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Gabor Lens Focusing of a Negative Ion Beam †

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Abstract

Gabor or plasma lenses have previously been used to focus intense beams of positive ions at energies from 10 keV to 5 MeV. It is the large electrostatic field of the non-neutral plasma in the Gabor lens which is responsible for the focusing. Focusing an ion beam with a given sign of charge in a Gabor lens requires a non-neutral plasma with the opposite sign of charge as the beam. A Gabor lens constructed at Fermilab has been used to focus a 30 keV proton beam with good optical quality. We discuss studies of the action of a Gabor lens on a beam of negative ions. A Gabor lens has been considered for matching an H⁻ beam into an RFQ in the redesign of the low energy section of the Fermilab linac.

Introduction

In the transport of space-charge dominated beams it is desirable to limit emittance growth due to dilution as much as possible. Space-charge driven emittance growth is what makes intense beams interesting as well as challenging, both experimentally and theoretically. One way to avoid emittance growth in low-energy beam transport (LEBT) is to neutralize the space-charge of the beam. If we allow the beam to pass through a non-neutral plasma which has a net charge with the opposite sign of the beam charge, and charge density much larger than the beam charge density the beam will be neutralized. In order to ensure neutralization of the beam space-charge the plasma density should be at least an order of magnitude larger than the beam density. This will also make the beam a small perturbation on the motion of the plasma.

The governing time scale for neutralization is the plasma period. For an electron plasma dense enough to neutralize a typical proton beam on the Fermilab ion-source test stand (plasma density > $10^9 cm^{-3}$), the plasma period is less than 4 ns. We have observed that the neutralization time for a proton beam in passing through a non-neutral electron plasma of this density is less than $1\mu s$. The beam density on the test stand is typically $10^8 cm^{-3}$. In order to focus and neutralize an H⁻ beam a pure ion plasma is required. For a pure ion plasma the plasma period is longer by a factor of $\sqrt{m_i/m_e}$ than it is for an electron plasma. One thus expects a longer neutralization time for a negative ion beam entering a pure positive ion plasma.

A Gabor[1,2] lens is a containment device for a non-neutral plasma column. Fig. 1 is a schematic of the lens. The other distinguishing characteristic of the lens besides non-neutrality is the azimuthal symmetry. Radial confinement is provided by a solenoidal magnetic field, axial confinement by the electric field of one or more electrodes. Brillouin[3] showed that the maximum stable charge

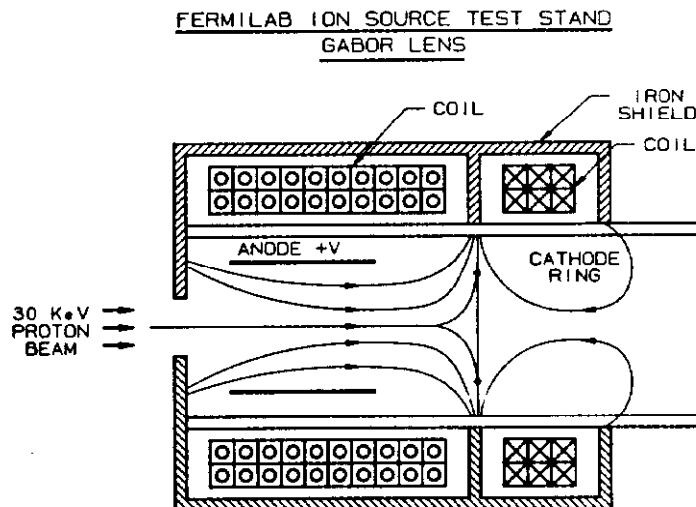FERMILAB ION SOURCE TEST STAND
GABOR LENS

Figure 1: Gabor lens with magnetic field cusp. The cusp adds stability to the plasma.

density of the plasma column depends on the strength of the central magnetic field through the relation (MKS units)

$$n = \left(\frac{2\epsilon_0}{m}\right) B^2 \qquad (1)$$

where n is the plasma density, ϵ_0 is the permittivity of free space, and m is the mass of the plasma charges. In terms of plasma parameters this condition can be written as $2\omega_p^2/\omega_c^2 = 1$, where $\omega_p = \sqrt{nq^2/\epsilon_0 m}$ is the plasma frequency and $\omega_c = qB/m$ is the cyclotron frequency. This upper limit on the plasma density is determined from a simple model, as will be shown, and is verified experimentally.[4,5,8,9] In the Fermilab Gabor lens we obtain a stable electron plasma with $2\omega_p^2/\omega_c^2 \simeq 7 \times 10^{-2}$.

Non-neutral plasmas are distinguished by large zeroth-order electrostatic fields. In the cylindrical geometry of a Gabor lens the field is an azimuthally symmetric focusing field. This means that the electric field has a strong axial component $E_r(r,z)$. It is also true that a beam with the same second moments in x, x' as in y, y' (a "round" beam) will still be "round" after passing through a Gabor lens. This is an important criterion for matching into an RFQ since an axisymmetric input beam is required for an ideal match.

Non-neutral Plasma Columns and the Brillouin Limit

The transport of intense low energy H⁻ beams is an important problem of accelerator physics today. The question has been raised as to whether a negative ion beam can be focused with a Gabor lens. Since the Gabor lens is a plasma device, it is not surprising that the answer comes from plasma physics. Fortunately there is a simple model which contains the relevant physics.[6,7]
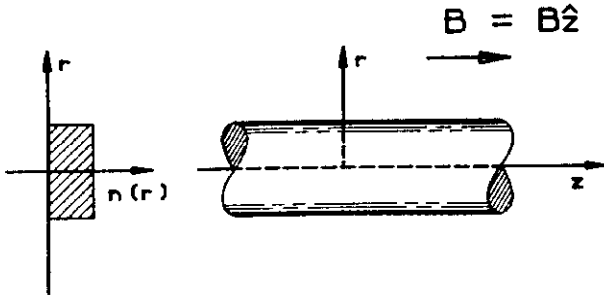
Figure 2: Non-neutral plasma column in an external magnetic field.

Consider the following non-neutral plasma system: a cloud of ions of charge q, mass m, and density n is in a uniform magnetic field B. There are no charges of the opposite sign within the cloud. Fig. 2 is a schematic of the situation. We enquire into the conditions necessary for the existence of a stable equilibrium of the plasma. The column is assumed to have length much greater than its radius so that axial motion may be neglected. We treat the plasma as a cold fluid.

The momentum transfer equation of a cold plasma neglecting collisions is

$$ mn \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = qn (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{2} $$

where $\mathbf{v}$ is the fluid velocity, and $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field vectors. We look for a solution to (2) with $\partial/\partial t = \partial/\partial\theta = 0$ and $n = $ constant. The only other relevant equation is Gauss's law; the self-magnetic field of the plasma is negligible for the densities we will consider.

From Gauss's law $2\pi r l E_r = nq\pi r^2 l/\epsilon_0$ the electric field of the column is

$$ E_r = \left(\frac{nq}{2\epsilon_0} \right) r = \left(\frac{m}{2q} \right) \omega_p^2 r \tag{3} $$

This is the field which is responsible for the focusing properties of the column. Note that if q is positive $\mathbf{E}$ points away from the axis and the lens is focusing for negative ions. If q is negative the lens is focusing for positive ions. The focal length is given by the expression[1]

$$ \frac{1}{f} = \sqrt{K} \sin \sqrt{K} L \tag{4} $$

where $K = -(m\omega_p^2/4T)(Q/q)$ is the focusing strength, $T = mv^2/2$ is the kinetic energy of the beam ions, and Q is the charge of the beam ions. Combining the expression for E_r with (2) we obtain the radial force balance equation

$$ -\Omega^2 r = \frac{1}{2} \omega_p^2 r - \omega_c \Omega r \tag{5} $$

where Ω is the angular rotation frequency of the fluid in the laboratory frame. The term on the left of (5) represents the inward centripetal acceleration of a fluid element; the first term on the right is the outward electrostatic force from E_r while the second term represents the inward magnetic force. Solving this quadratic equation for Ω yields the expression

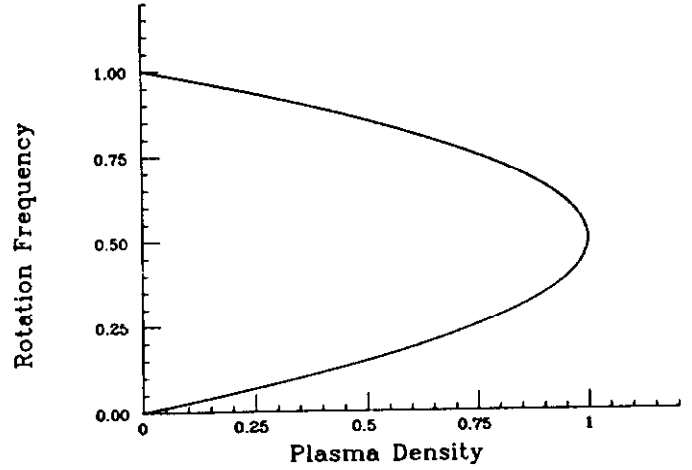$$ \Omega = \frac{\omega_c}{2} [1 \pm (1 - \frac{2\omega_p^2}{\omega_c^2})^{1/2}]. \tag{6} $$

Figure 3: Rigid-body rotation frequency of a non-neutral plasma column as a function of plasma density.

Fig. 3 is a plot of (6). For a given plasma density and magnetic field there are two possible rotation frequencies except when $2\omega_p^2/\omega_c^2 = 1$. This is the Brillouin limit mentioned above. It is the maximum possible stable density for a given B.

Measured radial profiles of these plasmas show a constant density region out to some radius with a sharp drop off to zero density on the scale of the Debye length.[8,9] Typical laboratory plasmas are a factor of 5 or more below the Brillouin limit.[4,5,8,9] We have already mentioned that a pure (positive!) ion plasma would have to be contained in the lens if one wishes to focus negative ions. As an example, take the H$^-$ beam from the Fermilab magnetron source. Typical beam densities are $\sim 10^8 cm^{-3}$. The lightest positively charged ion we have available is the proton. In order to neutralize and focus the beam we would like the plasma to have a density of at least $10^9 cm^{-3}$. From (1) the minimum magnetic field required is ~ 6 kG. In order to comfortably contain the plasma we would need a central field of 20 kG! Such a large magnet would create a number of problems. For example, a magnetron type source would have to be shielded from the magnetic field of the lens in order to operate properly. The magnet would be difficult to construct and would use a large amount of power. The focusing effect of the magnet itself would be at least as strong as the Gabor lens focusing, making the lens too strong.

This is to be contrasted with the electron plasma lens. On the Fermilab test stand we contain an electron plasma with a density of $\sim 10^9$ with a hand-wound magnet using solid core wire. The central field is ~ 200 G. No artificial cooling is required. The lens is self-starting via Penning discharge. Table 1 summarizes the parameters of negative and positive ion beam Gabor lenses.

Table 1

Plasma particles	Density needed (cm^{-3})	Confining magnetic field (Tesla)
electrons	$\sim 10^9$	3×10^{-2}
ions	$\sim 10^9$	≥ 2

Conclusion

We have shown that it is not feasible to focus a negative ion beam with a Gabor lens due to the large magnetic fields necessary to contain the non-neutral ion plasma. Gabor lenses show much

promise for the design of proton LEBT's. Further study of the action of a Gabor lens on an intense beam of protons is ongoing at Fermilab.

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