PERIODIC INTERACTIONS OF ION BEAMS WITH STATIC OR DYNAMIC ELECTRON PLASMAS

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Abstract

Production, confinement and control of a long static electron column in Gabor-lens device GL2000 were discussed and presented in previous IPAC conferences. Reachable electron densities of about n ~ $2.5 \cdot 10^{14}\mathrm{m}^{-3}$ and single pass ion beam transport with focusing in MeV range were demonstrated in 2025. The present study investigates the possible use of electron plasmas in periodic systems such as synchrotrons, which could be integrated locally to compensate the space charge. Two concepts for electron confinements are considered in comparison. One is the electron lens concept, a dynamic electron plasma (beam) generated by a source and the other one is the Gabor-lens, a static electron plasma achieved by a combination of transversal electric and longitudinal magnetic fields. Challenges in application, main technical features and parameters will be discussed. Studies have shown that it can be assumed, that both systems are promising for the use in periodic accelerator structures to compensate the ion's space charge in the interaction zone and thereby improve the acceptance and increase the critical space charge limit for an ion beam.

INTRODUCTION OF BOTH EXPERIMENTAL SETUPS

Gabor-Lens

The Gabor-lens device GL2000 provides a stable confinement of an electron plasma with a column length of 2 m [1]. Electron densities in the order of $10^{14}\,\mathrm{m}^{-3}$ are achieved. This was proven with spectrometer measurements [2]. Confinement is realized by a static axial magnetic field in combination with an electric field applied between the cylindrical ground electrodes and the anode. The potential inside the lens is positive, so that the ions are accelerated from the lens volume while the electrons remain confined. GL2000 can be implemented in beam transfer lines and particle accelerators for beam focusing, space-charge compensation and increasing luminosities on targets of respective experiments.

A propagating ion beam is overlapped with the electron ensemble. GL2000 is adjusted to its operation function when implemented in beam lines. In this operating mode, the density distribution is homogeneous. In addition, areas in which dynamic processes such as waves and instabilities occur will be investigated and could be used for hadron beam handling or collimation [3, 4]. GL2000s focusing properties have been demonstrated in experiments with with He^{1+}, Xe^{1+} and proton beams in an energy range from 500 keV to 2 MeV [5, 6].

Electron Lens

The electron lens (E-lens) is an alternative concept for beam focusing and space-charge compensation for circular accelerators, see Refs. [7–10]. It consists of an electron source, a beam transport section with two solenoid magnets, and a collector integrated within Helmholtz coils. An electron beam with a density on the order of $10^{14}\,\mathrm{m}^{-3}$ is extracted from the hot cathode surface of electron source TE², with an energy of 35 keV and a beam current of 10 A to provide a dynamic electron ensemble for focusing and space-charge compensation.

In the current project state, the electron beam is extracted at an electron density of ~$3.8 \cdot 10^{12}\,\mathrm{m}^{-3}$. In contrast to the Gabor-lens, where electrons are statically confined, the electrons in the E-lens form a dynamic plasma co-moving with an ion beam. The two concepts are compared in table 1 below.

Table 1: Dimensions for the Two Systems

Type	Gabor lens	E-lens
n_e	$10^{14}\,\mathrm{m}^{-3}$	$10^{14}\,\mathrm{m}^{-3}$
current status of n_e	$10^{14}\,\mathrm{m}^{-3}$	$10^{12}\,\mathrm{m}^{-3}$
B-field	18 mT	>0.1 T
Voltage Anode/Extraction	30 kV	35 kV
Dissipation power	300 W	525 kW
Production	cold cathode	hot cathode
Collector	no	yes
Temperature estimation	100 eV-10 keV	<10 eV

Figure 1 shows the electron plasma in both systems. On the left picture the dynamic electron ensemble extracted from TE² source is shown, on the right side the stable confined static electron plasma in GL2000 is presented.

Open Questions and Challenges

- B-field: A high magnetic field relative to the total density (Brillouin flow limit; see [11]) leads to instabilities in the electron beam (Diocotron; see [12]). The extent of the instabilities depends on the length of the interaction zone.
- Self B-field: Investigating the influence of the magnetic self field on particle confinement.
- Dissipation Power: To reduce the dissipation power generated in the electron beam, a concept for collecting

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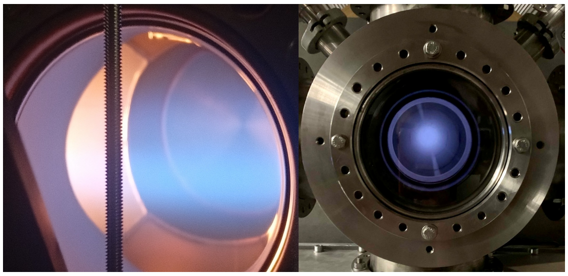

Figure 1: Left: Dynamic electron plasma extracted from TE² source. The plasma was made visible by the controlled inflow of residual gas. Right: Confined electron plasma in Gabor-lens GL2000. Visible is the residual-gas luminescence of argon during electron cloud confinement.

the beam and recovering its energy is necessary and being developed.

- Collective behavior of electron ensemble: Depending on the plasma frequency of the ensemble, the plasma may respond to a disturbance, such as a propagating ion beam.

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \tag{1}$$

$$\Delta t = \frac{\Delta l}{c},\ t_{transit} > \frac{2\pi}{\omega_{pe}} \tag{2}$$

A distinction must be made between two cases: The reaction time is longer than the transit time of the ion beam and therefore space charge compensation of the beam or a reaction time that is shorter than the transit time of the beam in which there is a collective response of the electrons due to the disturbance caused by ion beam. This should be investigated before the lens can be used in this regime.

- Dumping and excitation of plasma waves in electron columns: The coupling factor represents the relation between potential energy W_{pot} and kinetic energy W_{kin} of a plasma. For $>$ 1 the plasma is non-ideal, strongly coupled.

$$\Gamma = \frac{W_{pot}}{W_{kin}} \tag{3}$$

The behavior of these strongly coupled plasmas, characterized by high potential energies and low temperatures, is to be investigated in the future.

Subsequently, simulations are presented to demonstrate space-charge compensation by implementing a static electron plasma into the SIS18 synchrotron at GSI.

ELECTRON LENS EXTRACTION EXPERIMENTS

Heat-Up of the Cathode

The TE² electron source has already been described in detail in previous papers; see [1]. A heated tungsten filament

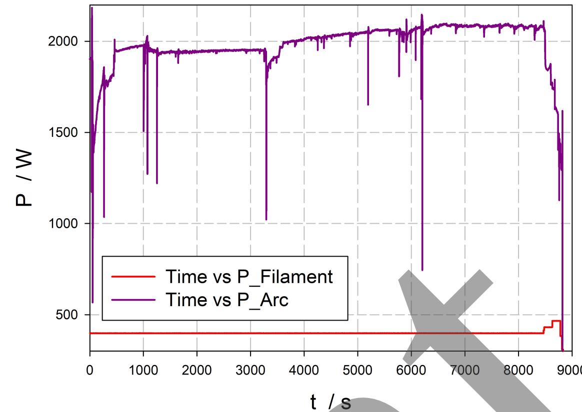

Figure 2: Power input during plasmastream. The additional power input is, on average, 1573 W higher than the power supplied by the filament power alone.

is used to initiate an arc discharge in the plasma chamber, between the filament and the cathode. The generated plasma consequently heats the cathode; see [13]. The heating power, and thus the cathode temperature, can be regulated via the power of the arc discharge. A control system was developed to maintain the temperature at the required value. Recent experiments have revealed a new behavior of the heating mechanism in the plasma chamber. During the experimental series aimed at achieving the minimum target field strength of 0.1 T in the magnets, there was evidence that the state of the plasma changed from conventional arc-discharge to a self-sustained plasmastream with increasing magnetic field $>$ 35 mT.

These can be observed by the additional power input on the filament's surface as shown in Fig. 2. The red line shows the power supplied by the filament. The purple line shows the power actually generated in the arc power supply. The filament current can be reduced during plasmastream mode, which results in a more economical way of operation. The measured power input comes from the plasma itself. Charged particles sputter against the filament more than in the conventional arc-discharge mode. The power in the plasma can therefore only be controlled by the residual gas pressure, which determines the ionization rate of neutral particles. The type of gas itself can also have a decisive influence on performance.

Extraction Experiments

Initial extraction experiments have been carried out. For the first time, an electron beam was successfully extracted, transported through the interaction region, and collected at the collector. The main objective of the first series of experiments was to record grid operation characteristics at a stable cathode temperature and to adjust the magnetic fields to the target field strength. Figure 3 shows the recording of a grid characteristic at grid voltages ranging from -800 V to -300 V and an extraction voltage of -1 kV. The temperature is set to 1600 °C. The field strengths of the magnets are 18 mT.

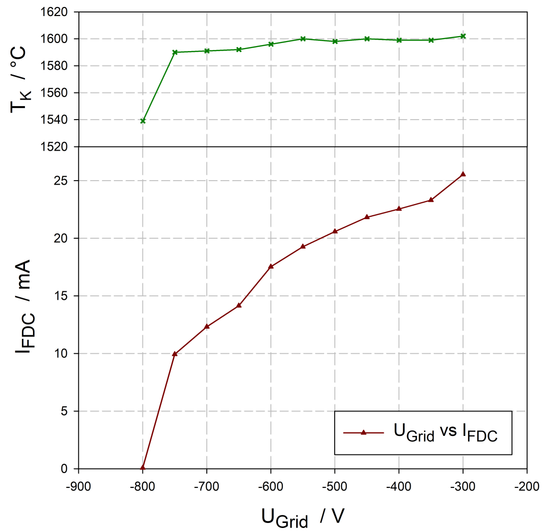

Figure 3: Electron beam extraction at ~1600 °C, both solenoids and Helmholtz coils are set to B = 18 mT. With the grid at -300 V and an acceleration voltage of -1 kV a beam current of 25.7 mA is measured.

At a grid voltage of -300 V, a maximum current of 25.7 mA was measured in the collector's Faraday cup.

BEAM TRANSPORT SIMULATIONS

The bare point of an ion beam, as defined in synchrotrons to describe optimal operation with minimal losses, is expanded by a certain area as a result of natural chromaticity. In addition, the beam spreads out due to its space charge, which further widens and shifts the bare point. The consequence is the intersection of resonance lines, which leads to losses and thus degrades beam quality.

The implementation of electron lenses in synchrotron accelerators e.g. the SIS18 is planned to minimize space charge effects and therefore the tune shift by providing a counter acting force. Assuming that the electrons completely compensate the space charge of the ions, a first approximation of the tune shift can be calculated with Eq. 4.

$$\Delta Q_{el,y,x} = \beta_{y,x} \cdot L \cdot \frac{Z}{A}\frac{r_0}{2}\frac{1}{\beta_i^2\gamma_i} \cdot \frac{I_e}{\pi R^2 e \beta_e c}\left[1 \pm \beta_e\beta_i\right] \quad (4)$$

Transforming the equation using the definition of electron density n_e (see Eq. 5), the tune shift can be rewritten as shown in Eq. 6.

$$n_e = \frac{I_e}{\pi R^2}\frac{1}{e v_e} = \frac{I_e}{\pi R^2}\frac{1}{e}\frac{1}{\beta_e c} \quad (5)$$

$$\Delta Q_{el,y,x} = \beta_{y,x} \cdot L \cdot \frac{Z}{A}\frac{r_0}{2}\frac{1}{\beta_i^2\gamma_i} \cdot n_e\left[1 \pm \beta_e\beta_i\right] \quad (6)$$

In this process, the space charge of the ions is reduced by the superimposed negative charge of the electrons. Figure 4 shows the spread bare point because of mainly space charge effects. The tune diagram is calculated for SIS18 synchrotron accelerator lattice at GSI with tune $Q_x = 4.282$ and $Q_y = 3.302$. The simulated ion species is a coasting beam of U^{28+} with a current of 18 emA. The simulation shows the status after 1000 turns which correspond to 4.6 ms. Figure 5 shows the resulting tune diagram for implemented electron ensembles in the SIS18 lattice. The simulation campaign is carried out with two lenses each with a length of 1.8 m and an aperture of 75 mm in every of the 12 sectors.
The beam envelopes had been calculated by TraceWin, FFT was done with 2^N respectively 2^{22} particles to gain information about the tune.

In comparison, simulated tune shift and spread due to natural chromaticity closely match the calculated values from Eq. 6.

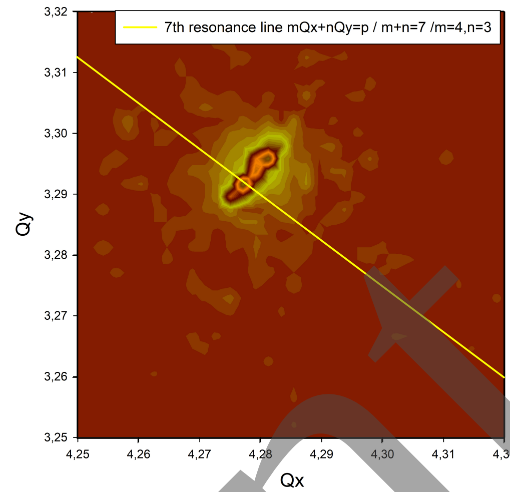

Figure 4: Tune diagram for an Uranium^{28+} coasting beam at 18 emA. Tune spread caused by space charge effects. The tune spread is increasing and the tune is also shifted to $Q_x = 4.279$ and $Q_y = 3.293$.

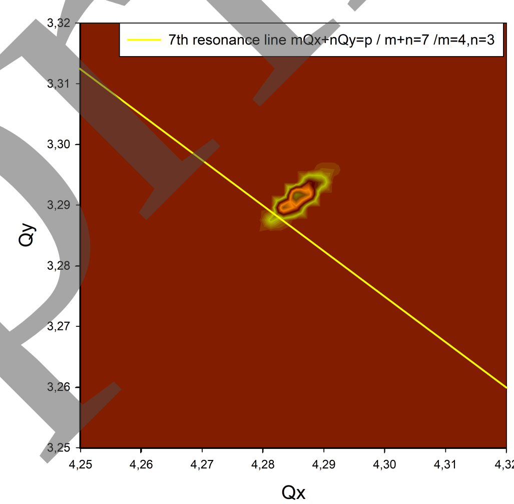

Figure 5: Space charge compensation with electron ensembles implemented, Uranium^{28+} coasting beam at 18 emA.

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