A 30 MW, 10 GHz GYROKLYSTRON WITH LINEAR COLLIDER APPLICATION*

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ABSTRACT

In this paper, the final preparations for bringing the University of Maryland's 10 GHz, 30 MW gyroklystron experiment on-line are discussed. We describe the initial operation of the modulator and the acceptance tests performed on the electron gun. We explain the enhanced circuit modelling and present a two-cavity design which predicts an efficiency of 33% and a gain of 27 dB. The realization of the design is also discussed. In addition, we briefly discuss the output waveguide and the diagnostics for beam and RF characterization. Finally, a four-cavity circuit design is presented with its predicted operating parameters that can achieve the necessary gain and efficiency required for accelerator application.

INTRODUCTION

The results of scaling studies for the next generation of linear electron-positron colliders have demonstrated a need for high pulse power, high efficiency, high gain microwave (8-30 GHz) amplifiers.¹ As part of our investigation into the suitability of gyrotron amplifiers for this application, we are constructing an X-band gyroklystron which is predicted to achieve a peak power of 30-50 MW.²⁻⁶ Successful operation of this device will increase the state-of-the-art power capability by three orders of magnitude and will establish the gyroklystron as a primary candidate to drive high-energy linear colliders.

A schematic of the major subsystems of the initial two-cavity gyroklystron is shown in Fig. 1. The axial magnetic field profile generated by the seven circuit coils and a coil placed directly over the cathode emitting strip is shown in Fig. 2. The nominal magnetic compression ratio is 12 and the flat field region is about 25 cm in length. The modulator supplies a 500 kV, 200 A, 1.5 μ s pulse with an intermediate voltage to a double-anode Magnetron Injection Gun (MIG). The MIG generates a rotating beam which passes through the circuit after being adiabatically compressed. The beam's phase-space distribution is modulated by a microwave signal which is injected into the first cavity. Energy is extracted axially through a coupling aperture in the second cavity and travels through a

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nonlinear waveguide to a half-wavelength output window. The beam expands in the decreasing magnetic field and impinges on a 35 cm section of the output waveguide. A directional coupler and water calorimeter (not shown) measure the peak and average microwave power. The nominal parameters of this configuration are listed in Table I and details of these subsystems are discussed below.

ELECTRON BEAM GENERATION

The 500 kV voltage pulse is generated by an 8-12 stage line-type modulator. Four pulse-forming networks (PFNs) in parallel are resonantly charged on command to 46 kV using a 0.68 H charging inductor. This charging cycle is triggered using a spark gap with an argon/air mixture and derives its energy from a 10 μ F capacitor bank. The PFNs are switched through two thyratrons into a 1:22 pulse transformer which provides the required potential of 500 kV and current of 400 A. Peak-to-peak ripple of better than two percent has been achieved by loading down the parasitic oscillations in the pulse transformer and by adjusting PFN inductors.

The electron gun is in the double anode MIG configuration and is shown in Fig. 3.⁷ Key dimensions of the gun design are listed in Table II and the simulated beam properties at 160 A are listed in Table I. The peak electric field at the cathode tip is less than 90 kV/cm. The stated cathode loading is 40 percent of the space charge limiting current. The axial velocity spread remains below $\Delta v_z = 10\%$ for a current range from 120 A to 240 A. The gun has been constructed by Varian Associates⁸ and has passed its acceptance test. A 1 μ s, 500 kV pulse was applied to the MIG when the cathode was cold. The voltage pulse and charging current are shown in Fig. 4a. Without the axial magnetic field, a 143 kV pulse was applied with the cathode hot ($\sim 950^\circ\text{C}$) and the control anode grounded. The resulting 120 A pulse represents a current density of 4.2 A/cm² and is shown in Fig. 4b. The current was limited by the impedance of the modulator. Preparations are being made to draw the full power beam.

TWO-CAVITY MICROWAVE CIRCUIT

To design the microwave circuits, we use a partially self-consistent steady state, numerical code that has evolved considerably during the past three years.²⁻⁶ The cold cavity field profiles are found from a scattering matrix formulation.⁹ The effect of ac space-charge waves¹⁰ has been incorporated both as a frequency shift and a perturbation on the perpendicular field profile. A schematic of the two-cavity circuit design is shown in Fig. 5. The parameters of the two-cavity design are listed in Table I along with the simulated results. The input cavity Q is simply assumed to be as indicated; below we detail the realization of that Q.

A linear start oscillation code based on the scattering matrix results is used to predict the stability of the system to the normal modes of the entire system.

Of particular concern are the TE_{11} , TE_{21} , and TM_{01} modes because they are not cutoff in the drift tubes at the operating frequency due to beam power constraints. Figure 6 shows the start oscillation calculation for the modes with one azimuthal period ($m=1$) assuming the tube boundary is a perfect conductor, and Table III identifies the modes. The dashed line indicates the operating current so it is evident that the metal tube has no stable region. Fortunately, start oscillation depends on the current times the circuit Q , so we can stabilize the system by introducing some dissipative loss. Most of the modes are unstable due to fields in the drift tube; only a few are unstable due to fields in the input cavity. Both types can be stabilized by the techniques described below.

The low Q of the input cavity is realized by two thin, carbon-impregnated aluminosilicate annuli located on either cavity end near the outer radius. Cold tests have revealed that we can achieve the required frequency and Q with such absorbers. The scattering matrix code was modified to include lossy dielectrics and was successfully compared to analytic results in simple geometries with lossy dielectrics and numeric codes (mafia and urmel-t) for complex geometries with loss-free dielectrics. The dielectrics have not yet been installed in the gyrokystron code, but the field profiles are similar to dielectric-free cavities and performance is expected to be similar. The input power is supplied by a $3\mu s$, 100 kW magnetron and is injected into the cavity through a single aperture on the outer wall ($r = \text{constant}$) of the cavity.

To suppress the "whole tube" modes in the region between the input and output cavities, a drift tube consisting of alternate washers of metal and lossy dielectric will be used. Again, both experimental and analytic results indicate the viability of this technique. Our first tube will utilize six rings of MgO with a 1% concentration of SiC. The dielectric rings are 22% wider than the alternating metal rings and have a depth of 1.6 cm. The drift tube provides 117 dB isolation for the TE_{01} mode and more than 16 dB isolation for the uncutoff modes at 10 GHz.

The output cavity Q is essentially diffractive and is sufficiently larger than the minimum Q so that a simple coupling iris can be used for the endfire system. Cold testing has confirmed both the frequency and Q predicted by the scattering matrix code for a variety of configurations. The placement of the lossy dielectric materials in the input cavity and in the drift tube region are shown in Fig. 7, a detailed design of the two cavity microwave circuit.

OUTPUT WAVEGUIDE

The vacuum vessel between the output cavity and the output window doubles as the microwave and beam transport system and is shown in Fig. 8. A nonlinear taper brings the waveguide radius from 2.60 cm to the beam dump radius of 3.57 cm in 19.5 cm. The smaller radius can support only the lowest circular electric mode (TE_{01}) at 10 GHz while the larger radius can support the lowest two circular modes. To minimize mode conversion, a raised cosine radius is used.

An approximate analytic solution predicts the mode conversion to be less than 1.1×10^{-4} percent in power.

Computer simulations of the beam with and without microwave interaction show that the beam is dumped fairly uniformly by the decaying magnetic field over a 35 cm distance in the beam dump. This keeps the instantaneous temperature rise below 20° and the average temperature rise sufficiently low to allow modest water cooling. A dumping magnet prevents the few high energy electrons from reaching the output window. The vacuum port consists of a stainless steel tube with 150 holes distributed uniformly in angle and axial position to provide sufficient conductance with minimal microwave interference.

A second nonlinear taper is used after the beam dump to bring the radius to 6.35 cm. At that radius, four circular electric modes can propagate, but the ideal mode conversion to all other modes is still less than 0.002 percent in power. A half wavelength BeO window, brazed to a stainless steel flange via a Kovar ring, provides the vacuum-to-air interface.

DIAGNOSTICS⁶

There will be several standard external current transformers in conjunction with current breaks to measure the instantaneous beam current at several locations along the system. Capacitive probes, which consist of four 90° sections and a sapphire insulator, will be used at several locations in an initial beam test to measure total beam density and beam alignment. The two diagnostics jointly will give an estimate of the average axial velocity and, along with the beam voltage, will provide information about the average velocity ratio.

The microwave diagnostics consist of both peak and average power measurements. The peak power measurement involves a mode selective directional coupler¹¹ combined with a crystal detector. Because the circular guide is highly overmoded and the rectangular guide is not, the phase velocity of the two waves cannot be the same and two sets of coupling holes are required. The 50 dB, $TE_{01}^0 \rightarrow TE_{10}^0$ coupler is designed to maximize TE_{01}^0 directivity (-83 dB) and minimize TE_{11}^0 coupling (-75 dB). The detector will provide the signal envelope and, with proper calibration, an estimate of the peak power. A non-resonant water calorimeter will provide the average power measurement and a check of the peak power measurement. Water is circulated between two 19.5 cm long cones to maximize sensitivity. The thickness is adjusted to guarantee a minimum attenuation of 28 dB.

FOUR-CAVITY MICROWAVE CIRCUIT

To achieve high gain, high efficiency gyrokystrons, multi-cavity circuits will be utilized. Simulations of a four-cavity design with two buncher cavities that have similar dimensions to the input cavity have been studied. The optimized design has an efficiency of 45% and a large signal gain of 63 dB with the simulated

beam parameters. This design is summarized below.³ The techniques of mode control and suppression in both the input and buncher cavities and in the drift spaces are assumed to be the same as described above for the two-cavity design.

The four-cavity circuit is shown in Fig. 9a along with a typical electric field profile in Fig. 9b. The dimensions of the cavities, drift spaces, output iris, and RF output region are tabulated in Table IV. An input signal is injected into the first cavity, the second and third cavities enhance beam bunching and hence gain, and the final cavity has a coupling iris in the endwall to launch the output signal into the waveguide. The beam parameters and optimized design results are tabulated in Table V. Contour plots of saturated efficiency as a function of the circuit magnetic field and the axial velocity spread of the beam are displayed in Fig. 10. For a cold beam, $\Delta v_z = 0$, the predicted optimum efficiency is $\sim 50\%$. For our beam with a $\Delta v_z/v_{z0} \sim 6.2\%$, this efficiency falls to 45.5% because the spread in velocity prevents tight phase bunching of the electrons. This degradation due to velocity spread is minimized in the design by keeping the drift sections short, which requires relatively large cavity fields. The corresponding large signal gain is ~ 63 dB.

The effects of phase bunching, the result of the negative mass effect, are displayed in Fig. 11. In these phase-space plots we have plotted $\beta_{\perp} = v_{\perp}/c$ versus phase [particles are initially disturbed uniformly around a cyclotron orbit] at (a) an axial position which represents the end of the third cavity, (b) the start of the fourth cavity (output cavity), and (c) the end of the output cavity. The enhanced phase bunching occurs in the drift region between the final buncher cavity and the output cavity, and a relatively large number of particles are at the appropriate phase for energy extraction in the output cavity. Additional considerations for increasing efficiency are the tuning of the penultimate cavity¹² and magnetic field tapering. These will be incorporated into later designs.

SUMMARY AND DISCUSSION

Current theoretical and experimental studies indicate that the design goals can be achieved. The 10 GHz, 30 MW four-cavity gyrokystron design is predicted to achieve acceptable efficiency ($\sim 45\%$) and gain (~ 60 dB) that would be necessary for accelerator application. The first system to be experimentally studied will be a two-cavity gyrokystron which will be able to test all the components required for high power operation. The modulator has been built and tested. It presently operates at 500 kV and 2 Hz with 400 A delivered to a resistive load. The MIG has been built and has passed its initial testing. The circuit components are in their final stages of design and cold testing. The input cavity properties are the most difficult to realize, primarily because of the simultaneous requirement of acceptable radial wall coupling and the proper frequency and Q. Incorporation of lossy dielectrics, which are needed to achieve a low input cavity Q, has been greatly expedited by the development of a state-of-the-art in-house vacuum tube processing facility. This facility contains components that allow

the purification of porous dielectrics, the impregnation of controlled amounts of lossy material, and the firing of these materials to obtain acceptable vacuum compatibility. We are also able to perform hydrogen/vacuum brazing of the various components. This capability of in-house processing has proved invaluable from a time standpoint. The construction of the vacuum chamber from the gun through to the output window is complete and is in its final stages of being checked for vacuum compatibility.

The first experiment to be performed on the gyrokystron system will be a beam transport characterization. This involves beam alignment, measurement of beam velocity partition, $\alpha = v_{\perp}/v_z$, etc. This experiment will be performed this summer. Following the beam transport experiments will be the two-cavity RF experiment. This is planned for early fall.

To achieve significantly higher power levels, the circuit will have to be modified considerably. The present limitation is the peak power capability of the magnetron injection gun. Scaling laws have been derived¹³ which predict the dependence of the beam power on beam voltage, peak applied electric field, and the beam radius. If $\gamma_0 = 1 + V_0/(mc^2)$ is the normalized beam energy, E_m is the maximum electric field and r_g is the average beam radius, then the peak power P_0 scales as follows:

$$P_0 \propto (\gamma_0 - 1)^2 (1 + \gamma_0^{-1}) E_m r_g.$$

From this relation we have designed a gun for a coaxial cavity (with twice the average beam radius) at an energy of 800 keV which should be capable of producing 180 MW of 10 GHz microwave power.¹ Further power increases would be possible if we were to relax the constraint on maximum electric field which is currently $E_m < 90$ kV/cm.

To achieve high frequencies, again the trade-off between power and frequency in the gun is fundamental. The MIG frequency scaling is $P_0 \propto f^{-1}$, which is superior to Pierce gun scaling when considering high frequencies. This scaling has been confirmed with numerical simulations and should make the gyrokystron an even stronger contender to power the linear supercollider if the proposed operating frequency exceeds 10 GHz. In addition, a binary power multiplier has also been considered¹⁴ as a method for increasing RF power.

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Table I.
The Two Cavity GKL Parameters - Beam and Circuit

Beam	Power P_0	80 MW
	Voltage V_0	500 kV
	Velocity ratio $v_{\perp}/v_z$	1.5
	Velocity spread Δv_z	7.0%
	Larmor radius r_L	0.43 cm
	Center radius r_g	0.79 cm
	Guiding spread Δr_g	0.20 cm
	Axial field B_0	0.565 T
	Mode (both cavities)	TE ₀₁₁
Circuit	Peak Efficiency	33%
	Gain	27 dB
	Injected Power	50 kW
Input Cavity	Radius	4.50 cm
	Length	1.53 cm
	Q	225
Drift Tube	Radius	1.50 cm
	Length	9.00 cm
	Q	165
Output Cavity	Radius	2.11 cm
	Length	2.38 cm
	Q	165
Aperture	Radius	1.50 cm
	Length	0.33 cm
Output Guide	Radius	2.60 cm

Table II.
The 80 MW MIG Electrode Specifications.

Cathode Radius r_c	0.0228 m
Emitter Strip Width ℓ	0.020 m
Cathode-Control Anode Gap d_{ac}	0.0613 m
Cathode Half Angle ϕ_c	20°
Compression Ratio f_m	12
Control Anode Voltage V_a	143 kV
Emission Current Density J_c (Uniform)	5.61 A/cm ²

Table III.
m = 1 Mode Identification for Figure 6.

Label	Frequency (GHz)	Diffractive Q	Dominant Mode
1	10.99	1162	TE ₁₂ (input cavity)
2	13.59	710	TM ₁₁ (drift tube)
3	14.18	398	TM ₁₄ (drift tube)
4	15.26	281	TE ₁₄ (input cavity)
5	17.03	1510	TE ₁₂ (drift tube)
6	17.03	1510	TE ₁₂ (drift tube)
7	17.21	577	TE ₁₂ (drift tube)
8	17.21	577	TE ₁₂ (drift tube)
9	22.74	893	TM ₁₂ (drift tube)
10	22.74	893	TM ₁₂ (drift tube)
11	23.00	236	TM ₁₂ (drift tube)
12	23.98	515	TE ₁₂ (drift tube)
13	26.60	347	TE ₁₂ (drift tube)
14	27.37	342	TE ₁₃ (drift tube)

Table IV.
GKL Four-Cavity Circuit Dimensions,
Q, and Resonant Frequencies

Cavity	Length (cm)	Radius (cm)	Q	Frequency (GHz)
1	1.53	4.50	235	10.0
2	1.53	4.50	235	10.0
3	1.53	4.50	240	9.9747
4	2.37	2.11	180	9.9950
<u>Drift Tube</u>				
1	4.5	1.5		
2	5.4	1.5		
3	3.9	1.5		
4	.34	1.5		
5	4.8	2.7		

Table V.
Beam Parameters and RF Results
for the Four-Cavity Circuit

Beam Voltage	500 kV
Beam Current	160 A
Beam Power	80 MW
Magnetic Field	5.55 kG
Velocity Ratio ($v_{\perp 0}/v_{z0}$)	1.5
Velocity Spread ($\Delta v_z/v_{z0}$)	6.2%
Input Power	18.3 W
Output Power	36.4 MW
Efficiency	45.5%
Gain	62.9 dB

Fig. 1. The University of Maryland 30 MW Gyrokystron.

Fig. 2. Nominal axial magnetic field profiles.

Fig. 3. The Magnetron Injection Gun (MIG) Layout.

a

b

Fig. 4. Modulator and MIG traces during acceptance testing. (a) A typical modulator pulse. The upper trace shows the voltage pulse (100 kV/div.), and the lower trace the modulator charging current (50 A/div.). The sweep rate is 1 μ s/div. (b) The MIG pulse. The upper trace shows the voltage pulse (50 kV/div.) and the lower trace the current pulse (50 A/div.). The sweep rate is 500 ns/div.

$$\eta = 33\%$$

$$\text{Gain} = 27\text{dB}$$

$$P_{in} = 50\text{kW}$$

Dimensions in cm

Fig. 5. The Two-Cavity GKL Design and predicted operation properties.

Fig. 6. Start oscillation current for $m = 1$ modes in the two-cavity GKL design.

Fig. 7. A detailed schematic of the two-cavity GKL design showing the placement of the lossy material (shaded regions).

Fig. 8. The Output Vacuum Vessel.

Fig. 9. (a) The GKL Four-Cavity configuration, and (b) the field profile.

Fig. 10. GKL efficiency contours as a function of magnetic field and axial velocity spread. The beam properties as determined by Herrmannsfeldt's Gun code is shown.

Fig. 11. Phase space plots of the particle distribution at various axial locations: (a) end of the final buncher cavity, (b) start of the output cavity, and (c) end of the output cavity.

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