DOE/ER/54324-1

PSI 1235
TR 1238

RECEIVED
APR 04 2000
OSTI

Testing of a 3 MW Coaxial Gyrotron

Contact DE-FG-95-ER54324

Final Report

Physical Sciences, Inc.

Prepared by:

M.E. Read
Physical Sciences Inc.
20 New England Business Center
Andover, MA 01810

September 25, 1998

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Summary

The primary goal of the program was to assist MIT in the testing of a 140 GHz, 3 MW coaxial gyrotron. This gyrotron was designed and fabricated under a DOE-sponsored SBIR program at PSI.

The program commenced shortly after the gyrotron was delivered to MIT. However, due to many factors, MIT did not complete the installation until almost a year following delivery. Subsequent testing was intermittent, with a full time graduate student being assigned to the program only after about two years. Thus, the PSI contract was extended from one to three years. Testing is not complete, but enough information regarding the gyrotron has been transferred to MIT personnel to allow them to complete the tests without significant further assistance.

The gyrotron was received in good condition, and the cathode activated without difficulty. Operation at full voltage and current was possible throughout the three year period.

The gyrotron was operated in two forms: (1) with an internal mode converter that produced a near-gaussian beam through a window transverse to the axis of the tube, and (2) with the collector modified so that the radiation was extracted via a window on axis. In the first configuration, the maximum power achieved was about 1 MW. The power could not be increased, even after careful alignment of the magnet, gun/cavity/anode, and inner conductor. From rough radiation pattern measurements there were indications that some of the radiation was being scattered by the mode converter into the tube. To avoid this power loss, the collector was extended to the end of the tube, and a quartz window placed at this point. However, this is arrangement did not produce significantly more power, even after very careful realignment. Measurements were then made of the current as a function of azimuthal angle. These measurements indicated that the cathode was emitting well on only one side (*i.e.*, from about ½ of its area.) This would be expected to excite unwanted, and probably low efficiency modes.

The cathode was subsequently replaced with a spare that had been acquired under the original SBIR program. The replacement was fairly straightforward since there was direct access via a copper-sealed flange to the cathode, which was mounted via machine screws. The only difficulty encountered was in the form of the cathode lead feed-through leads breaking during disassembly. This connector was known to be a weak point in the design, with its size being smaller than optimum because of a number of geometrical limitations. The connector was readily replaced, and the tube is now under vacuum. Activation and further testing will begin within a few weeks.

A secondary, and minor, part of the effort was to be devoted to a study of window materials for high power gyrotrons. PSI completed a paper study of window materials, and a copy of the results of same is attached. It was originally intended that PSI assist in locating sources of materials and coordinating measurements at a number of laboratories. This proved to be more difficult than anticipated, and no measurements were made under this program. However, during the three years, substantial progress has been made by the gyrotron community toward high power windows for gyrotrons, with a number of measurements being made.

Detailed Results

There have been several publications concerning the coaxial gyrotron, among them being the following:

(1) M.E. Read, G. Nusinovich, O. Dumbrajs, G. Bird, J.P. Hogge, K.E. Kreischer and M. Blank, IEEE Trans. Plasma Science, **24** (3), pp. 586-595, 1996.

(2) R. Advani, M.Perozzi, K.E. Kreischer, R. Temkin, and M.E. Read, "Operation of a 3 MW, 140 GHz Gyrotron with a Coaxial Cavity," Int. Conf. On IR&mm Waves, September, 1998.

These papers summarize the design and testing, to date, of the coaxial gyrotron. Copies are appended, as is a brief study of microwave windows.

Use of Diamond for Microwave Windows

Until very recently, the output window has been the primary limiting factor on the power of gyrotrons for fusion applications. Electron cyclotron heating (ECH) is an important mechanism for plasma heating and current drive in a number of next generation magnetic fusion devices, such as the International Thermonuclear Experimental Reactor (ITER) tokamak. Microwave frequencies to about 170 GHz are required[1,2]. For economical use of such heating systems, high-power single-mode continuous-wave (CW) gyrotrons with an output powers of at least 1 MW are currently under development [3]. The CW operation imposes extremely high demands on the material properties of the vacuum barrier windows, whether they be in the gyrotron (separating the high vacuum of the tube from the air) or at the entrance to the tokamak. These include large thermal conductivity, low dielectric permittivity, small loss tangent, and high fracture strength. Loss tangents of less than 10^{-5} are sought. For vacuum containment as a torus window of a Tokamak, it must be able to withstand a static pressure of 0.5 MPa as safety requirement in case of off-normal events [1]. Furthermore, its mechanical performance and electromagnetic properties must not be appreciably degraded by modest degrees of neutron and gamma irradiation. The ideal window for use in ECH systems should also have a high threshold for radiation damage, in addition to the previously stated requirements.

To characterize the parameters relevant to a gyrotron window, data taken from Thumm [1] has been augmented, and listed in Table 1. Most materials of interest for microwave windows are listed. Again, following Thumm, the last two parameters in the Table summarize "goodness". They are the load-failure resistance R' and the mm-wave power-transmission or power-handling capability P_T, which are respectively defined as [1]

$$R' = k \cdot \sigma_B \cdot (1-\nu) / E \cdot \alpha \qquad (1)$$

$$P_T = R' \cdot \rho \cdot c_p / (1+\varepsilon_1) \cdot \tan\delta \qquad (2)$$

where k is the thermal conductivity, σ_B is the ultimate bending strength, ν is the Poisson's ratio, ρ is the density, c_p is the specific heat, E is the Young's modulus, α is the thermal expansion coefficient, ε_1 is the (real part) permittivity, and $\tan\delta$ is the loss-tangent, defined as the ratio of the imaginary to the real part of the dielectric constant, i.e., $\varepsilon_2/\varepsilon_1$.

From the Table it appears that diamond is the best material for high-power mm-wave windows. Although its power-handling capacity around room temperatures is similar to that of Au-doped silicon, the latter has a tendency for a runaway effect, since its loss tangent is steeply increasing with higher temperatures [1]. In contrast, diamond has a loss tangent that is slightly decreasing with higher temperatures. It also has an extremely high thermal conductivity, 13.3 times higher

Table 1. Thermophysical, mechanical and dielectric parameters (room temperature values) related to thermal load-failure resistance and power-transmission capacity for some dielectric materials commonly used as edge-cooled windows (from M. Thumm [1], updated with most recent results).

Material	BN (CVD)	Si_3N_4 (comp.)	Sapphire (Al_2O_3)	Au: Silicon	Diamond MPACVD
Thermal Conductivity, k [W/mK]	50	59	40	150	2000
Ultimate Bending Strength, σ_B [MPa]	80	800	410	3000	600
Poisson Ratio, ν	0.25	0.28	0.22	0.1	0.1
Density, ρ [g/cm^3]	2.3	3.4	4.0	2.3	3.5
Specific Heat, c_p [J/g·K]	0.8	0.6	0.8	0.7	0.5
Young's Modulus, E [Gpa]	70	320	385	190	1050
Therm. Expansion Coeff., α [10^{-6}/K]	3	2.4	5.5	2.5	1.2
Permittivity (145 GHz), ε_1	4.7	7.84	9.4	11.7	5.67
Loss Tangent (145 Ghz), tanδ [10^{-5}]	115	30	20	0.35	0.6
Possible Size, Diameter [mm]	145	400	270	127	160
Cost	medium	high	high	low	very high
Failure Resistance, R'	**14.2**	**44.5**	**6.0**	**852**	**858**
Power-Handling Capacity, P_T	**0.04**	**0.36**	**0.09**	**318**	**375**

than silicon and 5 times higher than copper [1]. All these properties make the diamond by far superior to silicon, especially with regard to near room temperature applications as fluorocarbon-cooled or uncooled windows for gyrotrons and ECH systems. Being mechanically the hardest material ever known, while having the strongest lattice bonding, diamond is also the radiation-hardest window material appropriate for use in fusion reactors. The only drawback to diamond is its extremely high manufacturing cost, which is primarily due to the inherently slow deposition rate of the microwave-plasma-assisted chemical-vapor-deposition (MPACVD) process being used. The typical growth rate is a few µm/hr, which means a period of one week or more to grow a 1mm-thick diamond wafer. As of today, a 120mm-diameter, 2.25mm-thick diamond window with a loss tangent of $2 \cdot 10^{-5}$ is commercially available at a price of roughly $100,000.

References

[1] M. Thumm, Int. J. Infrared and Millimeter Waves 19 (1998) 3-14
[2] M. Thumm, W. Kasparek, Fusion Eng. and Design 26 (1995) 291-317
[3] M. Thumm, Fusion Eng. and Design 30(1995) 139-170

Operation of a 3 MW, 140 GHz Gyrotron with a Coaxial Cavity

R. Advani, M. Pedrozzi, K.E. Kreischer, R. Temkin

Plasma Science and Fusion Center, Massachusetts Institute of Technology
Cambridge, MA 02139

and M.E. Read

Physical Sciences, Inc., Alexandria, VA

Abstract

Operational details of a 3 MW, 140 GHz gyrotron are reported in this paper. A $TE_{21,13}$ coaxial gyrotron has been designed to operate at an efficiency of at least 30%. Initial operation of this gyrotron in the low velocity ratio regime yielded power levels of ~1 MW. Subsequently problems were found with the power output section leading to its redesign. Also, the large cathode emitter was found to be defective and has now been replaced.

Introduction

CW gyrotrons operating at 140-170GHz are typically designed to produce 1 MW per tube. This has been due to technological limitations imposed by the cavity heat load, mode competitions and the output window. The coaxial gyrotron attempts to increase this value to 3 MW per tube, thus reducing the number of tubes required for the future fusion experiments and the total system costs. Recent improvements in window design with double-disk, diamond, and dome-shaped windows mean that future tubes will be mostly limited by the maximum average cavity heat loading. About 1.8 kW/cm^2 can be handled in present designs.
The main advantages of a coaxial conductor in a gyrotron are[1]:

- Causes rarefied mode spectrum around the design mode
- Reduces the quality factor of competing modes
- Volume modes (higher radial index) can be chosen decreasing the ohmic losses
- Reduces voltage depression

Due to the ability to choose a volume mode in coaxial gyrotrons, greater output can be expected at the same level of cavity ohmic power.

Experimental set-up

The experimental set-up is shown in Fig. 1, and the theoretical operating parameters are summarized in Table 1. The electron gun is an inverted magnetron injection gun (IMIG) designed and built by PSI [2]. A 6.5 T superconducting magnet is used for the main magnetic field, and three gun coils allow the adjustment of the magnetic field at the cathode The inner conductor is made in two parts and is held at the anode and at the end of the tube and does not interfere with either the electron beam or microwave power. It is possible to isolate the gun from the tube by retracting the coaxial conductor and closing a valve. In order to simplify the design, the power at the output end is extracted longitudinally through a conventional quartz window. A previous design included a mode converter that directed the power through a side window.

Initial operation

In spite of all these advantages, the operation of the coaxial gyrotron has proven to be a challenge. Alignment of the inner conductor, beam (magnetic field), and the outer cavity to a accuracy of less than 0.25 mm has been difficult. Nevertheless we have been successful in operating the coaxial gun to parameters of 95 kV, 76 Amps, and the initial operation gave us 1 MW, at 140 GHz, with a 14% efficiency[3]. The peak power was found in the $TE_{27,11}$ mode. In initial operations, the gyrotron was operated in a low velocity ratio regime ($\alpha \approx 1.1$) and with a magnetic compression less than the design parameter. The initial operation used a mode converter and the power was extracted radially, which is complicated because of the coaxial conductor. Upon opening the tube after the initial runs, we saw evidence of some power hitting the flanges instead of making it out of the tube.

Improved design

Consequently, the output section of the tube was simplified. The mode converter was removed and replaced by a straight section of copper pipe which would now make the power output axial. This redesign ensured

Frequency	140 GHz
Mode	$TE_{21,13}$
Voltage	95 kV
Current	76 A
Velocity Ratio	1.7
Efficiency	41 %
Magnetic field	5.5 T
Compression	38
Cavity radius	2.33 cm
Coaxial insert radius	0.602 cm
Beam radius	0.812 cm
Emitter radius	5.01 cm
L/l	8.5
Diffractive Q	1400
Avg. ohmic losses	1.8 kW/cm2
Voltage depression	5.1 kV
Satellite modes	$TE_{18,14}$, $TE_{22,13}$

Table 1: Design parameters of the coaxial gyrotron.

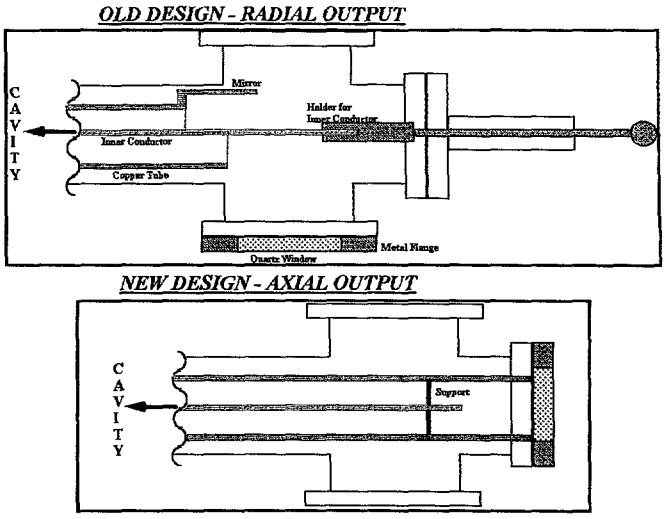

Figure 1: Schematic of the Coaxial Gyrotron

Figure 2: Initial design and new design

that all the power would exit the tube and be measured. A schematic of the old design and the new one is shown in Fig. 2.

The design and construction of this modification is complete and we re-tested the tube. In this iteration we first tested the tube in the empty cavity mode where the coaxial conductor was removed and the mode spectrum and power were measured. The measured frequencies of the modes were consistent with theory, but the power output continued to be low, less than 1 MW.

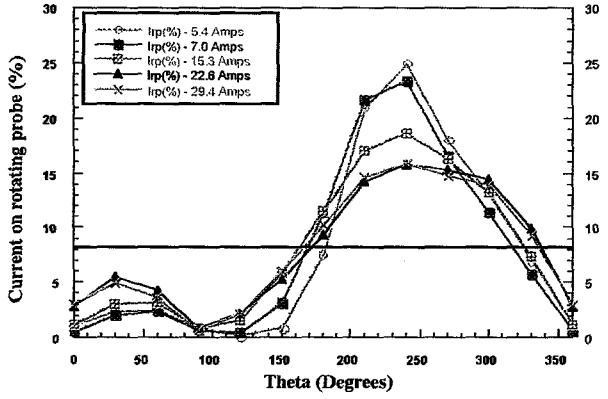

Figure 3: Measurement of beam measured by the 30° sector as a percentage of the total current.

Beam asymmetry measurements

Since the power output was low even in the empty cavity experiments, we decided to measure the electron beam. We first let the electron beam strike a witness plate and when that showed us that we may have severe asymmetries we followed it up with a rotating probe experiment. This experiment consisted of a simple 30° sector of Copper which could be rotated in the azimuthal direction. This probe would thus measure the current at different azimuthal positions. This measurement of the beam with the rotating probe is shown in Fig.3. It shows that the beam is quite asymmetric. Therefore we are now replacing the cathode emitter with a new one. After that, the alignment mechanism is going to be further improved and further testing will be done with the coaxial conductor reinserted. Besides the experimental work, a numerical analysis of the data will also be presented. A theoretical study of the sensitivity of the tube (and gun) to small misalignments in radius or axial displacements, of the anode will also be presented. A study of the critical parameters (velocity ratio and spread) versus changes in voltage, current, and magnetic field will be shown.

References

1 V.A. Flyagin, N.S. Nusinovich, Proceedings of the IEEE, 76, pp. 646, 1988.

2 M.E. Read, G. Nusinovich, O. Dumbrajs, G. Bird, J.P. Hogge, K.E. Kreischer and M. Blank, IEEE Trans. Plasma Science, vol 24, no 3, 1996.

3 J.P. Hogge, K.E. Kreischer, M.E. Read, 20th International Conference on Infrared and Millimeter Waves, pp. 417-418, Orlando, December 1995.