**Title: Novel Accelerator Design for 22 GeV CEBAF**

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Table of Contents

[Table of Contents ii](#_Toc159585542)

[1.0 Scientific Background 1](#_Toc159585543)

[1.1 Accomplished CBETA beam optics results directly related to the CEBAF Upgrade 2](#_Toc159585544)

[2.0 Project Objectives 3](#_Toc159585545)

[3.0 Proposed Research and Methods 4](#_Toc159585546)

[3.1 Extend Lattice Design to Map Full Complex 4](#_Toc159585547)

[3.1.1 Spreader/Recombiner Section and Horizontal Splitters 5](#_Toc159585548)

[3.1.2 FFA Arc to Recombiners and LINAC Transition Lattices Check for coherence 6](#_Toc159585549)

[3.1.3 Extraction system 9](#_Toc159585550)

[3.1.4 Diagnostics and Vacuum Hardware Integration into FFA Arcs Check, new 9](#_Toc159585551)

[3.2 Design Validation Beam Dynamics Studies 10](#_Toc159585552)

[3.2.1 Emittance Growth Budget CHECK THIS 10](#_Toc159585553)

[3.2.2 Tracking with field maps 11](#_Toc159585554)

[3.2.3 Refinement of initial 2D permanent magnet design 11](#_Toc159585555)

[3.2.4 Depolarization Effects of Synchrotron Radiation CHECK CONSISTENCY 13](#_Toc159585556)

[4.0 Project Planning and Management 14](#_Toc159585557)

[4.1 Timelines and Milestones 14](#_Toc159585558)

[4.2 Contingencies and Risk Mitigation 14](#_Toc159585559)

[4.3 Organizational Structure CHECK PII COMPLIANCE 15](#_Toc159585560)

[4.4 Communication Plan 15](#_Toc159585561)

[Appendix 1: Bibliography & References Cited 15](#_Toc159585562)

[Appendix 2: Data Management Plan 16](#_Toc159585563)

[Appendix 3: Promoting Inclusive and Equitable Research (PIER) Plan 17](#_Toc159585564)

# Scientific Background

Diagram

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Figure : General, simplified layout of proposed CEBAF Energy Upgrade

The proposed energy upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) from the present 12 GeV to energies up to 22 GeV, within the existing tunnel, is envisioned by increasing (nearly doubling) the number of recirculations, based on a novel approach to transport multiple energy beams through a pair of single FFA beam lines. The main thrust of the project is to extend the present lattice design to finalize a complete set of lattices, mapping out the entire accelerator complex. Furthermore, the beamline design will be validated through carrying out a S2E simulation. Finally, requirements for new diagnostics in the FFA arcs, along with BPM specifications, will be defined to assure its compatibility with currently planned instrumentation upgrade for CEBAF.

The design is based on the previous work demonstrated by the Cornell University BNL ERL Test Accelerator project ‘CBETA’ project. The Non-Scaling FFA approach allows beam acceleration within a small beam pipe size as in synchrotrons but without varying the magnetic field. This is accomplished using very strong focusing, reducing the dispersion function, Dx, from meters in synchrotrons down to cm and mm in the FFA. Different energy beams are transported in a small beam pipe with very small transverse orbit offsets due to the small dispersion function *Dx=Dx dp/p (*e.g., *Dx=±*2.4cm orbit offsets if the dispersion is 4 cm and energy range is 4 times)*.* The momentum or energy offset can be as large as *dp/p = ±* 60% or a factor four in energy, as in the CBETA example. The FFA concept has been confirmed by the commissioning of the CBETA project CITE where all requested milestones were fulfilled. Two additional proof-of-principle experimental results also confirm this concept: EMMA-Electron Model for Many Applications CITE at Daresbury Laboratory in UK, and the experiment at BNL Accelerator Test Facility (ATF) with 6 FFA arc cells CITE.

The Fixed Field Alternating (FFA) gradient arc design is supported by a novel permanent, open mid-plane magnet with high field >1.5 Tesla. A small prototype magnet, funded by an LDRD, has already undergone magnetic measurements at Brookhaven National Laboratory (BNL), and there is presently an LDRD project to do permanent magnet radiation damage studies at CEBAF. A previous Jefferson Lab LDRD made significant progress in a Start-to-End simulations, but significant changes in the baseline design, as well as missing design elements mean that this proposed project will need to build off the infrastructure developed during the LDRD to complete a full Start-to-End design. Namely, we will need to complete the designs of a new set of horizontal chicanes (referred to as a splitter), a new extraction system, and a transition lattice connecting the FFA arcs to the LINACs.

## Accomplished CBETA beam optics results directly related to the CEBAF Upgrade

The concepts of the CEBAF energy upgrade are based upon the developments in the CBETA CITE project. The CBETA multi-pass energy recovery linac (ERL), as shown in Figure 2, accelerated and energy recovered electrons from 42 to 150 MeV by using the Cornell superconducting RF cryomodule.

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Figure : The CBETA Energy Recovery Linac: superconducting linac (shown on the right) with a single FFA permanent magnet beam line (shown on the left).

The CBETA injector brought 6 MeV electrons to the MLC (Main Linac Cryo-Module) where they reached 150 MeV after four passes. All energies were transported by a single FFA beam linestarting with the first arc. The adiabatic transition from the arc to the straight section merged different electron energy orbits into a single orbit as shown in the prediction (Figure 3) and confirmed by beam measurements (Figure 4). This process was repeated four times during acceleration for a given electron bunch and in four deceleration passes during energy recovery. The energy of the decelerating electron bunch was used to accelerate new bunches, making the ERL 99.8% energy efficient.

Graphical user interface, chart

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Figure : Merging orbits of multiple electron energies into the single orbit in the “CBETA” project. The same principle is used in CEBAF energy upgrade proposal.

A close up of a map

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Figure : Orbits in the CBETA project within the single FFA beamline for the electron energy range of 42 to 150 MeV of accelerating and decelerating passes (7 passes are shown in all: 42, 78, 114, 150, 114, 78, 42MeV).

The electron beams are brought back to the linac with the momentum range -56.3% < p/p < 56.3% by continuing the single FFA linear gradient beam line with a second arc, after being de-merged from the single orbit in the straight section. This principle of merging and de-merging electron beams in the CBETA ERL will be applied similarly in the CEBAF energy upgrade proposal.

# Project Objectives

To upgrade the energy of CEBAF to 20+ GeV, we have proposed a design which uses a single pair of fixed field alternating gradient arcs that the beam will traverse up to 6 times, allowing several additional passes through the linacs while only building a single additional arc at each end of the machine. We understand what the basic structure of the machine would be: the existing vertical spreaders have been updated to return the beams for the higher energy passes down to LINAC height, which is the height of the FFA arc. For two of the linac to arc matching sections, a transition lattice similar to the FFA would transform the beam coming out of the FFA arcs to be matched to recombiners and LINACs. For the remaining two matching sections (from the LINACs and Spreaders to the FFA Arcs), we would construct horizontal splitters, similar to those successfully used in the CBETA ERL built at Cornell. We need these splitters to control the timing from one pass to the next as well as the energy dependence of that timing. After reaching the maximum energy, the beam must be extracted and transmitted to the 4 experimental beam lines.

The designs for each of these portions of the machines are at varying stages of completion: for instance the FFA and linac designs are complete, though we may want to improve them, while the horizontal splitter designs will require significant work to be completed. The primary goal of this proposal is therefore to have designs for the complete accelerator, from beginning to end. We will be able to track an electron beam through the entire machine and have the system “matched” such that the beam distribution has the appropriate shape in each section. The physical layout of the beamlines will be determined and will be compatible with the existing infrastructure. A significant fraction of this effort will be devoted to the designs of the horizontal splitters, the transition lattice, and the extraction system. Other sections will need some attention as well, in particular, the initial injection into the CEBAF North Linac, confirming whether the existing experimental hall beamlines will be compatible with the beam we will deliver, and integration of vacuum hardware and diagnostics into the FFA arc.

In addition to the completion of that full system design, we will need to adjust our design to take into account important effects from beam dynamics. Synchrotron radiation will increase the beam emittance and energy spread, so we should compute those effects in the machine. Polarization is important for the experiments, so we should compute the polarization for the beam that is delivered, including impact on that polarization from radiation, and consider if changes to the beamline design would be desirable to improve that. Simple magnetic field models for the magnets should be replaced with field maps in the particle tracking studies where needed. We will simulate these effects in parallel to the accelerator design process, so that the results can guide any design adjustments that will need to be made. We will use Bmad for the design and many of these simulations, and will update that code as necessary to ensure that we can perform all these simulations as well as design the full machine.

# Proposed Research and Methods

## Extend Lattice Design to Map Full Complex

Graphical user interface, website

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Figure : Simplified graphical description of the upgraded CEBAF facility.

Currently, several new parts of the CEBAF upgrade complex (shown schematically in Figure 5) have been simulated to various levels of accuracy. The linacs have linear lattice designs for the new energies that include focusing changes, as do the spreaders and recombiners. The splitters have a geometry in which dipoles for the five or six lines all fit in the tunnel and have the correct strengths and bending angles, but the lattice focusing structure is yet to be determined. The FFA arc cells have been tracked for all energies, including fringe fields and realistic magnet designs, however the match between the arcs and the splitter has not been consistently tracked in a single simulation.

As mentioned in the Project Objectives section, a major goal of this project is to get all of these lattice design parts to a similar level of detail, so that the simulations may be joined together in an “end-to-end” fashion. This can happen either in a single code, or by passing particle distributions from one code to the next. This will allow quantities such as total emittance growth through the entire lattice to be evaluated in a trustworthy way, as well as the effects of errors, correction, cumulative synchrotron radiation and so on.

### Spreader/Recombiner Section and Horizontal Splitters

A unique feature of CEBAF’s recirculating linac design is the energy-dependent, vertically displaced recirculating arcs which connect the two linacs. These arcs are designed so that the lowest-energy electron beam is steered to the top arc, and each successive pass will follow a lower path. For this project, we intend to replace the two highest-energy, lowest-displacement arcs with FFA arcs, capable of containing several simultaneous passes. An engineering diagram of the recombiners currently in the 12 GeV CEBAF machine is illustrated in Figure 6. The Spreaders have been re-designed to accommodate the higher injection energy and higher overall energies expected to be present in the upgrade. This re-design maintains the overall concepts for the first four electromagnetic passes, but adds a mirror-symmetric set of septa and dipoles to vertically recombine the remaining, FFA-destined passes into a colinear trajectory.

Diagram

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Figure : The 12 GeV CEBAF vertical beam recombiner, which merges five stacked energies into the same axis. This is a mirror-image to the Spreader, which is located on the upstream side of the Arc.

The time of flight in the FFA lines depends on energy; without correction the bunches would not be at the desired RF phases on each pass, and an undesired time-energy correlation would be introduced into the bunches. We will therefore design horizontal splitters, consisting of a set of beamlines, one for each energy, that will, for each pass, make the time of flight identical, remove any time-energy correlation in the bunch distribution, and perform matching between the linac and FFA line betatron functions and other optics parameters. Four such splitter lines were implemented on each side of the linac in the CBETA FFA-based ERL, and one of the scientists participating in this project was extensively involved in their design. Their layout is illustrated in Figure 7.

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Figure : The CBETA horizontal splitter for four different energies, which corrects and time-of-flight.

The horizontal splitters will occur immediately downstream of the CEBAF spreaders in the Northeast and Southwest corners of the machine. Strict matching of the Twiss optics parameters, dispersion and its derivative, time of flight (ToF), and R56 adjustments for each pass is required for multi-pass transport and matching into the FFA arcs.

Given the constraints of the upgrade within the pre-existing tunnel infrastructure and safety regulations, practical challenges arise in implementing any design. Equipment access points (found in the Northwest and Southeast corners of the machine) and personnel safety considerations (44-inch personnel clearance requirement) limit the placement of splitters to the upstream side of each FFA arc. Solutions like ramps over splitter lines, though feasible, may pose operational and safety concerns, necessitating thorough evaluation and exploration of alternative solutions to optimize functionality within the given constraints.

Further documentation on the constraints, requirements, and status of the Splitter design can be found [INSERT REFERENCES – 2 IPAC PAPERS, 1 TECH NOTE]

For this work, we will continue to develop a design for the Splitters which will meet beam and machine requirements, as well as abide the safety, physical, and operational boundary conditions required.

### FFA Arc to Recombiners and LINAC Transition Lattices Check for coherence

Transitioning from an arc to a linac requires a) suppression of the orbital offsets and dispersions down to zero for all energies and b) adjustment of the Twiss beta functions to values suitable for their transport through the linac. We plan to combine two novel techniques, namely, the adiabatic matching approach and parametric resonant optics excitation to fulfil these requirements.

The adiabatic matching approach provides a systematic control of the orbits and dispersion by gradually reducing the magnet bending angles over several arc cells following a polynomial pattern. The resulting behavior of dispersion and orbit in an adiabatic transition in CEBAF is shown in Figure 8. Note the lack of perturbation in β and therefore constant phase advance per cell. Incomplete suppression of the orbits and dispersions due the finite number of cells involved in the adiabatic transition sections will be more precisely controlled using harmonic correction of the individual energies. The harmonic correction is based on powering a corrector sequence with several kick harmonics corresponding to the betatron tunes. This may allow for greater deviation from adiabaticity and therefore reduction in the number of required cells. The design will be optimized within the scope of the proposed project.

The CEBAF linacs are relatively long straight sections with rather limited focusing. They require relatively large beta functions at the entrance for efficient control of the beam transport. Since the beta functions in the arcs are relatively small due to arcs’ strong focusing, the transition section must build them up from several meters up to the order of hundred meters. It is difficult to accomplish this within the paradigm of the adiabatic approach because it would require an unrealistic amount of space and/or a significant variation of the phase advance per cell not compatible with the adiabatic approach. Therefore, we propose to augment the adiabatic method with the parametric resonance excitation approach described below. It has the advantage of offering a systematic control of the individual energies as opposed to a brute-force optimization approach, which is not compatible with the adiabatic approach, requires a lot of space, and is not robust in the sense that variation of a single parameter affects all energies simultaneously making the design unstable against errors.

Using the difference in the phase advances of the different energies, one can develop a set of orthogonal knobs to control the passes mostly independently, by applying dipole and/or quadrupole kicks over multiple cells at a frequency correlated with the betatron oscillation frequency at a particular energy.  
Figures 9, 10, and 11 show that resonant excitation selectively controls the narrow band of energies. The width of this excited energy band is determined by the imposed resonance strength, which is proportional to the amplitude of the corrector magnet kick. This leads to the condition that at each energy, the resonance strength should be much smaller than the tune separation between the energies. If not, the resonance excitation of one energy would result in the excitation of another energy, resulting in the loss of independent control. By using a large number of cells, one can reduce the affected energy range.

At the same time, the resonance must be wide enough to cover the betatron tune spread in the beam. One must pay particular attention to this condition when implementing relatively large changes in βx. They may involve strong nonlinear effects in the beam dynamics, potentially leading to a significant increase in the tune spread. It is also worth noting that the corrector quadrupoles must be weak compared to the main focusing fields so that the betatron phase advance per cell is not significantly modified by them and the resonant condition is maintained. Finding a suitable resonance strength should not present a challenge because the tune spread of any particular beam pass is orders of magnitude smaller than the tune separation between any two consecutive passes.

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Figure : Orbit offset (top, left scale), dispersion (top, right scale) and horizontal (bottom, left scale) and vertical (bottom, right scale) Twiss β functions of the adiabatic part of the matching section.

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Figure : Twiss function at the end of the nth period, , versus the period number n for, = 0.05 (blue), 0.12 (green), 0.13 (red) and 0.14 (purple).

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Figure : Twiss function at the end of the 48th period, , versus the quadrupole kick phase for = 0.05 (blue), 0.12 (green), 0.13 (red) and 0.14 (purple).

A graph of a function

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Figure : Twiss function at the end of the 48th period, , versus the quadrupole kick phase for = 0.05 (blue), 0.12 (green), 0.13 (red) and 0.14 (purple).

### Extraction system

The fundamental RF frequency of accelerating cavities and the bunch structure of CEBAF is approximately 1.5 GHz. If one numbers the electron bunches, the odd number bunches are destined to go to Halls A, B, and C, and even number bunches end at experimental Hall D. In this way, separating the ABC beams from D beam is simple. If an RF separator with half frequency of 1.5GHz (750MHz) is used, the odd number bunches sit at the maximum of the sine wave and the even number bunches sit at the minimum. Therefore, the ABC beams get a small kick in one direction and D beam to the opposite direction. The small kick is then amplified using a set of quad and septa magnets until the beams are separated enough that ABC beams can be extracted. This is CEBAF’s procedure to extract ABC from D beams.

For the FFA lines, we propose to expand on this idea. We propose adding an RF separator, common to all passes, before the horizontal splitter to insert a small vertical kick to the ABC beams away from the D beam. Inside the horizontal Splitter, only for a selected pass, we amplify the small vertical kick. For that selected pass only, the separation increases and the ABC beams will be extracted out. At the end of the splitter, another RF separator, again common to all passes, will take out the small vertical kick for all the other passes that were not selected for extraction. The phases of the RF separators and the optics of the lines has to be properly set to have acceptable cancelation of the kicks. Once ABC beams are extracted out, the D beam will continue its journey to Hall D.

One of the main tasks of this current proposal is to develop the optics for extracting the beams to the appropriate experimental halls to have a complete start-to-end lattice.

### Diagnostics and Vacuum Hardware Integration into FFA Arcs Check, new

There is a strong incentive to have a high magnet packing factor in the FFA arcs, to bend the highest possible energy around the fixed CEBAF tunnel radius, while not exceeding the practical limits of permanent magnet fields.  However, other mandatory hardware is required in the arcs: vacuum pumps, beam position monitors, corrector magnets and radiation monitors.  Careful integration will be needed to include these while having minimal reduction of the magnet packing factor.  Current lattices for the FFA arc have drift spaces in the 8-12cm range.

 Vacuum pumps require a port of a certain size, which may be chosen by vacuum pumping simulations.  These should take account of the narrow geometry of the FFA arc vacuum chamber, plus the ante-chamber for absorbing synchrotron radiation.  In fact, the ante-chamber may provide a place to attach a pump that is not longitudinally between the magnets, while giving better gas transport out from the side of the small chamber section in the magnet aperture.

Four-button X-Y beam position monitors (BPMs) were placed in every cell of the CBETA FFA arc and worked extremely well for orbit correction purposes.  A similar system is expected to be essential for the CEBAF upgrade.  Notably, the CBETA BPMs were installed in a short 5cm gap between two magnets, as only the signal cables had to come outside the vacuum chamber, with the pickup buttons being internal.  There was a slight increase in outer chamber size as the BPMs were in a welded block, but there are clearly options for a longitudinally compact solution for CEBAF, which should be designed in 3D.

Window-frame corrector magnets can be installed surrounding the permanent magnets, as they were in CBETA, since the permanent magnets are transparent to fields coming from outside (materials have mr ~ 1).  Radiation monitors also need to be installed as near to the magnets and beam as possible, but a compact solution (ethernet CsI dosimeters) only 2cm wide were designed and used successfully at CBETA.

## Design Validation Beam Dynamics Studies

Certain quantities, such as cumulative emittance growth, the effects of fringe fields, correctors, and synchrotron radiation energy loss need to be evaluated through the entire lattice in order for the results to be believable. The following subsections describe the priority areas that will be investigated for this proposal, which best reduce the overall risk of the CEBAF energy upgrade design.

### Emittance Growth Budget CHECK THIS

Electron beam emittance growth due to synchrotron radiation is present in three dimensions: vertical, horizontal, and longitudinal. It needs to be examined in this proposal too, as it depends on the lattice design. There are two opposite effects occurring during electron beam circulation throughout the arcs: damping and heating. When the damping due to the loss of energy from synchrotron radiation is equal to the beam heating or emittance growth, a final beam equilibrium can be achieved. In equilibrium the growth and damping cancel. The time constant to approach equilibrium is long compared to the revolution time *T0=1/f0* around the accelerator or around the arc. The horizontal emittance is defined as [CITE]:

where *Cq*=3.84•10-13 m, *g= E0/(mc2)*, *Jx* is the partition number can be taken to be 1, and *r* is the bending radius of the magnet while is the Courant-Snyder invariant *dispersion action* ,“*curly* ”:

where *Dx* is the horizontal dispersion function, while *ax,* *bx,* and *gx* , are the betatron function parameters. The horizontal emittance growth after one turn can be expressed as [CITE]:

where *u(s)* is the photon energy emitted while *<u>g* average emitted photon energy, *Pg (s)* is the probability distribution, approximately the sum of squared energies is the product of the critical energy *uc* and the energy loss per turn. The critical synchrotron radiation energy is defined as [CITE]:

where *B* is the magnetic field, *e0=g mc2*, *h* is the universal constant, and *c* speed of light. Reducing the dispersion action reduces the emittance growth from synchrotron radiation. As the dispersion and betatron functions have very small values in the FFA lattice design, the effect on the emittance growth is reduced.

The impact of synchrotron radiation, in terms of energy loss and growth of transverse and longitudinal emittance, is a critical concern. Energy loss dictates both the beam energy available for users as well as the beam current limitation due to vacuum heating concerns. Reducing the emittance growth is desired to provide better beam to the experimental users and eases the design constraints for the transport lines to the experimental halls.

Evaluation of the impact of synchrotron radiation is done using two methods – particle tracking and radiation integrals. Given a lattice section, a particle distribution is created with the design parameters and tracked through the lattice, taking synchrotron radiation into account. At the end of the section, emittance growth and energy loss are calculated and propagated into the next section. Alternatively, the radiation integrals can be extracted from the lattice simulation and supplied to the appropriate formulae to analytically calculate the energy loss and emittance growth. Previous efforts using Bmad have shown good agreement between these two methods for sections of the current lattice design.

### Tracking with field maps

NEED SOMETHINIG HERE

### Refinement of initial 2D permanent magnet design

The permanent magnet design is produced in conjunction with the lattice cell design for the fixed-field arcs, because the feasibility of the magnet depends sensitively on the maximum fields and apertures required in these sections. 2D permanent magnet designs can be produced automatically from the required field parameters and apertures using the HalbachArea commandline tool [501], which contains an optimizer to select the size of the permanent magnet wedges. Short slices of some of these designs have also been built and verified to work in reality [502]. As a rough guide, if the maximum field required on the beams is 1.6 T or less, the magnet will work, but aperture and other factors also influence the final magnet cross-section.

During the course of this project, the parameters for the fixed-field arcs may change slightly. For example, changes in the energy range due to changing linac energy, or optimizations of the time-of-flight through the section. In these cases, 2D designs for the permanent magnets will be re-generated.

Another reason to refine the fixed-field arc is that the manually-chosen arc cell may not be the optimum from the point of view of minimizing total permanent magnet volume, which is closely related to the cost. Figure 12 shows the manual permanent magnet cross-sections compared to optimized versions and then optimized versions where a sextupole component was also allowed to be varied.

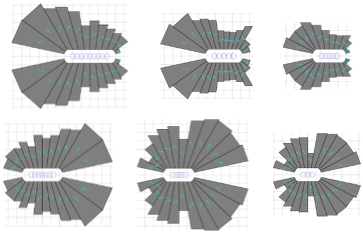


Figure : Focusing (top) and defocusing (bottom) 2D permanent magnet design comparison across three lattices. (Left) baseline design, (center) design optimized for minimum magnet volume, (right) design optimized for minimum magnet volume while allowing sextupole components. Grid is 1 cm spacing.

These design improvements were produced by the evolutionary algorithm in the Muon1 tracking code [503]. Each candidate cell is first checked for optical feasibility, i.e. that it transmits all the energies stably, and if so, magnets are automatically designed by calling HalbachArea from Muon1 and then calculating a figure of merit. The figure of merit here is the average cross-sectional area of permanent magnet material throughout the whole cell including drifts (which count as zero). This is directly proportional to the total magnet volume, which can be obtained by multiplying by the arc length. This value takes into account both lattice changes such as orbit excursion and focusing as well as magnet considerations. This approach represents a high degree of integration in the design process. Figure 13 shows the progress of one run of the evolutionary algorithm.

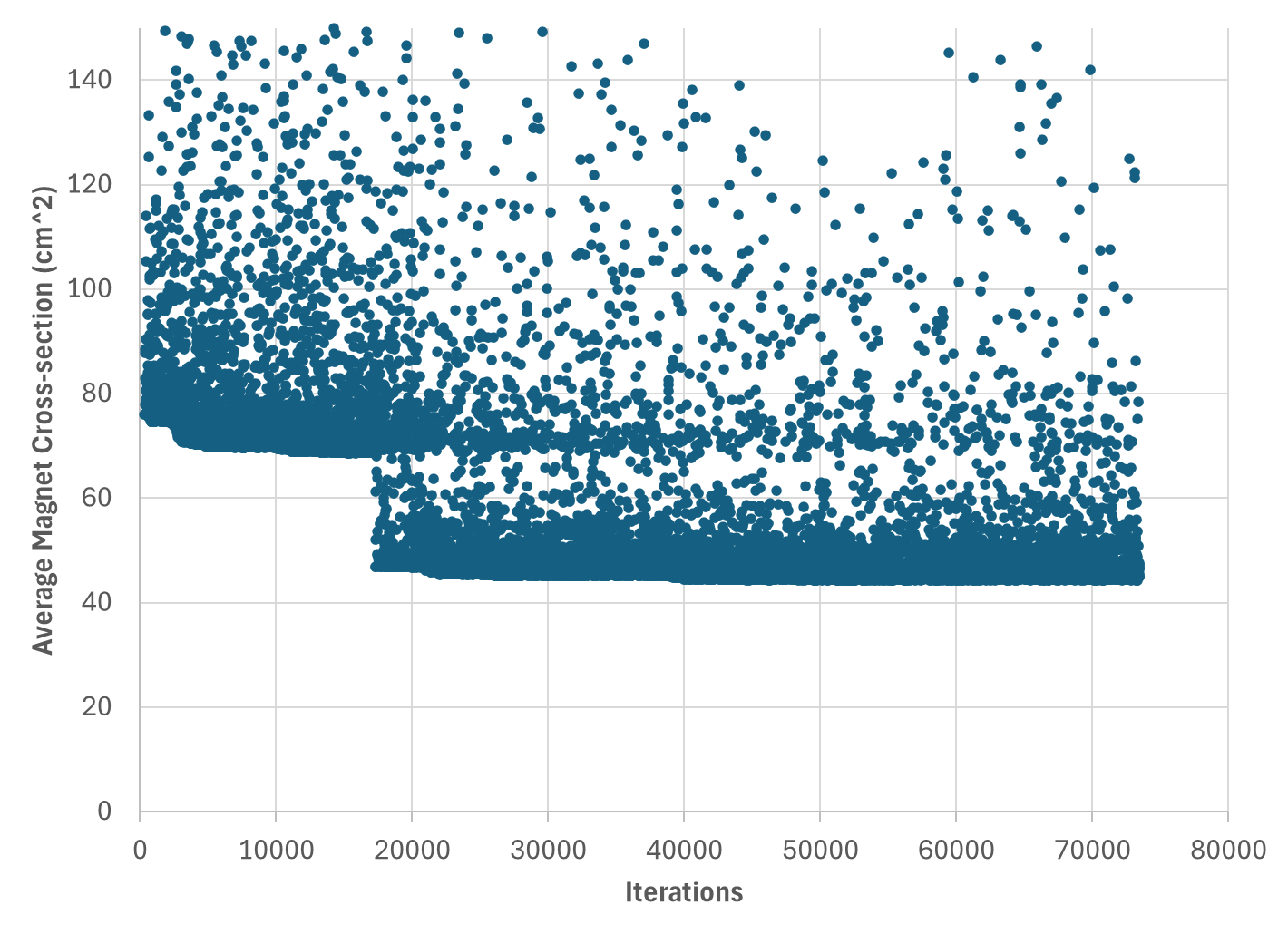


Figure : Progress of an evolutionary algorithm reducing the magnet cross-section area in an arc lattice cell. Here, sextupole field components are allowed to vary.

**Addition of Sextupole**

The linear field design of the fixed-field arc allows a range of energies to be stably transmitted that is adequate for nominal operation of the CEBAF energy upgrade, but does not contain extra energy range for low energies. This extra range would be needed if users desire the beam energy to be scanned to values between the energies of each turn, which is accomplished by reducing the energy of the linacs. Extra range is also useful to insure against RF cavity failures, which would also reduce the linac energy.

Adding a modest amount of nonlinearity in the form of a sextupole component in the arc permanent magnets appears to increase the stable energy range by slowing the tune variation with energy (lowering the chromaticity). Figure 14 shows the tune variation before and after adding up to 400 T/m2 of sextupole to the arc magnets.

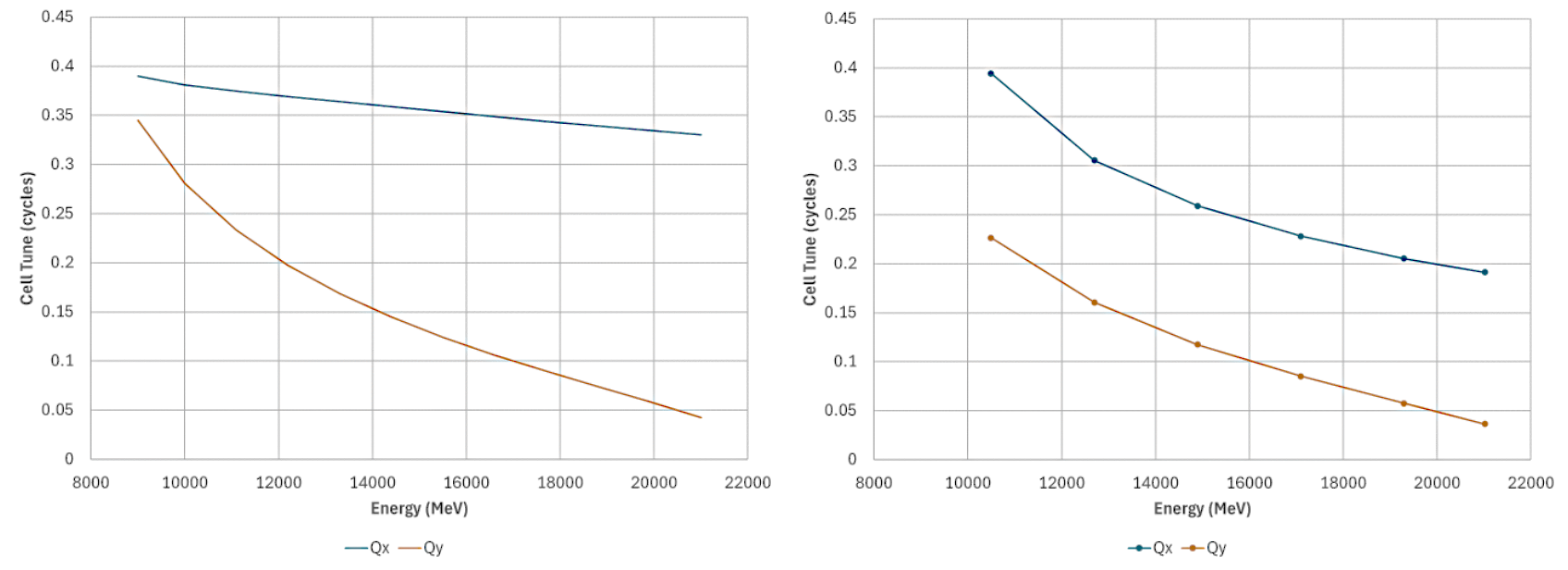


Figure : Tune variation as a function of beam energy in two fixed-field arc cells. (Left) the baseline cell with the nominal six energies shown. (Right) a cell including sextupole field components that has extended energy range down to 9 GeV, but slower variation of horizontal tune.

As shown already in Figure 12, there is no problem including sextupole and higher field components in the goal field for the permanent magnets. Each wedge piece produces a nonlinear field anyway and different field functions can be produced by changing the geometry, so they add to the correct amount.

A more important consideration with adding nonlinear field components is their effect on the dynamic aperture of the machine. With linear magnets, a large dynamic aperture is very likely, while with sextupole included, the stronger the nonlinearity, the smaller the stable region is likely to be. In this project the dynamic aperture will be evaluated for various designs.

There is also a possible knock-on effect to the orbit correction algorithm, as for large amplitudes the linear response matrix model may not be so accurate, so this will also have to be re-run (and possibly adapted) to make sure it works with sextupole. Another effect that happens even at the linear level is that the extended energy range will make the tunes of each orbit be closer together, making them less linearly independent. This may require more correctors to be added, or careful choice of the tune variation curve.

### Depolarization Effects of Synchrotron Radiation CHECK CONSISTENCY

CEBAF provides polarized electron beams for nuclear physics experiments, and also after an energy-increasing upgrade, high degrees of electron polarization will be required. Polarized beam is created in a polarized photo-cathode source and must be accelerated with minimal loss of polarization. Hitherto, polarized electron beam from linacs did not suffer large depolarization because (a) perturbances of spin dynamics only become destructive at high energies, and (b) depolarizing emission of synchrotron radiation only becomes relevant at high energies.

Spin dynamics is governed by the Thomas-BMT equation, which in the accelerator coordinate system, with the design path length as independent variable becomes:

with the magnetic anomaly of the electron, the upgrade’s relativistic of up to about 50,000, charge and longitudinal momentum and a curvature factor . The last parenthesis is only relevant for particles that oscillate around the design orbit, which is indicated by the index 0. The magnetic field component parallel and transverse to the momentum are multiplied by very different factors, the former by an of up to 60 and the latter by about 1.

Some observations can easily be drawn from these observations: (a) Transverse fields are by far the most relevant for high-energy spin motion. If the polarization is longitudinal, as usually in CEBAF, the parallel field term is additionally suppressed. (b) If a particle’s motion receives a kick in a transverse magnetic field, it’s spin is rotated by an angle that is up to 60 times as large.

The CEBAF upgrade has to address whether this can lead to significant depolarization. A simple estimate shows, that depolarization is benign during transport through linear sections, but can be significant in the arcs. The reason is that to first order in the spin’s angle from the longitudinal, it rotates around the same axis as the particle’s momentum with an angle that is multiplied by . For the full linac section, this angle amounts to only times the angular spread in the beam, measured in tens of micro-radians, i.e., too little for depolarization. However, in the arcs, spin rotation in dipole magnets does not commute with rotations in quadrupoles, and adding the effect of passing hundreds of magnets can add up to large spin rotations that can depolarize the beam. Additionally, there can be depolarizing effects from the emission of synchrotron motion at places with dispersion, also these need to be analyzed.

Bmad is the ideal tool to show that the CEBAF upgrade is able to provide large beam polarization on target, or to adjust the layout so that depolarization is avoided. Bmad is already widely used to analyze and optimize electron polarization in storage rings, e.g. the EIC, FCC-ee, and CEPC. In all these rings strong depolarization would occur if well-designed countermeasures were not developed. These countermeasures, e.g., eliminating depolarizing resonance strengths, linear spin matching, harmonic closed orbit spin matching, the BAGELS method of spin optimization are all implemented in Bmad and will help in the optimization of the CEBAF upgrade after they have been generalized to recirculating linacs.

Bmad is already the main tool for designing, modeling, and optimizing the CEBAF upgrade. Using it’s polarized beam abilities is therefore a natural extension. CBETA was also entirely design and operated with Bmad and the team is therefore very well versed with its abilities and intricacies. When Bmad was extended during the development of CBETA, it included special features unique to recirculating linacs and to FFA optics. When it was extended to the EIC and its ERL cooler, beam polarization and space charge forces were included. CSR forces, also relevant for the CEBAF upgrade are part of Bmad since some time. All these effects are relevant for the proposed work because a beam diluted by these nonlinear and coherent forces will suffer more severe depolarization. All this has made Bmad the most versatile beam simulation tool around, especially for the CEBAF upgrade. The team is therefore excellently equipped to perform the needed analysis of spin motion for beams that suffer nonlinear optics as well as coherent effects.

# Project Planning and Management

## Timelines and Milestones

Graphical user interface

Description automatically generated

## Contingencies and Risk Mitigation

The risks and contingency plans considered for each work package are given below.

* Accelerator and Lattice Design (JLAB and BNL)
  + *Design does not meet requirements on beam quality, for example if emittance growth is too high*. We have considered designs whose top energy varies between 20 and 22 GeV [40] and this energy can be easily varied by removing the last turn(s) of the machine. As synchrotron radiation is a steep function of energy, a lower energy is a strong mitigation here, with a small reduction in physics reach.
  + *Design does not fit in the existing CEBAF halls, e.g. too many splitter lines*. The number of lines may be reduced by reducing the number of turns. There are also proposed options to increase the linac energy gain from 1090 MeV to 1200 MeV that can reduce the loss of energy reach in this case. Otherwise, the costs of tunnel extension and excavation may have to be balanced against the costs and goals of the accelerator.
  + *Design is inconsistent with itself*. We aim to avoid this by having a common agreed master lattice file and table, from which all other input files for simulation are derived.
* Depolarization Effects of Synchrotron Radiation (Cornell and BNL)
  + *Polarization degraded beyond the NP spec set by CEBAF users*. Polarization study team is well positioned to perform detailed analysis of spin motion for beams effected by nonlinear optics as well as coherent effects. To mitigate nonlinear effects, there are several known ways to improve the field of permanent magnets. Such measures could be incorporated into an alternative magnet design.

## Organizational Structure CHECK PII COMPLIANCE

A proposed project brings together a well-balanced group of scientists and specialists from JLAB, BNL and Cornell University. The BNL and Cornell University teams already fully participated in the CBETA project, which makes use of their expertise in accelerator design and magnet production. Not only that the 230 produced magnets were of superb quality, but the project was well planned, and team execution resulted in the final magnet delivery two weeks before the project scheduled milestone.

## Communication Plan

The collaboration currently has weekly 1 hour video meetings to discuss progress and it is anticipated that this will continue through the period of this proposal. Additional ad hoc meetings may be organized for specific work packages. The accelerator lattice development will use a shared network area in which files defining the design can be downloaded in an agreed format. This will help analysis work to be consistent across labs. Results will be published at the annual IPAC accelerator conferences as well as peer-reviewed journals such as Physical Review: Accelerators and Beams. Another relevant annual conference is FFA (Fixed Field Accelerators). Communication with other working groups at JLAB will be maintained, particularly the positron group, who are also developing an upgrade option, and detector groups that define the beam requirements for physics. The budget includes funding for travel, which covers both in-person collaboration meetings a few times per year (scheduled as needed) and presentation of results at national and international venues: meetings, conferences, and workshops.

# Appendix 1: Bibliography & References Cited

CAREFULLY FILL THIS OUT

***References (for Stephen’s sections) - ADJUST***

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[303] CBETA note #029 “Online simulation tools for orbit correction in the CBETA Machine”, A. Nunez-delPrado and S. Peggs, BNL tech note BNL-211678-2019-TECH (2018), available from <https://www.osti.gov/servlets/purl/1514709>

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[502] “Open-Midplane Gradient Permanent Magnet with 1.53T Peak Field”, S. Brooks, Proc. IPAC 2023.

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[602] CBETA note #10 “Error Studies of Halbach Magnets”, S. Brooks, BNL tech note BNL-114543-2017-TECH (2017), available from <https://www.classe.cornell.edu/CBETA_PM/notes/CBETA010.pdf>

[603] CBETA note #36 “Radiation Limits for CBETA Halbach Magnets”, S. Brooks, BNL tech note BNL-211702-2019-TECH (2018), available from <https://www.osti.gov/servlets/purl/1515419>

# Appendix 2: Data Management Plan

*Types of Data Produced*

The data types generated by the research described in this project include:

* Design notes, calculations, algorithms and computer simulations
* Processes and controls
* Processed data (e.g., analyzed data, tables, graphs)
* Drawings and schematics
* Publications, talks and documents (e.g., papers in refereed journals, conferences and workshops, internal technical notes, competitive incentive proposals)

*The data management system will offer the following minimum capabilities:*

* Data capture and storage
* User-friendly graphical access to laboratory, industry and international collaborators
* Backup and archiving of data
* Compatibility with multiple formats (e.g., documents, spreadsheets, graphics, presentations)
* Access controls

*Plans for archiving and preservation*

The products of this research will be published in the open literature. The main venues are:

* Physical Review Special Topics – Accelerators and Beams
* Superconductor Science and Technology
* Proceedings of the International Particle Accelerator Conference
* Proceedings of the International Linear Accelerator Conference
* Proceedings of FFA Workshops

All the electronic files generated for this project will be preserved according to Jefferson Lab’s record management policy (https://www.jlab.org/div\_dept/cio/IR/records/index.html) and DOE's Research and Development Records Schedule.

*Policies for access and sharing, and provisions for appropriate protection/privacy*

Documents generated and classified in the course of this project will be shared among collaborators from the start of the project, and will be continually upgraded and updated. E-mail will be the most common method to share information. Prior to making them available for wider distribution, such as through journal publications or conference presentations, applications for the protection of Intellectual Property would be filed, as agreed upon by all collaborators.

Electronic documents created during this project will be stored in a project folder on a network drive maintained and backed-up daily by JLab’s Computer Science and Engineering Division. Access to the project folder will be limited to the JLab staff involved on the project. Jefferson Lab has robust cyber security processes and policies in place which will ensure data integrity and prevent unauthorized access.

*Policies and provisions for re-use and re-distribution*

With the exception of items that have potential for Intellectual Property rights, data and expertise acquired during this program will be either published, presented at conferences or both. Information will be made available to researchers elsewhere when the Intellectual Property rights are secured.

Any release of data will also be done in such a way to be compliant with any export control mandates where appropriate. Jefferson Lab does not believe this technology contains any export-controlled information; however, we are aware of the need for enhanced scrutiny in technology transfer to foreign entities; specifically, in the area of accelerator technology and will maintain protection of information generated under this initiative in accordance with the DOE’s S&T Risk Matrix. In addition, we will undertake the process of an -export control review to ensure any IP generated under this initiative is not subject to export control, and if it is, obtain the proper export licenses/waivers prior to release of any information.

# Appendix 3: Promoting Inclusive and Equitable Research (PIER) Plan

FILL OUT TEMPLATE, WITH EDITS, AND PUT HERE