Direct Coupled Gyrotrons for Plasma Heating

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Abstract: *High power gyrotrons typically produce RF power in a Gaussian free-space mode. An internal converter transforms the whispering gallery mode from the cavity to a Gaussian beam using a quasi-optical launcher and a series of mirrors. Transmission of this power typically requires transformation into an HE_{11} mode in corrugated waveguide. This conversion is achieved using a Mirror Optical Unit, which uses a second series of mirrors. The transformation of the whispering gallery mode to a Gaussian beam and then to an HE_{11} mode requires a complexity of RF structures, increasing cost and RF losses. This program is developing a coupler that transforms the whispering gallery mode directly into an HE_{11} mode inside the gyrotron. This results in significant reduction in gyrotron cost and RF losses and eliminates the Mirror Optical Unit.*

Keywords: gyrotron, electron cyclotron heating, tokamak, plasma heating

INTRODUCTION

Electron cyclotron resonance heating (ECRH) is a principal component of most major fusion plasma research programs. ITER, for example, will initially employ 24 MW of RF power for ECRH [1]. The DIII-D tokamak at General Atomics (GA) in San Diego employs RF power at 110 and 117 GHz, and the Wendelstein 7X tokamak uses 140 GHz power [2]. ECRH is also used in tokamaks in Russia, China, and Japan.

RF power for ECRH is provided by gyrotrons producing several hundred kW up to a 1 MW or more. The gyrotron converts power in the electron beam into RF power in a high order, whispering gallery mode. An internal launcher converts this power into a Gaussian, quasi-optical beam that is transmitted through a chemical vapor deposited (CVD) diamond window. As the RF beam emerges from the gyrotron, it enters a Mirror Optical Unit (MOU), which captures the beam and redirects it using specialized mirrors into a corrugated waveguide. The internal launcher-converter in the gyrotron consists of a launcher in the cavity output waveguide and three or four mirrors that shape the beam. One or more of the mirrors are specially machined to correct the phase across the beam to increase the Gaussian content. Typically 1-3% of the RF power is lost during this conversion.

The MOU is mounted external to the gyrotron and uses special structures to correct for the offset and tilt of the Gaussian beam relative to the window. An adjustable mirror inside the MOU captures the RF beam and focuses it to the input of a corrugated waveguide. The beam is converted to an HE_{11} mode propagating inside the waveguide which transmits the RF power to the tokamak.

In a previous program, Calabazas Creek Research, Inc. (CCR) developed a direct coupler that replaces the existing internal launcher and eliminates two of the four internal mirrors in short pulse gyrotrons [3]. The power is coupled directly into HE_{11} waveguide inside the vacuum. The direct coupler was integrated into the 110 GHz, 1 MW, short pulse gyrotron at MIT, shown in Fig. 1. Tests indicated that the gyrotron produced the same output power and efficiency as the conventional Gaussian

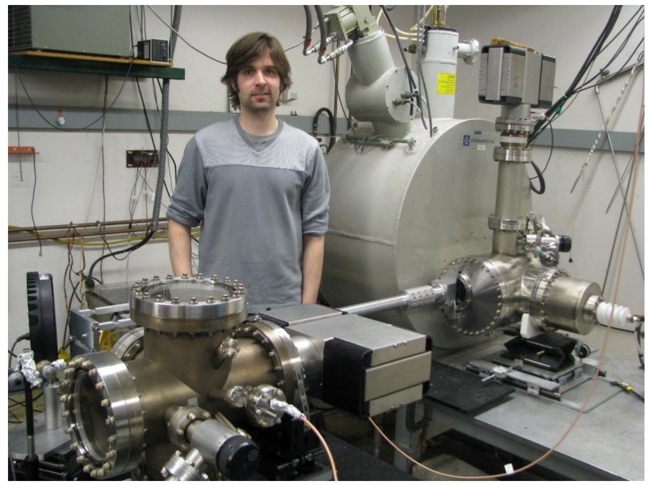

Fig. 1: MIT gyrotron showing corrugated waveguide output

optical system. Measurements indicated 97.5 % HE_{11} mode purity in the corrugated output waveguide.

CCR is funded to integrate a direct coupler into a long-pule gyrotron at General Atomics in San Diego. The gyrotron "Scarecrow" recently experienced an electron gun failure, and the Department of Energy is providing the tube as a test vehicle for direct coupler testing. CCR is funding replacement of the electron gun and collector and replacing the existing Gaussian optical system with the direct coupler. CCR is also funding replacement of the diamond output window. This work will be performed by Communications & Power Industries, LLC (CPI), the original builder of the gyrotron. Testing will also be performed at CPI.

DIRECT COUPLER DESIGN

Fig. 2 shows the conceptual configuration of the direct coupler in the output section of the Scarecrow gyrotron. A quasi-optical launcher radiates the RF power into a near-field mirror that directs the power to a second mirror. This second mirror focuses the power into the HE_{11} mode in corrugated waveguide. The power is transmitted through the waveguide to the output location where a 100^o miter bend redirects the beam into a second waveguide exiting radially from the tube. A diamond output window is integrated into the output waveguide.

The launcher and first mirror were designed and optimized using the Sobolev synthesis method. The second mirror was optimized using a 2D grid surface method. The miter bend uses a simple flat mirror. The computed HE_{11} content into the initial waveguide exceeds 99%, and the purity after the miter bend exceeds 97%. The estimated RF losses from the launcher to the output of the miter bend is 1%. This can be compared with the losses in the Gaussian optical system of 2% and the measured losses in the MOU at General Atomics of 4.4%.

CCR is designing and building the launcher section of the gyrotron, and General Atomics is building the output waveguide assembly from the second mirror to the output window. The output assembly must interface to both the mirror sections of the gyrotron and the vacuum envelope of the tube. This requires careful consideration of differential thermal expansions, primarily during the 450C bakeout.

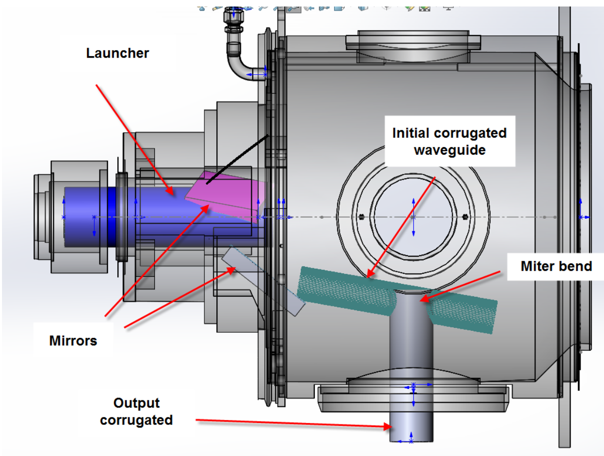

Fig. 2: Configuration of the Scarecrow gyrotron with direct coupler output. The images does not include the miter bend, which can be positioned anywhere along the initial waveguide (green).

Fig. 3 shows the solid model for the system. This will be a drop-in replacement for the Gaussian optical system in the Scarecrow gyrotron.

Schedule

Design for all major components is complete and most parts are on order. Parts for the electron gun have been received and assembly is in progress. Components for the collector and output window are due in fall 2020. The Body – Launcher section and the output waveguide assembly are scheduled for completion in January – February 2021.

The Scarecrow gyrotron will be shipped from General Atomics to CPI in early 2021, at which time the tube will be disassembled and inspected. Any unforeseen issues will be addressed, and the tube will be reassembled with the new gun, collector, and direct coupler system. Testing is anticipated in spring 2021.

Summary

Short pulse testing confirmed that the direct coupler can provide gyrotron operation with the same output power and

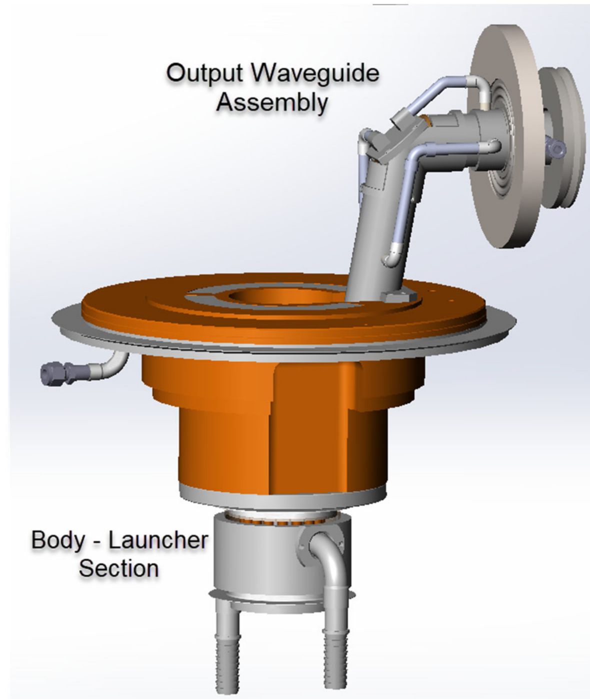

Fig. 3: Solid model of direct coupler support and cooling structure for Scarecrow gyrotron

efficiency as the conventional Gaussian mode system. This program will confirm coupler operation in a long pulse gyrotron. The direct coupler will reduce gyrotron cost and simplify the design. In addition, Mirror Optical Units will no longer be required, resulting in significant cost savings and simplification of the transmission line. The direct coupler is also expected to reduce RF losses by approximately 4% and increase the mode purity into the transmission line.

Acknowledgement

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References

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