# Alternative FFA Arc - Brainstorm
# JLAB-TN-23-076

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Original: December 7, 2023

## 1 Document Description

This document will describe the basic idea for an alternative FFA arc to be used in the FFA@CEBAF energy upgrade. These ideas are just that: ideas. No calculations have been performed for this, and all graphics are simply descriptive. This idea may not be feasible, and even if it is feasible, it is likely more complicated and may not be worth the extra effort and cost. Please keep this in mind when reading.

## 2 Background

The current design for the Fixed-Field Alternating Gradient (FFA) energy upgrade follows closely the CBETA design [[1]]. A generalized diagram of the CEBAF arcs is shown in Figure 1. The lowest energy pass takes the inner path, and each successive pass follows an orbit of slightly greater radius, with the highest energy pass taking the outermost path. This is shown in Figure 2.

Given the complexity of the constraints on the Splitter design [[2]], especially in combination with possible extraction systems, discussions started on how to alleviate some of the pressure on the Splitters. The ideas presented here started during a discussion with Reza Kazimi. He found that the path length of the highest energy pass was 156.26° of RF wavelength longer than the lowest energy pass, based on data from Bmad simulations on the current baseline lattice. His idea is to flip the orbits at the center of the FFA arc, so that the outermost orbit in the second half is the lowest energy pass, and the innermost path is the highest energy pass. At first, discussions of how to do this with conventional magnets was the focus: for example, using a Lambertson-style magnet to cross the passes over each other transversely, then re-order them and send them through the rest of the FFA arc. We weren't sure if this is feasible, given the high energies in the passes. Likely, it would take up a lot of space in the arc.

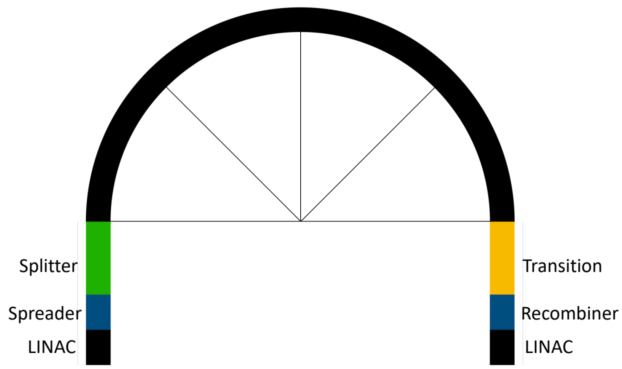


Figure 1: Generic diagram of the CEBAF Arcs for the FFA@CEBAF Upgrade.

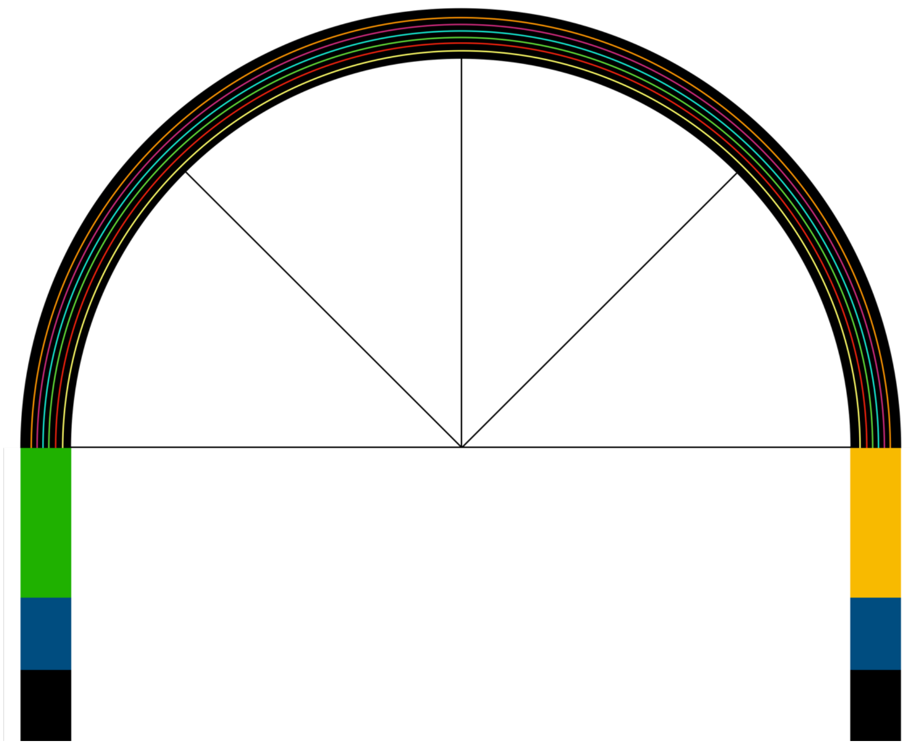

Figure 2: Basic diagram showing the orbit paths in the FFA arc. The innermost path is the lowest energy, and the outermost pass is the highest energy.

# 3 Adiabatic Flip

Recalling the work that Vasiliy Morozov an Randika Gamage did on creating an adiabatic transition (see Figure 3 for a simplified graphic of this idea), I thought this might be a better solution than quickly flipping the orbits at one location. One of the reasons that the adiabatic transition was not used for the baseline design is because it ends up being quite long, and uses a variety of different types of magnets. This remains true for the ideas presented here.

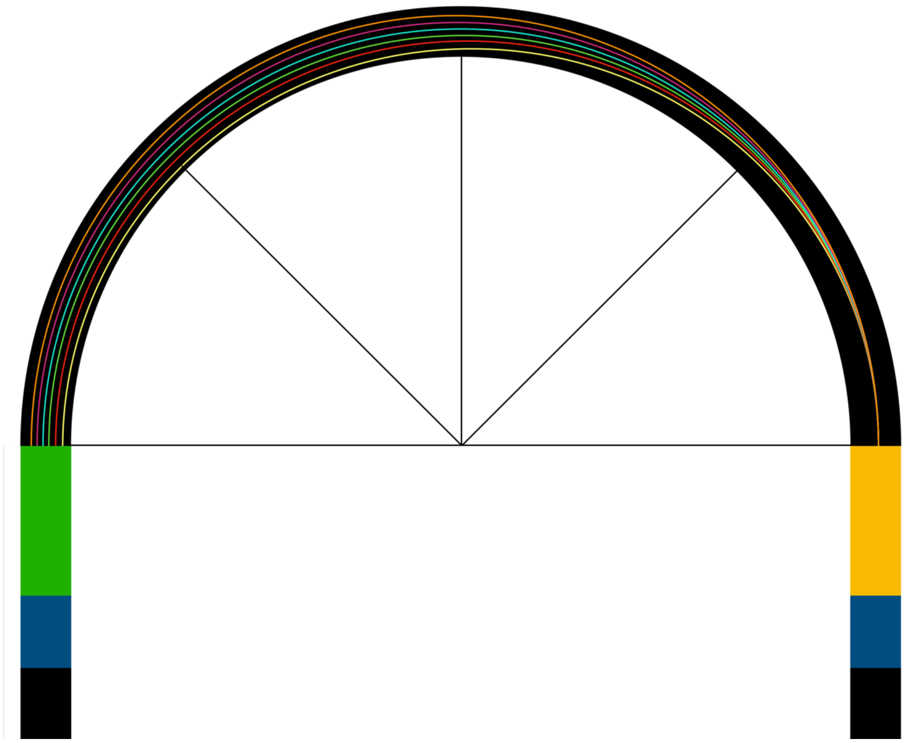

Figure 3: Simplified diagram of the adiabatic transition concept.

This idea might make better sense if it is used throughout the FFA arc - specifically by transitioning the orbits so that they slowly converge to colinearity, and then flip and slowly transition back to a fully-separated set of beams entering the downstream recombiner. This would mean the full FFA arc would consist of adiabatically changing permanent magnets, or a combination of different permanent magnets and additional EM correctors to assist in the transition. Figure 4 shows this concept graphically.

This will even out the path length differences from the different energy passes, and bring the time of flight (ToF) differences much closer together, easing some pressure on the Splitters. However, this will not ease the pressure on the design of the transition section currently being designed. The orbits are still fully separated when they enter the transition lattice, and must be both recombined and optically matched into the recombiner.

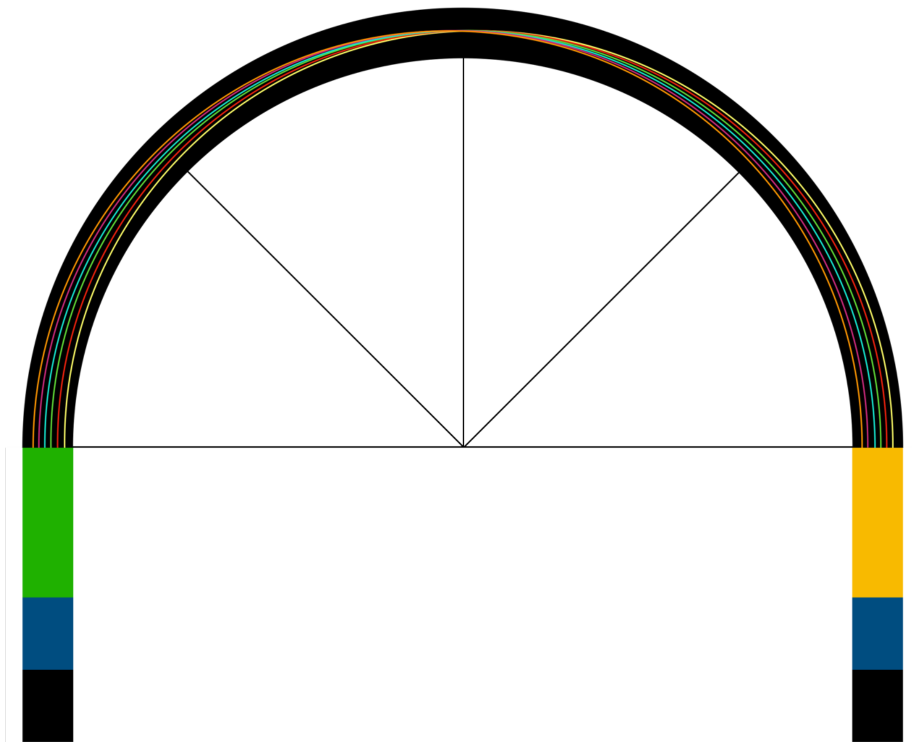

Figure 4: Simplified diagram of the adiabatic orbit-flip concept.

## 4 Orbit Flip and Transition

To further ease the design of the transition lattice, it may be helpful to have the orbits enter co-linearly. This would allow the transition section to be used for multipass optics correction alone, reducing the number of required knobs. Figure 5 shows the concept graphically (but not necessarily accurately - please read the caption). In this idea, one would calculate the ToF on each side of the orbit crossover point, and move the point until the ToF on both sides is balanced, cancelling out the difference. This fiducial point will no longer be in the center of the arc, as there is also an adiabatic transition to the end of the arc which brings the orbits back to co-linearity.

One could allow the final adiabatic transition to occur through the transition section as well, aiming for co-linearity at the beginning of the recombiner. However, this would not relieve any of the pressures currently placed on the design.

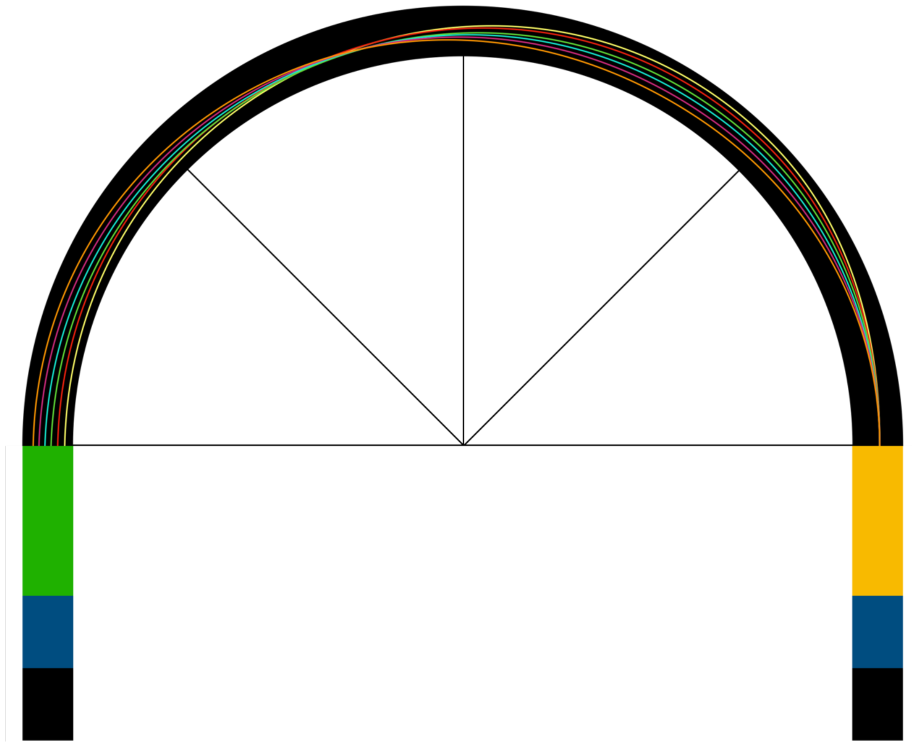

Figure 5: Simplified diagram of the adiabatic orbit-flip and merge concept. Please note that the fiducial point for the orbits in the upper left (second quadrant) is only there to demonstrate the concept. It will need to be moved to the appropriate location after calculations for ToF are performed.

# 5 Another Possibility - Supercells

Going a bit further, and considering each fiducial point as a sort of supercell beginning or end, one could divide the FFA arc into two supercells which are orbit-flipped in relation to each other. This would change the entry conditions from the splitters into the FFA arc, requiring the orbits enter co-linearly, but with different incoming orbit angles. The orbits would then adiabatically separate and re-merge at a central fiducial point, where the orbits would flip, and repeat the process (with orbits on opposite paths) on the other half of the FFA arc, finally entering the transition section co-linearly, but with an angular component which will need to be controlled. This setup (shown in Figure 6) would have two mirror-symmetric supercell lattices, which themselves are anti-symmetric from each other in that the ordering of the different passes is reversed.

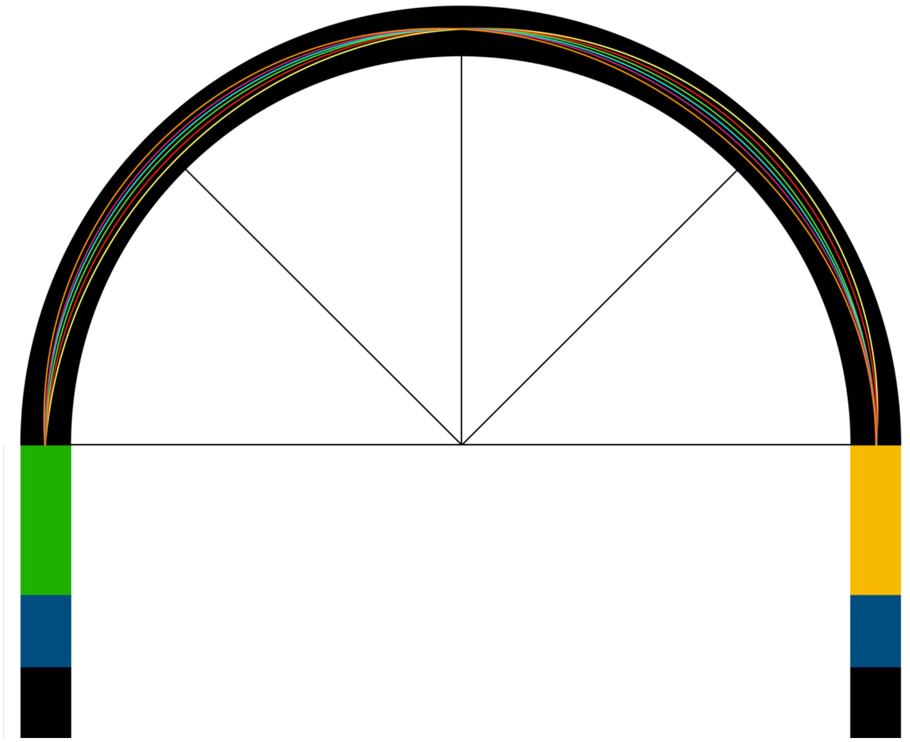

Figure 6: Simplified diagram of the adiabatic two-supercell concept.

# 6 Questions and Concerns

To reiterate, none of this work has been checked mathematically - it is purely conceptual at this point. The question of balancing the time of flight seems straightforward, however the impact on the Splitter design may be minimal, as ToF is not one of the harder aspects to correct in the splitters.

Importantly, $R_{56}$ is likely to impacted by these options, and it is unsure the nature of the impact. If this relieves some of the pressure on the $R_{56}$ as well, it may be even more worthwhile to investigate. However, the converse may also be true, in which case this is best left as an academic consideration.

Furthermore, the latter options involve varying the bending radii, which may also impact the synchrotron radiation losses.

Achieving the ideas presented here may not be possible, though similar ideas have been explored by Vasiliy Morozov at ORNL. To do this using permanent magnets, each magnet will need to be different to accommodate the transitions. This gets very expensive and complicated to simulate, design, build, and maintain. However, it may be possible to use a standard set of magnetic blocks, and vary how these blocks are placed around the beamline to accomplish the same or similar results. This also requires difficult and detailed design work, but would be less expensive than a set of custom magnet shapes.

It is also possible to use a combination of permanent magnets and corrector magnets to accomplish this. It would likely necessitate additional correctors added around the permanent magnet cells, as they would primarily be used for controlling the adiabatic transitions. This may complicate the correction scheme as well. However, this may balance the extra cost of all-custom permanent magnets.

Finally, the impact on the usability of these concepts by operations is completely unknown. Currently, the baseline requires very tight control of the beams as they enter the FFA arc. Once the beam is matched into the FFA arcs, they will generally make it through. With these more complicated design ideas, this may no longer be the case.

In the end, it is uncertain if the ideas presented in this note are worth further investigation. A basic investigation into ToF correction, $R_{56}$ impact, and feasibility are likely worth some level of effort. Depending on the conclusions drawn from those studies, it can be decided if the benefits of the added effort and cost outweigh the current baseline.

## References

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

[2] Ryan Bodenstein - JLAB-TN-23-069, *Horizontal Splitter Design for FFA@CEBAF: Focus on Geometry*