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Megawatt Power Level 120 GHz Gyrotrons for ITER Start-Up

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Abstract. We report operation of a 110 GHz gyrotron with 1.67 MW of output power measured in short pulses ($3\mu s$) at an efficiency of 42 % in the TE_{22,6} mode. We also present a preliminary design of a 1 MW, 120 GHz gyrotron for ITER start-up with an efficiency greater than 50 %.

1. Introduction

Gyrotrons have emerged as one of the most suitable candidates for electron cyclotron resonance heating (ECRH) and electron cyclotron current drive (ECCD) in magnetically confined plasma fusion experiments. The recent demonstration of 800 kW power at 140 GHz over 30 minutes continuously [1] by a Communications and Power Industries (CPI) gyrotron exemplifies the capability of gyrotrons for plasma heating. Research and development is underway on gyrotrons capable of producing over 1 MW in continuous wave at 110 GHz, 140 GHz, and 170 GHz [2]–[5]. With the successful achievement of over 1 MW power in long pulses at up to 170 GHz considerable effort is being made to improve the efficiency of gyrotrons to greater than 50 %. The use of a depressed collector has enabled the recovery of about 2/3 of the energy from the spent electron beam and thus reduce the overall recirculating power in the gyrotron. This has enabled the reduction in size of the collector and overall improvement in the efficiency of the gyrotrons. Improvements in the design of the internal mode converter and the matching optics unit (MOU) used to convert the high order gyrotron operating mode in to a free space Gaussian beam are also being studied.

In the United States gyrotron research is conducted as a collaboration of industry, including CPI, General Atomics (GA) and Calabazas Creek Research, with the university programs at the Massachusetts Institute of Technology, University of Maryland and University of Wisconsin. The development of an industrial tube at CPI is complemented by the design and development of a short pulse ($3\mu s$) prototype at MIT to study physics and microwave engineering issues over a wide range of parameter space which is not feasible in the industrial tube. This approach has been very successful in the development of a number of megawatt class gyrotrons being used for plasma heating at GA and elsewhere.

ITER will require three 1 MW, 120 GHz gyrotrons for plasma start-up. The design will be derived from the successful development of a 110 GHz gyrotron operating in the 1.2 to 1.5 MW range. In this paper we report on the progress in both the design of the 120 GHz gyrotron and

the latest progress on research on the short pulse, 1.5 MW, 110 GHz gyrotron at MIT. The goal of the 120 GHz gyrotron development effort will be a gyrotron output power level of at least 1 MW at an efficiency greater than 50 % with a depressed collector. The existing TE_{22,6} mode 110 GHz designs cannot be scaled to 120 GHz while keeping the ohmic loss on the walls about 1 kW/cm². Therefore, a new design will be undertaken. At MIT, a 110 GHz short pulse gyrotron system is in operation for testing the output power and efficiency of megawatt power level gyrotrons. Recently, using a low ohmic loss cavity an output power of 1.67 MW at 110 GHz was achieved with an efficiency of 42 %. These experiments were performed without an internal mode converter. The present experiments are being conducted with an internal mode converter and a depressed collector. A conceptual design for a 1 MW, 120 GHz gyrotron for ITER start-up will be presented.

In Section 2 we present the results from the 110 GHz gyrotron experiment. Section 3 is devoted to the conceptual design of the 120 GHz gyrotron for ITER start-up followed by a discussion in Section 4.

2. Gyrotron Experiments at 110 GHz

2.1. Cavity Optimization Study

Recently, we reported on the generation of 1.4 MW at 110 GHz in 3 μ s pulses at MIT [6]. The cavity used in these experiments is labeled V-2003 and its main parameters are listed in Table 1. The experimentally measured efficiency of 37 % was lower than 39 % predicted by a nonlinear gyrotron modeling code, MAGY [7]. To improve the electronic efficiency of the gyrotron we have begun a systematic study of the various parameters of the cavity to generate a map of efficiency versus basic cavity parameters such as length of the straight section, input taper angle and output taper angle. MAGY was used to study the beam wave interaction in the cavity in multimode operation, specifically a triplet of modes TE_{21,6}, TE_{22,6} and TE_{23,6} centered around the operating mode TE_{22,6}. The beam parameters were assumed to be 96 kV, 40 A, pitch angle, Alpha (α) = 1.43 which are the nominal operating parameters reported in [6]. In Figure 1 we show the variation of efficiency with variation in input and output taper angles and in Figure 2 we show the variation of the peak ohmic heating with the variation in input and output taper angles for a fixed cavity length of 1.8 cm.

	V-2003 Cavity	V-2005 Cavity
Input Taper Angle	2.5 deg	2.5 deg
Output Taper Angle	1.2 deg	0.7 deg
Length	1.79 cm	1.80 cm
Frequency	110.09 GHz	110.07 GHz
Total Q	934	837
Peak Ohmic Load	1.1 kW/cm ²	0.8 kW/cm ²
Norm. Length (μ)	15.5	16.1

Table 1. Comparison of the V-2003 and V-2005 cavities.

From Figure 1 we notice that there is a wide range of input and output taper angles over which high interaction efficiency can be maintained. From Figure 2 we notice that the peak ohmic load on the cavity walls diminishes with the decrease in the output taper angle while keeping the efficiency nearly constant. Hence, a cavity with a smaller output taper angle will have lower ohmic losses and thus will lead to a marginal improvement in the extraction of power generated in the cavity. Such a cavity may also support operation at higher output power in the same operating mode without increasing the peak ohmic load on the cavity walls. It is worthwhile to note that reducing the output taper angle results in a reduction of the total Q factor of the cavity making it more susceptible to stray reflections into the cavity. A new cavity, V-2005 was designed and fabricated with an output taper angle of 0.7 degrees. The cavity

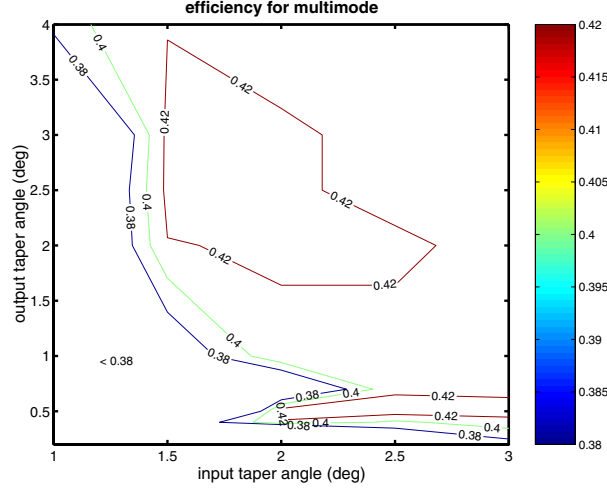


Figure 1. Contour plot of efficiency with variation in input and output taper angles for a fixed cavity length = 1.8 cm

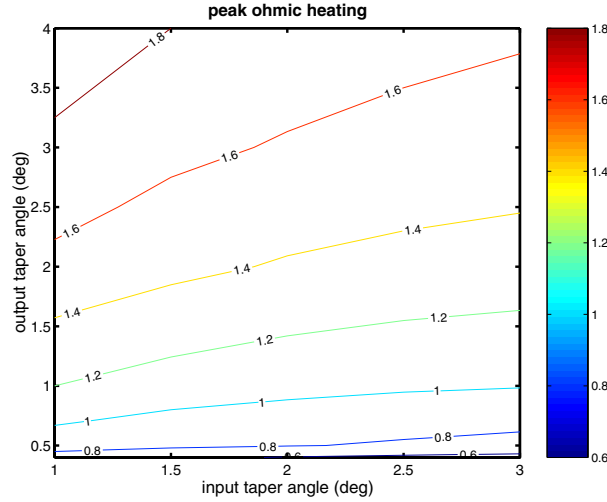


Figure 2. Contour plot of peak ohmic loss with variation in input and output taper angles for a fixed cavity length = 1.8 cm

was electroformed with 0.4 mil accuracy to ensure that the small taper angle was faithfully reproduced in the fabrication process. The input taper angle and length of the straight section were left nearly unchanged from the V-2003 cavity.

2.2. Experimental Results

The V-2005 cavity was installed in the gyrotron and was operated in the axial configuration, that is, without an internal mode converter in the tube. Detailed studies were conducted to generate a mode map showing the excitation of various modes and the output power and efficiency was measured over a range of operating parameters. A capacitive probe was installed in the tube to measure the axial beam velocity near the entry of the cavity to determine the beam velocity pitch factor, α . The measured value of α was about 1.3 around the high efficiency regime. The

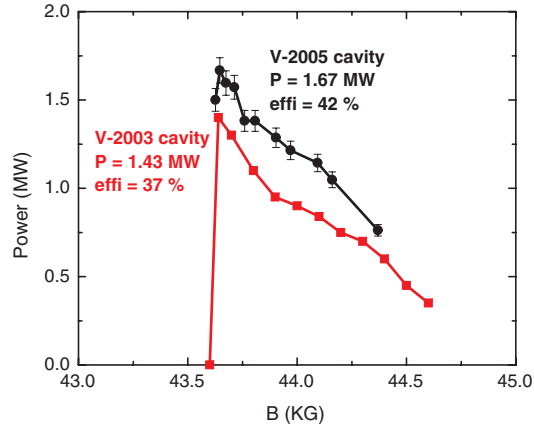


Figure 3. Variation of power with detuning in magnetic field for the two cavities.

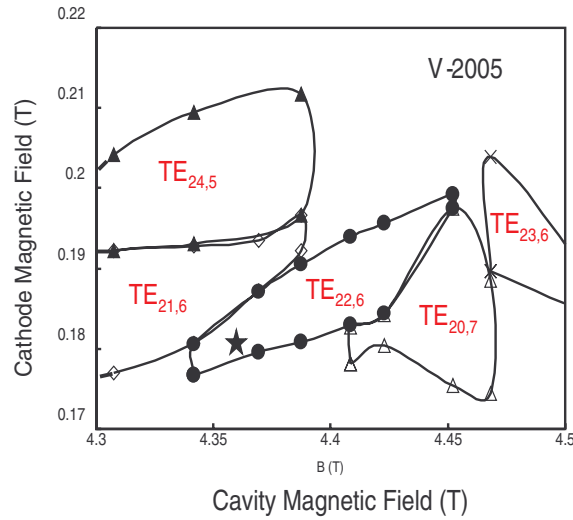


Figure 4. Mode map for V-2005 Cavity. The star denotes the point of highest efficiency for the operating $TE_{22,6}$ mode.

typical error in measurement of α is about 10 -15 % and thus the experimentally measured value of 1.3 was consistent with the design value of 1.43 for the electron gun. In Figure 3 the variation of the output power with the detuning of magnetic field is shown for both the cavities. The mode map for the V-2005 cavity is shown in Figure 4. and the mode map for the V-2003 cavity is shown in Figure 5 (from [6]) for the same operating parameters of 96 kV and 40 A. In the V-2005 cavity up to 1.67 MW power was generated at an efficiency of 42 % which significantly higher than the 37 % measured in the V-2003 cavity. Also, simulations in MAGY so far have not predicted such an increase in efficiency for the low ohmic loss cavity. More rigorous modeling in MAGY is underway to include the effect of velocity spread and the azimuthal asymmetry in the electron beam to explain the experimental results. The lower ohmic loss in the V-2005

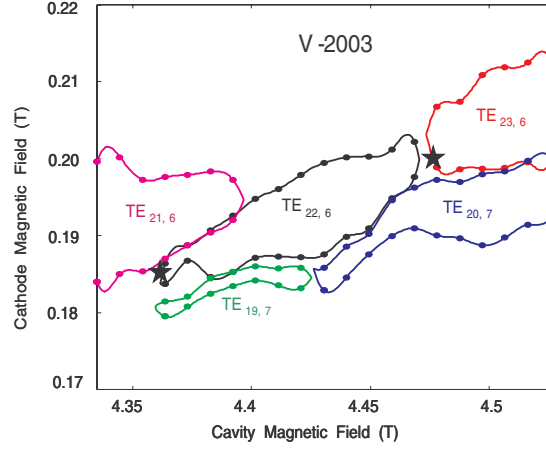


Figure 5. Mode map for V-2003 Cavity. The star denotes the point of highest efficiency for the operating $TE_{22,6}$ mode and the $TE_{23,6}$ mode.

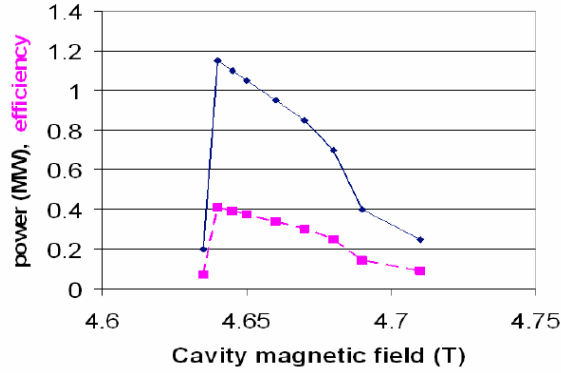


Figure 6. Power and efficiency characteristics of the 120 GHz gyrotron predicted by MAGY simulations.

cavity cannot completely explain the increase in efficiency. One possible explanation for the improvement in efficiency is the lack of the excitation of the parasitic $TE_{19,7}$ counter-rotating mode near the high efficiency operating point of the operating mode, $TE_{22,6}$ in the V-2005 cavity. This is evident from Figures 4 and 5. This means that a higher efficiency regime of the $TE_{22,6}$ mode can be accessed in the V-2005 cavity when compared to the V-2003 cavity. Rigorous MAGY simulations are being conducted to verify this hypothesis.

3. 120 GHz Gyrotron For ITER Start-Up

In this section we present an initial design of a 1 MW, 120 GHz gyrotron for plasma heating during ITER start-up. The operating mode $TE_{24,6}$ has been chosen to reduce mode competition and to limit the ohmic wall heating to allow continuous wave operation. The various design parameters are listed in Table 2.

Frequency	120 GHz
Mode	TE _{24,6}
Power	1.15 MW
Beam Voltage	70 kV
Beam Current	40 A
Power Supply Voltage	50 kV
Alpha	1.2
Magnetic Field	4.65 T
Perp. Vel. Spread	5.5 %
Beam Radius	1.01 cm
Cavity Radius	1.91 cm
Cavity Length	1.9 cm
Diffraction Q	1300
Peak Wall Loading	1.1 kW/cm ²
Efficiency w/o Depr. Coll.	40 %
Depression Voltage	up to 25 kV
Efficiency with Depr. Coll.	> 50 %

Table 2. Design parameters of the 120 GHz gyrotron for ITER start-up

The operating voltage has been chosen to be 70 kV which with a reasonable voltage depression of 20 kV will meet the specifications of the power supply of 50 kV, 45 A recommended for ITER. Multimode simulations were carried out using MAGY to predict the power and efficiency characteristics of the device and the results are shown in Figure 6. Up to 1.15 MW of power can be generated at a beam current of 40 A with an efficiency of 41 %. The analysis of the spent beam data from MAGY reveals that the collector can be depressed up to 25 kV without reflecting a large number of electrons towards the cavity. This analysis resulted in an optimum value of $\alpha = 1.2$ which allowed a collector depression of up to 25 kV and thus a high overall efficiency. The choice of $\alpha = 1.2$ for the 120 GHz design is lower than $\alpha = 1.43$ used in the 110 GHz design and is expected to reduce the velocity spread in the beam. At a depression of 20 kV the total efficiency of the gyrotron would be 57.5 %. Further MAGY simulations are being performed to determine the mode startup sequence to ensure that the operating TE_{24,6} mode is ultimately dominant during the rise of the voltage pulse. A nonlinear taper section will be incorporated in the output section of the cavity to minimize mode conversion and prevent further interaction of the beam and the electric fields in the cavity.

4. DISCUSSION

The experiments in short pulse at 110 GHz at MIT have demonstrated that improvements in cavity design and investigation of new operating regimes can lead to an increase in the electronic efficiency of megawatt class gyrotrons. The latest experiments using a low ohmic loss cavity have produced 1.67 MW of power at 42 % efficiency which is a significant improvement over previous experiments with the V-2003 cavity [6]. The low loss cavity is likely to be more sensitive to reflection of power back towards the cavity. However, the recent experiments conducted in the axial configuration which generally produce more reflections than an internal mode converter have not indicated any adverse effects. In the next step the V-2005 cavity is being tested with an internal mode converter and a depressed collector. Furthermore, in the V-2005 cavity the competition from the TE_{19,7} counter-rotating mode is reduced which allows access to a higher efficiency regime of the operating TE_{22,6} mode. Multimode simulations are being performed in MAGY to better understand the experimental results. A conceptual design for a 1.2 MW, 120 GHz gyrotron for ITER start-up has been presented. The design meets the ITER requirements of over 50 % total efficiency. More detailed design including analysis of mode competition and the start-up scenario are underway.

Acknowledgments

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