Experimental Gyroklystron Studies for TeV Linear Colliders*

W. Lawson, B. Hogan, H. W. Matthews, V. Specht, J. Cheng,
P. E. Latham, C. D. Striffler and V. L. Granatstein
Laboratory for Plasma Research
University of Maryland, College Park, MD 20742 USA

Abstract

At the University of Maryland we are exploring the feasibility of gyroklystrons as RF sources for future colliders. To this end, we have developed a 9.85 GHz tube which produces 1 μs pulses in excess of 27 MW at a saturated efficiency of 32% and a gain of 37 dB. The beam energy and current are 430 kV and 150-200 A, respectively. In this paper, we summarize our progress to date and describe our plans for future experiments that should culminate in amplifier outputs in excess of 100 MW.

Introduction

An international effort is underway to develop amplifiers in the 10-30 GHz range with peak powers in excess of 100 MW for driving future multi-TeV electron positron colliders [1]. At the University of Maryland, we are concentrating on the use of gyrotron amplifiers to achieve the required parameters. To date, we have constructed and tested a preliminary system which was designed to produce 30 MW near 10 GHz [2].

In our experimental facility, a 1-2 μs, 500 kV, line-type modulator provides the required beam power. A resistive divider provides the intermediate voltage required for the double-anode magnetron injection gun (MIG). The MIG is designed to have an axial velocity spread under 7% at the nominal current of 160 A with an average perpendicular to parallel velocity ratio of $\alpha = 1.5$. The design magnetic field is 0.565 T in the circuit region.

An schematic of the circuit region for a two-cavity tube is shown in Fig. 1. The downtaper is lined with lossy dielectrics, which are indicated in black. The tapered ceramics are a non-porous mix of 20% SiC in 80% BeO. The other ceramics are made in-house from carbon-impregnated alumino-silicate. Most of the drift tube is also lined with lossy ceramics to suppress instabilities. Power is injected from a 2 μs, 100 kW magnetron through a slit in the radial wall into the input cavity. Control over the quality factor (Q) in the input cavity is obtained from losses in a thin ceramic ring placed against the sidewall. The output cavity Q is predominantly due to diffractive losses from the cavity's output lip. The Q factors have spanned the range 125-500 in the various tubes, but the resonant frequencies have always been derived from TE_{01} modes at 9.85 GHz.

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Experimental Results

A total of six two-cavity and four three-cavity gyroklystron tubes have been tested. A summary of the progress toward achieving high peak power is shown in Fig. 2. The saturated gain at each power level is also indicated. The first two tubes were plagued by a multitude of instabilities and had signal gains less than 0 dB. These results occurred at a beam voltage of 183 kV, a current of 55 A, and a velocity ratio of $\alpha \approx 0.45$. The instabilities could be classified into four groups. Modes in the first class existed mainly in the output waveguide in frequency ranges where the window was a good reflector and were suppressed by amplifier operation. The second class existed in the output waveguide adjacent to the output cavity and were suppressed in Tubes 4 and beyond by a linear wall taper. Whole tube modes comprised the third class and had their energy mainly in the drift tube with reflections provided by the cavities. The final mode class included instabilities in the downtaper. Instabilities in classes 3 and 4 were the most troublesome and usually involved modes with one azimuthal variation.

Tubes 3 and beyond incorporated a downtaper and drift tube with sufficient attenuation to allow significant beam power. Tube 4 produced peak powers near 2.7 MW with a 427 kV, 130 A beam in a constant magnetic field of 0.537 T. Maximum efficiency was approximately 5%.

The final order of magnitude increase in power was achieved with Tube 5, which had additional loss in the downtaper and a higher Q in the output cavity (224). The primary performance increase came not from the circuit modifications but rather from the introduction of magnetic field tapering [3]. A careful search of parameter space showed that the optimal input cavity field was 0.545 T while the best output cavity performance occurred at 0.474 T. The beam voltage and current were 425 kV and 150 A, respectively. The simulated velocity ratio was $\alpha \approx 0.98$ in the output cavity and varied adiabatically with the magnetic field. The efficiency at the maximum was 31% and the gain exceeded 26 dB.

The three-cavity tubes had a tunable penultimate cavity whose Q (~270) was defined solely by an alumino-silicate ring on the outer wall. The output cavity Q in Tubes 7 and 8 were 200 and 350, respectively. The power performance of the two- and three-cavity tubes was similar at the 15% tapered field profile. The gain was typically improved, with a maximum saturated gain of 50 dB occurring at an operating point that produced 21 MW. Optimal performance occurred, however, when a 33% decrease in the output cavity magnetic field was introduced. A maximum peak power of 27 MW was obtained with an efficiency of 32%.

The final three-cavity tubes employed considerably longer output cavities in an attempt to explore the extraction mechanism, but no improvement in power was observed.

Future Experiments

With the success of the intermediate experiment, we are now contemplating our approach to a 100+ MW device. The high power requirement places several constraints on the electron gun and the microwave circuit. To produce a higher power MIG, we must either increase the beam voltage, increase the peak electric field in the gun, enlarge the average beam radius, or decrease the applied magnetic field [4]. The new microwave circuit must continue to be stable to spurious modes, provide inter-cavity isolation, and dissipate a fair amount of average power. Our options will be explored by performing cold test studies, constructing and testing additional tubes with the existing beam parameters, and designing MIGs and microwave circuits for 300-400 MW beams. Many configurations are being studied (e.g. Ref. 5). One such approach is detailed below.

One way to lower the magnetic field is to inject at the fundamental and extract at the second harmonic. We are testing this concept by replacing the output cavity of Tube 6 with a 19.7 GHz TE_{02} cavity (Fig. 3). A small cavity radius (r = 1.709 cm, ℓ = 4.254 cm) insures that the TE_{01} cannot exist at 9.85 GHz. Adiabatic wall transitions are used to minimize mode conversion to the TE_{01} at 19.7 GHz. A cold cavity design code indicates that the power flowing into the drift tube is 50 dB lower than the power extracted at the end of the system. Simulations of amplifier stability and operation have been performed assuming the nominal experimental beam parameters. The design quality factor of 700 exceeds the start oscillation requirement for magnetic fields above 0.545 T. Efficiencies of at least 25% have been predicted by the large signal code. The output cavity has been constructed and cold tested and we have just begun amplifier studies.

A second tube is planned which has a shorter, stable output cavity. It also has a 4 mm diameter coaxial insert, which will increase isolation between cavities. In the downtaper, the insert radius will be increased and lossy dielectrics will be added in an attempt to further suppress class 4 modes. This should result in a higher attainable velocity ratio which our large-signal code predicts will translate into better efficiency.

If the initial second harmonic experiment is successful, we intend to scale it to the 100 MW+ level by increasing the beam current. This will require a larger guiding center radius and a coaxial insert to maintain drift-tube isolation. We have been studying design scenarios from 10 to 20 GHz; an X-Band design is discussed below.

A schematic for a system that utilizes a TE_{01} input cavity and a second harmonic, 11.424 GHz TE_{02} output cavity is shown in Fig. 4. Tentative parameters include a magnetic field of 3.28 kG, a coaxial drift tube with an 18 cm length, and an inner(outer) radius of 1.6(3.9) cm. Scaling the current beam from 200 A to 600 A requires a three-fold increase in guiding center radius. The inner conductor will be supported at the end of the beam dump and will include lossy ceramics to enhance stability. The output cavity radius is selected to preclude fundamental TE_{01} operation but may have to be increased if spurious modes become a problem. Initial large-signal modeling has predicted efficiencies above 27%; we expect this value to increase significantly when the design is optimized.

A single-anode MIG which provides the required beam parameters has been designed [6]. The average cathode radius is 7.13 cm and has an average half-angle of 46°. The magnetic field compression is 7.55 at $\alpha = 1.5$. The peak electric field is less than 90 kV/cm on the cathode and 30 kV/cm on the anode. The nominal current is only 26% of the space-charge limiting value. The design can operate over an 800 A range with a velocity spread below 10% due to the laminar flow of electrons throughout much of the gun. This extended range will facilitate the study of high efficiency amplification in the 100+ MW regime.

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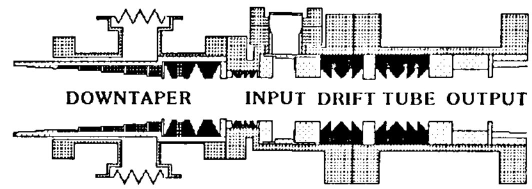

Figure 1. The two-cavity microwave circuit configuration.

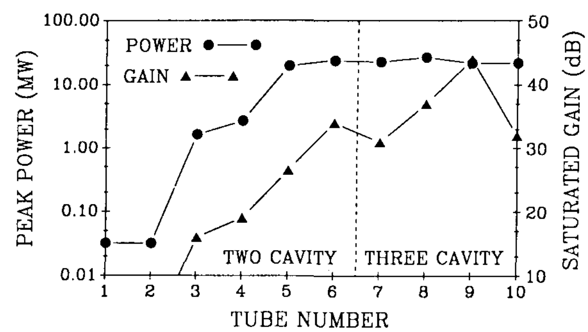

Figure 2. Summary of tube peak power performance.

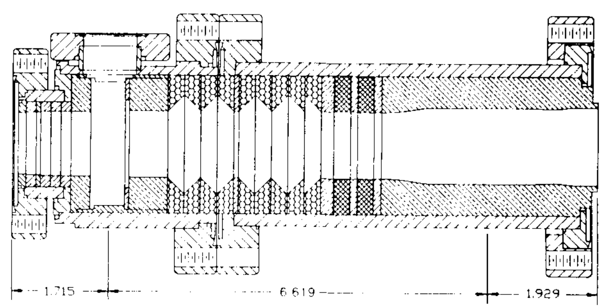

Figure 3. The initial two-cavity second harmonic circuit configuration.

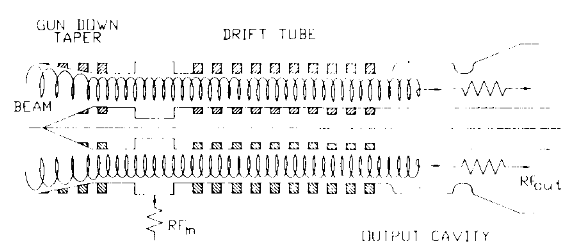

Figure 4. A coaxial second harmonic two-cavity circuit.