Acceleration Systems in a Muon Machine

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Muon Collaboration Meeting

Outline

- Introduction to Cost Model
- Study II RLA and motivation for FFAGs
- Optimized FFAG Lattices
- Low-Energy Acceleration
- Electron Model of an FFAG

Modified Palmer Cost Model

$$B_{i\pm} = B_0 \pm B_1 f_R R$$

$$B_{o\pm} = B_0 \pm B_1 R_{o\pm}$$

$$C_\pm = C_{m0} B_{e\pm}^{1.5} R_{o\pm}(L + f_E f_R R)$$

$$f_Q = \frac{|B_{e+} + B_{e-}|}{|B_{e+}| + |B_{e-}|} k_D + \frac{|B_{e+} - B_{e-}|}{|B_{e+}| + |B_{e-}|} k_Q$$

$$C_{\mathrm{mag}} = (C_+ + C_-)(n_0/n)^{1/3} f_A f_Q/2$$

$$R_{o\pm} = f_R R + t_C |B_{i\pm}|$$

$$B_{e\pm} = \begin{cases} B_{i\pm} & |B_{i\pm}| \geqslant |B_{o\pm}| \\ B_{o\pm} & |B_{i\pm}| < |B_{o\pm}| \end{cases}$$

$$C_{\mathrm{rf}} = k_C V G_0/G + k_P V G/G_0$$

$$C_{\mathrm{lin}} = C_L L_R$$

- Costs C_{mag} (magnets), C_{rf} (RF), and C_{lin} (linear)
- n magnets, magnet radius is $f_R R$, magnet length is L, central field is B_0, gradient is B_1
- Total installed voltage is V, RF gradient is G, ring length is L_R
- PB is our cost unit, the "Palmer Buck"

f_R	1.3	t_C	2 mm	C_{m0}	22.5 mPB/T$^{1.5}$/m^2	f_E	20
k_D	1	k_Q	1.5	n_0	300	f_A	1.5
k_C	30 PB/GV	k_P	26.8 PB/GV	G_0	16 MV/m	C_L	25 mPB/m

Motivation for FFAGs

- Acceleration was a substantial fraction of the Study II cost
- Study II RLA cost 386 PB, or 22.0 PB/GeV
  - 263 PB in RF, 123 PB in magnets+linear costs
  - Cost minimum is when these are equal
  - Want to go more turns to reduce cost
  - Switchyard prevents more turns
- FFAG addresses this problem
  - Can go many turns, no worry about switchyard
  - Longitudinal acceptance does limit number of turns

FFAG Lattice Cost Optimization

- Non-Scaling FFAG lattices designed to same design parameters

RF frequency	201.25 MHz	Voltage per cavity	7.5 MV
RF drift length	2 m	Short drift length	0.5 m
Minimum energy tunes	0.35	Normalized acceptance	30 mm

- Note acceptance larger than Study II: more muons/less cooling
- RF drift needed to keep fields low enough at SC cavities
- Short drift is space needed between doublet/triplet magnets
- Minimize cost by varying magnet lengths (pole tip fields)
- Compare different lattice types: triplet, doublet, FODO
- Look at different energy ranges

10–20 GeV Cost Optimized FFAGs

Type	FDF	FD	FODO 1 RF	FODO 2 RF
Cells	108	113	127	91
D Length (cm)	175	137	130	139
D Radius (cm)	10.2	8.7	9.7	10.1
D Pole Tip (T)	4.4	4.6	4.0	4.8
F Length (cm)	118	221	213	256
F Radius (cm)	11.9	13.8	15.5	19.3
F Pole Tip (T)	2.4	2.3	1.9	1.9
RF Voltage (MV)	811	849	950	1362
Circumference (m)	768	688	941	722
Magnet cost (PB)	39	34	33	38
RF cost (PB)	53	55	62	88
Linear cost (PB)	19	17	24	18
Total cost (PB)	111	106	118	144

- Modest (but SC) pole tip fields
- Doublet slightly less expensive than triplet
  - Triplet has lower RF cost: lower time-of-flight for given cell length
  - Triplet magnets are more expensive: quantity
- FODO is worst

Cost Optimized FFAGs: Doublet

Min Energy (GeV)	1.25	2.5	5	10
Max Energy (GeV)	2.5	5	10	20
$V/\omega\Delta T\Delta E$	1/4	1/6	1/8	1/12
Cells	93	85	98	113
D Length (cm)	59	105	119	137
D Radius (cm)	20.4	15.9	11.7	8.7
D Pole Tip (T)	2.0	2.3	3.3	4.6
F Length (cm)	106	160	188	221
F Radius (cm)	25.3	21.5	16.9	13.8
F Pole Tip (T)	1.3	1.2	1.7	2.3
RF Voltage (MV)	700	636	733	849
$\Delta E/V$	1.8	3.9	6.8	11.8
Circumference (m)	387	436	545	688
Magnet cost (PB)	31	23	27	34
RF cost (PB)	45	41	47	55
Linear cost (PB)	10	11	14	17
Total cost (PB)	86	76	88	106
Cost per GeV (PB)	69.1	30.2	17.6	10.6

- Cost per GeV rises rapidly as energy decreases
- $\Delta E/V$ also decreases at lower energies
- Advantage of 2.5–5 GeV FFAG over RLA doubtful
- 1.25–2.5 GeV FFAG no good
  - High cost per GeV (almost linac!)
  - Very low $\Delta E/V$
- 2.5–20 GeV with FFAGs is 269 PB, vs. 386 PB for RLA
  - Not counting transport, injection/extraction

Future Work

- Since low pole tip fields, maybe reduce magnet-cavity space
- Look at tighter magnet spacings
- Cost vs. transverse, longitudinal acceptance
  - Reduce transverse acceptance from 30 mm to 15 mm, 10–20 GeV is 90 PB, 5–10 GeV is 73 PB: 16% cost reduction
- Simulation (dynamic aperture, coupling)

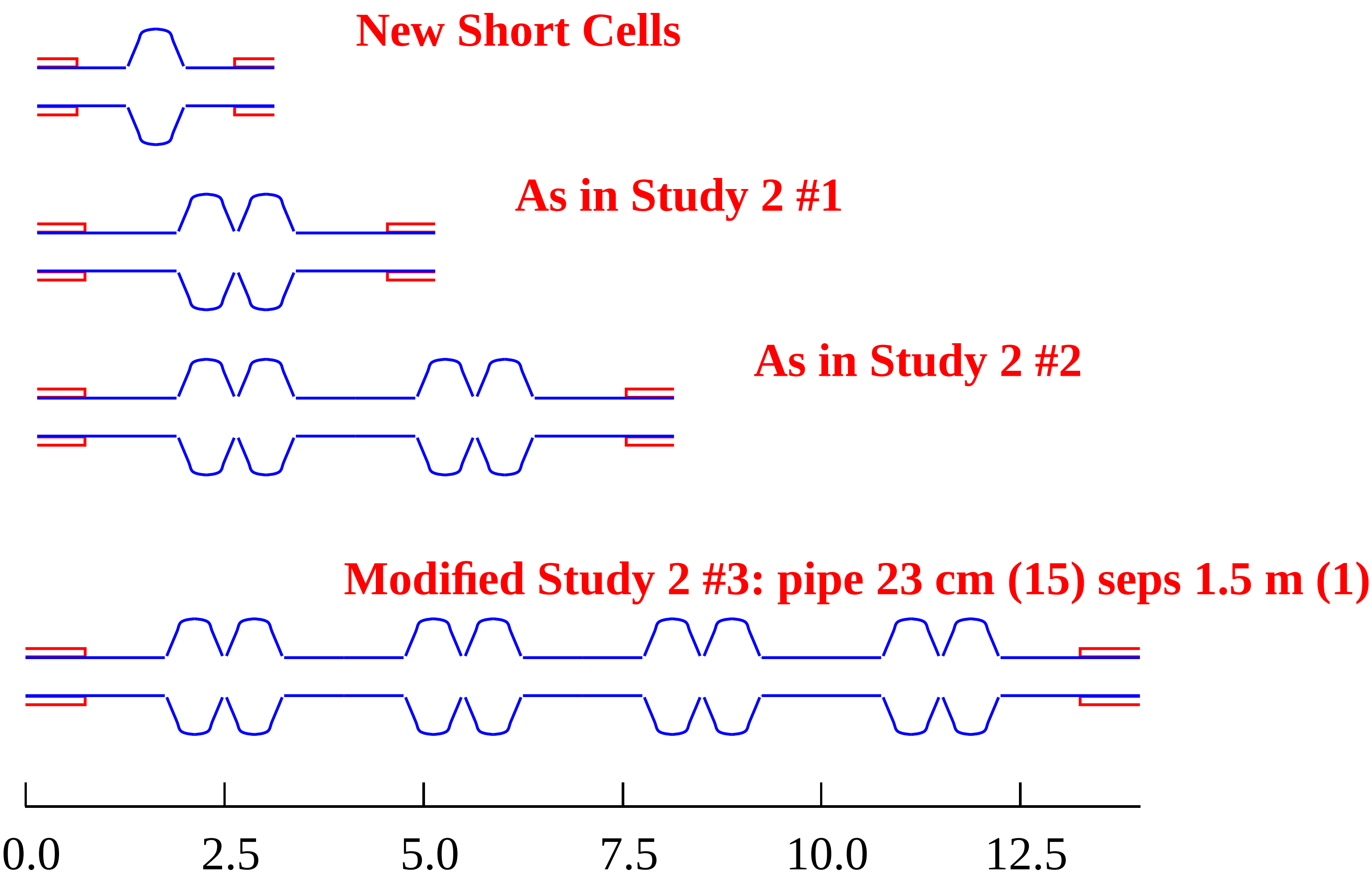
Low-Energy Acceleration

- Work mostly by Palmer
- FFAGs look good for accelerating from 5–20 GeV
- Below that, need two stages
  - Linac to accelerate beam until it can be injected into
    - Keep as short as possible: expensive, don't re-use RF
    - Try only to 1.5 GeV (2.5 GeV in Study II)
  - RLA to get to 5 GeV

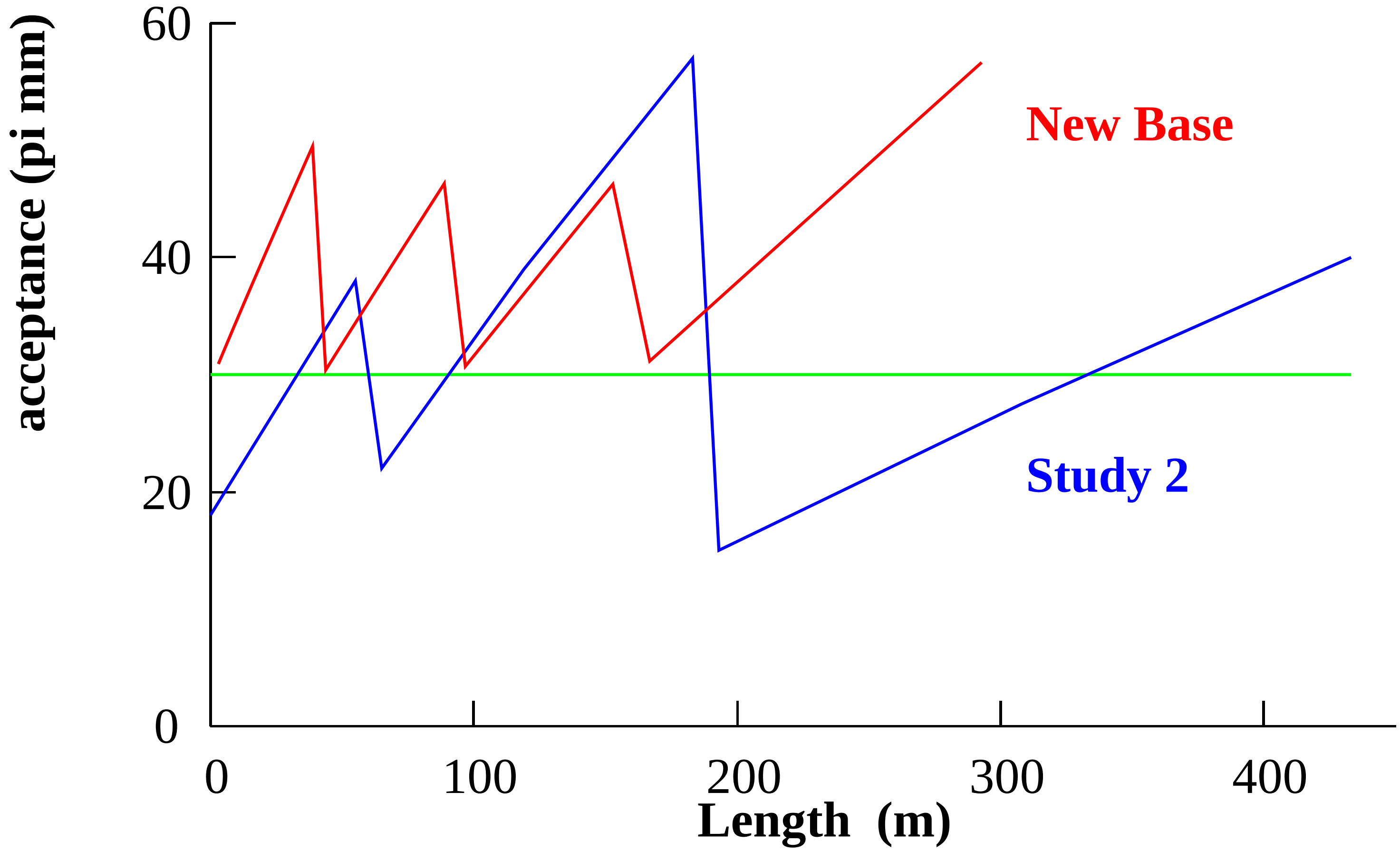
Initial Linac

- Increase acceptance to 30 mm normalized
  - Need shorter cells at beginning
  - Increase aperture at high-energy end

Initial Linac (cont.)



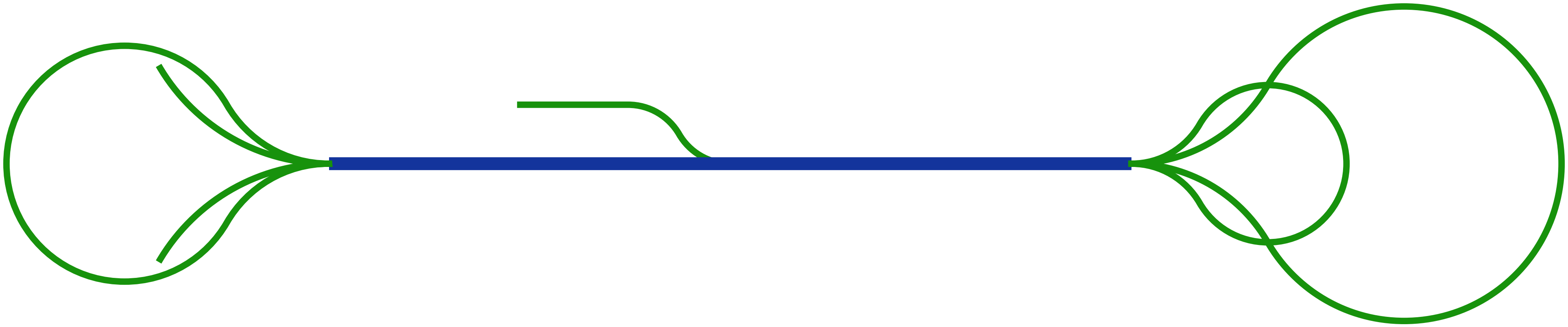
Initial Linac (cont.)



Recirculating Accelerator

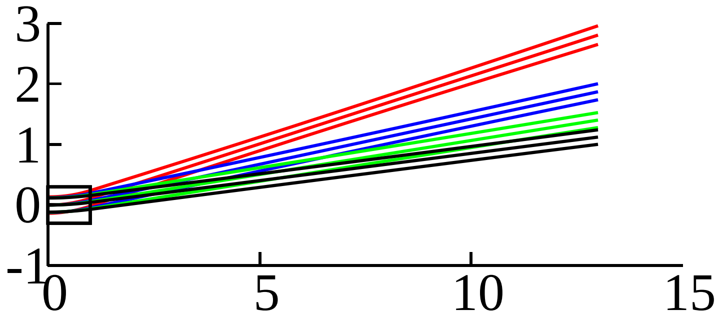
- Can do racetrack or dogbone shape
  - Dogbone has simpler switchyard
- Example with 1 GeV of linac
  - Total of RF in linac plus RLA is same as Study II linac
  - May be even less expensive if more RLA passes
- Keep quad gradients constant along linac
  - Necessary for dogbone
  - Beta functions rise as accelerate, but beam size about constant
  - May make match easier
  - Arcs trickier (cell phase advance, dispersion match)
- Velocity at low energy different from high energy
  - RF phase slip along linac, go off crest
  - Dogbone: long linac, inject in middle

Recirculating Accelerator (cont.)

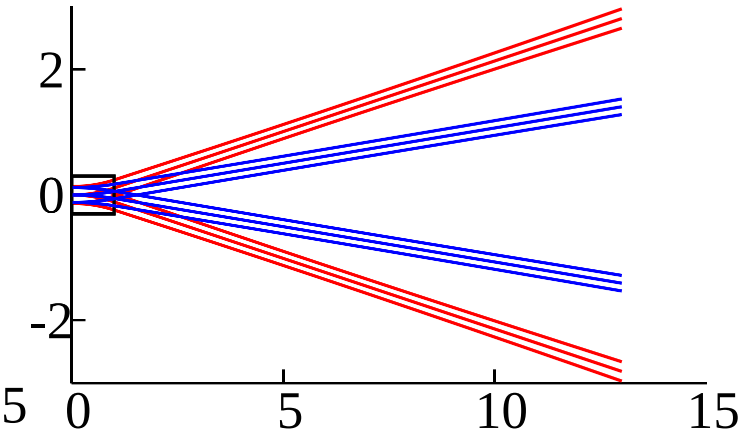


Recirculating Accelerator (cont.)

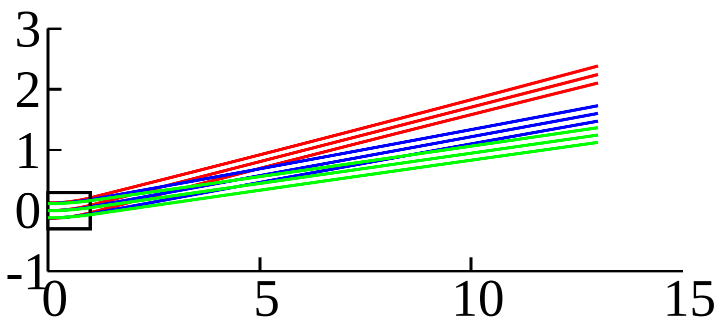
Racetrack End 1



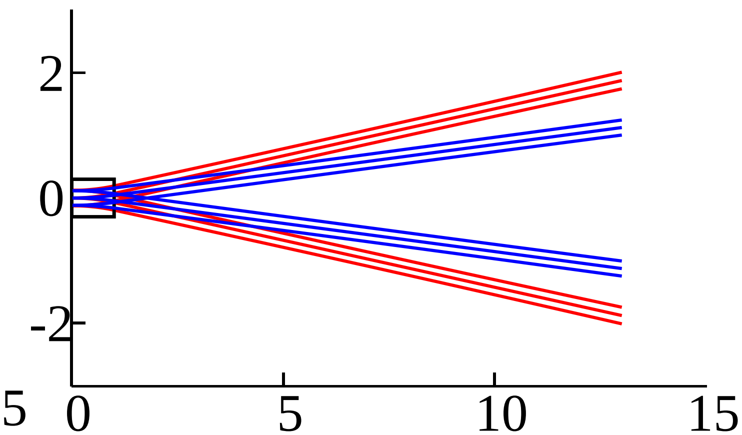
Dogbone End 1



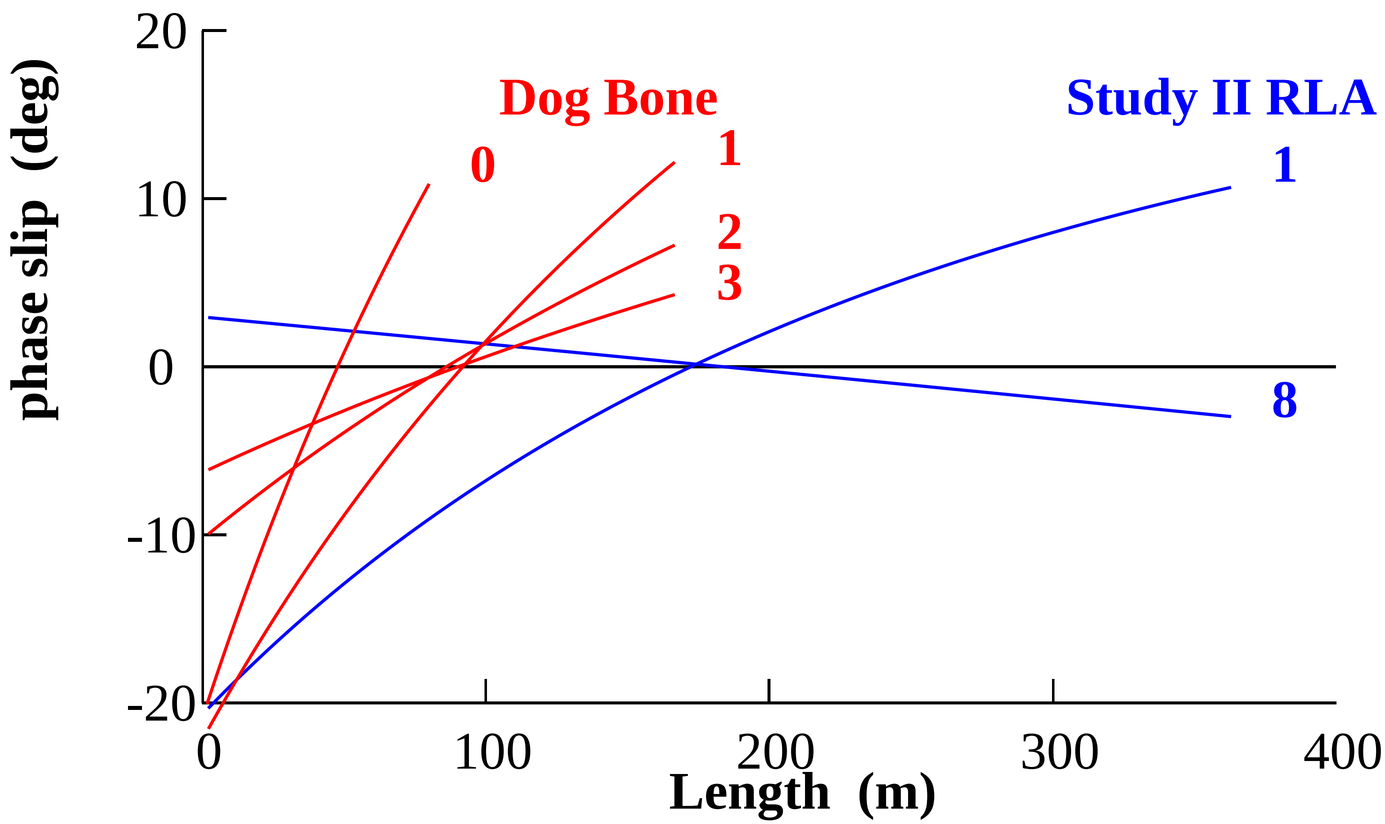
Racetrack End 1



Dog End 2



Recirculating Accelerator (cont.)



Work to be Done: Low-Energy Acceleration

- Everything is very preliminary: more careful work
- Design arcs: has been problematic for dogbone
- Choose number of passes: cost
- Simulation

Electron Non-Scaling FFAG Model

- No non-scaling FFAG has ever been constructed
- Test dynamics in such a ring
  - Acceleration as for muon acceleration
  - Test a range of values for $V/\omega\Delta T\Delta E$
  - Slow resonance crossing
- Keep cost low: small ring, use electrons, low energy

Electron Model Parameters

- 10–20 MeV
- Use 3 GHz RF
  - Power readily available
  - Compact size (5 cm half wavelength)
  - Could try 1.3 GHz, but looks worse overall: everything larger
  - Only need modest gradients
  - One klystron is overkill. Complex waveguide system to deliver power to multiple cavities
- Low-frequency RF system (about 20 MHz) to test resonance crossing

Electron Model Parameters (cont.)

- 5 cm between objects: enough space for your fingers
- Low pole-tip fields: 0.2 T or so. Easily achieved.
- Magnet sizes are a few cm.
- Circumferences typically in the 10–15 m range
- Several people have designs (Johnstone, Keil, Trbojevic, me)

Conclusions

- We have a plan to achieve significant cost savings in acceleration over Study II
- We have produced cost optimized FFAG designs
- FFAGs don't work well for low energy
  - Use a linac plus RLA
  - We have a design idea for these
- We are considering building a small electron model of a non-scaling FFAG to demonstrate the concept