20-24 GeV FFA CEBAF ENERGY UPGRADE*

S.A. Bogacz†, J.F. Benesch, R.M. Bodenstein, B.R.P. Gamage, G.A. Krafft, V.S. Morozov[1], Y. Roblin
Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
J.S. Berg, S.J. Brooks, D. Trbojevic, Brookhaven National Lab, Upton, New York, USA
G.H. Hoffstaetter, Cornell University (CLASSE), Ithaca, New York, USA
D. Douglas, Douglas Consulting, York, Virginia, USA
[1]now at Oak Ridge National Lab, Oak Ridge, Tennessee, USA

Abstract

Encouraged by recent success of CBETA, a proposal was formulated to increase the CEBAF energy from the present 12 GeV to 20-24 GeV by replacing the highest-energy arcs with Fixed Field Alternating Gradient (FFA) arcs. The new pair of arcs would provide six or seven new beam passes, going through this magnet array, allowing the energy to be nearly doubled using the existing CEBAF SRF cavity system. One of the immediate accelerator design tasks is to develop a proof-of-principle FFA arc magnet lattice that would support simultaneous transport of 6-7 passes, with energies spanning a factor of two. We also examine a possibility of using combined function magnets to configure a cascade, six-way beam split switchyard. Finally, a novel, multi-pass linac optics based on a triplet focusing lattice is being explored.

INTRODUCTION

The Cornell-BNL ERL Test Accelerator (CBETA) [1] demonstrated eight-pass beam recirculation with energy recovery (four accelerating beam passes and four decelerating beam passes) [2] through a complete TESLA-style SRF cryomodule. Simultaneous transport of multiple beams with energies spanning a factor of 4 was demonstrated through a single beamline. This wide energy bandwidth was achieved using the non-scaling FFA principle [3] implemented with Halbach-derived permanent magnets [4]. CBETA's maximum energy was 150 MeV, whereas CEBAF upgrades plan to extend this technology to higher beam energies.

ENERGY DOUBLING SCHEME

We propose to increase CEBAF energy from the present 12 GeV to 20-24 GeV using the existing SRF cavity system, which provides 1090 MeV per linac, as well as most of CEBAF tunnel and beamline infrastructure. The energy doubling would be accomplished by replacing the highest-energy arcs, ARC 9 and ARC A, with a pair of Fixed Field Alternating-Gradient (FFA) arcs. These very large momentum acceptance arcs will recirculate the beam for 6-7 additional passes through the same string of magnets - simultaneously transporting beams with energies spanning a factor of two. In the proposed acceleration scheme, passes 1-4 would be accomplished through the current 12 GeV CEBAF. Passes 5-10 (six passes) would be facilitated by constructing two 'CBETA-like' beam-lines, replacing the current highest-energy arcs.

PROOF-OF-PRINCIPLE FFA ARC

Energy Doubler FFA Arc Cell

The parameters of the main arc cell for the energy doubler are given in Table 1. This lattice uses very high gradients and the 10-22 GeV beams are all confined to a region $-5\text{mm} < x < 4\text{mm}$. The orbits and optics of the unit cell for the different energies are shown in Fig. 1.

Element	Length [m]	Angle [°]	Dipole [T]	Gradient [T/m]
BF	0.625	0.5	0.681	250.91
O	0.05	0		
BD	0.5382	0.5	0.941	-233.13
O	0.05	0		

Table 1: Energy doubler FFA arc cell.

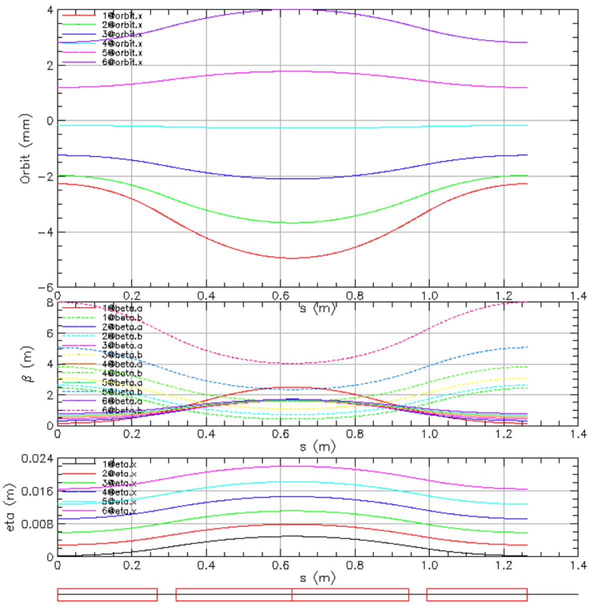

Figure 1: MAD-X optical functions for the 10-22 GeV energy doubler FFA arc cell.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contracts DE-AC05-06OR23177 and DE-SC0012704.

† bogacz@jlab.org

Energy Doubler FFA Racetrack

Fig. 2 shows how the beta functions are expanded and the dispersion matched adiabatically to zero in the straight sections of the racetrack-shaped lattice. The larger beta functions allow longer cells compatible with the higher-beta optics in the main CEBAF linacs.

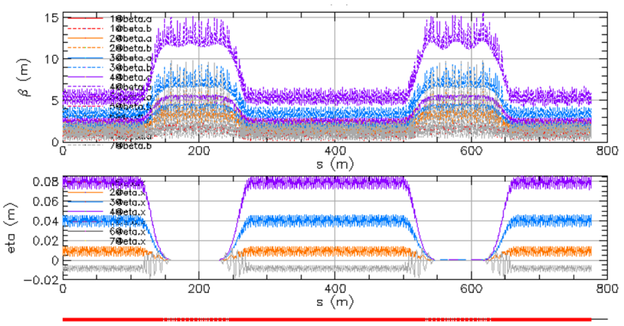

Figure 2: MAD-X optical functions for the entire 10-22 GeV energy doubler FFA racetrack lattice.

MULTIPASS LINAC

One of the challenges of the multi-pass (10+) linac optics is to provide uniform focusing in a vast range of energies, using fixed field lattice. Here, we configured a building block of of linac optics as a sequence of two triplet cells with reversed quad polarities flanking two cryomodules, as illustrated in Fig. 3, with a stable periodic solution covering energy ratio 1:18.

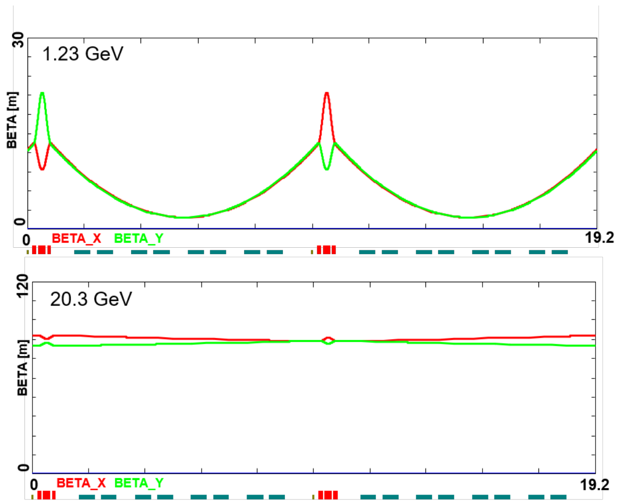

Figure 3: 'Twin-Cell' periodic triplet lattice at the initial and final linac passes : 1.23 GeV and 20.3 GeV. Initial triplets, configured with 45 Tesla/m quads, are scaled with increasing momentum along the linac.

1.2 GeV FFA BOOSTER INJECTOR

The current CEBAF facility is configured with a 123 MeV injector feeding into a racetrack recirculating linear accelerator (RLA) with a 1090 MeV linac on each side. The 123 MeV minimum makes optical matching in the first linac virtually impossible due to extremely high energy span ratio (1:180). Thus, it is proposed to replace the first pass by a new FFA-based booster, outputting an energy of 123 + 1090 = 1213 MeV into the South Linac.

This booster will have injector linacs of energy up to 1213/6 = 202 MeV, delivering either electrons or positrons (for circulation in the opposite direction). The booster resembles CBETA, with a linac on one side surrounded by splitter lines and an FFA return loop (Fig. 4). The booster linac operates at the same energy as the injector, meaning five passes in the booster linac (four passes in the FFA return loop) produces 1213 MeV. Energy tunability from 50 to 100% is produced by reducing the number of booster linac passes to three and the energies of both linacs to 1213/8 = 152 MeV. For more parameters, see Table 2.

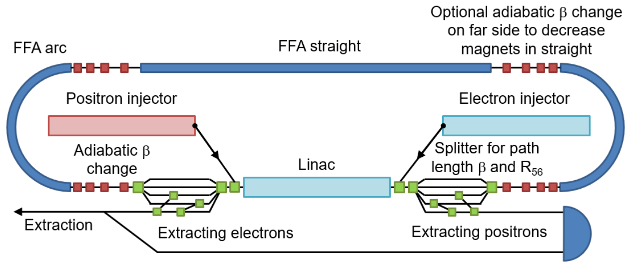

Figure 4: Proposed 1.2 GeV FFA booster for CEBAF.

Parameter	CBETA	FFA Booster	Units
Injector energy	6	152-202	MeV
Linac energy	36	152-202	MeV
FFA energy range	42-150	303-1011	MeV
Extraction energy	6 (ERL)	606-1213	MeV
Passes (FFA, linac)	7, 4↑4↓	2-4, 3-5↑	
Momentum ratio	3.572	3.333	×
Radius of curvature	5.08787	23.0	m
Effective avg. dipole	0.09834	0.1466	T
Cell length	0.444	0.803	m

Table 2: Comparison of CEBAF FFA booster to CBETA.

Booster FFA Arc Cell

One proposed cell for the booster FFA arc is given in Table 3, which has a bend angle of 2° per cell.

Element	Length [m]	Angle [°]	Dipole [T]	Gradient [T/m]
HD2	0.1112	0		
QF	0.2405	0	0	-23.681
D1	0.1193	-2		
BD	0.2206	0	-0.4566	22.834
HD2	0.1112	0		

Table 3: FFA booster arc cell.

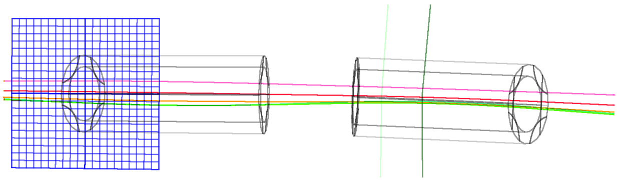

Figure 5: Orbits of 303, 404, 607, 809 and 1011 MeV particles in the FFA booster arc cell, tracked through Maxwellian 3D field models using the Muon1 code [5] (cm grid shown).

The orbits in this cell (Fig. 5) require a good field radius of 18mm. With 10mm clearance between the beam centroid and the vacuum pipe, a 2mm thick pipe and 3mm gap left for shims, the cell can be made using the permanent magnet cross-sections shown in Fig. 6 with a 33mm radius aperture. These are very similar to the CBETA magnets.

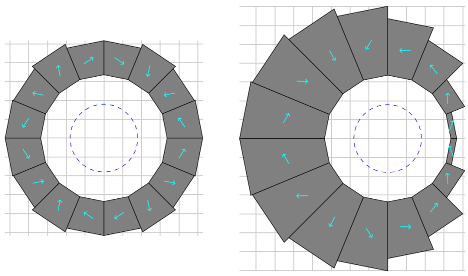

Figure 6: QF (left) and BD (right) arc cell magnets for the FFA booster (cm grid). Dotted circle is good field region.

Booster FFA Racetrack

The arc cell may be adiabatically transitioned into a straight cell that has zero curvature and greater length and beta functions, which reduces magnet count. Fig. 7 shows an early attempt at this, with particles merging to $x = 0$ in the straight section, with only small residual oscillations.

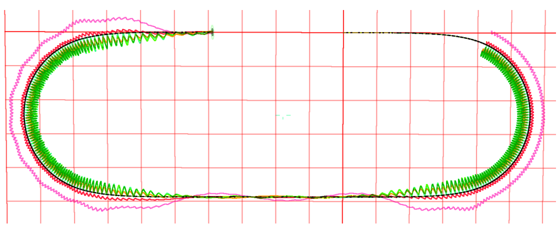

Figure 7: Orbits of 303, 404, 607, 809 and 1011 MeV particles in the FFA booster racetrack (10m grid shown). Orbits have been transversely exaggerated by 256×.

SYNCHROTRON RADIATION EFFECTS

Staying within CEBAF footprint, while transporting high energy beams (10-24 GeV) calls for increase of the bend radius at the arc dipoles (packing factor of the FFA arcs increased to about 87.6%), to suppress adverse effects of the synchrotron radiation on beam quality. Table 4 lists arc-by-arc dilution of the transverse, $\Delta\epsilon$, and longitudinal, $\Delta\sigma_{\frac{\Delta E}{E}}$, emittance due to quantum excitations calculated using analytic formulas:

$$\Delta E = \frac{2\pi}{3} r_0 \, mc^2 \, \frac{\gamma^4}{\rho} \tag{1}$$

$$\Delta\epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2}, \tag{2}$$

$$\frac{\Delta\epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \, \frac{\gamma^5}{\rho^2}, \tag{3}$$

Here, $\Delta\epsilon_E^2$ is an increment of energy square variance, r_0 is the classical electron radius, γ is the Lorentz boost and $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \approx 3.832 \cdot 10^{-13}$ m for electrons (or positrons). The horizontal emittance dispersion in Eq. 2, is given by the following formula: $H = (1+\alpha^2)/\beta \cdot D^2 + 2\alpha \, DD' + \beta \cdot D'^2$, where D, D' are the bending plane dispersion and its derivative, with averaging over bends defined as: $< ... > = \frac{1}{\pi} \int_{bends} ... \, d\theta$.

Arcs	Energy [GeV]	ρ [m]	ΔE [MeV]	$\Delta\epsilon_N^x$ [mm·mrad]	$\Delta\sigma_{\frac{\Delta E}{E}}$ [%]
Arc 1	1.2	5.1	0.02	0.003	0.0003
...	...	...	...	...	...
Arc 8	8.8	30.6	9	12	0.022
FFA 9	9.91	70.6	6	13	0.026
...	...	...	...	...	...
FFA 19	20.44	70.6	109	37	0.15
FFA 20	21.42	70.6	132	47	0.17
FFA 21	22.38	70.6	157	60	0.20
FFA 22	23.31	70.6	185	76	0.23

Table 4: Energy loss and cummulative emittance dilution (horizontal and longitudinal) due to synchroton radiation at the end of selected 180° arcs (not including Spreaders, Recombiners and Doglegs). Here, $\Delta\sigma_{\frac{\Delta E}{E}} = \sqrt{\frac{\Delta\epsilon_E^2}{E^2}}$

A more aggressive, 11.5 pass, 24 GeV design would promise to deliver a normalized emittance of 76 mm·mrad with a relative energy spread of $2.3 \cdot 10^{-3}$. Further recirculation is limited by large, 976 MeV per electron, beam loss due to synchrotron radiation.

CONCLUSIONS AND FUTURE WORK

A proof-of-principle concept for an energy-doubling, FFA-based upgrade to CEBAF is presented. This work expands upon much of the CBETA efforts, and shows a promising possible way forward for CEBAF after the 12 GeV era. Initial studies into the beam dynamics, possible machine layouts, and magnet designs paint a positive picture. The majority of the work in validating this conceptual design remains, including, but not limited to, full start-to-end beam dynamics simulations, detailed magnet designs, diagnostics, controls, and engineering concerns. Furthermore, the details of positron acceleration in the CEBAF machine must be further investigated.

REFERENCES

[1] *CBETA Design Report, Cornell-BNL ERL Test Accelerator*, G.H. Hoffstaetter *et al.*, `https://arxiv.org/abs/1706.04245` (2017).

[2] *CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery*, A. Bartnik *et al.*, Phys. Rev. Lett. **125**, 044803 (2020).

[3] *Design of a nonscaling fixed field alternating gradient accelerator*, D. Trbojevic, E.D. Courant and M. Blaskiewicz, Phys. Rev. ST Accel. Beams **8**, 050101 (2005).

[4] *Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator*, S. Brooks, G. Mahler, J. Cintorino, J. Tuozzolo and R. Michnoff, Phys. Rev. Accel. Beams **23**, 112401 (Nov 2020).

[5] *Muon Capture Schemes for the Neutrino Factory* (chapter 2), Stephen Brooks, D.Phil. thesis, University of Oxford, available from `http://ora.ox.ac.uk/objects/ora:4360` (2010).