RELATIVISTIC KLYSTRON RESEARCH FOR LINEAR COLLIDERS†

M. A. Allen, R. S. Callin, H. Deruyter, K. R. Eppley, K. S. Fant, W. R. Fowkes, W. B. Herrmannsfeldt, T. Higo,* H. A. Hoag, R. F. Koontz, T. L. Lavine, T. G. Lee, G. A. Loew, R. H. Miller, P. L. Morton, R. B. Palmer, J. M. Paterson, R. D. Ruth, H. D. Schwarz, Y. Takeuchi,* A. E. Vlieks, J. W. Wang, and P. B. Wilson

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

D. B. Hopkins and A. M. Sessler

University of California, Lawrence Berkeley Laboratory, Berkeley, California 94720

W. A. Barletta, D. L. Birx, J. K. Boyd, T. Houck, D. S. Prono, R. D. Ryne, G. A. Westenskow, and S. S. Yu

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

ABSTRACT

Relativistic klystrons are being developed as a power source for high gradient accelerator applications which include large linear electron-positron colliders, compact accelerators, and FEL sources. 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 on the design of our relativistic klystrons, the results of our experiments so far, and some of our plans for the near future.

1. INTRODUCTION

Large linear electron-positron colliders, compact accelerators, and FEL sources require a new generation of high gradient accelerators. Conceptual designs for large linear electron colliders for research at the frontier of particle physics call for beam energies of 250–1000 GeV and luminosities of 10^{33}–10^{34} cm^{-2}sec^{-1}. Accelerating gradients of 100–200 MV/m are desired in order to keep the accelerator length within acceptable limits. Frequencies of 10–30 GHz are desired in order to keep peak and average 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.

Pulsed beams of such high peak power can be obtained using the technologies of magnetic pulse compression and induction acceleration.[1] Beam pulses of 1 kA current and 50–100 nsec duration are routinely accelerated to several MeV at Lawrence Livermore National Laboratory (LLNL). These beams contain several gigawatts of peak power.

The first demonstration of RF power extraction from such a beam yielded an impressive 1 GW at 35 GHz, using a free electron laser.[2] A. M. Sessler and S. S. Yu, following a suggestion by W. K. H. Panofsky, proposed a more direct method for energy extraction by bunching a relativistic beam and passing it through extraction cavities.[3] Sessler and Yu suggested that if only part of the beam energy were extracted, the beam could be reaccelerated and energy could be extracted again. Repeated reacceleration and extraction was the concept they called a "relativistic klystron two-beam accelerator."[3] 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.

These ideas have led to a collaboration between Stanford Linear Accelerator Center (SLAC), Lawrence Berkeley Laboratory (LBL), and LLNL to study the combination of the klystron concept with induction accelerator and magnetic pulse compression 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. Four klystrons have been tested with this injector. They are, in chronological order as tested,

(1) SL3, a multicavity klystron with a conventional gun designed to operate at 8.6 GHz (three times the frequency of the SLAC linac),
(2) SHARK, a two cavity sub-harmonic drive relativistic klystron with 5.7 GHz drive and 11.4 GHz output,
(3) SL4, a high gain relativistic klystron at 11.4 GHz (four times SLAC frequency) designed specifically for the high power pulsed beam,
(4) SHARK-2, a three-cavity version of SHARK.

In this paper we discuss the design of these klystrons, report on the results of our experiments so far, and discuss some of our plans for the near future.

2. KLYSTRON SCALING

To motivate the increase in energy of the beam in an otherwise conventional klystron, it is useful to discuss the physics of the klystron interaction. In a two cavity klystron, the beam is velocity modulated by an RF drive cavity and allowed to drift until the velocity modulation bunches the beam. The bunched beam then is passed through another cavity which may be used to extract RF power. In practice, such a two cavity device has low gain. In most klystrons, there are several intermediate "idler" cavities. The first cavity bunches the beam. The bunched beam drives the second cavity to an RF voltage an order of magnitude greater than the first, which in turn bunches the beam more strongly. This process continues until the final idler cavity of the "linear gain region" of the klystron. The bunching is determined primarily by the voltage on the final idler cavity. After this cavity the bunches are allowed to drift until the RF current is maximum. At this point the beam is passed through two more cavities: a highly detuned "penultimate" cavity which sweeps still unbunched electrons into the bunch, and an output cavity which extracts energy by decelerating the beam. The output cavity could be replaced by a series of cavities or by a traveling wave structure.

An important parameter in klystron scaling is the beam plasma wavelength. Velocity modulation bunches a DC beam. However, space charge repulsion (modified by the drift tube) causes the beam to debunch. In the linear region, this process produces oscillations. The distances between cavities in a klystron are chosen to be approximately one-quarter of a plasma wavelength for optimal bunching. For a long relativistic

† Work supported by the U.S. Department of Energy under contracts DE-AC03-76SF00515 (SLAC), DE-AC03-76SF00098 (LBL), and W-7405-ENG-48 (LLNL), and by the U.S.-Japan Collaboration on High Energy Physics.

* Visitor from KEK, National Laboratory for High Energy Physics, Oho, Tskuba, Ibaraki 305, Japan.

current at that harmonic. With only two high Q resonant structures in this klystron, problems with beam breakup instabilities are minimized. However, the gain of a two cavity tube is low. Therefore, in order to achieve beam-to-RF power conversion comparable to that in multicavity tubes, a conventional 5 MW, 5.7 GHz klystron is used to drive SHARK. The RF fields in the input and output cavities are comparable for 2 MW of drive and 50 MW of output because of the different Q's.

SHARK was designed to serve as a test bed for cavity design to be used in relativistic klystron research. Its design allows study of a wide range of beam parameters and minimizes difficulties with beam propagation. The drift pipe and output cavity are easy to replace, making it possible to use SHARK to study different output cavities at several frequencies.

SL4 is a high gain, six cavity, relativistic klystron at 11.4 GHz which was designed specifically for the 50 nsec pulsed 1.2 MV, 1 kA Snowtron beam. Therefore, unlike most klystrons, it was designed without an integral gun assembly. In order to make the RF filling time of the SL4 cavities much shorter than the 50 nsec beam pulses, three of the gain cavities are coupled by irises and waveguides to absorptive ceramic wedges. This results in loaded Q's of 120, and filling times of 2–3 nsec for these cavities.

To reduce the difficulty of maintaining a well-focused electron beam over a 1 m drift length, the SL4 drift tube was tapered. The drift tube diameter in the first four cavities is rather wide, 14 mm. The tube then is tapered to 9.2 mm just upstream of the penultimate cavity. Tapering permits the use of solenoid magnets with axial field of 2.7 kG for most of the length of the klystron. A 5 kG solenoid surrounds the region of the penultimate and output cavities.

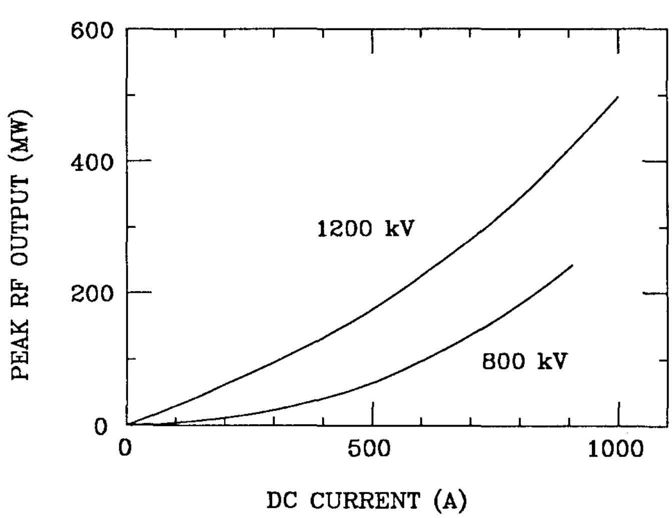

FIG. 2. MASK simulations of SL4 output power.

The design gain and efficiency for SL4, 65 dB and 40%, respectively, are obtained using the MASK computer code.[5] MASK simulations were used to optimize the SL4 design parameters and to predict the efficiency and gain at several different beam currents and voltages. Some simulation results are shown in Fig. 2. The saturation RF drive power is approximately 200 W, which is supplied by a 1 kW X-band TWT amplifier.

Because of the high peak electric fields in the penultimate and output cavities good vacuum is necessary to prevent cavity breakdown. Consequently, a 500 liter/sec cryopump evacuates the klystron collector section and two 8 liter/sec vac-ion pumps evacuate the output waveguide. In this configuration waveguide and collector pressures can be maintained at 10^{-8} Torr.

SHARK-2 is a modification of SHARK in which a third cavity resonant at 11.8 GHz was inserted between the input and output cavities to increase klystron gain and efficiency. In addition, the outer cylindrical wall of the cavity was fabricated from low carbon steel to shield the cavity interior from the axial magnetic field for reasons discussed below in Section 4.3.

3.4 Diagnostics

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 for SHARK was a pickup loop, recessed azimuthally in the beam pipe wall, which measured $\dot{B}_\phi$. The RF current diagnostic for SHARK-2 was a pair of probes, recessed radially in the beam pipe wall, which measured $\dot{E}_r$.

Forward and reflected RF drive power signals are sampled using 20 dB broad band waveguide directional couplers. Relativistic klystron output power and, in the SL4 experiment, the RF reflected back from the high gradient accelerator test section, were sampled using 56 dB waveguide directional couplers. The sampled RF signals are transported on individually calibrated, 25 m long, high quality Heliax cables from the couplers to the control room where they are measured with calibrated HP 8470B crystal diode detectors. Calorimetric measurement methods so far have been precluded by the low pulse repetition rate (less than 10 pulses/sec) necessitated by inadequate shielding.

3.5 High Gradient Accelerator

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 $r/Q = 14\,\mathrm{k}\Omega/\mathrm{m}$. The attenuation parameter is 0.14 nepers. The group velocity is $0.031c$, giving a filling time of 28 nsec. The iris diameter was chosen to be 7.5 mm. Parameters were calculated by the SUPERFISH code and confirmed by cold test measurements. Coupler dimensions were approximated by extrapolation from S-band data, and finalized by cold test. The accelerator was fabricated from machined "cups" which were stacked and brazed. A special tool permitted each cavity to be tuned up or down in frequency in order to obtain the correct phase advance per cell.

4. EXPERIMENTAL RESULTS

4.1 Beam Transmission

The design goal of 100% beam transmission through the klystrons has not been achieved experimentally, even after focusing adjustments were performed by empirical optimization using a diagnostic such as transmitted current or output RF. 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 is 65% at 500 A. Transmission is observed to be independent of RF drive for SHARK. However, for SL4 and SHARK-2, a slight decrease in transmission was noted at high RF output levels. (There was no downstream current monitor in the SL3 tests; transmission through SL3 was not measured.)

4.2 SL3 Demonstration

The SL3 test was designed to be a demonstration of the effects of putting a conventional klystron tube (stripped of its gun) in a high power pulsed beam. No unusual or unexpected phenomena were observed. No evidence of multipactor, beam of current I and radius a in a narrow tube of radius b the plasma wavelength on axis is

$$\lambda_p \simeq \lambda_{RF}\sqrt{\frac{17\,\mathrm{kA}}{I}\frac{(\beta\gamma)^5}{1+2\ln(b/a)}}$$

where λ_{RF} is the free-space RF wavelength, $\beta = v/c$, and $\gamma = 1/\sqrt{1-\beta^2}$. Increasing the beam energy ameliorates longitudinal space charge effects but increases the bunching distance. Increasing the frequency reduces the bunching distance. Our choice of 2.6 cm RF wavelength makes possible a multi-cavity klystron design that can bunch a 1 MV, 1 kA beam efficiently and extract power from it in a total distance of 1 m. For higher energy beams, bending magnets can be used to create differences in path length for particles of different energies. This permits bunching of higher energy beams even though their velocity is nearly independent of energy.

Another important parameter in klystron scaling is the magnetic field necessary to focus the beam. For a beam of uniform charge density and normalized edge emittance ϵ_n, the solenoid field B necessary to confine the beam current I to radius a is

$$B = \frac{2m_ec^2}{ea}\sqrt{\frac{2I}{17\,\mathrm{kA}}\frac{1}{\beta\gamma}+\frac{\epsilon_n{}^2}{a^2}} = \frac{3.4\,\mathrm{kG\,cm}}{\mathrm{a}}\sqrt{\frac{2I}{17\,\mathrm{kA}}\frac{1}{\beta\gamma}+\frac{\epsilon_n{}^2}{a^2}}.$$

In the relativistic klystrons discussed here both γ and I are greater than in conventional klystrons. At shorter wavelengths higher magnetic fields are needed to focus the beam since the radius of the drift tube scales with the wavelength. An estimate of the required field must include the effects of beam bunching. The peak current in the bunched beam typically is about four times the initial DC current. Thus, for a space charge dominated beam, the magnetic field required is typically twice that calculated for focusing a DC beam.

3. EXPERIMENTAL APPARATUS

3.1 Induction Accelerator

Most of the experimental studies described here were performed using the Snowtron injector at the ARC facility at LLNL. Snowtron is a linear induction injector composed of ten 150 kV induction cells driven by pulsed magnetics.[1] For klystron experiments, a triode electrode configuration was used with a cathode of 12.5 cm diameter and 35.6 cm spherical radius. The inner diameter of the anode drift tube was 8.8 cm. The cathode was placed 35 cm from the downstream end of the injector. Accelerating voltages up to 1.2 MV, beam currents up to 1.4 kA, and pulse widths up to 75 nsec FWHM have been obtained for the klystron experiments. The greatest stress on the injector is 260 kV/cm on the cathode shroud at peak voltage. The DPC computer code, which was used to design Snowtron, predicts peak currents of 2.3 kA at 1.2 MV.[4] However, the operating pressure of the injector led to cathode contamination which precluded uniform space charge limited emission.

3.2 Beam Transport

The distance from cathode to klystron was 4 m for the SL3 test and is 1.6 m for the SHARK and SL4 tests. Just downstream from the injector is a 30 cm taper where the beam pipe narrows from 8.8 to 1.9 cm diameter. The pipe diameter is narrowed further to 9.2 mm in the SHARK and SL4 klystrons. Nine 2.5 kG solenoid coils powered by five separate power supplies focus the beam between the cathode and the klystron. Three independently controlled 5 kG solenoids focus the beam in the relativistic klystron. Four sets of dipole magnets for horizontal and vertical steering are used to correct for beamline misalignments.

Beam transport calculations with the ST code have been used to estimate the required strengths of the focusing fields for 100% transmission of current through the klystron.[4] The result of such a calculation is shown in Fig. 1.

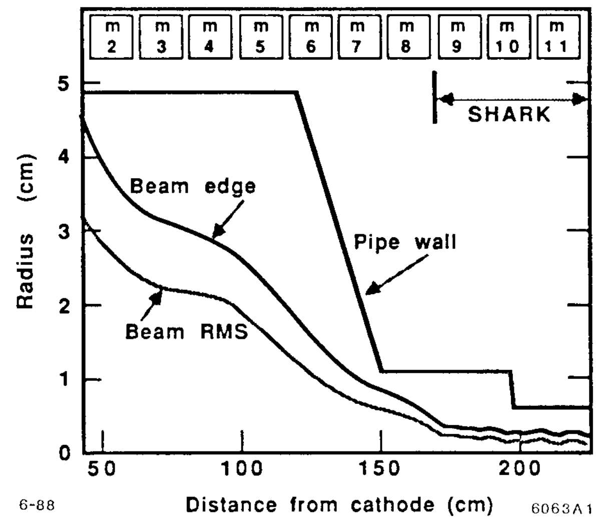

FIG. 1. Beam size calculated through SHARK.

	SL3	SHARK	SL4	SHARK-2
Output freq. (GHz)	8.57	11.4	11.4	11.4
Drive freq. (GHz)	8.57	5.7	11.4	5.7
Output power (MW)				
Peak (max)	75	47	200	117
Flat pulse (max)	75	47	68	80
Design gain (dB)	54	20	65	25
Efficiency (%)				
Design	60	20	40	40
Operation (max)	55	25	50	32
Beam Voltage (kV)				
Design	330	1200	1200	1200
Operation (max)	1000	1200	1000	1200
Beam Current (A)				
Design	300	1000	1000	1000
Operation (max)	350	750	750	800
Number of cavities	5	2	6	3
Total length (cm)	31	25	98	33
Beam-off loaded Q				
Input cavity	250	725	280	742
Idler cavities	4000	—	120	—
Penultimate cavity	4000	—	3800	3800
Output cavity	44	40	20	20
Drift tube diam. (mm)	11	19, 9.2	14, 9.2	19, 9.2

TABLE 1. Parameters of relativistic klystrons tested.

3.3 Klystrons

Parameters of the three relativistic klystrons tested are summarized in Table 1. Further descriptions are given below.

SL3 is a conventional high gain klystron designed to operate at 8.6 GHz with a conventional gun. With its design gun replaced by an induction accelerator, it served as an expedient first demonstration of a relativistic klystron. SL3 was driven by a 1 kW X-band TWT amplifier.

SHARK is a two cavity sub-harmonic drive relativistic klystron. The input cavity is driven by an RF source of several MW at 5.7 GHz which modulates the beam velocity. After drifting, the beam current has large Fourier components at 5.7, 11.4, and 17.2 GHz. Resonant cavities tuned to the higher harmonics can be used to extract power and measure breakdown fields at the higher frequencies. The 11.4 GHz output cavity is positioned after a 25 cm drift for maximum RF breakdown, parasitic oscillations, nor other instabilities was observed. RF pulse risetimes were 5–10 nsec. RF pulses reproduced the shape of the beam current pulses quite well. SL3 performance at beam energies much greater than design is illustrated in Fig. 3. Peak power of 75 MW was attained with an 800 kV, approximately 250 A beam. Observed output power agreed well with the predictions of the MASK simulation code.

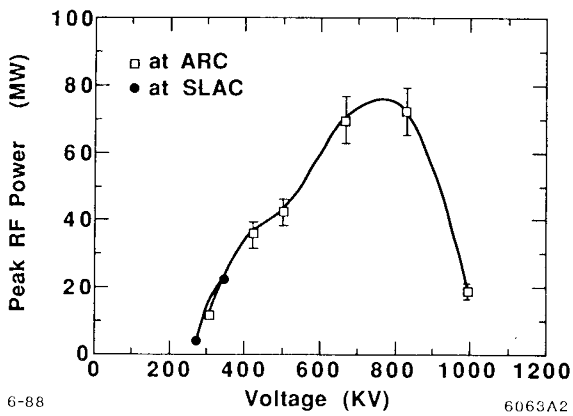

FIG. 3. SL3 performance.

4.3 SHARK and SL4

Peak output power of 200 MW at 11.4 GHz was attained with the SL4 relativistic klystron design using 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 (Fig. 2) 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.

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. This behavior in SHARK tests is illustrated in Fig. 4. 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 in our initial tests was only 68 MW. Low and high peak power SL4 pulses are illustrated in Fig. 5. The pulse shortening phenomenon is a serious impediment to making flat high power RF pulses. It is not beam breakup because the transmitted DC beam current pulse does not shorten with the RF pulse.

To understand the mechanism for output pulse shortening in SHARK, an experiment was performed in which simultaneous data on reflected power from the input cavity and on output power were recorded at a critical point for the onset of the shortening phenomenon. With no external changes in the beam condition and/or input power, the output alternated from pulse to pulse between the rectangular and triangular pulse shapes. When the beam turns on, there is a significant dip in the drive power reflected from the SHARK input cavity. Two distinctly different states have been observed in the reflected drive, as shown in Fig. 6, one having a much greater reflection during the beam-on time. Furthermore, the state with large reflection is correlated repeatedly with the narrow output pulse.

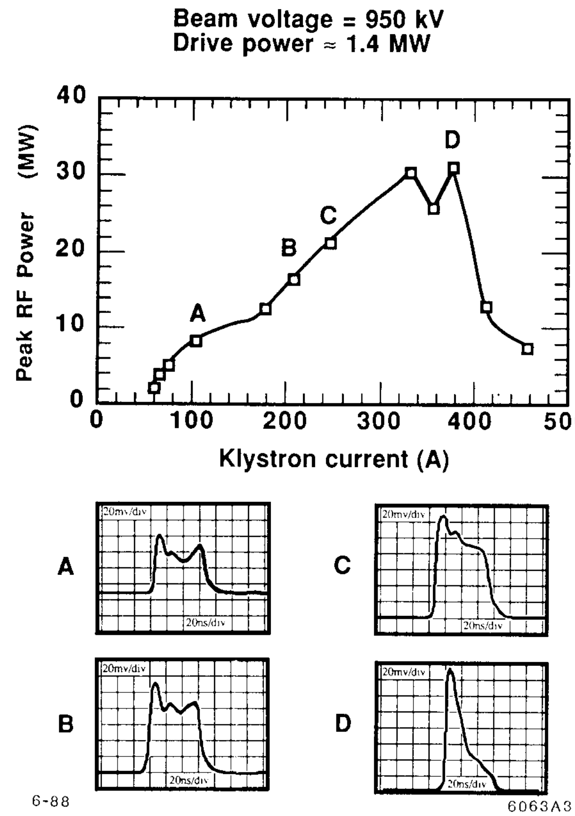

FIG. 4. RF pulse shortening observed in SHARK tests.

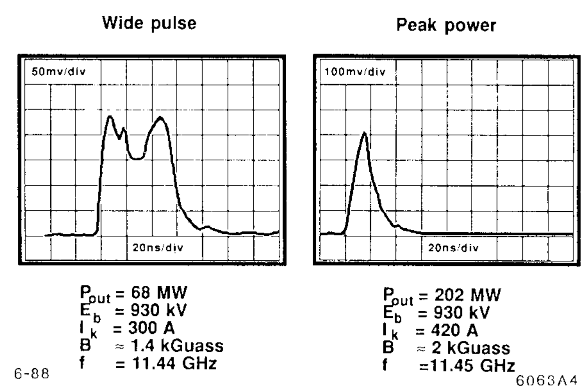

FIG. 5. Low and high peak power pulses in SL4 tests.

This observation can be reproduced with our 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. Results of the transient calculation are shown in Fig. 7 where the relatively flat output pulse with the low beam-on reflected power was obtained by using a beam loading generally consistent with MASK calculations and measurements. The narrow output pulse and increased reflection were obtained by arbitrarily increasing beam loading by a factor of 2.5.

The anomalous heavy beam loading which we believe causes pulse shortening appears to be a phenomenon similar to multipactor to the extent that it is sensitive to changes in focusing magnetic field and RF power level. The anomalous beam loading in fact may be multipactor.

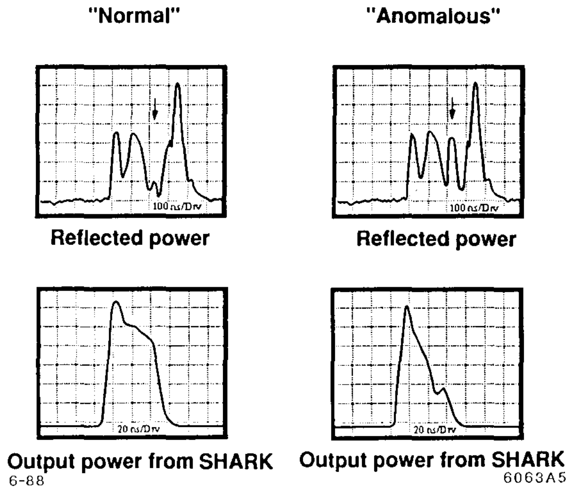

FIG. 6. SHARK reflected drive and output power. Arrows indicate the 50 nsec beam time in the reflected power.

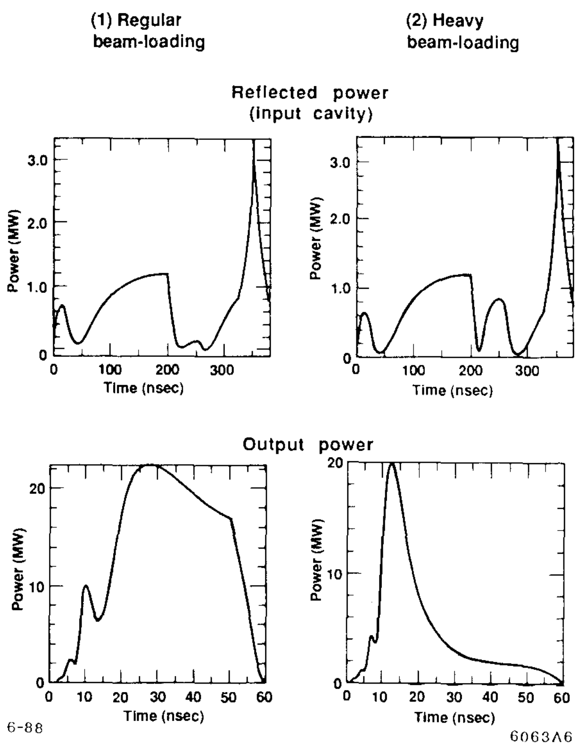

FIG. 7. Calculations of the effect of anomalous beam loading on SHARK reflected drive and output power.

Further studies of the SL4 relativistic klystron have demonstrated anomalous input cavity loading by charged particles when the RF drive level exceeds 40 W, even under cold cathode, beam-off conditions. Sometime after the onset of the RF drive pulse, the input cavity absorbs all of the incident RF drive that otherwise would be reflected from the beam-off, unloaded cavity. This power absorption is a function of drive level, and of axial magnetic field surrounding the cavity. No power absorption is present when the axial magnetic field is zero. This cavity loading phenomenon, which we have 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 associated with pulse shortening.

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 8 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. However, the output pulse shortening in the configuration with the iron input cavity occurs at a higher power threshold than in the original SHARK tests with a copper input cavity, and the output pulse shortening apparently starts in the output cavity. 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. Figure 9 shows multiple exposure photos of the output power pulses simultaneous with the input power reflected from the input cavity. The pulses in the figure were recorded during operation at the pulse shortening threshold. Both long and short output pulses are observed, while all reflected input pulses exhibit normal beam loading.

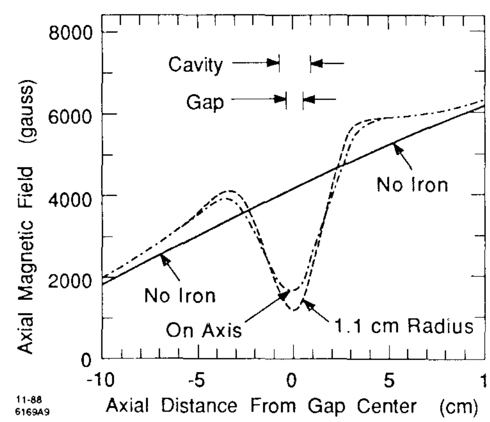

FIG. 8. Calculation of the axial magnetic field near the SHARK input cavity with and without iron. The cavity noses are at 1.1 cm radius.

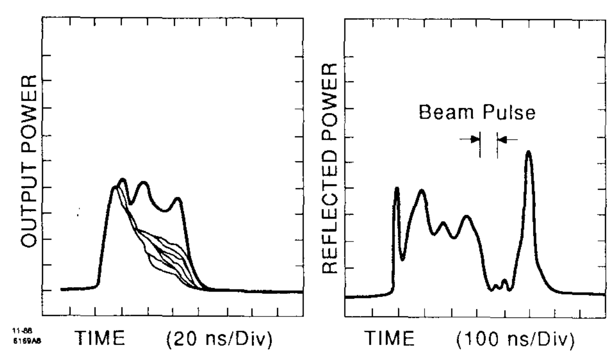

FIG. 9. Multiple exposure photos of long and short output power pulses simultaneous with "normal" reflected input power pulses in the SHARK with the magnetically shielded input cavity operating at the pulse shortening threshold.

4.4 SHARK-2

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 because the external Q of this output cavity is half that of the original SHARK output cavity. Results with this three cavity configuration, named SHARK-2, are summarized in Table 1.

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 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 two cavity SHARK.

Some improvement in the pulse shortening threshold has been observed with high power RF conditioning at 10 pulses/sec.

5. FUTURE PLANS

We are incorporating RF field probes in our designs of new intermediate cavities in order to ascertain where pulse shortening first occurs in multicavity relativistic klystrons, such as SL4.

In light of the apparent success of the iron magnetic shield at suppressing pulse shortening in the SHARK and SHARK-2 input cavities we plan to apply several techniques commonly used for multipactor suppression in order to raise the threshold for pulse shortening. We plan to add iron magnetic shields to downstream cavities. Consequently, we are studying the effect of the iron on the relativistic beam dynamics. We are fabricating and plan to test a cavity with slotted noses (as an alternative to iron). We plan to employ RF conditioning at higher pulse repetition rates with improved radiation shielding.

A traveling wave output structure which has been fabricated will be used in place of an output cavity in a relativistic klystron. This structure will have lower electric fields than a single output cavity and consequently the output power threshold for pulse shortening may be higher.

As soon as rectangular high power RF output pulses of sufficient duration are obtained, further studies of the high gradient accelerator structure described in Section 3.5 are planned. These tests will include studies of breakdown at 11.4 GHz and measurement of the accelerating gradient.

6. 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. Four different klystrons have been tested. 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. It is clearly not beam breakup since it does not correlate with shortening of the DC current pulse. 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. The loading is believed to be due to either secondary electrons or to photoelectrons produced by the copious supply of x-rays caused by beam interception. The power threshold for pulse shortening is sensitive to magnetic focusing field and to RF field strength. Magnetically shielding a klystron input cavity raised the power threshold for pulse shortening. A second and perhaps related problem is rather poor beam transmission through the klystrons, which has not exceeded 65%. The shortened 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.

ACKNOWLEDGEMENTS

We thank R. J. Briggs, G. J. Caporaso, M. Chodorow, H. Gasquet, Y. Goren, J. Haimson, E. W. Hoyt, V. K. Neil, A. C. Paul, C. Pearson, D. S. Prono, L. L. Reginato, A. C. Smith, K. Whitham, D. Yu, and L. Zitelli for their assistance. The authors from SLAC thank LLNL for its continuing hospitality.

REFERENCES

1. L. L. Reginato and D. L. Birx, "Pulsed High Power Beams" and "Recent Advances in Magnetically Driven Induction Linacs" in Proceedings of the European Particle Accelerator Conference, Rome, Italy, June 7–11, 1988.
2. T. J. Orzechowski *et al.*, "High Efficiency Extraction of Microwave Radiation from a Tapered Wiggler Free Electron Laser," *Phys. Rev. Lett. 54*, 889 (1985).
3. A. M. Sessler and S. S. Yu, "Relativistic Klystron Two-Beam Accelerator," *Phys. Rev. Lett. 58*, 2439 (1987).
4. J. K. Boyd, "Snowtron Numerical Calculations," LLNL-RM-87-48 (November 1987).
5. K. Eppley, "Algorithms for the Self-Consistent Simulation of High Power Klystrons," SLAC-PUB-4622 (May 1988), to be published in the proceedings of the Linear Accelerator and Beam Optics Codes Workshop, San Diego, California, January 19–21, 1988.