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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.

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[1,2]. 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

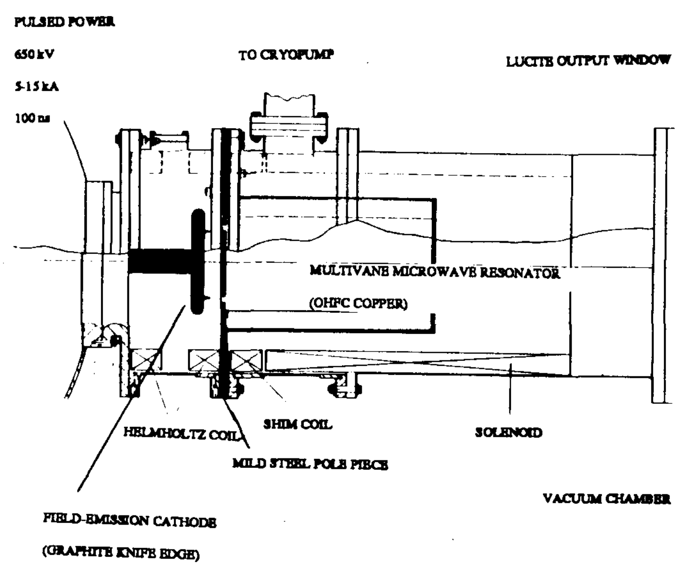

Figure 1. Cutaway drawing of the LOG oscillator experiment.

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 axis encircling, rotating beam is formed by passing the electron beam through a cusp magnetic field at the anode plane. For these experiments, the ratio of rotational velocity to axial velocity downstream of the cusp (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 mapping was performed of the power radiated from the device as a function of radial position off-axis. Of the total electron beam power available, 500 MW was injected into the resonator. The total power radiated from the device, within the solid angle monitored by this measurement, was 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. 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.

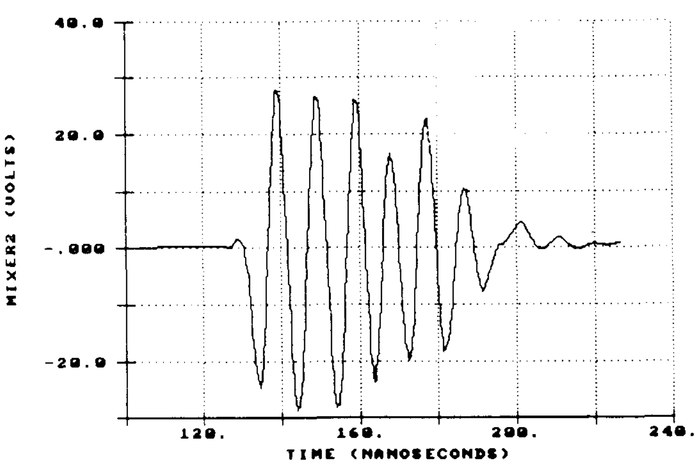

Figure 2. Sample downconverted RF for the LOG oscillator. The local oscillator signal for this measurement was 1.90 GHz, indicating a LOG frequency of 2.0 GHz.

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. 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^{o} with respect to the direction normal to the axis of symmetry. Experiments are now underway to test these computational predictions.

We also are computationally investigating approaches to the design of the LOG amplifier. One approach, a two stage device, is shown in Figure 3. 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.

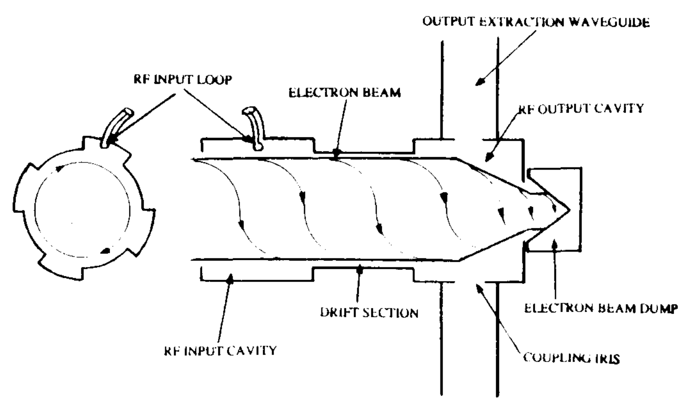

Figure 3. Conceptual arrangement of a LOG amplifier configuration.

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[3]. 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%, even without energy recovery schemes being applied.

The present work has progressed well and the relativistic klystron amplifier shown in Figure 4 is being tested.

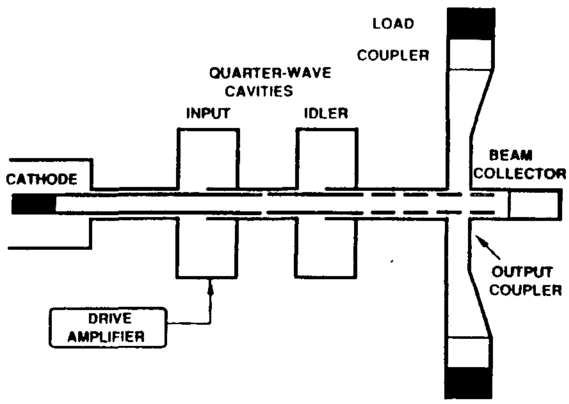

Figure 4. Los Alamos relativistic amplifier.

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. Pulse widths of modulated beam power range from 500 ns to 2,400 ns, with the highest gains at the shorter pulse widths. 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.

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[4], 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. 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.

ACKNOWLEDGEMENTS

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