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# Measurements on a Gabor Lens for Neutralizing and Focusing a 30 KeV Proton Beam[†]

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# MEASUREMENTS ON A GABOR LENS FOR NEUTRALIZING AND FOCUSING A 30 KEV PROTON BEAM

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## Abstract

We have reported previously on the use of a Gabor lens[1] (also referred to as a plasma or space charge lens) to focus and neutralize a low energy proton beam[2]. A different lens geometry and a higher anode voltage have been adopted to overcome a lack of stability present in the previous design. We report on studies in progress to measure the focusing properties of the Gabor lens and determine whether it can be used to match a 30 keV proton beam into a radio frequency quadrupole (RFQ) Accelerator.

## Introduction

It is well known that in the transport of intense low energy ion beams irreversible emittance growth occurs due to the space-charge of the beam acting on itself. One is faced with this problem in the matching of a space-charge dominated beam into a radio-frequency quadrupole (RFQ) accelerator. It is therefore desirable to keep the beam space-charge neutralized in a low energy beam transport system (LEBT). Perhaps the simplest way of achieving this is to raise the pressure in the LEBT to allow the beam to ionize the background gas and form a neutralizing plasma. In a pulsed beam , this can lead to a time-dependent emittance at the RFQ entrance. Beam-plasma instabilities can also result. If the pressure becomes too high, scattering losses occur. One is therefore led to seek other methods of neutralizing the beam.

Gabor lenses have been used previously to focus positive ion beams with energies from 10 keV to 1.2 MeV.[3,4,5] They contain a dense non-neutral plasma which creates an electric field to focus the beam. Given a particular beam charge density, one designs the Gabor lens to have plasma densities which are much larger. Thus the beam charge density is a small perturbation on the motion of the plasma and it is neutralized in passing through the lens.

Published reports (see ref. 3-5) of Gabor lens operation describe the excellent optical quality achievable and strong focusing. By strong focusing we mean the ability to focus the beam down to a small spot, necessary for matching into an RFQ. We are therefore studying the focusing properties of gabor lenses to determine whether they can be used to match a 30 keV $H^-$ beam into an RFQ. An RFQ with an injection energy of 30 keV and output energy of 2 MeV is envisioned as the central component in the re-design of the low energy section of the Fermilab linac.[6] As a first step in its development, the Gabor lens is being used to focus a 30 keV beam from a duoplasmatron on the Fermilab ion source test stand. Conditions required to focus a negative ion beam will be discussed below.

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## Theory of the Lens

The first discussion of the principle of the lens was given by Gabor in his original paper, although Borries and Ruska[7] mentioned the possibility of using a plasma to focus a beam in an earlier paper. Later treatments were given by Morozov and Lebedev[8] and ref. 4 and 5 above. We review some basic aspects of the theory here.

Consider the fluid equation of motion for the electron component of a plasma (MKS units)

$$m_e n_e \frac{d\mathbf{v}}{dt} = -en_e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \nabla p + \frac{en_e}{\sigma}\mathbf{j} \tag{1}$$

where $p = nk_bT$ is the pressure of the electron component, $\sigma$ is the plasma conductivity, j is the current density of the beam, and the other symbols have their usual meaning. We ignore the ion motion. Let us assume that the electrons are cold and the charge density of the beam is small compared to the plasma density $n_e$; then the last two terms on the right of (1) can be ignored. For an equilibrium to occur, the left side of (1) must vanish; thus we find

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \tag{2}$$

as the condition for equilibrium. Note that this result is independent of the sign of the charge and the density of the plasma component; thus the same result is true for any other component. Taking the cross product of B with (2) one finds $\mathbf{v}_\perp = (\mathbf{E}\times\mathbf{B})/B^2$, the familiar $\mathbf{E} \times \mathbf{B}$ drift. Consider now a solenoidal field. Since from (2) $\mathbf{E} \perp \mathbf{B}$ and we have $E_\theta = 0$ (azimuthal symmetry) the magnetic flux tubes are electric equipotential surfaces. This suggests a method for fixing the potential inside the lens by placing electrodes within the plasma to coincide with surfaces of constant magnetic flux. In our design, shown in Fig. 1, we employ a cusp in the magnetic field to set the potential on the axis to ground as Gabor suggested in his original paper.

Thus to have an electrostatic field exist within a plasma:

1. The plasma must be nonneutral.
2. There must be a magnetostatic field in the plasma.
3. There will be an $\mathbf{E} \times \mathbf{B}$ drift of the plasma components.

In the central region of the lens it is a good assumption that the magnetic field is uniform and axial. Assuming the charge density $n = Zn_i - n_e$ is uniform it follows from Gauss's law and the azimuthal symmetry of the charge distribution that

$$E_r = (\frac{ne}{2\epsilon_0})r \tag{3}$$

where r is the distance from the axis of the lens. This linear variation of E with r implies a quadratic dependence of $\phi$, the

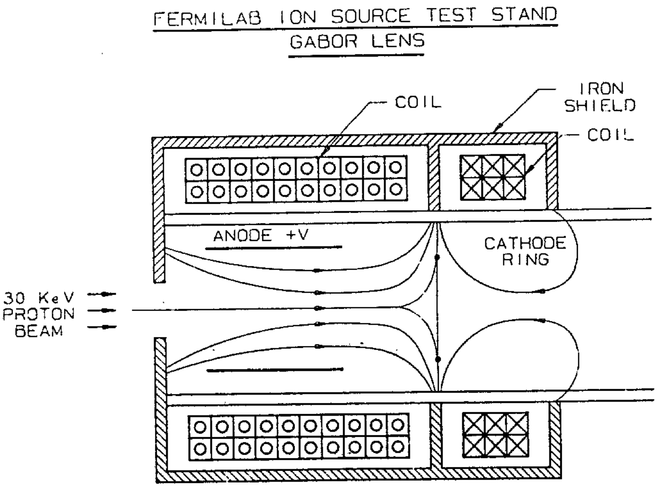


Figure 1: Gabor lens with cusped magnetic field

electrostatic potential, on r. If we place an electrode at radius $R$ charged to potential $V$ we find that

$$\phi = \phi_0 - (\frac{ne}{4\epsilon_0})R^2 \tag{4}$$

Here $\phi_0$ is the potential on the axis. If the on-axis magnetic field line is now made to come into contact with a grounded conductor, the on-axis potential will be zero and the charge density $n$ will be proportional to the electrode potential $V$. Numerically, one finds

$$n = 2.2 \times 10^6 V/R^2 \tag{5}$$

where $V$ is in volts, $R$ in cm and $n$ is in cm$^{-3}$. When the electrode is charged positively (negatively), the $E$-field will point towards the axis and the lens will be focusing for positive (negative) ions.

From (3) one finds the non-relativistic single particle equation of motion, valid in any transverse plane containing the optic axis (paraxial approximation)

$$r'' + \frac{V}{UR^2}r = 0. \tag{6}$$

$U = (1/2mv^2)/Ze$ is the total accelerating potential of the ions. Equation (6) is of the same form as the equation of motion in the focusing plane of a quadrupole magnet, thus one finds the expression for the focal length as measured from the principle planes

$$\frac{1}{f} = \sqrt{K} \sin \sqrt{K} L \tag{7}$$

where $K = V/UR^2$ for a Gabor lens, $K = B'/B\rho$ for a quad, and L is the length of the lens. Note that f is independent of the magnitude of the charge and the momentum of the ion for the Gabor lens. Thus it does not have a mass dispersing effect as a magnetic lens does. As a numerical example, a Gabor lens with $R$ = 5 cm, $V$ = 10 kV, and $L$ = 10 cm has a focal length of 9.5 cm for 30 keV protons. To obtain the same focal length for 30 keV protons a 10 cm long solenoid would require a central field of about 5.8 kilogauss and would consume almost 6 kW of power.

# Experimental Results

The experimental setup is shown in Fig. 2. When first pumped down the lens high voltage electrode requires an outgassing period of 30 minutes to an hour before operation. If powering up from a vacuum state the outgassing period is much shorter. With the source on, the pressure in the lens as measured on a nearby ion gauge is about $3 \times 10^{-6}$ torr. This is almost all due to hydrogen gas streaming out of the source. With the source off, pressures of $10^{-7}$ to $10^{-8}$ torr are achievable.

A duoplasmatron is used to form the beam of protons. Beam currents of 10–30 mA and 30 keV energy are passed through the lens. Emittance is measured both upstream and downstream of the lens with two slit emittance probes. Transmission through the lens at 30 keV is 100% up to 30 mA. While running, the discharge current from the lens anode is less than 1 mA at 10 kV. The two magnet coils are wound from solid core wire and are air-cooled. Typical magnet currents are 10 A in the large coil and 6 A in the small one. Total power consumption from the magnets and the high voltage supply is less than 100 watts. Stable operation of the lens has been observed for periods of 24 hours. The maximum high voltage which can be applied to the anode is limited to about 12 kV because of sparking. This can be increased by lowering the background pressure.

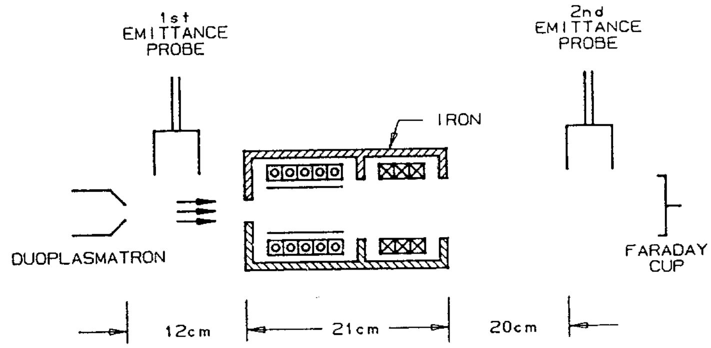


Figure 2: Experimental layout for Gabor lens Measurements

The raw data from the emittance probes is analyzed by a Masscomp computer. Section emittances as well as the rms emittance[9] are calculated. Alpha, beta, and gamma are calculated from the second moments of the beam using the rms formalism. We see a growth by a factor of approximately four in the rms and about three in the 90% section emittance as the beam propagates from the first to the second probe. This emittance growth was somewhat larger than expected. Computer simulations with a particle-in-cell code[10] show the rms emittance growing by a factor of three in the short drift between the source and the entrance to the lens due to the conversion of space-charge potential energy into transverse kinetic energy of the beam particles. It is not known how much growth occurs in the second drift or whether lens aberrations are causing emittance growth. The overall length of the line (50 cm) is fixed by the width of the vacuum chamber in the current design.

An interesting experimental result is the dependence of the rms emittance measured at the second probe on the focusing strength of the lens. A decrease by a factor of two is seen as the strength of the lens is increased. It should be noted that the 90% emittance appears to be independent of lens strength. We also find the angular distribution to be sharply peaked at the second probe. The results of the emittance measurements for several different anode voltages are presented in Fig. 3 and 4. The emittances have been "normalized" by multiplying by $\gamma\beta$ which is .008 for protons at 30 keV. The uncertainty in the emittances is 1%.

We have investigated the time dependence of the emittance over the length of the beam pulse (90 $\mu$s). Some variation was seen in the emittance measured directly out of the source. The instantaneous DC current of the source varies by as much as 10% over the length of the pulse so it is not surprising that the emittance changes. There was some variation on the second probe with time but this was expected given that the source emittance was changing. The neutralization time $\tau = (n\sigma v)^{-1}$ where $n$ is the gas density, $\sigma$ the ionization cross section, and v the speed of the beam particles is about 250 $\mu$s so one does not expect to see gross variations in the emittance as measured on the second probe.

## Conclusion

Measurements have been made on a Gabor lens at a beam energy of 30 keV and proton beam currents of 10 to 30 mA. The emittance is observed to grow by a factor of three to four as the beam propagates through the beam line. No significant time dependence of the emittance at the end of the beam line has been observed . Further study is planned to determine whether smaller emittances can be obtained and whether or not Gabor lenses are suitable focusing elements for a LEBT to match a 30 keV $H^-$ beam into an RFQ.

## Acknowledgement

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## References

1. D.Gabor, *Nature* **160**, 89 (1947).
2. J.A. Palkovic et al., *Bulletin of the American Physical Society* **33**, 1026 (1988).
3. V.V. Zhukov, A.I. Morozov, and G. Ya. Schepkin *ZhETF Pis. Red.* **9**, No. 1, 24-27, 14 (1969).
4. R. Booth and H.W. Lefevre, *Nuclear Instruments and Methods* **151**, 143 (1978).
5. R.M. Mobley, G. Gamel, and A.W. Maschke, *IEEE Trans. Nucl. Sci.* **26**, 3112 (1979).
6. C.W. Schmidt et al., this conf.
7. B. Von Borries and E. Ruska, *Zeitschrift für Physik* **76**, 649 (1932).
8. A.I. Morozov and S.V. Lebedev, *Reviews of Plasma Physics* **8**; New York, Consultants Bureau (1974).
9. P.M. Lapostolle, *IEEE Trans. Nucl. Sci.* **18**, 1101 (1971).
10. R.J. Noble, this conference.

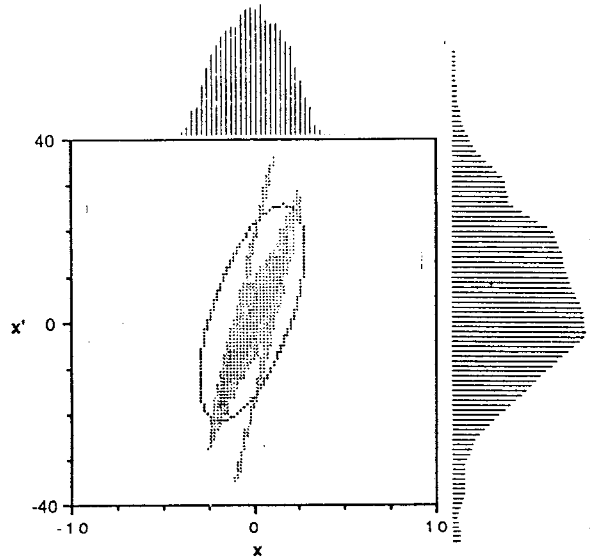


Figure 3: Source emittance; $\alpha = -.77$, $\beta = 0.15$, $\epsilon_{rms} = .56$, $\epsilon_{90\%} = 0.247$, I = 11 mA. The projection of the distribution on the $x$ and $x'$ axes are shown. Units are mm and mrad.

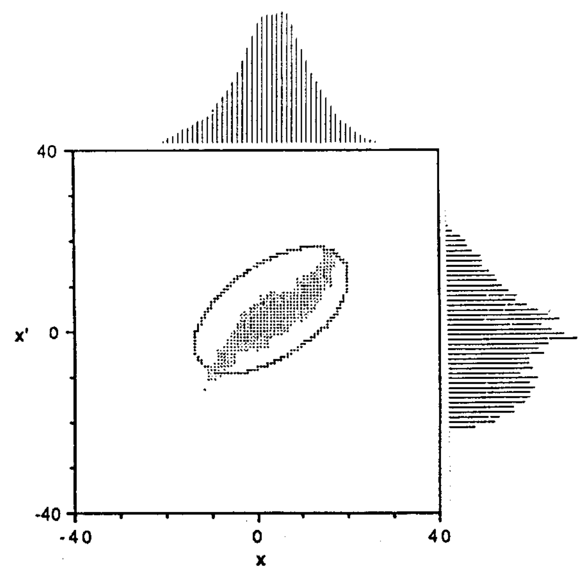


Figure 4: Downstream emittance; $\alpha = -.64$, $\beta = 1.3$, $\epsilon_{rms} = 1.93$, $\epsilon_{90\%} = 0.629$, I = 17 mA.