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eRHIC Ring-Ring: Correcting Proton/Ion Velocity Variation with a Chicane in the Electron Ring: Method and Results

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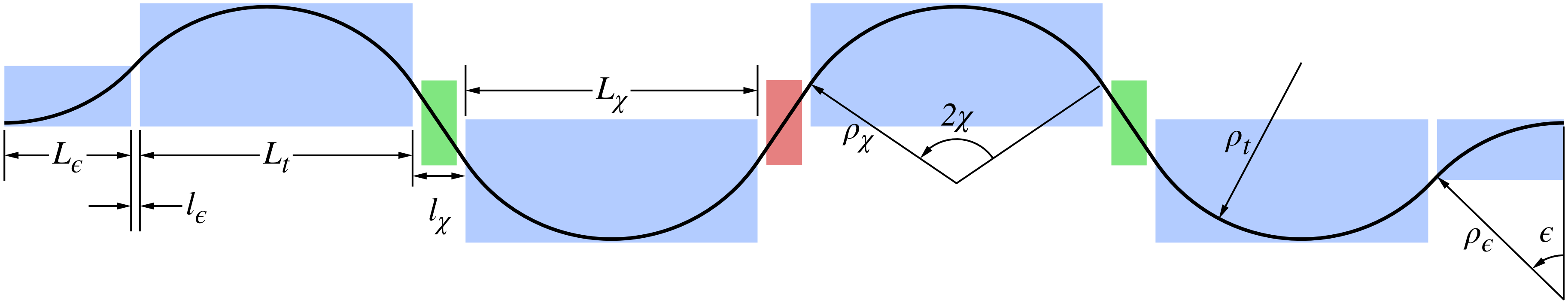
Motivation

- Orbit period must be same for proton/ion ring and electron ring to keep bunch trains in collision
- Wide range of energies desired in proton/ion ring: 50 GeV/n through 250 GeV/n
- Correct by changing orbit length of one or both beams
  - Range is 65 cm

Wiggling Chicane

- Create curved path to increase path length
- Chicane must be long, so need intermediate focusing quadrupoles
- Have beam cross straight axis, place quadrupoles at crossing point
  - Cyclotron-style dipole: continuous path length variation
  - Shared quadrupole for all path length corrections
  - No need to move magnets



Relevant Machine Parameters

Minimum proton energy	50 GeV
Maximum proton energy	250 GeV
Gold ion energy	100 GeV/n
Minimum electron energy	5 GeV
Maximum electron energy	20 GeV
Circumference	3833 m
Maximum proton/ion beam-beam tune shift	0.015
Proton/ion normalized emittance	2.5 μm
Proton/ion β_x at IP	2.16 m
Proton/ion β_y at IP	0.27 m
Maximum synchrotron radiation power	10 kW/m
Number of bunches	360
Electron arc dipole bneding radius	300 m
Arc average bending radius	380 m

Synchrotron Radiation

- Prefer to correct path length in electron ring
  - High magnet fields required in proton/ion ring
- Synchrotron radiation gives minimum bending radius in chicane
  - Smaller bending radius gives more compact chicane
- Depends on electron beam current
- Electron beam current limited by
  - Beam-beam tune shift of protons/ions (lower energies)
  - Synchrotron radiation in arc (higher energies)
- More radiation allows larger beam-beam tune shift on electrons
  - Helpful at lower energies

Synchrotron Radiation

- Synchrotron radiation power, per unit length

$$\frac{2}{3}\frac{en_bN_e}{T}\frac{e^2}{4\pi\epsilon_0 m_e c^2}\frac{(pc/e)^4}{(m_e c^2/e)^3}\frac{1}{\rho^2}$$

- In arc, replace ρ^2 with $\rho_{\text{dipole}}\rho_{\text{tunnel}}$ to get average
- Leads to limitation in N_e at high electron energies
- Given radiation power limit, current, and beam energy, find minimum ρ for chicane

Beam-Beam Limit

- Defined by "tune shift" parameter

$$\xi_x = -\frac{N_S \beta_{xW}}{\gamma_W \sigma_{xS}(\sigma_{xS} + \sigma_{yS})} \frac{e^2 Z_S Z_W}{8\pi^2 \epsilon_0 m_W c^2}$$

  - W beam feels the force, S beam produces the force
- Electron and proton beam sizes the same
- Proton/ion beam-beam tune shift:

$$\xi_{x,A} = \frac{N_e}{\epsilon_{n,A}(1 + \sqrt{\beta_{y,A}/\beta_{x,A}})} \frac{Z_A}{A_A} \frac{e^2}{8\pi^2 \epsilon_0 m_p c^2}$$

  - Determines N_e, depends only on tune shift and normalized emittance for proton/ion beam
  - Larger N_e allowed for ions

Beam-Beam Limit

- Electron beam tune shift determines proton beam current
- Strong radiation damping of electrons means electron beam-beam tune shift can be larger than protons
- Thus synchrotron radiation desirable at lower beam energies

Design Process

- Pick most challenging combination of required path length increase and electron beam energy
- Choose minimum arc radius at this energy based on synchrotron radiation limit. Use this radius for all bends.

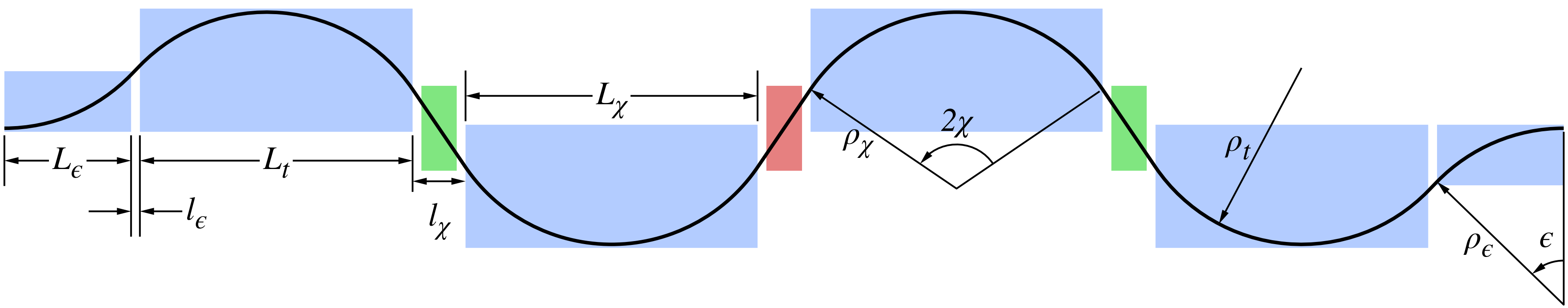
Design Process

- Find angles ϵ and χ meeting constraints
  - Beam crosses at centers of quadruopoles

$$2\rho_\epsilon \sin^2(\epsilon/2) + l_\epsilon \tan\epsilon = 2\rho_t \sin[(\chi-\epsilon)/2]\sin[(\chi+\epsilon)/2]$$

  - Required path length difference:

$$2(\rho_\epsilon\epsilon - L_\epsilon) + 2l_\epsilon(\sec\epsilon - 1) + 2[\rho_t(\epsilon+\chi) - L_t] + (n-1)(2\rho_\chi\chi - L_\chi) + nl_\chi(\sec\chi - 1)$$

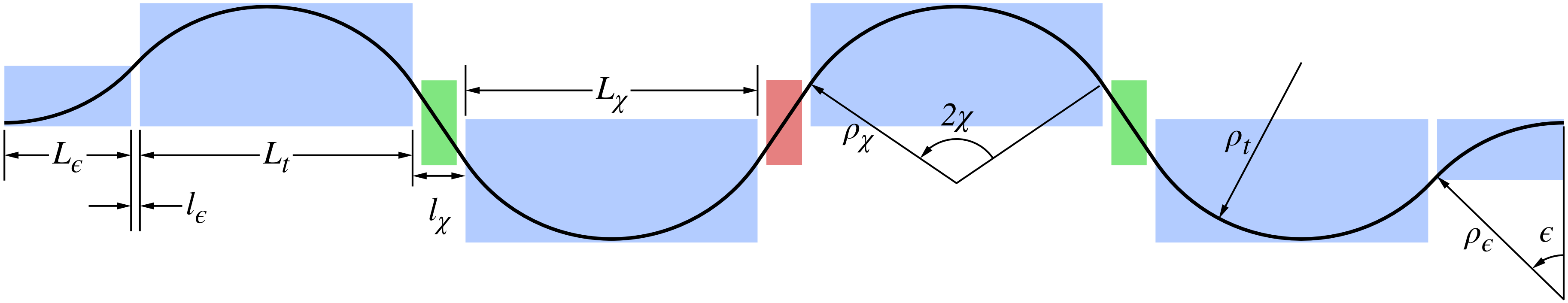


Design Process

- Different energies, path length corrections
  - Adjust ϵ, χ, ρ_ϵ, ρ_t, ρ_χ
  - Above constraints, plus L_ϵ, L_t, and L_χ

$$L_\epsilon = \rho_\epsilon \sin\epsilon \qquad L_t = \rho_t(\sin\epsilon + \sin\chi)$$
$$L_\chi = 2\rho_\chi \sin\chi$$

  - Steer beam to end, tangent to axis
  - Cross through quad centers with identical angles
  - Reach desired path length



Lattice Considerations

- Need to dispersion match: requires $n \geq 3$
  - For FODO: prefer internal DFD for $n = 3$, DFFD for $n = 4$
- Lower beta functions give lower electron beam emittance
  - Want short spacing between quadrupoles
  - Instead of FODO, could use, e.g., triplets between bends
    - Longer drift for magnets, means shorter bends: more synchrotron radiation, but more path length as well
  - Only horizontal matters: asymmetric horizontal/vertical focusing
- Beam crosses quadrupoles with angle χ; would like to keep this angle small

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Cases to Consider

- 20 GeV electrons on 100 GeV/n ions
  - Required for gold
  - 14 cm path legnth difference from 250 GeV protons
  - Synchrotron radiation: minimum bend radius 340 m
  - Electron current limited by synchrotron radiation in arcs (1.1×10^{11}, 360 bunches)
- 5 GeV electrons on 50 GeV protons
  - Largest path length increase required: 65 cm difference from 250 GeV protons
  - 29 m minimum bend radius
  - Electron current limited by proton/ion beam-beam tune shift (2.1×10^{11} per bunch)

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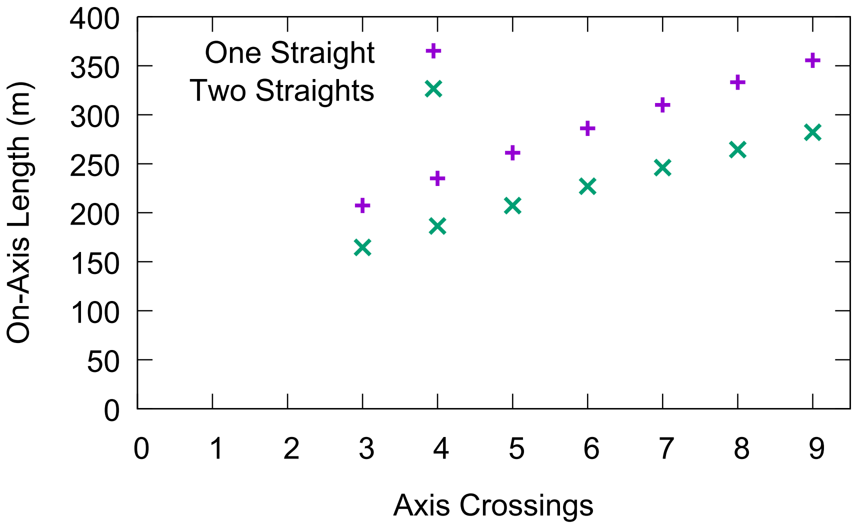
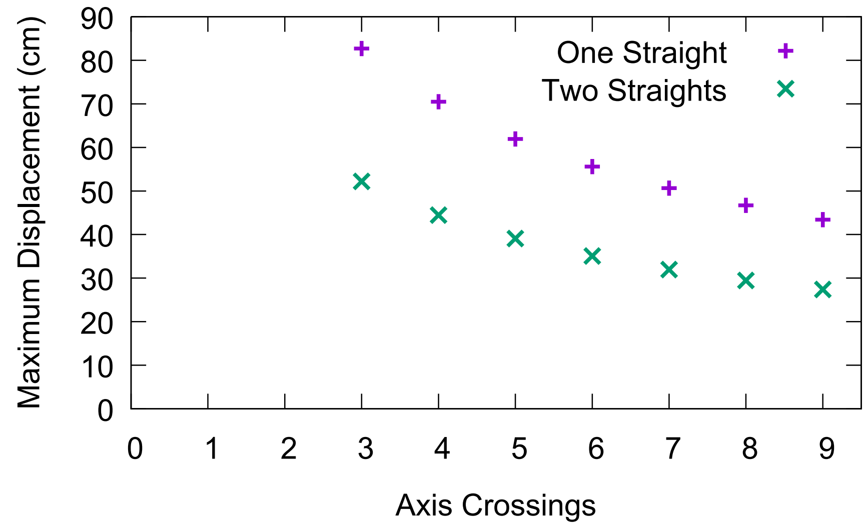
Design Constraints

Space between dipoles	10 cm
Space for quadrupole	80 cm
Straight length	313 m
Available Straights	2

- Comptue radiation ignoring space between dipoles and excess path length

20 GeV electrons & 100 GeV/n ions





- Use one or two straights; length per straight
- Displacements to correct 100 GeV/n; larger for 50 GeV/n
- Additional space required at ends for matching
- Large cell length: emittance growth

20 GeV electrons & 100 GeV/n ions

- 5 crossings in two arcs about optimal
- Chicane is really too long
  - Electron beam emittance growth
- Horizontal size will be huge
- I conclude is is impractical to use this chicane to correct 20 GeV electrons on 100 GeV/n ions
  - Fundamental reason is radiation limitation

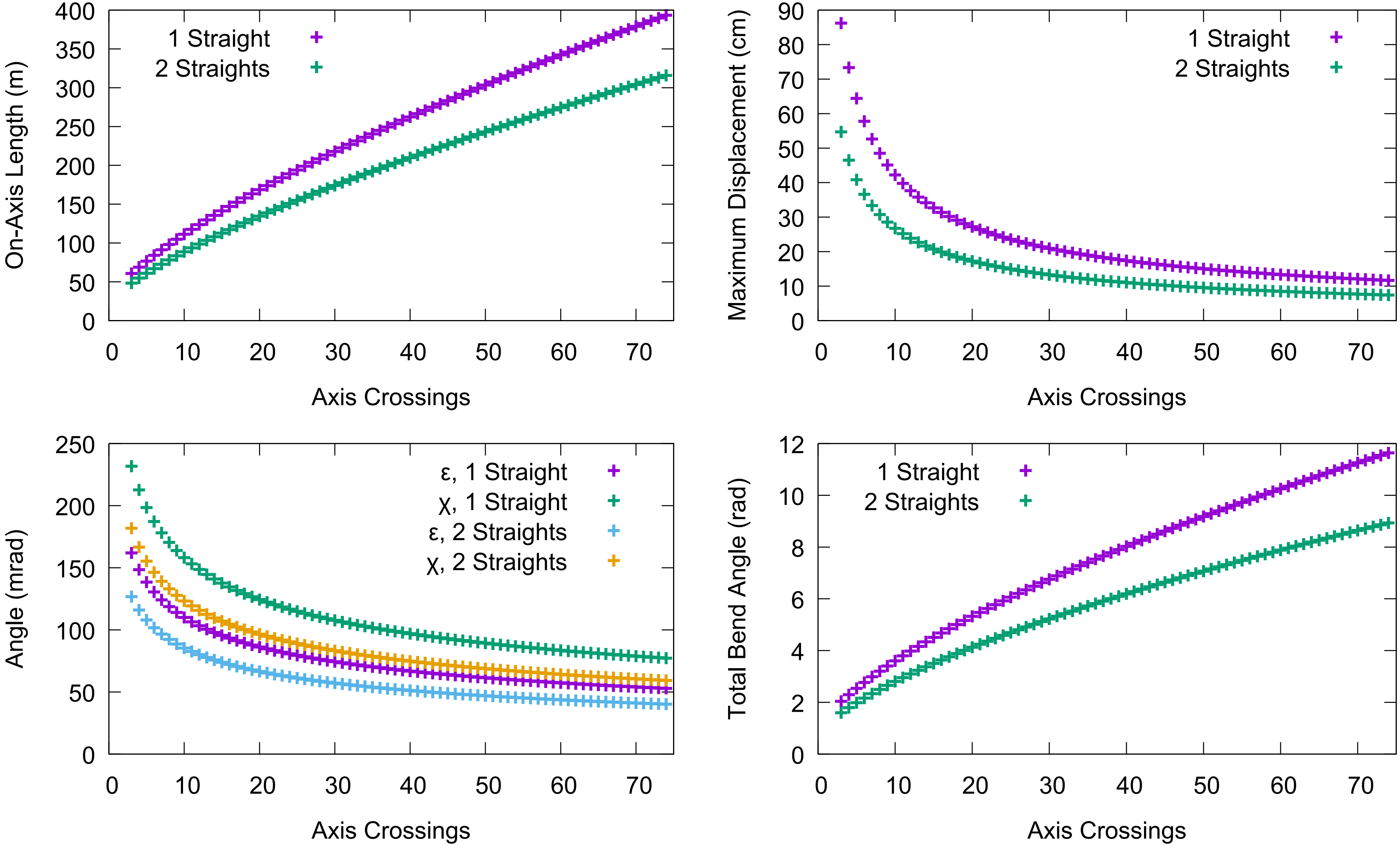
Alternatives to Chicane

- Only trying to correct difference between 100 GeV/n and 250 GeV/n: 14 cm
- Moving magnets in electron arc
- Steering beam off axis in magnets
  - Radiation and emittance issues if use electron ring
  - Displacements larger than you might think
- Superconducting chicane in proton/ion ring
  - Need relatively high fields (4–6 T)
  - Need switchyard
  - Magnet spacing will be an issue
- Use inner/outer rings for protons/ions

5 GeV Electrons & 50 GeV Protons

- Assume some solutions exists to correct 100 GeV
- 51 cm remaining to correct
- Find solution adding 51 cm to straight-line path length for 5 GeV electrons
  - Work at radiation per unit length limit
- Higher electron energies
  - Increase minimum bend radius to match radiation per unit length limit
  - Result is a minimum proton energy for which you can correct the path length

5 GeV Electrons & 50 GeV Protons

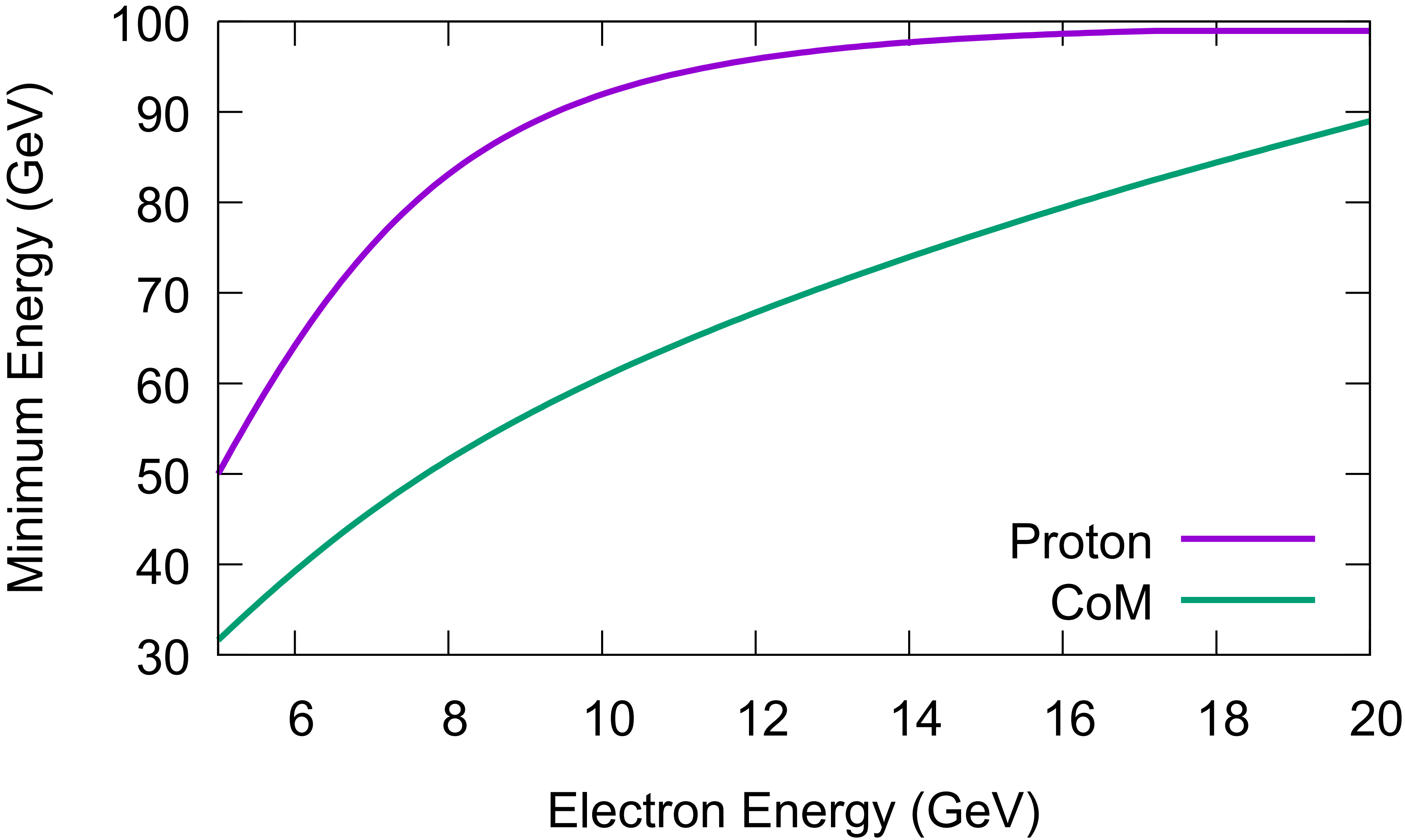


5 GeV Electrons & 50 GeV Protons

Straights	1	2
Overall length (m)	258	2×271
Maximum displacement (mm)	177	86
Crossings	39	2×59
Maximum crossing angle at quadrupole (mrad)	98	65

- Fill the straight(s): maximum energy loss, minimum horizontal size and angle at quadrupoles
- Could be shorter: less energy loss, wider magnets, larger angle at quadrupoles

Minimum Proton/CoM Energies



Conclusions

- Chicane with many axis crossings can correct path length
- Solution to lengthen 20 GeV electron beam to correct 250 GeV/n down to 100 GeV/n likely impractical
  - Need an alternative for this last 14 cm
- Good solution correcting between 50 GeV/n and 100 GeV/n
  - Gives lots of radiation for low energy beam: good for electron beam-beam tune shift
  - Compact cells, good for emittance
  - Could be made shorter, with some tradeoffs

Next Steps, if Desired

- Details of quadrupole lattice in chicane
  - Impact on emittance
  - Dispersion correction
- Quadrupole aperture/radiation due to finite crossing angle in quads
- Study reducing remaining path length vs. chicane cost/performance
- Look at solutions for last 14 cm

Acknowledgements

- Original idea for a chicane came from Bob. His version crossed only once, had magnets that had to be repositioned for each energy.