20-50 GeV Muon Storage Rings

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Introduction: Muon Storage Rings for a Neutrino Factory

- Neutrino beam/ Storage Ring energies — 20 and 50 (max) GeV
- Production Straight
  - **Muon beam divergence*** — **$0.1/\gamma \rightarrow 0.2/\gamma$**
  - **Muon beam normalized emittance*** — **$30{,}000\pi$ mm-mrad (95%)**
  - **Momentum acceptance** — **$\pm 1 \rightarrow 4\%$ (RF $\rightarrow$ no RF)**

  Note these two parameters dictate beam size in production straight
  - **Peak magnetic field (assume NBTi SC)** — **~7T**
  - **Declination angle: 3 and 7×10^3 km detector** — **~10° and 36°**
  - **Bunch train length** — **400 nsec (120 m)**
  - **Bunch train spacing** — **100 nsec**

Overiding design Goal:

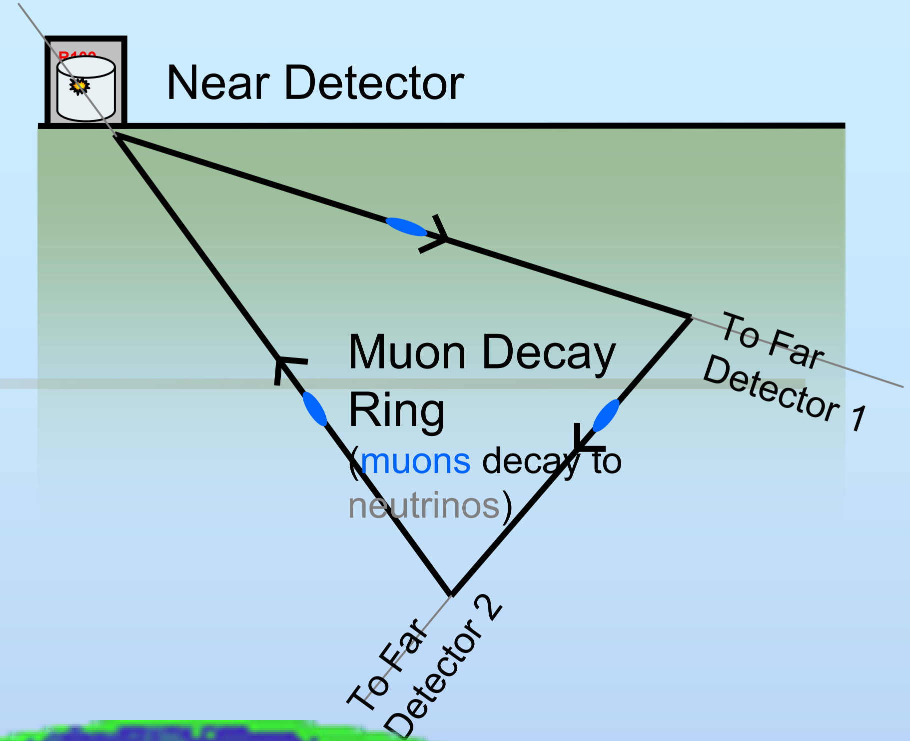
- **maximize muon decays in production straight or ratio of production straight(s)/circumference**

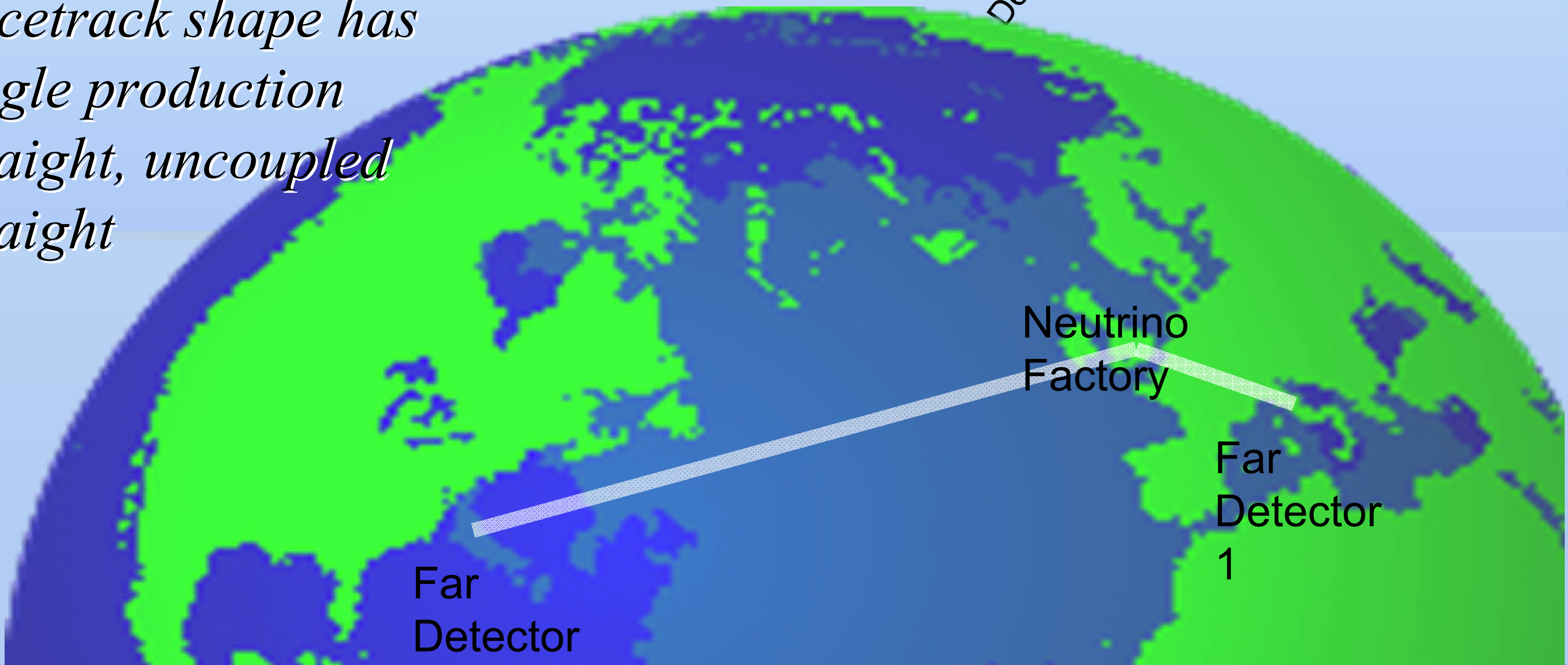
*small compared to neutrino beam divergence, rms ~$1/\gamma$

*assumes minimal, mainly transverse cooling

Muon Decay and Storage Ring

- *A triangular and bowtie shape with two production straights and two baseline experiments*
- *Racetrack shape has single production straight, uncoupled straight*





Storage Ring Designs

- Racetrack
  - 2 rings (2 tunnels): 2 detector sites*
  - 1 long production straight/ring ⇨ 1 detector site
  - Each ring supports both charge species of muons circulating in opposite directions (if opposing straights are identical)
  - Alternate injection batches between rings
- Isosceles Triangle Ring
  - 2 rings (in 1 tunnel): 2 detector sites
  - 2 production straights/ring ⇨ 2 detector sites
  - Each ring supports only one charge species
  - Interleave and separate μ^+/μ^- batches by 100 ns (requires RF)
- Bowtie Ring – new
  - Properties similar to triangle ring

*of course 1 ring/1 detector is also an option for the racetrack

20, 40, 50 GeV Current Design Overview

- 20, 40, and 50 GeV lattice ring designs complete
  - Arc: FODO cells with ~6T dipole fields:
    - 72° arc cells, combined-function magnets (triangle, for now)
    - 90° arc cells, separated-function, tunable magnets (racetrack design, for now)
    - Combined dispersion suppressor and matching sections
    - Designed for MW intensities - warm bores of SC
      - Clad with Pb (absorbs 80% of e± beam power)
      - 1 cm of W @50 GeV will also sufficiently protect SC coils
  - Production straight design:
    - SC solenoids - minimize beam size
    - NC, 30 cm -bore quadrupoles - confines cryogenics to arcs
    - Permanent magnet ~30 cm bore quads appear feasible
    - Background sweep dipoles at ends of production straights

20 $\rightarrow$ 50 GeV upgrade; present status

- Isosceles:
  - modify lattice + some magnet changes required; realignment
  - Muon/neutrino beam divergence fixed to $1/\gamma$ at both energies

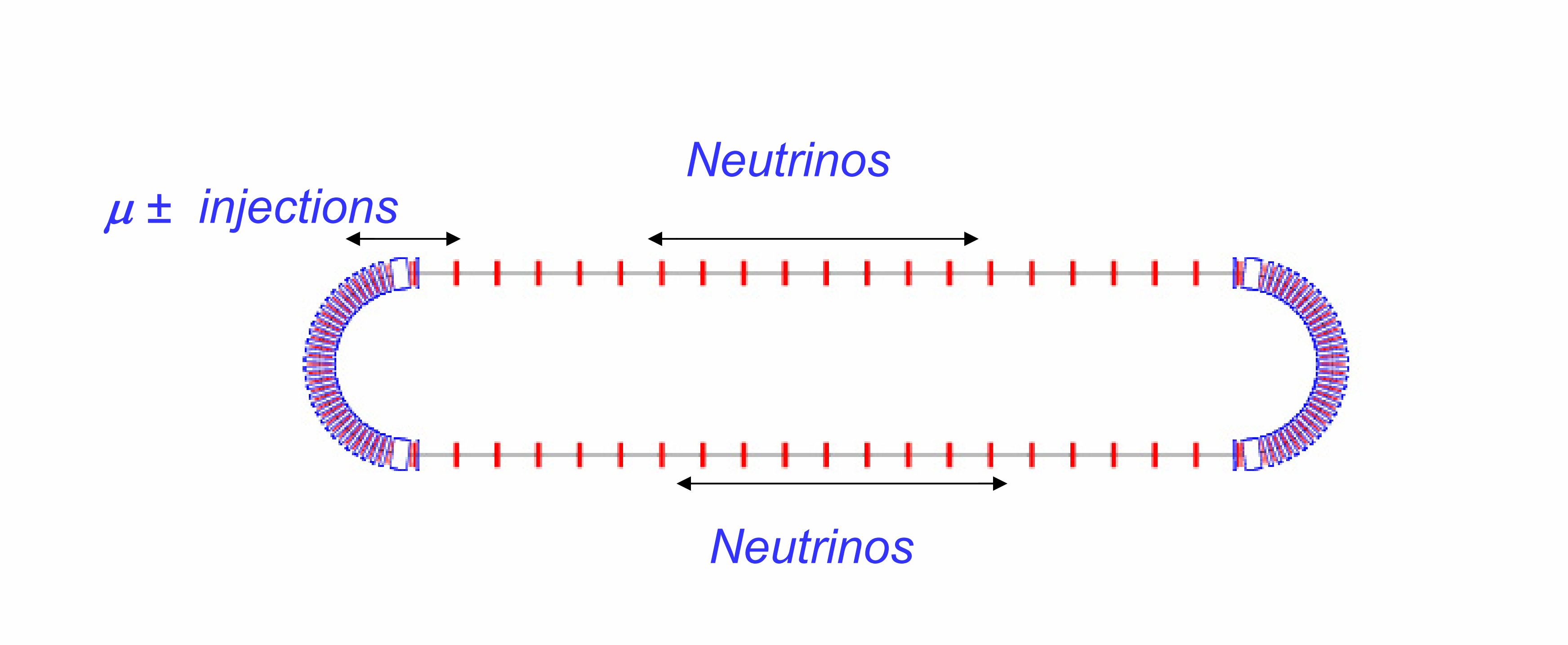
- Racetrack:
  - no changes: 40 /50 GeV ring installed and can be operated @20 GeV;
  - bores accommodate 20 GeV beam and shielding
  - Muon beam rms divergence increases from $0.1/\gamma$ @20 GeV to $0.14/\gamma$ @40 GeV and $0.19/\gamma$ @50 GeV

These approaches are not specific to storage ring shape

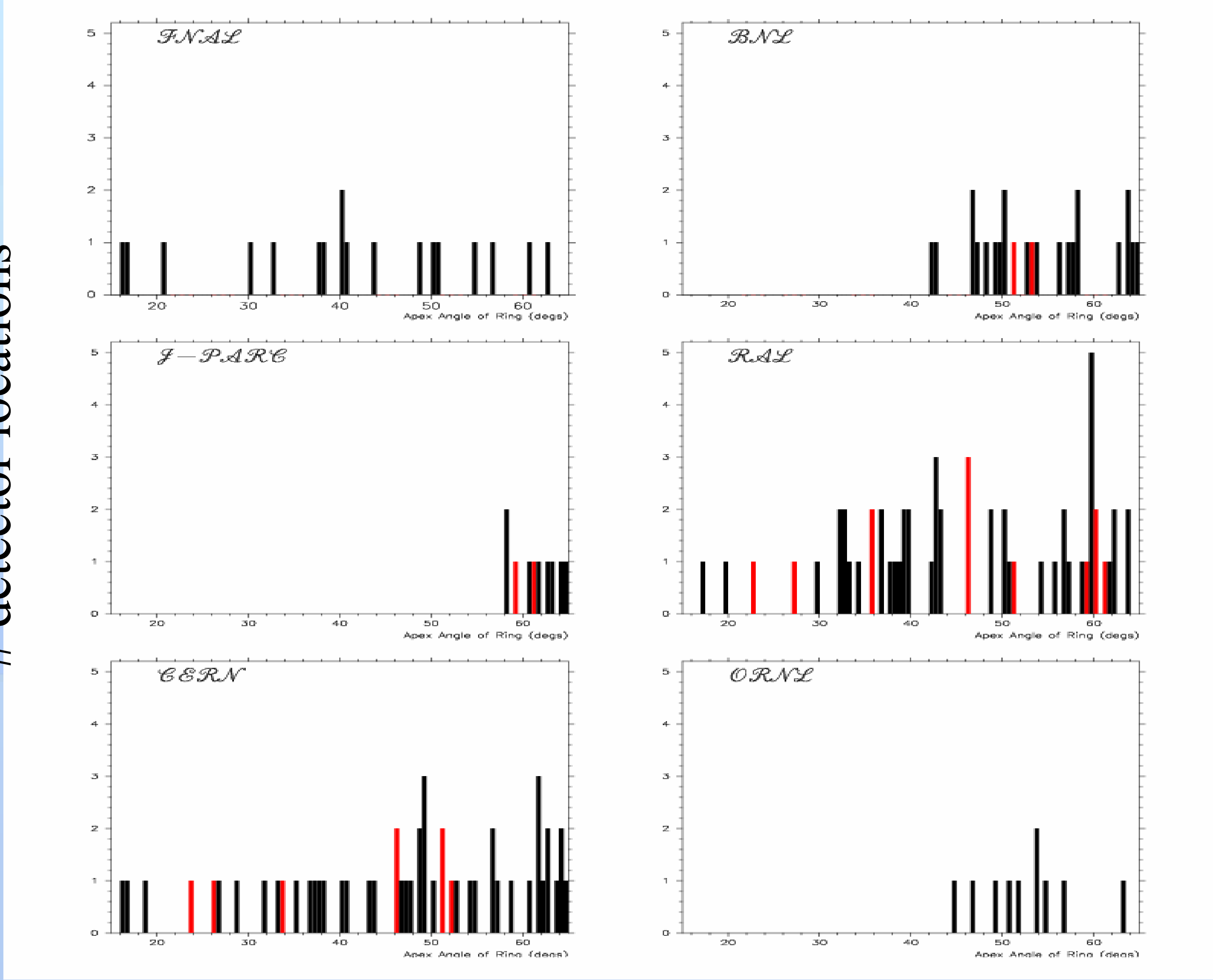
Racetrack Storage Ring

Ring operates at 20 and 50 GeV – Arc dipoles powered at 2.5 and 6.3 T

Background sweep dipoles at end of each straight



Potential dual far/near detector locations

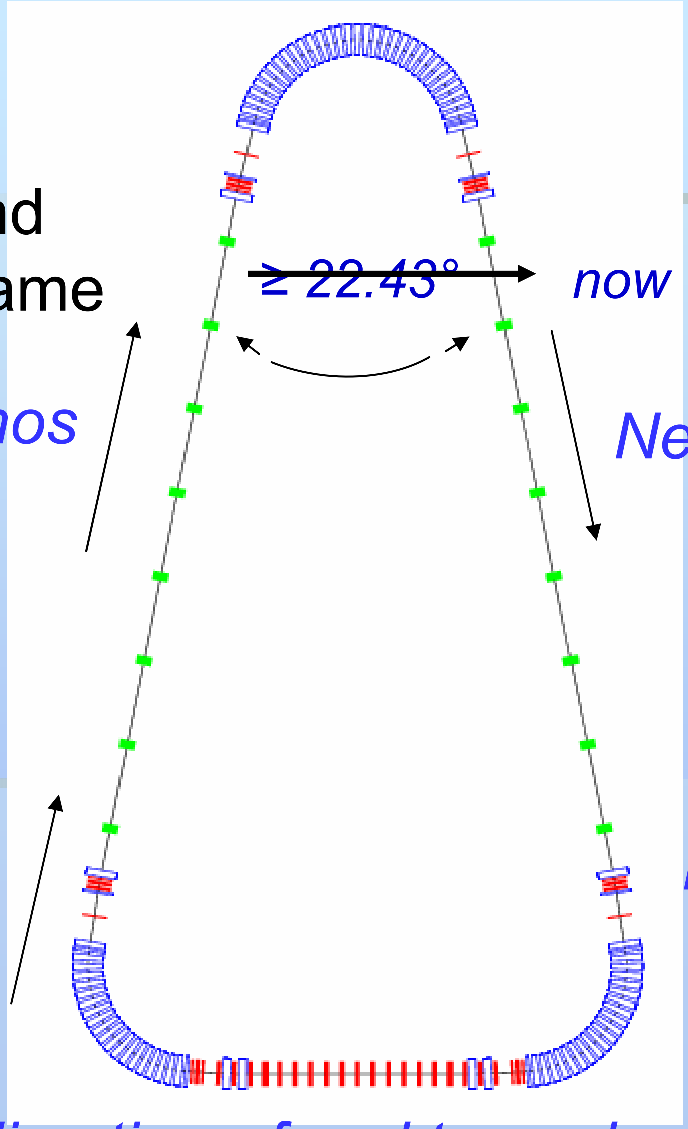


detector locations

Apex angle of storage ring triangle

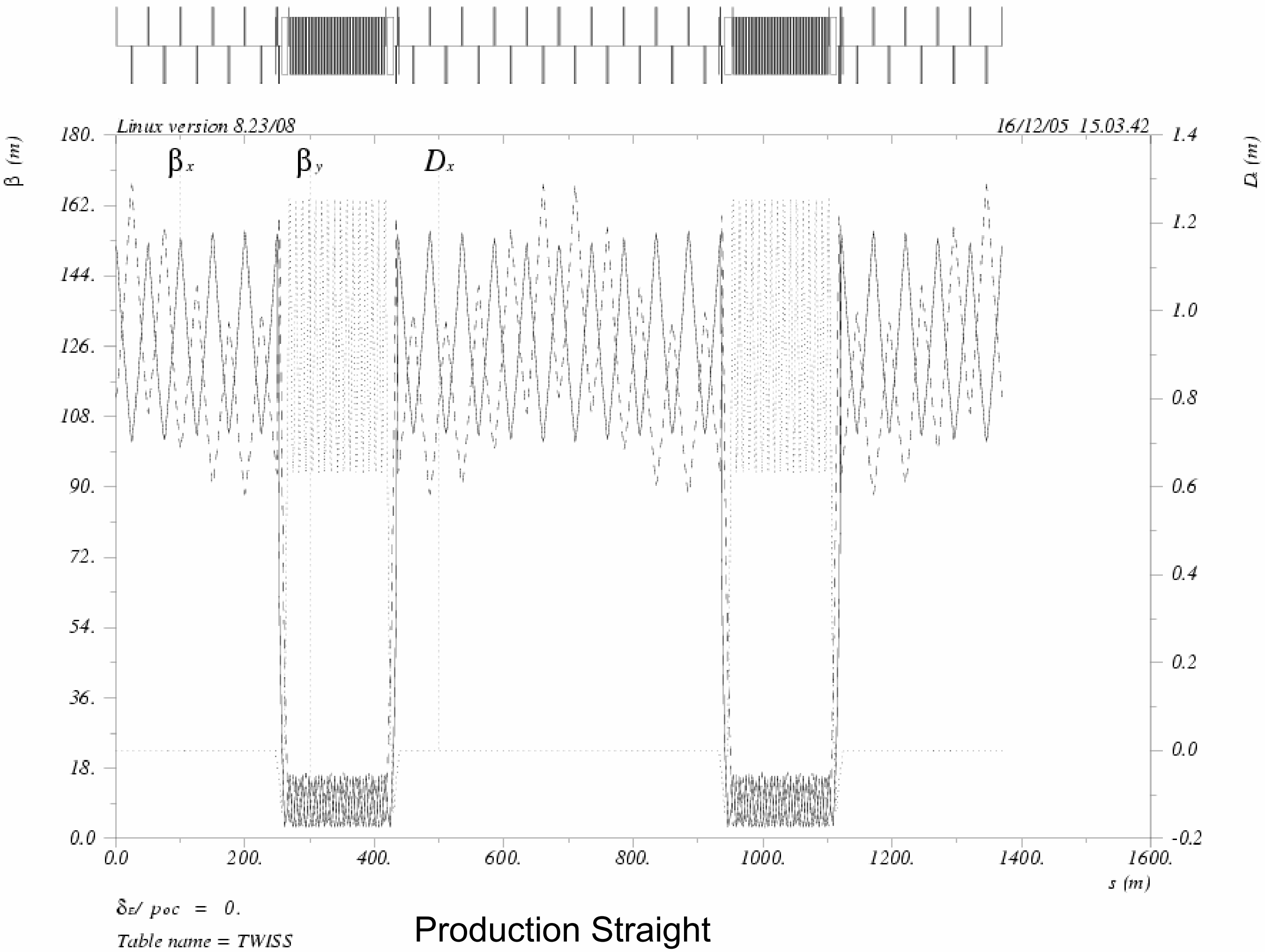
Triangular Muon Storage Ring

Designs for 20 and 50 GeV to fit in same tunnel



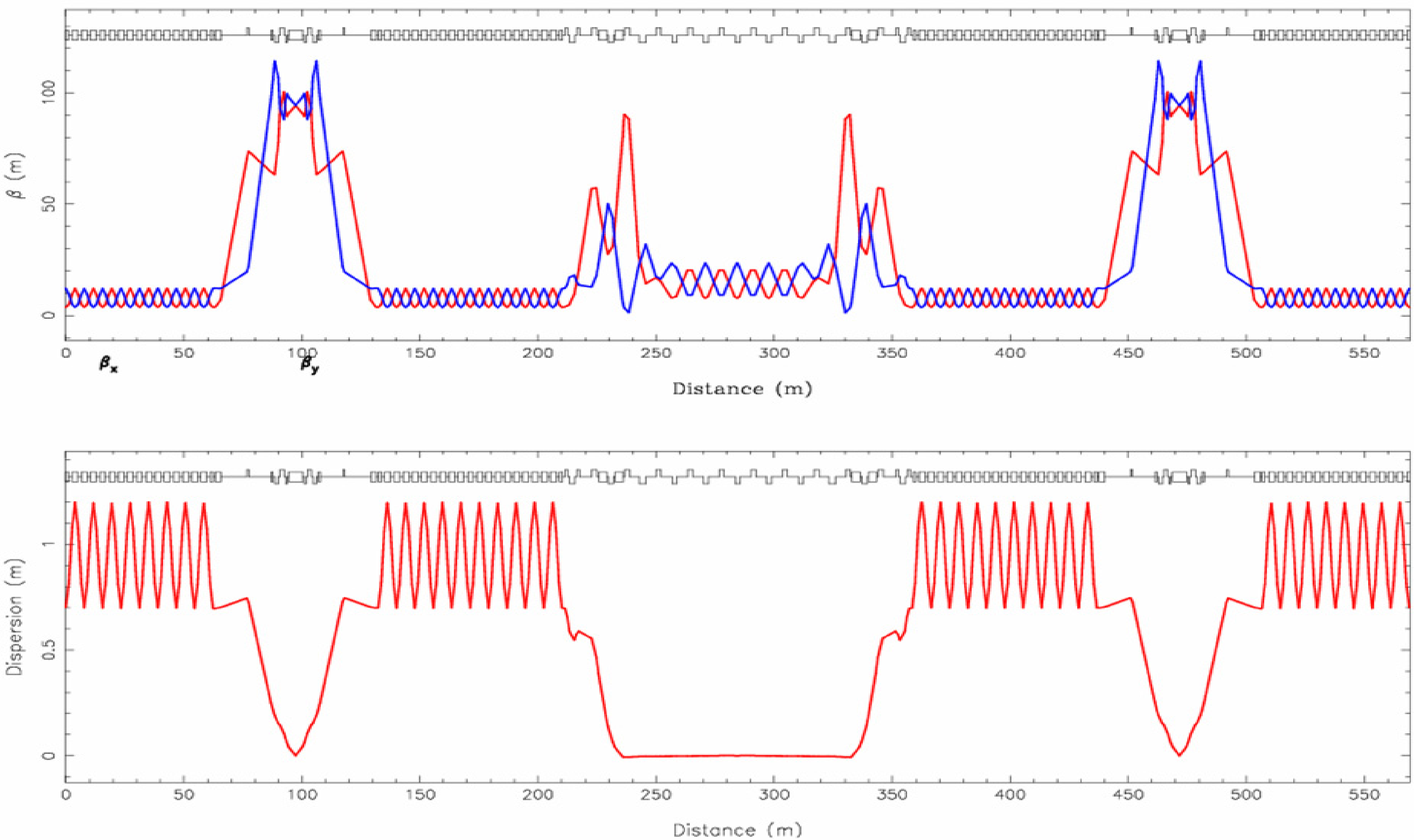
C.Prior
UKNF talk

20/50 GeV Lattice for Racetrack Ring



Production Straight

20 GeV Lattice Functions for Triangular Ring (Excluding Production Straights)



n Determines Minimum Ring Circumference:

Bunch Trains continued

20 GeV muon accelerator

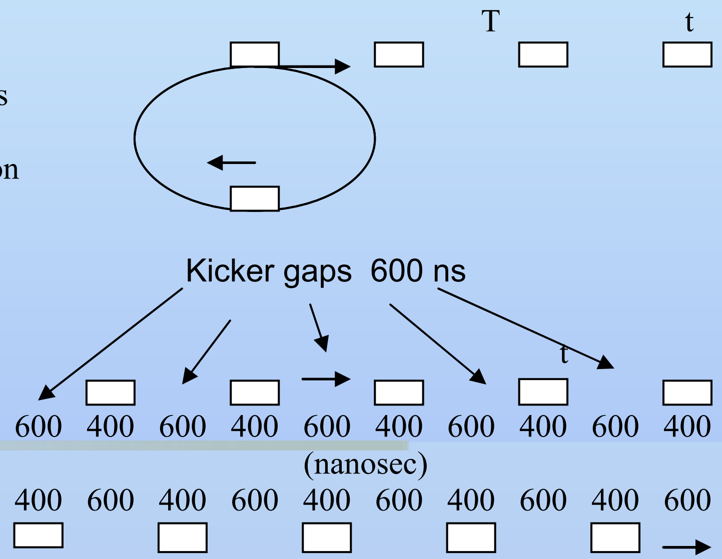
T= mT_{rev} ~ 25 to 50 μs , t = 400 ns

m = number of turns of acceleration

20/50 GeV μ^+ decay ring circumf.

C = 1500 m

20/50 GeV μ^- decay ring circumf.

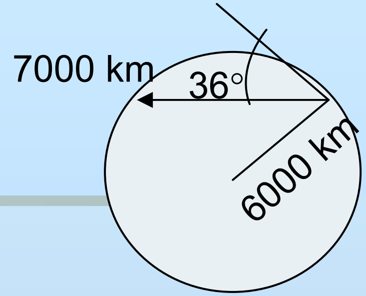


Triangular ring:

$\mu^+\mu^-$ interleaving – maintains 100 ns spacing between batches*

*no interleaving required in dual racetrack scheme

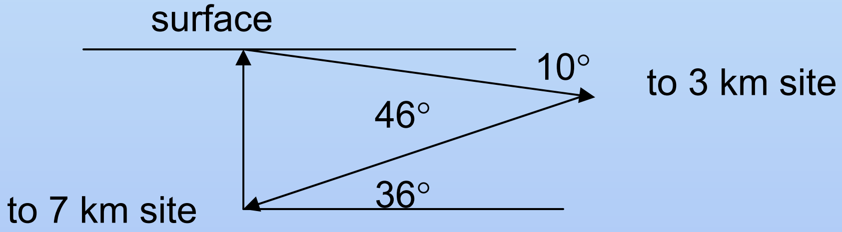
Site concerns for 7 & 3 x10³ km detectors



- Vertical depth (arcs << straights):
  - Racetrack:

$$Depth \approx {}^{C}\!/_{2} \sin(36°) = {}^{C}\!/_{2} (0.6) = 0.29C$$

  - Isosceles triangle:



$$Depth \approx {}^{C}\!/_{3} \sin(10°) + {}^{C}\!/_{3} \sin(36°) = {}^{C}\!/_{3} (0.8) = 0.25C$$

- Conclusion: relative depths of two similar circumference - triangular or racetrack - storage rings are very close

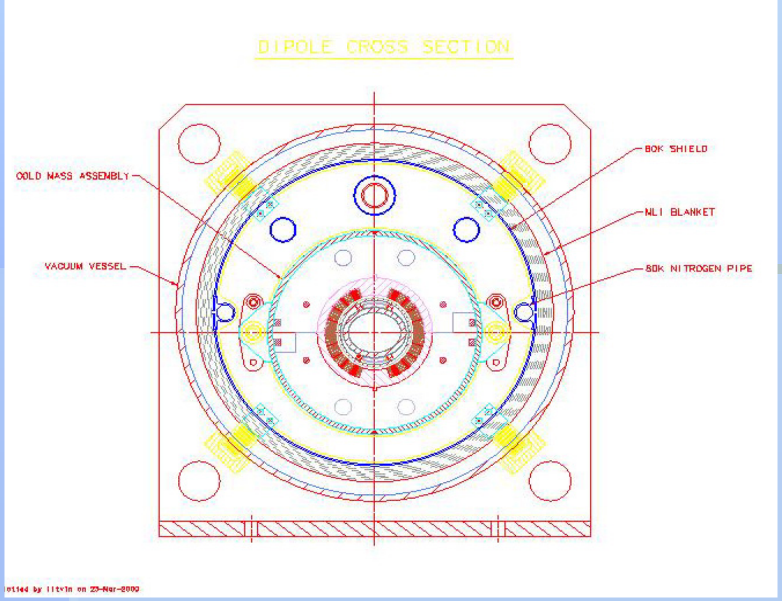
n=5 Storage Ring Parameters - updated

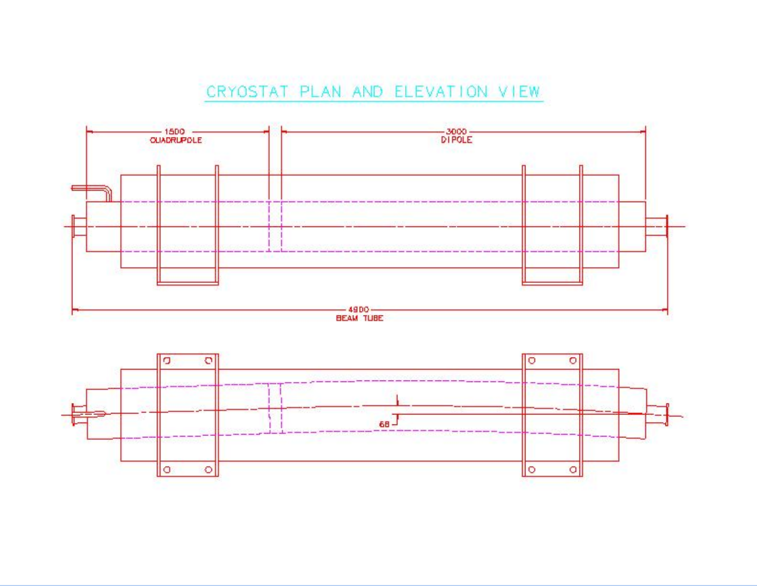
PARAMETER	TRIANGLE 20 : 50 GEV	RACETRACK 20 : 50 GEV
Circumference	1573 m	1573 m
Production straight	2x~378 m (2x~24%)	635 m (40%)
Depth	~340 m	~430 m
acceptance (beam emittance) normalized, 95%	4.8π cm (30π)	same
Momentum acceptance	$\pm$1-2% (RF determined)	$\pm$4%
rms prod divergence	0.10/γ : 0.12/ γ	0.12/γ : 0.19/ γ
Global Tune, υ_x / υ_y	10.79 / 11.15 : 10.44 / 10.64	10.23 / 9.24
βxmax/βymax	117 m : 184 m	155 m / 167 m
Peak Field arcs	6.4T	6.3T
Peak Field prod straight	4.3T : 6.4T*	0.2T**

* solenoids ** quadrupoles

Magnetic components:

- Racetrack:
  - Magnets, in particular SC arc magnets, will resemble design in feasibility I study – see figures below
- Triangle
  - Vertical mounting of SC elements in vertical return arc looks difficult
    - Should look at this aspect asap





Dipole (left) and cryostat design (right) for racetrack, Feasibility I Study

Site Considerations

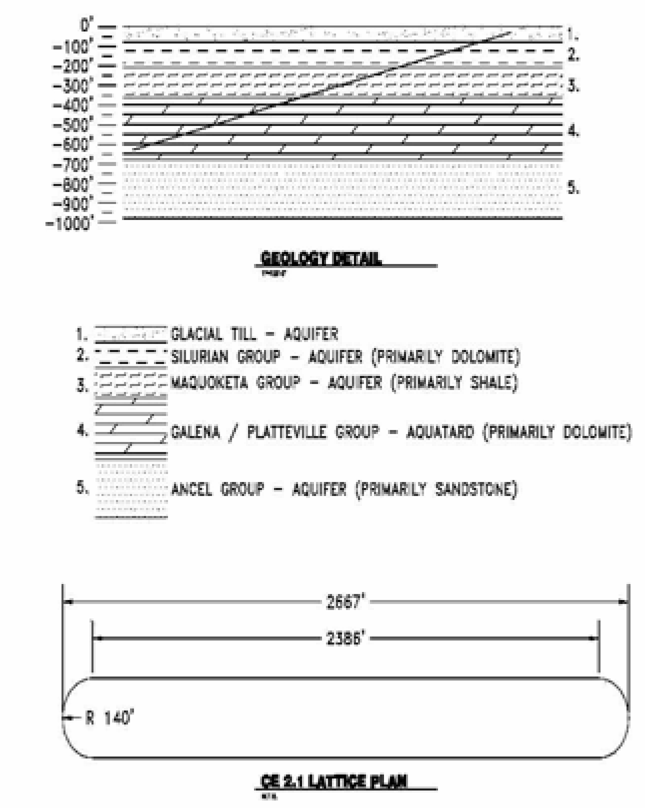
- Detector sites
  - Coupled near/far detector sites in triangular ring (apex angles>~60°, triangle production efficiency rapidly declines)
  - Uncoupled in dual-racetrack case
- Depth
  - Water tables
  - Geological constraints for tunnel construction
  - Civil engineering for tunnels “hundreds of meters” deep

Example: Fermilab Site-specific constraints:
from Feas. I Study for a U.S. Neutrino Factory

- 50 GeV Fermilab Storage Ring: racetrack
  - 13° declination angle
  - circumference, C = 1753 m
  - 39% ratio (1 prod str./C)

Design predicated on ~6T SC arc dipoles

600	Feet	Ring Vertical Drop
10	Feet	Tunnel ceiling to floor
10	Feet	Shielding above ring
50	Feet	Undisturbed bottom layer of Galena Platteville
10	Feet	For uncertainties in the above three numbers
680	Feet	Total from Surface to Bottom of Galena Platteville



Example: BNL site specific constraints:
from Feas. II study for a U.S. Neutrino Factory

- 20 GeV BNL Storage Ring: racetrack
  - 10° declination angle
  - C = 358 m
  - 35% ratio

Design predicated on ~7T SC arc dipoles- (hence the short circumference achieved at 20 GeV)

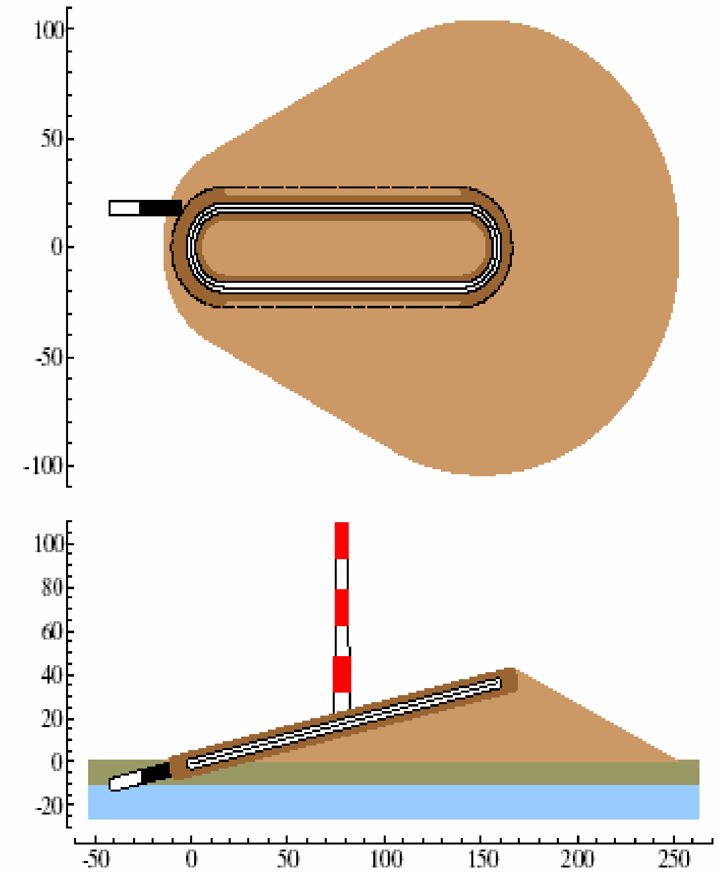


Figure 1.5: Top view and cross section through ring and berm. The 110 m tall tower, drawn to scale, gives a sense of the height of the ring on the BNL landscape.

General concerns

- Site depth and civil engineering:
  - Fermilab and BNL have depth constraints, for example; the larger of the two, restricted to <200m down.
  - The NUMI project at Fermilab entailed considerable civil engineering for an ~1 km long tunnel only 100 m deep – (won the 2005 civil engineering award)
  - Maintenance, water leaks are a problem even with the NUMI depth (muons are much nicer, however, from an activation standpoint)
- # of batches, assuming separate rings for $\mu^{\pm}$, determines ring size
  - ~300 m / batch (400 ns for batch, 600 ns for kicker window)
  - interleave $\mu^{\pm}$ batches in two different rings (otherwise only 1/2 # of batches for one ring)
- Number of batches + 7000 km detector site determines depth

Proposal: n=3 batches each sign muon in two racetrack rings

- Derived from 200 m depth constraint and two-ring, interleaving scheme for $\mu^{\pm}$ batches for the 7,000 and 3,000 detector sites.

$$Ring\ 1: \quad (l_1 + 2r)\sin(36^\circ) = 200m \quad \text{for 7,000 km detector}$$

$$Ring\ 2: \quad (l_2 + 2r)\sin(10^\circ) = 200m \quad \text{for 3,000 km detector}$$

$$\text{current} \quad r(arcs) \sim 48m$$

$$l_1 = 244m;\ l_2 = 1056m: \ \text{production} \quad \text{straight} \quad \text{lengths}$$

$$C_1 = 788m;\ C_2 = 2412m$$

$$Max\ eff_1 \approx \frac{244}{788} \approx 31\%$$

$$Max\ eff_2 \approx \frac{1056}{2412} = 44\%;\ \ avg \approx 37\%$$

Proposal: n=3 batches different sign muons in two triangular rings

- Derived from 200 m depth constraint and two-ring, interleaving scheme for $\mu^{\pm}$ batches.

$$2\ identical\ \ Rings\,(assume\ equilateral):$$
$$(l+r)\sin(10^\circ)+(l+r)\sin(36^\circ)=200m\quad \text{for}\ \ 3\ \text{and}\ 7\text{x}10^3\,\text{km sites}$$
$$r(arcs)\sim 48\text{-}64m;\ \ \text{dispersion}\quad\text{suppressor}\quad\text{dependent}$$
$$l=215m/199m;\quad \text{production}\quad\text{straight}\quad\text{length}$$
$$C=945m;/\,999m$$
$$Max\ eff\ \approx\frac{2\times 215}{945}\Big/\frac{2\times 199}{999}\approx 45-40\%$$

Circumference and efficiency comparisons: Triangle vs Racetrack

Circumference	Triangle 52.8° apex ∠	racetrack
1609	49.6%	38.2%
1258	42.8%	34.9%
944	33.2%	29.9%
804	27.6%	26.3%
629	4.7%	19.7%

Time Structures

- Racetrack rings: 3 batch scenario
  - Ring 1: 3 batches of either μ^+ or μ^-
    - 788 – 3x120 = 428/3 m or 475 ns for kicker window
  - Ring 2: 3 batches of either μ^+ or μ^-
    - For 3 batches: 2412 – 3x120 = 2052/3 m or 2280ns for kicker window.
    - This ring can handle 8 batches with 600 ns for kicker gaps
- Racetrack rings: 5 batch scenario
  - Ring 1: 1 batch of μ^+ and 1 batch μ^- counter-rotating
  - Ring 2: 4 batches of μ^+ and 4 batches μ^- counter-rotating
- Operate racetrack rings at different energies?
- Triangular ring: 3 batch scenario
  - Ring 1: 3 batches of μ^+ or μ^-
  - Ring 2: 3 batches of μ^+ or μ^-

General concerns:

- Site constraints
  - Depth
  - Detector sites/ different for triangle vs racetrack
- Emittance measurements:
- Injection
- Vertical orientation and mounting of SC magnets in triangular ring mechanically challenging?
- Tracking
  - Chromatic correction and other high-order correctors
  - Fringe fields

Recommendations for Future Work

- Further survey of potential detector sites with angular ranges covered by triangular and now bowtie storage rings – preliminary survey done
- Matching to FFAG accelerators
- Mechanical design for vertical mounting of SC magnets
- Design and comparison of injection
  - In production straight
  - In arcs
- Emittance measurement design and accuracy
- Tracking with fringe fields