ISBN: 978-3-95450-190-8 doi:10.18429/JACoW-ERL2017-TUIACC001

# LERF – NEW LIFE FOR THE JEFFERSON LABORATORY FEL*

C. Tennant†, S. Benson, J. Boyce, J. Coleman, D. Douglas, S. Frierson, J. Gubeli, C. Hernandez-Garcia, K. Jordan, C. Keith, R. Legg, M. McCaughan, M. Spata, T. Satogata, M. Tiefenback, S. Zhang, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

J. Balewski, J. Bernauer, J. Bessuille, R. Corliss, R. Cowan, C. Epstein, P. Fisher, I. Friščić, D. Hasell, E. Ihloff, J. Kelsey, S. Lee, P. Moran, R. Milner, D. Palumbo, S. Steadman, C. Tschalär, C. Vidal, Y. Wang, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA

T. Cao, B. Dongwi, P. Gueye, N. Kalantarians, M. Kohl, A. Liyanage, J. Nazeer, Hampton University, Hampton, Virginia, 23668, USA

R. Alarcon, D. Blyth, R. Dipert, L. Ice, G. Randall, B. Thorpe, Arizona State University, Phoenix, Arizona, 85004, USA

R. Cervantes, K. Dehmelt, A. Deshpande, N. Feege, Stony Brook University, Stony Brook, New York, 11794, USA

P. Evtushenko, HZDR, Dresden, Germany

M. Garçon, CEA Saclay, Gif-sur-Yvette, France

B. Surrow, Temple University, Philadelphia, Pennsylvania, 19122, USA

*Abstract*

In 2012 Jefferson Laboratory's energy recovery linac (ERL) driven Free Electron Laser successfully completed a transmission test in which high current CW beam (4.3 mA at 100 MeV) was transported through a 2 mm aperture for 7 hours with beam losses as low as 3 ppm. The purpose of the run was to mimic an internal gas target for DarkLight [1] – an experiment designed to search for a dark matter particle. The ERL was not run again until late 2015 for a brief re-commissioning in preparation for the next phase of DarkLight. In the intervening years, the FEL was rebranded as the Low Energy Recirculator Facility. In 2016 several weeks of operation were allocated to configure the machine for DarkLight with the purpose of exercising – for the first time – an internal gas target in an ERL. Despite a number of challenges, including the inability to energy recover without losses (precluding CW operation), beam was delivered to a target of thickness $10^{18}$ cm$^{-2}$ which represents a three order of magnitude increase in thickness from previous internal target experiments. Details of the machine configuration and operational experience will be discussed.

## BACKGROUND

After 15 years of consistent operation and upgrades Jefferson Laboratory's energy recovery linac (ERL) driven Free Electron Laser (FEL) ceased operation in 2012. Missing a steady funding for operations, the LERF has only been operational for a combined few weeks over the last five years. The common thread in all those run periods was the DarkLight experiment. This innovative experiment is searching for a dark matter particle by studying $e^-p$ scattering using a high power (1 MW) electron beam and a gaseous hydrogen internal target [2].

## 2012: APERTURE TEST

The DarkLight physics run requires continuously running a 1 MW beam into an internal target for 60 days. To address the technical challenges several different experiments were run at the LERF. One foundational question that needed to be answered is whether a high power, CW beam could be transmitted through an aperture consistent with that of an internal target with sufficiently low beam loss.

To mimic an internal target, apertures of (2, 4 and 6) mm diameter were drilled in a 127 mm long block of aluminum and the whole apparatus installed in the 3F region of the FEL (see Figs. 1 and 2). Though the target and detector package were ultimately located downstream in the 4F region, the 3F region was a natural choice for the initial test since it is well instrumented with BPMs, correctors and viewers, the beamline is well characterized (90° FODO cells) and it provides enough focusing to achieve the desired match with additional knobs available for halo control [3].

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
†tennant@jlab.org

ISBN: 978-3-95450-190-8 doi:10.18429/JACoW-ERL2017-TUIACC001

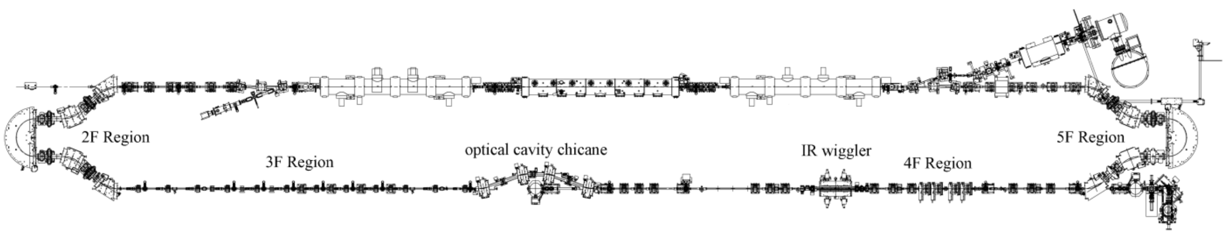


Figure 1: Schematic of the LERF (formerly FEL) without the UV bypass line.

Unlike running the machine as an FEL – which requires a short, high peak current bunch – DarkLight places a premium on long bunches with low energy spread so as to reduce dispersion errors and alleviate resistive wall heating. Establishing a longitudinal match to generate those kinds of bunches requires only changing the gang phase of one cryomodule and running the linac cross-phased. By switching the accelerating phase of the middle cryomodule (which has the same gradient as the two outboard cryomodules combined) to the falling side of the RF waveform the energy chirp is removed and nearly mono-energetic (~0.02% rms energy spread) at the exit (see Fig. 3).

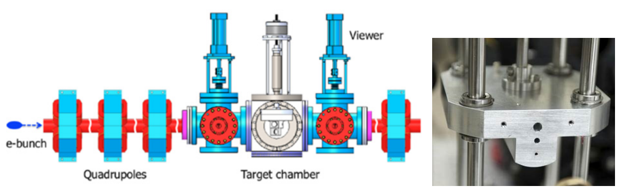


Figure 2: Schematic of the target chamber and diagnostics in the 3F region (left) and photo of the aperture block (right) showing the three different apertures (6, 4 and 2) mm (from top to bottom).

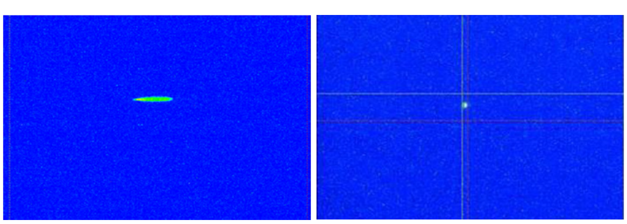

Figure 3: Energy spread as measured in the first arc for nominal operation (left) and with the linac cross-phased (right).

Installation of the test apparatus in the 3F region made the phase space exchange typically used to mitigate the multipass beam breakup instability (BBU) unavailable. Consequently, at currents above 4 mA we observed an interesting manifestation of BBU. Observant operators identified the onset of BBU by noting the characteristic vertical smearing of the beam image on a downstream synchrotron light monitor. By adjusting a vernier cavity in the linac by several 10's of keV, the vertical stripe returned to a normal round aspect ratio and the instability was averted. This behavior was due to the strong focusing needed to create a waist at the aperture (see Fig. 4), which led to higher than usual chromaticities; small fluctuations in the beam energy were thus sufficient to modify the turn-to-turn transfer matrix and lower the BBU threshold current. With a vigilant operator, however, the onset could be identified and controlled before the machine tripped.

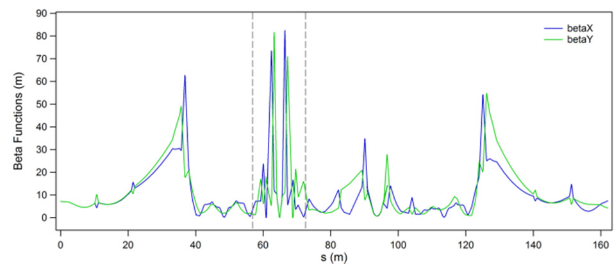


Figure 4: Beta functions in the LERF for the aperture test. The 3F region is marked by dashed lines. Note the strong focusing and beam waist at 65 m.

## 2015: RE-COMMISSIONING

In 2014 the FEL was renamed the Low Energy Recirculator Facility and rather than being a standalone, largely self-supported group, was absorbed into the Accelerator Division. Perhaps the most important consequence of the realignment is the LERF is now operated by members of the Operations group with supervision and guidance from subject matter experts. This presents a challenging transition since the FEL was never a user-facility, but rather an R&D platform in which beam and lattice configurations were always subject to change. Only a handful of "standard procedures" exist and trying to proceduralize 15 years of institutional knowledge is difficult, though progress is continually being made. An additional constraint is that due to the limited size of the Operations group, CEBAF and the LERF cannot be operated simultaneously.

In the fall of 2015 several days were dedicated to re-establish the configuration from the 2012 aperture test. Apart from expected minor hardware issues after 3 years of inactivity, the commissioning of the machine was incredibly efficient. During that period the gun was at its operating voltage of 350 kV for 70 hours (i.e. the amount of time operation with beam was possible). And in that span of time the machine was setup sufficiently to run CW beam. One major modification of the beamline from the 2012 run was the installation of a refurbished cryomodule (F100) in the first slot of the linac. This is the same cryomodule characterized by poor HOM damping, which

ISBN: 978-3-95450-190-8 doi:10.18429/JACoW-ERL2017-TUIACC001

lead to the onset of the beam breakup instability (BBU) [4]. Whereas previously the module was in the second linac slot, with its current location at the start of the linac where the beam energy is lower, the beam breakup threshold was expected to be lower than initially measured (2.5 mA for the nominal configuration without invoking the phase space exchange). In fact during the few minutes we ran CW beam (the photocathode quantum efficiency was dropping precipitously) we observed the tell-tale signs of the onset of BBU – repeatable machine trips at a given current due to localized beam loss and an associated vertical smear on the downstream synchrotron light monitor – at currents less than 2 mA (see Fig. 5).

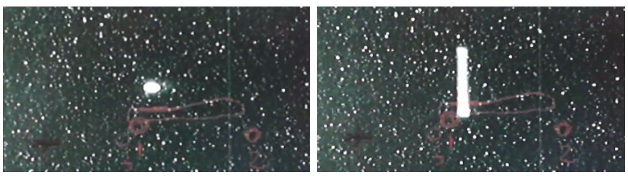

Figure 5: Screenshot of an SLM showing stable operation (left) and at the onset of BBU (right).

## 2016: ENGINEERING RUN

With the success of the aperture test, several weeks in 2016 were allocated to commissioning the machine with the DarkLight experimental package installed. The interaction region was installed in place of the IR wiggler (4F region) and consists of a 0.77 m long gaseous hydrogen target, detector, 5 kG solenoid and Moller dump. A staged approach was taken wherein commissioning started with only the solenoid and Møller dump installed ("engineering run"), followed by a run with the target installed ("target run"). Significant re-work immediately upstream and downstream of the interaction region were required to integrate the experimental package. The beamline must match (transversely and longitudinally) the beam to the target, ensure that the linac-to-linac transport exchanges the transverse phase spaces (to mitigate BBU), and cleanly transport a degraded beam to the dump. After interacting with the target, the electron beam will have increased energy spread, transverse size and be transversely coupled. To achieve a swap of the transverse phase spaces, skew five-quadrupole telescopes were embedded between two triplets for each side of the interaction region to complete the solenoid-induced partial phase space exchange (21.5° from each telescope and 47° from the solenoid). A schematic of the beamline is shown in Fig. 6. By uniformly distributing the exchange modest quadrupole strengths are maintained so as to avoid ringing in the beam envelopes – alleviating aberrations and helping to avoid beam losses from the degraded beam [5].

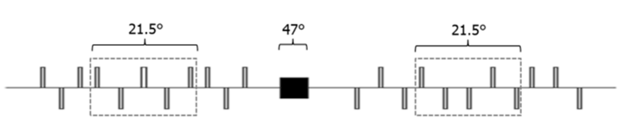


Figure 6: Schematic of the 4F beamline showing the target (black box) and skew quadrupole telescopes on either side.

Operation of the machine deviated from the previous practice of running 12 hour day shifts. With around the clock staffing available from the Operations group, we ran 24 hours/day for 8 days. The primary goal of the engineering run was to exercise high beam power (CW beam up to 4.5 mA at 100 MeV) with the skew quadrupoles and solenoid on. However a number of factors precluded us from being able to establish a lossless, CW setup even with the skew quadrupoles and solenoid off. We experienced considerable growing pains in making the transition to an element database. For much of the engineering run magnet settings from previous all-saves were not loaded correctly or the incorrect field map was being applied. Not being able to trust magnet settings – in addition to troubleshooting a variety of diagnostics systems (BPMs, viewers, Happek bunch length monitoring system) – created less-than-ideal conditions for a major rework of the machine setup. It was also discovered that when powered, the solenoid generated significant vertical steering due to a winding issue which proved difficult to correct. Though unable to achieve a CW-compatible machine setup, we were able to run 6% duty factor at 1.25 mA with minimal losses.

## 2016: TARGET RUN

The goal of the target run was to pick up where the engineering run left off and be able to run high beam power with the target installed – which includes a series of Kapton baffles, with small (3 mm diameter) apertures and differential pumps to isolate the target from the ERL transport system. Despite being able to match the beam to the solenoid and correcting for the vertical kick, transmission through the interaction region was poor. A post-mortem on the target baffles revealed that they were misaligned – there simply was no way to achieve good beam transmission. Losses on the apertures and the inability to energy recover precluded CW operation with high power beam. Nevertheless, the DarkLight collaboration was able to exercise the target with 300 mTorr of gas and demonstrate stable operation of the system. Data was also recorded with and without gas in the target for various solenoid settings. Under these conditions, there was no obvious effect on the electron beam.

Toward the end of the run opportunities became available to characterize the beam at multiple points in the machine using quadrupole scans to extract the emittance and Twiss parameters [6]. Data was taken in the 2F region (before the first Bates bend), in the 3F region (before the optical cavity chicane) and in the 4F region (before the DarkLight solenoid). Results of the analysis are summarized in Fig. 7. It is clear that there is degradation of the horizontal emittance after traversing the first Bates bend. In a typical LERF setup for FEL operation there are multiple parasitic compressions in the arc (where the bunch goes through a full compression), this would not be at all surprising. However, since the beam is cross-phased and does undergo over-compression, it is unclear what the source of degradation is. There also appears to be a jump

ISBN: 978-3-95450-190-8 doi:10.18429/JACoW-ERL2017-TUIACC001



in the vertical emittance in the 3F region. Note that the data was taken on two separate occasions a week apart and in the intervening period the gun photocathode was re-cesiated, which may account for some of the discrepancy.

As is often the case, as the running period came to an end the machine was just hitting its stride. Many of the hardware issues had been resolved and the various sub-systems (gun, drive laser, RF, magnets, most diagnostics) were running well.

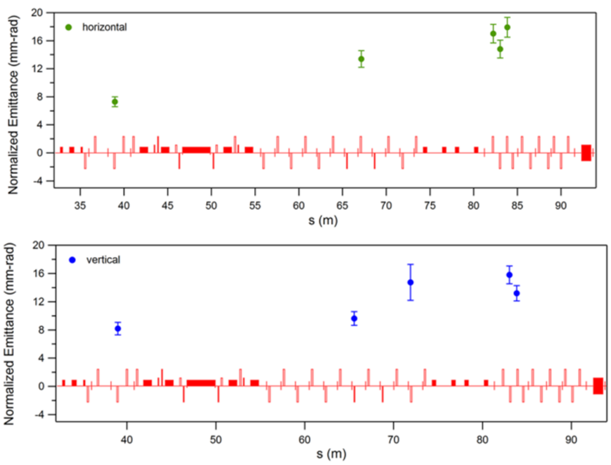


Figure 7: Measured normalized horizontal (top) and vertical (bottom) emittances from the exit of the linac to the exit of the target.

## LOOKING FORWARD

Though the results of the target run were encouraging, there remain of number of issues to work through before a dedicated DarkLight physics run can commence. Achieving alignment of the target baffles and correction of detector solenoid deflecting fields are the highest priorities so as to allow full beam transmission through the interaction region. Many of the software and hardware issues that plagued us early on have been resolved and the operations staff is now proficient with LERF operations. Despite the challenges and a shorter than anticipated run schedule, in the end beam was run to an internal target with thickness $10^{18}$ cm$^{-2}$ – representing a three order of magnitude increase in thickness from previous internal target experiments.

In addition to supporting DarkLight, there are a wide range of other proposals for using the LERF. Looking to the immediate future, the laboratory's highest priority is the design of the Jefferson Laboratory Electron-Ion Collider (JLEIC), a machine which collides polarized electrons (originating from CEBAF) with medium energy ions (originating from a new ion complex) [7]. In order to achieve the specified luminosity ($10^{-34}$ cm$^{-2}$s$^{-1}$), several stages of electron beam cooling are utilized. The most challenging is the high energy, bunched beam cooler designed to cool 100 GeV protons. The cooler requires handling a low energy, high power electron beam. The current baseline design uses an ERL to accelerate and condition the beam for delivery to a non-equilibrium circulating cooler ring (CCR) where it makes up to 20 turns before being returned to the ERL via a beam exchange region for recovery. Several key areas of technical risk could be addressed in the LERF, some requiring little modification (studies of CSR shielding) and some requiring significant changes to the existing infrastructure (installing a CCR and testing the design of the beam exchange region).

Other novel applications are being considered as well. In addition to its ability for high power lasing in the IR and UV regimes, the LERF is being considered for medical isotope production, studying photonuclear activation at low energy and as a source of intense positrons [8].

## REFERENCES

[1] R. Alacorn *et al.*, Phys. Rev. Lett. **111**, 164801 (2013).
[2] P. Fisher *et al.*, JLAB PR12-11-008 (2011).
[3] D. Douglas *et al.*, JLAB TN 13-009 (2012).
[4] C. Tennant *et al.*, Phys. Rev. ST. Accel. Beams, **8**, 074403 (2005)
[5] D. Douglas, *JLAB TN in preparation*.
[6] C. Tennant, JLAB TN 16-047 (2016).
[7] S. Abeyratne *et al.*, arXiv:1504.07961 (2015).
[8] https://www.jlab.org/indico/event/199/