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Experimental Study of the Relativistic Klystron Two-Beam Accelerator Concept*

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Abstract. We recently demonstrated the reacceleration of a modulated electron beam through an induction accelerator cell in support of the two-beam accelerator concept. We present the results of this experiment including amplitude and phase measurements of the extracted microwave power at 11.424 GHz. We also describe our proposed program for constructing a prototype relativistic klystron power source for a 1 TeV linear collider.

INTRODUCTION

Relativistic klystrons (RKs) are being developed as an rf power source for high gradient accelerators applications that include compact accelerators, large linear electron-positron colliders, and FEL sources. In a relativistic klystron two-beam accelerator (RK-TBA), the drive beam passes through a large number of rf output structures (1). High conversion efficiency of electron beam energy to rf energy can be achieved in the relativistic klystron by alternating the extraction of power with acceleration of the modulated drive beam. We have conducted a series of experiments to study the physics and technical issues of importance to relativistic klystrons (2,3). In this paper, we report on a recent experiment that involved the reacceleration of a modulated beam in a RK. We also describe a proposed experiment that involves the construction of a prototype RK suitable for powering the Next Linear Collider. The emphasis of our program is shifting to questions of cost and total system efficiency as we gain a better understanding of the physics issues.

REACCELERATION EXPERIMENT

The Reacceleration Experiment was designed to study the RK-TBA concept. Specifically, the adequacy of beam dynamic computer codes used in the design was verified and technical issues identified. Figure 1 is a schematic of the experiment. A 5-MeV, 1-kA induction beam is modulated by a transverse deflection technique (Chopper) to generate several hundred amperes of rf current at 11.4 GHz. The extraction section is comprised of three traveling-wave output structures and two induction cells which are located between the output structures. The output structures

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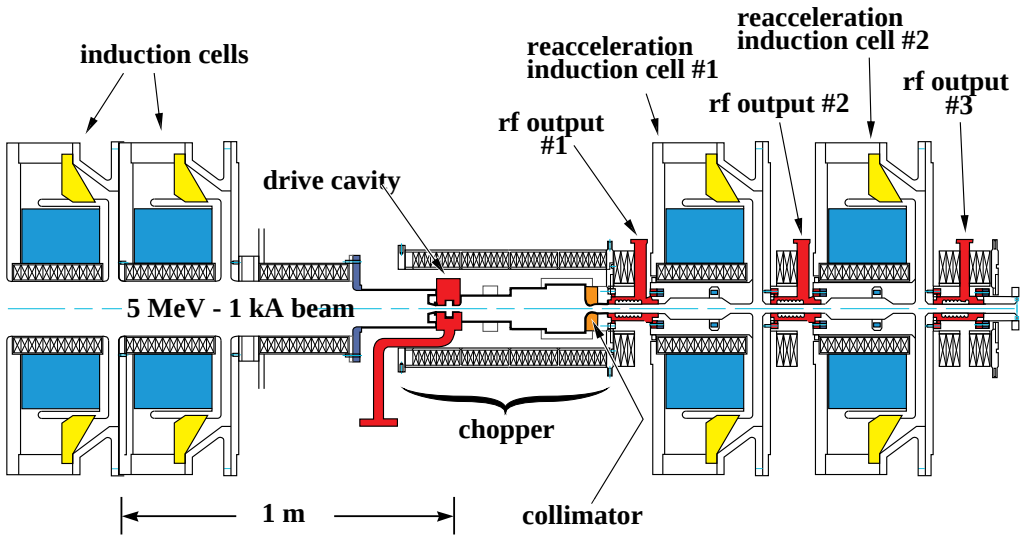

FIGURE 1. Schematic of the Reacceleration Experiment.

operate at 11.424 GHz in the TM_{01} mode with a $2\pi/3$ phase advance per cell and phase temperature sensitivity of about 0.1°/°C. Additional parameters are listed in Table 1. The induction cells used for reacceleration of the modulated current are each pulsed at 250 kV. The design of the modulator and the experiment has been described in detail elsewhere (4,5). Here, we report on the results.

Microwave Power Measurements

Figure 2 shows the maximum power achieved (but not on the same shot), with no pulse shortening, from each output. The "flat top portion" of the pulse lasts about 25 ns. This time is the length of the current pulse minus both the transient time of the drive cavity in the modulator and the fill time of the output structures. Linear collider applications place severe constraints on amplitude and phase variation. The anticipated requirements are for phase to be within ±1°, and for amplitude to be within ±1% over the power pulse (6).

Output power was limited by the vacuum pressure and hydrocarbon contaminants in the vacuum system. The induction cells use neoprene o-ring seals and insulating oil. These cells represent the major source of the contaminants. The operating pressure was in the mid 10^{-7} torr range at the vacion pumps in the output waveguides. The highest rf output power levels obtained were about 20% greater

TABLE 1. Parameters for the output structures in the Reacceleration Experiment.

Design Parameter	#1	#2	#3
# of Cavities (Undamped)	4	5	6
# of Cavities (Damped)	2	2	0
Aperture (mm)	13	14	14
Fill Time (ns)	1.35	1.22	1.05
Group Velocity	0.13 c	0.167 c	0.167 c
Max. Surface E-field at 250 MW	120 MV/m	130 MV/m	130 MV/m

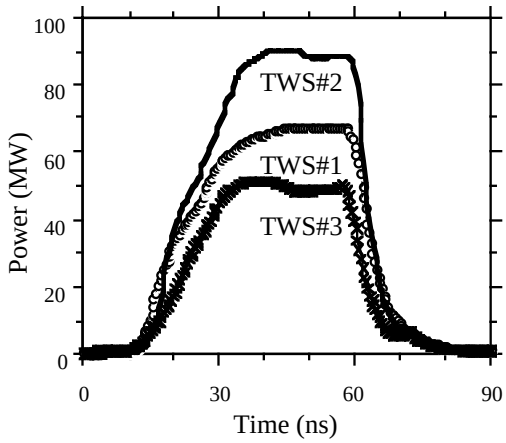

FIGURE 2. Maximum "flat top" power for levels for each output.

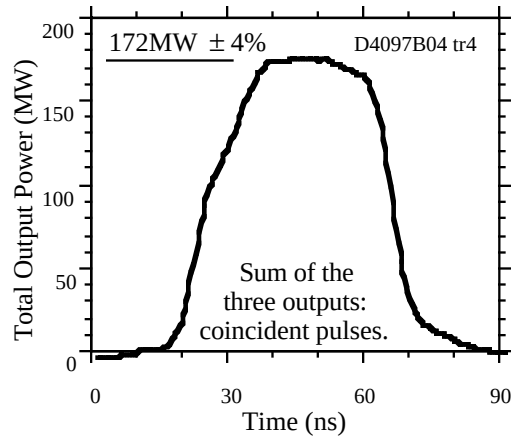

FIGURE 3. Combined power level coincident output pulses.

than those shown in Figure 2. However, these higher power pulses exhibited pulse shortening due to gas loading and/or electrical breakdown. Table 2 lists power levels and maximum sustainable surface electric fields for each output structure. By limiting the beam current to approximately two thirds of the design value, it was possible to achieve full width pulses from all outputs. The total output power, which scales as the square of the beam current, was reduced to one half of the designed value of 355 MW. Figure 3 shows a combined, coincident power pulse for the three outputs.

Output Power Phase Measurements

Figure 4 shows the phase of the power from the first output structure with respect to the modulator reference. The phase is measured by mixing the output power pulse of the first structure with the frequency doubled modulator drive pulse in a double balanced four-diode ring mixer. The variation shown in Figure 4 is primarily due to beam loading of the drive cavity in the modulator. The contribution due to energy (velocity) variation of the beam is negligible for two reasons: the short drift distance from the point the beam is modulated to the output structure and the high beam energy.

Figure 5 shows the phase of the power from the third output structure with respect to the first. The phase variation can be explained by the beam energy variation during the pulse. For this case, the energy variation is about ±2.5% and the phase variation is ±3°, in agreement with the standard equation

$$\Delta\varphi = -\frac{L\omega}{c}\left\{(\gamma - 1)(\gamma + 1)^3\right\}^{-1/2}\frac{\Delta V}{V}, \qquad (1)$$

TABLE 2. Maximum rf output powers achieved for each structure.

Output	"Flat top" Power (MW)	Surface E-Field (MV/m)	Peak Power (MW)
TWS#1	64.5±4%	60	86
TWS#2	88.5±3%	75	101
TWS#3	50.0±3%	60	59

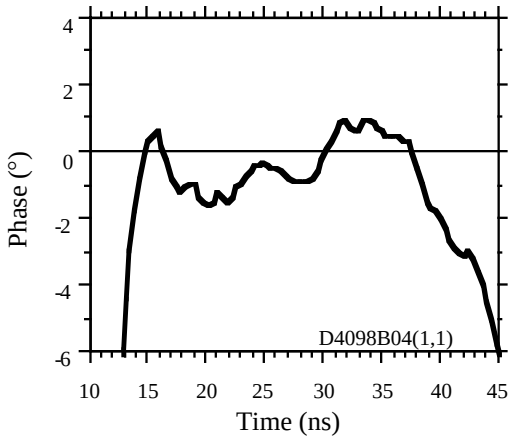

FIGURE 4. Phase of the first output with respect to the modulation reference.

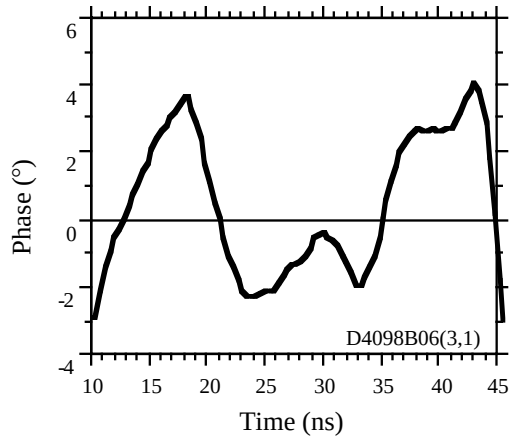

FIGURE 5. Phase of the third output with respect to the first output.

where L=0.95 cm is the distance between the two outputs, V ≈ 4.6 MeV is the beam energy, and the modulation frequency is 11.424 GHz.

Current Transport and Beam Breakup

Current transport below 500 amperes was not an issue in the experiment. Figure 6 shows a comparison of current entering the modulator and exiting the last output structure without modulator drive. The two curves agree to within the uncertainty of the diagnostics indicating no measurable current was lost. Measurements taken at two intermediate positions also confirmed full current transport.

Beam breakup (BBU) was observed for dc current levels above 550 amperes and with a beam energy of 4.6 MeV. A typical current pulse exhibiting BBU is contrasted with a full width pulse in Figure 7. The 550 ampere current appeared to be the threshold as beam loss was not observed on all pulses at this current level.

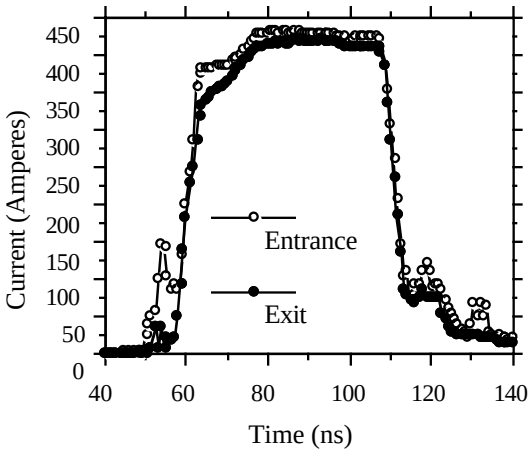

FIGURE 6. Current pulses entering and leaving the experiment show low losses.

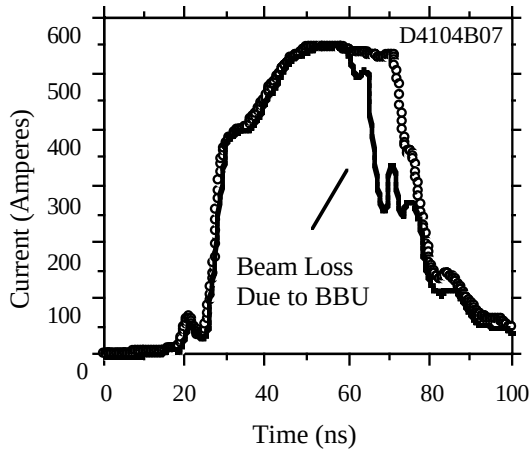

FIGURE 7. Evidence of beam breakup. in the transmitted current

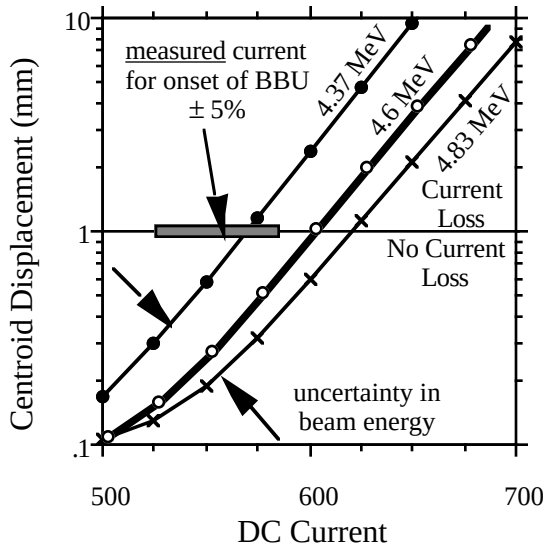

FIGURE 8. Results of computer simulations of the growth of transverse displacement of the beam centroid as a function of current and for three different energies.

This also indicates the susceptibility of BBU to the shot-to-shot variation of the induction accelerator pulsed power system. The 550 amperes is a substantially greater dc current than when the beam is modulated (≈ 380 amperes), and agrees with computer simulation to the accuracy of the energy and current diagnostics. The OMICE Code (7), formerly called the BBU Code, was developed at LLNL to study transverse instabilities in RK's and has been benchmarked against our experiments. Figure 8 shows simulation results of the OMICE Code predicting the expected threshold current for beam break-up. The 1 mm centroid displacement for current loss was estimated from beam transport simulations using the RKS2 Code (8).

PROTOTYPE RK FOR A RK-TBA BASED COLLIDER

Our experience gained from the RK experiments has enabled us to design an efficient and cost effective RK-TBA microwave power source (9). The chopper for this design is similar to that used in the Reacceleration Experiment. The transverse modulation technique is phase stable and compact. Its efficiency is enhanced by

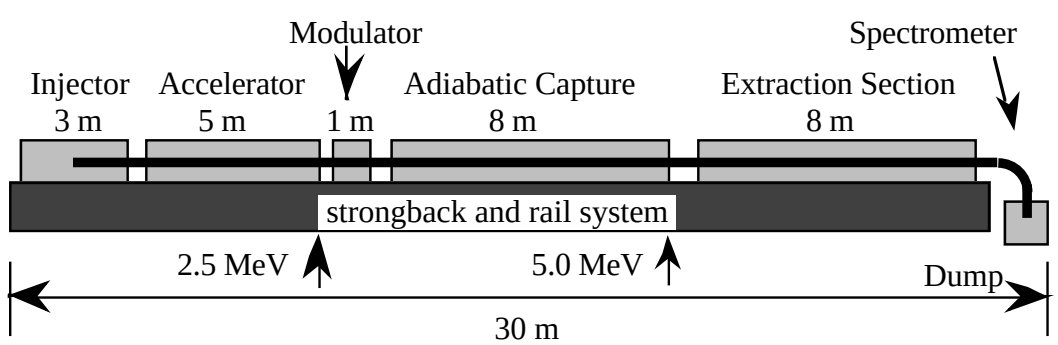

FIGURE 9. Proposed beamline of prototype relativistic klystron experiment.

partially modulating the beam with the chopper and then further compressing the phase space with idler cavities. Also, the transverse modulation is performed at an intermediate energy. The beam is accelerated to full energy during the compression stage. The induction cells are constructed of Metglas™ with each core driven at 20 kV for 200 ns of "flat top." Five cores are sleeved to produced 100 kV across an accelerating gap. This technique eliminates the need for an external high voltage step-up transformer.

We intend to build a prototype RK based on this design. To reduce the cost of the experiment, the prototype RK will operate at a beam energy of 5 MeV and have four extraction sections. Figure 9 is a schematic of the proposed beamline. All the major components of the full scale RK are incorporated into the prototype RK. This allows issues of component cost and efficiency to be addressed. Beam dynamics from the cathode through the first 8 meters of the RK, including modulation, phase compression, and acceleration, will be studied. Detailed comparison of experiment with computer simulations will be made to provide confidence in our ability to extrapolate the beam dynamics simulations to full scale RK performance.

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