High Peak and Average Power Microwave Source Research at Physics International

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ABSTRACT

CLIA (Compact Linear Induction Accelerator) is a 750 kV, 10 kA pulse power generator using magnetic switching to produce 100 ns long pulses at 200 Hz (150 kW average power) for longer than 1 second. An L-band magnetron, an S-band, frequency-agile klystron and an L-band, high perveance klystron have been successfully operated in bursts with peak powers exceeding 1 GW and average powers approaching 10 kW.

1. Introduction

The generation of microwaves at high power (> 100 MW) has progressed largely on single shot devices. Yet applications will require repetitive operation at substantial repetition rates[1], implying high average power. Only a few repetitive high power experiments have been conducted and in most the pulse duration was < 50 ns, so average powers have been less than a kilowatt. In contrast, conventional microwave tubes have operated at high average power, but the peak power is low. The results of the experiments described here extend high peak power source operation out to average powers near 10 kW: **new territory between the established domains of HPM and conventional microwave technology!**

The technical challenge of achieving both high peak and high average power is that repetitive operation may 1) evolve material from surfaces which raise the background neutral pressure, causing breakdown on successive pulses in the high electric fields (~ 100 kV/cm) and 2) prevent emission of electron beams from cold cathode surfaces by evaporating monolayers (of gas, oil, water, etc.) and firing again before they can recondense. [It has been suggested that monolayers are the seat of plasma formation from cold cathodes, rather than plasma formation from exploded metal micro-projections.] The vacuum poisoning issue can be addressed by better high vacuum techniques, but only by actually operating at high peak power (> 100 MW) and high repetition rates (> 100 Hz) can the practical limitations be found.

A particularly attractive pulsed power system for such experiments is the hard-core (i.e., central cathode shank, not e-beam) linear induction accelerator (LIA), first used in high power microwave research[2] by the Tomsk group. They operated an S-band relativistic magnetron at 300 MW, 60 nsec, 50 Hz, for an average power of 0.5 kW. The system is compact, which is an advantage for most applications. The basic reason for the compactness is that voltage from individual sections is added in vacuum so that the peak voltage appears only on the load. The system described here, CLIA (Compact Linear Induction Accelerator), is a LIA using magnetic pulse compression for switching. This technology has inherent long lifetime, eliminating the erosion problems of spark gaps.

The first microwave source operated on CLIA was an L-band relativistic magnetron. The goal was to produce a pulse train of 100 shots at 100 Hz, each with peak power of 1 GW. This extends the parameters of the S-band 1.) three shot bursts at 100-160 Hz experiment[2], 2.) 50 Hz continuous operation[2] and 3.) 1 Hz sustained operation[3], all previously reported, producing high peak and average microwave power simultaneously. We are now operating both low perveance and high perveance klystrons on CLIA. In this paper we describe the CLIA pulse power system and report the results of the 1 GW peak, 6 kW average L-band magnetron, the .1 GW peak, 200 W average, S-band frequency-agile klystron and the 1 GW peak, 10 kW average L-band klystron experiments.

2. CLIA System

The CLIA system consists of a ten-cell accelerator with a cathode stalk to sum the cell voltages up onto a single diode load, ten magnetically switched water insulated PFLs, a single two-stage magnetic compression unit (MCU) to charge the PFLs, and a thyratron switched intermediate energy store (IES) and command resonant charge (CRC) units to drive the MCU.

A linear induction accelerator system permits all pulse compression to be done at moderate voltage (40 to 150 kV) and then uses the accelerator structure to add parallel voltage pulses into a single high voltage output (750 kV). This technique allows the switching to be done at moderate voltage and also makes the use of hydrogen thyratrons and magnetic switches possible. The full system has been tested to average power levels exceeding its design specifications. Repetition rates of 250 Hz at over 600 kV matched load voltage have been achieved.

Figure 1 is a section through the accelerator, showing two of the ten cells. The inner diameter of the core is 8.5 inches. The width of the cores is 2 inches. The cores are wound from 0.6 mil 2605CO Metglas with 3.5 micron mylar insulation. The outer radius of the core is 15.5 inches. A cathode stalk runs up the center of the accelerator and the full diode voltage appears across the A-K gap at the load end. The actual effective length of each cell is 10 cm, giving an accelerator gradient of 0.75 MV/meter.

A more detailed description of each of the CLIA subcomponent physical and electrical characteristics is provided in reference 4.

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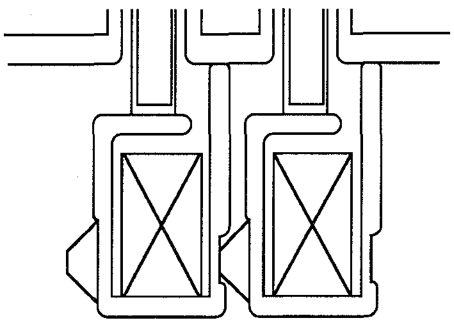

Figure 1. Cross section of the CLIA accelerator structure.

3. Repetitive, Multigigawatt, L-Band Magnetron Operation

We modified an existing L-band magnetron[5] for repetitive operation for this experiment. It has six cavities, with cathode, anode and vane radii of 1.27, 3.18, and 8.26 cm, respectively, and oscillated in the π-mode at 1.1 GHz. This magnetron had produced 3.6 GW when connected to single pulse Marx bank/water line drivers. Our expectations were for significantly less power because the magnetron, at ~ 25 Ω, is a poor electrical match to CLIA, at 75 Ω.

The modifications for repetitive operation consisted of cooling the anode vanes (via water channels 3 mm below the surface) and the downstream surface where the axial current emitted from the cathode tip is collected. Additionally, we paid particular attention to creating good electrical contact between parts and to avoiding virtual leaks. We also used a cryo-pump for our vacuum system to eliminate possible contamination from backstreaming oil. Base pressure was 4×10^{-6} torr. Previous single shot experiments have shown that peak power is increased by lowering base pressure.[6]

As shown in Figure 2, the microwaves were extracted from two opposing resonators which were connected to WR650 waveguide through quarter-wave transformers and absorbed by dummy loads, all in vacuum. Power samplers (≈80 db coupling) allowed for power, pulse shape and frequency diagnostics. The signal was viewed two ways: by the response of a crystal detector recorded on each pulse and directly on a high speed oscilloscope on one pulse (not necessarily the first) within the burst. The only electrical diagnostic used was a Rogowski coil measuring the total current into the magnetron. The voltage was determined from the current, the CLIA charge voltage and a measured load line.

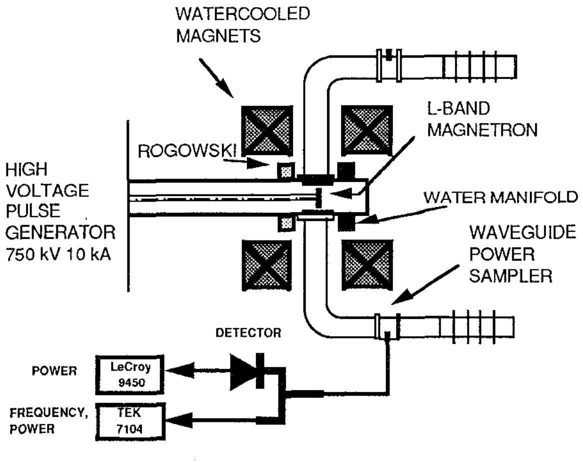

Figure 2. L-Band magnetron CLIA.

At a repetition rate of 100 Hz, we produced pulse trains of 1.0 GW, 50 ns FWHM pulses with 44 J each yielding 4.4 kW average power. Figure 3(a) shows the current and microwave pulse trains (each spike is a separate pulse, the data acquisition system does not record during the time between pulses) for a 50 shot burst, Figure 3(b) is an expanded view of one pulse in the middle of the burst. The recorded microwave signal is the crystal output on one of two extraction arms. This produces the nonlinear scale for power. To determine total extracted power we have doubled the power measured on one arm since we know, from other measurements, that the two extraction arms have nearly identical powers.

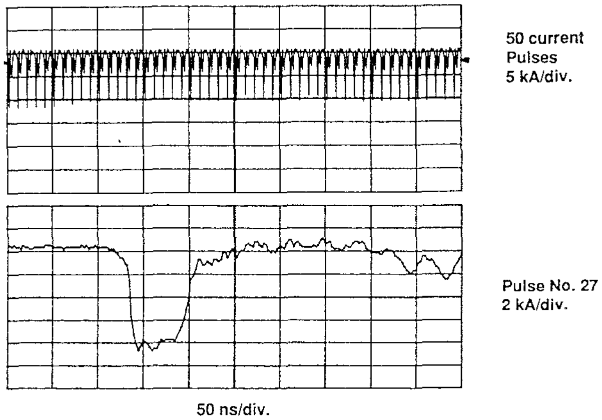

Figure 3. Current and microwave power for (a) a 50 shot burst at 100 Hz and (b) an expanded view of one pulse within the burst.

As can be seen from Figure 3, all the pulses are nearly identical. The microwave pulses last as long as the current pulse, *i.e.* there is no indication of impedance collapse or shifting of the operating point off resonance (effects conjectured to limit the pulse length in other relativistic magnetron experiments). A significant feature of magnetron operation on CLIA is that the pulse duration of the microwaves (50 ns) is only slightly less than that of the electrical pulse (60 ns). In many previous relativistic magnetron experiments, the ratio is typically 1/3.

The first few pulses are slightly more powerful because there is slightly more current. This is due to the time it takes to establish a steady state within the CLIA power conditioning system. This effect becomes more obvious as the repetition rate is increased, causing a decrease in the peak power even though the average power is still increasing. At 200 Hz the typical peak power dropped to 700 MW while the average power rose to 6.0 kW. At 250 Hz, the trend continued to yield 600 MW peak power and 6.3 kW average power. We tested the system with a 5 shot burst at 1000 Hz (far beyond the average current specification for CLIA) to see if there was a minimum recovery time between pulses. The magnetron operated at 1000 Hz even though CLIA is capable of only a few pulses. Therefore, evolved gas clearing time is < 1 msec. Based on the lowest third pulse, we estimate the average power to be about 25 kW, with a peak power of 600 MW. These results are summarized in Table I.

Table I. Summary of magnetron peak and average power as a function of repetition rate.

Repetition Rate (Hz)	Peak Power (MW)	Average Power (kW)	Number of Shots
100	1000	4.4	50
200	700	6.0	100
250	600	6.3	100
1000*	600	25	5

* based on third shot of 5 shot sequence

4. High Perveance Gigawatt L-Band Klystron Development

The high-current relativistic klystron amplifier (RKA), using an annular electron beam propagated near the drift tube wall, has produced in excess of 15 GW at 1.3 GHz[7]. The development that led to this capability has been in the single shot mode. We seek to extend this technology, at a more modest 1 GW level initially, to 100 Hz repetitive operation. To do this, we will employ the CLIA to generate a 5 kA, 500 kV electron beam to drive a suitable RKA.

The design of this RKA is based on a previous 5 kA, 500 kV, 1.3 GHz tube.[8] The main features are shown in Fig. 4. An annular electron beam is emitted from a graphite cathode in a foilless diode configuration and transported in a solenoidal magnetic field. Microwaves are input in one arm of a four-arm cross. Tuning stubs in the other arms, and one other coaxial tuning stub, are used to produce an azimuthally uniform electric field at the interaction gap in the modulating cavity. This provides the initial perturbation to the electron beam at the input microwave frequency. A second cavity, located an adjustable distance from the first cavity, enhances the modulation and produces a beam with a high degree of bunching at a point further downstream. Extraction of microwave power would occur at the point of peak bunching.

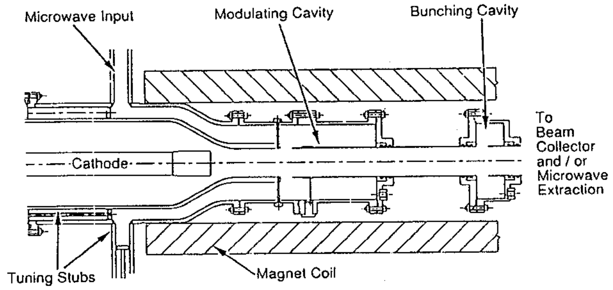

Figure 4. RKA design.

At this time, there is no extraction hardware. Our immediate goal is to demonstrate repetitive modulation. Extraction will be tackled subsequently.

The modulated beam current was measured with a B-dot probe in the drift section. The data acquisition system, consisting of two LeCroy 7200 digital oscilloscopes and a Tektronix 7250 oscilloscope (6 GHz bandwidth), can capture the DC current and voltage waveforms for 200 pulses at kHz repetition rates and provide a direct view of the modulated current for 15 pulses at 10 Hz.

Typical data for a 100 shot, 10 Hz burst at 400 kV is shown below. Figure 5 is the current traces for the first, fifteenth and one hundredth shot in the sequence. The steady decrease in current, pulse-to-pulse, as opposed to the equilibrium reached after a few pulses as observed earlier, is presently unexplained.

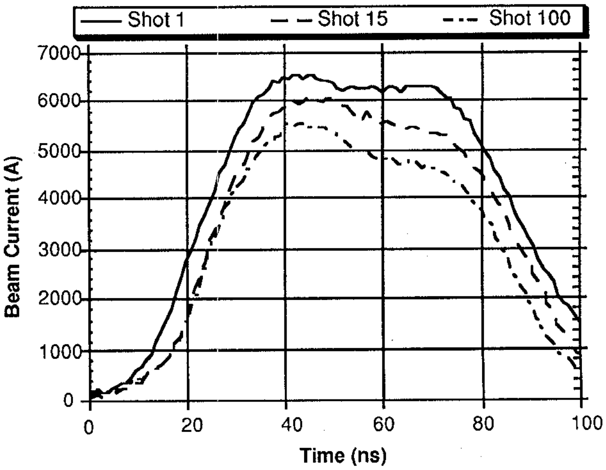

Figure 5. Current waveforms for a 100 shot burst at 400 kV and 10 Hz on CLIA. The second bunching cavity had been removed for these test.

The envelope of the modulated current is shown in Fig. 6 for the first and fifteenth shots of the burst (the first and last we could record; the shots between were similar). There is no sign of degradation in the fifteenth shot due to the previous fourteen. In this initial testing, there is no sign of limitation due to the repetition rate. Furthermore, although the time variation during the shot may be indicative of some mis-tuning or misalignment,.the degree of beam modulation after the first cavity ($2I_1 \approx 10\% \, I_0$) is consistent with previous experiments.[8]

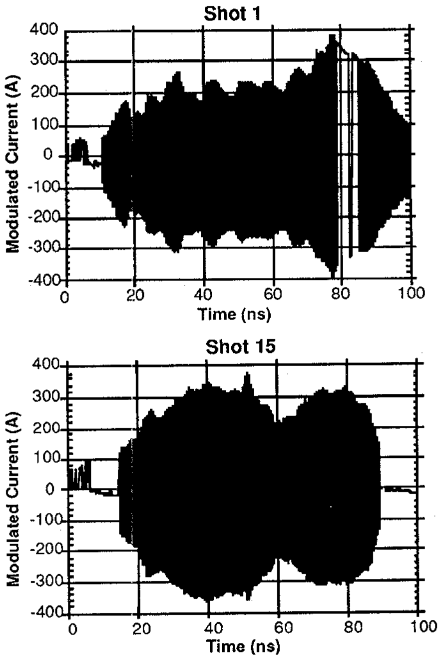

Figure 6. Current envelope for pulses 1 and 15 in the 100 shot burst of Fig. 5.

5. High Power, S-Band, Frequency-Agile Klystron Operation

The narrowband HPM sources developed to date are "laboratory prototypes" constructed with limited lifetime components and designed without great attention given to engineering reliability issues. In response to this lack of what could be termed a "deployable" HPM microwave source, Physics International has developed a high power, S-band, klystron that scales conventional technology to the 200 MW level.

The electron gun and 7 bunching cavities are patterned after a SLAC design[10]. Rather than sync-tuned the 5 bunching cavities are stagger-tuned to produce a modulated beam with frequency components filling in a 10% bandwidth. A coupled-cavity output section which feeds a single WR-284 output arm allows microwave extraction across the entire 200 MHz band. The design uses a thermionic cathode, metal-ceramic hydron-brazed assemblies and bake-out procedures characteristic of hard vacuum tubes. Sufficient water cooling has been incorporated to permit operation up to 1 μs pulse duration (at 100 Hz repetition rates).

Table II shows the design parameters against the measured parameters after the initial two week operation. 140 MW peak power at 15% electronic efficiency has been generated despite the perveance values being 50% higher than design. Thus far the device has only been operated at 1 Hz repetition rate, however, this does not represent a limit. The klystron amplifies its 1 kW drive signal across its entire instantaneous bandwidth. A spurious competing mode at about 2.9 GHz is also present in all cases. Its cause and subsequent suppression is the subject of current research.

Table II. Design vs. Measured Operational Parameters

Parameter	Design	Measured
Beam Voltage	625 kV	620 ± 20 kV
Collector Current	1.0 kA	1.5 ± .5 kA
Perveance	2.0 μpervs	3.1 ± .9 μpervs
Peak RF Power	250 MW	140 MW (@ 2.9 GHz)
Center Frequency	2.9 GHz	~ 2.85 GHz
Instantaneous Bandwidth	200 MHz	> 200 MHz
Extraction Efficiency	40%	15.1 ± 5.5%

At any given frequency the klystron output is quite stable and reproducible. Figure 7 is an overlay of 5 shots at 2.95 GHz, and 126 MW peak power. The foreshortened pulse (FWHM = 20 ns) is probably due to the lack of a voltage flat top in the 60 ns CLIA drive pulse which is poorly matched to the klystron impedance.

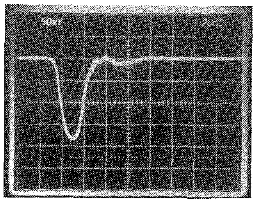

Figure 7. Five shot overlay of rf output.

6. Summary

After about 1 year experience operating magnetron and klystron loads on CLIA we have not discovered any unanticipated limits to repetitive microwave source operation at high peak power. In 1 sec, 100 Hz bursts there is no problem of neutral gas build up that produces impedance collapse or in other ways interferes with the magnetron resonance or the klystron beam bunching or output cavity interaction. There is no diminution of cold cathode emission after several thousand discharges and no significant erosion in the magnetron anode vanes or the klystron anodes is observed. We are proceeding to long pulses, higher electric fields and currents to continue delimiting trade-offs between high peak and average power operation.

7. References

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