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Measurement of Plasma-Neutralized Super-Vacuum Currents in a Gyrotron Configuration

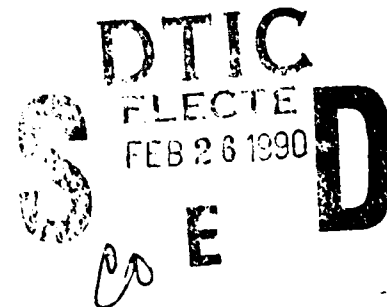
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Measurement of Plasma-Neutralized Super-Vacuum Currents in a Gyrotron Configuration

A high power microwave device typically consists of an intense relativistic electron beam driving a beam-wave interaction in an evacuated cavity or interaction volume. This includes slow-wave devices such as backward-wave oscillators (BWO)^{1,2} and relativistic klystrons, and fast-wave devices such as gyrotrons^{3,4} and free-electron lasers^{5,6}. A fundamental limit to the power of such devices can be obtained by multiplying their theoretical interaction efficiency by the maximum beam power that can be propagated. For a particular voltage and geometry, the maximum beam power is set by the vacuum limiting current. This limit on the beam current arises from the fact that the electron beam loses an amount of energy corresponding to the capacitive voltage drop between the electron beam and the conducting boundary.

Recently there has been much interest in exceeding the space-charge limit in high power microwave devices, notably the gyrotron and BWO^{7,8,9}. The space-charge limit is severe in the gyrotron due to the nature of the gyrotron interaction, which is more favorable when the beam α is large ($\alpha = \beta_{\perp}/\beta_{\parallel}$, the ratio of perpendicular to parallel velocities). The space-charge limiting current for a cold annular beam of vanishing thickness is given by¹⁰

$$I_{L0} = I_A \frac{\gamma_0 [1 - (1 - \beta_{z0}^2)^{1/3}]^{3/2}}{2 \ln(R_w/R_{beam})} \quad (1)$$

where I_A is the Alfven current (17.07 kA), $\gamma_0 = 1 + (eV_0/m_0c^2)$ is the relativistic factor associated with the electron energy in the absence of any space-charge depression, $\beta_{z0} = v_{z0}/c$, v_{z0} is the electron axial velocity prior to any space-charge depression, R_w is the radius of the conducting boundary, and R_{beam} is the radius of the electron beam. The large beam α which is desirable for operation of the gyrotron corresponds to low β_{z0} , and therefore low limiting currents.

One possible means to circumvent this obstacle is to use a neutral background plasma to short out the self-electric field of the electron beam. This concept of a neutralizing

background plasma has been investigated extensively in the Soviet Union⁷, and has recently been the focus of some investigations with regard to the BWO⁹. In order for the background plasma to cancel the effects of the electron beam self-electric field, the density of the neutral plasma must be greater than the density of the beam electrons, so that sufficient background electrons may be expelled from the region of the transiting electron beam to provide for space-charge neutralization.

In this paper we report on the achievement of super-vacuum currents (beam currents in excess of the vacuum space-charge limit) in a configuration directly applicable to gyrotron oscillators. The experimental arrangement is shown in Fig. 1. The VEBA pulseline accelerator ($V \sim 0.6 - 2.5$ MV, $I \sim 20 - 100$ kA, $\tau \sim 60$ ns) is used to energize an electron gun which produces an annular electron beam. The electron gun consists of a hollow cylindrical cathode and an anode mask with an annular aperture. Both the cathode and the anode are fabricated from reactor-grade graphite. The annulus in the anode mask has an inner radius of 1.6 cm and an outer radius of 1.9 cm. The cathode-anode gap is 2.1 cm. Directly downstream from the anode mask is a Rogowski coil which measures the emitted beam current on each accelerator pulse. Immediately following is an array of four plasma guns¹¹, equally spaced in azimuth. The plasma guns are individually energized by an array of four $0.22 \mu\text{F}$ capacitors which are typically charged to 14 kV. The entire system is immersed in a uniform 10 kG axial guide magnetic field, produced by an external solenoid. In addition, as shown in Fig. 1, there is a field reversed, thin-solenoid "dip" magnet which is used to spin up the electron beam¹², and a Helmholtz pair positioned symmetrically about the cavity region. In these experiments the cavity region is composed of a simple straight wall drift space. The magnetic field in the center of the cavity region is 29 kG.

The plasma density produced in the cavity region has been characterized by 70 GHz quadrature microwave interferometry and by time-integrated photography of the light emitted by the plasma. The photographs of the light emitted by the plasma in the cavity region indicate that while the plasma is relatively uniform in the azimuthal direction, significant

non-uniformity exists in the radial direction, with the peak density being close to the cavity wall. Close inspection of the interferometry data shows the presence of cutoff-level densities early in the plasma pulse, when the line-averaged plasma density is computed to be about 10^{13} cm^{-3} . Since the plasma cutoff for our 70 GHz interferometer occurs at $n_p = 6 \times 10^{13} \text{ cm}^{-3}$, this would suggest peak densities on the order of a factor of five greater than the line averaged densities. The data presented here are obtained with line-averaged plasma densities in the range $1.5 - 5 \times 10^{11} \text{ cm}^{-3}$, corresponding to peak background plasma densities in the range $0.8 - 3 \times 10^{12} \text{ cm}^{-3}$.

The achievement of super-vacuum currents is demonstrated by measuring the beam current transported through the cavity region with and without the background neutralizing plasma, while varying the amplitude of the "dip" magnet. This data is shown in Fig. 2(a), where we plot the measured cavity current against the amplitude of the "dip" magnet for both the vacuum and plasma-neutralized cases. For the plasma-neutralized case the data represent the maximum measured signals across a sample of neutral plasma densities. This step is necessary because with too little plasma background the beam is not neutralized, while with too much plasma background the beam current is partially neutralized and the Rogowski measurement gives an artificially low account of the beam current. Similarly, as the "dip" magnitude increases the average beam axial velocity decreases, which results in an increase in the local number density of beam electrons. The higher number density of beam electrons requires a greater background plasma density to provide for neutralization. The variation of the plasma density is achieved by varying the time delay between the firing of the plasma guns and the firing of the accelerator. For our measured beam parameters, and using the estimated beam alpha, the peak number density of the beam electrons is in the range $1 - 3 \times 10^{12} \text{ cm}^{-3}$. Combined with our previous estimate of the relative non-uniformity of the neutral background plasma, the condition for neutralization of $n_b \approx n_p$ appears to be well met.

The variation of α with the amplitude of the dip magnet is shown in Fig. 2(b). Here

we plot the average and spread in α for the calculated trajectories of an ensemble of non-interacting particles, using the measured magnetic fields and electron beam voltage. The calculated transmitted current for these single particle ensembles is shown in Fig. 2(a) as the "mirror limiting current". In this case, the loss of current is due wholly to mirroring of individual particles in the region of the magnetic compression. It can be seen that there is good agreement between this curve and the measured data for the plasma neutralized case. Similarly, we can use the calculated beam alpha to calculate space-charge limiting current for a zero-temperature beam of non-zero thickness¹⁰, and the space-charge limiting current for a zero-thickness beam with a non-zero thermal spread in velocity¹³. These curves are shown in Fig. 2(a) as $I_{SC}(\Delta r)$ and $I_{SC}(\Delta \alpha)$, respectively. Both curves are seen to agree reasonably well with the measured data for the vacuum case. It should be noted that for pump amplitudes corresponding to an average beam α of 1 to 2, the presence of the neutralizing plasma results in an increase in the beam current propagated through the cavity by a factor of about three.

The calculations of $I_{SC}(\Delta r)$, $I_{SC}(\Delta \alpha)$, and the mirror limiting current shown in Fig. 2(a) are obtained using a very simple electron beam distribution function. The inner and outer radii of the electron beam correspond to the inner and outer radii of the anode mask aperture. The velocity distribution assumes a uniform spread in initial diode α ranging from 0 to 0.1. This range gave good agreement for both the roll-over point of the mirror limiting current, and for the space-charge limited current in the case of no pump field. Deviations of the theoretical curves from the data, for both the vacuum and plasma-neutralized cases, are probably due to the details the electron beam distribution function which are grossly simplified in the calculations. Further, no accounting has been made of the possibility of diamagnetic effects associated with the high- α beam, nor do the calculations consider the effect of space charge on the "spinning up" of the electron beam by the pump magnet.

In conclusion, we have demonstrated transport of beam currents in excess of the vacuum space-charge limit in a plasma-filled, gyrotron type cavity. For values of the beam alpha in

the range of 1 to 2 the increase in electron beam current is approximately a factor of three. Comparison of the measured transmitted vacuum current with the theoretical vacuum space-charge limited current shows good agreement. In the case of the plasma neutralized measurements, we obtain good agreement from a simple calculation of magnetic mirroring of an ensemble of non-interacting electrons, where the ensemble is taken to represent a uniform, low initial temperature, annular beam of radial dimensions given by the anode mask. The higher intra-cavity beam currents achieved with the aid of the neutralizing background plasma should enable higher power operation in existing intense beam gyrotron designs¹⁴.

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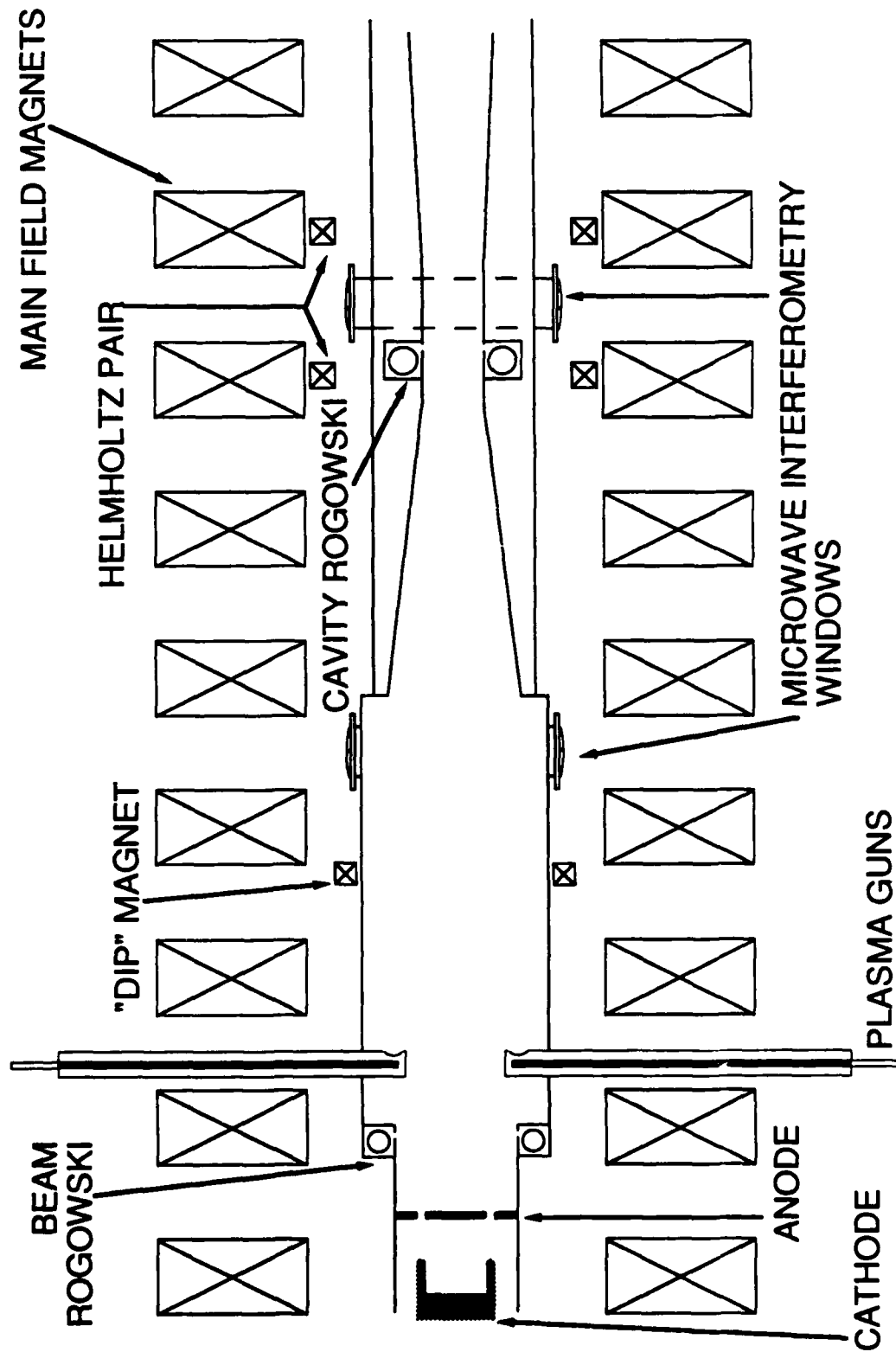


Fig. 1. The schematic layout of the VEBA plasma-neutralized gyrotron experiment, showing the magnet positions, inner conducting wall, vacuum chamber, microwave interferometry windows, plasma guns, and cathode-anode positions.

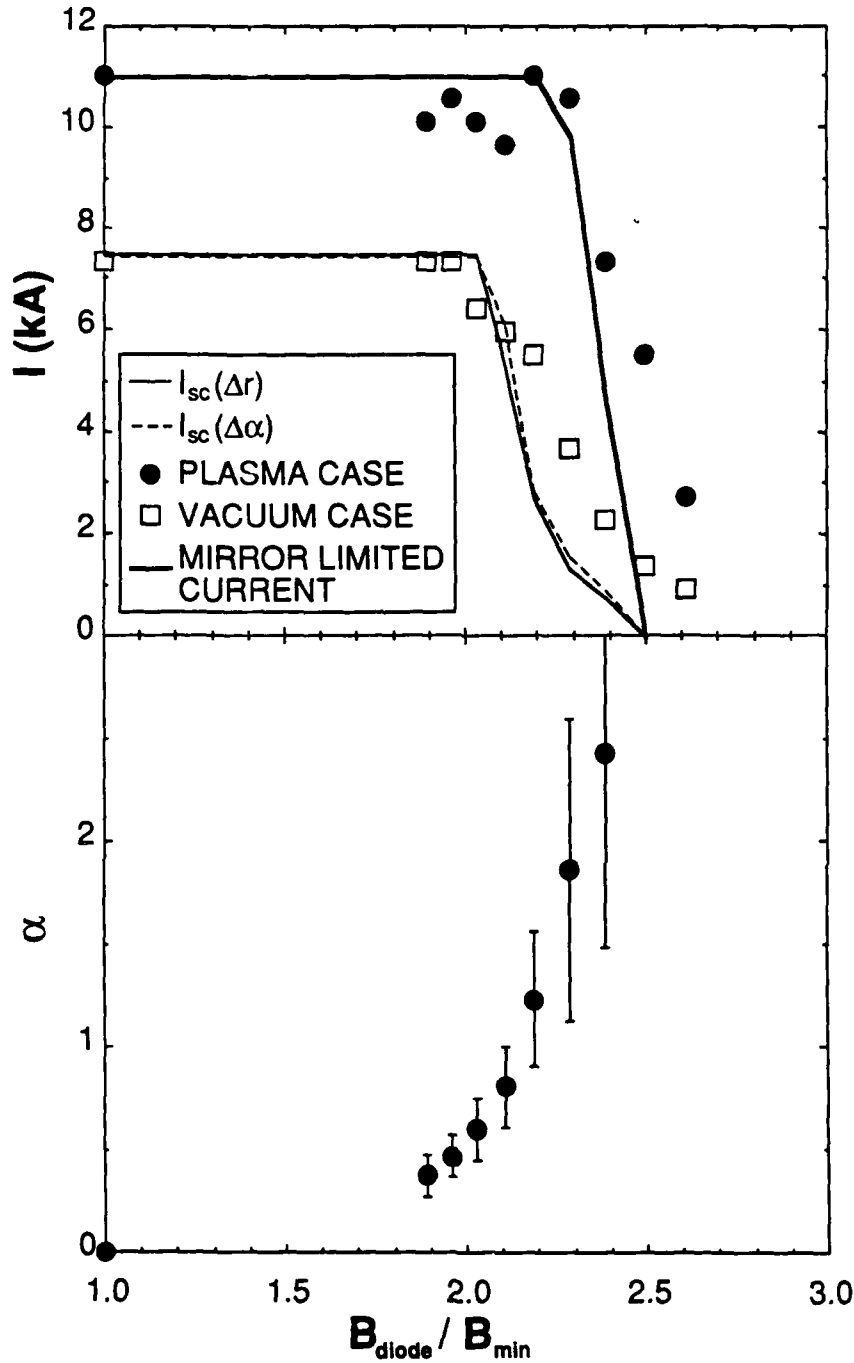


Fig. 2. The current measured by the Rogowski coil positioned in the cavity region, for the vacuum case (open circles) and for the plasma-neutralized case (solid circles), shown with the calculated vacuum space-charge limiting current for a beam of non-zero thickness (dotted line), the calculated vacuum space-charge limiting current for a beam with non-zero thermal spread (thin line), and the calculated transmitted current for an ensemble of non-interacting electrons (bold line).

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