Neutrino Factory Storage Ring

J. Scott Berg
Brookhaven National Laboratory
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Storage Ring Goals

- Maximize neutrinos to detector
  - Minimize dynamic losses
  - Maximize flux toward detector
- Supply two detector sites, different baselines
- Keep flux uncertainty sufficiently low
- Provide a well-known polarization
  - Probably zero!
- Handle both muon signs

Ring Geometry

- Two signs of muons
- Two detectors
- Maximize efficiency
- Reduce depth
- Rings contain
  - Production straights: maximize fraction
  - Utility straights
  - Arcs, plus matching

Ring Geometry
Production Straight Angle

- Angle to horizontal:

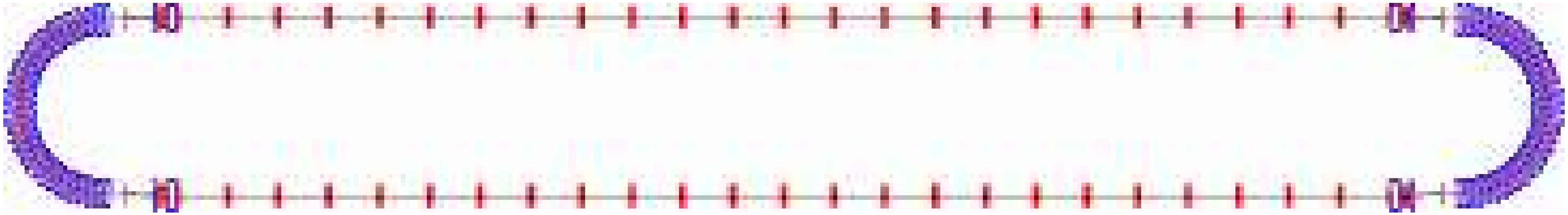
$$\theta = \sin^{-1} \frac{L}{2R}$$

- L is baseline, R is Earth's radius
- Depth proportional to L/R

Ring Geometry
Racetrack

- Two long straights connected by 180° arcs
- If only one detector: one ring
  - Two production straights, one each sign
  - Timing to prevent overlap
  - Difficult to inject/extract
- Two detectors: two rings
  - One production straight in each ring
- Around 35% efficiency

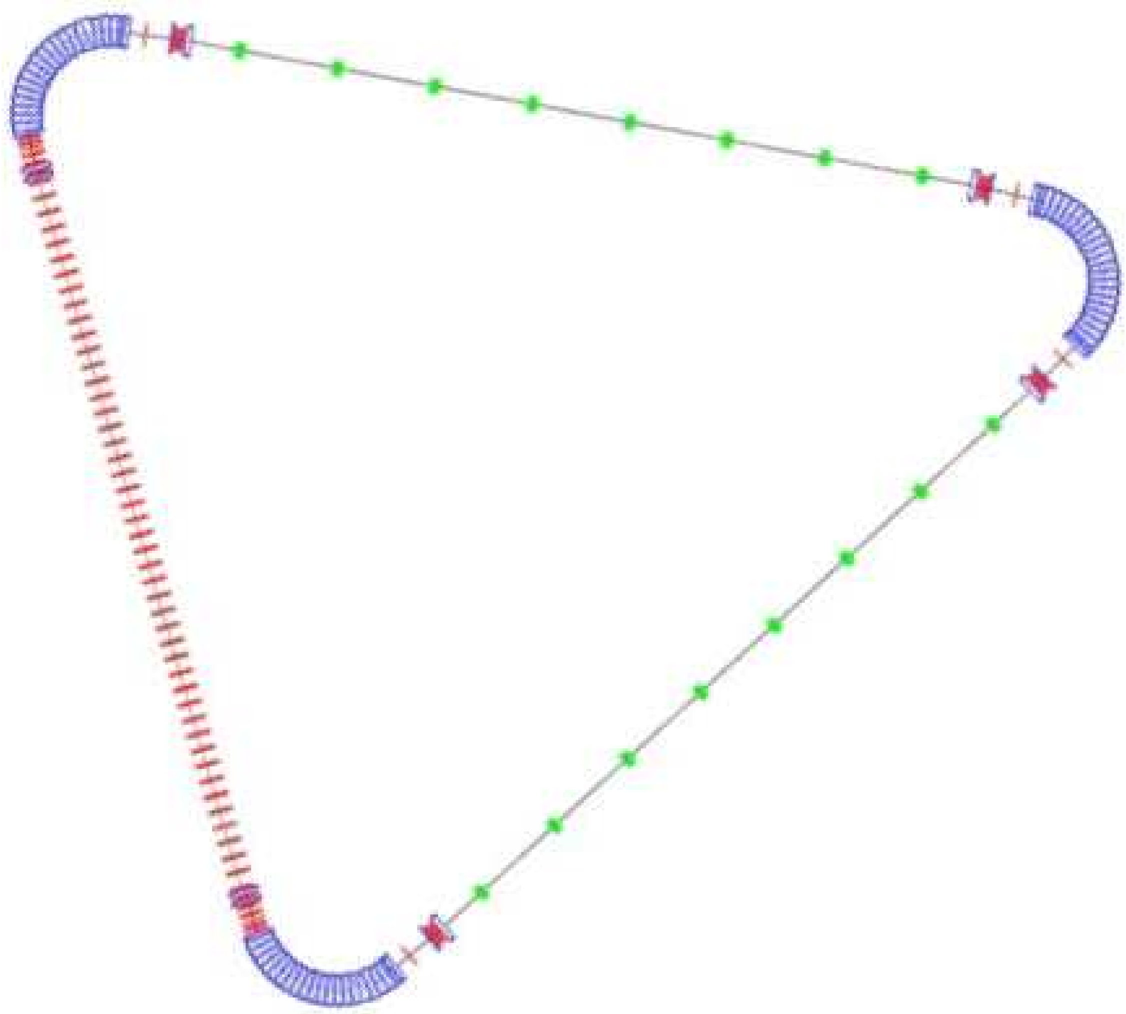
Ring Geometry
Racetrack



Ring Geometry
Triangle

- Two sides of triangle point to two detectors
- Two parallel rings, one for each sign
- Increased efficiency
  - Two sides of triangle used, both rings
  - Best if two detectors are opposite directions
- Greater depth then racetrack
- Third arc reduces efficiency

Ring Geometry
Triangle



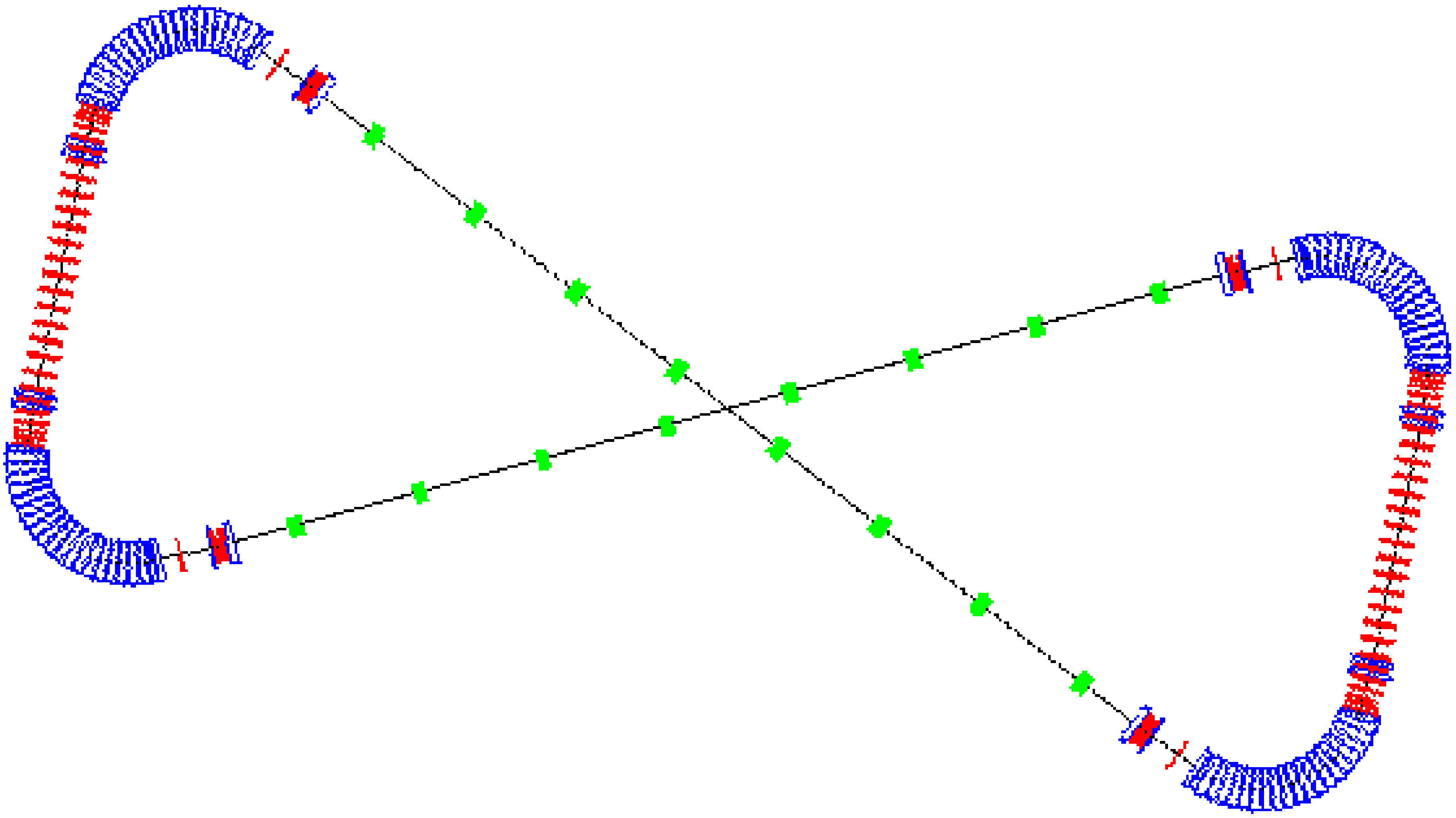
Ring Geometry
Triangle: Straight Directions

- Maximize efficiency
  - Two sites in opposite directions
  - Ring lies in vertical plane
  - Deviations increase length of third side

Ring Geometry
Bowtie

- Same idea as triangle: two useful straights
- Reduced depth
- If no arcs, would have triangle efficiency
  - Fouth arc reduces efficiency

Ring Geometry
Bowtie



Neutrino Flux

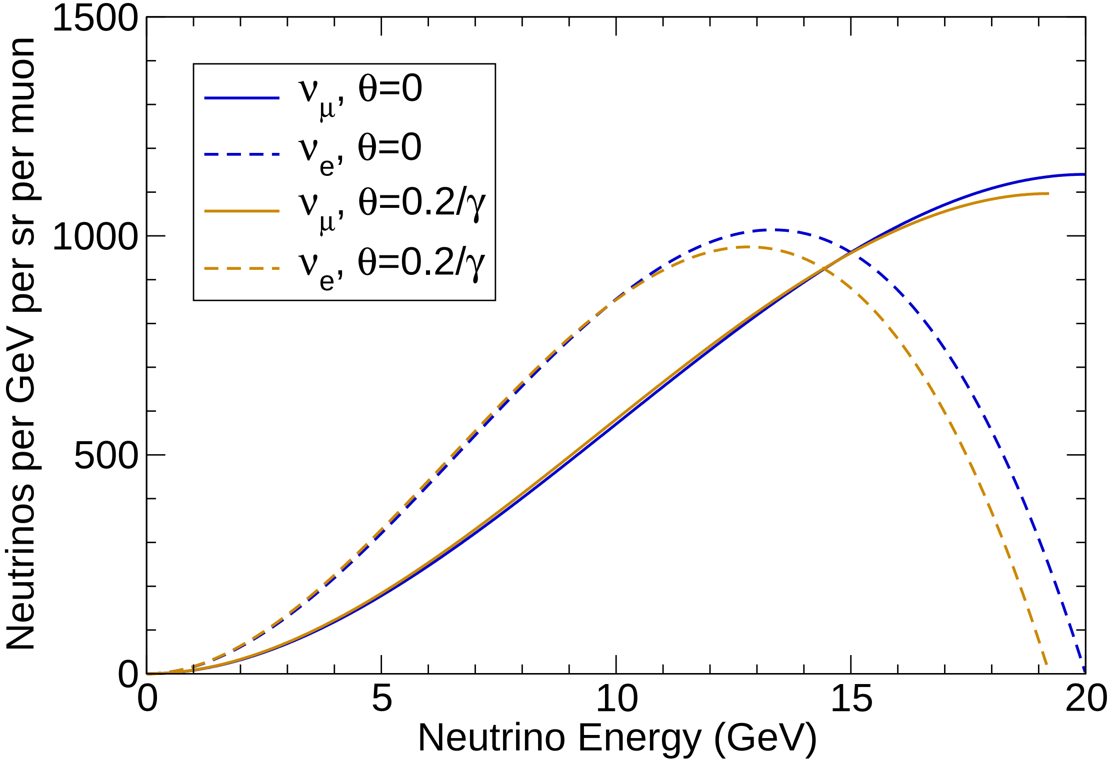
- Neutrino spectrum, CoM angle θ, $x = 2E_\nu / m_\mu$, $\mu^\pm$ polarization $\mathcal{P}$

$$\frac{d^2N_{\nu_\mu}}{dx\, d\cos\theta} = Nx^2[(3-2x) \mp \mathcal{P}(1-2x)\cos\theta]$$
$$\frac{d^2N_{\nu_e}}{dx\, d\cos\theta} = 6Nx^2[(1-x) \mp \mathcal{P}(1-x)\cos\theta]$$

- Strong dependence polarization, angle (when $\mathcal{P} \neq 0$)

Neutrino Flux
After Relativistic Boost

- Angular dirvergence $\approx 1/\gamma$
- Energy spectrum depends strongly on angle



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Flux Uncertainty

- Beam not perfect
  - Nonzero angular spread
  - Nonzero energy spread
  - Not perfectly aligned to detector
  - Beam direction depends on energy
- Could compute ν spectrum if perfectly known
- Uncertainties in these quantities
  - Accurate measurements damage beam
  - Non-destructive measurements: 10–20%

Angular Divergence

- Neutrinos: natural angular divergence $\approx 1/\gamma$
- Muons with no angular divergence: flux determined entierly by decay distribution
- Muons with angular divergence $\gg 1/\gamma$
  - Decay divergence small by comparison
  - Flux $\propto 1/\sigma_\theta^2$
- Keep angular divergence small to avoid flux reduction

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Flux Uncertainty

- Total flux uncertainty linear in angular spread
  - Uncertainty in distribution more complicated
- Flux spectrum linear in polarization
  - Know polarization well
- Parameters for small flux uncertainties
  - Angular spread: $< 0.1/\gamma$
  - Polarization known to 1%
  - Beam direction known to $0.6\sigma_\theta$

Spin Precession

- Governed by the Thomas-BMT equation

$$\frac{\boldsymbol{P}}{dt} = \boldsymbol{\Omega} \times \boldsymbol{P}$$

$$\boldsymbol{\Omega} = -\frac{Ze}{m\gamma}\left[(1+G\gamma)\boldsymbol{B}_{\perp} + (1+G)\boldsymbol{B}_{\parallel} + \left(G\gamma + \frac{\gamma}{\gamma+1}\right)\frac{\boldsymbol{E}\times\boldsymbol{v}}{c^2}\right]$$

- On design orbit, only $\boldsymbol{B}_{\perp}$ (except solenoids)

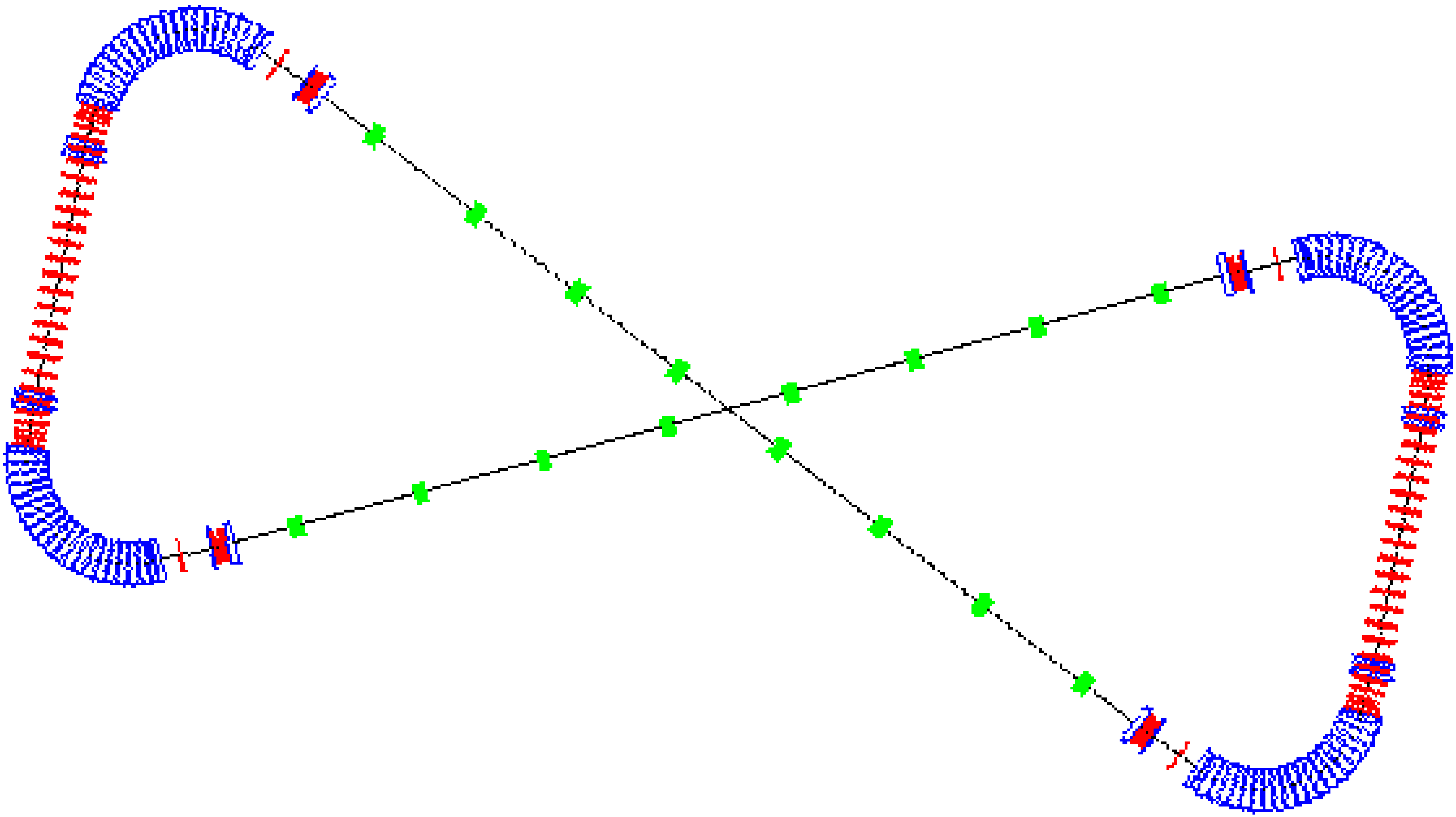
Spin Precession

- Vertical fields bend particle in closed orbit
- Spin precesses about vertical
- Amount of precession depends on energy
  - Full precession in one turn: 90.622 GeV
  - Half precession in one turn: 45.311 GeV
- Off energy: polarization will average to zero
  - Flux is linear in polarization
  - Use average polarization in flux expression

Spin Precession
Preserving Polarization

- Could operate at 45.311 GeV
  - Polarization flips on each turn
  - Energy spread in beam depolarizes
    - Get synchrotron oscillations with RF cavities: average energy deviation zero
- Bowtie has no net bend
- Problem: initial polarization not well known
  - Preferred to let beam depolarize
  - Bowtie a problem

Ring Geometry
Bowtie



Courant-Snyder Lattice Functions

- Particle motion (on energy) described by

$$x = \sqrt{2\beta_x(s)J_x}\cos\bigl(\theta_x + \psi_x(s)\bigr)$$

$$p_x/p = -\sqrt{2J_x/\beta_x(s)}\Bigl[\sin\bigl(\theta_x + \psi_x(s)\bigr) + \alpha_x(s)\cos\bigl(\theta_x + \psi_x(s)\bigr)\Bigr]$$

- J_x and θ_x describe initial conditions
- Beam size $\sqrt{\beta_x\epsilon_x}$ (ϵ_x emittance, average J_x)
- Angular size $\sqrt{\epsilon_x(1+\alpha_x^2)/\beta_x} \equiv \sqrt{\gamma_x\epsilon_x}$

Courant-Snyder Lattice Functions

- Small angular size requires
  - Small emittance
  - Small γ_x, therefore large β_x
- Example: 20 GeV, RMS normalized emittance 5 mm
  - $0.1/\gamma = 0.53$ mrad
  - $\gamma_x = 0.0106$ m^{-1}, $\beta_x > 95$ m
  - Average radius 5 cm, maximum $\approx$12 cm

Arc Design

- Beam has nonzero energy spread
- Want beam direction independent of angle
  - Orbit dependence on energy: dispersion
- Enter and leave arc without dispersion
- Arc must have at least 2π phase advance
  - Change in ψ_x
  - $d\psi_x/ds = 1/\beta_x$

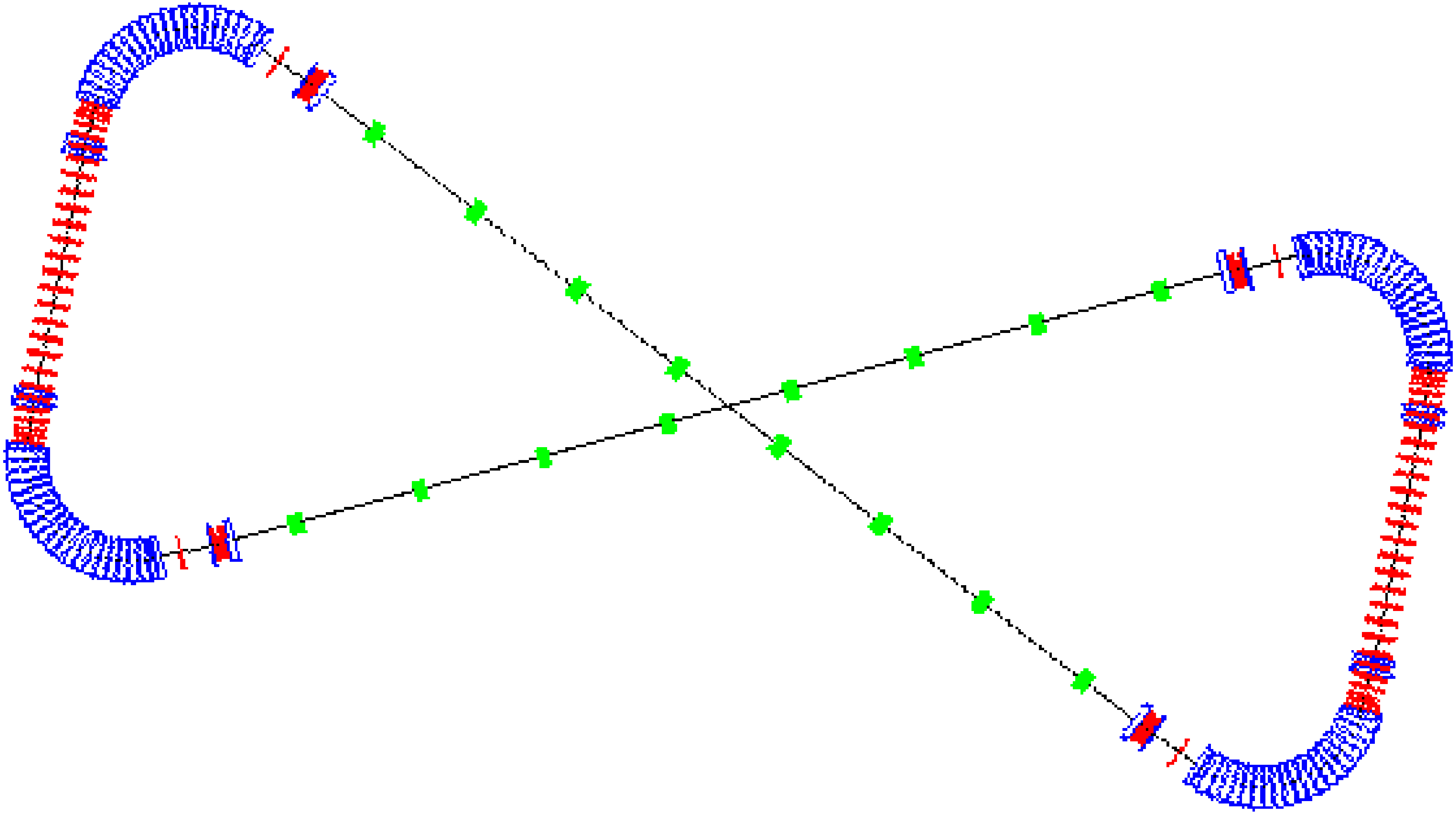
Arc Design

- Arc length at least $2\pi\beta_x$
- High efficiency racetrack: straight length at least 3 times arc
- If $\beta_x = 95$ m, arc at least 600 m long, straight at least 1800 m long
- Arc must have low β_x, production straight high β_x

Matching Sections

- Lattice designed to change low β_x to high β_x
- Must occur between arcs and straights
- Beam divergence too high in these sections
  - Contributes little to flux
  - But quite a bit to the flux uncertainty
- Small final bend next to production straight
  - Point matching beam away from detector

Ring Geometry
Bowtie



Nonlinearities

- Energy spread is relatively large (around 1%)
- Beam size is extremely large
- Linear lattice description not perfect
- Nonlinearity made worse by matching sections

Consequences of Nonlinearities

- Particles get lost if
  - Transverse oscillation amplitude to high
  - Too far off energy
- Beam distribution not so well known
- Nonlinear angular dispersion
  - Muons far off energy going wrong direction
- Nonlinearities difficult to correct
  - Few turns, but may hurt distribution