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GABOR LENSES*

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Introduction

Stable operation of Gabor[1] lenses has been reported by at least three experimental groups.[2,3,4] At Brookhaven we have been experimenting with several lens designs since February, 1978 with very good results. The lens concept is simple, operation is less complicated than anticipated, and the focussing strengths attainable make them very attractive alternatives to magnetic focussing for heavy ion beams at low energies.

In this paper we will describe results obtained with five different configurations. The lenses work well, and we are now mainly concerned with fine details of their beam-optical performance.

I. Principle of the Lens

Consider a cylindrical electrode of radius R at positive potential V in a solenoidal magnetic field. This is a trap or bottle for electrons which can be filled by cold cathode emission, secondary electrons from beam scraping, or as Gabor suggested, a hot cathode in a cusp magnetic field region at one end. The electrons must lose energy in the trap to be constrained at the ends and the magnetic field strength must be sufficient to provide a containment time long compared to the electron capture time.

One hopes that with the help of trochoidal magnetron orbits, collisional diffusion, and ionization of the background gas, a uniform and stable distribution of negative space charge density ρ is established. That this is the case is established experimentally by the linear focussing of ion beams.

We obtain a simple expression for the field strength by applying Gauss's Law in the radial direction with the two assumptions that ρ is uniform and that ρ produces an exact ground potential on the axis. Then:

$$\vec{E}(r) = 2Vr/R^2 \tag{1}$$

and

$$\rho = 4\varepsilon_0 V/R^2, \tag{2}$$

We obtain the thin lens focal length f by considering the transverse momentum p_t imparted to a parallel ion of momentum p_ℓ at the full radius R:

$$p_t/p_\ell = VL/TR = R/f \tag{3}$$

and

$$f = TR^2/VL. \tag{4}$$

in which L is the length of the electrode and T is the accelerating potential for the ion.

The thick lens focal length F, obtained by considering a truncated cosine orbit, is

$$F = L/2 + R\sqrt{\frac{T}{V}}\,\mathrm{ctn}\,\frac{L}{R}\sqrt{\frac{V}{T}}. \tag{5}$$

The actual lens strengths are weaker due to incomplete filling, as one expects.

Gabor[1] estimated that the critical magnetic field for stable operation should be enough to give a Larmor radius < R/2 for electrons of kinetic energy eV:

$$B_{crit} \geq 6.75 \times 10^{-6} \frac{V^{1/2}}{R} \text{ (mks units)} \tag{6}$$

The following numerical formulas are also relevant:

$$\rho = 2.2 \times 10^8 \; V/R^2 \text{ electrons/m}^3 \tag{7}$$

$$f_p = 1.33 \times 10^5 \; V^{1/2}/R = \text{plasma frequency in Hz} \tag{8}$$

$$f_c = 28 \text{ B GHz} = \text{electron cyclotron frequency}$$

$$f_d = f_{drift} = V/\pi R^2 B = \frac{1}{2}\frac{f_p^2}{f_c} \tag{9}$$

Where f_d is the frequency of revolution as electrons drift around the axis, for electrons at an average radius greater than their Larmor radius.

If we assume a thermal velocity of the electrons acquired by being accelerated to a potential V, then one can define the Debye length λ_d for the system. One expects the electron temperature will be less.

$$\lambda_d \leq R/2 = \text{radius of curvature in } B_{crit} \tag{10}$$

II. Experimental Results

We successfully operated the lens types shown in Figure 1, with the parameters shown in Table I. The shape of the field is not critical. The background vacuum had to be < 4 x 10^{-6} torr for the long lenses (a), (b) and (c) and <10^{-4} for the short lenses (d) and (e).

The usual mode of operation is to switch the magnetic field on in ∿50 msec. Otherwise, the current drain to the electrode increases above a few ma, the power loading causes outgassing, and the lens starts a continuous high density glow discharge. The short lenses can be operated dc. The time for the discharge to develop is >300 msec.

The B field values indicated in Table I are optimum values of a broad range like $B \pm \sqrt{B}$. The optimum values are about twice the right side of Eq. (6), and roughly follow the $V^{1/2}$ dependence.

We have not found current-dependent effects with H^+ beams of 100 ma (700 keV) and 200 ma (40 keV) and Xe^+ beams of 10 ma (700 keV).

The limiting beam current should be less than a hypothetical i_{max} for which the beam charge density equals ρ.

$$i < i_{max} = \beta V/30 \text{ amperes} \tag{11}$$

in which β is v/c for the ion. If additional electrons enter the lens as the beam current increases i_{max} is not a limit.

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Lens (b) was used successfully[4] in an rf buncher drift tube operating at 50 kV and 16 MHz.

Lens (c) was used in an experiment[5] on bunched beam neutralization. The electron density can be higher than ρ if ρ is a net negative density.

$$\rho = \rho(e) - \rho(x^+).$$

In such a case, the plasma frequency may be high enough to allow enhanced longitudinal implosion.

We have noticed gross variations in lens strength (gross noise) over 500 μsec beam pulses. This appears to be due to non-optimum magnetic strength or to a delay in lens ignition. Usually results as in Figure 2 are obtained.

Fine noise effects are seen when the beam is focussed through a small hole, as in Figure 3. An emittance measurement result, shown in Figure 4, also suggests some fine noise.

III. Remarks

Filling occurs in 10-50 μsec largely by processes which occur after a small population of electrons enter the trap. Since charge buildup of internal ionization requires expulsion of the background positives, the short lenses work at higher background pressures. The long lens (c) didn't work at all until the ground rings were added. A stable dynamic equilibrium is obtained with a variety of electrode and magnetic field configurations.

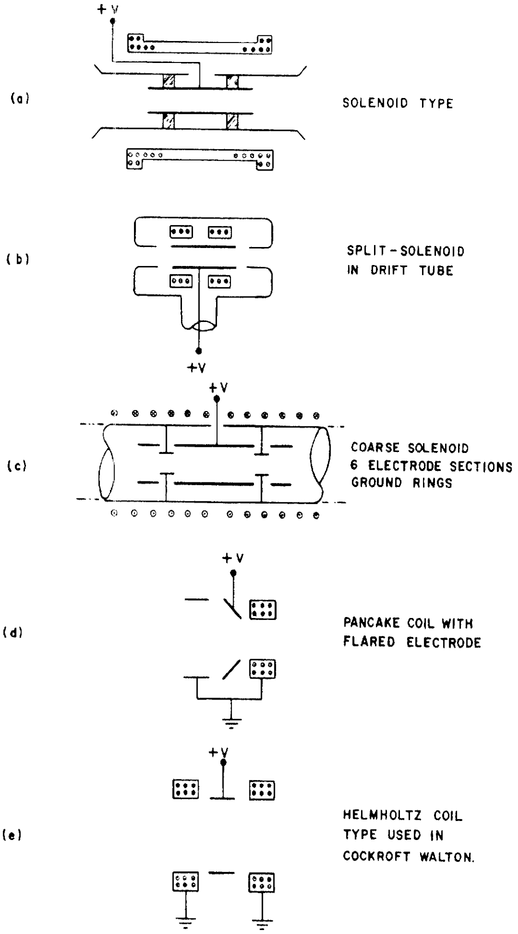

Figure 1. Schematics of lens types successfully operated. Electrode materials are stainless steel or copper.

Acknowledgements

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References

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TABLE I

Lens	Electrode R(in.)xL(in.)	B(gauss) at center	V(kV) Op. Range	Fth/Fex*
(a)	1-7/16 x 11	377	5-20	.58
(b)	1-7/16 x 4½	585	5-20	.81
(c)	2 x 72	110	1-2	∿3/4
(d)	(1½-2) x 1	200	1-10	-
(e)	2-5/8 x 2	100	1-12	-

*Ratio of theoretical (Eq.(5)) to measured focal length Lenses (d) and (e) work, but have not been measured yet.

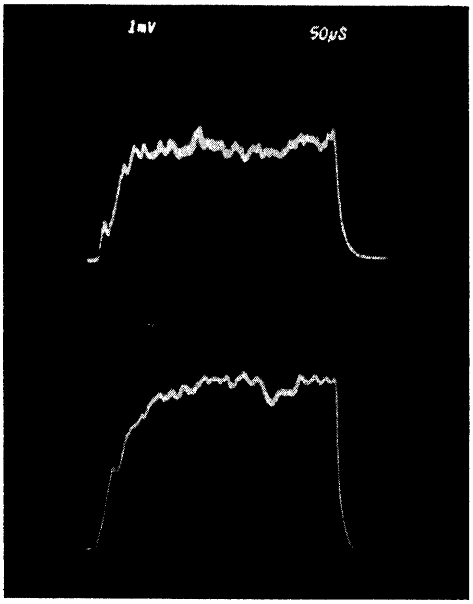

Figure 2. Xe$^+$ beam at 700 keV from duoplasmatron in Cockroft-Walton. Lens (a) used to focus beam through 3/8" diameter hole in Faraday cup, with 50 ohm termination. Upper trace is unfocused signal of 60 μa. Lower trace is focused signal of 2 ma. This shows that this noise is characteristic of the source, not the lens.

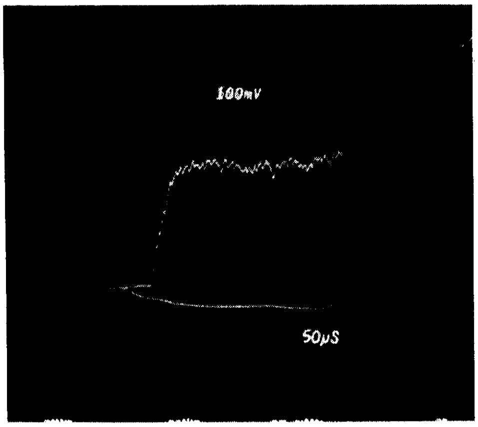

Figure 3. A 550 keV Xe^+ beam focused through a 1/8" diameter hole during a focal length measurement using Lens (b). In this case, 100 kHz fine noise is observed due to the lens. The difference from Figure 2 is that the hole size here is slightly smaller than the beam spot size.

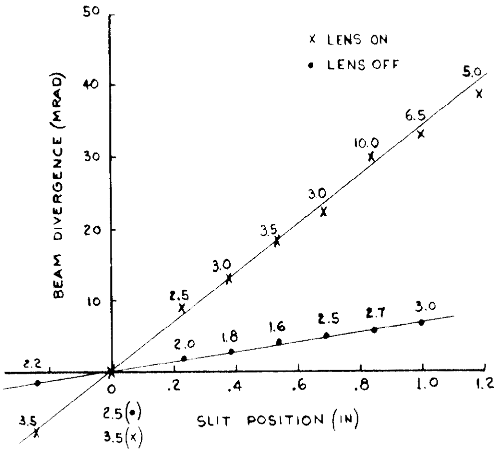

Figure 4. Emittance measurement of 500 keV Xe^+ beam using a moveable slit and moveable pickup wire. Lens (b) was used to produce a crossover halfway between lens and slit for the lens on case. The lines indicate the tilt of the emittance "ellipses", and the associated numbers are full width divergences in mrad. This shows that the focusing is linear across the lens aperture within 5%. The increase in the divergence widths may be due to fine noise.