Experimental Studies of Stable Confined Electron Clouds using Gabor Lenses

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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.

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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 500 keV

- **lens properties:**
  - $\Phi_{A,\text{max}} = 65\text{kV}$
  - $B_{z,\text{max}} = 220\text{mT}$
radial force balance equation

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

\(E_r\) given by Poisson equation:

\[\frac{1}{r^2} \frac{\partial}{\partial r} \left( r E_r \right) = \frac{en_e(r)}{\varepsilon_0}\]

integration for \(0 < r < R_p\):

\[E_r = \frac{1}{2\varepsilon_0}en_e r\]

\[\omega_e = \frac{V_{e,\Theta}}{r}\]

\[\omega_{pe}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}\]

\[\Omega_e = \frac{eB_z}{m_e}\]

\[-\omega_e^2 = \frac{\omega_{pe}^2}{2} - \omega_e \Omega_e\]
Longitudinal Confinement

longitudinal potential well

\[ \Phi_r \text{ is determined from Poisson's equation:} \]

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

integrated for \( 0 < r < R_p \)

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

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

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

GaborM

- fluid description
- steady state

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

GabLensM2

- kinetic description
- dynamic processes
- 3D-Particle-In-Cell Simulation
three segmented Gabor lens for the development electron cloud diagnostics
optical diagnostics

Diagnostics of the Confined Electron Cloud

Electron density distribution as a function of the confinement

Estimation of $T_e$ using opt. spectroscopy
Diagnostics of Collective Behaviour

diocotron instability

symmetry breaking within a symmetric confinement

rise and fall of instabilities
Diagnostics Using the Emitted RF
measurement 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:

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

\( p = 10^{-7} \text{ hPa} \)
measurement of the rise time of the electron density using an ion beam focusing and deflection?
characterisation of lens aberration by estimation of emittance growth

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

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

beam properties:

\[ W_b = 110 \text{ keV/u} \]
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focussing of micro bunches passing a Gabor lens @ 108MHz, $\Delta\phi = 60^\circ$

- losses due to chromatic aberrations
- apparent beam cooling due to Landau damping
- space charge compensation
- no beam induced instabilities were observed

emittance as a function of the transverse electron confinement
Simulation of EC – Beam Interaction

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Thank you for your attention.

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