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Status of Experiments at LLNL on High-Power X-band Microwave Generators*

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ABSTRACT

The Microwave Source Facility at the Lawrence Livermore National Laboratory (LLNL) is studying the application of induction accelerator technology to high-power microwave generators suitable for linear collider power sources. We report on the results of two experiments, both using the Choppertron's 11.4 GHz modulator and a 5-MeV, 1-kA induction beam. The first experimental configuration has a single traveling-wave output structure designed to produce in excess of 300 MW in a single fundamental waveguide. This output structure consists of 12 individual cells, the first two incorporating de-Q-ing circuits to dampen higher order resonant modes. The second experiment studies the feasibility of enhancing beam to microwave power conversion by accelerating a modulated beam with induction cells. Referred to as the "Reacceleration Experiment," this experiment consists of three traveling-wave output structures designed to produce about 125 MW per output and two induction cells located between the outputs. Status of current and planned experiments are presented.

1. RELATIVISTIC KLYSTRON PROGRAM AT LLNL

In the early 1980's it was noted that Free Electron Lasers driven by induction accelerators were capable of producing the high peak powers required to power the high gradient accelerators currently being studied.¹ If induction accelerator cells were placed after the FEL, the induction beam could be passed through additional FEL's for increased beam to rf power conversion. A variation of this concept using resonant microwave structures in place of the FEL is referred to as the Relativistic Klystron Two-Beam Accelerator (RK-TBA).² The Relativistic Klystron Program at LLNL began in 1987 to develop microwave sources based on induction accelerator technology which could be suitable drivers for a future TeV linear e^+e^- collider. Initial experiments used a 1.2-MeV, 1-kA electron beam to drive velocity modulated, conventional design klystrons. Substantially higher output power levels were obtained with the use of traveling-wave structures which reduced the electrical surface field stresses.³ Also, design studies indicated that with higher beam energy, higher beam to rf conversion could be produced. During the past year we completed testing of a microwave generator called the Choppertron^{4,5} on a 5-MeV, 1-kA beam using traveling-wave output structures. The Choppertron has demonstrated high-power pulses, >180 MW per output at 11.424 GHz with stable phase and amplitude and >400 MW total peak power with conversion efficiency (beam energy to microwaves) of about 30%. Table 1 summarizes the experimental results achieved with the different traveling-wave output structures used with the Choppertron.

The power requirements for initial operation of the Next Linear Collider (NLC) as proposed by the Stanford Linear Accelerator Center has evolved with the design work on the high gradient accelerator. The power required per meter of collider is now estimated⁶ as 180 MW with accelerator feeds about every two meters and pulse length of 250 ns. A costing study and design effort is currently being pursued to establish an efficient induction accelerator design for a RK-TBA which will meet these requirements.⁷ The emphasis of our experimental program has changed from maximizing power from a single output structure to reducing the strength of transverse instabilities caused by excitation of higher order modes in the traveling-wave output structures. The initial tests of the Choppertron experienced beam breakup due to these instabilities. Techniques which we have utilized to control transverse instabilities include external damping of individual cavities in the traveling-wave output structures, staggered tuning, and variable geometry structures. In this paper we will describe the testing of a variable geometry, 12-cavity traveling-wave output structure. An

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experiment in progress which involves the acceleration and power extraction of a modulated beam is also discussed. The design of this last experiment, which we refer to as the Reacceleration Experiment, was presented last year.⁸

Table 1. Traveling-wave Output Structures Used in the LLNL Relativistic Klystron Program

Structure Name	Beam Energy (MeV)	# of Active Cav.* ¹	Uniform Structure	HOM Damp-ing	Power Gain (db)	Beam Aperture (mm)	Fill Time (ns)	Power (MW) peak	Current (A) peak* ²	Power (MW) wide	Surface Field* ³ (MV/m)
MOK-2	1.2	6	no	no	15.2	14	1.01	300	500	300	152
TW1&2	2.5	6	yes	no	15.5	14	1.05	220	390	180	114
TW3	2.5 & 5	4	yes	yes	11.8	13	1.35	120	310	120	80
TW4* ⁴	2.5 & 5	5	yes	yes	11.5	14	1.05	154	300	100	78
TW5	5.0	10	no* ⁵	yes	16.6	16	1.72	260	340	180	70

*¹ Number of undamped cavities. Structures with HOM damping had two damped cavities. *² Estimate from computer modeling. *³ Maximum sustainable electrical surface field. *⁴ TW1 upgraded with HOM damping. *⁵ Shunt impedance of cells varied.

2. 12-cell Traveling-wave Output Structure

A schematic of the Choppertron with the 12-cavity traveling-wave output structure (TW5) is shown in Fig. 1. The initial part of the Choppertron is a transverse modulator. The electron beam is deflected transversely as it passes through a resonant cavity. The drift section is immersed in a solenoidal field. By matching⁵ this field to the energy and emittance of the beam, emittance growth is minimized and the beam's radius is maintained. After drifting a quarter betatron wavelength, the beam intercepts a collimator causing the transported portion of the beam to be modulated at twice the deflection cavity frequency. Parameters of the output structure are given in Table 2.

2.1 Transverse Instabilities

A major concern with this experiment was the possibility of excitation of higher order modes (HOM) in the output structure resulting in beam loss. TW1, a single 6-cavity structure with no external damping, exhibited beam breakup at current levels above about 750 amperes. TW3, a damped six-cavity structure,⁹ was tested to over 1,000 amperes without beam loss and computer simulations¹⁰ indicate that the threshold current for beam loss should be about 2,400 amperes. The damping was accomplished with a broad band HOM de-Q-ing circuit constructed by the Haimson Research Corporation.⁹ The de-Q-ing circuit consisted of two slots in the outer wall of each of the first two cavities which magnetically couple to both orientations of the dipole mode. Power extracted through these slots was absorbed into external loads attached directly to the outside of the cavities. The primary mechanism for transverse instabilities in traveling-wave output structure is regenerative beam breakup. The threshold current at which the transverse instability would drive the beam into the wall for regenerative beam breakup varies inversely with the cube of the structure length.¹¹ If TW5 would have been a uniform structure, we would have expected a significantly lower threshold current.

Figure 1. Schematic of the Choppertron.

A photograph of TW5 is shown in Figure 2. The orientation of the picture has the entrance of the structure on the right. The large disk structure on the right surrounds the first two cavities and contains the absorbing load for the damping circuit. The larger disk structure towards the exit (left) of the structure contains a damping cavity to absorb electromagnetic energy which propagates down the beam line. A future experiment will use two TW5 outputs in series and this second damping circuit is designed to prevent electromagnetic coupling between the structures. TW5 was tested up to 750 amperes with no indication of beam breakup. By intentionally off setting the beam into the output structure it was possible to excite the transverse instability sufficiently to cause minor beam loss. Figure 3 shows the power extracted through the rectangular output waveguide and is contained in the frequency band associated with the transverse instability for TW1 and TW5 as a function of current. Power measurements for the figure are uncalibrated and different for the two cases shown as the microwave diagnostics were not calibrated for this frequency range. The power growth for TW1 grew abruptly to the saturation point at which beam-wall interception occurred. The important result of this plot is the substantial decrease in power growth (slope of the lines in Figure 3) with current for TW5. This decrease can be attributed to aggressive HOM damping, and the reduced shunt impedance and transverse impedance for the nonuniform geometry of TW5.

Figure 2. Photograph of TW5, a 12-cell traveling-wave output structure with HOM damping.

Table 2. 12-cell Output Choppertron Parameters

Design Parameter	TW5
Fundamental Resonant Freq.	11.424 GHz
Fundamental Mode	TM ₀₁₀
# of Cavities	12
Phase Shift per Cavity	120°
Aperture Diameter	16 mm
Fill Time	1.72 nsec
Output Power	Designed* 400 MW
	Achieved† 180 MW
	Peak Value# 260 MW

*for 420 amperes of rf current

†full width pulse

#narrow pulse corresponding to ~340 amperes

Figure 3. Variation in BBU power extracted in the rectangular waveguide as a function of current incident on the entrance of the modulator.

2.2 Maximum Output Power Limited by Vacuum Conditions

TW5 was designed to produce 400 MW when driven with 420 amperes of modulated current. The peak output power levels grew as expected with increased modulation current. However, at high rf output powers the pulse was very narrow due to electrical breakdown in the output structure. To preclude damage to the rf output of the TW5 structure we limited modulated current to an estimated 340 amperes which generated a narrow 260 MW pulse. At lower power levels the output power pulse was similar to the current pulse. Figure 4 shows an example of a "full width" lower power pulse. Ramping the current pulse (slower rise time) increased the power level achievable before breakdown. This technique was used to produce pulses of over 200 MW which were similarly shaped to the current pulse.

The pressure measured in the output waveguides was typically in the mid 10^{-7} torr range during operation. The pressure on the beamline within the TW5 structure was assumed to be an order of magnitude larger during the modulated current pulse. While this is a typical pressure in the Advanced Test Accelerator induction cells which use O-ring seals, it is not acceptable for the electrical field levels associated with high power microwave structures. The initial experiment listed in Table 1 was performed on the Accelerator Research Center's accelerator which used Freon rather than insulating oil as an insulating medium in the induction cells. Thus there were fewer hydrocarbons present in the contaminants than in the later experiments. As seen in Table 1 we realized our highest sustainable surface fields in this configuration. Our current accelerator uses an oil insulating fluid in the induction cells. Initially, when operating at 2.5 MeV, the Choppertron was separated from the accelerator by a one-meter long, 2-cm aperture collimator which provided differential pumping. At 5 MeV, an assembly of 10 induction cells was located prior to the modulator with no isolation. This progression has led to reduced sustainable surface fields in the output structures as reflected in Table 1. We plan to modify the beam line by adding a short collimator and pumping ports to provide additional differential pumping and help isolate all induction accelerator cells from the rf experiments. For a final RK-TBA design, the induction accelerator cells would have all metal-ceramic seals for improved vacuum properties.

Figure 4. Full width rf output power pulse from the TW5 structure.

3. Reacceleration Experiment

The Reacceleration Experiment is a demonstration of the efficiency enhancement in a Relativistic Klystron Two-Beam Accelerator. As designed the modulator section of the Choppertron is used to generate about 320 amperes of modulated current from a nominal 1-kA, 5-MeV beam. This modulated beam passes through the first output structure generating over a 100 MW lowering the average beam energy by about 300 keV. The beam then passes through an induction cell gaining an energy of about 250 keV. This cycle is repeated a second time followed by a final power extraction. A principle goal of the experiment is to validate the theory and computer codes used in its design.

A schematic of the experiment is given in Figure 6. The experiment has been performed in stages to verify the performance of major components. The beam energy was increased to 5 MeV by the addition of 10 induction cells and the new beam characteristics measured. Computer simulations indicated that at 2.5 MeV space charge forces would significantly reduce the modulation of the beam during the 50 cm drifts between output structures. The modulator was lengthened and a safety collimator added to the beam line to avoid beam interception at the entrance of the Choppertron. The first two output structures have damping circuits (TW3

and TW4 in Table 1). The ATA induction acceleration cells have a 13.5 cm aperture. To allow a more compact design, avoid large aperture variations, and provide space for beam diagnostics a sleeve was inserted inside the induction cell and the gap plates modified for a 1.4 cm aperture. Pumping ports were installed on the back plate of the cell to improve the vacuum in the vicinity of the output structure and isolate the beamline from the oil/vacuum interface at the outer boundary of the cell. The reacceleration induction cells are mounted on rails and a slip joint is used to mate the sleeved section to the output structure. We have just completed testing of the experiment through the second output structure and are moving the second induction cell and final output structure to the beam line.

Figure 6. Schematic of the Reacceleration Experiment.

From the design studies, beam transport was expected to be a major issue. Resistive wall current monitors are located prior to the modulator, on the sleeve section within the reacceleration cells, and after the final output structure. During testing of the Choppertron on the 5-MeV beam we found that the beam had a halo containing approximately 10% of the current. To obtain a more accurate measurement of the current entering the modulator, rf loops were installed in the safety collimator at the entrance of the modulator. Any current passing through this collimator will enter the modulator. The output signals of the loops are integrated and summed. Figure 7 compares the output from these diagnostics. The rf loop has a better response and gives a more accurate depiction of the shape of the leading and trailing edges of the current pulse. Essentially all the current can be transported through the experiment when the beam is not modulated.

Typical rf output pulses after about 150,000 conditioning pulses are shown in Figure 8. The rounded corner on the trailing edge of the rf pulse from the second output is indicative of additional loading associated with impending electrical breakdown. Another contributing factor to the rounded corner could be current loss within

Figure 7. Current pulses measured at entrance to the modulator and at exit of last output structure.

the structure from the increased energy spread induced by rf power extraction in the first output structure. Simulations indicated that the modulated current would be larger at the second output. This is due to a combination of the effect of the first output structure on the beam and preferential current loss during transport between the structures. The measured power ratio between the two outputs was consistent with an increase in modulated current. Our experience with conditioning the output structures in the Choppertron experiments is that 300 to 400 thousand pulses are required before the maximum output power is achieved. Also, the additional pumping at the reacceleration induction cell improved the vacuum measured in the output waveguides by a factor of two. For these reasons we feel that the design power levels of about 100 MW per output structure is achievable once rf conditioning has been completed.

Figure 8. RF output power pulses from the two traveling-wave output structures.

4. Future Work

The Reacceleration Experiment will continue for the next several months. The second induction cell and last output structure are being readied for installation. In addition to this experiment, several projects are planned for the next year.

- 1) We will be testing a new transverse modulator this spring. This modulator will be better matched for the emittance of our induction beam and will have higher efficiency than the present modulator. By next fall we are scheduled to test the Choppertron II. It will consist of this modulator and two TW5 output structures.

- 2) The beam line will be modified this summer by inserting a short collimator and more pumping ports to provide additional differential pumping and help isolate induction cells from the rf experiments. We expect this to improve the operating vacuum and substantially reduce the hydrocarbon contaminants in the experiments.

- 3) A study of ferroelectric cathodes¹² is being done on a test stand at the Microwave Source Facility. If the results are positive, the cathode will be moved from the test stand and installed in the main accelerator for further testing.

- 4) Concurrently with the above experiments, we will continue testing a feed forward phase and amplitude stabilization system as time permits.¹³

5. Summary

Experiments using the Choppertron on a 1-kA, 5-MeV drive beam have been completed. Beam breakup due to the excitation of higher order modes in the traveling-wave output structures has not affected recent experiments, but is still a major concern as we study longer and multiple output structures. Specifically, the 12-cavity TW5 structure had excellent transverse stability. We have identified hydrocarbon contamination from the insulating oil of the induction cells as a serious limitation to maximum sustainable electric fields in our output structures. Corrective measures to reduce this contamination will be incorporated into the beam line

prior to testing of the Choppertron II. Several phases of the Reacceleration Experiment are completed. All major components have been "hot" tested on the beam line and performed as expected from simulations. The last stage of this experiment will be installed next month.

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