HIGH POWER RF AMPLIFIERS FOR ACCELERATOR APPLICATIONS: THE LARGE ORBIT GYROTRON AND THE HIGH CURRENT, SPACE CHARGE ENHANCED RELATIVISTIC KLYSTRON

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ABSTRACT

Los Alamos is investigating a number of high power microwave (HPM) sources for their potential to power advanced accelerators. Included in this investigation are the large orbit gyrotron amplifier and oscillator (LOG) and the relativistic klystron amplifier (RKA). LOG amplifier development is newly underway. Electron beam power levels of 3 GW, 70 ns duration, are planned, with anticipated conversion efficiencies into RF on the order of 20 percent. Ongoing investigations on this device include experimental improvement of the electron beam optics (to allow injection of a suitable fraction of the electron beam born in the gun into the amplifier structure), and computational studies of resonator design and RF extraction. Recent RKA studies have operated at electron beam powers into the device of 1.35 GW in microsecond duration pulses. The device has yielded modulated electron beam power approaching 300 MW using 3-5 kW of RF input drive. RF powers extracted into waveguide have been up to 70 MW, suggesting that more power is available from the device than we have converted to-date in the extractor. We have examined several aspects of operation, including beam bunching phenomena and RF power extraction techniques. In addition, investigations of the amplifier gain as a function of input drive, electron beam parameters (energy, current, and position in the device) and axial magnetic field strength also have been explored. The effect of ions formed during device operation also has been considered.

Introduction

Los Alamos has been investigating novel high power RF sources for the past eight years. Included in this research have been various vircator designs, magnetron-like designs (including the large orbit gyrotron (LOG), and the magnetically insulated line oscillator), and most recently, the relativistic klystron amplifier (RKA). Of these, the large orbit gyrotron, operated as an amplifier, and the RKA appear to us to offer the most promise as RF drivers for future improvements in particle accelerator design.

The Large Orbit Gyrotron

During the past three years we have investigated the large orbit gyrotron experimentally as an oscillator operated at a frequency of 2 GHz. These results have encouraged us to begin, during the ongoing year, the initial work we hope will lead to an amplifier based upon the LOG's basic operating principles. The LOG amplifier is attractive for linear collider applications, since it requires relatively modest applied magnetic field requirements, only a few hundred gauss, since it operates at a harmonic of the cyclotron frequency. It can operate at frequencies of 15 GHz or more with these small magnetic fields. RF breakdown problems should be relatively small, as well, since the electrons move to smaller orbits, away from the walls of the device, as they convert their energy into microwaves. Hence electron bombardment of the walls, which can lead to breakdown, is relatively modest.

The oscillator we recently investigated is depicted in Figure 1. The device is powered by a

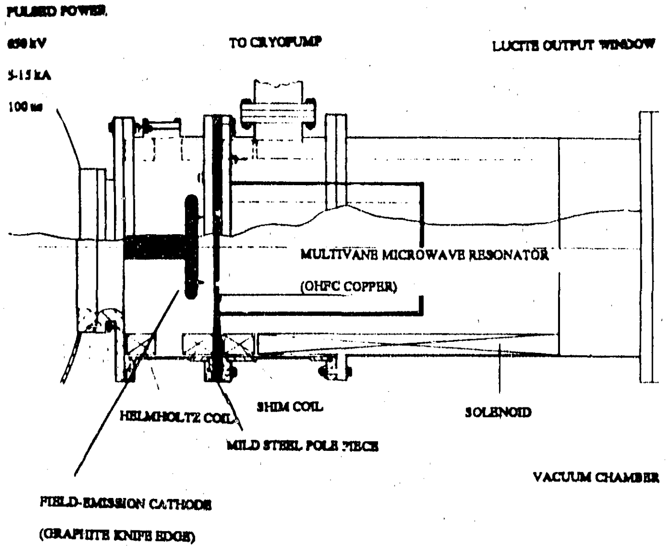

Figure 1. Cutaway drawing of the LOG oscillator experiment.

Marx-Blumlein pulser operated at 650-700 kV, 6 kA, for pulse lengths of 70 ns FWHM duration. RF power was radiated out of the device axially into a chamber lined with microwave absorber. RF radiated into the chamber was monitored with waveguide receivers, either standard gain horns or waveguide stubs. The signals were then coupled to coaxial cable and RF power was measured with crystal detectors. Heterodyning circuits monitored the frequency.

The device operates as follows. A 12.5 cm diameter annular electron beam is formed in an axial magnetic field having a magnitude of 500-800 gauss. An annular aperture at the anode plane is situated in a cusp-shaped magnetic field formed by opposing magnetic fields. The fields are formed by two oppositely wound coils which surround the diode and the RF resonator region downstream of the anode. The cusp shape is enhanced by a 2 cm mild steel plate at the anode, which concentrates the region of magnetic field transition between regions of axial and radial field direction such that the cusp is predominantly within the thickness of the steel. The beam enters the cusp after it has been accelerated in the diode. There the beam acquires a rotational velocity component which is axis encircling, while still retaining a component of axial velocity. Thus the beam spirals in the resonator downstream, with a pitch angle given by the ratio of rotational velocity to the axial velocity. For a sufficiently large magnetic field, all of the axial velocity acquired in the diode can be converted into rotational motion, and the beam will not propagate downstream, but instead, reflect back into the diode. For these experiments, this ratio of rotational velocity to axial velocity, designated α, had a value in the range of 1.5 to 1.7.

Azimuthal bunching of the electron beam occurs through the negative mass instability. A periodically varying boundary along the circumference of the resonator serves to bunch the beam with a periodicity such that it interacts with the resonator, converting beam energy to RF standing wave energy in the cavity.

A representative RF output pulse from the device operating at 2 GHz is shown in Figure 2. A spatial map of power radiated from the device into the absorber-lined chamber is shown in Figure 3. With an electron beam power of 500 MW injected into the resonator, the total power radiated from the device, within the solid angle monitored by this measurement, is 35 MW. This result corresponds to a conversion efficiency from electron beam power to microwave power of 7 percent. Only a portion of the total power radiated by the device was measured by this spatial scan, since the power was not zero in the wings of the measurement, far off axis. We were prevented from moving the receiving antenna to larger radial positions by physical barriers in the chamber. Hence the true efficiency in this experiment may be larger than that cited here. Further efficiency improvement may be achieved by increasing the ratio of rotational electron beam energy to axial beam energy in the resonator region. For this experiment, the ratio was 2-3. Values for this ratio as high as 6-8 should be achievable, providing more available rotational beam energy from which to extract. Measuring all of the currently generated RF, combined with increases in the fraction of rotational beam energy, should increase the efficiency to as much as 20 percent.

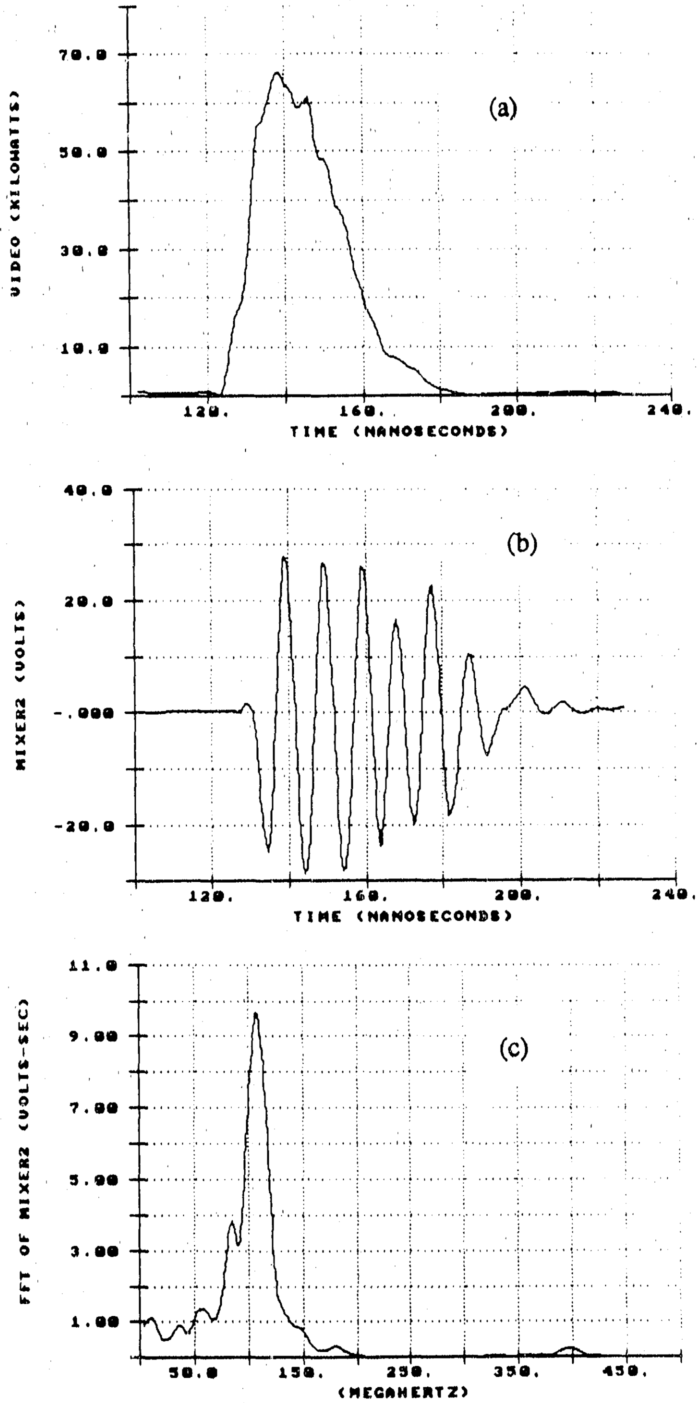

Figure 2. Sample RF data for the LOG oscillator, shot 2136. a) is a detected signal received over an effective area of 65 cm^2. b) is the frequency downconverted RF signal with a 1.90 GHz local oscillator frequency. c) is the fast Fourier transform of the downconverted signal.

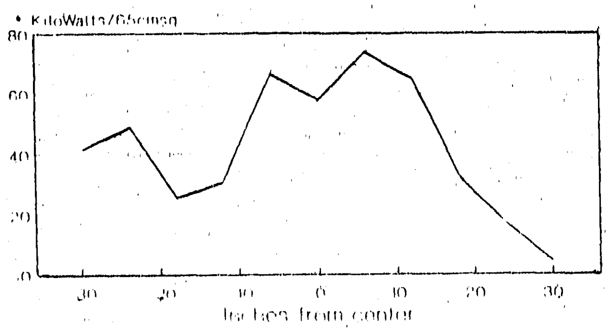

Figure 3. Radial position scan of the power received by a waveguide stub antenna. The asymmetry is caused by the resonator having a three vane azimuthal periodicity. The left half of the pattern is azimuthally aligned with a resonator vane, the right side is aligned with the position of the smooth wall connecting adjacent resonator vanes.

Our initial step in developing an amplifier has been to examine methods of increasing the current fraction injected into the resonator from the diode, and to properly position the higher current in the interaction space. Computational modelling has been performed with the particle-in-cell code ISIS. Modelling has indicated that increasing the fraction of diode current injected into the resonator as a rotating beam and establishing a final rotating beam diameter of 12.5 cm can be achieved by launching the beam from a 2 mm thick annular cathode having a diameter of 14 cm. Care must be taken to launch the beam such that radial oscillations (zeroth harmonic cyclotron frequency) in the beam motion as it travels down the resonator are not generated. Such a condition was found computationally to be achieved by placing the emission annulus on a conical equipotential surface, having an angle of 22.5° with respect to the direction normal to the axis of symmetry. Experiments are now underway to test these computational predictions. The control of the beam trajectory as a function of cathode equipotential angle, electron energy, and ratio of rotational velocity to axial velocity are among the beam injection parameters being examined.

We are computationally investigating approaches to the design of the LOG amplifier. One approach, a two stage device, is shown in Figure 4. The device consists of a preliminary RF input stage which initiates electron beam bunching, and a final RF output stage in which the fully bunched electron beam generates a strong RF standing wave in an output resonant cavity. These stages constitute discrete, separate entities, separated by a beam transport section in which the bunching of the rotating electron beam develops to a maximum prior to entering the RF output section. The two stage design offers the flexibility to separately optimize the RF input and output sections of the device.

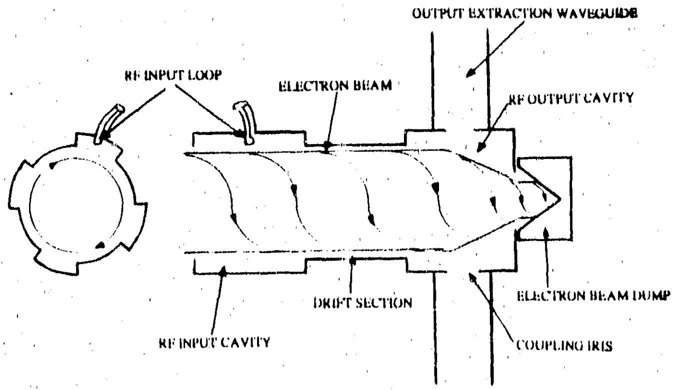

Figure 4. Conceptual arrangement of a LOG amplifier configuration.

In one configuration under consideration, the first stage consists of an azimuthally periodic wall boundary in a resonant cavity with cylindrical symmetry. RF is injected by a loop or iris coupler into this structure. The standing wave energy stored in this cavity velocity modulates the rotating electron beam. The RF is contained in this structure by designing the cavity to be beyond cutoff for axial RF propagation. The beam, now with an azimuthal velocity modulation, is transported by the axial magnetic field through a smooth, cylindrical section where azimuthal spatial bunching of the beam develops due to the velocity modulation. Adjustment of the length of this drift section will optimize the degree of spatial bunching achieved at the end of the transport. Downstream of the transport section the beam enters a second periodic wall structure which converts the rotating, spatially bunched, beam energy into RF standing wave energy. This energy is then coupled into waveguide through either an axial or side extraction coupler. A mode converter would pipe the output RF into an array of rectangular waveguides. Evaluation of amplifier approaches is ongoing, with initial hardware designs expected to be completed in the summer, 1991.

The Relativistic Klystron Amplifier

One of the most promising concepts that we have begun to investigate experimentally at Los Alamos is the high current relativistic klystron amplifier (RKA) pioneered by M. Friedman and co-workers at the Naval Research Laboratory. This RKA, as tested by Friedman, has produced several gigawatts of power with 40% efficiency at 1.3 GHz in a 100 ns long pulse on a single shot basis. Peak electron beam currents of 13 kA at 1.3 GHz have been produced. We have identified the high current relativistic klystron as a very promising source with great potential, that has exhibited very good performance in a very limited parameter space. We currently are engaged in a modest 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. The attraction of this device for accelerator applications, aside from amplifier operation, is its demonstrated high efficiency of 40%, event without energy recovery schemes being applied.

The present work has progressed well and the relativistic klystron amplifier shown in Figure 5 is being tested.

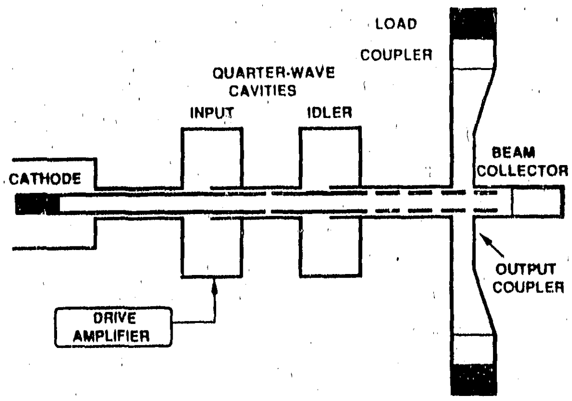

Figure 5. Los Alamos relativistic amplifier.

This device 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. For RF beam modulation measurements the output coupler is replaced on the beam line with a beam pipe containing a linear array of B-dot loops. So far we have produced a modulated electron beam for one microsecond with a voltage of 350 kV, and a peak RF current of 0.9 kA after the second cavity. 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. The component of beam power at the microwave drive frequency (1.3 GHz) is approximately 350 MW. The RF drive level is 5 kW which will result in a gain of 42 dB if one can extract this power with an efficiency of 25% (a conservative estimate). Efforts to extract this power into the waveguide coupler are underway.

Figure 6 shows the frequency down-converted mixer (IF) signal from a calibrated B-dot probe located on the beam pipe after the second cavity. This signal indicates the RF current modulation on the beam which lasts for 900 ns.

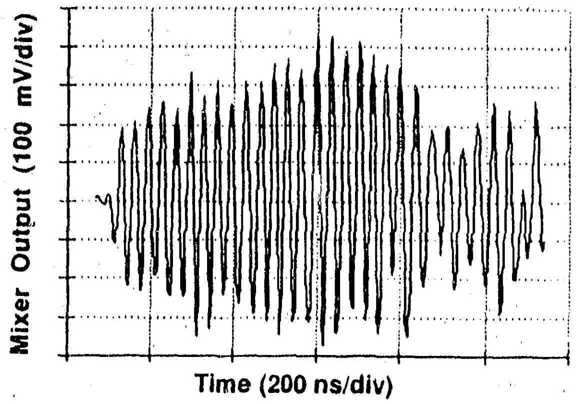

Figure 6. Frequency downconverted (IF) mixer signal from B-dot probe located downstream of RKA idler cavity showing RF current modulation on the electron beam.

The performance of the RKA can be enhanced significantly with several experimental modifications. More input RF drive power should result in greater output power. The diode must be adjusted for optimal beam diameter and more efficient current injection into the device. Very careful design is needed for a one microsecond device because a number of phenomena that can be ignored on a 100 ns-time-scale cannot be ignored when the longer, microsecond timescale is required. For example, the formation of a plasma can have a deleterious effect on beam quality and the production of microwave energy. The electron beam, striking a surface inside the device can create a plasma which can migrate several cm per µs to interfere with the electron beam dynamics and microwave production. Therefore carefully controlling the beam quality is essential for successful operation of the RKA. A relatively thin annular beam is needed, streaming at a controllable radius in the beam pipe, with minimal oscillation in the radial dimension. Because the axial electric fields in the cavity gaps are highest at the radius corresponding to the beam pipe wall, the highest gain is obtained with the beam operating as close to the wall as possible, consistent with the constraint that the beam current density be large enough to approach the space charge limit. The downside of operating the beam close to the wall is that a few stray electrons can strike surfaces creating plasma and inducing high voltage breakdown. Part of the effort will involve determining the tradeoff between radius, gain, and the pulse stability on the microsecond time scale.

Pulsed Power

The availability of the BANSHEE pulsed power modulator currently driving the RKA makes possible high power microwave source development in a relatively unexplored pulse length regime. BANSHEE, which is described in detail elsewhere, is designed to deliver a 1 µs pulse at 1 MV and 10 kA at a 5 Hz repetition rate. The rep-rate capability is essential over the long term, because RF conditioning of the microwave tubes will be necessary to achieve reliable high power operation on the microsecond time scale. RF conditioning has historically been proven to be a necessity for reliable operation of high power microwave tubes and RF cavity accelerating structures.

Summary

Work on a large orbit gyrotron amplifier has recently begun. Computational modelling of improved electron gun designs has been performed to increase the fraction of the diode current entering the microwave tube, and to achieve improved beam placement in the tube as well. Electron injections experiments are now underway. Preliminary designs for an amplifier now are being considered. The relativistic klystron amplifier is in the initial stages of experimentation, and has achieved to date 900 ns of bunched beam with a peak current of 0.9 kA. Efforts to extract this power into rectangular waveguide are in progress. The RKA has been designed with future repetitive operation in mind, when the BANSHEE pulser has been fully qualified for rep-rate operation.