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[54] APPARATUS FOR AND METHOD OF CONTROLLING RELATIVISTIC CHARGED PARTICLE BEAM DISTRIBUTION AND TRANSPORT

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[52] **U.S. Cl.**.....**250/49.5 R,** 219/121 EB, 313/83, 328/228

[51] **Int. Cl.**.....**H01j 35/00**

[58] **Field of Search**.....250/49.5 R; 219/121 EB; 313/83, 74; 328/228

[56] **References Cited**

UNITED STATES PATENTS

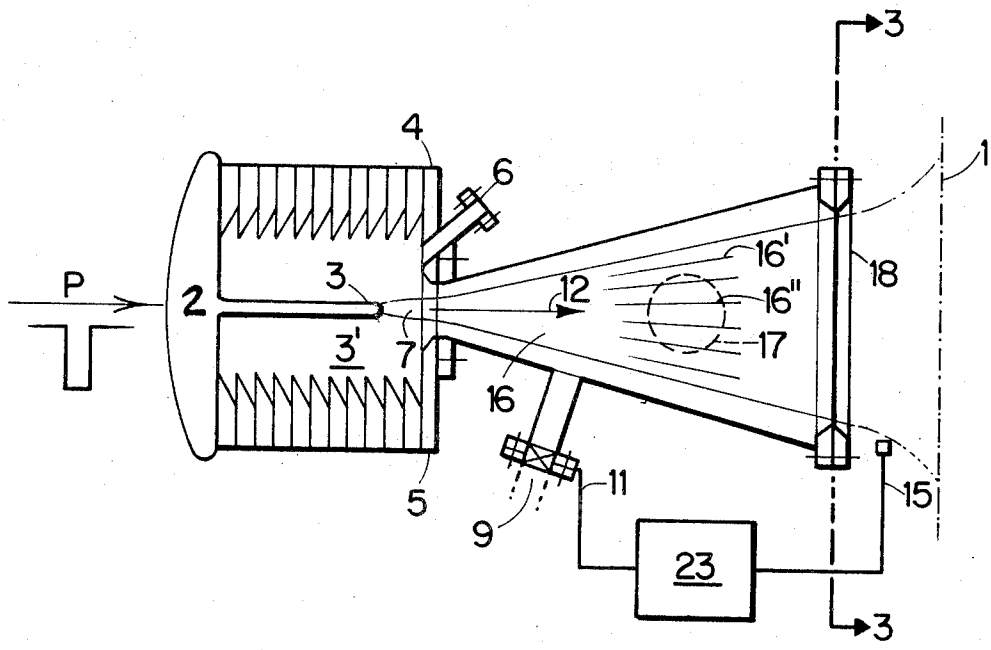
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[57] **ABSTRACT**

The present disclosure involves methods and apparatus for actively controlling the charged particle density in a controlled pressure region or in the ambient atmosphere, from an accelerator capable of producing high intensity relativistic charged particle streams in a pulsed manner. The techniques are applicable to both high repetition rate applications, typical of industrial processors, electron tubes or accelerator/fusion reactor injectors, and to single pulse or low repetition rate systems. These methods utilize the self-magnetic forces of relativistic beams to accomplish controlled distribution, and avoid the complexities of electromagnetic scanners or lenses heretofore used for this purpose. Methods are also disclosed which utilize force control in partially charged neutralized beams as well as plasma conductivity control in freely drifting beam systems.

12 Claims, 5 Drawing Figures



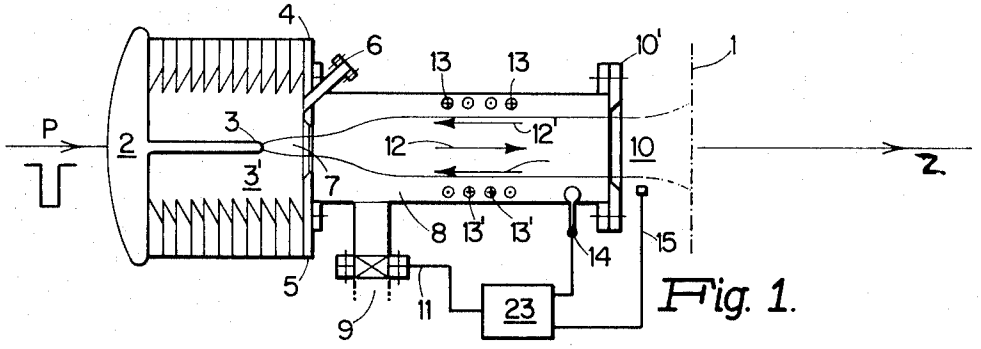


Fig. 1.

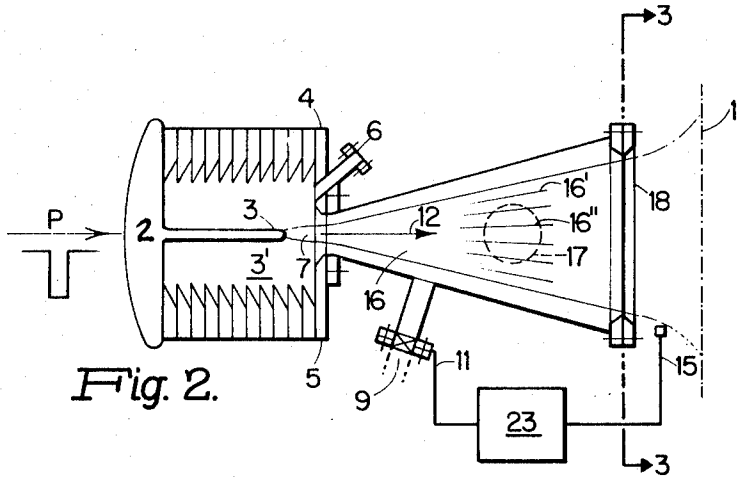


Fig. 2.

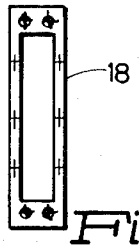


Fig. 3.

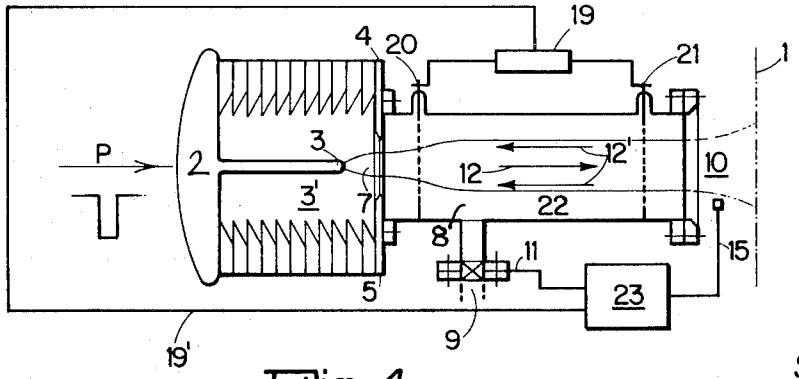


Fig. 4.

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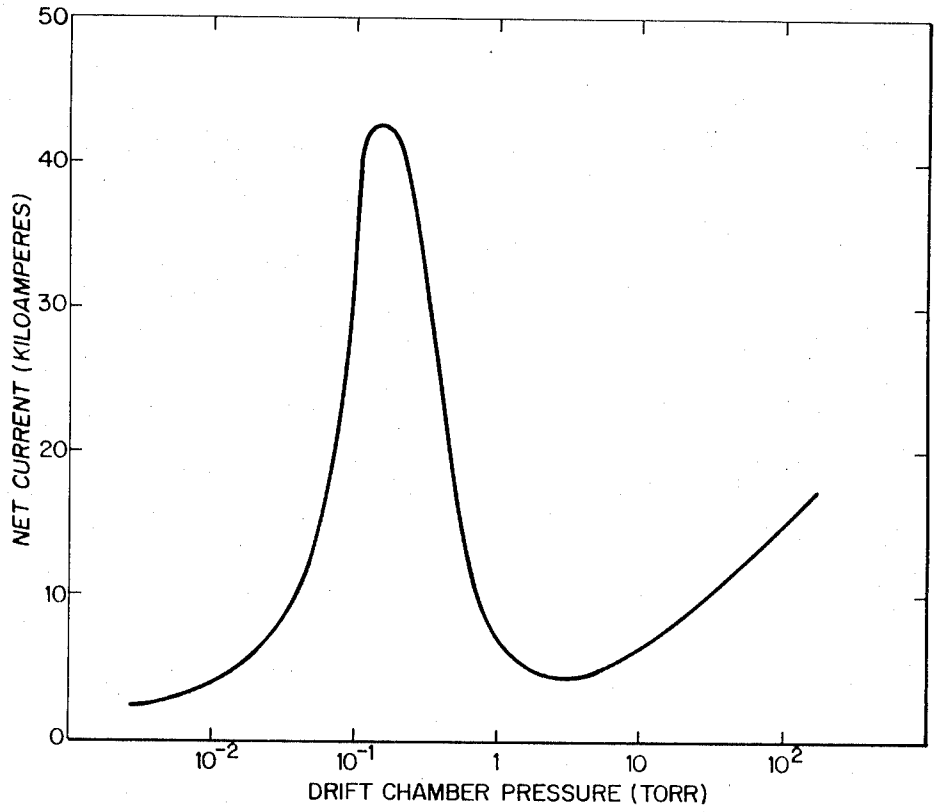


Fig. 5.

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APPARATUS FOR AND METHOD OF CONTROLLING RELATIVISTIC CHARGED PARTICLE BEAM DISTRIBUTION AND TRANSPORT

The present invention relates to apparatus for and methods of controlling a relativistic charged particle beam distribution and transport, including automatically and continually controlling the charge particle density distribution of high intensity electron and other charged particles.

Various techniques have been employed over the years to try to ensure a uniform or other predetermined high intensity electron or other beam density at a target or window region over a predetermined area. These prior proposals have included the utilization of scanning or deflection mechanisms that cause the beam repetitively to scan over a predetermined area in different types of scanning paths, and thus try to accomplish the above objective, as described, for example, by M. L. Rossi et al., "A Wide Area Electron Beam Scanner," IEEE Transactions on Nuclear Sciences, Volume NS-12,Number 3, June 1965, page 279. Unfortunately, such techniques have the disadvantage that they require deflection and scanning equipment. In addition, they inherently do not provide for the simultaneous presence of the desired beam density at all points of the predetermined area and because they scan the beam at the current densities provided by the accelerator, high instantaneous dose rates are encountered in the irradiated matter, often leading to decreased radiation induced changes in, or degradation of, the target material.

Another approach has been to control the focusing of the beam, as in electron beam welding and similar systems; but this again is not suited to the problem of controlling the beam density over sizeable areas, since the focusing adjustment is only most effective for converging the beam onto a small point or area.

It is to the solution of this problem of effective and automatic control of high intensity charged particle beam density over predetermined target or window areas and the like, accordingly, that the present invention is primarily directed, it being an object of the invention to provide a new and improved method of and apparatus for such control of relativistic charged particle beam distribution and transport.

In applications where the electron beam or other charged particle beam is to be pulsed, moreover, as in the case of nanosecond high voltage pulses of the order of tens of thousands of amperes, with energies of hundreds of kilovolts, such prior art scanning and focusing techniques are not useful in view of the indexing and location problem inherent in turning the beam on and off and ensuring that the beam energy covers exactly the predetermined area during each pulse. More than this, the use of very high energy beam pulses requires the spreading out of the beam over a predetermined area to avoid local damage in the target area.

A further objective of the invention, therefore, is to provide novel apparatus for such control of high energy pulsed charged particle beams.

Other and further objects will be explained hereinafter and are more particularly delineated in the appended claims. In summary, however, the invention contemplates, in one of its important aspects, beam-permeable window-separated high vacuum charged-beam-generating and low-pressure drift-space chambers. The charge density at or near the exit window of the drift-space chamber is monitored and used to control the gas pressure within the low-pressure chambers to insure the desired predetermined beam density and area coverage at the exit window. Preferred details are hereinafter set forth.

The invention will now be described with reference to the accompanying drawings,

FIG. 1 of which is a combined longitudinal section and schematic circuit diagram of apparatus constructed in accordance with a preferred embodiment that practices the method of the invention;

FIG. 5 is a graph illustrating net beam current behavior as a function of gas pressure in the low-pressure drift chamber of the apparatus of FIG. 1;

FIGS. 2 and 4 are views similar to FIG. 1 of modifications; and

FIG. 3 is a longitudinal section taken along the line 3 — 3 of FIG. 2, looking in the direction of the arrows.

The practical application of intense charged particle beams, particularly electrons, largely depends upon the ability to deliver such beams in a controlled manner into the atmosphere, so that the current density (i.e. flux of energy or dose rate) delivered at the ultimate product plane, shown at 1 in FIG. 1, may be precisely controlled. Suitable means for the generation of such intense pulsed streams, typically of tens of thousands of amperes at energies of hundreds of kilovolts or above for periods of tens of nanoseconds, are described, for example, in U.S. Letters Pat. Nos. 3,397,337 and 3,344,398. In general, these beams are formed by the application of negative high voltage impulses P, FIG. 1, to an insulated collector plate 2, to which a cold cathode 3 is affixed, such that electrons are released from the cathode 3 during the tens of nanoseconds duration of each pulse. Electrons are accelerated within the chamber or region 3' to ground plane 5 from the gas plasma formed about the cold cathode surface 3 in the region of field intensification. Typical applications of such beams, as described, for example, in my prior U.S. Letters Pat. No. 3,489,944 with A. S. Denholm, have involved their transfer from the relatively high vacuum acceleration chamber or region 3', maintained at approximately 10^{-5} torr by means of active pumping through port 6, through an electron permeable window 7, into a relatively low pressure chamber or drift region 8. The chamber or drift region 8 is maintained at a pressure differing from that of the accelerating region 3' by means of a differential pumping port 9 in chamber 8, which can be fitted with, for example, a variable conductance butterfly valve 11 to permit precise pressure control of the volume enclosed by chamber 8, typically filled with ambient air or nitrogen gas. Beam entrance to the atmosphere is defined by a second electron permeable window 10 at the far end of the chamber 8 and which is capable of supporting one atmosphere across the opening. The electron windows may, for example, be of 0.001 inch Titanium foil clamped in a vacuum fitting flange as at 10', as described in my said prior patent and in my article with S. E. Graybill entitled "The Generation and Diagnosis of Pulsed Relativistic Electron Beams Above 10^{10} Watts," Proc. IEEE Transactions on Nuclear Sciences, Volume NS-14, No. 3, page 782, 1967.

The behavior of a high current density beam of sufficient intensity that self-magnetic focusing results, was predicted by W. H. Bennett, Phys. Rev. 45, p. 890, 1934 and 98, p. 1584, 1955 and others. Bennett showed that electrostatically neutralized beams could be self-focusing for currents above

$$I^2=(8\pi/\mu_o)\,Nk\,(T_e+T_i),$$

where N is the number of charges per unit length of the beam, k is the Boltzmann constant, μ_o is the permeability of vacuum ($4\pi\times 10^{-7}$), and T_e and T_i are the electron and ion temperatures, respectively. This prediction was first confirmed experimentally by the said Graybill and me, Applied Physics Letters, 8, p. 18, 1966, with apparatus in which current density (energy flux) behavior was first measured experimentally with relativistic electron beams of sufficient intensity to permit controlled study of these phenomena.

Study of the current-field balance in the relatively low-pressure chamber or drift region **8** has resulted in a good understanding of those conditions providing optimum beam propagation and current density where no external fields are applied. In the region of 1 mm pressure for the conditions experienced with the apparatus of my said prior patent, a condition of magnetic neutrality results. Thus, in the system of FIG. **1**, an azimuthal magnetic field, schematically designated at **13**, is generated by the primary beam **12**, and it is neutralized or counteracted by an opposed field **13'** generated by the return current **12'** flowing in the plasma generated by the primary stream. Under conditions of electrostatic neutralization (i.e. $N_i = N_e$), this condition will result in laminar or parallel flow of the electron beam. Precise control of the plasma conductivity (through pressure variation in chamber **8**) will in turn define the current **12'** and counterfield **13'**. As a result, the diameter and current density distribution at the exit window **10** can be determined through control of the pumping conductance valve **9**. As illustrated in FIG. **5**, for example, increased pressure will lead to decreased current density at **10** (i.e. beam expansion, defocusing or increased magnetic neutralization); while decreased pressure will lead to increased magnetic focusing or current density at **10** (i.e. beam compression or focusing). Active control of the butterfly or leak valve **11** in port **9** of the chamber wall **8**, is effected by a feed back system **23** from a charge monitor or sensor **15** of any conventional type, which may be internal or external to **8**, as shown, and preferably is disposed adjacent the window **10** at the periphery of the beam. Alternatively, a Rogowski loop sensor **14** may be inserted into the drift chamber **8** near the window **10** such that the proper level of magnetic neutrality in the drifting stream is continuously and actively maintained. Further control of the system to provide active control of the integrated charge or dose delivered ultimately at the product plane **1** can be effected utilizing an integrated charge monitor in the wall of **8** (not shown) which detects back-scattered electrons from window **10**. The magnetically neutralized configuration proposed renders this monitoring technique possible since unneutralized systems result in intense azimuthal fields which present charge particle flow to the periphery of the system.

The magnetic neutralization scheme is practically useful, however, only for pulsed systems, since the induced return current **12'** and associated azimuthal field **13'** arise or are induced in the plasma during the passage of the front or rising edge of the primary current pulse **12**. Experiments with 40,000 ampere, 30 nanosecond, 1.5 million electron volt beams, as described in my before-cited publications with Graybill, have shown that the return current density holds up well beyond the time defined by the rising portion or leading edge of the primary current pulse due to the dependence of the induced or back electromotive force on the difference between currents **12** and **12'**. An example of the high degree of magnetic neutralization in the 1–10 torr pressure region is demonstrated by the graph of such a stream. In this case, the net current (current **12** minus current **12'**) flowing in chamber **8** is plotted along the ordinate, indicating the control region of interest (0.5 – 10 torr), for automatic pressure variation stabilization of the exit current density, plotted along the abscissa in FIG. **5**.

In the modification of FIG. **2**, a conducting chamber **16** is used for the low-pressure drift chamber, preferably with a plurality of conducting vanes **16'** to improve current density uniformity at the ultimate window **18**, as now to be explained.

The condition of force neutralization in a relativistic beam where the radial electrostatic forces are just neutralized by the focusing magnetic forces, is described by the condition.

$$\bar{\nu}\times\bar{B}=\bar{E}_r,$$

where $\bar{B}$ is the azimuthal self magnetic field generated by the beam **12** in FIG. **2** and $\bar{E}_r$ is the radial electric field generated by the unneutralized charge in the beam. For a beam of small divergence, uniform ionization and current density with constant longitudinal velocity as experienced in drift chamber section **16**, J. D. Lawson has shown (Journal Electronics and Control, **5**, p. 146, 1958) that the force neutralized condition is realized when f, the ion-electron density ratio in the drift region occupied by the beam, is equal to $1-\beta^2$, where β is the ratio of the particle drift velocity to that of light.

Now for typical operating conditions, as explained in my said Applied Physics Letters article with Graybill, with medium energy (0.5 – 10 MeV) relativistic electron beam accelerators, β^2 is large and approaches unity; e.g., for force-neutralized conditions in a 2 million electron volt beam where $\beta = 0.98$, $f = 1-\beta^2 = 0.04$. Since such a condition is appropriate for both efficient propagation and current density variation in a large area beam, positive ion densities only a few percent (4 percent at 2 MeV), of those of the primary beam electron density are required. Numerically, a 2 MeV intense electron beam at a current density of 100 amperes/cm^2 possesses a charge density of only 2.1×10^{10} e/c.c. and requires a resident ion density of only 8×10^8/c.c. to accomplish force neutralization.

Under such conditions of beam drift with the primary beam **12** delivered to an external target at plane **1** beyond the conducting vessel **16**, shown as somewhat conical, and fitted with differential pumping ports **6** and **17**, shown dotted, the only return current flowing in the walls of the vessel **16** results from the small

amount of charge stopped in the window assembly **18** and that resulting from secondary charge generated by ionization and scattering of **12** in the chamber **16**. Under these conditions, the image current forces due to the charge in the conducting walls of **16** are repulsive to primary stream **12**, since the attractive forces are less than $1-\beta^2$ of the repulsive forces arising from these walls charges. As a consequence, the primary stream is affected by the image charge distribution in the conducting wall **16**.

The geometry of FIG. **2** has been employed to utilize this effect in "scanning" or "redistributing" an initially cylindrically symmetric beam generated by cathode **3** at window **7**, into a "strip" or two dimensional distribution as shown in the longitudinal section at plane **18** of chamber **16** in FIG. **3**. An improvement of this simple self-distributing geometry under neutralized flow is represented by the addition of spaced converging planar conducting vanes **16'** in chamber **16**, substantially parallel to the opposite portions of the walls of chamber **16** and of floating potential, such that stronger image force distribution results in the central region of the beam, with a resulting improvement in the current density uniformity at window **18** and the ultimate product plane **1**.

A further improvement in the simple image force-self-distributing geometry of FIG. **2** would be represented by the use of dielectric layers, such as quartz or titania, at opposing or inner regions **16''** of the planar vanes **16'** near the beam centerline, so that the image field effects will be enhanced by the such high permittivity material. The combination of conducting vanes in the beam and such high permittivity surfaces above the beam centerline in the chamber **16** provides for enhancement of the lateral spreading image forces on the beam.

A further variation of the system to improve the uniformity of the initially cylindrically symmetric beam **12** will be the use of a chamber **16** cross-section of double hyperbdic or "dumbell" geometry, instead of the single conically curved wall, or flattened frustum, to improve the image force distribution in spreading the stream into the uniform two dimensional profile desired at exit window **18** and product plane **1**.

A further modification is shown in FIG. **4**, wherein a gas discharge in the chamber **8** of FIG. **1** is maintained by a power supply **19** which applies a discharge voltage suitable for maintenance of glow discharge conditions in the drift chamber **8**, at reduced pressure, by means of electrodes **20** and **21** positioned in said chamber **8**, or by other means of ionization, pulsed or dc. By this technique, a preformed plasma of constant conductivity is generated so that the elapsed time required to establish sufficient conductivity in the drift region, to maintain the return current **12'**, is not required. This is particularly important for very short pulses where significant amounts of primary current **12** are lost until adequate conductivity is established to support return neutralizing current **12'**. This time is given by $\tau \approx (1-\beta^2) / n\sigma\beta C$, where β = the particle velocity velocity of light, n is the ambient gas number density and σ the ionization cross section. For example, for an electron energy of 2 MeV ($\beta = 0.98$) and $\sigma = 10^{-19}$ cm^2/gas atom for nitrogen, $\tau = 12$ nanoseconds for 100 μ pressure and varies as $1/\rho$. It is observed that this loss can be significant for 20–30 nanosecond beams in the control pressure region indicated in FIG. **5**, especially for beams whose risetimes are a significant fraction of the total pulse width. For very narrow pulses in the 10 nanosecond range, such a "preformed" plasma technique is mandatory for efficient transport and manipulation of such relativistic streams.

The current density distribution of beam **12** at window **10** and at product pulse **1** can be controlled by conductivity variation of plasma **22** sustained in the drift chamber **8** by conducting electrodes **20** and **21**. Detector **15** (or loop **14** of FIG. **1**), used in conjunction with integrating monitor **23**, may be used to determine current density distribution near the plane **10** of exit into the air, so that feedback control via **19'** of the supply **19** can be used to vary the voltage of electrodes **20–21**, thereby varying gas conductivity, also to readjust the exit current density to the value preselected by charge integrator **23**. The described technique is particularly important for the control of beam current density distribution and propogation over great distances, in the conductivity-dominated regime of relativistic flow, typically 500 μ – 10mm of air for electron beams of medium energy (0.5 – 10 MeV).

Further modifications will also occur to those skilled in this art and are considered to fall within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. Apparatus for controlling charged relativistic particle beam flux over a predetermined area, having, in combination, high-vacuum and low-pressure gas-containing chambers interconnected by low-pressure beam-permeable window means and with the low-pressure chamber provided with a further beam-permeable window means communicating with the external atmosphere and over a predetermined area of which a predetermined beam density is to be maintained, means for propagating the said beam from the high-vacuum chamber through said low-pressure window means and upon said predetermined area of said further window means, means disposed proximal to said further window means for monitoring the charge density at a region of said predetermined area, and means controlled by the monitoring means for varying the gas pressure within said low-pressure chamber in accordance with the density monitored by said monitoring means in order to maintain the said predetermined beam flux over said predetermined area of said further window means.

2. Apparatus as claimed in claim **1** and in which means is provided for pulsing said beam.

3. Apparatus as claimed in claim **2** and in which means is provided for adjusting the beam current density to a value of sufficient intensity to enable self-focusing of said current within said low-pressure chamber, acting as a drift space.

4. Apparatus as claimed in claim **2** and in which the walls of said low-pressure chamber are conducting and there is provided intermediate and within the drift space thereof, a plurality of spaced conducting vane members.

5. Apparatus as claimed in claim **4** and in which dielectric layer means is provided at the vane members near the centerline of the beam.

6. Apparatus as claimed in claim 4 and in which the said walls are curved.

7. Apparatus as claimed in claim 2 and in which means is provided in the low-pressure chamber for maintaining a predetermined glow discharge.

8. Apparatus as claimed in claim 7 and in which means is provided, responsive to the said monitoring means, for controlling the glow discharge to effect control of the said beam density over the said predetermined area of said further window means.

9. Apparatus for controlling charged relativistic particle beam density over a predetermined area having, in combination, a conducting low-pressure drift-space chamber, means including a high-vacuum chamber for propagating a charged particle beam into and along said drift-space chamber, and a plurality of spaced electrically floating conducting vane members dispersed along said drift-space chamber for producing beam image charge forces in the central region of the beam.

10. Apparatus for controlling charged relativistic particle beam density over a predetermined area having, in combination, a low-pressure chamber having means including a high-vacuum chamber for introducing a charged particle beam at one end and for permitting exit of the same at its other end through beam-permeable window means, means for maintaining a predetermined glow discharge in said low-pressure chamber, means disposed proximal to the window means for monitoring the charge density at a region thereof, and means controlled by the monitoring means for varying the said glow discharge in said low-pressure chamber in accordance with the density monitored by said monitoring means.

11. Apparatus for controlling charged relativistic particle beam density over a predetermined area having, in combination, a gas-containing low-pressure chamber having means including a high-vacuum chamber for introducing a charged particle beam at one end and for permitting exit of the same at its other end through beam-permeable window means, means disposed proximal to the window means for monitoring the charge density at a region thereof, and means controlled by the monitoring means for varying the conductivity of the said gas in the said low-pressure chamber in accordance with the density monitored by said monitoring means.

12. A method for controlling the charged relativistic particle beam density over a predetermined area of a beam-permeable exit window of a gas-containing low-pressure chamber, into which chamber high intensity charge-particle beam impulses are introduced from a high-vacuum chamber, said method comprising, propagating said introduced beam through said low-pressure chamber as a drift space to the exit window, subjecting the beam to image charge force distribution along the low-pressure chamber to control self-focusing of the beam, monitoring the beam density near said exit window, and controlling at least one of the gas pressure and gas conductivity within said low-pressure chamber in response to said monitoring.

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