CBETA
Cornell-BNL ERL Test Accelerator

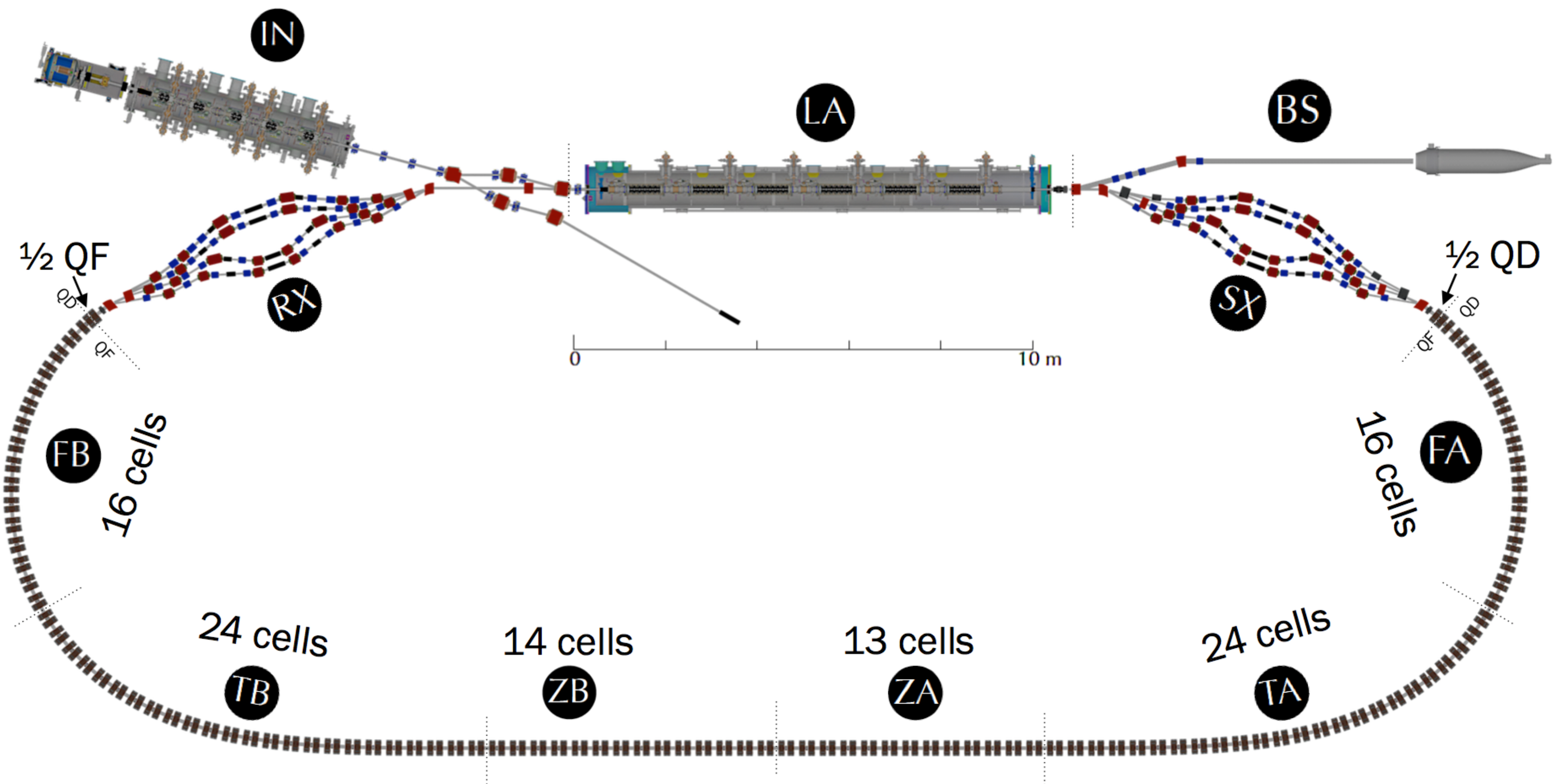
BROOKHAVEN NATIONAL LABORATORY

CBETA: FFAG Beamline Design

J. Scott Berg
Brookhaven National Laboratory
FFAG17 Workshop
September 9, 2017

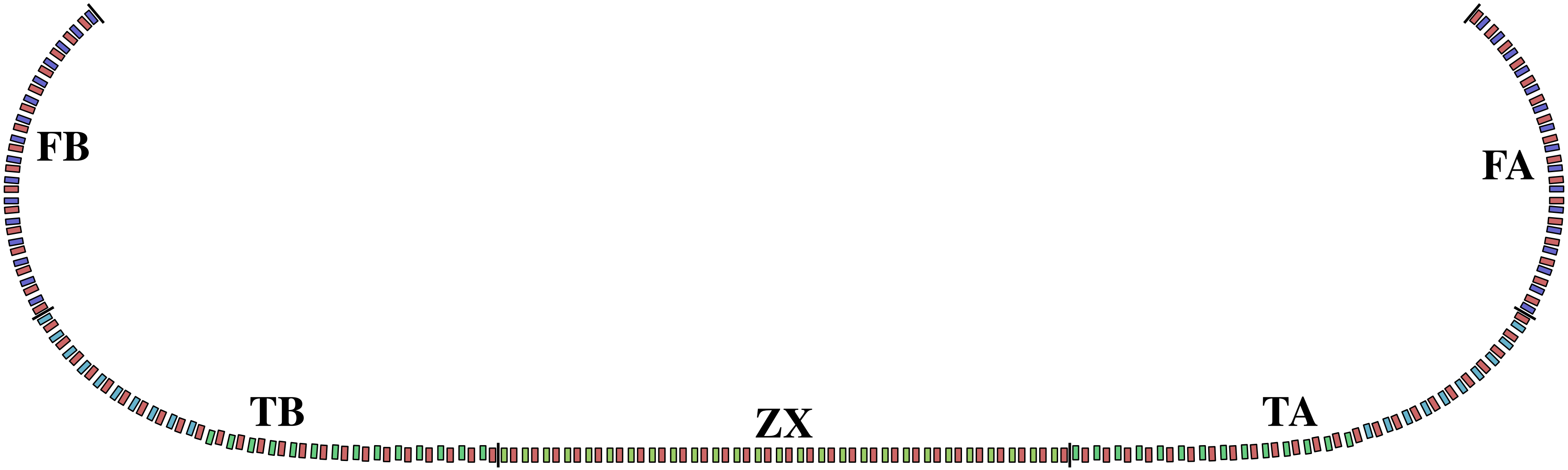
U.S. DEPARTMENT OF ENERGY
Office of Science

Overview



- Discussing FFAG return loop: FA, TA, ZA, ZB, TB, FB

Three Sections



- Arc (FA/FB): turns the beam around; small radius of curvature to keep machine compact
- Straight (ZX): covers distance to linac, needed due to linac, compaact arcs
- Transition (TA/TB): adiabatically change from arc to straight

Parameters

Energies (MeV)	42, 78, 114, 150
Radius of curvature, arc (m)	≈ 5
Minimum long drift (m)	123
Minimum short drift (mm)	66
Focusing quad length (mm)	133
Defocusing quad length (mm)	122
Integrated F gradient (T)	-1.538
Integrated D gradient (T)	1.360

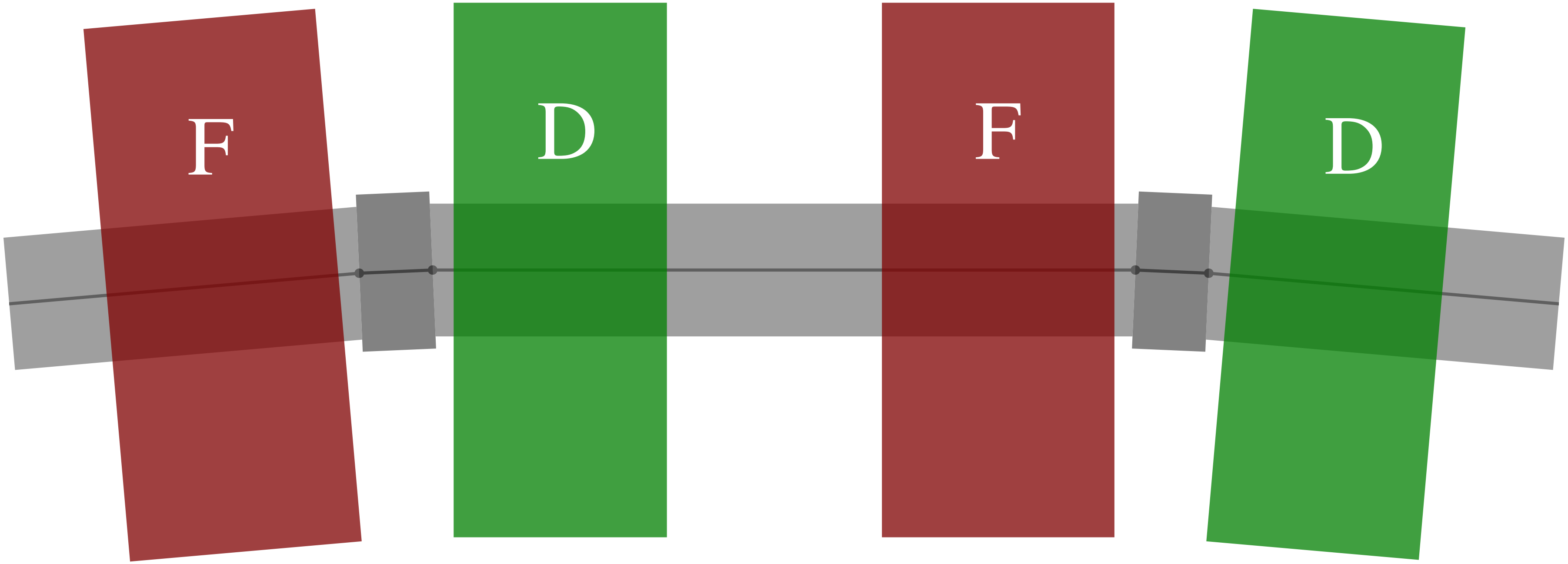
FFAG

- We use linear magnets
  - Huge transverse acceptance
  - Magnet fields stay reasonable (vs. nonlinear magnets)
  - Consequence: tune varies with energy
- Orbit mismatch in the presence of chromaticity leads to emittance growth
  - Orbit correction important: we have dipole (F normal, D skew) correctors on every magnet, BPMs in every cell
  - Multiple beams passing through same magnets and correctors complicates this
  - Keep random variation of magnet fields small
  - Orbit matching should be right in design

Arc Section

- Arc cell is basic building block
- Ideally use repeated arc cell everywhere
- Space considerations prevent this

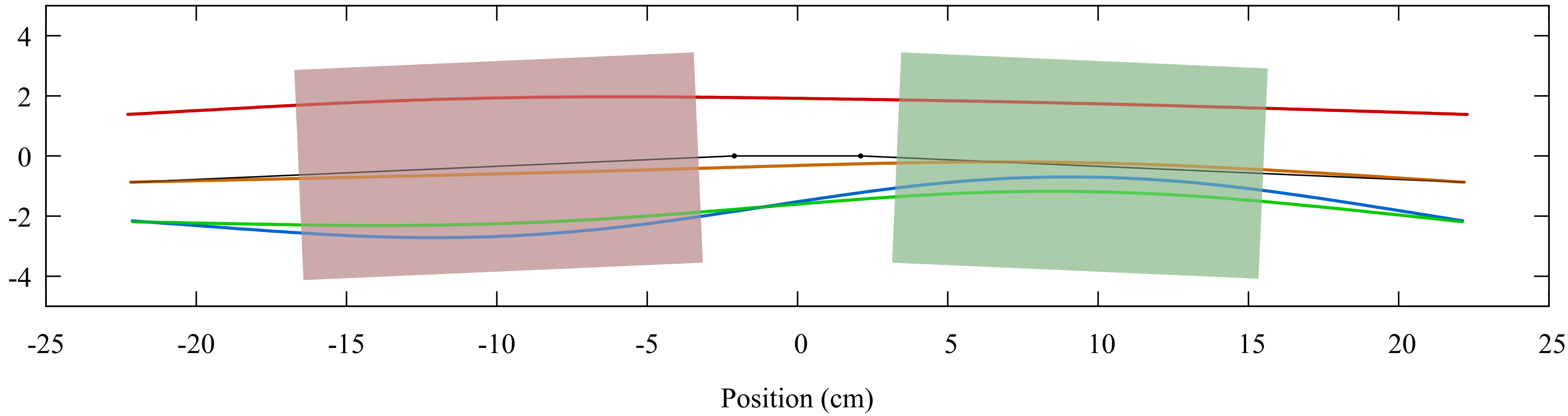
Cell Structure



- Doublet cell, “long” drift for sundry hardware
- Short drift can hold BPM block
- Focusing magnet quadrupole centered in pipe
- Defocusing magnet linear combined-function

Orbits

- Orbits at design energies (42, 78, 114, and 150 MeV):

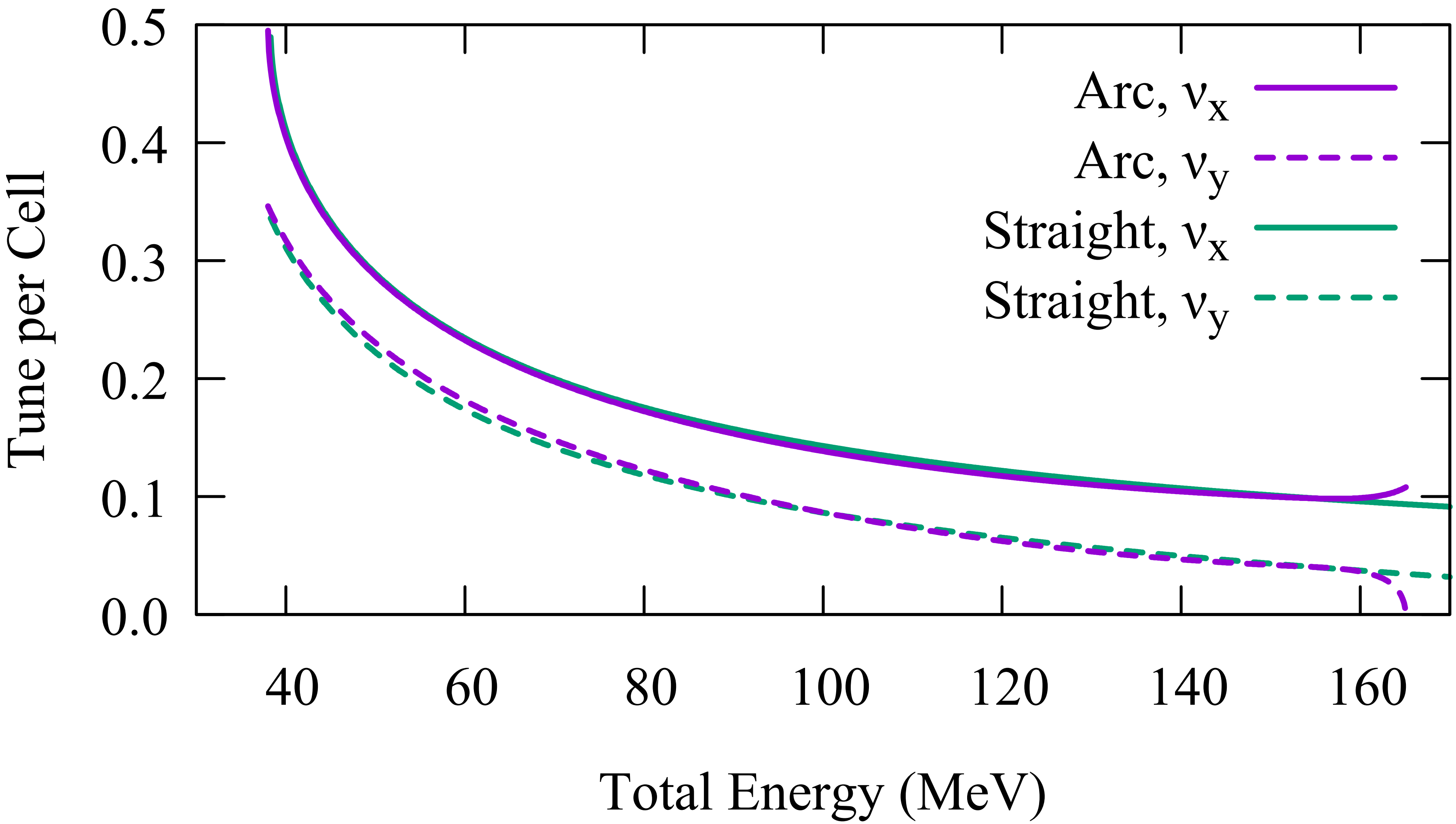


- Magnets short with relatively large aperture: use field maps for most calculations

Tune per Cell

- Linear magnets: tune varies with energy
- Low energy, stay clear of half integer
- Horizontal tune higher: strong focusing to reduce orbit excursions
- High energy limits
  - Lower horizontal tune, focusing doesn't compress orbits: wide aperture
  - Vertical can become unstable

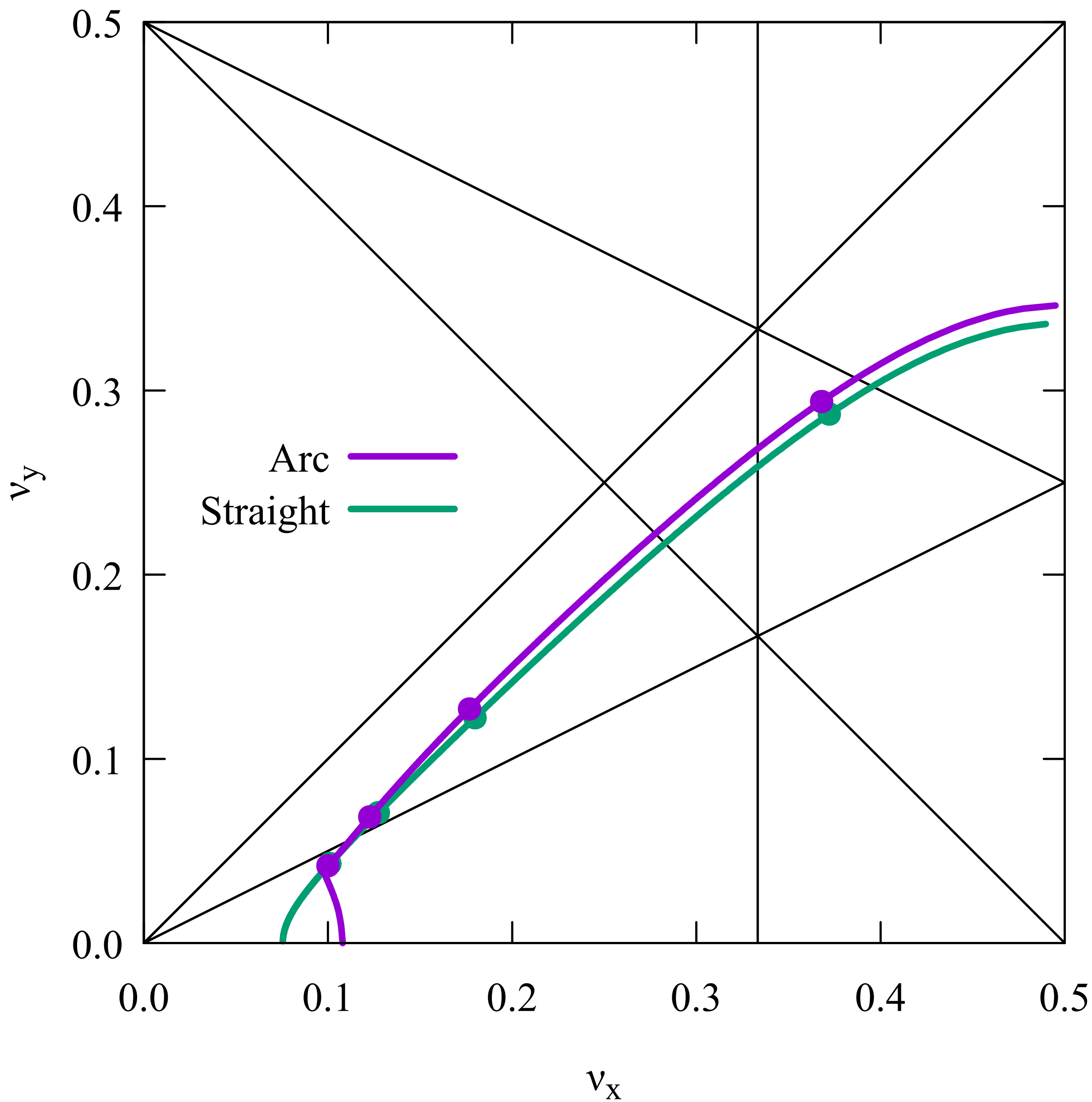
Tune per Cell



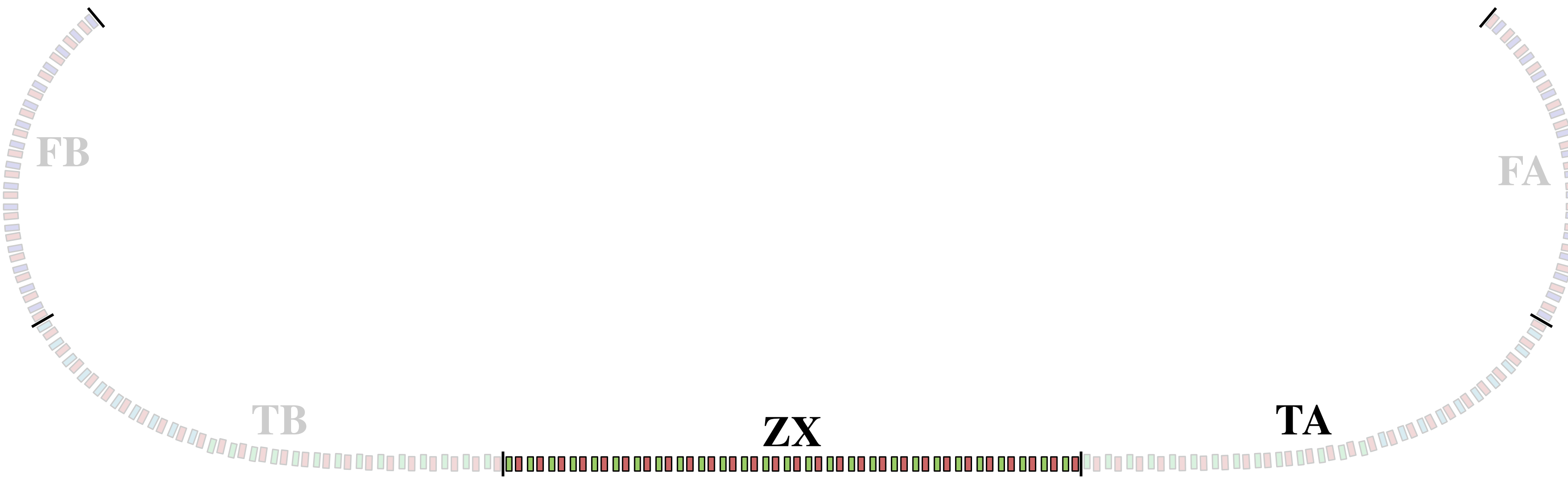
Tune per Cell

- Avoid emittance growth, stay clear of low order nonlinear single-cell resonances
- Working point chosen so that
  - Distance of low energy from $\nu_x + 2\nu_y = 1$ is same as distance of high energy from vertical instability
  - "Distance" defined in terms of minimum required fractional change in gradients to reach the line in question
  - Distance is about 3%
  - Also, keep 114 MeV and 150 MeV points equidistant from $\nu_x - 2\nu_y = 0$
    - Only about 1%, but this line is less important

Tune per Cell

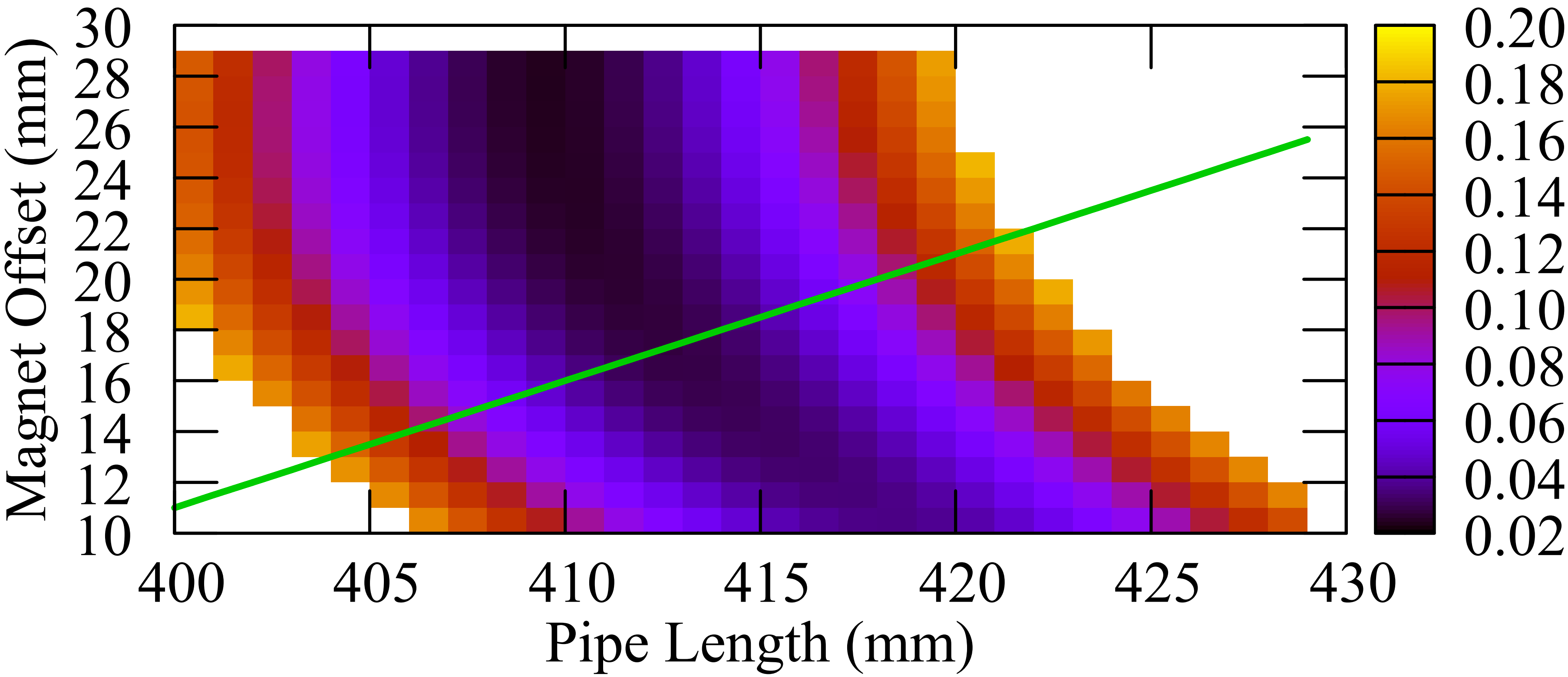


Straight



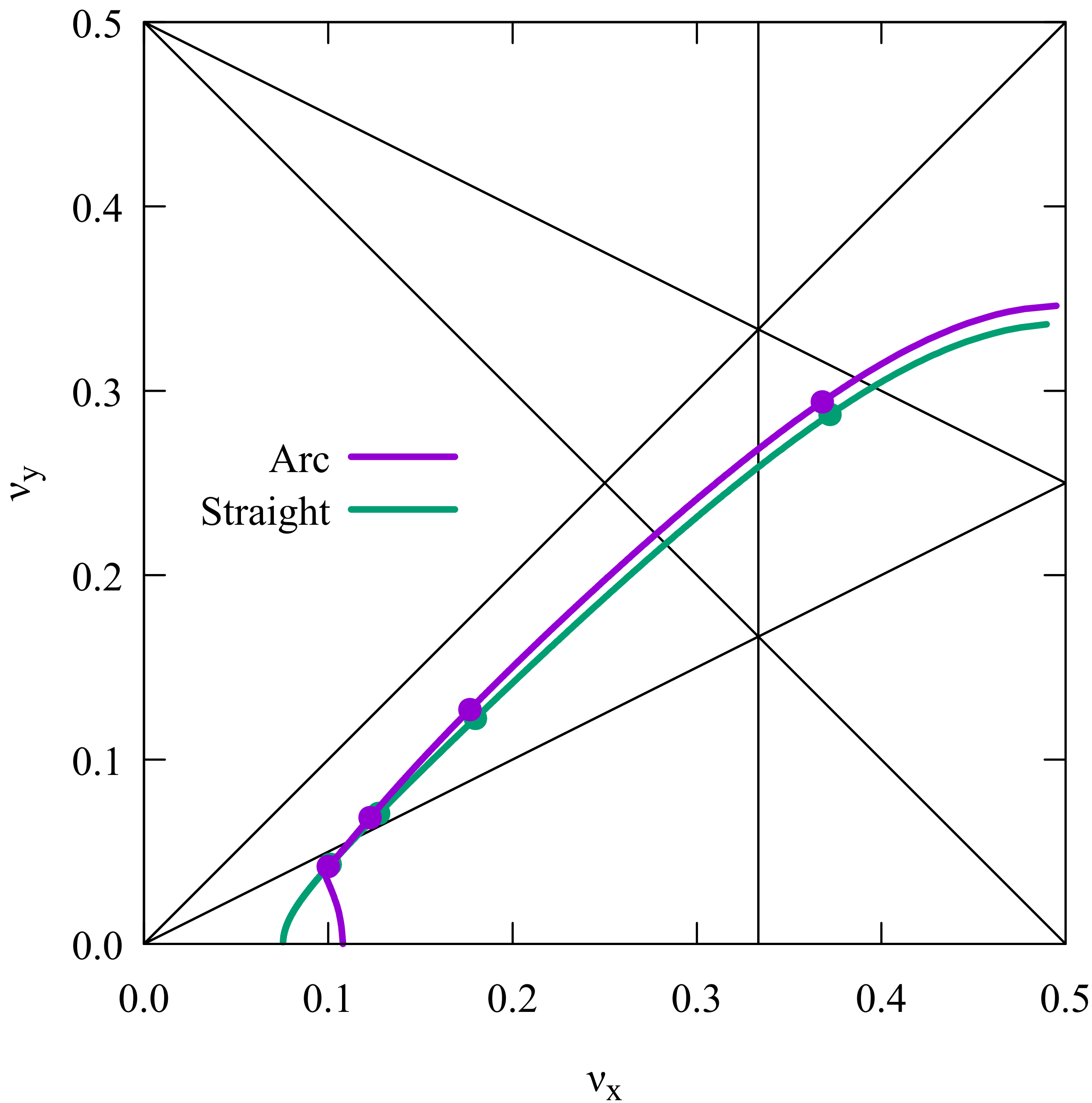
- Needed due to compact arcs
- Integrated gradients same as arc (makes transition work)
- Match tunes as best as possible: avoid resonance crossing, keep good match
- Adjust drifts for match

Straight



- Scan drift lengths, minimize tune difference
- Keep long drift at least as long as in arc
- Can’t make match perfect, but close
- Result: short drift 66 mm (arc) to 77 mm (straight)

Straight



Transition

- Smoothly vary bend angle, dipole field, drift lengths in cells from arc to straight
- Integrated gradients same for all magnets
- Adjust dipole field by shifting magnets
- Goal: orbits for full 42–150 MeV energy range end up on axis in straight

Transition

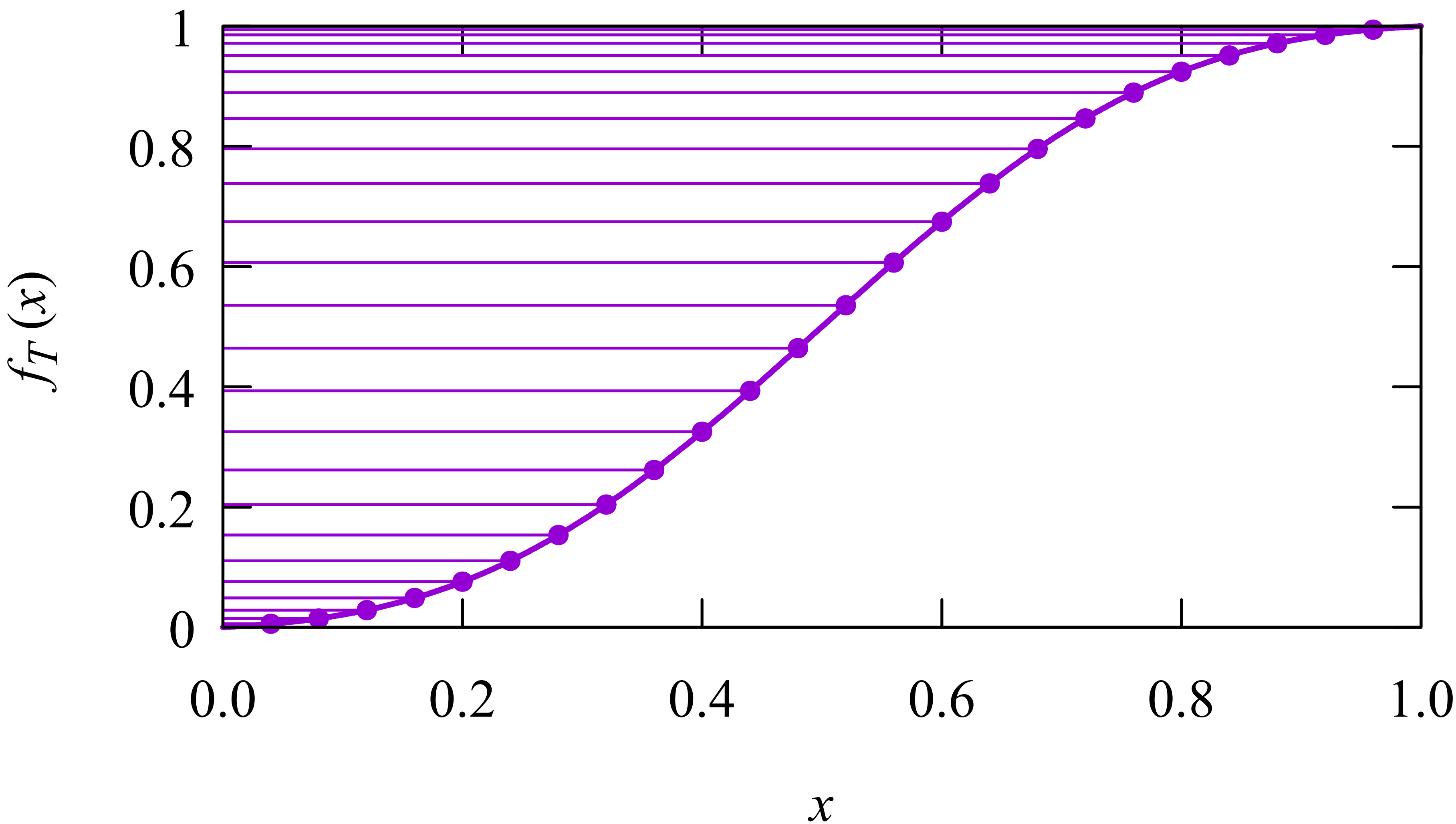
- Parameters follow smooth function, adjust coefficients for best orbit match

$$p_i = \left[1 - f_T\left(\frac{i}{n_T+1}\right)\right] p_{\mathrm{arc}} + f_T\left(\frac{i}{n_T+1}\right) p_{\mathrm{str}}$$

$$f_T(x) = \frac{1}{2} + \left(x - \frac{1}{2}\right) \sum_{k=0} a_k \binom{2k}{k} x^k (1-x)^k$$

  - $a_0 \ldots a_n$=1, n continuous derivatives at ends
  - $f_T(1-x) = 1 - f_T(x)$
- More adiabatic at ends if better continuity, but more continuity makes center steeper
- Parameters varied: drift length, angle, dipole component in defocusing quad

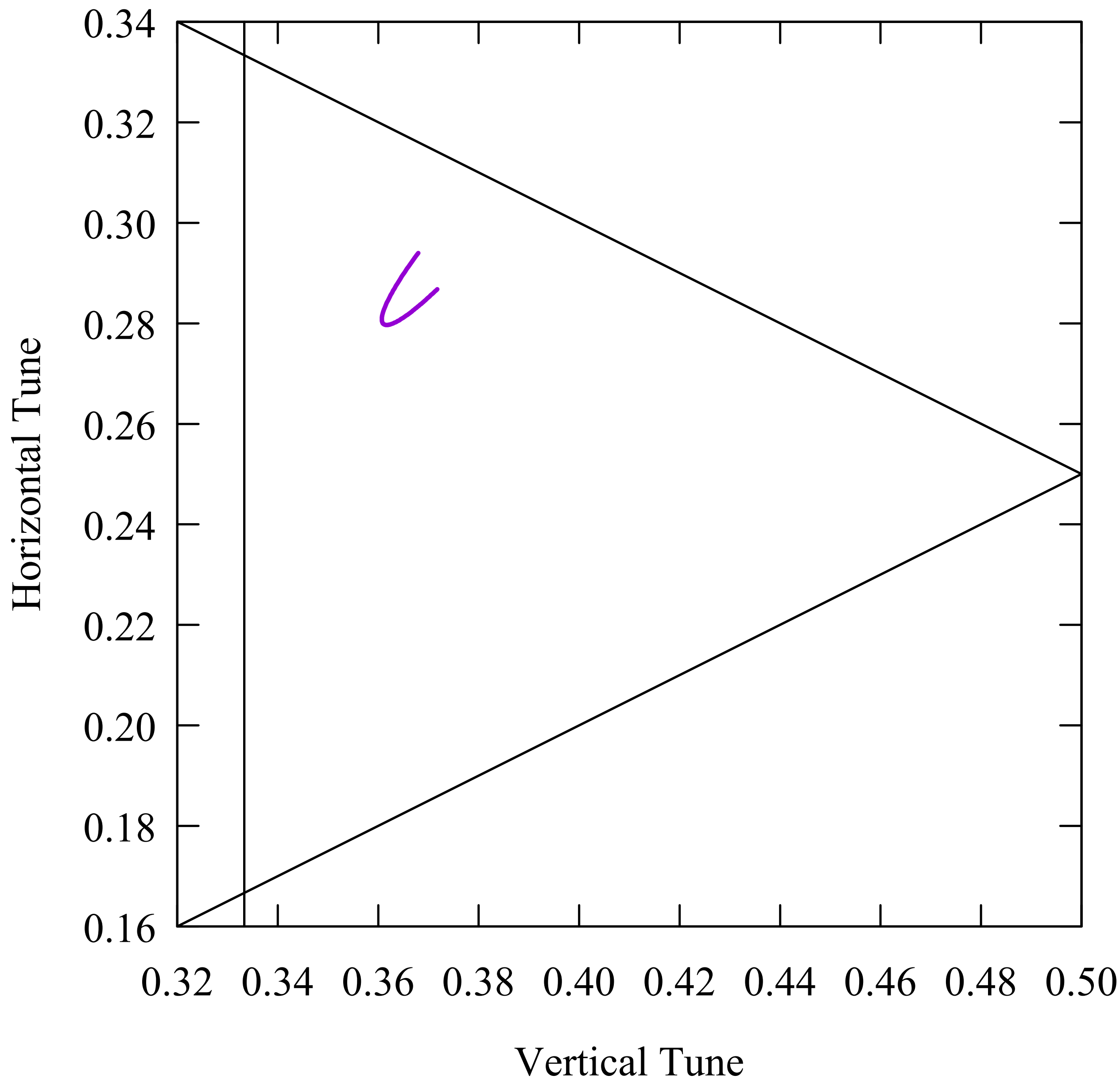
Transition



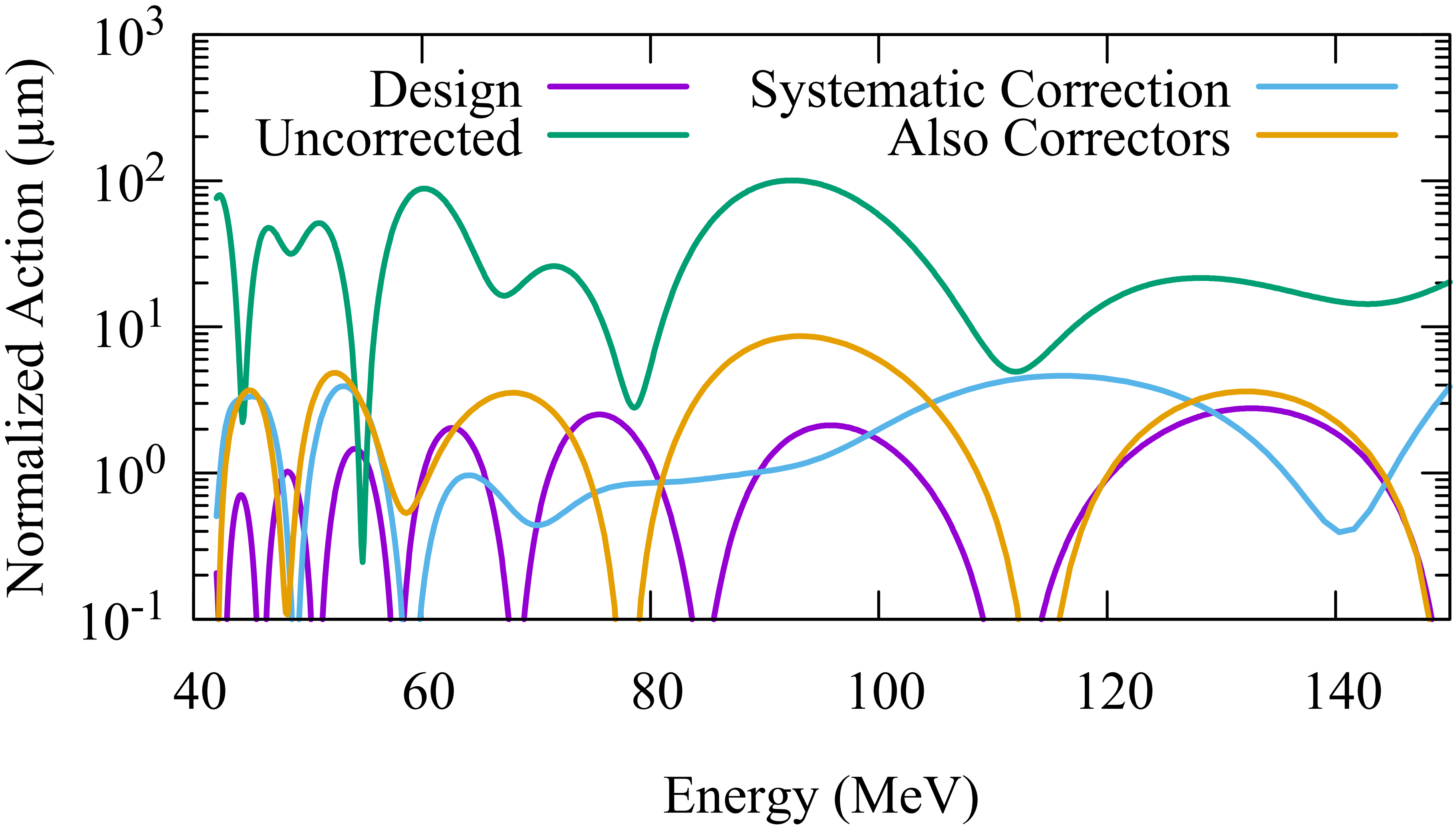
Transition

- Cell tunes move a bit
  - Could make a straight line from arc to cell, but fit is worse
  - Reason: to minimize tune change, dipole field goes quadratically with angle; makes behavior non-adiabatic at one end
- Computed using hard-edge approximation for speed
- Track closed orbit in arc to straight, plot invariant action (compare to emittance) in straight cell space
- Adjust a_k to minimize action for all of 42–150 MeV, maintaining low energy adiabaticity
- Use correctors to get exactly right at design energies
- Transition insures only weak correctors needed

Transition


0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
Horizontal Tune
0.32 0.34 0.36 0.38 0.40 0.42 0.44 0.46 0.48 0.50
Vertical Tune

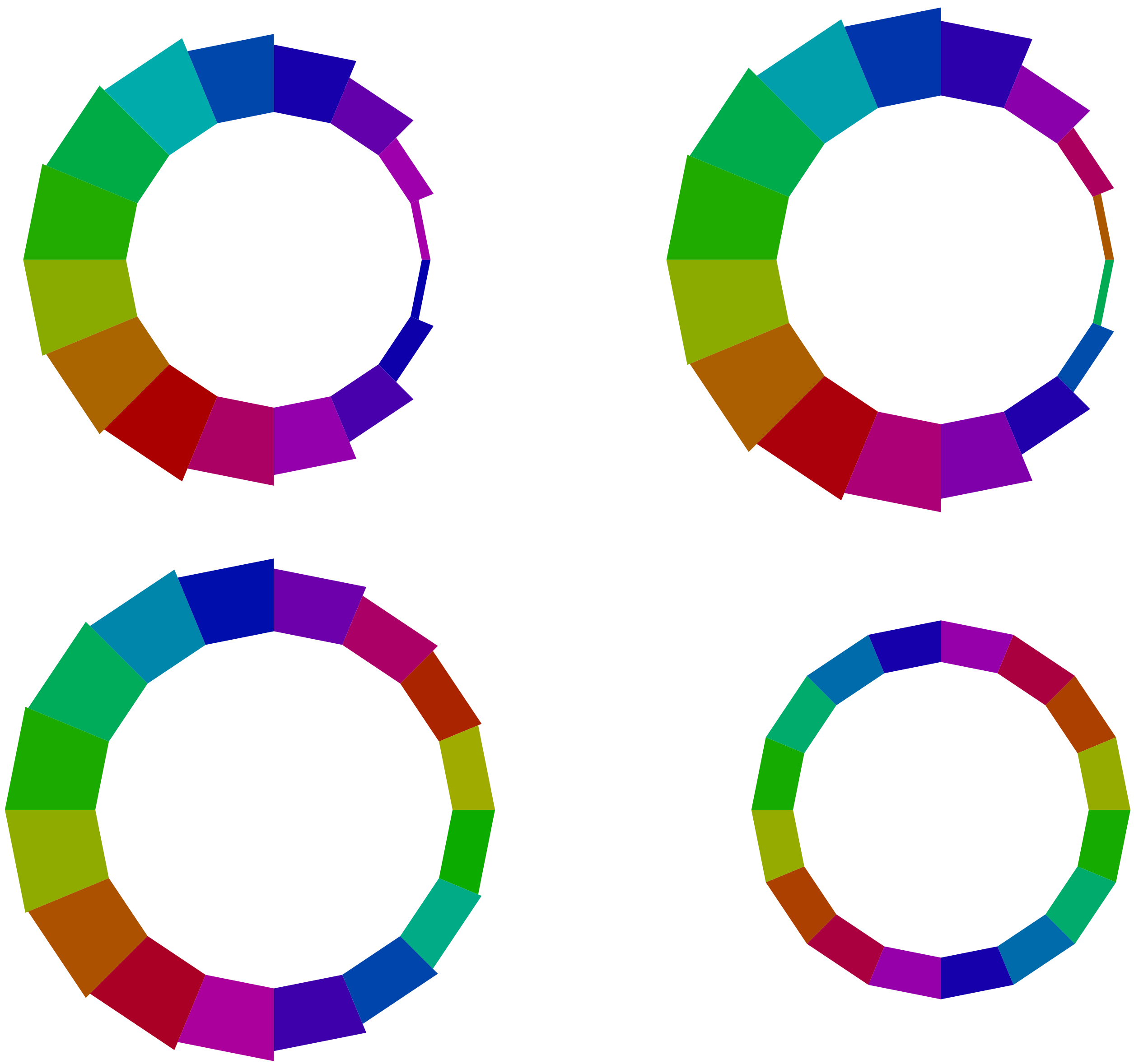
Transition


Design
Uncorrected
Systematic Correction
Also Correctors
Normalized Action (µm)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
40
60
80
100
120
140
Energy (MeV)

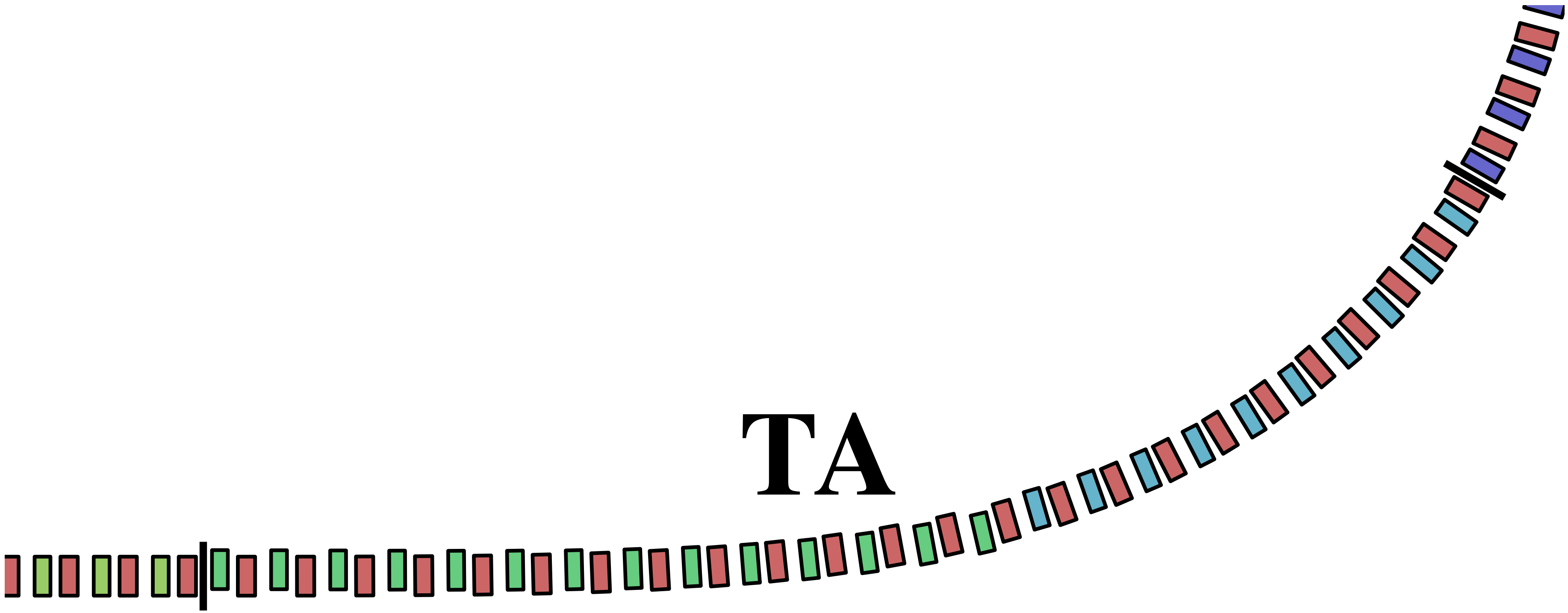
Magnet Types

- Same focusing quadrupole (QF) used everywhere, centered on beam pipe
- Permanent magnet Halbach designs, with corrector coils
- Four types of combined-function defocusing magnets used
  - Same gradient, varying dipole field at center
  - BD in arc
  - BDT2 (10) and BDT1 (14) in transition; shift horizontally within their range
  - QD (pure quadrupole) in straight
- When use real magnets, transition works poorly

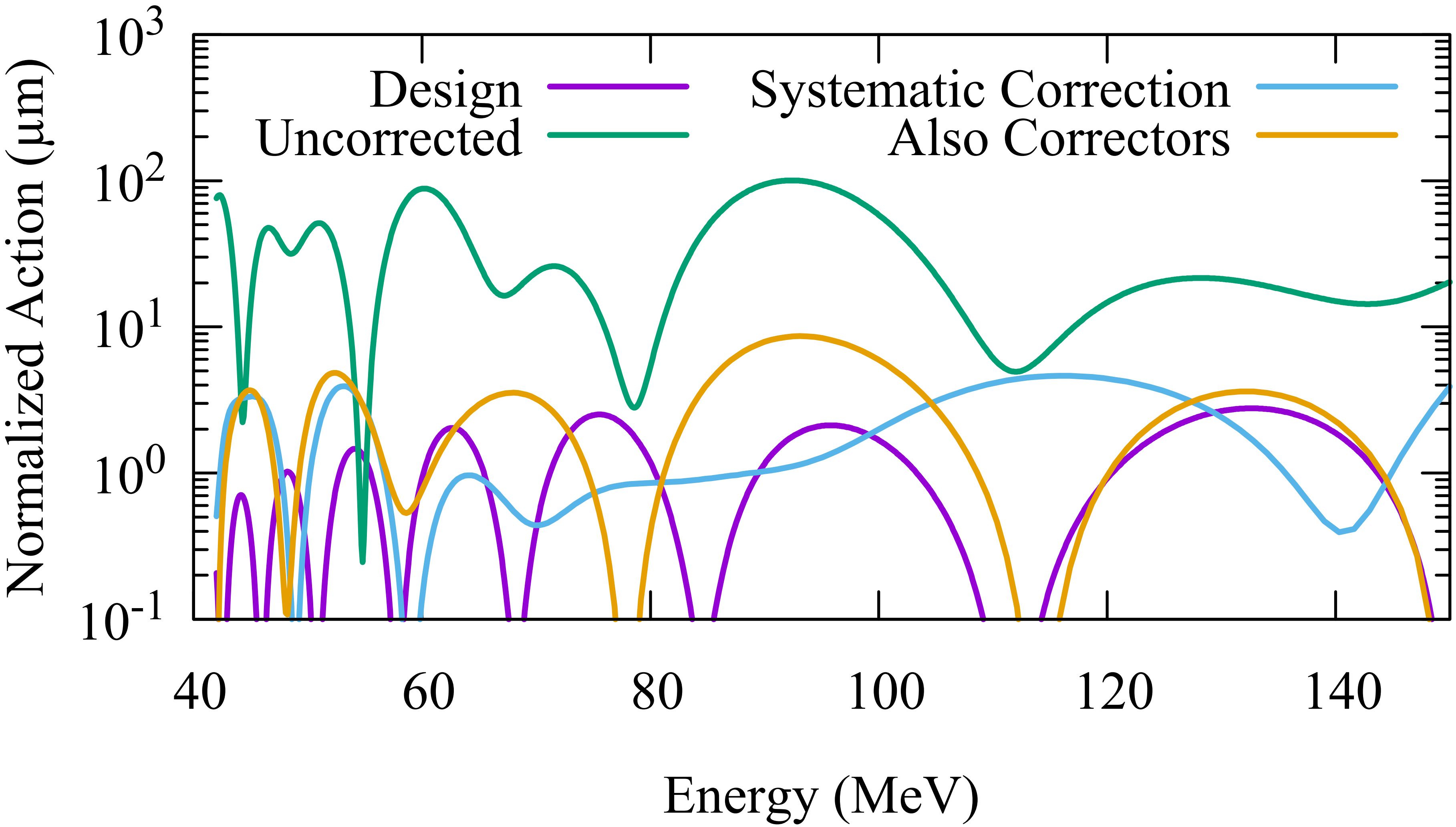
Magnet Types



Magnet Types



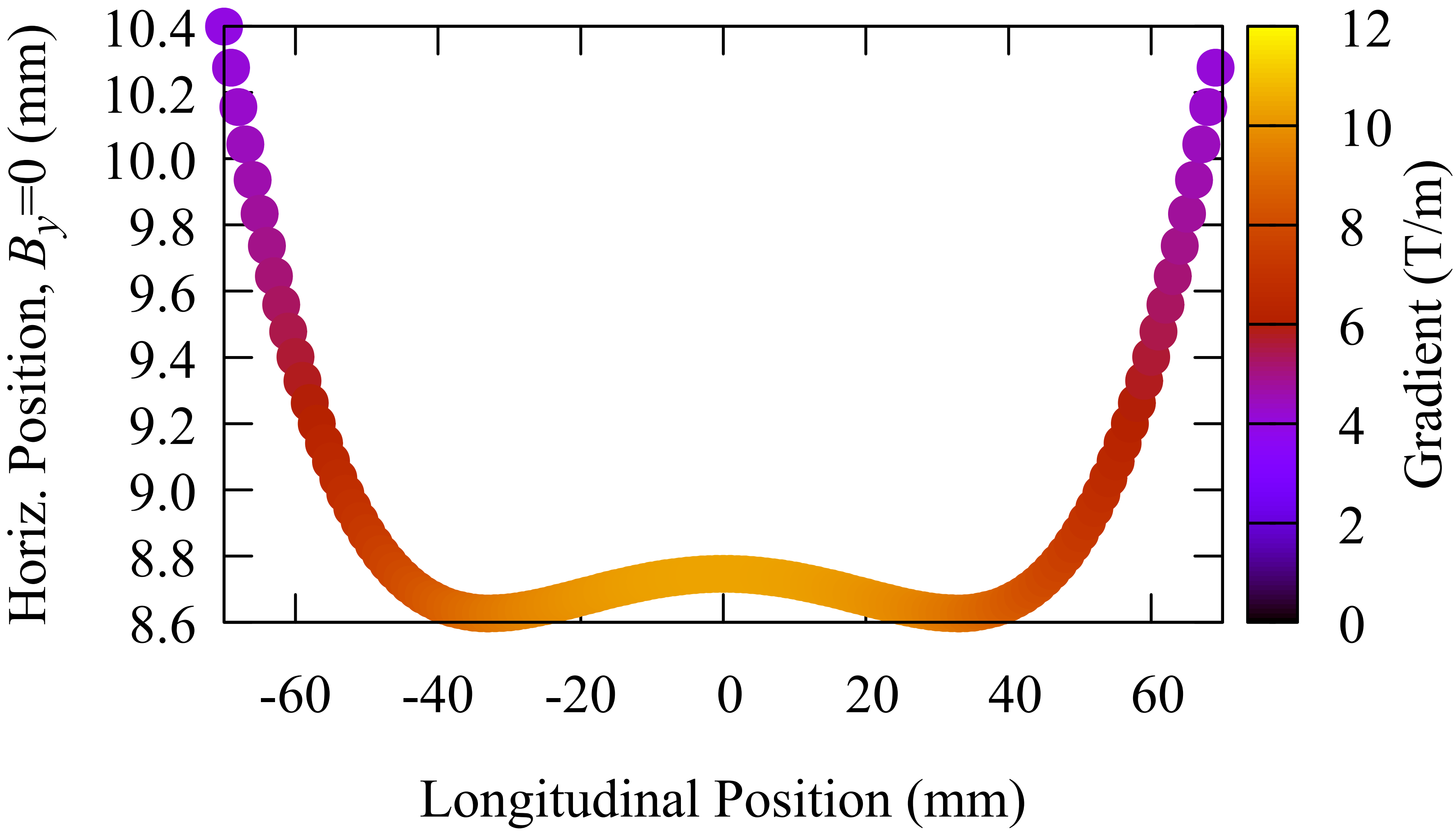
Magnet Types



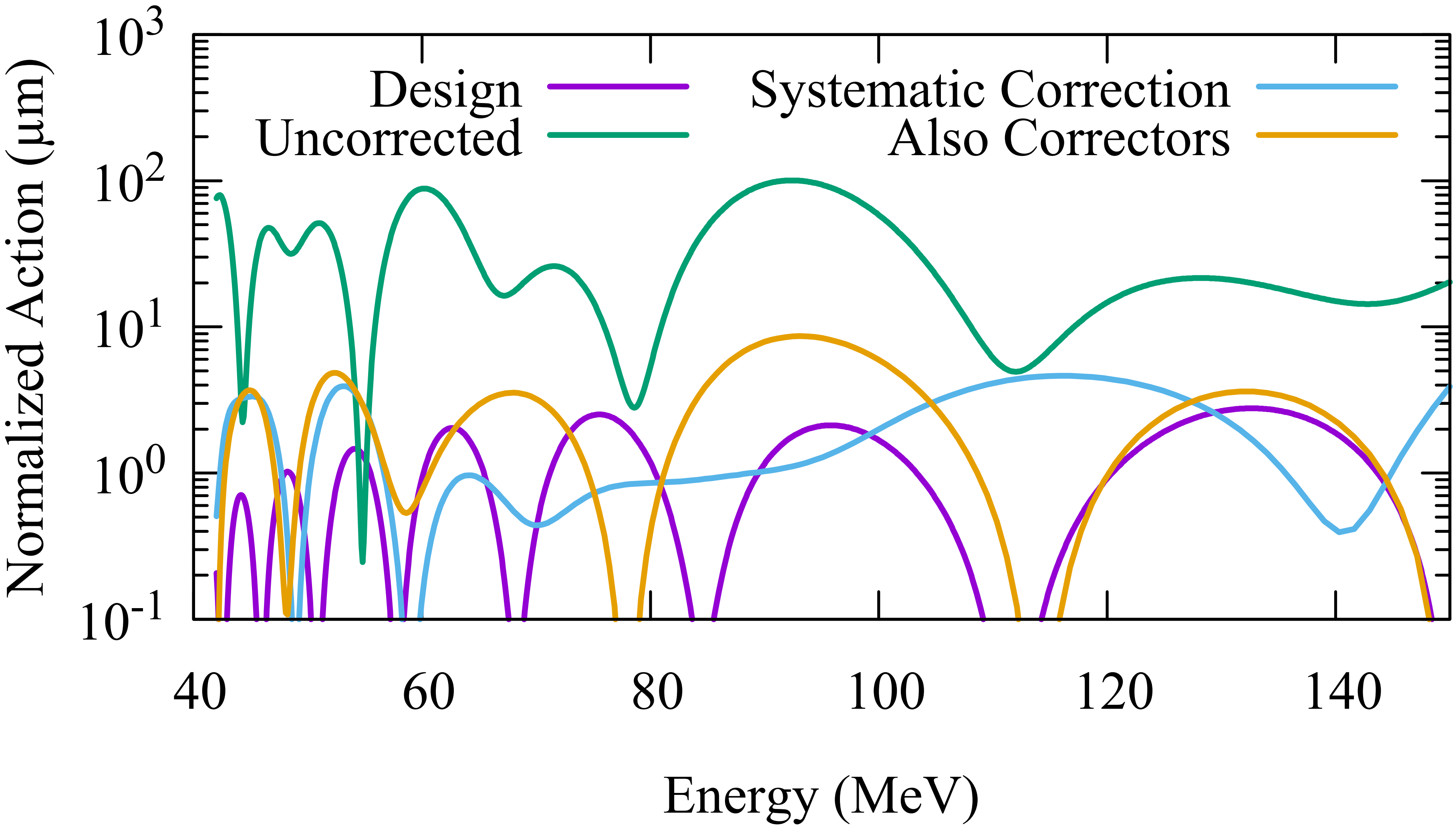
Magnet Types

- Source of problem: two different magnet types, shifted so their zero-field axes are in the same location, are not perfect replacements for each other
- Example: zero-field line in BDT1, which is adjacent to a cell with QD (with a straight zero-field line), has a curved zero-field line
  - Effected exacerbated by short magnets
- Solution: add a monotonically-varying offset each set of transition magnets (both QF and BDTn);
  - Improves orbit match where cells with different magnet types meet
  - Largest shifts are around 200 μm
  - Resulting performance nearly as good as design

Magnet Types



Magnet Types



Conclusion

- Have a return arc that transmits any beam between 42 and 150 MeV
- To keep compact, have a compact arc, then adiabatically transition to a straight
- To minimize orbit mismatch, emittance growth, and correction requirements
  - Stay clear of low-order nonlinear cell resonances
  - Keep parameters invariant to the extent possible (cell structure, magnet types, integrated gradients, tunes, etc.)
  - An transition with adiabatically varying parameters can put orbits on design orbits almost perfectly
    - Can't be completely perfect, but careful design ensures that only weak correction is required