Waveguide Assembly and Circular Polarizer for 2450 MHz ECR Ion Sources

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Abstract

Proper coupling of the rf power to the plasma in an electron-cyclotron resonance (ECR) ion source is probably the most important factor in achieving satisfactory performance of overdense plasmas in high-current ECR sources. Poor coupler design can lead to a variety of undesirable effects such as high reflected power, low plasma density, unstable operation, and poor performance. Scientific Solutions has produced an alternative rf waveguide feed assembly for 2450 MHz ECR ion sources currently being used in the community. This new waveguide assembly converts from standard WR-284 waveguide into dielectric-loaded circular waveguide whose transverse dimensions are substantially smaller than the original waveguide. The benefits of this transition assembly are reduced dimensions of the rf window and opening into the plasma chamber, greater freedom in the design of the rf/plasma interface, concentration of the rf energy on the axis of the plasma chamber, a choice of using circularly polarized rf waves, and improved protection of the rf source from reflected rf energy. This assembly is a direct replacement for the WR-284 waveguide and rf window assemblies used in ECR sources and should improve the performance and efficiency of the rf feed system in those sources.

1. BACKGROUND

Proper coupling of the rf power to the plasma in an electron-cyclotron resonance (ECR) ion source is the most important factor in achieving satisfactory performance of such sources. Poor coupler design can lead to a variety of undesirable effects such as high reflected power, low plasma density, unstable operation, and poor performance. Because the electrons circulate only in a particular direction with respect to the applied magnetic field, only that component of the rf field that rotates in the <u>same</u> sense as the electrons is strongly absorbed by the electron-cyclotron resonance. For aligned magnetic field and rf Poynting vectors, only right-hand circular (RHC) polarization is absorbed whereas for antialigned vectors, only left-hand circular (LHC) polarization is absorbed. Since the linearly polarized rf in the waveguide is comprised of equal parts of RHC and LHC polarization, only half of the rf energy ccan couple to plasma via the ECR resonance.

The maximum electron density achievable by rf excitation of an unmagnetized plasma is given by the classical relationship: $m_e\omega_p^2 = 4\pi e^2 n_e$, where m_e is thelectron mass, ω_p is the rf frequency, and n_e is the plasma density. This relationship yields a maximum electron density of ~7.5×10^{10} cm^{-3} for 2450 MHz rf--far below the density necessary for an efficient, high-current ion source. Hence some other mechanism is needed to increase the plasma density to more than $50n_e$, a value typical of efficient high-current ECR sources.

The magnetic field permeating the plasma provides the additional modes of interaction between the rf and the plasma. Of particular importance is the so called upper hybrid (or whistler) mode. A discussion of this and other modes in a magnetized plasma can be found in references [1] and [2]. Note however that the whistler mode also depends on rotation in a particular sense relative to the applied magnetic field. Hence the rf coupling through this mode is also strongly dependent on the polarization of the rf wave.

Stevens et al.[3] develop a model for the impedance of the plasma and provide a discussion of matching that impedance to the rf waveguide. From a comparison of their model with experimental data, Stevens et al. postulate that *"various parameters...which have been noted to affect the efficiency of plasma production, may in fact be related more to the microwave coupling properties of the ER device."* This conclusion is also supported by the results of Shimada, et al.[4].

Finally some benefit has also been noted for concentrating the rf energy on the axis of the plasma chamber. Taylor and Mouris [5] utilized a tapered, double-ridged waveguide segment to couple the rf into their ECR source. LANL also uses this waveguide section in the APT ion source.[6]

2. DESIGN FEATURES

In an attempt to take advantage of the three features described above, Scientific Solutions has implemented an rf feed system for 2450 MHz ECR sources. This feed system starts with a conventional WR-284 waveguide and transforms the rf energy through 1) a rectangular waveguide transition assembly, 2) a rectangular-to-circular waveguide transition assembly, 3) a circular polarizer, and 4) an rf vacuum window/coupler assembly. The ECR ion source rf feed configuration may utilize one or more of these devices in sequence. Each device has particular advantages in the rf feed system and are discussed separately below.

2.1 Rectangular Waveguide Transition Assembly.

The rectangular waveguide transition assembly (Figure 1) transforms the rf energy from a standard WR-284 waveguide into a rectangular WR-137 waveguide filled with boron-nitride ($\varepsilon\approx4.5$). This configuration substantially reduces the transverse dimensions of the waveguide and concentrates the rf energy into a smaller volume. This reduction in transverse dimensions reduces the size of the opening into the plasma chamber and the corresponding dimensions of the rf vacuum window.

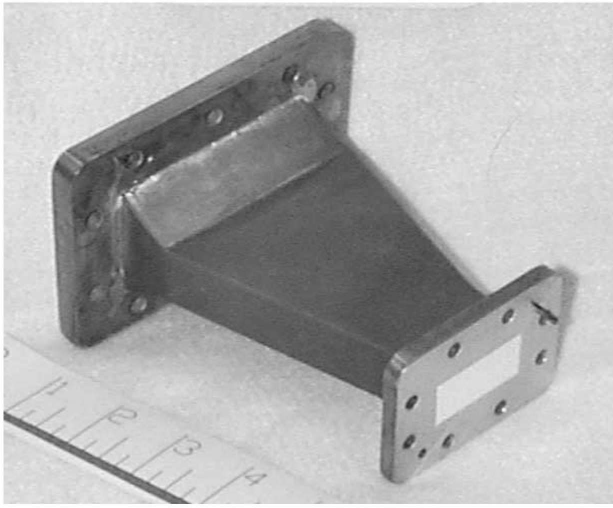

Figure 1. Rectangular waveguide transition assembly. This assembly converts from standard WR-284 waveguide to dielectric-filled WR-137 waveguide.

Another advantage of this configuration is that the rf vacuum window can be positioned well back from the ion source plasma chamber and protected from backstreaming electrons. In ECR ion sources with coaxial rf waveguide, electrons generated by ionization of the residual gas in the high-voltage column are accelerated into the ion source and can damage the rf window. Some ECR installations protect the rf window by placing a thin slab of boron-nitride immediately in front of the window to absorb the energy of the backstreaming electrons. Sputter erosion of this slab by backstreaming electrons limits the operational lifetime to a few hundred hours. The thickness of this slab cannot be increased substantially without incurring increased rf energy reflection from the impedance mismatch between the air-filled waveguide ($\varepsilon \approx 1$), rf vacuum window ($\varepsilon \approx 9$), boron-nitride protector ($\varepsilon \approx 4.5$), and the plasma.

By moving the rf window behind several inches of boron-nitride, the impedance step can be moved to an upstream location where the impedances on both sides of the window are more easily controlled. The boron-nitride also blocks the plasma from expanding into the waveguide. Additionally, using this rectangular waveguide transition should improve the rf efficiency because of the increased rf energy density on the axis of the plasma. Finally note that the reduced dimensions of the waveguide input allows relocating the rf input penetration off the axis of the plasma chamber and out of the path of the backstreaming electrons.

Another potential benefit of the dielectric-loaded waveguide system is that the coupling of the rf to the plasma might be enhanced by extending the boron-nitride dielectric beyond the end of the metal waveguide surfaces. This “dielectric waveguide” can protrude into the plasma volume and the rf coupling to the plasma can be optimized by modification of the shape and extended length of the dielectric protruding from the end of the waveguide.

2.2 Circular Waveguide Transition Assembly.

The second component of the rf input apparatus is a rectangular-to-circular waveguide transition. This device starts with the boron-nitride filled WR-137 waveguide. While maintaining constant impedance, the rectangular cross section of the waveguide is transformed into a circular 1.61” ID tube that is also filled with boron-nitride. This transition assembly matches the rectangular waveguide geometry to the cylindrical symmetry typical of ECR ion sources. All of the operational advantages noted above for the dielectric-filled rectangular waveguide also apply to the circular waveguide assembly. However an important additional feature of cylindrically symmetric waveguide is that it transports circularly polarized rf waves.

2.3 Circular Polarizer Assembly.

The third component of the wavguide apparatus is the circular polarizer. Using the appropriate sense of circular polarization potentially doubles the efficiency of the rf in producing the plasma and eliminates the destabilizing influence of the LHC polarization. Stevens et.al. [3] used a hybrid coupler and phase shifter to generate the circularly polarized rf wave directly in the plasma chamber. SSolutions has simplified this process by converting from the rectangular waveguide into a circular waveguide and employing a simple vane polarizer.[7] The vane polarizer is analogous to the quarter-wave plate commonly used in laser optics

An rf quarter-wave plate is formed by the introduction of a rectangular dielectric vane across the center of the circular waveguide (figure 2). The propagation velocity of the rf wave with the electric field parallel to this vane differs from the velocity of an rf wave with a perpendicular electric field. Circular polarization results when the phase delay between these two components equals ±90°. If the dielectric vane is rotated to +45° relative to the input polarization plane, RHC polarization is the result. If the vane is rotated to –45°, LHC polarization is the result. Hence one can change between RHC and LHC polarizations simply by rotating the quarter-wave polarizer. Note also that positioning the polarizer at either 0° or 90° passes the linear polarization of the input waveguide. Hence one can directly compare the relative performance of linear and circular polarization simply by rotating the polarizer.

2.4 Virtual Isolator

An important additional benefit of the vane polarizer is the creation of a virtual rf isolator. This virtual isolator concept for ECR sources is most easily described by using the quarter-wave-plate analogy introduced above. In laser optics a “photon diode” is created by using a quarter-wave plate in conjunction with a linear polarizer. The laser light passes unaffected through the polarizer when the polarization axis of the light is parallel to the axis of the polarizer. A quarter-wave plate downstream of the polarizer converts the linear polarization into RHC or LHC polarization as discussed above. The important feature of this particular configuration involves the interaction of circularly polarized light reflected back towards the laser from downstream of the quarter-wave plate. In passing back through the quarter-wave plate, the reflected circularly polarized light is converted back into linearly polarized light. However the polarization plane is now perpendicular to the initial polarization axis and the light is not passed by the polarizer. Hence the laser is protected from reflected photons by the quarter-wave plate/polarizer combination.

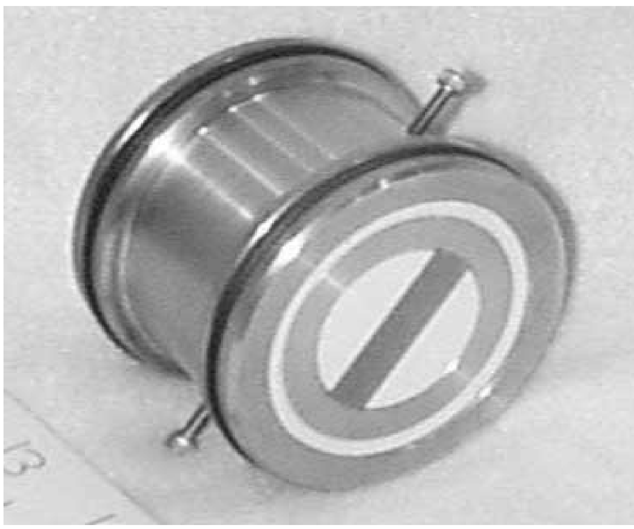

Figure2. Isometric view of the circular polarizer assembly.

The vane polarizer assembly works in an analogous manner. In the rf case, the reflected circularly polarized rf wave is transformed into a linearly polarized rf wave. However the new polarization axis is now aligned with the “wide” axis of the rectangular waveguide and cannot couple into the waveguide. Hence the reflected rf energy is again reflected at the rectangular waveguide interface back towards the plasma, passing through the circular polarizer a third time. Any rf energy reflected a second time from the plasma passes again through the circular polarizer and the polarization axis is returned to the initial orientation. Note however that the rf must interact with the plasma at least twice before escaping back towards the rf source. For any reasonable absorption of rf energy by the plasma, the reflected energy is reduced compared with direct coupling of the waveguide without a circular polarizer. Hence the circular polarizer assembly also acts as an isolator and protects the rf source from direct reflection of rf energy from the plasma.

2.5 Plasma Coupler

Experience has suggested the importance of concentrating the rf energy in the center of the ECR plasma. Achieving such a concentration of rf energy is difficult with 2450 MHz ECR plasmas because the transverse dimensions of the plasma chamber are usually comparable to the dimensions of the WR-284 waveguide. Both Chalk River and Los Alamos concentrated the rf energy by using a ridge-loaded, half-height waveguide and have claimed improved performance as a result.[5],[6] The waveguide assemblies described above provide such concentration of rf energy because the transverse dimensions of the waveguide are reduced substantially compared with their air-filled counterparts. In addition, the transverse and longitudinal dimensions of the boron-nitride dielectric can be tailored to optimally match the rf energy into the plasma chamber as discussed in reference [3]. The dielectric-loaded waveguide assemblies provide a great deal of flexibility in optimizing the rf coupler because the dielectric constant can be decreased as well as increased to optimize the rf coupling to the plasma.

3. CONCLUSION

The 2450 MHz rf feed system described in this paper provides a number of specific advantages over conventional rectangular waveguide systems. Use of this waveguide system should promote better rf coupling to the plasma, more stable plasma operation, and isolation of the rf power system from reflected rf power. These benefits should translate directly into improved performance, greater stability of the ion source parameters (ion current, species ratio, etc.), improved rf efficiency, and protection of the rf power system from reflected rf energy. In addition the user can directly compare differences in ion source performance between operation with linear, RHC, and LHC polarizations by simply rotating the circular polarizer. Tests to verify the benefits of this system are scheduled to take place later this year.

4. REFERENCES

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