Neutrino Factory at BNL,
A Special Symposium,
May 4, 2001 at BNL

Muon Collaboration

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

A Compact 20 GeV Muon Storage Ring

The Muon Collider Magnet Working Group:

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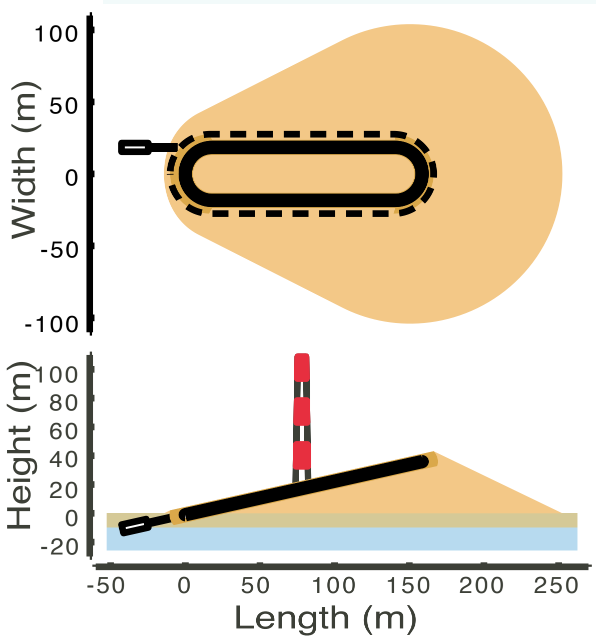
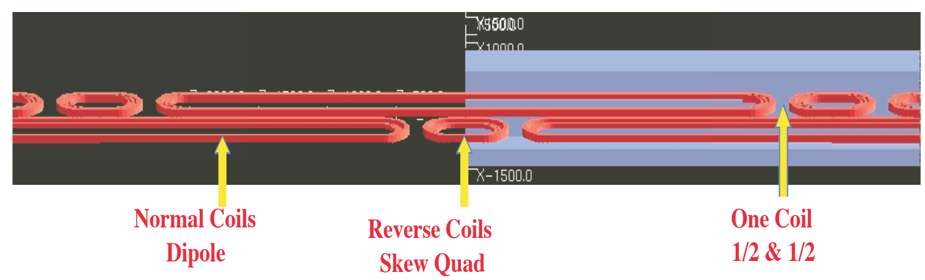
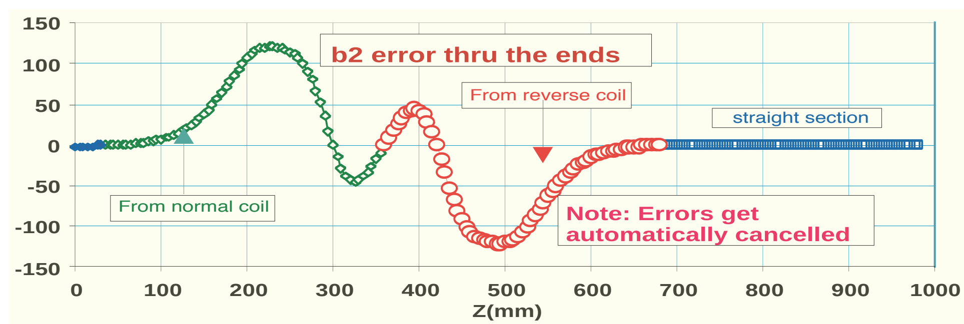
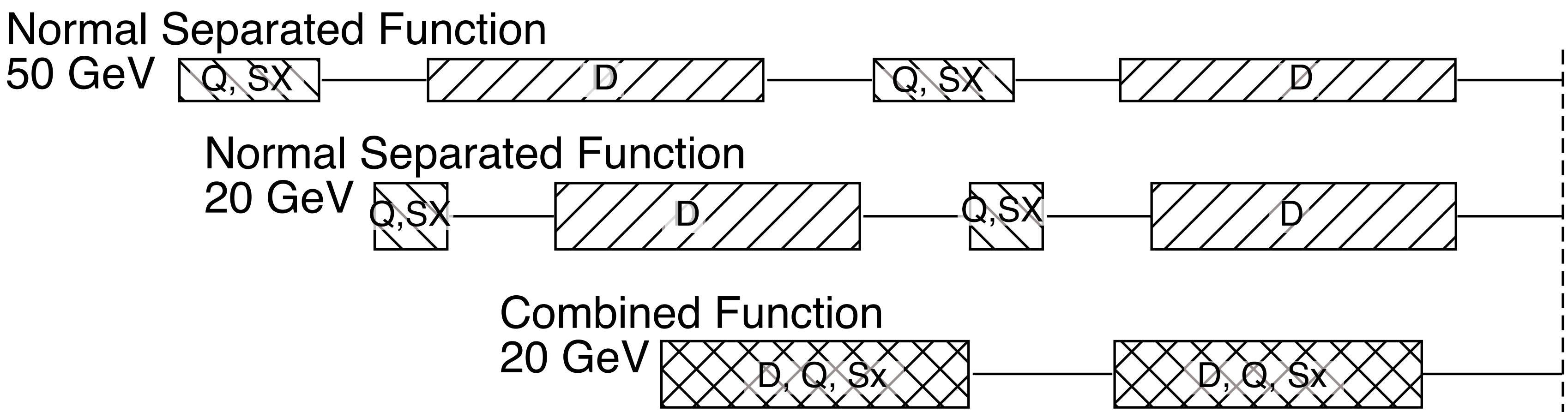


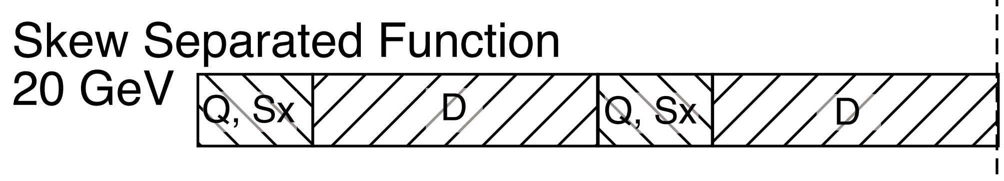




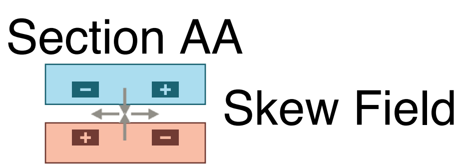
Storage Ring Footprint: Arc Cell Scaling

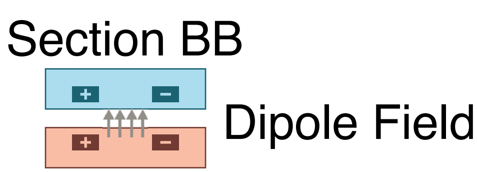


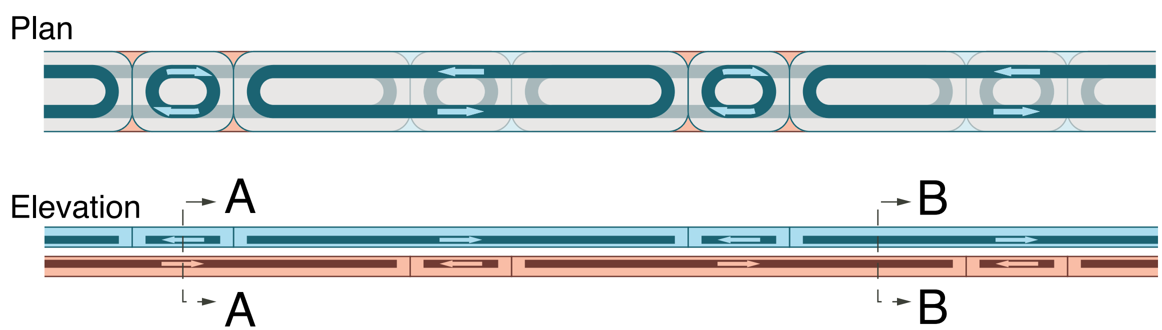
Compact configurations have little or no space lost at coil ends & interconnects.



Stagger top and bottom flat coils for continuous bending and/or focusing.







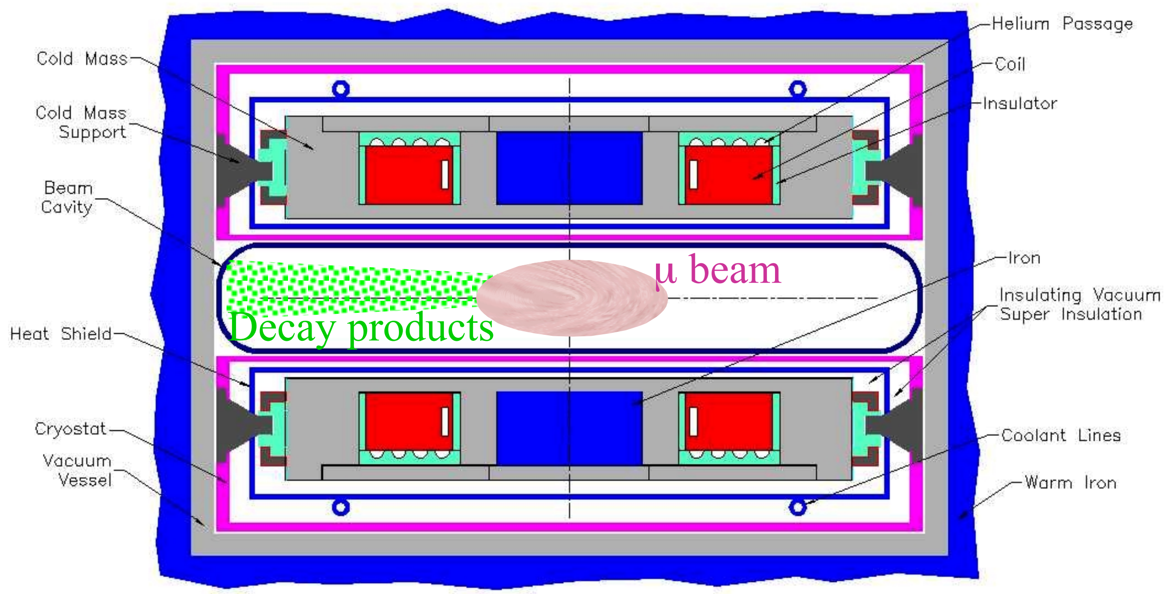
Magnet Design for ν Factory

Design Principles and Requirements:

Decay products clear superconducting coils

Compact ring to minimize the environmental impact (the machine is tilted)

⇨ Need high field magnets and efficient machine design



Storage ring magnet design

(simple racetrack coils with open midplane)

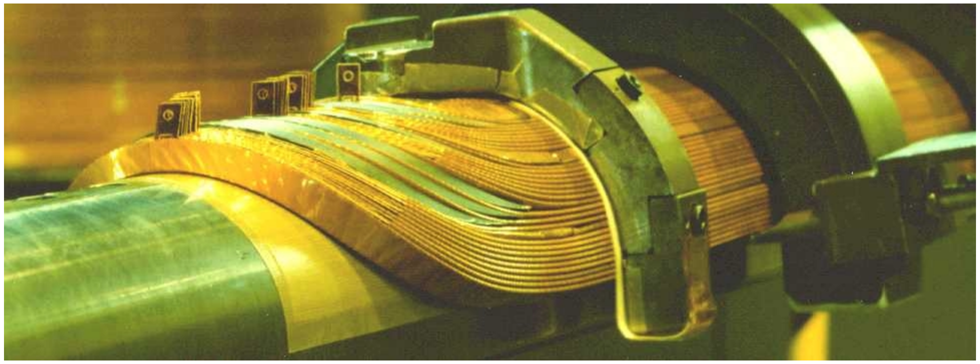
High Field Magnet Design

Design Issues:

- Must use brittle superconductors

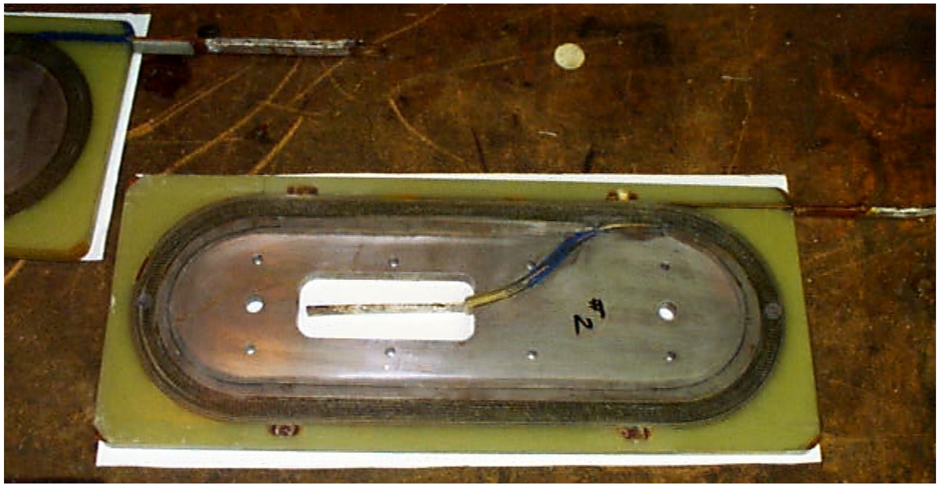
  Nb_3Sn, HTS

- Large Lorentz forces
- Large energy deposition
- Cold coils, Warm iron
- Need compact cryostat
- Large heat leak



Conventional design (e.g., RHIC magnets)

- Complex 3-d geometry -- not suitable for high fields



Conductor friendly racetrack coil geometry (separate program)

- Suitable for high field magnets with brittle material

Muon Storage Ring Arc Magnet Design Harmonics

Dipole Error Summary*

n	$\langle b_n\rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n\rangle$	$d(a_n)$	$\sigma(a_n)$
1	0	0.2	0.2	0	1	2
2	-1	1	2	0	0.1	0.5
3	0	0.1	0.1	0	0.3	1
4	-1	1	1	0	0.05	0.2
5	0	0.03	0.03	0	0.1	0.5
6	-0.3	0.2	0.1	0	0.03	0.1
7	0	0.03	0.01	0	0.03	0.1
8	-0.1	0.1	0.02	0	0.03	0.1
9	0	0.03	0.01	0	0.03	0.1
10	-0.03	0.02	0.02	0	0.03	0.1

Skew Quadrupole Error Summary*

n	$\langle b_n\rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n\rangle$	$d(a_n)$	$\sigma(a_n)$
1	0	0.2	0.2	0	1	2
2	-0.5	0.5	1	0	1	0.5
3	0	0.1	0.1	2	2	1
4	-0.5	0.5	0.5	0	0.05	0.2
5	0	0.03	0.03	1	1	2
6	0	0.2	0.1	0	0.03	0.1
7	0	0.03	0.01	0.5	0.5	0.3
8	0	0.1	0.05	0	0.03	0.1
9	0	0.03	0.01	0.1	0.03	0.1
10	0	0.02	0.01	0	0.03	0.1

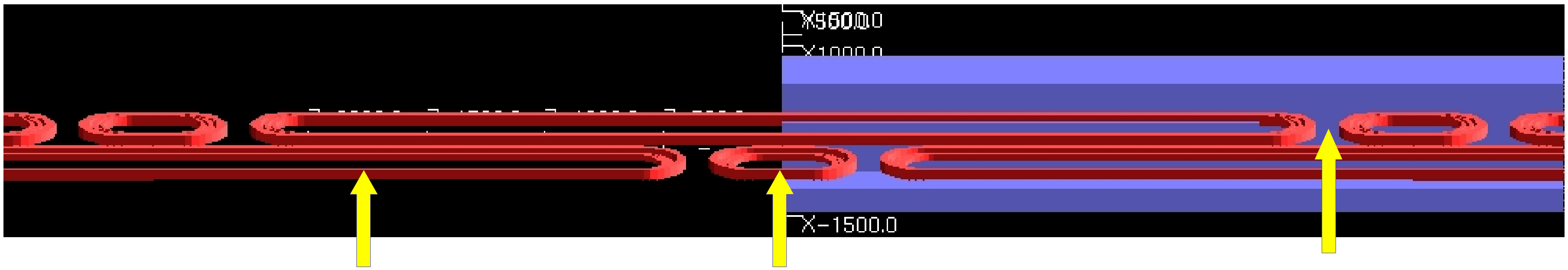
- Coil geometry adjusted so as to give very good body harmonics in both the dipole and skew quadrupole cross sections.
- Coil end harmonics opposite between the neighboring sub-coils for a natural integral cancelation of unwanted harmonics.
- If harmonic goals are relaxed, coil sizes forces etc. could be reduced (beam only has to last for ≈1000 turns).

Estimated errors at a 20 mm reference radius. $\langle b_n\rangle$ and $\langle a_n\rangle$ are the expected means to the normal and skew terms. $d(b_n)$ and $d(a_n)$ are systematic uncertainties arising from design and manufacturing errors, and $\sigma(b_n)$ and $\sigma(a_n)$ are the random uncertainties in those values. Note that n =2 corresponds to a sextupole term.

*Errors given in units, 1 unit = 10^{-4} field deviation.

More Innovations for 3-d Effects

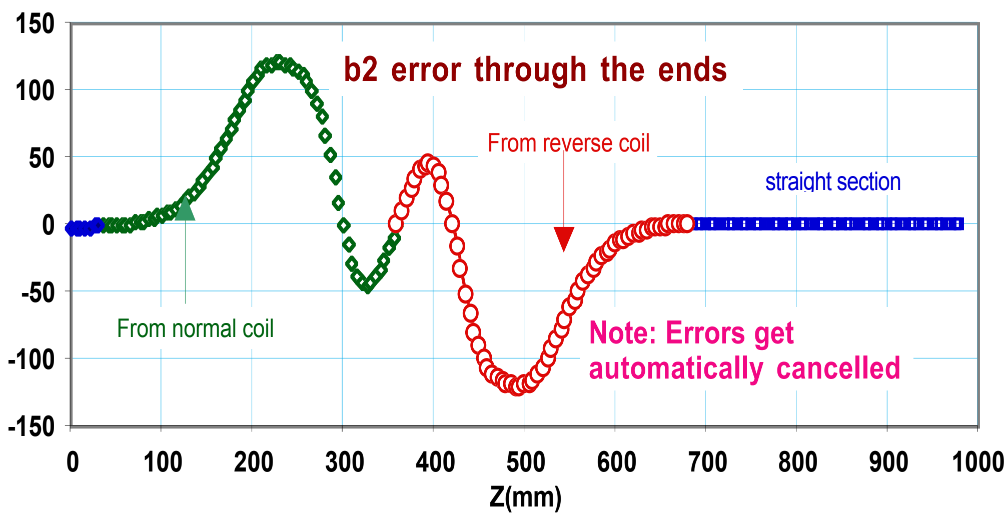
Reverse coils to cancel all field errors in the ends



Normal Coils
Dipole

Reverse Coils
Skew Quad

One Coil
1/2 & 1/2



New Magnet System Design

> Good field quality

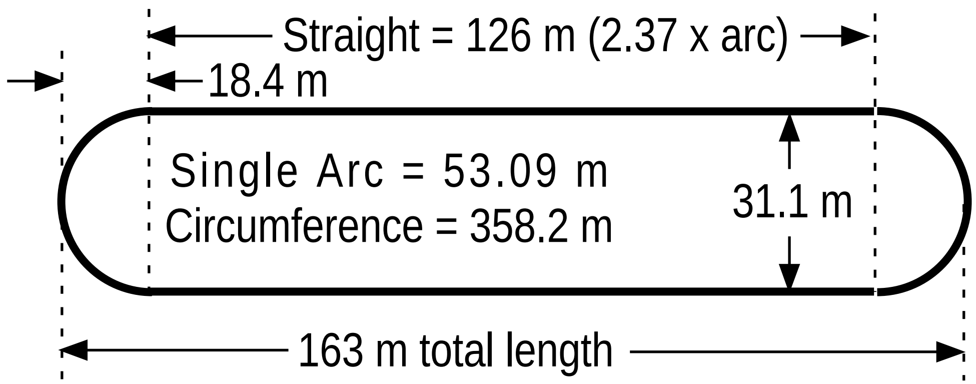
> Makes ring small

Important for BNL site

Ring Layout & Arc Magnet Parameters

Arc Magnet Parameters:

B_1 = 6.93 T, G_1 = 0 T/m, L_1 = 1.89 m
B_2 = 0. T, G_2 = 35.0 T/m, L_2 = 0.76 m
Average B = 4.94 T, L_{cell} = 5.3 m



10 Cell Solution
60° Arc Cell Phase
β_{arc} = 8.69 m

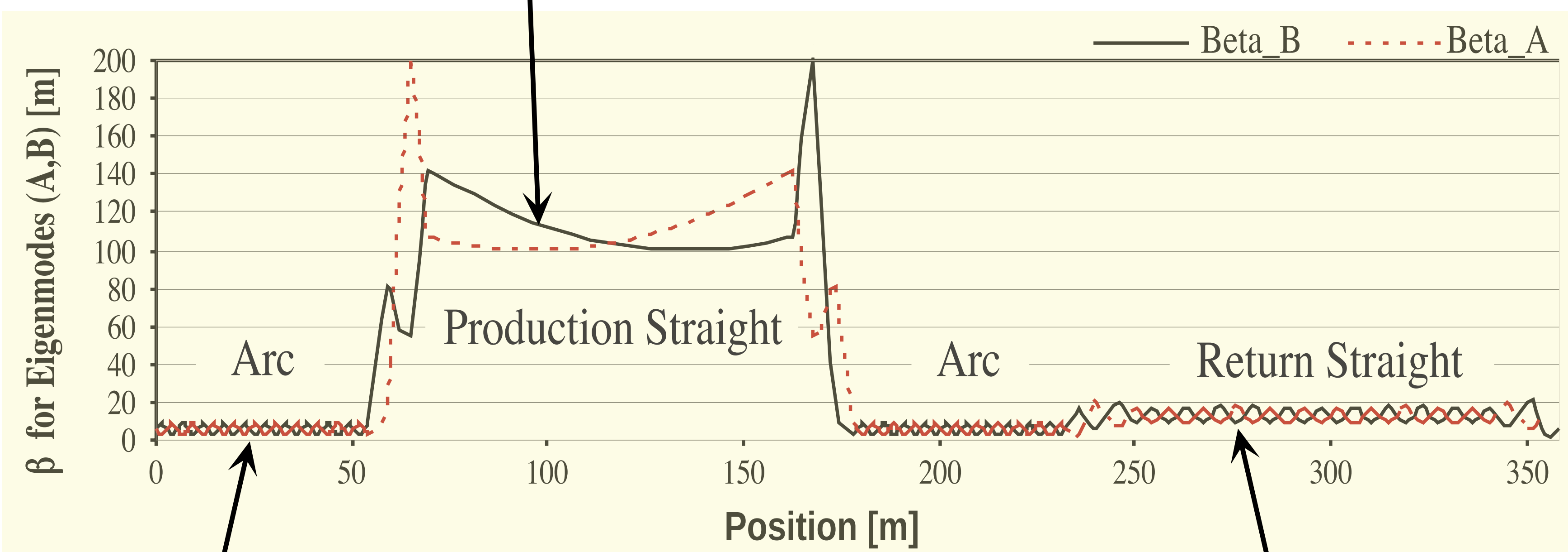
Empty cell has
warm quadrupoles
with G = 27.2 T/m.

Geometric Decay Ratio = $\frac{126 \text{ m}}{358 \text{ m}}$ = 0.35 per straight section

File set: mu_10cell2s, 23-Mar-01, B. Parker

Ring Optics: Arc & Straight Section Summary

126 m production straight section has increased β for reduced beam angular spread and uses normal conducting quadrupoles.

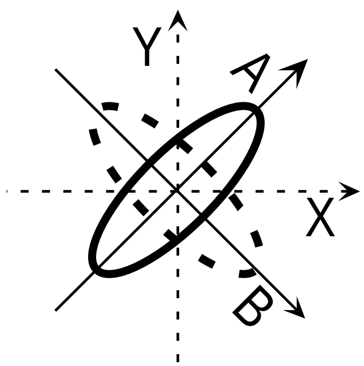


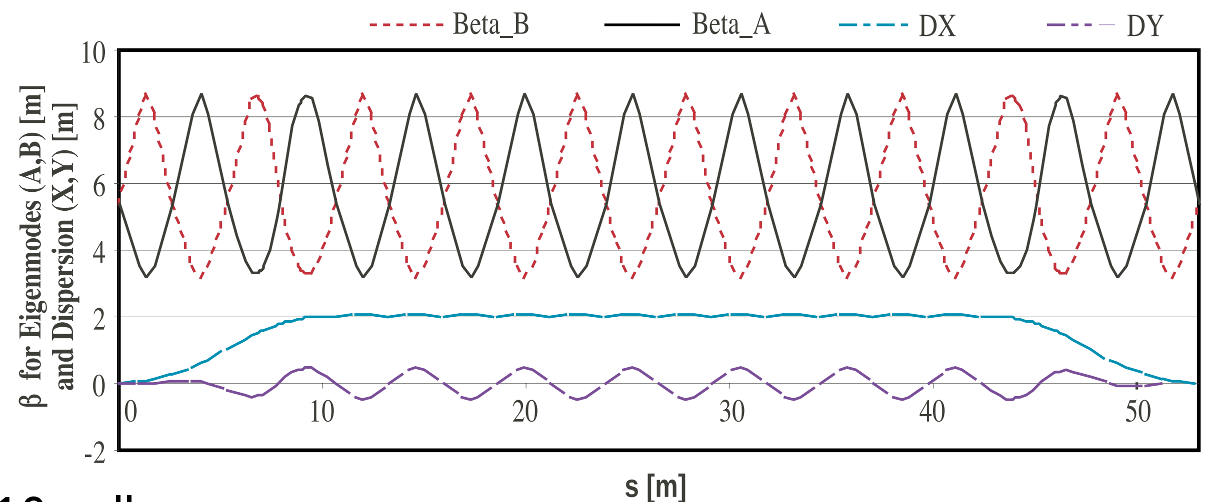
53 m arc is mostly superconducting but has warm sections near each end for collimation.

126 m return straight is used for injection and other machine utility functions. Optics details are TBD.

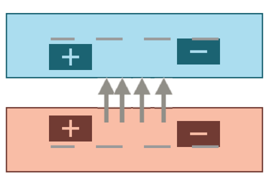
Arc Optics: Linear Optics and Dispersion Suppression

- Eigenplanes are at ±45°.

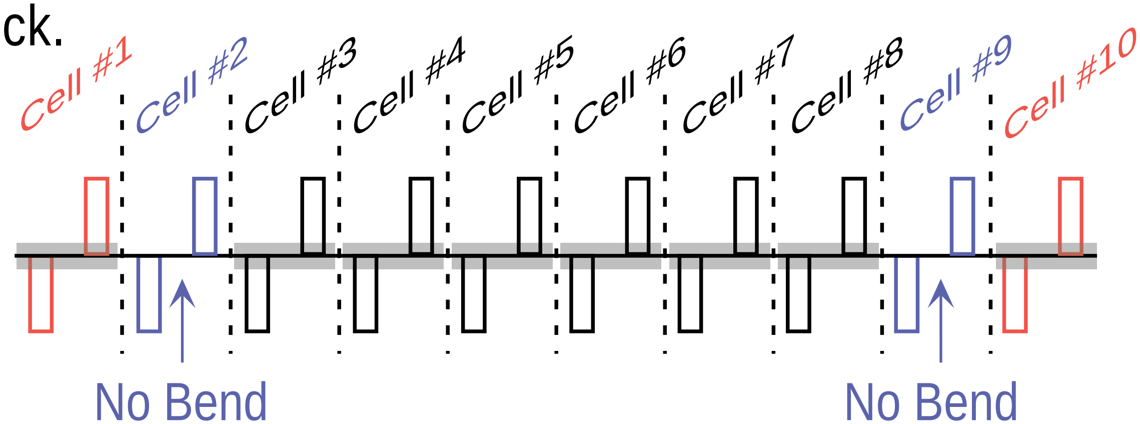




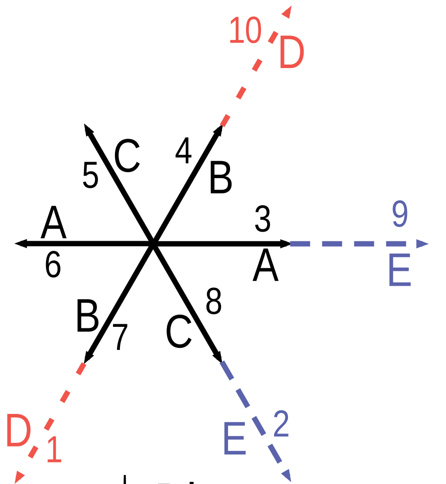
- Use 60° phase advance, 10 cells.
- Add $k_{dipole} = -1/2\rho^2$ (for decoupling).
- Less than 1 mm Δ does the trick.



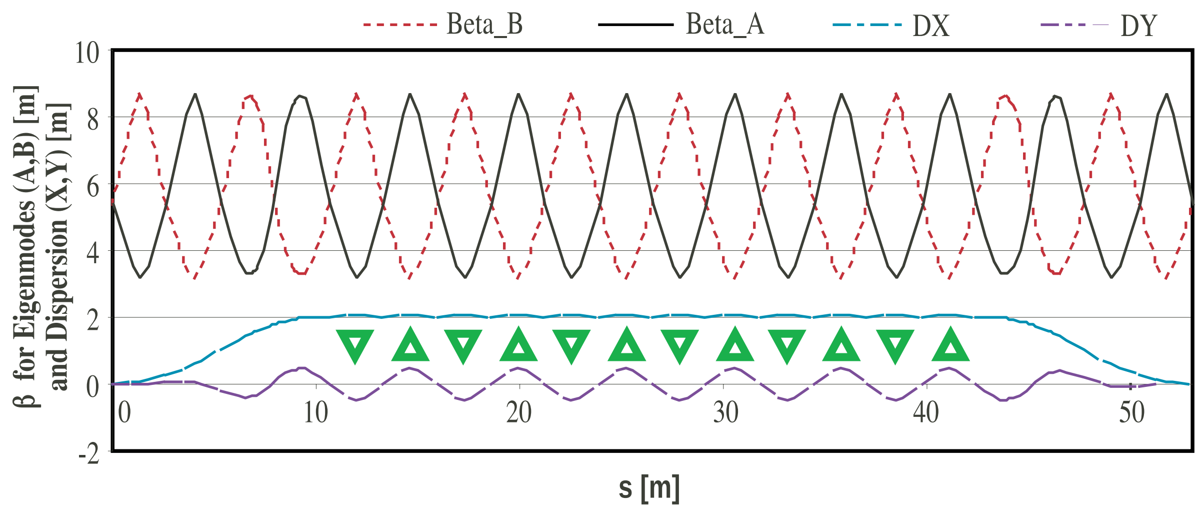
Dipole Section

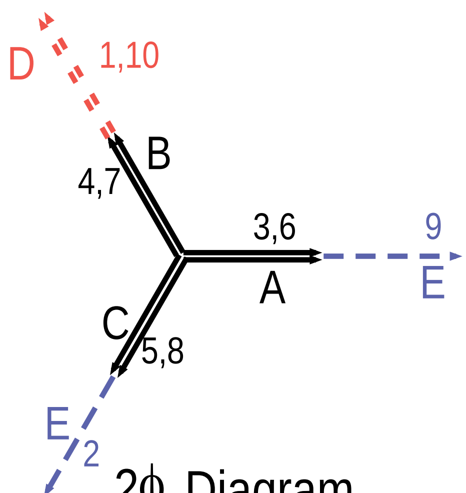


Arc Optics: Skew Sextupoles for Chromaticity Control

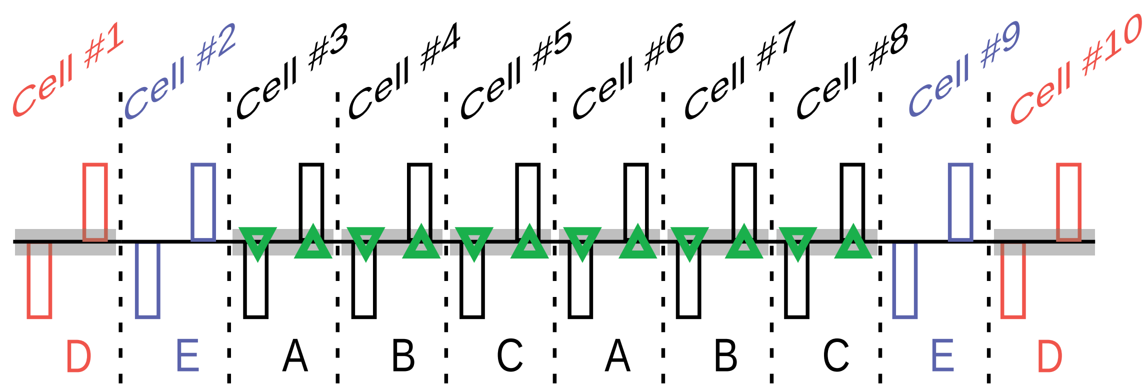


ϕ Diagram
Phase Advance = 60°





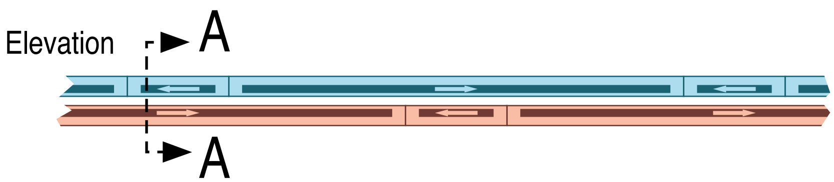
2ϕ Diagram
Phase Advance = 120°



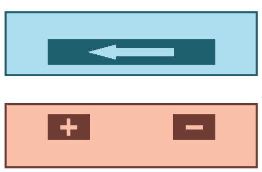
▲ = Skew Sextupole Location

Correction for Solenoidal Field Coil End Effects

At subcoil ends there are solenoidal fields which alter the cell tune and introduce coupling between the A-B planes (seen effectively as a rotation of the eigenplanes).



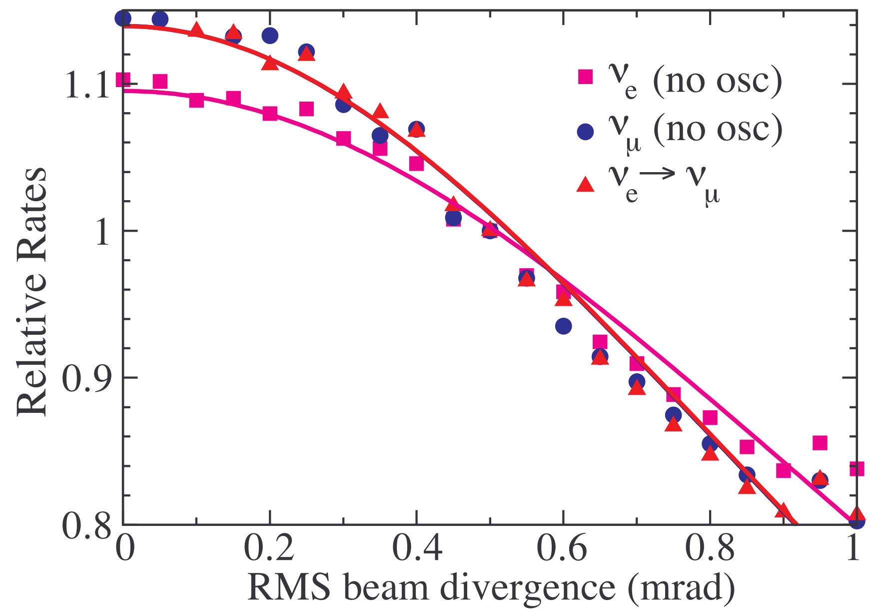
Section AA

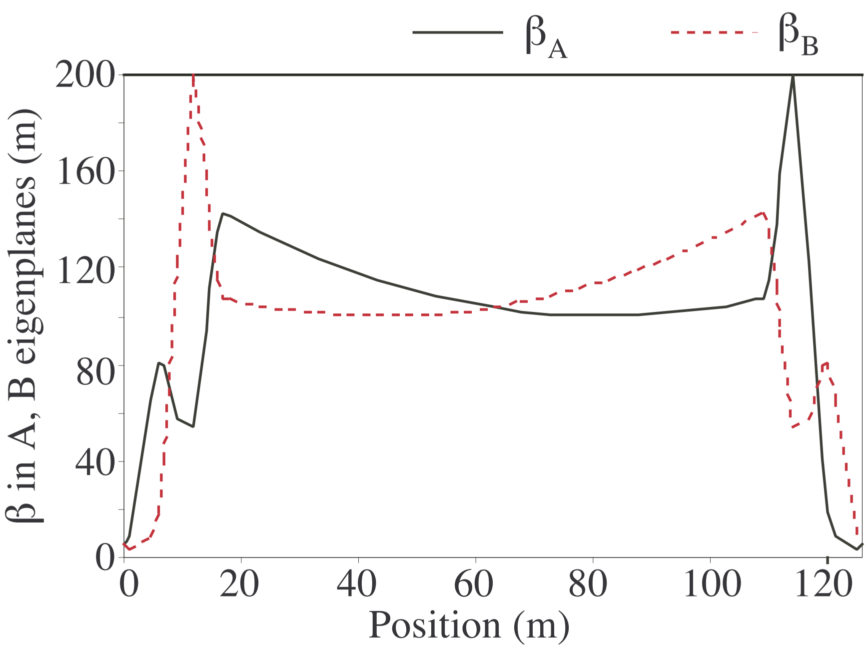


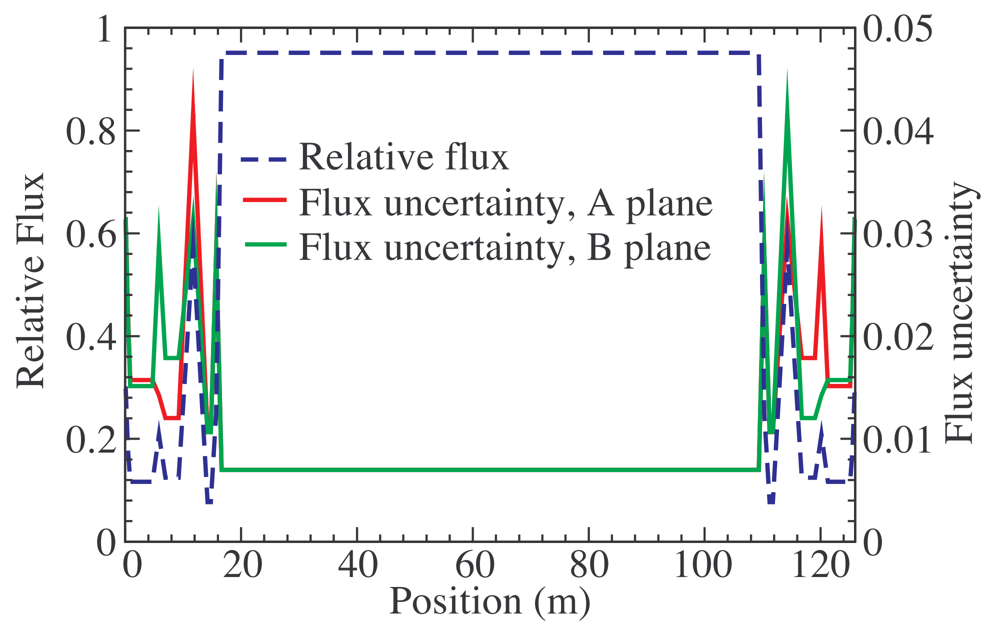
- The rotation can be accurately predicted and like the weak focusing due to the bends can be corrected for with only small coil motions.
- Important to provide the proper arc cell phase advance (cancelation of resonance driving terms and dispersion matching).

Production Straight Optics Requirements

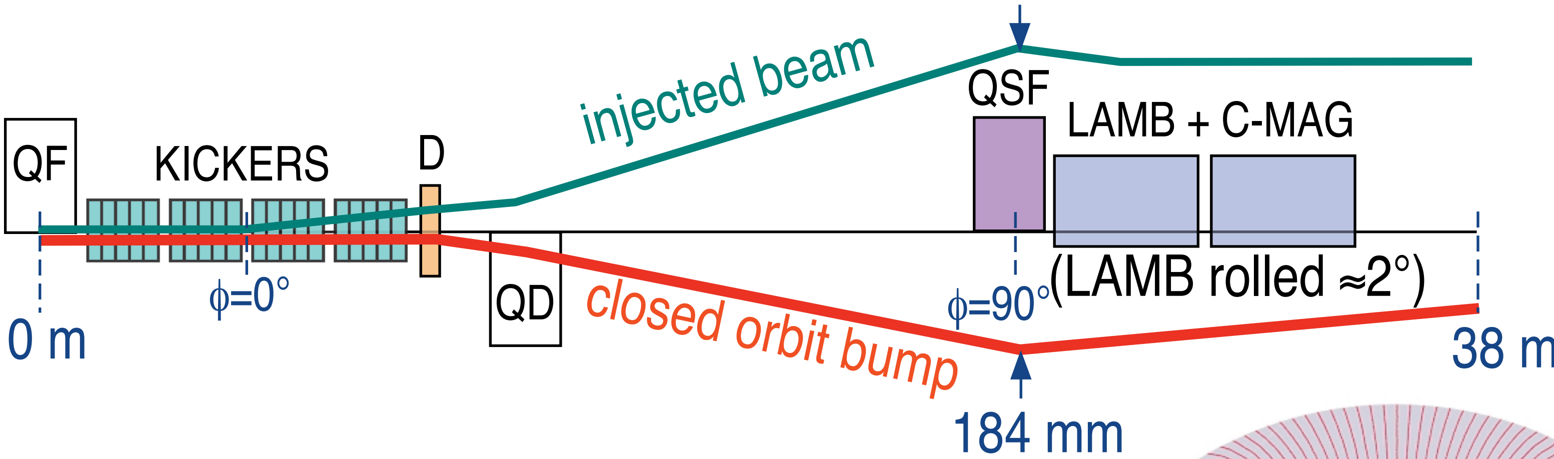
- For smallest uncertainty in ν flux have to keep divergence due to optics small (small $\gamma = \{1+\alpha^2\}/\beta$).
- We do this with long central drift.
- Make matching section short.
- But then γ is large & contributes to uncertainty (add extra bends).





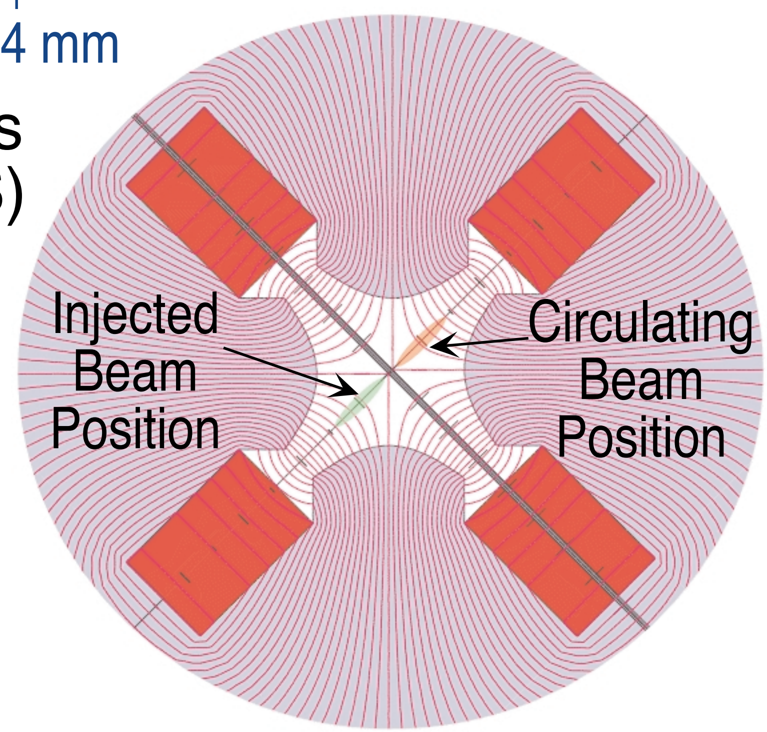


Muon Storage Ring Injection Layout Schematic



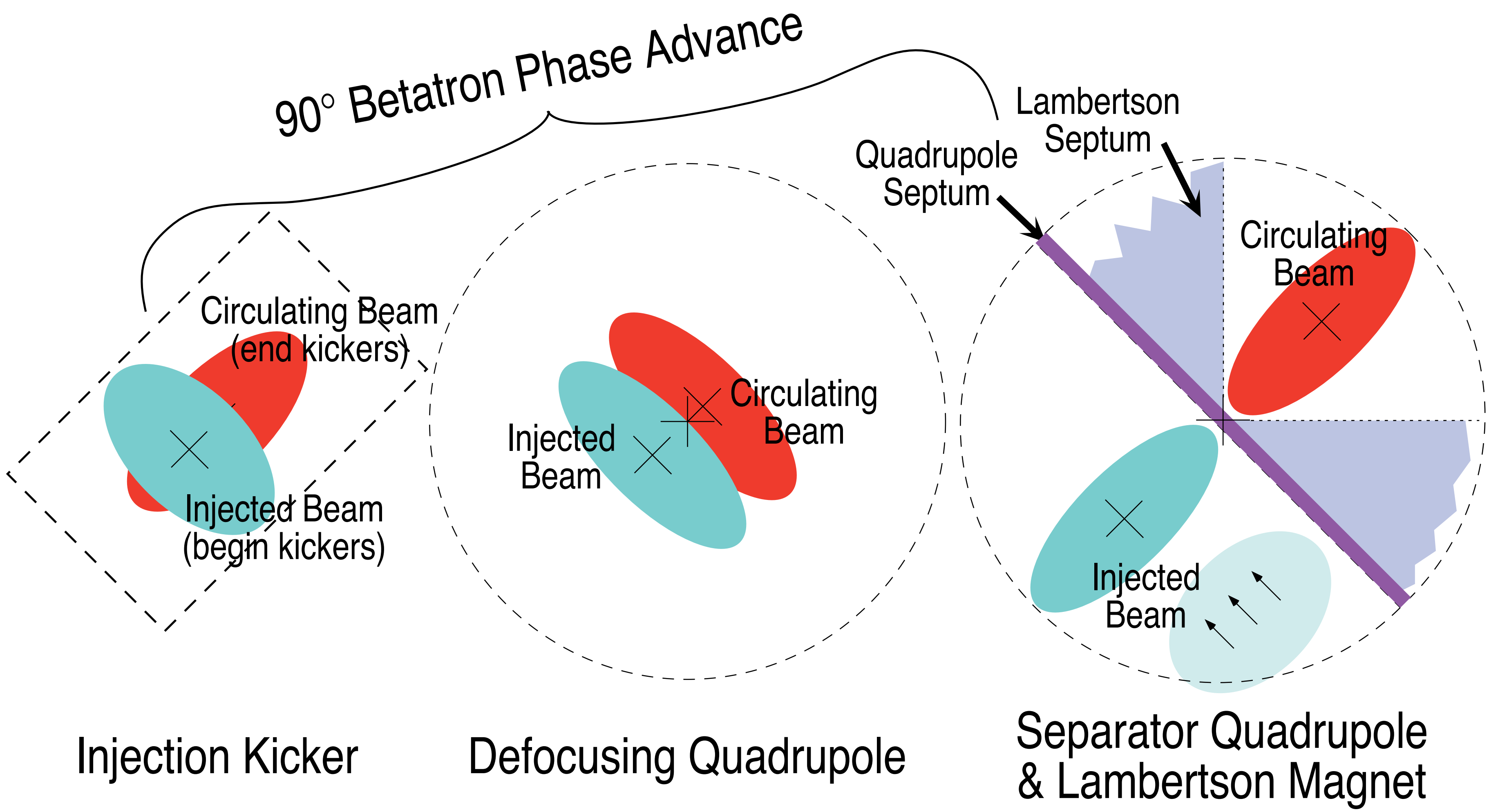
- 20 SNS style kickers, but $\tau = 0.8\mu s$ (4 x SNS) and B = 0.05T (2 x SNS) for total 6 mrad kick.
- FODO cell with peak β = 44m and 25.6m cell length.
- 90° phase advance between kickers and septum magnets.

About 30% of the return straight length is used for injection with this scenario.



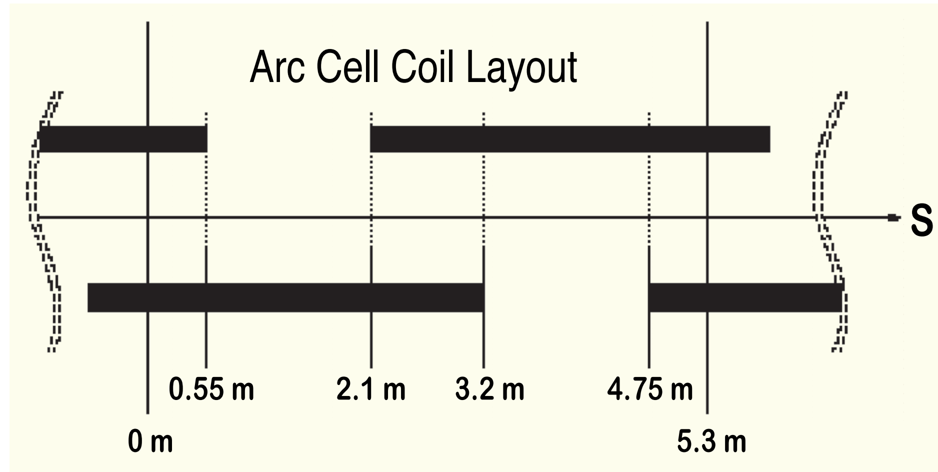
Quadrupole Separator Septum Magnet, QS, made from existing type (same as QF & QD)

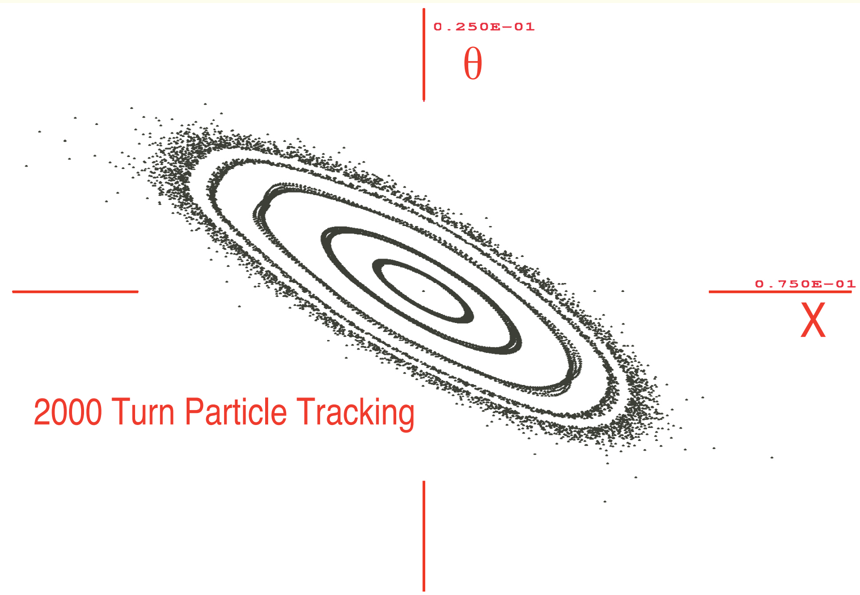
Muon Storage Ring Injection Aperture Schematic



Preliminary Particle Tracking Studies

- Tracking studies performed on single arc cell using COSY INFINITY.
- Studies made using original arc cell configuration (e.g. no counter coil).
- Look at nonlinear fields and end effects.
- Should adjust cell to regain 60° phase (correct for fringe and solenoidal fields).





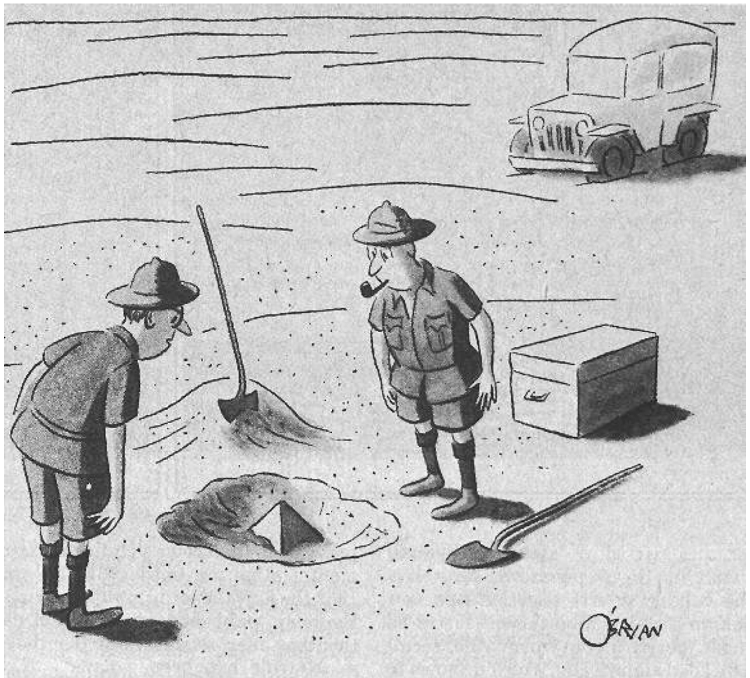
	No Fringe Field Effects	With Fringe F. Effects
Initial approximation	0.166667 (60°) 0.166667 (60°)	N/A
Thick lens model	0.168422 (+0.6°) 0.168422 (+0.6°)	0.168040 (+0.5°) 0.166919 (+0.1°)
With solenoids	0.162584 (-1.5°) 0.174157 (+2.7°)	0.162190 (-1.6°) 0.172703 (+2.2°)

Linear Tunes for the Two Orthogonal Planes

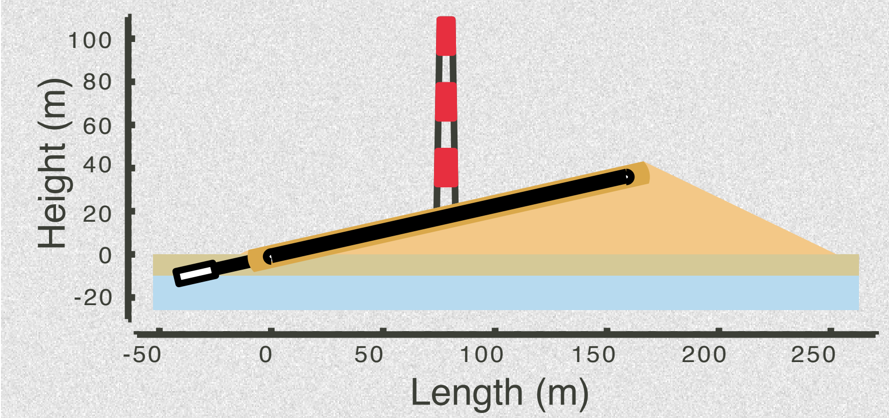
Summary and Some Areas for Future Work

- We now have a 20 GeV muon storage ring lattice:
  - ◊ with a compact arc that reduces the hill size,
  - ◊ a long high-β drift (ν beam divergence goals),
  - ◊ and a straight section that has space for injection and other machine utility functions.
- Need to continue tracking and energy deposition calculations (final field harmonics, aperture, coil and cryostat specifications).
- Work out orbit correction schemes and design of skew sextupole coils.

A Compact 20 GeV Muon Storage Ring



"This could be the discovery of the century. Depending, of course, on how far down it goes."



This could be a machine at Brookhaven. Depending of course, on how far it goes up and down.

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