High-Gradient Electron Accelerator Powered by a Relativistic Klystron

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We have used relativistic-klystron technology to extract 290 MW of peak power at 11.4 GHz from an induction linac beam, and to power a short 11.4-GHz high-gradient accelerator. We have measured rf phase stability, field emission, and the momentum spectrum of an accelerated electron beam. An average accelerating gradient of 84 MV/m has been achieved with 80 MW of relativistic klystron power.

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Electron-positron colliders offer a promising tool for direct precision studies of TeV-scale physics.[1,2] The use of storage rings at energies much above those of LEP-II (100 GeV/beam) is impractical because of synchrotron-radiation losses,[3] and linear colliders must be employed.[2-4] Conceptual designs for a 1-TeV linear collider[5] call for accelerating gradients of 100 to 200 MV/m and for rf frequencies of 10 to 30 GHz. The peak power necessary to drive a traveling-wave accelerator structure in the desired frequency range with the desired gradient is 0.2 to 1 GW/m with a pulse length of 50 to 100 nsec, necessitating the development of a new generation of rf power sources and high-gradient accelerator structures.

Pulsed beams containing gigawatts of peak power are produced at Lawrence Livermore National Laboratory using magnetic-induction accelerators powered by energy storage devices switched by magnetic saturation.[6,7] The first demonstration of rf power extraction from such a beam, using a free-electron laser, yielded 1 GW at 35 GHz.[8] Sessler and Yu, following a suggestion by W. K. H. Panofsky, proposed a method for energy extraction, appropriate to lower frequencies, by bunching a relativistic beam and passing it through extraction cavities.[9] If only part of the beam energy were extracted, the beam could be reaccelerated and energy could be extracted repeatedly—a concept they called a "relativistic klystron two-beam accelerator."[9] 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 full two-beam device extending several kilometers. Here, we report the development of a relativistic klystron at 11.4 GHz, and its use to produce high longitudinal gradients in a short accelerator structure. The experimental configuration is shown in Fig. 1.

The conventional high-power klystrons that power the Stanford Linear Collider extract 67 MW of rf power from a 35-μsec pulsed 350-keV electron beam modulated by a low-power rf driver.[10] In the work reported here we have scaled this conventional klystron technology to hundreds of MW by increasing the kinetic energy of the klystron beam to more than 1 MeV by using a pulsed high-power electron beam produced by an induction linac injector at Lawrence Livermore National Laboratory. The cathode has 12.5-cm diameter and 36-cm spherical radius of curvature. The anode-cathode gap is 14 cm. The inner diameter of the anode drift tube is 8.8 cm. Accelerating voltages up to 1.4 MV, beam currents up to 1 kA, and pulse widths up to 50 nsec FWHM have been obtained for the klystron experiments.

Velocity modulation bunches a dc beam, while space-charge repulsion (modified by the drift tube) causes the beam to debunch. The wavelength of this space-charge oscillation is called the plasma wavelength, λ_p. Distances between cavities in a klystron are chosen to be approximately $\frac{1}{4}\lambda_p$ for optimal bunching. On axis, a bunched beam with dc current I and radius a in a tube of radius b (which is small compared to the bunch length) has[11]

$$\lambda_p \simeq \lambda_0 \{[(17\ \mathrm{kA})/I](\beta\gamma)^5/[1+2\ln(b/a)]\}^{1/2},$$

where λ_0 is the free-space rf wavelength, βc is the beam velocity, and $\gamma=(1-\beta^2)^{-1/2}$. 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 ex-

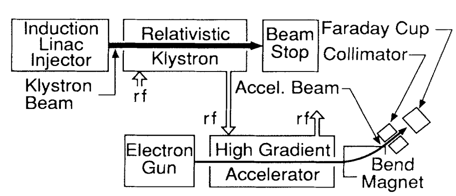

FIG. 1. Experimental configuration.

tract power from it in a total distance of 1 m.

The minimum solenoid field necessary to confine a radially uniform beam of current I and normalized edge emittance ϵ in a drift tube of radius a ($\approx \frac{1}{5}\lambda_0$) is

$$B = \frac{3.4\ \mathrm{kG\,cm}}{a}\left[\frac{2I}{17\ \mathrm{kA}}\frac{1}{\beta\gamma} + \left(\frac{\epsilon}{a}\right)^2\right]^{1/2}.$$

The bunched-beam peak current typically is 4 times the dc current. In our experiments, solenoid fields of up to 5 kG are used to focus the beam between the cathode and the klystron beam stop. Beam transmission of 70% has been achieved when rf output is maximized.

We have obtained experience with two basic types of 11.4-GHz relativistic klystrons:[12] a high-gain six-cavity klystron (SL4), and a two-cavity subharmonic buncher relativistic klystron (SHARK). In all of our relativistic-klystron tests, the pulsed dc klystron beam current is monitored by measuring image currents in the beam pipe upstream from the input cavity and at the beam stop. The rf power signals are sampled using waveguide directional couplers and measured with crystal diode detectors.

The rf filling time of the SL4 klystron is 10 nsec. Each of the three gain cavities is coupled by an iris and waveguide to an absorptive ceramic wedge, resulting in 3-nsec filling time per cavity. A highly detuned "penultimate" cavity which optimizes bunching immediately precedes the output cavity. Just upstream of the penultimate cavity the drift tube is tapered from 14 to 9.2 mm. The single resonant output cavity, which extracts rf power from the bunched relativistic beam, is of reentrant geometry with 6-mm gap. The length from input to output cavity is 98 cm.

Numerical simulations[13] were used to optimize the SL4 design parameters and to predict 65-dB gain and 40% efficiency for a 1.2-MV, 1.0-kA beam. The saturation input power level was calculated to be 200 W. In practice, 1-kW input is necessary to overcome beam-independent multipactor in the input cavity.[12,14] The input rf is supplied by an X-band traveling-wave-tube amplifier.

In our initial experiments, a peak rf power of 200 MW was achieved, but only for a time much shorter than the 40-nsec, 930-kV, 420-A beam pulse. The maximum rf pulse of 40-nsec duration achieved in our initial tests was only 70 MW from a 930-kV, 300-A beam. The high-power-pulse-shortening phenomenon was not due to beam breakup since no shortening of the dc current pulse was observed.

Understanding of the rf-pulse-shortening phenomenon came from experiments with SHARK.[12] The SHARK input cavity is driven by a 4-MW conventional klystron at 5.7 GHz. After drifting and bunching, the beam current has large Fourier components at 5.7, 11.4, and 17.1 GHz. The 11.4-GHz output cavity is positioned after a 25-cm drift for maximum rf current at that harmonic (60% of the fundamental rf current).

In the first SHARK experiments, pulse shortening was observed above 50 MW and is believed to have been caused by an observed increase in loading of the input cavity by charged-particle currents in addition to the beam, probably either secondary electrons or photoelectrons produced by a copious supply of x rays due to beam interception.[12] The power threshold for pulse shortening increased with decreasing focusing field. Consequently, we tested a 5.7-GHz subharmonic input cavity surrounded by iron. The iron acts as a magnetic shunt, decreasing the focusing field on axis in the region of the cavity gap by 50%. The iron input cavity did not exhibit anomalous loading, with or without beam. Pulse shortening continued to occur, but at a higher power threshold than in the original SHARK all-copper configuration. Evidence that this pulse shortening occurred in the output cavity was the lack of correlation with any anomaly in either the input-cavity reflected power or the rf current monitored by a probe downstream from the input cavity.

In order to reduce the output electric field levels present in SHARK, the output cavity was replaced by a six-cell traveling-wave (TW) extraction structure.[15] Since the output electric fields are inversely proportional to the rf interaction length, the multicell extraction structure, in general, exhibits significantly lower electric fields than the single resonant extraction cavity for equal power levels.[12] However, the longer interaction length makes the TW structure more susceptible to higher-order mode difficulties and, in particular, to the buildup of beam-breakup fields.[12]

The 11.4-GHz TW structure[15] is comprised of six $\frac{2}{3}\pi$-mode cells with beam apertures of 14 mm (0.53 free-space rf wavelengths), and has 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 is designed to generate 250 MW of output power when operating under synchronous conditions at an rf current of 520 A. At this power level the average electric field in the output coupler is 40 MV/m, and the peak loss of beam energy in traversing the circuit is approximately 0.9 MeV.

The SHARK-TW configuration consists of an iron-shielded input cavity and the TW output structure. The rf output level obtained using the SHARK-TW configuration was 100 MW from a 1.1-MV, 420-A beam, limited by saturation. At higher currents, output power was limited by beam loading of the input cavity.

Success at suppressing rf pulse shortening by reducing electric field strengths in the SHARK output structure prompted us to replace the SL4 output cavity with the same six-cell TW extraction structure.[15] The SL4-TW configuration consists of an input cavity, three gain cavities, and the TW output structure. A 13.8-GHz deflecting mode is excited by the beam in the TW structure. To suppress this mode from propagating backwards toward the input cavity, and from causing oscillation and beam breakup, an rf collimator, 11.4 mm in diameter and 25 mm in length, was installed between the last SL4 gain cavity and the TW output structure. With beam breakup suppressed by the collimator, peak rf output power levels up to 170 MW have been measured using a 1.3-MV, 630-A beam. The rf pulse width then was comparable to the *full* duration of the transmitted beam current.

In our most recent and highest-power rf-generation experiment, a detuned resonant cavity was added to the SL4-TW klystron between the upstream cavities and the TW extraction structure. This new cavity serves two purposes: It improves the bunching at the TW extraction structure, and it extracts power. With a 1.3-MV, 550-A klystron beam, the additional bunching provided by the new cavity has made it possible to extract 230 MW from the TW structure while the new cavity itself simultaneously extracts 60 MW. Together, the two outputs extract 290 MW with approximately 40% klystron efficiency.

Peak surface electric fields present in the resonant cavities and TW structures, calculated for given power levels, are shown in Table I.

In order to study rf phase stability we measured the output rf phase relative to the input in the SL4-TW klystron, and relative to the frequency-doubled input in the SHARK-TW klystron. Phase variations as small as 20° were observed across high-power rf pulses of approximately constant amplitude. These variations are due primarily to klystron beam-energy variation. They are acceptable for single-bunch acceleration, and presumably can be reduced, by improvements anticipated in induction-linac technology,[7] to the 4° required for multiple-bunch energy compensation.[16]

The rf generated by the SL4-TW relativistic klystron was used to power a 26-cm-long section of 11.4-GHz accelerator structure operating in the $\frac{2}{3}\pi$ traveling-wave mode. This constant-impedance structure consists of thirty cells and has $r/Q = 14$ kΩ/m. Power through the structure is attenuated by 24%. The group velocity is $0.031c$, giving a filling time of 28 nsec. The iris diameter was chosen to be 7.5 mm. The peak accelerating field on axis, for rf power P, is $(100\ \text{MV/m})[P/(100\ \text{MW})]^{1/2}$. The ratio of peak surface electric field to accelerating field is 2.3.

Electrons from a 0.5-cm^2 thermionic cathode were injected into the accelerator using a 35-kV gun pulsed for 5 nsec. Figure 2 shows pulses observed during stable operation of the relativistic klystron and high-gradient accelerator.

Field emission in the high-gradient accelerator was measured in the absence of any injected beam. The field-emission current was measured by integrating the charge deposited in a Faraday cup at the output end of the accelerator, and assuming that the duration was comparable to that of the rf pulse. After 80 h of rf operation at 1 pulse/sec, the field-emission currents measured as a function of klystron power P in the range 30–100 MW were consistent with the empirical relationship, $(250\ \text{nA})\exp[P/(17\ \text{MW})]$. Fowler-Nordheim analysis[17] of the data indicates a local surface-field enhancement factor between 60 and 70. At klystron power levels in excess of 100 MW, arcing in the accelerator becomes persistent. The above field-emission results were obtained in the presence of surface contamination by barium from the gun cathode. Prior to the installation of the gun, persistent arcing was not apparent at power levels as high as 160 MW; field emission was not measured at that time.

The beam emerging from the accelerator was momentum analyzed using a spectrometer consisting of a 40° horizontal bend, a 2.5-cm-diam collimator, and a Faraday cup. The momentum resolution of the spectrometer

TABLE I. Comparison of surface fields. Values in parentheses are extrapolations. The asterisk indicates pulse shortening.

Structure	Peak power (MW)	Peak surface field (MV/m)
SL4 input cavity	0.001	4
SHARK input cavity	2.4	180
SHARK output cavity	(200)	(450)
SL4 output cavity	200*	300
TW structure	200	130
SL4 output cavity	80	190
TW structure	(460)	(190)

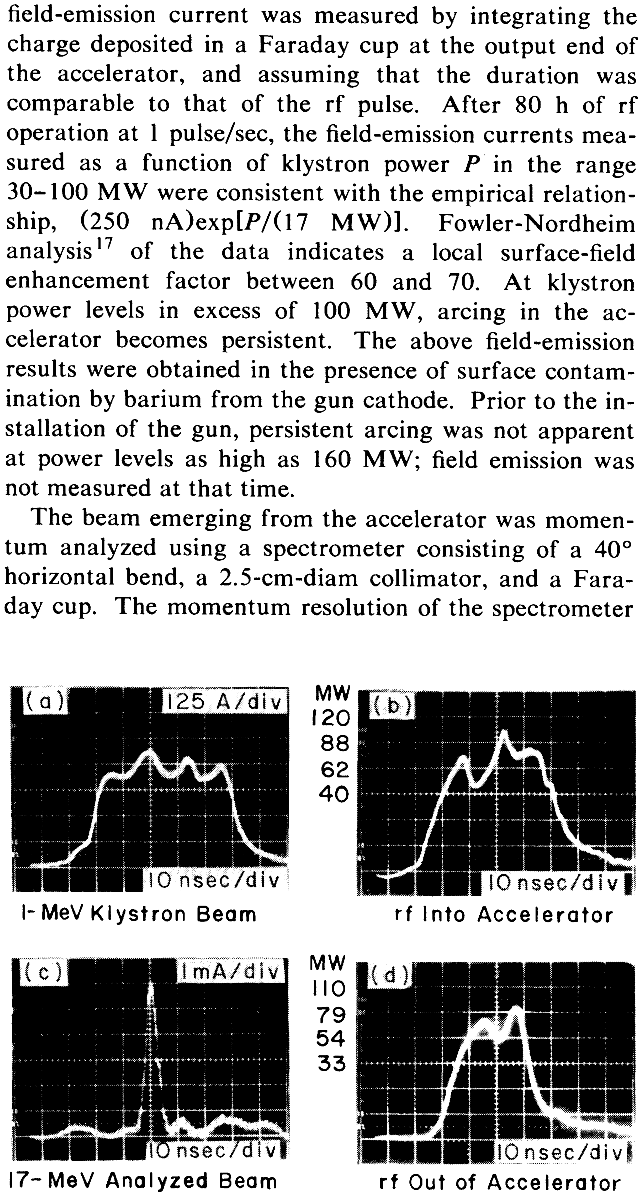

FIG. 2. Measured pulses of (a) 1-MeV (kinetic energy) klystron beam current near the beam stop, (b) rf power into the high-gradient accelerator, (c) 17-MeV analyzed accelerated beam current, and (d) rf power transmitted through the high-gradient accelerator.

is $\sigma_p/p \approx 14\%$ due to the combined effects of collimator acceptance and of multiple scattering in the 0.5-mm-thick aluminum window at the end of the accelerator and in the 50-cm path through air.

The measured momentum spectrum of the accelerated 5-nsec beam of injected electrons is nearly Gaussian with peak $p=17$ MeV/c, half-width $\sigma_p=3$ MeV/c, and a slight low-momentum tail. Computer modeling of the accelerator beam dynamics using the particle-tracking code PARMELA indicates that the injected electrons slip in phase relative to the rf wave, and that for 80 MW of klystron power, as measured, the total energy gain expected is 16 MeV, consistent with that observed. The maximum energy gain for synchronous particles, calculated from the 80-MW power level, is 23 MeV, corresponding to an average accelerating gradient of 84 MV/m in the 26-cm-long accelerator. The power measurement is uncertain by 10%, corresponding to an uncertainty of 5% in the gradient.

In summary, we have used a relativistic klystron to extract 290 MW of peak power at 11.4 GHz from an induction linac beam, and to power a short 11.4-GHz high-gradient accelerator. We have measured rf phase stability, field emission, and the momentum spectrum of an accelerated electron beam. An average accelerating gradient of 84 MV/m has been achieved with 80 MW of relativistic klystron power.

In future experiments, we plan to use the rf from multiple extraction structures in one relativistic klystron to power a multisection high-gradient 11.4-GHz accelerator. Eventually we hope to test the full two-beam accelerator concept with multiple extraction and reacceleration.

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[1]C. Ahn *et al.*, SLAC Report No. SLAC-329, 1988 (unpublished); CERN Report No. CERN-87-07, 1987, edited by J. H. Mulvey (unpublished).

[2]*Snowmass 1988 Summer Study on High Energy Physics in the 1990's,* edited by S. Jensen (World Scientific, Singapore, 1989).

[3]B. Richter, in *Snowmass 1982 Summer Study on Elementary Particle Physics and Future Facilities,* edited by R. Donaldson *et al.* (American Institute of Physics, New York, 1983), pp. 128–133.

[4]K. Johnsen *et al.*, CERN Report No. CERN 87-12, 1987 (unpublished).

[5]R. B. Palmer, in *New Developments in Particle Acceleration Techniques,* edited by S. Turner (CERN Report No. CERN-87-11, Geneva, 1987), pp. 80–121.

[6]L. L. Reginato and D. L. Birx, in *Proceedings of the First European Particle Accelerator Conference, Rome, Italy, 1988,* edited by S. Tazzari and K. Huebner (World Scientific, Singapore, 1989), pp. 75–77 and 459–460.

[7]J. C. Clark *et al.*, in *Proceedings of the 1988 Linear Accelerator Conference* (Continuous Electron Beam Accelerator Facility Report No. CEBAF-R-89-001), pp. 19–23.

[8]T. J. Orzechowski *et al.*, Phys. Rev. Lett. **54**, 889–892 (1985).

[9]A. M. Sessler and S. S. Yu, Phys. Rev. Lett. **58**, 2439–2442 (1987).

[10]M. A. Allen *et al.*, in *Proceedings of the 1987 Particle Accelerator Conference, Washington, DC, 1987,* edited by E. R. Lindstrom and L. S. Taylor (IEEE, New York, 1987), IEEE Catalog No. 87CH2387-9, pp. 1713–1715.

[11]T. L. Lavine *et al.*, in Ref. 7, pp. 589–591.

[12]Part of this work was reported previously by M. A. Allen *et al.*, in *Proceedings of the 1989 Particle Accelerator Conference,* edited by F. Bennett and L. Taylor (IEEE, New York, 1989), IEEE Catalog No. 89CH2669-0, pp. 1123–1127.

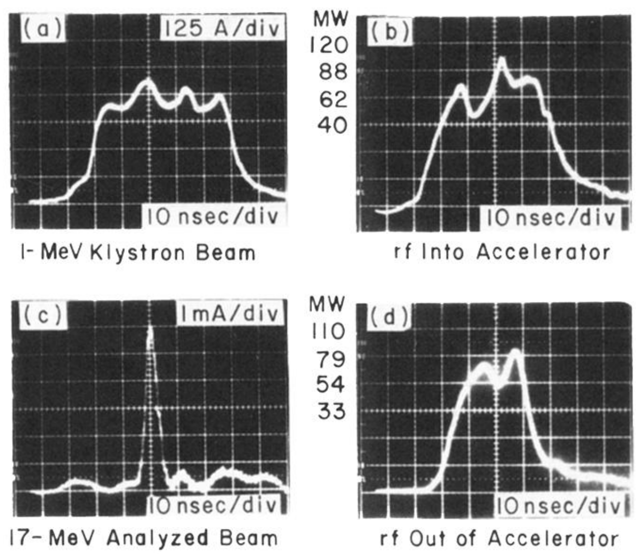
[13]K. Eppley, in *Linear Accelerator and Beam Optics Codes,* edited by C. R. Eminhizer, AIP Conference Proceedings No. 177 (American Institute of Physics, New York, 1988), pp. 313–322.

[14]See also R. F. Koontz *et al.*, in Ref. 12, pp. 159–161.

[15]J. Haimson and B. Mecklenburg, in Ref. 12, pp. 243–245.

[16]R. D. Ruth, in Proceedings of the ICFA/INFN Workshop on Physics of Linear Colliders, Capri, Italy, 1988 (to be published) (SLAC Report No. SLAC-PUB-4541).

[17]Following J. W. Wang and G. A. Loew, in Ref. 12, pp. 1137–1139.



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