Design of 100 MW, Two-Cavity Gyroklystrons for Accelerator Applications*

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Abstract

We present designs for gyroklystron amplifiers capable of producing 100-150 MW of output power in 1-2 μs pulses.* For accelerator applications we plan to employ a second harmonic output cavity operating at 17.136 GHz. Initial experiments to test our new beam production and transport facilities will involve energy extraction from the fundamental cyclotron harmonic at 8.568 GHz. In both cases the microwave circuits employ coaxial cavities and drift tubes to limit spurious oscillations and cavity cross-talk.

I. INTRODUCTION

Our group at the University of Maryland has been examining the possibility of using gyroklystrons to energize future linear electron-positron colliders for the past several years. Previously we have produced approximately 30 MW of output power in 1 μs pulses at both 9.85 and 19.7 GHz, using fundamental and second harmonic output cavities, respectively [1,2]. All these experiments employed a beam power near 100 MW and efficiencies ranged from 28-35 %. In order to meet the projected 100-150 MW power level requirements needed for collider applications, we are upgrading our experimental facilities to produce a 400 MW electron beam. New coaxial microwave circuits with 17.136 GHz second harmonic output cavities will be described below, along with plans for an initial 8.568 GHz fundamental experiment.

II. EXPERIMENT DESCRIPTION

The electron beam for the experiments is produced by a single anode magnetron injection gun, powered to 500 kV at up to 800 A by a line type modulator. This modulator is a reconstructed version of our existing 400 A device; the extra current is produced by an increase in the number of pulse forming networks from 4 to 8. Additionally, in the older system only 250 A was available for the electron beam since the remainder of the current powered a modulation anode via a resistive divider. In the new configuration the entire modulator output is available to the gun. The new modulator has been completely constructed and tested. A representative voltage vs. time pulse for a resistive load is shown in Fig. 1. It is characterized by a 1.5 μs rise time and 1.5 μs flat-top time. We expect the pulse to be considerably smoother when the gun is connected to the system, due to the filtering action of the gun capacitance.

The electron gun was constructed at Varian Associates and is now in our possession, awaiting final installation and testing. Simulations indicate that the new gun can produce a beam with an average alpha of 1.5 and a velocity spread below 10% over the full range of currents. Over the lower current range of 0-500 A, the spread remains below 6%. The final beam has an average guiding center radius of 2.56 cm and a total beam thickness of 1.26 cm. A diagram of the electrode geometry and representative orbits is displayed in Fig. 2. Filament power for the gun is expected to be 1200 W or less.

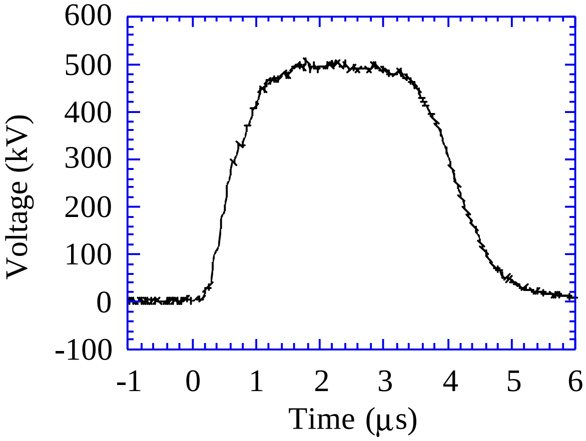

Figure 1. Modulator output pulse

The microwave circuit under test is located within an existing set of seven water cool pancake coils. These coils, plus an additional large coil located around the gun at the axial position of the cathode, create a central field near 5.1 kG and a circuit to cathode magnetic compression ratio of 8.8. Considerable tapering of the magnetic field profile is also possible in this configuration. We are currently performing measurements of magnetic field as a function of position prior to installation of the gun; this should allow more accurate modeling of the electron trajectories than simply using theoretical magnet coil profiles. Located between the electron gun and the microwave circuit is the gun downtaper, a conical vacuum vessel lined with lossy dielectrics of various compositions and thicknesses to suppress spurious (mainly TE_{1m} and TE_{2m}) oscillations. A close-up of a typical microwave circuit is shown in Fig. 3. In this diagram the beam flows into the TE_{011} input cavity, which has a pair of input windows and coupling slots located on opposite sides of the cavity and driven in phase. This arrangement helps produce good coupling to the low-Q (about 50) cavity and provides considerable immunity to the excitation of unwanted modes. The cavity itself is formed by

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a decrease in the inner conductor radius from the normal 1.83 cm to 1.1 cm, over a length of 2.29 cm. Lossy dielectrics line on the cavity endwalls. We will drive the input cavity with a 150 kW, 3 µs microwave pulse from a magnetron. The input waveguide system will be filled with SF_6 to discourage breakdown at the waveguide to window interface.

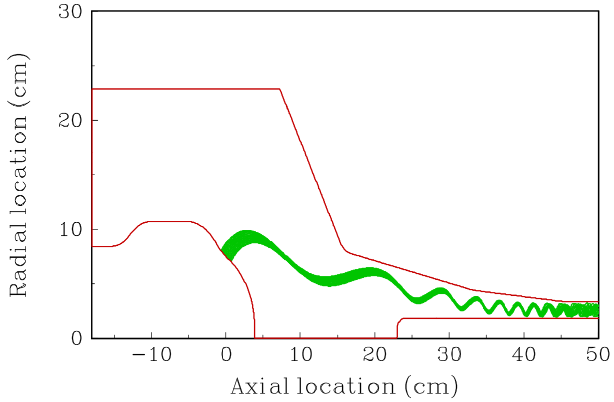

Figure 2. Diagram of the gun electrodes and electron trajectories

The drift tube is lined with lossy dielectrics on both the inner and outer conductors. The inner and outer beam tunnel radii are 1.83 and 3.33 cm, respectively. On the outer conductor there are two concentric layers of material, with the inner layer consisting of carbon impregnated aluminum silicate (CIAS) and the outer layer made from 80% BeO-20% SiC. The inner conductor is lined by alternating regions of CIAS and the BeO-SiC material. Calculated values of attenuation per unit length associated with a variety of hybrid n=1 modes in this structure are shown in Fig. 4. Further theoretical analysis based on these results indicates that this 9 cm long configuration should reduce the quality factors of all spurious drift tube modes to below 15 over the 0-25 GHz range. More importantly, the quality factors are below 5 at those frequencies where the fundamental or second-harmonic beam lines intersect with the dispersion curves associated with electromagnetic modes.

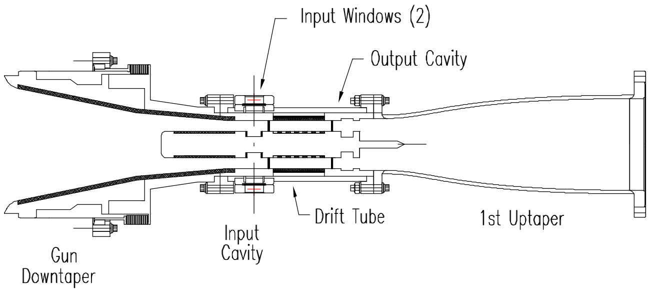

Figure 3. Diagram of the microwave circuit, shown here with the gun downtaper, first uptaper, and the fundamental output cavity.

Because we are retrofitting these tubes into an existing horizontal system, the inner conductor is supported by pins located on each side of the dielectrically lined region (after the input cavity and before the output cavity). The pins will intercept no more than 3% of the electron beam. Ultimately we will use diamond pins (with tantalum cores for charge removal), but initially we will use 2 mm diameter tungsten pins. Calculations indicate that the tungsten will withstand the beam heating at 0.5 Hz. Higher repetition rates will require the use of the diamond. Of course, in a production tube for linear collider applications, one would employ a vertical arrangement in which the inner conductor hangs down from radial vane supports located beyond the beam dump. This arrangement may also be combined with an inverted magnetron injection gun geometry for added inner conductor support.

Initial designs for a TE_{02} second harmonic output cavity operating at 17.136 GHz have been completed. A diagram of the cavity appears in Fig. 5. It is formed by increasing the outer drift tube radius to 3.65 cm over a 3 cm transition length, followed by a 0.64 cm long flat section. The energy is extracted through an axial output lip of 0.1 cm length and 3.58 cm radius, with a 1 cm long transition region between the lip and the cavity body. All of the transitions are smooth to minimize mode conversion. This geometry exhibits a Q of 530 and a forward to reverse power ratio of 24 dB. Theoretical modeling predicts an efficiency of 35% with the expected beam velocity spread of 6%. Higher efficiencies should be achievable with the use of a buncher cavity. Start oscillation studies predict that this design is marginally stable to TE_{1m} modes at 500 A; we plan to further explore mode competition in this geometry with a multi-mode code. We are also currently investigating the tradeoffs between stability and efficiency in this style of cavity.

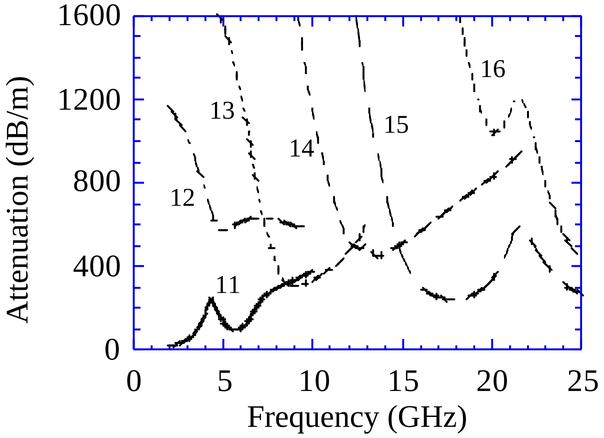

Figure 4. Attenuation per unit length of the drift tube to various n=1 hybrid modes.

We are also considering a complex TE_{02}/TE_{03} second harmonic cavity with an overall physical length of 10.6 cm, a Q of 295, a forward to reverse power ratio of 36.5 dB, and an output radiation purity of 96% TE_{03}. It is formed by a variety of smooth and abrupt transitions on both the inner and outer conductors. This design is considerably more stable than the cavity described above. However, at present the efficiency is only 20%, which is far too low for practical applications. Further analysis has indicated that the low efficiency is caused by competition with third harmonic operation, and that this can be minimized by careful selection of the cavity radii relative to the beam guiding center radius. Further work to understand this phenomenon and improve efficiency is under way.

The first tube to be studied on our new test bed will actually employ a fundamental 8.568 GHz TE_{01} output cavity (pictured in Fig. 3). This initial step is required to simplify the study and suppression of any instabilities which may occur in the drift tube and gun downtaper regions. The cavity employs abrupt transitions, and is realized by decreasing the inner radius to 1.01 cm and increasing the outer radius to 3.59 cm. This main section is 1.7 cm long, and it is followed by an axial energy extraction lip 0.9 cm in length with the same radii as in the main drift tube. Simulations indicate that this cavity will operate with nearly 40% efficiency at 6% velocity spread and 600 A beam current.

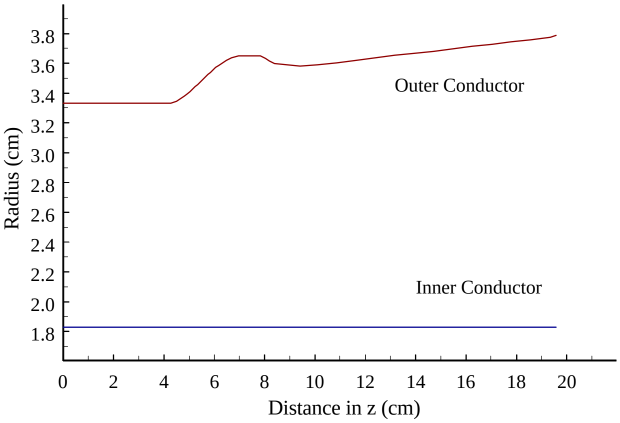

Figure 5. Radial profile of the TE_{02} second harmonic coaxial output cavity.

The post-output cavity system is being completely rebuilt to accommodate the different operating frequencies and higher power levels present in the new experiments. Following the output cavity will be a 40 cm long nonlinear taper which will raise the beam tunnel diameter to 12.7 cm, at which point the electron beam will land in a water cooled copper beam dump. An iron-cored electromagnet, located at the end of the beam dump, produces a transverse magnetic field at up to 800 G to ensure that all electrons are collected. This magnet has been constructed and tested. The output radiation will pass though a perforated pumping manifold and arrive at a 12.7 cm diameter aluminum oxide output window which will be a half wavelength long at the fundamental and a whole wavelength long at the second harmonic. These windows have been procured and are currently being brazed into vacuum flanges. The custom-built pumping manifold has been completed. We will employ two 60 l/s ion pumps to maintain the downstream vacuum during operation; two additional 60 l/s pumps will be located near the electron gun. We expect base pressures in the low 10^{-9} torr range, and operating pressures near 10^{-8} torr.

A number of microwave diagnostics will be used to study the output radiation. Initially a second nonlinear uptaper will be placed between the window and an anechoic chamber. This uptaper will be about 1m long and will raise the diameter to 25.4 cm, at which point the radiation electric field will be below the breakdown limit of air. The taper itself will be filled with SF_6 and will employ a thin Mylar window on the anechoic chamber side. A movable antenna located within the far field region inside the anechoic chamber will allow measurement of output power and radiation patterns. We are also designing a 12.7 cm diameter, SF_6 filled, mode selective directional coupler with side arms optimized for the TE_{01} mode at 8.568 GHz and the TE_{02} and TE_{03} modes at 17.136 GHz. It will be used in conjunction with a new liquid calorimeter for peak power and pulse energy measurements.

III. SUMMARY

The modulator upgrade and electron gun construction for this new experiment have been completed, and we are currently constructing and procuring the remaining beam transport hardware. Following a period of cold tests, we will arrive at a final design for a vacuum-compatible version of the fundamental tube. Construction will follow immediately afterward. Efficiencies of 35-40% appear likely in both fundamental and second harmonic devices, with the possibility of higher efficiency with the addition of a buncher cavity. We anticipate the production of output power levels in the 100-150 MW range at frequencies suitable for collider applications in the near future.

IV. REFERENCES

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[2] H.M. Matthews, *et. al.*, “Experimental studies of stability and amplification in a two cavity second harmonic gyroklystron,” IEEE Trans. Plasma Sci., **22**, 825 (1994).