PROGRESS ON A ONE GIGAWATT, ONE MICROSECOND PULSE LENGTH, HIGH CURRENT RELATIVISTIC KLYSTRON

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Abstract

The development of a one gigawatt, high current relativistic klystron tube is underway for producing one microsecond long, 1.3 GHz microwave pulses at a 5 Hz pulse repetition frequency. This paper describes the theory, modeling, and experimental development of the microwave tube. The one microsecond pulse length is almost an order of magnitude beyond what has been achieved with a high current relativistic klystron. Achieving a peak power approaching 1 GW for 1 μs requires a stable electron beam on that time scale, and an optimized extraction efficiency in the output cavity. The microwave tube design was guided by theory and particle-in-cell code modeling that relate output cavity extraction efficiency to the amplitude of the beam harmonic current modulation and output cavity shunt impedance. Current experimental results are presented. The 1 MV, 10 kA, 1 μs pulse length, 5 Hz pulse-repetition-rate pulsed power modulator used to power the relativistic klystron is also described.

Theory and Modeling

In this section, we review basic relativistic klystron amplifier (RKA) physics. We show how the power extraction from the device depends on both the harmonic current content of the beam and also on its excess kinetic energy, which is the difference between the actual kinetic energy and the minimum required to transport the beam. As the beam is bunched, the kinetic energy is decreased, and there exists an optimum amount of bunching which leads to the maximum power extraction. For devices operating on time scales of 1 μs, the optimum harmonic current is only about 75%, leading to a dc-beam to microwave efficiency of less than 35%. The theory and modeling results, briefly summarized here, are treated much more extensively in references [1] and [2].

In our RKA, an annular, intense (5 kA), mildly relativistic (500 keV) electron beam passes through three cavities. The first cavity is externally driven and impresses an axial momentum variation on the initially uniform beam. Current modulation grows as the beam travels, as the momentum variation causes variations in the beam's axial density. We can describe the beam current in terms of its Fourier components

$$I(t,z) = I_0 + I_1(z)\cos(\omega t + \phi_1) + I_2(z)\cos(2\omega t + \phi_2) + \ldots .$$

The maximum harmonic current possible, for a delta function bunch of current, is twice the DC current. The fundamental current I_1 is typically around $1.4 I_0$ for conventional klystrons. For an RKA, the harmonic content is usually $\leq 1.0 I_0$. We must simultaneously maximize I_1 and extract the maximum kinetic energy from the beam in order to have the highest microwave power.

We wish to understand how $\Delta\gamma$, the maximum kinetic energy we can extract from the beam, depends on I_1. The amount of available energy is the difference between the injection energy (the depressed kinetic and potential energy) and the minimum injection energy (again summing the kinetic and potential energies) required to transport the bunched beam. Two effects are occurring as the beam is bunched and then decelerated in the output cavity. First, as the beam is bunched, the kinetic energy is depressed and the beam velocity decreases because more energy is required in the space-charge fields. Additional conversion from kinetic to potential energy is required in the output cavity as the bunch velocity is decreased further. As the bunched beam current is increased, we see that the kinetic energy available for extraction is decreased by both the larger potential depression requirement and by the larger minimum kinetic energy needed for transporting the higher current beam.

The largest permissible beam current, I_{max}, corresponds to a beam potential energy increase (and kinetic energy decrease) of

$$e\phi_b = \left(\gamma_{inj} - \gamma_{inj}^{\frac{1}{3}}\right) m_o c^2 \qquad \text{so}$$

$$I_{max} = \frac{2\pi\varepsilon_o m_o c^3}{e} \frac{\left(\gamma_{inj}^{\frac{2}{3}} - 1\right)^{\frac{3}{2}}}{\ln \frac{r_w}{r_b}} .$$

We see that the kinetic energy drop is not the injection voltage and that there is residual kinetic energy. One might think that since some kinetic energy remains, additional current can be pushed through the cylinder. However, removal of any additional kinetic energy drops the beam velocity v_o, which in turn increases the charge density and requires more increased potential energy from the beam than was given by the drop in the kinetic energy. This nonlinear slowing of the bunch as it forms aids its growth, and can be responsible for significant harmonic beam currents (greater than 1.0 I_o). If the beam current is near the threshold current I_{max}, and is increased slightly, a significant reduction in the beam's kinetic energy (and velocity) is possible. At the threshold current, a majority of the injection energy is partitioned into the potential energy fields; in Fig. 1 we see the partitioning of the total energy into kinetic and potential energy parts as a function of the injection gamma, γ_{inj}, and the beam current.

We can invoke energy conservation to calculate the minimum total beam energy for a given beam current. Solving for the minimum potential and kinetic energy gives

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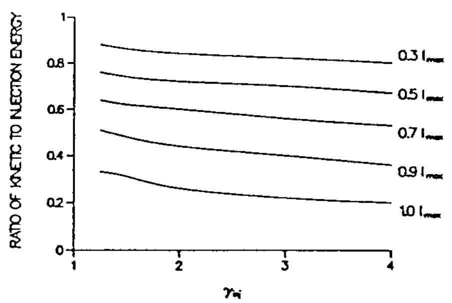

Fig. 1. Partitioning of injection energy for different injection energies and beam currents

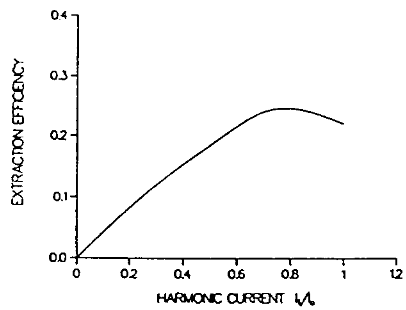

Fig. 2. Extraction efficiency versus harmonic current for a 500 kV, 5 kA beam with radius of 3.2 cm and wall radius of 3.65 cm. Best extraction is for 65% harmonic current.

$$\gamma_{min}^{\frac{2}{3}} = \left(\frac{PE+KE}{m_0c^2} + 1\right)^{\frac{2}{3}} = \left(\frac{I_{peak}}{8.5\ \text{kA}} \ln\frac{r_w}{r_b}\right)^{\frac{2}{3}} + 1 \quad .$$

For a given peak current, I_{peak}, the difference between γ_{inj} and γ_{min} is the available kinetic energy for conversion to microwaves. The maximum power extraction possible is

$$P_{out,max} = \frac{1}{2} I_1 \,(511\ \text{kV})\,(\gamma_{inj} - \gamma_{min}) \quad .$$

It is clear we want to simultaneously generate as much beam harmonic current as possible while minimizing γ_{min}. If the beam was collected by a conducting surface within the output cavity, this limitation would no longer be valid, since the beam's potential energy would be reconverted into kinetic energy. However, the plasma generated will become too large for microsecond pulse lengths.

Although a smaller beam radius leads to more harmonic current, we found that the maximum extraction occurs at the minimum beam-to-wall spacing possible. For a beam pipe radius of 3.65 cm and beam at 500 keV and 5 kA, the maximum extraction for a beam radius of 3.2 cm occurs with a harmonic current of 70% (dc beam to microwave efficiency of 25%), and for a beam radius of 3.4 cm with a harmonic current of 75% (efficiency of 30%). In both cases, beam harmonic current could easily exceed 100%. In Fig. 2 we plot extraction efficiency versus harmonic current for a 5 kA beam at a radius of 3.2 cm. We see that the maximum extraction, 25%, occurs at a fundamental current component of only 70%, far below the maximum current we can generate.

Experimental Tube Development

The first generation RKA has been constructed and operated on the BANSHEE pulsed power modulator. These results are described in detail elsewhere [3,4], but are briefly summarized here. The RKA design consists of a field emission diode producing a hollow beam that passes through the coaxial quarter-wave input cavity and idler cavity, and on to the rectangular waveguide output coupler placed transversely to the beam. The RKA drift pipe diameter is 7.3 cm. The rf drive to the input cavity is 5 kW and is coupled to the input cavity through a loop. The annular electron beam is supplied by a 6.35 cm-diameter circular stainless-steel field-emission cathode. Guiding of the electron beam is accomplished by a pulsed, strong uniform magnetic field (0.5 to 1.0 T) along the electron beam axis. For rf beam modulation measurements, a linear array of eleven B-dot loops were placed 5 cm apart along a section of drift pipe. Annular beam thickness is 2 to 4 mm.

Early RKA work produced a modulated electron beam for 1 μs with a peak rf current (I_1) of 1 kA and a voltage of 350 kV. Some experimental configurations produced beam modulation in excess of 2 μs which was the full width of the pulsed-power modulator pulse driving the RKA. The dc beam current was about 2.5-3 kA giving approximately a 30% beam modulation ($I_1/I_0 = 0.3$). The component of beam power at the microwave drive frequency (1.3 GHz) was approximately 175 MW. Approximately 50-70 MW was coupled into rectangular waveguide and gains of 20-40 dB were measured. The modulated-beam power to microwave output power coupling efficiency was ~30%. The low output coupling efficiency was due primarily to the inability to adjust the output gap tuning and shunt impedance.

A second generation RKA design, currently being tested [5], has incorporated the following three major design improvements: (1) The nominal input beam voltage and current produced from the field emission diode electron gun and transported through the RKA has been increased from 350 kV and 2.5 kA, to over 600 kV and 5 kA with a pulse duration of 1 μs. (2) A measurement of the output power dependence on input power level gave no hint of saturation up to the maximum available 5 kW drive level, indicating that a higher input drive would give a larger output power. A 500 kW magnetron source has replaced the 5 kW input drive amplifier previously used. (3) The theory and modeling indicate the sensitivity of output power on output gap shunt impedance, tuning, and Q. A new output cavity, described in reference [5], has been built with variable tuning, loading, and shunt impedance to allow adjustments of these parameters for optimal conversion efficiency of modulated-beam power to microwave output power.

A new input cavity was needed because the microwave input drive was increased from 5 kW to 500 kW by the installation of a high power magnetron. Power was coupled to the original cavity through a loop fed by 0.5 in coaxial cable. Since this scheme was inadequate for the new 500 kW power level, a new input cavity was designed that is fed through an iris by reduced-height rectangular waveguide. The stainless steel cavity is a quarter-wavelength coaxial line, shorted at one end and capacitively loaded by the gap at the other end. The loaded Q of the cavity, at low power without beam, was measured to be 20. The customary copper plating is unnecessary because the beam loading is so heavy (cavity Q with full beam loading is ~10, compared to an unloaded Q of ~400) that resistive losses in the cavity walls are negligible compared to the power absorbed by the beam. This is seen by comparing the beam impedance, which is 2000 to 4000 ohms, to the cavity shunt impedance which is around 100,000 ohms. Since the magnetron driver must be matched to the cavity at full beam loading for efficient power transfer, the cavity, without beam, had to be strongly overcoupled to the magnetron. This condition results in a VSWR (looking into the cavity from the input waveguide) of 27 without beam. The VSWR approaches 1 with full beam loading.

Figs. 3 and 4 show the beam current pulse overlaid with the magnetron reflected power and the modulated beam current envelope 25 cm downstream from the input cavity gap. The salient features that should be noted are that: 1) the reflected magnetron power goes to zero as the beam current increases from zero indicating good coupling to the beam loaded cavity, 2) the rf pulse length of the modulated beam is about 2.5 µs, and 3) the rf current on the beam is about 8% with 60 kW of rf drive. Only about 5% modulation is needed from the first cavity for the RKA to operate as we have designed it.

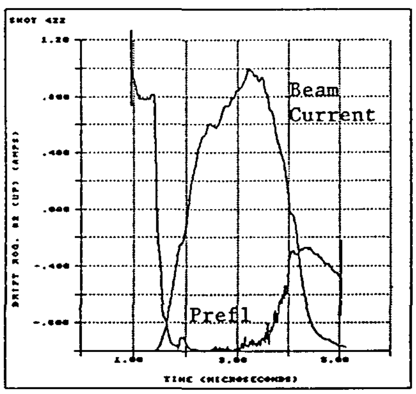

Fig. 3. Beam current overlaid on magnetron reflected power signal showing how the impedance change due to beam loading leads to a matched condition between the input waveguide and the input cavity. (Scale on vertical axis is arbitrary.) Peak beam current is 4.5 kA.

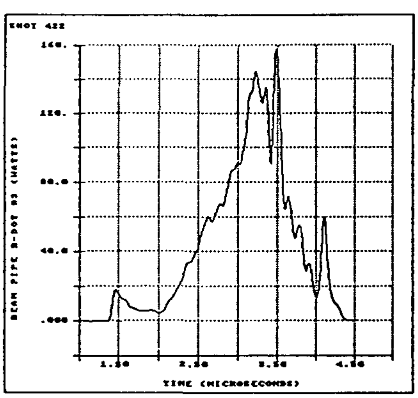

Fig. 4. Detected signal from B-dot loop located 25 cm downsteam from the input cavity gap. This B-dot loop measures the 1.3 GHz current modulation on the beam. The rf modulation imparted to the beam by the input cavity with 60 kW of input power is about 8% or I_1/I_0 = 0.08.

Repetitively Pulsed Modulator Development

BANSHEE is the repetitively pulsed, high voltage modulator used to produce a high current relativistic electron beam for high power microwave tube development at microsecond pulse lengths. The design goal for BANSHEE is to achieve a 1 MV, 10 kA pulse, with a 1 µs flat-top, driving a load impedance in the range of 100 Ω at a pulse repetition frequency of 5 Hz. The long term goal is a prf of 100 Hz. With BANSHEE, thyratron-switched line-type modulator technology is being extended to the megavolt and multi-kiloampere level. Performance to date has achieved 600 kV at 6 kA for 1 µs at a 1 Hz prf [6]. A prf of 5 Hz at 600 kV and 5 kA has been also been achieved for 60,000 shots. The successful operation of two state-of-the-art high power thyratrons in parallel, at a voltage, current, and pulse length appropriate for 1 µs, repetitive-pulse development of the RKA has been demonstrated.

Summary

We have described our RKA experimental results and our second generation RKA design that is currently being tested. We have added to the understanding of RKA physics with the importance of the role of intense space charge in limiting the efficiency of the device because of the beam potential depression that reduces the kinetic energy available for conversion to microwaves. We have produced a stable 650 kV, 5 kA annular beam of microsecond duration from an explosive field emission cathode. Repetitively pulsed, 1 µs pulse-length RKA operation is possible because of the capability of the BANSHEE thyratron-switched line-type modulator. Rep-rate RKA development awaits the availability of a dc magnet for beam transport through the klystron.

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