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Progress regarding the optics configuration of ER@CEBAF 7+ GeV, 5-pass, energy recovery experiment

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DISCLAIMER

PROGRESS REGARDING THE OPTICS CONFIGURATION OF ER@CEBAF 7^+ GEV, 5-PASS, ENERGY RECOVERY EXPERIMENT*

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Abstract

In the frame of a BNL-JLab collaboration, as part of the Electron-Ion Collider project studies in the US, a 7^+ GeV, 10-pass, energy recovery experiment will be performed at JLab, using the CEBAF 12 GeV recirculator. The experiment will study beam recirculation and ER in the presence of synchrotron radiation, provide opportunity to develop and test multiple-beam diagnostic instrumentation, probe BBU limitations. A new, dedicated optics is necessary to perform the 5-pass up/5-pass down acceleration and ER cycle. This paper gives a brief overview of the project and its present status, and of the progress in the optical design of the experiment.

CONTEXT

Energy recovery linacs (ERL) accelerate electron bunches of linac quality, possibly polarized, and essentially preserve these qualities up to users' energies. ER adds high power efficiency and beam dumping at low energy. These are major ingredients in the interest they present in the EIC and other applications.

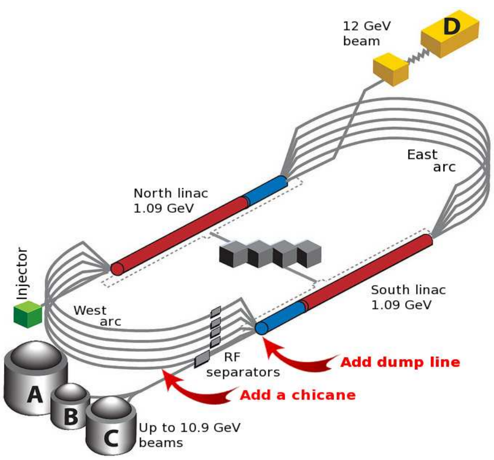

Figure 1: 12 GeV CEBAF recirculator.

Electron-Ion Colliders, and accelerator science

The EIC is the next high priority large facility in the 2015 DOE NP Long Range Plan [1]. In that context BNL is developing an ERL-ring scheme based on RHIC collider [2, 3]. ERL technology in the EIC application brings (i) high brightness (an electron bunch undergoes a single collision and is then ER'ed), (ii) high beam power with reduced RF drive power, (iii) yet beam current and thus SR power loss in the low side, (iv) low energy, low power beam dump. Wall-plug efficiency on the other hand is a condition of viability with beams of 100s of MW. A version of eRHIC ERL arcs using FFAG technology is also studied, see companion paper [4]. ERL technology is contemplated in a variety of other applications, including high current injectors (high power), radiation sources (high brightness, femtosecond science), FELs (small 6D emittance), electron cooling and other [5].

An ER experiment at CEBAF

A 7^+ GeV, 10-pass, energy recovery experiment will be performed at JLab, using the CEBAF 12 GeV recirculator (parameters in Tab. 1), beyond the March 2003, highest ever energy recovery demonstration with superconducting RF structures [6]. The objective is to perform studies regarding 6D bunch phase space preservation, which also means commissioning and operation of a large-scale superconducting recirculating linac in energy recovery mode. The experiment will investigate 6D optics and beam dynamics issues in ER regime, such as emittance growth, stability, beam losses, synchrotron radiation (SR) effects, multiple-pass orbit control/correction, multiple-pass beam dynamics in the presence of cavity HOMs, BBU studies, halo studies, beam diagnostics instrumentation. It will evaluate limitations and ultimate performance, provide guidance and allow anticipating on eRHIC ERL operation, and forming people.

ER@CEBAF requires adding a phase chicane in Arc A, an extraction line and dump at the exit of the South Linac (Figs. 1, 2) and dedicated diagnostics instrumentation, a 6 month about installation work. Beam time planned is 25 weeks, in two periods.

In July 2016 the experiment has received approval from JLab PAC 44, *"very interested in seeing this experiment performed [...] Because of the potential for major impact on proposed EIC designs"* [7], and detailed plans will be submitted (preparation work is on-going) to a dedicated technical advisory committee charged with *"[reviewing] the proposal to validate the methods and to identify the appropriate resources"* [7].

ER@CEBAF OPTICS [6]

The optics for ER@CEBAF require careful consideration, these address the high-energy ER concerns of phase space matching, phase space preservation, and halo control. Establishing beam tuning to experimentally explore these

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Table 1: CEBAF parameters.

	CEBAF
Energy [GeV]	12
Beam current, max. [mA]	0.1
SR loss, max. [MW]	0.005
Numb. of linacs	2
Linac passes	≤ 11
Injection energy	$E_{\mathrm{linac}} \times 123/1090$
Pathlength control tolerance [deg]	0.25
Dump power [kW]	20
Bunch :	
Bunch frequency [MHz]	31-1497
ppb, max. [10^{10}]	10^{-4}
rms $\epsilon_{x,y,\mathrm{norm.}}$, inj. [$\pi\mu$m]	3
rms length [μm]	90-150
rms $\Delta E/E$	$< 10^{-4}$
Linac :	
Linac energy [GeV]	1.09
Length [m]	250
RF freq. [MHz]	1497
Numb. of cavities	2×200
Cavity type	5- & 7-cell
Cavity gradient [MV/m]	7 - 20
ER specifics :	
Linac energy [GeV]	< 0.8
Linac passes, up to	5 up + 5 down
linac FODO phase advance [deg]	60

three items in a world-class ER experiment is one of the main objectives of ER@CEBAF.

Longitudinal Match - The longitudinal stability is dependent upon RF phase, the initial bunch length and energy spread of the beam, and the chromatic characteristics of the return arcs. ISR-driven energy loss in the high-energy arcs results in two beams of different momentum in each arc. Finally, as a consequence of anti- damping during deceleration, the relative energy spread of the beam becomes larger during deceleration and energy recovery. All of these effects can be mitigated by performing the appropriate longitudinal phase space manipulations. The injection chicane, located at the end of the injector, can be used to perform initial bunch compression. Linac phases can also be separately adjusted for acceleration and deceleration passes, and M56 controlled in each arc.

Initial estimates of the momentum acceptance have been established based on classical SR theory (Fig. 3). From this it is determined that the maximum feasible energy gain for ER@CEBAF is 700 750 MeV/linac.

Longitudinal phase space at the ER dump for 750 MeV/linac is shown in Fig. 4. The beam is energy recovered at 86 MeV/c with an energy spread of 2-3%. This can be optimized further by altering the M56 in the arcs and the linac phases, powering sextupoles in the arcs and installing sextupoles in the chicane to correct the second order curvature by adjusting the T566.

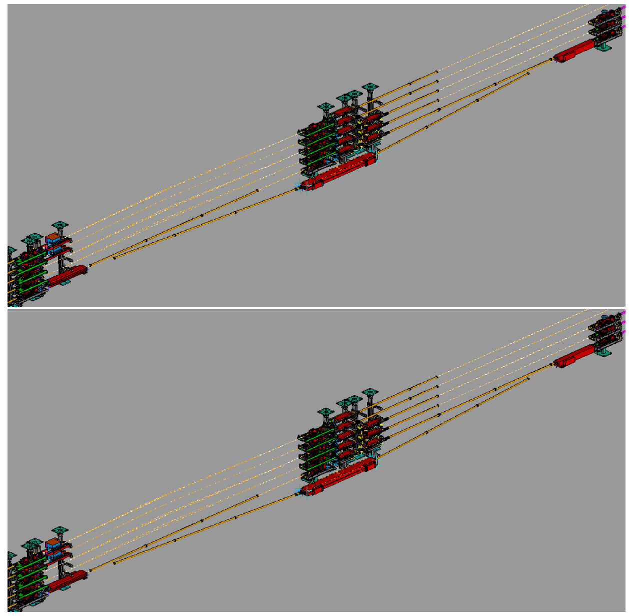

Figure 2: Top: 3-bend $\lambda/2 = 10$ cm phase chicane along Arc A. Bottom: switch to dump line at end of SL (switch bend on the left, East spreader vertical dipole on the right).

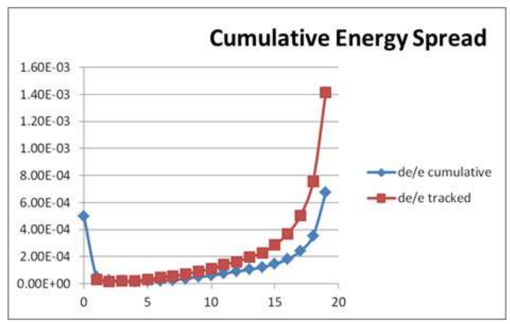

Figure 3: Energy spread in ER regime.

Momentum Acceptance The limiting factor for ER@CEBAF with 5 passes is the ARC momentum acceptance, which places a bound on the maximum energy gain in the linacs. Above that energy gain, ISR losses are sufficiently large that the energy separation between accelerated and decelerated beams in the last arcs is larger than the ARC momentum acceptance. The standard configuration for the CEBAF ARC1 and ARC2 is high dispersion optics (8 and 6 meters peak respectively). For the CEBAF ER experiment, these optics are redesigned to be low dispersion (≈2.5 m peak) like the other arcs in the nominal CEBAF 12 GeV design to give them larger momentum acceptance. This only requires changes to quadrupole magnet setpoints. All arcs are first order (but not second) achromats (Fig. 11). The model includes the non-zero second order T566 terms that are present in all the return arcs.

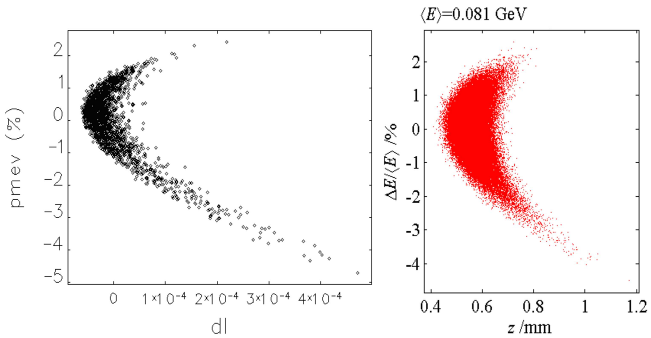

Figure 4: Phase space at the ER@CEBAF dump, for elegant [9] (left) and LiTrack [10] (right).

The optimum linac optics is based on a FODO like, 60^o phase advance lattice, the focusing profile for both North and South linacs is shown in Fig. 5. Both linacs uniquely define the optical functions for the arcs: the NL fixes input to all odd arcs and output to all even arcs, while the SL fixes input to all even arcs and output to all odd arcs.

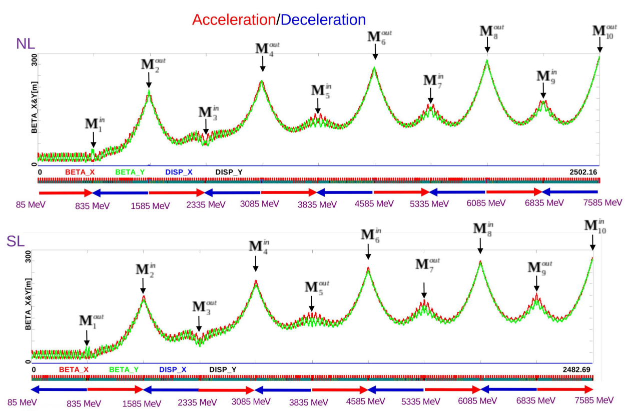

Figure 5: ER Optics in North and South linacs.

The Arc Optics will be modified for ER, to meet the new values of optical functions at both arc ends as addressed earlier (Fig. 5). Re-matching the spreader and recombiner sections for that, leaves the arc proper intact. A sample of the resulting end-to-end 5-pass up / 5-pass down optics is illustrated in Fig. 6.

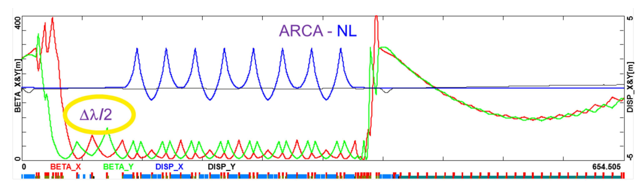

Figure 6: Arc A and North Linac - deceleration, indicating location of pathlength chicane at start of Arc A.

The optics has been translated to MADX-PTC from ELEGANT for cross-checks [11], this is illustrated in Fig. 7.

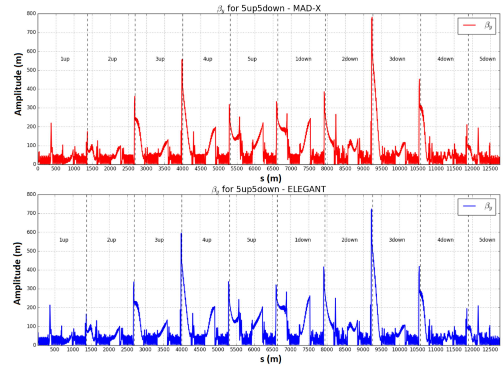

Figure 7: Vertical betatron function comparison between MADX and ELEGANT for 5-up / 5-down.

End-to-end 6D simulations Further refinement of this matching is being performed, where the accelerator modeling code Zgoubi [12] is being used to model CEBAF. This code is a field integrator, which is an advantage when modeling and optimizing the (different energy) accelerating and decelerating beams in Arcs 1-9 for ER@CEBAF [13]. Typical 6-D tracking outcomes are displayed in Figs. 8.

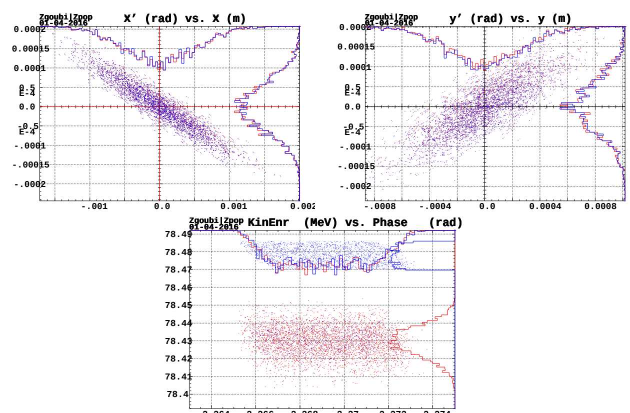

Figure 8: Phase-space portraits of the ER'ed bunch, observed at the dump, in a 1 GeV, 1-pass up/1-pass down, 6D simulation. Red: is in the presence of SR; blue: without SR.

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