

ER@CEBAF - A HIGH-ENERGY, MULTIPLE-PASS ENERGY RECOVERY EXPERIMENT AT CEBAF*

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Abstract

A high-energy, multiple-pass energy recovery (ER) experiment proposal, using CEBAF, is in preparation by a JLab-BNL collaboration. The experiment will be proposed in support of the electron-ion collider project (EIC) R&D going on at BNL. This new experiment extends the 2003, 1-pass, 1 GeV CEBAF-ER demonstration into a range of energy and recirculation passes commensurate with BNL's anticipated linac-ring EIC parameters. The experiment will study ER and recirculating beam dynamics in the presence of synchrotron radiation, provide opportunity to develop and test multiple-beam diagnostic instrumentation, and can also probe BBU limitations. This paper gives an overview of the ER@CEBAF project, its context and preparations.

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 application. These properties render that technology appealing in a number of other applications.

Table 1: eRHIC EIC - in Short

Luminosity [cm^2/s]	$10^{32} - 10^{34}$			
Center-of-mass energy [GeV]	20 to 140			
Species	e	p	^3He	A
Energy, max. [GeV, GeV/u]	20	250	167	100
Beam current, max. [mA]	50	400	200	
Polarization [%]	80	70	70	-

Electron-Ion Colliders

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 (Fig. 1), parameters in Tables 1, 2 [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.

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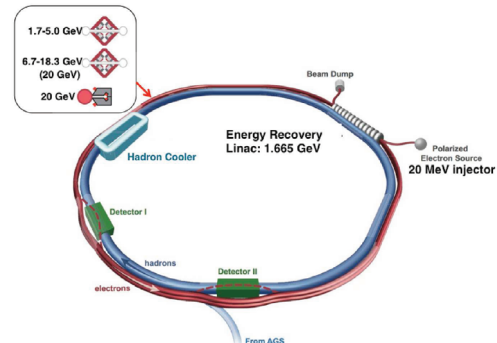


Figure 1: eRHIC ERL (linac and recirculation loops, red) along RHIC collider Blue ring.

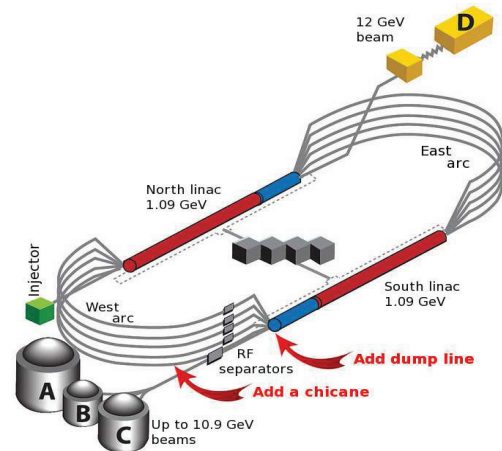


Figure 2: 12 GeV CEBAF recirculator.

Wall-plug efficiency on the other hand is a *sine qua non* condition of viability with beams up to 100 s of MW.

Beyond the EIC

For the very reasons that render it attractive for the EIC, 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 [4].

Motivation for ER R&D at CEBAF

The development of ERL technology raises issues in a host of sectors. These include beam optics, beam stability and losses, instrumentation, commissioning and operation experience, application-specific implementation aspects. This is the motivation for this R&D project: an

anticipating on EIC ERL operation, investigating difficulties, experimenting, learning.

Table 2: CEBAF and eRHIC Parameters

	CEBAF	eRHIC
Energy [GeV]	12	3.3 - 20
Beam current, max. [mA]	0.1	26 - 50
SR loss, max. [MW]	0.005	2.5
Linac energy [GeV]	1.09	1.67
Linac passes	≤11	≤12
<i>Bunch :</i>		
Bunch frequency [MHz]	31-1497	9.4
rms $\epsilon_{x,y, norm.}, inj.$ [$\pi\mu m$]	3	10 - 70
rms length [mm]	0.09-0.15	3
rms $\Delta E/E$	$< 10^{-4}$	$< 10^{-3}$
<i>Linac :</i>		
Length [m]	250	176
RF freq. [MHz]	1497	647
Numb. of cavities	2×200	80

Table 3: Operated ERLs, in Short

Facilities	CEBAF -ER	JLab IR	JLab UV	BINP	KEK
Linac E [MeV]	1050	165	135	10	17
Num. of passes	1	1	1	4	1
Current [mA]	0.08	9	2.5	30	0.1

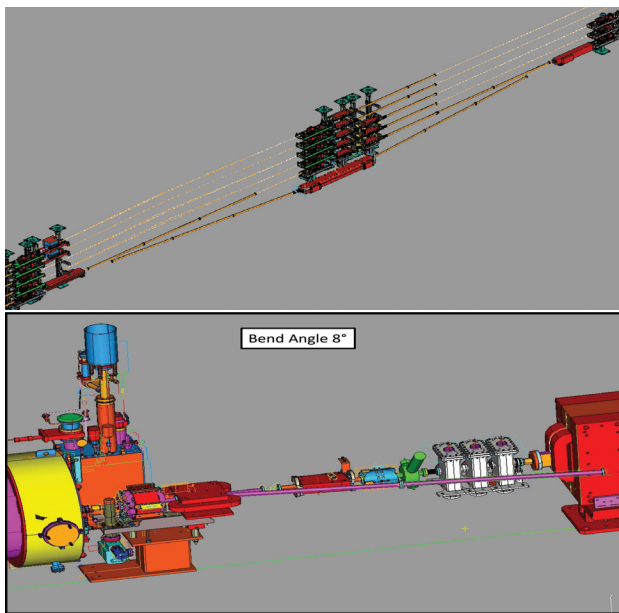


Figure 3: Top: 3-bend phase chicane along Arc A. Bottom: switch to dump line at end of SL (switch bend on the left, East spreader vertical dipole on the right).

Following a recent upgrade from 6 GeV which brought the energy in the North ('NL') and South ('SL') linacs to 1.09 GeV and added a 10th recirculation 'arc A' (Figs. 2, 3-top), CEBAF accelerates CW beams for delivery to Hall D

at 12 GeV (11 linac passes) and Halls A-C at 11 GeV and below (up to 10 linac passes).

CEBAF is the only installation, worldwide, that potentially allows multiple-pass, multi-GeV ER. Other running installations are limited in the number of passes and in energy, see Table 3. On the other hand, CEBAF energy and number of turns in a possible ER regime (respectively, up to 11 GeV, 5 up+5 down), are commensurate with eRHIC parameters (up to 20 GeV, 12 up+12 down) (Table 2).

ENERGY RECOVERY AT CEBAF

JLab has a broad expertise in the design, commissioning, operation of multiple ERLs : the CEBAF Front-End Test (early 1990s), CEBAF-ER (2003) [5], IR FEL Demo, IR FEL Upgrade, UV FEL Driver (1997-2014) (Table 3).

CEBAF-ER, of which the present proposal can be seen as an extension, demonstrated high energy, 1-pass up/1-pass down energy recovery. Measurements included transverse emittances and momentum spread of accelerated and ER'ed beams, halo, RF system response to ER [6]. Multiple-pass ER at 5-10 GeV, with a 20 mA beam (100-200 MW), was further contemplated at that time [5].

ER@CEBAF

Objectives

The objective of ER@CEBAF 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, SR effects, it will evaluate limitations and ultimate performance, provide guidance for eRHIC project in that matter, it will allow anticipating on eRHIC ERL operation and forming people.

Setup

Hardware: ER@CEBAF requires adding in CEBAF a phase chicane ($\lambda/2 = 10$ cm) in Arc A, an extraction line and dump at the exit of SL (Figs. 2, 3), and dedicated diagnostics instrumentation. Chicane and beam dump sections are both transparent to CEBAF NP program, they could be maintained in place in view of long term R&D programs. A dump in place at SL exit further offers a means for linac calibration during normal operation of CEBAF.

Optics: Modifications to CEBAF for ER include 60 deg phase advance in linacs (standard is 120 deg) for optimal focusing of accelerated and decelerated beams (constant focusing at lower energy), Fig. 4 [7], and matched spreaders/recombiners, Fig. 5 [8]. CEBAF arcs include sextupoles, not used in normal operation, which can be powered if/when needed (e.g., 2nd order path length, chromatic aberrations). SR will degrade the beam energy spread and cause energy loss, this must be allowed for by the longitudinal match, and phases and momentum compactions must

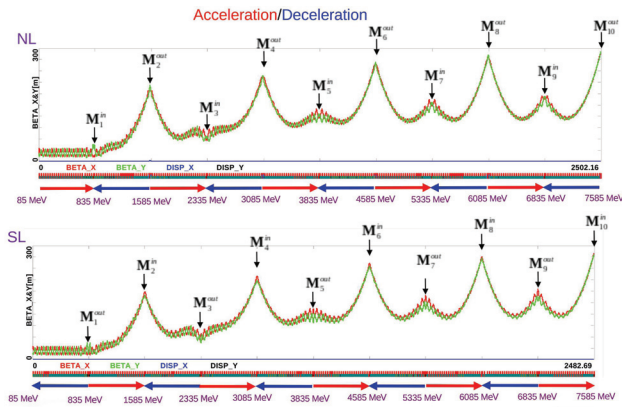


Figure 4: ER Optics in North and South linacs.

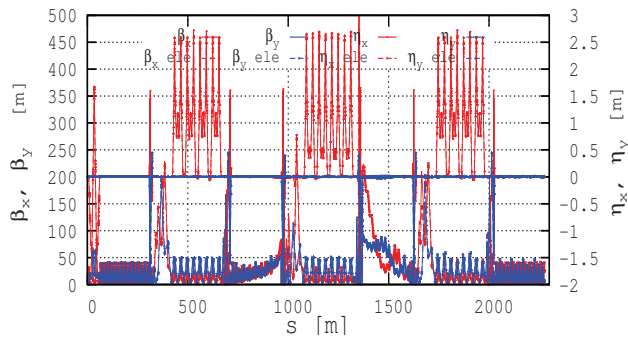


Figure 5: Typical 1-turn CEBAF optics in ER regime, case of 1 GeV, 1-pass up/1-pass down ER.

be adjusted to insure that the beam stays within the machine momentum aperture during recovery. CEBAF transport system provides phase (path length) and compaction (M_{56} trim) knobs providing appropriate controls. Start-to-end tracking simulations will demonstrate the feasibility of lossless transport to the dump. Preliminary investigations indicate that the maximum energy will be 700+ MV per linac, with limitation the energy difference between up and down beams in an arc in regard with arc acceptance, $\Delta E/E = 2 \sim 3 \times 10^{-3}$. An estimate of the energy spread with 700 MV/linac is displayed in Fig. 6.

Experiment

Staggering of the ER experiment is under investigation. A possible procedure prior 7 GeV, 5-pass up/5-pass down ER, could be (this is purely indicative): (i) 1 pass up to 1 GeV (500 MV/linac), followed by 1 pass down (possibly using the - 12 GeV upgrade - 7-cell cavities to avoid RF skew focussing issues) via Arc A and the phase chicane, ending with extraction to the dump line at injection energy. (ii) Similar to what precedes, with staggered increase of linac energy. (iii) Possibly a 3-pass up/3-pass down step. (iv) 5-pass up at low enough energy to stay away from SR effects, with staggered ER using RF separators for beam extraction on arbitrary intermediate passes down. (v) Increase beam current. Maximum beam intensity is an open

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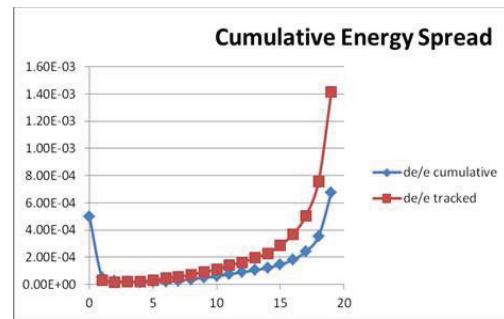


Figure 6: Energy spread in ER regime.

topic, possibilities are under investigation.

Measurements

Regular beam controls are part of the measurements to be performed to characterize the ER regime, including current, energy, orbit, time of flight, separation between up and down beams in arcs, etc. On the other hand, beam emittance provides a quantitative understanding of bunch evolution over the acceleration/deceleration cycle. The ultimate goal of the measurements is a characterization of the bunch at all steps in the ER process, of the ER'ed bunch in dump line in particular, which comprises bunch length and momentum spread. 6D tomography at the dump is an open topic. Transverse emittance measurements can be performed in Hall C line at any energy, up or down, by extracting the beam using RF separators. Measurements will also include RF systems. More on this, including lessons from the 2003 ER experiment, can be found in [6].

Beyond ER

Additional possibilities of experiments with CEBAF in ER mode include multiple-pass orbit control/correction, multiple-pass beam dynamics in the presence of cavity HOMs, BBU studies, halo studies, eRHIC related beam diagnostics instrumentation R&D. CEBAF also offers the possibility of studying polarization transport to 12 GeV.

REFERENCES

- [1] http://science.energy.gov/~media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf
- [2] E.C. Aschenauer et al., eRHIC Design Study. An Electron-Ion Collider at BNL, arXiv:1409:1633, (2014).
- [3] V. Ptitsyn, eRHIC project overview, this proceedings.
- [4] ERL2015, 56th ICFA Advanced BD Workshop, BNL, June 7-12, 2015, <https://www.bnl.gov/erl2015/>
- [5] A. Bogacz, A. Hutton et al., CEBAF-ER Experiment Proposal, JLab, June 2002.
- [6] C. Tennant, Studies of Energy Recovery Linacs at Jefferson Laboratory, PhD Dissertation, JLab, 2006.
- [7] Choice of multi-pass optics for CEBAF-ER, S.A. Bogacz, JLAB-Pub TN 15-050 (2015).
- [8] ER@CEBAF : Modeling code developments, F. Méot and Y. Roblin, BNL Tech. Note C-A/eRHIC/52 (2016).