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RELATIVISTIC KLYSTRON RESEARCH FOR HIGH GRADIENT ACCELERATORS†

M. A. ALLEN, H. S. CALLIN, H. DERUYTER, K. R. EPPLEY, W. R. FOWKES, W. B. HERRMANNSFELDT, T. HIGO,* H. A. HOAG, 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, 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 first 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, for example, call for center-of-mass energies of 1-2 TeV and luminosities of 10^{33}–10^{34} $cm^{-2}sec^{-1}$. 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.

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 again could be extracted. 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. Three 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 sub-harmonic drive relativistic klystron with relatively low gain,

(3) SL4, a high gain relativistic klystron at 11.4 GHz (four times SLAC frequency) designed specifically for the high power pulsed beam.

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 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 beam of current I and radius a in a narrow tube of radius b the plasma wavelength on axis is

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

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

where $\beta = v/c$ 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 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. 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 space charge dominated beam of uniform cross section the solenoid field B necessary to confine the beam current I to radius a is

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

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 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 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 1.5 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 Figure 1.

3.3 Klystrons

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

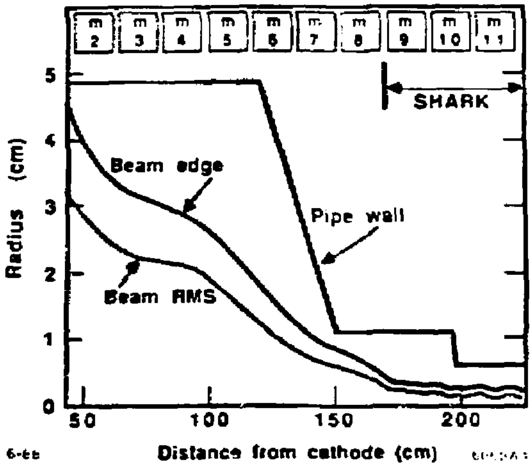

FIG. 1. Beam size calculated through SHARK.

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.

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 17.1 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 optimal bunching 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 [illegible]

[illegible] to study different output [illegible] 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.

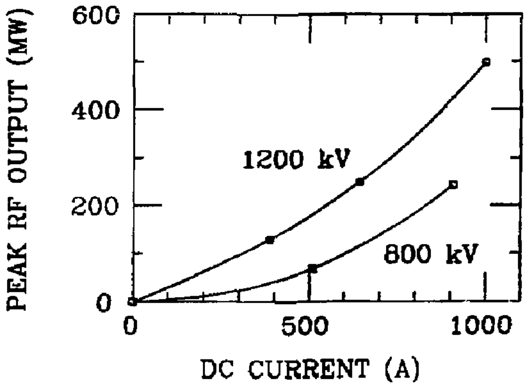

FIG. 2. MASK simulations of SL4 output power.

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 Figure 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.

3.4 Diagnostics

Current Monitors [illegible] DC beam [illegible]

RF Power D[illegible] sampled [illegible] dB [illegible] waveguide directional couplers. Re[illegible] klystron output power and, in the SL4 experiment, the RF reflected back from the high gradient accelerator test section, were sampled using 50 dB waveguide directional couplers. The sampled RF signals are transported on individually calibrated 1.25 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 a 1 Hz pulse repetition rate 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 $r/Q = 14.2\,\mathrm{k}\Omega/\mathrm{m}$. The attenuation parameter is 0.136 nepers. The group velocity is $0.031c$, giving a filling time of 28.4 nsec. The iris diameter 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, 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, 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 Figure 3. Peak power of 75 MW was attained with an 800 kV, approximately 250 A beam. Output power observed agreed well with the predictions of the MASK simulation code.

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.

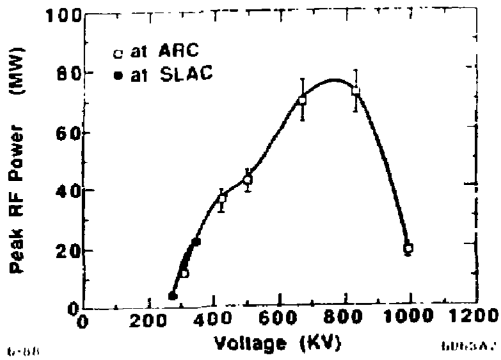

FIG. 3. SL3 performance.

However, agreement is excellent between output power measured at lower currents and the MASK predictions (Figure 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.

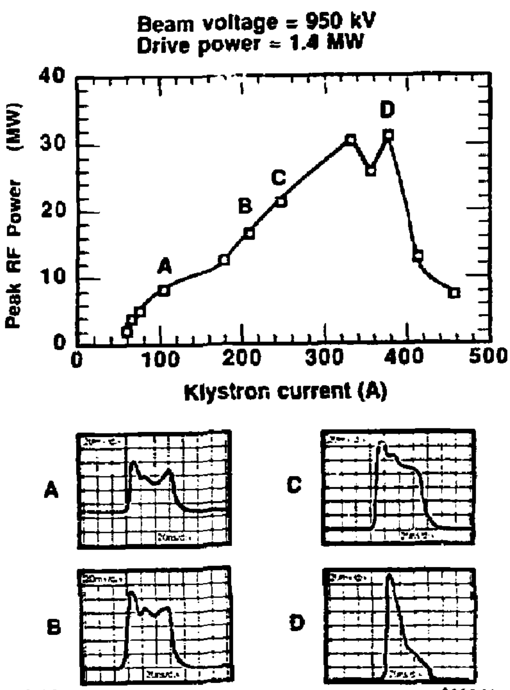

FIG. 4. RF pulse shortening observed in SHARK tests.

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 Figure 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 was only 60 MW. Low and high peak power SL4 pulses are illustrated in Figure 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. Two possible pulse shortening mechanisms, (a) "anomalous" beam loading and (b) transient effects, are described below.

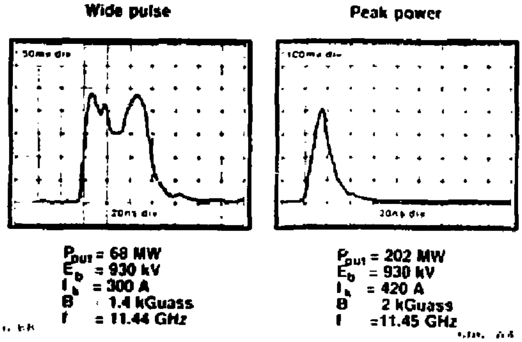

FIG. 5. Low and high peak power pulses in SL4 tests.

(a) Pulse Shortening by Anomalous Beam Loading

To understand the mechanism for the limited power output and 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 alternates from pulse to pulse between the rectangular pulse and the triangular pulse.

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 Figure 6, one having a much greater reflection during the beam-on time. Furthermore, the state with large reflection is correlated repeatably with the narrow output pulse.

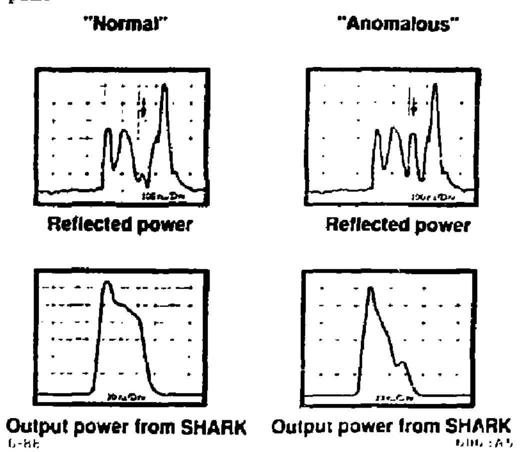

FIG. 6. SHARK reflected drive and output power. Arrows indicate the 50 nsec beam time in the reflected power.

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 Figure 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.

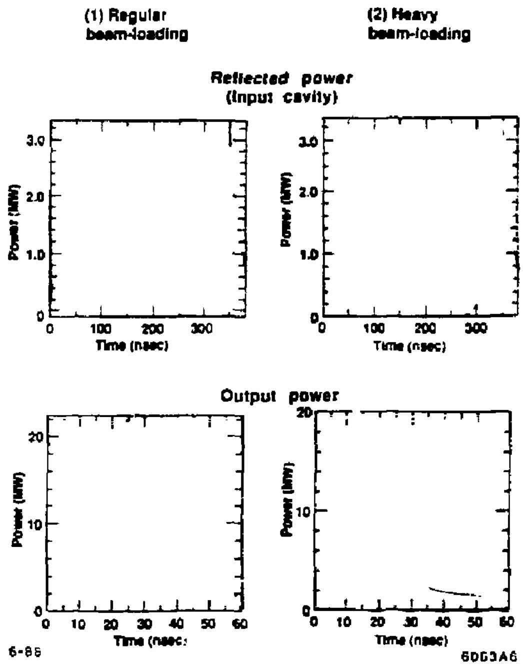

FIG. 7. Calculations of the effect of anomalous beam loading on SHARK reflected drive and output power.

A proposed mechanism follows. During the beam-on time, *secondary electrons produced by impinging x-rays are emitted* from the high field regions around the cavities. When the cavity field is low, these secondaries oscillate in trajectories close to the cavity walls with no net absorption of energy. At higher field gradients, the secondary electrons have longer path lengths. Above a critical field value, the path lengths are long enough for secondaries to hit the opposite nose cone, depositing their kinetic energy in the walls in the process, which constitutes a loading phenomenon.

The proposed mechanism is qualitatively consistent with several observations: Pulse shortening does not occur below an input power of 500 kW. The voltage across the gap at this critical drive power level is 360 kV. If secondary electrons move in straight lines, the path length during half a period is approximately 1 cm. This is consistent with the gap length being 8 mm at the neck. As the focusing field is reduced, the secondary electrons have curved paths, and require higher field gradients to hit the opposite wall. This is consistent with the observed increase in threshold power with reduced solenoid B field.

The secondary electrons in the anomalous beam loading mechanism may be caused by x-rays from the beam. Hence, they turn on and off with the beam. Note that during the experiment, roughly 200 A of current was lost in traversing the taper-klystron system. Preliminary calculations indicate that the x-rays produced are consistent with secondary electron currents required to account for the additional loading (5–10 A). This hypothesis is also consistent with the observation of reduced power output with increasing beam current, since the x-ray dosage is generally increased with beam current.

(b) Pulse Shortening by Transient Effects:

In addition to anomalous beam loading, 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. The beam-cavity coupling is sensitive to the radial charge density distribution in the beam. Since this distribution is unknown and sensitive to focusing, it is desirable to measure, rather than to calculate, the beam loading and detuning.

Measurements made on the SL4 input cavity so far indicate a beam loading Q of 670 and detuning by +22 MHz at 500 A beam current and 950 kV beam voltage. These measurements differ from the predictions of MASK simulations, most likely due to the sensitivity of the calculation to the true radial distribution of charge in the beam.

The beam pulses from the induction accelerator have a "rounded" energy distribution, dominated by the rise and fall times of the accelerating voltage (which are comparable to the switching time of the magnetic energy compressor that drives the induction cells). Consequently, transient effects of beam loading and detuning are expected to be more significant near the beginning and end of the pulse, where beam energy and current are reduced and are changing rapidly. In the SL4 klystron, for which we have begun to measure the input cavity beam loading and detuning, the minimum beam loading Q is comparable to the external Q values of the drive and idler cavities, and the maximum detuning is comparable to the stagger tuning differences between cavities.

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.

4.4 Other Observations

SHARK Input Cavity Breakdown: The drive cavity of SHARK was afflicted with breakdown problems. When first installed the cavity would operate at drive [illegible] as high as 2 MW without arcing. As testing progressed the arcing threshold [illegible] 1 MW. The arcing was evident [illegible] the input cavity reflection coefficient suddenly jumping to unity and staying there [illegible] the [illegible] of the RF drive pulse. At threshold the arcs were initiated apparently at random times during the pulse. At drive levels well above threshold the arcs would occur on every pulse and start early in the drive pulse. It was possible to raise the threshold from 1 MW to about 1.5 MW by RF processing at 15–20 pps with the beam off. The cavity was processed in this way for 1–2 hours. However, when the repetition rate was reduced to 1 pps and the beam was turned on (inadequate radiation shielding limited the repetition rate to 1 pps with beam on) the threshold would quickly decrease again to about 1 MW. The arcing was a serious limitation for the klystron tests and limited the maximum output power which could be obtained.

SHARK Input Cavity Cyclotron Resonance: There was also evidence of multipactoring or some other electronic activity in the SHARK input cavity. The pressure in the SHARK vacuum system was monitored while the solenoid field was varied with the RF drive on and the beam off. A sharp rise in pressure was observed at a field strength of about 1035 G. The cyclotron dipole resonance for the 5.7 GHz drive occurs at 2041 G. However, the linear dependence of the radial electric field produces a quadrupole resonance at half that field.

SL4 Input Cavity Multipactoring: The reflection coefficient of the SL4 input cavity is a function of drive power even when the beam is off. At low drive levels, less than 40 W, the reflection coefficient is constant and equal to that measured during cold testing. Above 40 W drive, the reflection coefficient drops rather abruptly. Since the cavity is heavily over-coupled (9.5 standing wave ratio) this reflection coefficient means that something is absorbing power from the cavity. The threshold for the onset is sensitive to the solenoid B field. We feel this is evidence of multipactor. Nevertheless, stable output power was observed.

SL4 Parasitic Oscillations: 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. This can occur with or without RF drive. The 13.2 GHz pulse appears to be much larger than the RF drive pulse, but since the RF components have not been calibrated at 13.2 GHz, we do not know how much power the pulse contains. The 13.2 GHz signal probably arises from dipole mode resonance in the input and one of the downstream cavities. Since 13.2 GHz will propagate (in the TE_{11} mode) through the 14 mm drift tube of the klystron, a signal can feed back from the idler cavities to the input cavity. Consequently, the system can oscillate. The phenomenon does not appear to affect the gain of the klystron. The 13.2 GHz signal has not been observed in the klystron output.

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. Power at this frequency was detected by measuring the distance between nulls on a sliding stub tuner placed in the output path. This parasitic oscillation can be eliminated by adjusting the beam focusing and steering.

5. FUTURE PLANS

At present, SL4 and the high gradient accelerator section are in the experimental area and tests are continuing. To further understand transient effects measurements of input cavity beam loading and detuning as discussed in Section 4.3(b), will be continued on SL4. Similar studies will be initiated on the high-field SHARK input cavity when it is reinstalled. We hope to study correlations between input cavity beam loading and output pulse shapes [illegible] focusing [illegible] SHARK [illegible]

[illegible]

[illegible] conditioning at higher [illegible] rate [illegible] ting the [illegible] of the [illegible] cavity [illegible] emission, and (4) locally perturbing the focusing magnetic field at the cavity with a magnetic shunt.

Several modifications to the current SHARK 11.4 GHz output cavity are planned. The SHARK output cavity will be replaced by the penultimate and ouput cavities of SL4 (which were designed as a modular section). The addition of a penultimate cavity to SHARK in this way should improve bunching and increase output power. A traveling wave output structure which has been fabricated will also be used to replace the SHARK output cavity. New output cavities at the 5.7 and 17 GHz harmonics may be built and tested.

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. 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. 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. Since this loading occurs only when the beam is on, it is believed to be due to either secondary electrons or 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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