COUPLING MICROWAVE POWER INTO ECR ION SOURCE PLASMAS AT FREQUENCIES ABOVE 20 GHZ

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Abstract

Electron Cyclotron Resonance (ECR) ion sources have been built to operate at frequencies from 5 GHz to 28 GHz and typically use a plasma chamber that serves as a multi-mode cavity. For small sources operating at 6 to 14 GHz cavity mode-like behavior has been reported. In these cavities the vacuum mode density is low enough that it may be that the RF power distribution can be understood in terms of excitation of a few modes. The large superconducting ECR ion sources, such as VENUS[1] operating at higher frequencies have a much greater mode density and very strong damping from plasma microwave absorption. In this type of source, how the RF is launched into the plasma chamber will strongly affect the microwave coupling and the chamber walls will be less important.

The VENUS source uses over-sized round waveguide excited in the TE_{01} to couple to the plasma, while most modern fusion devices use quasi-gaussian HE_{11} waves for injection into plasmas. In this paper we will describe the potential advantages of applying this technology to superconducting ECR ion sources as well as designs for doing so with VENUS.

INTRODUCTION

In an ECR ion source the microwave power couples to the electrons through electron cyclotron resonance heating. The electrons are confined by a solenoidal magnetic mirror in the axial direction and by a multipole field, typically a sextupole, in the radial direction. The combined magnetic fields produce a closed surface where electron cyclotron resonance frequency equals the applied microwave frequency. The coupling can be modeled in the case of very low plasma density and single particle models. [2,3] This is generally done by assuming a microwave field distribution that is independent of the plasma density. One approach used is to assume the microwave fields are those of an undamped microwave cavity and to then assume only a single mode is excited. [4] For a cylindrical cavity, the cavity modes can be calculated and the RF electric fields determined. The typical unloaded Q of such a cylindrical cavity with aluminum walls is in the range of 2000 to 4000. On the other hand the damping of the plasma can lower this Q_o significantly and this will decrease the RF stored energy and the resulting RF electric fields.

To date neither experimental measurements nor calculations using the best simulation codes can accurately predict the actual microwave field distribution or even the level of stored energy in a ECR ion source with plasma loading. It is difficult to probe either the plasma density or the RF field strength in an ECR ion

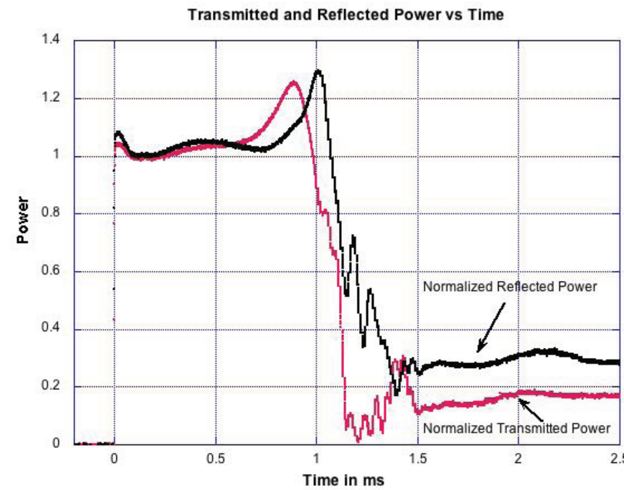

Figure 1: Time dependence of the reflected and transmitted 18 GHz power for the VENUS ECR ion source. At time t=0, the microwave power is switched on. As the plasma reaches maximum density at about 1 ms, the transmitted power decreases rapidly. Both reflected power and transmitted power are normalized to their initial values just after the power is switched on and before the plasma builds up.

source because if a probe is inserted into the chamber the hot electrons in the plasma will destroy it. With two microwave ports on the plasma chamber, both the reflected power on the input port and the transmitted out the second port can be measured. Since the stored microwave energy is proportional to the transmitted power, the relative stored energy versus time can be determined.[5] This was done with VENUS by injecting 18 GHz though the input port and detecting the transmitted power out the 28 GHz port. In Fig. 1 the time dependence of the reflected and transmitted microwave power is shown where the RF power is switched on at t equals 0 with zero plasma density in the chamber. The microwave fill time for the chamber is on the order of 1 μs while the plasma breakdown is on the order of 1 ms. At about 1 ms the plasma density increases rapidly and begins to load the cavity. At this point the transmitted power, which is proportional to the stored energy in the plasma chamber drops almost to zero as the plasma loading depresses it. At about 1.5 ms after some oscillations between the stored RF energy and the plasma density, the microwave fields reach a rough equilibrium. In the initial stage the empty plasma chamber acts as a high Q cavity (with a Q_o of a few thousand) and the high fields can produces a burst of hot electrons and ions in the preglow [6], but as the plasma loading builds up it drastically damps the RF stored energy by about 1/10 in this case. For CW operation, it is this reduced RF field

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level that continues to heat the electrons. The strong plasma damping means that we cannot view plasma as a small perturbation on the RF fields.

The second difficulty with assuming individually exited cavity modes comes from the fact that as the plasma damps the modes, their bandwidth becomes much wider than the average mode spacing and therefore the RF power can be distributed across many modes simultaneously.[7,8] For a small source such as CAPRICE-14 GHz the average mode spacing is 17.5 MHz [9,10] and once the cavity Q is less than 230, the modes will overlap. For low density plasmas and weak microwave coupling, it is possible to see quasi-single mode behavior in a low frequency, 14 GHz, small volume, .54 l cavity like CAPRICE.[8] For a large superconducting source such as VENUS with an operating frequency of 28 GHz and a volume of 9 l the situation is quite different. Since the mode density scales as inversely with the product of the volume times the square of the microwave frequency, in VENUS the average mode spacing is only 160 kHz, so that hundreds of modes will be simultaneously excited. This means for the large volume, high frequency sources the cavity model with a single or few microwave modes excited is not realistic.[10] For these reasons, we describe below a different approach based on studying the field distribution produced by the antenna as it launches a RF into the cavity and we can look at the field strengths in the first pass absorption.

RF COUPLING IN ECR ION SOURCES AND PLASMA FUSION DEVICES

A number of different approaches including coaxial antennas have been used over the years to couple microwave power into the plasmas of high charge state ECR ion sources. [11,12] In recent years, the most common approach to couple power from a klystron or TWT microwave generator is to use an off-axis rectangular waveguide, extending slightly into the plasma chamber from the injection end. The waveguides are typical just terminated by square cut. The rectangular waveguide is excited with a single TE_{11} waveguide mode, which has its RF electric field transverse to the axial magnetic field of the source. The 18 GHz waveguide system in the VENUS source was initially made this way, but it was modified to use a tapered termination of the waveguide as can be seen in Fig. 2. The tapered cut significantly reduced the reflected power in steady state and may also have increased the local RF field strength on axis at the ECR zone.

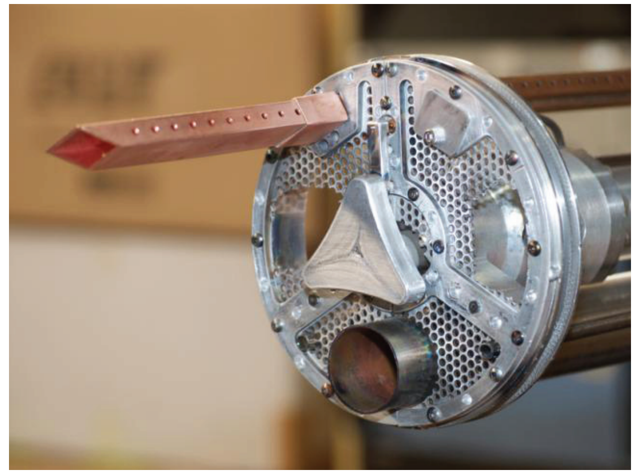

Figure 2: Plasma chamber injection system. Upper left shows the 18 GHz waveguide with a tapered termination. Bottom center is the 28 GHz waveguide injection. The triangular object in the center is the biased disk.

The 28 GHz microwave system for VENUS uses a transmission line that converts the TE_{02} mode produced by the 10 kW CW CPI gyrotron to a TE_{01} round waveguide mode, which is then transported about 4 meters and injected into the VENUS plasma chamber. The TE_{01} microwaves are launched through a simple terminated waveguide into the 9 l plasma chamber, which has a diameter of 144 mm and a length of 500 mm. This approach was chosen because TE_{01} mode has low attenuation. The working assumption was that the chamber walls would serve as a microwave cavity and the power would then couple effectively to the plasma. With this coupling the VENUS source has produced many record beams such as 11 mA of He^{2+}, 3 mA of O^{6+} and 440 μa of $^{238}U^{33+}$. However, certain aspects of its tuning behavior indicate that the coupling of the 18 GHz power launched from a TE_{11} waveguide is more efficient than the coupling of the 28 GHz power launched from the round TE01 mode. This has prompted us to look into methods to modify and improve the launching of the 28 GHz power into VENUS.

Much of the technology used in the ECR ion source community has come from plasma fusion research including the Geller's first high charge state ECRI ion source, SUPERMAFIOS, which was a converted plasma fusion mirror device.[11] The gyrotrons and RF coupling methods developed for fusion test devices such as tokamaks and stellerators[13-16] offer exciting possibilities for ECRIS applications. In these machines the microwaves are converted for modes such as TE_{01} or TE_{02} into the HE_{11} mode before being launched into the plasma chamber. The HE_{11} mode is a quasi-gaussian polarized mode, which can be launched in a relatively narrow cone into the plasma chamber. This is described by Doane as follows: "The HE_{11} mode in a corrugated waveguide is in many respects ideal for use near plasma devices. Its radiation pattern from an open-ended waveguide has a narrow central beam containing 98% of

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the radiated power. The radiation is linearly polarized with virtually no cross-polarization. Since the field distribution of the HE_{11} mode inside a corrugated waveguide is a close approximation to a gaussian mode, the HE_{11} will couple efficiently to a free space gaussian mode."[14] The power distribution for the HE_{11} mode in a round waveguide is illustrated in the upper left panel of Fig. 3. This mode is linearly polarized as shown in the upper right panel. In contrast to this the power distribution of the TE_{01} mode now utilized in VENUS shows a field distribution with the electric field in a circular direction with zero power on axis as shown in the lower panel of Fig. 3 and the electric field lines are circular. In addition in VENUS the power is launched off-axis and rapidly expands due to the diffraction at the termination of the waveguide. In this case, the first pass absorption is likely to be minimal and the plasma heating relies on multiple reflections at the plasma wall to coupling power into the ECR zone. For right hand wave coupling in an ECR ion source a focused linearly polarized HE_{11} mode directed onto the ECR zone on axis should provide strong heating of the electrons transverse to the local magnetic field.

One of the major differences between the current fusion devices and ECR ion sources is that the fusion devices are circular so that the electrons can be heated in the direction of the toroidal field since there are no end losses, while ECR ion sources are mirror machines and only electrons with large ratio of transverse to longitudinal energy will be reflected by the solenoidal mirrors at injection and extraction. In fusion devices the RF is usually launched at 90 degrees to the toroidal magnetic field and either O-mode (ordinary) with the RF electric field in the same plane as the magnetic field or X-mode (extra-ordinary) with the RF electric field perpendicular to the local

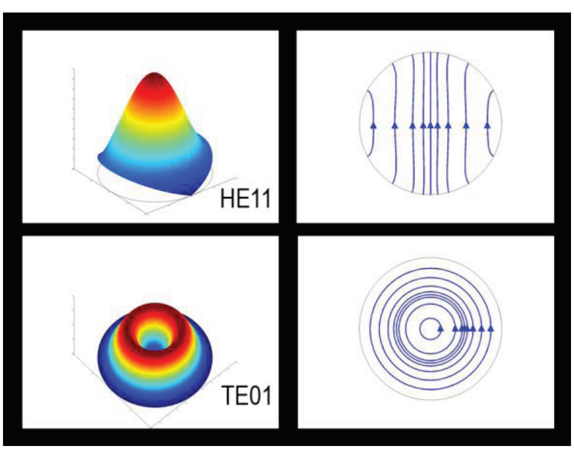

Figure 3: On the top, the power distribution for the Gaussian HE_{11} mode, which is linearly polarized and strongly peaked on axis, and on the bottom is the power distribution for the TE_{01} mode, which has a circular electric field pattern and zero power on axis and a maximum at about .5 times the waveguide radius.

magnetic field is used. Due to the differences between the fusion devices and ECR ion source, the advantages of launching a pencil like beam with transverse polarization onto the central area of the ECR zone will need experimental verification.

APPLICATION TO VENUS

Various options are being explored to modify the existing 28 GHz transmission line and coupling system for VENUS, which is shown in Fig. 2, so that it can launch the microwaves in a HE_{11} gaussian like pattern to maximize the first pass absorption. Although several methods have been developed to convert TE_{01} into HE_{11}, the challenge is to find the best approach given the physical constraints of the present installation. One approach would be to use a waveguide snake[16] to convert the TE_{01} to TE_{11} and then use a corrugated waveguide to convert to HE_{11}. In principle, this could be installed in the waveguide used to transport the microwaves from the injection flange to the launch point in the plasma chamber. The advantage of this approach is that the existing high voltage break, microwave vacuum window, and set of two 90 degree corrugated bends could all be used since the conversion to HE_{11} would be made down stream of them. A preliminary analysis of this approach shows that a conventional waveguide snake would be too long to fit into the straight waveguide section. Recent developments of more advanced snakes may allow efficient conversion is a shorter length waveguide.[18] A second approach would be to modify the last 90 degree bend so that it has 40 degrees of corrugated waveguide followed by 50 degree of smooth waveguide bend, which will convert the TE_{01} mode to TM_{11}, which can then be converted to HE_{11} in the straight section prior to injection into the plasma chamber. While the smooth waveguide bend with a large radius can convert TE_{01} to TM_{11}, the radius in the existing system is relatively small and this may cause too much growth of the TE_{21}, which has an undesirable field distribution for coupling to the plasma.[14] Another approach might be to convert to HE_{11} in the waveguide section between the gyrotron and the existing HV break and then use quasi-optical mirrors to inject the Gaussian beam directly into the plasma chamber similar to the system on SMIS 37.[19]

Modification the microwave coupling for the 28 GHz power in VENUS to take advantage of the advances made in the plasma fusion community has the potential to significantly improve its performance and these techniques could also be employed on future Fourth Generation ECR ion sources, which are in the conceptual stage. [20]

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