NNP
Non Neutral Plasma
Physics Group

GOETHE UNIVERSITÄT
FRANKFURT AM MAIN

Ion Beam Transport

Oliver Meusel

517. WE-Heraeus-Seminar

Bad Honnef

2012

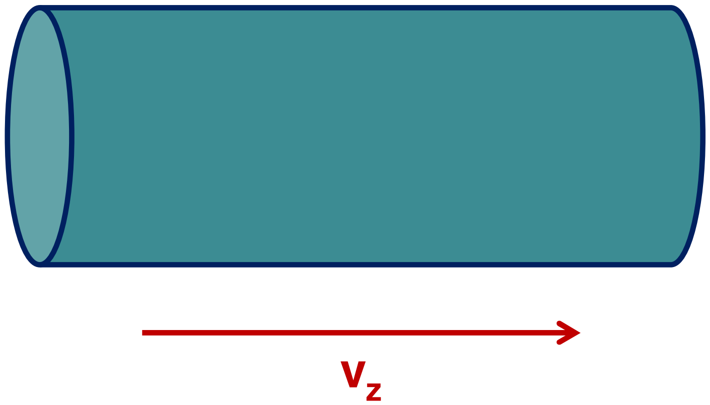
NNP
Non Neutral Plasma Physics Group

Ion Beam

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

an ion beam can change into a non-neutral plasma (NNP).

- charge distribution with $n_i(x,y,z)$
- $v_{x,y} << v_z$



1. Number of particles in Debye sphere

$$n\lambda_D^3 >> 1$$

2. Debye length smaller than size of plasma

$$\lambda_D < L$$

3. Observed time scale longer than

$$t > 2\pi/\omega_p$$

nonrelativistic, coasting beam (DC) with cylindrical symmetry

Luminosity

Requirements on Accelerator physics
- Luminosity

$$L = \frac{\dot{N}}{\sigma_S}$$

→

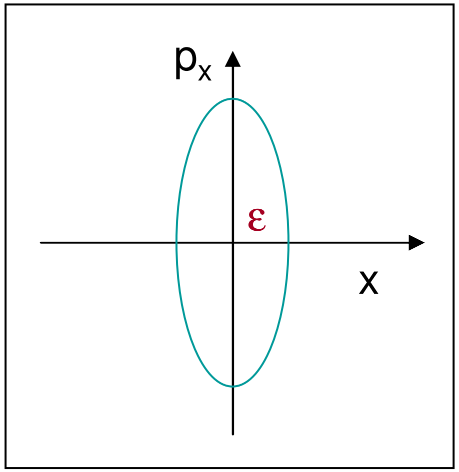
Current density at „Final Focus“

$$J = \frac{1}{A} \cdot \dot{N}$$

minimum spot size

Beam current I_s

Beam emittance



$$r_{\min} = \frac{\varepsilon_\perp}{p_\perp}$$

Space Charge !

↓

Beam emittance vs. Beam current

Emittance Growth

F. Sacherer   rms - emittance

$$\varepsilon = \varepsilon_{x,rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\varepsilon_{n,rms} = \beta\gamma\varepsilon$$

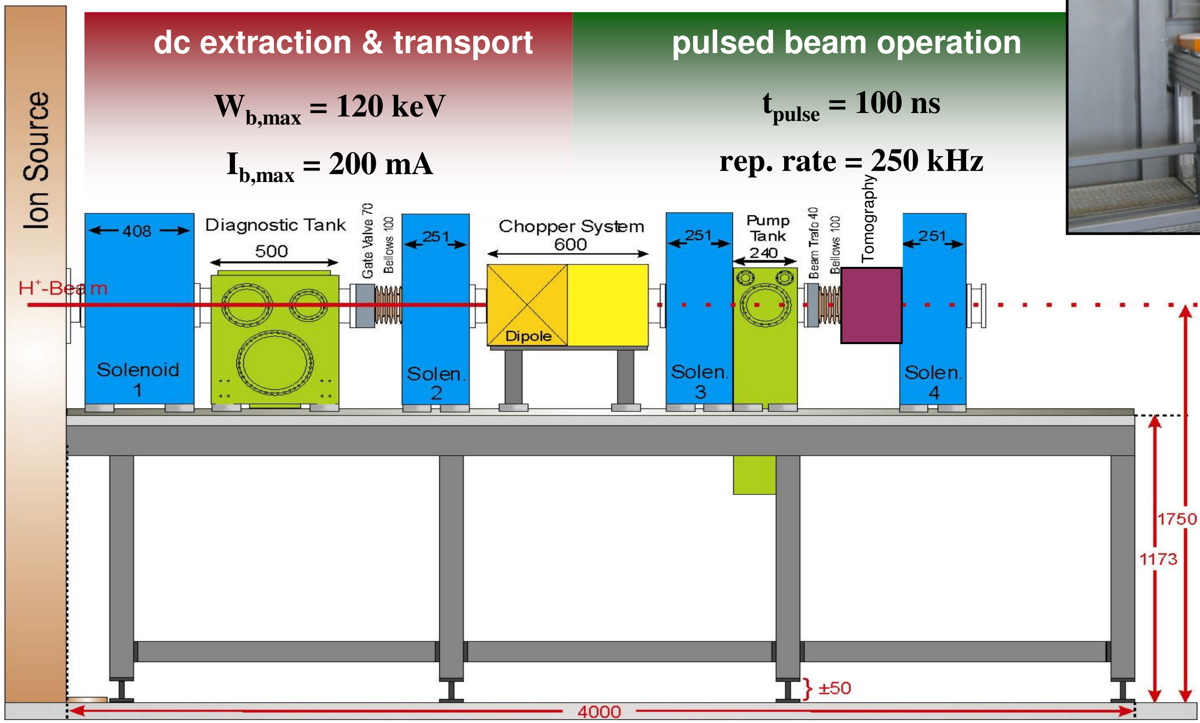
- Beam induced
- Space charge compensation induced
- Beam optics

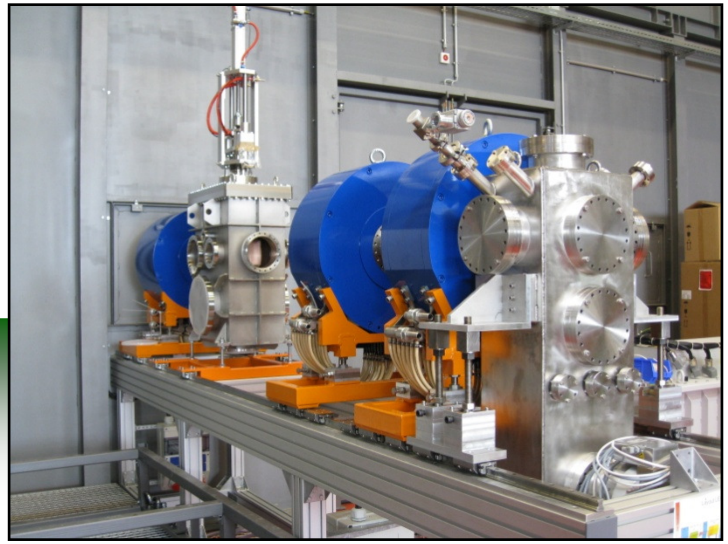
NNP
Non Neutral Plasma Physics Group

Beam Transport - Example

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Low Energy Beam Transport

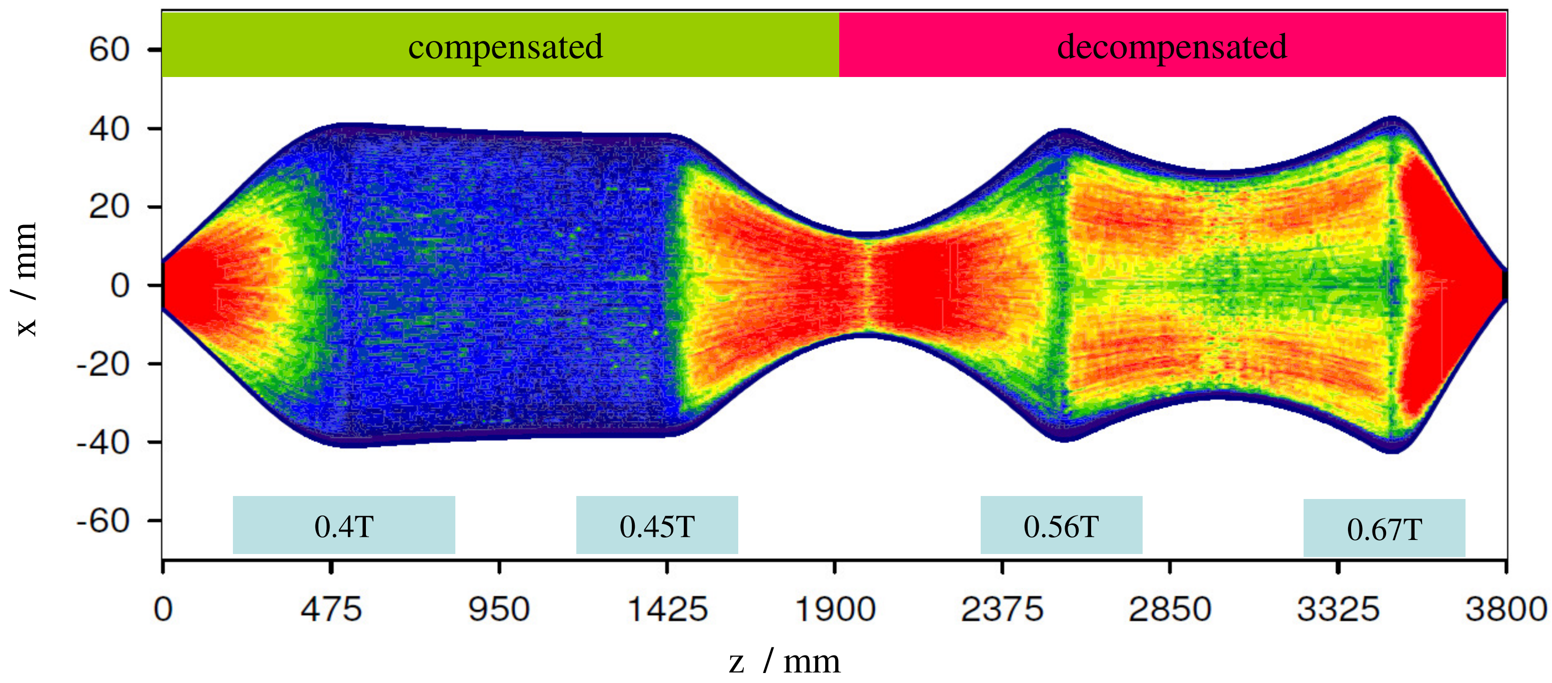




Emittance Growth

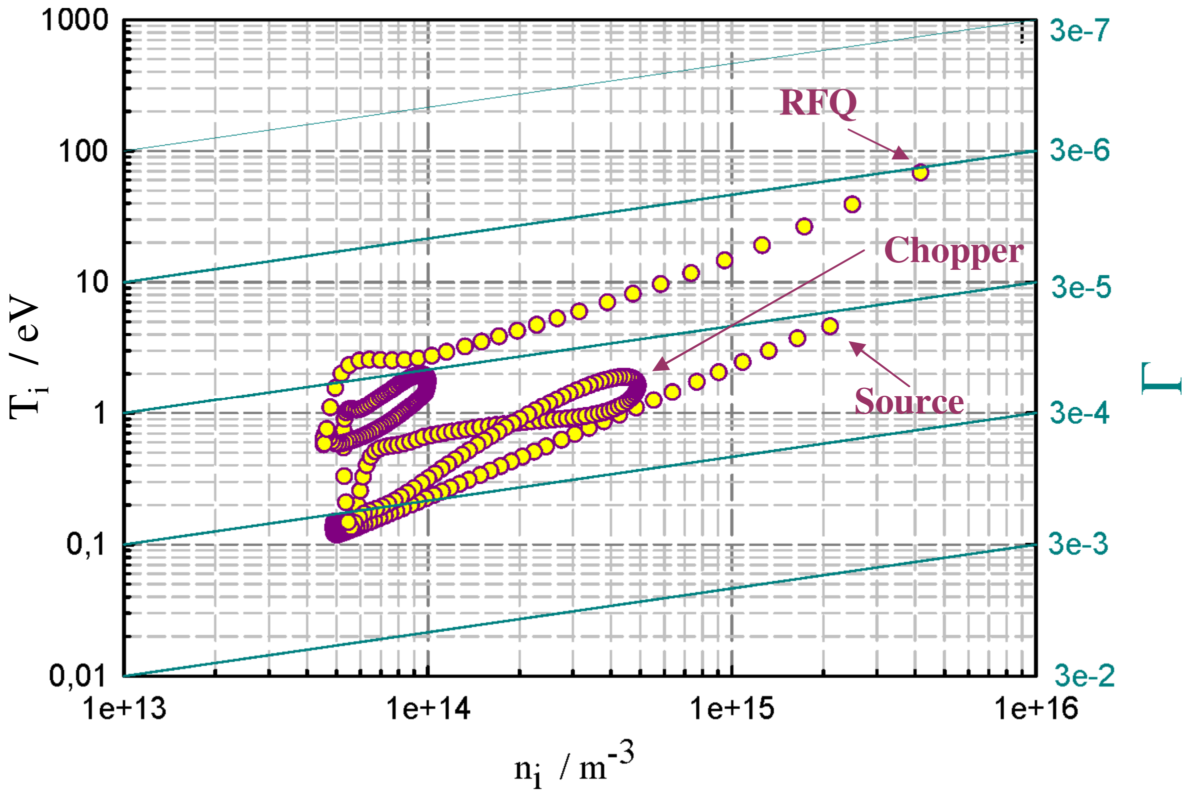
Beam transport under consideration of CE dynamics

Emittance Growth by a factor of 3



Emittance Growth

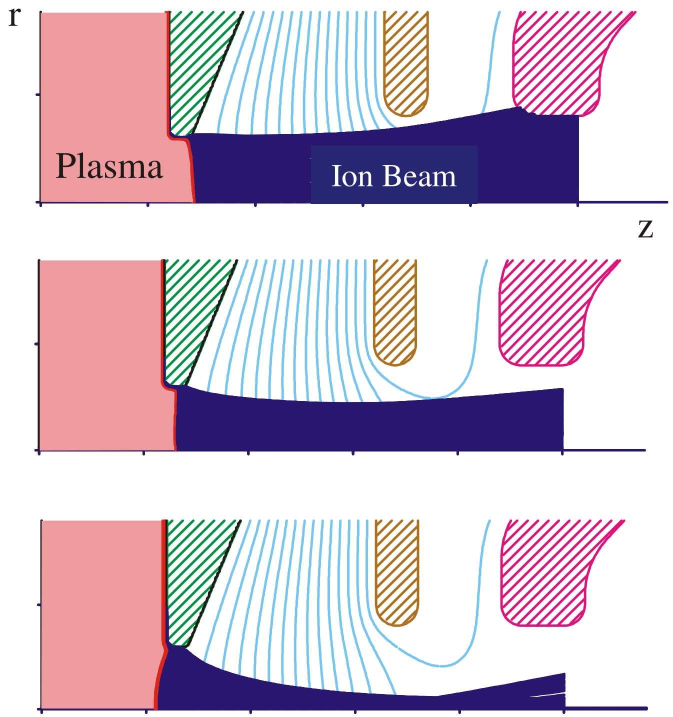
Emittance Growth due to Collective Processes



phase diagram of the proton beam during the transport through LEBT section

Longitudinal Density Fluctuations

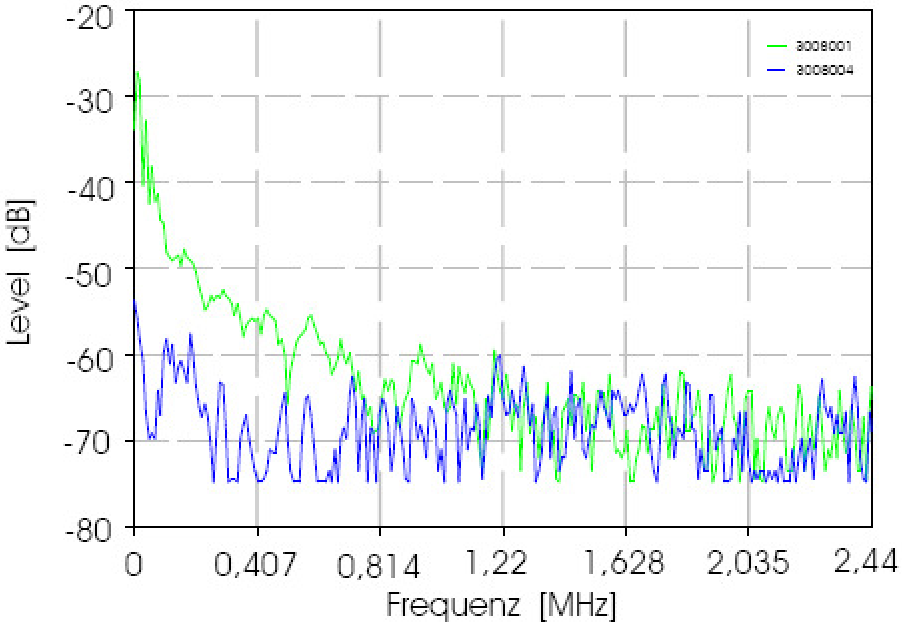
Current fluctuation due to source noise



$E_{int} > E$

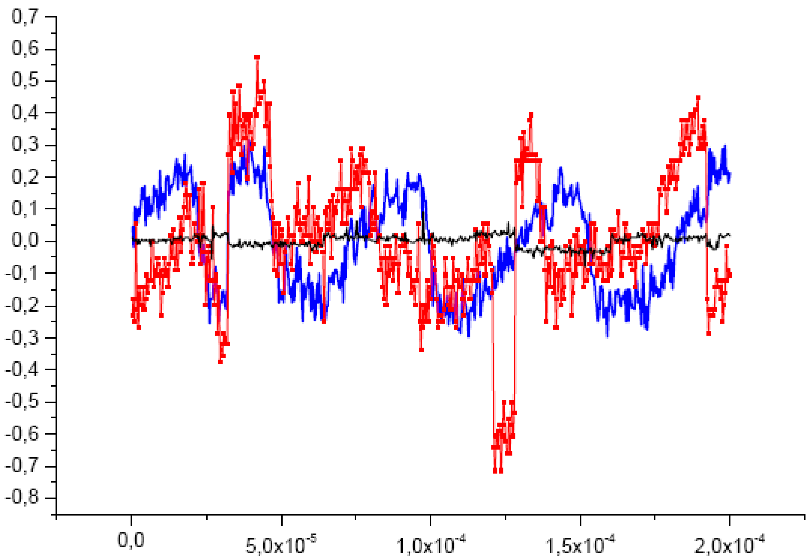
$E_{int} = E$

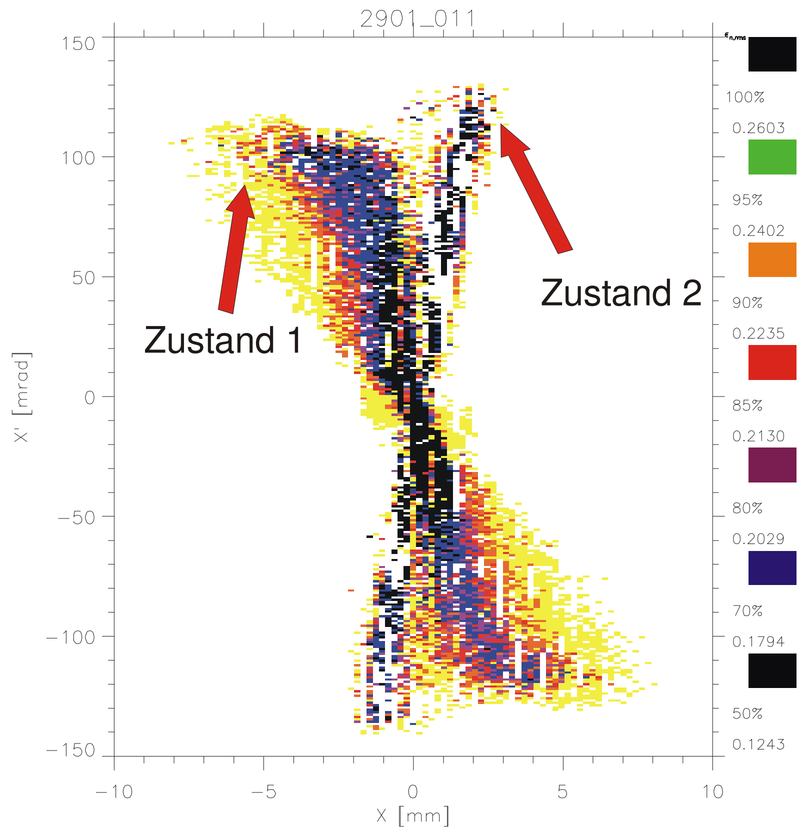
$E_{int} < E$



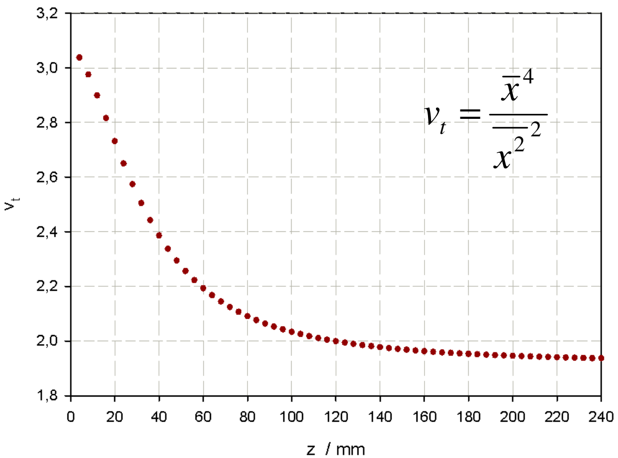
Longitudinal Density Fluctuations

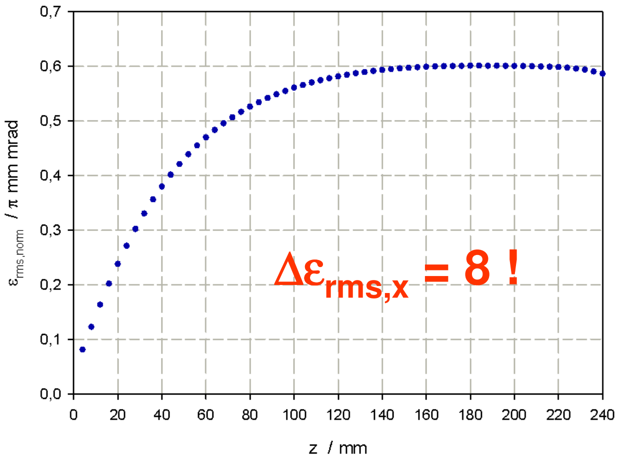
Current fluctuations due to plasma instabilities



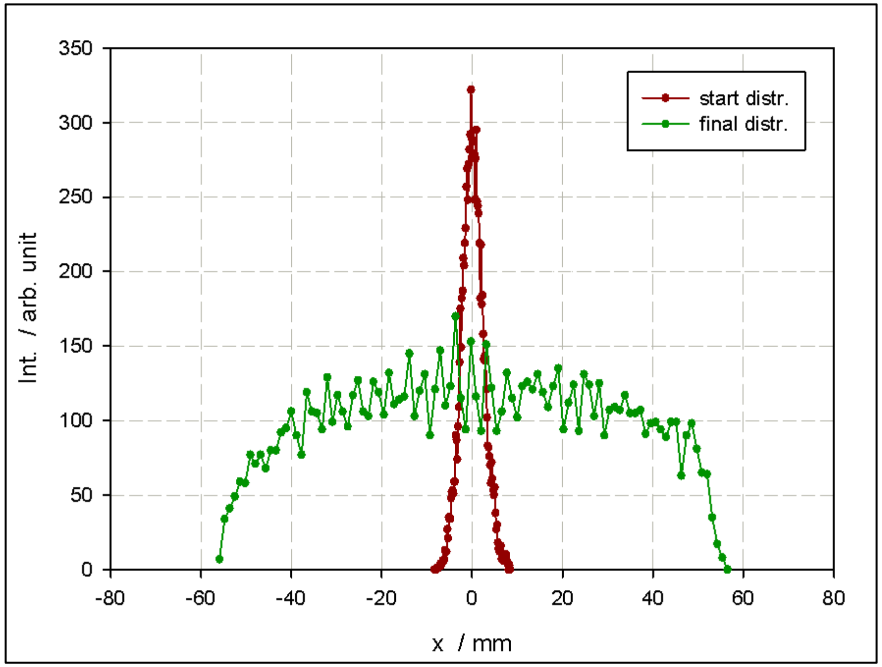


Emittance Growth due to Thermalisation





Gaussian start distribution

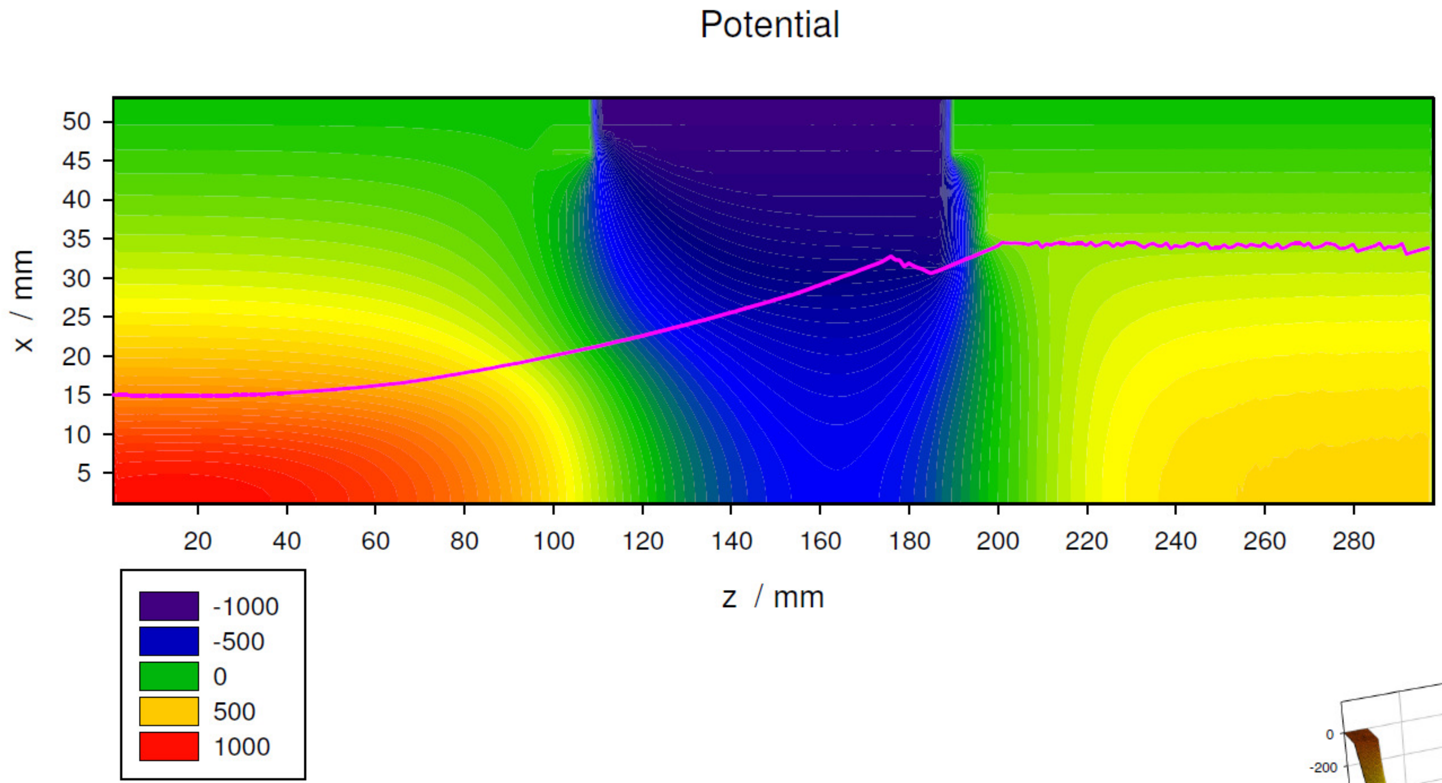


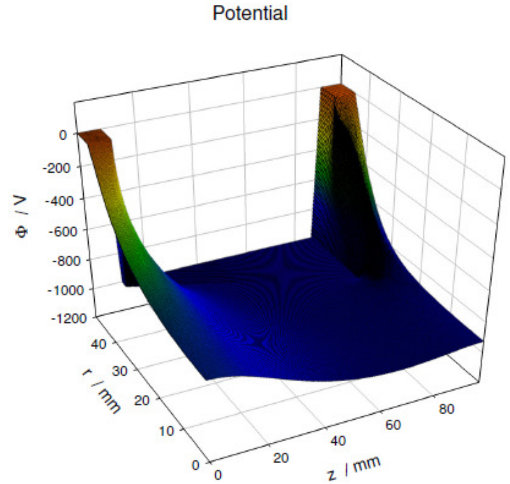
$$\Delta\varepsilon_{rms,x} = \sqrt{\varepsilon^2_{rms,x,final} - \varepsilon^2_{rms,x,start}} = \sqrt{\frac{\langle x^2 \rangle K \Delta W_{nl}}{8}}$$

NNP
Non Neutral Plasma
Physics Group

Beam Potential

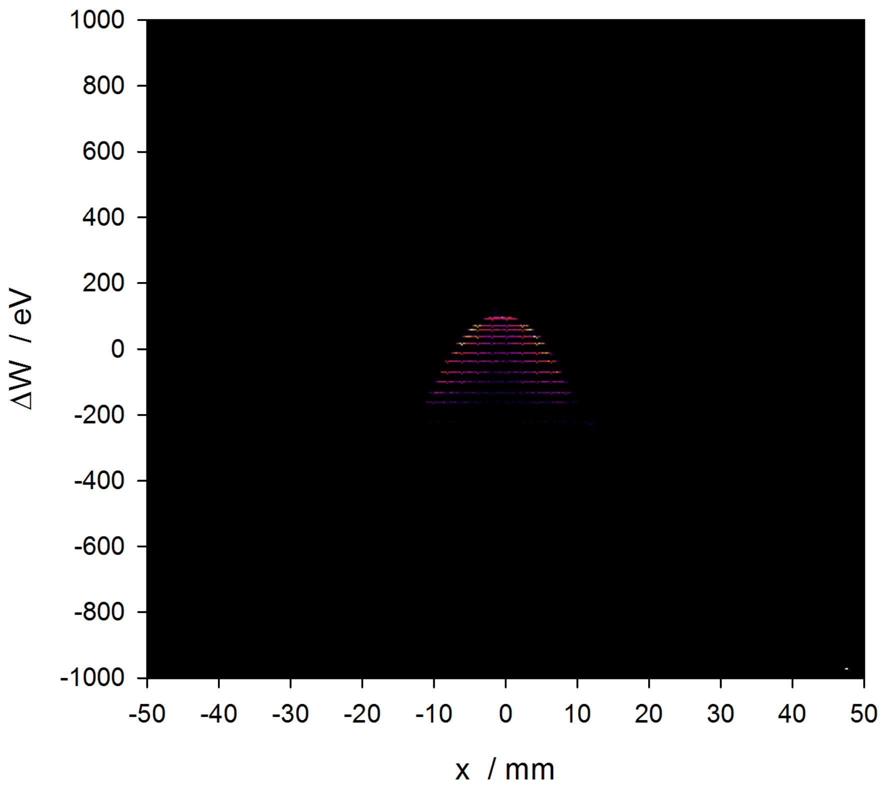
GOETHE UNIVERSITÄT FRANKFURT AM MAIN





Beam Potential

expansion and compression of the ion beam



comparison of focusing strengthes

Solenoid

weak focusing

$$k = \frac{qB}{2mv}$$

MSQ / ESQ

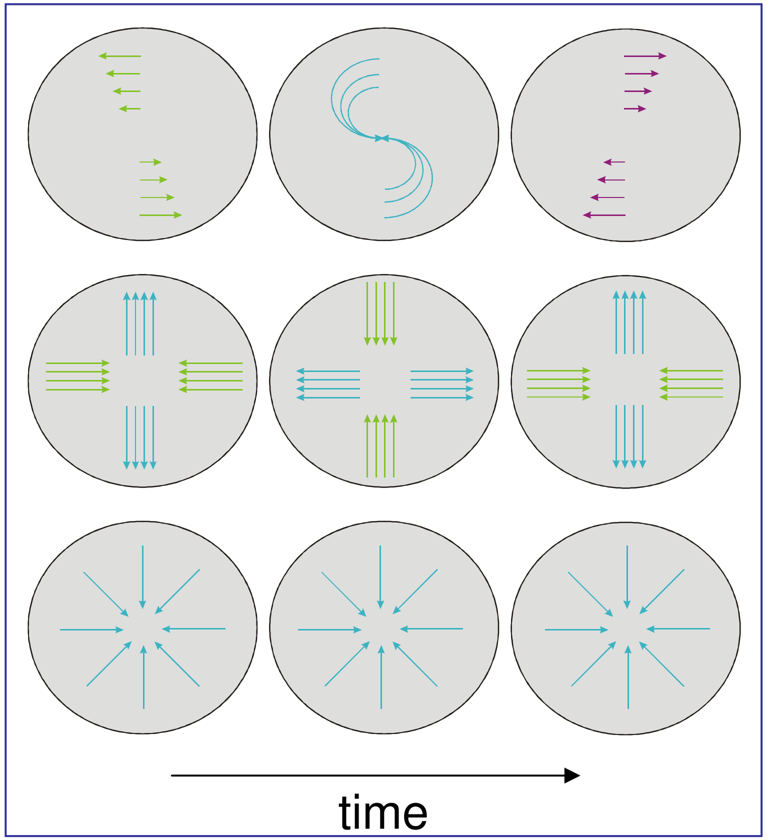
strong focusing/defocusing

$$k = \sqrt{\frac{qg}{mv}} \Big/ k = \sqrt{\frac{qg}{mv^2}}$$

SCL

strong focusing

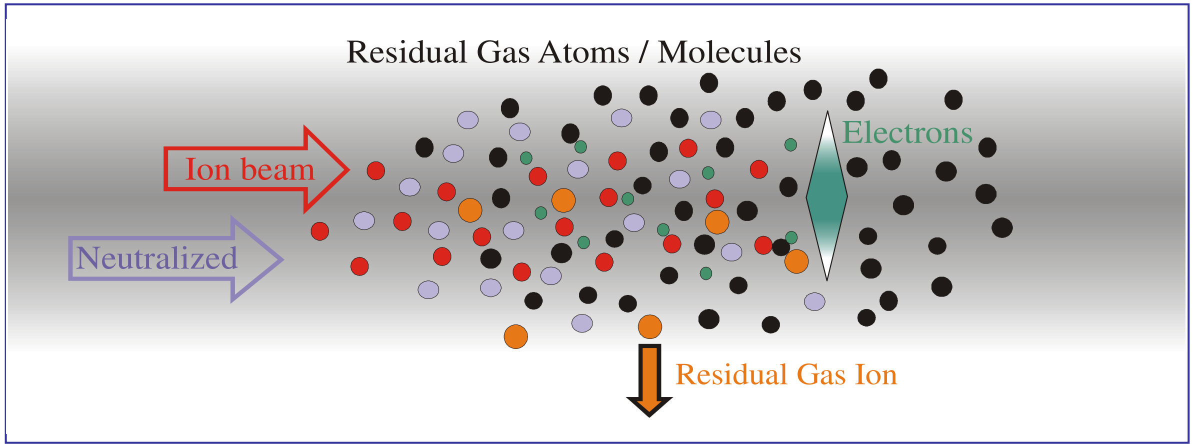
$$k = \sqrt{\frac{\kappa q e B_z^2}{8 m_e W_b}}$$



Chromatic, geometric and spherical aberrations

Space Charge Compensation

Production of compensation electrons (CE)

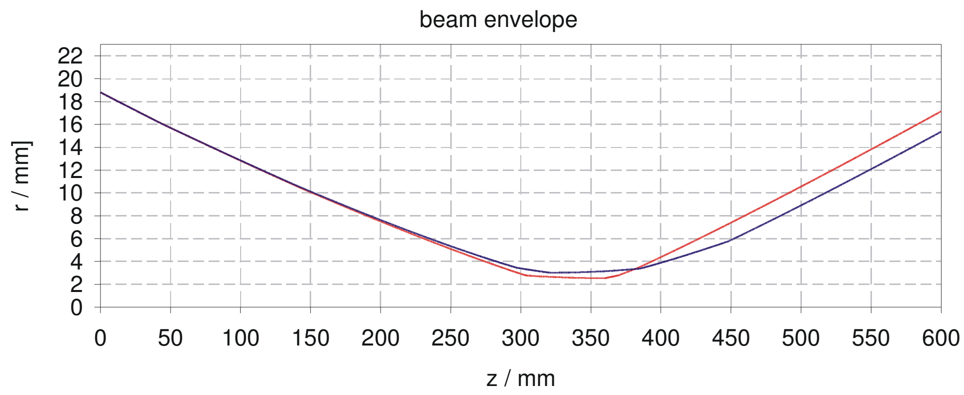


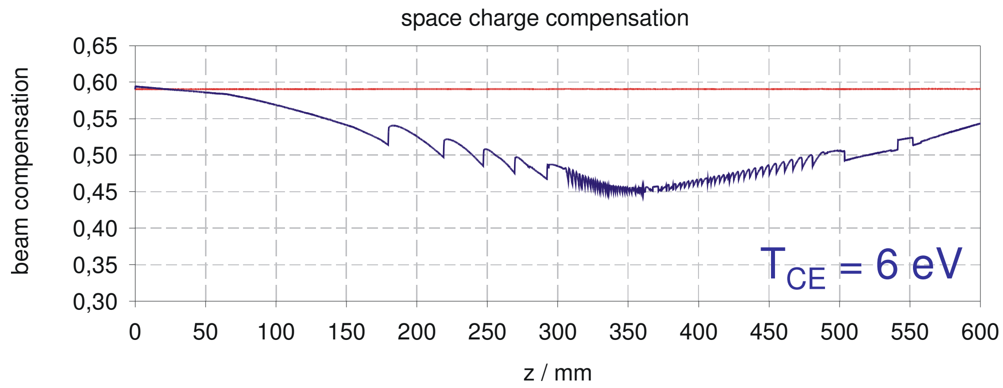
Confinement of CE within the beam potential

$$\frac{\partial f_k}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f_k + \frac{q_k}{m_k} \left[\left(\vec{E}_{ext} + \vec{E}_{self} \right) + \left(v \times (\vec{B}_{ext} + \vec{B}_{self}) \right) \right] \cdot \vec{\nabla}_v f_k = 0$$

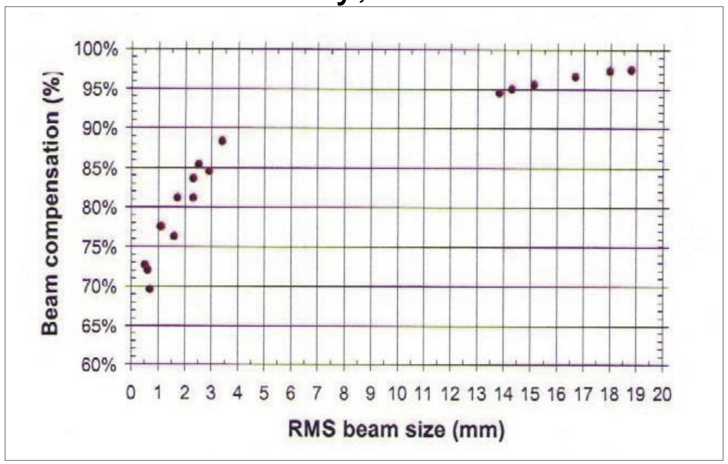
Space Charge Compensation

Transport without focusing fields – beam drift





© cea saclay, R. Gobin et. al.



measured space charge compensation as a function of the beam radius

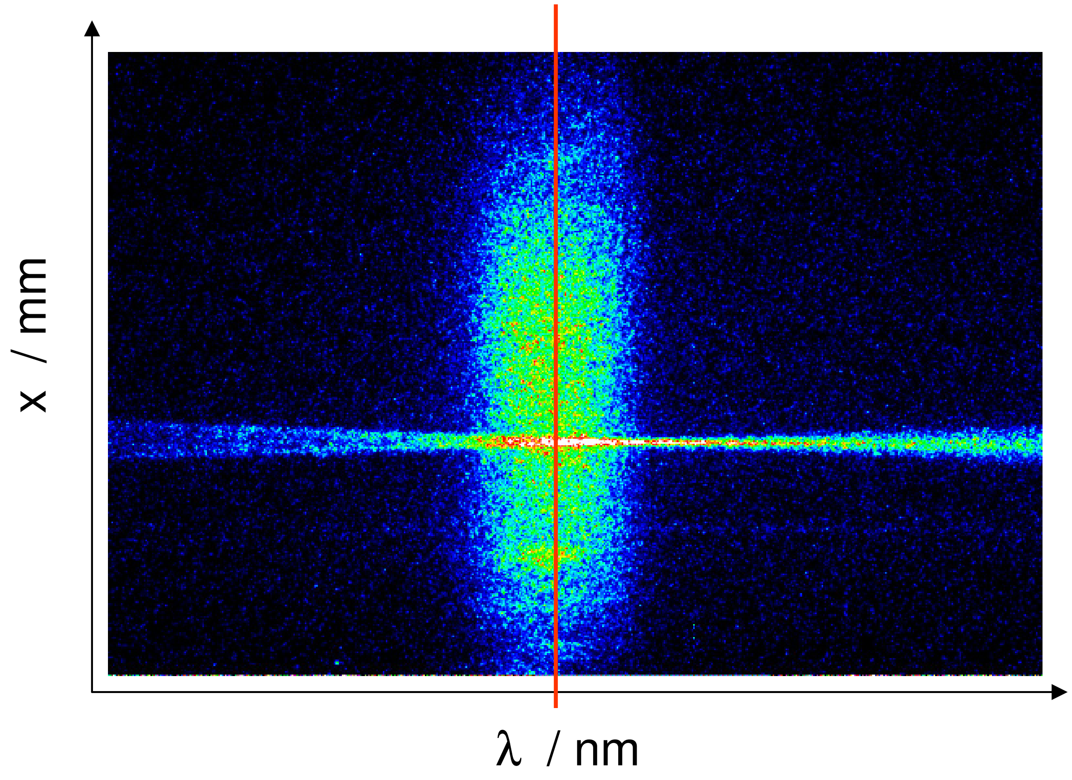
Boltzmann distribution of CE

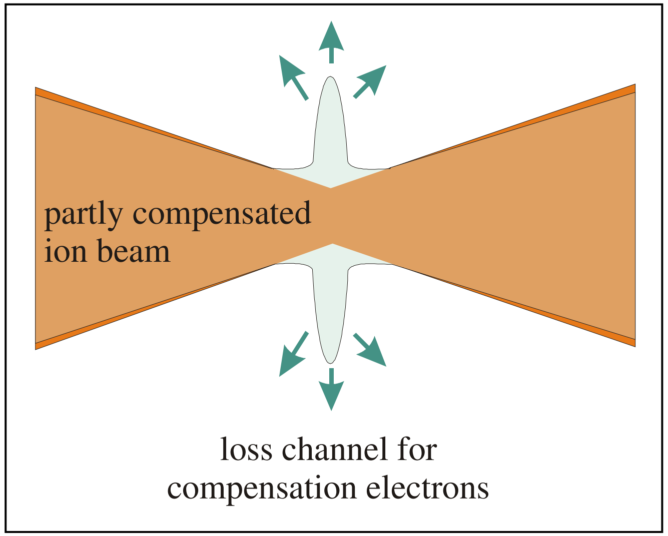
$$n_e(r) = n_e(r = \Phi_{b,\max}) \cdot e^{-\frac{e(\Phi_{\max} - \Phi(r))}{kT_{CE}}}$$

Space Charge Compensation

Loss channel for the CE

beam focussing leads to global decompensation



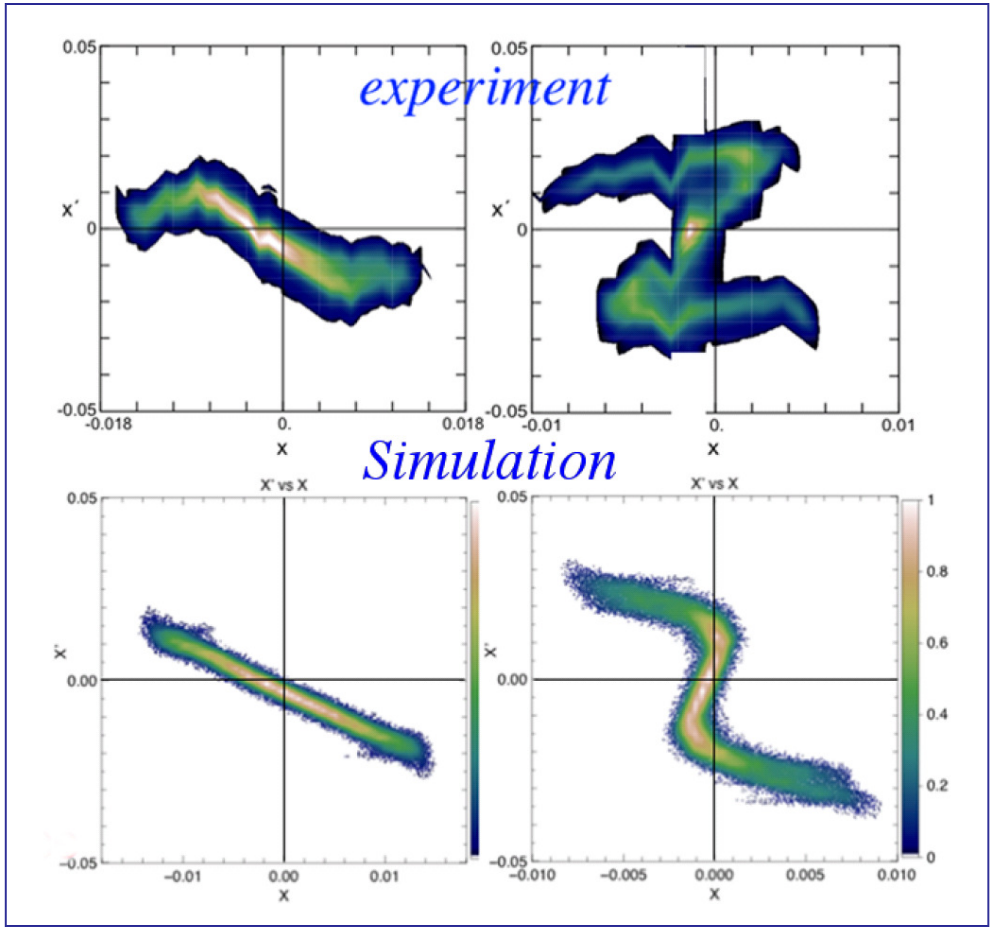


λ = 820 nm exciting of vacuum window by lost compensation electrons

Space Charge Compensation

Influence of beam optics on CE density distribution

decompensated compensated



Example: MSQ

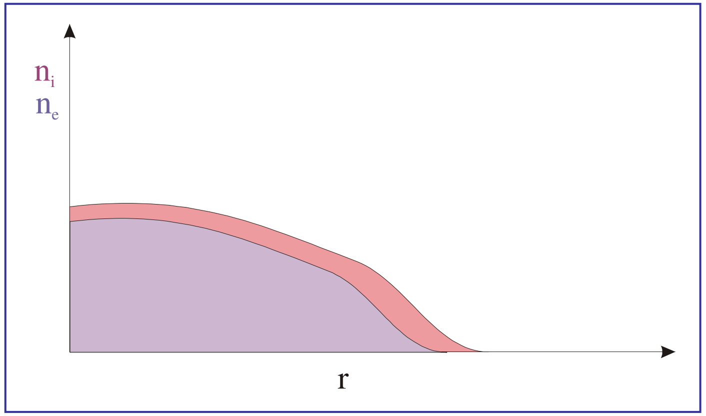
K^+ beam

5µs / I_{peak} = 190 mA / 1 MeV

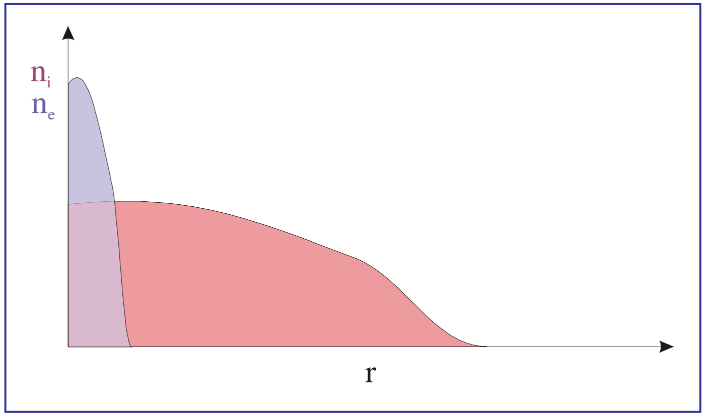
© F.M. Bieniosek et. al. HIF News March 2005

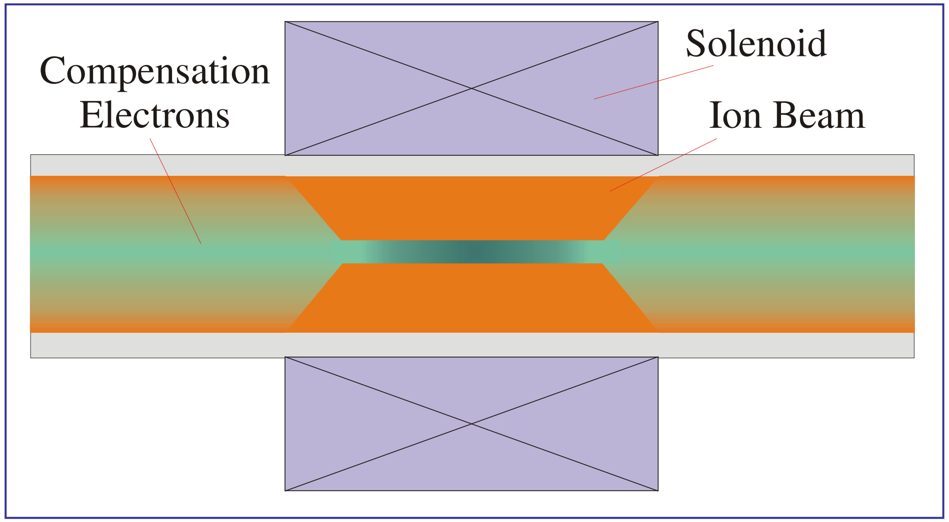
Space Charge Compensation

Influence of beam optics on CE density distribution



particle density distribution outside of the solenoid





changing of the density distribution of the compensation electrons along the beam path through a solenoid

$$v_\lambda = \left(\frac{v_\perp}{v_\parallel}\right)_B$$

$$\Phi_b = \frac{e r_b^2}{8 m_e} \cdot B_z^2$$

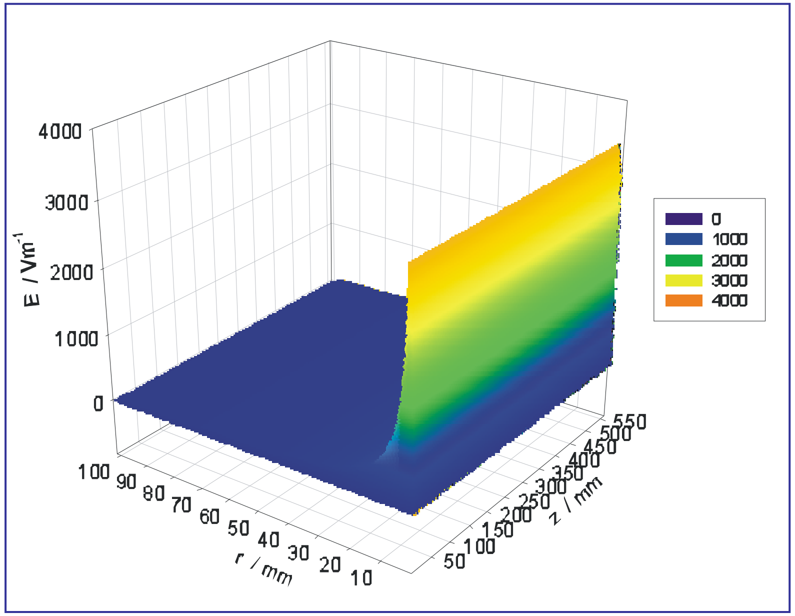
Approximation of CE distribution inside a solenoid

$n_e = 3.12 \cdot 10^{14}\ m^{-3}$

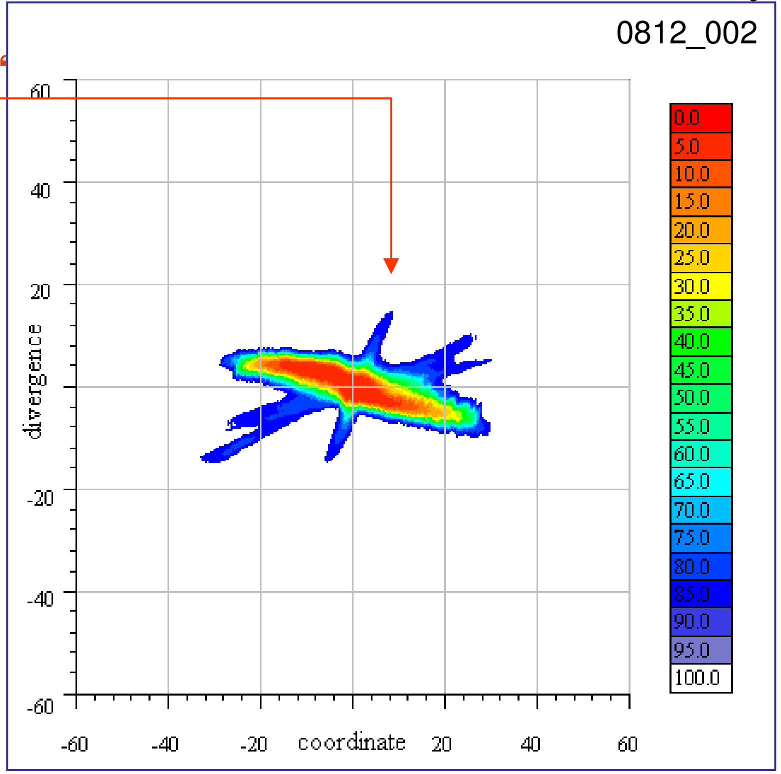
$r_e = 1$ mm

Leads to „Satelits“

measured @ cea - Saclay



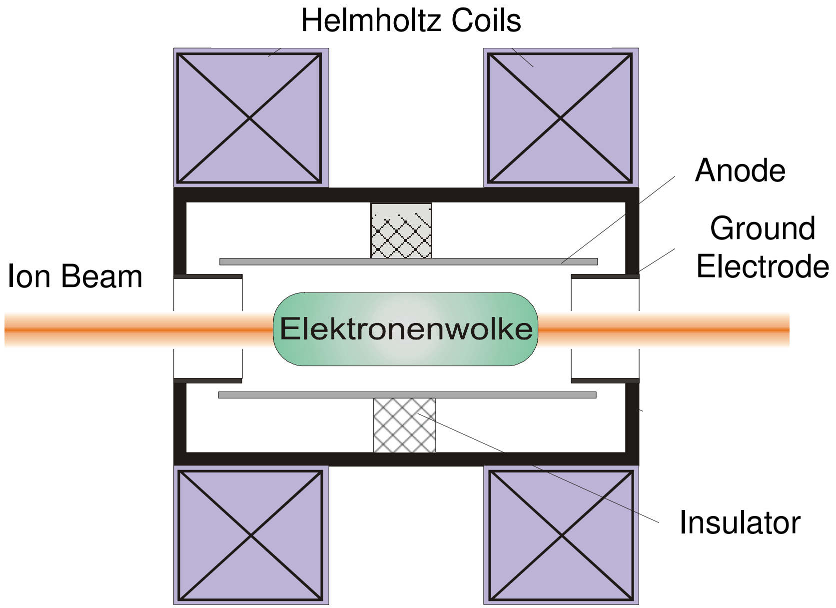
Field distribution of an homogenious filled electron columne inserted into the solenoid

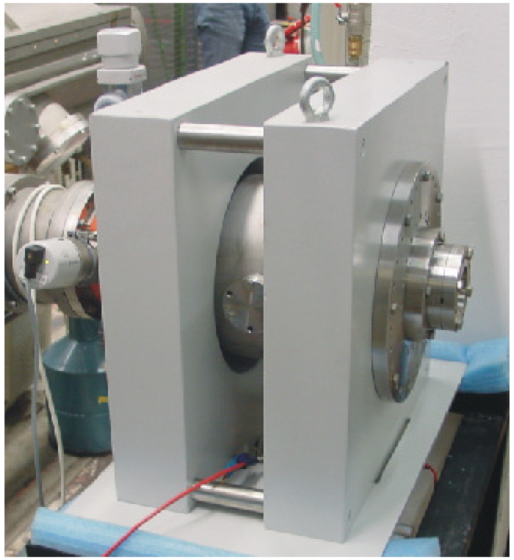


Measured phase space distribution of an intense proton beam $W_b = 95$ keV I = 98 mA

Focussing under fully space charge compensation

Parameters of the lens: $\Phi_{A,max}$ = 65 kV $B_{z,max}$ = 0.2T



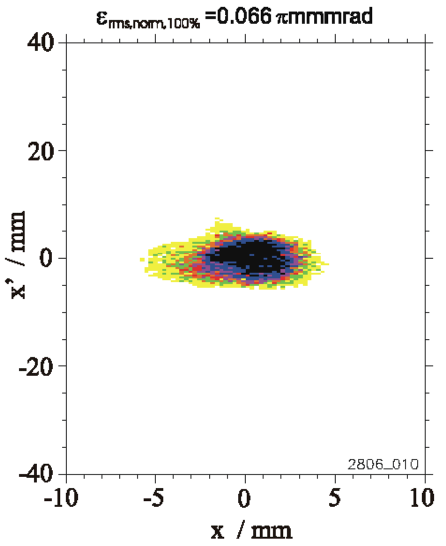


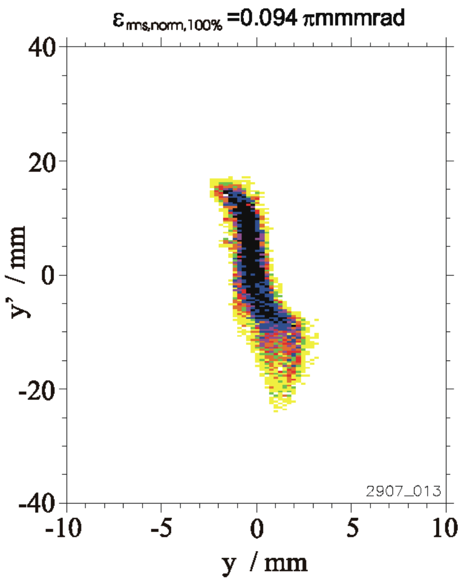
Gabor lens for beam energies up to 500 keV

Performance of Space Charge Lenses

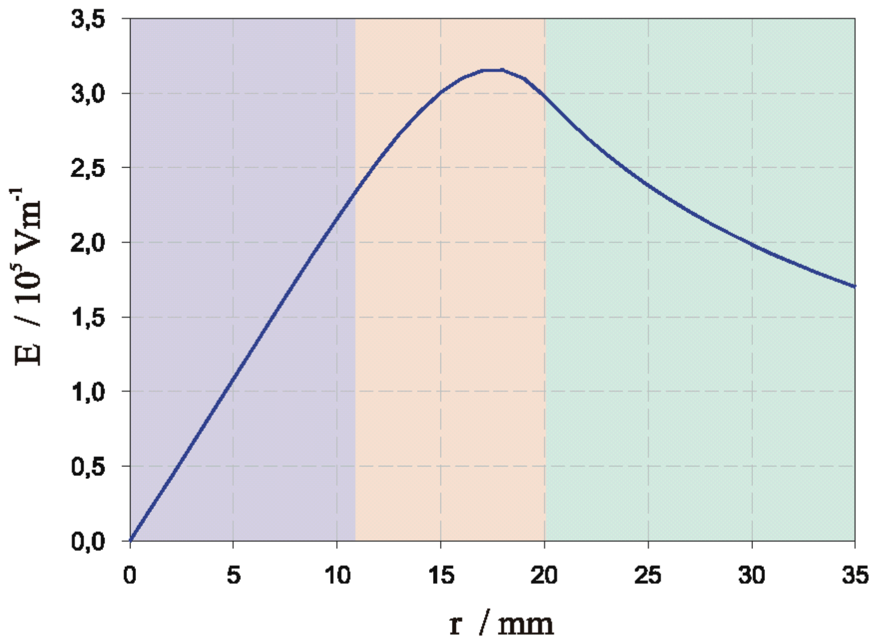
NNP
Non Neutral Plasma Physics Group

GOETHE UNIVERSITÄT FRANKFURT AM MAIN





He+, 440 keV, 1 mA



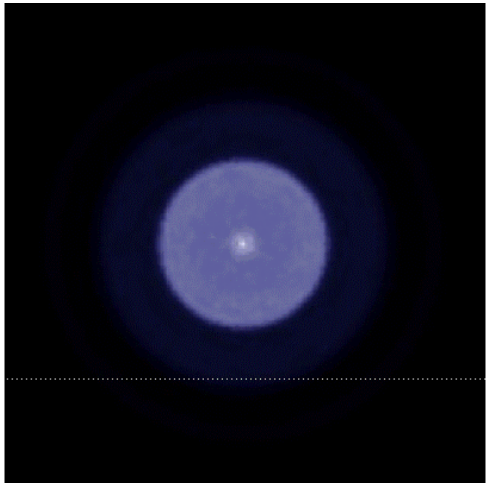
NNP
Non Neutral Plasma
Physics Group

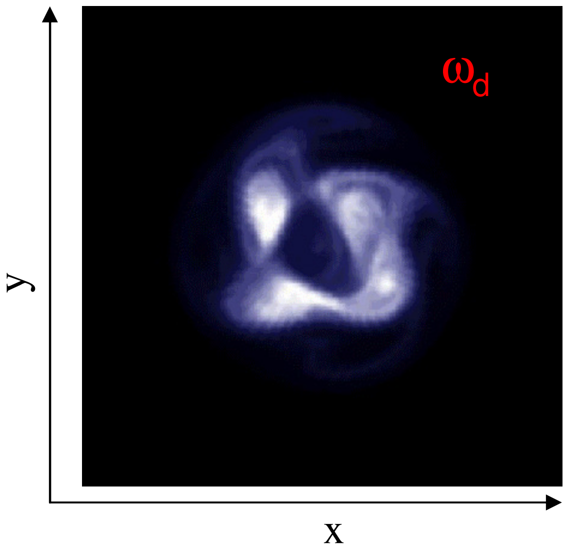
Performance of Space Charge Lenses

GOETHE UNIVERSITÄT
FRANKFURT AM MAIN

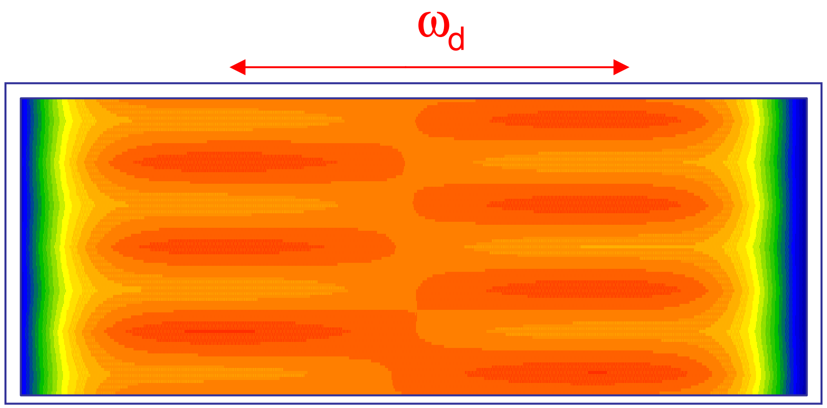
Instabilities of confined nnp

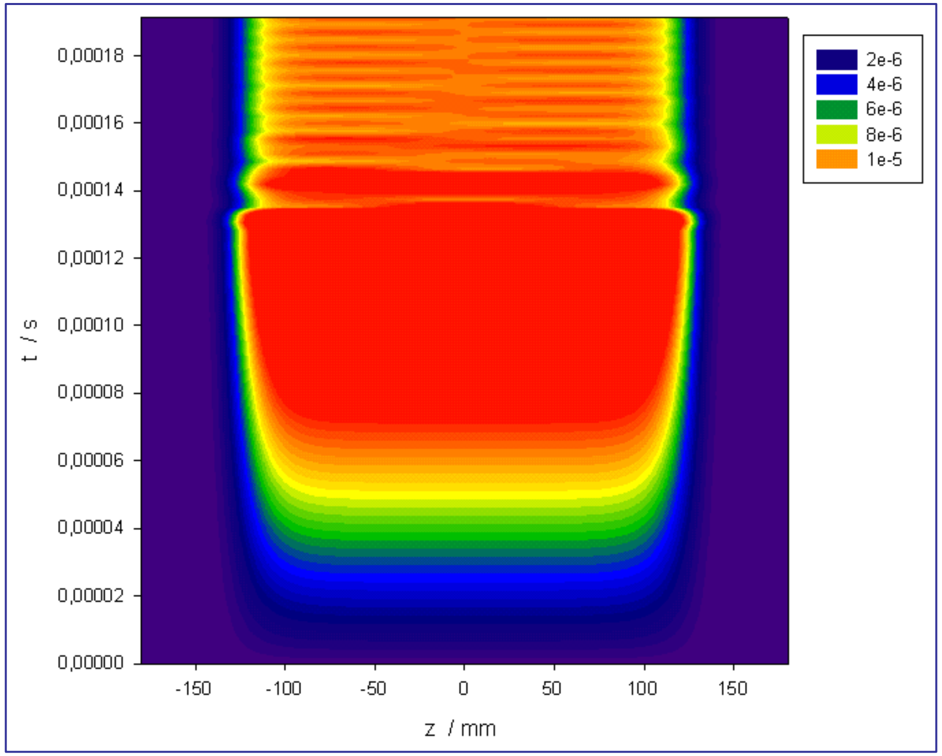
transverse plane



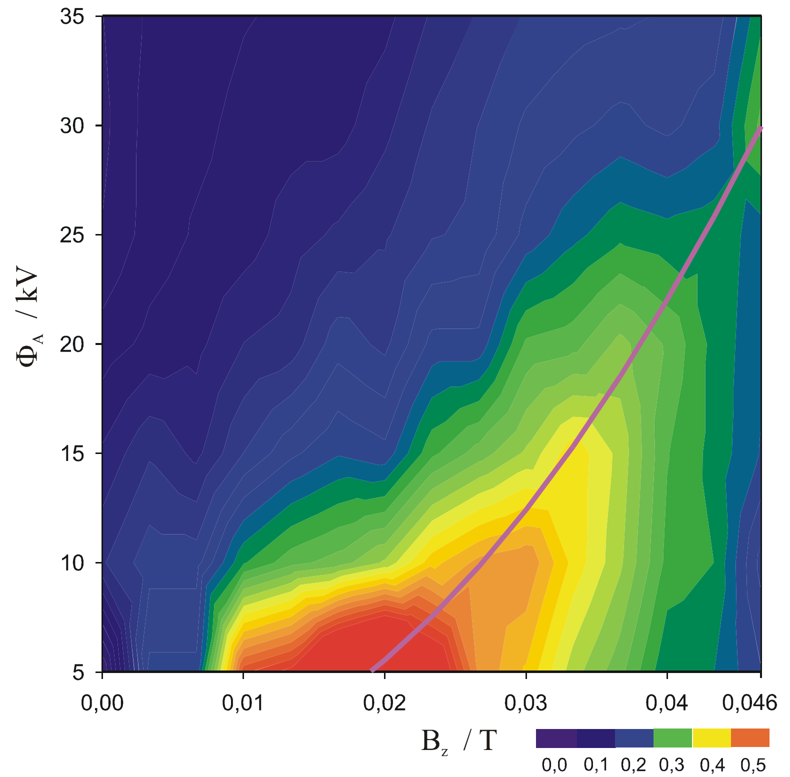


longitudinal

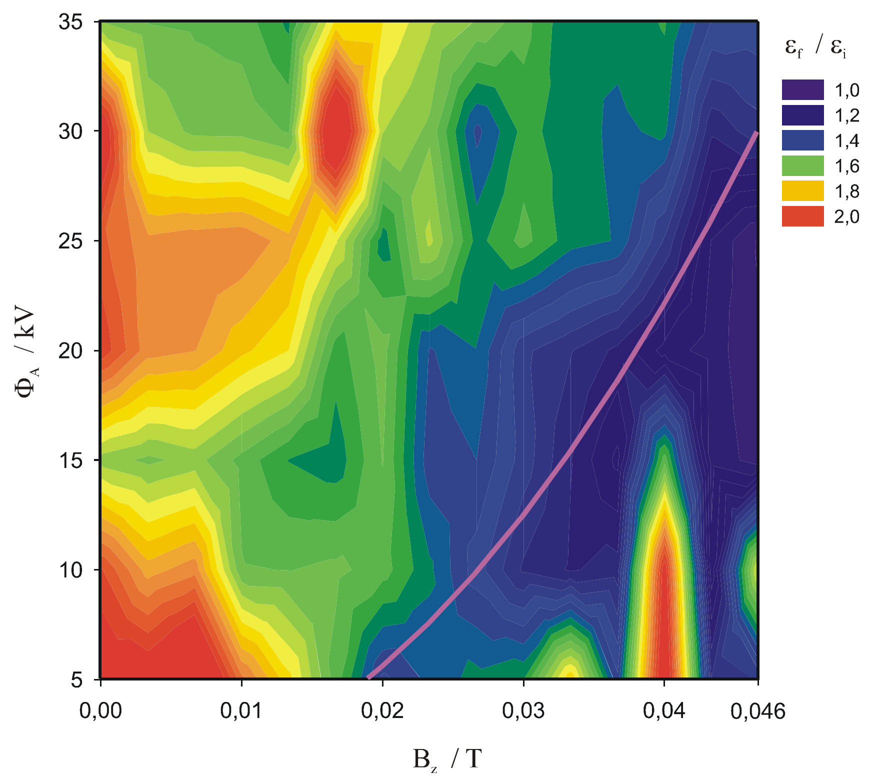




Focussing and Mapping capabilities of Gabor Lenses



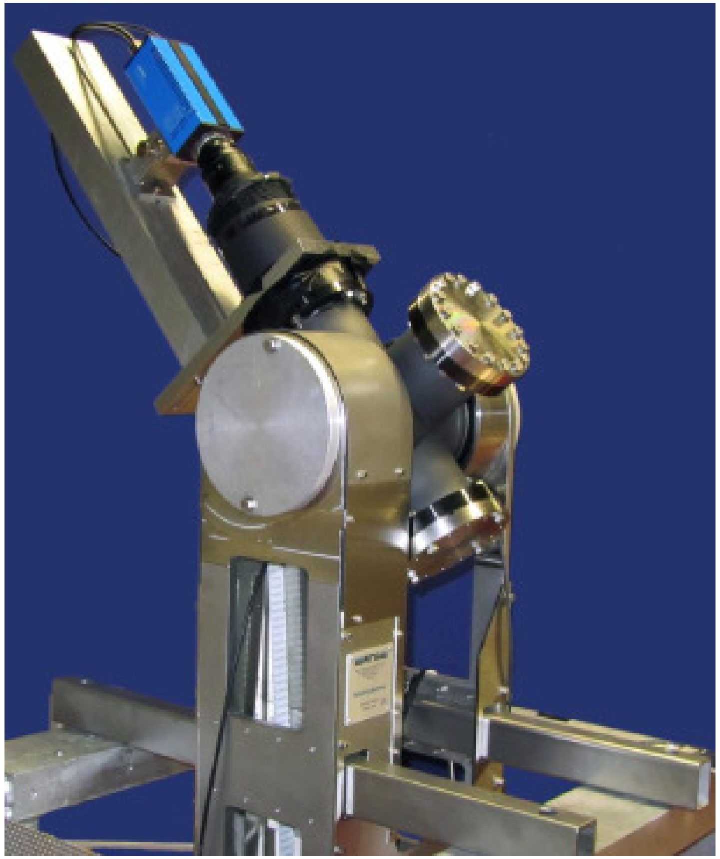
Trapping efficiency as a function of the lens parameters

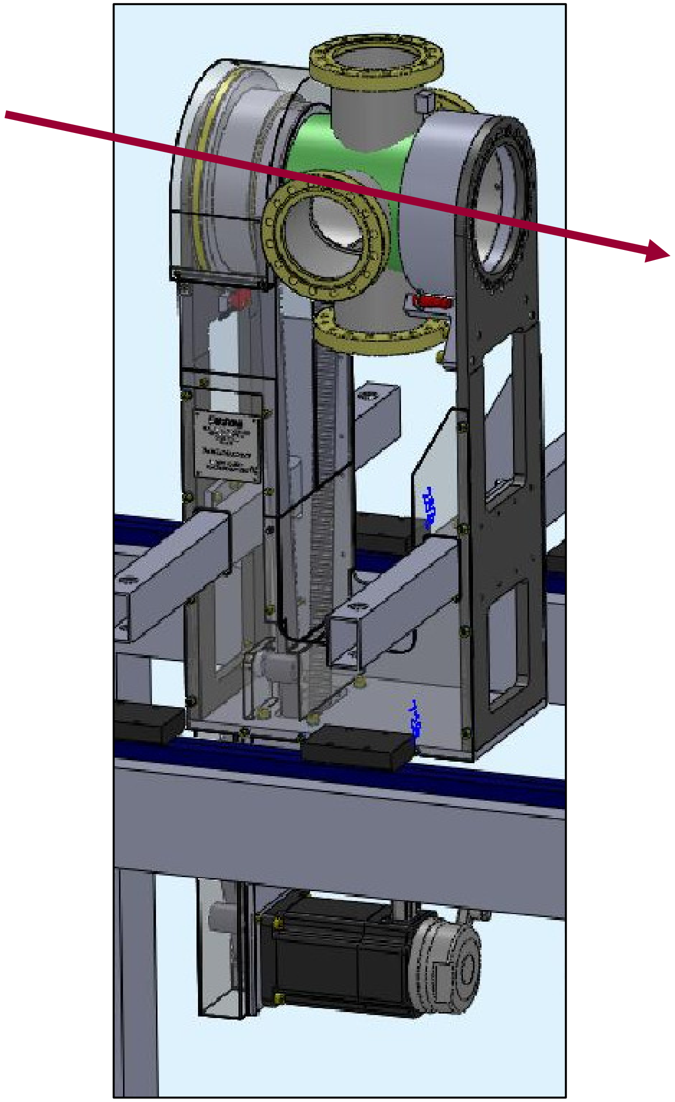


Emittance growth as a function of the lens parameters

Beam Diagnostics

Rotatable Vacuum Chamber





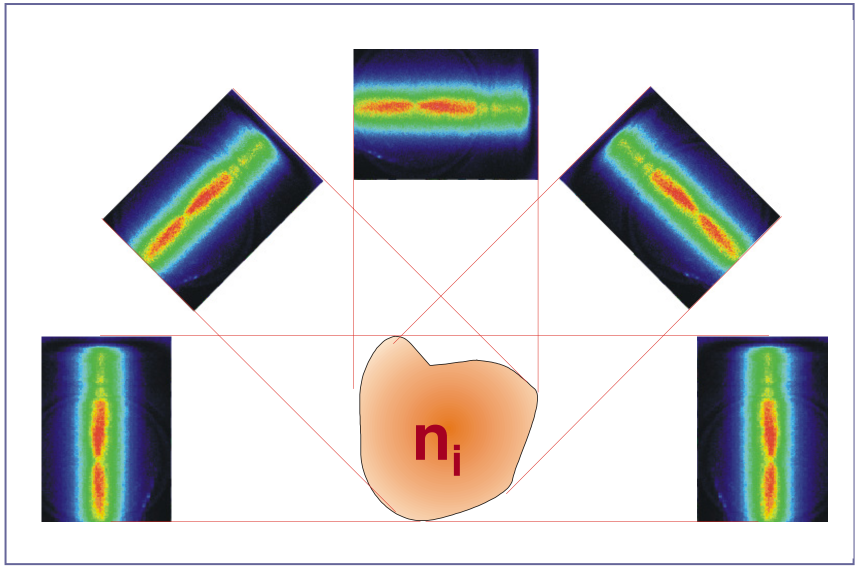
NNP
Non Neutral Plasma
Physics Group

Beam Diagnostics

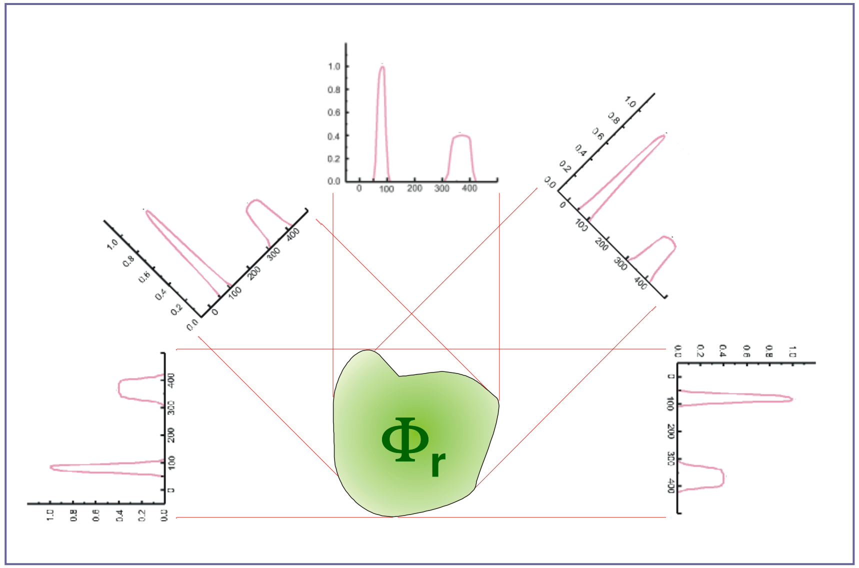
GOETHE UNIVERSITÄT
FRANKFURT AM MAIN

Beam Tomography

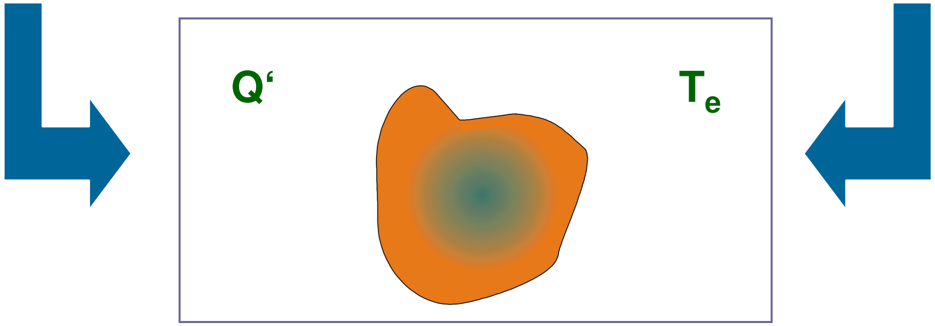
optical profiles



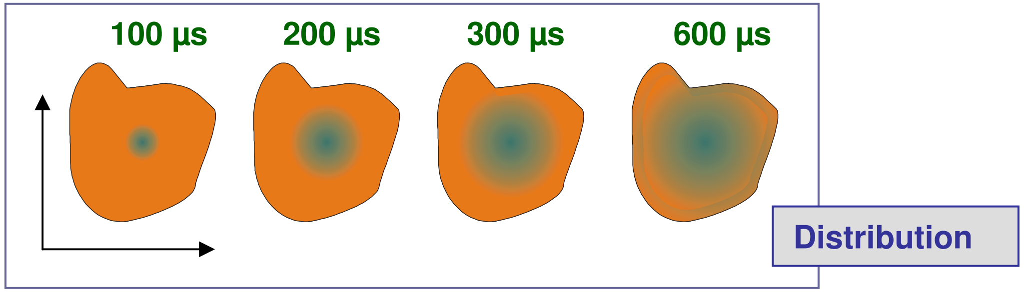
potential distribution

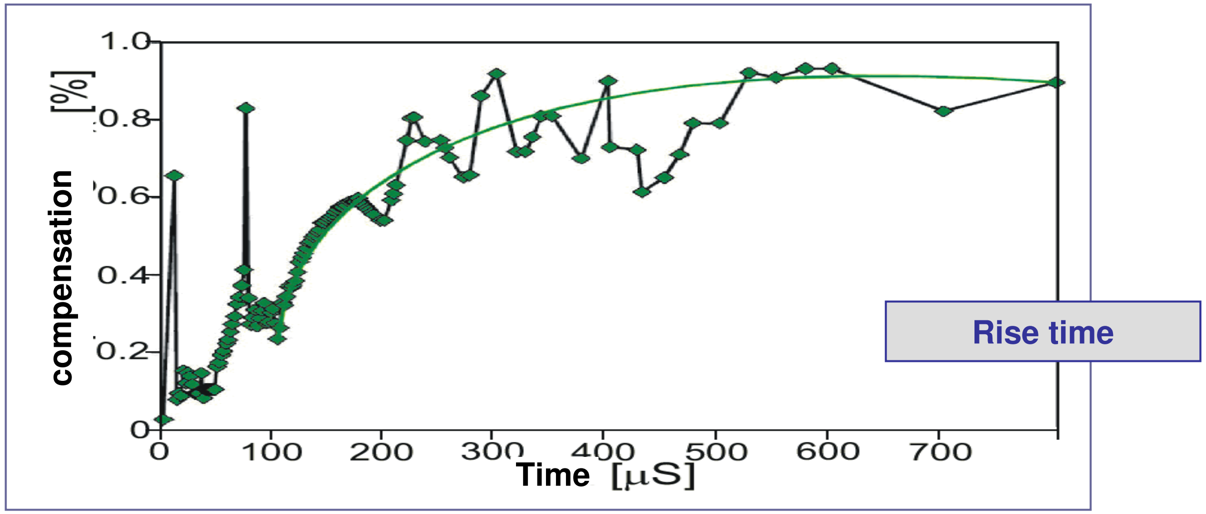


local compensation electron distribution



Dynamics of space charge compensation





Conclusion

Requirements on Accelerator Physics

Luminosity

$$L = \frac{\dot{N}}{\sigma_S}$$

Thank you for your attention.

NNP Group

http://nnp.physik.uni-frankfurt.de

HIC for FAIR
Helmholtz International Center

http://hicforfair.de