Optimized FFAG Designs

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Muon Collaboration Meeting

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Outline

- Review of optimization process
- Review of previous results
- Updated Cost Model
- Characteristics of optimal lattices
- Minimum cost rings
- Decay cost
- Parametric dependencies of lattices
- New lattices
- Remaining work
- Conclusions

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Review of Optimization Process

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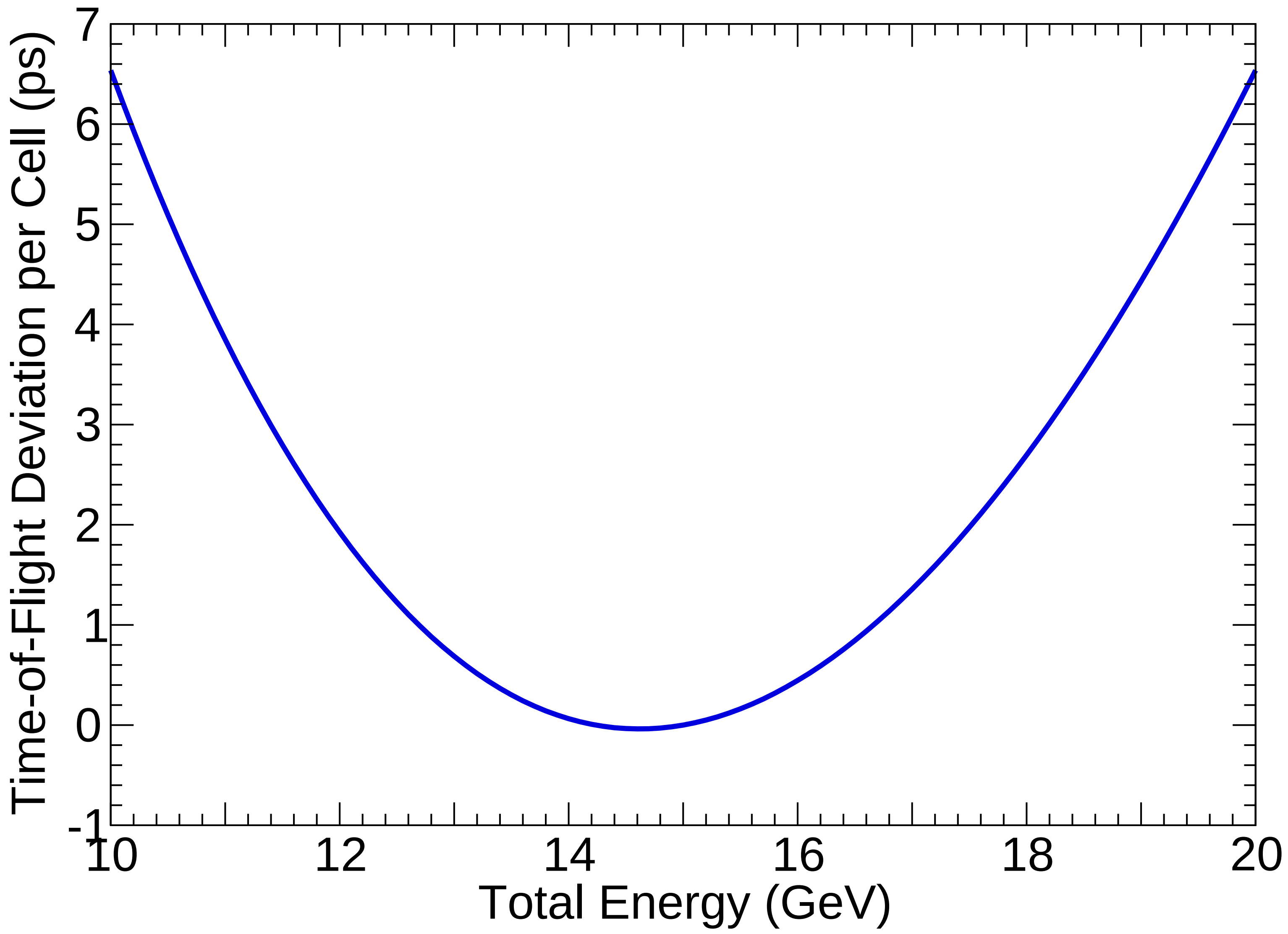
- Muon FFAG lattices consist of several identical cells of a particular type (doublet, FDF triplet, FODO)
- Assume 201.25 MHz RF
- A drift of at least 2 m is specified for the RF cavity
  - Purpose: keep field on superconducting cavities below 0.1 T
- Leave 0.5 m of space between magnets in doublet/triplet
- Time-of-flight vs. energy is parabolic-like; set height of parabola at min and max energy to be same
- For longitudinal acceptance, constrain $a = V/(\omega\Delta T\Delta E)$
  - ΔT is height of parabola (one turn), V is total voltage installed
  - Value of a depends on energy range, empirically chosen, increases with decreasing energy
- Factor of 2 in energy: 2.5–5 GeV, 5–10 GeV, 10–20 GeV

Time-of-Flight vs. Energy



Review of Previous Results of Optimization

- Doublet lattice is most cost effective
  - Triplet lattice has lowest voltage requirement, but
  - Three magnets per cell drives up magnet cost
  - Difference FD $\rightarrow$ FDF $\rightarrow$ FODO is around 5% each
- Cost per GeV of acceleration increases rapidly as energy decreases
  - 2.5–5 GeV of questionable cost value for muon acceleration

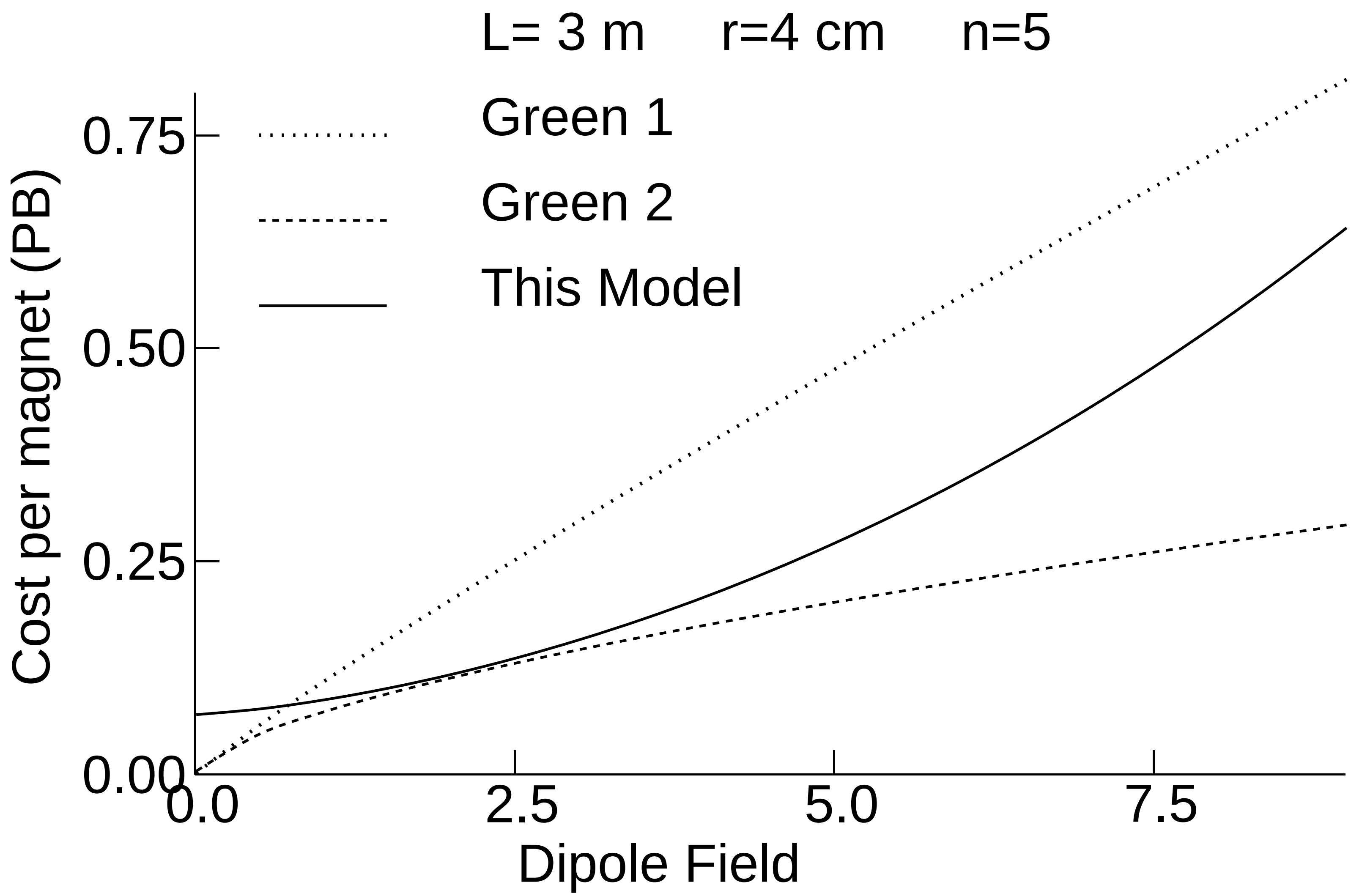
Updated Cost Model (Palmer)

- Compared to previous model
  - Cost at zero field for fixed magnet size does not go to zero
  - A new symmetry factor (quad/dipole/combined function) is used
    - ⋆ Proportional to amount of coil needed
    - ⋆ Factor is identical for dipoles and quadrupoles
    - ⋆ Factor is less than 1 for combined function
- Basic formula: product of 4 factors

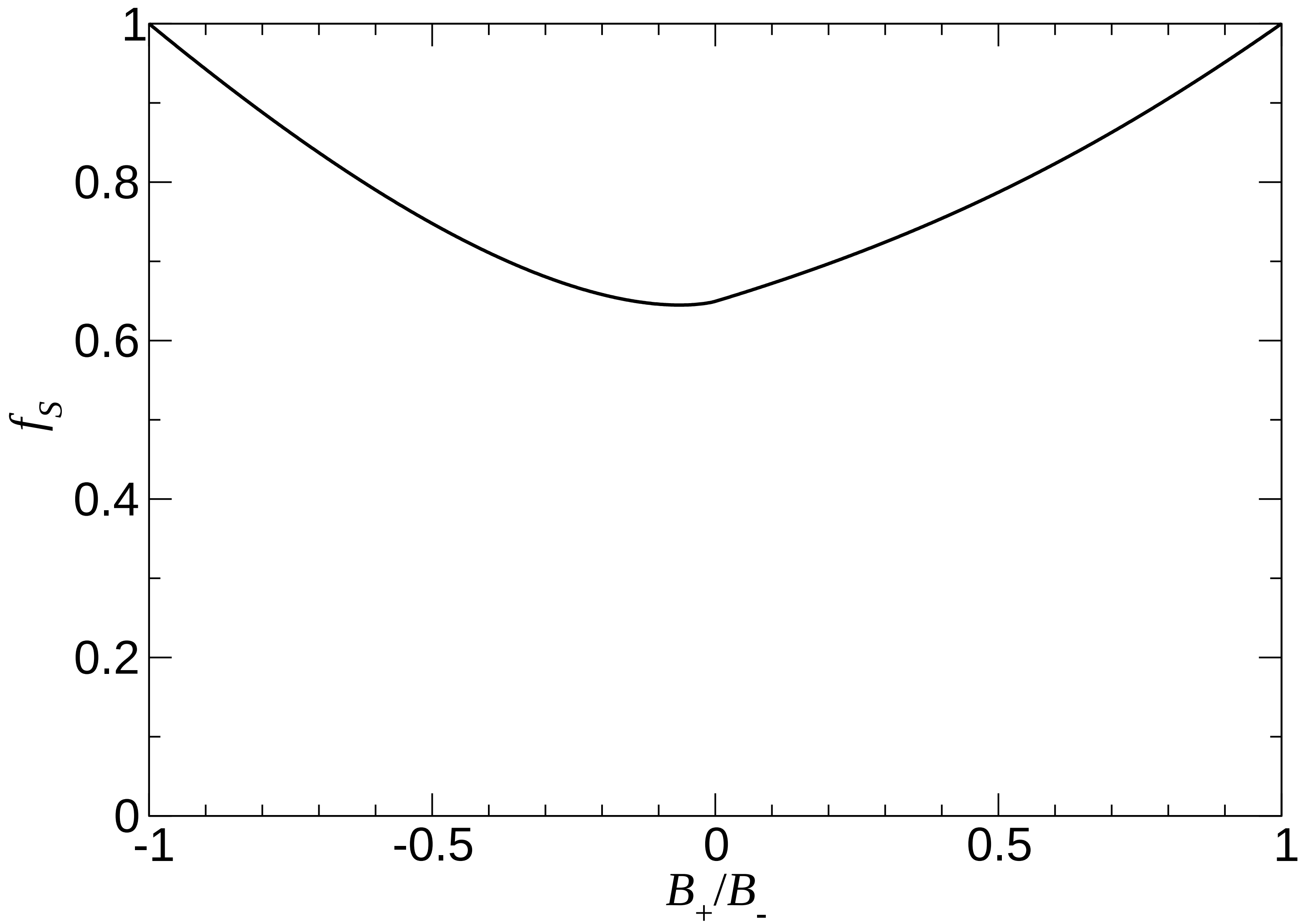
$$f_B(\hat{B}) f_G(\hat{R}, L) f_S(B_-/B_+) f_N(n)$$

  - f_B: dependence on field
  - f_G: geometric dependence: magnet length L
  - f_S: symmetry dependence
  - f_n: dependence on number of magnets being made n

Updated Cost Model (cont.)



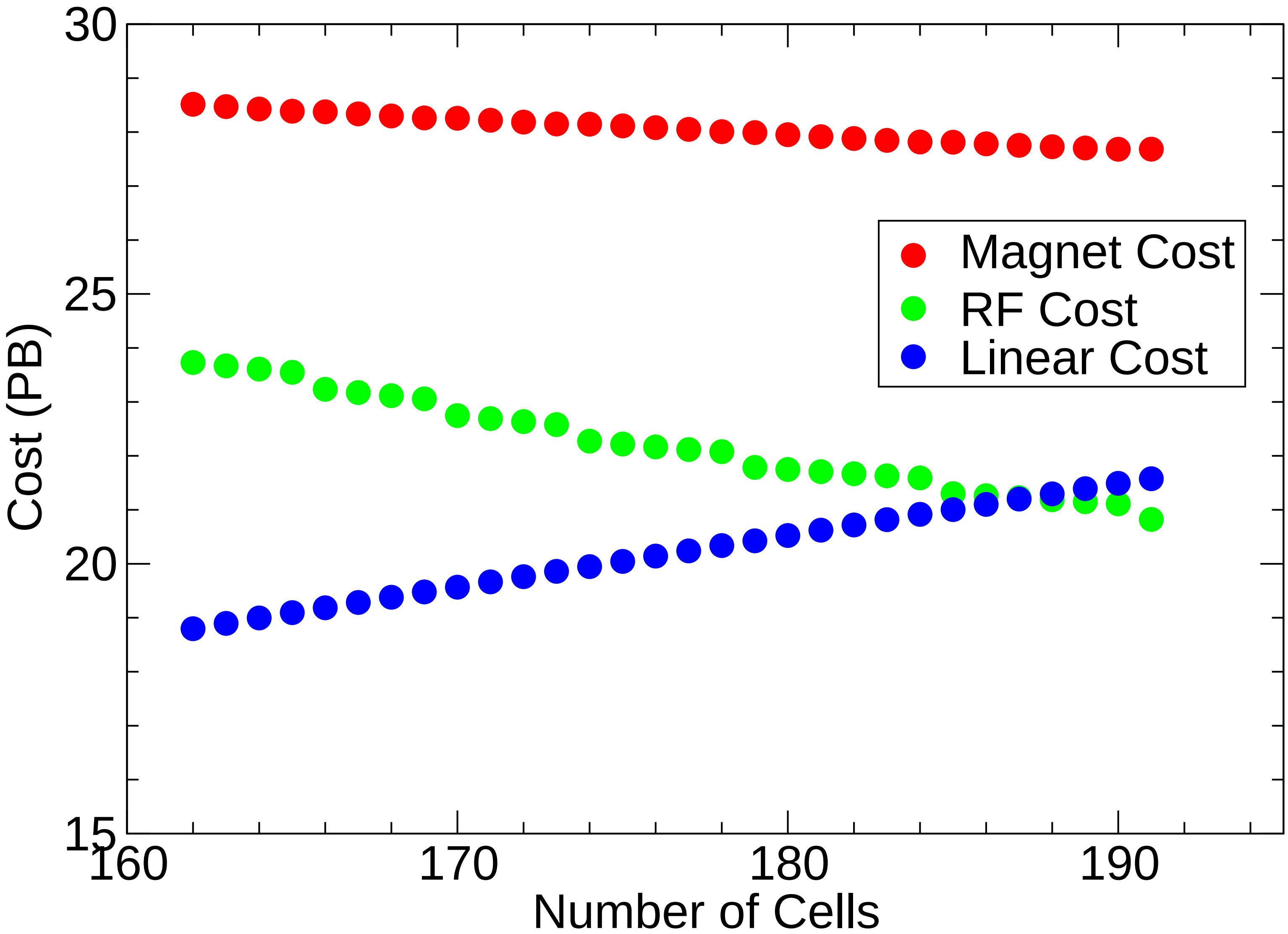
Updated Cost Model (cont.)



Characteristics of Optimal Lattices

- For modest lengths, lattice (magnet+linear) cost decreases with increasing circumference
  - Reduced dispersion reduces aperture requirement
  - Remarkably, this cost reduction is goes down more quickly than inversely in the number of cells
  - At some point, this stops as the nonzero transverse beam size stops the decrease in the aperture
  - The minimum-cost solution does not have every cell filled with RF!

Costs vs. Number of Cells



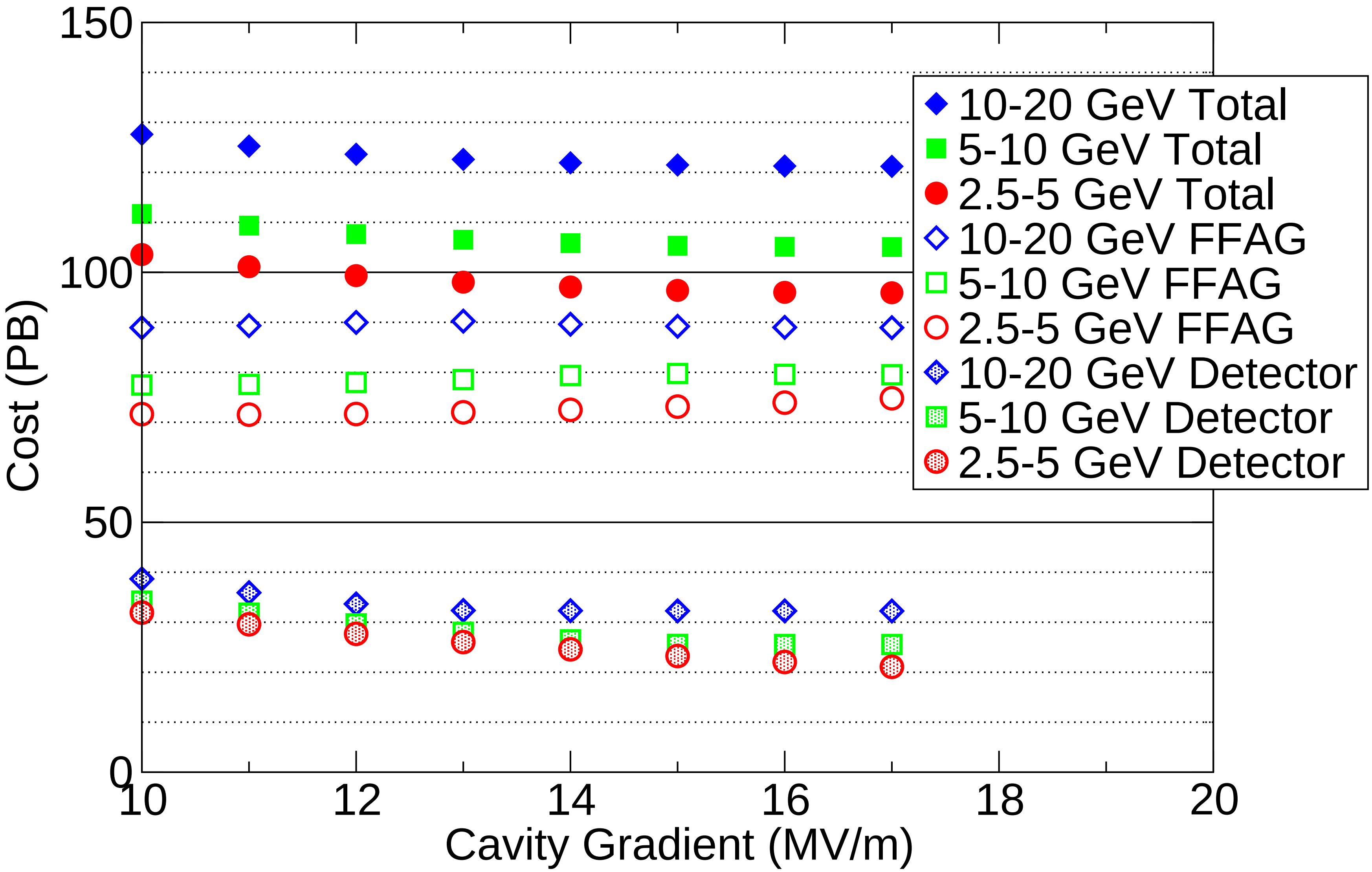
Decay Cost

- The minimum cost rings are extremely long
  - Decays are unacceptably high
- Need to incorporate tradeoff between decays and cost of acceleration into optimization
  - Simplest thinking: can always make detector larger to make up for lost particles
  - Multiply detector cost by fractional loss
  - Over-simplifies things (e.g., as detector gets larger, fractional increase costs more)
  - Baseline: detector costs 500 PB

Cost vs. Gradient

- Relatively weak dependency: higher gradient may not be worth it
  - Assumed structure costs independent of gradient
    - Might need better surface
    - Tougher requirements on input couplers
  - Higher cryo costs
- FFAG cost increases with increasing gradient for low gradients
  - Total cost decreases since detector cost decreases
  - Ring is filled
    - Total voltage increases faster than cost per voltage
    - Ring circumference decreases, increasing ring cost
- Higher gradients, can partially fill ring
  - Roughly same voltage and circumference
  - Fewer cavities

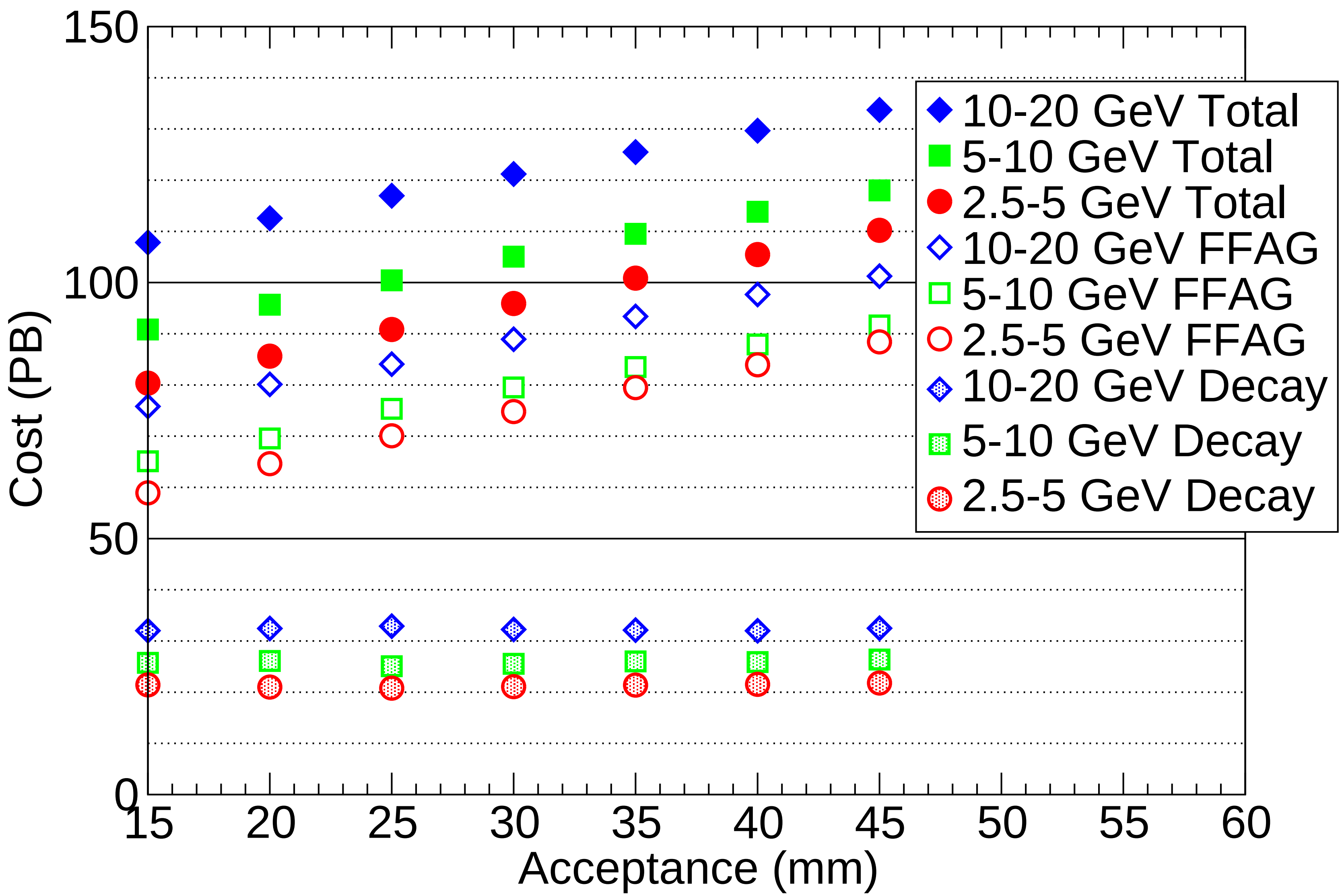
Cost vs. Gradient



Cost vs. Acceptance

- Strong dependence of cost on acceptance
- Primarily caused by increased magnet cost
  - Primarily coming from increased size (length and aperture)
  - Not really coming from increased fields

Cost vs. Acceptance



Another Mind-Numbing Lattice Table

Gradient (MV/m)	10			17		
Minimum total energy (GeV)	2.5	5	10	2.5	5	10
Maximum total energy (GeV)	5	10	20	5	10	20
No. of cells	64	77	91	50	65	82
D length (cm)	54	69	91	63	77	97
D radius (cm)	13.0	9.7	7.3	13.4	10.0	7.4
D pole tip field (T)	4.4	5.6	6.9	4.5	5.7	7.1
F length (cm)	80	99	127	96	113	141
F radius (cm)	18.3	14.5	12.1	21.2	16.3	13.1
F pole tip field (T)	2.8	3.6	4.5	2.7	3.5	4.3
No. of cavities	56	69	83	42	49	56
RF voltage (MV)	419	516	621	534	620	704
Turns	6.0	9.9	17.0	4.7	8.2	15.0
Circumference (m)	246	322	426	204	286	400
Decay (%)	6.4	6.8	7.7	4.2	5.1	6.5
Total cost (PB)	71.6	77.5	88.9	74.8	79.5	88.9
Cost per GeV (PB/GeV)	28.7	15.5	8.9	29.9	15.9	8.9

Analysis of Table

- Acceptance 30 mm
- Compare gradients
  - Machine costs very similar for different gradients
  - Decays significantly lower for higher gradient
    - Fewer turns/higher voltage at higher gradients
    - Smaller circumference at higher gradients
- Pole tip fields are higher than previously
  - Decays force magnets shorter
- 2.5–5 GeV is borderline

Remaining Work for Optimization

- Choice of $V/(\omega\Delta T\Delta E)$ still empirical
  - I have a method of doing this, just haven't finished the calculations
- Work on choice of cavity drift length and inter-magnet drift
  - Let it depend on the magnet fields/apertures? How?
- Choice of aperture: should be coupled to cooling design
  - Can compute cooling cost vs. aperture when muon cost is included
  - Cooling cost decreases with increasing aperture
  - Add cooling cost and acceleration cost vs. aperture
  - Presumably there is an optimum aperture

Conclusions

- I am using an improved cost model from Palmer
- An earlier notion that magnet costs increase with increasing number of cells was wrong. This has been addressed by including decay costs in the model.
- I have a set of lattices which are optimal to my current understanding
- I can produce “optimal” lattices at will for given constraints
- There are always improvements to be made. . .