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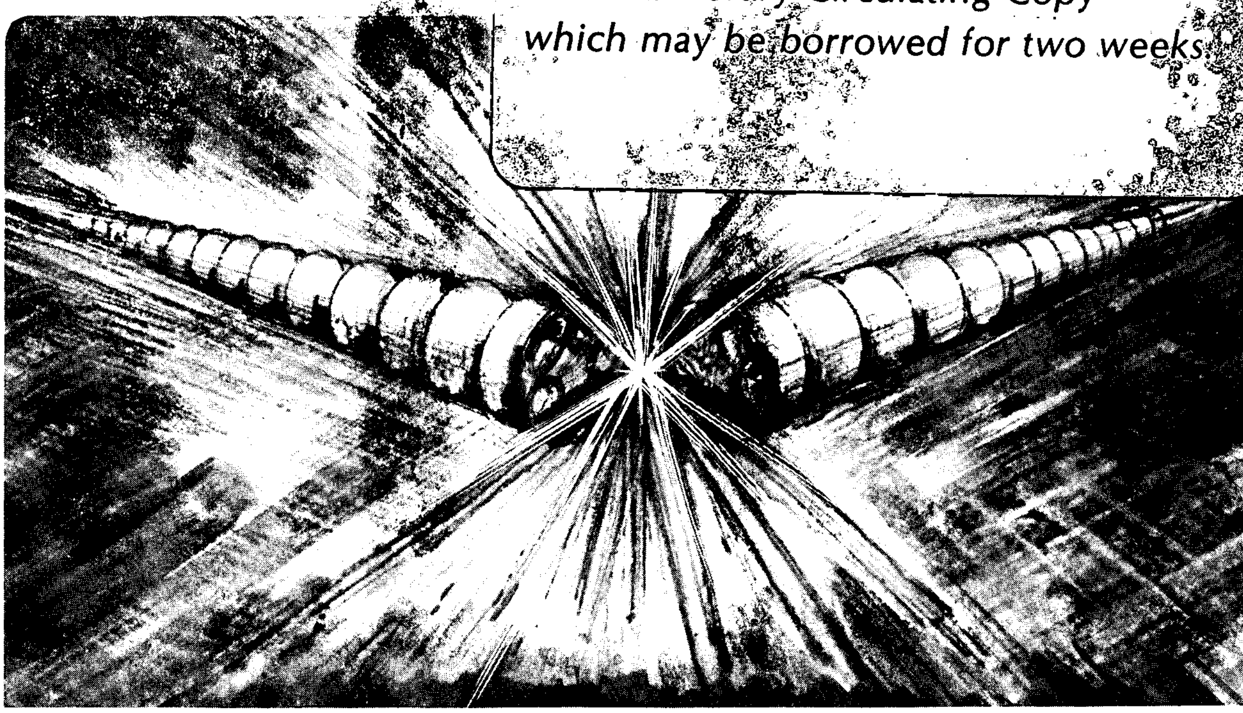

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EFFECT OF RESONANT MICROWAVE POWER ON A PIG ION SOURCE*

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ABSTRACT

We have investigated the effect of applying microwave power at the electron cyclotron frequency on the characteristics of the ion beam extracted from a hot-cathode PIG ion source. No change was seen in the ion charge state distribution. A small but significant reduction in the beam noise level was seen, and it is possible that the technique may find application in situations where beam quiescence is important.

INTRODUCTION

In a PIG ion source the plasma is a reflex arc discharge in which the electrons are confined radially by a uniform magnetic field and axially by the electrostatic well established between the two cathodes by a hollow anode. Ionization of the feed gas occurs by electron impact of the reflexing primary electrons. Stepwise ionization to successively higher charge states occurs, and the equilibrium ion charge state distribution is determined by the product *nt* of primary electron density and ion residence time within the discharge, and by the primary electron temperature T_e. The PIG ion source is well understood, and a review of PIG performance for multiply charged heavy ion production has been given by Bennett[1].

The electron component of a plasma can be heated by coupling rf power at the electron cyclotron frequency into the plasma. The electron cyclotron frequency is given by $\omega_{ce} = eB/m$ where *e*, *m* are the electron charge and mass and *B* the magnetic flux density; for convenient fields of a few kilogauss the resonant frequency is in the microwave regime. In this kind of plasma - the ECR plasma [2,3] - the electrons can gain substantial energy from the microwave field; electron energies of over 1 Mev can be produced under the appropriate conditions. In an ECR plasma, the hot electrons provide a stripping medium for the confined ions, and a source of multiply stripped ions can be made in this way. This is the basis of the ECR ion source developed over the last decade or so[4,5,6].

It is thus a natural speculation to consider what effect, if any, might be induced by superimposing microwave power at the ECR condition onto a standard PIG ion source. Even though the parameters of the PIG plasma are far from ideal for good ECR coupling into the plasma, nonetheless the concept is intriguing and warrants a closer look. Effects that one might hope for would include (a) enhanced ion beam output due to increased ionization within the source, (b) an upward shift of the charge state distribution due to increased electron temperature, (c) a reduction in beam current fluctuation level due to stabilization of the PIG plasma by the surrounding warm plasma.

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THEORETICAL BACKGROUND

Microwave power will couple into a magnetically confined plasma when the microwave frequency equals the electron cyclotron frequency, $\omega = \omega_{ce}$. In the classical scenario it is also necessary that the wave frequency be greater then the electron plasma frequency, $\omega > \omega_{pe} = (n_e{}^2 / em)^{1/2}$, in order that the wave be able to propagate. For electron densities above the critical density, $n_c = em\omega^2 / e^2$ the 'ordinary mode' ($E \parallel Bo$, $k \perp Bo$) does not propagate in the infinite, homogeneous, linear plasma theory[7].

It is important to note, however, that results have been reported by a number of workers indicating efficient coupling of microwave power into the plasma at densities many times the critical density[8-16]; such a plasma is called 'overdense'. Overdense plasmas have been observed over a wide range of experimental conditions, and an equally wide range of theoretical explanations has been proposed to explain these anomalous results. These theories have included non-linear absorption due to high rf field strength[17-19], finite geometry effects[20], upper hybrid absorption[21], and wave transformations[22-24]. Thus a substantial body of both experimental and theoretical research exists which indicates that efficient coupling of microwave power to a plasma can occur even for the case when the plasma is substantially overdense. Certainly, however, this behavior is not well understood; it is problematical.

Quite apart from bulk electron heating, microwave power can couple into the low density plasma regions around the periphery of the primary reflex arc discharge. In this manner, warm plasma may be created in the end regions, between the central plasma and the hot cathodes at either end. This warm plasma may serve to enhance electron mobility along the magnetic field lines between the main plasma body and the conducting end-plates, thus providing a means of suppressing the growth of transverse electric fields and associated plasma noise. This stabilization mechanism, provided by low density background plasma, is of pertinence to mirror-confined plasma experiments; it has been studied theoretically[25,26] and observed experimentally[27]. In the present case there might be some reason for expecting a reduction in the noise level of the extracted ion beam due to this effect.

In all of these above considerations we are assuming that the electrons are confined long enough for them to gain an appreciable amount of energy from the microwave electric field. In the usual situation this requirement is satisfied by virtue of the mirror magnetic field[28] in which the plasma is confined. Electrons reside within the mirror for a large number of transits back and forth through the resonant zones, gaining energy at each transit. In the present case, however, the magnetic field is uniform and there is no axial magnetic confinement. We must rely completely on the electrostatic well in which the plasma resides. This is a unique and unusual situation, and this geometry may not support electron cyclotron resonance heating to any significant extent.

THE EXPERIMENT

Our experiment was simply to couple microwave power into the plasma discharge region of a hot cathode PIG ion source and monitor the characteristics of the extracted ion beam. The PIG source was of the kind routinely used in the ABEL injector of the LBL SuperHILAC, and has been described in full by Gavin[29]. Here, the source was mounted in a test-stand and not in the injector. We operated the source in a non-sputtering mode using argon gas under fairly moderate operating conditions. We ran in a pulsed mode, with pulses several milliseconds long at a repetition rate of about 30 Hz.

Microwave power at 10.6 GHz and typically 100 Watts was coupled into the reflex arc discharge cavity via a small loop antenna terminating a solid-jacket coaxial cable. The loop was in the transverse plane (referred to the static, homogeneous magnetic field of strength about 3.8 kG in which the PIG was located) so as to maximize coupling into the transverse electric field component. The loop was housed in a partially recessed location so as to minimize the amount of plasma actually within the loop itself, while still allowing the antenna to couple into the entire arc chamber. A schematic drawing of the source with antenna is shown in Figure 1.

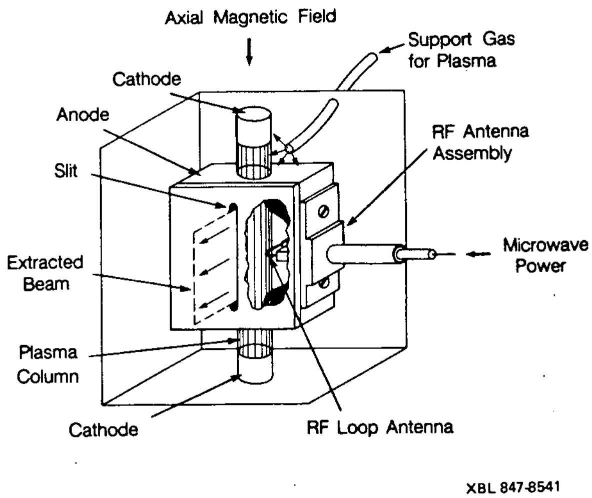

Fig. 1. Schematic drawing of the PIG source showing the manner in which microwave power is coupled into the cavity.

It is important to note that the plasma electron density is way above the critical density. The electron density in the core of the PIG plasma is in the range 10^{13} - 10^{15} cm^{-3} [30,31,32], while the critical density for a microwave frequency of 10.6 GHz is 1.4 x 10^{12} cm^{-3}. Thus the plasma is highly overdense, $n/n_c \sim 10$ - 10^3, and coupling of microwave power into the main body of the plasma is to be expected only via anomalous processes. There may still be, however, some power transfer into the lower density boundary plasma regions.

With this configuration the source was operated and the argon ion beam extracted, typically at 20 kV. The magnetically analyzed beam was monitored with a Faraday cup whose location within the magnet could be remotely moved so as to scan the complete charge state spectrum. The Faraday cup signal was monitored as the parameters of the experiment were varied - magnetic field strength, microwave power, cup position, gas feed, arc input power.

The charge state spectrum showed argon ions of charge q = 1 up to q = 9, with a peak intensity at q = 3. We saw no change in the spectral distribution with or without microwave power. This was the case for the entire parameter range over which we were able to search.

We noted a small decrease in magnitude of the Faraday cup signal when the microwave power was applied, for the case when we tuned to monitor the peak of a given charge state (ie, analyzed beam optimally entering the Faraday cup); and we saw a small increase in magnitude of the Faraday cup signal when the microwave power was applied, for the case when the tuning indication of a departure from optimum extraction optics due to the microwave power. Presumably the plasma is modified by the microwave power to some extent, perhaps in the anode slit through which ions are extracted, thus spoiling the extraction optics for which the parameters had been optimized.

We observed a significant effect on the beam noise. The extracted ion beam has a level of fluctuations, $\Delta i/i$, which is determined by the noise level of the PIG arc plasma. Depending on the operational parameters, the beam noise can vary from a low of around 10% up to as high as 100%. During the present experiments the noise level was typically about 20%. When the microwave power was applied the noise level was reduced. A swept spectral analysis of the Faraday cup signal over the frequency range 0 to 400 kHz, with and without microwave power applied, is shown in Figure 2. The reduction in noise is around 6 to 10 dB, but since the current itself is reduced by the microwave power by 3 dB (at most), the net improvement in $\Delta i/i$ is approximately 3 to 6 dB.

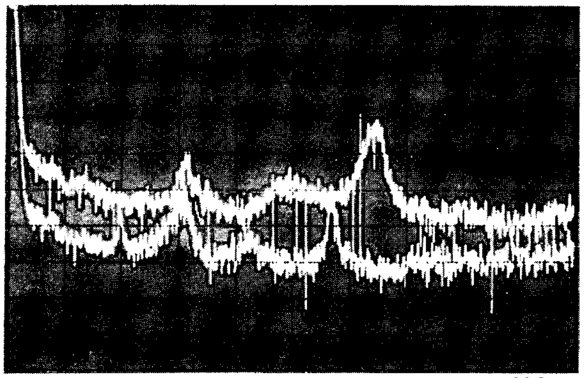

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Fig. 2. Spectral analysis of the fluctuations in ion beam current. Upper trace, without microwaves; lower trace, with microwaves. Vertical scale is noise amplitude, 5 dB/division. Horizontal scale is frequency, 0 to 400 kHz.

CONCLUSIONS

We have reported a simple experiment in which we've looked at the effect of coupling microwave power at the electron cyclotron frequency to a PIG ion source. We saw no change in the ion charge state distribution, and a small reduction in the extracted beam current which we ascribe to defocussing of the extraction. We saw a reduction in the beam noise, $\Delta i/i$, of around 3 to 6 dB.

Improvements that could be made in the future would include: operating at a higher microwave frequency; coupling the microwave power into the plasma differently; and especially, adding small magnetic mirrors to the PIG magnetic geometry so as to provide some hot electron confinement.

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