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HIGH-POWER MICROWAVE TRANSMISSION AND LAUNCHING SYSTEMS FOR FUSION PLASMA HEATING SYSTEMS*

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INTRODUCTION

Microwave power in the 30- to 300-GHz frequency range is becoming widely used for heating of plasma in present-day fusion energy magnetic confinement experiments. Microwave power is effective in ionizing plasma and heating electrons through the electron cyclotron heating (ECH) process. Since the power is absorbed in regions of the magnetic field where resonance occurs and launching antennas with narrow beam widths are possible, power deposition location can be highly controlled. This is important for maximizing the power utilization efficiency and improving plasma parameters.

Development of the gyrotron oscillator tube has advanced in recent years so that a 1-MW continuous-wave, 140-GHz power source will soon be available [1]. Gyrotron output power is typically in a circular waveguide propagating a circular electric mode (such as $TE_{0,2}$) or a whispering-gallery mode (such as $TE_{15,2}$), depending on frequency and power level. An alternative high-power microwave source currently under development is the free-electron laser (FEL) [2], which may be capable of generating 2-10 MW of average power at frequencies of up to 500 GHz. The FEL has a rectangular output waveguide carrying the $TE_{0,1}$ mode. Because of its higher complexity and cost, the high-average-power FEL is not yet as extensively developed as the gyrotron.

Along with the development of the gyrotron and the FEL, advances in power transmission and launching systems have been necessary. High average power levels in the > 30 GHz frequency regime require the use of either overmoded waveguides or Gaussian beam optical transmission techniques. Preservation of mode purity in these systems is usually essential so that the launching structure can produce a controlled output beam. The choice between a waveguide system and an optical beam system depends on frequency, power level, and distance between the source and the plasma. Waveguide systems require less alignment and are naturally enclosed for evacuation. The diameter must be kept large to reduce losses and occurrence of breakdowns. Mode conversion due to bends and imperfections is proportional to d/λ therefore to maintain an acceptable level of mode purity (>97% is desirable), alignment requirements increase proportionally with frequency. Gaussian beam optical transmission systems can handle power levels of >10MW. However, alignment is critical, and repeating mirrors must be either large in diameter or closely spaced.

In this paper, several types of operating ECH transmission systems are discussed, as well as systems currently being developed. The trend in this area is toward higher power and frequency due to the improvements in plasma density and temperature possible. Every system requires a variety of components, such as mode converters, waveguide bends, launchers, and directional couplers. Some of these components are discussed here, along with ongoing work to improve their performance.

CIRCULAR ELECTRIC MODE TRANSMISSION SYSTEMS

Currently operating ECH systems employ gyrotron tubes that oscillate in a circular electric mode, such as $TE_{0,2}$. A narrow, linearly polarized beam launched into the plasma is

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desired at the output of the system which is not produced by a radiating circular electric mode. Therefore, some mode conversion is required which usually takes place in several steps. As an example, a block diagram for the ECH transmission system used on the Advanced Toroidal Facility (ATF) plasma confinement experiment at Oak Ridge National Laboratory is shown in Figure 1 [4]. Since this system uses highly oversized circular waveguide ($d/\lambda = 11$) and broad-band miter bends, it can be considered a quasi-optical transmission system. At the Institute for Plasma Physics, Garching, FRG, an ECH system has been built for operation on the W7-AS stellarator which uses radius bends and small-diameter-waveguide mode converters [5]. This system operates at 70 GHz and has many of the same types of components as the ATF system shown in Figure 1. Many more bends are necessary, because of differences in the experimental setup.

Ripple wall mode converters can be used to convert the power from the $TE_{0,2}$ to the $TE_{0,1}$ mode, which has very low resistive loss (for example 0.01% per meter at 53 GHz with $d/\lambda = 11$). Design procedures for these converters are based on periodic perturbation of the waveguide diameter at the beat wavelength of the two modes of interest [3]. By careful control of the perturbations, it is possible to convert >99.5% of the power between adjacent circular electric modes in two or three beat wavelengths. If the waveguide diameter to wavelength ratio is large, the beat wavelengths will be long, and this converter will be impractical for higher frequencies (converters > 3m long are required at 150 GHz with $d/\lambda = 11$). Analysis of these converters is usually performed by numerically integrating first-order telegrapher's equations with 5-10 modes included and coupling terms based on the waveguide wall slope.

Launching systems are designed to convert from the $TE_{0,n}$ transmission mode to a linearly polarized narrow beam. Polarization control is usually required to optimize the coupling of power to the plasma. Several schemes have been developed for this conversion.

The Vlasov mode-converting launcher converts a circular electric mode to a linearly polarized beam with a polarization purity of >95% and a main-beam power efficiency of typically 85%. The beam can be focused and steered by mirrors, and the polarization can be adjusted by using a grooved grating mirror. This technique was used on the ATF ECH launcher shown in Figure 2 [5]. The Vlasov antenna points at an angled, grooved metal grating. The groove orientation can be rotated to vary the output polarization to any plane. The beam is then focused by an ellipsoidal (spherical) mirror for minimum possible beam width at the plasma center. A -20dB beam width of 12 cm was obtained for this design.

Other techniques are also used for generating linearly polarized beams from circular electric modes. A series of perturbed-wall mode converters (serpentine shape) can convert the $TE_{0,1}$ mode to the $TE_{1,1}$ mode, which can easily be converted into an $HE_{1,1}$ mode that couples efficiently to a Gaussian beam [3]. Mode purity of this arrangement can be as high as 97%. Like the ripple wall converter described previously, this conversion scheme requires relatively small diameter waveguide for reasonably short lengths; thus, higher resistive losses and electric fields result. Polarization control requires rotating the plane of the serpentine-shaped mode converter.

Perhaps the most difficult problems to deal with in the design of overmoded waveguide systems are bends. It is usually necessary to have at least two 90° bends in an ECH system. Bends must be designed to produce minimum mode conversion. Two approaches have been developed. With large-diameter waveguide ($d/\lambda > 10$), it is possible to use quasi-optical miter bends and suffer relatively small amounts of mode conversion per bend. In the system shown in Figure 1, two bends are used, and $d/\lambda = 11.3$. Mode conversion per bend is about 4%. With increasing d/λ, mode conversion will decrease and resistive losses will decrease. Unfortunately, mode conversion due to lack of waveguide straightness increases, and thus alignment requirements increase.

A second approach to handling bends is to use corrugated-waveguide radius bends [3]. Corrugations remove the degeneracy between $TE_{0,n}$ and $TM_{1,n}$ modes, which thereby reduces their coupling in bends. If the bend radius is carefully controlled, mode conversion can be canceled out over a narrow frequency range. This type of bend requires a relatively small waveguide diameter ($d < 5\lambda$) for an acceptably short bend radius of about 1 m. Mode conversion levels of <1% are typical for good bend designs. If lower-loss, large-diameter straight sections are desired, diameter tapers are required with each bend. Diameter tapers must also be designed for minimum mode conversion by using similar mode cancellation techniques.

Power and mode purity measurements are necessary for analyzing the mode purity of a system and the gyrotron performance. Since there are many possible propagating modes with closely spaced wave numbers, design of a conventional directional coupler is difficult. Two new methods of mode measurement have been developed for use with overmoded ECH transmission systems. The waveguide mode analyzer (WMA) [4] and the k-spectrometer [6] are devices that consist of an array of radiating holes spaced along the waveguide wall.

In the WMA, the holes are spaced so that the radiated power is focused at a point about 100 cm off the waveguide axis. The actual focus point varies with mode since each mode has a slightly different phase velocity. A measure of mode content is possible by scanning a detector along the line of focus points. Relative amplitudes must be corrected by a factor that accounts for relative wall magnetic fields for each mode.

Operation of the k-spectrometer directional coupler concept developed at Stuttgart University is similar to that of the waveguide mode analyzer except that the radiating array is not designed to focus off the side. The radiating holes are equally spaced so each mode radiates at the same angle off axis at which it propagates inside the waveguide. This device has an advantage over the WMA in that it can operate in both forward and reverse directions. There are some disadvantages to the k-spectrometer design, however, such as the difficulty in seeing low-order modes in large diameters since they have very small propagating angles. Also, the scanning device for measuring mode content must scan over a large angle.

WHISPERING-GALLERY-MODE GYROTRON SYSTEMS

Higher power gyrotrons at higher frequency must operate in rotating whispering-gallery (WG) modes to improve the stability of oscillation. Gyrotrons oscillating at 140 GHz in the $TE_{15,2}$ mode are currently under development at Varian Corp. under contract with the Department of Energy [1]. Several fusion energy research installations worldwide are designing ECH systems that will use this type of gyrotron.

WG modes have significantly higher wall losses than circular electric modes; and, since electric fields are not zero at the wall, WG modes have a higher tendency to arc at joints and wall imperfections. They have radiation patterns which, like circular electric modes, are not very useful for launching directly into a plasma. A mode conversion scheme is necessary to convert to a mode useful for propagation and launching.

The Vlasov mode-converting antenna can be configured to work with a WG mode. This device is currently being investigated extensively to quantify its performance and improve its coupling efficiency for coupling to a Gaussian beam waveguide or an $HE_{1,1}$ corrugated-waveguide mode. Both theoretical and experimental efforts are under way. The rotating WG mode can be modeled as a set of rays that have both axial and azimuthal wave numbers that are bouncing along the inside wall of a circular waveguide. If the wall is cut with an axial slot as shown in Figure 3, the rays will exit with a uniform amplitude in the axial direction and a quasi-circular wave front in the azimuthal direction. A parabolic-trough reflector converts this wave front into a plane wave with linear polarization. Radiation patterns for this device can be calculated numerically, by using aperture field integration techniques or more exact methods like the geometric theory of diffraction. Measurements of patterns can be performed by using actual gyrotrons or low-power mode transducers (currently under development) to generate the WG mode in the laboratory. Efficiencies of only 80% (percentage of power in the main lobe) are calculated, although accurate measurements have yet to be performed. Because this efficiency is unacceptably low, efforts are under way to improve the radiation pattern by shaping the waveguide exit area and adding shaped reflectors.

The Vlasov launcher can be situated above the gyrotron so that power is radiated into the Gaussian beam or corrugated-waveguide transmission system [7]. Both types have extremely low loss and have ideal launching patterns. It is possible to use both types of waveguide in a system and also combine several gyrotrons into one optical system for higher power [8]. Polarization control is possible with grating mirrors, although power handling capability must be demonstrated. Many of the design principles for Gaussian beam and corrugated-waveguide $HE_{1,1}$ modes are well established. The technology must still be demonstrated at a high power level to answer concerns about arcing and actual beam quality.

SUMMARY AND FUTURE DIRECTIONS

Technology for reliably transporting 28-70 GHz microwave power in overmoded waveguide from 200 kW circular electric mode gyrotrons is well developed. Several reliable operating ECH systems using this technology exist worldwide. Many new components such as the waveguide mode analyzer, high mode purity bends and beam launchers have been developed for these systems. Higher frequency (100-140 GHz) systems at 1 MW power level are currently under development. Some difficult problems, such as improving the whispering gallery to Gaussian beam coupling efficiency, are being worked on by several groups, and some progress has been made. More work in improving electromagnetic modeling of launching structures and design of relevant components is still necessary. Some existing component designs for circular electric mode systems such as the mode analyzer can be easily adapted to whispering gallery modes. Whispering gallery mode transducers must be perfected to allow low power testing of launchers and systems and to verify theoretical models. Work is underway in the area of Gaussian beam waveguide transmission systems to combine power from several gyrotrons and launch the optimum wave polarization into a plasma. New designs for power sources such as the FEL and alternate gyrotron concepts will require different transmission system designs. It is likely that these designs will consist of a beam waveguide line fed by a mode converter or launcher optimized for a Gaussian beam generation and that this launcher may be more efficient than the whispering gallery mode converter due to a closer match in field distribution.

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