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Timothy Houck and Glen Westenskow

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Status of an Induction Accelerator Driven, High-Power Microwave Generator at Livermore*

T. L. Houck, and G.A. Westenskow

Lawrence Livermore National Laboratory
University of California, Livermore, California 94550

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ABSTRACT

We are testing an enhanced version of the Choppertron, a high-power rf generator which shows great promise of achieving greater than 400 MW of output power at 11.4 GHz with stable phase and amplitude. This version of the Choppertron is driven by a 5-MeV, 1-kA induction accelerator beam. Modifications to the original Choppertron included aggressive suppression of high order modes in the two output structures, lengthening of the modulation section to match for higher beam energy, and improved efficiency. Final results of the original Choppertron experiment, status of the ongoing experiment and planned experiments for the next year are presented.

1. INTRODUCTION

The motivation of our research program at the LLNL Microwave Source Facility is to develop microwave sources which could be suitable drivers for a future TeV linear e^+e^- collider. During the past year we completed testing of a microwave generator called the Choppertron.^{1,2} The Choppertron³ used transverse modulation of a 2.5-MeV, 1-kA drive beam and two traveling-wave output structures to generate X-band microwaves. The Choppertron demonstrated high-power pulses, >150 MW per output at 11.424 GHz with stable phase and amplitude and >400 MW total peak power. The conversion efficiency of beam energy to microwaves was only about 30%. To be a competitive rf source for a collider the conversion efficiency would have to be significantly increased. One means of improving the efficiency is by reaccelerating the beam and extracting additional power. The application of this concept to a linear collider is referred to as the Relativistic Klystron Two-Beam Accelerator (RK-TBA).⁴

We gained considerable experience working with high current, intense electron beams in the experiments with the original Choppertron which is applicable to the RK-TBA. The most important result of these experiments involves our work to reduce 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. We are now preparing for a reacceleration experiment to study the feasibility of the RK-TBA concept. An early design study⁵ of an experiment based on the 2.5-MeV Choppertron involving the reacceleration of a modulated beam indicated that higher beam energy would be required. As a preliminary study to a reacceleration experiment, we have chosen to test a modified version of the Choppertron using a 5-MeV drive beam. This has proved to be a relatively ambitious project requiring the addition of 10 induction accelerators cells to double the beam energy, an increase of the beam line by nearly a factor of two, the installation of the ancillary pulse power, vacuum, and fluid systems, upgrade of the Choppertron's modulator section, and the modification of one of the output structures. We will describe below the final results of the original Choppertron experiment and explain how we are incorporating these results into our current experiments.

2. ORIGINAL CHOPPERTRON EXPERIMENT

Last year we reported on the status of the Choppertron operating with a 2.5 MeV drive beam. For reference, a schematic of the Choppertron is shown in Fig. 1. At that time we had just modified the extraction section such that the first traveling-wave output structure incorporated a de-Q-ing circuit to dampen higher order modes. The excitation of these higher order modes had resulted in significant transverse instabilities of the drive beam and beam loss due to wall interception of the deflected beam. During the final testing of the

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Choppertron, the damped traveling-wave structure proved effective at eliminating beam loss due to growth of transverse instabilities. As described below, the maximum achieved power output was limited by beam emittance.

Figure 1. Schematic of the original Choppertron.

TABLE 1
Parameters for the RF Output Structures

Design Parameter	TW1 & TW2	TW3
Fund. Resonant Freq.	11.424 GHz	11.424 GHz
Fund. For. Traveling Mode	TM ₀₁₀	TM ₀₁₀
# of Active Cavities	6	4
Phase Shift per Cavity	120°	120°
Aperture Diameter	14 mm	13 mm
Fund. Fill Time	1.05 nsec	1.35 nsec
Est. Q for first two cells*	1200	10
Est. R/Q for BBU mode	110 Ω	110 Ω
Output Power Achieved	250 MW	120 MW

*of the BBU mode

2.1 Transverse Instabilities

The relativistic klystron two-beam accelerator (RK-TBA) concept⁴ involves the transport of high current beams through many small resonant output structures. The electromagnetic wake from the passage of the drive beam will excite the higher order modes (HOM) of these output structures. Unless care is taken in the design and operation of the RK-TBA the HOM fields will build up to a level where the drive beam will be swept into the walls, resulting in rf pulse shortening. Within each of the output structures being studied for a RK-TBA, the regenerative beam breakup (BBU) is the principal BBU mechanism. However, for longer RK-TBA systems, the cumulative BBU must also be addressed.

Experiments have demonstrated high rf output powers with the original rf output structures (TW1 and TW2), but with narrow pulse widths. The maximum total output power was about 420 MW with about 980 A of input current and 0.9 MW of drive power. The current pulse out of the choppertron was also narrow for this case indicating beam-wall interception. For input currents below 600 A, the choppertron rf output was well modeled by computer codes. Figures 2 and 3 show scans where the beam transport before the choppertron was changed to

Figure 2. RF output for different input current. The current through the output section is $\sim 1/2$ of input.

Figure 3. Through current for different input currents.

vary the input current. Figure 2 shows the rf power for several input currents. Figure 3 shows the current pulse transported through the choppertron for different input currents (without drive power applied to the choppertron's modulator section). For input currents above 600 A the through current pulses generally had a sharp notch after ~20 nsec (see the 1000 A curve in Figure 3). Below about 600 A of input current, the rf output power would increase proportionally with the square of the input current.

The narrowing behavior of the through current and rf power output pulses is believed to be caused by the growth of transverse electrical fields in the output structures. The dispersion curves for the two different traveling-wave structures used in the Choppertron are shown in Figures 4 and 5 (URMEL predictions for an infinitely repeating cell structure). The lower branch of the HEM₁₁ mode crosses the speed of light line at approximately 13.6 GHz. The power near 13.6 GHz had a sharp rise for current above ~600 amps. Also, measurements of the spectral content of the electron beam after the Choppertron under conditions just at the onset of beam breakup exhibited a resonance at 13.6 GHz. The short fill time of the structure might explain the recovery of the beam current in the second part of the current pulse shown in the 1000 A case in Figure 3.

Figure 4. Dispersion graph for monopole mode for the traveling-wave output structures.

Figure 5 Dispersion graph for dipole mode (lower HEM₁₁ branch) for the traveling-wave structures.

2.1.1 Damped Output Structure

A third traveling-wave output structure (TW3) was designed⁶ with a broadband HOM de-Q-ing circuit for damping the HEM₁₁-like transverse modes, and was constructed by the Haimson Research Corporation. The de-Q-ing circuit consists of two slots in each of the first two cells of TW3. The slots magnetically couple to both orientations of the dipole modes in each of the first two cells. The extracted power is absorbed into external loads attached directly to the outside of the cell. This design facilitates the use of these structures in the small bore solenoids that typically surround the output sections.

With the new TW3 replacing an original output structure, the choppertron produced stable, wide rf pulses, but the maximum output power achieved with 1000 A input current and full modulator drive power was only about 120 MW from TW3. Heavy damping of the dipole mode will lower the shunt impedance for the fundamental monopole mode in the first two cells. The bottom portion of the HEM₁₁ branch is lower than the fundamental extraction frequency (11.424 GHz). Since the field levels in the first two cells for the fundamental monopole mode are low, only a modest amount of fundamental power is absorbed by the de-Q-ing circuit. It was also especially important to damp the dipole mode oriented in the plane 90° from the main extraction port since this orientation previously had the higher Q. Transmitted currents up to 800 amps without transverse beam instability (compared to a threshold current of about 400 A for the original experiment with undamped structures) were achieved.

2.1.2 Pulse Length Considerations

There is a current threshold level for the onset of the instability to have an effect for the choppertron within the 40-nsec beam pulse. Both experiments and simulations show a rapid exponential dependence of the HOM power with drive current. Once the mode is excited it has an explosive nature. The slope of the decay in output current indicates that once the instability starts the beam current is lost within about 5 nsec. For our design conditions, if the rf power in the BBU mode reaches about 1% that of the fundamental extraction mode the transverse momentum "kick" given to the particles will be enough to drive the beam into the walls. Simulations⁷ indicate that the current threshold is about 230 amperes for TW1 driven by a long electron pulse ($\sim \mu\text{sec}$) which enters the structure with a 0.1 mm offset from the axis. Peak power operation of the choppertron was with currents over 4 times higher than this long pulse threshold value. The LLNL experiments have been with short rf pulses (40 nsec). For application to a collider at this frequency we will need to work with pulse lengths of 100-200 nsec.

Figure 6 shows the effect of the pulse length on the threshold current in the computer simulations. This case is for single output structure of the TW1 type. The electron drive beam is at 2.5 MeV. The beam is entering the structure parallel to the output structure's axis and with an offset from the axis of 0.1 mm. The beam's initial radius is 4 mm. The structure is immersed in a 2 kilogauss magnetic field along the axis. The threshold current is determined when the beam's outer radius begins to hit the wall at 7 mm. The dipole mode being studied has a frequency of 13.6 GHz and is "lower HEM_{11} " like with a phase velocity near the speed of light and a group velocity approximately equal to 0.12 c.

The decrease in threshold current in Figure 6 is relatively flat once the HOM power loss becomes comparable to the HOM power induced by the beam. The threshold current for a single structure (regenerative BBU) has a Q/R dependence.⁷

Figure 6. Threshold current verse time.

Figure 7. The beam current which can be used before the beam hits the wall for a given number of structures.

2.1.3 Multi-output RK-TBAs

The choppertron had trouble with BBU only when running with two output structures. The drift tube connecting the output sections in the experiments to date has had a radius small enough to reduce the rf coupling between the output structures for the lower HEM_{11} branch. The threshold current for transverse excitation is drastically reduced if the rf power of a transverse mode is coupled between structures with similar geometries.

The use of additional output structures in a RK-TBA will increase the problem with cumulative BBU. For a long uniform system with cumulative BBU the transverse beam motion grows exponentially with a scale length L_{BBU} . The beam entering a latter output section of the RK-TBA will have a larger transverse beam motion at its characteristic frequency. This motion will drive the regenerative BBU within this output section.

The following illustration is given to demonstrate the importance of damping the HOM in the output sections and emphasizes the importance of other damping mechanisms in a long RK-TBA system. Figure 7 shows a simulation using TW1 and TW3 structures that are closely packed with a fixed beam voltage of 2.5 MeV (no energy spread). The output sections are spaced at 11.2 cm intervals and the magnetic field is 2 kilogauss. The beam's initial radius is 4 mm. The threshold current is determined when the beam radius becomes larger than the drift tube's inner radius (7 mm) after 40 nsecs. The structures are the types shown in Table 1. For a given magnetic focusing field, the steady state cumulative BBU growth rate⁸ is independent of the beam voltage in machines where the betatron wavelength is much smaller than the system. For a given growth rate and beam current, the number of sections which could be used will be proportional to the magnetic field.

Staggered detuning of the HOM frequencies is being actively pursued for the main accelerator structures being considered for linear colliders. This is accomplished by the use of cells with different geometry but with the same rf properties for the fundamental accelerating mode. Detuning requires that the frequency shift between noninteracting sections, δf , be large compared to $f/(2Q)$. The Q's of the HOM for the output sections being considered for RK-TBA are relatively low and require that $\delta f \approx 1$ GHz. There are only about three usable geometries for the structures where the HOM response of one type of structures is shifted enough to move its response out of the range of the response of the other types of structures. Still this should allow about three times the total number of output sections in an overall system using detuning than in a system in which all the structures have the same geometry.

2.1.4 Phase Mixed Damping

It was recognized early⁴ that phase mixed damping from an instantaneous energy spread in the electron beam would be essential in a long RK-TBA to limit the growth rate of BBU. The output sections now being considered have a higher shunt impedance than that of the standing-wave cavities used in the original analysis of RK-TBA designs.⁴ Code work is being pursued to develop a consistent design for a RK-TBA with realistic output structures.⁷ We will also investigate the design of output sections which have lower Qs for the HOMs. If additional damping is needed in a long system we will investigate BNS damping (introducing a head-to-tail energy spread within the electron pulse).

Let k_β be the betatron wave number, γ the relativistic factor, ω_0 the BBU frequency, $Z_\perp$ the shunt impedance of a structure, L_g the average spacing between structures, and I_b the beam current. If there is a spread in k_β^2 values, δk_β^2 , such that

$$\delta k_\beta^2 \gamma > \pi \left[\frac{I_b}{17 \text{ kA}} \right] \left(\frac{\omega_0 Z_\perp}{L_g} \right) \quad (1)$$

then there will be no growth in transverse beam position.⁹ For solenoid transport, k_β is inversely proportional to the particle energy and, therefore, a spread in k_β occurs if there is a spread, $\delta\gamma$, in γ . In the RK-TBA the value of $\delta\gamma/\gamma$ is typically large from the interaction of the beam with the structures during different parts of the fundamental rf period. Preliminary simulations with an energy spread during the fundamental rf period have shown a lower cumulative growth rate than simulations for a constant energy.

2.2 Power Levels and Quality

The Choppertron demonstrated good quality rf output with phase and amplitude variation kept to $\pm 2^\circ$ and 124 MW $\pm 2\%$ from a single output structure over a 30 ns pulse. Single output, flat topped pulses up to 150 MW and combined output, peak power of > 400 MW were measured. The onset of beam breakup was thought to be the principle limitation to achieving the designed 250 MW full width pulses. However, operation with a single output structure, or with the damped/undamped set of structures, where beam breakup was not an issue did not result in increased power levels. Another possibility that we mentioned briefly last year had to do with the issue of beam transport through the Choppertron. We now believe that beam transport, because of higher than expected emittance, is the primary factor in limiting the obtainable output power. Our reasoning is described below.

In our experiments, the emittance of the beam determines the beam radius at various positions along the beam line. This is especially important in the modulator section where the betatron resonance and emittance are matched to produce a desired betatron wavelength and beam radius. A collimator, consisting of a 2-cm diameter, 1-m long pipe surrounded by four solenoids, located after the injector serves as an emittance selector allowing only the portion of the incident beam which can maintain a radius equal or smaller than the pipe radius to pass. We shall define an edge emittance by use of the envelope equation for the radius of a beam in a solenoidal magnetic field which can be expressed as:^{10,11}

$$R'' + \left(\frac{e B_z}{2 \gamma \beta m c} \right)^2 R - \frac{\epsilon_N^2}{\gamma^2 \beta^2 R^3} = \frac{2 I}{17 (\gamma \beta)^3 R}, \text{ where} \quad (2)$$

ϵ_N is normalized emittance (π -m-rad), R is the beam radius (m), I is beam current (kA), B_z is the axial magnetic field (T), e/m denotes the electron charge/mass (coulombs/kg), and prime denotes a derivative with respect to z , the longitudinal dimension. We take ϵ_N to be the edge emittance and R to be the maximum radius of the beam. Although equation (1) is based on rms values of the parameters, our values should be proportional to the rms values with multiplicity constants depending on the cross sectional charge distribution. As the charge distribution is not well known, we have chosen our definition to be consistent with that used in the design of the Choppertron.^{3,5} By setting $R'' = 0$ (the beam maintains a constant radius in the pipe), and measuring the solenoidal field in the collimator and amount of current transmitted, equation (2) can be used to determine ϵ_N . Figure 8 shows the results of recent measurements.

Figure 8. Emittance measurement on the ATA injector.

The emittance of our beam is about 110 π -cm-mr for one kiloampere of current. When the Choppertron was initially being designed, the intention was to operate it on a different accelerator which had an emittance of about 60 π -cm-mr. A calculation indicates that the larger emittance leads to a beam radius larger than the modulator slit (see Figure 1) so that only about 80% of the beam can be transported into the output section. This effect reduces the expected output power to about 65% of design or 162 MW.

3. Enhanced Choppertron Experiment

This experiment is being performed at the LLNL Microwave Source Facility which uses the Advanced Test Accelerator¹² (ATA) injector to generate a 8-kA, 2.5-MV electron beam. The current from the injector is then reduced to the desired 1 kA by a collimator located after the injector. The original Choppertron was placed on the beam line after this collimator. For the current experiment, the Choppertron was removed from the beam line and a ten-cell module from the accelerator section of ATA placed after the collimator. The module increases the beam voltage by 2.5 MV. The beam exiting the ten-cell module has an energy of 5 MeV and current variable up to about 8-kA by adjusting the solenoids surrounding the collimator. A stretched wire alignment procedure¹³ was performed to magnetically align the 34 solenoids used on the beam line. The enhanced Choppertron was reinstalled after the ten-cell module.

Prior to installing the Choppertron, several modifications were accomplished. A safety collimator with a 1.2 cm aperture was placed at the entrance of the Choppertron. This collimator restricts misalignment of the beam and includes a current diagnostic. The drift section of the modulator was lengthened from 29.3 cm to 54.7 cm (quarter betatron wavelength) to accommodate the higher energy beam. The second traveling-wave structure had a de-Q-ing circuit installed similar to the first structure. Although transverse instabilities would

not have been a problem with only one damped structure, our next experiment will use three output structures and a minimum of two of the structures must be damped to avoid beam breakup.

The experiment is fully in place and under vacuum. Currently we are conditioning the drive cavity of the modulator and performing final diagnostic calibrations prior to turning on beam.

4. Future Work

In addition to the experiment on the enhanced Choppertron, we have several projects being prepared for the next year.

1) As indicated above, we are planning an experiment to study the reacceleration of a modulated beam. A design study for this experiment is almost completed. A schematic of the planned experiment can be found in reference 5. Results of the current Choppertron experiment will be incorporated into the design study.

2) We intend on testing an 12-cell traveling-wave output structure constructed by the Haimson Research Corporation which is capable of producing 400-MW at 11.4 GHz when driven by 420 amperes (modulated current). This structure has mode suppression similar to the de-Q-ing circuits used in the present Choppertron output structures plus suppression of higher order modes propagating down stream of the structure.

3) Concurrently with the above experiments, we will be testing a feed forward phase and amplitude stabilization system.¹⁴

4) A code is being developed to evaluate the relative cost of induction accelerator driver systems for relativistic klystrons.¹⁵ The code incorporates beam generation, transport and pulse power system constraints to provide an integrated design tool. The code calculates dimensions of accelerator mechanical assemblies and values of all major electrical components for given input parameters. Cost factors for machined parts, raw materials and components are applied to yield a total system cost. Work is in progress on refining the costing algorithms used in the code.

5. Summary

Experiments using the Choppertron on a 1-kA, 2.5 MeV drive beam have been completed. Beam breakup due to the excitation of higher order modes in the traveling-wave output structures was identified and successfully suppressed. The suppression techniques and knowledge gained on transverse instabilities is being applied to a subsequent series of experiments based on the Choppertron modulator. We also identified beam emittance as being a constraint on maximum achievable rf output power. While the emittance problem is still an issue, we are more confident in our ability to predict output power. A new experiment with a modified Choppertron driven by a 1-kA, 5.0 MeV beam is installed and ready for operation.

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7. REFERENCES

- 1 T.L. Houck, et al., "Relativistic Klystron Research for Two-Beam Accelerators," SPIE Symposium on Intense Microwave and Particle Beams II Proceedings Vol. 1629-47 (1992).
- 2 T.L. Houck and G.A. Westenskow, "Status of the Choppertron Experiments," Proceedings of the 16th Int'l LINAC Conference, Ottawa, Ontario, Canada, Aug. 23-28, 1992.
- 3 J. Haimson and B. Mecklenburg, "Design and Construction of a Chopper Driven 11.4 GHz Traveling Wave RF Generator," Proceedings of the 1989 IEEE Particle Accel. Conf., pp. 243-245.

- 4 A.M. Sessler and S.S. Yu, "Relativistic Klystron Version of the Two-Beam Accelerator," *Phys. Rev. Lett.*, 58, 2439, 1987.
- 5 G.M. Fiorentini, T.L. Houck, and C. Wang, "Design of a Reacceleration Experiment Using the Choppertron," *SPIE Proceedings Vol. 1872-17*, 1993.
- 6 J. Haimson and B. Mecklenburg, "Suppression of beam induced pulse shortening modes in high power RF generator TW output structures," *SPIE Proceedings Vol. 1629-71*, 1992.
- 7 T.L. Houck, G.A. Westenskow, and S.S. Yu, "BBU Code Development for High-Power Microwave Generators," *Proceedings of the 16th Int'l LINAC Conference, Ottawa, Ontario, Canada, Aug. 23-28, 1992*.
- 8 G. J. Caporaso, "High Current Electron Transport", *The Physics of Particle Accelerators*, AIP Conference Proceeding 249, Vol 2, pp. 1615 (1992).
- 9 G. J. Caporaso, et. al., "Laser Guiding of Electron Beams in the Advanced Test Accelerator", *Phys. Rev. Lett.* 57, 1591 (1986) .
- 10 E.P. Lee and R.K. Cooper, "General Envelope Equation for Cylindrically Symmetric Charged-Particle Beams," *Particle Accelerators*, 7, 83 (1976).
- 11 E.P. Lee, S.S. Yu, and W.A. Barletta, "Phase-Space Distortion of a Heavy-Ion Beam Propagating Through a Vacuum Reactor Vessel," *Nuclear Fusion*, 21, No. 8, 1981.
- 12 S. Humphries, Jr., Principles of Charged Particle Acceleration, pp. 288-301, Wiley, New York, 1985.
- 13 L.V. Griffith and F.J. Deadrick, "Progress in ETA-II Magnetic Field Alignment Using Stretched Wire and Low Energy Electron Beam Techniques," *Proceedings of the 15th Int'l LINAC Conference, Albuquerque, NM, Sep. 10-14, 1990*, pp. 423-425.
- 14 D. Hopkins, D. Yu, T. Orzechowski, G. Vestenskow, and S. Yu, "Phase and Amplitude Stabilization of Short-Pulsed, High-Power Microwave Amplifiers," *Proceedings of the 1991 IEEE Particle Accel. Conf.*, pp. 1335-1337.
- 15 G.J. Caporaso, A.L. Brooks, and H.C. Kirbie, "Induction Technology Optimization Code," *Proceedings of the 16th Int'l LINAC Conference, Ottawa, Ontario, Canada, Aug. 23-28, 1992*.

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