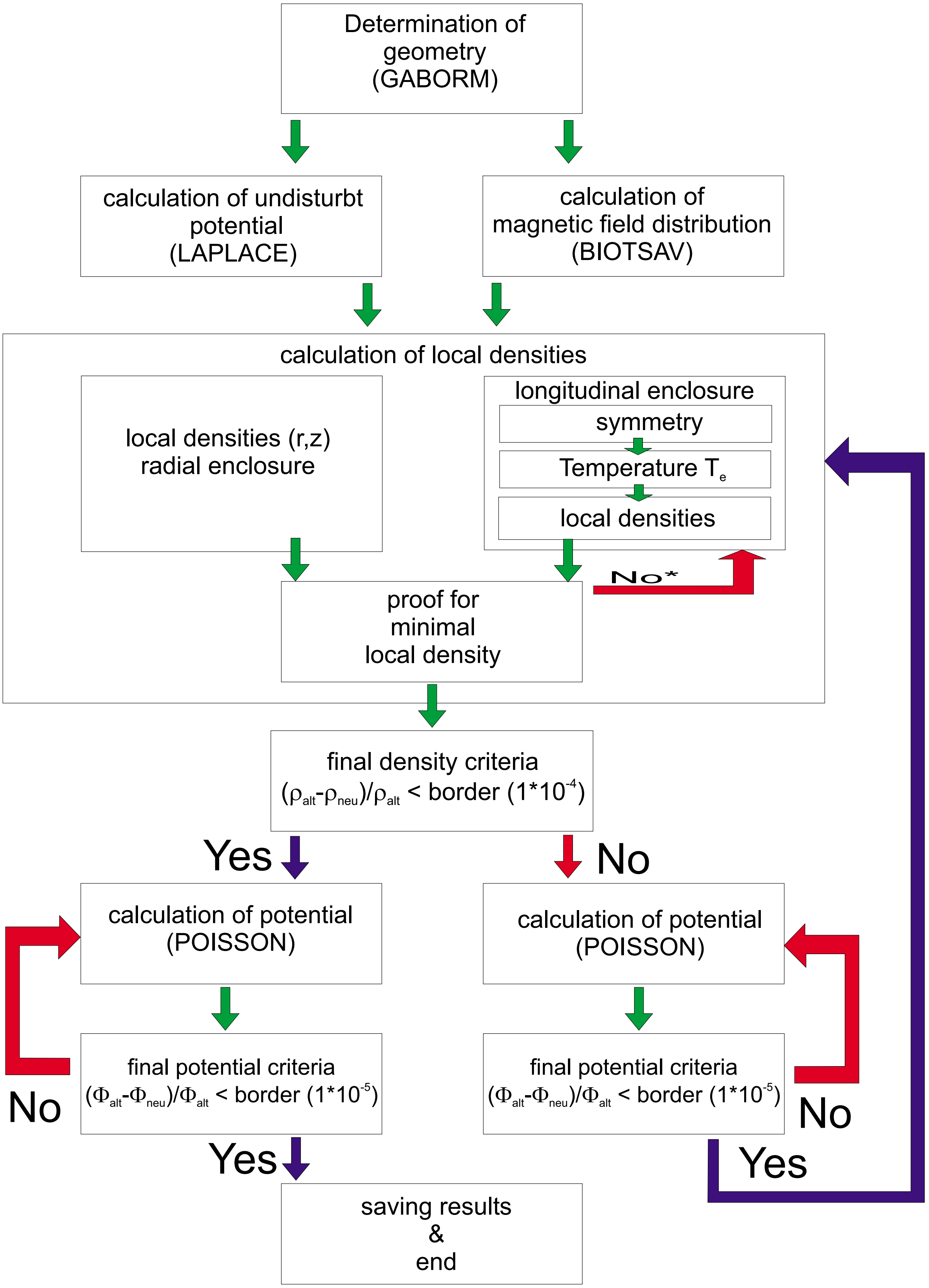

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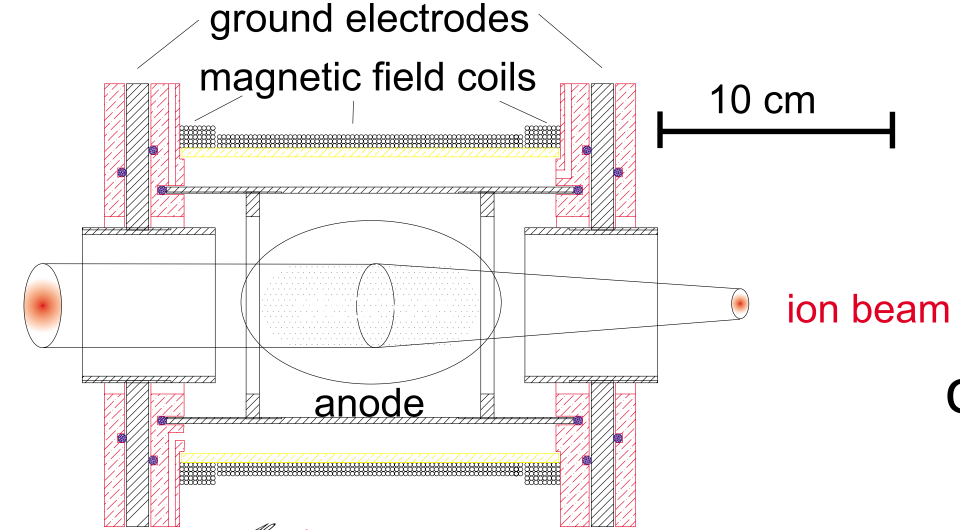
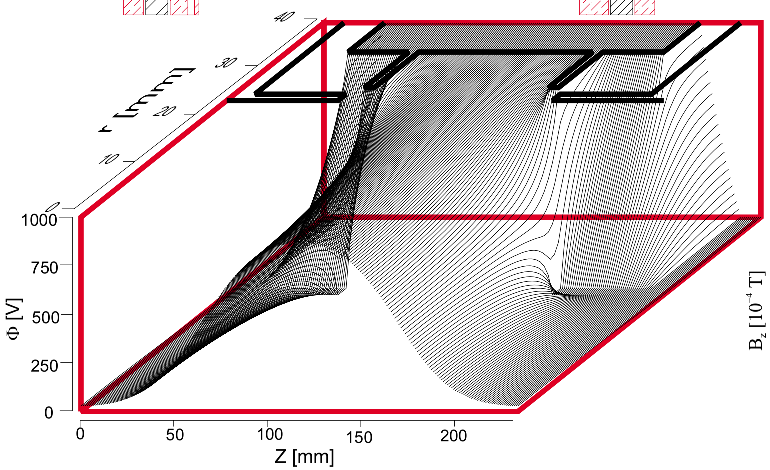
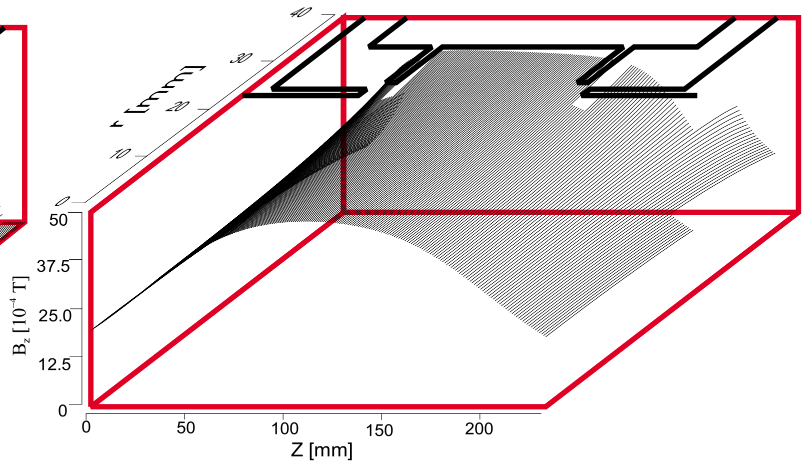
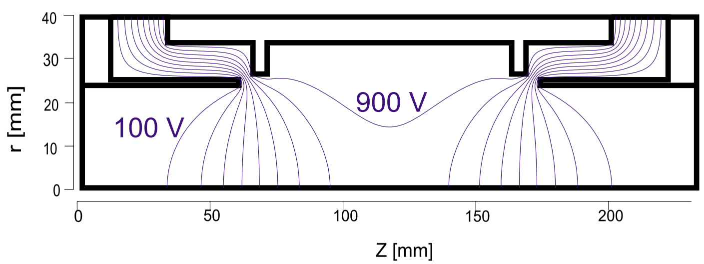
Layout and distribution of external fields of the first Frankfurt Gabor lens



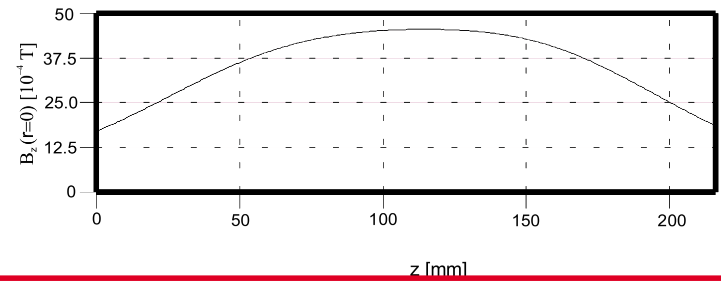




potential distribution



magnetic field



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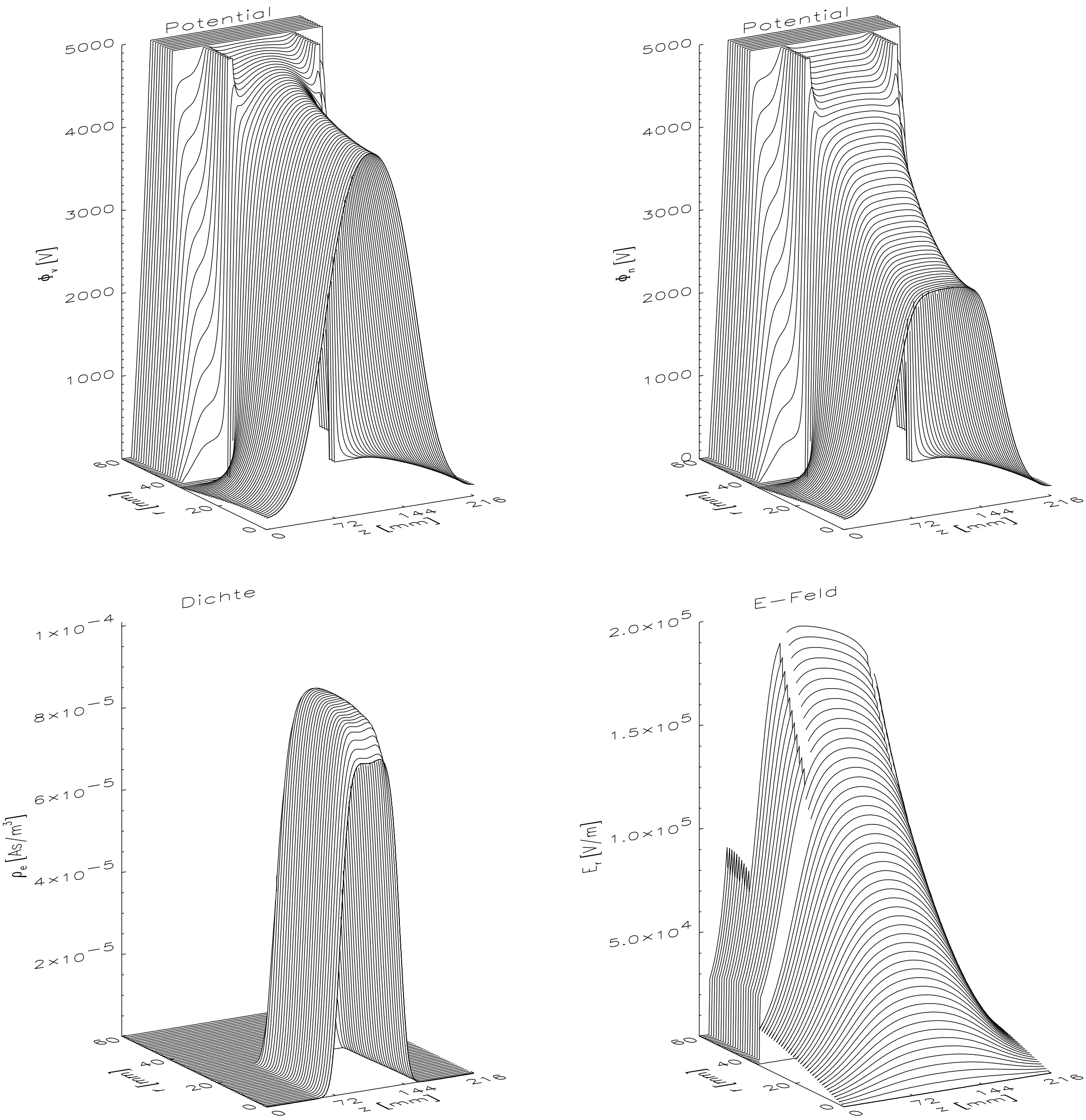
Result of a simulation

U_A = 5000 V

$B_{z,max}$ = 0.0112 T

long. losses = 1 μA



$\rho_{e,max}$ = 8*10^{-5} As/m^3

$\Delta\Phi$ = 1870 V

N_e = 6*10^{10}

$E_{r,max}$ = 200 000 V/m

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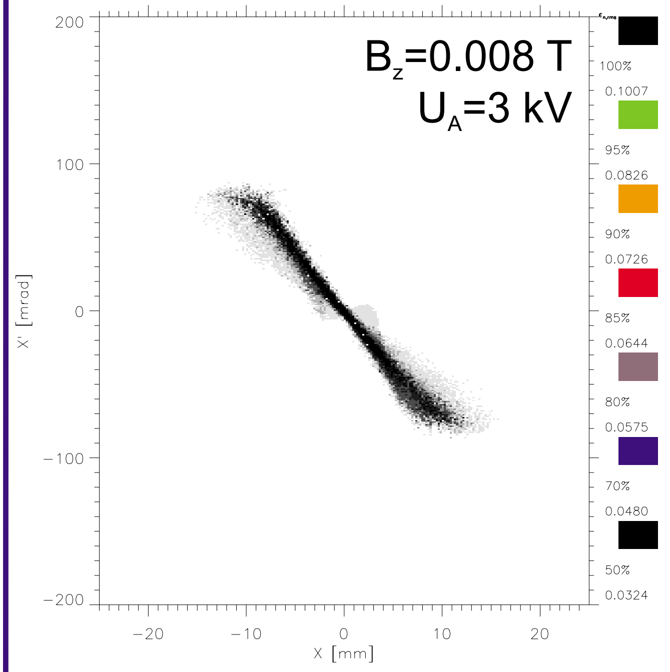
Comparison between measurements and simulations

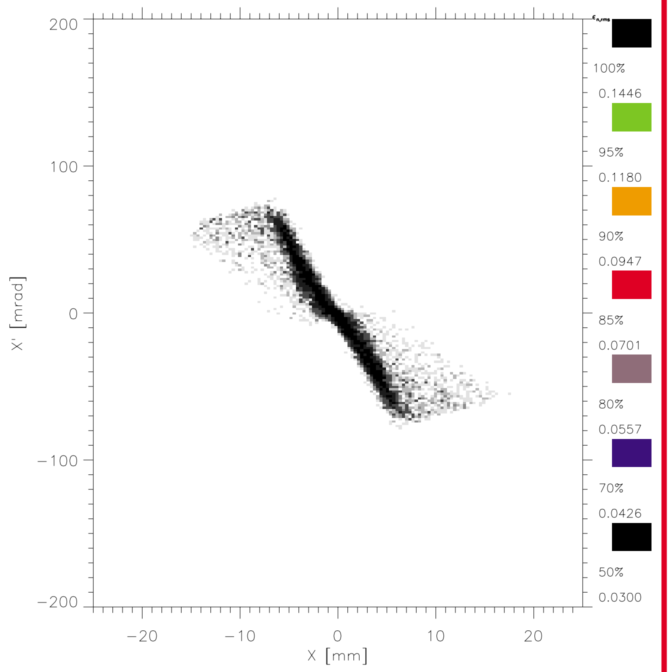
He^+ , 10 keV, 3.35 mA

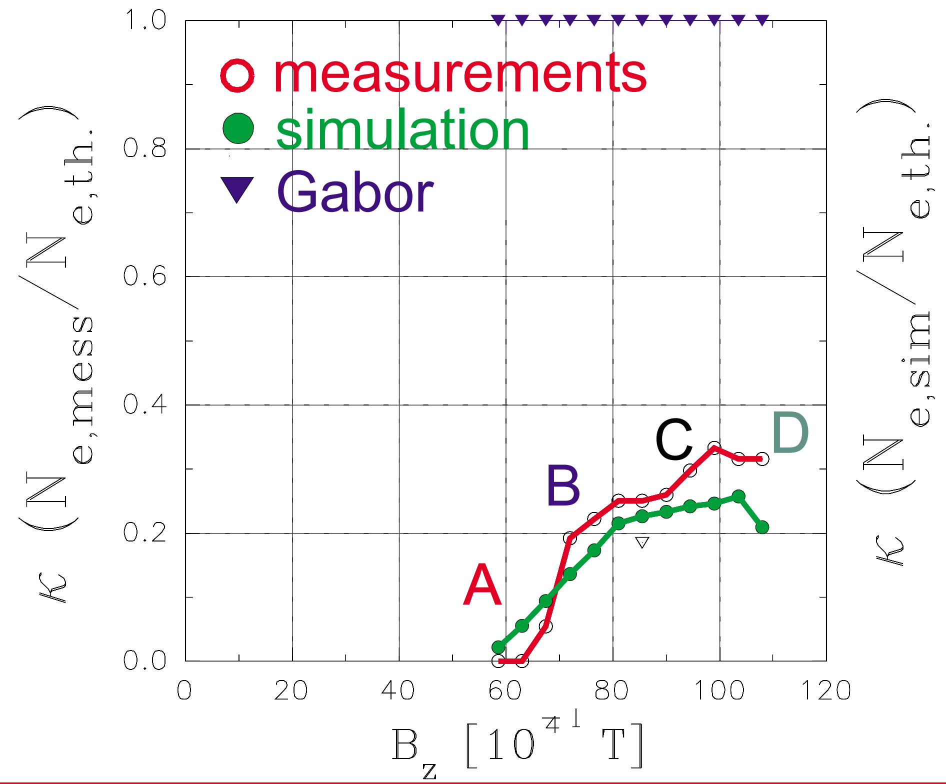
Emittance

measured



simulated





Low energy beam transport using an Gabor lens doublet

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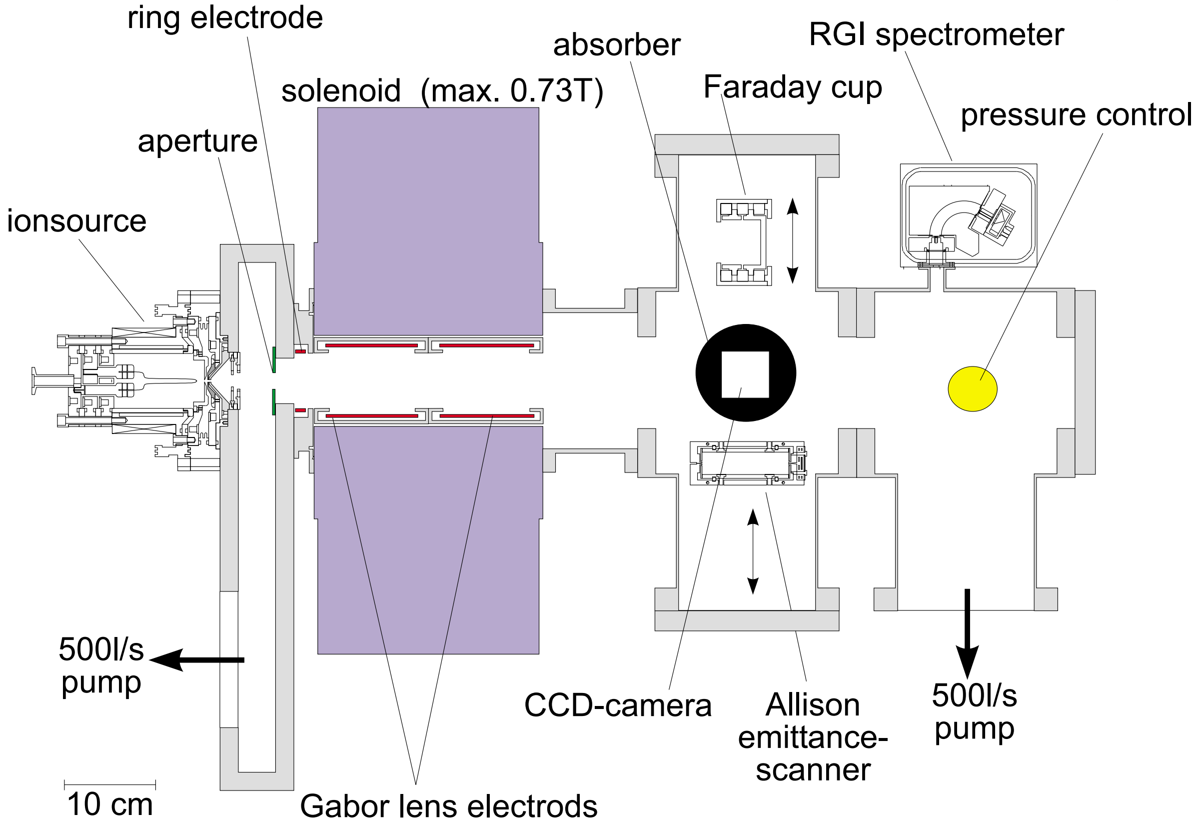

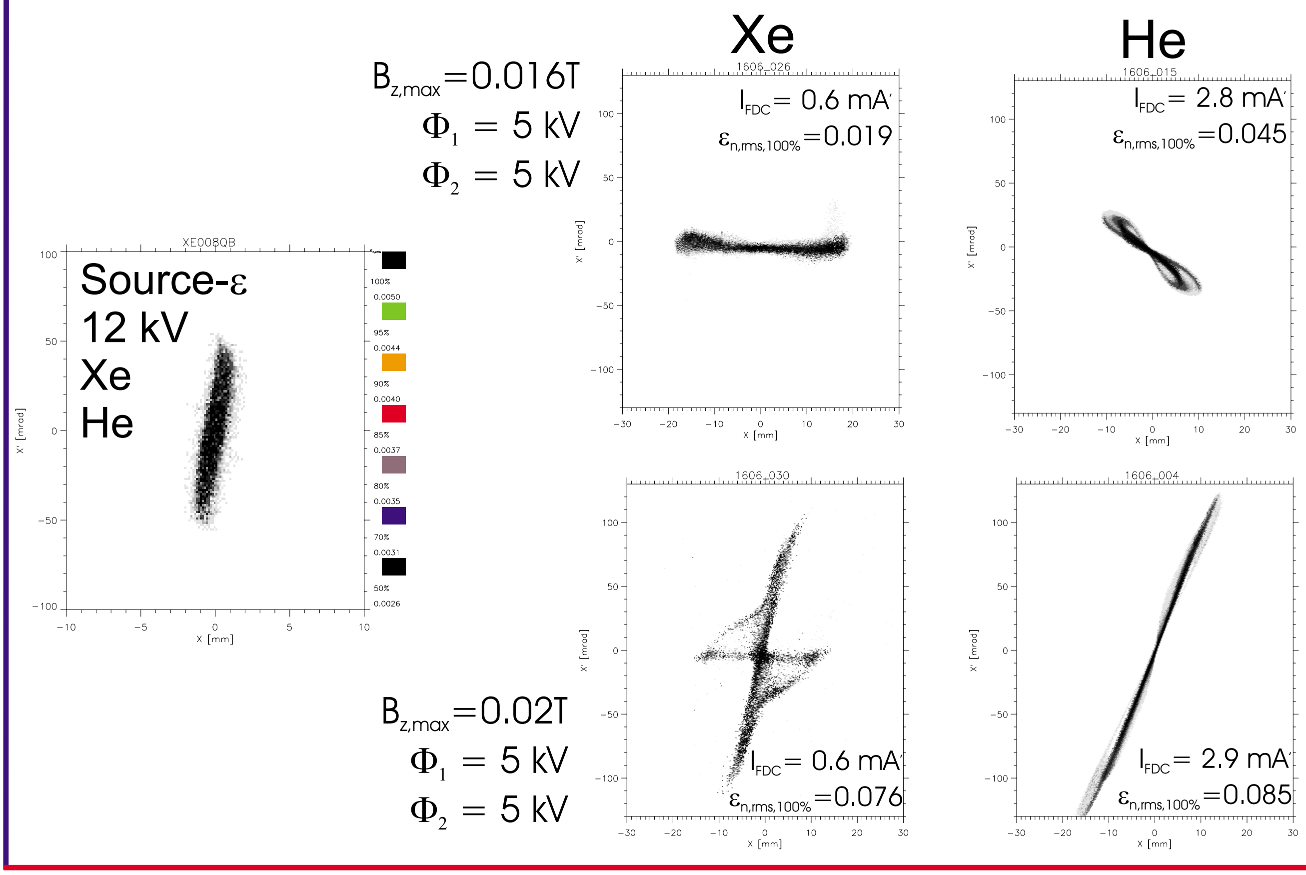

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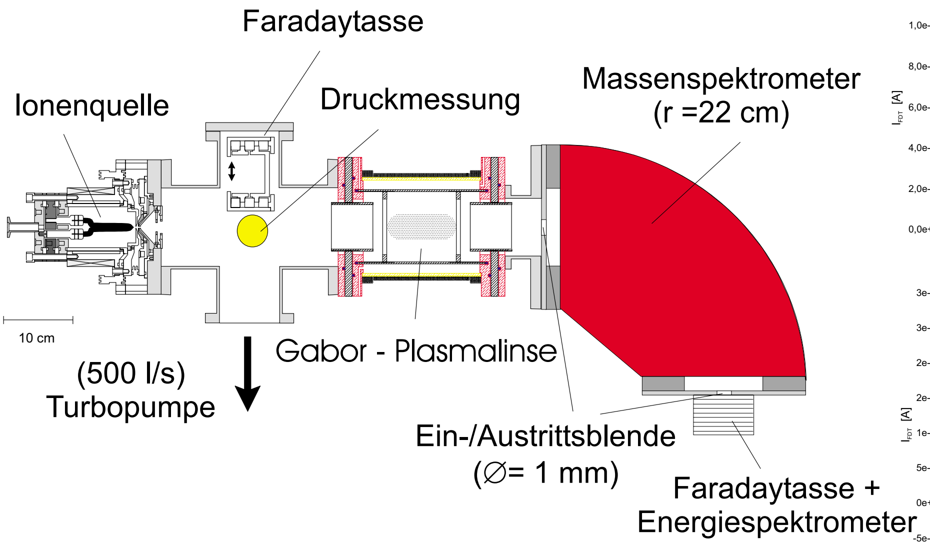
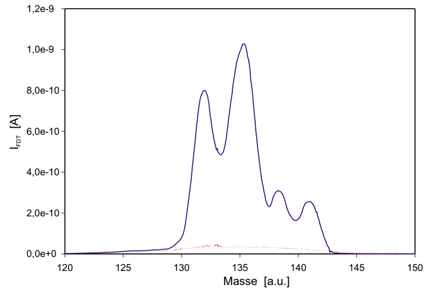
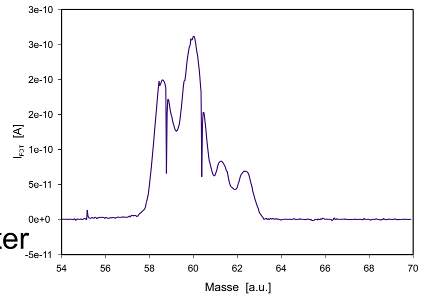
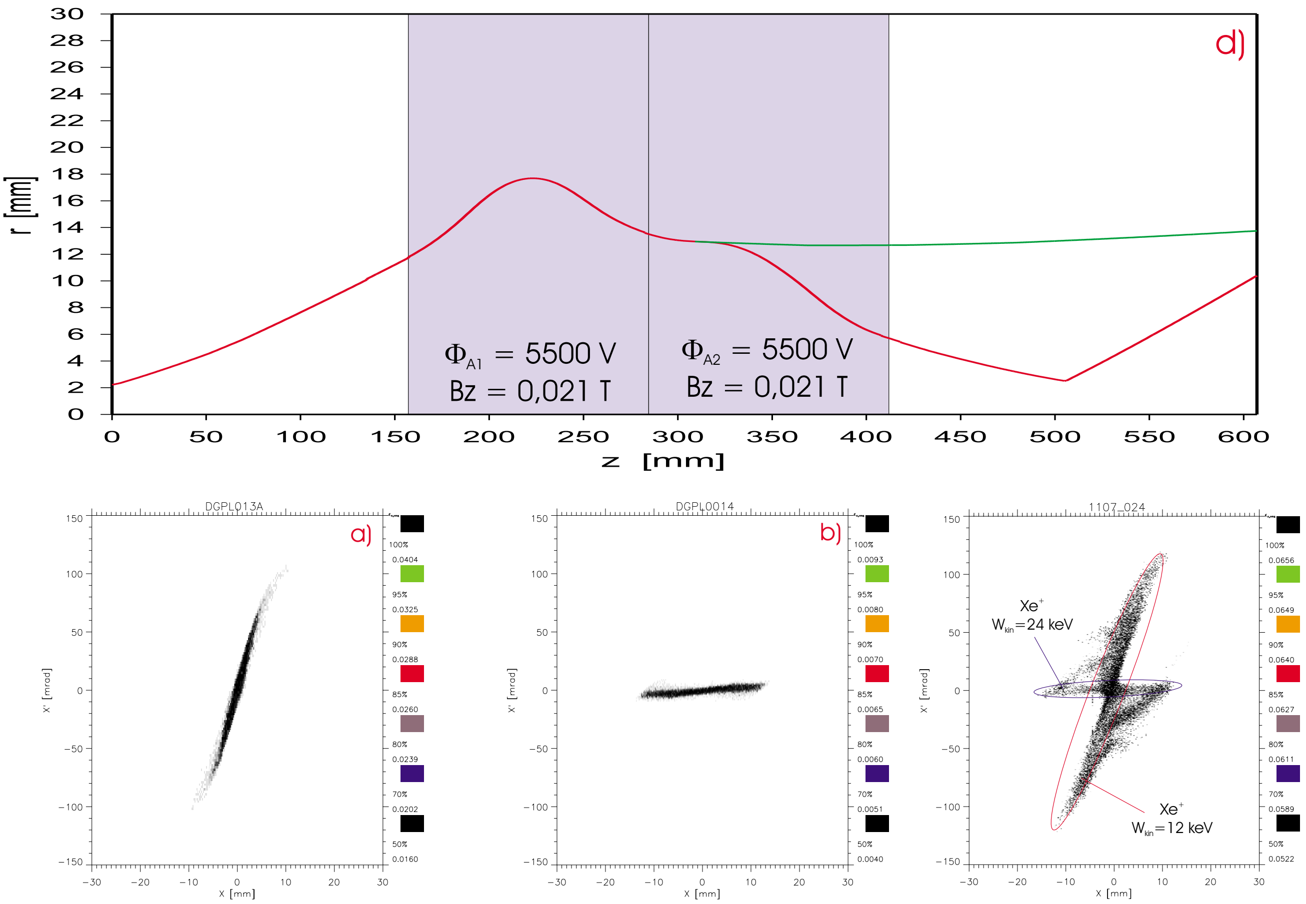
Emittance growth due to charge exchange with lens plasma ?









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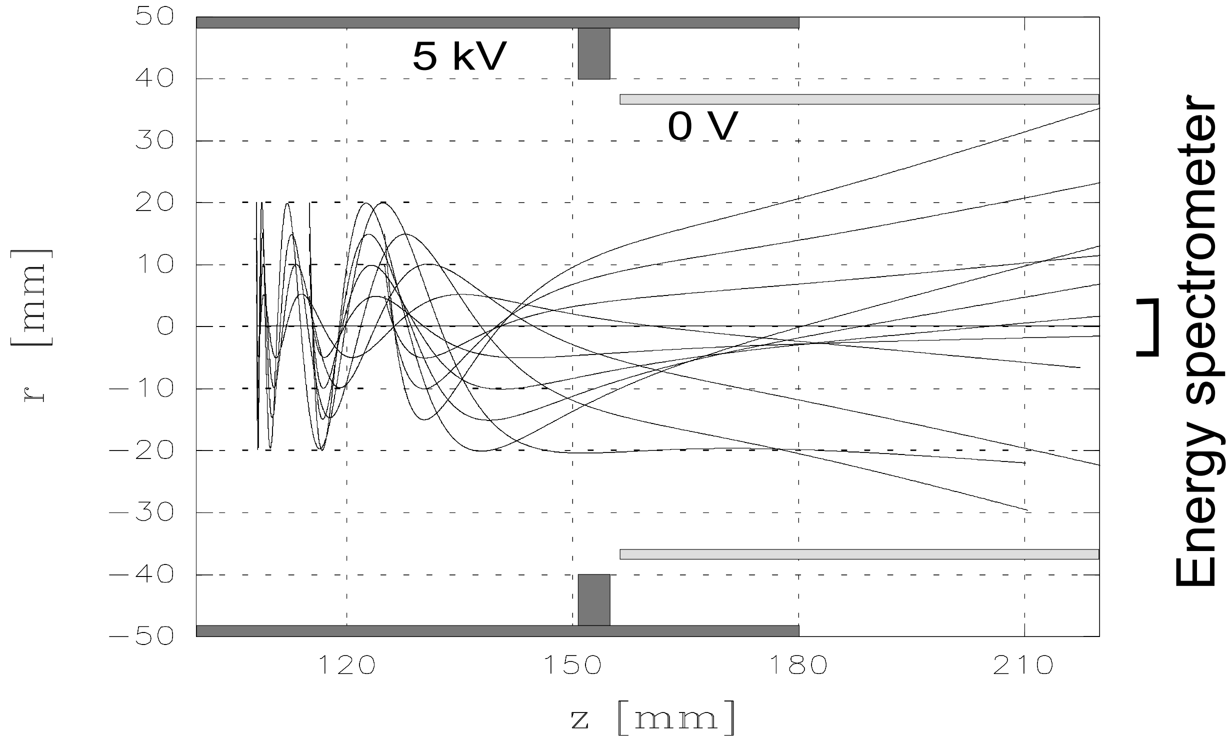
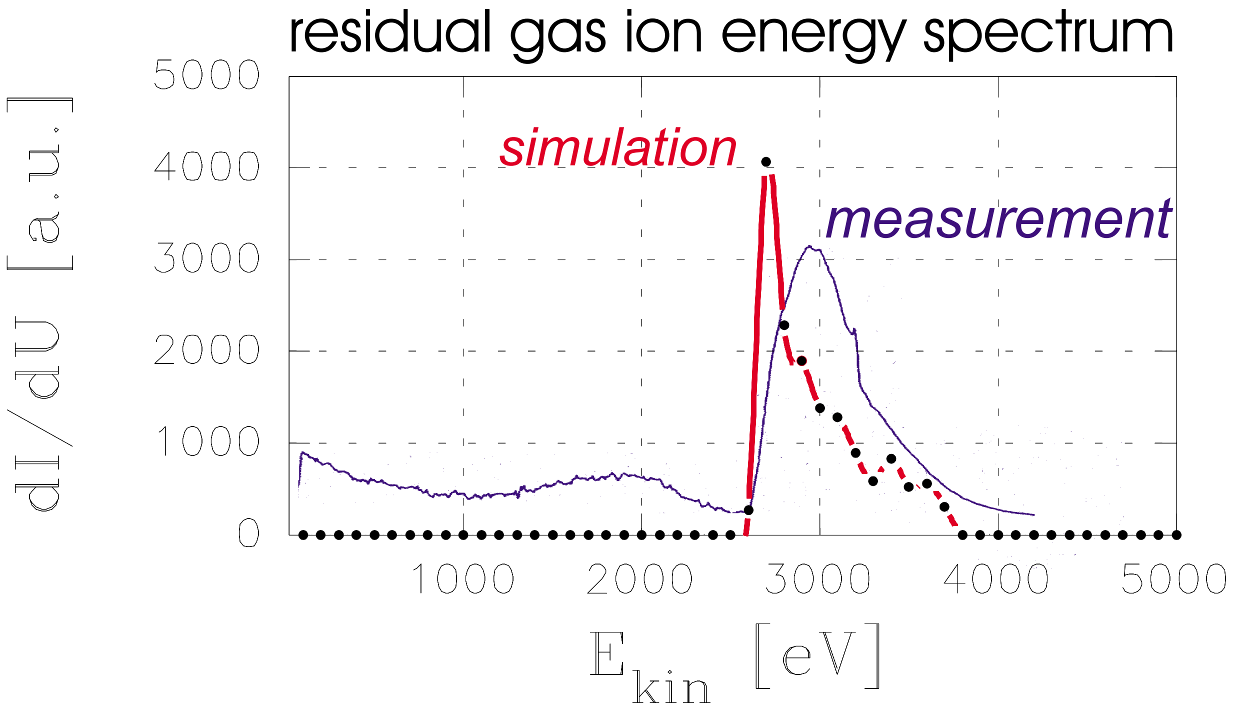
Analysis of the space charge cloud by determination of the residual gas ion energy spectrum





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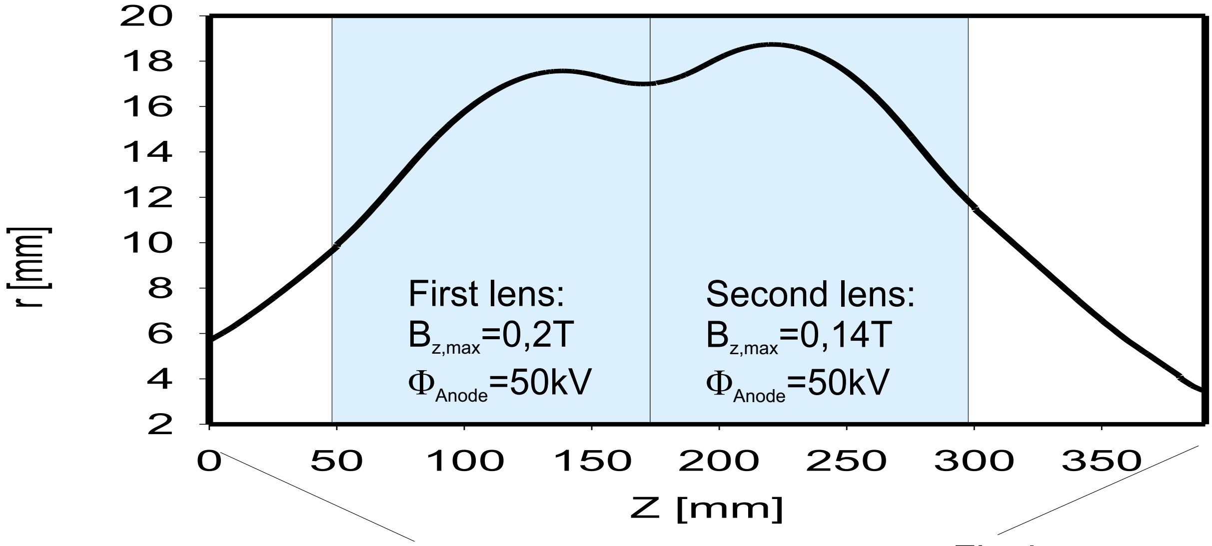
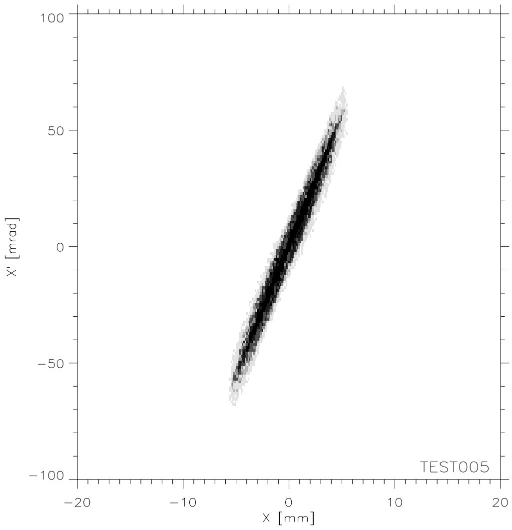
Beam transport calculations for the proposed HIDIF injector using a double Gabor lens LEBT

Beam-envelope Bi^{+} U_{EX}=156kV I_{EX}=40mA



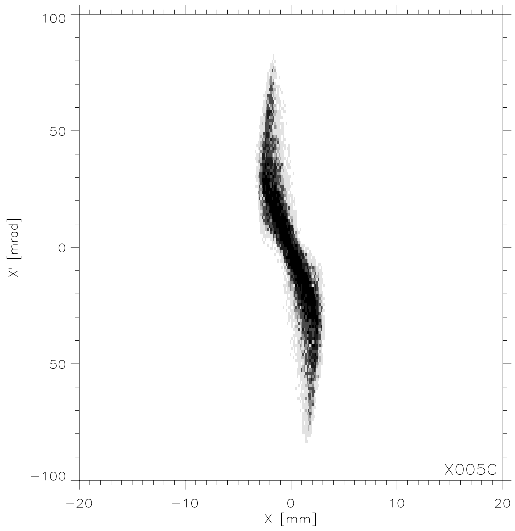
Initial

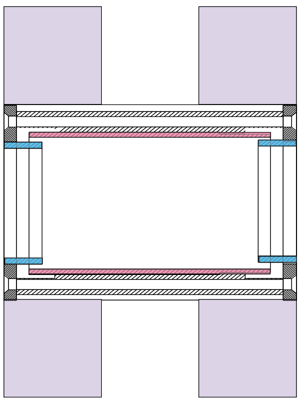
$\varepsilon_{rms,100\%}$=0,0163 πmmmrad



Final

$\varepsilon_{rms,100\%}$=0,0301 πmmmrad





Helmholtz - coils
$B_{z,max}$ = 0,2 T
with
Gabor lens electrods

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Summary :

Gabor lenses combine
strong cylindersymetric
electrostatic focussing
together with preservation of
space charge compensation

- strong focussing at moderat external fields
- comparable emittance growth
- reduced influence on source noise
- reduced technical efforts (money)
- long MTBF

- limited experience
- charge exchange mechanisms (?)

In the moment they are recomented
for space charge dominated
heavy ion beams at
moderate beam energies
(40-500 kV)