

CONFINEMENT OF ELECTRON CLOUDS IN A BENDING MAGNET

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Abstract

Dipole magnets in linear accelerators or synchrotrons are used to bend ion beams. In case of intense ion beams, space charge compensation is a strategy to overcome intensity limits. So far the reduction of the beams space charge is not investigated in bending magnets by experiments. Therefore, a Gabor-lens was constructed and immersed in a H-type bending magnet to provide a pure electron plasma. Usually, Gabor-lenses are ion optical devices used for focusing and deflecting ion beams. With the setup presented in this paper it will be possible to compare the bending of intense ion beams with and without space charge compensation. Furthermore, the impact of spontaneous built-up of electron clouds observed in synchrotrons can be studied. First experimental results compared with numerical simulations regarding the confinement of electron plasmas within the dipole-Gabor-lens system will be presented. First beam dynamic simulations will show the impact of space charge compensation within bending magnets.

INTRODUCTION

To enhance the performance of linear accelerators and synchrotrons, such as GSI and FAIR facilities, for achieving more accurate experiments, the intensity of ion beams must be increased. However, the space charge generated by heavy-ion beams within the beam pipe counteracts the focusing effect of the enclosing magnets. Consequently, the acceleration of a bunch consisting of a high number of positively charged particles is limited and leads to unstable beam transport. Due to the negative charge of electrons, their corresponding electromagnetic fields can be used to compensate the space charge of high-intensity ion beams [1].

Additionally in high-energy particle accelerators, such as the Large Hadron Collider (LHC) at CERN, the formation of electron clouds (EC), driven by photoemission and secondary electron emission (SEE), causes beam instabilities. These clouds grow exponentially in the presence of positive charged, high-density bunches within the beam pipe [2]. To study these effects under controlled laboratory conditions, a Gabor-lens was developed with an electrode system integrated into a dipole-magnet and oriented orthogonally to the beam axis.

SETUP

The dipole-Gabor-lens (DGL) consists of a H-type dipole-magnet, chosen for its superior mechanical stability and field homogeneity compared to C-type magnets, providing a homogeneous magnetic field B_y . Within the vacuum chamber,

a cylindrical copper anode ($R_A = 0.05$ m, $L = 0.1$ m) is immersed vertically, perpendicular to the beam axis and aligned parallel to the magnetic field lines, as illustrated in Figs. 1 and 2. The dual box end caps made of non-magnetizable stainless steel serve as ground electrodes. Additionally these caps enable the investigation of the SEE impact on the plasma properties. Moreover the anode wall incorporates two rectangular apertures (65 mm×25 mm) along the beam path for optical diagnostics, radial diffusion measurements, and future ion beam passage. Furthermore, shortening tubes made of magnetizable iron are mounted to transform the magnetic field distribution along the beam path, facilitating the radial investigation of particles.

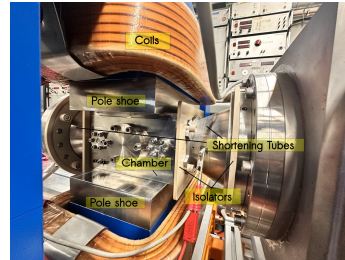


Figure 1: Experimental setup: Axial view along the beam path.

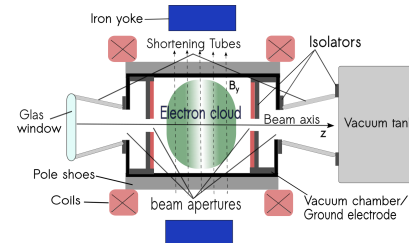


Figure 2: Schematic representation of setup illustrated in the yz -plane.

Electron Confinement

The confinement of charge carriers within the DGL is realized by the superposition of magnetic and electric fields in two directions. For a more accurate description of the dipole-Gabor-lens, the y -axis, which is parallel to the B -field lines, is defined as the symmetry axis of the cylindrical anode.

Longitudinal confinement The electric potential well, generated by the applied potential Φ_A to the anode, confines electron in y -direction, which is reduced by radial space charge potential Φ_r of confined non-neutral plasma. Under full potential depression ($\Phi_A = -\Phi_r$), the maximal axial electron density is proportional to the applied voltage [3].

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Radial confinement Radial trapping is achieved via orthogonally oriented unified dipole field B_y . The magnetic force at equilibrium state overcomes the sum of centrifugal and the radial electric field E_r of the space charge, as shown in Fig. 3. For the description of electron motion it is assumed that plasma temperature is sufficiently low, that no ions are present within the plasma lens, and that the diamagnetic field caused by the rotation of space-charge is negligible. The electron density can be mathematically expressed as [4]:

$$n_e = \frac{\epsilon_0 B_y^2}{2m_e}. \quad (1)$$

The operation function can be defined for this kind of Gabor-lens which indicates the maximum of electron density at a given anode potential and B-field. Additionally the plasma behavior are studied for higher magnetic field strengths than theoretical determined values.

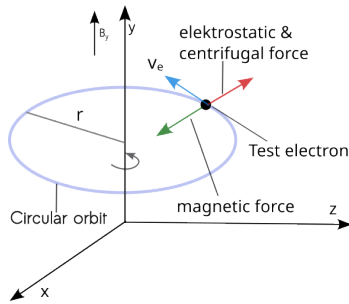


Figure 3: Graphical representation of a radial electron confinement.

NUMERICAL SIMULATIONS

Magnetic Field Distribution

The magnetic field distribution of the dipole-Gabor-lens is shown in Figs. 4 - 6. The field simulations conducted without shortening tubes were validated by experimental measurements (black dots). It illustrates the significant impact of the field-shaping modifications. Without the shortening tubes implementation, the magnetic field at the anode center extends over a wide interval from -0.15 m to 0.35 m. Through these specific structures, this range is narrowed by 0.1 m from each side along the z -axis, as shown in Fig. 4. The magnetic field strength is at the tubes regions clearly high which is reflected by the two blue peaks at both sides, as illustrated in Fig. 5. Following a substantial decrease, the field within the anode remains comparatively unified and largely corresponds to the field distribution without the presence of the shortening tubes. This indicates that the diffusing particles experience magnetic force only until they reach the chamber boundaries.

Electron Density

Numerical simulations of plasma density at various anode potentials Φ_A and their corresponding B-field values, according to the operation function, confirmed the confinement under existing experimental conditions. Despite deviations

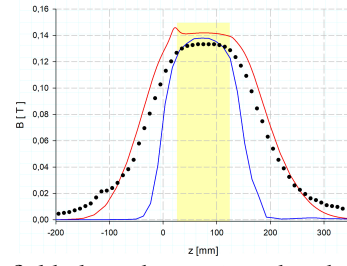


Figure 4: B-field along the z -axis and at the anode center $x = 0$.

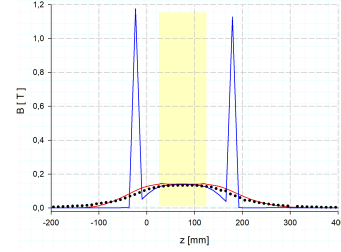


Figure 5: B-field at the right edge of anode, parallel to the z -axis.

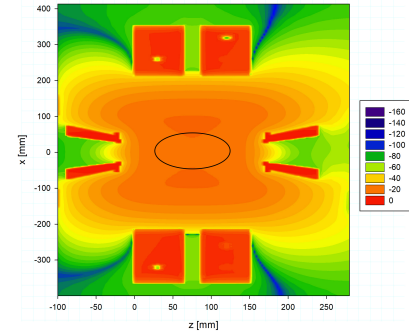


Figure 6: Two-dimensional representation of B-field distribution within the DGL on the xz -plane and at $y = 0$.

from theoretical densities based on many approximations, simulated values are acceptable for plasma formation within the lens. Furthermore, the density differences are decreasing from low to high potentials and they iterate to constant values, which refers to stable electron clouds, as shown in Fig. 7. Compared to simulations without the dual apertures, electron densities under considering these openings do not differ drastic and can be neglected.

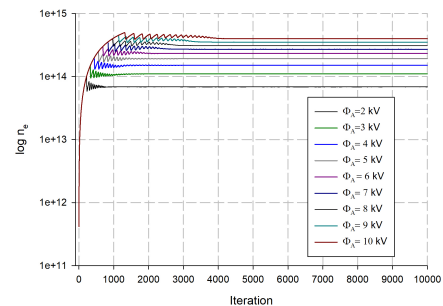


Figure 7: Simulation of max. electron density over iteration at various anode potential Φ_A .

EXPERIMENTS

Optical Diagnostics

The luminous intensity, observed inside the DGL, are generated by impact of electrons on residual gas atoms at a pressure of 1.2×10^{-5} mbar. The initial free electrons for plasma buildup are provided by cosmic background radiation and natural radioactivity. These confined charge carriers ionize further atoms, and the resulting ions are accelerated longitudinally toward the end caps. Although electron production depends primarily on ionization, SEE caused by ions on the electrode surface can not be neglected. As shown in Figs. 8 and 9, the maximum of plasma intensity is achieved at lower magnetic fields, close to field value (0.065 T), determined by the operation function for a constant potential of $\Phi_A = 2.5$ kV.

Despite the theoretical expectations, the maximum intensity is observed at a potential ($\Phi_A \approx 4.15$ kV) significantly lower than half of theoretical value ($\Phi_A \approx 9.29$ kV) predicted by the operation function. This phenomenon may be attributed to secondary electron emission; as the potential rises while the magnetic field remains constant. The increased energy of incident particles enhances the secondary electron emission yield.

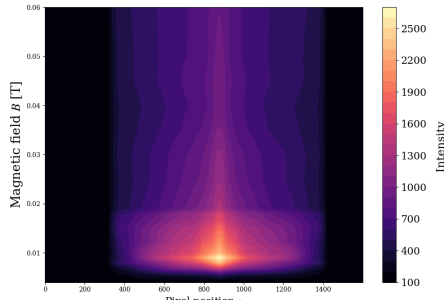


Figure 8: Luminous Intensity of non-neutral Plasma at $\Phi_A = 2500V = const.$

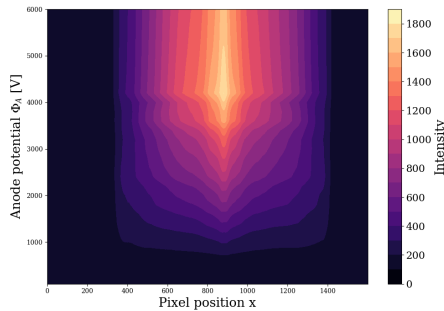


Figure 9: Luminous intensity distribution within the dipole-Gabor-Lens $B = 0.013T = const.$

Investigation of Radial Flows

The radial electron losses in the present setup can be measured by the anode current I_A and shortening tubes current I_{Tu} . Neglecting longitudinal electron diffusion, the anode determines all loss flows still exposed to the magnetic field.

However, some electrons with high kinetic energy can escape the lens through the dual apertures in the anode wall. The maximum anode current is observed at a higher B-field (from 8 mT to 11 mT) than the theoretical value of 8 mT, as shown in Fig. 10.

While the tube current exhibits similar behavior, its value is three orders of magnitude lower than the anode diffusion flow, as illustrated in Fig. 11. The anode currents go to an instable state at a very specific value of magnetic field for various potentials close to the operation function. This can be attributed to lower confinement potential at the top of potential well. At this level, the electron trap reaches its maximum density, allowing negatively charged particle to escape the cloud more easily than at a lower density.

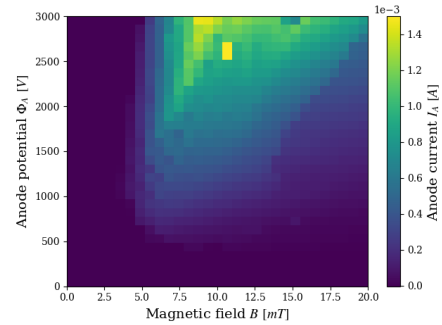


Figure 10: Two-dimensional representation of anode current I_A and magnetic field B .

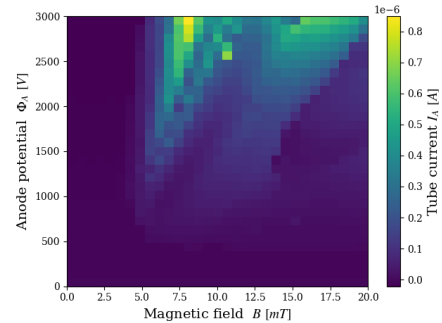


Figure 11: Two-dimensional representation of shortening tube current I_{Tu} and magnetic field B .

CONCLUSION

The development of the dipole-Gabor-lens demonstrated the formation of electron clouds in transverse magnetic fields with metallic end caps. The radial current measurements suggest very high peaks near the operation function at high anode potentials, which can be attributed to high secondary electron emission. However, stable confinement is observed at higher magnetic field strengths. These results show that the non-neutral Plasma can be established within high-field dipole magnets. By effectively shaping the field and utilizing specialized diagnostics ports, this setup provides a robust platform for investigating electron cloud effects critical for high-intensity accelerators.

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