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Non Neutral Plasma
Physics Group

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Focusing of Intense Heavy Ion Beams with Plasma Lenses

Oliver Meusel

12th Heavy Ion Accelerator Technology Conference

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Historical Remarks

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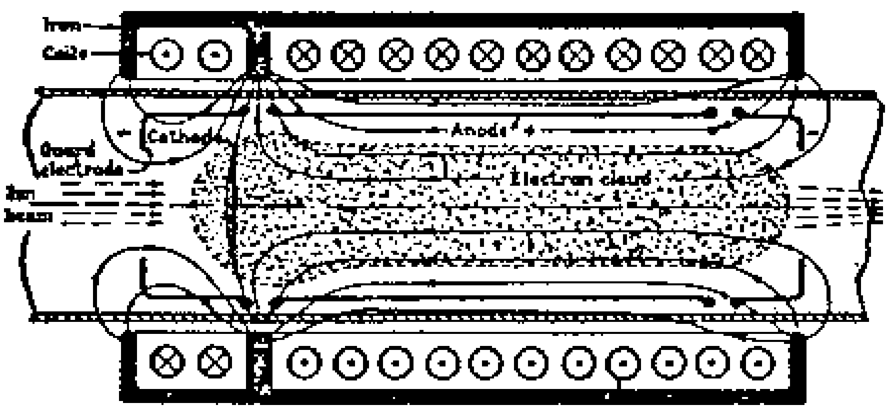
A Space-Charge Lens for the Focusing of Ion Beams

SOME time ago I proposed a magnetron of special design as a divergent lens for electron beams[1]. It now appears that the same device may become useful as a very powerful concentrating lens for positive ions, particularly for ion beams of extreme energy.



MAGNETRON LENS FOR ION BEAMS

Proposal of a SCL by Gabor, July 1947

Dennis Gabor
(1900-1979)

Electrical & Electronic Engineering Department, Imperial College London

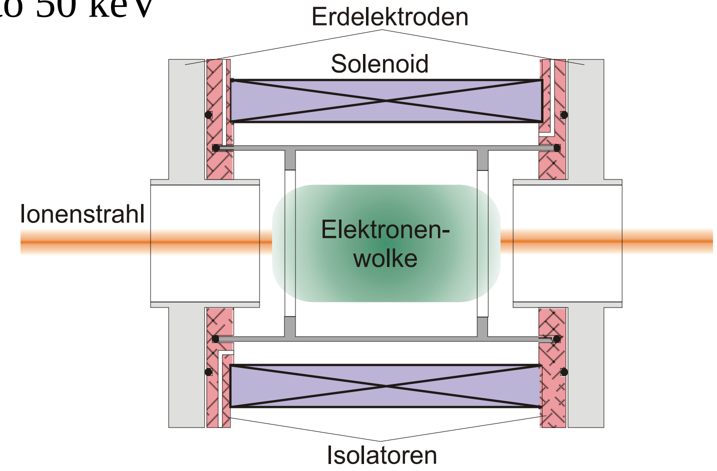
Space Charge Lenses

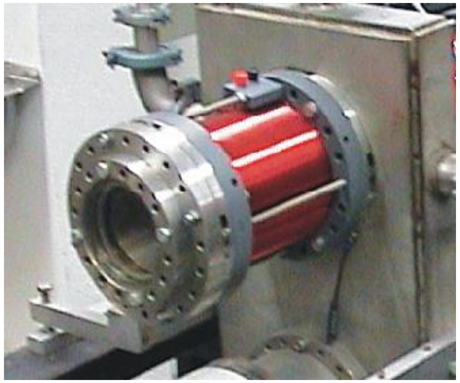
Gabor lens for beam energies up to 50 keV

lens properties:

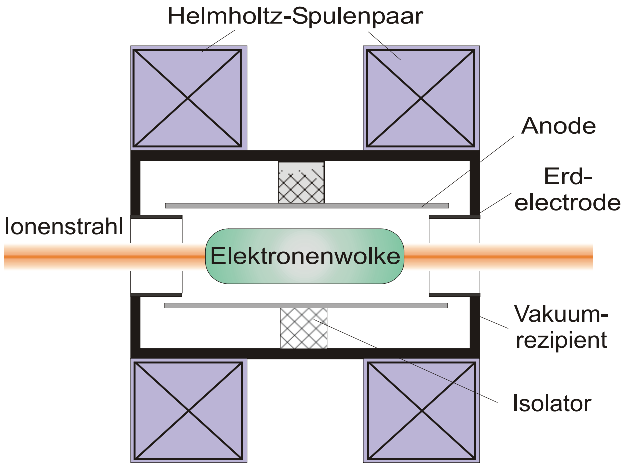
$\Phi_{A,max} = 6.5kV$

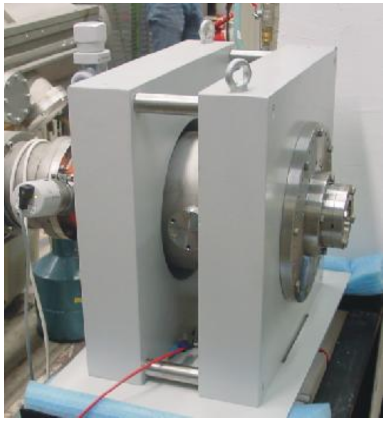
$B_{z,max} = 48mT$





high field Gabor lens for beam energies up to 500keV





lens properties :

$\Phi_{A,max} = 65kV$

$B_{z,max} = 220mT$

Radial Confinement

radial force balance equation

$$\frac{-m_e v_{e,\Theta}^2}{r} = -eE_r - e v_{e,\Theta} B_z$$

E_r given by Poisson equation:

$$\frac{1}{r}\frac{\partial}{\partial r} r E_r = \frac{e n_e(r)}{\varepsilon_0}$$

integration for $0 < r < R_p$:

$$E_r = \frac{1}{2\varepsilon_0} e n_e r$$

$$-\omega_e^2 = \frac{\omega_{pe}^2}{2} - \omega_e \Omega_e$$

$$\omega_e = \frac{v_{e,\Theta}}{r}$$ **angle velocity**

$$\omega_{pe}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$ **plasma frequency**

$$\Omega_e = \frac{eB_z}{m_e}$$ **cyclotron frequency**

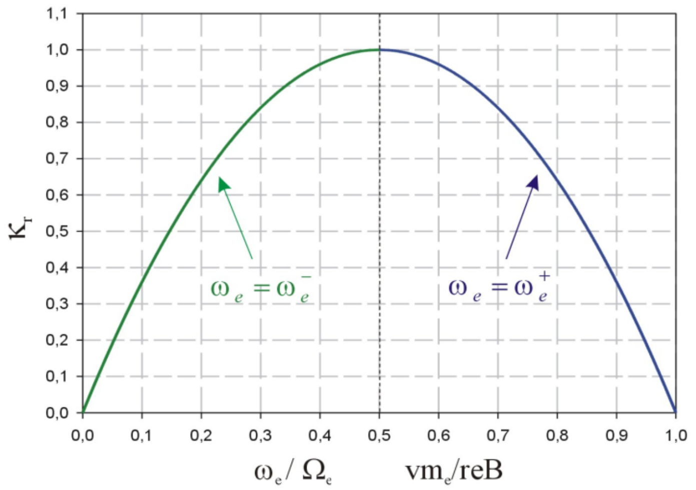
Radial Confinement

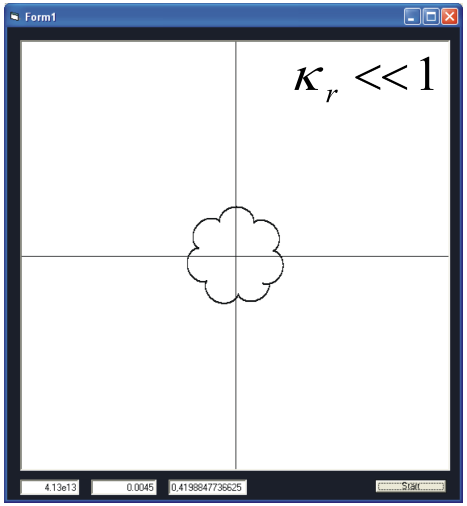
solution: $$\omega_e = \omega^{\pm} = \frac{\Omega_e}{2}\left[1 \pm \left(1 - \frac{2\omega_{pe}^2}{\Omega_e^2}\right)^{\frac{1}{2}}\right]$$

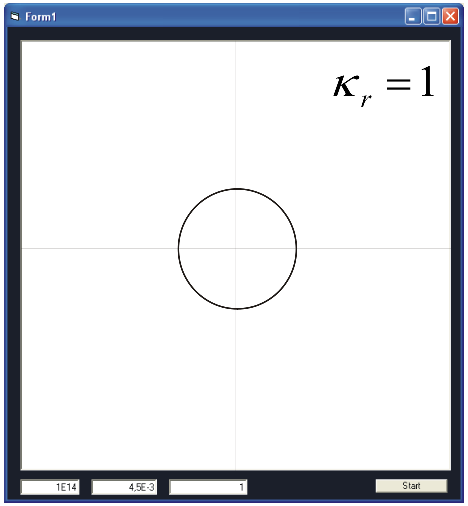
maximum density by a trapping efficiency of

$$\kappa_r = \frac{2\omega_{pe}^2}{\Omega_e^2} = 1 \Rightarrow n_e = \frac{\varepsilon_0 B_z^2}{2m_e}$$

$$\omega_e^- \cong \frac{\omega_{pe}^2}{2\Omega} = \frac{E_r}{rB_z} \; ; \; \omega_e^+ = \Omega_e \qquad \omega_e^- = \omega_e^+ = \frac{\Omega_e}{2}$$

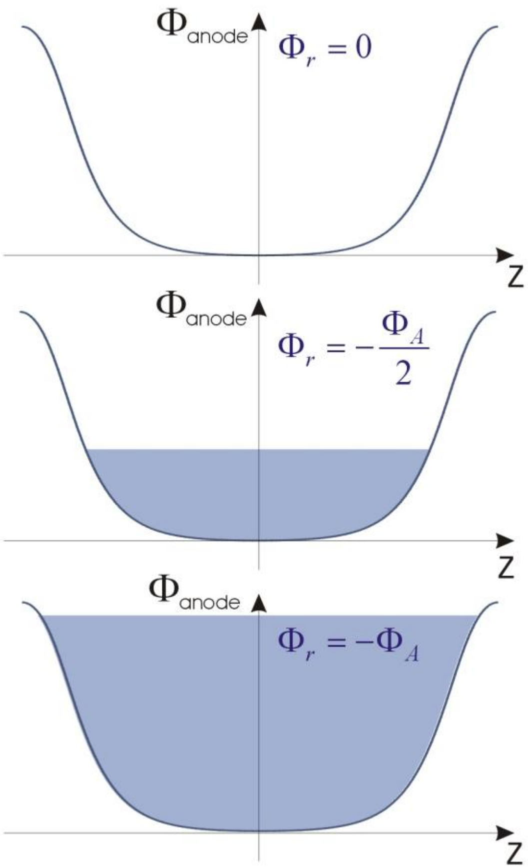






Longitudinal Confinement

longitudinal potential well



Φ_r is determined from Poisson's equation:

$$-\frac{1}{r}\frac{\partial \Phi_r}{\partial r} - \frac{\partial^2 \Phi_r}{\partial r^2} = \frac{e n_e(r)}{\varepsilon_0}$$

integrated for $0 < r < R_p$

$$\Phi_r = -\frac{e n_e r^2}{4\varepsilon_0}$$

maximum density at $\Phi_{anode} = -\Phi_r$

$$\Rightarrow \quad n_e = \frac{4\varepsilon_0 \Phi_A}{e r^2}$$

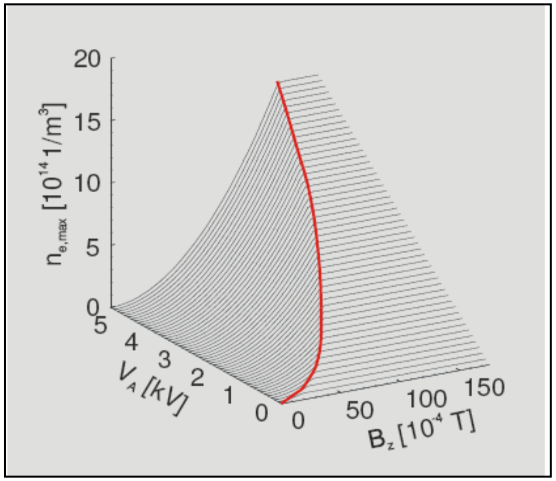
Numerical Simulation

two different simulation methods

GaborM

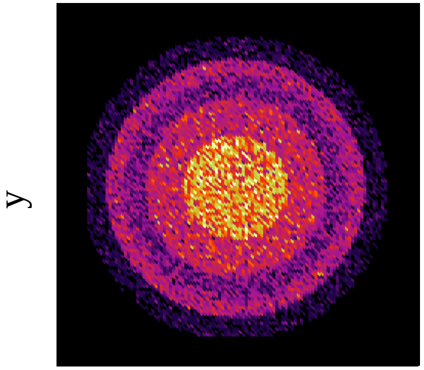
- fluid description
- steady state

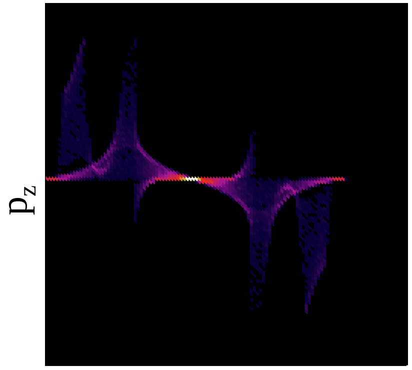
$$\Phi_A = \frac{e r^2 B_z^2}{8 m_e}$$



GabLensM2

- kinetic description
- dynamic processes
- 3D-Particle-In-Cell Simulation





Focusing Strength

comparison of focusing strengthes

Solenoid

weak focusing

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

MSQ / ESQ

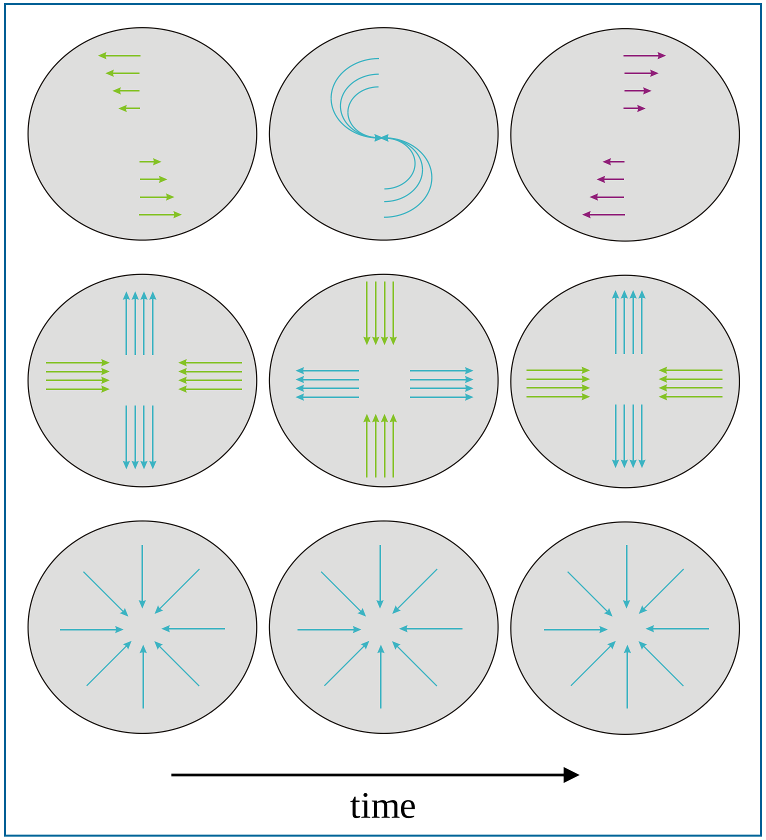
strong focusing/defocusing

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

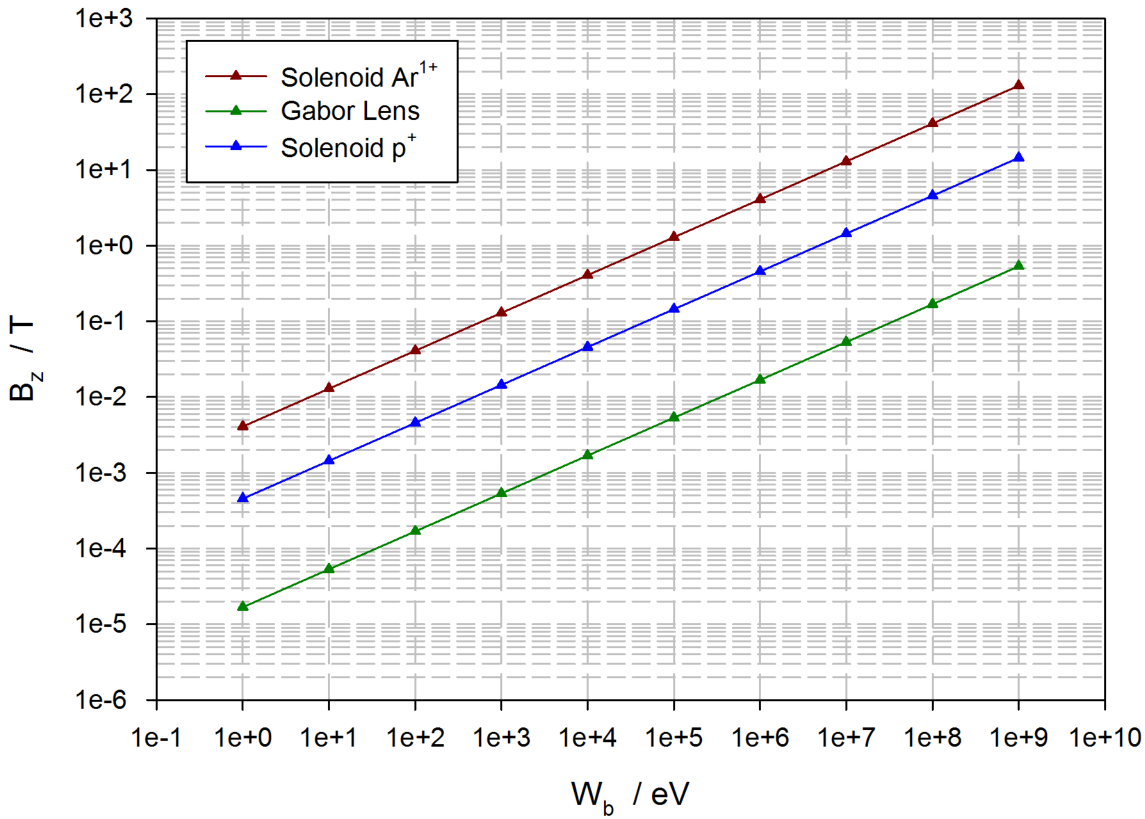
SCL

strong focusing

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



Comparison of Focussing Strengthes



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

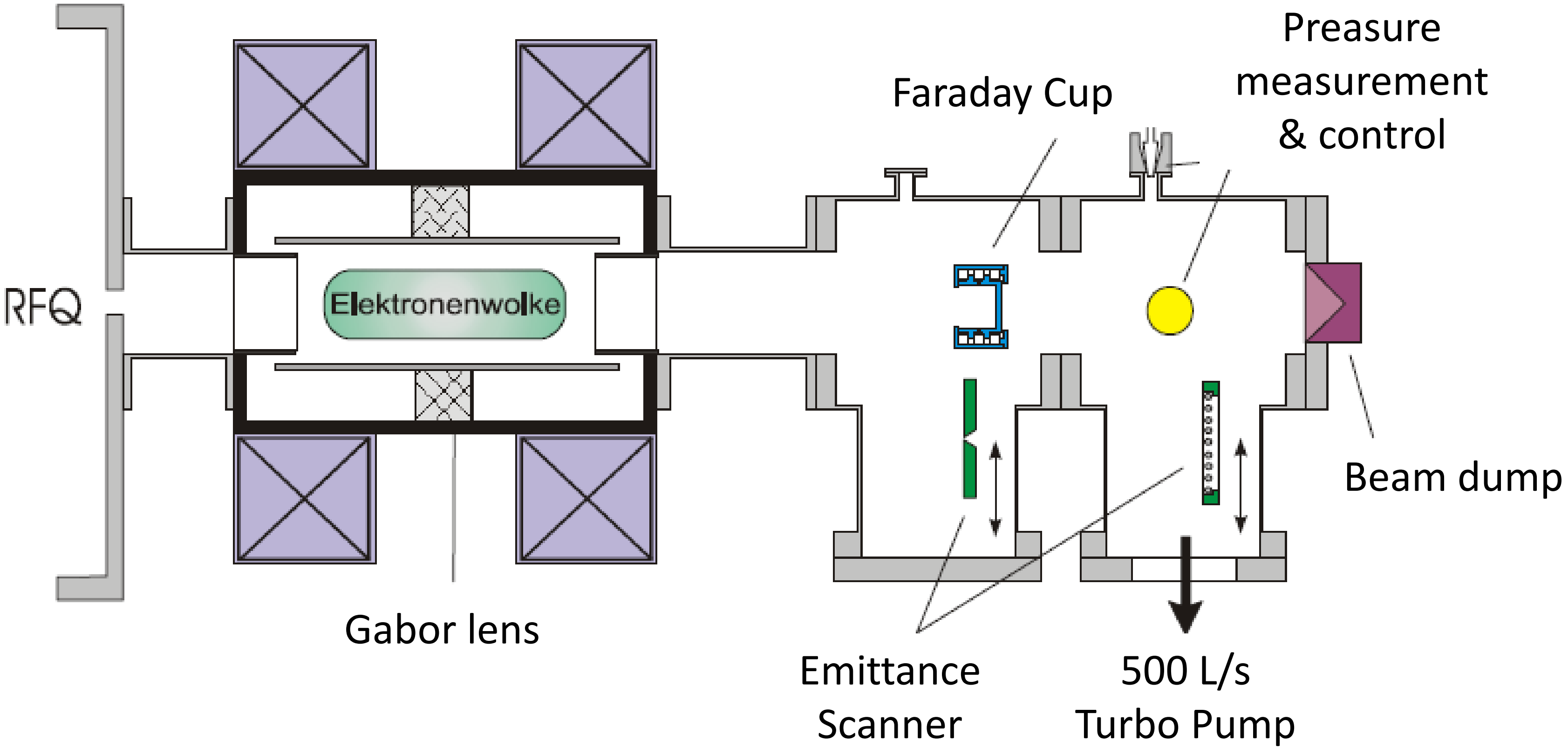
$$k = \frac{qB}{2 m_i v_i} \cdot \sqrt{\kappa \frac{m_i}{m_e}}$$

Filling degree κ depends on:

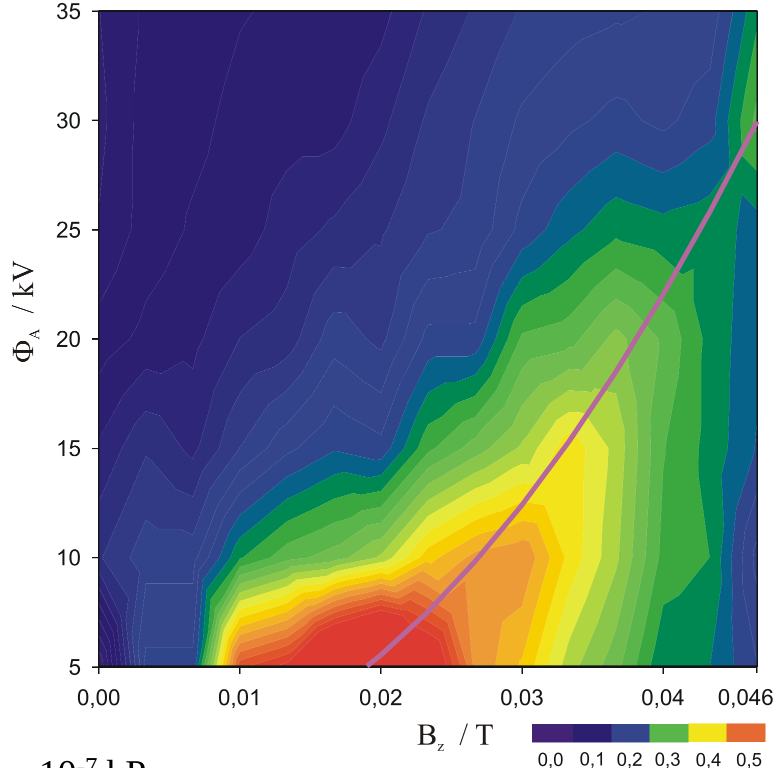
- electron temperature
- loss and production rates

Beam Transport Experiments

focussing of micro bunches passing a Gabor lens @ 108MHz, $\Delta\phi$ = 60°



measurement of the electron density using an ion beam



p = 10^{-7} hPa

$$\frac{1}{f} = \frac{\Delta x'}{x_0} = k^2 l = \frac{e n_{e,\exp}}{4\varepsilon_0} \frac{l}{W_b}$$

$$\kappa_r = \frac{n_{e.\exp}}{n_{e,theo}}$$

beam properties:

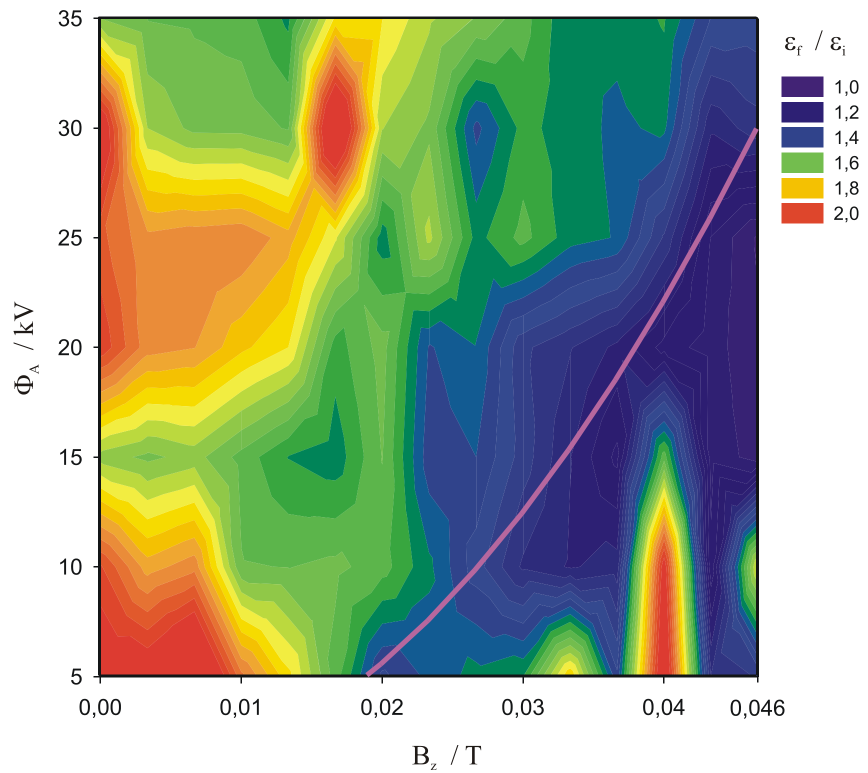
W_b = 110 keV/u

I = 1.2 mA

He^+

Beam Emittance Growth

characterisation of lens aberration by estimation of emittance growth



$p = 10^{-7}$ hPa

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

$$\Delta\varepsilon_{rms} = \frac{\varepsilon_{rms,out}}{\varepsilon_{rms,in}}$$

beam properties:

W_b = 110 keV/u

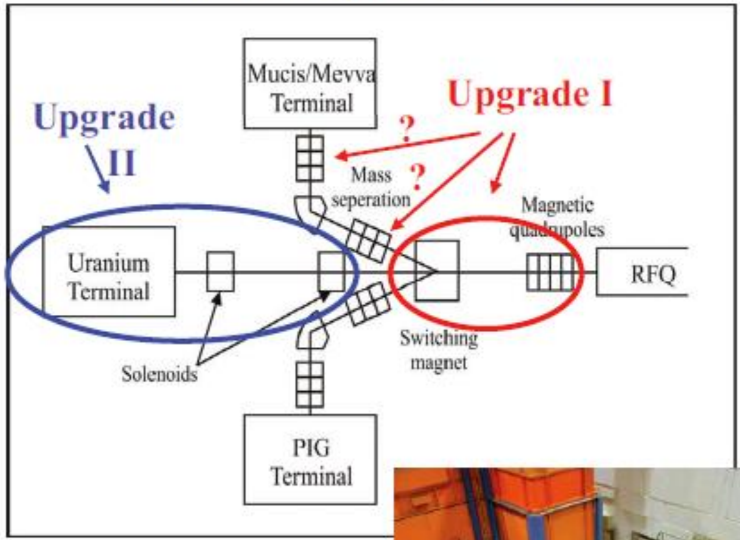
I = 1.2 mA

He^+

Planned Experiments

HSI-LEBT Upgrade

Schematic layout of the LEBT



Upgrade 0

- High Current test stand measurements

Upgrade I

- Switching magnet with increased aperture
- Quadrupole quartet (matching to the RFQ) with increased apertures

Upgrade II (**Compact LEBT**)

- Beam line with direct injection to the RFQ (integrated into the existing layout)

Previous simulations: Compact LEBT + New RFQ
→ 20 mA behind RFQ !

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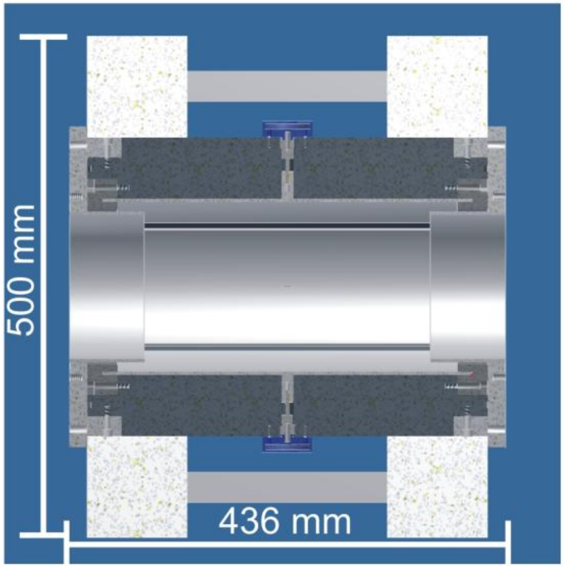
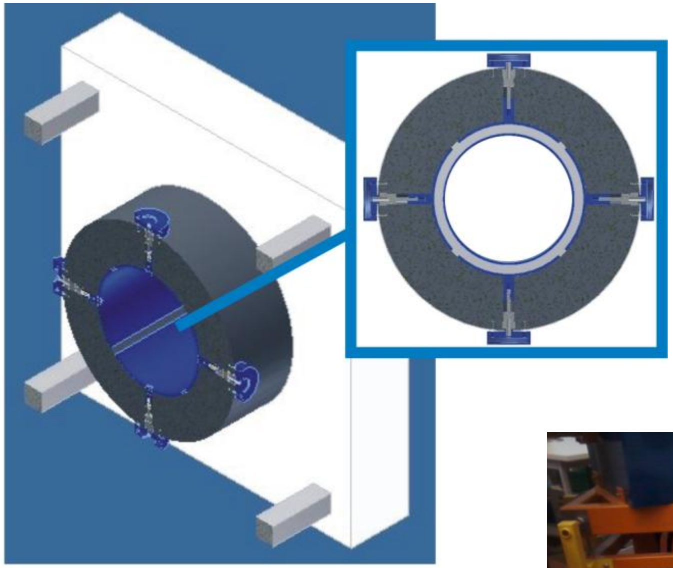
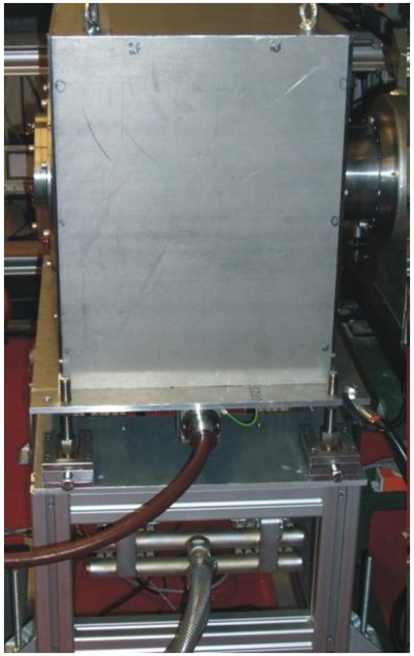
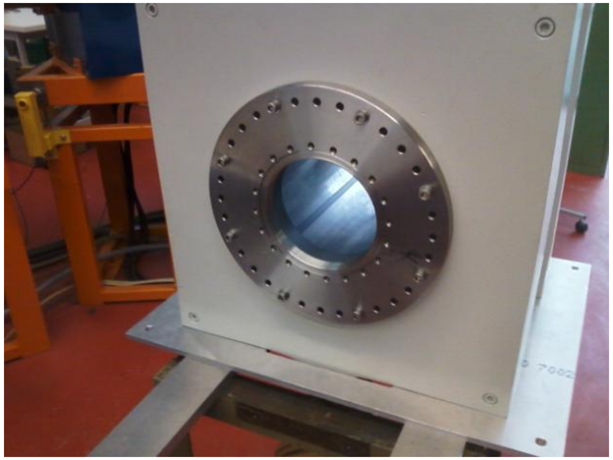
High Field Gabor Lens

HF-GL prototype for HSI upgrade









lens properties	
r_{anode} :	85mm
B_{max} :	50mT
Φ_{max} :	50kV

- ceramic insulator
- HV-contacting
- UH vacuum sealing

DN CF 160

Performance Test of the HF-GL

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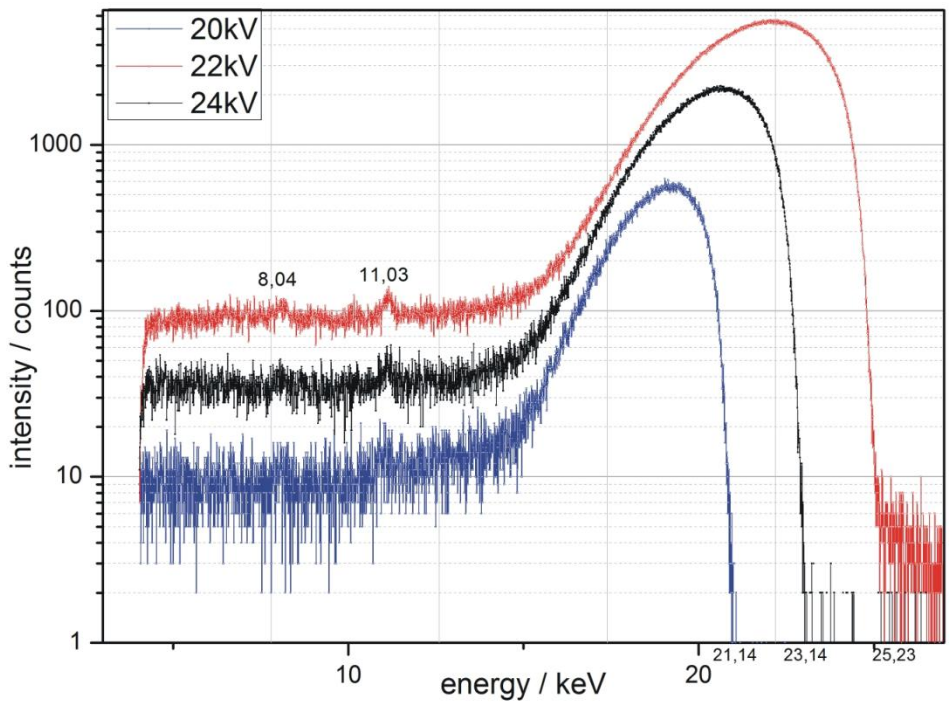
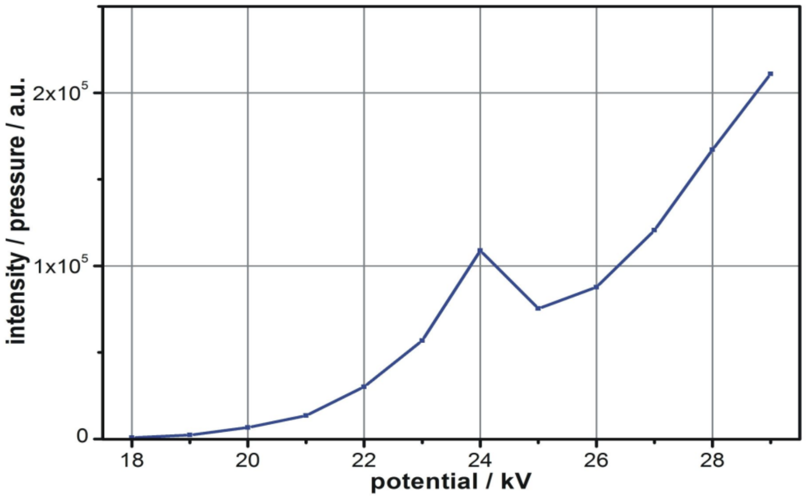
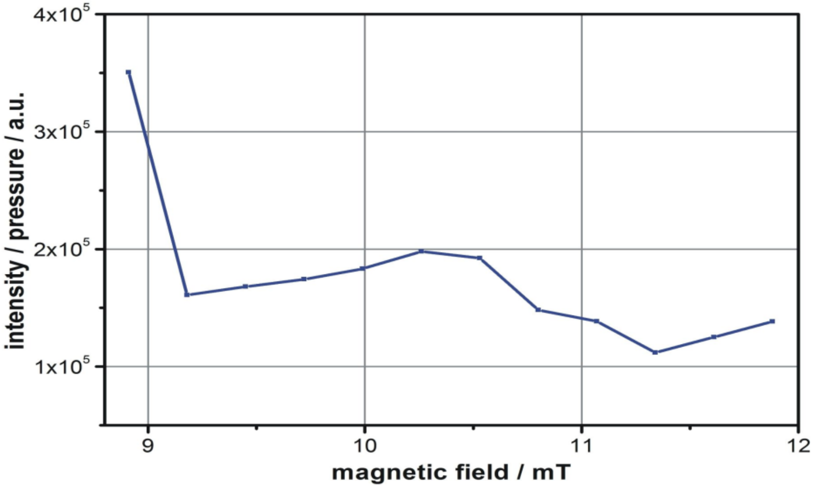
emitted bremsstrahlung spectra

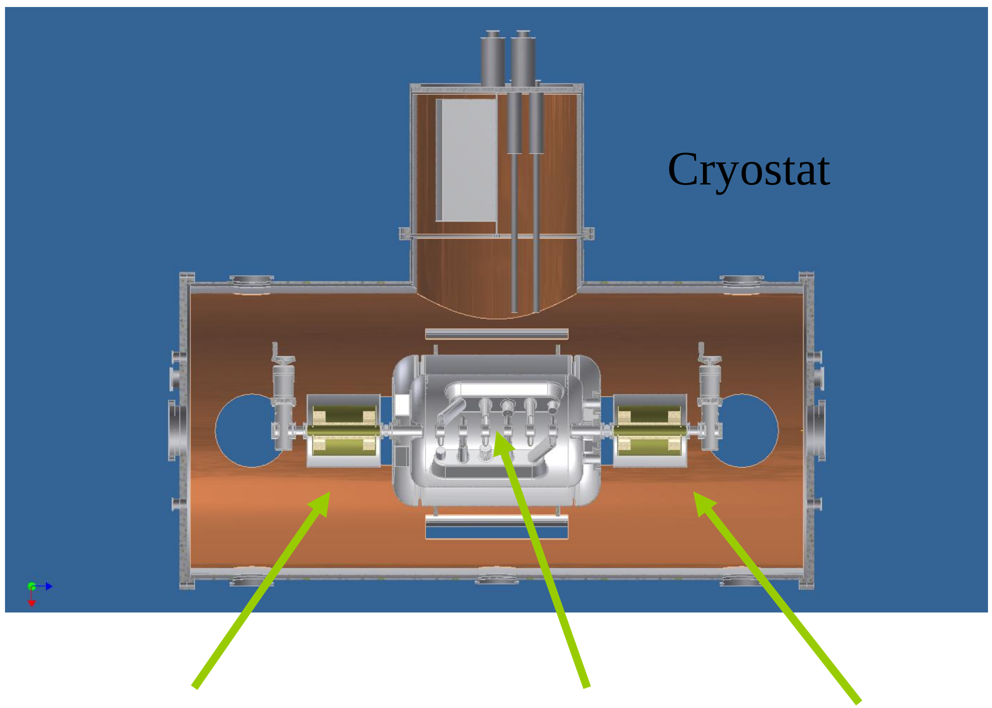






loss and production rates at preasures below 10^{-12} mbar

Is it possible to use a Gabor - lens in a cryogenic interior?



Thank you for your attention.

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