First Experimental Studies of a Gabor-Plasma-Lens in Frankfurt*

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Abstract

The non-neutral plasma of a Gabor-Plasma-Lens, mainly formed by electrons and trapped in a crossed electromagnetic field configuration, combines strong axissymmetric electrostatic focusing and preservation of space charge compensation of positive ion beams. This type of lens is a promising candidate for the transport of high intensity and low energy ion beams and the injection into an RFQ for example. A compact lens has been built and tested. The basic theory of the lens is presented together with experimental results of the plasma diagnostics and first beam tests.

Introduction

For intense low energy ion beams the required focusing strength is mainly a function of the perveance if particle loss should be avoided. One way to reduce the perveance of a positive ion beam without reduction of the beam current is the space charge compensation by electrons.

A problem of high interest is the influence of the beamline on the space charge compensation. Electrostatic focusing elements such as Einzellenses or quadrupoles prevent compensation by distraction of the electrons. In contrast magnetic elements (solenoids, quadrupoles, dipols) preserve or even enhance space charge compensation but they suffer from the weak focusing for low velocity and high mass ion beams.

The concept of the Gabor-Plasma-Lens allows transport without disturbance of the compensation outside the lens volume combined with strong axisymmetric electrostatic focusing at low power consumption and acceptable costs for construction and use.

Lens Theory

Basic theory

Figure 1 shows the concept originally suggested by Gabor [1]. The enclosed electrons are trapped radially by the solenoidal magnetic field and axially by the electrostatic field. The path of an electron inside the lens is given by the total acting force composed of the external electric and magnetic lens forces and the internal electric forces produced by the ion beam and the trapped electrons within the lens region.

The radial electron loss is given by the electrostatic force resulting from the external field plus the space charge, trying to accelerate the electrons radially, and the Lorentzforce acting against it. Neglecting the external electric field (which could be taken into account for a given structure) gives the following analytically solvable equation :

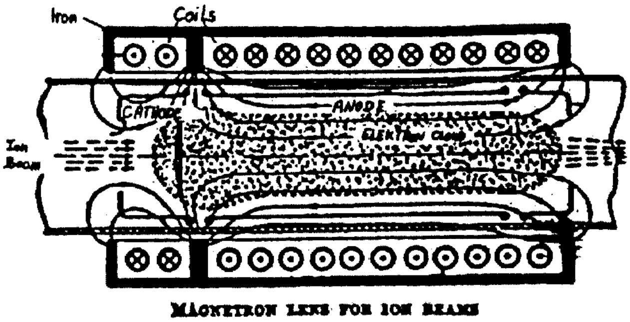

Fig. 1 Original suggestion by D. Gabor

$$\vec{v} \times \vec{B} = \frac{1}{\varepsilon_0 * r} \int_0^r \rho_e(r') * r' \, dr \qquad (1)$$

Where $\vec{v} \times \vec{B}$ is the Lorentzforce divided by e, ρ_e is the electron density and r is the radial distance from the lens axis. Thus assuming a homogeneous filling of the lens, the electron density is a function of the magnetic field :

$$\rho_e = \frac{e * \varepsilon_0 * B_z^2}{2 * m_e} \qquad (2)$$

With B_z is the z component of the magnetic field, e is the electron charge and m_e is the electron mass.In longitudinal direction no magnetic force is acting and therefore the potential depression in the lens by the external electric field has to be filled with electrons before an emerging electron can escape. This leads to an axial trapping condition which should be fulfilled for optimum performance [6]were U_L is the depth of the potential depression, z the integration path along the

$$U_L = \int_0^z \frac{1}{\varepsilon_0 * z'} \int_0^{z'} \rho_e(z'') * z'' \, dz'' \, dz' \qquad (3)$$

lens axis and ρ_e the electron density within the lens. Assuming an homogeneous magnetic field and electron production, the resulting electron density is homogeneous too. This leads to a linear radial dependence of the resulting force needed for aberration free focusing.

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Filling mechanisms

The mechanisms filling the lens with electrons are of great interest not only for the lens construction but also for the physics of the lens. To fill the lens with electrons three mechanisms have to be taken into account:

1.) Electron production by collisions of the beam ions with the residual gas. This mechanism always takes place and will usually produce electrons near the axis. The time needed for filling the lens is mainly a function of the residual gas pressure.

2.) The production of electrons by a hot cathode. This is the way originally suggested by D.Gabor. It delivers a high amount of electrons, but it is not sure that the electrons reach the central area of the lens.

3.) The production of electrons by a gas discharge is very efficient (depending on the pressure) . One problem with gas discharges is that there seems to be no way to control the production density in different regions inside the lens.

Numerical simulations have shown, that electrons move from regions with an electron density higher than the radial limit for trapping into outer regions with lower density. The result of this behavior is an homogenisation of a non homogeneous electron density distribution .

Discharge Experiments

The lens built in Frankfurt (Fig. 2) is designed for an electron production by the beam itself and by gas discharge. The first experiments studied the behavior of the gas disscharge for different external fields, different pressure and gases.

In the pressure range used (10^{-4} - 10^{-7} hPa) normally no ignition occurs without magnetic field (Paschen curve). But only about 50 Gauss in the center of the solenoidal field configuration are necessary to ignite the discharge.

Typical operating parameters are: Anode voltage between 1 and 5 kV, magnetic field strength between 50 and 300 Gauss and a resulting discharge current of some mA. From the measurements at different pressures and gases (He,Ar,N) we can make the following conclusions:

- the type of gas does not change the discharge behavior significantly

- at low pressure (up to 10^{-6} hPa) the discharge current is approximately proportional to $U_L^{3/2}$

- in the range of 10^{-4} to 10^{-5} hPa the dependence of the discharge current on voltage and magnetic field shows maxima, corresponding to optimum values of mean free paths and electron accelerating voltage (fig. 3).

- at pressures higher than $4 \cdot 10^{-4}$ hPa the discharge current increases rapidly.

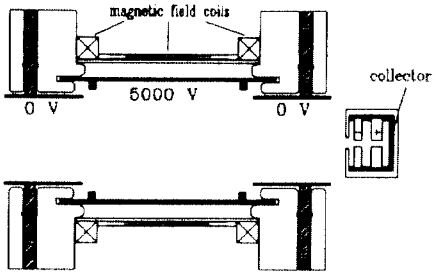

Fig.2 Frankfurt Gabor-Plasma-Lens. Schematic cutthrough with the retarding field spectrometer mounted axially

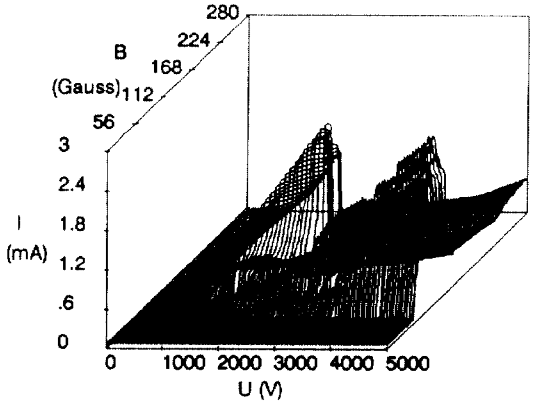

Fig. 3 Discharge current as a function of lens voltage and magnetic field with Helium as residual gas and a pressure of $p = 5 \cdot 10^{-5}$ hPa

Measurements of the Potential Depression

Information about the electric potential distribution in the lens is important for the operation of such a device. We performed measurements with an on axis energy spectrometer with the gas discharge on (without an ion beam). The investigated lens acts as a PIG ion source emitting approximately 100 μA . The ion energy contains information about the potential distribution and corresponding filling rates. We measured the ion energy with an retarding field spectrometer axially mounted at one end of the lens (Fig.2).

Figure 4 shows a typical differential energy spectrum for residual gas ions leaving the lens in longitudinal direction. Assuming that the maximum detected energy is gained by ions created near the axis, the corresponding potential value gives a lower limit for the degree of lens filling (in the presented example Fig. 4 about 40 %). These measurements show that the energy distribution of the detected ions is a function of the magnetic field and the type of discharge. In the case of the "high" pressure discharge no net space charge occured (all detected ions had about the energy corresponding to anode potential).

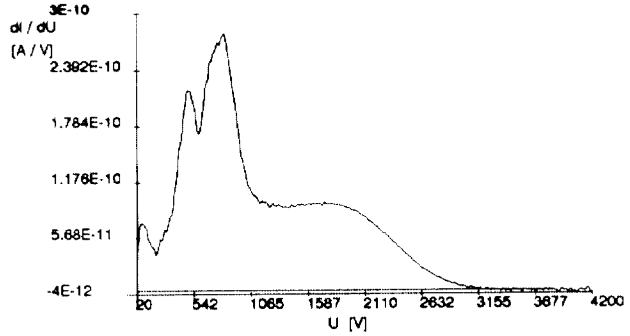

Fig. 4 Energy distribution of the escaping residual gas ions, $B = 180$ Gauss, $U_L = 5$ kV, $p = 5*10^{-6}$ hPa

Experiments with an ion beam

Measurements of the focusing properties of Gabor-Plasma-Lenses have been performed by other groups [2,3,4,5]and have shown beam aberrations and severe emittance growth due to incomplete and inhomogeneous electron filling.

To investigate the focusing properties of our lens in a beam experiment, we have set up a short beamline consisting of a duoplasmatron ion source, an accel/decel extraction system, the plasma lens and an emittance measuring device at the end of the line.

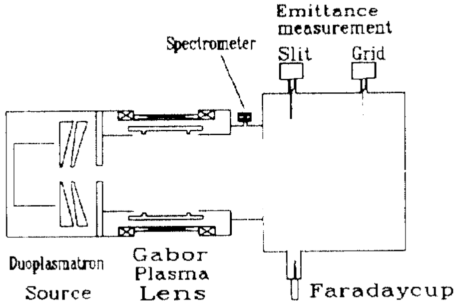

Fig. 5 Experimental setup for ion beam experiments

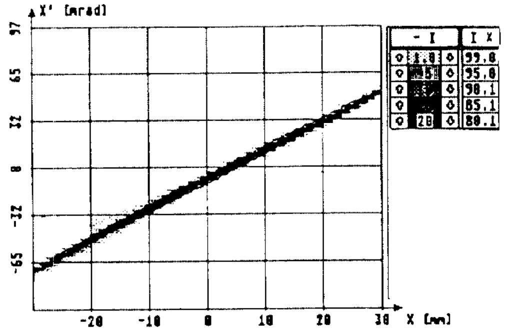

Fig. 6 Emittance pattern downstrem the lens with the discharge off.

For a 10 keV, 800 μA Helium beam and the lens off we measured a normalized emittance of app. 0.19 πmm*mrad. Without discharge, but with either a magnetic field of 300 Gauss or an anode voltage of 5 kV the emittance is only slightly altered. For an on axis magnetic field of 280 Gauss, an anode voltage of 1.5 kV and a pressure of $1*10^{-5}$ hPa we were able to focus the beam with a focal length of 20 cm (Fig.7) with negliable emittance growth. From the theoretical point of view however the focal length should be 5 cm. This indicates that the lens was filled only to appr. 25 % of the radial trapping limit.

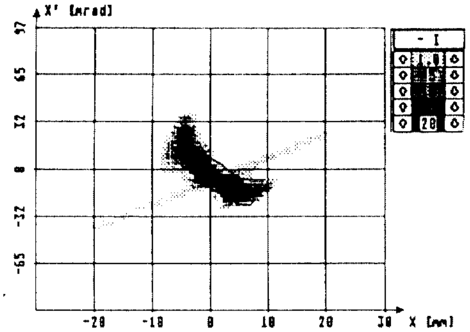

*Fig. 7 Emittance pattern downstream the lens with discharge on. The emittance is about .17 πmm*mrad, the neutral beam is not affected by the lens.*

Other experiments with similar conditions showed a wide spectrum of behavior. Sometimes emittance growth by a factor of 4 occured.

Using Ar^+ instead of Helium the focusing strength of the lens decreased by a factor of 3. Low escaping rates of the heavy Ar^+ residual gas ions seem to be the reason for that.

The space charge compensation of the beam behind the lens was at the same level as in the case of the lens off. It was measured with a radially mounted retarding field spectrometer.

Conclusions

Beam measurements have shown that the Gabor-Plasma-Lens is capable of focusing a low energy ion beam. Aberrations and emittance growth in some operational modes show that design and operation of the lens have to be adjusted very carefully to a given problem. Besides the production mechanisms and the problems of homogeneous lens filling there are several more problems not taken into account yet. In a more advanced model the diffusion of electrons over magnetic fieldlines has to be taken into account as well as the disturbance of the lens electrons by the beam itself and the influence of the non ideal external fields.Theoretical and experimental work still has to be done to leave the stage of an experimental device.

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