CEBAF 22 GeV with Fixed Field Alternating (FFA) Gradient Design

Developing a pre-conceptual design for an FFA racetrack in the existing CEBAF tunnel to reach ~22 GeV

September 2025

Donish Khan on behalf of the FFA@CEBAF Collaboration

Jefferson Lab

U.S. DEPARTMENT of ENERGY

The FFA@CEBAF Collaboration

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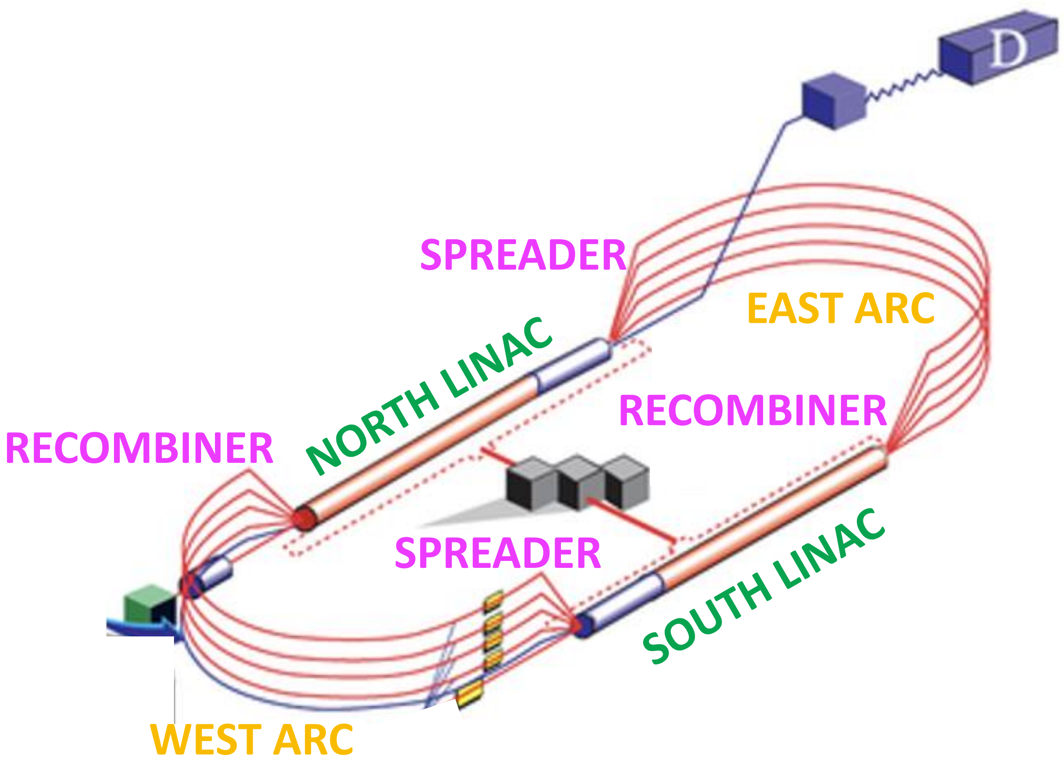
Introduction: CEBAF @ Jefferson Lab

Jefferson Lab

- The Continuous Electron Beamline Accelerator Facility (CEBAF) is a racetrack accelerator consisting of:

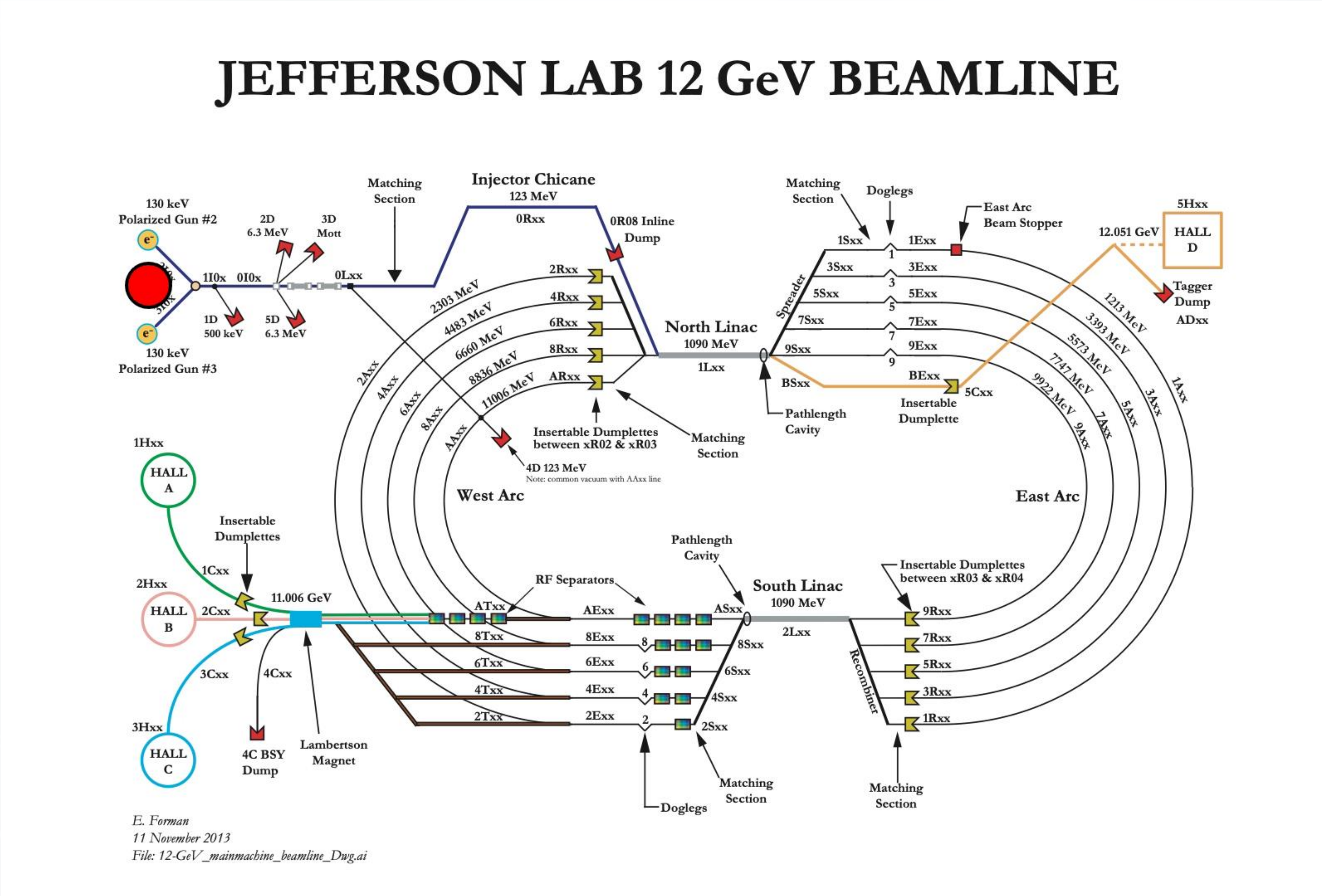
  1. Injection from Low Energy Recirculating Facility (LERF) with 135 MeV electron beam.
  2. Two (North and South) anti-parallel superconducting linacs ($\Delta E_o \sim 1.1\ GeV$).
  3. Two (East and West) $180°$ multi-level recirculating arcs.
  4. Beams separated via electromagnetic vertical bend systems Spreader/Recombiners.

- These components in act together to get the beam to a final energy of 12 GeV.

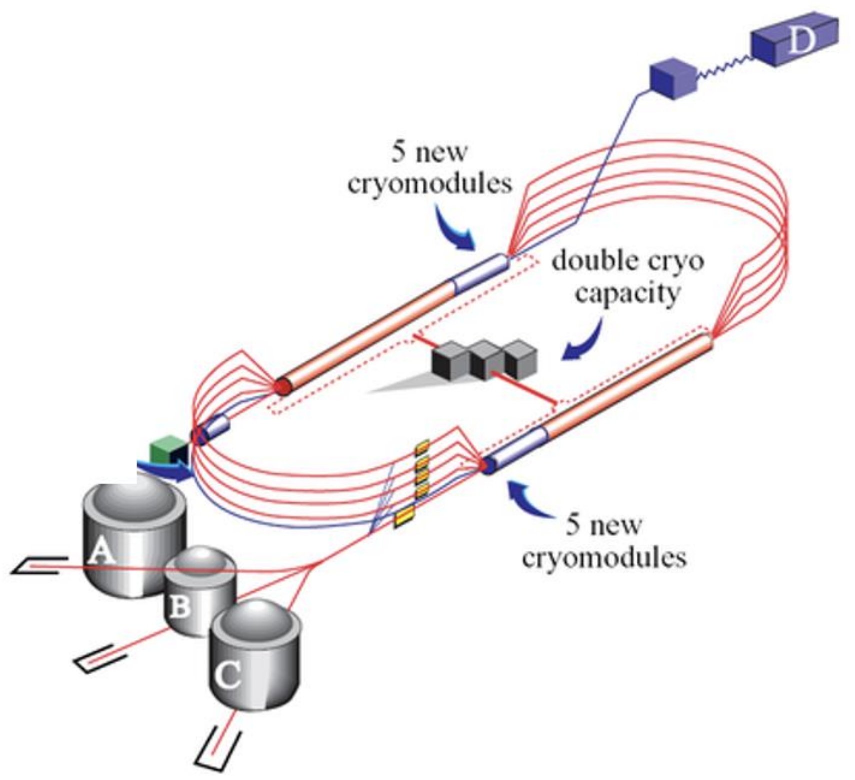


DOI: https://doi.org/10.22323/1.172.0001

Introduction: CEBAF @ Jefferson Lab



CEBAF's Energy Upgrade



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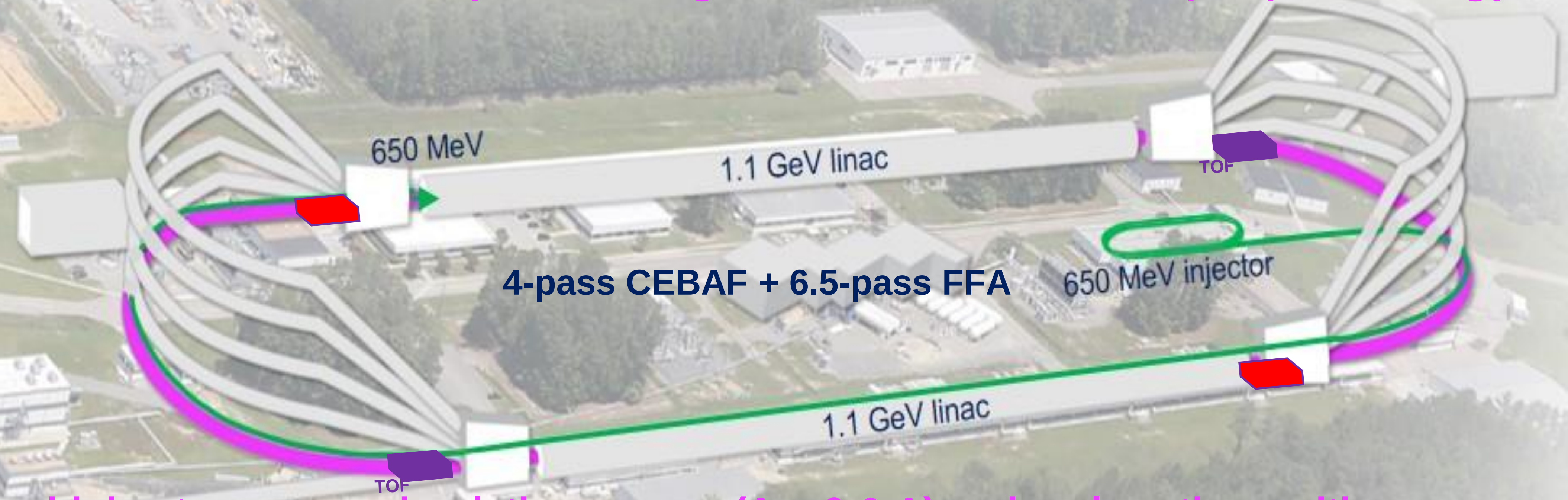
- The last energy upgrade (6 GeV to 12 GeV) in ~2015 was achieved by adding additional RF cryomodules in linacs free space:
  - 5 Cryomodules per linac
  - Cryomodule energy change: 100 MV

- Next Energy upgrade (12 GeV to 22 GeV):
  - Existing footprint preserved.
  - No room for additional cavities.
  - Need to be clever; leverage advancement of magnet/accelerator technology.

FFA@CEBAF

Increase the number of recirculation passes using Fixed Field Accelerator (FFA) technology



1. Remove the highest energy recirculation passes (Arc 9 & A) and replace them with two FFA arcs
2. Include time-of-flight (TOF) Splitter bend systems.
3. Include adiabatic matching section back into the linacs.
4. New 650 MeV recirculating injector

A. Bogacz

Modifications Overview

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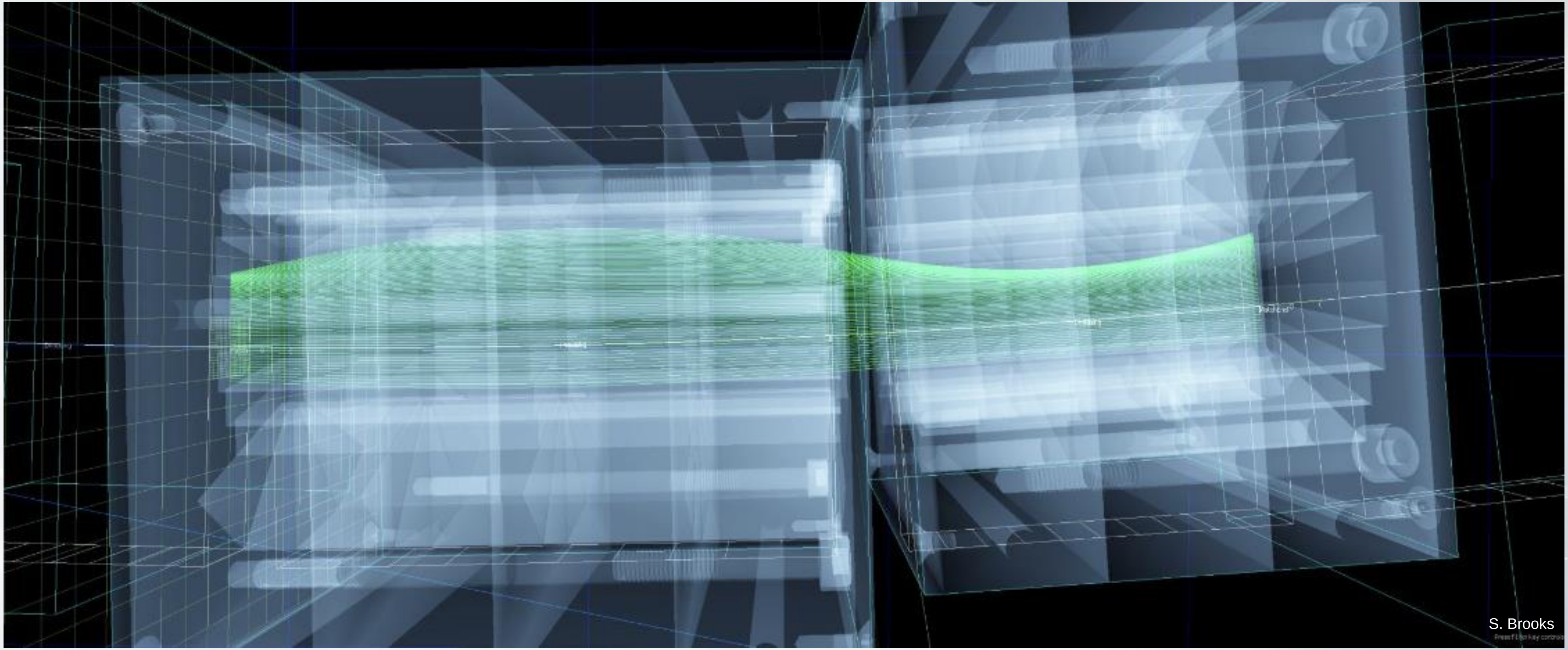
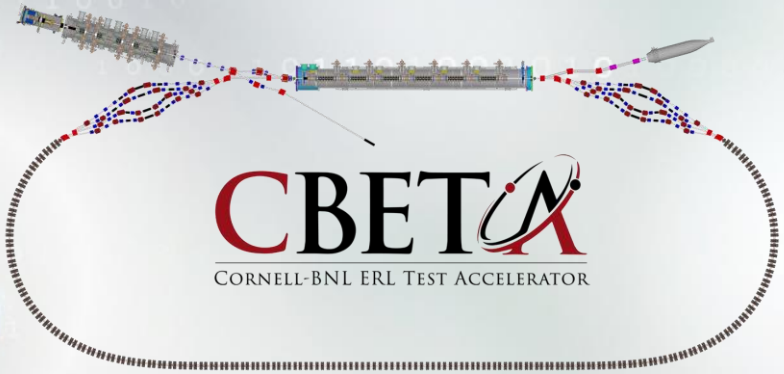
- For the current 22 GeV baseline (650 MeV inj + 4-pass CEBAF + 6.5-pass FFA) we have the following modifications:
  1. FFA arc(s) in highest-energy recirculating arc location(s)
  2. 135 Mev → 650 MeV injector upgrade
  3. New multi-pass linac optics
  4. Design of modified CEBAF EM arcs and switchyard(s):
     a) Arcs 1-8
     b) TOF correction ‘Splitters’
     c) Arc-To-Linac Transition Section

FFA Arc - FODO Cell

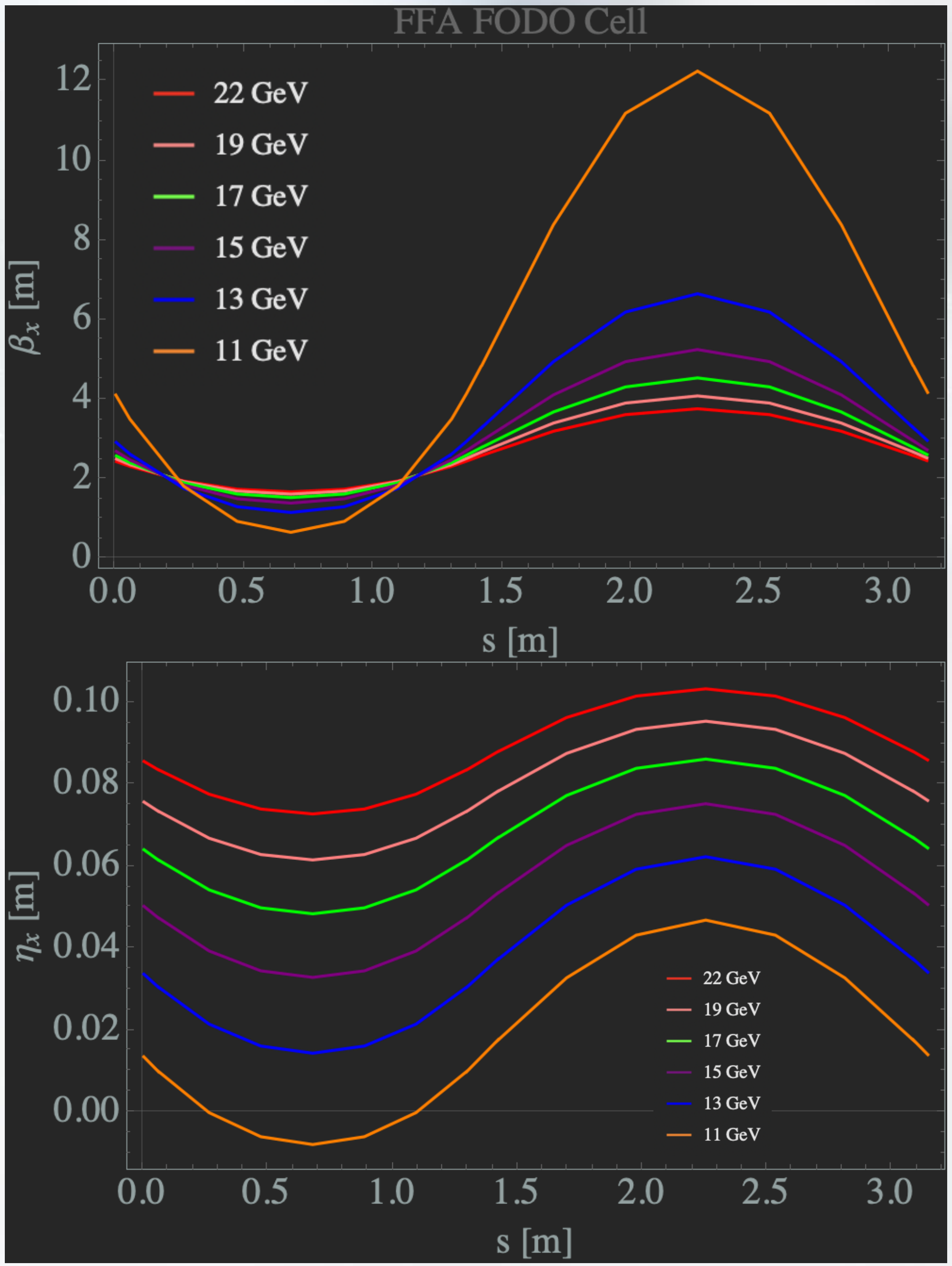


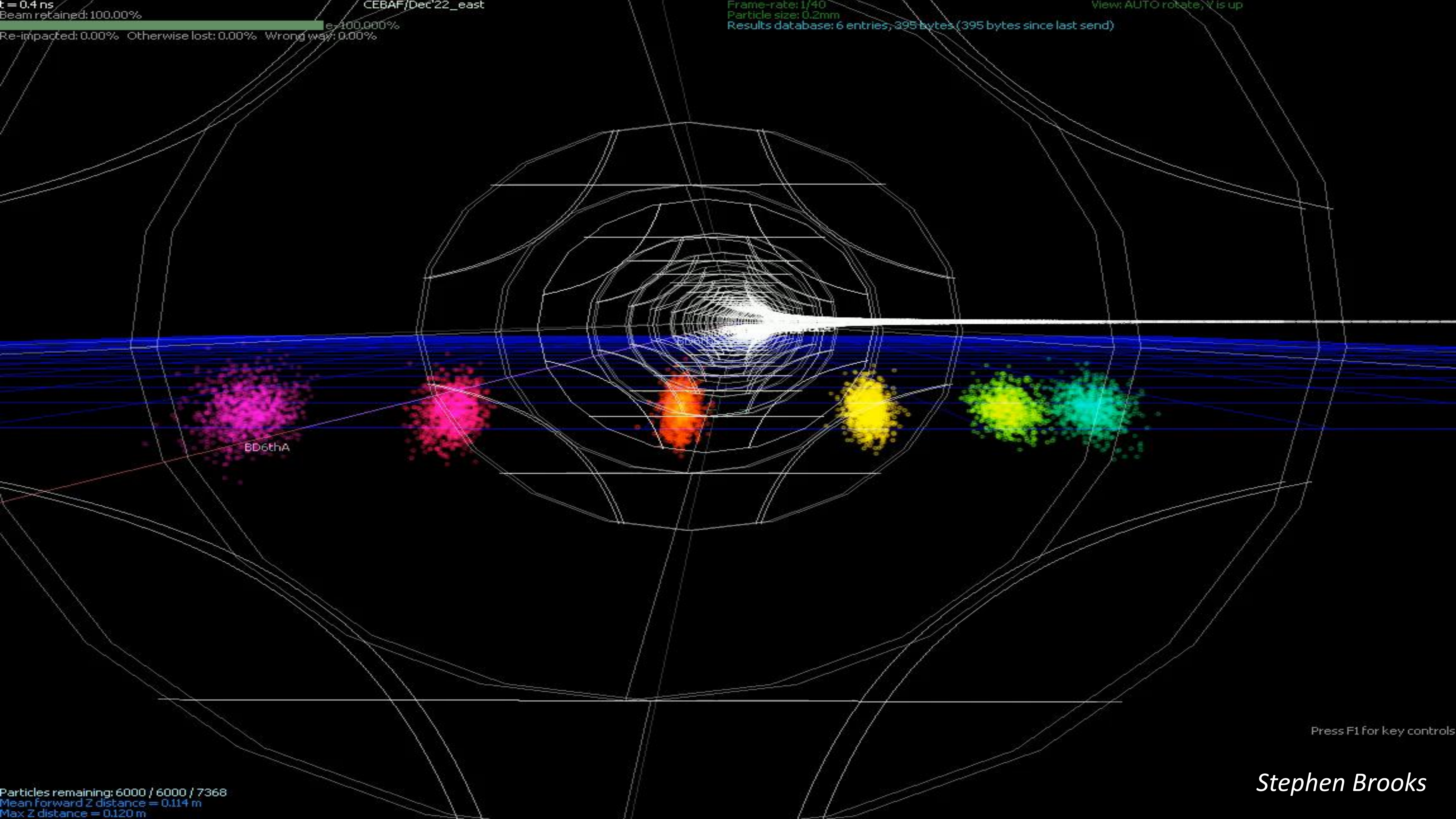
FFA Arc – Compact FODO Cell

Inspiration taken from Cornell-BNL ERL Test Accelerator (CBETA, 40 - 150 MeV):



- Large momentum acceptance; transport 6 beams with energies spanning a factor of two (11 - 22 GeV)
  - Compact cells: $L_{cell} = 3.15$ m
  - Small betas (sub 10 m)
  - Low dispersions (a few cm)
- Closely spaced orbits for all six beams (~ 4 cm)

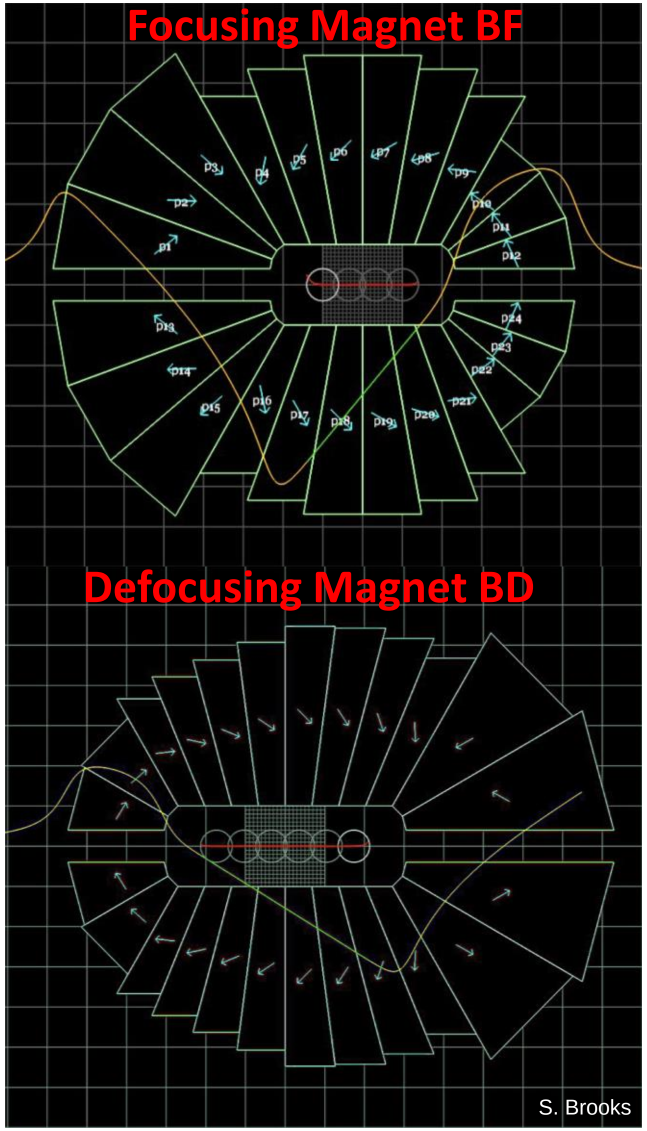


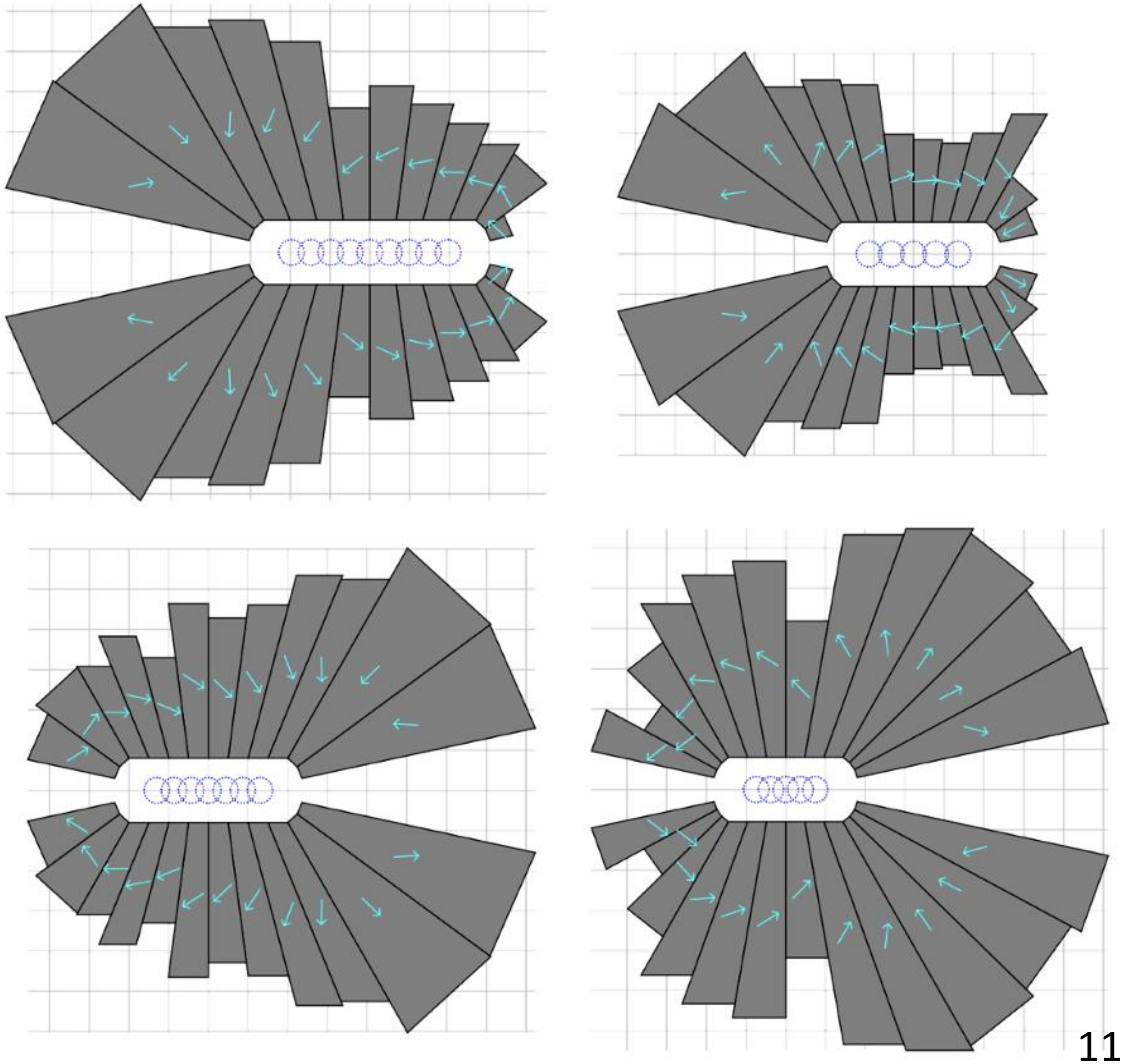


Stephen Brooks

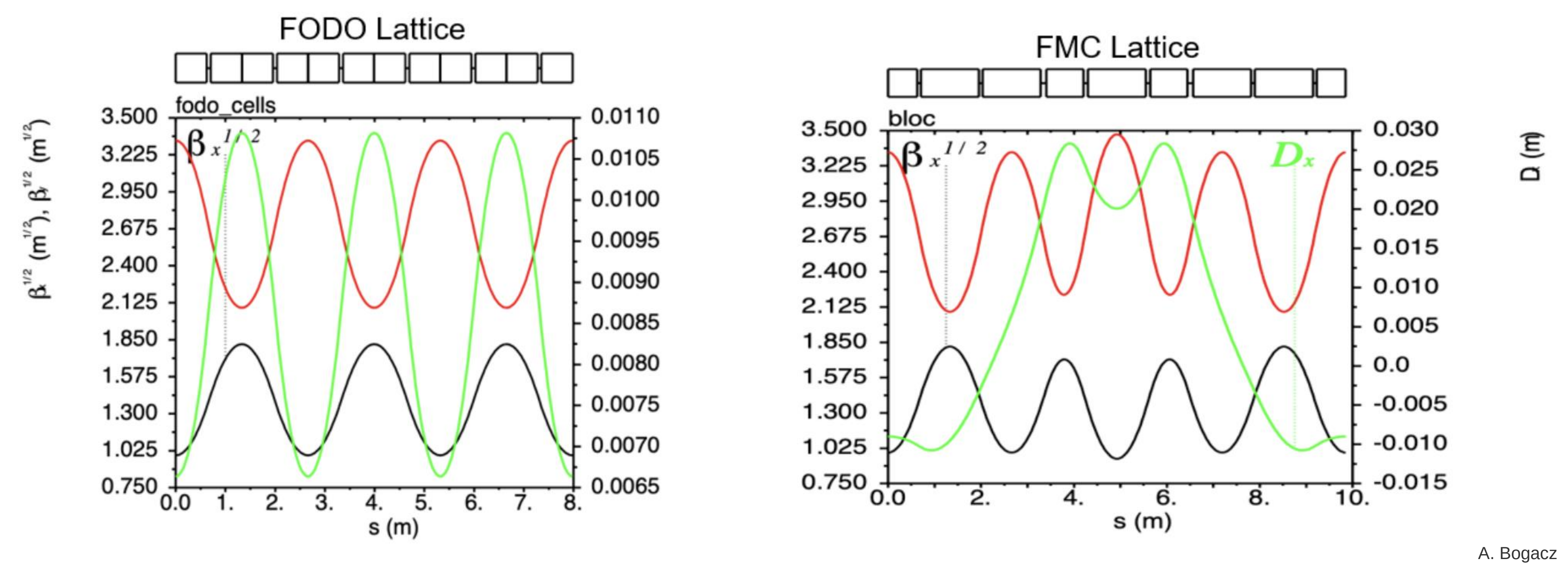
Halbach Permanent Magnet Design

- ***Compact*** compared to conventional electro-magnets.
- Allows for accommodating 6 additional passes in CEBAF tunnel.
- Provides power and cost savings.
- Open mid-plane geometry
- Concept successfully tested at CBETA.





Exploring Different FFA Optics



- FFA arc optics are flexible enough to have several options.
- Exploring a Flexible Momentum Compaction (FMC) lattice.
  - Similar betatron function amplitudes.
  - Larger dispersion amplitude but quasi-isochronous (R_{56}~0) across all 6 passes.
  - Relax stringent constraints (e.g. R_{56}, time of flight, dispersion, derivative of dispersion, and Twiss parameters) on the upstream systems, such as: the 'Splitter' and the FFA arc-to-linac 'Transition'.

FFA Beam Transport Test at CEBAF

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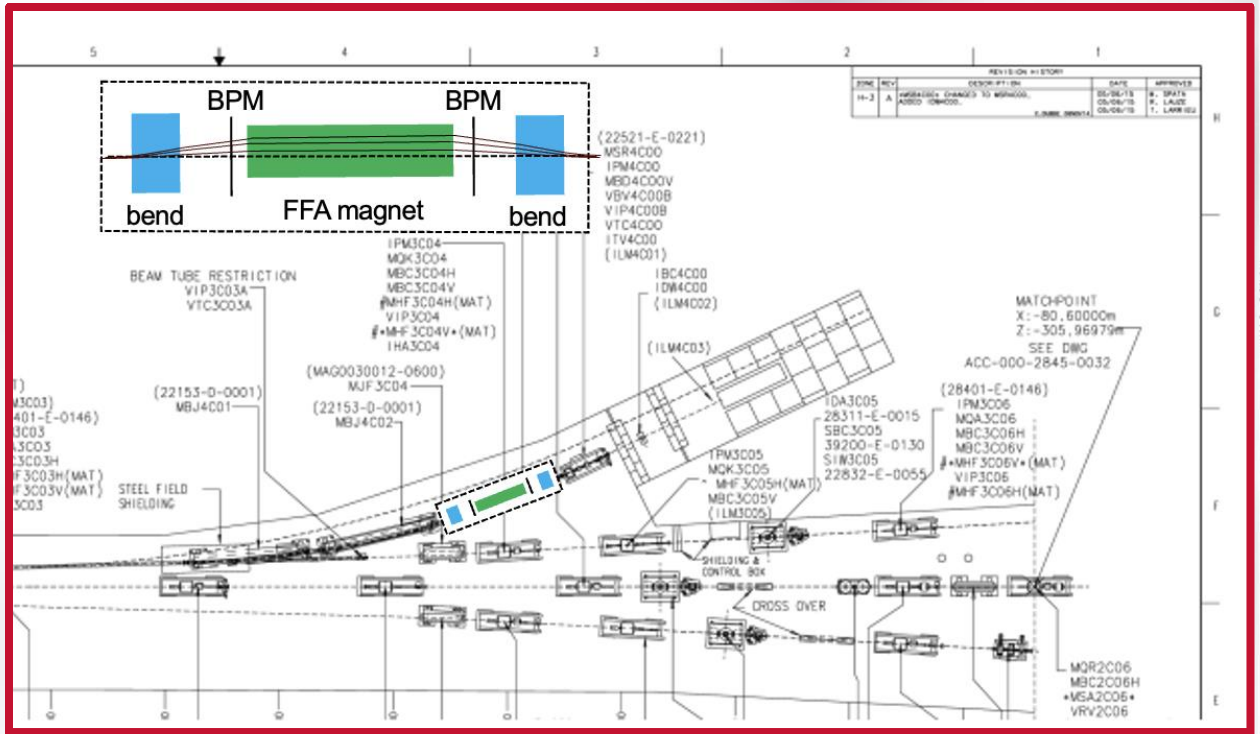
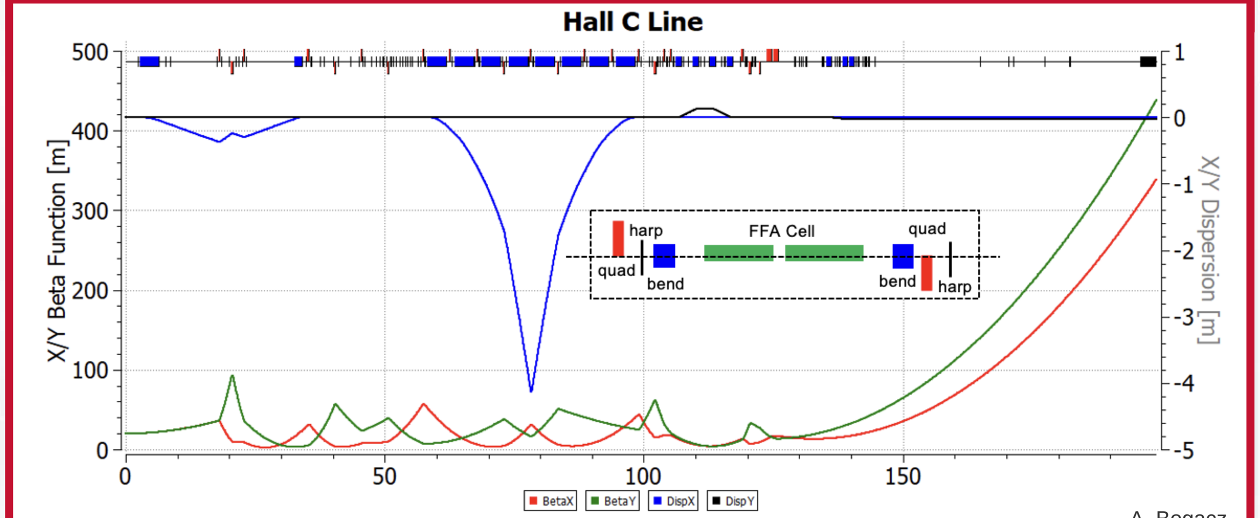
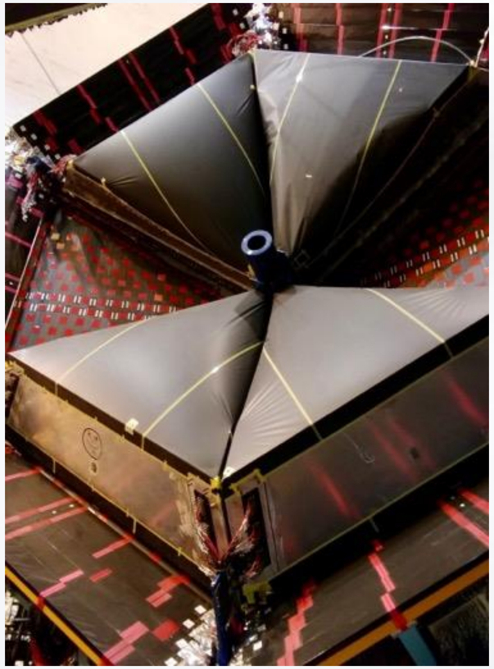
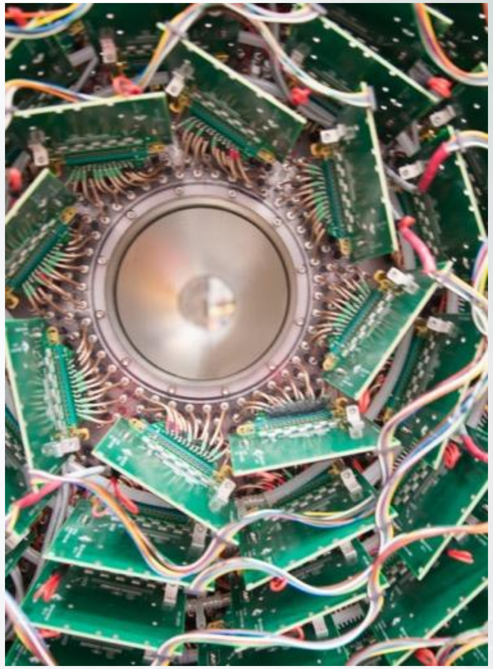
- Expand on the low-energy demonstration at CBETA.
  - Transport beams of multiple/higher energies spanning a factor of ~2.5:
    - 4.5, 6.7, 8.9 & 11 GeV
  - Orbit/Optics validation for FFA Cell
  - Technology demonstration
- Two potential (dispersive) sites:
  - BSY Dump
  - Hall C
- Actual study is pending funding via Jeffferson Lab's LDRD program.



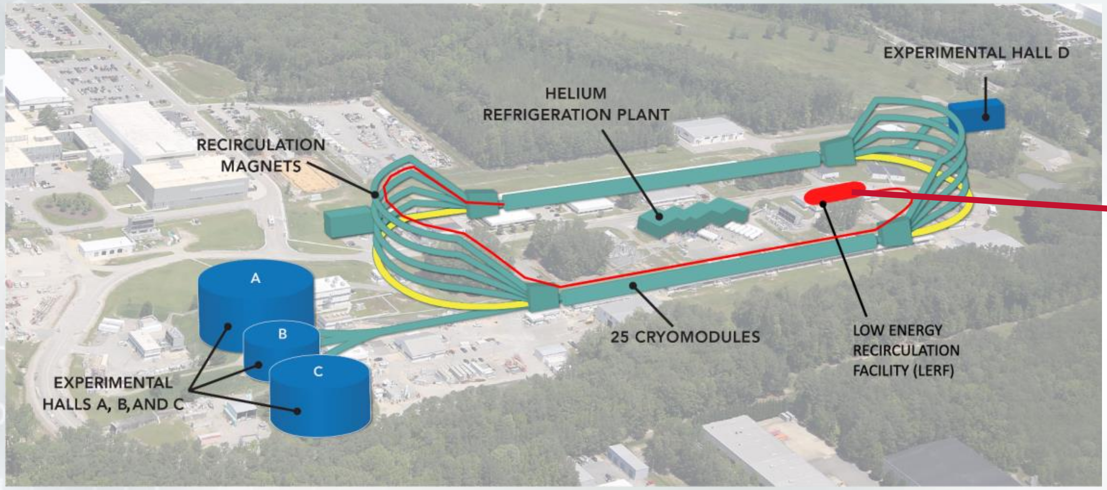


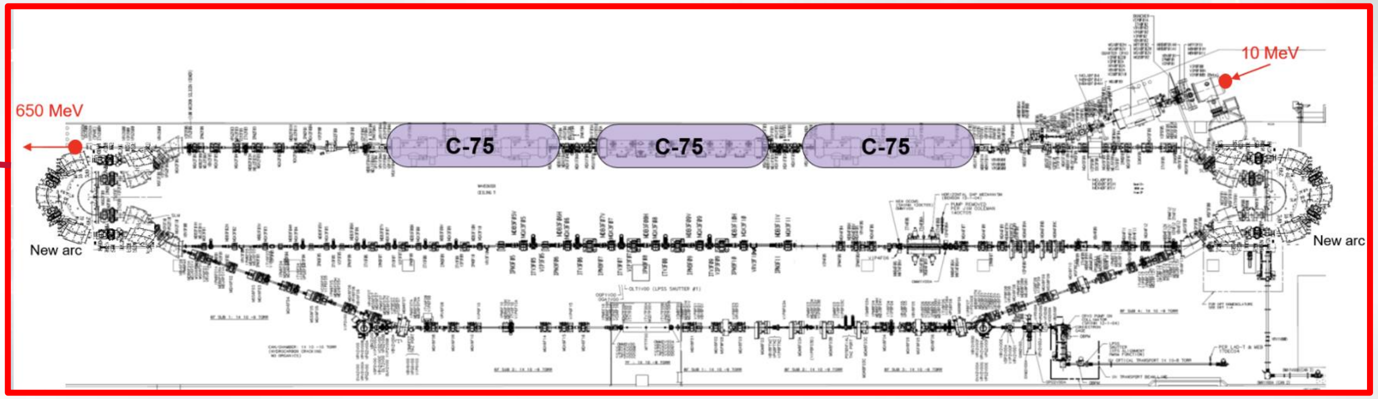
A. Bogacz

Injector Upgrade

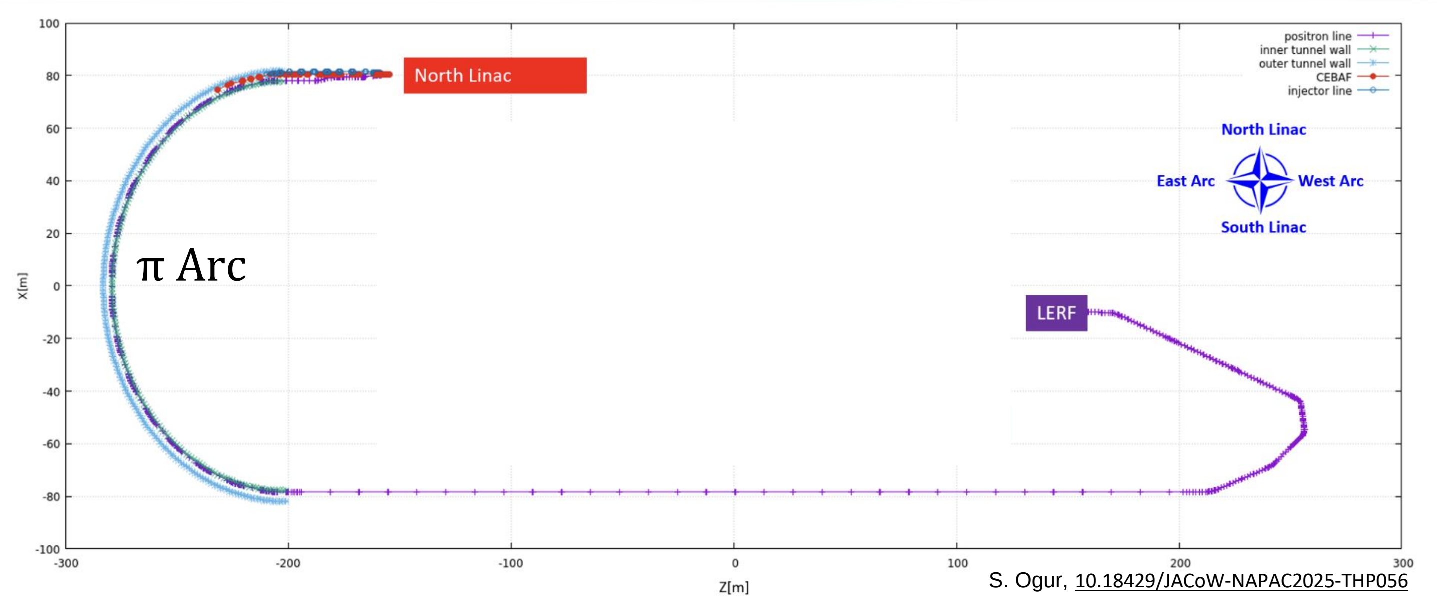
Injector Upgrade – 650 MeV Recirculating Injector

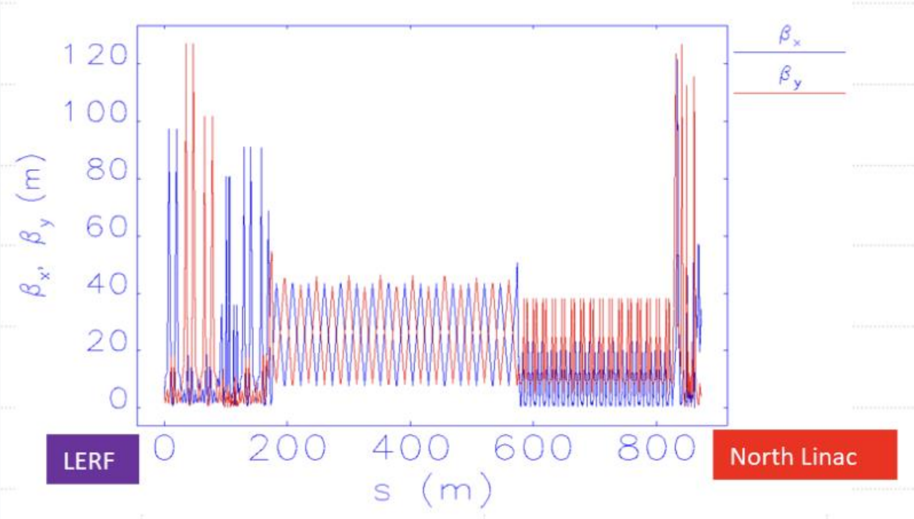


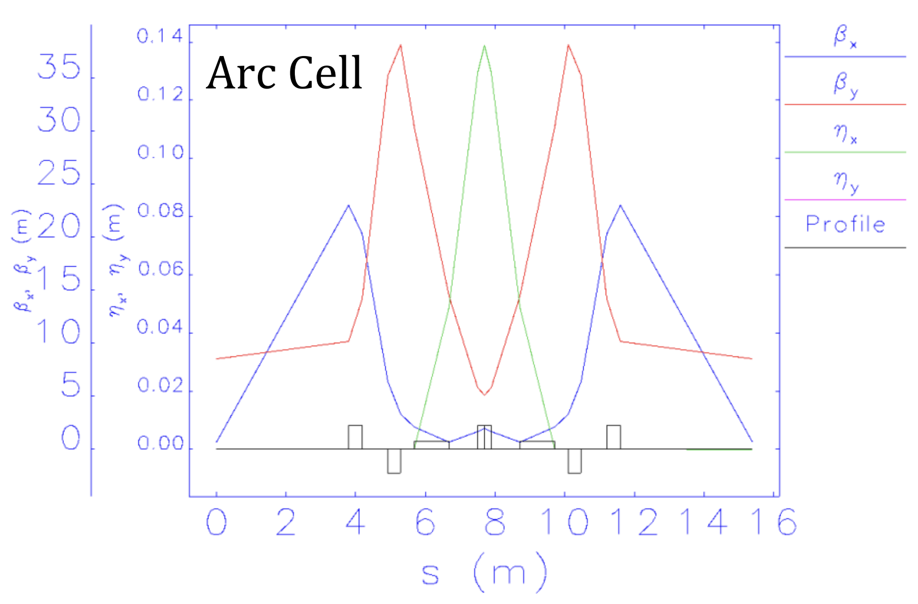


- With the present 135 MeV injector, the difference in the first and final pass energies in the North Linac is too large (1:175) to effectively control the beam.
- 650 MeV recirculating injector (3-pass) based on Low Energy Recirculator Facility (LERF) will allow a manageable difference in energies (1:33)

Injector (LERF) Transfer Line Optics







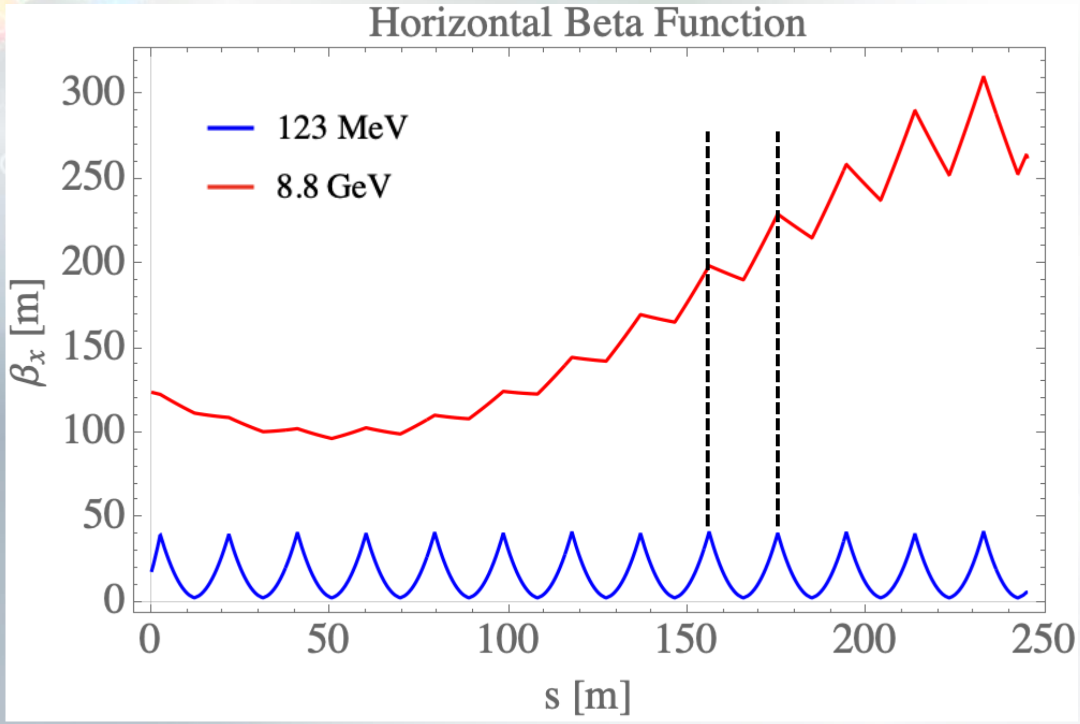
- LERF to North Linac transfer line has been designed.
- Composed of several beamlines:
  1. LERF Transfer Line (LTL)
  2. South Transfer Line (STL)
  3. West transfer Line (WTL)
  4. Merger Transfer Line (MTL)

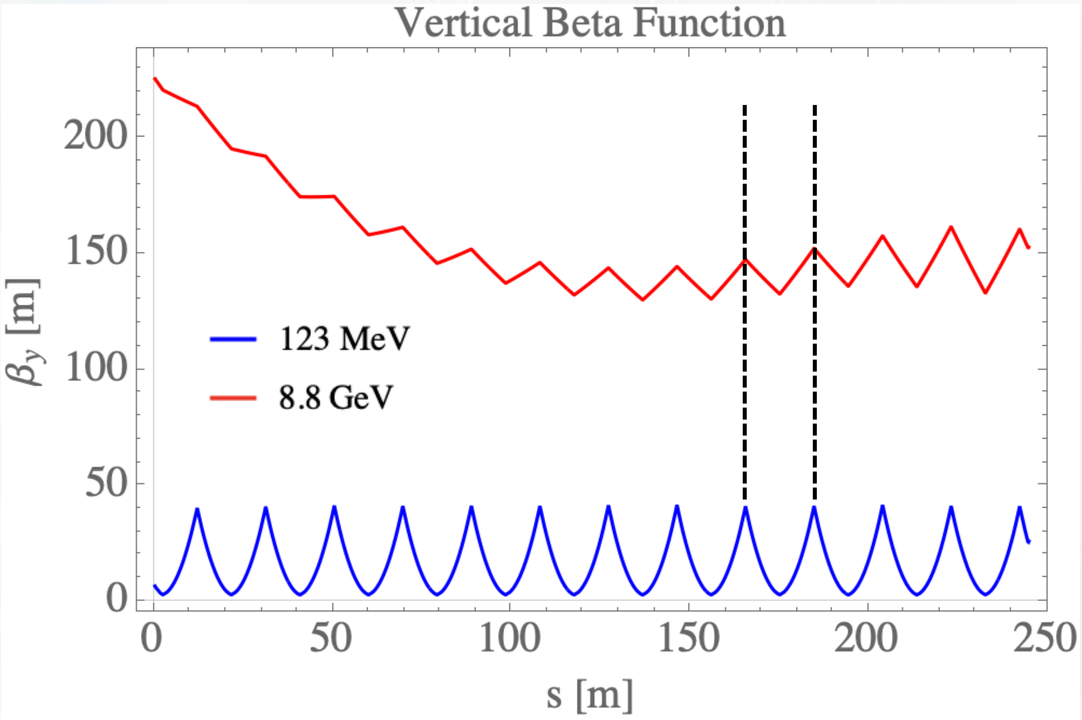
3 simulation cross validation: elegant, Bmad, OptiM

Linac Optics Upgrade

12 GeV CEBAF Linac Optics

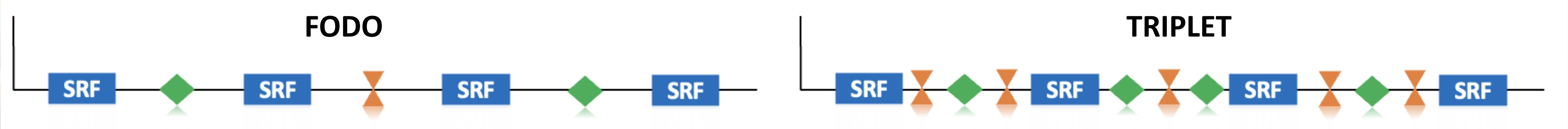
- Current CEBAF linac is composed of FODO cells.
- There is no electromagnet “ramping” implemented.
- From ~0.1 GeV injection to 12 GeV final energy the focusing structure is static.
- Energy increases with each pass and via higher beam rigidity nullifies the focusing.
- Error in the focusing creates beta-beating.

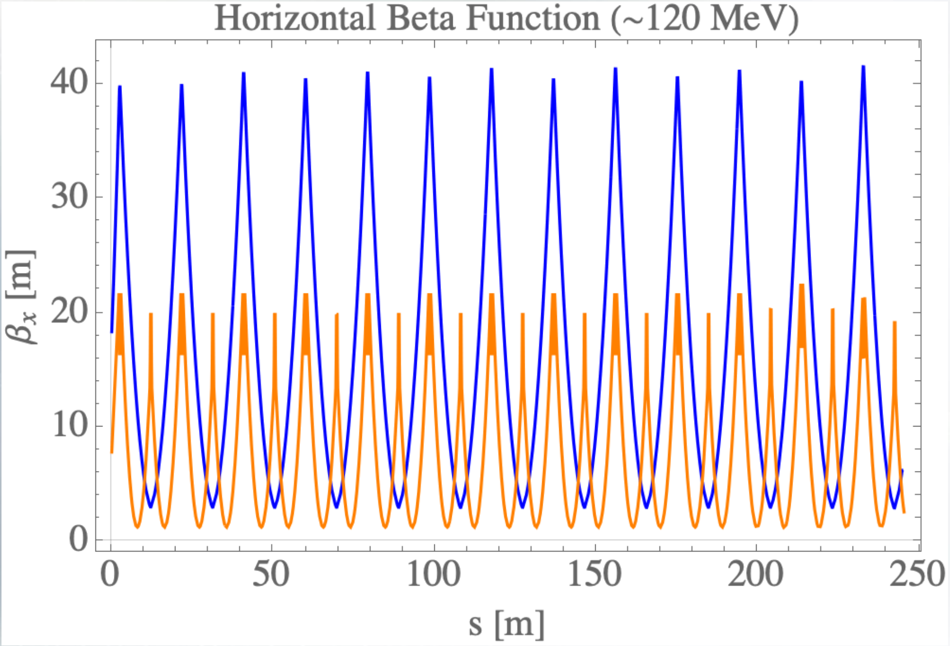


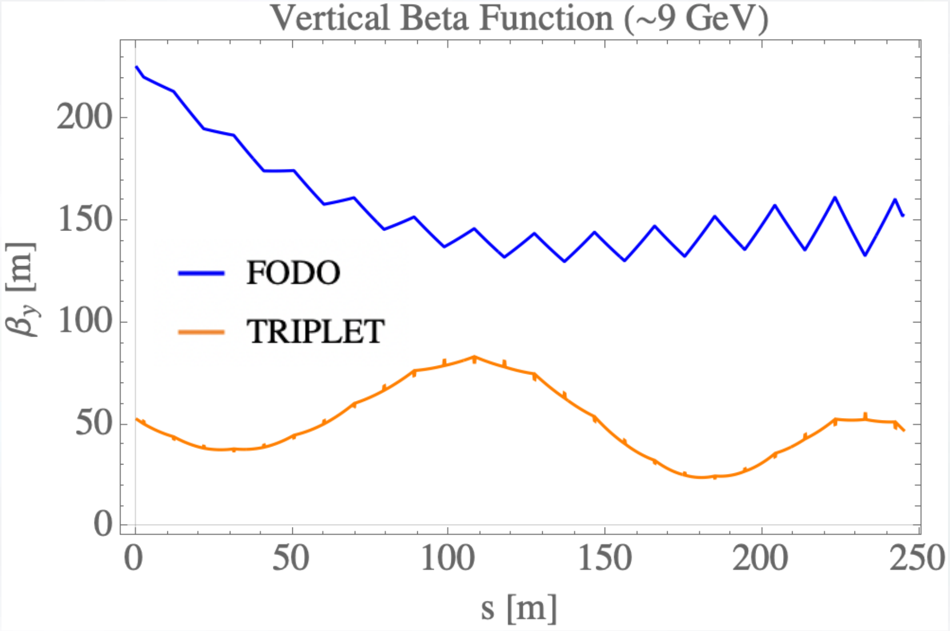


Linac FODO to Triplet

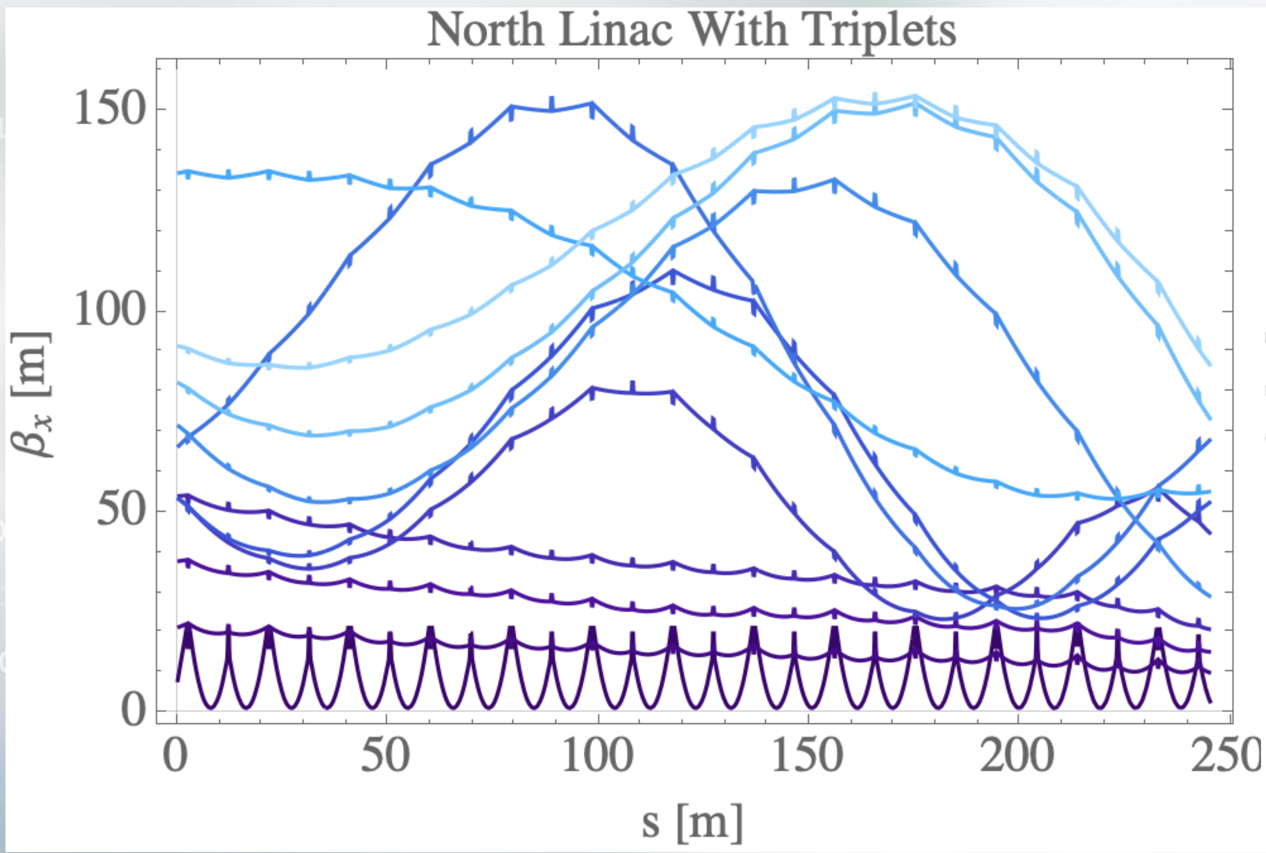
- Present FODO linac offers periodic optics generates large beta beating for higher passes (beta ~1000 m), which is not compatible with the acceptance of the SRF linac or the small betas (~5 m) in the potential FFA arcs.
- Replacing FODO with alternating triplets – more uniform beam envelope (beating still exists).

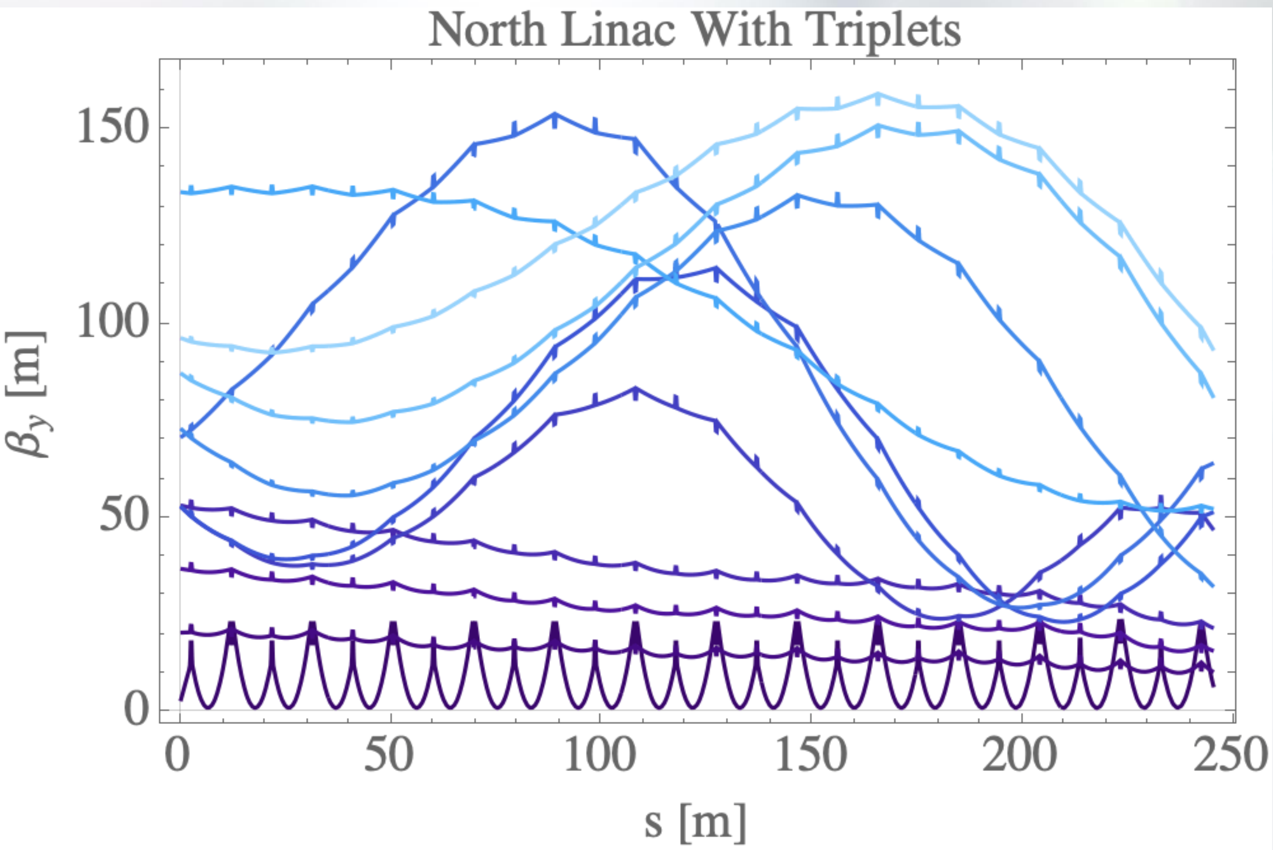






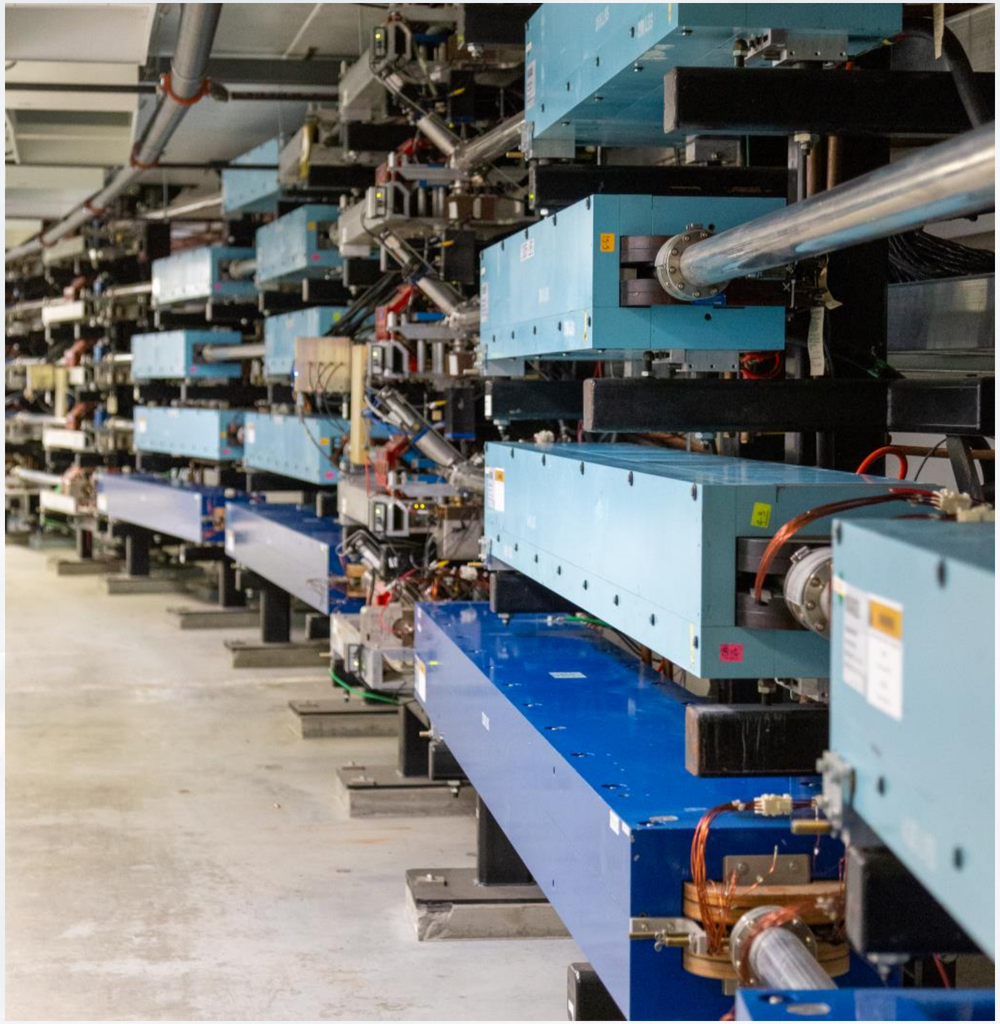
‘Beta Beat’ Linac Optics for FFA Passes (passes 5-10)





- Deviate from optics periodicity $\Rightarrow$ Induce and optimize β beat in linacs $\Rightarrow$ Reasonably small β’s at both ends of each linac at the expense of increase in maximum β inside the linacs, α’s adjusted to nearly zero as favored by FFA matching $\Rightarrow$ Greatly relaxed matching requirements

Modified Arcs/Switchyard to FFA



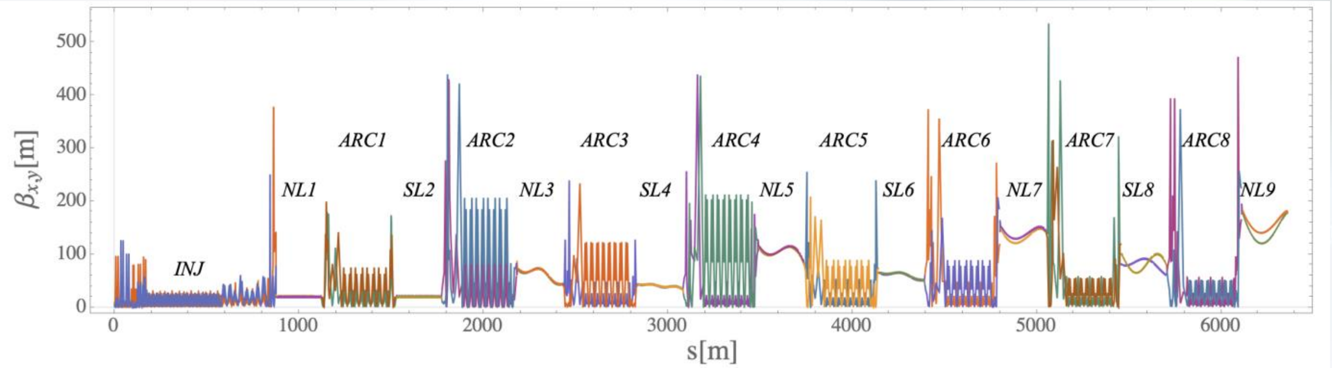
Electromagnetic (Non-FFA) Arcs

- The recirculation arcs are composed of bend magnets that are rated for limited B-field limit.
- The new beam energy would require certain arcs to exceed their B-field limit.
- Low-cost solution (Jay B.) upgrade arcs by moving them vertically by one slot, discarding ARC1 (too weak).
- Rematch new incoming/outgoing optics from Linacs to periodic optics of Arc.

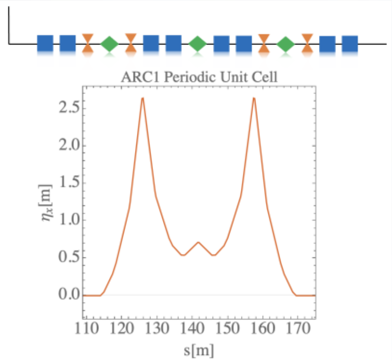
Current electromagnetic recirculation arcs in CEBAF

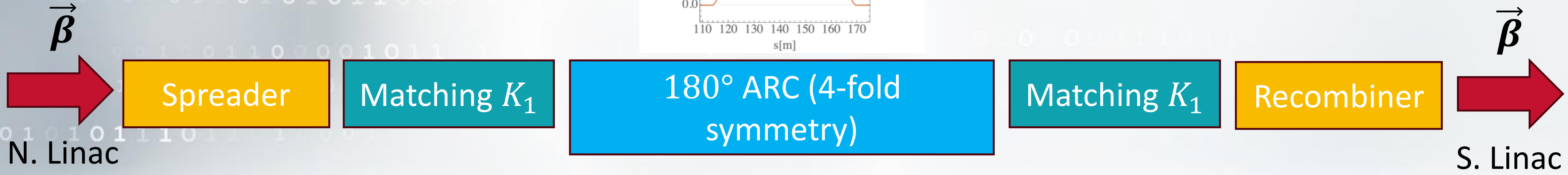
Electromagnetic Arcs Optics

- Recirculation arcs are responsible for matching the beam:
  1. From Linac to Arc periodic optics.
  2. From Arc periodic optics to Linac.
- Constraints:
  1. Use existing footprint of arc.
  2. Spreader ($R_{56} < 0$) + Recombiner ($R_{56} < 0$) + Arcs beamline is isochronous ($R_{56} = 0$).
  3. Arcs are composed of cells with 4-fold symmetry.

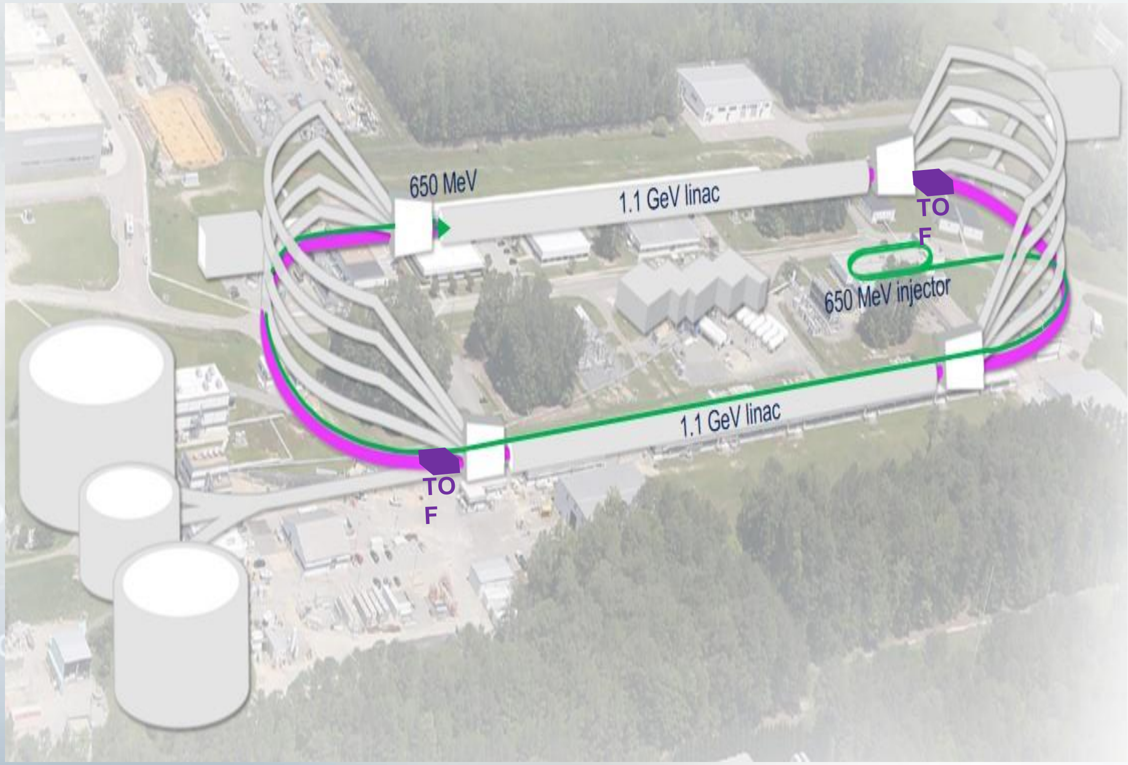


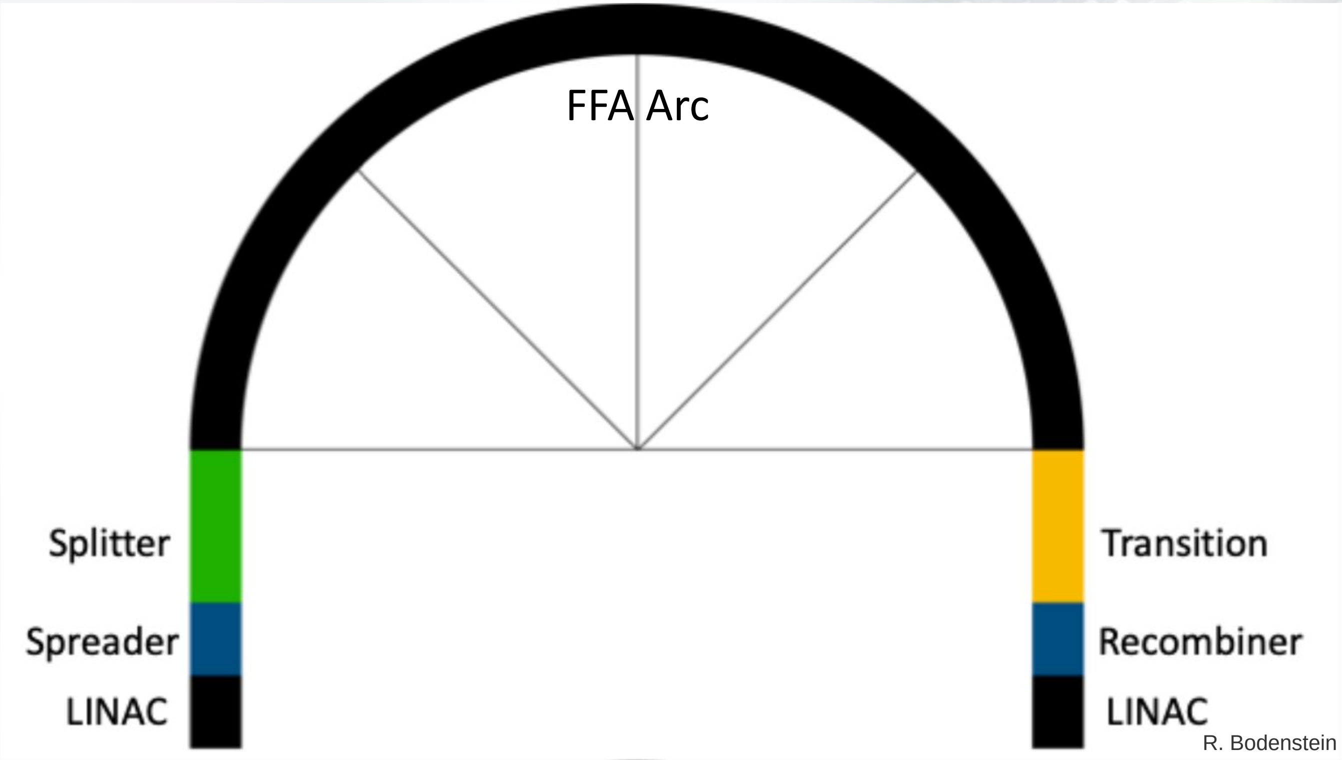
Linear optics matched from injector to start of FFA





FFA Switchyard Components





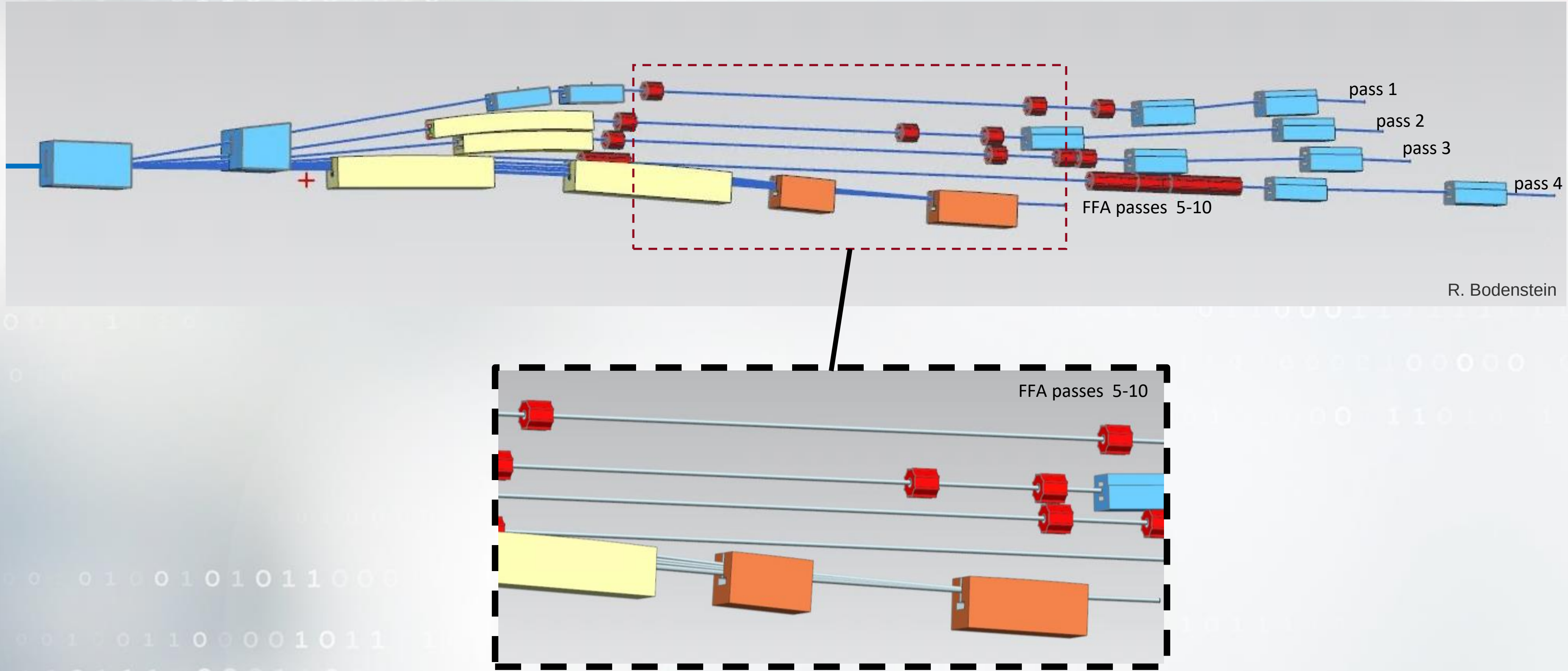
1. **Spreader/Recombiner**: Vertical bend system transporting beam to FFA arc.

2. **Splitter**: Comprehensive matching section into FFA arc.

3. **Transition**: Matching section from FFA arc to linac.

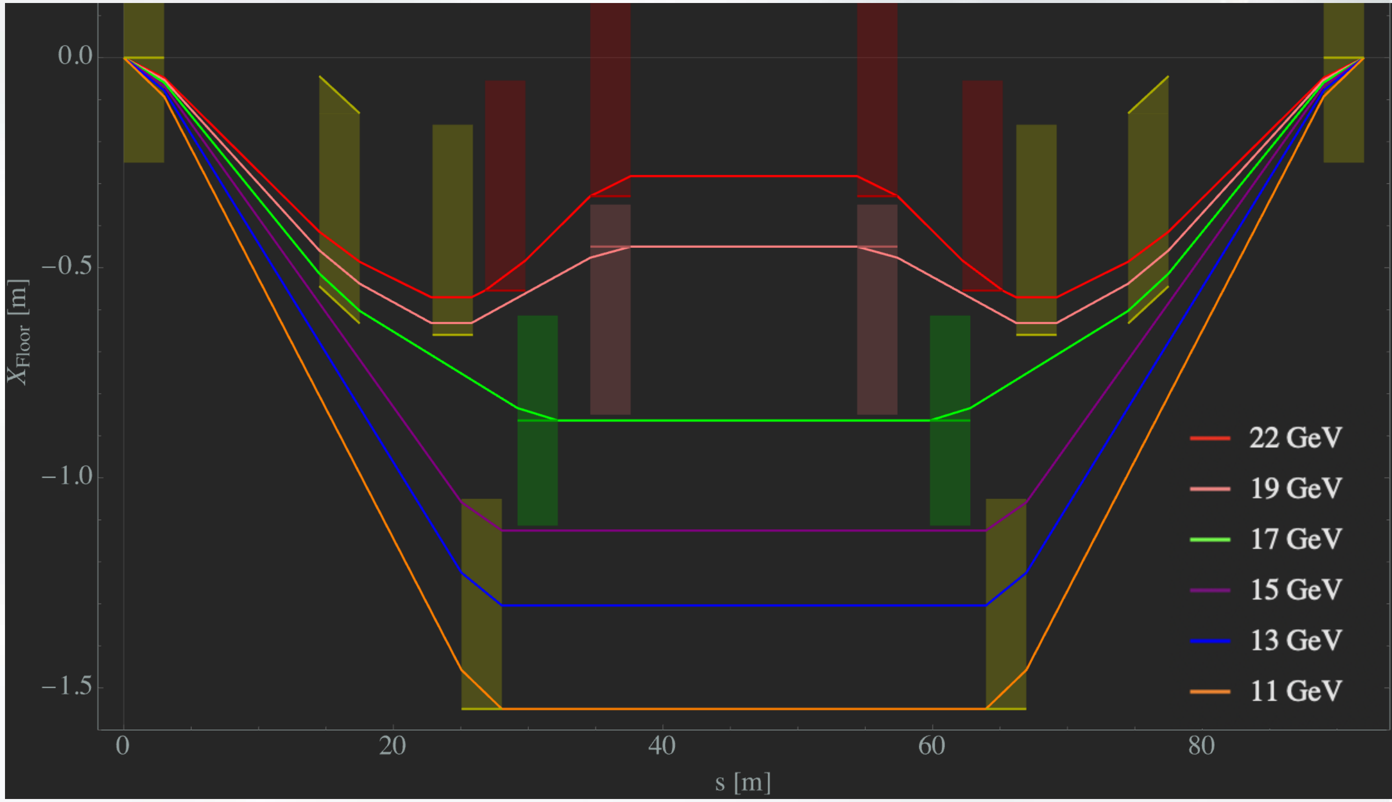
1. FFA Pass Spreader/Recombiner

- The vertical bend system (Spreader/Recombiner) that transports the beam to the FFA arc will need to be modified.
- The higher energy of the FFA passes will require larger/stronger dipole magnets to transport from linac-to-FFA.



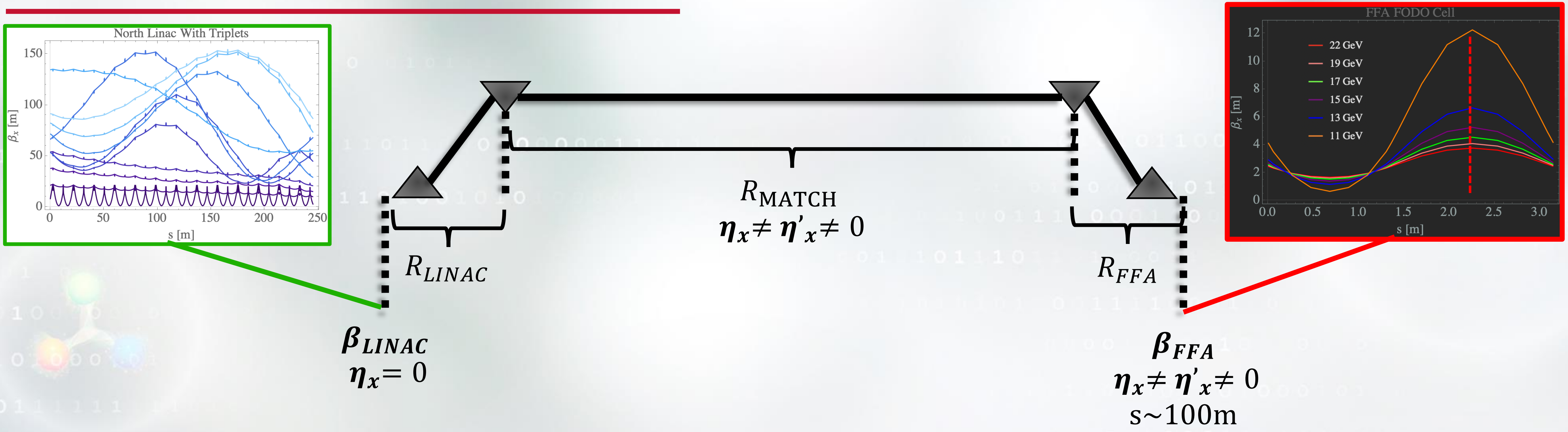
2. Splitter Section

- Required to match from the linac to the FFA for all 6 passes
- Heavy payload for matching:
  - Twiss parameters: $\beta_{x,y}$, $\alpha_{x,y}$
  - Dispersion: η_x,η'_x
  - Momentum compaction: R_{56}
  - Time of flight tuning for machine variability
- Current baseline "Symmetric" design
  - Matches all parameters
  - Working on optimizing betatron amplitudes; large linac optics to small FFA optics is a challenge
  - Global optimization of optics to control emittance dilution (i.e. $\langle\mathcal{H}\rangle$)



Symmetric Splitter Design (quadrupoles not pictured)

2. Splitter Design

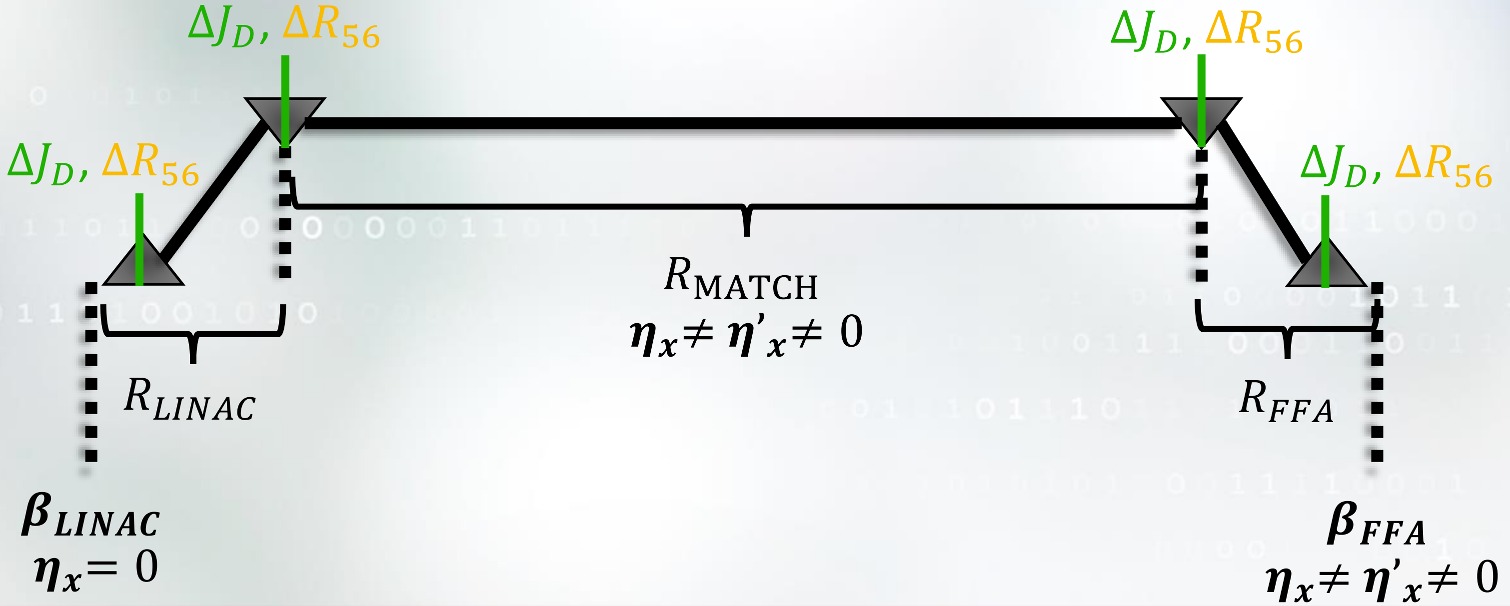


- R_{LINAC} and R_{FFA} roughly static (no space for the tuning quadrupoles) magnetic responsible for beam separation.
  - Optics on linac side (R_{LINAC}) are nicely behaved.
  - Optics on FFA side (R_{FFA}) resemble final focus optics behavior due to the small FFA matching optics.

- R_{MATCH} will contain space to facilitate matching linac to FFA optics; space between different beamlines/passes require some interleaving of magnets.

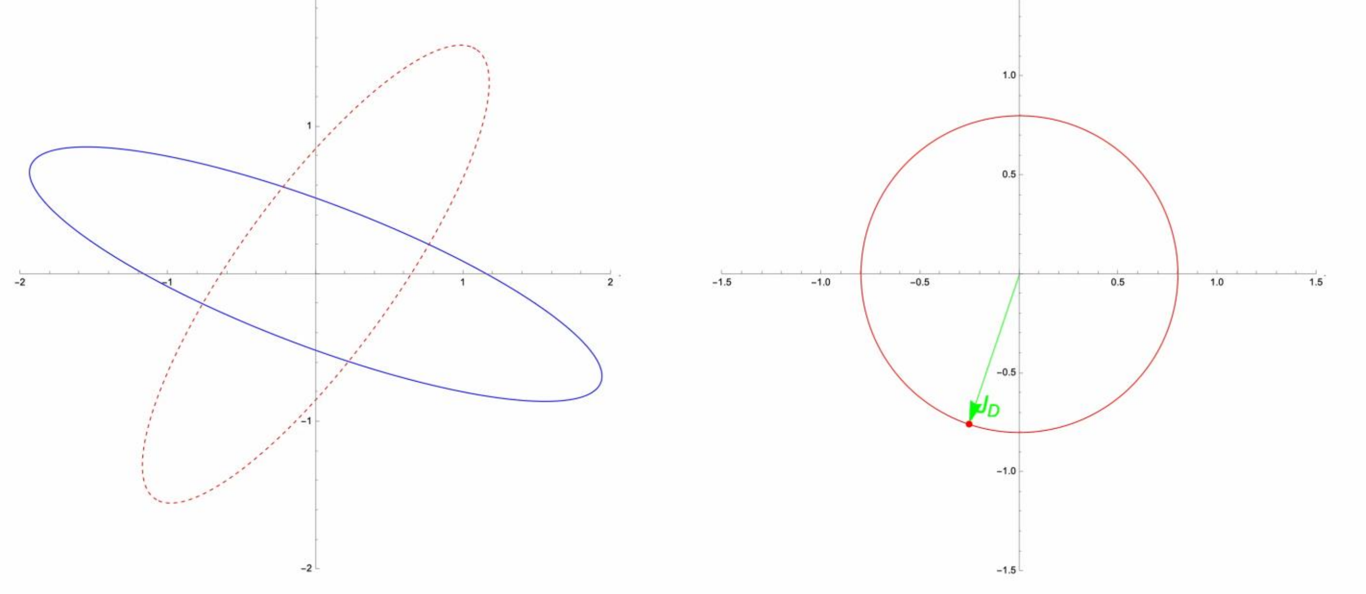
- Difficulty lies in matching Twiss optics while tuning R_{56}.

2. Splitter Design



Transverse Phase Space

Normalized Dispersion Phase Space



Beta/alpha matching

$$x'' + Kx = 0 \rightarrow \frac{\partial \epsilon}{\partial s} = 0$$

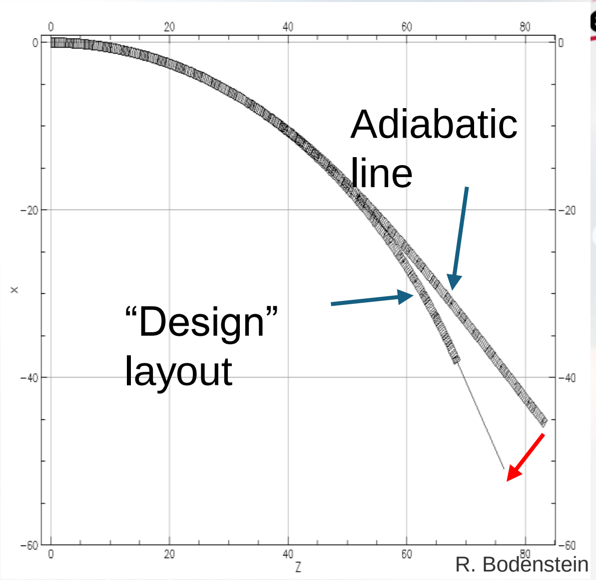
Dispersion/R56 matching

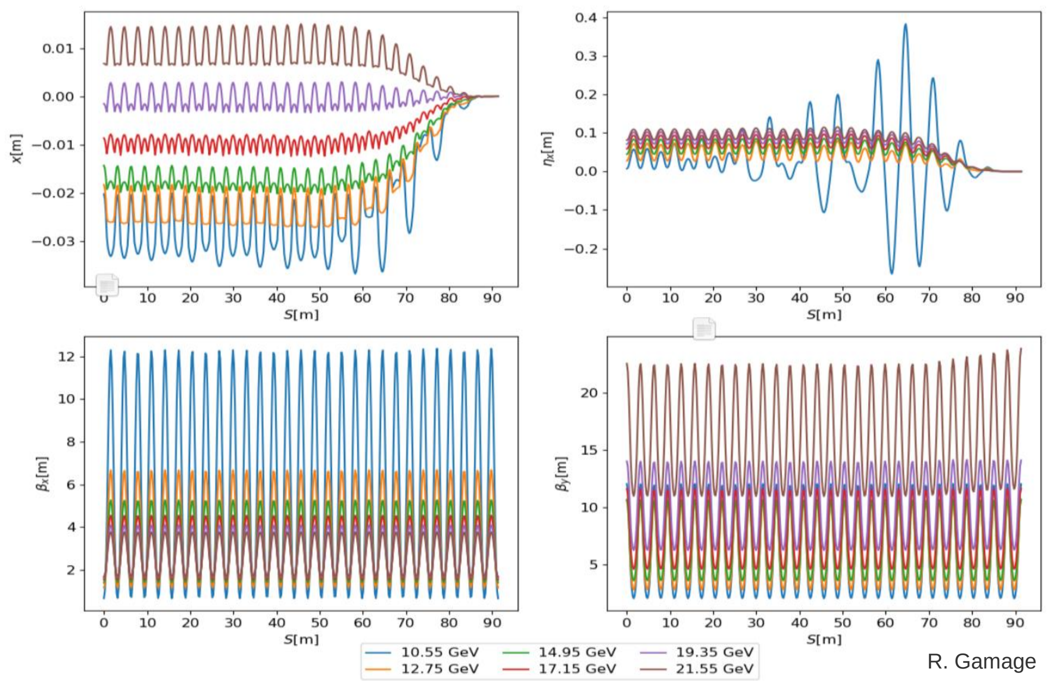
$$\eta'' + K\eta = \frac{1}{\rho} \rightarrow \frac{\partial J_D}{\partial s} \neq 0$$

$$R_{56} = \frac{\partial z}{\partial \delta} = \int \frac{\eta}{\rho} ds$$

3. Transition Section

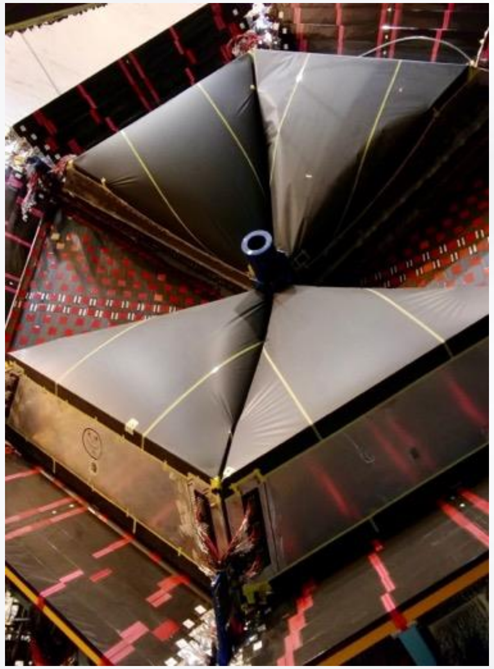
- In FFA transition, the different-energy passes must be match simultaneously $\Rightarrow$ Change in a single magnet parameter affects all passes $\Rightarrow$ Challenging to find a solution
- Resonance-based systematic matching approach
  - Individual passes differ in their phase advance per cell
  - Make use of the phase advance difference to selectively control particular passes
  - Use resonance to selectively excite β functions of a particular pass
  - Focusing quadrupole kicks applied at twice the frequency of natural betatron oscillations

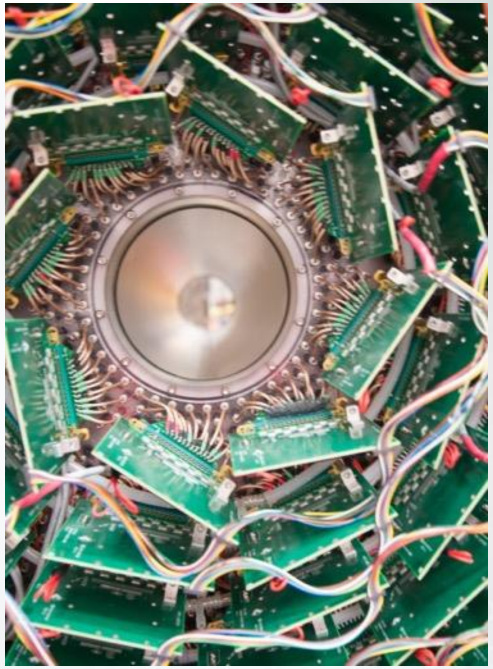




Arc-To-Linac transition section optics.

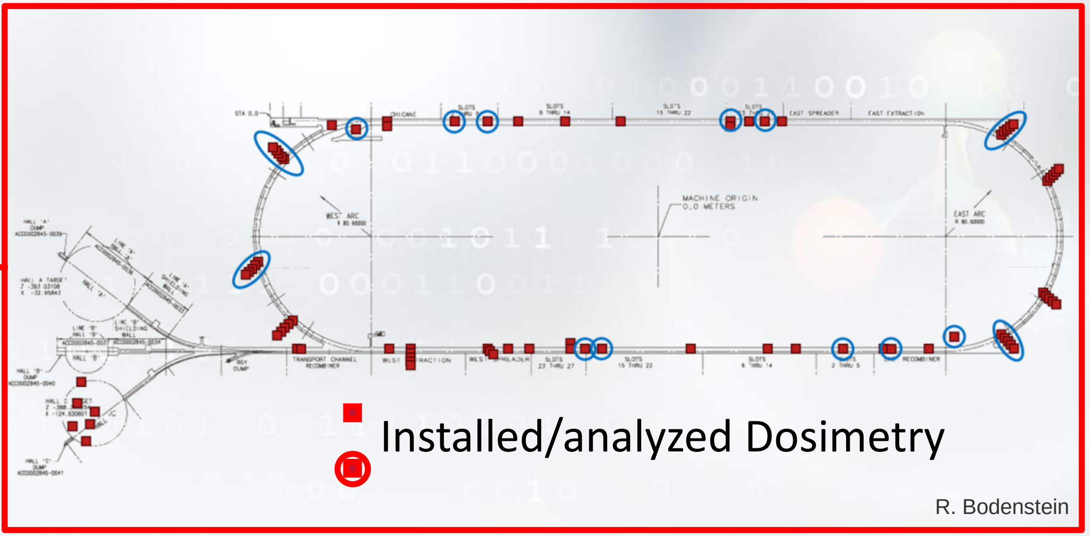
Next Steps



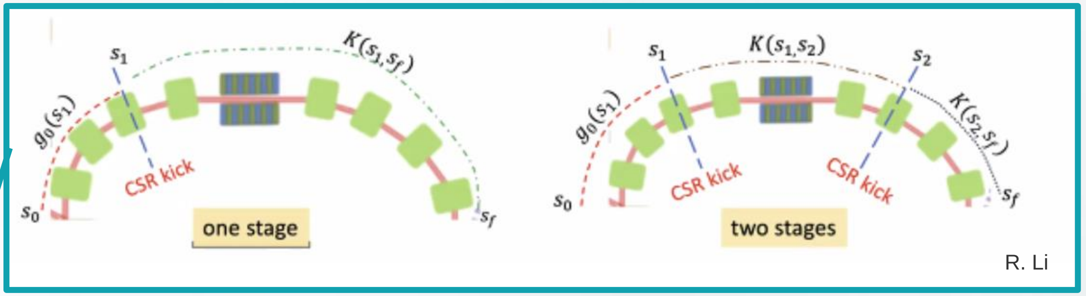


Future Work

- Study the effects of radiation on permanent magnets (JLAB funded LDRD)
  - Test the radiation resiliency of permanent magnets in this high energy environment
  - Test performed at JLAB could provide permanent magnet research to a wide range of applications: complex bend in light sources/rings etc.



- Integration of all beamline sections S2E simulation
  - Allows us to further validate the preconceptual design
  - Iterate and improve design strategies
  - Evaluate beam quality



- Optimization of current preliminary design and study of various effects:
  - Integrate new extraction paradigm
  - Beam break up (BBU)
  - Coherent synchrotron radiation induced emittance dilution in FFA arcs

Thank you