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RELATIVISTIC KLYSTRON RESEARCH AT SLAC AND LLNL[†]

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We are developing relativistic klystrons as a power source for high gradient accelerator applications such as large linear electron-positron colliders and compact accelerators. We have attained 200 MW peak power at 11.4 GHz from a relativistic klystron, and 140 MV/m longitudinal gradient in a short 11.4 GHz accelerator section. We report here briefly on our experiments so far.

Large linear electron-positron colliders and compact accelerators require a new generation of high gradient accelerators. Conceptual designs for linear colliders for research at the frontier of particle physics call for beam energies of 500–1000 GeV. Accelerating gradients of 150–200 MV/m are desired in order to keep the accelerator length within acceptable limits. Frequencies of 11–17 GHz are desired in order to keep peak power requirements and beam loading reasonably small. The peak power necessary to drive a traveling wave structure in the desired frequency range with the desired gradient is of order 1 GW/m with a pulse length of 50–100 ns. New RF power amplifiers are needed to meet these requirements. Pulsed beams with gigawatt peak power levels can be accelerated using magnetic pulse compression and induction linac technology as developed at Lawrence Livermore National Laboratory (LLNL), where kiloampere beams are routinely accelerated to several megavolts.[1]

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A. M. Sessler and S. S. Yu, following a suggestion by W. K. H. Panofsky, proposed accelerating a bunched beam in an induction linac and extracting RF power from conventional klystron output cavities.[2] If only part of the beam energy is extracted at each cavity, the beam can be reaccelerated and energy can be extracted repeatedly, making possible very high efficiency. Alternatively, without reacceleration, the relativistic klystron can be expected to operate as a conventional high power klystron with efficiency approaching 50%.

These ideas have led to a collaboration between Stanford Linear Accelerator Center (SLAC), Lawrence Berkeley Laboratory (LBL), and LLNL to develop relativistic klystron technology. The first experiments have been done at the Accelerator Research Center (ARC) at LLNL using as a gun an induction accelerator designed to produce 1 kA currents with 1.2 MeV kinetic energy for up to 75 nsec duration. In this paper we report briefly on the results of our experiments so far. Reference 3 is a more compreshensive report on our klystron designs, our experimental results, and our plans for the near future.

EXPERIMENTAL APPARATUS

In the relativistic klystrons discussed here, beam energy, beam current, and RF frequency are greater than in conventional klystrons. Increasing the beam energy ameliorates longitudinal space charge effects but increases the bunching distance. Increasing the RF frequency reduces the bunching distance. Our choice of 2.6 cm RF wavelength makes possible a multicavity klystron design that can bunch a 1 MV, 1 kA beam efficiently and extract power from it in a total distance of 1 m. At shorter wavelengths higher magnetic fields are needed to focus the beam since the radius of the drift tube scales with the wavelength.

We have tested three relativistic klystrons with the ARC induction injector. Summarized in Table 1, they are, in chronological order as tested:

1. SL3, a conventional multicavity klystron designed to operate at 8.6 GHz (three times the frequency of the SLAC linac). With its 330 kV gun replaced by an induction accelerator, it served as an expedient first demonstration of a relativistic klystron.
2. SHARK, a two cavity, low gain, sub-harmonic drive relativistic klystron with 5.7 GHz drive and 11.4 GHz output.
3. SL4, a six cavity klystron at 11.4 GHz (four times SLAC frequency) designed specifically for the high power pulsed beam.

The beam pipe is tapered from 8.8 to 1.9 cm diameter, and further narrowed to 9.2 mm in the SHARK and SL4 klystrons. Solenoid coils provide up to 5 kG focusing fields. An achievable focusing configuration has been calculated to provide full transmission of the bunched relativistic beam.[4]

Klystron	SL3	SHARK	SL4
Output freq. (GHz)	8.57	11.4	11.4
Drive freq. (GHz)	8.57	5.7	11.4
Output power (MW)			
Peak (max.)	75	47	200
Flat pulse (max.)	75	47	68
Design gain (dB)	54	20	65
Efficiency (%)			
Design	60	20	40
Operation (max.)	55	25	50
Beam Voltage (kV)			
Design	330	1200	1200
Operation (max.)	1000	1200	1000
Beam Current (A)			
Design	300	1000	1000
Operation (max.)	350	750	750
Number of cavities	5	2	6
Total length (cm)	31	25	98
Beam-off loaded Q			
Input cavity	250	725	280
Idler cavities	4000	—	120
Penultimate cavity	4000	—	3800
Output cavity	44	40	20
Drift tube diam. (mm)	11	19, 9.2	14, 9.2

TABLE 1. Parameters of relativistic klystrons tested.

MASK simulations were used to optimize the SL4 design parameters and to predict efficiency and gain.[5] Design values are in Table 1. Simulation results at different beam power levels are shown in Figure 1.

To complement the SL4 experiment, a 26 cm long section of 11.4 GHz accelerator structure operating in the $2\pi/3$ traveling wave mode has been built. The constant impedance structure consists of 30 cells and has $r/Q = 14.2\,\mathrm{k\Omega/m}$. The attenuation parameter is 0.136 nepers. The group velocity is $0.031c$, giving a filling time of 28.4 nsec. The iris diameter is 7.5 mm.

The pulsed DC beam current is monitored in three places: at the injector, upstream from the input cavity, and downstream from the output cavity. The DC current monitors measure image currents in the beam pipe wall. An RF current monitor is placed downstream from the SHARK output cavity. The RF current diagnostic is a pickup loop, recessed azimuthally in the beam pipe wall, which measures $\dot{B}_\phi$. Forward and reflected RF drive signals are sampled using 20 dB broadband waveguide directional couplers. Relativistic klystron output power and, in the SL4 experiment, the RF reflected back from the high gradient accelerator test

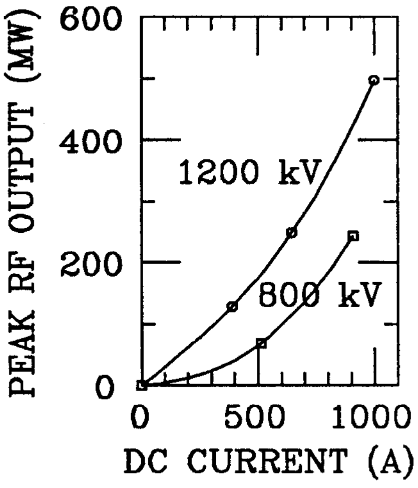
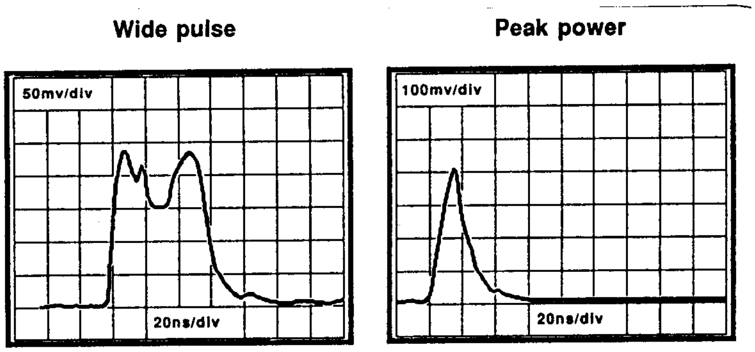


FIG. 1. MASK simulations of SL4.



P_{out} = 68 MW
E_b = 930 kV
I_k = 300 A
B ≈ 1.4 kG
f = 11.44 GHz

P_{out} = 202 MW
E_b = 930 kV
I_k = 420 A
B ≈ 2 kG
f =11.45 GHz

FIG. 2. Low and high peak power pulses in SL4 tests.

section, were sampled using 56 dB waveguide directional couplers. The sampled RF signals are measured with crystal diode detectors.

EXPERIMENTAL RESULTS

The maximum current transported through SHARK is 750 A, only 65% of the maximum current entering the klystron. Up to 80% transmission has been achieved at 400 A. Transmission achieved through SL4 (which is four times longer than SHARK) is 55% at 800 A, and 65% at 500 A. Transmission is observed to be independent of RF drive for SHARK. However, for SL4, a slight decrease in transmission was noted at high RF output levels.

The SL3 test produced peak power of 75 MW from an 800 kV, approximately 250 A beam. RF pulses had 5–10 nsec risetimes and reproduced the shape of the beam current pulses quite well. Output power observed agreed well with the predictions of the MASK simulation code.

The high field drive cavity of SHARK was afflicted with breakdown problems. The arcing occured above a threshold of about 1 MW and severely limited the maximum output power which could be obtained.

The SL4 relativistic klystron has attained peak output power of 200 MW at 11.4 GHz from a 930 kV, 420 A beam. SL4 has not yet operated at its 1000 A design current. However, agreement is excellent between output power measured at lower currents and the MASK predictions (Figure 1) for operation at these currents. The 200 MW peak power delivered by SL4 to the 11.4 GHz accelerator corresponds to a longitudinal accelerating gradient of 140 MV/m. Early indications are that there is appreciable dark current in the accelerator when the accelerating gradient exceeds 90 MV/m.

Under certain focusing and steering conditions a large RF pulse at 13.2 GHz is radiated from the SL4 input cavity, coincident with the beam pulse. The 13.2 GHz signal probably arises from dipole mode resonance in the input and one of the downstream cavities. The 13.2 GHz signal has not been observed in the klystron output and does not appear to affect the gain of the klystron. In addition to the 11.4 GHz drive frequency, a spurious 11.8 GHz frequency has been observed in the output from SL4 in the presence of drive. This parasitic oscillation can be eliminated by adjusting the beam focusing and steering.

In our tests of both SHARK and SL4, we observe that as the beam current through the klystron is increased up to a certain level, the output power pulses remain relatively flat. However, if the beam current is increased beyond this level, the trailing edges of the output power pulses diminish in amplitude, while the leading edges continue to grow with the beam current. We have demonstrated that our ability to obtain flat output power pulses is affected by beam current, RF drive level, and focusing magnetic field strength. The practical importance of these observations is that even though 200 MW of RF was produced with SL4, the maximum reasonably flat RF pulse achieved was only 60 MW. Low and high peak power SL4 pulses are illustrated in Figure 2. The pulse shortening phenomenon is a serious impediment to making flat high power RF pulses. Two possible pulse shortening mechanisms, "anomalous" beam loading and transient effects, are described below.

Pulse Shortening by Anomalous Beam Loading

SHARK pulse shortening at high drive power levels is correlated strongly with an abrupt large increase in the power apparently absorbed by the beam. This abrupt increase, which we call "anomalous" beam loading, is observed as a change in the reflection coefficient of the SHARK input cavity.

This observation can be reproduced with a computer code for transient analysis. In the code, we use a circuit model to compute the time varying voltage across the input gap. The reflected power is calculated from the time-varying voltage by power balance. Code calculations of reflected drive power agree qualitatively with experimental observations at low power with normal beam loading. The narrow output pulse and increased reflection observed at higher power are obtained in the calculation by arbitrarily increasing beam loading by a factor of 2.5.

We suspect that the anomalous beam loading may be due to photoelectrons produced by x-rays impinging on the high field regions around the cavities. During the experiment, roughly 200 A of current was lost in traversing the taper-klystron system. Reduced power output and increased x-ray dosage were correlated with increasing the beam current. Preliminary calculations indicate that the x-rays produced are consistent with photoelectron currents required to account for the additional loading (5–10 A). When the cavity field is low, the photoelectrons oscillate in trajectories close to the cavity walls with no net absorption of energy. At higher field gradients, the photoelectrons have longer path lengths. Above a critical field value, the path lengths are long enough for photoelectrons to hit the opposite nose cone, depositing their kinetic energy in the walls in the process, which constitutes a loading phenomenon.

Pulse Shortening by Transient Effects

Transient effects due to normal resistive loading and reactive detuning of cavities by a high power pulsed beam influence the output power pulse shapes in relativistic klystrons. The transient nature of the pulsed beam energy and current make the loading and detuning time dependent.

We analyze the effect of transient beam loading and detuning on the shape of the output power pulse in the following way. Using a resonant circuit model, we calculate the time-development of the voltage on a driven cavity. Then, by calculating the beam velocity modulation produced by the calculated cavity voltage, we estimate the RF current that drives another cavity downstream. Following this analysis through all six cavities of the SL4 klystron, we can study how the shape of the output power pulse develops as a function of the different time dependent Q's and detunings of the individual klystron cavities.

The output pulse shapes we have calculated look strikingly similar to some of the pulses we have observed. The shapes may be described qualitatively as being composed of transient precursors followed by a flat pulses. The precursor primarily is due to the transient detuning that results from reactive beam loading and, in some cases, may be of much larger amplitude than the trailing flat part of the RF pulse. The precursor peak power level has broad bandwidth and is minimized by appropriate choice of driving frequency. High power flat-top RF pulses have emerged in our calculations with a driving frequency bandwidth narrower than, and shifted upward from, the bandwidth of the large precursor phenomenon. The shift in driving frequency necessary to obtain rectangular pulses in our calculations is the typical cavity detuning. We have not observed these rectangular pulses from SL4 yet at any frequency, presumably due to the "anomalous" beam loading described in the previous section.

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. Three different klystrons have been tested. Two parasitic oscillations (at 11.8 and 13.2 GHz) have been observed but do not appear to be debilitating and have been avoided by suitable choice of operating parameters. Peak RF power of 200 MW has been achieved, but only with an RF flat top much shorter than the beam current pulse. This pulse shortening phenomenon is by far the most serious problem encountered. Experimental evidence from one of the klystrons (SHARK) indicates that pulse shortening is caused by loading of the input cavity by anomalous charged particle currents. Since this loading occurs only when the beam is on, it is believed to be due to photoelectrons produced by the copious supply of x-rays caused by beam interception. A second and perhaps related problem is rather poor beam transmission through the klystrons, which has not exceeded 65%. Finally, the 200 MW peak RF pulses have been transmitted into a 26 cm long high gradient accelerator structure. This power corresponds to an accelerating gradient of 140 MV/m.

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