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Transmission of Megawatt Relativistic Electron Beams through Millimeter Apertures

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High-power, relativistic electron beams from energy-recovering linacs have great potential to realize new experimental paradigms for pioneering innovation in fundamental and applied research. A major design consideration for this new generation of experimental capabilities is the understanding of the halo associated with these bright, intense beams. In this Letter, we report on measurements performed using the 100 MeV, 430 kW cw electron beam from the energy-recovering linac at the Jefferson Laboratory’s Free Electron Laser facility as it traversed a set of small apertures in a 127 mm long aluminum block. Thermal measurements of the block together with neutron measurements near the beam-target interaction point yielded a consistent understanding of the beam losses. These were determined to be 3 ppm through a 2 mm diameter aperture and were maintained during a 7 h continuous run.

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The energy-recovering linear accelerator (ERL) [1] offers significant advantages for delivery of relativistic electron beams for research: low emittance, small spatial size, high brilliance, and high power. Successful operation of an ERL based on superconducting rf [2] has sparked interest over the last decade in groups worldwide to seriously pursue ERL technology for new applications. These include light sources [3], electron-ion colliders [4], and the delivery of electron beams to cool high energy hadron beams [5].

At present, there is significant interest [6] in the possibility to utilize megawatt power electron beams from ERLs at energies of order 100 MeV on windowless gas targets to carry out new types of experiments to explore subatomic matter at low momentum transfers. The measurements reported here are motivated by the optimal design of the proposed DarkLight experiment [7] at the Jefferson Lab free electron laser (FEL), which will search for a new boson beyond the standard model with a mass in the range 10 to 100 MeV/c2. This type of experiment demands a thick, windowless, gas target which can be achieved by flowing gas through low conductance apertures with transverse dimensions of order millimeters. The target gas leaking through these tubes would be pumped away in stages to maintain vacuum in the beam pipes. To minimize the size and cost of these vacuum pumps and to maximize the gas target density, the tube diameters need to be minimized. At the same time, beam losses in traversing the tubes need to be kept extremely small to minimize background. The experiment is feasible only if the power losses of the megawatt electron beam as it traverses these narrow conductances is tolerable (≤ 10 ppm) and the resulting background rates are manageable.

The measurements reported here were carried out using the 100 MeV electron beam from the ERL at the 3F region on the IR beam line at the FEL facility at the Jefferson Laboratory with the apparatus shown schematically in Fig. 1. At a modified section of the electron beam (see Fig. 2) between two quadrupole triplets, a remotely controllable aperture block made of aluminum containing three apertures of 2, 4, and 6 mm diameter and 127 mm length was mounted in the beam pipe. The block also carried an optical transition radiation monitor (based on an aluminized silicon wafer) and a yttrium aluminum garnet (YAG) crystal—both viewed by a TV camera—to measure beam profiles and beam halo. Any of these apertures or profile monitors could be placed on the beam axis by remote control. The temperature of the aperture block was monitored by a resistance temperature detector. The block temperature, beam current, repetition rate, and bunch

FIG. 1 (color online). Schematic layout of the experiment at the FEL beam facility at Jefferson Laboratory. For ease of illustration, the drawing is not to scale.
charge were recorded. Neutron and photon background monitors were placed near the aperture block and around the beam lines and the linac, and their readings were continuously recorded.

The beam requirements for the transmission test were to achieve the maximum average beam current with small momentum spread and rms beam radius as well as minimal beam halo outside a 1 mm radius at the test aperture. This was to be done while managing collective effects, particularly, resistive wall heating in the aperture and the beam breakup (BBU) instability. These constraints imply a need for small beam envelope at the aperture, control of large amplitude beam components independently from control of the beam core, and mitigation of field emission from superconducting radio frequency cavities. These requirements were met by running a nearly standard machine configuration at a novel operating point [8]. The backleg 3F region of the IR FEL recirculator (Fig. 2) provides almost the exact configuration needed for the test. Only minor hardware modifications were required; all were adjacent to, and associated with, the installation of the test apparatus.

To migrate to the new working point, an optimized 60 pC/bunch injector tuning normally reserved for UV FEL operation in a separate recirculation transport line was grafted onto the IR FEL driver ERL, in which 135 pC/bunch is typically used. Although this combination reduced the available current from 10 to 5 mA, it provided multiple advantages. At the lower charge, the beam has smaller normalized rms emittance (5 mm mrad vs 10 mm mrad in both transverse planes, and 50 keV ps vs 80 keV ps longitudinal) and a less intense halo. With this injector tuning, the injected rms energy spread was 10 keV at a bunch length of order 3 ps rms. Much of the decrease in longitudinal emittance at lower charge is thus achieved through a reduction of intrinsic energy spread; the bunch length is approximately the same in each case.

For the test, we adopted a longitudinal match intended to reduce the 0.35%–0.4% rms relative energy spread delivered during FEL operations and to provide a significantly longer bunch so as to mitigate resistive wall heating. In this case, the first and last cryomodules chirped the bunch by accelerating 10° ahead of crest, and the remaining one—the center high-gain module—accelerated 14° after crest. For the cavity gradient profile used to achieve 100 MeV, this cross-phased acceleration completely dechirped the bunch, resulting in a very small full energy spread of 0.2% consistent with user requirements. The bunch length was as a consequence insensitive to recirculator momentum compaction and therefore remained long (3 psec rms as compared to as small as 0.12 psec rms during FEL operations) throughout transport, reducing the impact of any lattice dispersion errors, mitigating momentum tails, and minimizing resistive wall heating. Heating from resistive wall effects was evaluated with a model [9] based on the analysis of Bane and Sands [10], in which power deposition in an aperture of radius $r$ scales as $\sigma_z^{-3/2}/r$. Numerical estimates indicated that the uncompressed 3 psec bunch would deposit 0.05 W into a smooth 2 mm Al aperture of 127 mm length. Given the scaling with bunch length, this was deemed small compared to either heating by the compressed bunch or that anticipated from even limited levels of beam loss. Measured wall heating (see Table I) indicates a value of
about 0.5 W, probably due to the considerable surface roughness of the 2 mm bore.

Cross-phased acceleration also provided complete energy recovery: the injected and recovered energies were equal. The recirculator was operated isochronously by leaving the compaction of the first arc and FEL insertion at the nominal FEL operational value ($M_{56} = -0.2$ m) while adjusting the compaction of the second Bates bend (to $M_{56} = +0.2$ m) to compensate. With the overall momentum compaction thus set to zero ($M_{56} = 0$ m), reinjection timing variations with energy drifts were suppressed, and the system had a simple signature of the correct recovery phase: the beam energy at the dump was linearly independent of (and thus insensitive to) the reinjection phase, but the momentum spread was minimized when properly phased. This was verified experimentally by observing the energy-dispersed beam after energy recovery at the beam dump. With this choice of compaction schedule, it was also possible to use standard operational methods with only minor modifications. We only needed to move the dechirping module phase from 14° to 14° ahead of crest to approximate the settings used to run the FEL. All diagnostics and procedures previously validated were then immediately applicable.

A slight modification of the IR recirculator backleg 3F beam transport region (Fig. 2) provided a pair of six-quad telescopes that were used to match the FEL recirculator beam envelopes from FEL design values at the end of the first arc to a design "minibeta" waist with $\beta^* \sim 0.1$ m at the test aperture (which was installed at the center of 3F) and then back to the nominal envelopes at the entrance to the downstream FEL insertion. The final triplet of the upstream telescope, the test block, and the first triplet of the downstream telescope are shown in Fig. 1. With the nominal 5 mm mrad normalized emittance of the UV injector, the design $\beta^*$ of 0.1 m gives a 100 MeV spot size of 50 $\mu$m at the test aperture. This was as observed (Fig. 3). Because of the strong focusing, the variation of phase advance with momentum was over twice that during FEL operation (recirculator $\partial \psi / \partial \delta_{DL} \sim 25$; $\partial \psi / \partial \delta_{FEL} \sim 11$). However, the impact of increased chromaticity was more than offset by the reduction in momentum spread provided by cross phasing of the rf.

The design solution thus used the "normal" transverse match through nearly all the system while mimicking an "interaction region" in 3F (Fig. 2). This freed multiple quadrupole families for phase advance control. Without the five-quad rotator (which was modified to provide minibeta focusing), this was needed for BBU management [11]; it defines the turn-to-turn transfer matrix and thus the instability threshold. Phase advance was also used for halo management. Beam envelopes of large amplitude (halo) components of beam are mismatched to the core, and can be changed by varying the phase advance using selected quads known operationally to couple only weakly to the beam core envelopes. This can reduce halo amplitudes at constrained apertures essentially independently of the core matching condition. Development of this capability was a crucial determinant for successful transmission at low loss.

We note that the test aperture was located at the site of minimal halo response for the IR recirculator: large amplitude oscillations are minimized at this location [12], reducing potential losses. In addition, the full complement of beam position and profile monitors and orbit correction magnets standard to this region of the machine allows robust local control of the beam orbit, betatron envelopes, phase advance, and halo.

A final change in working point was driven by user requirements on energy and radiation background. Field emission from superconducting radio frequency cavities and secondaries from halo scraping during recirculation and recovery are primary background sources. Field emission was mitigated when the energy was reduced from 135 to 100 MeV. Halo loss radiation was managed as described

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TABLE I. Wakefield power and beam transmission losses.

| Run | Aperture | $P_B$ (W) | $P_W$ (W) | $P_H$ (W) | $I_{ave}$ (mA) | Beam loss | mm | W | W | mA | ppm |
|-----|----------|-----------|-----------|-----------|----------------|-----------|-----|---|---|----|-----|
| 1   | 6        | 0.33      | 0.08      | 0.5       | 3.84           | 1.3       |     |   |   |    |     |
| 2   | 4        | 0.52      | 0.10      | 0.9       | 3.93           | 2.1       |     |   |   |    |     |
| 3   | 2        | 1.95      | 0.50      | 2.9       | 4.25           | 6.8       |     |   |   |    |     |
| 4   | 2        | 1.09      | 0.50      | 1.2       | 4.23           | 2.8       |     |   |   |    |     |

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FIG. 3 (color online). Transverse beam profile distribution measured using the optical transition radiation at the aperture position. The frame enclosed between the cursors is $2 \times 2$ mm. The best Gaussian fits (red lines) to the horizontal ($x$) and vertical ($y$) projections (white lines) of the transverse profile are also shown. The $\delta \sigma_{x,y}$ are the uncertainties in the fit parameters given by the nonlinear least squares fit of the Gaussian model to the data.
above by controlling the evolution of phase advance along the machine to differentially focus halo and core.

Operations were conducted using nearly standard methods [13]. Starting with a low-power beam, longitudinal match, lattice dispersion, and betatron match were set; tunings were refined after each beam power increase. The minibeta section was tuned by first centering and recording the beam orbit through the 6 mm and subsequently the 2 mm apertures. After inserting the beam viewers, the beam spot at the aperture position was then minimized, as shown in Fig. 3. We tested various betatron matching solutions in an effort to limit loss of halo, reduce background, and control BBU, only to determine that the design solution proved to be most effective.

Loss management involved the same processes and level of effort, as was typical of FEL operations; after achieving acceptable transmission through an aperture, the beam was then retuned for low loss downstream. Several combinations of bunch charges and repetition rates were tested for minimal background and aperture block heating in transmission through the 4 and 2 mm apertures. Finally, with fixed 60 pC bunch charge, beam transmission through the 2 mm aperture was optimized for increasing steps of beam power, fine-tuning the beam after each step, until it reached its full power of about 450 kW (4.5 mA, 100 MeV).

Over the course of the two-week test run, we determined it was possible to compensate for machine drifts and suppress halo during cw operation by tuning on the drive laser timing (which affects the transverse match and consequently changes the injector energy). Halo losses were monitored by ion chambers and photomultiplier tubes distributed around the machine, and were kept minimal by fine adjustment of selected orbit correctors and quadrupole families while monitoring background. This limited temperature rise and neutron or photon backgrounds at the test block. Although a round beam spot of 50 μm radius was achieved, operations were typically conducted with 100 μm spot radii at the aperture. A novel manifestation of BBU was encountered during high-power cw operation. As the usual emittance exchange was unavailable due to quadrupole reassignment for halo control and core beam matching at the aperture, BBU control depended on the choice of the net turn-to-turn transfer matrix. However, the focusing required by the minibeta waist led to strong dependence of phase advance on energy. This high chromaticity coupled to typical linac energy drifts on the order of 0.1% and produced changes in phase advance (and thus transfer matrix); as a result, the system drifted across the instability threshold. This was readily managed operationally. Chromatic aberrations and onset of the instability made the beam size as viewed in real time on synchrotron radiation monitors grow large vertically, providing a clear signature of energy drift. When this was observed, operators simply shifted the energy back to the optimum value (reducing the vertical beam size) using a vernier cavity; during the 7 h run, this method effectively controlled the instability. These observations call into question the effectiveness of recent proposals to use chromaticity or Landau damping as a means of BBU stabilization [14]. It also contrasts with experience gained during IR FEL operation, during which chromaticity appeared, anecdotally, to alleviate BBU, but in a case where the beam energy spread was 50 times larger and the chromaticity ∼2 times smaller.

The wakefield and beam power losses were determined using temperature measurements of the aperture block as well as measurements of the neutron production downstream of the target. They are described in detail in Ref. [15] and are summarized here.

The power $P_B$ deposited by the beam in the aperture block is

$$P_B = c_p m \left( \frac{dT}{dt} \right)_{\text{block}} + P_C, \quad (1)$$

where $c_p m = 917 \text{ J/°C}$ and $(dT/dt)_{\text{block}}$ are the heat capacity and the rate of change of block temperature, respectively. $P_C$ is the power lost from the block through heat conduction and radiation to the beam pipe.

From the cooling data, we found an exponential cooling time $\tau = 357 \text{ min}$ and a base temperature of $T_0 = 27.2 \text{ °C}$. The integrated beam energy deposited in the block during a run from time $t_1$ to $t_2$ is the determined from $\Delta T = T(t_2) - T(t_1)$, the temperature rise during the run time $\Delta t = t_2 - t_1$, and $T_{\text{ave}}$ the average temperature during the run from

$$E_B = \int_{t_1}^{t_2} dt P_B = c_p m \left[ \Delta T + (T_{\text{ave}} - T_0) \frac{\Delta t}{\tau} \right]. \quad (2)$$

The power of the beam halo intercepted by the aperture block was only partly deposited in the block. Using the FLUKA code [16], a simulation showed that about 50% of the energy of the halo electrons entering the block near the 2 mm aperture is deposited in the block.

The neutron fluxes from the aperture block and the surrounding beam pipe were measured by a Canberra NP100B neutron REM counter positioned 1.9 m downstream of the aperture block and 24° to the left of the beam axis. From the plot of neutron dose rates $R_n$ vs the block power $P_B$, a linear relation was deduced of the form $R_n = 0.9[\text{REM}/(Wh)](P_B - P_W)$, where the straight-line intercept $P_W \approx 0.5 \text{ W}$ was interpreted as the power deposited by the wakefields of the beam. Since the rms width of the beam at the aperture was less than about 0.1 mm or 10 times smaller than the 2 mm aperture, it is reasonable to assume that the wakefields are largely governed by the bunch charge and time structure of the beam which was kept fixed throughout all four transmission runs.

As FLUKA simulations have shown, the power $P_H$ of the intercepted halo is about twice the difference between $P_B$ and $P_W$, such that $R_n \approx 0.45[\text{REM}/(Wh)]P_H$. 

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In order to compare this measured flux with theoretical predictions, the neutron flux at the neutron detector was modeled using the MCNP code [17]. The resulting neutron flux density was $dN_n/dAdt = 3300$ (neutrons/cm$^2$ W s) $P_H$. Using the neutron energy spectrum folded numerically with the response function (effective dose conversion factor) $c_n$ of the neutron detector [18], and the expected neutron flux density obtained using MCNP above, we obtained an expected dose rate of $R_n \approx 0.38$ [REM/(Wh)] $P_H$, which is only about 15% below the measured value reported above. Table I shows a summary of average results for the four transmission runs using this analysis.

In summary, the measurements reported here indicate that a 100 MeV electron beam of 0.43 MW average power can be passed indefinitely through a 2 mm diameter aperture of 127 mm length with an average beam loss of about 3 ppm with an estimated uncertainty of ±20%. This level of losses is acceptable for the DarkLight experiment, and the beam backgrounds generated are manageable. Substantial improvement on this performance can be achieved by employing both movable and fixed collimators upstream of the experiment, as has been established in experiments with internal gas targets in electron storage rings [19,20]. In addition, improvements in halo management can be obtained by further optimization of beam line tuning, particularly by incorporating data made available by large dynamic range measurement methods tested during the beam operations period [21]. Thus, luminosities of order $10^{36}$ nucleons cm$^{-2}$ s$^{-1}$ are expected to be achievable with megawatt electron beams of energy $\sim$100 MeV from ERLs incident on windowless gas targets.

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