Acceleration System

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Acceleration System Goals

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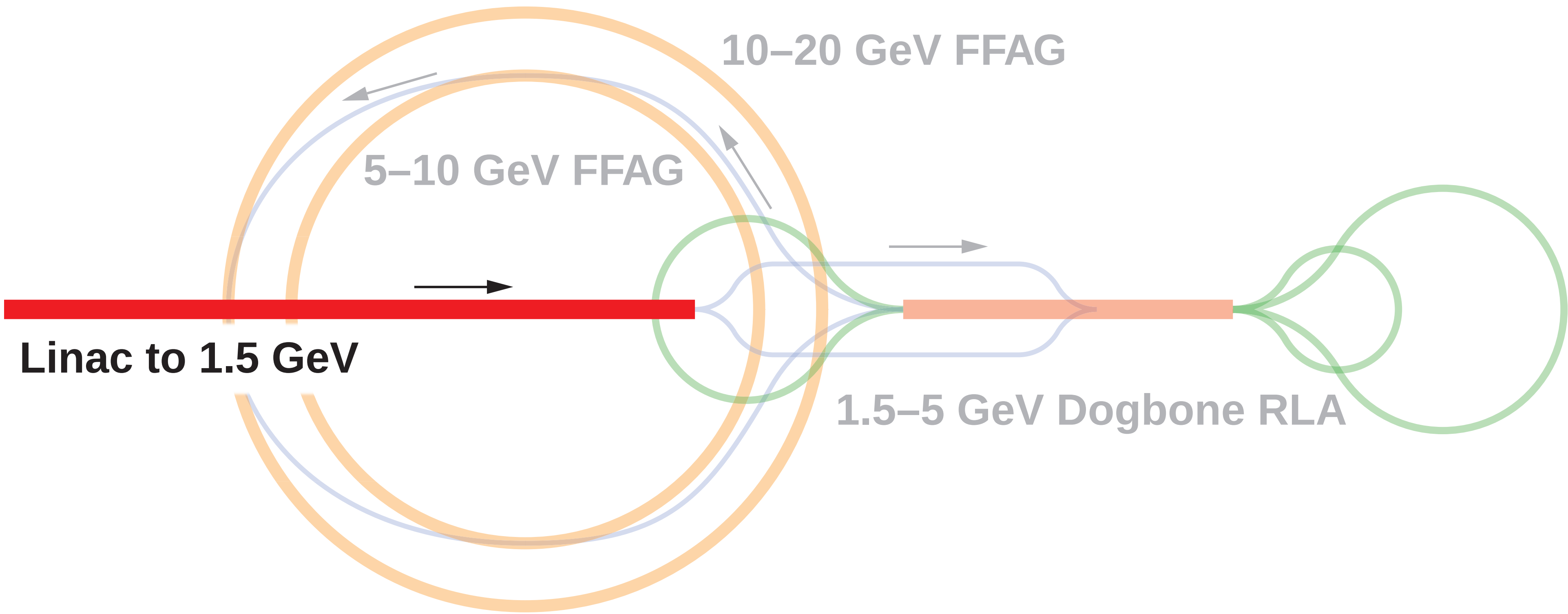
- Accelerate muons from cooling (momentum 200 MeV/c) to storage ring (total energy $\gtrsim$ 20 GeV)
- Accelerate rapidly to minimize decay
- Minimize dynamic particle loss
- Minimize emittance growth (longitudinal and transverse)
- Keep costs down

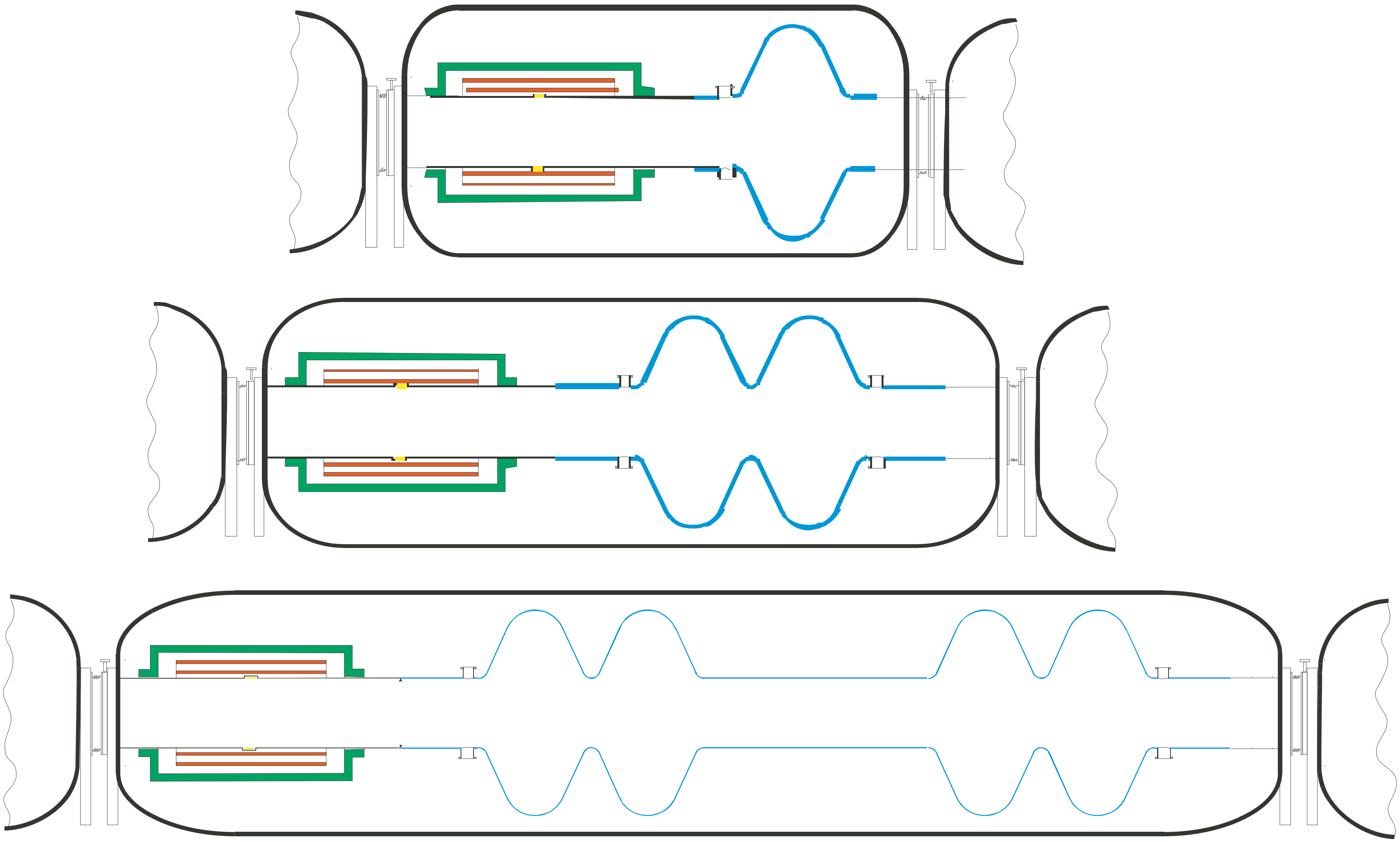
Linac



Linac

- Low energy requires short, inefficient cells for transverse acceptance
  - Shorter cells than Study II: larger transverse acceptance
  - Don’t use for most acceleration
- In RLA, each pass through linac must have nearly the same velocity; otherwise RF gets out of sync
  - Stay in first linac until reach sufficient energy
- Since lower energy, use solenoid focusing
- Have complete design
- Longitudinal acceptance is tight. To increase acceptance
  - Go to higher field, shorter solenoids at start, reducing cell length
  - Start further off-crest (but this increases linac length)

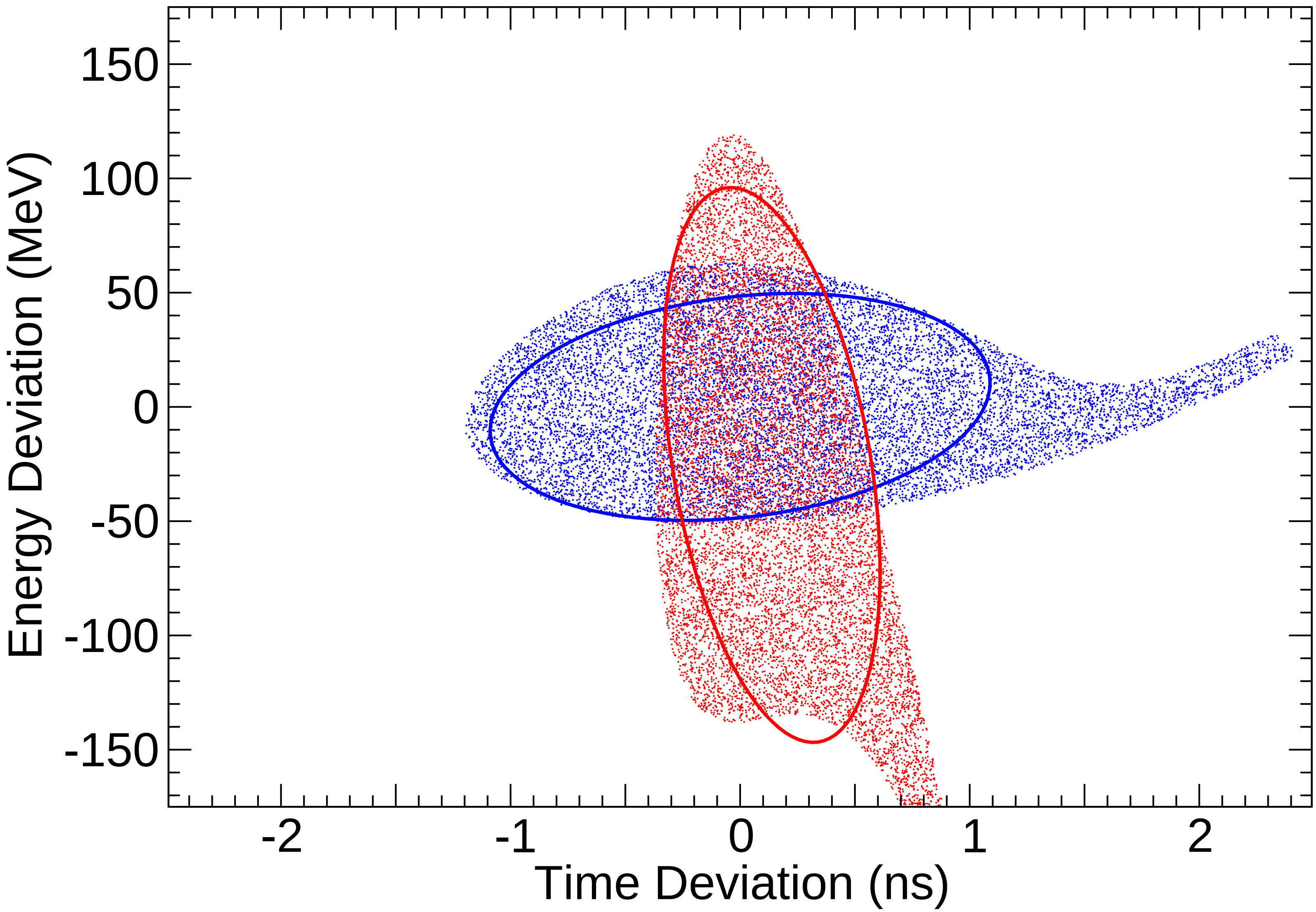
Linac Cryostats



Linac Parameters

Period length (m)	3	5	8
Cavities per period	1	1	2
Cells per cavity	1	2	2
Periods	12	18	22
Average gradient (MV/m)	3.8	4.5	5.6
Max solenoid field (T)	1.5	1.9	3.9

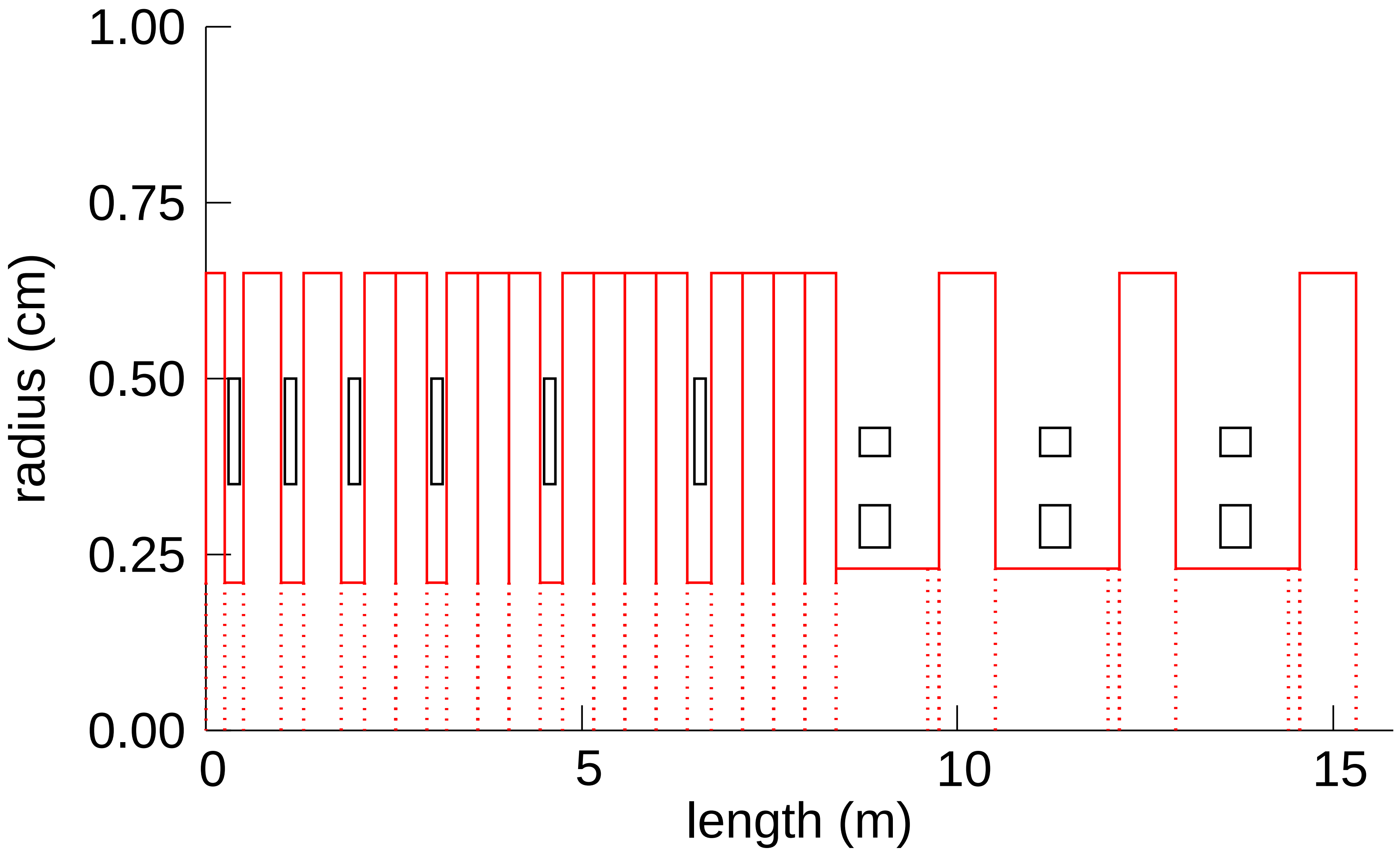
Linac Longitudinal Acceptance



Matching

- Need to match from cooling to acceleration
- Beta functions somewhat different
  - Not as different as in Study II (cooling went up, linac went down)
  - Thus much simpler
- Need to accelerate a bit also
  - SC linac started at $p = 273\ \text{MeV}/c$ due to acceptance concerns (cooling at 200 MeV/c)
- Use combination of cooling cavities and SC cavities
  - Gradually increase cell length in cooling cavities
  - Do matching over a large momentum range
- Result: pretty good transmission (3% loss)

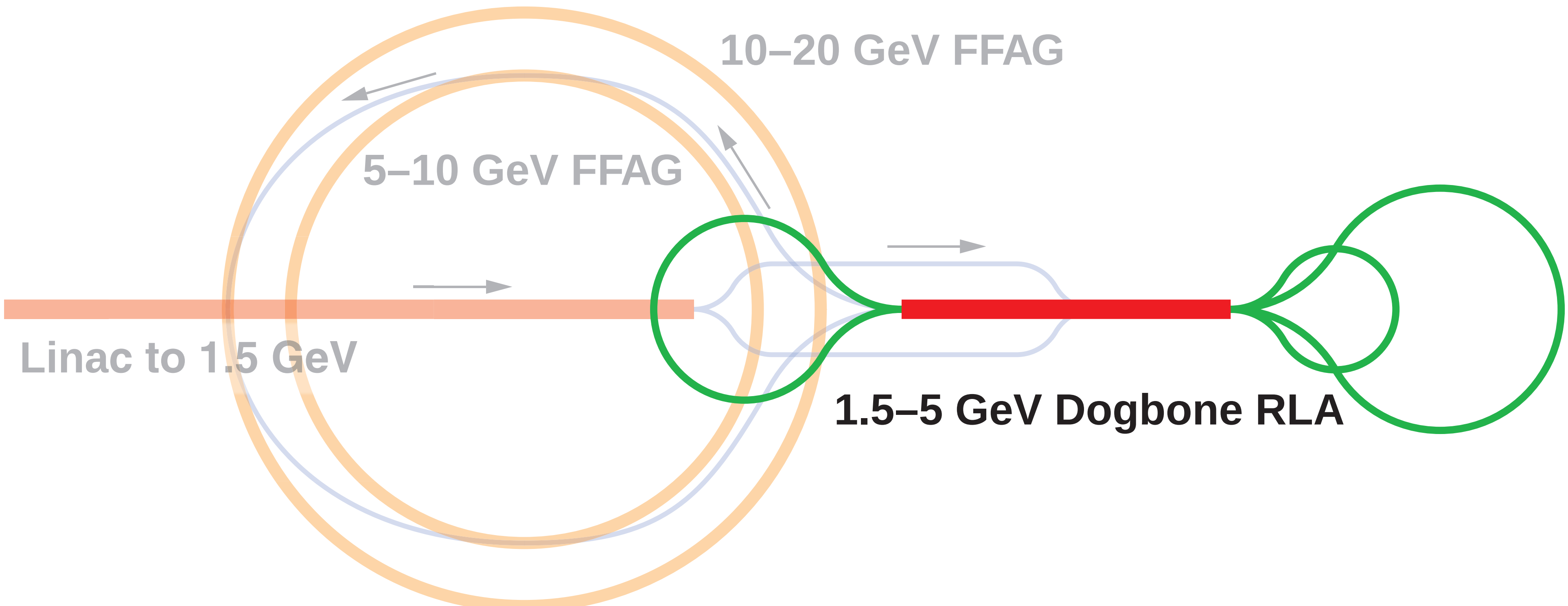
Matching Section



Linac: Next Steps

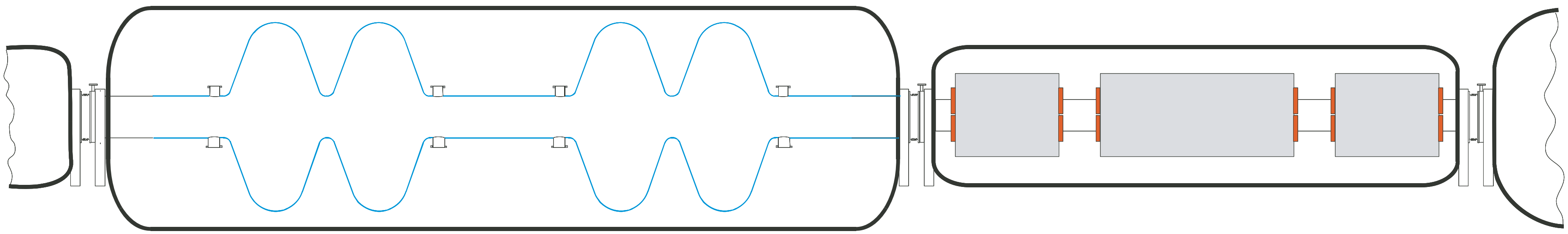
- Do tracking with real magnet end fields, looking for emittance growth
- Do tracking in 6-D
- Integrate matching design with linac design
- Try to improve longitudinal acceptance
  - Shorter linac cells
  - Improved RF phase profile

Dogbone RLA



Dogbone RLA

- FFAGs inefficient at low energies; use RLA
- Use dogbone over racetrack due to
  - Better energy separation at switchyard
  - More cost effective (?)
- Triplet lattice, 2 cavities per cell (larger acceptance)

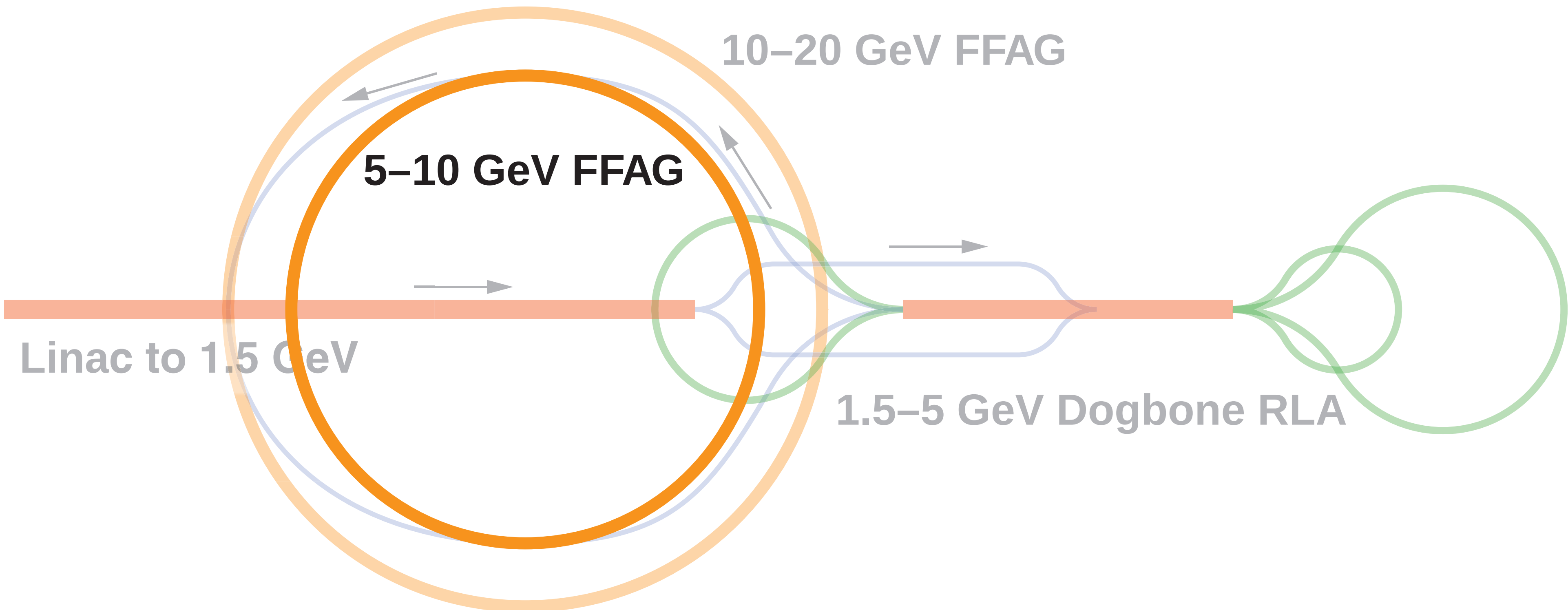


- Switch to FFAGs when they become more cost effective
- Most of the pieces are there, but still needs to be finished off

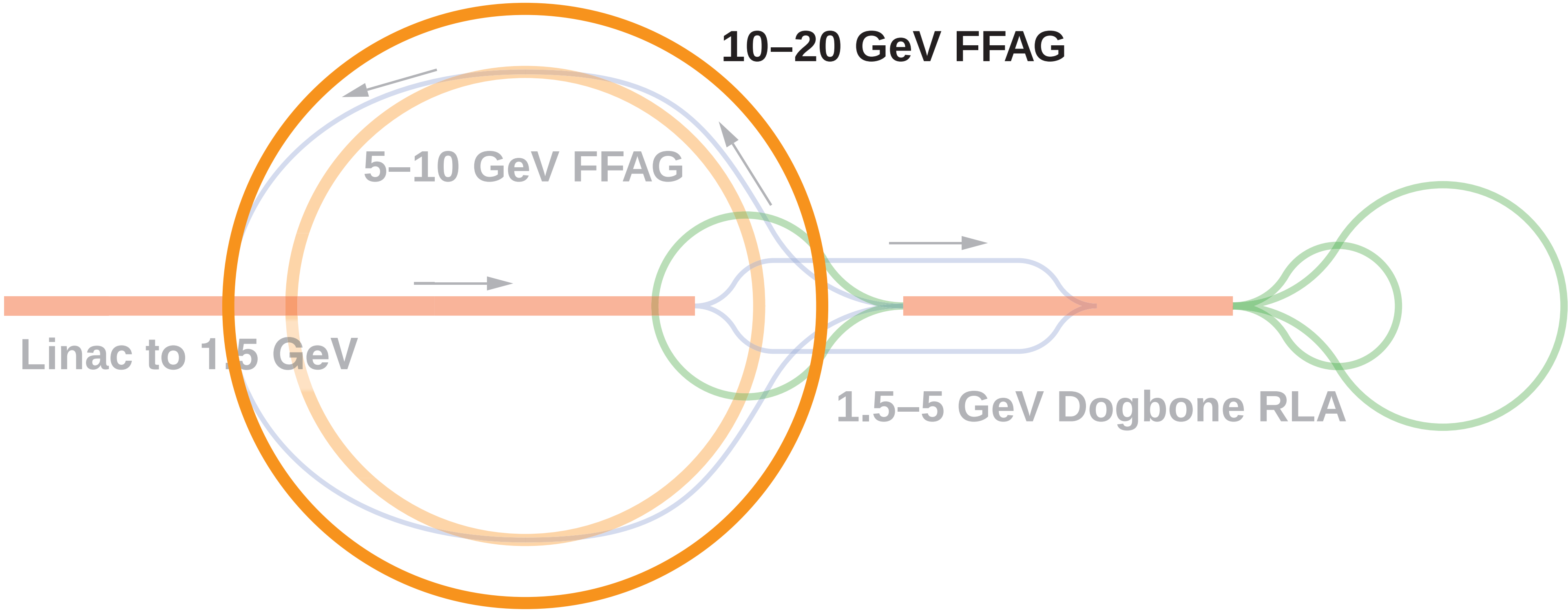
Dogbone RLA: Next Steps

- Finish off the existing design, and get component specifications
- Do 6-D tracking through the machine
- Optimize number of turns

5–10 GeV FFAG



10–20 GeV FFAG



FFAGs: Previous Work

- Had used an early version of an optimization procedure to determine FFAG designs
- Using triplet designs, had done
  - Injection/extraction scheme
  - Tracking study
- There is a wide collaboration interested in FFAGs
  - Internationl (Canada, Europe, Japan)
  - Frequent workshops (twice per year)
  - Desire to build a model of the new type of FFAGs considered for muon acceleration (next talk)

FFAG Optimization

- Choose FFAG machine parameters by minimizing a cost function
- We have made improvements to the cost function in the last year
  - Changed magnet cost model so that zero-field magnets with nonzero size have nonzero cost
  - Assigned a cost to decays
    - Minimum-cost rings had unacceptable decays
    - Use detector cost as a baseline: for given performance, can make acceleration more efficient or make detector larger
- These changes cause fields to be higher than before
- Doublets are the most cost effective (as we've always found), compared with triplets, FODO

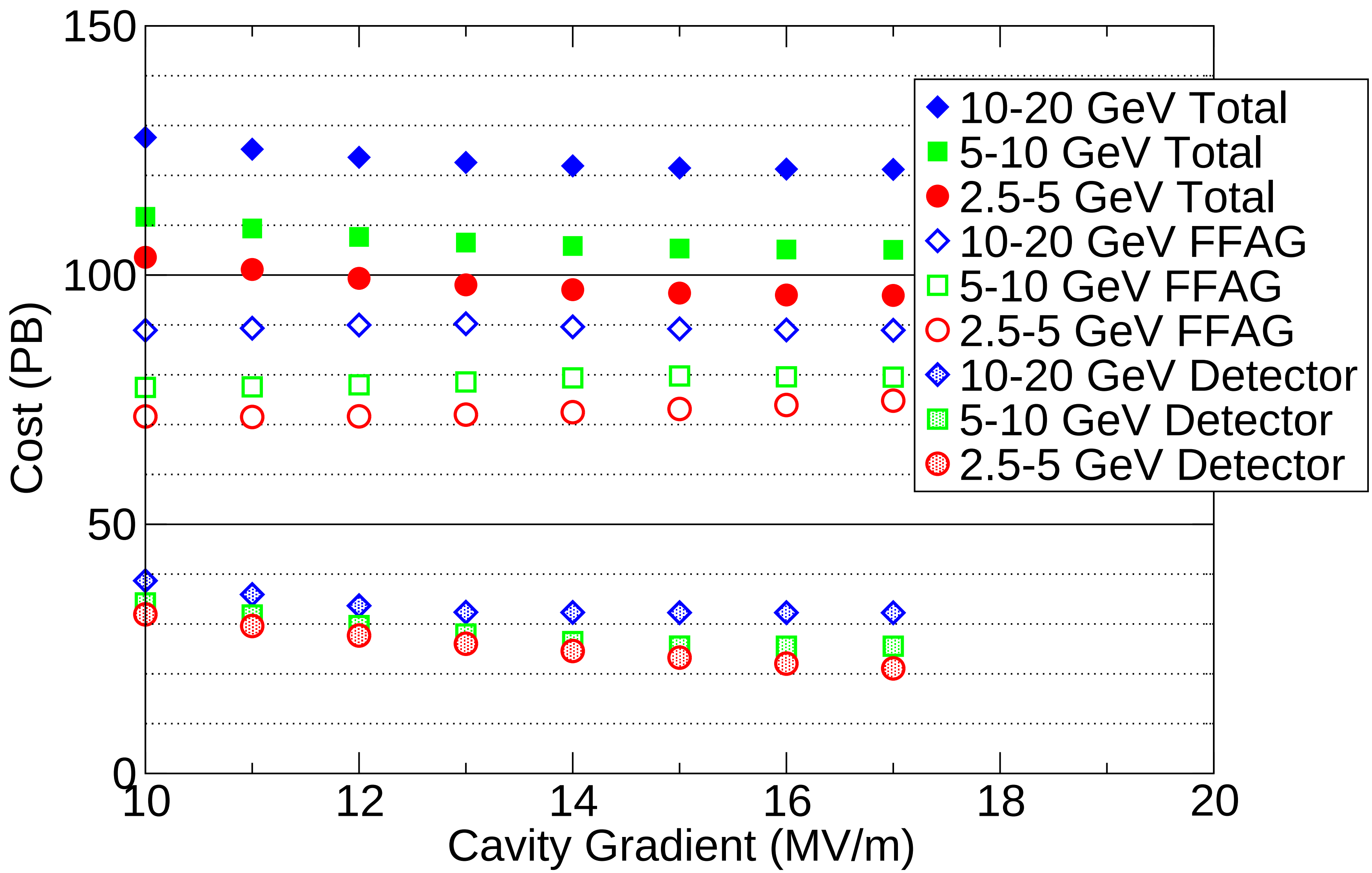
Lattice Parameters

Gradient (MV/m)	17		
Minimum total energy (GeV)	2.5	5	10
Maximum total energy (GeV)	5	10	20
No. of cells	50	65	82
D length (cm)	63	77	97
D radius (cm)	13.4	10.0	7.4
D pole tip field (T)	4.5	5.7	7.1
F length (cm)	96	113	141
F radius (cm)	21.2	16.3	13.1
F pole tip field (T)	2.7	3.5	4.3
No. of cavities	42	49	56
RF voltage (MV)	534	620	704
Turns	4.7	8.2	15.0
Circumference (m)	204	286	400
Decay (%)	4.2	5.1	6.5
Total cost (PB)	74.8	79.5	88.9
Cost per GeV (PB/GeV)	29.9	15.9	8.9

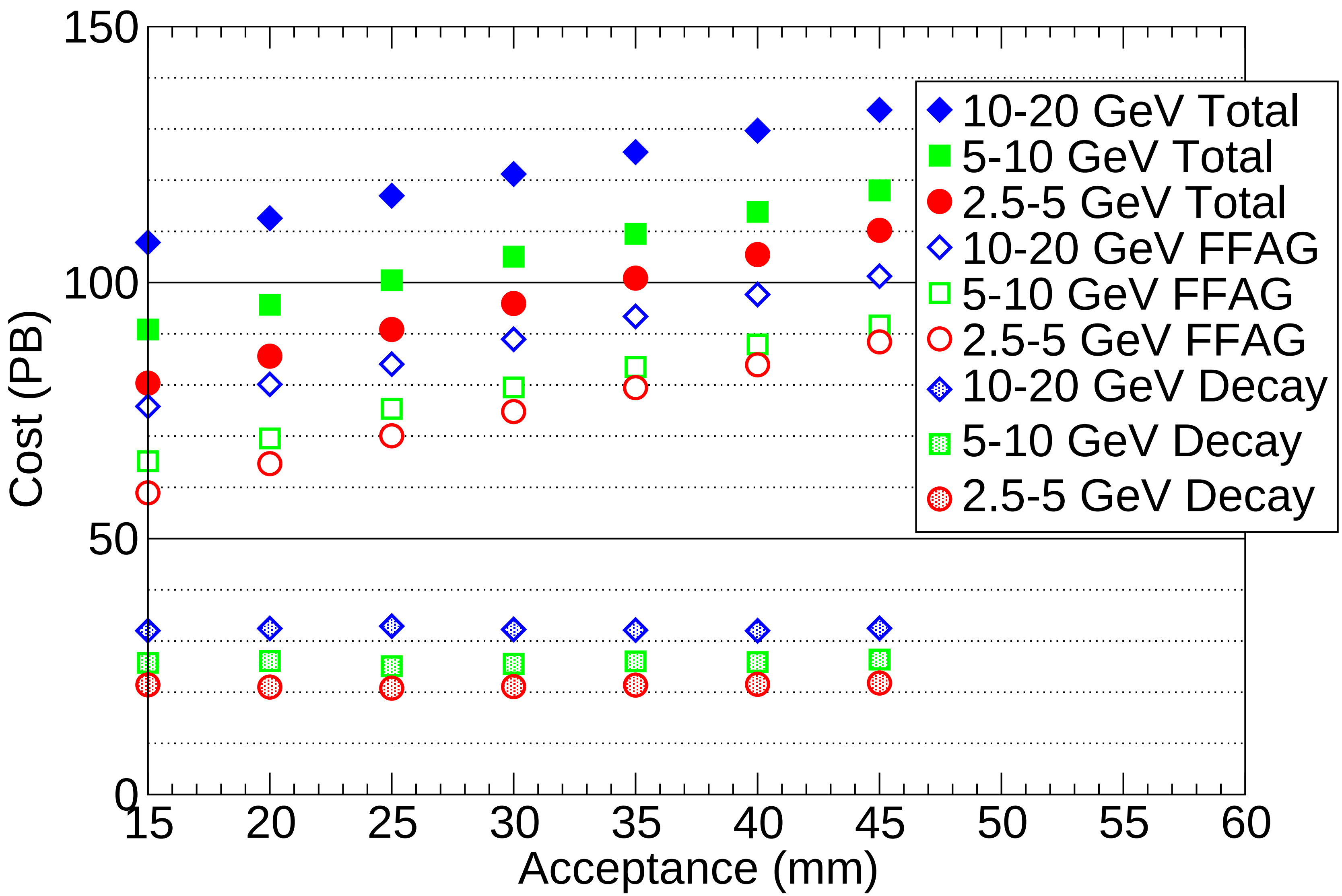
Other Optimization Results

- Costs vs. Gradient
  - Relatively weak dependence on gradient in 10–17 MV/m range
  - Assumption is that only RF power costs increase with gradient
    - If this is wrong (e.g., extra cryo costs, increased structure costs), cost benefit of 17 MV/m over 10 MV/m may be lost
- Costs vs. Transverse Acceptance
  - Cost depends strongly on acceptance
  - To do next: optimize cooling length and acceleration aperture together, considering decay cost

FFAG Cost vs. RF Gradient



FFAG Cost vs. Transverse Acceptance



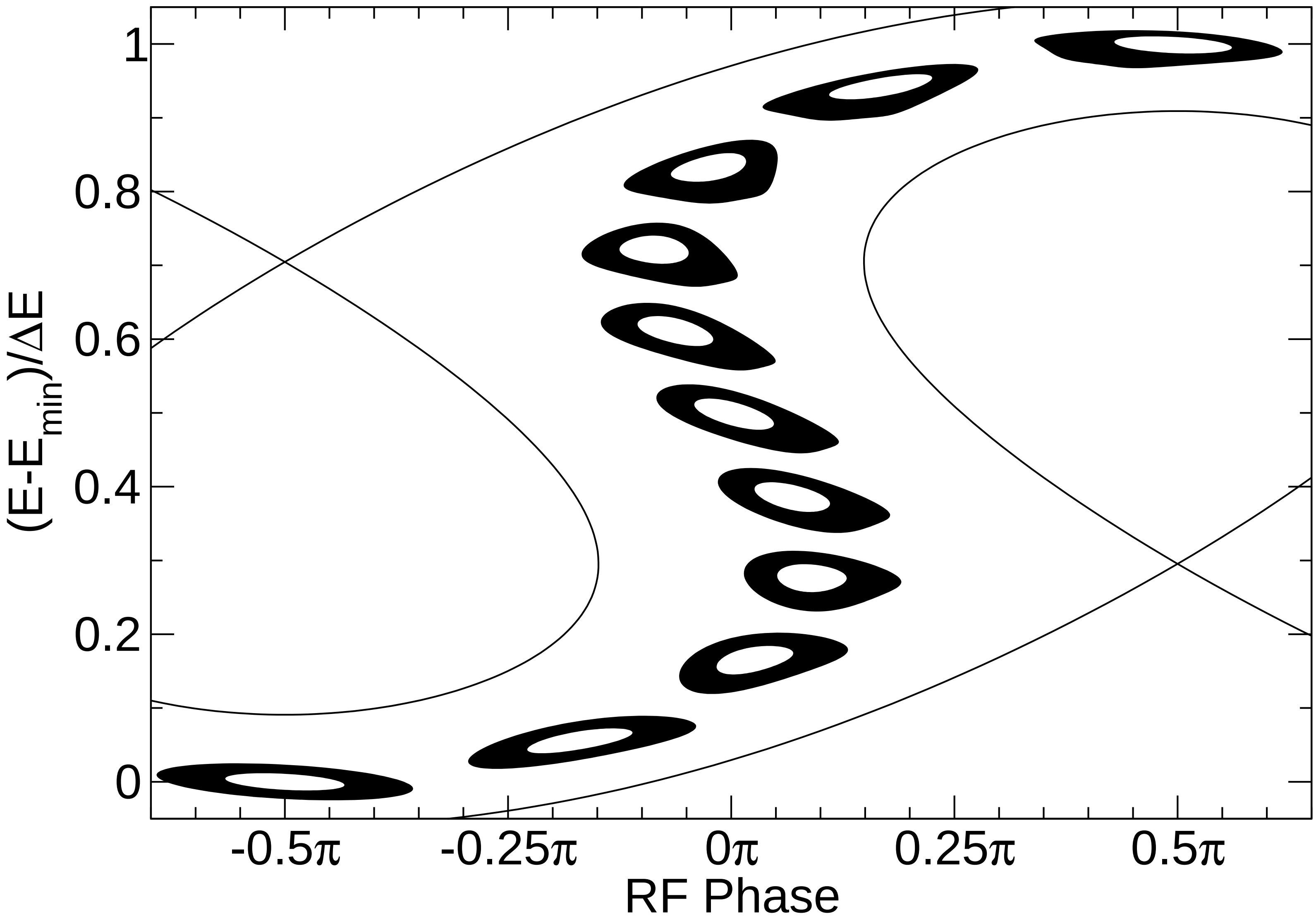
Longitudinal Parameter Choice

- Longitudinal motion in muon FFAGs described by two parameters

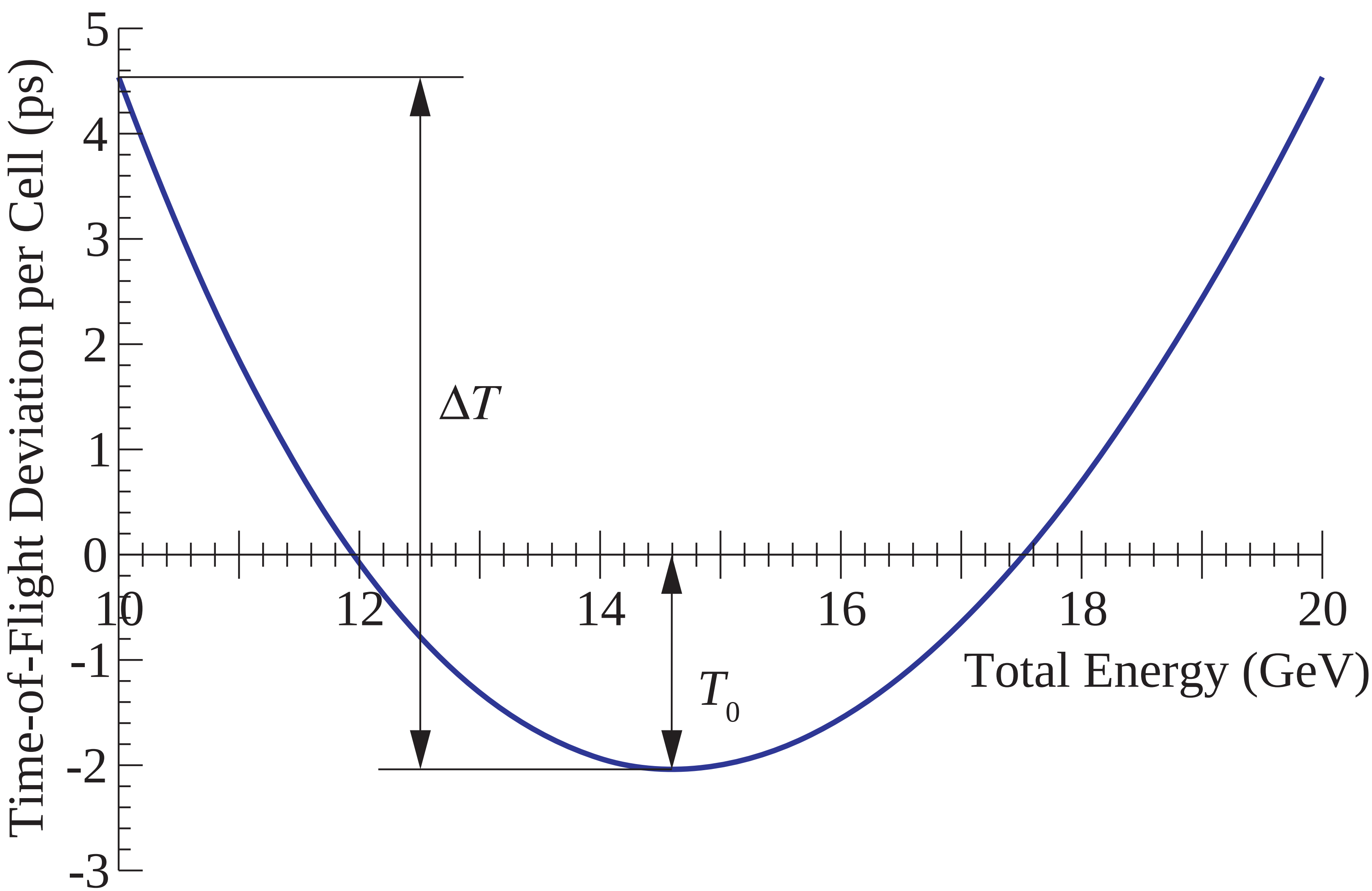
$$a = qV/\omega\Delta T\Delta E \qquad\qquad b = T_0/T$$

- As a reduces, get more longitudinal distortion
- Choice of a drives the FFAG design
- We have developed a technique for computing distortion from ellipticity as a function of these parameters
  - Get optimum phase space ellipse orientation in the process

Longitudinal Motion in FFAG



Time-of-Flight in an FFAG



Stages in FFAGs

- Different numbers of stages to get from 2.5 to 20 GeV
- 2 stages significantly more expensive than 3
- 3 stages wins slightly over 4
  - Machine cost slightly lower for 4, but decays make 4 stages worse
  - Extra cost of transfer line also adds to 4 stage cost
  - Prefer fewer stages to more

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Stages in FFAGs: Table

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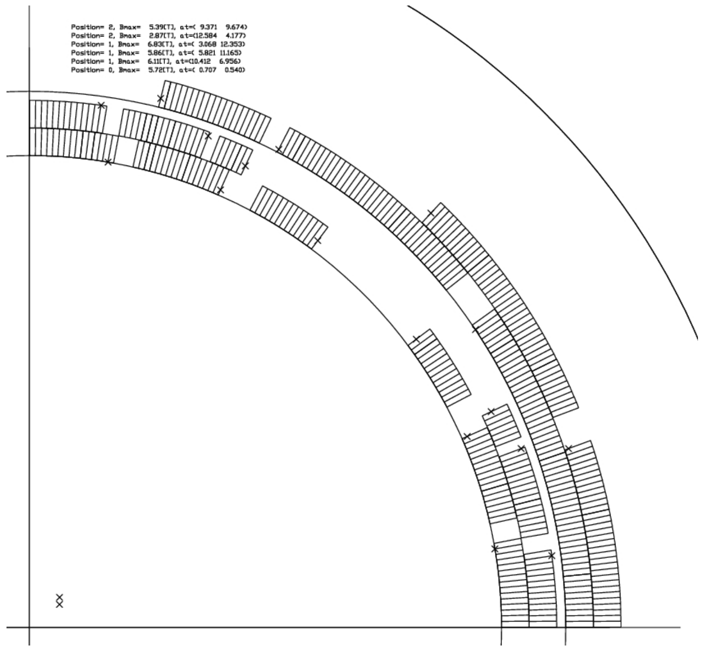
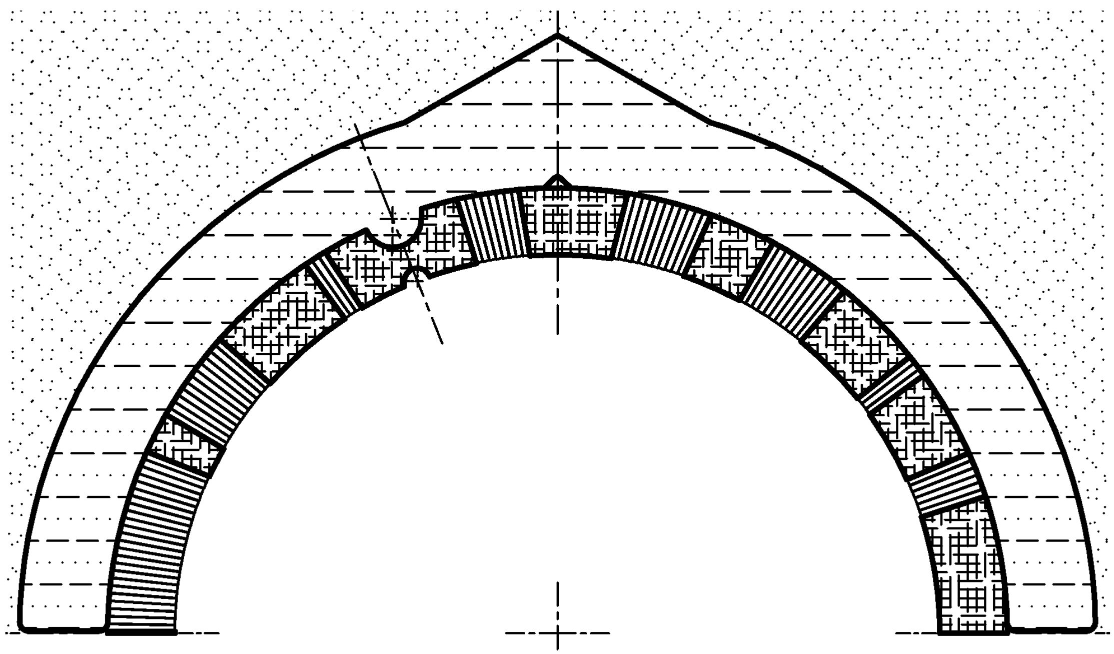
Number of stages	4				3			2	
Min. total energy (GeV)	2.5	4.2	7.1	11.9	2.5	5.0	10.0	2.5	7.1
Max. total energy (GeV)	4.2	7.1	11.9	20.0	5.0	10.0	20.0	7.1	20.0
Number of cells	34	38	46	57	50	63	82	101	152
Number of cavities	26	30	35	38	42	48	56	88	97
RF voltage (MV)	331	382	434	477	534	606	704	1114	1230
Turns	5.2	7.6	11.4	17.7	4.7	8.5	15.0	4.2	11.3
Circumference (m)	144	174	228	306	204	279	400	389	653
Decay (%)	3.6	3.8	4.4	5.4	4.2	5.1	6.5	5.8	9.1
Machine cost (PB)	53.0	56.7	61.5	68.1	74.8	78.9	88.9	138.1	142.0
. . . per GeV (PB/GeV)	31.1	19.8	12.8	8.4	29.9	15.8	8.9	30.2	11.0
Marginal decay cost (PB)	18.0	18.9	21.9	27.1	21.1	25.6	32.3	28.9	45.5
Total machine cost (PB)	239.3				242.7			280.1	
Total decay cost (PB)	85.9				78.9			74.5	

FFAG Magnets

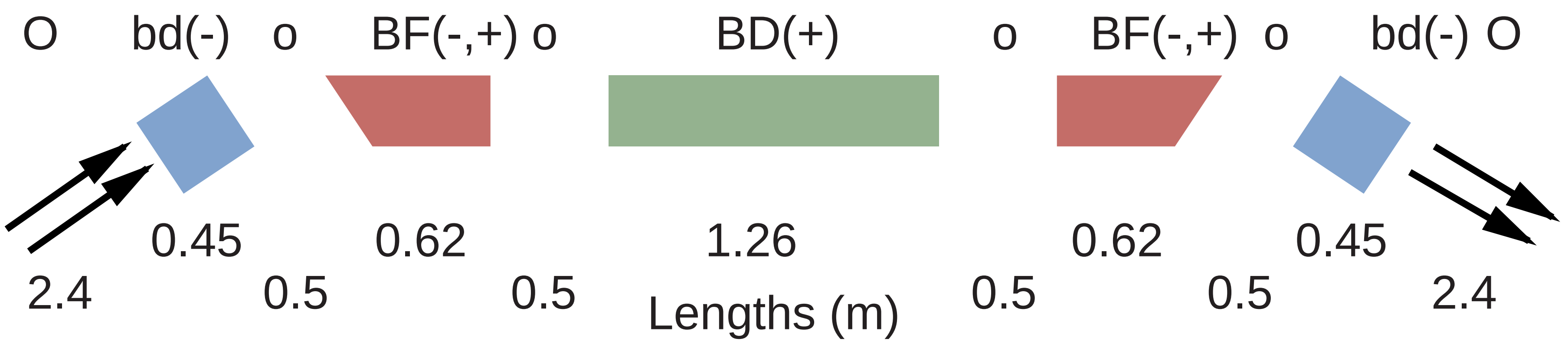
- Preliminary design of FFAG magnet was done for costing purposes (Caspi/Hafalia)
- Did design with separate dipole/quadrupole layers
- J-PARC 50 GeV proton line, have built a SC single-layer combined-function magnet: uses less coil





Other Types of FFAGs

- FFAGs with warm magnets may be more cost-effective at low energy
- FFAGs with nonlinear magnets are also being looked at
  - Concern: poor dynamic aperture due to nonlinear magnets
  - Graeme Rees has proposed a lattice which is much more isochronous than our lattices

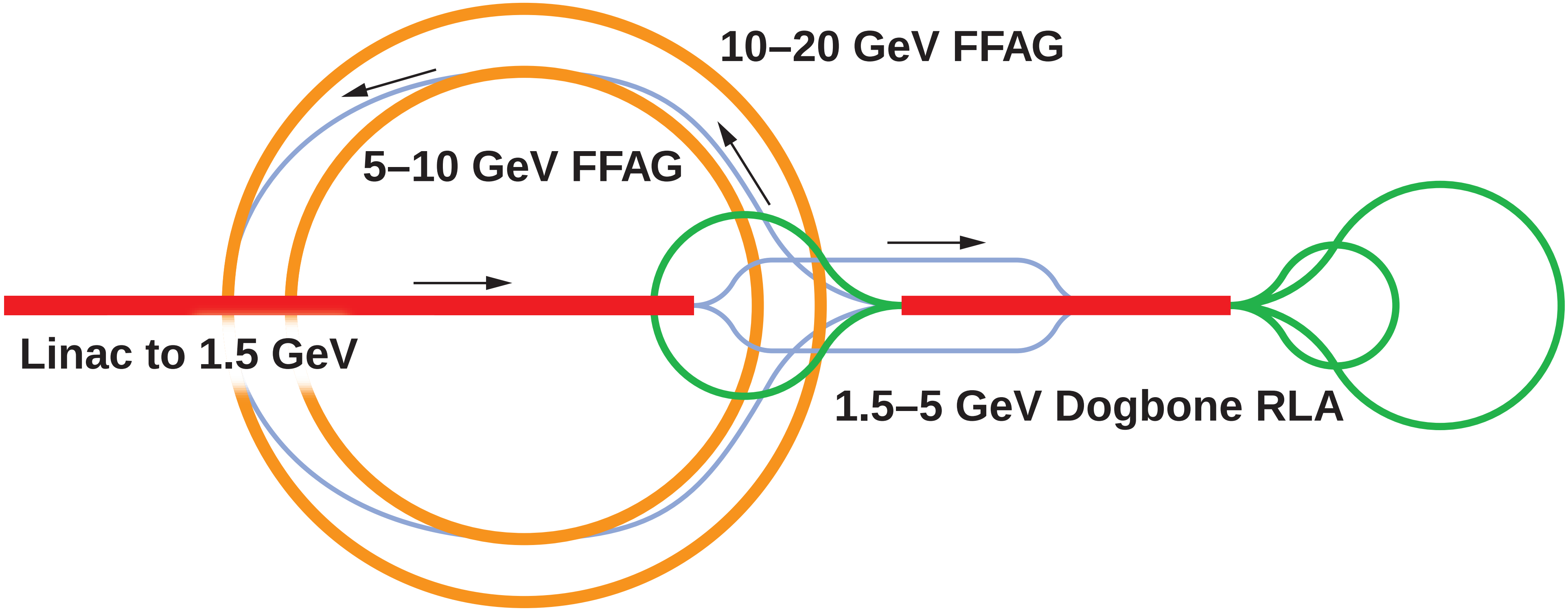


    - ⋆ Lower RF requirement and/or shorter lattice
    - ⋆ Currently has dynamic aperture problems, but it doesn't seem too far off (tracking by François Méot)

FFAGs: Next Steps

- Re-do optimization with consideration for longitudinal distortion calculation
  - For given a, choice of b gives tradeoff between acceptance and decay
- Use optimization procedure to choose dividing point between stages
- Injection/extraction scheme with doublet lattice
- Do tracking studies with chosen lattices
- Get a more detailed magnet design

Full Machine



Overall: Next Steps

- Understand parametric dependence of designs of all stages (e.g., dependence on acceptance)
- Develop method for choosing when to switch stages
- Develop transfer line designs
- 6-D tracking through entire system