Updates of FFA-Based Proposals

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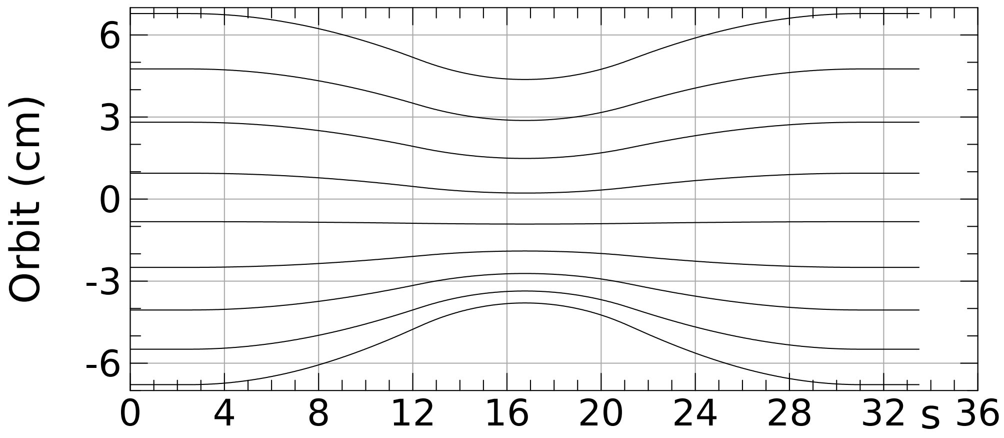
Why FFAs for Acceleration?

- Hybrid pulsed synchrotrons are our baseline for reaching high energies
  - Relatively small magnet apertures
  - Well-behaved longitudinal dynamics with an RF bucket
- Why would one choose an FFA?
  - If pulsed supplies for magnets become a cost driver
  - Energy reach of a hybrid pulsed synchrotron does not scale well with superconducting magnet field, and pulsed magnet fields limited by iron

$$p_{\max} = \frac{qLB_C B_W}{\pi[(1+r)B_W + (1-r)B_C]} \xrightarrow[B_C \to \infty]{} \frac{qLB_W}{\pi(1-r)}$$

What is an FFA

- **F**ixed **F**ield **A**lternating gradient accelerator
- Large energy range (e.g., factor of 2) in a single beamline
- Magnet fields do not vary with time
- Alternating gradient focusing in compact cells for small orbit excursion



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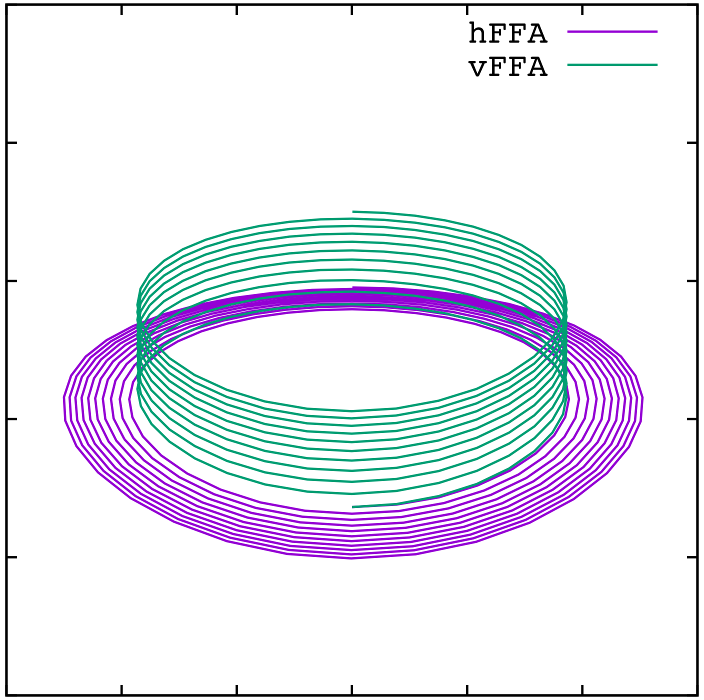
Vertical and Horizontal FFAs

- Original FFAs are midplane-symmetric: “horizontal”
  - Closed orbits in the midplane
  - Orbit length varies with energy
    - Variation small; stay near RF crest, “serpentine” acceleration
- Vertical FFAs
  - Closed orbits displaced vertically
  - Orbit lengths same: fixed RF frequency
  - Skew focusing
  - Complex magnetic fields (exponential vertically)



Vertical FFA Status

- Design work continuing with a Ph.D. Student at RAL
- No major updates since previous collaboration meeting
- Preliminary designs exists, but need and expect some improvements
  - Large orbit excursions (but note large energy range)
    - Maybe dispersion-suppressed region for RF
  - Reduce circumference
  - Ensure good dynamic aperture (very nonlinear)

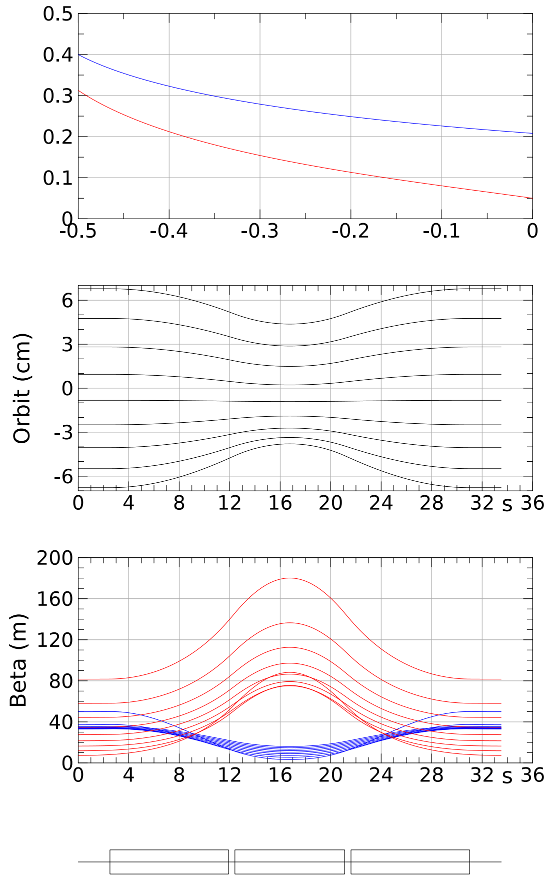
	FODO	FDF
Energy	50 GeV to 1.5 TeV	50 GeV to 1.5 TeV
Cell length	35 m	52.5 m
Magnet length	2 x 15 m	3 x 15 m
# of cell	810	540
Maximum field	8.7 T	10.6 T
Field index m	6.8	3.0
Orbit excursion	0.50 m	1.13 m
Cell tune	0.3957 / 0.0861	0.3510 / 0.1515

Midplane-Symmetric FFA Study

- Consider the final acceleration stage
- Fit on the Fermilab site (16 km circumference)
- 12% of circumference is RF
  - 3.5 MV/m average acceleration for 30 MV/m RF cavities
- 50 cm space between objects
- Use an FDF triplet cell with RF (or injection/extraction) in long drifts
  - Reflection symmetry needed to inject both signs
- Linear magnets
- Optimization to minimize peak field in magnets

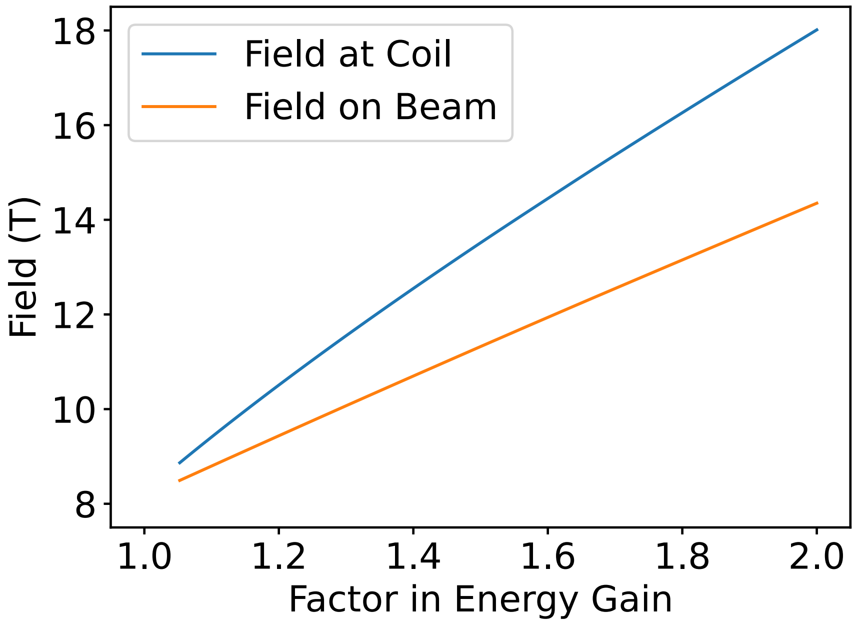
Sample Result

- Sample result for factor of 2 energy gain
- Just under 480 cells
- 4 m for RF (or injection/extraction)
- Optimization for field
- F field is 12.4 T at outside
- D field is −5.3 T at outside
    - Reverse bend



Field and Energy Range

- Assume maximum energy of 5 TeV
- Magnet field depends on minimum energy
- Plot shows field at coil, at 1.5 times beam radius, and field at beam
- Factor of 2 energy gain possible, but high fields
- Limitations similar to pulsed synchrotron
  - Minimum energy 3.9–4.5 GeV for 5 TeV max for 10 T max
  - Factor of 2, maximum energy 2.8–3.5 TeV for 10 T max



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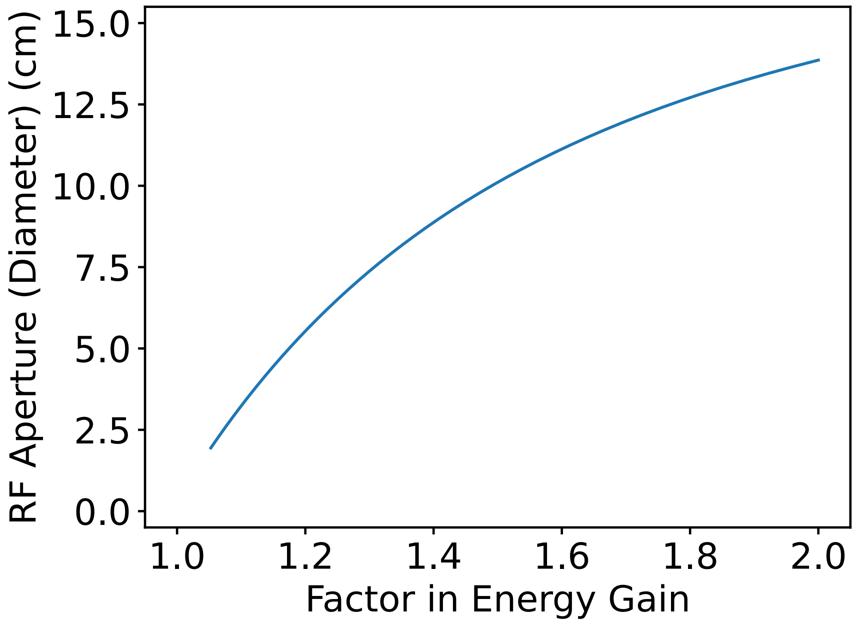
Aperture

- For factor of 2, too large for Tesla cavities
- 650 MHz probably possible
  - Reduced gradient may require longer straight
- SC magnet apertures are also large

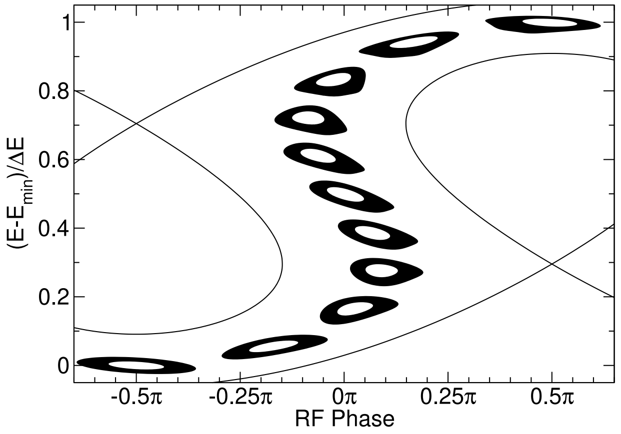


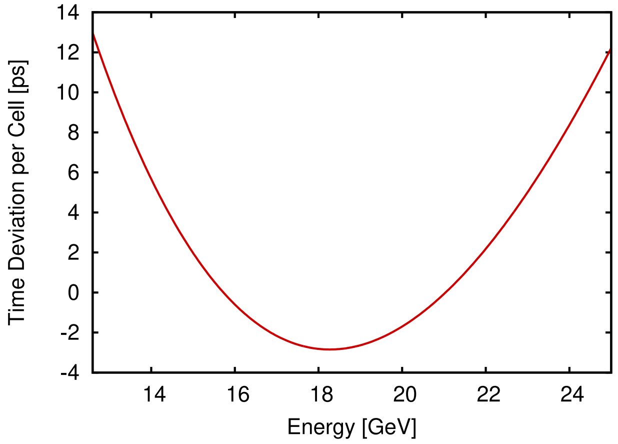
Injection/Extraction

- This configuration (FDF) makes horizontal favorable
  - Beam near inner/outer edge of magnet
- Number of straights for kickers to get separation
  - For 0.2 T kickers, about 3 straights for extraction
  - Injection harder due to tune near 0.4. Reducing tune would lead to higher main magnet fields
- Challenge is extraction septum. Ideas to manage:
  - Generate angle and position at septum
  - Pipe penetrating into aperture
  - Special magnets with larger apertures (higher fields!)
  - Longer straights (larger fields); maybe taper straight length

Acceleration

- Design is optimized for peak field
- Need to consider longitudinal dynamics
- One option is to shift RF phase
- Without shifting phase, can do serpentine acceleration
  - Requires designing for a more symmetric time of flight vs. energy
  - Will lead to higher fields





Final Comments

- This is a very early study
- Additional areas of study needed
  - Look at longitudinal dynamics; do we need to adjust the lattice?
  - More direct comparison of DFD triplet
  - To what extent to nonlinear fields help?
  - Need a concrete injection/extraction design
  - Look at tapered design to get longer drifts for injection/extraction
- FFAs can be applied to lower energies also (over RLAs)
- Energy reach not so different from pulsed synchrotrons