RELATIVISTIC KLYSTRONS FOR HIGH-GRADIENT ACCELERATORS*

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Abstract

Experimental work is being performed by collaborators at LLNL, SLAC, and LBL to investigate relativistic klystrons as a possible rf power source for future high-gradient accelerators. We have learned how to overcome our previously reported problem of high power rf pulse shortening and have achieved peak rf power levels of 330 MW using an 11.4-GHz high-gain tube with multiple output structures. In these experiments the rf pulse is of the same duration as the beam current pulse. In addition, experiments have been performed on two short sections of a high-gradient accelerator using the rf power from a relativistic klystron. An average accelerating gradient of 84 MV/m has been achieved with 80-MW of rf power.

Introduction

During the past year researchers at Stanford Linear Accelerator Center and Lawrence Berkeley Laboratory have continued a collaborative effort with investigators at Lawrence Livermore National Laboratory to study some basic physics issues involved in combining linear induction accelerators with relativistic klystrons. In previous papers[1,2] we have reported results obtained with three experimental relativistic klystrons: a subharmonic buncher relativistic klystron ("SHARK"); a multicavity klystron at 11.4 GHz ("SL4"); and a multi-output klystron ("MOK-2"). These experiments were performed using beams with ≈1.2 MeV of kinetic energy and ≈700 A of current with a ≈50-ns duration.

SHARK is a low-gain, two-cavity tube driven by a 4-MW, 5.7-GHz source and has output power at 11.4 GHz. The maximum rf output level obtained from SHARK is 100 MW from a 1.1-MV, 400-A beam. SL4 is an 11.4-GHz, six-cavity, high-gain klystron. Use of a traveling-wave output structure[7] increased the flat pulse to 170 MW. This configuration had three intermediate gain cavities, a gain of ≈52 dB, and about 30% efficiency.

A feedback system is being studied to help reduce the nonrandom rf phase and amplitude variations for induction driven rf sources . We have also been working[6] on computer modeling of the TW output structures used in these sources.

MOK-2 Klystron

MOK-2 is a <u>m</u>ulti-<u>o</u>utput <u>k</u>lystron with two outputs operating with high-gain klystron at 11.4 GHz. The tube was designed for a 1.3-MV beam. The first four cavities are the same as those used in SL4. The first output is a single standing-wave (SW) resonant cavity. This output cavity serves two purposes: it extracts power from the beam, and it further bunches the beam. The second output is a traveling-wave (TW) structure and is located 14 cm beyond the SW output cavity. The 11.4-GHz TW structure[3] is comprised of six $2\pi/3$-mode cells with an rf filling time of 1 ns, and a phase velocity ≈0.92c. The TW circuit was 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 the output coupler is 40 MV/m, and the peak loss of beam energy in traversing the circuit is approximately 0.9 MeV.

The highest total power measured from both structures is 330 MW (30 MW from the SW cavity and 300 MW from the TW structure). The current through the klystron was 600 A and the beam voltage was 1.3 MV.

High-Gradient Accelerator

To study high-gradient acceleration, we built two 26-cm-long sections of 11.4-GHz accelerator structures operating in the $2\pi/3$ traveling wave

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mode. The constant-impedance structures consist of 30 cells and have r/Q = 14 kΩ/m. The filling time of the structure is 28 ns and the group velocity is 0.031c. The accelerating field on axis, for klystron power P, is 100 MV/m x $[P/(100MW)]^{1/2}$. Power through the structure is attenuated by 24%. The iris diameter was chosen to be 7.5 mm. Early experiments were done with a single section of HGA, and without an electron gun attached, using rf power from the SL4 klystron. The next experiments were performed using an electron gun. Finally experiments with both sections were performed using the MOK-2 klystron. The drift length between the two HGAs could be adjusted to achieve proper phasing of the two sections.

Field emission in the high-gradient structure (HGS) was measured in the absence of any injected beam. Figure 1 shows the field emission current for the second HGS. The measurements were taken after 500,000 rf pulses. The pulse shapes were triangular with about 10 ns FWHM. Levels were appreciably higher than earlier reported levels[2]. Although the surfaces of the first HGS might have had lower field emission currents the new values are in better agreement with several other measurements made on the first section.

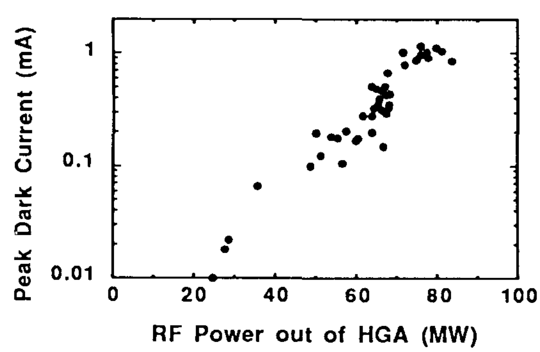

Figure 1. Peak field emission current from HGS

Electrons from a thermionic cathode were injected into the accelerator using a 80-kV gun pulsed for 5 ns. Prior to installation of the gun, persistent arcing was not apparent in the HGS at power levels as high as 160 MW. After installation arcing became persistent at klystron power levels in excess of 100 MW. There was evidence of barium on the surfaces of the HGA after running with the electron gun. In large colliders, where contamination from the cathode should not limit the maximum surface electric field levels, perhaps higher accelerating fields can be achieved.

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

In the single section test the measured momentum spectrum of the accelerated electron beam was nearly Gaussian with peak p = 17 MeV/c. 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.

Results of the dual section test are shown in Figure 2. It was difficult to operate both HGA structures near their maximum holdoff values while operating MOK-2 at beam voltage which would yield useable phase stability during the pulse. For a comparable power level to the test shown in Figure 2 the first HGA earlier (during the single section test) yielded 11 MeV electrons. Assuming similar behavior the second HGA added about 19 MeV of energy; corresponding to a gradient of 70 MV/m in the second structure.

Two unanticipated features of the observed rf output pulses from the HGAs were their shape (significantly narrower and triangular compared to the input) and the output peak power levels (only weakly correlated with and sometimes greater than the input peak powers). Studies[4] of transient effects for short pulses (comparable to the filling time of the HGA) lead to an explanation of these features. Understanding the

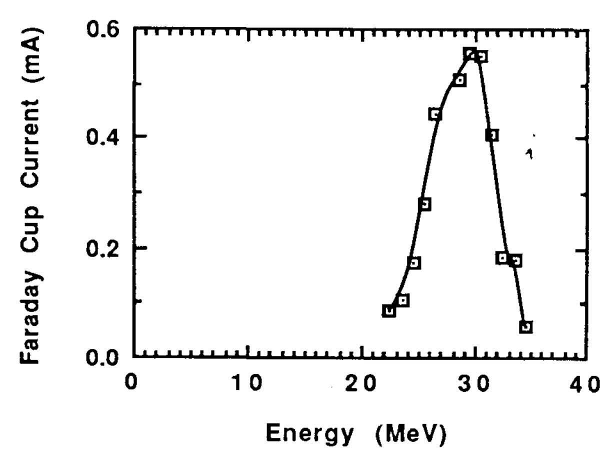

Figure 2. Analyzed momentum spectrum from the dual section HGA experiment.

transient behavior of the pulsed rf power in the type of high gradient accelerator planned for linear colliders will be important.

Future work

We are starting a new set of experiments to look at rf power sources at the Microwave Source Facility. For the initial studies we will be using the existing injector (3 MeV, up to 10 kA) at the Advanced Test Accelerator. The facility will provide a place to study high-frequency high-power microwave sources such as relativistic klystron, FELs[5], CARMs, TWT amplifiers and two-beam accelerators. Researchers from other institutions will be able to test their devices and structures without the duplication of the major effort involved with providing the drive beam. Its major objectives are:

1. To develop induction-linac-based relativistic klystrons and FELs into economically viable power sources.
2. To test key physics issues of two-beam accelerators schemes.
3. To provide a user facility for studying novel microwave sources and structures.

The first rf experiment[3] planned at the Microwave Source Facility is the Choppertron (shown in Figure 3). The first section is a 5.7-GHz chopping system designed to produce a train of short beam pulses with a period corresponding to 11.4 GHz from the initial uniform beam. The chopper design has reduced sensitivity to beam-energy sweep of the induction beam. Emittance growth in the chopper is reduced by operation with an axial magnetic field matched to the beam emittance and the betatron resonance.

The next section of the rf generator consist of two 11.4-GHz traveling-wave output structures. The use of high-group-velocity structures with short interaction regions provides a broadband, phase and temperature insensitive circuit. The chopper is designed to generate about 500 MW of pulsed rf power at 11.4 GHz when driven by a 1-kA, 3-MeV induction beam.

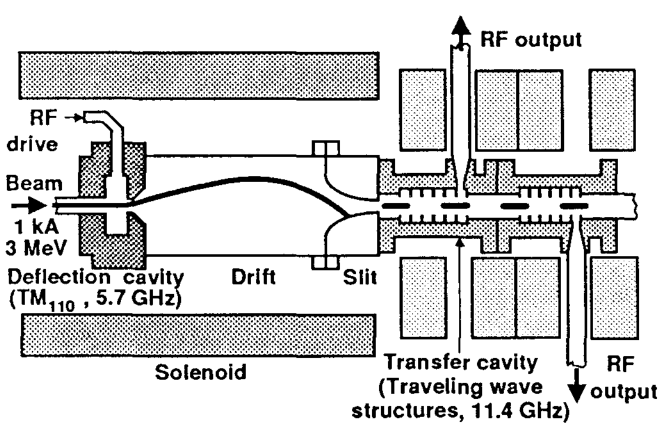

Figure 3. Schematic of the Choppertron.

The chopper will also be used to generate high-energy 11.4-GHz rf current for latter experiments. We want to study the key physics issues involved with reacceleration of a bunched beam by induction cells. We also wish to build a multiple output section to follow the chopper which utilizes inductively detuned output cavities to increase the efficiency.

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