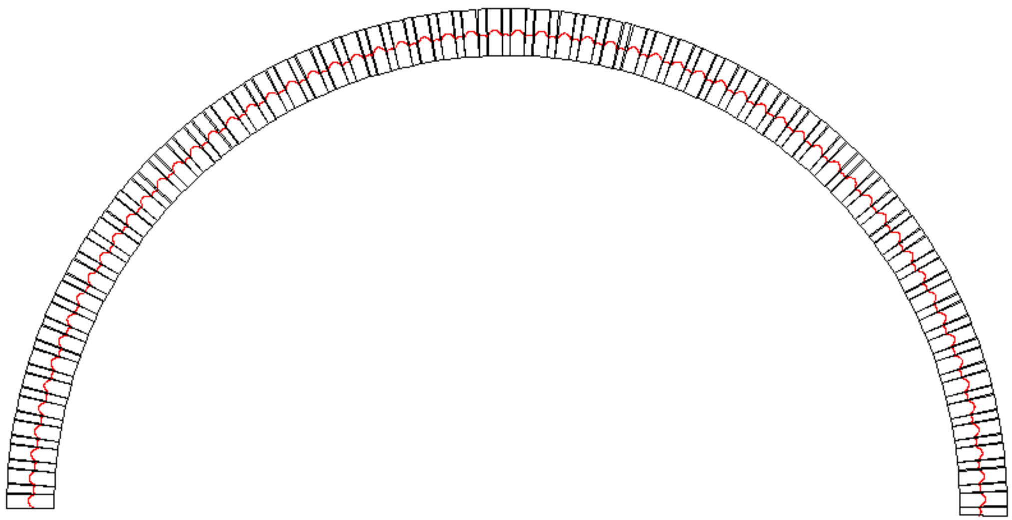
Fixed-Field Alternating-Gradient Accelerators

FFAs, for short;

Combined-function magnets used to increase energy acceptance.



Alexander Coxe

Friday, February 2, 2024

FFAs in principle

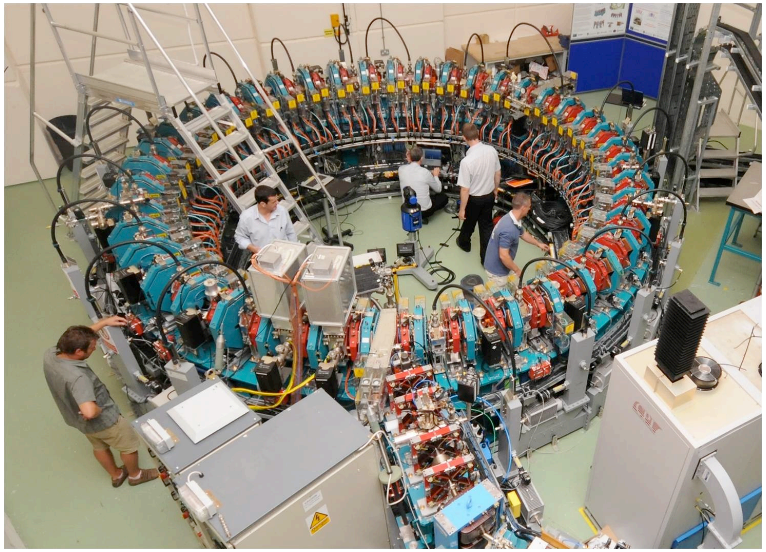
- Combined-function magnets allow us to (*eg*) modulate the strength of a bending field in one of the transverse dimensions
- This can permit beams with different rigidity to bend along the same radius at different transverse positions in the beam pipe
- At present 'transverse' can only be exactly horizontal or exactly vertical
  - 'HFFAs' and 'VFFAs' are qualitatively different types of machines, VFFA magnets are far more complex
  - The rest of this discussion will be restricted to HFFA technology and science.

Scaling vs. Non-scaling FFA

- Scaling and non-scaling refer to the 'image' of the orbit through the lattice at different energies
- Scaling FFAs have orbits which are geometrically similar, i.e. each beam in the pipe has the qualities of every other beam multiplied by a constant scaling factor
  - Higher energy orbits look like photo-enlarged versions of lower energy orbits
  - Make the most sense in rings
  - Often require non-linear magnets for chromaticity and tune corrections.
- Non-scaling FFAs allow the tune to vary with energy
  - Conveniently they are often designed with only linear components, dipole and quadrupole magnets.

Proof of Concept: FFA Accelerators around the World

- EMMA: UK, Daresbury
  - Non-scaling, electron beam
  - ‘Synchrotron like’
- POP-FFAG: Japan, KEK
  - Scaling, proton beam
  - ‘Synchrotron like’
- RACCAM: France, LPSC
  - Scaling, proton therapy
  - ‘Synchrotron like’
- CBETA: USA, Cornell
  - Non-scaling, electron beam
  - RLA



EMMA: https://www.quantumdiaries.org/2012/02/15/brookhaven-scientists-help-develop-model-for-future-accelerators/

POP-FFAG: https://www.researchgate.net/figure/Color-A-picture-of-PoP-FFAG_fig1_30421283

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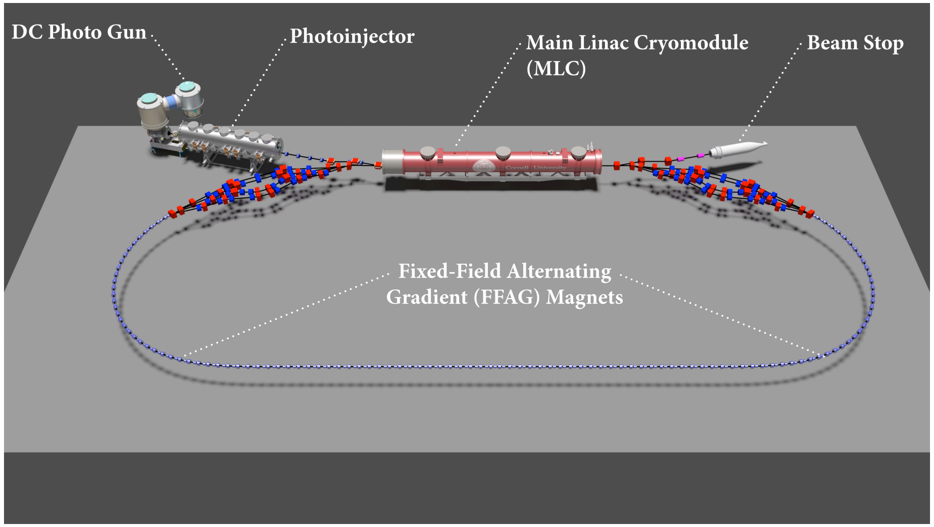
FFA RLA: Proof of concept at CBETA

- CBETA (Cornell Brookhaven ERL Test Accelerator): SRF Linac with FFA recirculating arcs
- Designed to recirculate electron beam 4 passes increasing energy to a peak of 150MeV, then 4 passes energy recovery
- Beam 'splitter' and 'recombiner' required to separate the beam into discrete orbits for recirculation
- Design, commissioning, and operation from 2005-2020



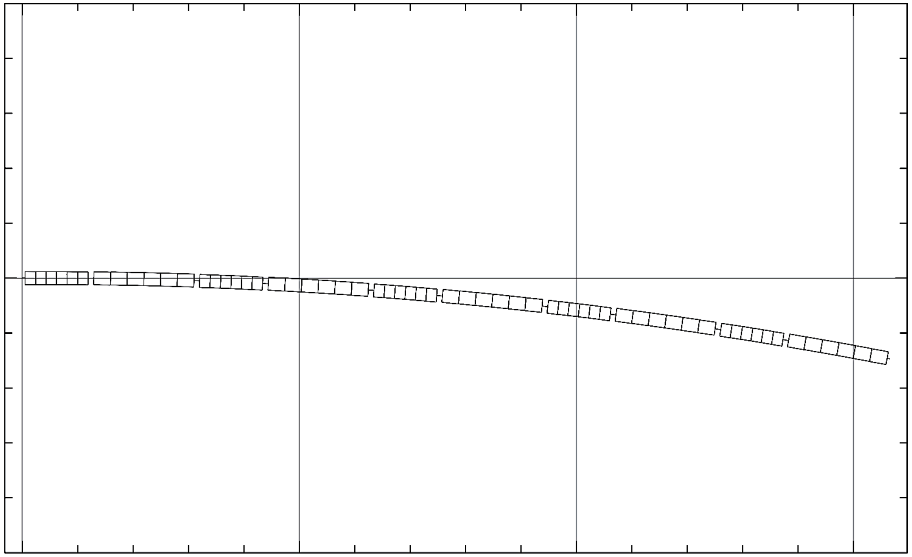
CBETA: https://www.classe.cornell.edu/rsrc/Home/Research/ERL/CBETA/

Energy Upgrade at CEBAF

- Proposal to increase the number of passes through the machine from 5.5 to 10.5
  - Each full pass includes two linacs which increase energy of particles by ~1.1 GeV each
    - Five more passes increases final energy by ~11 GeV
- Taking a hint from CBETA, plan to replace highest energy EM recirculating arc on each side (East/West) with FFA arcs

FFA@CEBAF Collaboration

- Collaboration between scientists at JLab, BNL, ORNL
- Working to design a feasible upgrade structure for CEBAF
- So far, design of a non-scaling FFA lattice for each recirculating arc is underway, good solutions exist but haven't been finalized
  - Baseline FFA magnets have been designed and prototyped
- Splitter and recombination lattices aren't yet complete



5 cells in the design lattice

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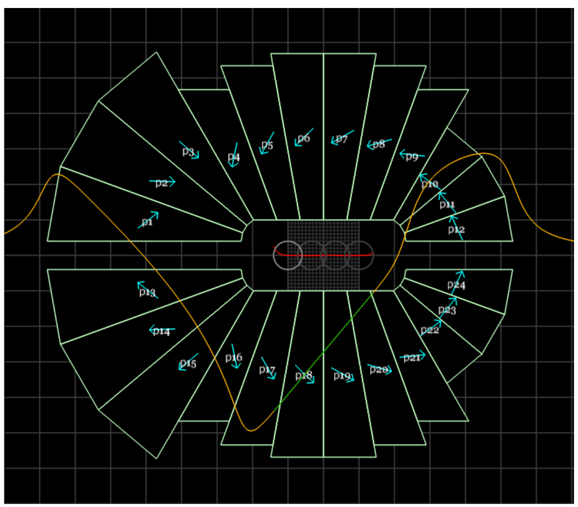
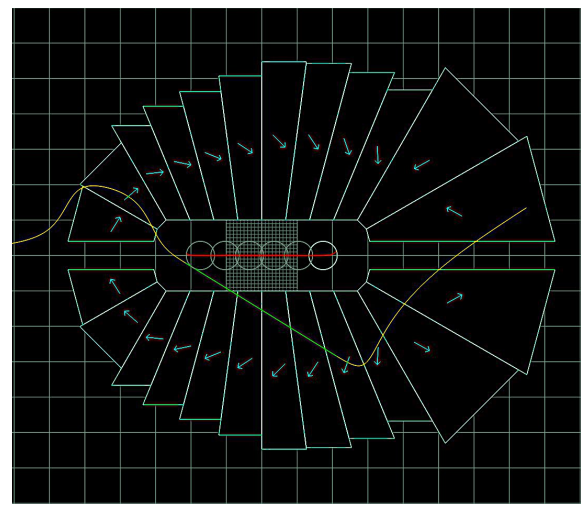
FFA magnets for CEBAF

- Permanent magnets constructed in a Halbach array
  - Exterior fields cancel
- Combined function: dominant magnetic moments are dipole and quadrupole
- Effective B field varies along the midline: this is really what allows large energy acceptance



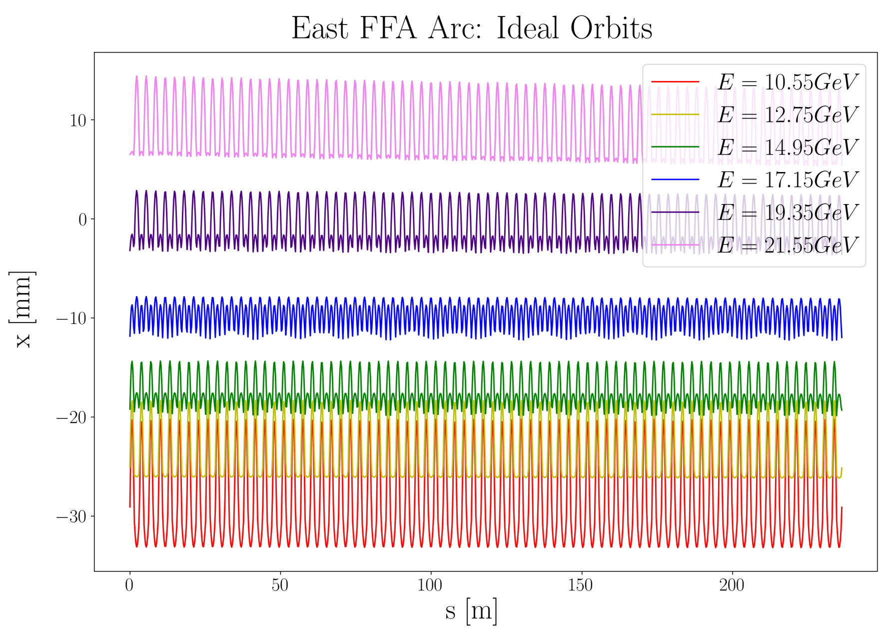
BD magnet

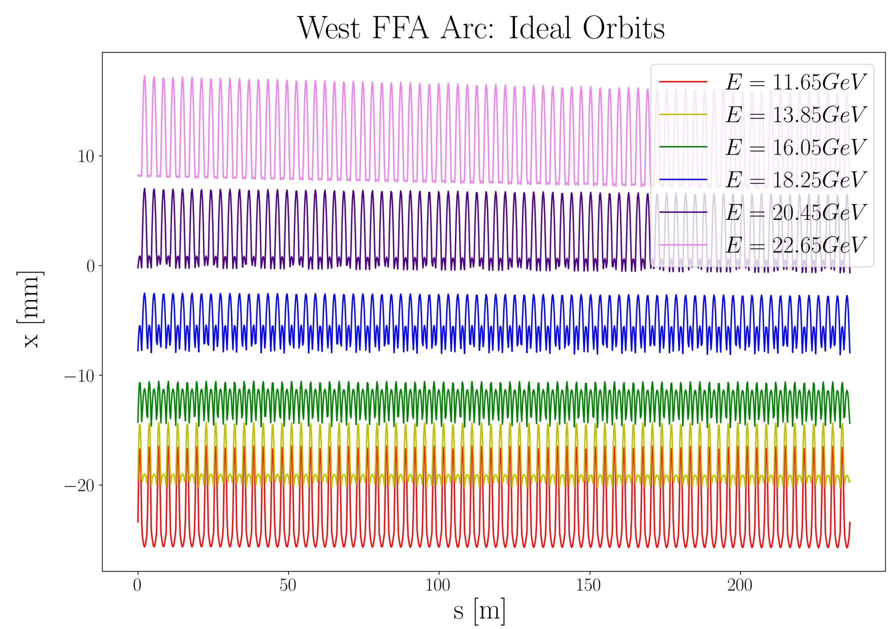


BF Magnet

FFA@CEBAF Nominal Orbits

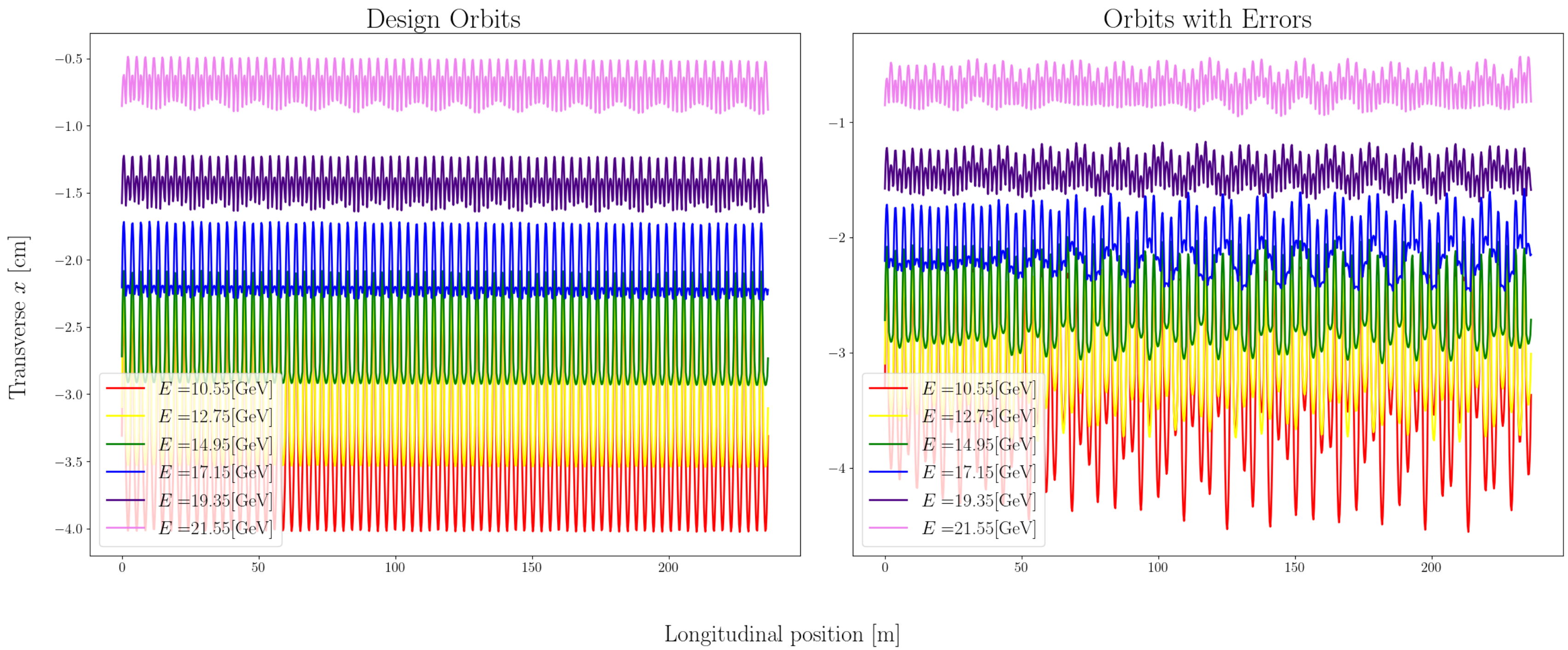
- Energy ranges are staggered for East and West since there's a linac between the first pass through the East arc and the first pass through the West
  - East: 10.55-21.55 GeV
  - West: 11.65-22.65 GeV





Lattice and Beam errors

- Now we know what the ideal orbit looks like, but how could it go wrong?
- Survey errors: magnets may be improperly placed or aligned by up to .2 mm
- Beam may be delivered to the arc with ‘incorrect’ optics or orbit parameters



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Lattice Error Mitigation

- Each BF (red) or BD (blue) magnet consists of six identical Halbach sections, offset from each other by a small amount
  - Increases 'good field' region by 'following' the beam trajectory with the shape of the magnet
  - Allows larger deviation from design orbit before beam loss
  - Small drift regions mean the beam is bending almost continuously
- As a result, the FFA lattice is fairly robust to errors

Scale representation of a single cell in the FFA@CEBAF lattice

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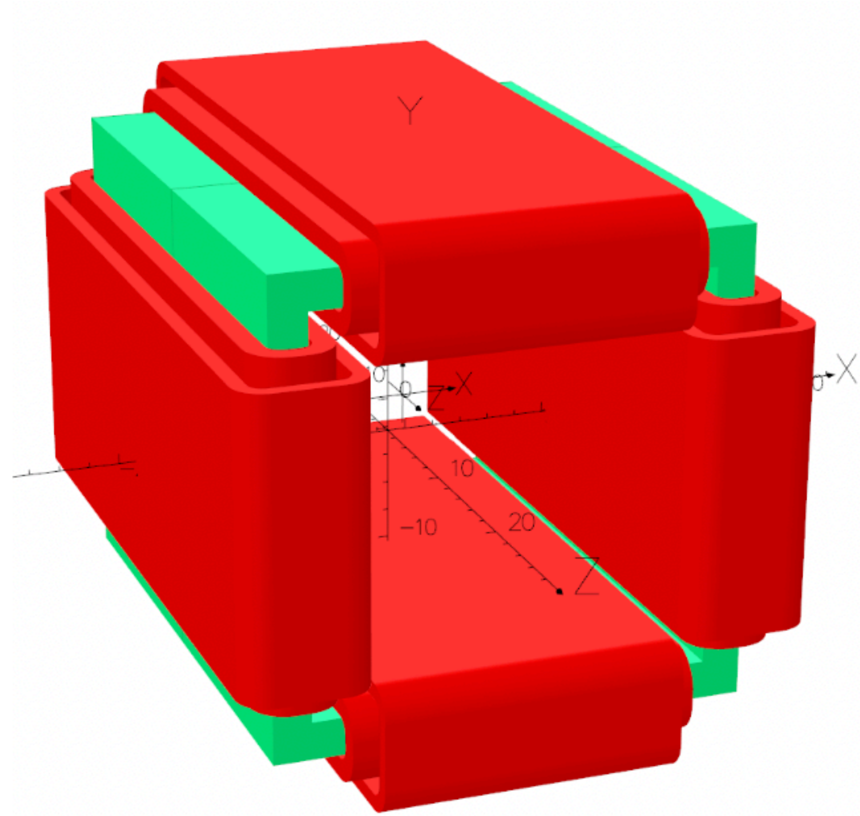
Lattice Error Correction

- Corrector magnets are Panofsky quadrupoles with additional dipole windings
- Window frame structure allows correctors to be superposed on the FFA magnets
    - Since the permanent magnets have very small exterior fields, corrector fields simply add to the existing field inside the pipe
- Maximum dipole field 320 Gauss = 0.032 Tesla
- Maximum quadrupole gradient 188 mT/m



Schematic of FFA@CEBAF corrector magnet

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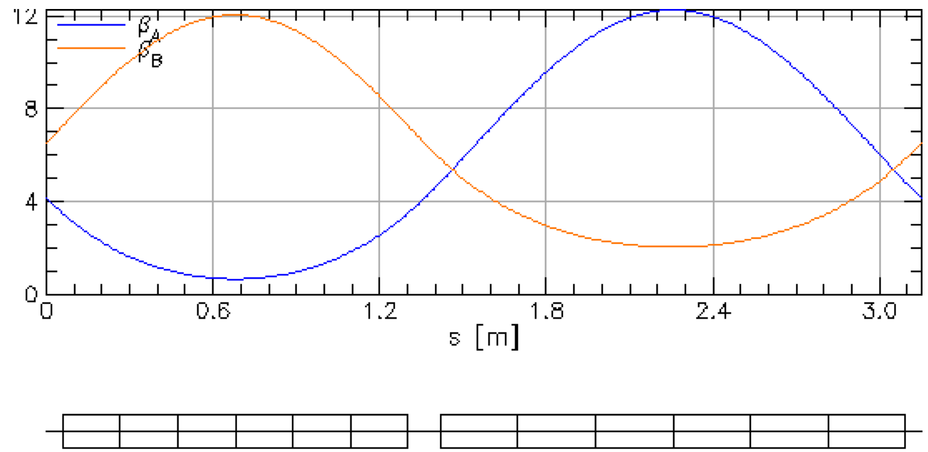
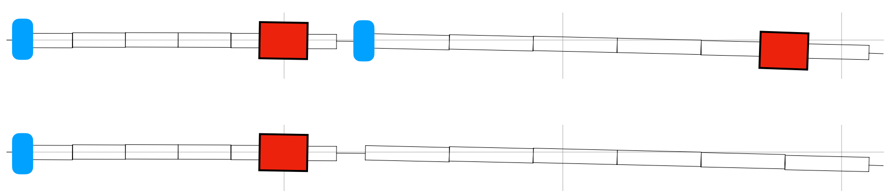
Optimal corrector placement

- FFA magnets are three times longer than correctors
- How do we position PQs for maximum effect on:
  - Vertical steering,
  - Optics, and
  - Horizontal Steering?
- Consider beta functions, get some statistics
- From beta, I expected that correctors at the beginning of magnets **or** the end could work well
  - Statistics show that this is true, and the end is a little better than the beginning



Single cell (ideal) beta function



Double/single corrector/bpm placement for one cell (bpms/correctors not to scale)

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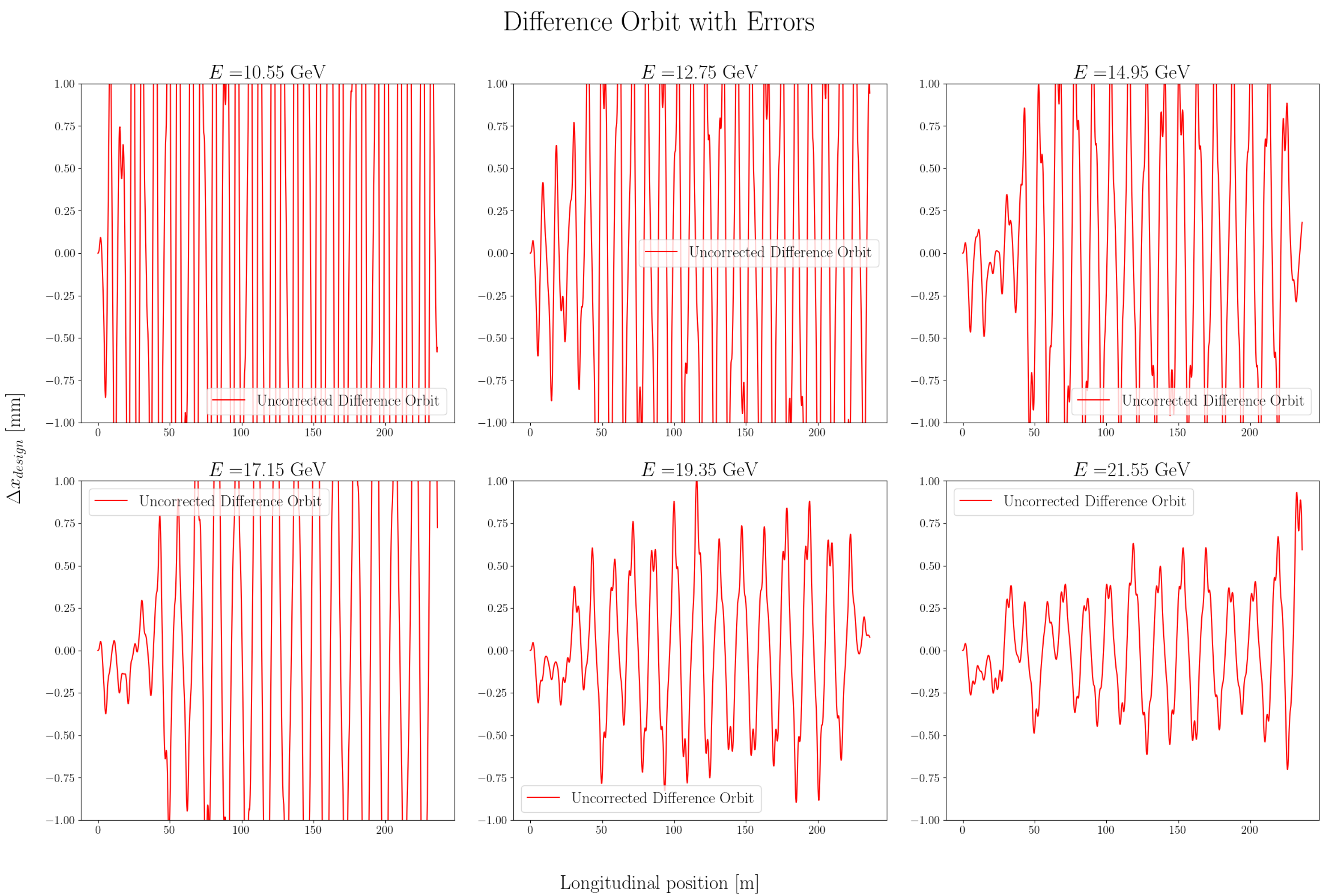
Error Corrections

- In spite of a robust lattice, it's very important to deliver beam close to on-design at the end of the FFA arc
  - The recombination transition (incomplete) will certainly be very sensitive to beam optics, and likely to orbit parameters as well.
- Necessary to correct six beams simultaneously, without losing *any* of the passes
  - Especially tricky, since the lowest energy is most susceptible to external fields (lowest rigidity)
  - I'm using a modified SVD algorithm that prioritizes the end of the arc, and freezes the end of each pass before attempting to correct the next (if you're curious, you can ask me about it)

- To see the efficacy of corrections, let's define some beam parameters
  - Longitudinal position: s Transverse design position: $x_0(s)$
    Transverse actual position: $x(s)$ Difference orbit: $\Delta x(s) = x(s) - x_0(s)$

Difference Orbit with Errors



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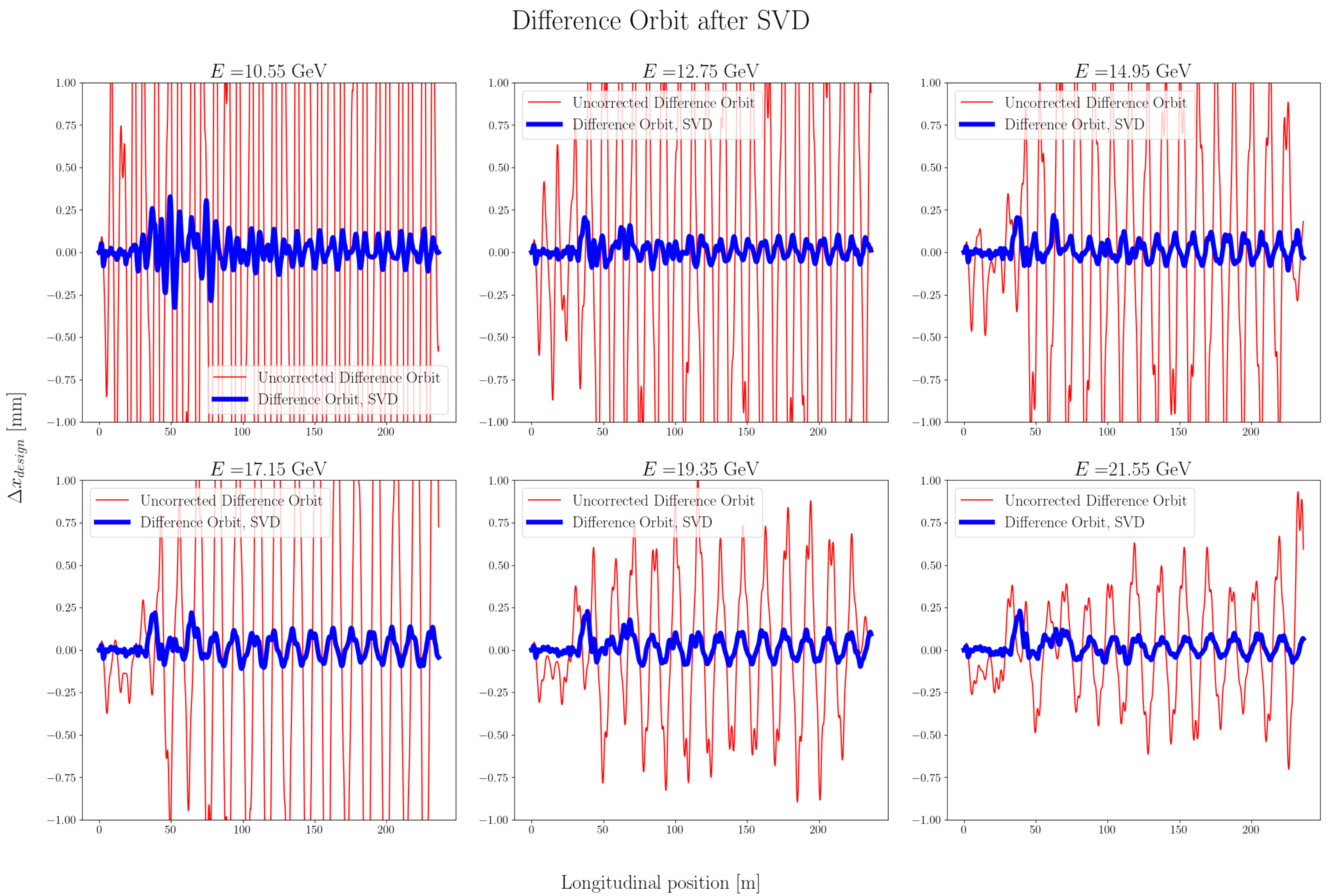
Difference Orbit Comparison



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Correction Notes

- The SVD algorithm I use can’t be implemented on a machine in CW operation
  - Requires real time knowledge of BPMs for each pass *individually*
    - No such BPM multiplex scheme exists
  - Corrects beams in ascending energy order, and assumes higher energy beams don’t exist
  - Could be feasibly applied in ‘tune mode’ or pulsed, diagnostic operation
- Is there a way around these issues?
  - Does machine learning offer us a way out?
    - Train on the beam averaged BPM readings, and the corrector output

Difference Orbit Comparisons II

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Questions?

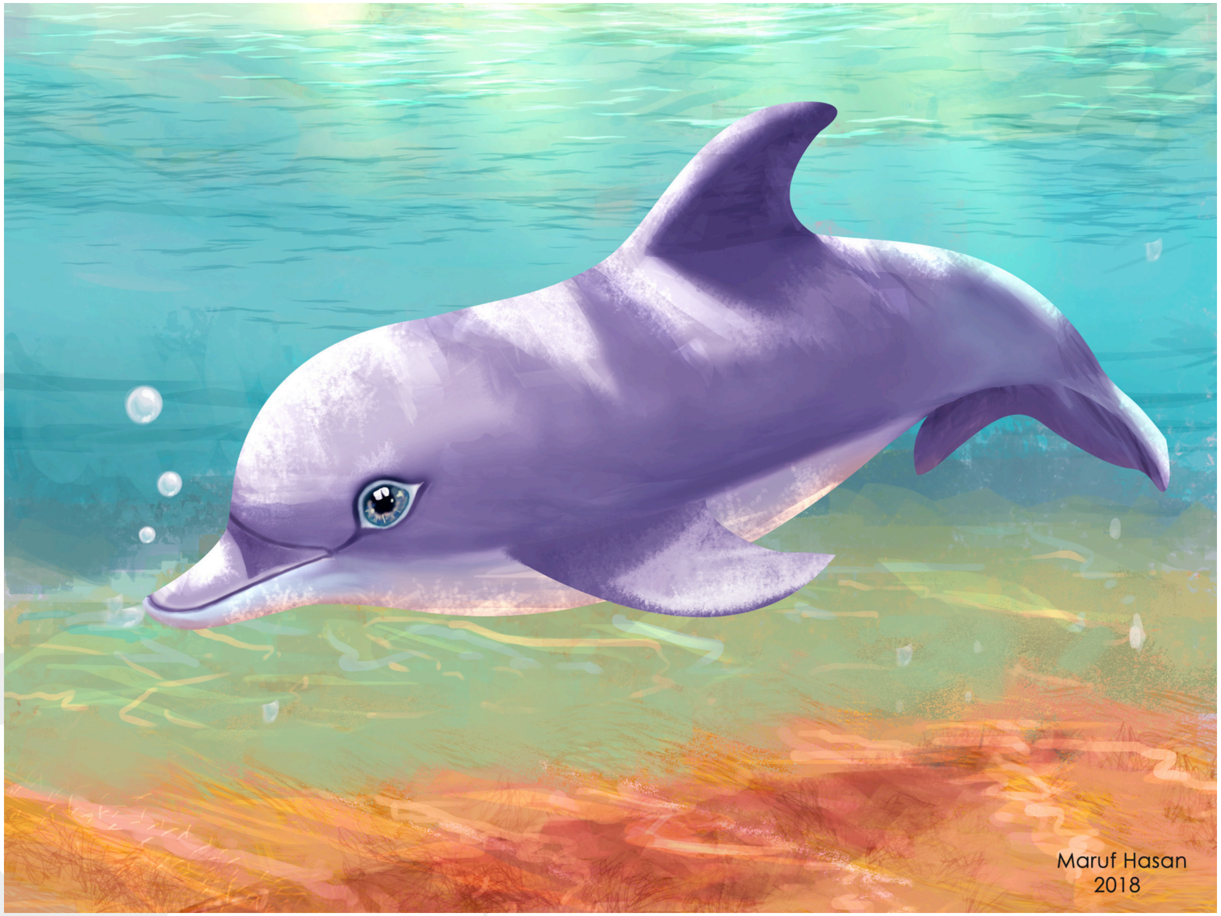

Image from: https://dribbble.com/shots/5117048-Cute-Happy-Dolphin