13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOST023

CURRENT STATUS OF THE FFA@CEBAF ENERGY UPGRADE STUDY*

R.M. Bodenstein†, J.F. Benesch, S.A. Bogacz, A.M. Coxe, K.E. Deitrick, B.R. Gamage, G.A. Krafft, K.E. Price, Y. Roblin, A. Seryi, Jefferson Lab, Newport News, VA, USA
J.S. Berg, S.J. Brooks, D. Trbojevic, Brookhaven National Lab, Upton, NY, USA
V.S Morozov, Oak Ridge National Lab, Oak Ridge, TN, USA
G. H. Hoffstaetter, Cornell University (CLASSE), Ithaca, NY, USA
D. Douglas, Douglas Consulting, York, VA, USA

Abstract

This work will describe the current status of the FFA@CEBAF energy upgrade feasibility studies. Technical updates are given, but more specific details are left to separate contributions. Specifically, this work will discuss improvements to the FFA arcs, a new recirculating injector proposal, and numerous modifications to the current 12 GeV CEBAF which will be required, such as the spreaders and recombiners architecture, splitters (time-of-flight chicanes), the extraction system, and the hall lines.

BACKGROUND OF PROPOSAL

Thomas Jefferson National Accelerator Facility must investigate paths forward for the post-12 GeV era of the laboratory. Approved and funded experiments will keep CEBAF's experimental schedule booked throughout this decade, at an operational pace of 32 weeks a year. Approved but yet-to-be funded experiments can keep CEBAF busy through the middle of the next decade. Once these experiments are completed, the lab must examine what can come next. One possible path forward involves increasing the energy of the CEBAF machine [1].

At IPAC21, we presented an initial proposal for an energy-doubling upgrade to CEBAF based on Fixed-Field, Alternating-Gradient (FFA) technology [2]. This proposal would upgrade the highest-energy recirculating arcs of CEBAF with permanent, FFA magnets, and allow for energies ranging from 20-24 GeV by recirculating the beam for several additional passes. Initial studies were presented, and we have made significant improvements based upon these optimization studies. This work will present the current state of the proposed upgrade, including a general description of the changes that have been made.

UPDATES TO BASELINE DESIGN

FFA Arcs

In the initial design, a single FFA arc on each side of the racetrack was considered. However, in order to reduce the required maximum magnetic fields for the permanent magnets, as well as decrease synchrotron radiation, two FFA arcs are

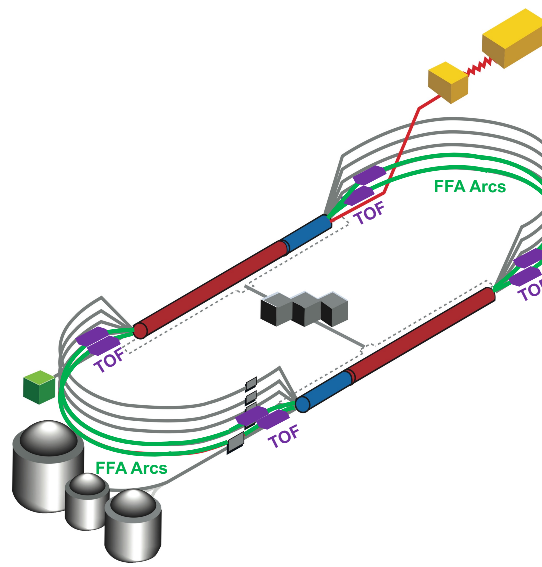

Figure 1: Overview schematic of 2-FFA CEBAF.

now under consideration [3]. Figure 1 shows a generalized layout of the two-FFA option. In this case, the first three energy passes will remain in the current electromagnetic arcs, and FFA arcs will replace the two highest-energy arcs on both the east and west sides of CEBAF. In total, there will be 3 electromagnetic passes and 8 FFA passes, for a total of 11 passes in CEBAF.

Table 1: Comparing 1 vs. 2 FFA Options

Option	**Max Field** [T]	**SR Loss** [MeV]
1 FFA	2.007	1211.48
2 FFA (4 + 4)	1.495	964.44
2 FFA (5 + 3)	1.489	935.30

Table 1 compares three options for the proposed upgrade: a single FFA option [2], a 2-FFA option with 4 passes in each of the new arcs, and a 2-FFA option with 5 passes in the first set of arcs and 3 passes in the second set of arcs. The 2-FFA options significantly reduce the maximum required field for the permanent magnets, and initial studies also show that SR loss is also decreased. The reduction in required fields has a further benefit of being more radiation hard. These options are all being weighed in terms of benefit and feasibility in terms of complexity and available space. Currently, the 2-FFA option with four passes in each set of

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177, Brookhaven Science Associates, LLC under Contract No. DE-SC0012704, and UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE).
† ryanmb@jlab.org

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOST023

arcs is our baseline, as designing the splitters for the 5-pass option may be space-limited. As the design work progresses, this baseline may be subject to change. Table 2 shows the energies at various locations and passes for the 2-FFA option with 4 passes in each set of arcs.

Table 2: Estimated Energies

Location	**Pass Number**	**Energy** [GeV]
Arc 1	0.5	1.850
Arc 2	1	3.049
Arc 6	3	7.830
FFA Arc 8	7	17.108
Extraction	11	22.580

Injector Upgrade

Our IPAC21 work described a 1.2 GeV booster injector into the South Linac (SL). While this option is certainly attractive, it is also a large endeavor, requiring significant down time planning. Instead, we thought of ways to use our current injector. Due to the energy ratio of the lowest and highest energies in the North Linac (NL) being 1:175, the beam cannot be injected into the North Linac (NL) as it is in the current 12 GeV CEBAF (123 MeV electrons are injected into the NL, with each linac providing 1090 MeV to the beam). To reduce this ratio, a recirculating, 650 MeV injector has been proposed. With this injection energy, the energy ratio in the NL would be reduced to a more manageable 1:33.

The current space for our 123 MeV injector will need to be expanded to accommodate a single-pass recirculating injector. This injector is foreseen to use three of CEBAF's C-90 cryomodules, and Bates Bends to complete the two 180-degree bends required. The beam would be injected into the recirculator at 110 MeV, and pass through the three, 90 MeV cavities twice, yielding a total injection energy of 650 MeV into the NL. Figure 2 shows a conceptual layout of this injector setup.

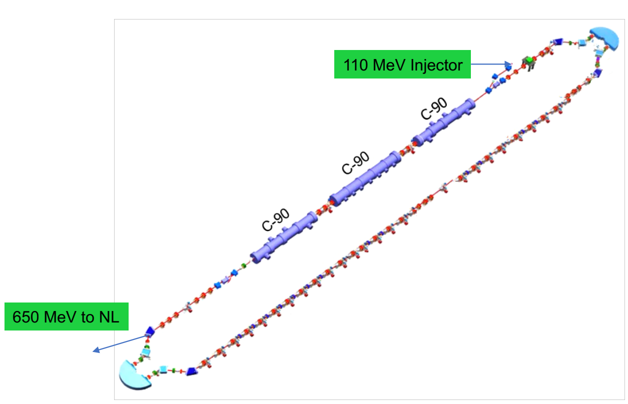

Figure 2: Conceptual 650 MeV injector.

After entering the NL, the beam will go through the triplet lattice [2]. It will then be recirculated through three electromagnetic passes, then eight FFA passes to reach maximum energy. However, this will require further updates to the current CEBAF machine. They are discussed in the next section.

Required Modifications to CEBAF

Spreaders In addition to the injector upgrade, there are current plans to refurbish and improve the current CEBAF cryomodules. This process will improve the linac gradients to over 1200 MeV per pass. This means that, by the time the beam reaches the first spreader in the northeast corner of the lab, the beam will be 1850 MeV instead of the current 1213 MeV. The spreaders will need to be redesigned to accommodate the higher energies, as well as the space for the FFA arcs.

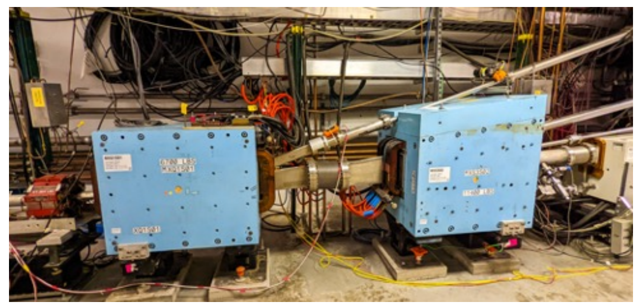

Figure 3: Common line spreader dipoles.

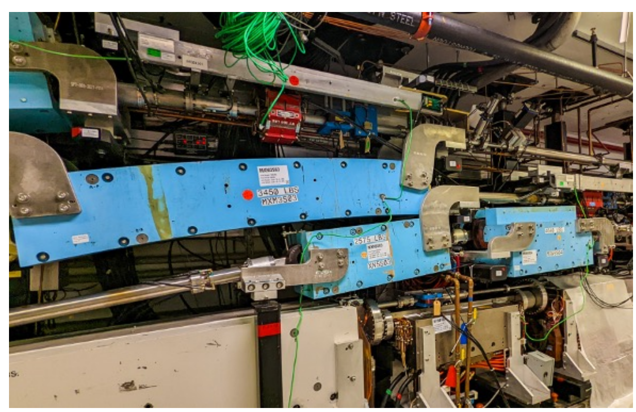

Figure 4: First-step dipoles in Spreader.

The higher energies will present difficulties with the current magnets. For example, the current common dipole magnets, which act as energy separators for each pass in the arcs, and the first pass spreader dipoles will not be able to accommodate the expected 1850 MeV beam from the first pass. Figure 3 shows the first two common dipoles in the northeast Spreader. Downstream of these, each pass follows its own beamline. Further separation is provided by a series of dipoles, interspersed with quadrupoles. These dipoles are placed to allow a two-step elevation change, which when combined with appropriately placed quadrupoles, allows the spreaders to be achromatic. Figure 4 shows some of the dipoles which make up the first step in this two-step design.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOST023

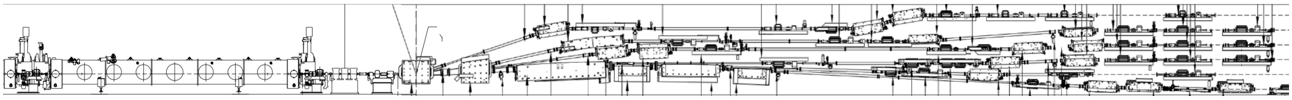

Figure 5: This diagram shows the end of the North Linac and the start of the Spreader in the northeast corner of CEBAF. All passes must exit the linac and be bent by the common dipole magnets into energy-dependent beamlines around the arcs. The lowest-energy passes are bent upward the most, and each successive pass follows a lower beamline along the arcs.

Figure 5 shows the engineering diagram for the end of the NL into the Spreader region.

Space is very tight in this region. The increased beam energy will necessitate stronger magnets, and more space. We are currently looking into redesigning the spreaders to accommodate this and allow for space for the FFA lines, including the splitters.

Splitters and Adiabatic Matching In addition to the spreaders, we must design the time-of-flight splitters for each of the energies which pass through the FFA arcs. These will be located along the new FFA arcs, downstream of the spreaders. Conceptually, they will be similar to those at CBETA [4], which are shown in Fig. 6. They will need to fit in the space currently occupied by the highest-energy passes in the CEBAF recirculating arcs. To reiterate, our current baseline has two FFA lines with four passes through each. This would necessitate four time-of-flight splitters in each line which are capable of adjusting the M_{56}.

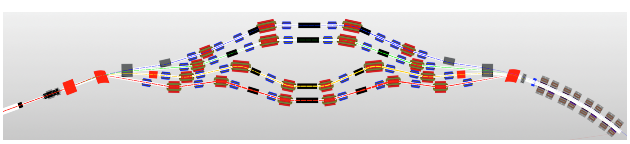

Figure 6: The CBETA splitters [4].

In addition to the splitters, we are designing an adiabatic matching section consisting of FFA cells which slowly vary in strength and size. These will allow the beams to be matched from the splitters into the proper FFA arcs [5].

Extraction and Hall Lines Given the greater total energies expected with this upgrade, we are also investigating the impact this will have on our extraction system and beam delivery to the experimental halls. For the extraction system, this will depend partly on the needs of the experimental program, and partly on how we choose to extract the beam. At this stage, this investigation is only in the initial stages.

For the beam delivery to the halls, the hall beamlines are currently under investigation. Improvements to the magnetic septa are expected to be required, and the dipoles to the hall lines will need to be strengthened and improved as well. The overall optics will require some adjustments, but should be manageable, assuming that the beam is extracted.

INSTITUTIONAL SUPPORT

In support of these efforts, to Laboratory Directed Research and Development (LDRD) grants have been provided; one at Jefferson Lab and one at Brookhaven National Lab.

Jefferson Lab LDRD

The Jefferson Lab LDRD project is titled "Start-to-End Optics Validation of FFA-Based Energy Upgrade to CEBAF." This project will perform detailed studies of the designs as they are prepared by the overall collaboration. This will include detailed optics and beam dynamics studies, beam loss and power deposition studies, and provide insights for the necessary diagnostics of the upgrade. The final goal is to have complete Start-to-End simulations for the FFA@CEBAF upgrade.

Brookhaven LDRD

The Brookhaven LDRD project is titled "High-Gradient Permanent Magnets for Emerging Accelerator Applications." Part of this project involves investigation of the permanent magnets required by FFAs, and will include those needed for the FFA@CEBAF upgrade [3].

CONCLUSION

The FFA@CEBAF collaboration has been working for approximately a year and a half on the proposed energy upgrade to CEBAF. In this time, the collaboration has made rapid progress toward an overall design. We are now looking into further details of the design, and iterating with the necessary changes. While we are not at a full conceptual design status at this time, the support we are receiving through our respective institutions, and the work that we are performing, is clearing a path toward such a milestone. There is much work that remains, but this work is underway.

REFERENCES

[1] J. Arrington *et al.*, "Physics with CEBAF at 12 GeV and future opportunities", 2021. doi:10.48550/arXiv.2112.00060.

[2] S. A. Bogacz *et al.*, "20-24 GeV FFA CEBAF energy upgrade", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 715–718. doi:10.18429/JACoW-IPAC2021-MOPAB216

[3] S. J. Brooks *et al.*, "Permanent magnets for the CEBAF 24 GeV upgrade", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, paper THPOTK011, this conference.

[4] G.H. Hoffstaetter *et al.*, "CBETA design report, Cornell-BNL ERL test accelerator", 2017. doi:10.48550/arXiv.1706.04245

[5] V. S. Morozov *et al.*, "RLAs with FFA arcs for protons and electrons", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, paper MOPOTK053, this conference.