Low Energy DC Electron Beam Transport by Means of a Beam-Generated Plasma

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Abstract

Neutralization of the space-charge forces of an intense DC electron beam by the beam-generated plasma is well known. The purpose of this investigation was to identify the ranges of background gas pressure and other parameters which would permit stable neutralized electron beam propagation with linear self-focusing forces. The electron beam energy and current ranges studied were 30-130keV and 100-600mA. Theories which describe the radial distributions of plasma densities generated by a uniform electron beam and conditions for uniform neutralization were tested. Experiments were performed using nitrogen in the pressure range 10^{-6}-10^{-4}Torr.

1. Purpose

A space-charge dominated electron beam will only remain self-repulsive if it propagates through a very high vacuum or if the beam generated positive ion plasma formed from residual gas in the vacuum chamber is instantly and continuously removed. Such conditions are the norm in most beam transport systems since uncontrolled or partial positive ion accumulation can lead to serious loss of beam quality. The motivation for this investigation was to establish conditions under which the positive ion plasma could be allowed to accumulate in the beam, leading to full beam neutralization and self-focusing, while maintaining high quality stable beam optics and a much reduced beam spot size.

2. Beam Optics Modes

Various modes of focusing an electron beam over a single beam optical stage are shown schematically in fig 1. Fig 1(a) illustrates the situation for very low perveance beams where beam self-forces are negligible. In this case the final beam spot size may be determined from simple optical theory.

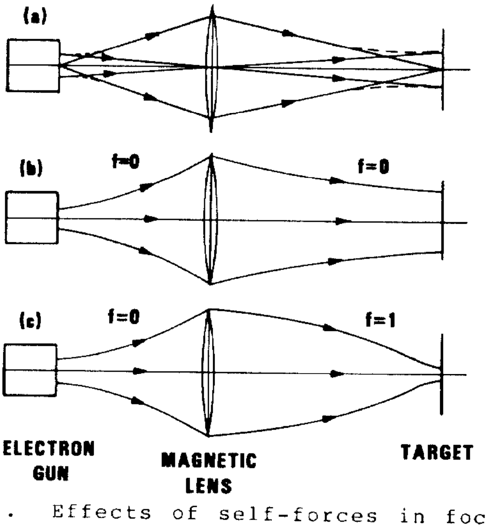

Fig 1. Effects of self-forces in focusing an electron beam. (a) Negligible self-forces, (b) Space-charge dominated beam, (c) Space-Charge repulsion before lens, complete charge neutralization after lens.

Fig 1(b) shows the more realistic and common case of a space-charge dominated beam in which the electron density is sufficient to cause mutual repulsion of the electrons and in which approximately laminar flow results. Usually a beam can still be focused under these conditions but unless the image distance is less than the object distance the overall magnification of the system cannot be less than unity.

The focusing method investigated in this study is shown in fig 1(c). Here the beam is allowed to expand in the space-charge limited mode until it reaches the lens (a magnetic solenoid). The beam is then fully neutralized by the beam generated plasma for the remainder of its path so that it becomes self-focused by magnetic forces. The result is a final beam spot size much less than the initial beam dimensions even for an image distance which is greater than the object distance.

3. Conditions for Linear Beam Optics

The necessary conditions for linear optics in a beam with significant self-forces can be deduced from an examination of the envelope equation(1) for a beam with cylindrical symmetry. More specifically, if the beam, at least for a short distance, is considered to be in a state of laminar flow, the envelope equation can be adapted to describe a cylindrically symmetric surface of radius, r(z), within the beam, containing a fixed fraction of the beam current:

$$\frac{d^2r}{dz^2} = \frac{\gamma^2 S(r)(1-f(r)-\beta^2)}{2r} + \frac{\varepsilon(r)^2}{r^3} \qquad \ldots(1)$$

where z is the distance along the beam axis, $S(r) = \sqrt{2m/e}\, I(r)/\{4\pi\varepsilon_0[V(1+eV/2mc^2)]^{3/2}\}$, $I(r) = \int_0^r 2\pi r' j(r')dr'$ is the current enclosed by the radius, r, j(r') is the current density, eV is the kinetic energy of a beam electron, f(r) is the average neutralization fraction of the beam inside the radius, r, β is the speed of an electron divided by the speed of light (c), $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor and $\varepsilon(r)$ is the "enclosed" emittance.

The beam optics are linear if the RHS of equation (1) is proportional to r. With this condition the beam will be aberration free and transportable over a long distance. Its behavior will also be calculable by using only its envelope equation.

We are mainly concerned here with cases in which the first term on the RHS of equation (1) is dominant. The most straightforward way to satisfy the linearity condition is then to make the current density, j(r) and the neutralization fraction, f(r) constant at the position z.

The requirement of a constant current density or uniform beam is initially a matter of electron gun design. If a uniform beam can be injected into the system and if the neutralization fraction, f(r) is always independent of radius (but not necessarily of z),

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then the beam will remain uniform and the optics linear.

Conditions under which f(r) is constant have been investigated in an earlier study(2). It was found that this criterion could only be satisfied if f(r) = 0 or 1. The former case can only be guaranteed by extracting positive ions from the beam as they are generated.

In the latter case it was found by beam sheath tracing that the optics would be adequately linear for the range $0.98 \leq f(r) \leq 1.02$. Several conditions have to be satisfied to achieve complete neutralization to this accuracy.

First it is necessary to consider the plasma generation mechanism. This determines the minimum time required for a beam to become completely neutralized:

$$t_n = 1/\beta c \sigma N_A \qquad \ldots(2)$$

where σ is the production cross section (3) and N_A is the atomic density of the background gas.

As an example, if it is required to completely neutralize a beam of 60keV electrons propagating through nitrogen, in less than 1 ms, then the gas pressure must be greater than 3×10^{-7} Torr. Such considerations set the lower gas pressure limit for plasma focusing.

Secondly the behavior of both the positive ion and secondary electron plasmas generated by the beam can influence the uniformity of neutralization. Results of a theoretical study(2) of this problem are shown in fig 2 for a 60keV, 270mA beam. This study shows that for gas pressures at the lower end of the range of interest, the positive ion plasma, inside the beam, behaves as a thermodynamic gas at the temperature of the neutral gas, while outside the beam the ions flow ballistically to the wall of the beam tube. As the pressure increases this ballistic behavior extends inside the beam ("Hybrid Model") until at a certain pressure, ions are formed sufficiently rapidly that all motion is ballistic.

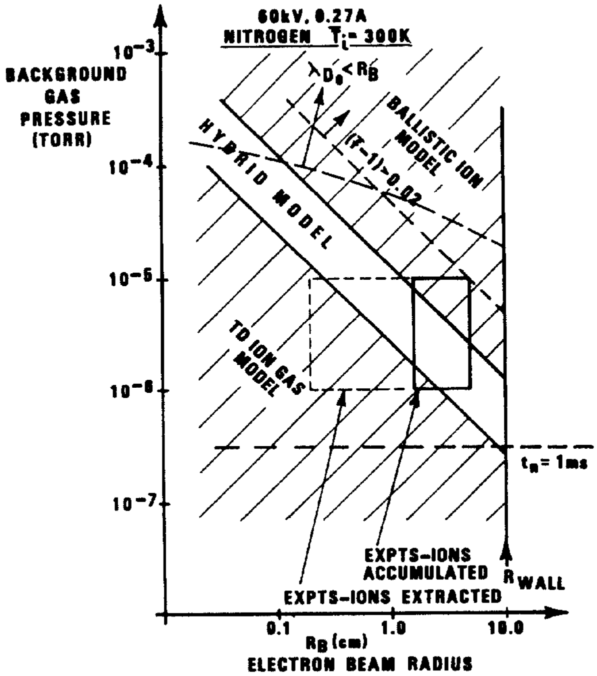

Fig 2. Regions of validity of beam generated plasma models and limits of linear beam self-forces for an electron beam of 60keV, 270mA propagating in nitrogen.(From reference 2. Experiments referred to are for an expanding beam only.)

A limitation on the background gas pressure follows from this model and from the limitations on the neutralization uniformity. The upper pressure limit may be expressed by a condition on the neutralization time:

$$t_n \geq \sqrt{\frac{2\varepsilon_0 M}{0.02 e^2 N_B}} \quad \text{for } (f(r)-1) \leq 0.02 \qquad \ldots(3)$$

where M is the mass of an ion and N_B is the density of the beam electrons. The boundary corresponding to equation (3) is shown in fig 2.

A similar boundary occurs where the Debye length of the secondary electron plasma becomes less than the beam radius (4) and the secondary electron density is sufficient to cause significant non-uniformity of the neutralization fraction.

As a result of these limitations, for the beam parameters studied here, the order of magnitude of the gas pressure could not exceed 10^{-4} Torr.

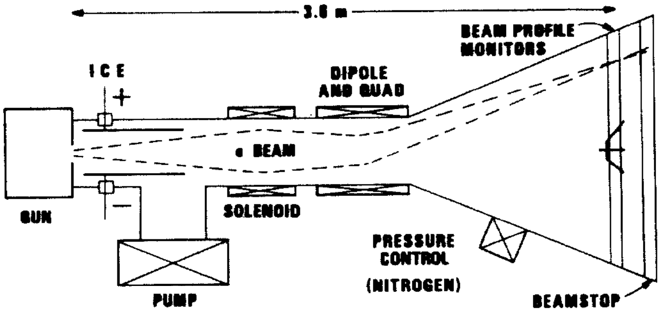

Fig 3. Experimental apparatus

4. Experiments

The apparatus used to investigate plasma focusing is shown schematically in fig 3. It consists of an evacuated drift tube with a conical extension, cryogenic vacuum pump and pressure controller with a supply of nitrogen gas, an electron gun, ion clearing electrodes, a focusing solenoid, a deflecting dipole with quadrupole windings incorporated, a set of beam profile monitors and a tungsten beam stop. The whole apparatus is 3.6m long, the solenoid being centered at 1.25m downstream from the gun.

A DC space charge limited beam is produced by the gun. At its exit, the beam radius is approximately 2 mm. It expands by self-repulsion in the region of the ion clearing electrodes after which it becomes neutralized and focused by the solenoid and quadrupole and deflected by the dipole. Because of the high power density in the final beam spot (up to 80 kW/mm²) it is necessary to scan the beam continuously across the beam stop at speeds of not less than 30m/sec. The quadrupole coils are used to adjust the eccentricity of the beam spot ellipse as required. Circular beam spots were used in general.

The uniformity of the beam at the gun exit was confirmed by calculation using the program EGUN(5) and by measuring the beam profile at the solenoid(2).

The beam spot profile is monitored by scanning it across a trident shaped tungsten wire(6) as shown in fig 4(a). The current

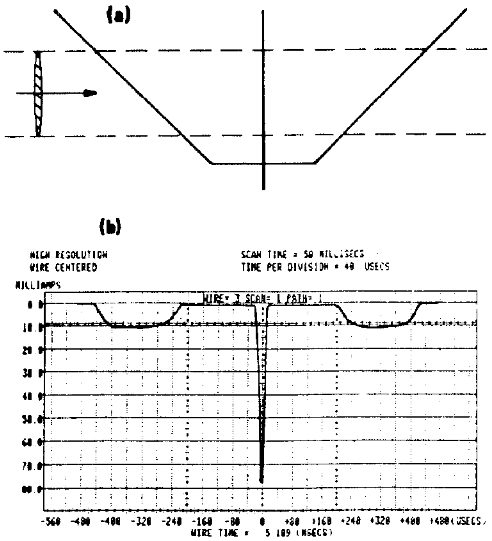

Fig 4. (a) Trident wire beam monitor. The beam spot traverses the wire from left to right. (b) Current signal from trident wire monitored by a digital oscilloscope for an electron beam of 131keV, 602mA. One time division corresponds to 2.6mm.

flowing to this wire is monitored by a digital storage oscilloscope. An example of the output is shown in fig 4(b). The cleanness of the central pulse in this display at each high voltage value is evidence of linear beam optics throughout the beam path length.

5. Results

All experiments were performed with a gun perveance of 0.0127 μ Perv. The high voltage current combinations were 34.9kV, 83mA; 64.9kV, 210mA and 131.0kV, 602mA.

At nitrogen pressures of 8×10^{-7}, 3.5×10^{-6}, 1.3×10^{-5} and 3.5×10^{-5} Torr, there was no evidence of pressure dependence of the plasma focusing, as predicted by theory and the focusing was apparently linear. At 10^{-4} Torr, possible aberrations start to appear.

For each high voltage, data at the lower 4 pressures were averaged and the beam spot radii are plotted in fig 5. (The radii used are half the FWHM of the beam profile corrected for the monitor width.) Results of a beam envelope tracing also plotted there show that all beam spot sizes are consistent with an emittance of 16.5 π mm mr. This value is significantly higher than the emittance expected due to the thermionic cathode(7) of the electron gun: 6.0 π mm mr. Since the emittance is the same for all 3 beams and since their beam envelopes are virtually identical, it is assumed that the major part of this emittance is due to aberrations in the beam optical system. Multiple scattering is negligible and does not account for it.

6. Conclusions

The data points and the lower curves in fig 5 indicate that beam generated plasma focusing is a viable mode of operation for the range of beam parameters and pressures investigated. The magnification achieved was up to 6 times smaller than the ratio of the image to object distances.

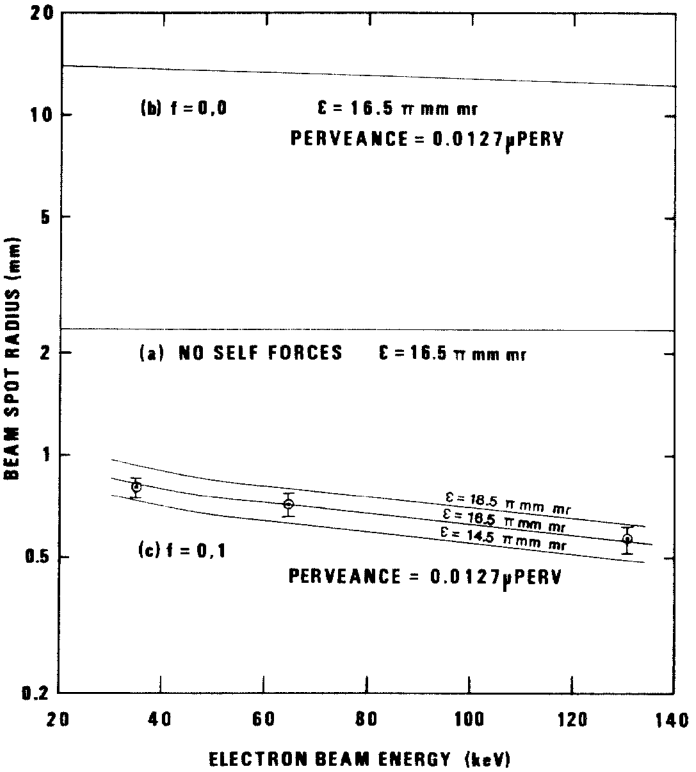

Fig 5. Beam spot radii for beams of various energies focused in the apparatus shown in fig 3. (a) No self-forces as in fig 1(a)(calculated), (b) Space-charge dominated as in fig 1(b)(calculated), (c) Focused as shown in fig 1(c). Data are average values for pressures from 8×10^{-7} to 3.5×10^{-5} Torr. Calculations are for various values of emittance.

In fig 5, beam spot radii are also plotted for a hypothetical or low current beam with no self forces and for beams with the same perveance as those used experimentally but propagating in a perfect vacuum (ie zero neutralization), corresponding to the optical modes shown in figs 1(a) and 1(b) respectively.

Clearly plasma focusing is preferable in any application where a small beam spot is required.

7. Acknowledgements

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