INITIAL OPERATION OF A 100 MW X-BAND GYROKLYSTRON FOR COLLIDER APPLICATIONS

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Abstract

In this paper we present the design details of a first harmonic two-cavity coaxial gyroklystron circuit. The tube utilizes a TE_{011} output cavity and a TE_{011} input cavity which is driven by a 150 kW magnetron at 8.568 GHz and is expected to be at least 40% efficient. We present details of all system aspects, including the test bed modifications, simulated beam properties, and simulated circuit interactions. Cold test results are described and our near-term experimental plans are outlined.

Introduction

At the University of Maryland, we have a comprehensive program to study the suitability of gyroklystrons as drivers for linear collider applications. Previously reported experimental results were achieved on a test bed which produced a small-orbit beam with a nominal voltage and current of 450 kV and 200 A, respectively. Published accounts of our effort include an amplified power level of 27 MW at 32% efficiency in a three-cavity first harmonic gyroklystron [1]; 32 MW at 28% efficiency in a two-cavity second harmonic gyroklystron [2]; and 28 MW in a second harmonic coaxial gyroklystron [3]. Large signal gains have typically been in the 25 - 40 dB range.

In this paper we present the design details of a first harmonic two-cavity coaxial gyroklystron which is predicted to produce about 100 MW of output power with an efficiency of nearly 40%. This tube utilizes a fundamental mode TE_{011} input cavity which is driven by a 150 kW magnetron at 8.568 GHz. The tube also has an 8.568 GHz TE_{011} output cavity. We present details of all system aspects, including the test bed modifications required to produce the enhanced beam characteristics, simulated beam properties, and simulated circuit interactions. Cold test results of both cavities are discussed.

In the next section we describe the test bed and in the following section we present the results of our simulations. The cold-test results are described in the fourth section and a description of our future plans is given in the fifth section. The project status is summarized in the final section.

Test Bed Modifications

We have just completed an upgrade of our facility which should enable us to produce amplified microwave powers in excess of 100 MW (see Fig. 1). Our modulator voltage and current have been increased to 500 kV and 800 A, respectively. We have designed, installed, and completed acceptance testing of a single-anode Magnetron Injection Gun (MIG) which is capable of producing a 480 - 720 A rotating electron beam at the nominal beam voltage with an axial velocity spread less than 7%. The simulated space-charge-limited perveance of 5.5 μP was in good agreement with the measured result.

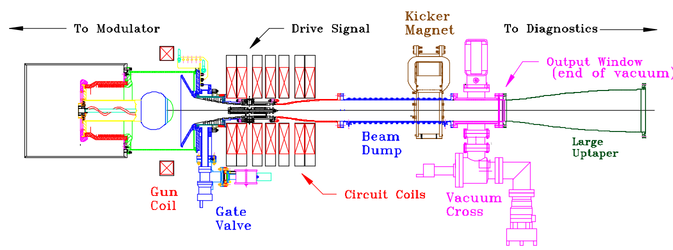

Fig. 1. The gyroklystron test bed.

The original water-cooled magnets have been used, but a larger power supply for the gun coil was required because of a decrease in the magnetic compression. We reduced our drive frequency from 10 GHz to exactly three times the current SLAC frequency, so a new coaxial magnetron and a modified input waveguide were required. The output waveguide (uptapers, beam dump, window, kicker magnet, pumping cross) was totally rebuilt to accommodate the expected larger peak powers. The anechoic chamber was modified to accommodate the new output waveguide and the directional coupler diagnostic was completely redesigned.

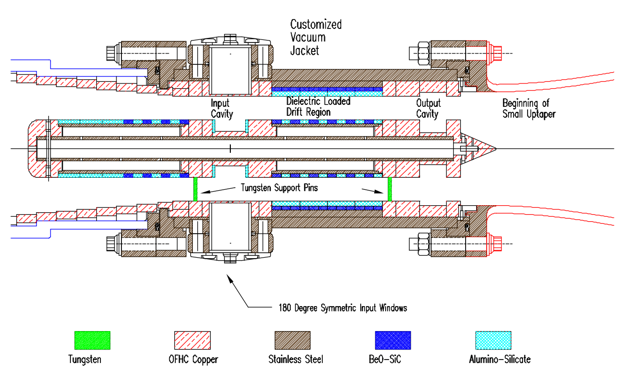

Fig. 2. The first harmonic two-cavity tube.

Theoretical circuit performance

A detailed design analysis has been carried out with the aid of our partially self-consistent nonlinear code. The two-cavity first harmonic tube is shown in Fig. 2 and consists of an input cavity and an output cavity separated by a drift section. The input cavity is defined by a decrease in the inner conductor radius only and the quality factor is brought down to Q ≈ 50-65 by loading the cavity with two thin rings of carbonized aluminum-silicate placed at either end of the cavity. The inner radius is 1.05 cm and the length is 2.29 cm. Power is injected through two radial coupling ports which are separated by 180° and excited in phase. Our start-oscillation code predicts that the input cavity is completely stable up to a current of 800 A.

The drift section has inner and outer radii of 1.825 cm and 3.325 cm, respectively. The inner conductor is required so that the drift tube is cutoff to the operating mode. The regions adjacent to each cavity are made of copper, but lossy ceramics line the majority of the drift tube to eliminate spurious modes. The total length of the drift region is 9.1 cm. Lossy ceramics are also used in the downtaper between the gun and the input cavity.

The output cavity is defined by changes in both radii and has a length of 1.70 cm. Power is extracted axially into the output waveguide via a coupling aperture. The aperture has the same radii as the drift tube and has a length of 0.9 cm. The diffractive quality factor is about 122. The start-oscillation code also predicts the output cavity to be stable at the nominal current, which is given in the middle column of Table 1 along with the other operating parameters. The efficiency is nearly 40% and the output power is about 95 MW. The dependence of tube efficiency on axial velocity spread is plotted in Fig. 3 with the solid line. The simulated velocity spread of the electron gun is 6.4 % at the nominal current. The curve shows a slow but steady decrease in efficiency with increasing spread and indicates that an efficiency of 37% is still possible if the spread is as high as 10%.

Table 1
Comparison of the 1st and 2nd harmonic designs.

Parameters	1st harmonic	2nd harmonic
Voltage	500 kV	500 kV
Current	480 A	770 A
Velocity ratio	1.508	1.508
Input Cavity Q	50	50
Buncher Cavity Q	-	389
Output Cavity Q	122	320
Gain	21 dB	49 dB
Efficiency	39.4%	41.1 %
Output Power	94.6 MW	158.2 MW

Cold-test results

Considerable progress has been made on the construction and cold testing of the first experimental tube. Preliminary cold-testing yielded the approximate dimensions of the input cavity required to achieve the frequency of 8.568 GHz and a quality factor of 55. They are quite near the theoretical estimates given in the previous section. The lossy ceramic ring dimensions have also been finalized. The vacuum-compatible version of the drive cavity has reached the final stages of its construction. The actual injection slots have yet to be cut, but their final size will be determined soon from a final cold test.

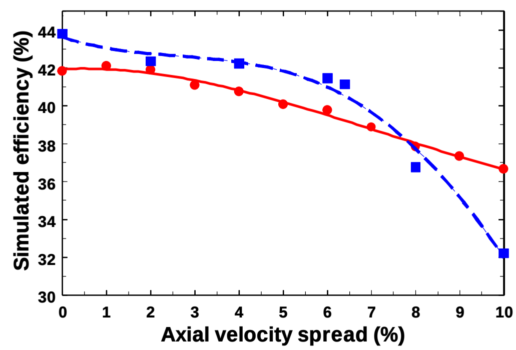

Fig. 3. Efficiency of the first (solid line) and second harmonic (dashed line) tubes vs. velocity spread.

All of the metal hardware for the inner and outer drift tubes has been fabricated. All lossy ceramics have been constructed or procured. Cold-test drift tube attenuation measurements are in progress.

The output cavity has twelve separate metal pieces and has been completely fabricated and cold-tested. The cavity's outer radial wall extends to 3.59 cm while the inner radial wall dips to 1.007 cm. As indicated in Fig. 2, a fairly short taper of the inner conductor radius follows immediately after the diffractive lip to convert the coaxial waveguide to a circular waveguide. Cold testing of the output cavity (and adjacent drift tube region) was performed with a symmetric injection scheme and the resonant frequency and quality factor of the operating TE_{011} mode were found to be 8.565 GHz and 134, respectively.

The construction of the vacuum jacket is well under way. The stainless steel housing for the microwave circuit has been machined. Custom flanges are required in order to fit the tube into the bore of our existing magnetic field coils. These flanges have all been roughed out and are awaiting the final machining of the gasket grooves and brazing tabs. The final step will be to braze the flanges onto the stainless steel housing.

Future Plans

Upon completion of the hot tests of the first two-cavity system, we are planning on testing one or two three-cavity configurations. Both tubes have been designed and are in various stages of cold-testing. The first three-cavity circuit is achieved by placing a buncher cavity in the middle of the drift region which has the same dimensions as the input cavity and is inserted primarily to increase the circuit gain. Simulations indicate that the efficiency of the tube is not dramatically different for the two- and three-cavity first harmonic systems, so the later tube will be tested only if the former tube is found to be gain-limited. The initial gain estimate listed in Table 1 indicates that this could well be the case.

The second planned tube is a three-cavity system for which the buncher and output cavities interact with the beam at the second harmonic of the cyclotron frequency. These cavities are resonant in the TE_{021} mode at 17.136 GHz. The input cavity, however, remains the same as for the first harmonic circuits. The buncher cavity is defined by abrupt radial wall transitions on both conductors in a way that minimizes mode conversion from the TE_{02} to the TE_{01}. The quality factor is achieved by placing the drift tube ceramics in the fringing fields of the cavity. An aluminum mock-up of the buncher cavity has been constructed and cold-tested. Preliminary results have indicated that the required quality factor and frequency can be achieved for this design. A mock-up of the second harmonic output cavity, which also uses abrupt transitions and has an axial coupling aperture is currently under construction.

The nominal design parameters are given in the final column of Table 1. The optimal current according to the simulations is 770 A and the estimated peak output power is over 150 MW. The corresponding gain and efficiency are 49 dB and 41%, respectively. The dependence of efficiency on velocity spread is shown as the dashed line in Fig. 3. Note that the efficiency begins to drop off fairly rapidly for spreads above 7%. However, these simulations are not re-optimized with respect to magnetic field profile, etc., at each point, and additional investigations indicate that higher efficiencies can be achieved if the velocity spread is higher than expected.

The buncher cavity is predicted to be stable at the operating point but the output cavity is highly overmoded and is linearly stable only up to a current of 400-450 A for the operating regime from 4.8 kG to 5.0 kG. The beam can excite various other modes at higher current levels. In the actual system, the signal injected in the input cavity modulates the beam. The length of the drift section is chosen such that the beam is tightly bunched (in gyro-phase) when it enters the output cavity. The well-bunched beam at 8.568 GHz leads to forced excitation of the operating mode (TE_{021}). The operating mode grows in amplitude first. Then, in the presence of the large amplitude operating mode, the gain of the other modes is suppressed. Nonlinear gain calculations show that the cavity is stable under the operating conditions given in Table 1.

We continue to work on improving our simulation capabilities. We have recently started using the commercial High-Frequency Structure Simulator software package (HFSS). We have been using it to model the second harmonic buncher cavity and preliminary results indicate good agreement with experiment. We have also begun to model the drive cavity in order to optimize the design of the coupling apertures. Preliminary simulations with output cavities which extract the power radially and are expected to be completely stable to spurious modes have also met with initial success.

Time-dependent capability has been added to our nonlinear (single-mode) code by researchers from the Naval Research Laboratory and initial results have confirmed the steady-state code predictions. We hope in the future to add multi-mode capability to our time dependent code.

Summary

The upgrade of our facility is essentially complete. We have designs of first and second harmonic tubes that promise to produce peak powers of 100 MW or more with efficiencies of at least 40%. The cold-testing of the initial microwave tube is at an advanced stage and all the results are encouraging. This September we expect to complete the fabrication and assembly of all components necessary for the two-cavity first harmonic system. The first hot test results are expected early this fall. The second harmonic tube test is expected to begin early next year.

References

[1] S. Tantawi, et al. *IEEE Trans. Plasma Sci.*, **20**, (1992) 205.

[2] H. W. Matthews et al., *IEEE Trans. Plasma Sci.*, **22**, (1994) 825.

[3] M. K. E. Flaherty, et al., *J. Appl. Phys.*, **76**, (1994) 4393.