High-Current Relativistic Klystron Amplifier Development for Microsecond Pulse Lengths*

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Abstract

Los Alamos is extending the performance of the Friedman-type, high-current relativistic klystron amplifier (RKA) to the microsecond regime while attempting to achieve the gigawatt-level peak power capability that has been characteristic of the RKA at shorter pulse lengths. Currently the electron beam power into the device is about 1 GW in microsecond duration pulses, with an effort underway to increase the beam power to 2.5 GW. To date the device has yielded an rf modulated electron beam power of 350 MW, with up to 50 MW coupled into waveguide. Several aspects of RKA operation under investigation that affect RKA beam bunching efficiency and amplifier gain include cavity tuning, beam diameter, beam current, and input rf drive power, and the development of an output coupler that efficiently couples the microwave power from the low impedance beam into rectangular waveguide operating in the dominant mode. Current results from experimental testing and code modelling are presented.

I. BACKGROUND

One of the most promising gigawatt-class microwave tube concepts is the high current relativistic klystron amplifier pioneered by M. Friedman and co-workers at the Naval Research Laboratory [1]. The RKA is similar to the classical klystron in that it has an input cavity, idler cavities, and an output cavity. The high-current relativistic klystron differs from a classical klystron in several significant ways. Most importantly, the current, at 2-10 kA, is much higher, by 1-2 orders of magnitude. The electron beam is relativistic, with an energy of 300-1000 keV. The important distinction is the potential energy associated with the beam 's space charge. In the classical klystron the potential energy of the beam is small compared to the kinetic energy. In the high-current relativistic klystron the potential energy (due to the much higher space charge) is comparable to the kinetic energy. The practical implication of this phenomenon is that a small velocity modulation on the beam (produced in the first cavity) causes a dramatic increase in the space charge potential energy. This potential causes the beam to slow down and strongly bunch. This bunching effect is much more dramatic than in a classical klystron, and is due primarily to the fact that the beam current is much more intense. The high-current relativistic klystron is therefore inherently a high power device. Because the RKA uses an annular electron beam, the space charge limiting current is higher than with a solid beam of the same energy. This fact allows for the propagation of a higher power beam through the drift pipe, resulting in higher output power capability. Also since the electron beam is annular and several inches in diameter, the device is more suitable for high power operation because the larger surrounding cavity structures are less likely to be plagued by high voltage rf breakdown.

The high current relativistic klystron has exhibited very encouraging performance. The most recent single-shot experiments by Friedman produced 16-20 GW of power at 1.3 GHz in a 100-ns-long, triangular-shaped pulse [2]. The NRL group's earlier experiments produced several gigawatts of output power, with 40% beam-to-microwave power efficiency, and measured a phase stability of less than 3^{o} between the input drive signal and the output [1]. This RKA has been used to drive a simple accelerating structure [3] that produced a 60 MeV electron beam of ~200 A in a 1-m-long structure. At Los Alamos we are currently engaged in an effort to extend the performance envelope of this device from a 100-ns to a 1 µs pulse-length, and eventually to repetitively pulsed operation at these very high power levels with output quality suitable for driving high gradient electron and ion accelerators.

II. EXPERIMENTAL RESULTS

The relativistic klystron amplifier shown in Fig. 1 is currently being tested. So far we have produced a modulated electron beam for one microsecond with a peak rf current of 1 kA and a voltage of 350 kV. In some cases we have observed beam modulation in excess of 2 microseconds. The dc beam current is about 3 kA giving approximately a 30% beam modulation. Greater than 100% modulation should be possible, as demonstrated by Friedman at the 100 ns pulse length. The component of beam power at the microwave drive frequency (1.3 GHz) is approximately 350 MW. Up to 50 MW has been coupled into rectangular waveguide and gains of 20-40 dB have been measured. The input driver amplifier provides 5 kW to the RKA input cavity.

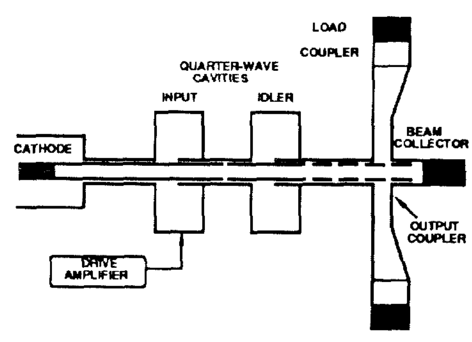

Figure 1. Relativistic klystron amplifier.

The modulated-beam power to microwave output power coupling efficiency is ~15%, which is a rather low output coupling efficiency. A new output cavity is being designed to address this problem. In these experiments the nonresonant output coupler consisted of reduced-height WR-650 waveguide with the beam passing through the broad-wall of the waveguide and coupling to the electric field associated with the

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TE_{10} mode. The waveguide height was reduced to better match the beam impedance. About 30 cm from the beam axis the waveguide tapered up to full-height WR-650 waveguide. Although this design was simple and easy to fabricate, it did have some serious drawbacks. There was no provision for tuning the impedance of the output gap; and since the coupler was not a resonant cavity, the output loading was not adjustable. The design of the new output cavity will have these features in order to optimize the extraction efficiency.

An annular, stainless steel, explosive field-emission cathode is used to produce the electron beam for the RKA. This type of cathode is not ultimately desirable for this application, but this cathode is being currently used for its ability to easily supply a multi-kiloampere, high current density electron beam. Electron guns with explosive field-emission cathodes characteristically have a constantly changing impedance throughout the pulse because of the ion plasma expanding from the cathode surface. The changing beam impedance complicates the operation and the understanding of the physics of the device. Long term needs necessitate the development of alternative cathodes with high current density, constant impedance characteristics.

III. THEORY AND MODELLING: CURRENT MODULATION AND RF EXTRACTION

There are three aspects to maximizing the power extraction. First, the klystron's initial dc beam current, I_0 must be modulated as much as possible, as little kinetic energy must be lost to the beam's potential energy as possible, and the power associated with the rf current must be extracted in a resonant structure. These conclusions can be seen from Ramo's theorem [4], which describes the modulation in the idler and output cavities,

$$\int \vec{J}(\vec{r}, t)\cdot\vec{E}(\vec{r},t)d\vec{r} = V_{gap}(t)\, i_{ind}(t) \qquad (1)$$

where $i_{ind}(t)$ is the instantaneous induced current in the cavity circuit model (Fig. 2), V_{gap} is the cavity voltage on axis

$$V_{gap}(t) = \int_{-\infty}^{\infty} E_z(r=0, t)\, dz$$

and $\vec{J}$ is the beam current density. The gap voltage is related to the fundamental Fourier component of the induced current by

$$V_{gap}(t) = i_{ind_1} \cos(\omega t + \phi_1)\, Z_{cav}$$

where Z_{cav} is the usual cavity impedance. We see from (1) that if the cavity gap is short and if the fields are radially uniform, then the induced current is the beam current

$$i_{ind}(t) = I(t)$$

and the fundamental component is equal to the fundamental beam current harmonic

$$i_{ind_1} = I_1$$

where

$$I(t) = \sum_{n=0}^{\infty} I_n \cos(n\omega t + \phi_n).$$

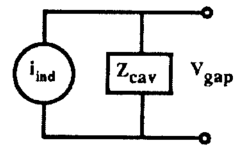

Figure 2. Cavity circuit model.

From (1), we also see that the maximum power that one can extract from a modulated beam is only the power contained in the beam's kinetic energy. Given a cavity modulation voltage equal to the kinetic voltage V_{kin}, we could expect to extract a power of

$$f\int_0^{1/f} V_{gap}(t)\, i_{ind}(t)dt = \frac{1}{2} V_{kin}\, I_1.$$

100% extraction is only possible with complete modulation ($I_1 = 2I_0$) and if there is no power lost to the beam's potential fields ($V_{dc} = V_{kin}$).

A modulated beam is rich in harmonics, so a resonant output cavity is required to preferentially extract just one mode. Designing a resonant output cavity is relatively simple. The major challenge in the RKA design is to maximize the beam harmonic current while not appreciably lowering the average kinetic energy. For an annular beam of radius r_b injected with gamma, γ_{inj}, into a pipe of inner radius r_w, the space-charge limiting current is

$$I_{max} = \frac{8.5\,(\gamma_{inj}^{2/3} - 1)^{3/2}}{\log \frac{r_w}{r_b}}$$

In Fig. 3 we see the partitioning of energy into potential and kinetic components as a function of how close we are to the limiting current. In our case ($\gamma_{inj} \sim 2$), we require $I_{max} \sim 5I_0$ in order to keep the beam's kinetic energy approximately 90% of the injection kinetic energy.

$$V_{dc} \sim 0.9\, V_0\, .$$

This requires the beam radius $r_b = 3.2$ cm for a pipe radius of $r_w = 3.65$ cm.

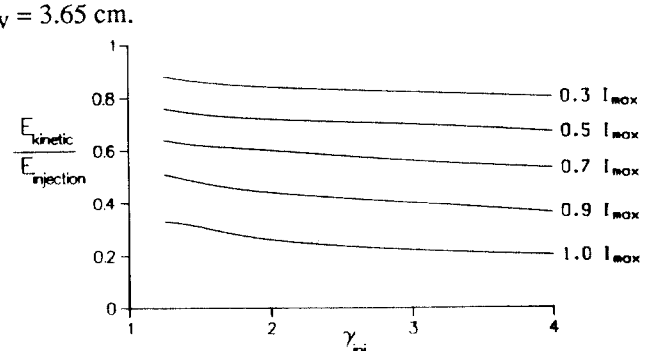

Fig. 3. Partitioning of total energy into kinetic and potential components for different injection energies and beam current.

In a three cavity RKA, the first cavity initiates an oscillating space-charge wave on the beam, in a purely small-signal manner. The second cavity modulates the beam as much as possible, in preparation for extraction in the third cavity. The beam modulation due to the second cavity is a large-signal effect, and is aided by the temporarily smaller space-charge limiting current (due to the changed boundary conditions) within the cavity gap. This change in the space-charge limiting current lowers the kinetic energy of the decelerated electrons at the front of the bunch more than the kinetic energy of the electrons at the tail of the bunch, thereby enhancing the bunching. When the particles re-enter the drift pipe, the potential energy is retransformed into kinetic energy, but the bunch remains mostly intact. This is called the gating effect [1].

The gating effect is primarily a one-cavity effect; however multicavity effects also occurs. Detuning the second cavity makes the cavity gap voltage out of phase with the current modulation driving it, allowing inductive bunching which enhances the gating. In Fig. 4 we see the maximum current modulation after the second cavity as a function of the first cavity drive for different tunings of the second cavity, as calculated with the PIC code ISIS [5]. In Fig. 5 we see an ISIS simulation of a two cavity RKA, extracting 0.75 GW from a beam with 65% current modulation. Shown is the geometry and the gap voltage in the output cavity.

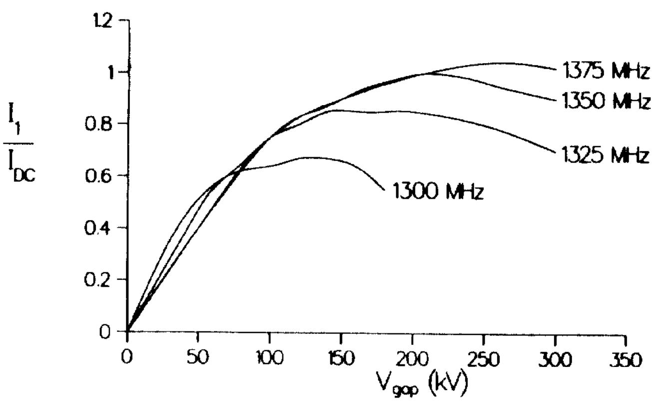

Fig. 4. Maximum current modulation after second cavity as a function of first cavity drive for different tunings of second cavity.

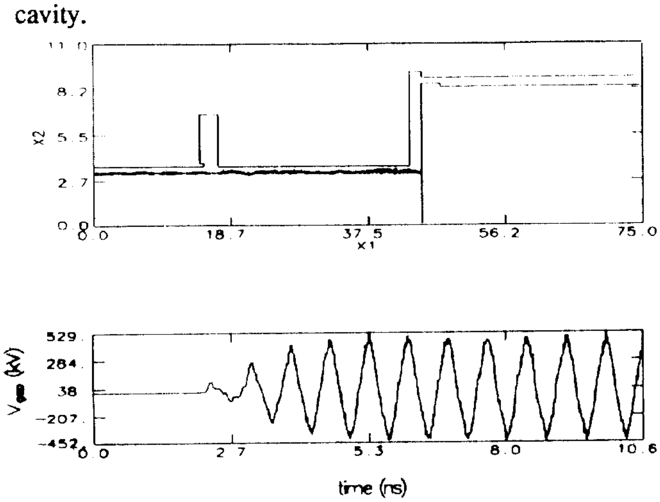

Fig. 5. Isis simulation of a two cavity RKA. Power extracted with 0.65 current modulation is 0.75 GW at 1.3 GHz.

IV. EXPERIMENTAL MODIFICATIONS IN PROGRESS

A number of modifications are in progress to enhance the performance of the RKA. The input drive amplifier has been upgraded from 5 kW to 500 kW, so the output power should no longer be drive limited. The electron gun is being redesigned to increase the beam current from 3 kA at 350-400 kV to 5 kA at 500 kV. A new output cavity is being designed for improved extraction efficiency.

V. REFERENCES

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