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TITLE: RECENT RESULTS FROM THE LOS ALAMOS FREE-ELECTRON LASER

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MASTER

RECENT RESULTS FROM THE LOS ALAMOS FREE ELECTRON LASER*

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ABSTRACT

In this paper we review the most recent experimental results of the Los Alamos free-electron laser program. Three major efforts will be described: lasing at improved efficiency over that previously attained, electron beam improvement, and energy recovery. An extraction efficiency of 2% was achieved with a wiggler having a 12% wavelength taper. The beam has been improved so that limits to its quality are now caused, not by injector performance, but by wake fields related to the high peak currents achieved. Limits to optical power are set by mirror damage. Experiments are described that demonstrate the successful operation of an energy-recovery system.

I. INTRODUCTION

Major modifications have recently been made to the accelerator of the Los Alamos free-electron laser (FEL) to provide a beam with higher peak

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current and better quality and to install the extra beamline and the decelerators required by the energy-recovery experiment.

In previous experiments, the efficiency of the Los Alamos FEL for converting electron beam energy to laser light at 10 μm was 1.0% for a uniform-period wiggler¹ and 1.3% for a tapered wiggler. The intracavity peak optical power was about 800 MW, corresponding to a peak output power of 2 MW. Ideally, we had expected to achieve efficiencies of 1.2% and 3 to 4% for the uniform-period and tapered wigglers, respectively, and correspondingly higher power levels, but we were limited by several factors related to accelerator performance. In particular: (1) the electron beam emittance and energy spread were excessive, (2) the maximum charge we could accelerate was limited, (3) the temporal shape of the electron micropulse included extensive nonlasing wings, and (4) noise and fluctuations in the accelerator field magnitude and phase and in the electron gun current and timing reduced gain and efficiency. Detailed descriptions of these problems can be found in the literature.²⁻⁵ Over the last year we have modified the accelerator in an attempt to reduce these problems and to improve the reliability and operating flexibility of the system.

In Sec. II of this paper we describe accelerator modifications (Sec. II-A), the improvements we have realized in accelerator performance (Sec. II-B), the resulting laser performance (Sec. II-C), a comparison with theoretical predictions (Sec. II-D), a serious new problem we have encountered: deterioration of beam quality caused by wake fields (Sec. II-E), and a summary (Sec. II-F).

The other major effort in the Los Alamos FEL program has been the demonstration of efficient energy recovery from the electron beam after passing through the wiggler. Section III of this paper describes the general rationale for energy recovery (Sec. III-A), the configuration of the apparatus used for energy recovery (Sec. III-B), the experimental results we have obtained (Sec. III-C), the results of theoretical simulations of recovery (Sec. III-D), and our conclusions with respect to the success of this experiment and the eventual extension of energy recovery to large systems (Sec. III-E).

II. Accelerator Modifications

A. Modifications

Figure 1 is a plan view of the experiment including the accelerator, beamline, wiggler, optical cavity, and diagnostics. (The part of the line including and after the 180° bend is used for energy recovery and is described in Sec. III-B). In most respects the beamline is unchanged from our previous configuration.¹ Modifications were made on the following:

- **Subharmonic Buncher:** The number of subharmonic bunchers was reduced from two to one for simplicity; the position was changed to improve emittance and micropulse shape, and the buncher was fabricated of stainless steel rather than copper to damp beam-driven cavity modes.
- **Fundamental Buncher:** This buncher was moved closer to the accelerator to improve emittance, micropulse shape, and beam capture by the accelerator.
- **Axial-Field Solenoids:** These solenoids were extended over the first 5 MeV of the accelerator to increase capture and to reduce emittance.
- **Feedback System:** Major efforts were made to reduce noise in the accelerator field. In particular, the rf system was moved closer to the accelerator so that both the rf waveguide and the feedback cables could be shortened. At present, the feedback electronics are being improved, and a redesign of the gun electronics is under way to further reduce noise from these sources.
- **Dispersive Magnets:** As discussed in previous reports,^{2,4} the 60° achromatic "bends" have two effects in addition to their intended one of bending the electron beam by 60° into coincidence with the optical beam. Because of their nonisochronous nature, the bends have a larger transit time for low-energy electrons than for high-energy electrons. This property can be used to bunch the electrons in each micropulse. We normally take advantage of this bunching

to shorten the micropulses by a factor of 2 and thereby increase the peak current accordingly. Conversely, the nonisochronous nature of the bends causes a second, unfavorable effect i.e., fluctuations in the arrival time of the micropulses at the wiggler whenever their energy fluctuates. This is our most common source of noise. It causes nonuniform lasing intensity and can reduce the efficiency. We built a second magnet system that provides the 60° bend along with isochronous properties but, so far, have not chosen to employ this system and make the trade-off of noise improvements for lower peak current.

B. Improvements Realized

These changes have caused the following improvements in accelerator performance:

- Peak accelerated charge is no longer limited by clipping the beam at the entrance to the accelerator because of the beam's excessive diameter. The limiting charge has been raised from 3 to 6 nC, and this limit is now imposed by available rf power.
- Emittance, energy spread, and micropulse shape have been improved, especially at low charge, but are still excessive (see Fig.2) above ~3nC.
- Micropulse length has been measured with a streak camera. At the wiggler, the micropulse is shorter than 16 ps and the beam current exceeds 300 A.

C. Laser Performance

We have used our improved accelerator to drive our 10- μ m FEL oscillator, using both a uniform-period wiggler and a wiggler with a 12% wavelength taper. The measurement procedure and diagnostic tools were similar to those reported previously.^{1,2} As expected, extraction efficiency and power levels were increased. We achieved an efficiency of 2.0% with the

tapered wiggler, with intracavity peak power levels and output of 2000 and 40 MW, respectively. More extensive synchrotron sidebands were seen than before, covering a spectral range as large as 10%. The FWHM of the detuning curve was 40 μm for the uniform-period wiggler and 4 μm for the tapered one. Strong fluctuations in efficiency, optical power, and spectra are still seen from shot to shot and within a single macropulse because of accelerator noise.

Lasing occurred when the micropulse charge was varied from 6 nC to as little as 0.25 nC. The maximum extraction efficiency of 2.0% was attained with 3 nC. With a larger charge, the emittance and energy spread (see Fig. 2) exceeded the critical values, 3 mm-mrad and 1.5%, respectively, so that the efficiency fell. These critical values are determined by the "emittance" of the 10- μm optical beam and the width of the positive lobe of the gain curve at saturation for our wiggler. Thus, emittance and energy spread are still important limits on the performance of this laser.

Another limit was excessive loss caused by damage to the multilayer dielectric mirrors (ZnSe/ThF₄). During these tests we used a new on-line efficiency-measuring system, which quickly evaluated the percentage of energy lost by the electron beam during lasing. We routinely compared the efficiency measured in this way with the efficiency calculated from the measured optical power. Normally, we found reasonable agreement, but not when we attempted to produce a very high efficiency by using a large micropulse charge and high reflectivity mirrors. This combination was expected to maximize the intracavity optical power and, thus, the extraction efficiency. However, the threshold for mirror damage was surpassed. Damage quickly accumulated and increased the cavity losses by a factor of 3 (from 1.5 to 5%). The damage tended to be self-limiting; that is, damage occurred whenever the average intracavity optical power exceeded the damage threshold (about 500-700 kW/cm²). The growth of the damage sites increased the cavity losses and reduced the intracavity power and efficiency until the optical power fell below the damage threshold. The damage on the mirrors was manifested as a collection of many small elongated pits in the dielectric coating plus, usually, one or two larger (1- by 1-mm.²) pits penetrating to the ZnSe substrate.

The disagreement between electron-beam-derived efficiency and optically derived efficiency occurred whenever damage occurred. The disparity was large, sometimes as much as a factor of 30, and signified that most of the light generated was not being collected but was lost by scattering or absorption at the mirror. We have considered various possibilities, such as color-center absorption in the ZnSe transmitting optics or absorption and scattering in laser-induced microdischarges at damage sites. The damage mechanism most consistent with the observed morphology is heating of microscopic absorbing defects leading to film rupture by excessive stress. Specific laser damage tests will be needed to more properly understand these results. This damage phenomenon established a power-density limit at the mirror that could not be exceeded with the ZnSe/ThF₄ multilayer dielectric mirrors.

D. Comparison of Measured and Calculated Extraction Efficiency

Table I shows the measured and calculated values of extraction efficiency for the tapered and uniform wigglers used in this experiment. Four theoretical values are shown, which were computed using the electron-beam parameters that gave the highest measured efficiency (total charge 3 nC, pulse width 25 ps FWHM, fractional energy spread 1.85%, peak current 127 A, and emittance 3 n·mm·mrad). (After this series of calculations, the streak-camera measurements indicated that the pulses probably had been shorter and the peak currents correspondingly higher. We have not yet performed calculations under such conditions.) The four theoretical approximations are as follows:

- 1-D single wavefront, (the simplest estimate).
- 1-D finite pulse, (includes spectral evolution caused by sideband formation and the effects of a time-varying electron density in the micropulse).
- 3-D single wavefront (includes emittance and transverse spatial overlap between the optical and electron beams but no finite pulse or sideband effects).

- 3-D periodic boundary condition (includes both sideband and emittance effects, but not finite pulse length, and is expected to be representative of the extraction at the peak of the electron micropulse). A comparison of these different calculations reveals the relative importance of sidebands, emittance, and finite pulse effects.
- The fifth column represents our estimate of the extraction efficiency had we been able to perform a calculation to include all physics effects simultaneously, i.e., synchrotron sidebands, finite pulse, emittance, and spatial overlap. Too great a reliance cannot be placed on this estimate, which is in good agreement with the data. A full, time-dependent extension of the present 3-D code is being developed, which will allow a more reliable comparison with the experimental data.

E. Wake Fields

Initially, measurements of emittance were made at the entrance of the wiggler (point 3 of Fig. 1) and of energy spread at the electron spectrometer (point 5 of Fig. 1). The results are shown in Figure 2. The data had a large scatter, but the trend was that the emittance appeared to be independent of micropulse charge at low charge and varied more or less linearly with charge at larger values. The energy spread varied essentially linearly with micropulse charge. The values of emittance and energy spread were in reasonable agreement with numerical simulations of the accelerator at low charge, but the rapid increase was not in agreement with the simulations.

The large increases in emittance and energy spread placed severe limits on the use of the electron beam for lasing and discouraged us from attempting to achieve still higher charges. We have employed several diagnostic devices to isolate the source of the emittance and energy spread. To measure emittance, we have used various combinations of Cerenkov radiation screens and focusing quadrupoles to determine electron-beam spot sizes. These measurements gave the emittance averaged over the 2000 micropulses in a

macropulse. We established three emittance measuring stations in the beamline shown by ① to ③ in Fig. 1. Measurements were made at two micropulse charges, 1.1 and 5.5 nC, and under two conditions of magnetic bunching in the 60° bends. The peak current I was estimated from the charge and representative streak-camera pulse-width measurements. Table II summarizes the measurements supplemented by the following observations:

- The emittance of the electron beam at station ① was (within measurement error) independent of charge and well below our critical value of 3 n.
- There was a large growth in emittance through the 60° bends and a significant growth in the subsequent straight section of beamline.
- The growth in emittance at stations ② and ③ increased with micropulse charge and depended on how well the charge was bunched in the magnetic buncher, i.e., peak current.

Similar measurements were made of energy spread as a function of charge and bunching at two well-separated stations, ④ and ⑤ shown in Fig. 1. The spread was an average taken over the entire macropulse. The results shown in Table III prompt three conclusions:

- The energy spread at station ④ was acceptable at all micropulse charges and was independent of charge.
- A large growth in energy spread occurred along the beamline.
- The growth in energy spread increased with increasing charge and stronger bunching, i.e., with increasing peak current.

To provide a more detailed diagnostic of energy spread, we employed the fast deflector-spectrometer combination.³ This diagnostic tool enables investigation of the energy time dependence of a single micropulse. It revealed unexpected detail within the micropulse. A part of what we had been calling "energy spread" was actually an energy droop within each micropulse. This droop was proportional to the instantaneous current within the

micropulse and reached 3-4%. Photographs of these measurements are hard to reproduce adequately, so we have performed a series of four simulations that reproduce the droop and agree well with our observations. Figure 3(a) shows the expected cosine-dependence of electron energy versus time in a micropulse. Figure 3(b) is modified by the nonisochronous nature of the bends, which skews the cosine curve characteristically. Figure 3(c) includes a realistic time spread and energy spread in the electron distribution. Figure 3(d) includes an energy droop proportional to instantaneous current. The proportionality constant used in Fig. 3(d), 1.4%/100 A, was chosen to agree with the measurements, and was found to be consistent with theoretical estimates. Figure 3(e) shows a real measurement.

Our explanation for the energy droop is wake fields,⁶ i.e., interactions of each micropulse with the wall currents that follow behind it. These interactions drain energy from the micropulse and are most serious at wall discontinuities such as bellows. Wake fields can also deflect an electron beam transversely in nonaxially symmetric systems or when the beam is allowed to move off-center in axially symmetric systems. The deflection is proportional to the instantaneous current. Such a deflection, when averaged over a micropulse, would be diagnosed as emittance growth. Beamline discontinuities that occur in a bend or that are not radially symmetric, or an electron beam that is not well aligned, can also cause this kind of emittance growth.

Calculations have been performed⁷ using the computer codes TBCI⁸ and LTRACK⁹ to estimate the magnitude of the longitudinal and transverse wake-field effects. Within a factor of 2, the major discontinuities we have identified provide an explanation for all the growth of emittance and energy spread that we have seen.

F. Summary

Improvements have been made in the injector region of the Los Alamos rf linear accelerator allowing beams to be produced with higher charge, higher current, and better quality. The quality then suffers degradation further

down the beamline because of wake-field effects. In spite of this degradation, a wiggler efficiency of 2.0%, and peak intracavity optical-power levels in excess of 1 GW have been achieved. At this power level, significant damage to the mirrors was observed. Without this damage, even higher efficiencies and power levels could have been obtained. Efforts are now being made to reduce wake-field effects by eliminating unnecessary discontinuities in the beamline and by ensuring that the beam remains centered in the beamline throughout its length. Modifications to the optical cavity to prevent mirror damage will include use of copper mirrors and increased cavity length.

III ENERGY RECOVERY

A. Rationale for Energy Recovery

After passing through the FEL, the electron beam will have more than 95% of its original energy and will retain intact its charge, emittance, and microbunch structure. The electrons have an energy spread of approximately 10% introduced by the lasing action. This large energy spread makes it unfeasible to improve the system efficiency by recirculating the electron beam through the wiggler. However, the overall efficiency of the system can be enhanced if most of the residual energy in the electron beam can be recovered.

For the present currents in rf-driven FELs, a recovery scheme is not attractive because most of the rf power goes into "structure," i.e., resistive losses into the accelerator cavity walls and not into electron beam. (This is, of course, not necessarily true for superconducting machines.) In addition, power costs are not a driving factor in small system costs. For large FELs, beam loading in the accelerators will rise to levels at which efficient recovery of power from the electron beam would make a significant impact on capital and operating costs.

Energy recovery has been demonstrated in rf linacs^{10, 11} and in an electrostatic accelerator used in the FEL at University of California at Santa Barbara.¹² In one of the rf-linac experiments at Chalk River,¹⁰ deceleration was achieved by running the beam backward through the accelerator after turning it through 180°. In the linac experiment at Stanford,¹¹ the

configuration was a racetrack, or loop, with the electrons phased for deceleration on the second pass. Both recovery systems were economical with regard to rf structure power loss because the deceleration occurred in the same structure as acceleration (This factor was not relevant in the Stanford experiment because the accelerator was a superconducting one).

The reverse-path scheme has an advantage in that the accelerating and decelerating beams have the same energy at any point in their common structure. This configuration eases beam-transport problems. The scheme has an important disadvantage: when the distance between pulses is less than the length of the accelerator, i.e., long accelerators and high average current, counterpropagating pulses will overlap at some point and space-charge effects will defocus the beam and make beam transport difficult. This defocusing effect would make the reverse-path scheme difficult to scale up to large, high-current machines.

The racetrack configuration will, in general, have beam-transport difficulties because accelerating and decelerating beams are copropagating and will have different energies at the same point in the structure. Bending and focusing devices will not treat both beams in the same way. This problem did not arise in the experiment of Ref. 11 because the transport was a simple one, with the only steering and focusing at the midpoint of the accelerator where both beams had the same energy. In addition, the accelerator was symmetric front to back with no graded- β sections.

In both of these configurations, both beams occupy the same structure, which allows for strong feedback. One would expect that both would be susceptible to beam breakup instabilities at high beam currents.

Because of the projected difficulties with the configurations of Refs. 10 and 11, we have chosen to investigate energy recovery in a configuration in which the beam is accelerated and decelerated in separate structures. The advantages are that the structures can be separately optimized for beam transport and can have graded- β sections, and the new device needed to couple power from the decelerator to the accelerator can be designed to isolate the structures from each other at the frequencies expected to be involved in beam breakup instabilities. The main disadvantages of this scheme is the extra cost

of the decelerating structure and the extra power losses in it. A problem common to all energy-recovery schemes in FELs is that the wiggler will produce a spread in the beam energy, and beam transport after that point becomes a problem. An alternative is to have the wiggler and decelerator in a straight line.

The net improvement in system efficiency by recovery depends on the recovered beam power relative to structure losses. For large systems projected for the future, beam power is much larger than structure losses. Because the use of separate accelerator and decelerator may avoid beam breakup, there is a broad range of currents in which energy recovery using separate decelerating structures will be preferred. The present experiments were intended to be proof of principle, and did not, with the current available, produce a net increase in system efficiency.

B. Apparatus

1. Accelerator. The configuration of the beamline for the energy-recovery experiments is shown in Fig. 1. The accelerator in the present experiments is very similar to that used previously.^{1,2} As described above, the injector system and solenoids have been modified to increase the charge that can be injected into and transported through the accelerators, although problems remain with respect to achieving low emittance at high micropulse charge. The rf accelerator tanks consist of two 10-MeV sections operating at 1300 MHz. The accelerators are standing-wave structures operating in the $\pi/2$ mode. The rf power is supplied by two Thomson CSF 5.5-MW klystrons. Feedback circuits maintain the fields in the accelerators during the ~ 120 - μ s macropulse constant to within $\sim 0.3\%$. The wigglers used in these experiments are 1 m long and use permanent magnets in a Halbach arrangement.^{1,7}

2. Beamline. After passing through the wiggler (W), the beam is transported around the 180° bend (R) and through the decelerators (D) to an electron spectrometer. The decelerators are coupled to the accelerators (A) and to the klystrons through the resonant bridge couplers (BC). The electrons are brought into the decelerators with a phase that causes them to be opposed

by the rf field present and to lose energy. The rf power generated is shared with the accelerators through the resonant bridge couplers.

The critical element in the transport part of the beamline is the 180° bend and the sections after it to the decelerators. The beamline must be sufficiently achromatic and isochronous that the large energy spreads produced by lasing can be transported without causing beam loss or debunching after the wiggler.

After passing through the 180° bend, the beam drifts for about 3 m, passes through an isochronous 60° bend, and then is matched into the decelerators with four quad singlets, QS7. To make the bend symmetric, quadrupole singlets QS1 and 4 and 2 and 3 were originally connected in series in the 180° bend, and singlets QS5 and 6 were connected in series in the 60° bend. This beamline design was validated using the envelope code TRANSPORT with an unnormalized beam emittance of $\epsilon = 0.25 \text{ n-mm-mrad}$ and was able to transmit a beam with a $\pm 3\%$ energy spread.

As the emittance at the entrance of the 180° bend increased, the beam diameter became larger in the bend, until a point was reached ($\epsilon \sim 0.8 \text{ n-mm-mrad}$) at which there could not be 100% beam transmission, together with no emittance growth in the bend. To avoid this problem, we investigated modifying the available components. For emittances greater than 0.8 n-mm-mrad , the quads were detuned from their isochronous settings, and the bend was allowed to become less achromatic to achieve 100% transmission. If the emittance of the beam exiting the 180° bend became too large ($>5 \text{ n-mm-mrad}$), the four quad singlets at the entrance of the decelerators QS7 could no longer match the beam into the decelerators. Simulations using the particle tracking code PARMELA showed that in the original, symmetrical configuration, the correct matching was very critical and hard to achieve for initial emittances greater than 0.8 n-mm-mrad . PARMELA also indicated that the minimum emittance growth around the 180° bend was about 2.5 n-mm-mrad for 100% beam transmission with an initial beam emittance of 1 n-mm-mrad .

The beam that actually enters the 180° bend has an emittance of $\sim 4 \text{ n}\cdot\text{mm}\cdot\text{mrad}$. To have 100% beam transmission through the bend, it was necessary to severely mistune the quad pairs. The emittance growth in the bend was so large ($\sim 25 \text{ n}\cdot\text{mm}\cdot\text{mrad}$) that the beam could not be matched into the decelerators. This severely limited the total charge that could be transported through the entire system.

A satisfactory solution exists if the quad pairs in the bend are decoupled, i.e. each quad operates independently. In this case, the emittance grows only slightly, from 4 to 5 $\text{n}\cdot\text{mm}\cdot\text{mrad}$. The isochronous 60° bend is physically large enough to accommodate this beam, and the four quad singlets are able to manipulate the beam so that it matches the admittance of the decelerators. This permits, as described below, 100% beam transmission through the decelerators, and the bend is still almost isochronous.

The phase of the electrons entering the decelerators is controlled by translating the 180° bend, which changes the length of the beamline. This phase control is required to assure that the electrons enter the decelerators at the proper time for deceleration. The bend can be translated a distance of 13 cm, corresponding to a phase change of more than 350° at 1300 MHz.

3. Decelerators. Each decelerator is electrically the mirror image of its corresponding accelerator and is capable, for this resonant bridge coupler design, of decelerating the electrons from the initial energy approximately to zero. One goal of the experiments is to study the transport of the beam as the energy becomes only a few million electron volts.

4. Resonant Bridge Couplers. The resonant bridge couplers have been described before¹⁴ and will be only briefly discussed here. Each coupler consists of three tuned cavities and has three ports as shown in Fig. 4. The center cell couples from the waveguide to two side cells; one side cell couples to an accelerator tank and one to a decelerator tank. The system operates in the $\pi/2$ 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. The ability to change the relative coupling arises from the fact that unequal

insertion of the posts causes an admixture of cavity modes. This admixture has unequal field intensities at the coupling slots as illustrated in Fig. 5. The net result of such a coupler is that a given ratio of electric fields is maintained in the accelerator and decelerator. Any rf power generated in the decelerators is automatically shared between the structures and will result in a decrease in the power required from the klystrons to maintain the fields. A low-power aluminum test model was built first, and the final couplers were constructed on the basis of measurements made on that model. The measurements indicated that the fields in the decelerators relative to those in the accelerators should be adjustable from ~ 15 to 120%. A coupling system such as the one described above has the complexity associated with adjustable structures, e.g., sliding tuning posts. When operating in the $\pi/2$ mode, it has the powerful advantage with respect to traveling-wave structures that the phase shifts between accelerator and decelerator are relatively insensitive to power flow.

5. Diagnostics. There are several diagnostics especially important for the energy-recovery experiments. Two electron spectrometers, one after the wiggler and one after the decelerators, measure the change in average energy and in energy distribution before and after deceleration. The charge in each micropulse is measured by wall current monitors along the beamline. Pop-in Čerenkov screens show the beam profile at a number of points.

Waveguide directional couplers allow measurements of the forward and reflected power for each accelerator/decelerator pair. Loop probes are placed in each of the accelerators, decelerators, and resonant bridge coupler cavities. These probes are used for initial tuning of the resonant structures, relative measurements of the field strengths in the various structures, and control of both the amplitude and phase of the rf power from the klystrons.

C. Results

1. Deceleration. The resonant bridge couplers are adjustable over the range of deceleration, $\sim 15\%$ -100%, which is in reasonable agreement with tests on preliminary models. As expected, the $\pi/2$ mode of operation of the couplers is very stable. We changed the temperature of one of the accelerators by 10°C ,

enough to alter its resonant frequency by several line widths. In a weakly coupled system, this would produce a phase change of 90° between the accelerator and decelerator and a large amplitude difference between the two tanks. In the present case, the phase difference between the two tanks was less than 1° and the amplitude difference less than 4%.

The energy of the beam after traversing the decelerators will vary with the time of arrival of the micropulses at the decelerators. The energy is expected to depend on the position of the 180° bend in a sinusoidal fashion. Figure 6 shows an example of this behaviour with an initial energy of 16 MeV and a deceleration of 8 MeV.

The maximum deceleration measured has been $\sim 75\%$. In this measurement, the fields in each decelerator were close to those in the corresponding accelerator. Measurement of larger decelerations was limited by our ability to transport lower energy beams, below ~ 3.5 MeV into the spectrometer after the decelerators. This limitation precluded measuring energy as a function of the bend position to the lowest energy. The curve, however, did extrapolate to zero energy.

2. Beam Transport. The critical parts of the beam-transport system are the sections in and after the 180° and 30° bends, where the beam tends to spread out in the plane of the bends, and the decelerators, where the beam becomes progressively lower in energy and more susceptible to defocusing effects and to stray magnetic fields. We have been able to achieve $\sim 100\%$ transport of the charge in a beam of 4% energy spread from the end of the wiggler through the decelerators. We are limited in knowing the exact degree of charge transport by unknown uncertainties in the calibration of our wall-current monitors. The conclusion about complete beam transport is supported by the observation that, without changing the settings of the transport line after the wiggler, we were able to vary the energy of the beam by 5% without changing the ratio of the charge after the decelerators to the charge after the wiggler. The simplest explanation for this behavior is that over this range (plus the energy spread of $\sim 4\%$) there is no appreciable scraping of the beam on the walls.

The profile of the beam as it propagates around the bends and through the decelerators is qualitatively similar to that found by simulations. The lowest energy beam transported was ~ 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 injector and accelerator.

The maximum charge that we have transported is 4.6 nC (equivalent to 0.1 A average current). 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 solenoid fringe fields, and charge was lost.

3. Power Flow Measurements. The net rf power supplied to each accelerator-decelerator pair by its corresponding klystron is the sum of the power dissipated in the structures and the power used to accelerate the beam minus the power recovered from the beam. The reflected power is dependent on the match of the resonant bridge-coupler/accelerator-decelerator system to the waveguide and may change with different adjustments of the resonant bridge couplers.

Measurements of power flow were made under conditions of 16 MeV acceleration, 50% deceleration, and 0.065-A average beam current through the decelerators. The measured difference in net forward power 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 measurements, and the powers measured were consistent with estimates of copper losses in the structures and beam loading. We are quite close to break-even; i.e., recovered power is approximately equal to decelerator plus bridge-coupler losses and would be able to surpass it with higher beam loading.

In addition to power flow measurements, we examined the higher frequency components of the fields in the decelerators to look for evidence of dipole beam-breakup modes and symmetric nondecelerating modes. Estimates¹⁶ have indicated the possibility that the latter could cause the loss of $\sim 2 \times 10^{-2}\%$ 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. The two strongest modes, at 1.56 and 1.72 GHz, were observed at about 50-60 dB below the fundamental.

4. Instabilities. The beamline shown in Fig. 1 will tend to develop instabilities at sufficiently high currents. These instabilities follow from the fact that in any beam-transport system, charge will be scraped (lost to the walls) if the energy varies enough. In our case, ~ 10 -25% of the beam is purposely scraped at the 60° bend after the accelerator to eliminate a low-energy tail in the electron energy distribution. The location of the scraping is a peculiarity of our current design and could be changed in the future. 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, changing the amount of energy that is recovered and fed back to the accelerator. Depending on how the beam is being scraped, the details of the bridge coupler, and of the feedback system in use, the amplitude and phase of the change in energy recovery may be such as to make the deviation grow.

Simple physical arguments, and theoretical treatments described below, indicate that one would expect that scraping on the low-energy side of the beam would excite a dc instability that causes the energy of the beam to drop below the acceptance window of the beam transport and cut the current off. Scraping on the high-energy side should result in an ac instability.

5. 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. In the present case, the beam-transport system is capable of handling the energy spread produced by lasing at this fairly low efficiency. Very high efficiency wigglers would pose more of a design problem for the beamline, and these problems are now being addressed.

D. Simulations

Based on an equivalent circuit model of parallel tuned circuits representing an accelerator, a decelerator, and a bridge coupler, and with the recovered

beam power providing the feedback mechanism, two theoretical treatments of the system stability have been performed.^{16,17} One approach¹⁶ is a numerical solution of the equivalent circuit equations. The other approach¹⁷ is an analytical linearized stability calculation. In both cases, parameters are chosen to match as well as possible the observed frequencies, frequency splittings, and Q s of the coupled accelerator/bridge coupler/decelerator system.

For both treatments, several approximations are made. Only a single accelerator-decelerator pair is treated, and each accelerator and decelerator is treated as a single tuned circuit. Having two accelerator-decelerator pairs means that there are several loops around which power can flow. Modeling an accelerator as a single cavity means that power flow back and forth among the multiple cells of each tank is not taken into account. The feedback system, which tends to work against instabilities, is neglected. The numerical simulation does not include the nonisochronous nature of the 60° bend. This nonisochronicity produces a variation with energy in arrival time at the decelerator, hence a variation of the fraction of energy recovered.

Two examples of computer results are shown in Fig. 7. Figure 7(a) shows the instability that results when the beam is being scraped on the low-energy side. As the energy decreases, less beam current reaches the decelerators; thus, less energy is recovered and the gradient in the accelerators falls further. This ultimately causes all of the beam to be scraped and the energy to be clamped outside the acceptance range of the transport system. Figure 7(b) illustrates the other instability in which the energy rises, current is scraped at the high-energy side of the window, and a steady-state oscillation of the current and energy results. These calculations were done for average currents of 0.1 A.

An example of stability boundaries calculated from linearized stability analysis is shown in Fig. 8. The two parameters are b , twice the derivative of the beam current into the decelerator with respect to the accelerator voltage (di_d/dV_a) and h , the derivative of the phase of the beam current into the decelerator with respect to the accelerator voltage ($d\phi_d/dV_a$). The solid shaded region indicates the region of stable operation. For a given fraction of beam

current transported from the accelerator to the decelerator, the calculated stability boundary is independent of the value of the beam current in the accelerator (or into the decelerator). A qualitative agreement between the theoretical and measured stability boundaries has been obtained by relating the b value to the energy spectrum of the electrons as calculated from the computer code PARMELA and using measured values of current and scraping fractions when instabilities are deliberately induced. We have observed both types of instabilities. Figures 9 and 10 illustrate types of instability in accelerator voltage and beam current, respectively, that are observed when the beam is scraped sufficiently to induce instabilities. Figure 10(a) shows a typical current macropulse when the system is stable (The slow variation is not related to instabilities). Figures 9a and 10b show examples of the experimentally observed accelerator voltage and current when the dc instability is induced by scraping the low energy side of the beam. The high-frequency instability is illustrated by the accelerator voltage in Fig. 9(b) and the beam current in Fig. 10(c). The blurred appearance of Fig. 10(c) is caused by an oscillation at the frequency of Fig. 9(b). Note that the time scale of the voltage trace in Fig. 9(b) is 1 μ s/div, whereas in 9(a) it is 20 μ s/div. The experimental behavior of accelerator voltage and current are more complicated than the theory shown in Fig. 7 because of the rf feedback system. The behavior of Fig. 7(a) is modified because, after the initial droop, the rf feedback (which tries to hold the fields constant) overcomes the initial drop in field and, with the time constant of the cavities, drives the gradients back up to their nominal values. After a period dependent on the current, and typically ~ 20 μ s, the sequence repeats. If the feedback is turned off, the current remains zero and the voltage remains outside the band pass of the transport system. The high-frequency oscillation produced by scraping on the high-energy side of the beam is not appreciably affected by the feedback, whose high-frequency cutoff is well below the frequency of the oscillation (~ 0.9 MHz). Figure 9(c) was a case in which low-energy scraping first produced a voltage drop as in Fig. 7(a). Then, when the feedback brought the voltage back up, it overshot, produced scraping on the high-energy side and momentary oscillation as in Fig. 7(b) before repeating the process.

In general, our experimental results are in qualitative agreement with the results of the theory. The decay time for the current in the low-energy scraping instability and the oscillation frequency of the high-energy scraping instability are in reasonably good agreement. The oscillation seen in Fig. 10(b) represents the beating together of the $n/2$ mode with a mode of the coupled system (accelerator, decelerator, and bridge coupler) in which the accelerator and decelerator oscillate out of phase. A mode with the proper splitting (0.7-0.9 MHz) is experimentally observed in the frequency spectrum of the coupled system and is in agreement with the theory when the parameters of the tuned circuits are fit to the other constants of the system. The stability of the system in the computer simulation is somewhat less than that experimentally observed, but this difference may be due to the simplifications of the theory noted above.

Our results indicate that these instabilities can be a very serious consideration in future designs unless care is taken in design and implementation to avoid beam loss in those parts of the transport system that affect the energy-recovery process.

E. Conclusions

We have determined that the components of the energy recovery system functioned properly. Large deceleration of the beam was produced, and the decelerator gradients were adjustable over a range consistent with the nominal design of the resonant bridge couplers. Under nominal conditions, 100% of the beam was transported through the decelerators at least down to an energy of 3.5 MeV. Power flow measurements have been made, and the results confirmed that the energy lost by the electrons went into rf power at the fundamental-mode frequency and was recovered. The system was stable against oscillation under our normal operating conditions, but the predicted instabilities could be induced and had the expected characteristics. The mechanisms for the several modes of instabilities are qualitatively understood. Lasing at about 1% extraction efficiency did not degrade the performance of the system, but high-extraction efficiency wigglers will impact

system design. On the basis of our measurements to date, we can conclude that energy-recovery could be usefully applied to large FEL systems.

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Figure Captions

Fig. 1. The beamline includes B: buncher; A: accelerators; B: decelerators; W: wiggler; R: 180° bend; QS: quad singlets; QT: quad triplets. Emittance is measured at stations ①, ②, and ③; energy spread at stations ④ and ⑤.

Fig. 2. Emittance (a) and energy spread (b) vs the charge in a micropulse. The emittance is unnormalized and corresponds to the FWHM of the electron spatial distribution.

Fig. 3. Simulations of accelerator energy vs time in a micropulse: (a) shows relationship before 60° bends; (b) after the bends; (c) includes energy spread and time spread of the beam injected into the accelerator; (d) includes wake fields, i.e., an energy droop proportional to the instantaneous current at 1.4%/100A. Figure 3 (e) is a photograph of a typical measurement to be compared with (d). The energy range of the figures is 4%; the time range is 140 ps; the micropulse charge is 2.5 nC.

Fig. 4. Simplified cross section of bridge coupler.

Fig. 5. Mode structure in center cell of bridge coupler for different extension of tuning posts.

Fig. 6. Electron energy after deceleration vs position of 180° bend: accelerator energy, 13 MeV; maximum deceleration, 8 MeV.

Fig. 7. Simulation of beamline instabilities caused by (a) scraping beam on low-energy side, (b) scraping beam on high-energy side.

Fig. 8. Result of stability calculation; parameters are (b) twice the derivative of the beam current into the decelerator with respect to the accelerator voltage ($2 di_d/dV_a$), and (h), the derivative of the phase of the beam current into the

decelerator with respect to the accelerator voltage ($d\phi_d/dV_a$). The shaded region indicates stable operation.

Fig. 9. Accelerator voltages in the presence of instabilities: (a) when scraping the low-energy side of the e-beam, 20 $\mu\text{s}/\text{div}$; (b) when scraping the high-energy side of the e-beam, 1 $\mu\text{s}/\text{div}$; (c) when scraping the low-energy side of the e-beam, 20 $\mu\text{s}/\text{div}$ (see text for discussion). In each case, excursions represent approximately 3% in energy. (In the absence of instabilities, voltage excursions are $\sim 0.1\%$.)

Fig. 10. The e-beam current from the accelerator in the presence of instabilities, 20 $\mu\text{s}/\text{div}$: (a) no scraping; (b) scraping on the low-energy side of the e-beam; (c) scraping on the high-energy side of the e-beam [the blurred region is an oscillation at the same frequency as in 9(b)].

TABLE I
MEASURED AND CALCULATED EXTRACTION EFFICIENCY (%)

	Measured	1-D Single Wavefront	1-D Finite Pulse	3-D Single Wavefront	3-D Periodic	Estimated Theoretical
Uniform wiggler	1.3 ± (.2)	0.7	2.2	0.6	1.7	1.4
Tapered wiggler	2.0 ± (.3)	5.0	3.3	2.4	2.6	2.2

TABLE II
EMITTANCE MEASURED AT THREE STATIONS
FOR VARIOUS PEAK CURRENTS

Charge (nC)	Magnetic Bunching	I(A)	Emittance (n·mm·mrad)		
			c(1)	c(2)	c(3)
1.1	weak	30	1.3	---	2.0
1.1	strong	70	1.3	2.8	4.7
5.5	strong	300	1.4	4.7	6.0

TABLE III
ENERGY SPREAD AT TWO STATIONS
FOR VARIOUS PEAK CURRENTS

Charge (nC)	Magnetic Bunching	I(A)	Energy Spread (%)	
			$\Delta E(4)$	$\Delta E(5)$
2.7	strong	150	1.2	1.5
5.0	moderate	200	1.2	2.2
5.2	strong	300	1.2	2.7

FIG. 2

TIME ♦

(a)

(b)

(c)

(d)

(e)

Fig. 5

Fig 5

Fig. 6

Fig 8

Fig 9

(a)

(b)

(c)