The Los Alamos Free-Electron Laser Energy-Recovery Experiment*

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Abstract

We have concluded experiments demonstrating energy recovery in conjunction with the Los Alamos free-electron laser. In this paper, we discuss measurements of electron-beam transport during decelerations greater than 70% from 21 MeV down to 5 MeV. Power-flow measurements demonstrate the efficient conversion of beam power back into rf power and its reuse in the accelerator. We also describe instabilities of the system and compare them with simulations.

Introduction

In the present phase of the free-electron laser (FEL) experiment at Los Alamos, we have examined the recovery of power from the electron beam after it has passed through the wiggler and generated light. The electrons will have more than 95% of their original energy left and an energy spread of approximately 8 to 10% introduced by the lasing action. The overall efficiency of the system could be enhanced if most of the residual power in the electron beam could be recovered.

Energy recovery has been demonstrated in several rf linacs[1,2] and in an electrostatic accelerator used in the Santa Barbara FEL.[3] Recovery is accomplished in an rf system through deceleration in rf-excited linear accelerator structures; the kinetic energy of the beam is converted with high efficiency directly back into rf power. The net improvement in system efficiency depends on the recovered beam power relative to the rf power dissipated in the decelerating structures and, thus, improves with average current. The present experiments are intended to be proof of principle and do not, with the beam current now available, produce a net increase in system efficiency. In this paper, we will describe the present configuration of the apparatus, the results that we have obtained, simulations, and our conclusions.

Apparatus

Accelerator

The configuration of the beamline for the energy-recovery experiments is shown in Fig. 1. The rf accelerator consists of an injector, subharmonic buncher, fundamental buncher, and two 10-MeV accelerator sections operating at 1300 MHz.[4] The wiggler used in this experiment is 1 m in length and uses permanent magnets in a Halbach arrangement.[5]

Beamline

After passing through the wiggler (W), the beam is transported around the 180° bend (R) and through the decelerators (C and D) to an electron spectrometer. The decelerators are coupled to the accelerators (A and B) and to the klystrons through the resonant bridge couplers (BC). The electrons are brought into the decelerators with a phase that causes them to lose energy and generate rf fields. The rf power generated is shared with the accelerators through the resonant bridge couplers.

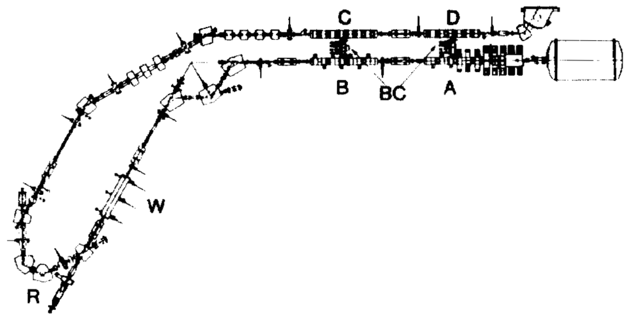

Fig. 1. Energy-recovery beamline arrangement.

The phase of the electrons entering the decelerators is controlled by translating the 180° bend in a "trombone" fashion that changes the length of the beamline. The bend can be translated a distance of 13 cm, corresponding to a phase change of more than 360° at 1300 MHz.

Decelerators

Each decelerator section is electrically the mirror image of its corresponding accelerator and is capable, for this resonant bridge-coupler design, of decelerating the electrons from their initial energy to approximately zero energy; with the electrons phased for acceleration in the decelerating structures, the electron energy can be doubled.

Resonant Bridge Couplers

The resonant bridge couplers have been described before[6] and will be discussed here briefly. Each coupler consists of three tuned cavities and has three ports as shown in Fig. 2. The center cell couples from the

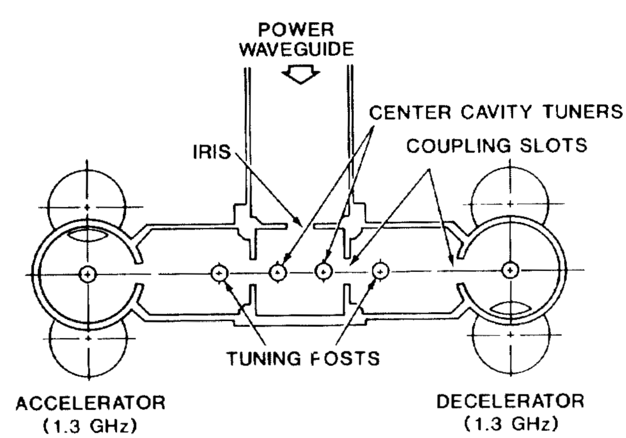

Fig. 2. Resonant bridge-coupler cross section.

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waveguide to two side cells; one side cell couples to an accelerator tank and the other to a decelerator tank. The system operates in the π/2 mode, with 180° phase difference between the center cell and an accelerator (or decelerator). Each side cell is fine tuned by a single movable post. The center cell has two movable posts. These allow the simultaneous tuning of the cell and adjustment of the relative coupling to either side.

Results

Deceleration

The resonant bridge couplers are easily tuned and can be adjusted to provide deceleration from 15 to 100% in reasonable agreement with tests on preliminary models. The energy of the decelerated electrons should depend on the position of the 180° bend in a sinusoidal fashion. We found this to be the case.

We observed a maximum deceleration of ~75% when the voltage gradients in each decelerator were approximately equal to those in the corresponding accelerator. As the phase of the electrons entering the decelerators was varied by moving the 180° bend, the final energy was changed from a maximum of 28 MeV (twice the 14-MeV accelerator voltage) to a value of 3.5 MeV. Larger decelerations were not observed because of our inability to transport lower energy beams, below ~3.5 MeV, into a spectrometer. This precluded measuring energy as a function of the bend position to the lowest energy. The curve, however, did extrapolate to zero energy.

Beam Transport

We have transported ~100% of the charge in a beam of 4% energy spread from the end of the wiggler through the decelerators. The maximum charge that we have transported is 4.6 nC/micropulse (0.1-A average current). The lowest energy beam efficiently transported has been ~3.5 MeV. At large decelerations, we were forced to add trim coils along the decelerators to compensate for the fringe fields from the solenoids around the accelerator.

We were able to transport the full charge from the scraper in the 60° bend through the decelerators down to an energy of ~5 MeV. Between 5 and 3.5 MeV, we were able to keep the beam focused through the decelerators, but steering became progressively more difficult because of fringe fields.

Power-Flow Measurements

Measurements of net power flow to the accelerators were made under conditions of 16-MeV acceleration, 50% deceleration, and 0.065-A average beam current through the decelerators (1-MW beam power). The measured difference in power delivered to the accelerator from the klystrons with and without energy recovery was 0.7 MW; the difference calculated from the current and deceleration was 0.52 MW. The two numbers agree within the accuracy of our measurement, and the powers measured were consistent with estimates of copper losses in the structures and beam loading.

In addition to power-flow measurements, we examined the frequency spectrum of the fields in the decelerators to look for evidence of high-frequency dipole beam-breakup modes and symmetric nonaccelerating modes. Estimates[7] have indicated that the latter would cause the loss of <1% of the electron energy. Over the frequency range of 1.1 to 2.8 GHz, no modes with an intensity within -40 dB of the accelerating mode were observed.

Instabilities

The beamline shown in Fig. 1 should develop instabilities at sufficiently high currents. These instabilities follow from the fact that in any beam-transport system containing bends, charge will be scraped (lost to the walls) if the beam energy varies enough. Any fluctuation of the energy of the electrons leaving the accelerator will cause a change in the fraction scraped and in the charge reaching the decelerators. The result will be a change in the amount of power recovered. Depending on where the beam is being scraped and the details of the beamline and the feedback system in use, the phase of the change in energy recovery may be such as to lead to an instability.

Several possible instabilities have been modeled and are described in two papers in these proceedings.[8,9] A computer simulation[9] has been carried out in terms of five tuned circuits representing an accelerator, a decelerator, and the three-celled bridge coupler, with the recovered beam providing the positive feedback mechanism. A second simulation[9] is an analytical stability calculation using essentially the same model. Several simplifying assumptions are made in both analyses, including treating each accelerator and decelerator as a single tuned circuit and neglecting the rf feedback system. Two examples of computer results are shown in Fig. 3. The window shown is the energy band-pass of our system. Electrons with higher or lower energy scrape the walls and are lost.

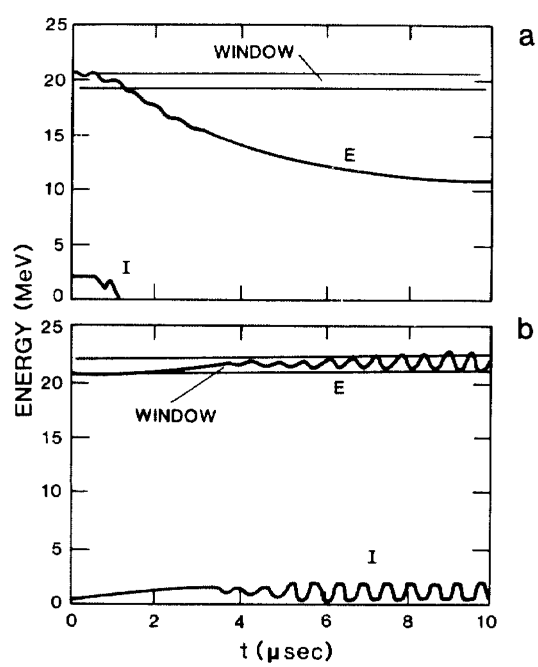

Fig. 3. Instabilities caused by scraping the beam within the energy-recovery loop on the (a) low-energy side and (b) on the high-energy side.

Figure 3a shows the calculated results when the low-energy edge of the beam is being scraped. As the energy decreases, less beam current reaches the decelerators; thus, less energy is recovered and the voltage gradient in the accelerators falls further. This sequence eventually causes all the beam to be scraped, and the energy to be clamped outside the acceptance window of the transport system. Figure 3b illustrates another calculated instability in which the energy rises, current is scraped at the high-energy side of the energy window, and a steady-state oscillation of the current and energy results. This oscillation occurs at a higher frequency and involves a 180° phase shift across the bridge coupler. These calculations were done for an average current of ~0.08 A, approximately our normal operating point.

We have observed both types of instabilities and confirmed qualitative agreement with the models by deliberately scraping a sufficiently large fraction of the charge on either the low- or high-energy side by adjusting the magnetic fields in the 60° bend. With sufficiently high currents, the present beamline arrangement would be uncontrollably unstable, but a different design could avoid this problem by, for instance, removing all deliberate scraping from inside the energy-recovery loop.

Lasing with Energy Recovery

The energy-recovery system has been operated while lasing at 0.7% extraction efficiency, 0.1-A average current, and 68% deceleration. The lasing did not degrade the performance or stability of the system and energy recovery had no effect on the lasing. High-efficiency wigglers would generate a larger energy spread and pose more of a design problem for the beamline; these problems are now being addressed.

Conclusions

The components of the energy-recovery system are functioning properly. The decelerator gradients are adjustable over a range consistent with the nominal design of the resonant bridge couplers, and large deceleration of the beam can be produced. Transport of the beam in the beamline is approximately 100% efficient under nominal conditions, and transport of the beam through the decelerators is reasonably efficient above 3.5 MeV. The results of power-flow measurements confirm that the power extracted from the electron beam is recovered as rf power with high efficiency. The system is stable against oscillation under normal operating conditions, but the predicted instabilities can be induced and will have the expected characteristics. Lasing at about 1% extraction efficiency does not degrade the performance of the system, but high extraction-efficiency wigglers may impact system design. On the basis of our measurements, we conclude that energy recovery could be successfully applied to large FEL systems.

Acknowledgments

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