Muon Collaboration

Editors Meeting
January 29-31
2001at BNL

BROOKHAVEN
NATIONAL LABORATORY

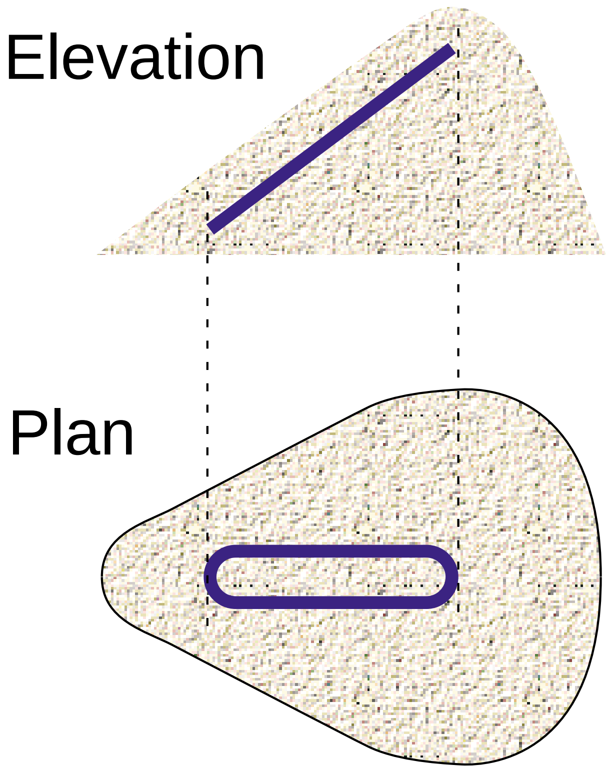
Superconducting
Magnet Division

Neutrino Factory Feasibility Study-II

Storage Ring Lattice

Magnetic Design

Study-II Challenge: Storage Ring Footprint



Ring Layout

For Study-II it is important to find a solution that gives a very compact arc.*

- For given straight section decay ratio a shorter arc reduces the site footprint.
- For given straight section length a shorter arc increases ν production efficiency.

*Here arc definition includes all regions with dipoles.

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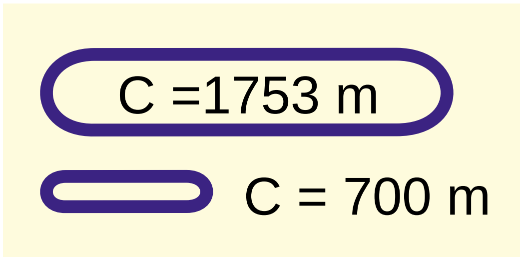
How small can we go?

Storage Ring Footprint: Ring Scaling Part 1

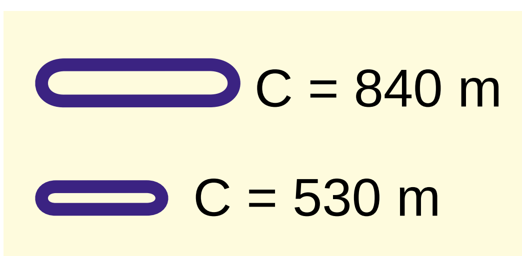
First consider energy scaling from 50 to 20 GeV



Overly naive scaling gives:

1753 m x (2/5) $\approx$ 700 m

- The magnet ends do not follow above scaling.
- 250% larger emittance at 20 GeV drives larger magnet apertures (longer ends, weaker fields).
- So want to have shorter cell lengths to reduce arc beta and dispersion maxima.



More involved scaling yields 20 GeV circumference > 840 m.

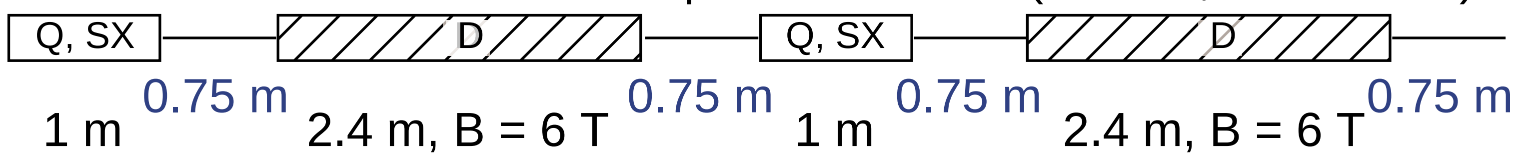
Yet our design has 530 m.

Storage Ring Footprint: Ring Scaling Part 2

But in practice we see that most of the reduction comes from having fewer cells. We expect to have only a small reduction in cell length (example 15%).

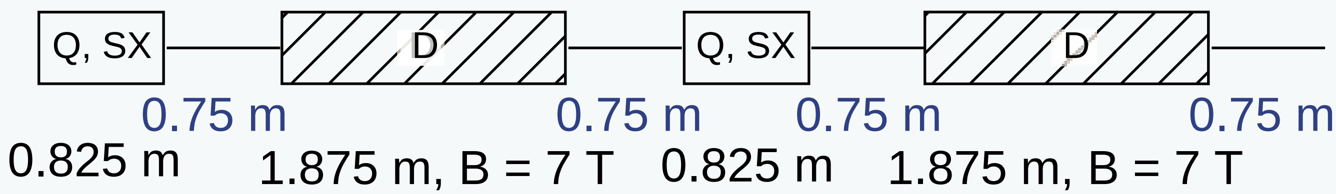
Study-I Cell: separated function, 90° phase advance and 9.8 m length.

Max. beta ≈ 16 m & Max. Dispersion ≈ 1.1 m (50 Gev, 173 mr/cell)



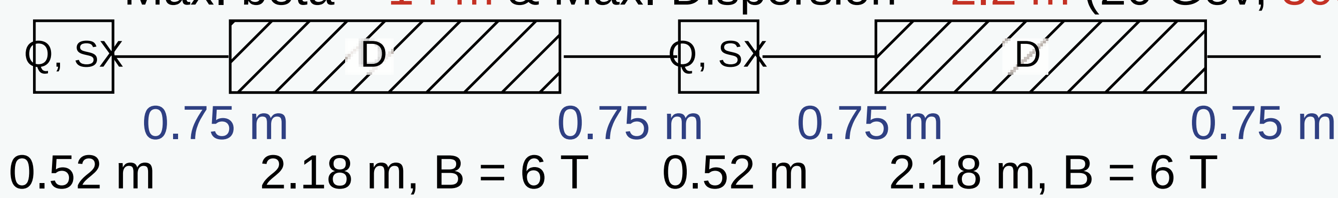
1'st Try: separated function, 90° phase advance and 8.4 m length.

Max. beta ≈ 14 m & Max. Dispersion ≈ 2.2 m (20 Gev, 393 mr/cell)



2'nd Try: separated function, 90° phase advance and 8.4 m length.

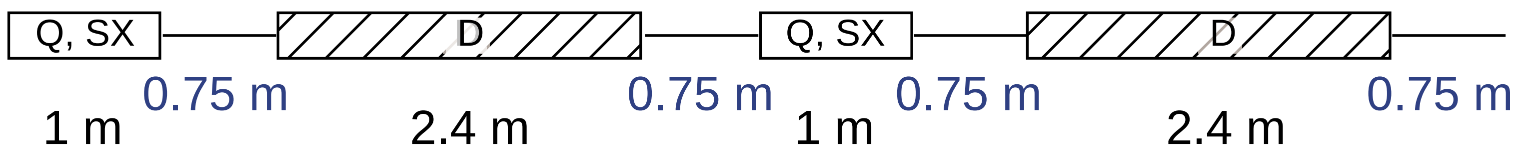
Max. beta ≈ 14 m & Max. Dispersion ≈ 2.2 m (20 Gev, 393 mr/cell)



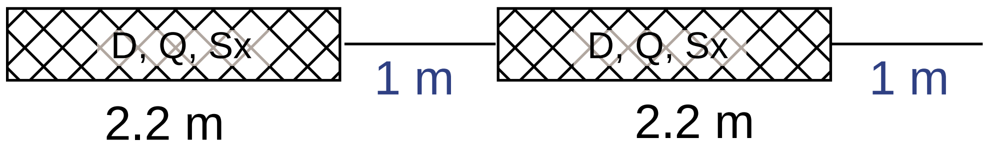
Storage Ring Footprint: Ring Scaling Part 3

Significant compaction can come from eliminating some magnet interconnects and adding dipole plus quadrupole fields (combined function lattice).

Study-I Separated Function Cell: 9.8 m length.



Combined Function Cell: 6.4 m length.

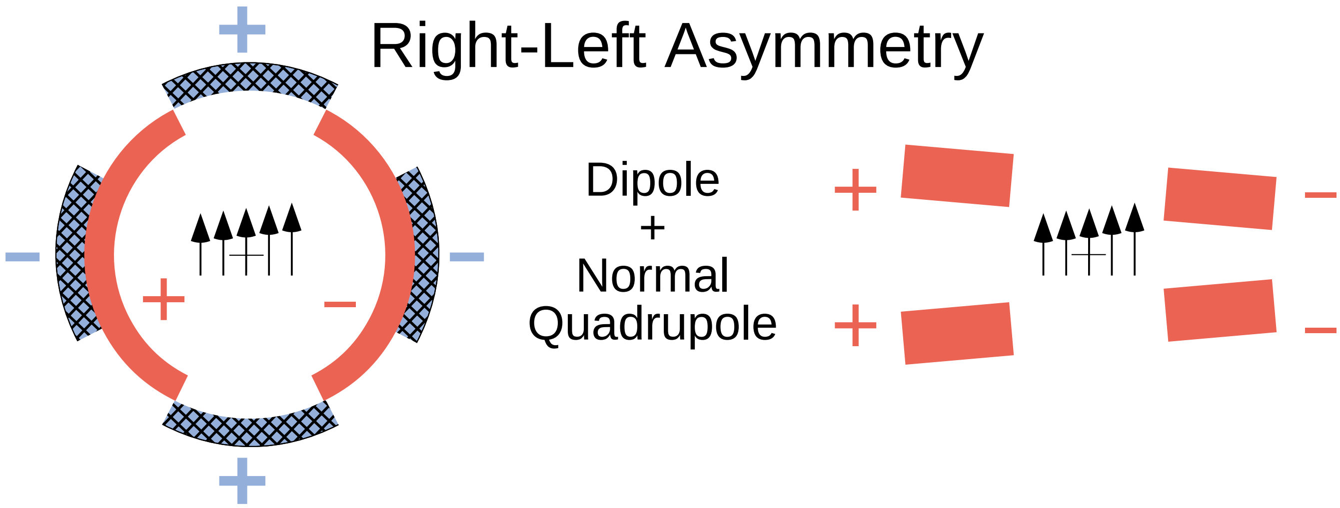


Note: Magnet interconnect distance relaxed so as to take up same relative fraction as for Study-I cell.

- **Combined function avoids bending dilution in quadrupoles.**
- **Permits more space for interconnect without great penalty.**
- **Works with either upright or skew-quadrupole focusing.**

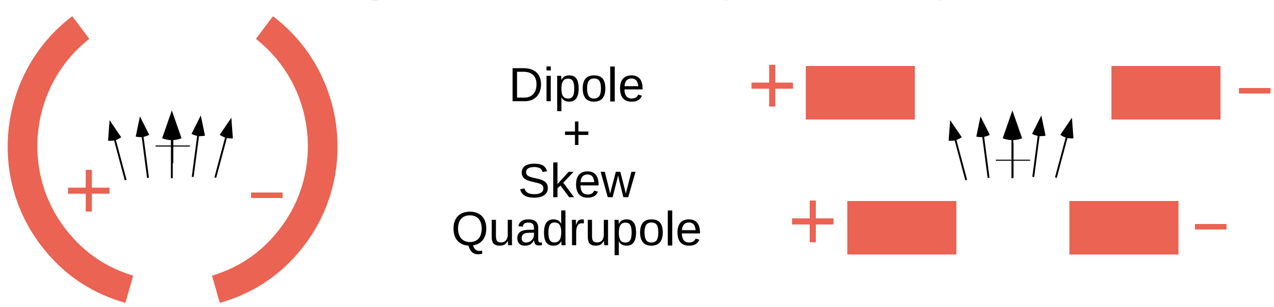
Some Combined Function Magnets

Right-Left Asymmetry



Top-Bottom Asymmetry

Top-Bottom Asymmetry



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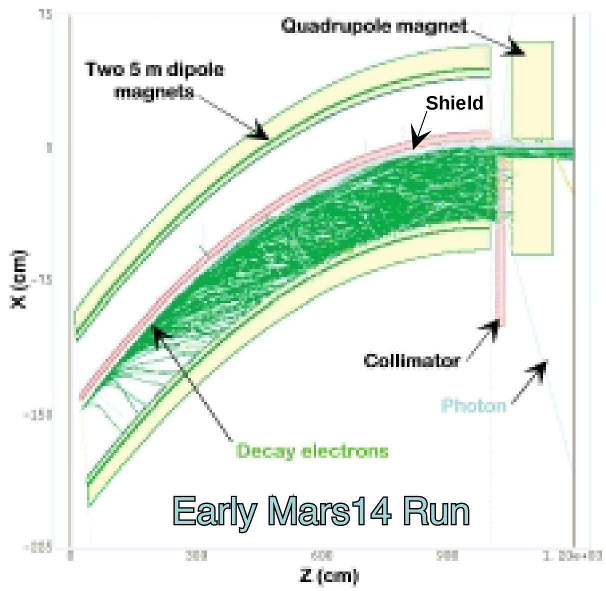
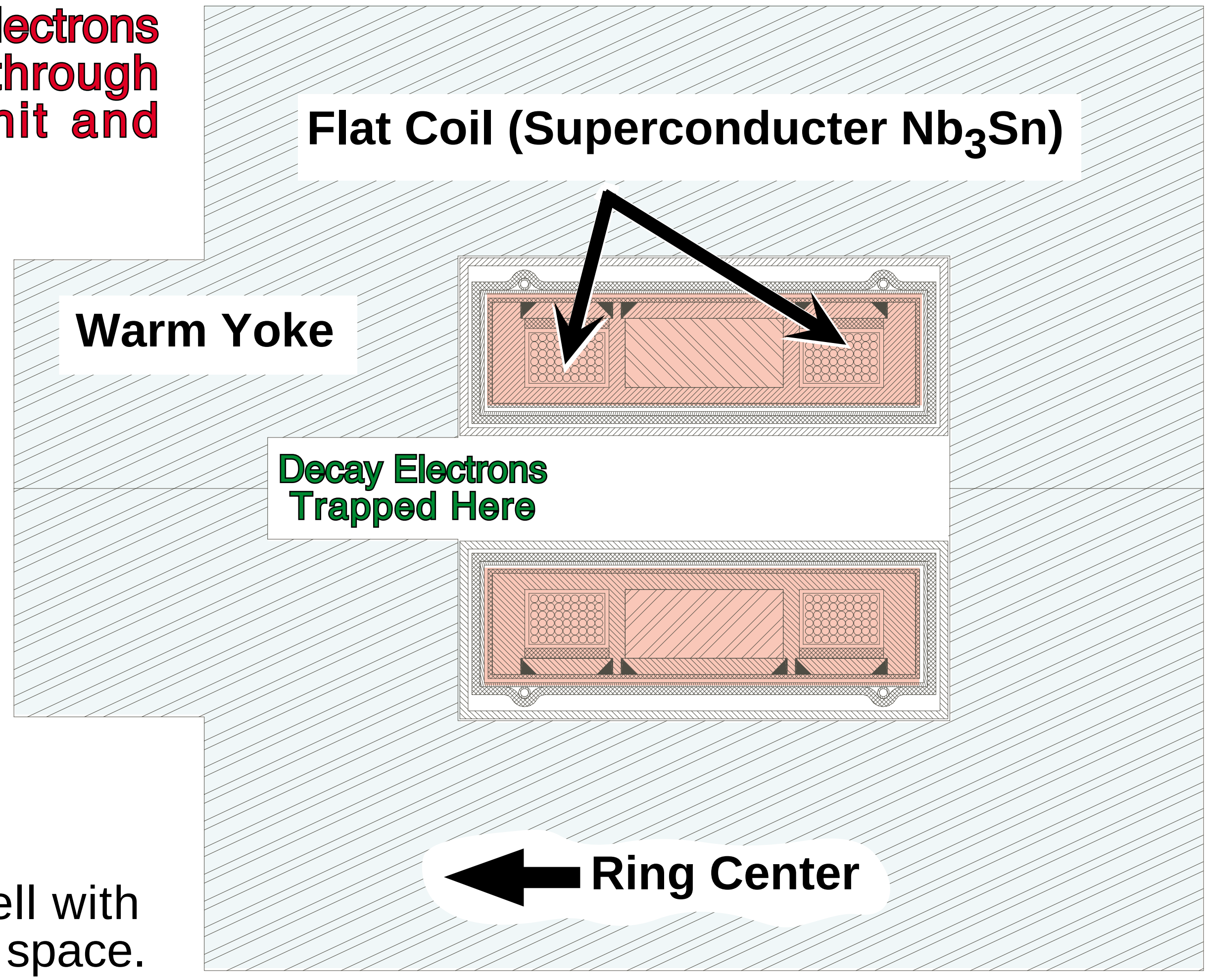
Original Storage Ring Dipole Concept

We anticipated that decay electrons either passed completely through the magnet or at worst hit and showered in warm material.



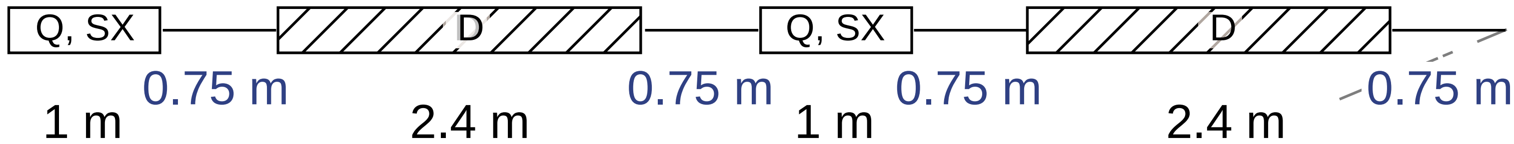
But a separated function cell with a warm quadrupole uses up space.



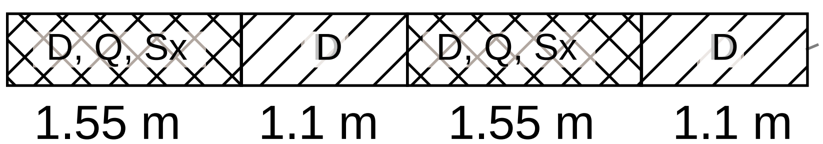
Storage Ring Footprint: Ring Scaling Part 4

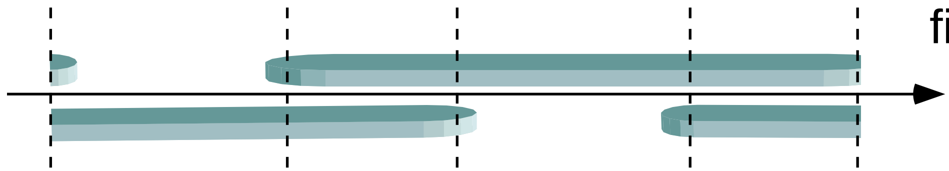
Most compact configuration has dipole field throughout cell and no space lost to coil ends or interconnects.

Study-I Separated Function Cell: 9.8 m length.



Compact Combined Function Cell: 5.3 m length.





Transition from high to low field takes place at coil ends.

Coil Schematic

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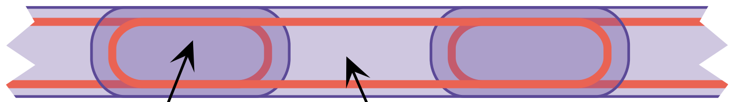
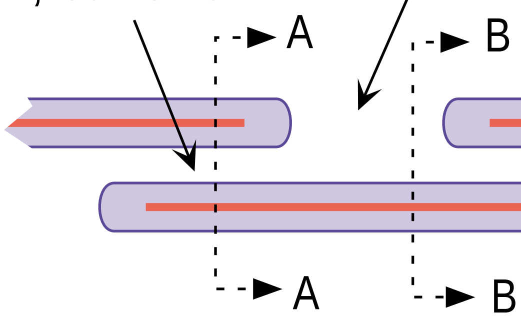
Combined Function Skew Quadrupole Cell Principle

Plan View



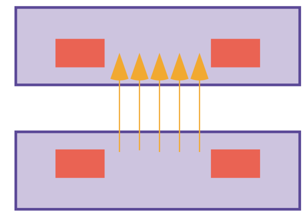
Full coil overlap gives the full field, B = 7 T, but G=0

Single coil for half field, B = 3.5T, but G=20T/m



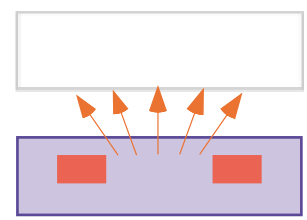
Elevation View

Section A-A



B = 7 T
G = 0 T/m
No skew

Section B-B

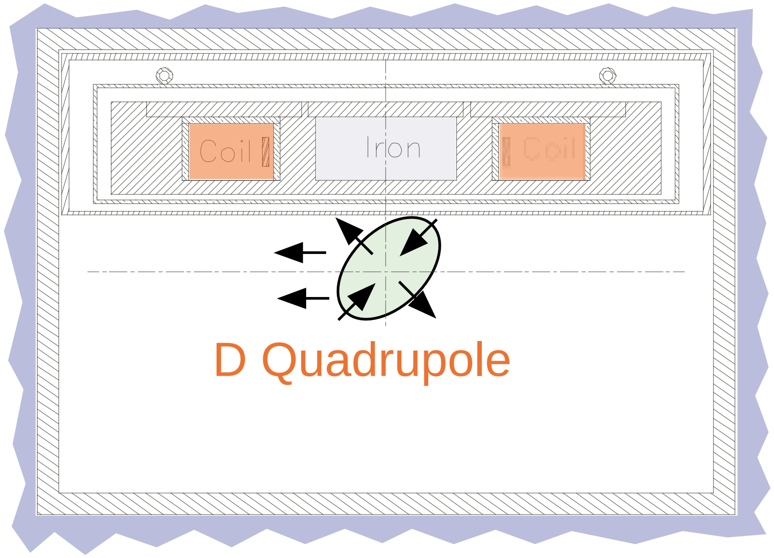


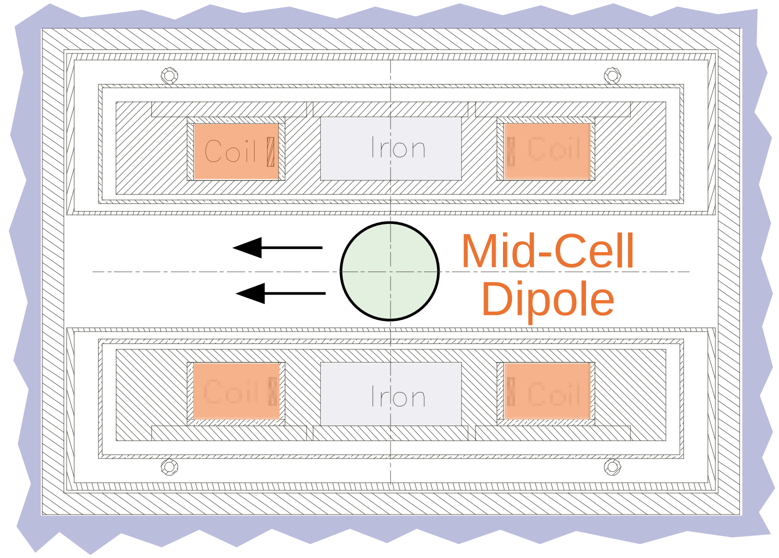
B = 3.5 T
G = 20 T/m
Skew Quad

Net result is to use space which is normally wasted between coil ends.

- Flat coils are longitudinally staggered in a warm iron yoke.
- Coil ends are spread longitudinally to adjust integral harmonics.
- Coils bend in the horizontal plane to follow circulating beam.

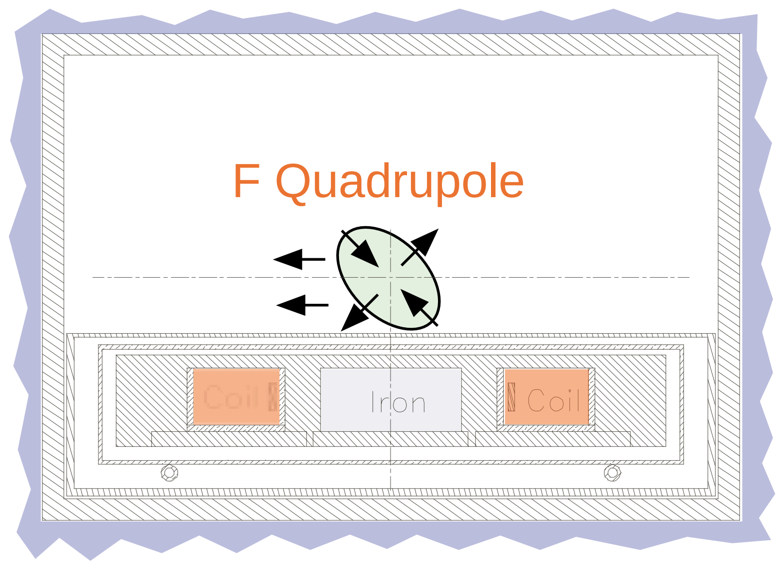
Skew Focusing Lattice Concept





- Round beam at dipole center.
- Tilted ellipse where focused.
- Independent betatron motion (profile does not tumble).

Note beam sizes are drawn for areas where dispersion is almost zero, near the beginning and end of the arc.



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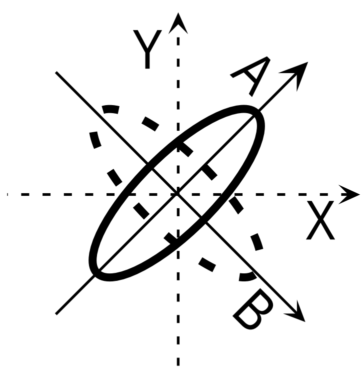
Skew Quadrupole Lattice Design Principles

Skew Quadrupole Lattice ≢ Fully Coupled Lattice

The lattices presented here are uncoupled. They are special only in that the betatron eigenplanes (denoted A,B) line up with ±45° rather than the horizontal (X) and vertical (Y) axes.



Useful Trick:

Every dipole with bend radius, ρ, has a weak normal focusing component, $k = -1/(2\rho^2)$ added in order to make the focusing cylindrically symmetric.

What is the lattice like?

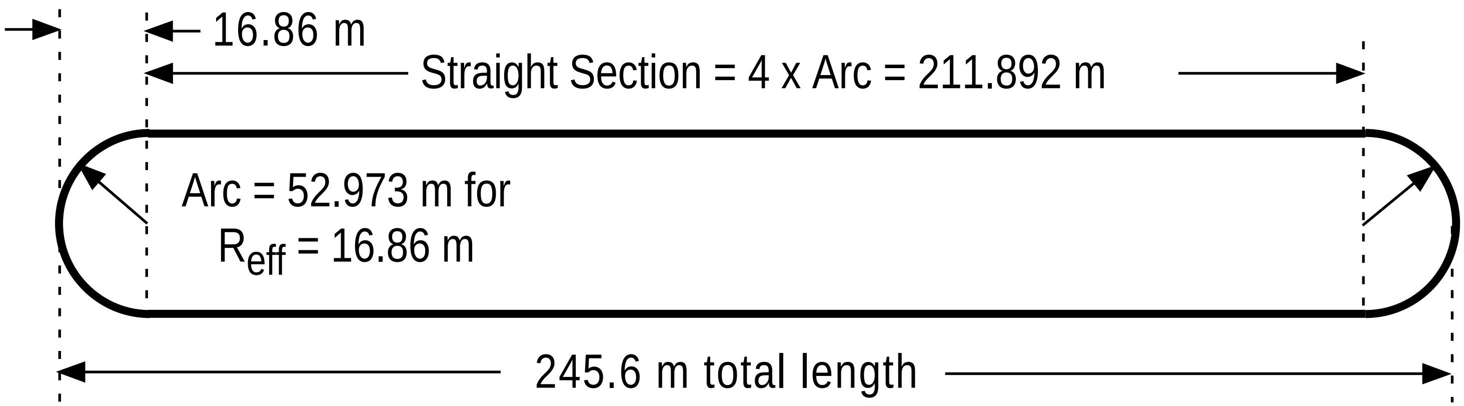
Ring Layout & Arc Magnet Parameters

Arc Magnet Parameters:

B_1 = 6.986 T, G = 0 T/m, L_1 = 1.10 m

B_2 = 3.493 T, G = 20.0 T/m, L_2 = 1.55 m

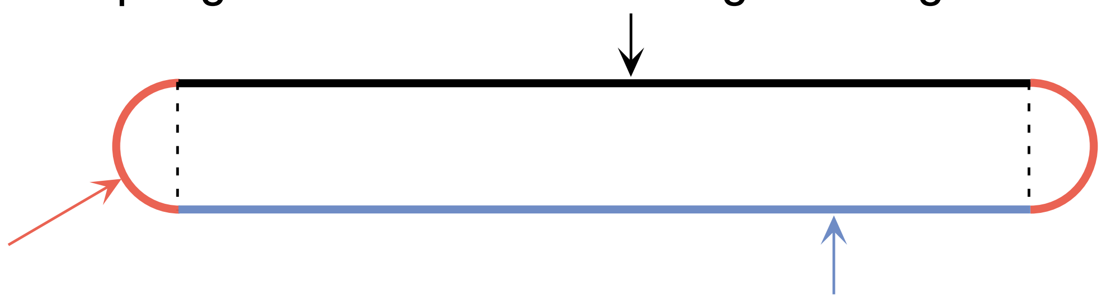
Average B = 4.943 T, L_{cell} = 5.3 m



$$\text{Decay Ratio} = \frac{211.892\ \text{m}}{529.730\ \text{m}} = 0.4 \ \text{per straight section}$$

Storage Ring Lattice Modules and Their Functions

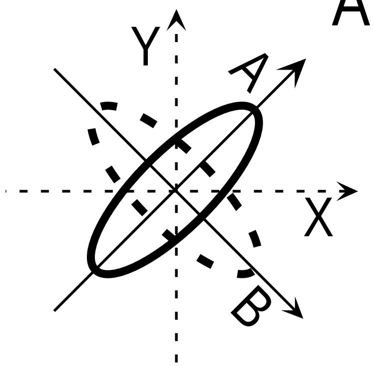
Production straight is 4 times longer than arc for a 0.4 decay length ratio. Average beta of 91 m adds 1% to the ν-beam divergence. Will introduce normal quadrupoles for coupling control. Also use long drift regions for RF?



Arcs have 10 cells
Beta peak = 8.8 m
Phase/cell = 60°
Cells w/o bending near ends
for dispersion suppression
Skew-sextupoles are used in 6
central cells for chromaticity
correction

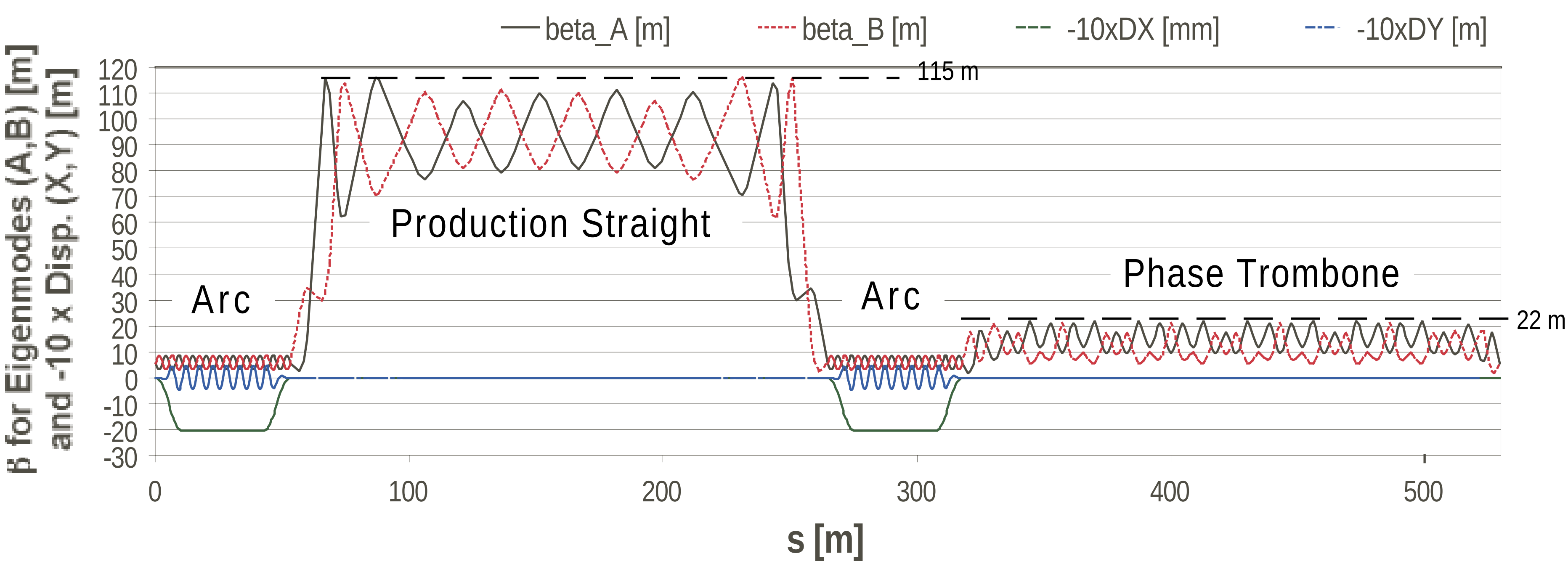
Second straight has natural beta about double that in arcs but cells are adjusted to make a phase trombone yielding 1 unit phase difference between A and B eigenplanes. Ring tune adjustment is done here. Also can introduce injection elements here.

Skew Combined Function Ring Lattice



Arc Cell Parameters: $\Delta\phi = 60°$ $\nu^{Ring}_{A,B} = (6.81, 7.82)$

$\beta^{(A,B)}_{max} = 8.78$ m	$\eta_X = (\eta_A+\eta_B)/\mathrm{sqrt}(2)$	$\eta_Y = (\eta_A-\eta_B)/\mathrm{sqrt}(2)$
$\beta^{(A,B)}_{min} = 3.17$ m	$\eta^{(A,B)}_{Long} = 1.779$ m	$\eta^{X}_{max} = 2.067$ m
$\beta_{avg} = 5.97$ m	$\eta^{(A,B)}_{Short} = 1.144$ m	$\eta^{Y}_{max} = 0.449$ m



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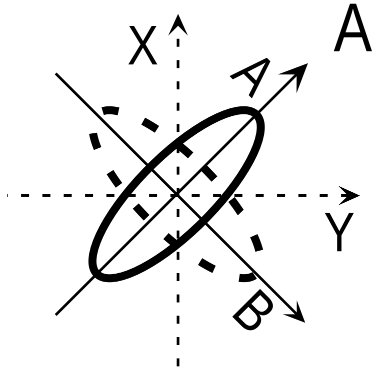
Arc Lattice Functions Detail



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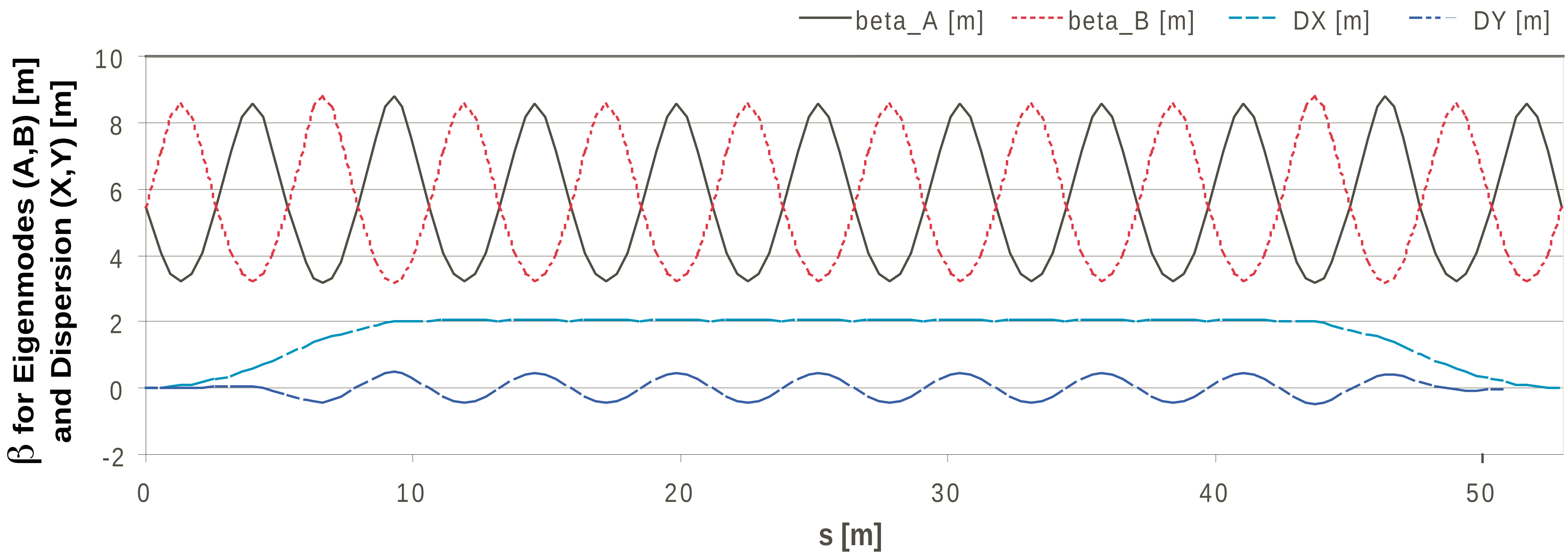

Phase advance = $1.\overline{666}$ & chromaticity contribution = -1.635 in both planes.

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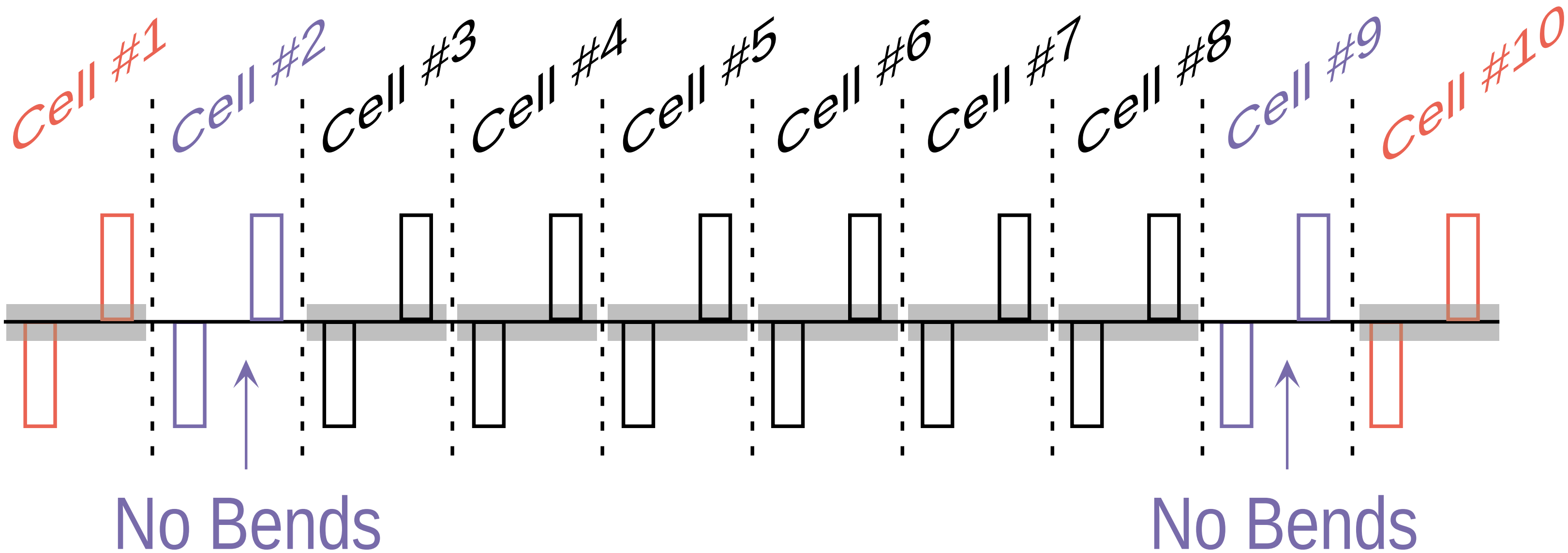
Arc Lattice Dispersion Suppression Scheme

With 60° phase advance*, the central six cells make up an achromat. Peak dispersion is reduced via two additional cells at each arc end where one of the cells has zero dipole bending.

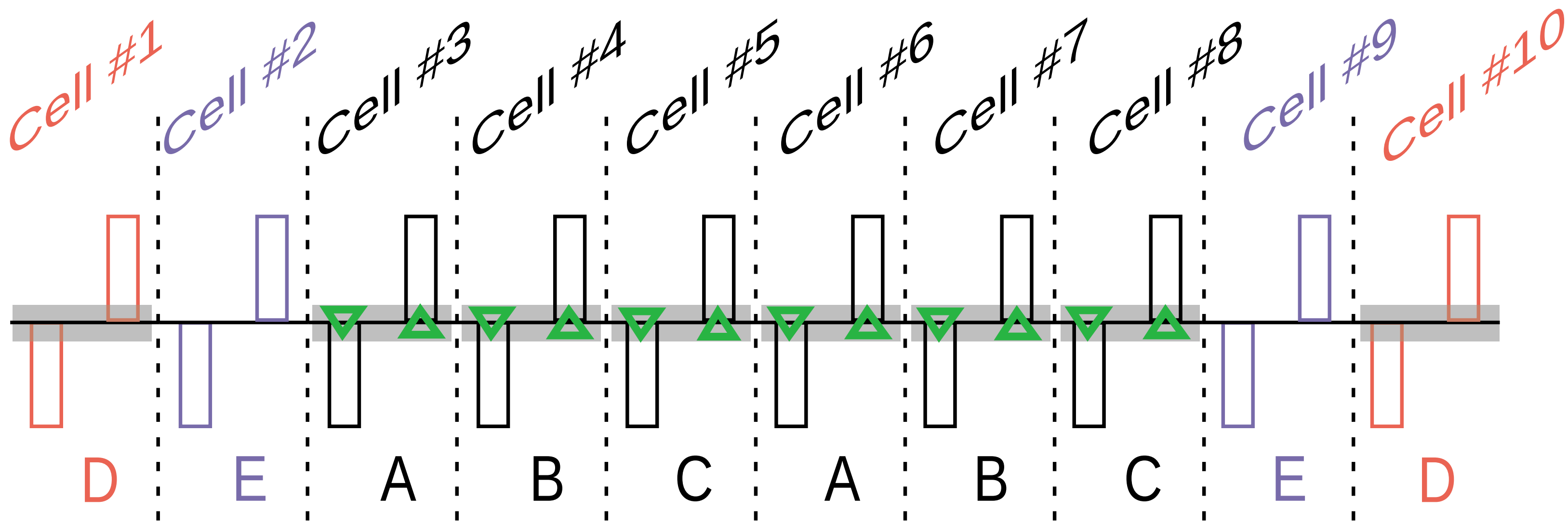


Focusing is different in no bend cells and this leads to a small mis-match which is fixed by adjusting cell length and quadrupole strength. Could also match by only adjusting strengths in outer cells (1-2,9-10).

*Note for 90° phase advance the outer cells (1-2,9-10) should have 1/2 dipole bending.

Skew Sextupole Chromaticity Correction Schemes

With a phase advance per cell of 60° it is possible to make a chromaticity correction scheme using the central six cells (3-8) very similar to the original HERAe correction scheme which is very flexible and exhibits good dynamic aperture.



For the skew quadrupole lattices considered here, we find it much better to use skew sextupoles than normal sextupoles for chromaticity correction as the needed strengths are at least a factor 4.5 lower!

Note with three skew sextupole families it should be possible to make complete chromatic correction at an arbitrary location in the ring (e.g. injection kicker).

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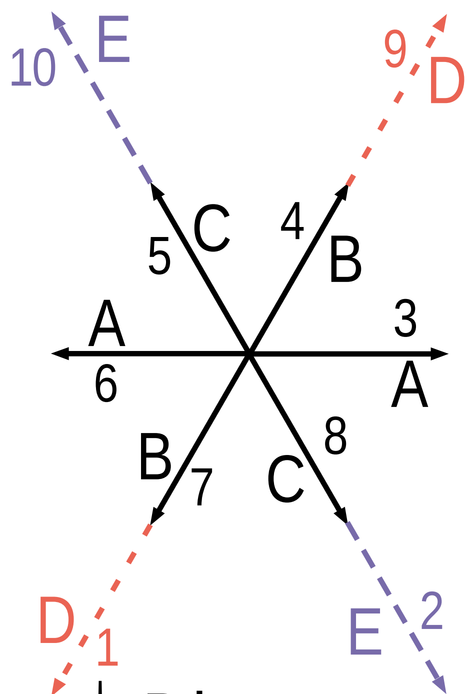
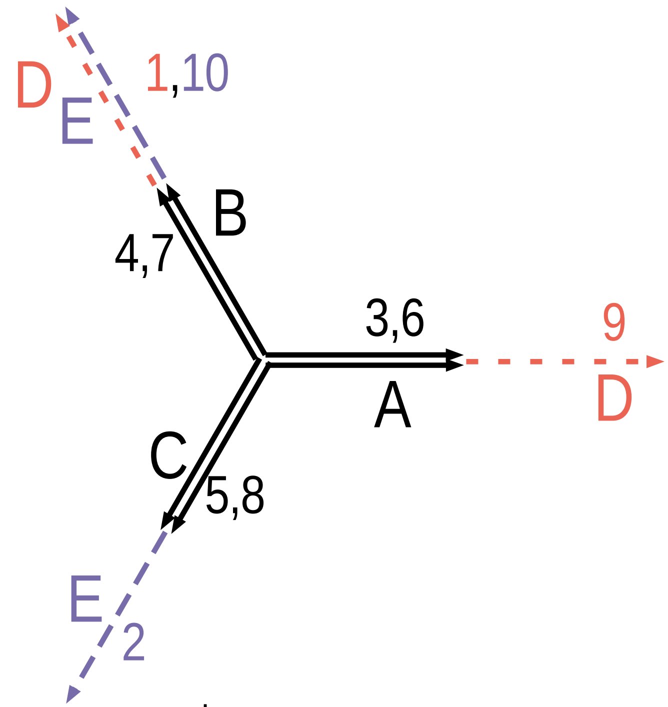
Skew Sextupole Chromaticity Correction Schemes

For central 6 skew sextupoles both first order and higher order moments cancel!



ϕ Diagram
Phase Advance = 60°



2ϕ Diagram
Phase Advance = 120°

While using all 10 locations reduces strengths needed for linear chromaticity correction, such an arrangement would likely drive higher order resonances.

Arc Optics: Why Pick 60° Phase Advance?

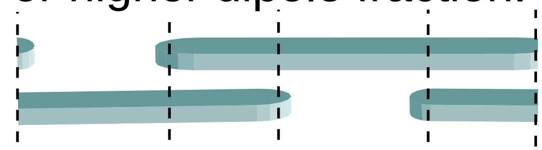
Maximum and minimum dispersion closer in magnitude for 60° than 90° for more complete cancelation and lower effective vertical dispersion.

Dispersion for FODO Cell (Separated Function)

$$\eta_{max,min} = \frac{\theta L}{\sin^2(\frac{1}{2}\mu)}\left(1 \pm \frac{1}{2}\sin^2(\frac{1}{2}\mu)\right)$$

60° takes less integrated quadrupole gradient than 90°.

For higher dipole fraction.

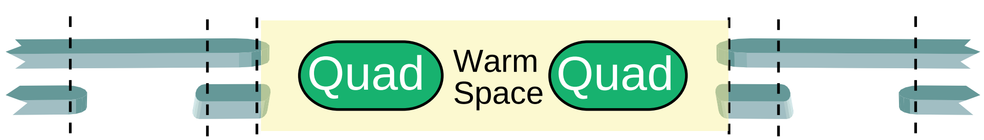


Can push to shorter cell length for lower β_{eff} and dispersion.

Not as much negative chromaticity.

Chromaticity compensation can be done with minimal higher order resonance driving for both 60° and 90°; however, 60° gives extra phase flexibility.

60° dispersion matching is done using cells with no dipole bending.



Place collimation in warm space near beginning of arc to catch charged particles and neutrals coming from straights.

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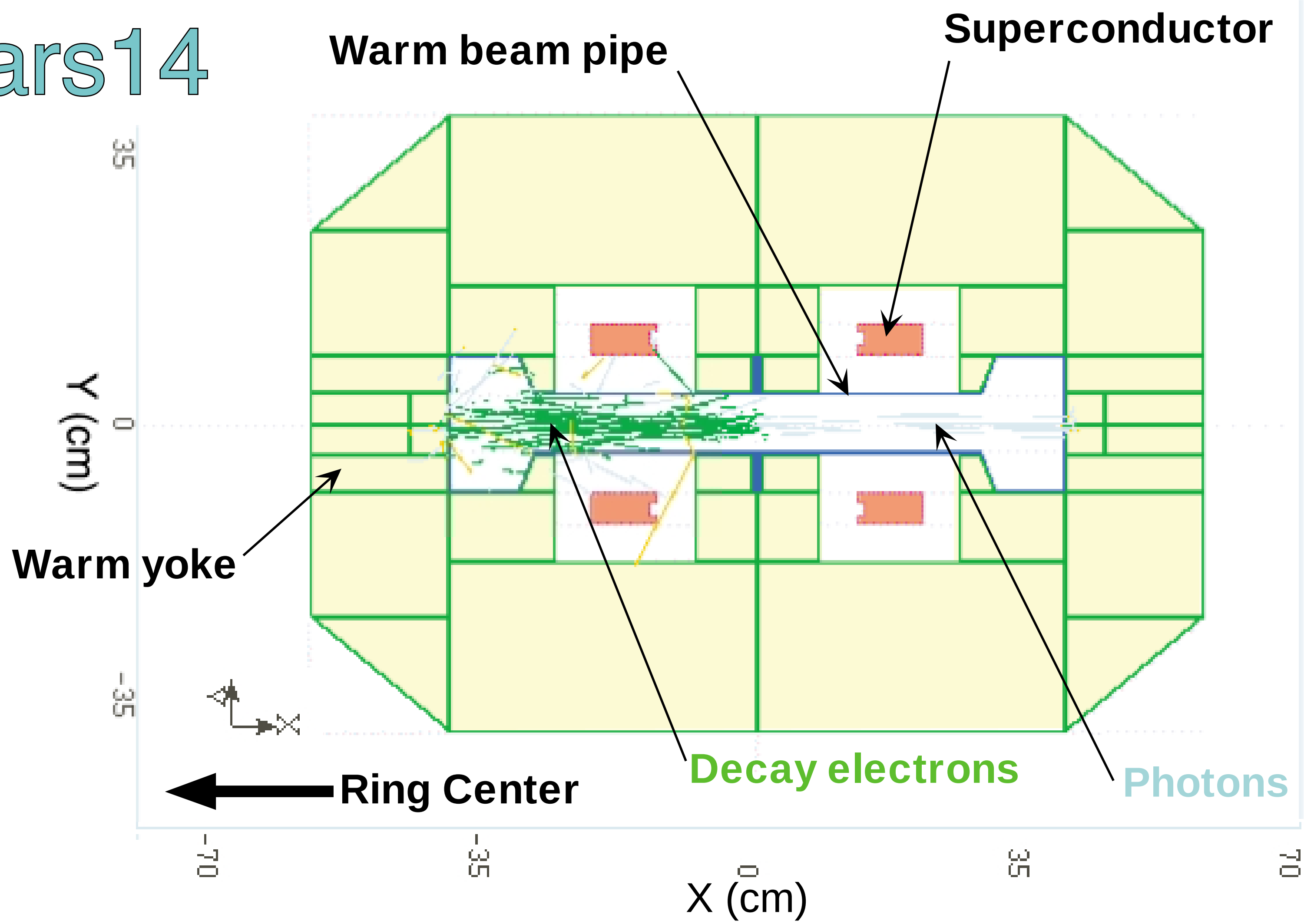
Superconducting Magnet Division

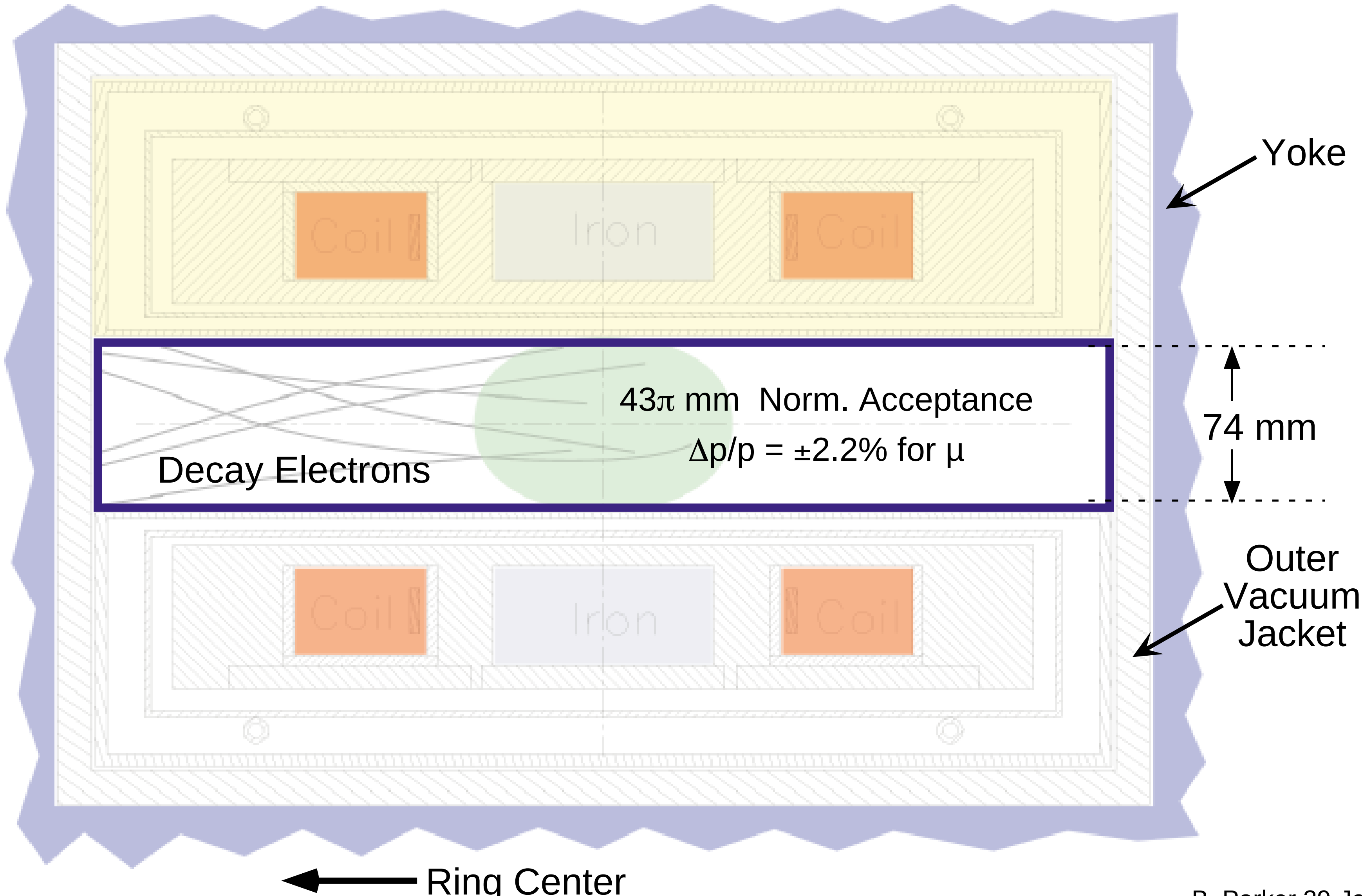
What does the dipole magnet cross section look like for the toy model study?

Mars14



What are the magnets like?

Magnet Cross Section Schematic: Double Coil



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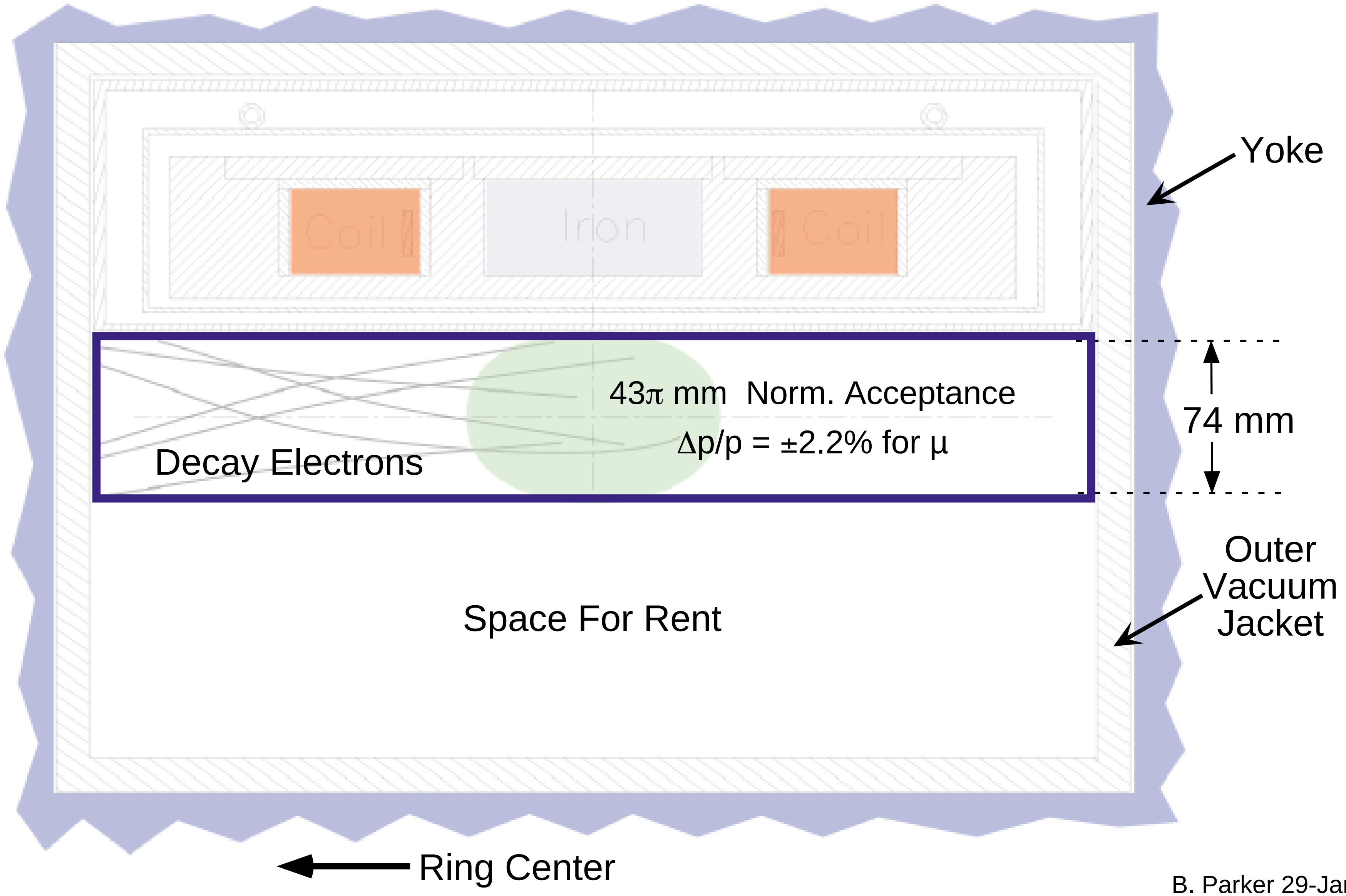
Magnet Cross Section Schematic: Single Coil



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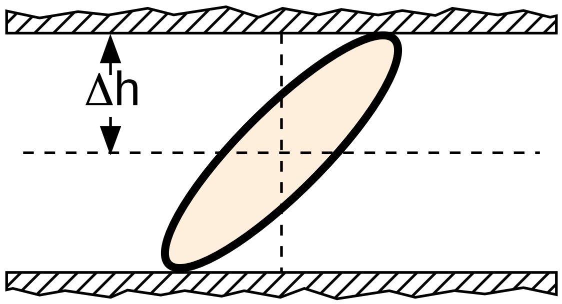
Storage Ring Acceptance: Part 1



$$\beta_{eff} = (\beta_A + \beta_B)/2$$

$$A = \frac{(\Delta h)^2}{\beta_{eff}}$$

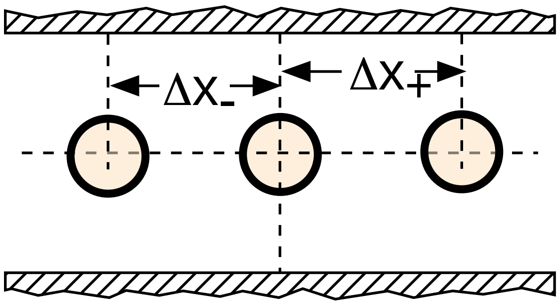
$$A_n = \gamma A$$

Δh = 37 mm $\Delta p/p = 0$	β_A (m)	β_B (m)	β_{eff} (m)	A_n (π mm)
Dipole Center	5.444	5.444	5.444	47.6
Regular Quad.	8.521	3.249	5.885	44.0
Disp. Sup. Quad.	8.778	3.169	5.974	43.4

If the vertical aperture is the same in the empty cell as elsewhere, the vertical acceptance limit is 43π mm normalized.

Note design goal is to be greater than 30 π mm.

Storage Ring Acceptance: Part 2



$\Delta X \approx \eta_X \times \Delta p/p$

$\Delta Y \approx \eta_Y \times \Delta p/p$

Closed Orbit Calculation for Δp/p = ±2.2% (Linear Approx.)	η_X (m)	η_Y (m)	$\lvert \Delta X \rvert$ (mm)	$\lvert \Delta Y \rvert$ (mm)
Dipole Center	2.029	0	45	0
Regular Quad.	2.067	0.449	45	10
End Disp. Sup.	2.030	0.324	45	7

For large Δp/p we find that β and η are changed from the linear optics.

And the closed orbit does not move symmetrically for ±Δp/p.

Worst Case*:

For Δp/p = -2.2% we find ΔX = -63 mm, ΔY = -16 mm

For Δp/p = +2.2% we find ΔX = 46 mm, ΔY = 12 mm

(±54 mm)

*With chromaticity correction turned on (even larger beta-beat if it is turned off).

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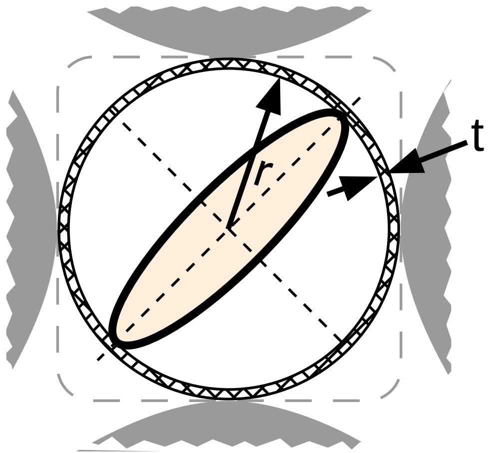
Storage Ring Acceptance: Part 3

Warm Skew Quadrupole Schematic



$\eta_A = \eta_B = 0$ $A_n = \gamma\, r^2/\beta_{max}$	β_{max} (m)	r (mm)	r_{pole} (mm)	B_{pole} (T)	A_n (π mm)
Production	115	170	175	0.62	48
Phase Trombone	22	71	75	0.93*	43

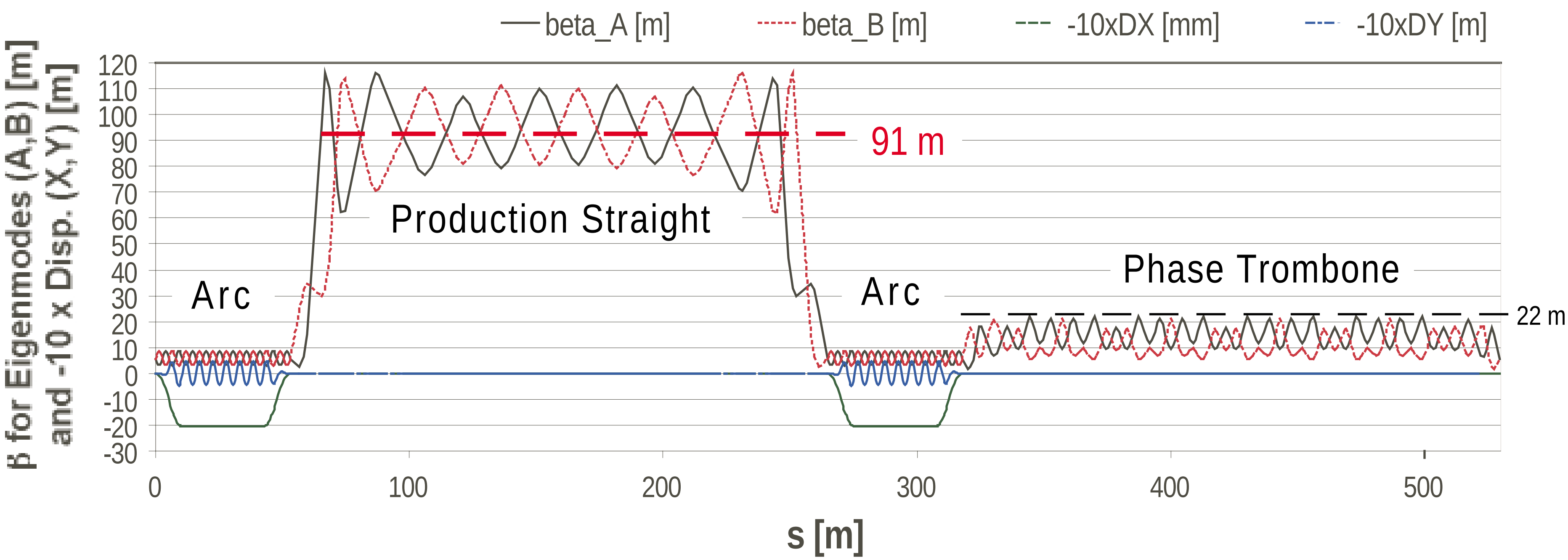
***Phase trombone quadrupoles with largest gradient have smaller β so r and B_{pole} could be reduced; however providing full aperture for injected beam, while it is off axis, may not allow this reduction.**

Use max(β_A,β_B) for circular aperture acceptance in the straights.

- **Straight section warm quadrupole parameters look plausible.**
- **By defining more magnet types (length, pole radius) could optimize trade off between production and operating costs.**
- **Must consider constraints from other accelerator systems (vacuum, rf, injection, tuning/abort and diagnostic).**
- **In some areas a non-circular beam pipe may be appropriate.**

Special Considerations?

Storage Ring Optics Summary



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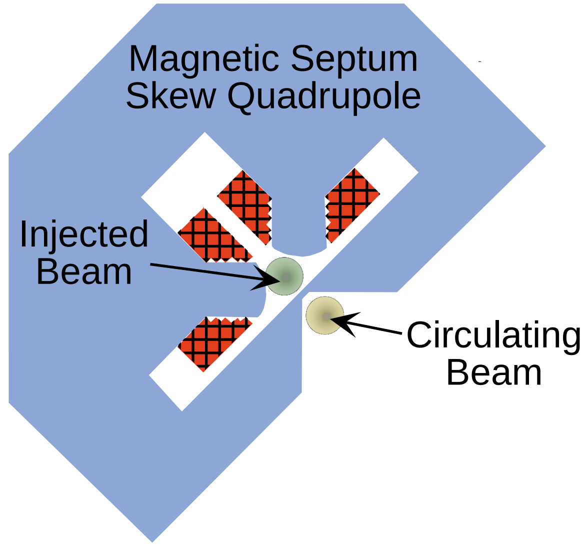
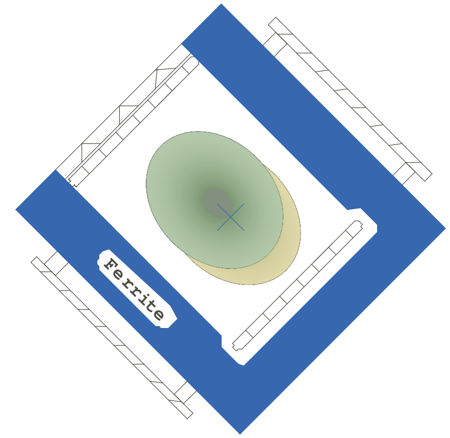
Some Thoughts About Storage Ring Injection

GM, the HERA Luminosity Upgrade
Magnetic Septum Quadrupole (MSQ)



Rotated Injection Kicker
(Scaled From Study-I)



- Inject into upward going straight.
- MSQ may be useful to maximize acceptance (e.g. PETRA–HERA).
- Place kicker ≈ 90° phase advance.
- Try rotating injection kicker 45°.

Placing MSQ in early return-straight midcell location allows optic matching close to kicker for smaller β-peaks in transfer line. A rotated normal dipole could send tune up beam into an absorber. Note that the injection kicker is also strong enough to send the circulating beam to an absorber.

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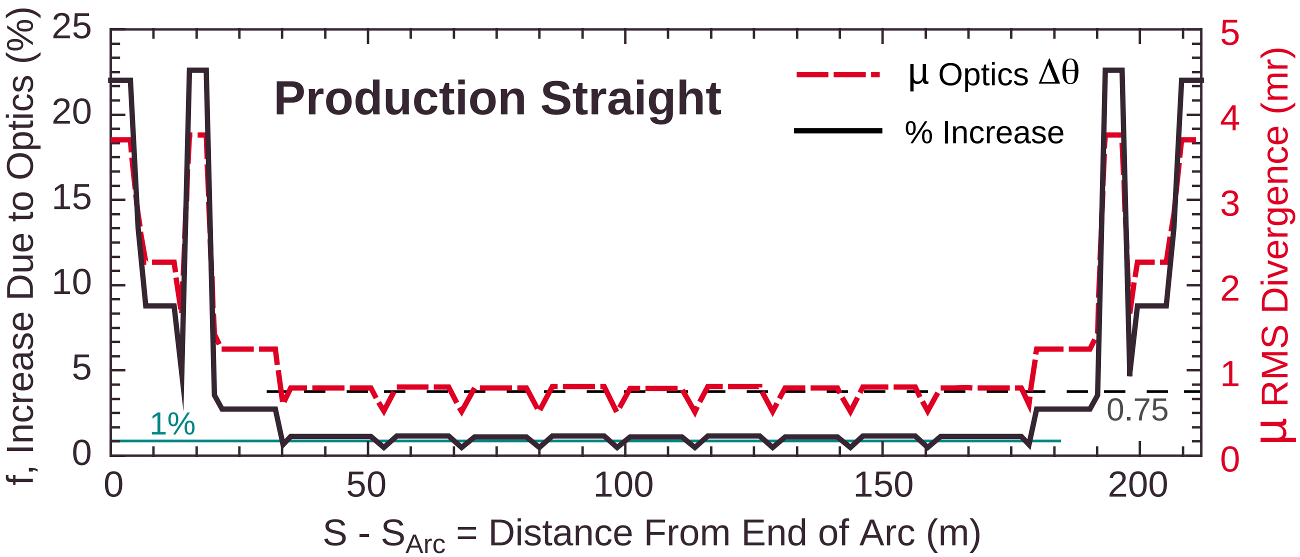
μ Optics Contribution to ν Beam Divergence



$$\Delta\theta = \sqrt{\frac{\varepsilon\,(1+\alpha^2)}{\beta}}$$

$$\Delta\theta_{eff} = \sqrt{\Delta\theta_A \times \Delta\theta_B}$$

$$\Delta\theta_\nu \approx 1/\gamma$$

$$f = \sqrt{1 + \left(\frac{\Delta\theta_{eff}}{\Delta\theta_\nu}\right)^2}$$

RMS ε = 25 π mm x mr (not 17 π from Study-I)

Design $\overline{\beta}$ = 91 m –> $\Delta\theta_{eff}$ = 0.75 mr

Decay $\Delta\theta_\nu$ = 5.3 mr (need 0.53 for 1% combined)

In center high-β region, flux density drops 2%

Averaging over S –> 8% drop (40% –> 37%)

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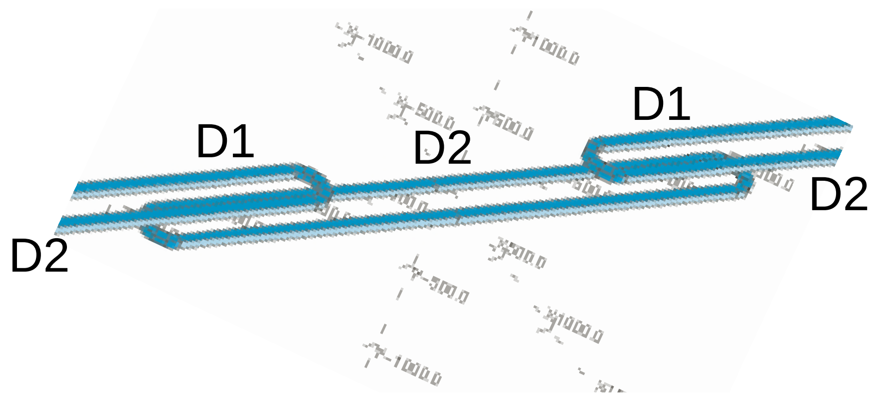
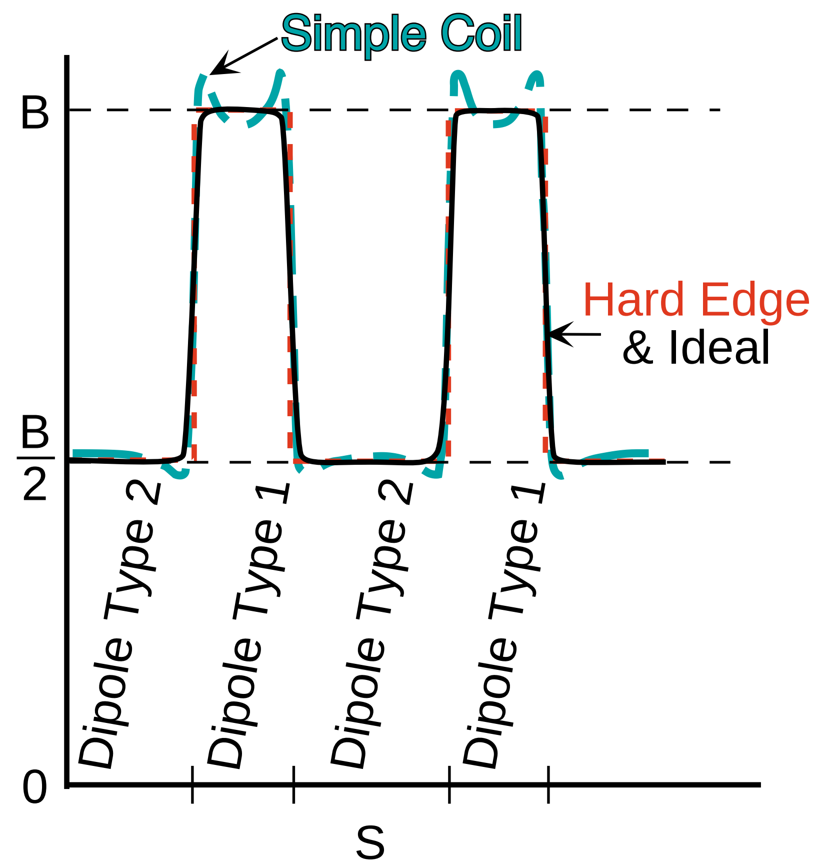
Comparison of Magnetic Field Distributions

- Simple racetrack coil without optimized ends gives undershoot and overshoot (poor harmonics).
- Present lattice design effectively uses hard edge approximation (unphysical).
- In future work need to determine coil + yoke configuration that gives smooth transition between high and low field.



Simple Coil Configuration



Vertical Field at beam Center

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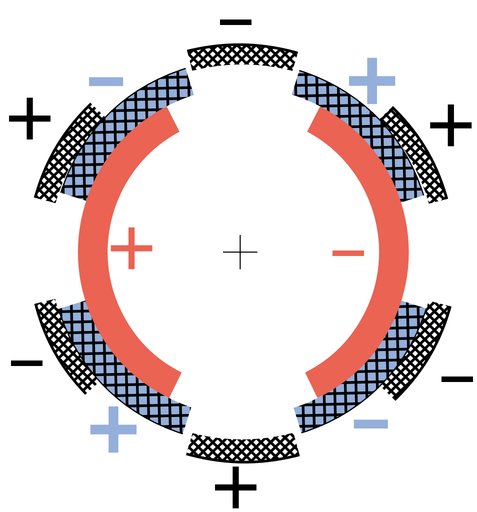
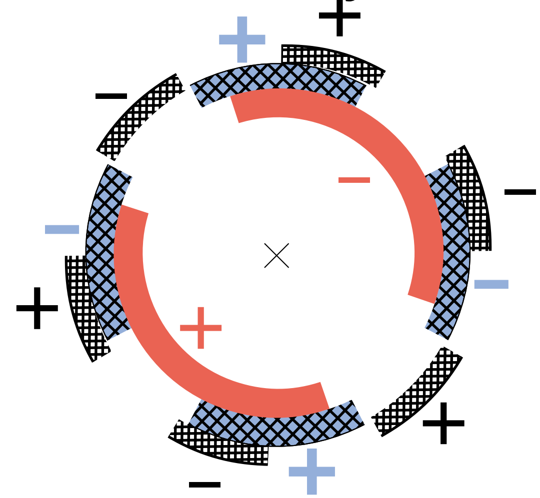
Skew Combined Function Optics Calculation

True Configuration



Rotated By 45°



- Useful trick: rotate system 45° for upright eigenplanes
  - skew quadrupole –> normal quadrupole
  - dipole –> dipole rotated by 45°
  - skew sextupole –> sextupole rotated by 15°
- Would like to avoid slicing by using a program which calculates correctly with combined fields (dipole + quadrupole + skew quadrupole + skew sextupole ...)

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Storage Ring and Magnet Design Summary

- ✓ How small can we go?
- ✓ What is the lattice like?
- ✓ What are the magnets like?
- ✓ Special Considerations?

Help? Yes, much still to do!