RELATIVISTIC KLYSTRONS†

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ABSTRACT

Experimental work is underway by a SLAC-LLNL-LBL collaboration to investigate the feasibility of using relativistic klystrons as a power source for future high gradient accelerators. Two different relativistic klystron configurations have been built and tested to date: a high gain multicavity klystron at 11.4 GHz and a low gain two cavity subharmonic buncher driven at 5.7 GHz. In both configurations power is extracted at 11.4 GHz. In order to understand the basic physics issues involved in extracting RF from a high power beam, we have used both a single resonant cavity and a multi-cell traveling wave structure for energy extraction. We have learned how to overcome our previously reported problem of high power RF pulse shortening, and have achieved peak RF power levels of 170 MW with the RF pulse of the same duration as the beam current pulse.

1. INTRODUCTION

As part of an effort to develop a high gradient RF accelerator, work is underway to investigate several concepts for generating large amounts of RF power at X-band frequencies. One of these schemes is the relativistic klystron approach. The relativistic klystron, as conceived by Sessler and Yu[1] is a longitudinal bunching device in which the drive beam is sufficiently relativistic that space charge forces are unimportant, and such that beam velocity changes little during significant energy extraction and, perhaps, reacceleration. Repeated reacceleration and extraction was the concept Sessler and Yu called a "relativistic klystron two-beam accelerator." The idea of a relativistic klystron, however, is not limited to the two-beam accelerator concept. Relativistic klystrons can be imagined which span the range from a 1-GW device powering 1-m of accelerator, to a 10-GW device powering 10-m, to a two-beam device extending several kilometers. The relativistic klystrons with which we have been experimenting are designed to extract power from 1-kiloampere, 1.2-Megavolt electron beams.

In previous papers[2,3] we have reported results obtained with three experimental relativistic klystrons: a multicavity klystron at 8.6-GHz ("SL3") designed for a conventional gun but tested in a 1-MV, 350-Amp beam; a two cavity subharmonic buncher relativistic klystron ("SHARK") with 11.4-GHz output; and a multicavity klystron at 11.4-GHz ("SL4") designed to operate with high efficiency and high gain in a 1.2-MV, 1-kAmp beam. The pulsed high power electron beam for our klystron experiments is produced by a linear induction injector at the Accelerator Research Center at Lawrence Livermore National Laboratory.

Since then, we have built and are testing several variants of SHARK and SL4 with the goals of improving their performance and understanding some of problems we observed. Here, we discuss power gain in subharmonic drive klystrons and energy extraction in relativistic klystrons, we recap briefly our previous results with SHARK and SL4, and we report new results from our modifications of SHARK and SL4. These modifications include: using cavities with iron magnetic shielding and slotted noses to combat multipactor, adding a penultimate cavity to SHARK to improve gain and efficiency, and replacing the single output cavity of a relativistic klystron with a six-cell traveling-wave (TW) output structure to reduce electric fields. We have also begun to make measurements of phase stability in relativistic klystrons.

2. GAIN IN SUBHARMONIC DRIVE KLYSTRONS

Bunching is a non-linear process in which the beam is modulated at harmonics of the drive frequency. The theory of modulating a relativistic beam at the fundamental frequency of a bunching cavity has been discussed in our previous reports.[2,3] A single bunching cavity, such as the SHARK input cavity which is resonant at 5.7-GHz, can produce second harmonic (11.4 GHz) RF currents with 60% of the magnitude of the fundamental.

The effect of DC beam current on klystron output is complicated by two issues: beam loading of the input cavity, and voltage gain from input cavity to output cavity. At lower currents the input cavity loading is dominated by the external Q. At higher currents the input cavity loading is dominated by the beam conductance. Increasing the klystron beam current increases the voltage gain of the klystron. However, the additional beam current increases the loading of the drive cavity, which

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decreases the input cavity voltage. As beam current through the SHARK klystron is increased above about 400 Amps, the increase in beam loading decreases the input cavity voltage sufficiently to overcome the increase in gain.

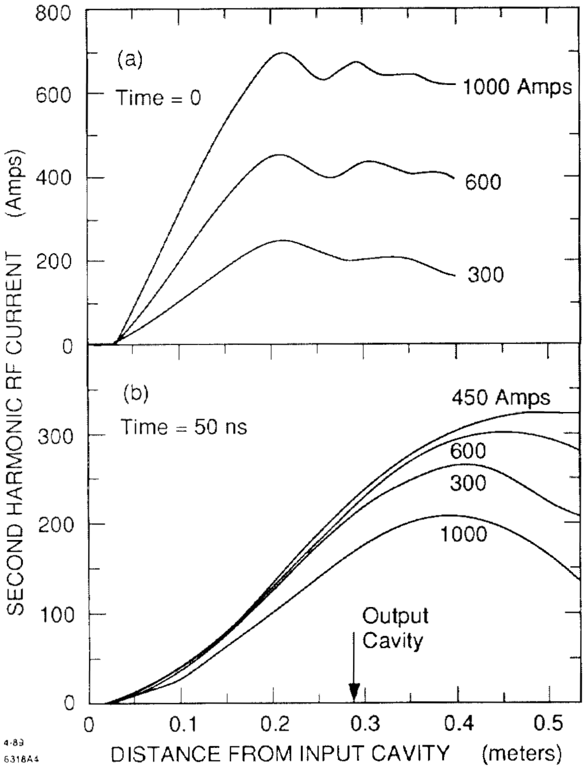

FIG. 1. Calculated second harmonic (11.4-GHz) RF current downstream from the SHARK input cavity for several different DC beam currents (a) immediately after turn-on of a DC beam of 1-MeV kinetic energy, and (b) after 50 nsec of uniform DC beam current.

We have used a computer simulation[4] to calculate the 11.4-GHz RF current downstream from the SHARK 5.7-GHz input cavity. Figure 1 shows the calculated RF current for several different DC beam currents. Figure 1(a) shows the RF current immediately after the turn-on of a DC beam which has 1-MeV kinetic energy and fills 6-mm of a 10-mm diameter beam tube. Figure 1(b) shows the RF current after 50 nsec of uniform DC beam current. The input cavity becomes loaded by the beam during the 50-nsec interval between Figures 1(a) and (b). The figure shows that, at the location of the SHARK output cavity, the RF current after 50 nsec is approximately 200 Amps for DC beam currents between 300 and 600 Amps. If the DC current is increased to 1000 Amps, the RF current is decreased to 150 Amps.

3. ENERGY EXTRACTION

We have used both a single resonant cavity and a multi-cell TW structure to extract RF power from a bunched relativistic beam. Here, we discuss the relative merits of these two extraction methods.

Energy extraction characteristics and scaling relationships for a single resonant cavity and a TW structure are compared in Table 1. Since the output electric fields are inversely proportional to the respective circuit interaction lengths, the multicell structure in general will exhibit significantly lower electric fields for equal power levels. Thus, for electric field-limiting applications, the TW structure will be capable of operating at significantly higher power levels than a single resonant cavity. Conversely, the longer interaction length makes the TW structure more susceptible to higher order mode difficulties and, in particular, to the buildup of HEM_{11} (beam breakup) fields.

TABLE 1. Comparison of Output Structures at 11.4 GHz.

	Single Resonant Cavity		TW-Structure[5]	
Parameter	Scaling	Value	Scaling	Value
Breakdown power	$1/g^2$	80 MW	$4/L^2$	460 MW†
Surface E-field*	$1/g$	190 MV/m	$2/L$	80 MV/m
Average E-field*	$\Delta V/g$	75 MV/m	$2\Delta V/L$	25 MV/m
Filling time	$4Q/\omega$	2 ns to 95%	L/v_g	1 ns to 100%
$(R/Q)_\perp$	g	20Ω	L	100Ω

Notes: * Field at 80-MW power level. † Extrapolated.
g = Effective cavity gap length. L = TW structure length.
ΔV = Beam energy loss. v_g = Group velocity.
$(R/Q)_\perp$ = HEM_{11} mode transverse shunt impedance.

The single resonant output cavities used in our experiments were of reentrant geometry with 9-mm apertures and 6-mm gaps. The 11.4-GHz TW structure[5] is comprised six $2\pi/3$-mode cells with beam apertures of 14-mm (0.27 free-space wavelengths), an electrical length of 4.8 cm, a filling time of 1 nsec, and a varying phase velocity tapering from $0.94c$ at entry to $0.90c$ at the output coupler. The TW circuit was designed to generate 250 MW of output power when operating under synchronous conditions at an RF current of 520 Amps. At this power level the average electric field in the output coupler is 37.5 MV/m, and the loss of beam energy traversing the circuit is approximately 0.9 MeV. Initial RF power measurements using this TW structure in configuration with SHARK and SL4 are described below in Sections 4.6 and 4.7.

4. RF POWER EXPERIMENTS

4.1 Original SL4 Experiment

In our previous reports,[2,3] peak RF power of 200 MW had been achieved, but only with an RF flat top much shorter than the beam pulse (930 kV, 420 Amp). The maximum reasonably flat RF pulse achieved in our initial tests was only 70 MW from a 930-kV, 300-Amp beam. The high power pulse shortening phenomenon was by far the most serious problem encountered. It was clearly not beam breakup since it did not correlate with shortening of the DC current pulse.

The shortened 200 MW peak RF pulses were transmitted into a 26 cm long high gradient accelerator structure.[2,3] This power corresponds to an accelerating gradient of 140 MV/m. Appreciable dark current was observed at accelerating gradients above 90 MV/m.

Our studies of the SL4 relativistic klystron demonstrated anomalous input cavity loading by charged particles (presumably multipactor) when the RF drive level exceeded 40 W. This loading phenomenon, once initiated by electrons from the warm gun cathode, was observed to persist, even with the cathode cold and the beam off, being sustained by the presence of an axial magnetic focusing field. The anomalous power absorption was a function of drive level, and of axial magnetic field surrounding the cavity. No anomalous power absorption was present when the axial magnetic field was zero. This cavity loading phenomenon, which we observed in the SL4 input cavity both with and without beam, may occur in any of the cavities of a multicavity klystron and may be related to pulse shortening. However, anomalous loading of the SL4 input cavity does not seem to affect the RF pulse width.

In our most recent experimental work, we have increased the available input power from 700 W to 1400 W, and observed that the anomalous loading of the SL4 input cavity is reduced at the newly available 1400-W input power level. This supports our suspicion of multipactor.

4.2 Original SHARK Experiment

Experimental evidence from SHARK indicated that pulse shortening was caused by loading of the input cavity by anomalous charged particle currents. The loading was believed to be due to either secondary electrons or to photoelectrons produced by the copious supply of x-rays caused by beam interception, and hence was named anomalous beam loading.[3] The power threshold for pulse shortening was sensitive to magnetic focusing field and to RF field strength. The maximum RF power level attained in our original SHARK experiments was 50 MW.

4.3 Iron Cavity SHARK Experiments

In the original SHARK experiments, the power threshold for RF pulse shortening was observed to increase with decreasing magnetic focusing field. Consequently, we tested a SHARK (5.7 GHz subharmonic) input cavity surrounded by iron which shunts the focusing field away from the beam axis in the region of the cavity gap. Figure 2 shows the effect of the iron on the axial magnetic field profile near the SHARK input cavity.

The iron input cavity does not exhibit anomalous loading, with or without beam. Output pulse shortening continues to occur above a threshold in output power. The output pulse shortening in the configuration with the iron input cavity occurs at a higher power threshold than in the original SHARK all-copper configuration. The evidence that pulse shortening occurs in the output cavity is that no correlation is observed between the output pulse shortening and either the input cavity reflected power or the RF current as monitored by an RF probe in the drift downstream from the input cavity.

Since we have shown that pulse shortening in the SHARK input cavity can be alleviated by shunting the magnetic field at the cavity, we plan to apply the same technique to the output cavity where RF pulse shortening remains a problem.

4.4 Slotted Input Cavity SHARK Experiment

The iron SHARK input cavity suppressed anomalous beam loading by reducing axial focusing at the input gap. However, problems in relativistic beam dynamics arise from perturbing the axial focusing field with iron. As an alternative to the iron magnetic shunt, we are considering using an input cavity with radially slotted noses to suppress multipactor by reducing the probability of electron emission from one nose and arrival at the other nose. In order to allay our concerns that slotting may lead to increased electric field strengths and cause RF breakdown, we have tested without beam a SHARK input cavity with 31 radial slots at 2.2 MW input power and found no breakdown problems to occur. We plan to incorporate this slotted nose cavity in future relativistic klystron beam tests.

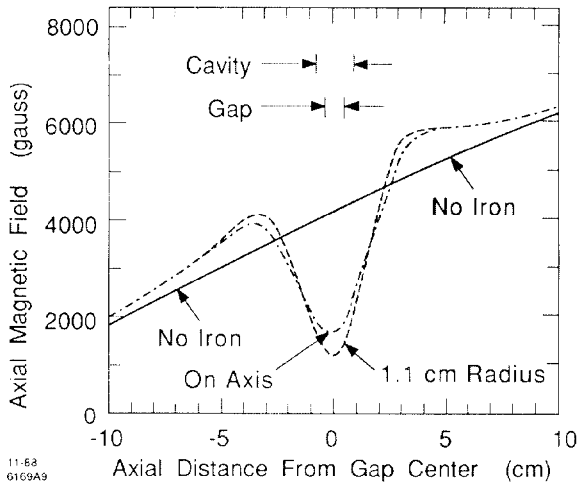

FIG. 2. Calculation of the axial magnetic field near the SHARK input cavity with and without iron. The cavity noses are at 1.1 cm radius.

4.5 SHARK-2 Experiment

The observation that RF pulse shortening did not occur in the iron SHARK input cavity but did occur in the copper SHARK output cavity, as discussed in the previous section, prompted us to test a three cavity subharmonic drive klystron configuration consisting of the iron SHARK input cavity and copper penultimate and output cavities. (The penultimate and output cavities are the output section of the modularly designed SL4 relativistic klystron.) In this configuration we expect lower electric fields in the output cavity for fixed output power because the external Q of this cavity in SHARK-2 is half that of the original SHARK output cavity.

Output pulse shortening is observed in the three cavity SHARK-2 at some point downstream from the iron input cavity. However, the power threshold is higher than in the two-cavity iron input SHARK, presumably due to the lowered external Q of the output cavity. Flat output pulses of 80 MW amplitude and 45 nsec duration (FWHM) have been obtained from a 1.2-MV, 360-Amp beam using the three cavity subharmonic SHARK-2 before the onset of pulse shortening. This is 70% more flat-top RF power than we obtained from the original two cavity SHARK.

4.6 SHARK/TW Experiment

In order to reduce the electric field levels present in the SHARK output cavity and, consequently, to raise the output power threshold for pulse shortening, the SHARK output cavity was replaced by a six-cell traveling wave (TW) output structure. The SHARK/TW configuration consists of an iron-shielded input cavity, and a six-cell TW output structure.[5] Beam diagnostics include a pair of E_r probes located between the final gain cavity and the TW output structure, and, downstream from the output cavity, a resistive foil current monitor.

The RF output level obtained using SHARK/TW was 100-MW from a 1.1-MV, 300-Amp beam. At this current, output power was limited by saturation. At higher currents, output power was limited by beam loading of the input cavity. RF phase measurements were performed, and are described below in Section 5.

4.7 SL4/TW Experiment

In order to reduce the electric field levels present in the SL4 output cavity and, consequently, to raise the output power threshold for pulse shortening, the SL4 output cavity was replaced by a six-cell traveling wave (TW) output structure. The SL4/TW configuration consists of an input cavity, three gain or idler cavities, and a six-cell TW output structure. Beam diagnostics include a pair of E_r probes located between the final gain cavity and the TW output structure, and, downstream from the output cavity, a pair of dB_ϕ/dt loops and a resistive foil current monitor.

At first, beam tests revealed a large amount of power at 13.8 GHz radiated from the input cavity into the reflected drive diagnostic. This signal was present with or without RF drive, and was sensitive to changes in the focusing configuration for transporting the beam through the klystron. Also, the beam current pulse was reduced in pulsewidth, indicative of beam breakup. Analysis of the higher order modes of the TW output section revealed that a beam breakup mode existed at approximately 13.2 to 13.7 GHz and could propagate backwards from the TW structure to the input cavity causing oscillation.

A collimator 11.4-mm in diameter and 25-mm in length, designed to suppress propagation of 13.8-GHz by 30 dB was inserted between the last gain cavity and the TW output section. With this collimator in place, no beam breakup was observed and the 13.8-GHz signal at the input cavity was reduced significantly.

With beam breakup suppressed by the collimator, peak RF output power levels up to 170 MW have been measured using a 1.4-MV, 400-Amp beam. The RF pulse width is comparable to the full duration of the transmitted beam current. This is different from our previous experiments (performed with a single output cavity instead of the TW output structure) in which RF pulse shortening (relative to the beam current) was a significant problem. The reduction in electric field strength afforded by the TW structure appears to have alleviated RF pulse shortening.

4.8 Summary of RF Power Experiments

The RF power levels attained with the various klystron configurations are summarized in Table 2.

TABLE 2. Comparison of RF power experiments at 11.4 GHz.

Klystron	Peak RF Out (MW)		Limitation
	Short	Wide Pulse	
SL4	200	70	Pulse shortening
SHARK	50	50	Anomalous beam loading
SHARK-2	120	80	Output cavity breakdown
SHARK/TW	—	100	Input cavity beam loading
SL4/TW	—	170	Present status

Insight into the relative power levels achieved can be gained by considering the surface electric fields present in the resonant cavities and TW structures. Peak surface electric fields calculated for given power levels are shown in Table 3. Several points can be made about Table 3: (1) The anomalous beam loading observed with SHARK may be related to or exacerbated by the high electric fields in the SHARK input cavity. (2) The peak fields in the output cavity of SHARK are significantly greater than in SL4 for equivalent output power level because the external Q of the SHARK single output cavity is twice as large as in SL4. This may explain why pulse shortening occurs at lower power levels in SHARK than in SL4. (3) The choice of TW output structure instead of the single resonant cavity output for both SHARK and SL4 significantly reduces electric field strengths. The 80-MW power level achieved with SHARK-2 suggests that with similar peak fields (and more beam power) 460 MW may be attainable using TW output. However, electrical breakdown in the gain cavities may become a problem before 460 MW of output is actually attained.

TABLE 3. Comparison of surface electric fields.

Structure	Peak Power (MW)	Peak Surface Field (MV/m)
SL4 input cavity	0.001*	4
SHARK input cavity	2.4*	178
SHARK output cavity	200	445
SL4 and SHARK-2 output cavity	200**	300
TW structure	200	125
SL4 and SHARK-2 output cavity	80*	190
TW structure	460	190

* *Achieved.* ** *Achieved with pulse shortening.*

5. RF PHASE MEASUREMENTS

One design for a future linear collider calls for accelerating closely spaced multiple bunches of electrons with tolerances on RF phase stability of several degrees.[6] If relativistic klystrons are used to power this collider, they must have this RF phase stability. Since the phase shift through a klystron is inversely related to the average electron velocity, sensitivity of the output phase to variations in beam energy are less important with a relativistic beam. At kinetic energy $eV = 1.4$ MeV, the RF phase change in SHARK is calculated to be approximately $320°\Delta V/V$.

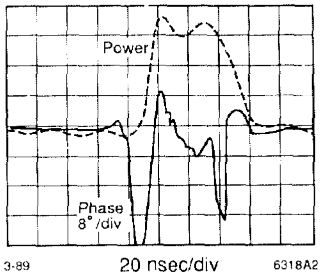

FIG. 3. Measurement of RF power and phase in the SHARK/TW relativistic klystron. Stability of the phase-amplitude product (solid trace) is maintained to within 16° during the 35 nsec period of 60-MW peak RF amplitude (dashed trace).

We have made measurements of phase stability in the SHARK/TW klystron (Section 4.6). The phase reference was the frequency-doubled subharmonic input signal. The phase detector was a double-balanced mixer which measures the product of RF phase and amplitude. This phase-amplitude product is a measure of phase only during periods of constant amplitude. The phase bridge was balanced while the beam was on. Figure 3 shows a simultaneous measurement of RF power and phase in the SHARK/TW klystron. Stability of the phase-amplitude product is maintained to within 16° during the 35 nsec period of 60-MW peak RF amplitude. While the measured phase stability is not sufficient for multibunch tolerances,[6] the phase variation is due primarily to beam energy variation and presumably can be improved.

6. FUTURE PLANS

Further studies of the high gradient accelerator structure described in References 2 and 3 are planned, using stable high power RF output pulses of duration greater than the filling time. These tests will include studies of breakdown at 11.4 GHz and measurement of the accelerating gradient.

In light of the apparent success of the iron magnetic shields and traveling wave output structures at suppressing pulse shortening in our recent experiments, we are beginning to design a high efficiency, high gain, relativistic klystron similar to SL4. The design will incorporate some combination of magnetically shielded cavities, slotted noses, reduced-field output structures, and beam diagnostics.

We also hope to test the chopper driven 11.4-GHz traveling wave RF generator described in Reference 5.

7. SUMMARY

We have been working to develop a high power (500 MW) short wavelength (2.6 cm) relativistic klystron with beam kinetic energy greater than 1 MeV. We have attained peak power levels of 200 MW at 11.4 GHz with RF pulse shortening, and 140-MV/m longitudinal gradient in a short 11.4 GHz accelerator section. We have overcome our previously reported problem of high power pulse shortening by applying multipactor suppression techniques and by using traveling wave output structures. Peak RF power of 170 MW has been achieved with the RF pulse of the same duration as the beam current pulse. We have begun to make measurements of the RF phase stability of relativistic klystrons.

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REFERENCES

1. A. M. Sessler and S. S. Yu, "Relativistic Klystron Two-Beam Accelerator," *Phys. Rev. Lett. 58*, 2439 (1987).
2. M. A. Allen *et al.*, "Relativistic Klystron Research for Linear Colliders," SLAC-PUB-4733 (September 1988), published in Proceedings of the Linear Accelerator Conference, Williamsburg, Virginia, October 3–7, 1988, and in DPF Summer Study: Snowmass '88, High Energy Physics in the 1990's, Snowmass, Colorado, June 27–July 15, 1988.
3. M. A. Allen *et al.*, "Relativistic Klystron Research for High Gradient Accelerators," SLAC-PUB-4650 (June 1988), published in Proceedings of the European Particle Accelerator Conference, Rome, Italy, June 7–11, 1988.
4. R. D. Ryne, "A Fast Algorithm for Calculating Space Charge Effects in One-Dimensional Klystron Simulations," LLNL Beam Research Program, Research Memo 89-12 (March 1989).
5. J. Haimson and B. Mecklenburg, "Design and Construction of a Chopper Driven 11.4 GHz Traveling Wave RF Generator," 1989 PAC IEEE Conference Records 89CH2669-0 (these proceedings).
6. Ronald D. Ruth, "Multibunch Energy Compensation," SLAC-PUB-4541 (February 1988), published in proceedings of the ICFA/INFN Workshop on the Physics of Linear Colliders, Capri, Italy, June 13–17, 1988.