CEBAF ENERGY RECOVERY EXPERIMENT*

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Abstract

A successful GeV scale energy recovery demonstration with high ratio of accelerated-to-recovered energies (50:1) was recently carried out on the CEBAF recirculating linear accelerator. Future high energy (multi-GeV), high current (hundreds of milli-Amperes) beams would require gigaWatt-class RF systems in conventional linacs - a prohibitively expensive proposition. However, invoking energy recovery [1] alleviates extreme RF power demands; required RF power becomes nearly independent of beam current, which improves linac efficiency and increases cost effectiveness. Furthermore, energy recovering linacs promise efficiencies of storage rings, while maintaining beam quality of linacs: superior emittance and energy spread and short bunches (sub-pico sec.). Finally, energy recovery alleviates shielding, if the beam is dumped below the neutron production threshold. Jefferson Lab has demonstrated its expertise in the field of Energy Recovery Linacs (ERLs) with the successful operation of the Infrared FEL, where 5 mA of average beam current have been accelerated up to 50 MeV and the energy stored in the beam was recovered via deceleration and given back to the RF power source. To date this has been the largest scale demonstration of energy recovery.

MOTIVATION

Presently there are designs for several ERL based accelerator systems world-wide. These include designs for FELs (KAERI, BINP Accelerator-Recuperator), synchrotron light sources (Cornell/J-Lab ERL, ERLSYN, 4GLS, BINP MARS), electron cooling devices (BNL-BINP) and electron-ion colliders (ELIC, eRHIC). Some of the ERL-based accelerator applications that are being proposed require beam currents of the order of 100 mA, while the beam energy for these applications ranges from the currently achieved 50 MeV up to 5 GeV. There are several important accelerator physics and technological issues that must be resolved before any of these applications can be realized. The J-Lab FEL Upgrade, presently under construction and designed to accelerate 10 mA up to 150-200 MeV and then subjected to energy recovery, and the proposed Cornell/J-Lab ERL Prototype, designed to accelerate 100 mA up to 100 MeV and then decelerated for energy recovery, will be ideal test beds for the understanding of high current phenomena in ERL devices. Last year, in an effort to address the issues of energy recovering high-energy beams, Jefferson Lab proposed a minimally invasive energy recovery experiment utilizing the CEBAF accelerator [2]. The experiment was successfully carried out at the end of March '03 by demonstrating energy recovery of a 1 GeV beam. Until this experiment, there were no plans aimed to address issues related to beam quality preservation in systems with large final beam energy (up to 1GeV) or a large energy ratio between final and injected beams (a factor of 50).

THE EXPERIMENT

General Layout

A schematic representation of the CEBAF with Energy Recovery experiment is illustrated in Figure 1. Beam is injected into the North Linac at 56 MeV where it is accelerated to 556 MeV. The beam traverses Arc1 and then begins acceleration through the South Linac where it reaches a maximum energy of 1056 MeV. Following the South Linac, the beam passes through a newly installed phase delay chicane. The chicane was designed to create a path length differential of exactly ½-RF wavelength so that upon re-entry into the North Linac, the beam is 180^0 out of phase with the cavities and will subsequently be decelerated to 556 MeV. After traversing Arc1 the beam enters the South Linac - still out of phase with the cavities - and is decelerated to 56 MeV at which point the spent electron beam is sent to a dump. In this way the beam gives energy back to the RF system, which may be used to accelerate subsequent beam.

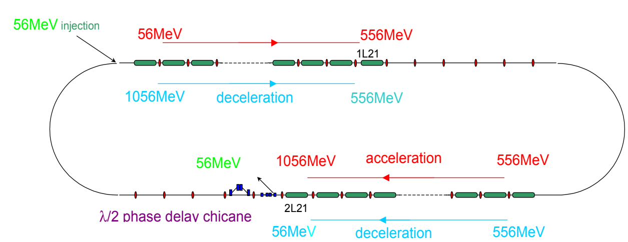

Figure 1: CEBAF Energy Recovery Experiment - layout

Beam Transport – Linac Optics

The linac optics were optimized for the two beams so that the lower energy beam in each linac had a tight, 120^0 betatron phase advance per cell lattice, as illustrated in Figures 2 and 3. Appropriate optics design for the spreader and recombiner of Arc2 (following South Linac) facilitates compensation of beta mismatches introduced by optimizing the linac optics for the lower energy beam.

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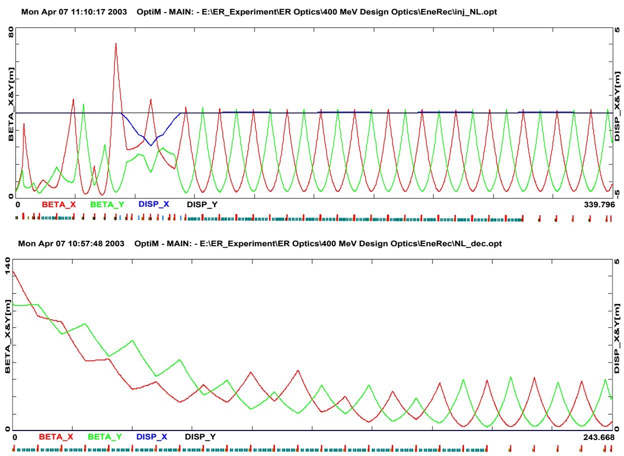

Figure 2: North Linac – top: 120° per cell lattice for the accelerating beam (56–556MeV) and bottom: mismatched optics for the decelerating beam (1056–556MeV)

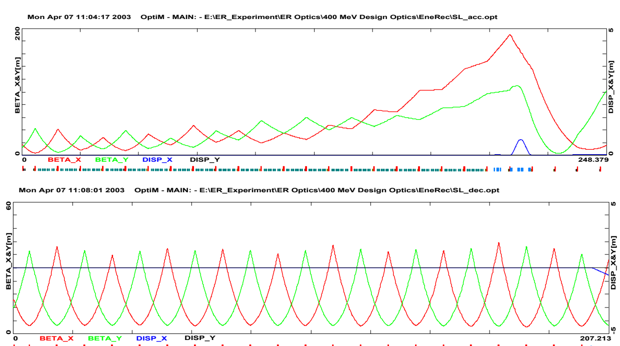

Figure 3: South Linac – top: mismatched optics for the accelerating beam (556–1056MeV) and bottom: 120° per cell lattice for the decelerating beam (556–56MeV)

MEASUREMENTS

To gain a quantitative understanding of the beam behavior through the machine, an intense effort has been made towards planning measurements for the experiment [2]. One of the most critical is measuring the beam emittance, which serves as a figure of merit by characterizing the extent to which beam quality is preserved during energy recovery. A scheme has been implemented to measure the emittance of the energy-recovered beam prior to being sent to the dump [3], as well as in the injector and in each arc. In this way one can understand how the emittance evolves through the machine. One of the performance limitations of high-energy beams is a beam halo or small regions of phase space outside the beam core. Furthermore, the halo was measured at several locatins: in the injector, in both arcs and in the extraction dump to ascertain what effects energy recovery has on halo formation and evolution. In addition to the beam-based measurements mentioned above, another important class of measurements deals with the RF system's response to energy recovery. It tested the RF system response by measuring the gradient and phase stability with and without energy recovery for selected cavities throughout the North and South Linac. Once satisfactory measurements have been obtained using the nominal 56 MeV injection energy, a parametric study exercising high final energy (1020 MeV) to injection (20 MeV) ratios was carried out with the measurements repeated

RESULTS

Initial evidence of energy recovery mode is illustrated in Figure 4 by a synchrotron light monitor view of two beams in Arc1: the accelerated and half-way-energy-recovered beams at 556 MeV.

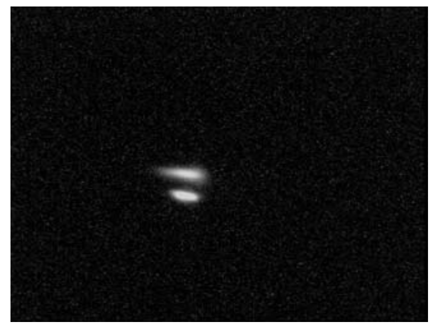

Figure 4: Arc1 synchrotron light monitor – two 'spots': accelerated/decelerated beams at 556 Me

Similarly, Figure 5 shows the two beams further downstream (end of South Linac): almost-fully-accelerated (~1GeV) and almost-fully-energy-recovered (~100MeV) beams as seen on a viewer.

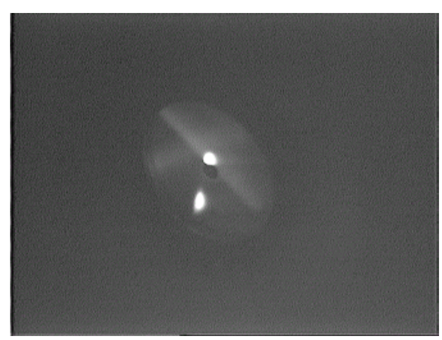

Figure 5: Two beams (~ 1 GeV and ~ 100 MeV) at the end of South Linac - SL16 beam viewer (E_{inj} = 20 MeV)

Finally, a fully energy recovered beam at 56 MeV, as seen on an optical transition radiation monitor in the extraction line is illustrated in Figure 6.

Emittance Measurements

Transverse emittance has been measured with wire scanners for altered optics (quads scan with 'closed beta bump') at several locations throughout the energy recovery cycle: at injection, in both arcs and right before extraction into the dump. A typical wire scan with two beams is illustrated in Figure 7.

Figure 6: Energy recovered beam (56 MeV) at the dump (optical transition radiation monitor view)

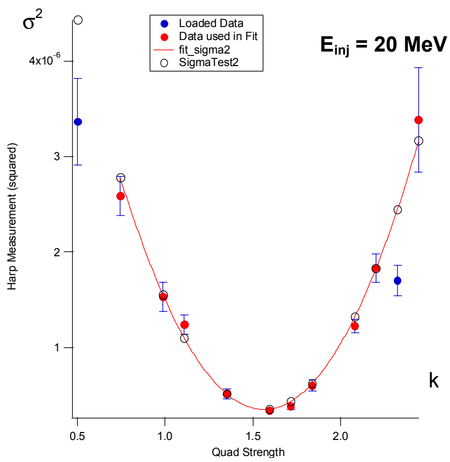

Figure 7: Wire scan with two beams – fully accelerated and energy-recovered beams

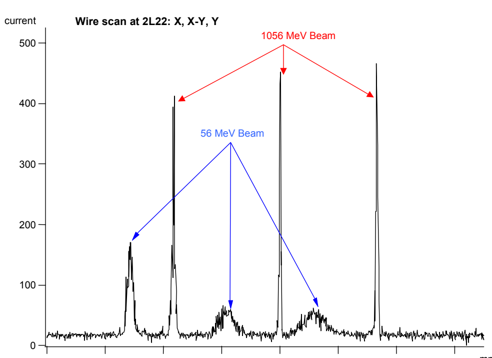

Figure 8: Emittance as extracted from least-squares quadratic fit

Emittance measurements in the quad-drift-wire configuration were carried out for varying quad strength (a quad directly upstream from the scanner). Parabolic dependence of measured beam profile (σ^2 vs quad strength k) is described in Figure 8.

Halo Measurement

Large dynamic range beam profile measurements of the energy recovered beam were carried out in front of the extraction dump. The measurements were made with a wire scanner and three photomultiplier tubes located 60cm downstream [4]. Figure 9 shows the measured beam profiles (X on right, Y on left) the Y profile is consistent with a Gaussian distribution through five decades of beam intensity.

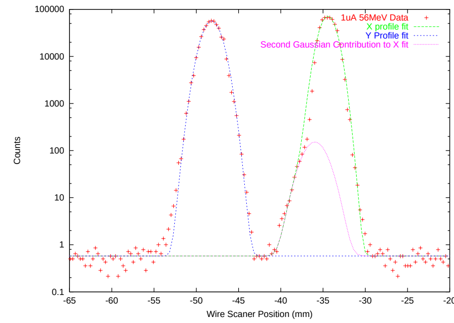

Figure 9: Beam halo (56 MeV, 1µA beam)

RF Transient Measurement

Finally, RF transients at full charge were measured for the last cavity in South Linac. Forward power required by the cavity with and without energy recovery is shown in Figure 10. One can see significant drop in forward power in the energy recovery mode.

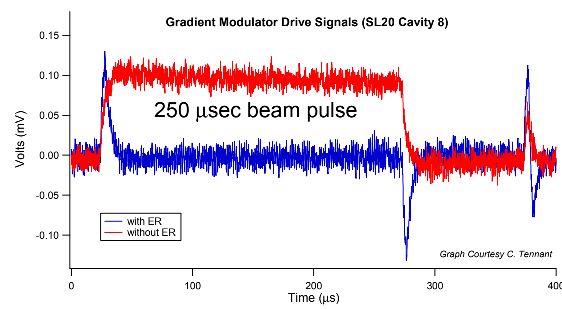

Figure 10: Forward power with/without energy recovery

SUMMARY

Measured beam quality characteristics show no degradation of the initial phase space during the energy recovery process. Beam profile is consistent with a Gaussian distribution. Analysis to obtain limits on the amount of beam halo is in progress. There is expectation for future R&D activities on Energy Recovery at CEBAF.

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