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INTO AN INHOMOGENEOUS MAGNETIZED PLASMA

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Abstract

INJECTION OF A RELATIVISTIC ELECTRON BEAM INTO AN INHOMOGENEOUS MAGNETIZED PLASMA.

The interaction of a high-power relativistic electron beam (REB) with an inhomogeneous magnetized plasma has been investigated. The REB (400 keV, 10 kA, 70 ns) is injected along the magnetic field into a plasmoid ($n \leqslant 5 \times 10^{13}$ cm^{-3}), which is generated near the anode of the high-voltage diode and moves in the same direction as the REB. By varying the time delay t_D between the plasma and beam injections, it is possible to vary both the length and the longitudinal density profile of the plasma column into which the beam is injected. Propagation of the REB through the system and plasma heating are examined for various t_D. The maximum heating (diamagnetic signal corresponding to $nE_{\perp}S = 5 \times 10^{17}$ eV·cm^{-1}) is observed if the plasma column is not in contact with the collector plate. At least 10% of the injected beam energy is transferred into the plasma. Energetic charge-exchange neutrals escaping radially from the plasma indicate the presence of ions with energies up to 30 keV. Formation of a virtual cathode and partial reflection of the beam electrons are observed. A one-dimensional theoretical model of a system with the virtual cathode has been investigated. The feasibility of the accumulation of relativistic electrons within the plasma column and the acceleration of the ions at the plasma-vacuum boundary are demonstrated.

INTRODUCTION

In the search for possibilities promising a higher efficiency of REB energy deposition in a magnetized plasma, arrangements with beam electrons re-entering the plasma seem to be attractive. The beam electrons can be reflected most simply if they create a virtual cathode at the plasma-vacuum boundary. Then, the plasma column must not be in contact with the end plate of the vacuum chamber, the injected beam current has to exceed the vacuum value and radial losses should be suppressed by a strong longitudinal magnetic field. Besides the higher density of the energetic electrons interacting with the plasma column, also acceleration of plasma ions to high energies in the region of the virtual cathode is to be expected. Moreover, the theoretical analysis of a system with virtual cathode suggests that effective accumulation of relativistic electrons can be achieved within a plasma.

In what follows, starting with the description of the experimental device, data on the transmission of the REB under various plasma configurations and results of plasma heating investigations are presented. Further, we report on the formation of a virtual cathode and the occurrence of reflected beam electrons. Basic theoretical ideas and results concerning both the high-voltage diode and the region of the virtual cathode in the presence of accumulated beam electrons are sketched in the last part of the paper.

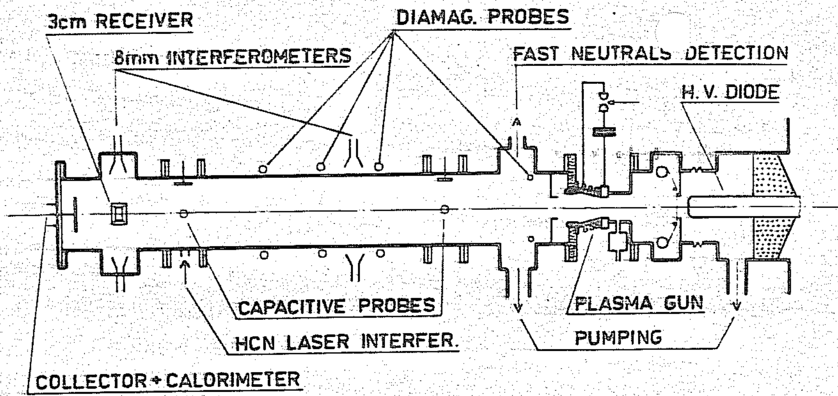

FIG.1. Schematic diagram of Rebex device.

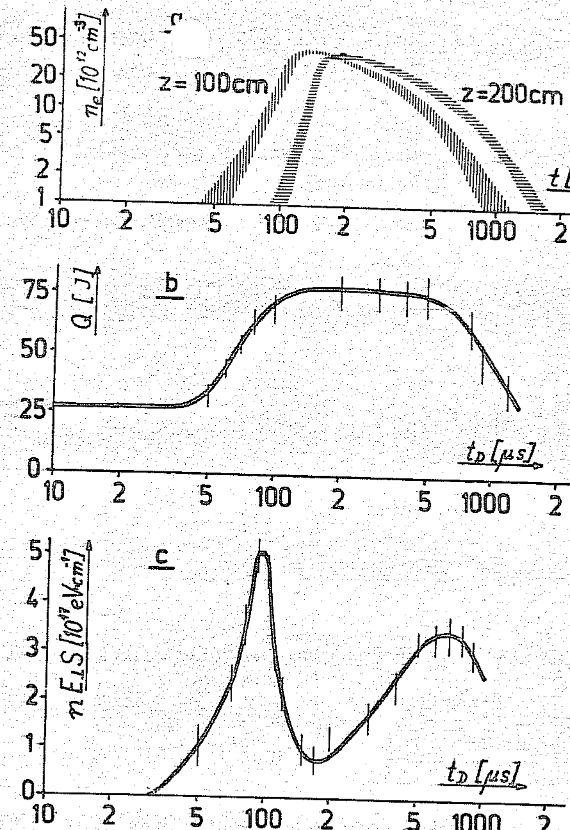

FIG.2. a) Temporal behaviour of plasma density $n_e(t)$ measured at distances $z_1 = 100$ cm and $z_2 = 200$ cm from the high-voltage diode.
b) Total beam energy transmitted through the system Q versus time delay t_D.
c) Transverse energy of plasma $nE_\perp S$ as a function of the time delay t_D, $B_0 = 4.5$ kG.

APPARATUS

Experiments have been performed on the Rebex machine schematically shown in Fig.1. A plasmoid generated by a modified conical plasma gun is injected into a magnetic mirror trap. A fully ionized front of the hydrogen plasma moves with a velocity of $2–8 \times 10^6$ cm·s^{-1}, the maximum density reaches 5×10^{13} cm^{-3}. The conducting vacuum chamber is 15 cm in diameter and 200 cm long. The magnetic field in the homogeneous part can be varied up to 9 kG, the mirror ratio being 1.5. The REB is injected axially in the same direction as the plasma with some time delay t_D. The electron accelerator consists of a Marx generator driving a $2 \times 8\Omega$ water-filled strip pulse line which feeds a diode. It is capable of producing a 30-kA pulse of 500-keV electrons lasting 70 ns. The beam current, however, was kept below 10 kA. The high-voltage diode consists of the cathode 28 mm in diameter and a 30 μm thick Al anode foil. By varying t_D it is possible to vary both the length and the longitudinal density profile of the plasma column. Thus, regimes with the plasma well separated from the end plate of the vacuum chamber can be adjusted, too.

Plasma diagnostics includes microwave and laser interferometry (8 mm; 0.337 mm), diamagnetic loops, capacitive probes, X-ray and microwave detectors and a time-of-flight energy analyser of charge-exchange neutrls. The beam diode voltage U_b and current I_b are measured by voltage dividers and shunts. The current and the total energy of the beam leaving the system are recorded by a collector with a calorimeter. Witness plates are used for detection of the REB cross-sections.

BEAM TRANSMISSION

The temporal evolution of the plasma density measured at two distances from the REB entrance ($z_1 = 100$ cm, $z_2 = 200$ cm; plasma front velocity 2×10^6 cm·s^{-1}) are shown in Fig.2a. At times $t < 50$ μs the plasma density near the collector is negligible. Within the time interval 100–600 μs, the plasma fills the whole interaction region, its density being at least by an order of magnitude higher than the beam density. At even longer times, the plasma density decreases becoming, at first, comparable to that of the REB near the plasma gun.

In Fig.2b, the total REB energy transmitted through the machine versus the time delay t_D is plotted. For $t_D < 50$ μs, the transmitted energy of 25 J and the collector current of 1 kA correspond to the critical vacuum values, in good agreement with theoretical estimates. The best beam transmission is achieved at time delays $t_D \doteq 100 - 600$ μs, the maximum transmitted current (about 5 kA) being roughly half of the diode current. Additional measurements prove that the current is lost in the plasma gun region only. At $t_D > 600$ μs, an additional ionization takes place during the REB injection. In the transition regime (50 μs $< t_D < 100$ μs) the transmitted REB energy increases gradually. The collector current exhibits a deep modulation and is sometimes split into several peaks.

The witness plate placed at the collector shows that the vacuum beam being rather hollow reproduces the cross-section of the cathode (Fig.3a). At $t_D = 100 - 600$ μs, the REB transmission is accompanied by deformation and radial displacement of the beam comparable with its initial radius (Fig.3c). In the transition regime the beam remains almost co-axial, but energetic electrons are detected also at large radii (Fig.3b).

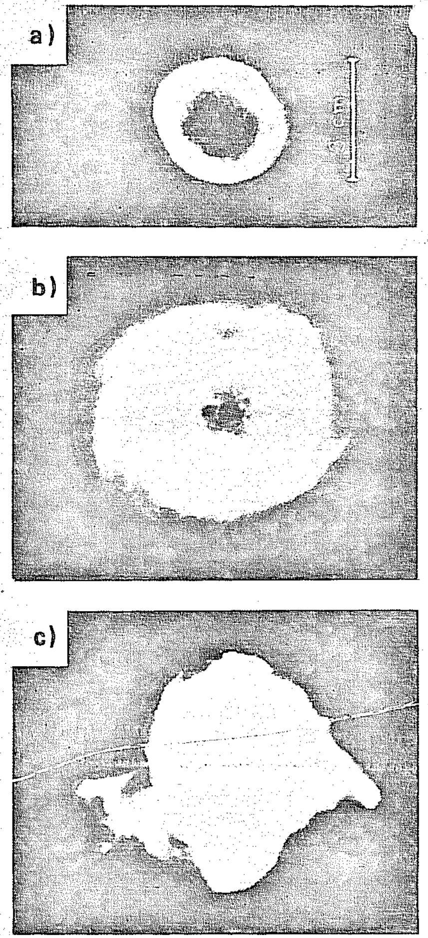

FIG.3. Cross-section of the REB recorded by witness plates:
a) vacuum beam;
b) transition regime;
c) dense plasma regime.

PLASMA HEATING

The efficiency of plasma heating by the REB was investigated for various time delays t_D. Strong microwave radiation in the X-band is observed during the injection. The detected soft X-rays last substantially longer. More detailed information on the plasma heating is obtained from diamagnetic measurements. The diamagnetic signals are composed of two parts. The first short pulse of higher amplitude follows roughly the shape of the collector current. Its typical value $nE_\perp S = 10^{18}$ eV·cm^{-1} suggests that the beam transverse energy $E_{b\perp}$ is only several times less than the total beam energy E_b. This relatively high perpendicular energy has its origin in the beam-plasma interaction since no measurable signal is observed if the REB is injected into vacuum.

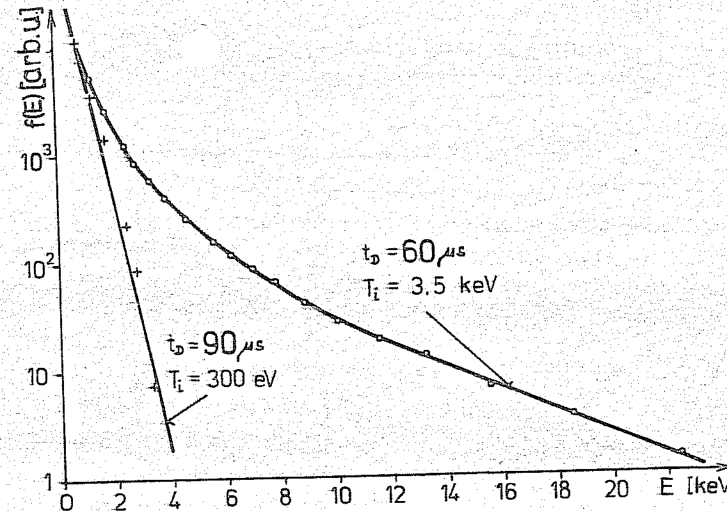

FIG.4. Distribution functions of charge-exchange neutrals measured at $t_D = 60\ \mu s$ and $t_D = 90\ \mu s$.

The slower component of the diamagnetic signal lasts for several microseconds. The dependence of its amplitude on the time delay t_D (Fig.2c) exhibits two maxima. The second maximum ($t_D \approx 700\ \mu s$) corresponds to the injection into a decaying, almost homogeneous plasma ($n < 10^{13}$ cm^{-3}; $I_b = 5$ kA). The first maximum, on the other hand, is achieved at the injection into a strongly inhomogeneous plasma ($t_D \approx 90\ \mu s$). No diamagnetic signals are observed if the plasma column is shorter than 60 cm ($t_D < 30\ \mu s$).

The maximum diamagnetic signals indicate that the plasma heating efficiency is at least 10%. The experimental conditions (low injected beam current) and X-ray observations suggest that, preferentially, plasma electrons should be heated. An energy analysis of fast charge-exchange neutrals, however, indicates that also some ion heating occurs for $t_D = 50 - 600\ \mu s$. The fastest particles (up to 30 keV) are observed for $t_D = 60\ \mu s$. The maximum energy, in the keV range, falls very slowly for $t_D \geqslant 90\ \mu s$. Two typical distribution functions are plotted in Fig.4. It is apparent that for $t_D = 60\ \mu s$ the distribution is not Maxwellian. The total number of fast particles is by an order of magnitude higher for 90 μs. Nevertheless, in both cases, the estimated amount of hot ions is too low for the values indicated to be the ion temperatures. These results are supported by measurements using an electric probe placed near the chamber wall.

VIRTUAL CATHODE

If there is a vacuum gap between the plasma and the collector ($t_D \leqslant 70\ \mu s$), a capacitive probe located in this region measures a potential comparable to the cathode voltage. Simultaneously, the witness plate mounted on the back side of the entrance diaphragm detects backward electrons originating at the plasma-vacuum boundary. For larger t_D, both these phenomena disappear. It seems, therefore, reasonable to attribute them to the formation of a virtual cathode and to partial reflection of the beam electrons.

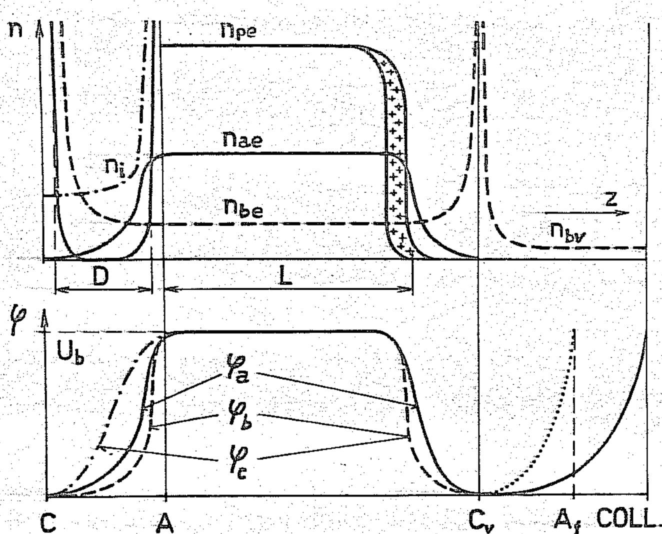

FIG.5. Schematic drawing of particle and potential distributions along the magnetic field in systems with virtual cathode.

THEORETICAL MODEL

If we study a simple model of a system with a virtual cathode, we realize that the reflected beam electrons can be effectively accumulated inside the plasma column and, simultaneously, acceleration of ions to high energies can occur at the plasma-vacuum boundary. The corresponding particle and potential distributions along the magnetic field are schematically drawn in Fig.5. Four relatively autonomous regions can be distinguished: the high-voltage diode, the plasma column (including the foil), the plasma-vacuum boundary and the vacuum beam region.

Electrons with density n_{be} are extracted from the cathode plasma. After reflection from the virtual cathode C_v, a fraction of these electrons adds to the accumulated electrons having the density n_{ae}. Subsequently, ions with the density n_i are extracted from the anode plasma towards the cathode C. If the plasma density $n_p \gg n_{be}, n_{ae}$, the plasma potential φ remains very close to the anode potential U_b. At the plasma-vacuum boundary, the course of $\varphi(z)$ is determined by the energetic electrons and by the accelerated plasma ions. To include qualitatively the vacuum current into the one-dimensional model, we add a fictive anode A_f placed at a certain distance behind the plasma-vacuum boundary.

If the plasma length exceeds the anode-cathode distance ($L \gg D$), the electrons in the high-voltage diode and in the virtual cathode are distributed quasi-stationarily for times longer than 2L/c. Their distribution functions are then determined by that in the plasma region and (in the diode) by the diode current. As the reflected electrons are decelerated and elastically scattered both in the plasma and in the foil, the density n_{ae} is a growing function of the potential φ being zero at the cathode $\varphi = 0$. The density of the beam electrons, on the other hand, behaves as

$$n_{be}(\varphi) \sim \varphi^{-\frac{1}{2}} \quad \text{for} \quad e\varphi \ll m_e c^2; \quad n_{ae}(\varphi = 0) = 0 \tag{1}$$

Three regimes of operation of the high-voltage diode seem to be of most interest:
(a) Diode without accumulated electrons ($n_{ae} = 0$, curve φ_a).
(b) Reflex diode ($n_{ae} \neq 0$) without ions ($n_i = 0$, curve φ_b).
(c) Reflex diode ($n_i \neq 0$) with quasi-stationarily distributed ions freely extracted from the anode plasma (i.e. $L^2 \gg D^2 m_i/m_e\gamma_0$ curve φ_c).
In all the cases the Poisson equation can be integrated as follows:

$$D(t) = \int_0^{U_b} \left[8\pi e \left[\int_0^{\varphi} (n_{be}(\varphi',t) + n_{ae}(\varphi',t))d\varphi' - \delta_{ie}\left(1 - \sqrt{\frac{U_b - \varphi}{U_b}}\right) \times \int_0^{\varphi} (n_{be}(\varphi,t) + n_{ae}(\varphi,t))d\varphi \right]\right]^{\frac{1}{2}} d\varphi \tag{2}$$

The time dependence of the cathode-anode distance D(t) is due to the motion of the cathode and anode plasma sheets; $e > 0$, $\delta_{ie} = 0$; 1 ad a), $\delta_{ie} = 0$ ad b), $\delta_{ie} = 1$ ad c).
a) In the case $n_{ae} = 0$, we obtain the modified Child-Langmuir solution

$$n_{be}(D) = n_{bl}(D) \equiv \frac{U_b}{\pi e D^2 \alpha}\left[1 + (\sqrt{2} - 1)\delta_{ie}\right]; \quad \alpha \to 9 \text{ for } \gamma_0 - 1 \ll 1, \quad \alpha \to 2 \text{ for } \gamma_0 \gg 1 \tag{3}$$

The ion extraction increases the diode current by a factor of $\sqrt{2}$ only.

(b) If $n_{ae}(D) \gg n_{bl}(D)$ and $\delta_{ie} = 0$ the accumulated electrons have to be concentrated near the anode foil and the diode current is strongly suppressed ($n_{be}(D) \ll n_{bl}(D)$). As, however, conditions for ion extraction from the anode plasma are significantly improved, the following regime should be established rapidly:

(c) In the reflex diode with $\delta_{ie} = 1$ the total number of extracted ions is significantly increased if $n_{ae}(D) \gg n_{bl}(D)$. As the ions reach the cathode region, also extraction of electrons is substantially increased and the diode current can exceed the Child-Langmuirs value ($n_{be}(D) > n_{bl}(D)$). The role of ions is manifested most expressively if only the elastic scattering of the beam electrons is respected. Then, $n_{be}(D) \to 0$ for $\delta_{ie} = 0$, whereas $n_{be}(D)$ grows exponentially for $\delta_{ie} = 1$ at large times for U_b and D fixed.

All theoretical conclusions are based on the assumption that a stable virtual cathode is formed. Analytical estimates predict the possibility of an increase in the density of the energetic electrons inside the plasma, at least by one order of magnitude, and a systematic acceleration of the ions from the plasma-vacuum boundary up to energies exceeding several times eU_b. The total number of ions increases with increasing efficiency of accumulation of the beam electrons. Regimes optimum for either ion acceleration or electron accumulation could be adjusted, e.g. by choosing the proper type of ions in the plasma and in the diode regions. The energy of accumulated electrons can be released in a short pulse of roughly 2L/c duration if the virtual cathode breaks down rapidly. As this cathode moves with the velocity of accelerated ions, the observed large peaks in the collector current could be attributed to its spontaneous breakdown in the transition regime.

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