GA–A27107

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This is a preprint of a paper to be presented at the 36th International Conf. on Infrared, Millimeter, and Terahertz Waves, Houston, Texas, October 2–7, 2011 and to be published in the *Proceedings.*

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Work supported in part by
the U.S. Department of Energy
under DE-FC02-04ER54698 and DE-AC02-09CH11466

GENERAL ATOMICS PROJECT 30200
AUGUST 2011

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Transmission Line Performance and Plans for the Gyrotron Complex on the DIII-D Tokamak

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Abstract— **A major upgrade to the electron cyclotron heating complex on the DIII-D tokamak is underway. Two depressed collector gyrotrons are being added to the complex and the transmission lines are being upgraded. Transmission line efficiencies are being increased by reduction in the number of miter bends together with improved alignment resulting in improved mode purity.**

I. Introduction

THE electron cyclotron heating and current drive (ECH/ECCD) system on the DIII-D tokamak comprises six gyrotrons all of which operate at 110 GHz. Pulse lengths in the DIII-D application are limited administratively to 5 s out of concern for the gyrotron collector fatigue lifetimes, but five of the tubes have generated about 600 kW for 10 s pulses at the factory and 1.0 MW for 5 s pulses at DIII-D. The sixth tube has performed at about 80% of these power numbers. The system is in regular experimental service, providing localized heating and current drive for a wide variety of experiments at DIII-D, among which are transport studies, suppression and preemption of neoclassical tearing modes, sawtooth studies, profile control, plasma initiation and control of current penetration times.

The existing system is being improved incrementally. The waveguide lines for all systems were rerouted to reduce the number of miter bends and decrease their lengths. These changes eliminated 15 miters, each of which contributed about 1.5% in mode conversion losses, yielding about 120 kW additional injected power for the entire system. Steering mirrors in the ECH launchers were upgraded to dc electric motor drives with substantially higher scan speeds and better pointing accuracy. With these motors, a full range 40º poloidal scan takes less than 2 s with accuracy of the positioning of the rf beam of better than 1 cm at the center of the tokamak. A full range toroidal scan of ±20º at slower scan speed is also now available.

Because the miter bends in the waveguide transmission lines account for a large fraction of the transmission losses, a project to reduce these losses has been undertaken. This involves careful control of the propagating modes in the waveguides and at the miter bends. The miter bend developments, waveguide performance and present status of the major parts of the upgrades are presented in the remainder of the paper.

II. Transmission Lines

Transmission line efficiency is a major issue for high power millimeter wave systems. The DIII-D waveguide lines average 90 m in length, typically have eight normal miter bends and two polarizing miters, and have an overall efficiency of about 75%. Gains in injected power can be realized at modest cost by reducing the losses in these lines. In addition, cw or quasi-cw operation on the next generation of superconducting machines will require efficiencies around 95% to reduce requirements for cooling and to increase the injected power. For the 3 mm 110 GHz wavelength, the DIII-D system uses 31.75 mm diameter evacuated corrugated waveguide with circular cross section. Not including the miter bends, the intrinsic loss of the 90 m long waveguide run [1] is calculated to be -0.18 dB, about 4.5% for the sum of transmission and coupling between the free space Gaussian beam and the waveguides.

Mode conversion in miter bends is due to diffraction, and the higher order modes generated in miters can increase the transmission loss per miter by more than 1% of the transmitted power. It has been shown [2] Moeller and Doane and [3] Chirkov *et al.*, that mode conversion losses at miter bend mirrors can be greatly reduced by proper control of the mode mixture at the mirrors to reduce diffraction. This is done by generating, in the miter input arm, a controlled mode mixture with modes of proper phase and amplitude to reduce the rf beam footprint, hence reducing diffraction at the miter mirror. After reflection from the mirror, the inverse process reciprocally recovers the $HE_{1,1}$ mode in the output arm. In principle, miter losses due to diffraction can be reduced nearly to zero, with a reduction of overall miter loss from ~1.5% to ~0.3% owing to Ohmic loss in the mirror.

Reducing miter bend losses by reducing diffraction was investigated on the DIII-D transmission system. A low diffraction miter bend that was nearly a direct replacement for the existing DIII-D miter bends was designed and a number of miters were built and tested at high power, with the result that, rather than decreasing the mode conversion losses, the losses increased substantially to ~5% per miter. To understand this, careful mode purity measurements, done by launching the propagating rf beam into free space and performing a phase retrieval analysis [4,5] on the power profiles measured at several points from the waveguide as the rf beam was launched into free space, showed that the waveguides were not carrying a pure $HE_{1,1}$ mode. Therefore the mode mixture generated in the miter input tapers did not result in a low diffraction beam at the mirrors.

As a result of this exercise, the original miter bends were reinstalled temporarily and a study was begun in an effort to decrease contamination from higher order modes propagating in the waveguides. This led to the realization that the alignment, both in offset and tilt, of the rf beam at the input to the waveguide was not within ±0.5 mm and ± 0.1º [6] desired for required HE_{11} excitation and this was contributing to undesired non-HE_{11} modes, for which the miters were not designed. The first step was to improve the propagating beam quality.

The Matching Optics Units (MOU) on the DIII-D ECH system [7] are unusual in that they have a single mirror, rather than a pair, to focus and direct the rf beam after it has left the gyrotron. In order to compensate for the steering limitations imposed by this design, the following setup procedure is used when a gyrotron is first installed. The rf beam is propagated into free space directly from the gyrotron window using short pulses several ms. in length. Power profiles of this beam are measured at several locations separated by about 10 cm out to about 1 m from the window. For the high quality rf beams now being produced by gyrotrons, these measurements indicate the offset and tilt of the Gaussian rf beam at the window. Using these data, an offset and tilted spool piece designed to compensate for the imperfect beam trajectory is built to couple the MOU to the gyrotron. This places the centroid of the rf beam onto the optical axis of the MOU, presumably striking the single MOU mirror in its center and allowing a geometrical alignment, constrained by requiring zero offset at the waveguide input, to result in zero tilt as well. The small diameter waveguide could then be bent with large curvature radius to align with the waveguides carrying the power to the tokamak. Although the single MOU mirror can still translate the rf beam in the horizontal plane and tilt both in the horizontal and vertical planes, this procedure proved to provide an inadequate constraint for ensuring both low tilt and offset at the waveguide input. Because it was easy to determine the beam offset at the waveguide input, but difficult to determine the tilt, in order to reduce the mode conversion due to tilt, a new procedure was developed.

Using the specialized spool piece based on propagation measurements without the MOU, the rf beam was propagated into the MOU, reflected from the single focus mirror and launched into free space with no waveguide in place. The MOU mirror was adjusted for minimum tilt and offset at the location of the waist where the waveguide was to be located. This was accomplished by viewing the beam, either with an ir camera or thermally sensitive paper, at an aligned target mounted on an optical beam at several points spaced different distances from the MOU. This produced a relatively good alignment. Then several pieces of waveguide having different lengths from about 30 cm to 60 cm were attached to the MOU, the rf beam was coupled to the guides in turn and the beam radiating from the open end of each piece of guide was observed by an ir camera. Using the same technique as previously, a phase retrieval analysis on the radiating rf beam was performed to determine the mode content at the waveguide mouth. This technique reduces problems with beats among modes having different phase velocities. The alignment of the MOU mirror was then slightly adjusted to give maximum $HE_{1,1}$ content in the propagating beam. Using this technique, up to 94.4% pure $HE_{1,1}$ mode, close to the theoretical maximum coupling between a Gaussian free space beam and $HE_{1,1}$ of 98%, was produced and verified.

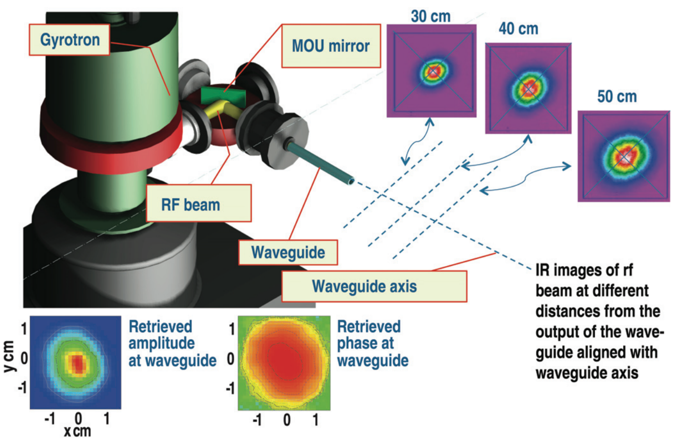

Fig. 1. After alignment of the rf beam without the waveguide in place, the waveguide was installed and rf was propagated into free space through different lengths of waveguide. The IR images then were subjected to phase retrieval analysis to calculate the mode content of the rf beam in the waveguide.

Once a high quality, approximately single mode, rf beam had been excited in the waveguide, it was carried in the waveguide to a high power dummy load located near the tokamak. Direct power measurements were made calorimetrically and these were correlated with the calorimetric measurements of power loading on various cooled components of the gyrotron. It was determined that the generated and transmitted rf power were linearly correlated with the power loading on the gyrotron cavity. The calibration coefficient was determined and this became the basis for injected power measurements during experiments. Because the free space measurements were made using short rf pulses to avoid breakdown in air, it was necessary to verify that both short and long pulses gave the same results. This was checked using a four-port power divider.

The divider is a miter bend having a water-cooled perforated mirror, passing a pickoff fraction of -77 dB to one port and reflecting the rest of the power like a standard miter bend. This power is then analyzed for rf beam quality using either an orthomode transducer to determine both linear polarizations at the miter or a directional coupler to feed a mode analyzer capable of differentiating among several possible low order modes, for example TE_{01}, HE_{21} and HE_{11}, propagating in the waveguide. Because the four-port miter is vacuum compatible at high power, both short and long pulses could be analyzed and this verified that short pulses analyzed using infrared profiles subjected to phase retrieval were valid for longer pulses as well. Cold tests also were performed using an uncooled mirror with larger perforations and having a pickoff fraction of -17 dB.

Although this work has not resulted thus far in a substantial reduction in the transmission line losses, it did provide an accurate injected power calibration and provided a basis for future work on mode conversion miters and loss reduction.

Table 1. Summary of the transmission measurements and mode purity for the six systems. Theoretical efficiency for the waveguide lines including miter bends is 82.3%-83.5% depending on the exact configuration. Including MOU loss and coupling between the Gaussian and HE_{11} mode, the expected transmission is about 75% for all the lines. Note that there are weak correlations between MOU loading and HE_{11} fraction and between HE_{11} fraction and total transmission efficiency.

Gyrotron	MOU Loss (%)	HE_{11} (%)	Waveguide Losses Including Miters (%)	Total Transmission [dB (%)]
SCARECROW CPI s/n 101R	4.44	88.3	79.4	-1.20 (75.6)
TINMAN CPI s/n 102	3.14	91.4	82.8	-0.96 (80.2)
LION CPI s/n 103	3.48	92.0	81.2	-1.06 (78.4)
LUKE CPI s/n 104	7.47	84.6	77.8	-1.43 (72.0)
HAN CPI s/n 105	3.85	90.9	77.4	-1.28 (74.4)
LEIA CPI s/n 106	6.68	94.4	81.0	-1.21 (75.6)

III. Future Plans

The long-term plan for ECH on DIII-D calls for 10 gyrotrons, each of which will generate 1.5 MW, for pulse lengths appropriate for the capability of the tokamak, approximately 10 s. An important part of this plan has been initiated, with the commitment to install two additional gyrotrons with higher unit power than has previously been available and with the necessary ancillary equipment. A 110 GHz gyrotron designed for 1.2 MW, 10 s pulses, is in the final stages of production at Communications and Power Industries (CPI). This tube has a dispersion strengthened CuCrZr collector and a depressed collector geometry to increase the rf generation efficiency and should be in test operation at the end of 2011.

In addition to this gyrotron, the program has committed to installing an eighth tube. The eighth gyrotron has been designed to generate 1.8 MW for short pulses and 1.5 MW for 10 s pulses in normal experimental operation. Also a depressed collector diode design with CuCrZr collector, this gyrotron will be the first tube at DIII-D to operate at the higher frequency of 117.5 GHz, to maximize the plasma performance at the highest possible magnetic field. The 117.5 GHz gyrotron is in the final stages of conceptual design and is scheduled for delivery to DIII-D in early 2013. Success of these developments will increase the injected power on DIII-D from 3.5 MW to 5.5 MW and lead to acquisition of additional gyrotrons with higher unit power than the present tubes, generating the higher 117.5 GHz frequency at high efficiency.

These improvements require substantial investments in infrastructure as well. At present a new high voltage power supply having dual tetrode modulators and a solid-state crowbar is being tested, a new dual launcher is being built [9] and the waveguide systems for the seventh and eighth tubes are being installed.

IV. Conclusion

Transmission line performance is consistent with theoretical predictions for the individual components on the DIII-D ECH system. An attempt to reduce the transmission losses substantially by replacement of standard miter bends with low diffraction units showed that contaminating non-HE_{11} waveguide modes, revealed by phase retrieval analysis of propagating rf beams, needed to be reduced. These modes result from small misalignments between the waveguides and the coupled rf beams. New alignment procedures are being applied and further tests are being made.

The DIII-D ECH system is being upgraded over the next two years by the addition of two new depressed collector gyrotrons and ancillary equipment, which will increase the injected rf power by 2 MW to 5.5 MW. The longer term plan calls for an additional two gyrotrons and replacement of the present six tubes with ones having generated power of 1.5 MW, resulting in injected rf power of 12 MW from 10 gyrotrons.

Acknowledgment

This work was supported in part by the U.S. Department of Energy under DE-FC02-04ER54698 and DE-AC02-09CH11466.

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