Focusing of Intense Heavy Ion Beams with Plasma Lenses

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Historical Remarks

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. 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
Space Charge Lenses

Gabor lens for beam energies up to 50 keV

lens properties:
$\Phi_{A,\text{max}} = 6.5\text{kV}$
$B_{z,\text{max}} = 48\text{mT}$

high field Gabor lens for beam energies up to 500keV

lens properties :
$\Phi_{A,\text{max}} = 65\text{kV}$
$B_{z,\text{max}} = 220\text{mT}$
Radial Confinement

radial force balance equation

\[-m_e v_{e,\theta}^2 = -e E_r - e v_{e,\theta} B_z\]

\(E_r\) 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

\(\Omega_e = \frac{e B_z}{m_e}\) cyclotron frequency
Radial Confinement

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

maximum density by a trapping efficiency of

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

\[ \omega_e^- \approx \frac{\omega_{pe}^2}{2\Omega} = \frac{E_r}{rB_z}; \quad \omega_e^+ = \Omega_e \]

\[ \omega_e^- = \omega_e^+ = \frac{\Omega_e}{2} \]

\[ \kappa_r < < 1 \]

\[ \kappa_r = 1 \]
\( \Phi_r \) is determined from Poisson’s equation:

\[
-\frac{1}{r} \frac{\partial \Phi_r}{\partial r} - \frac{\partial^2 \Phi_r}{\partial r^2} = \frac{en_e(r)}{\varepsilon_0}
\]

integrated for \( 0 < r < R_p \)

\[
\Phi_r = -\frac{en_e r^2}{4\varepsilon_0}
\]

maximum density at \( \Phi_{\text{anode}} = -\Phi_r \)

\[
\Rightarrow n_e = \frac{4\varepsilon_0 \Phi_A}{er^2}
\]
two different simulation methods

GaborM

• fluid description
• steady state

\[ \Phi_A = \frac{er^2 B_z^2}{8m_e} \]

GabLensM2

• kinetic description
• dynamic processes
• 3D-Particle-In-Cell Simulation
Comparison of focusing strengths

Solenoid
weak focusing

MSQ / ESQ
strong focusing/defocusing

SCL
strong focusing

\[ k = \frac{qB}{2mv} \]

\[ k = \sqrt{\frac{qg}{mv}} \]

\[ k = \frac{\kappa qe B_z^2}{\sqrt{8m_e W_b}} \]
Comparison of Focussing Strengths

Filling degree $\kappa$ depends on:

- electron temperature
- loss and production rates

\[ k = \frac{\kappa q^2 B_z^2}{8m_e W_b} \]
\[ k = \frac{qB}{2m_i v_i} \sqrt{\kappa \frac{m_i}{m_e}} \]
focussing of micro bunches passing a Gabor lens @ 108MHz, $\Delta\phi = 60^\circ$
measurements of the electron density using an ion beam

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

\[
\kappa_r = \frac{n_{e,\text{exp}}}{n_{e,\text{theo}}}
\]

beam properties:

- \( W_b = 110 \text{ keV/u} \)
- \( I = 1.2 \text{ mA} \)
- \( \text{He}^+ \)

\( p = 10^{-7} \text{ hPa} \)
characterisation of lens aberration by estimation of emittance growth

\[ \varepsilon_{rms} = \sqrt{\left\langle x^2 \right\rangle \left\langle x'^2 \right\rangle - \left\langle xx' \right\rangle^2} \]

\[ \Delta \varepsilon_{rms} = \frac{\varepsilon_{rms, out}}{\varepsilon_{rms, in}} \]

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Planned Experiments

HSI-LEBT Upgrade

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!
High Field Gabor Lens

HF-GL prototype for HSI upgrade

lens properties

- \( r_{\text{anode}} \): 85mm
- \( B_{\text{max}} \): 50mT
- \( \Phi_{\text{max}} \): 50kV

- ceramic insulator
- HV-contacting
- UH vacuum sealing

DN CF 160
Performance Test of the HF-GL

emitted bremsstrahlung spectra

Graphs showing intensity as a function of energy, potential, and magnetic field.
loss and production rates at pressures 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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