RESONANT MATCHING SECTION FOR CEBAF ENERGY UPGRADE*

B.R. Gamage†, R.M. Bodenstein, S.A. Bogacz, A.M. Coxe, K.E. Deitrick, R. Kazimi,
D. Khan, G.A. Krafft, K.E. Price, Y.R. Roblin, T. Satogata, A. Seryi, D.L. Turner
Jefferson Lab, Newport News, VA, USA
V.S. Morozov, Oak Ridge National Lab, Oak Ridge, TN, USA
J.S. Berg, S.J. Brooks, F. Meot, D. Trbojevic
Brookhaven National Lab, Upton, NY, USA
G.H. Hoffstaetter, Cornell University, Ithaca, NY, USA

Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab) currently studies the feasibility of upgrading its energy to 22 GeV [1, 2]. It considers addition of six more linac passes. The highest energy passes will share two new arcs designed using the Fixed-Field Alternating Gradient (FFA) technology. The FFA arcs are built using permanent combined-function magnets. They will be connected to the linacs through transition sections that will match the optics of all six passes to the linacs. With the high number of constraints and the limited space available, we are investigating a parametric resonance technique to match the optics quasi-independently at each energy. A resonance is excited at each individual energy to selectively control its optics. The resonant dipole and quadrupole kick harmonics are imposed for all energies simultaneously using Panofsky corrector magnets placed throughout the FFA arcs. This paper presents the current progress on that transition section design.

INTRODUCTION

Jefferson Lab considers upgrading the energy of its Continuous Electron Beam Accelerator Facility (CEBAF) by about doubling the number of the beam accelerating passes through its linacs. Due to the tunnel space limitation and a significant increase in the number of recirculating arcs being impractical, it is planned to add only two new FFA-type arcs to the existing infrastructure that will transport all of the additional passes. In the current CEBAF configuration, each linac pass goes through its individual Electro-Magnetic (EM) arc. A section known as the recombiner channels the different-energy beams from multiple arcs into a single beamline before they reach the linac. Since the additional passes from the new FFA arcs are already in the same plane, they are combined with the EM passes by means of a dipole chicane. The chicane contains no knobs for individual control of the different-energy beam optics. Thus, a dedicated transition section is needed to optically match the FFA passes to the linac. Separating the FFA passes into individual beam lines for independent matching of the different passes is impractically complicated. Therefore, we consider a scheme where the different-energy passes are matched to the linac simultaneously within a single FFA-type beamline.

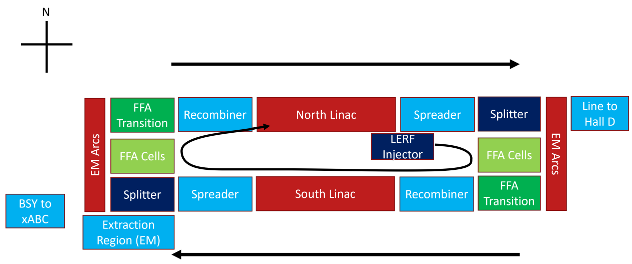

Figure 1: A block diagram layout of CEBAF for the proposed energy upgrade using FFA arcs .

Transitioning from an arc to a linac requires,

1. suppression of the orbital offsets and dispersions down to zero for all energies
2. adjustment of the Twiss functions to values suitable for their transport through the linac

ADIABATIC MATCHING SCHEME

The transition section includes two novel techniques, namely, the adiabatic matching approach [3, 4] 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 as show below,

$$\theta_i = A_i \theta_0, \tag{1}$$

Where the scaling factor is given by the third order polynomial,

$$A_i = 2\left(\frac{i}{C_n+1}\right)^3 - 3\left(\frac{i}{C_n+1}\right)^2 + 1, \tag{2}$$

with C_n being the number of cells used in the adiabatic section.

The resulting behavior of the dispersions and orbits in the adiabatic matching section is shown in Fig. 3. Note the lack of perturbation in the β functions and therefore constant betatron phase advance per cell. Incomplete suppression

* THIS MATERIAL IS BASED UPON WORK SUPPORTED BY JEFFERSON SCIENCE ASSOCIATES, LLC UNDER CONTRACT NO. DE-AC05-06OR23177, BROOKHAVEN SCIENCE ASSOCIATES, LLC UNDER CONTRACT NO. DE-SC0012704 AND UT-BATTELLE, LLC, UNDER CONTRACT NO. DE-AC05-00OR22725 WITH THE U.S. DEPARTMENT OF ENERGY.

† randika@jlab.org

of the orbits and dispersions due to the finite number of cells involved in the adiabatic transition section 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 required number of cells.

The existing tunnel geometry and the fixed location of the linac start point impose tight constraints on the transition section layout. One must make sure that the layout resulting from tapering down of the dipole field according to the 3^{rd} order polynomial in Eq. 2 fits within the tunnel boundaries. To solve this problem, before reducing the dipole field to zero, we first adiabatically increase it by about +3% of its value in a regular FFA cell as shown in Figure 2.

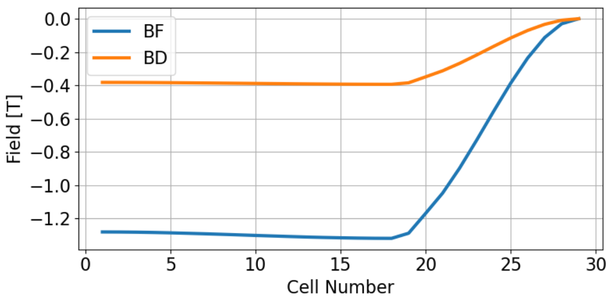

Figure 2: Variation of the dipole field strength of the combined function magnets used in the adiabatic transition section. Initially, the field strength increases across 18 cells, followed by a decrease to zero across 10 cells. The starting values are BF=-1.28T and BD=-0.38T.

RESONANT EXCITATION

The CEBAF linacs are relatively long straight sections with rather limited focusing. They require comparatively large β functions at the entrance for efficient control of the beam transport. Since the β 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 tens of 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.

Consider evolution of the particle coordinates in a beamline composed of a series of periodic cells under angular kicks applied every cell at a particular frequency

$$\begin{pmatrix} x_N \\ x'_N \end{pmatrix} = \sum_{n=1}^{N} \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}^{(N-n-1)} \begin{pmatrix} 0 \\ \Delta x'(n) \end{pmatrix}, \quad (3)$$

where

$$\Delta x'(n) = x'_{corr} \cos\left(2\pi\nu_{corr}(n-1) + \phi_{corr}\right) \quad (4)$$

and

$$\begin{aligned} A_{11} &= \cos(2\pi\nu_x) + \alpha_x \sin(2\pi\nu_x) \\ A_{12} &= \beta_x \sin(2\pi\nu_x) \\ A_{21} &= -\left(1+\alpha_x^2\right)\sin(2\pi\nu_x)/\beta_x \\ A_{22} &= \cos(2\pi\nu_x) - \alpha_x \sin(2\pi\nu_x) \end{aligned} \quad (5)$$

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 x'_{corr}. 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 excitation of another energy, resulting in the loss of independent control. By using a large number of cells, one can reduce the required kick amplitude and therefore 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 β. 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.

Figure. 3 shows the resulting behaviour of the orbits and dispersions. It is important to note that the resonant excitation using the dipole component of the corrector magnets did not change the phase advance of the cells.

Table.1 shows the orbit and dispersion numerical values at the end of the transition section.

The second step of this matching scheme is to match the Twiss parameters, αs and βs, to the recombiner entrance. This can be accomplished through exciting a parametric resonance in the optics by applying quadrupole focusing

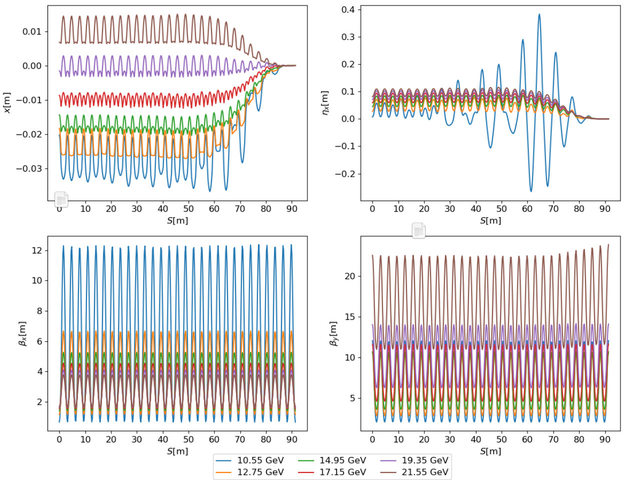

Figure 3: Twiss parameters of the north-west transition section with only the orbit and dispersion corrected. The top left and right plots show the horizontal and vertical β functions, respectively. The bottom left plot shows the orbit and the bottom right plot shows the dispersion.

Table 1: Orbit and dispersion values at the end of the transition section after the harmonic correction.

Energy GeV	**orbit m**	**orbitpx**	η_x **m**	η'_x
1	-8×10^{-10}	2×10^{-11}	-6×10^{-8}	1×10^{-7}
2	-5×10^{-9}	-1×10^{-8}	-5×10^{-8}	-2×10^{-8}
3	-3×10^{-8}	1×10^{-7}	3×10^{-7}	3×10^{-7}
4	-1×10^{-5}	1×10^{-5}	-6×10^{-9}	1×10^{-8}
5	-3×10^{-5}	3×10^{-5}	-5×10^{-8}	1×10^{-8}
6	-9×10^{-6}	5×10^{-5}	6×10^{-9}	-2×10^{-8}

kicks at twise the frequency of the betatron oscillations. It is convenient to apply resonant excitation after suppressing the orbit and dispersion so that they are not affected by the quadrupole kicks.

However, the CEBAF space constraints do not allow for implementation of the two matching steps sequentially. Matching of the Twiss β and α must be combined with adiabatic orbit and dispersion suppression. Quadrupole kicks affect the orbit and dispersion when applied in a region where they are not zero. This effect may then need to be accounted for by harmonic correction. At the same time, the maximum size of the orbital offset and beam size combination must be kept with the magnet aperture limitations [5]. This complicates the matching procedure. Figure 4 illustrates the result of combining the resonant optics match of the first FFA pass with the previously attained orbit and dispersion solution.

SUMMARY AND FUTURE PLANS

It has been demonstrated that the adiabatic and resonant matching approaches can provide effective optics solutions when used separately. We are exploring the possibility of applying them in the same section simultaneously to minimize

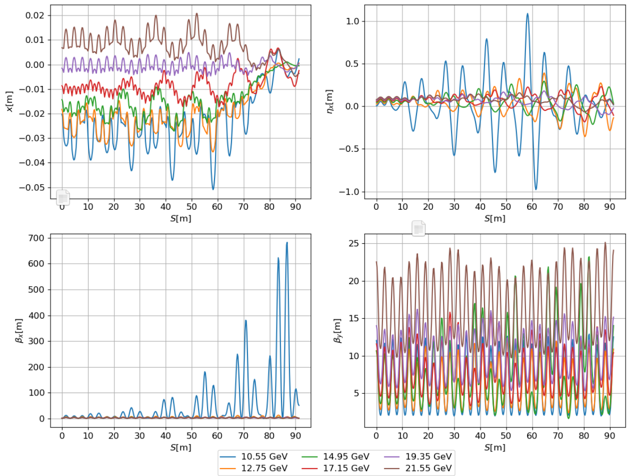

Figure 4: Twiss parameters of the north-west transition section with the orbit and dispersion corrected and the optics of the first FFA pass matched to the linac. The top left and right plots show the horizontal and vertical β functions, respectively. The bottom left plot shows the orbit and the bottom right plot shows the dispersion.

the matching space requirements. The matching problem can be simplified by relaxing the optics constraints at the entrance into the linac. As long as the beam can be transported through the linac efficiently, a certain level of optics variation at the linac entrance can be accounted for in the splitter section [6] at the end of the linac where the different energy beams are separated into individual beamlines and can be matched independently. The level of the optics flexibility at the linac entrance is being explored.

REFERENCES

[1] J. Benesch *et al.*, "CEBAF 22 GeV FFA energy upgrade", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 962-964. `doi:10.18429/JACoW-IPAC2023-MOPL182`

[2] D. Khan *et al.*, "Current status of the FFA@CEBAF energy upgrade", in *Proc. IPAC'24*, Nashville, TN, USA May 2024.

[3] V. Morozov *et al.*, "Proton and electron RLA optics design", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 958-961. `doi:10.18429/JACoW-IPAC2023-MOPL180`

[4] V. Morozov *et al.*, "Development of FFA RLA design concept", in *Proc. IPAC'24*, Nashville, TN, USA May 2024.

[5] S. Brooks, "Open-midplane gradient permanent magnet with 1.53 T peak field", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3870-3873. `doi:10.18429/JACoW-IPAC2023-WEPM128`

[6] R. Bodenstein *et al.*, "Horizontal splitter design for FFA@CEBAF energy upgrade: current status", in *Proc. IPAC'24*, Nashville, TN, USA May 2024.