THE CEBAF ENERGY RECOVERY EXPERIMENT: UPDATE AND FUTURE PLANS*

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Abstract

A successful GeV scale energy recovery demonstration with a high ratio of peak-to-injection energies (50:1) was carried out on the CEBAF (Continuous Electron Beam Accelerator Facility) recirculating superconducting linear accelerator in the spring of 2003. To gain a quantitative understanding of the beam behavior through the machine, data was taken to characterize the 6D phase space during the CEBAF-ER (CEBAF with Energy Recovery) experimental run. The transverse emittance of the accelerating and energy recovered beams was measured in several locations to ascertain the beam quality preservation during energy recovery. Measurements also included the RF system's response to the energy recovery process and transverse beam profile of the energy recovered beam. One of the salient conclusions from the experiment is that the energy recovery process does not contribute significantly to the emittance degradation. The current status of the data analysis will be presented as well as plans for a GeV scale energy recovery experimental run with current doubling.

INTRODUCTION

Several future accelerators rely on energy recovering linacs (ERLs) to achieve their design goals [1]. The broad issues with these future designs can be categorized into two categories:

- Energy recovery of high current (~100mA) beams. In this case the large bunch charge of the beam excites high order modes (HOMs) of the accelerating structure. These HOMs can result in beam breakup unless they are sufficiently damped.
- Energy recovery with large peak energy to injection energy ratio beam (50:1). In this case the large number of accelerating cavities in the linac must propagate the two beams concurrently without introducing significant transport changes.

This paper focuses on the latter issue, where using the CEBAF accelerator the electron beam was successfully accelerated to 1GeV and then energy recovered by the introduction of a $180°$ phase chicane. During this experiment 39 superconducting RF sections participated and simultaneously transported both beams. The experiment was executed during March 2003. This paper summarizes the results of the March run as well as the offline data analysis.

ACCELERATOR CONFIGURATION

A schematic representation of the CEBAF-ER experiment (for 55MeV injection energy) is shown in Figure 1. During the ER run, the beam was injected into the linac with energies of 20MeV or 55MeV. Each linac was configured to provide 500MeV of acceleration so that the total energy at the end of the two linacs was 1GeV plus the injection energy. After the second linac the beam went through the $\lambda_{RF}/2$ phase chicane, so that the beam was $180°$ out of phase with the accelerating RF system. The out-of-phase beam then passed through the same RF structures and subsequently returned energy back into the RF cavities. At the end of the first linac, both beams now are equal in energy and are simultaneously transported through the arc. By the time the beam passes through the second linac for the second time, it had an energy equal to the inital injection energy. At this point it was deflected into a beam dump. The peak energy to injection energy ratio for the two configurations are 19 [55MeV injector energy] and 50 [20MeV injector energy].

During the ER experiment, the nominal CEBAF diagnostic equipment was used to characterize the beam transport. Additional instrumentation for the new beam dump and $\lambda_{RF}/2$ chicane were added. This instrumentation included beam position montitors, wire scanners, beam current cavities and optical transistion radiation monitors. The beam dump diagnostics provided measurements of the beam energy, current and transverse profile after energy recovery.

The machine optics were optimized for the lowest energy beam in each linac. Only one beam was present in the second arc and optics in the second arc, including the spreader/recombiner regions, was designed match the high energy beam back into the first linac [2]. In this way the effects of the different transverse kicks of the RF cavities was minimized.

A limited time period was set aside to perform this experiment. The first beam to be energy recovered was with the injection energy of 55MeV. Figure 2 shows the image from the synchrotron light monitor in the first arc, clearly showing the presence of the two beams. We were able to acheive full 80μA CW operation with this configuration. Data was taken to characterize the 6D phase space of this

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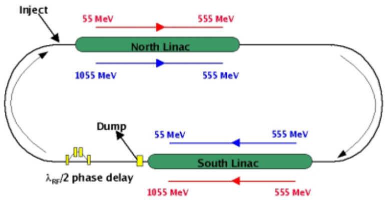

Figure 1: CEBAF Energy Recovery Experimental layout for the 55MeV injection configuration.

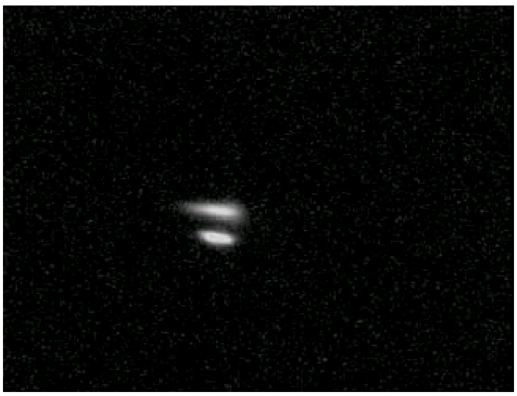

Figure 2: Synchrotron light image in Arc-1, showing the presence of the accelerated and energy recovered beam.

configuration and then the injector energy was lowered to 20MeV to achieve a larger peak to injection ratio of 50:1. In this configuration only modest [$\sim 1\mu$A] amounts of CW beam current was energy recovered. The limitations are not precisely known, but with such a low injection/dump energy the beam size in the dispersive bend to the dump were very large. This large horizontal beam resulted in beam scraping and limited the amount of CW beam that could be delivered. The following sections describes some of the measurements made during the experiment.

PHASE SPACE MEASUREMENTS

In order to study any degradation to the 6D phase space of the beam, emittance measurements were made at four locations [3]:

1. The injector; beam energy is equal to the injection energy [s=30m].
2. The first arc, accelerating beam; beam energy is 500MeV plus the injection energy [s=360m].
3. The second arc; beam energy is 1GeV plus the injection energy [s=985m].
4. End of the first arc, recirculated beam; beam energy is near the injection energy[s=2100m].

These four points provide information on beam properties from injection to full energy and then back at the injection energy. The data was acquired via wire scanners at these locations with multiple optics. Some of the issues that were dealt with include:

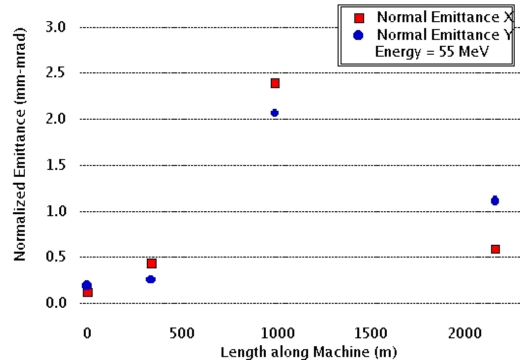

Figure 3: Emittance measurements for the 55MeV injector/dump energy.

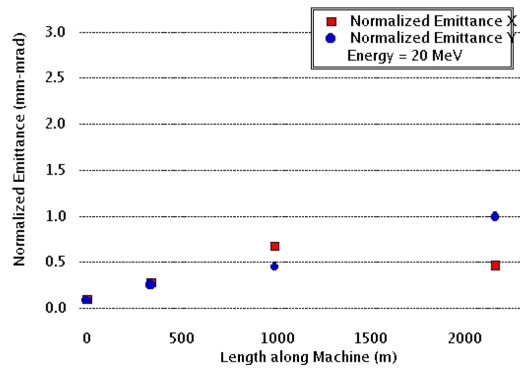

Figure 4: Emittance measurements for the 20MeV injector/dump energy.

- Two beams co-propagating in the first arc, resulting in twice the number of peaks in the wire scan data.
- Obtaining multiple optic settings to measure the emittance of the energy recovered beam without affecting the accelerating beam.

The normalized emittance for the 55MeV injection configuration is shown in Figure 3. The Arc-2 measurement appears anomalous and is not consistent with the other data points or with the data taken with the 20MeV injection configuration. The emittance for the 20MeV injection configuration is shown in Figure 4. The 20MeV data is much more self consistent. Ignoring the anomalous Arc-2 measurement in the 55MeV configuration, the data shows that the emittance does indeed degrade from injector to the dump. The degradation is the same for the accelerating beam and the recirculating beam suggesting that energy recovery is not causing any additional phase space degradation.

BEAM HALO

Large dynamic range beam profile measurements of the energy recovered beam were made with a wire scanner located right before the dump [4]. Figure 5 shows the profile for the 55MeV configuration and the profile for the 20MeV configuration in shown in Figure 6. The 55MeV profile

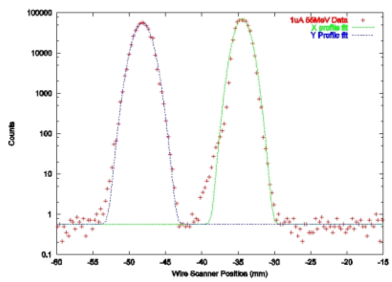

Figure 5: Beam profile after energy recovery for the 55MeV injection configuration.

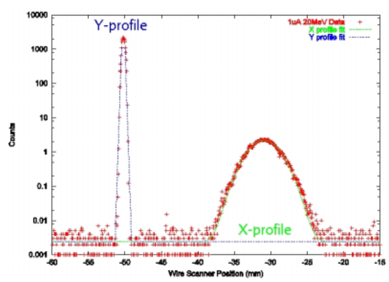

Figure 6: Beam profile after energy recovery for the 20MeV injection configuration.

shows a clean beam distribution over almost five decades of amplitude. The wide horizontal beam profile in the 20MeV configuration is what limited the CW beam current delivery.

RF FORWARD POWER

The lure of ERLs is that one can obtain beams of enourmous power with only modest amounts of RF power. In Figure 7 the forward RF power in an RF cavity is shown. The data was taken with *tune* beam which has a 250μsec duration. The red curve is with only one beam propagating through the cavity, clearly showing the RF load. The blue curve is for energy recovery configuration where the forward power is consistent with no beam operation. The short pulse at the begining and end of the energy recovered data are due to the 4μsec transit time of the machine and are an artifact due to the use of *tune* beam to acquire the data.

CONCLUSIONS

Energy recovery of a beam with a peak to injection energy ratio of 50:1 has been successfully demonstrated. Measurements of the beam phase space show that energy recovery does not introduce any substantial phase space degradation. Beam profiles after energy recovery do not show any distortions and for the 55MeV configuration the beam was Gaussian over almost five decades. Many lessons were learned during this first run. The wire scanner software has been upgraded to more easily handle wire

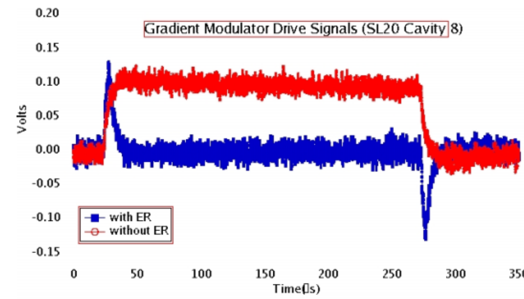

Figure 7: Forward RF power for a RF cavity. The red data is for a single beam propagating through the cavity. The blue data is for in phase and $180°$ out of phase beams co-propagating through the cavity.

scans with two beams present. Additional diagnostics has been identified that would help to quantify some of the beam parameters include, large dynamic range wire scanners in the injector and beam current cavity located just before beam extraction to the dump. This beam current cavity should measure zero beam current in the presence of the two beams and with appropriate electronics would measure beam loss at better than the 1ppm level.

Other ER efforts at JLAB include energy recovering 10mA of beam at the JLAB FEL and investigating the excitation of HOMs in the cavities. Energy recovery with current doubling in CEBAF is also planned for the future. ER with current doubling involves reconfiguring the $\lambda_{RF}/2$ chicane into a $\lambda_{RF}/4$ chicane. In this configuration the beam is accelerated on the first pass, receives no significant energy adjustments on the second or forth passes and is energy recovered on the third pass.

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REFERENCES

[1] L. Merminga, "Physics Challenges for ERL Light Sources", in *these Proceedings, MOYCH02*.

[2] A. Bogacz *et al.*, "Cebaf Energy Recovery Experiment", in *Proceedings of the 2003 PAC*, http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOAC006.PDF.

[3] C. Tennant *et al.*, "Beam Characterization in the CEBAF-ER Experiement", in *Proceedings of the 2003 PAC*, http://accelconf.web.cern.ch/accelconf/p03/PAPERS/RPPG032.PDF.

[4] A. Freyberger, "Large Dynamic Range Beam Profile Measurements", in *Proceedings of the 2003 PAC*, http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPPB070.PDF.