A 500 MW ANNULAR BEAM RELATIVISTIC KLYSTRON

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Abstract

This paper describes the experimental development of a long pulse, high current, annular beam relativistic klystron amplifier. The desired performance parameters are 1 GW output power and 1 μs pulse length with an operating frequency of 1.3 GHz. The electron beam voltage and current are nominally 600 kV and 5 kA. Peak powers approaching 500 MW have been achieved in pulses of 1 μs nominal baseline-to-baseline duration. The half power pulse width is 0.5 μs. These pulses contain an energy of about 160 J. The design of this class of tube presents some unique challenges, particularly in the output cavity. The output cavity must exhibit a very low gap shunt impedance in order to obtain reasonable conversion efficiency from the low impedance modulated electron beam to microwave power, while still maintaining a reasonable loaded Q for mode purity. The physics of this device is dominated by space charge effects which strongly impact the design. Current experimental results and theoretical design considerations for this class of tube, and scaling to higher frequency operation, suitable for the Next Linear Collider are discussed.

I. Relativistic Klystron Description

The RKA configuration is shown schematically in Fig. 1. The electron beam is formed from a 6.2-cm-diam. annular explosive field-emission cathode made of stainless steel. The beam is guided and slightly compressed by a converging 0.5 T axial magnetic field to a nominal 5.9 cm diameter beam with a 5 mm thickness. The RKA drift pipe diameter is 7.3 cm. The typical beam voltage is 620 kV with the current increasing from 3 to 6 kA during the pulse. The beam has a microperveance of about 11. The increasing current is caused by the drop in electron gun impedance during the pulse due to plasma closure of the anode-cathode gap. The input and idler cavities are of the quarter-wave coaxial geometry type. The input cavity is coupled through an iris into reduced-height WR-650 waveguide that tapers to full height and connects to a 500 kW L-band magnetron. The idler cavity has an annular tuning ring which gives flexibility in inductively tuning the cavity over a range of about 100 MHz.

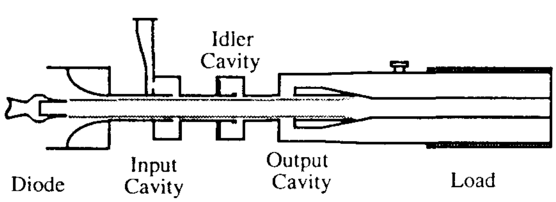

Fig. 1: Schematic diagram of the RKA

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The output cavity is a noseless pillbox design with annular coupling irises near the outer diameter that couple the microwave power into a low impedance coaxial transmission line. A tapered impedance transformer transitions to standard 50 Ω, 6-in-diameter coaxial line dimensions. In this 50 Ω section of line is a calibrated, high directivity, in-house-designed b i-directional coupler for accurate measurement of the microwave power traveling in the TEM mode. The directivity of the coupler is 20 dB. The 50 Ω coaxial transmission line is terminated with a matched (VSWR = 1.2) coaxial dummy load built into the end of the coaxial transmission line. The entire structure, including the load, is under vacuum. This was done in order to avoid having to simultaneously develop a high power window capable of reliably transmitting 1 GW of power. The operating vacuum measured by an ionization gauge tube at the location of the directional coupler in the 6-in-diam. output coaxial transmission line is typically about 7 x 10^{-7} Torr. The vacuum at the output cavity gap is estimated to be about 1 x 10^{-6} Torr. A more complete description of the RKA and the experimental work can be found elsewhere [1].

The output cavity is the most critical part of the relativistic klystron tube. The microwave power extracted from the beam is given by Ramo's Theorem as

$$P(t) = \int_V \vec{J}(r,t) \cdot \vec{E}(r,t) dV \ ,$$

where J is the beam current density, and E is the electric field across the cavity gap. From this equation one can see that only the beam's kinetic energy can be extracted, and since $E \sim e^{j\omega t}$, power can only be extracted from the fundamental harmonic component of the current. To produce the highest microwave output power, one must simultaneously maximize the fundamental harmonic current, I_1, and extract the maximum kinetic energy from the beam.

The output cavity must be designed to produce an electric field across its gap of sufficient magnitude and phase that the electron bunches are significantly slowed, thereby giving up kinetic energy to the microwave field in the cavity. The output cavity must be made resonant, and the output cavity gap shunt impedance must be matched to the beam impedance to provide the gap voltage that extracts most of the available kinetic energy. If the output cavity gap voltage is too high, two things can happen. Beam electrons can be reflected back upstream causing disruption of tube operation, and rf breakdown can occur in the output cavity. Too low a gap voltage produces very little slowing of the electron bunches resulting in very poor conversion efficiency of electron kinetic energy to microwaves. If the output cavity is not resonant, most of the power will be lost in higher order modes. Our high-current RKA has a nominal harmonic current (I_1) impedance of around 200 Ω. In a microwave cavity, where R_s is the shunt impedance and Q is the loaded Q, the quantity R_s/Q depends only on the geometry [2]. In a TM_{010}-type cavity the value R_s/Q is around 50, and there is little one can do to alter the geometry. If one desires to match the cavity impedance to the beam impedance of 200 Ω, this implies a Q of about 4.

II. Experimental Results

The beam modulation section of the RKA consists of the input cavity and one idler cavity. This section of the tube is performing as designed, and is providing a modulated electron beam with a harmonic current $I_1 = 0.65\ I_0$ where I_1 is the fundamental harmonic at 1.3 GHz and I_0 is the dc beam current. The modulated beam current pulse, I_1, at the full drive power level of 300 kW, lasts for the entire duration of the pulsed power pulse when the output cavity is not on the tube. When the output cavity is in place the electron reflection at the output gap causes the beam modulation to be prematurely disrupted. The performance of the input cavity is detailed in reference [1] and will not be repeated here.

A. Idler Cavity

The role of the idler cavity is to substantially increase the beam modulation that is initiated by the input cavity. The idler cavity is placed at the position downstream of the input cavity where the beam modulation reaches its highest value, which is where I_1/I_0 is about 10%. The idler cavity can be inductively tuned over about 100 MHz, from 1300-1400 MHz. Measurements were made of beam harmonic current modulation (I_1) as the rf input power was varied and as the idler cavity tuning was changed. The harmonic current increases, as predicted, as the idler cavity tuning moves toward the 1.30 GHz rf drive frequency for a given amount of input drive. We could not adjust the idler cavity frequency any closer than 1325 MHz because the peak surface field at the idler cavity gap exceeded the level for rf breakdown.

Beam modulation data were taken for different idler tuning frequencies and input cavity drive powers to find the best combination for maximum beam modulation. This data showing beam modulation (I_1/I_0), at the location of the output cavity gap, as a function of input drive power, is plotted in Fig. 2. The data showing the beam modulation as a function of idler cavity tuning is somewhat incomplete because we installed the output cavity as soon as it was available.

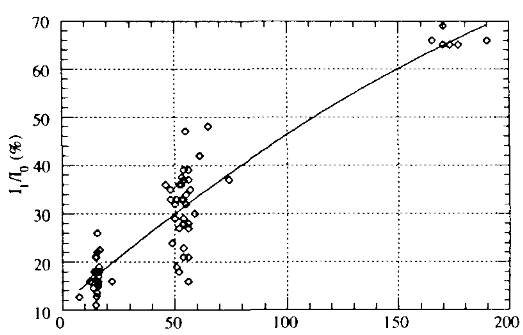

Fig. 2: Beam modulation (%) after the idler cavity as a function of input drive power.

From PIC code simulations, the amount of modulated current out of the idler cavity for maximum output was determined to be 65-75% [3]. The amount of extractable beam power is usually given as $P = (V \times I_1) / 2$. For this case with a voltage of 620 kV and a harmonic current of 3.3 kA, about 1 GW of power is in the fundamental harmonic. Because of the effect of the space charge potential depression [3], the output cavity can only extract about 70% of this power, and should produce 700 MW of rf output power or 700 J per pulse.

B. Output Cavity

The original output cavity downstream endwall (the wall containing the coupling irises) was modified, based on cold tests, to have a loaded Q of ~10. The much lower loaded Q resulted in much lower electric fields across the cavity gap thereby reducing the rf breakdown problem. This change created a better match between the modulated beam impedance and the cavity shunt impedance for better conversion efficiency from beam power to microwave power.

So far, the highest energy obtained with the modified output cavity, in a single pulse, has been 160 J. Data are shown in Fig. 3 where rf output power, beam voltage, and beam current are all overlaid on the same time scale. The peak power is 375 MW. Note that the rf power goes away before the beam voltage reaches its maximum value. This will be discussed later. Other shots have recorded higher peak powers (475 MW), although at a slightly lower energy per pulse (140 J).

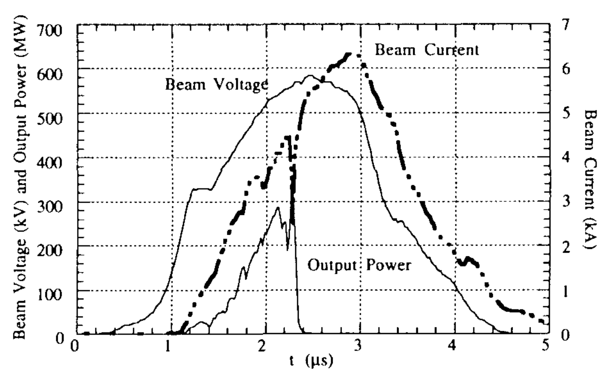

Fig. 3: Output power, beam voltage and current for shot 1308.

The signals from the two B-dot loops located 90 degrees apart on the upstream wall of the output cavity are shown in Fig. 4. They track together indicating that the output cavity is operating in the proper mode. The B-dot signals are plotted in Fig. 4 in terms of the output cavity gap voltage they represent. The actual voltage across the 2.76 cm output gap at 375 MW reaches 370 kV producing an average electric field of about 134 kV/cm. From the HFSS simulation [4], the magnitude of the peak gap voltage, across the geometrical cavity gap, was found to be as high as 538 kV with a peak surface electric field of 225 kV/cm when 500 MW was being coupled into the output coax. This gap voltage is high enough to turn electrons around in the beam. Therefore, it was obvious that the modified output cavity would never be able to reach the desired output power level of 1 GW.

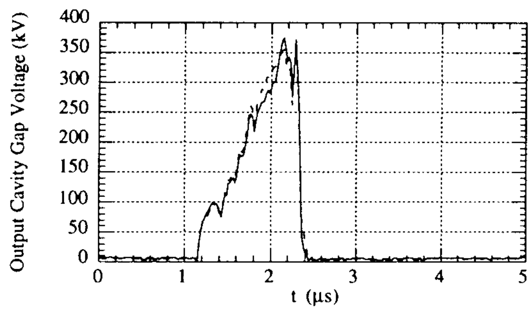

Fig. 4: Output cavity gap voltage for shot 1308.

At this point it was not yet certain why the rf pulse was terminating prematurely. The most reasonable explanation at that time was that the output cavity was producing fields high enough to reflect electrons back up the beam-line and/or start some oscillation phenomenon such as a virtual cathode. Fig. 5 shows traces representing magnetron forward and reflected power, the B-dot loop signal in the idler cavity, and the B-dot signal in the input cavity.

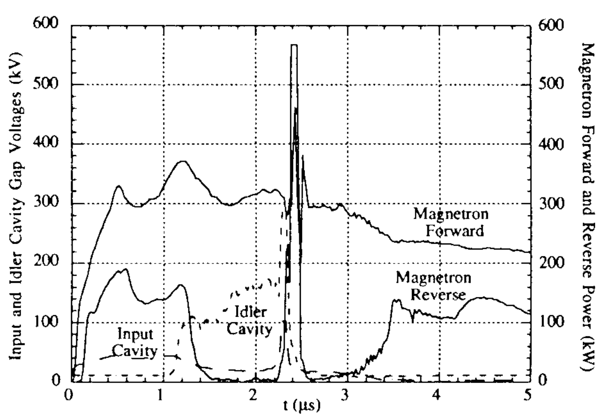

Fig. 5: Input and idler cavity gap voltages and magnetron power for shot 1308.

All of these signals have a spike at the time the rf output power goes away. These signals are bandpass filtered with a bandwidth of several hundred MHz around 1.3 GHz, so the spike appears to be the result of an rf modulation on the beam (space charge wave) traveling back up the beam toward the cathode. The interpretation of the observation is complicated by the fact that the output gap appears to be breaking down at this time as well.

C. New Output Cavity Design

A completely new output cavity with a lower loaded Q has been designed using HFSS. The new output cavity has a lower output gap voltage, thereby reducing the chance for electron reflection across the gap. For an output power of 500 MW, the geometrical gap voltage is calculated to be 365 kV, and the peak surface field is 246 kV/cm. The peak surface field has not increased substantially over the value in the modified original cavity, but the gap voltage has been drastically decreased. The peak surface field is what causes the rf breakdown, while electron reflection is determined by the line integral of the electric field along the electron trajectory across the geometrical output gap and the fringing fields just inside the drift pipe flanking the gap. The lower gap voltage should allow the new cavity to consistently extract 0.5 to 1 GW for the microsecond-long beam pulse. The output cavity section is coupled to the low impedance coaxial line though 4 irises defined by 4 posts. The output coax then tapers to the standard 6-in-diam., 50Ω line dimensions. This cavity has a resonant frequency of 1300 MHz and a loaded Q of about 4.1 according to HFSS. To date, the latest version of the cavity has only produced approximately 120 MW average for 500 ns. The exact cause of the pulse termination has not yet been identified.

Scaling the RKA to higher frequencies would involve decreasing all of the dimensions appropriately which would drop the output power considerably, or extracting the large amount of power present in the higher beam harmonics.

III. Summary

Peak powers approaching 500 MW at 1.3 GHz have been produced in pulses of 1 µs nominal baseline-to-baseline duration. The half power pulse width is 0.5 µs. These pulses contain an energy of about 160 J. Rf output begins on the rising portion of the current pulse and terminates just before the highest part of the pulsed voltage curve is reached.

Theory and modeling work has elucidated some important aspects of the space charge dominated physics of the RKA that have been supported by the experimental results. We now have a qualitative understanding of the various tube parameters and their impact on RKA design. These parameters include voltage, current, beam diameter, beam drift pipe diameter, and output cavity shunt impedance. Three dimensional cavity modeling has proven to be critical for designing the very low Q output cavity needed for converting the low impedance modulated electron beam to microwaves. The thrust will be to increase the output power to 1 GW and to widen the pulse to 1 µs.

References

[1] M.V. Fazio, W.B. Haynes, B.E. Carlsten, and R.M. Stringfield, "A 500 MW, One Microsecond Pulse Length, High Current Relativistic Klystron," submitted to the *5th Special Issue on High Power Microwave Generation of the IEEE Trans. on Plasma Sci.*, October 1994.

[2] E.L. Ginzton, *Microwave Measurements*, McGraw-Hill Book Co., 1957, p. 435.

[3] B.E. Carlsten, R. J. Faehl, M.V. Fazio, W.B. Haynes, and R.M. Stringfield, "Intense Space-Charge Beam Physics Relevant to Relativistic Klystron Amplifiers," submitted to the *5th Special Issue on High Power Microwave Generation of the IEEE Trans. on Plasma Sci.*, October 1994.

[4] High Frequency Structures Simulator code marketed by Hewlett Packard.