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SIMULATION STUDY ON AN ELECTRON CLOUD AND PLASMA WAVES CONFINED IN GL2000 DEVICE

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Abstract

GL2000 Gabor-lens (GL) is a 2 m long device constructed and successfully operated at Goethe University. The confined electron column is much longer compared to previous constructed lenses and offers unique opportunity for investigation of electron cloud dynamics. Especially, kind of fingertip stopband structures were precisely measured in production diagram (operation function) in the year 2023. This fully reproducible behaviour and dependence on a rest gas pressure left unexplained. For this purpose, a large scale multi-particles simulation PIC(particle-in-cell)-code was written in C++ and implemented on FUCHS-Cluster of the Goethe University. The main objective is to find an optimal operation parameter set for a stable operation of GLs, which is crucial for high energy hadron beam transport and focusing. Further topic will be investigation of possible longitudinal handling of bunched ion beams. The first simulation result will be presented and discussed.

INTRODUCTION

Gabor-lens (GL) [1, 2] is a cylindrical trap designed to produce and confine rotating electron clouds and to apply such a configuration for focusing of hadron beams. Many types of various GL devices were already built, developed and studied at Goethe University over more than 20 years. It has to be differentiated clearly between GL and experiments with Penning-Malmberg traps [3] due to present steady electron production process, cross-field electron transport, interaction with walls, longitudinal residual gas ion extraction and balance between production and losses.

New high precision measurements of the operation map diagram (anode current I_A as a function of magnetic field B and anode potential ϕ) with enhanced vacuum level feedback control were fulfilled for GL9000 [4, 5] and GL2000 devices recently. Results showed an existence of reproducible stable curves of increased and damped confinement as seen in Fig. 1 and Fig. 2. Both devices are representative in respect to the anode length (L_A = 0.335 m for GL9000 - l, L_A = 2 m for GL2000) and therefore confined length of electron column. Anode radius R_A is slightly the same in both cases. It was important to proof the existence of discrete curves in the operation diagram for two different devices and to collect data for further examination and comparison.

A first explanation suggests an occurrence of electrostatic plasma waves in GL such as Trivelpiece-Gould (TG waves) [6], Bernstein [7], Diocotron [8] at discrete external parameter conditions. These kind of waves could be excited naturally from thermal motion of electrons at certain resonances and influence electron production process and losses either.

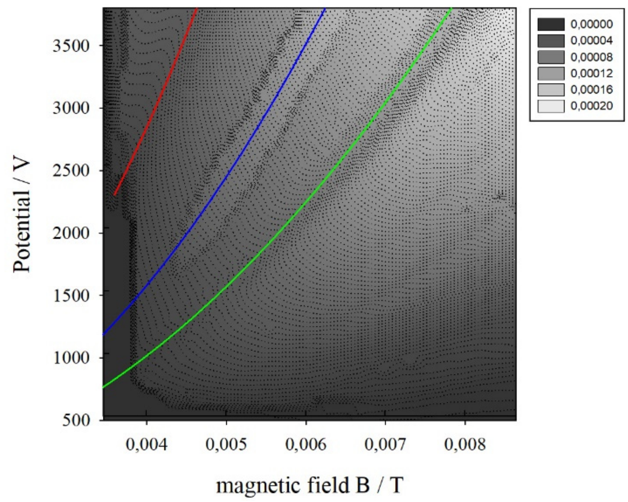

Figure 1: Measured anode current I_A intensity map dependent on magnetic field B and anode potential is shown for GL9000 device [5]. Anode current value is proportional to the electron production efficiency and gray-scaling is given in Ampere. Red-curve gives constant ratio n/n_B=1.1, blue n/n_B=0.605, green n/n_B=0.385 under assumption of homogenous electron cloud. Whole measurement was performed at constant residual He gas pressure p=6.6e-4 Pa.

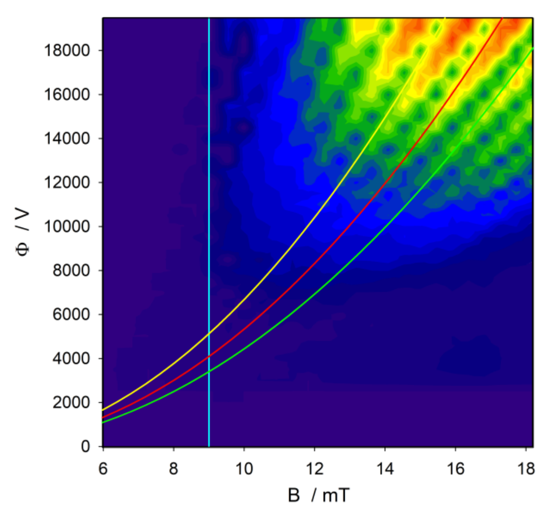

Figure 2: Operation map diagram for GL2000 device measured at p=7e-4 Pa He residual gas vacuum level [2].

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THEORY

Theory of electrostatic plasma waves in non-neutral plasma confined inside of cylindrical geometry was developed over past decades. General theory with basic dispersion relation could be found for example in Davidson [9] Eq. (67). In a first investigation, we applied an assumption of full filled GL with pure homogenous electron cloud rotating with Ω_- frequency, which corresponds to the ExB drift motion in low density limit. The solution of dispersion relation for the wave with frequency ω could be then given in the form:

$$\omega = m_\theta \Omega_- \pm \Omega_c \sqrt{1-\frac{s_e}{2}} \sqrt{1 \pm \sqrt{1 - \frac{2k_z^2}{k^2} \frac{s_e(1-s_e)}{\left(1-\frac{s_e}{2}\right)^2}}} \quad (1)$$

The parameters are defined as follows:

$$s_e = \frac{n}{n_B}, n_B = \frac{\varepsilon_0 B^2}{2m_e}, k_z = \frac{m_z \pi}{L_p}, k_r = \frac{j_{m_\theta m_r}}{R_A},$$

n- electron density,
(m_r, m_θ, m_z)- mode numbers,
$j_{m_\theta m_r}$- Bessel-function zero´s,
L_p - length of a plasma column,
$k^2 = k_r^2 + k_z^2$,
$\Omega_\pm = \frac{\Omega_c}{2}\left(1 \pm \sqrt{1-s_e}\right),\ \Omega_c = \frac{eB}{m_e}.$

We concentrated our studies on lower hybrid branch (we assume minus sign "-" in second ± term in Eq. (1)), which is also known as an attractive branch for rf heating of fusion plasmas. An example of mode spectrum dependent on self-field parameter s_e is depicted in Fig. 3. The parameter set was chosen typically for GL9000 device.

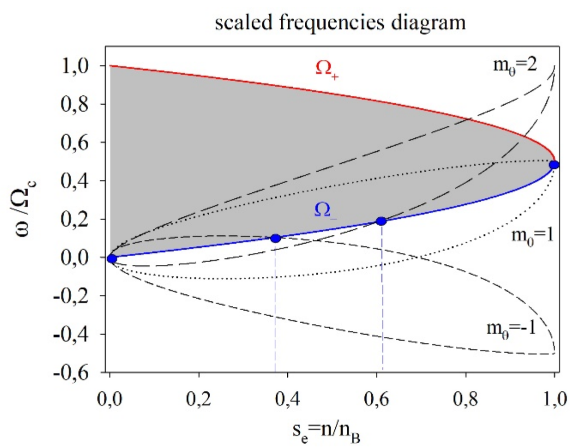

Figure 3: Scaled frequency of lower hybrid modes m_θ=(2,1,-1), m_r=1, m_z=1 dependent on s_e parameter. Length of the plasma L_p=0.19 m, anode radius R_A=0.085 m and temperature correction due to the Debye length λ_D=0.01 m are considered.

We depicted basic frequencies $\Omega_\pm$ belonging to bi-harmonic particle motion and shaded area of a stable radial confinement also. Now, some crossing points(blue points, $\omega/\Omega_c=\Omega_-$) can be identified, where plasma wave frequency is coupled with the particles natural motion, or vice versa, plasma wave could be excited resonant from particle motion. Two crossing points $s_e=n/n_B=0.605$, and $n/n_B=0.385$ are also possible candidates for explanation of effects seen on Fig. 1.

SIMULATION

In order to evaluate confinement stability and filling process in GL2000 device, a large scale parallel multi-particles simulation PIC(particle-in-cell)-code *gab_lens_m3* was written in C++ and implemented on FUCHS-Cluster [10] of the Goethe University. Symplectic algorithm for particle push and global iteration BiCGSTAB (Bi-Conjugate Gradient Stabilised) method for fields calculation on cylindrical numerical mesh were implemented. Typically, up to 10^8 macro-particles were simulated on 35 processors in parallel.

The particles, which are lost transversally or longitudinally on electrodes, are randomly redistributed back in GL volume (production process), so global confined charge amount is a constant and chosen as a start parameter. Electron distribution, initial homogenous, is evolving till it reaches balance between losses, production and distribution function. Static anode potential ϕ_A =10 kV and magnetic field B = 9-18 mT were used as starting condition typically. Dependent on starting condition, various type of plasma waves can be excited. An example is shown in Fig. 4.

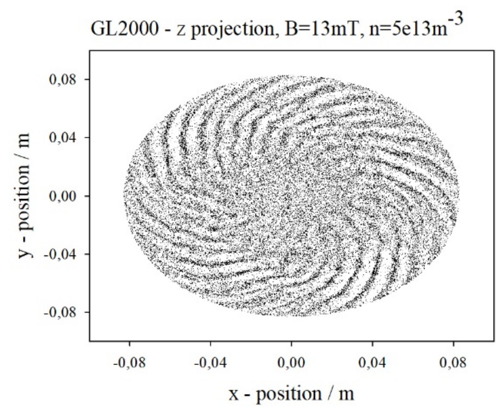

Figure 4: Transversal profile of simulated electron column in time step τ=1.27 µs. Electrostatic plasma wave with poloidal mode number m_θ=26 at self-field parameter s_e=0.073 can be identified.

During evolution in time, electron distribution function is changing and adapting to the external fields. The local electron density in the middle of confinement is slightly growing in 10% interval and there is a change in se parameter respectively. Various waves are self-excited and some of them are damped later. Mode numbers (mr, mθ, mz) can be identified with help of transversal density profiles (Fig. 4), longitudinal macro-particles momentum p_z (Fig. 5) and field information E_θ (Fig. 6).

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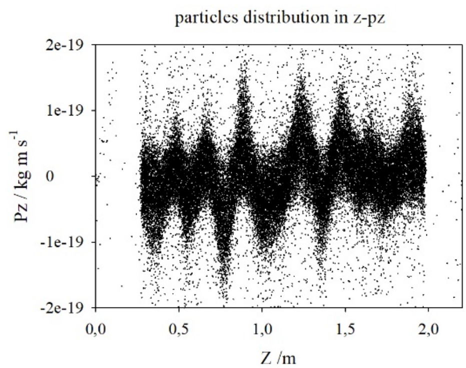

Figure 5: The longitudinal momentum p_z distribution along z-Axis at the same time step τ=1.27 µs as in Fig. 4. Mixed wave modes around m_z=8 can be identified. Similar information is obtained from on-axis potential. Dipole mode m_z=1 can be detected as well (centre of gravity of the particle distribution on both boundaries in z has opposite sign).

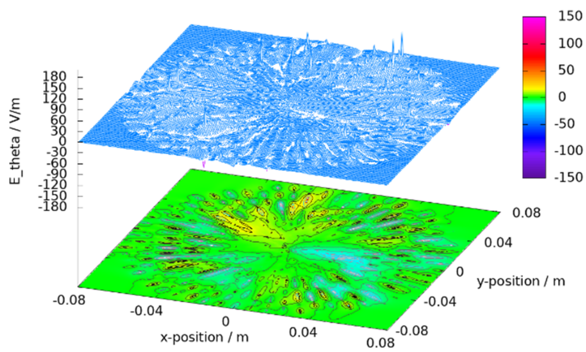

Figure 6: The transversal distribution of the electric field E_θ in the middle of the GL2000. Islands of higher and lower field levels can be identified in comparison with zero level (green) for homogenous distribution. This field component can enhance transversal transport and hence also losses.

Particle loss information on electrodes (longitudinally, anode, ground) are collected in every time step (Fig. 7). For an example, longitudinal electron losses show oscillatory behaviour and asymptotic approach to the equilibrium in approximately 1 µs. Similar behaviour is observed on anode and ground electrode too. Current signal is analysed through FFT (Fast Fourier Transformation) and corresponding frequency spectrum is calculated. Two main frequencies corresponding to Ω_+ and Ω_- depending on starting condition can be observed.

Investigation is still ongoing, simulation with one parameter set requires about 30 days. Nonetheless, self-excited plasma waves in GL seem real and higher order modes are excited in systems with longer anode. Reversely, higher order plasma waves can be used for confinement enhancement or plasma heating.

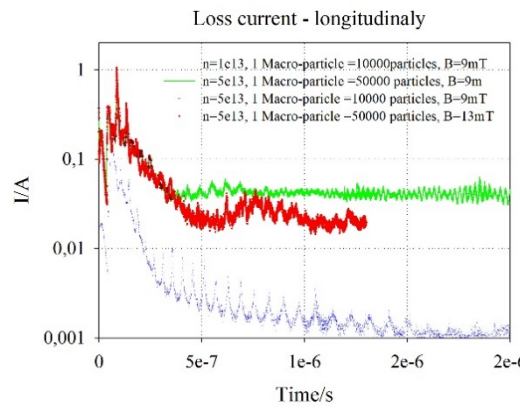

Figure 7: Detected electron loss current longitudinally. Plasma wave frequencies could be identified.

CONCLUSION

A two-meter-long electron column was investigated to identify different sources of instabilities. Experimental and numerical results show possible excitation of plasma waves and therefore further experiments are in preparation with the aim of direct wave detection.

The design of GL2000 was chosen to produce and confine cold electron plasmas compared to other Gabor lenses built to date. This is a result of the ratio of the lens volume with a significant electric field compared to the field free region. On the other hand, a two-meter-long non-neutral plasma column can be treated as a portion of a charged particle beam [11] immersed in a two-meter-long solenoid in our case. Therefore, it is important to compare the properties and instabilities with an experiment with co-moving electron column used in e-lenses [12].

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