

CEBAF-ER: An Energy Recovery and Current Doubling Operational Mode for the Continuous Electron Beam Accelerator Facility

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Abstract

Successful IR Demo operation [1] has led to widespread consideration of the application of energy recovery to large-scale SRF linacs. Cornell University [2], Brookhaven National Laboratory [3], Jefferson Lab [4] and Lawrence Berkeley National Laboratory [5] have all manifested interest in the design and construction of energy recovered linac (ERL) based light sources; various groups [6] are similarly investigating the use of such devices in electron-proton and electron-ion colliders. Ongoing consideration of these systems has led to the awareness – enunciated by Hutton [7] and implemented in two small machines (the Bates linac [8] and the JLab IR Demo [9]) – that recirculated linacs can effectively “current double” through appropriate longitudinal gymnastics.

We describe a means by which the community investment represented by CEBAF can be leveraged using local FEL experience in energy recovery, thereby executing a proof-of-principle demonstration of these forefront technologies on scales relevant to the emergent interest. Specifically, we relate a simple means of testing both energy recovery and current doubling in CEBAF.

Concept & Requirements

CEBAF-ER is simply “CEBAF with Energy Recovery”, an operational mode readily generated through the appropriate installation of RF-phase-lag-inducing doglegs. A concept for the implementation of energy recovery in CEBAF has been detailed previously [10]. As discussed by Hutton [11] and executed both at Bates [12] and in the IR Demo [13], such of manipulations can – in addition to allowing energy recovery – also double the current transported in a recirculated linac. In this note, we provide a discussion of system requirements and a design for a simple and inexpensive version of CEBAF-ER based on components available at Jefferson Lab. In addition to demonstrating energy recovery and current doubling on a large scale, CEBAF-ER will allow at least initial investigation of machine performance as a function of the injected-to-full energy ratio, an issue of some contention amongst machine designers [14].

System Requirements – CEBAF-ER must:

- noninvasively provide quarter- and half-RF-wavelength phase differentials so as to allow the desired technology demonstrations to be interleaved with “main-mission” CEBAF user activities,
- allow for extraction of energy recovered beam,
- provide a means of examining injected:full energy ratio effects, and
- present reasonable beam transport/beam optical properties to ensure robust machine operation.

These requirements must be viably addressed at low cost and thus should be met using existing Jefferson Lab hardware.

Generation of Path-Length Differentials – Key to meeting the above requirements is the availability of appropriate components. Generation of RF phase delays/path length differentials can most easily be accomplished using doglegs (magnetic chicanes), as can extraction of the energy-recovered beam. These would ideally be based on some JLab standard dipole sets and should be designed so as to accommodate rapid, noninvasive transitions between nuclear physics service and machine physics studies.

Fortuitously, the JLab FEL drivers utilize components that support this activity. Decommissioning of the IR Demo will make eight DW dipoles available; construction of the IR/UV upgrade will bring to the lab ten GW dipoles. Properties of these magnets are given in Table 1. We note that the back end of both the north and south linacs contain blank zones that allow introduction of the chicanery needed for CEBAF-ER. The linac pitch is 9.35 m; the resulting available space (allowing for girders, *etc.*) will permit installation of chicanes somewhat over 8 m in length (modules are 8.25 m long). The shortest chicane using maximally excited GW dipoles that can produce a half-wavelength phase lag at 445 MeV is 8.6 m in length; the layout of such a chicane is shown in Figure 1. Such chicanes will therefore not serve to generate half wavelength offsets at 845 MeV, but can do so at 445 MeV. Noting further that the induced path length differential scales like chicane length \times (angle)², we see that the only location in the accelerator that could potentially accommodate a half-wavelength chicane at 845 MeV would be the 2E extraction region, and even there, interferences with extraction components may preclude implementation. Higher energies are, furthermore, not manageable with the available components.

Table 1: Dipole and chicane parameters

Property		Magnet type	
		DW	GW
Nominal Top Momentum (MeV/c)		79	210
Design radius (m)		1.0918	1.2
Design angle (degrees) (symmetric entry/exit)		21.514	20.246
Effective Length (m)		0.4076	0.4218
Angle (degrees) at	45 MeV/c (normal entry)	21.921	n/a
	400 MeV/c (normal entry)	n/a	9.548
	800 MeV/c (normal entry)	1.139	5.011
Path-length increment (cm)	for 4 m chicane 45 MeV 845 MeV	Extracted 0.50	n/a
	for 8.6 m chicane 445 MeV 845 MeV		10.01 2.74
Transverse offset at center of chicane (m)	for 6 m chicane, 845 MeV beam	0.028	
	for 8.6 m chicane at 445 MeV offset of $\lambda_{RF}/8$ offset of $\lambda_{RF}/2$		0.326 0.624

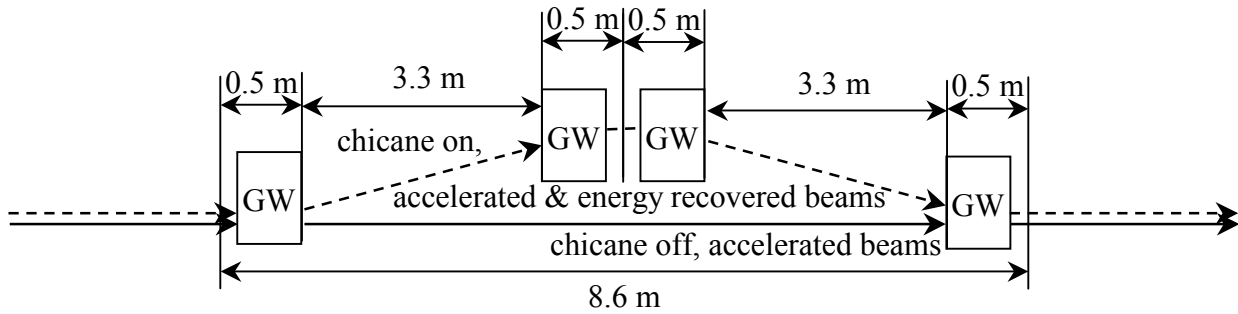


Figure 1: Chicane geometry.

Given the limitation of the fully recovered energy to 845 MeV by the maximum GW field integral, we therefore propose a CEBAF-ER design that introduces a half-wavelength offset at the end of the north linac, and a quarter-wavelength offset at the end of the south linac. This will allow all operational modes of interest (at least for two to three passes through the linacs), and, inasmuch as the beam elevation is identical in the CEBAF linacs and the FEL, this design will allow immediate use of not only the existing dipoles, but of their stands and power supplies as well.

The DW dipoles will serve at the basis of an extraction/recirculation chicane at the end of the south linac while a set of four GW dipoles provide a half-wavelength phase delay at 445 MeV (after the north linac). Given the availability of ten GWs, we suggest construction of a pair of “ $1/8^{\text{th}}$ wavelength” (2.5 cm differential) chicanes at the end of the south linac for current doubling tests. As we shall see in subsequent discussion, this avoids dealing with the complexity of multiple beams at multiple energies (as would occur in current doubling tests with chicanes at the end of the north linac [15]). This will require a) acquisition of an additional pair of GWs (at a cost of $\sim 40\text{k}\$$ each), b) use of a pair of other suitable dipoles (CEBAF spares may be appropriate, especially for the “outboard” pair of a chicane), c) removal of the north linac $\lambda/2$ chicane and reinstallation in the south linac after energy recovery tests are complete, or d) running the GWs $\sim 40\%$ high in current (field) to produce ~ 7.4 kG (rather than the nominal 5.8 kG. As we shall see below, the latter alternative may be the most attractive, inasmuch as other constraints on current doubling may limit the peak energy to values lower than 845 MeV, thereby presenting a less imposing requirement in this regard.

These choices, with their inherently simple geometry, also serve to simplify vacuum chamber construction – simple bent tubes with smaller apertures can be employed, avoiding the costs associated with a built-up weldment or the large aperture chamber required to accommodate beams steered to generate different path length offsets. A diagram of the extraction/recirculation chicane is given in Figure 2.

We thus propose a CEBAF-ER design based on four chicanes: a half-wavelength GW based chicane (supporting energy recovery) at the end of the north linac, a pair of eighth-wavelength GW based chicanes (for current doubling) in two south linac blank zones,

and a DW-based extraction/recirculation chicane immediately following the south linac. This concept is depicted in Figure 3. It simplifies vacuum chamber design for all chicanes, allows modular operation with simple transitions between end-user and machine physics studies, and provides both two-pass (one up, one down) energy recovery operation and current doubling studies with up to two simultaneous passes in some recirculation arcs and three in the linacs. As the native energy recovery mode involves only a single arc at each end, it will in addition allow testing of injected:full energy ratios without constraints imposed by spreader/recombiner acceptances.

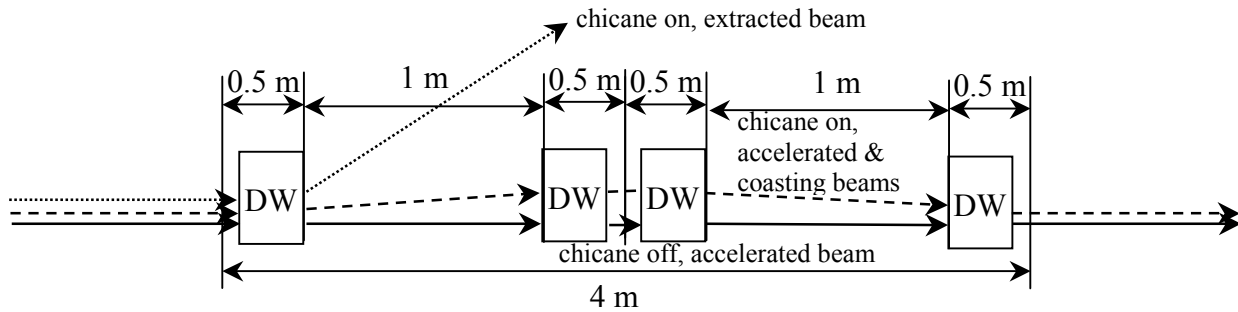


Figure 2: Extraction/recirculation chicane geometry

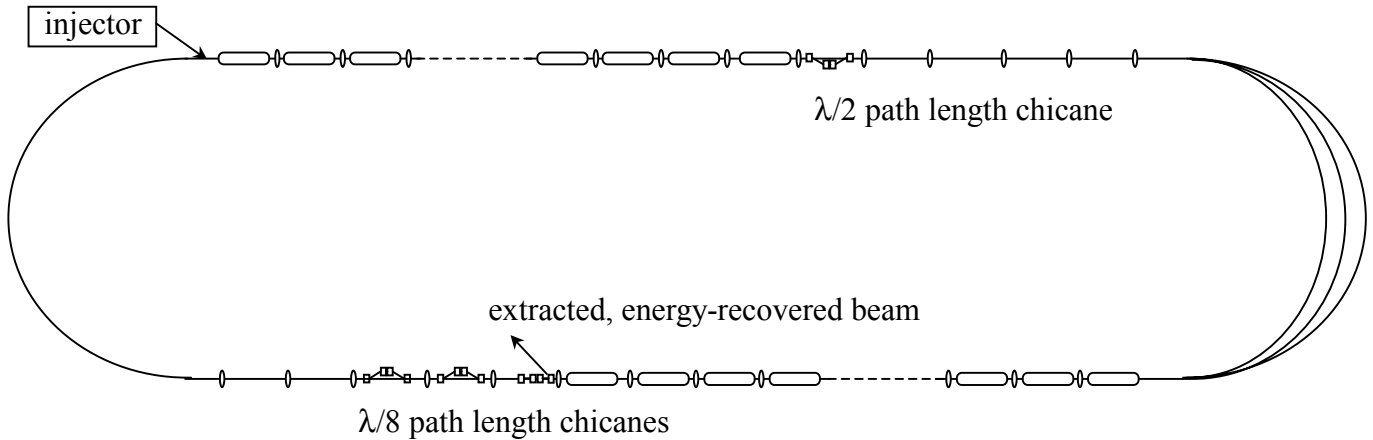


Figure 3: CEBAF-ER Design Concept. A $\lambda/2$ path-length shifting chicane is installed in the blanks zones at the end of the north linac; a pair of $\lambda/8$ chicanes is placed following the south. An extraction chicane is installed immediately after the south linac (allowing strong focusing in the downstream quads). Yes, it may, in some cases, use 3 east arcs. Read on...!

Optical Design

Optics for CEBAF-ER can be based on standard CEBAF solutions using installed hardware. A preliminary solution for the two-pass energy-recovery operation allowed by the available dipole sets has been developed. It has the following features.

- Graded-gradient focusing [16], wherein the north linac quads are set to constant focal length (providing 120° /FODO cell) for the first pass accelerated beam, and the south linac quads are similarly set to constant focal length (same phase advance) for the second pass energy recovered beam.
- The above solution for linac optics exhibits energy-focusing structure mismatch at the end of the south linac (for the accelerated beam) and the beginning of the north linac (for the energy recovered beam). This is aggravated by a betatron symmetry violation introduced by the blank zones at the linac ends, wherein no acceleration occurs. These mismatches are in part compensated by extraction of the energy-recovered beam immediately following the final active zone of the south linac. The quadrupoles in the remaining blank zones are thus not constrained by the presence of low energy beam and thus can then be excited to focus the full energy beam. They are in fact used in this solution to match the full energy beam to the west arc nominal first-pass acceptance.
- When excited, the path length differential chicane following the north linac imposes a half-RF-wavelength phase lag. After traversing arc 1, the beam enters the south linac, which would be back-phased (gang phase incremented by 180°) from the nominal set-point to continue acceleration to “full” energy. Transport through arc 2 returns the beam to the north linac out of phase (due to the path length differential); energy recovery then commences. After transiting the north linac, the beam undergoing recovery passes through the chicane (which phase-delays it appropriately to ensure energy recovery in the south linac), traverses arc 1 for a second pass (incidentally doubling the average current in the arc), and is subsequently energy recovered to the injection energy as it passes through the south linac.
- Longitudinal matching is rudimentary: acceleration occurs on crest, the transport is isochronous, and energy recovery occurs in trough. Insofar as the injected bunch is short and small momentum spread (*i.e.*, has the nominal CEBAF characteristics), behavior should be similar to typical operational experience.
- The simultaneous transport of both accelerated and energy recovered beams through the east arc imposes interesting steering and matching problems. The steering problems are rather more entertaining than those encountered in the CEBAF linacs, where independent control of each pass is available just prior to reinjection and pass-to-pass energy differences provide differential response to steering, thereby promising at least the potential of simultaneous optimization of multiple orbits. In this case, upstream steering in the injector and arc 2 provide the only independent knobs available that differentiate between the two beams. Orbit correction thus should be accomplished as locally as possible on the first pass, so as to ensure the second pass is similarly corrected.

Betatron matching suffers from similar commonality. In an ideal system, a solution that is reflectively symmetric about the highest energy transport could in principle be employed to ensure uniform matching for multiple beams in a common structure. As noted above, CEBAF will manifest deviations from this symmetry because of the blank zones at the back end of the linac. In the solution under consideration, the arc 2 reinjection condition (set by the 2R matching quads) was adjusted to optimize beam envelopes for the energy recovered beam on the second pass through the linacs and arc 1.

Figure 4 presents beam envelopes and dispersions for the preliminary solution. It is matched to nominal arc acceptance during acceleration and (due to the aforementioned asymmetry) slightly mismatched during energy recovery. Maximum envelopes are of order 150 m. The solution shown here (as with those shown below) does not include the betatron effect of the chicanes; as they are of modest size and strength, it can reasonably be expected that said effect can be compensated using matching quadrupoles.

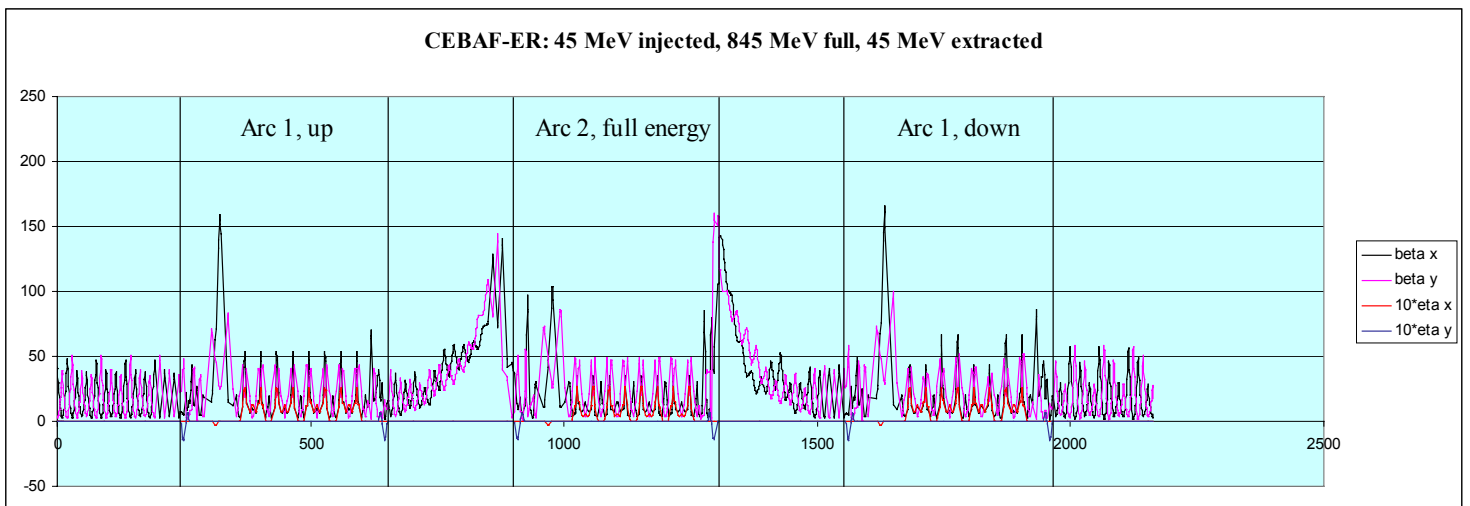


Figure 4: CEBAF-ER beam transport solution.

Current Doubling

The average current in portions of an energy-recovering linac can be doubled by subjecting the beam to a quarter-wavelength phase lag in the recirculator, rather than the typical half-wavelength nominally required for energy recovery [17]. The Bates recirculator [18] and the JLab IR Demo [19] have been run in this way. Momentum spread management is an issue during such operation; various approaches (some machine-specific [20] and some more general [21]) have been used or suggested to contend with this issue. CEBAF-ER can in principle support such operational scenarios. The key to implementation is not the longitudinal gymnastics, but rather accommodation of energy profile constraints imposed by spreader/recombiner acceptance.

Table 2 presents various acceleration/energy recovery scenarios for CEBAF-ER without and with current doubling (CEBAF-ER/CD). As simple energy recovery involves only a

single acceleration and single energy-recovery pass; recirculator acceptance is not an issue. Current doubling, however, requires transport of accelerated, coasting, and energy recovered beams. If the usual CEBAF energy profile of 45 MeV/445 MeV/845 MeV (or any scaled value) is used the east spreader will have to accommodate beams of both 445 MeV and 845 MeV; the resulting 445:845 energy ratio is well outside the design ratio of 445:1245 for the acceptance of the first two passes. This case is shown in Table 2 as CEBAF-ER/CDb – CEBAF-ER with Current Doubling and balanced linacs. Benesch [22] has observed, however, that higher pass transport lines have energy ratios much closer to this value. For example, the nominal arc 5 to arc 9 ratio is 2045:3645 = 0.561, within a few percent of the value of 445:845 = 0.527 required in this case. The match can be made exact by raising the injection energy and dropping the linac gains. A solution for this case is given in as CEBAF-ER/CDb'. The east arc would be operated at (severely!) depressed energies, with the first and third pass (accelerated and energy recovered) beams transported through arc 5 and the second pass (full energy coasting) beam transported through arc 9. The west arc would be operated in an essentially normal fashion at full (but low) energy, with arc 2 transporting two full energy beams – immediately following acceleration, and following the coasting pass, just prior to energy recovery. Adjustment of the injector, injection and re-injection chicanes away from the design 45:845 energy ratio would be a modest deviation from the typical operation configuration. Observing that the full energy is suppressed, we remark that the quarter-wavelength required can possibly be supplied by a single chicane rather than a pair of smaller chicanes. Various other east arc transport arrangements are possible. A second example using arcs 3 and 5 is given as CEBAF-ERb". Further variants are discussed below.

Table 2: CEBAF acceptance constraints on CEBAF-ER and CEBAF-ER/CD

Mode	$E_I:E_{NL}:E_{SL}$	N_{pass}	S/R Energy Ratios	Viability
CEBAF	45:400:400	5	E: 445:1245:2045:2845:3645 W: 45:845:1645:2445:3245:4045	Nominal
CEBAF-ER	45:400:400	2	E: 445:445 W: 45:845	Allowed
CEBAF-ER/CDb (balanced linacs)	45:400:400	3	E: 445:845:445 W: 45:845:845	Not allowed – outside east spreader acceptance
CEBAF-ER/CDb' (balanced linacs)	65:234:234	3	E: 299:533:299 (=2045:3645) W: 65:533:533	Allowed – recirculate through arcs 5 and 9
CEBAF-ER/CDb'' (balanced linacs)	65:117:117	3	E: 182:299:182 (=1245:2045) W: 65:299:299	Allowed – recirculate through arcs 3 and 5
CEBAF-ER/CDa (asymmetric linacs)	65:117:351	3	E: 182:533:416 (=1245:3645:2845) W: 65:533:533	Allowed – recirculate through arcs 3, 9, and 7
CEBAF-ER/CDa' (asymmetric linacs)	65:117:234	3	E: 182:416:299 (=1245:2845:2045) W: 65:416:416	Allowed – recirculate through arcs 3, 7, and 5

Optics – Longitudinal optics for CEBAF-ER/CD must include various manipulations for momentum spread management and are being documented elsewhere [23]. Here, we simply remark that appropriate manipulation of arc momentum compactions can be used to manage the momentum spread of the coasting beam, and note that further comments will be made below.

Transverse optics must behave essentially as in CEBAF-ER, with additional constraints imposed by matching requirements for the extra pass – the full energy coasting beam used to current double. As this suggests, the beam handling cycle will comprise an acceleration pass (with propagation through a “low energy” east arc), a coasting beam pass (with transport through a single west arc and a “high energy” east arc), and an energy recovery pass (in which the beam traverses the west arc and the low energy east arc). In the simplest case, a quarter-wavelength RF phase delay is provided by the pair of chicanes at the end of the south linac; this leads to coasting beam during the second pass and energy recovered beam during the third. Installation of the phase delay at the end of the south linac avoids the complexity of handling of multiple beams at multiple energies, as noted above [24].

Figure 5 presents a solution for the linac optics in this case. At this time, the arc optics have not been developed, though there is no obvious impediment to do so. One simply needs only match the arcs to the envelopes at each end of the linacs during the first half of the cycle; assuming the internal mismatch in the matching regions and/or during the second current-doubling passes is not excessive, the solution is straightforward.

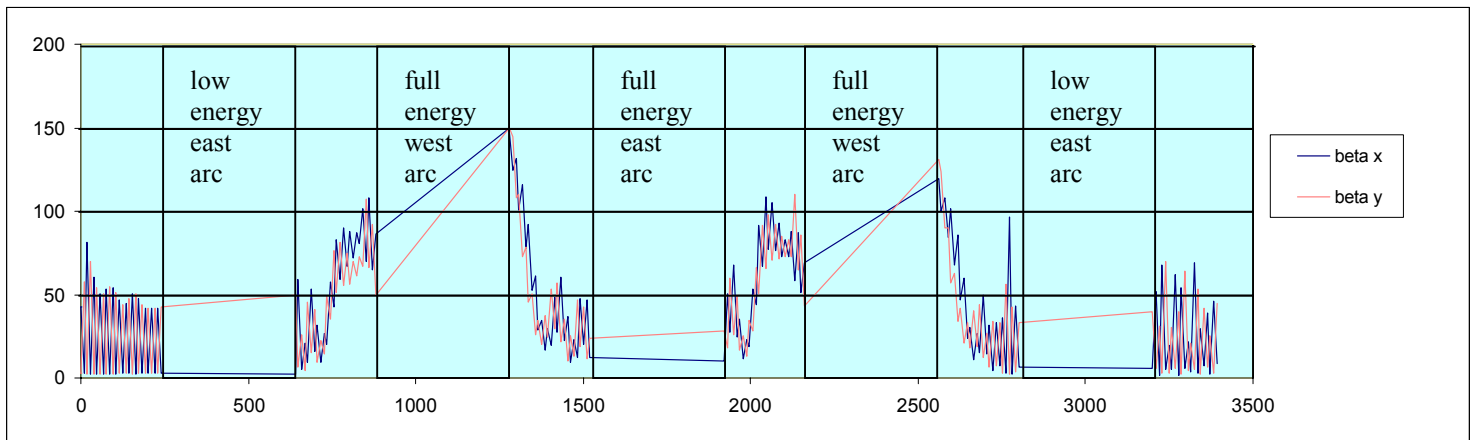


Figure 5: CEBAF-ER/CD optics. “Gaps” in envelope values correspond to recirculation arcs, with ordering as indicated.

Momentum Spread Management – If the momentum compaction of the high-energy east arc is properly set, the momentum spread induced while coasting down the north linac can be compensated by an energy compression performed while coasting down the south linac. Denote by E_I , E_{NL} , and E_{SL} the energy gains in the injector, north and south linacs; let E_T be the total energy (here, $E_T = E_I + E_{NL} + E_{SL}$); let δl be the half-length of the bunch.

The half-energy spread induced by coasting down the north linac at zero-crossing is then as follows.

$$\Delta E = E_{NL} \sin (2\pi \delta l/\lambda) \cong E_{NL}(2\pi \delta l/\lambda)$$

The head of the bunch is thus shifted by ΔE from the centroid, and arrives at $\delta l/c$ before the centroid. This effect can be compensated by setting the high-energy east arc momentum compaction to *retard* the head such that it arrives at a time $\delta l'/c$, for which the energy spread $\Delta E'$ imposed by the south linac compensates that induced by the north. The cancellation $\Delta E = \Delta E'$ occurs provided the path length offset $\delta l'$ relates to δl as follows:

$$\Delta E = \Delta E' \Rightarrow E_{NL}(2\pi \delta l/\lambda) = E_{SL}(2\pi \delta l'/\lambda)$$

or

$$\delta l' / \delta l = E_{NL} / E_{SL}$$

The compaction-driven path length increment generating $\delta l'$ must first retard the arrival of the head of the bunch by $\delta l'$. Thus,

$$M_{56} (\Delta E/E_T) = \delta l + \delta l'$$

whereby

$$\begin{aligned} E_{NL}(2\pi \delta l/\lambda) &= E_{SL}(2\pi \delta l'/\lambda) = E_{SL}(2\pi/\lambda) [M_{56} (\Delta E/E_T) - \delta l] \\ &= E_{SL}(2\pi/\lambda) [M_{56} (\{E_{NL}(2\pi \delta l/\lambda)\}/E_T) - \delta l] \end{aligned}$$

Munching through the algebra gives the following result for the required compaction.

$$M_{56} = (\lambda/2\pi) E_T [(1/E_{NL})+(1/E_{SL})]$$

For typical cases ($E_l \ll E_{NL} \sim E_{SL}$); thus $M_{56} \sim 2\lambda/\pi$, which, in our case, is $\sim 1/8^{\text{th}}$ m. More detailed and sophisticated discussions may be found in the aforementioned references.

Beam Performance Management – As in CEBAF-ER, commonality of steering and focusing may prove problematic in CEBAF-ER/CD. The desire to “current double” so as to increase synchrotron radiation source brightness indicates in particular that extremely tight control over beam position and cross section must be maintained. Initial experience with current doubling in the IR Demo suggests this will be a nontrivial task [25]. Figure 5 also gives some indication of this; the beam envelopes differ on each pass through the recirculation arcs, implying one or the other (or both) pass(es) will exhibit internal mismatch with a resultant reduction in source brightness. We therefore have considered alternative CEBAF-ER/CD operational modes that might provide additional control over beam behavior. These are based on asymmetric linac solutions [26], wherein the north and south linacs are run at different energy gains. The injector and linac energy gains are selected to match to east arc spreader/recombiner acceptances. The resulting recirculated beam goes through a common west arc during both acceleration and coasting passes, but

traverses three separate east arcs, thereby providing multiple opportunities for independent steering and focusing of each pass. Examples are given in Table 2 as CEBAF-ER/CDa (“a” for “asymmetric linacs”) and CEBAF-ER/CDa’.

RF Issues

Until the onset of energy recovery, the beam pulse will be accelerated by forward power from the RF drive system and by cavity stored energy. This is regularly accomplished in the IR Demo at currents exceeding those in CEBAF-ER (typically as much as 2-3 mA), but only over a time interval much shorter than that in CEBAF-ER (300 nsec vs. the CEBAF circulation time of $\sim 4 \mu\text{sec}$). Concern about potential gradient sag in CEBAF-ER is, however, readily eliminated. The stored energy in a cavity scales as the square of the gradient: $\mathcal{E} \propto g^2$. Thus, relative deviation of the gradient is half that of the stored energy: $\delta g/g = (1/2) \delta \mathcal{E}/\mathcal{E}$. The stored energy drawn from a cavity accelerating a current I for time δt without energy recovery is $\delta \mathcal{E} = g I \delta t$; the relative gradient sag in this situation is therefore as follows.

$$\delta g/g = (1/2) (g I \delta t)/\mathcal{E}.$$

A CEBAF cavity at the nominal gradient $g \sim 5 \text{ MV/m}$ has a stored energy $\mathcal{E} \sim 1 \text{ J}$; if we try to accelerate $200 \mu\text{A}$ for a single turn ($4 \mu\text{sec}$) without energy recovery, we will therefore experience a gradient sag $\delta g/g \sim 0.002$. This is a rather large transient for CEBAF hardware to accommodate. Any difficulty this might impose can however be avoided by ramping the current up from lower levels in current steps inducing acceptable gradient sags during the acceleration/energy recovery transition. Steps of $10 \mu\text{A}$ would, for example, induce gradient sags of only 10^{-4} .

Even with energy recovery, CEBAF-ER currents are injector-limited to $200 \mu\text{A}$. The available RF forward power will therefore act to stabilize this effect. We note that in IR Demo operation, 2 – 3 mA beams are regularly turned on with lasing and the CEBAF-type RF system stabilizes the energy to remain within the machine acceptance. Moreover, during IR Demo 3 pass operation, transients visible in the RF system GASKs for the 1 mA pulsed test beam were stabilized in $\sim 50 \mu\text{sec}$ or so [27]. RF and other collective issues are therefore not expected to be problems during these technology demonstration tests.

Potential for Multipass Operation

Given that the beam envelope behavior presented in Figures 4 and 5 is reasonable, we have briefly investigated the potential for multipass CEBAF-ER operation. Optical constraints are similar to those for single pass up/single pass down operation. Path length differential chicanes will, however, have to be built using higher field integral dipoles and must be installed in the arc transporting the highest energy pass. Conceptual optics for CEBAF-ER/2, a two pass up/two pass down energy recovering recirculator, are presented in Figure 6. The beam handling cycle comprises two standard acceleration passes, generation of a half wavelength path length differential by a chicane (most easily embedded in the 4E region), followed by two energy recovery passes.

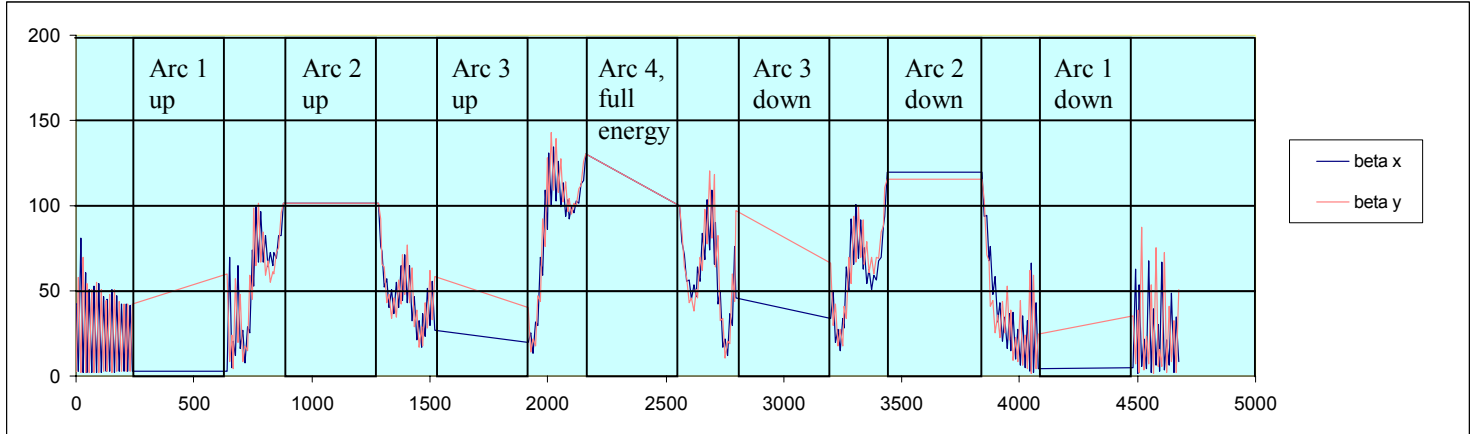


Figure 6: CEBAF-ER/2 – conceptual optics for multipass operation of CEBAF with energy recovery.

As in Figure 5, the “blanks” represent the arc transport, for which solutions have not yet been derived. Beam envelopes through the linacs are not unreasonable, but some consideration must be given to the potential mismatch of the energy-recovered beam during its traversal of the common transport. For example, the initial and final envelopes for arc 3 are rather different on each pass. If the transport is matched to the first pass, it may exhibit untoward mismatch through the second. Construction of new machines should therefore consider the use of reflectively symmetric optics (which, of course, are unavailable in this system due to the nature of the linac focusing structure) and or perform simultaneous matching on multiple passes. Arc steering and focusing corrections should be done locally if possible (so as to correct all common beams). If nonlocal steering is required, it might most profitably be performed in the linac. Because of the energy profile each beam responds differently to a single common correction. Simultaneous correction of multiple beams on multiple passes with multiple correctors can then be executed.

Acknowledgments

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