Gas-Filled Rings for Muon Beam Cooling

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Quad-Dipole Rings with LiH Absorbers

Before studying gas-filled rings, many lattices were designed for cooling with short LiH absorbers. Their performance was simulated with ICOOL.

The magnet lattices used various arrangements of dipoles and quadrupoles, or of dipoles alone with edge focusing.

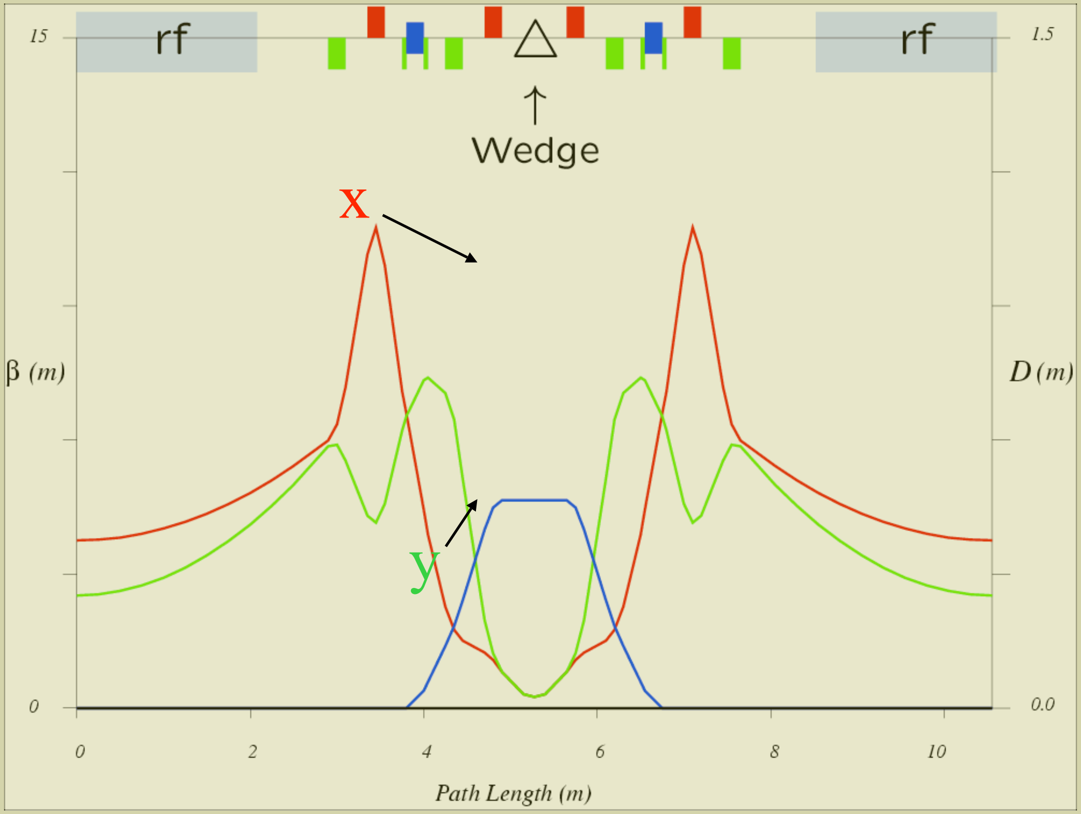
The main objectives were:

- Low betas in the absorbers to reduce heating,
- Minimizing betamax elsewhere for large acceptance
- Reducing cell lengths for cooling efficiency

The Snowmass Lattice

- 4 m drift available for rf
- Low β (25 cm) at wedge shaped absorber
- Pseudo-combined function dipole
- Allows for matching straight sections
- 45^0 bending cell

  $\beta_{x\,max} > \beta_{y\,max}$
- Cell tune is ~ 3/4



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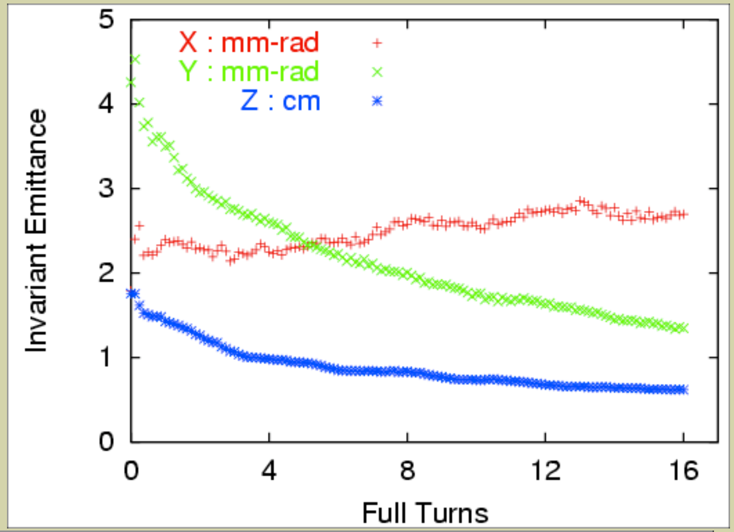
Snowmass Lattice Performance

Beam momentum 500 MeV/c
25 cm LH_2 wedges
Wedge angle 10^0
Rf frequency 201.25 MHz
E_{max} = 10 MV/m

Σ



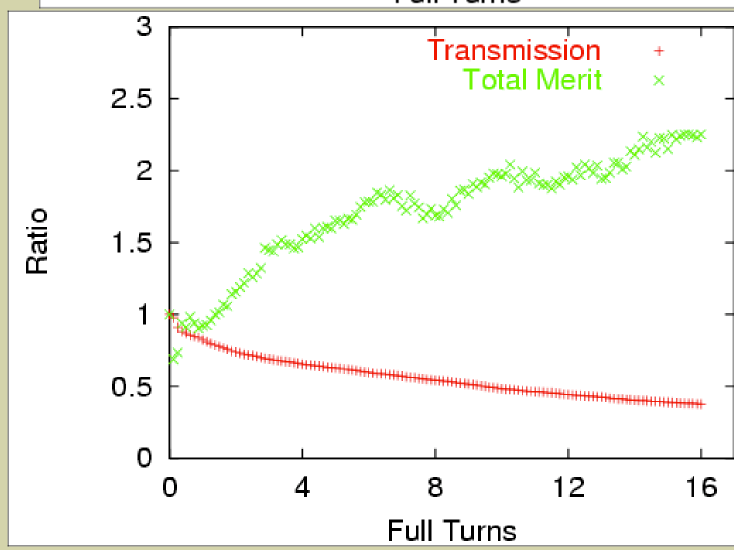
Δ R

- initial ε_y > initial ε_x
- ε_y and ε_z decreases
- ε_x increases

Δ V

- Transmission 40%

Total Merit = Transmission *x* $(\varepsilon_x \varepsilon_y \varepsilon_z)_{initial} / (\varepsilon_x \varepsilon_y \varepsilon_z)_{final}$



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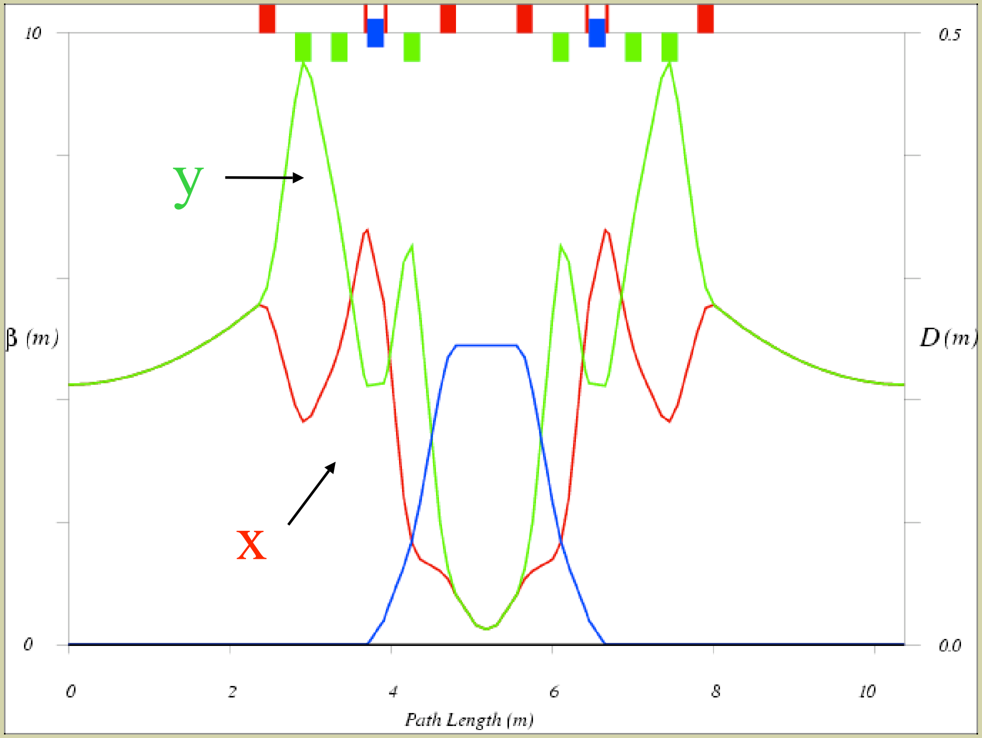
The Berkeley Lattice

- 4 m drift available for RF
- Low β (25 cm) at absorber
- Pseudo-combined function dipole
- Allows for matching straight sections
- 22.5^0 bending cell

  $\beta_{y\ max} > \beta_{x\ max}$
- Cell tune is ~ 3/4

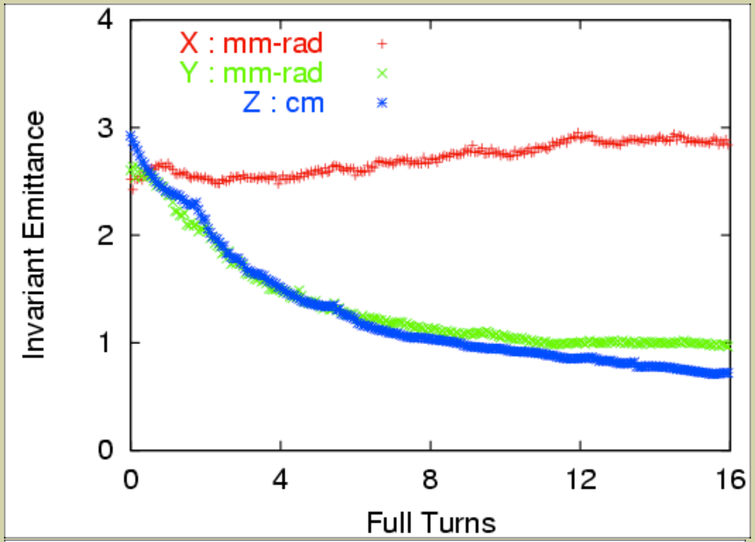


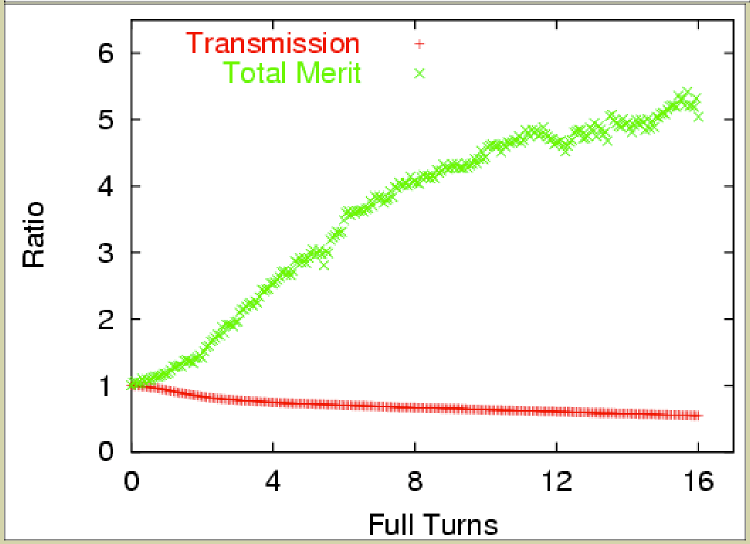
Berkeley Lattice Performance

Beam momentum 500 MeV/c
25 cm LH_2 wedges
Wedge angle 20^0
RF frequency 201.25 MHz
E_{max} = 8 MV/m

- ε_y and ε_z decreases
- ε_x nearly constant
- Transmission 60%

Total Merit = Transmission *x* $(\varepsilon_x\, \varepsilon_y\, \varepsilon_z)_{initial} / (\varepsilon_x\, \varepsilon_y\, \varepsilon_z)_{final}$

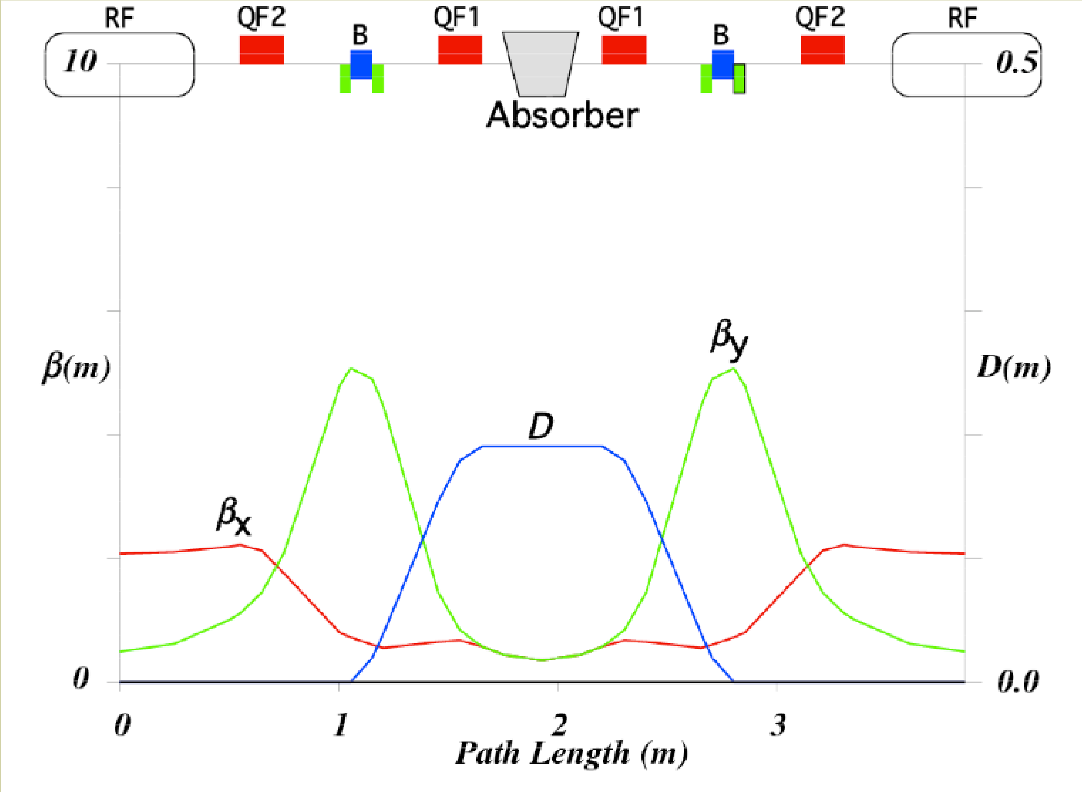




A Quad/Dipole Lattice

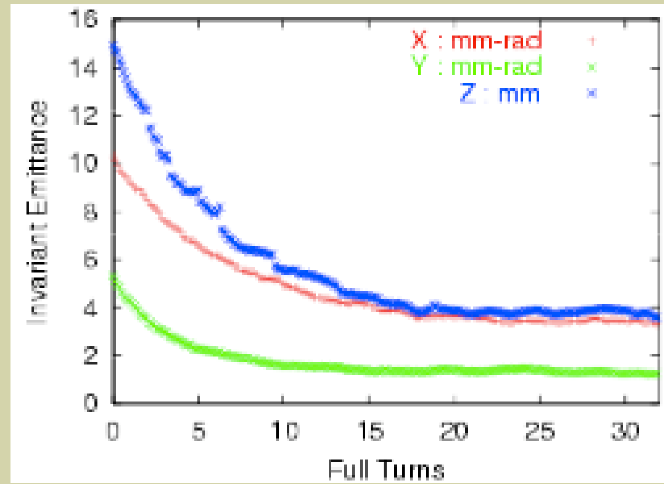
- Compact Chasman-Green lattice
- 1 m drift available for RF
- Low β (25 cm) at absorber
- Combined function dipole simulated
- Dispersion only at absorber
- Allows for matching straight sections--injection/ ejection
- 45^0 bending cell

  $\beta_{y\ max} > \beta_{x\ max}$
- Cell tune is ~ 3/4



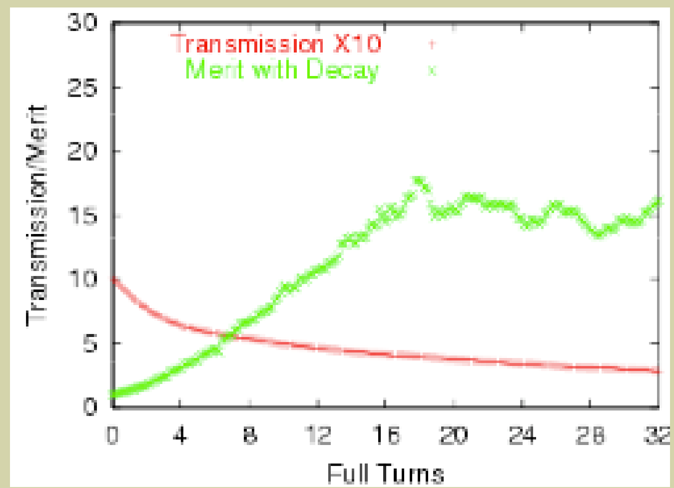
Chasman-Green Lattice Performance

Beam momentum 250 MeV/c
25 cm LiH_2 wedges
Wedge angle 20^0
rf frequency 201.25 MHz
E_{max} = 16 MV/m



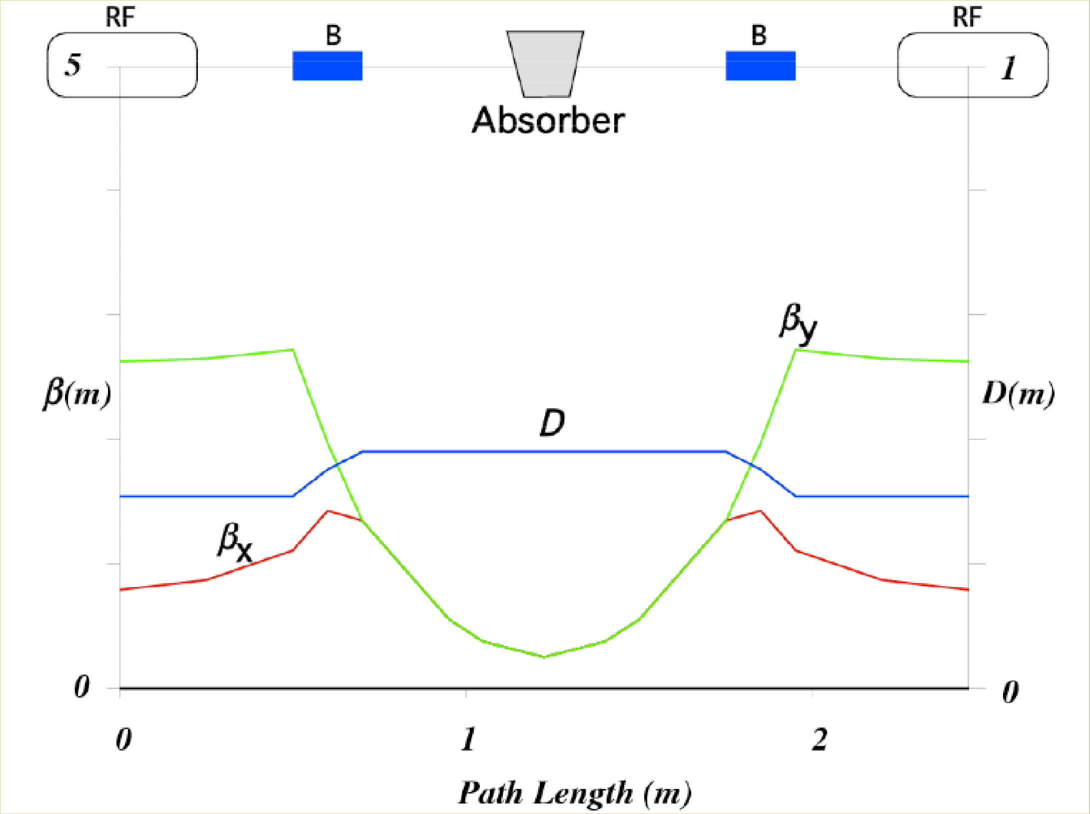
- ε_x, ε_y, and ε_z all decrease
- Transmission 50%

Total Merit = *Transmission* x $(\varepsilon_x \varepsilon_y \varepsilon_z)_{initial} / (\varepsilon_x \varepsilon_y \varepsilon_z)_{final}$



A Dipole-only Lattice

- 4 cell ring
- 1 m drift available for RF
- Low β (25 cm) at absorber
- Edge focusing
  - 22^0 entrance angle
  - -7^0 exit angle
- Dispersion throughout cell
- 45^0 bending dipoles
- Very compact (9.8 m circumference)

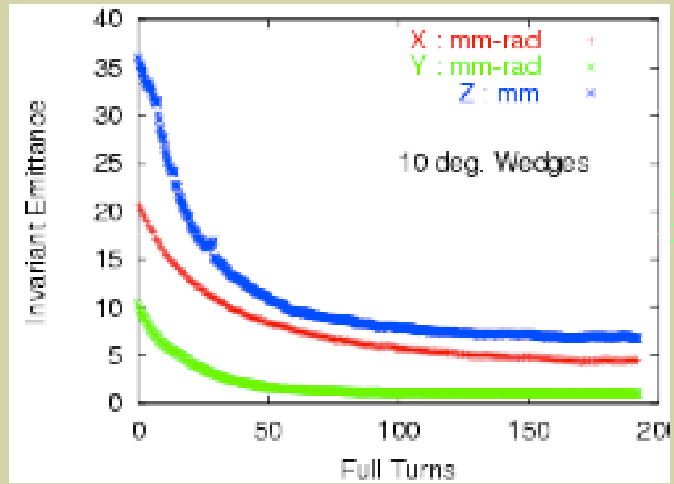


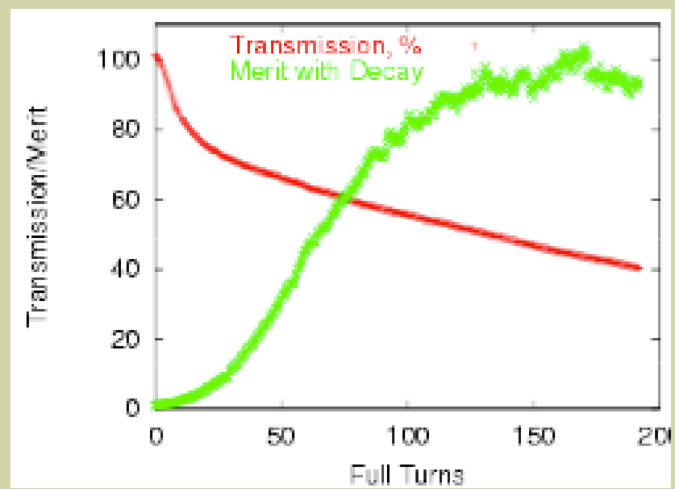
Dipole-only Lattice Performance

Beam momentum 500 MeV/c
24 cm LH_2 wedges
Wedge angle 10^0
Rf frequency 201.25 MHz
E_{max} = 16 MV/m

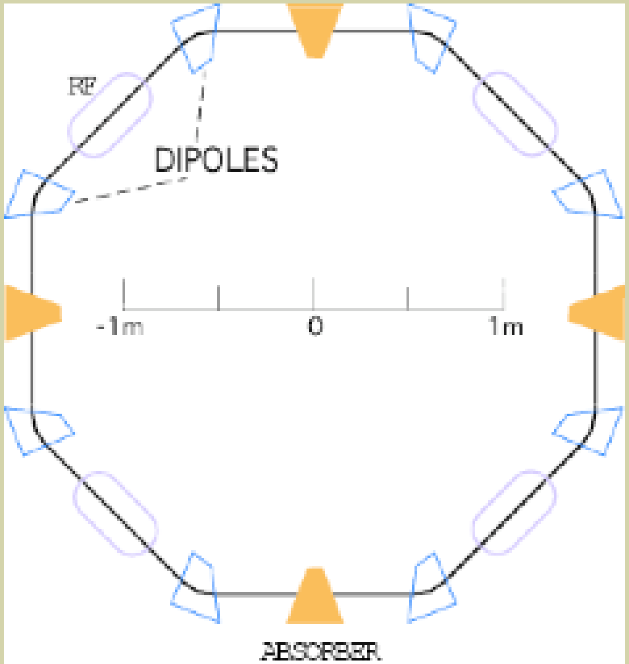
- ε_x, ε_y, and ε_z all decrease
- Transmission 50%

Total Merit = *Transmission* x $(\varepsilon_x \varepsilon_y \varepsilon_z)_{initial} / (\varepsilon_x \varepsilon_y \varepsilon_z)_{final}$ = **100**

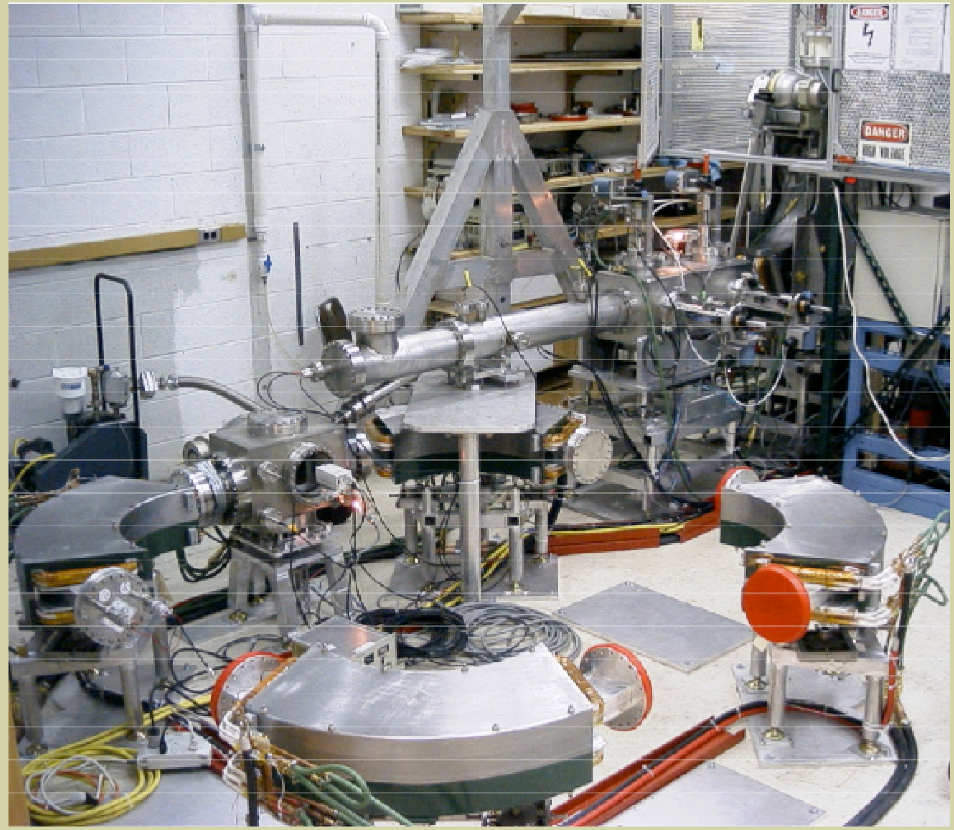




Dipole-only Ring Layout



- 9.8 m ring circumference
- 4 cells
- 45^0 bending dipole



NSCL at Michigan State Isochronous Ring

26^0 face angles and 7 cm gaps

2 cells 90^0 bending dipoles

Principles adopted for gas-filled ring designs

- Rings instead of straight channels
  ---> less size and cost
  --->enables longitudinal and transverse cooling
  but
  ---> Channel cannot be tailored to the shrinking beam size
  ---> Injection and extraction are difficult

- Rings filled with high-pressure hydrogen gas to serve as the energy loss absorber.
  --->efficient cooling (absorber everywhere)
  --->RF breakdown voltage increased

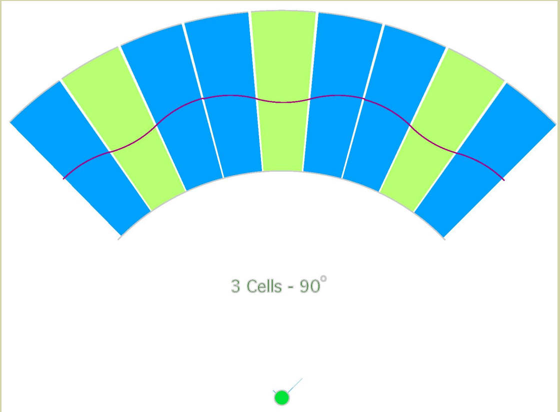
- Dipole-only, scaling lattices
  --->compact rings
  --->lower betamax values, high acceptances

Types of Scaling Lattices Considered

- FFAG Alternating Gradient Rings
  12 cell ring
- Zero-gradient wedge dipole rings, hardedge
- *i.e* field constant in wedges, zero between them
  6 cell ring
  4 cell ring …
  (used for cooling demonstration)

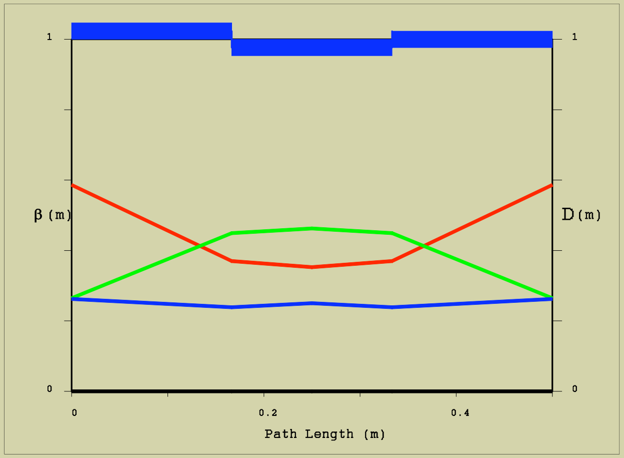
An FFAG-like Lattice

Lattice consists of alternating vertically defocusing and horizontally focusing magnets. No drift spaces between dipoles.



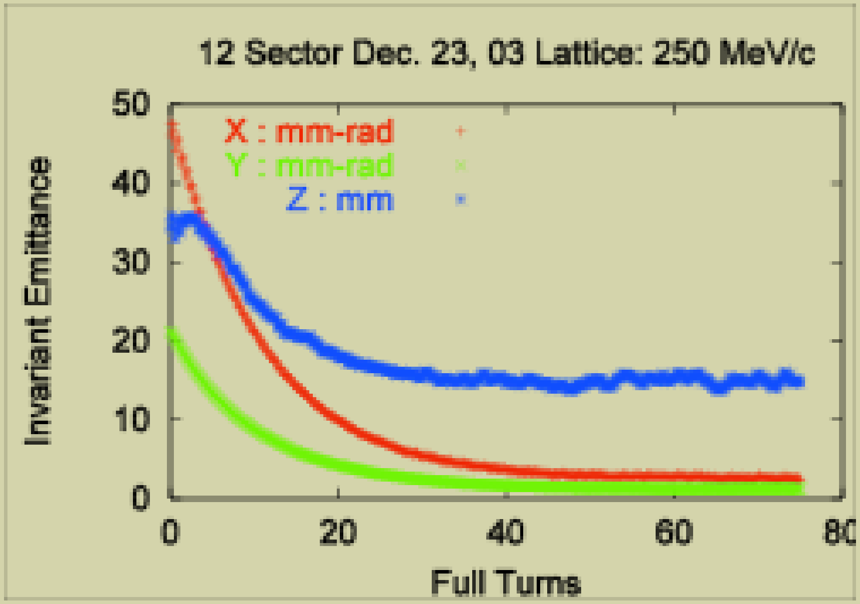
Parameters

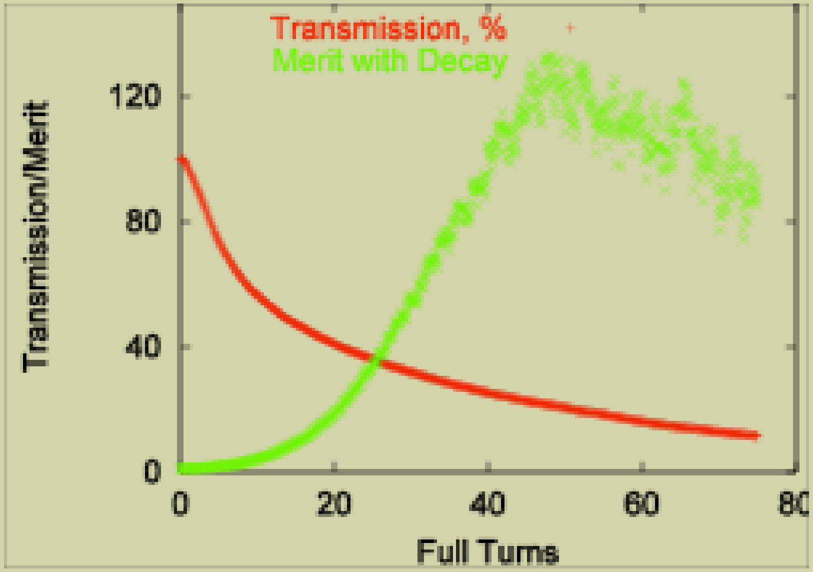
12 cells
Bend angles 30º and –15º
Circumference = 6m
B_o = 2.6T and P_o = 250 MeV/c
Dispersion = 25 cm



Strong Focusing Ring Performance

n = -0.6   RF at 8 MV/m





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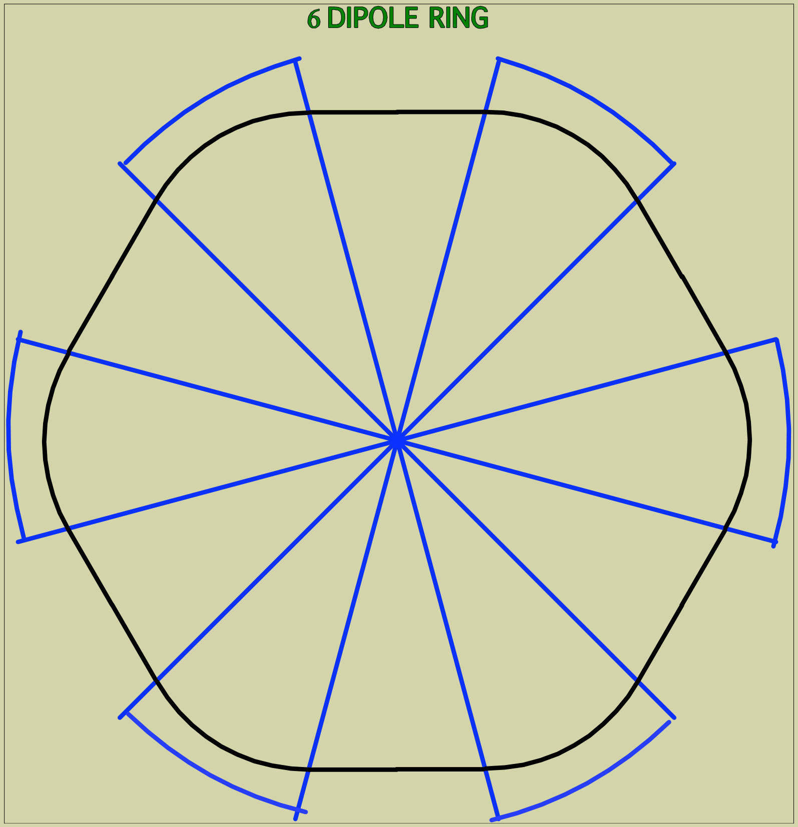
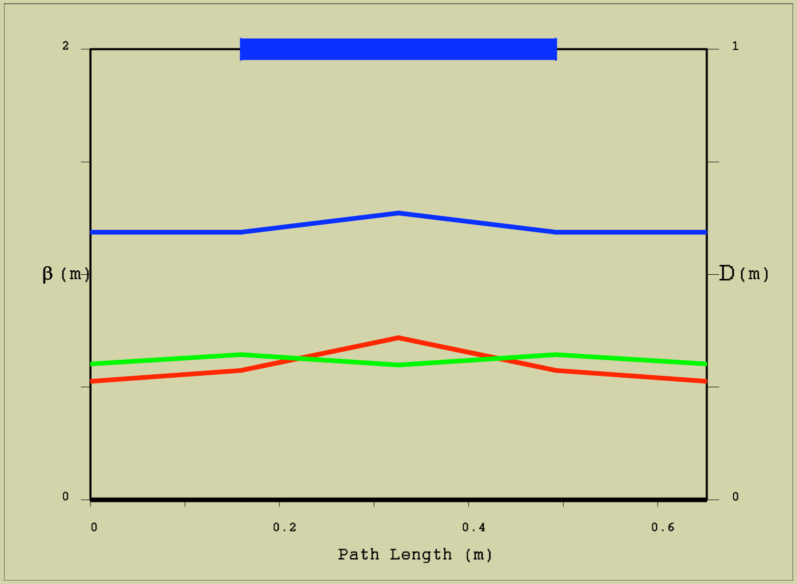
Gas-filled 6-Dipole Wedge Ring





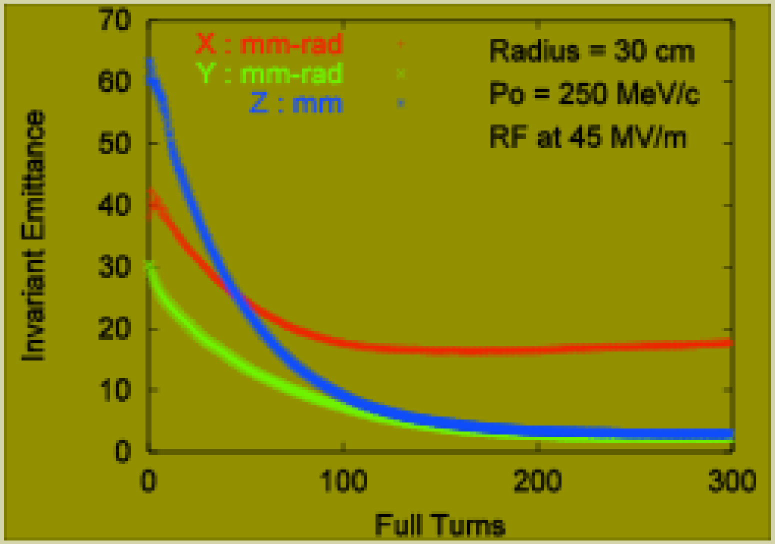
Key parameters at r = 60 cm

β_x = 53 to 72 cm ; β_y = 60 to 64 cm

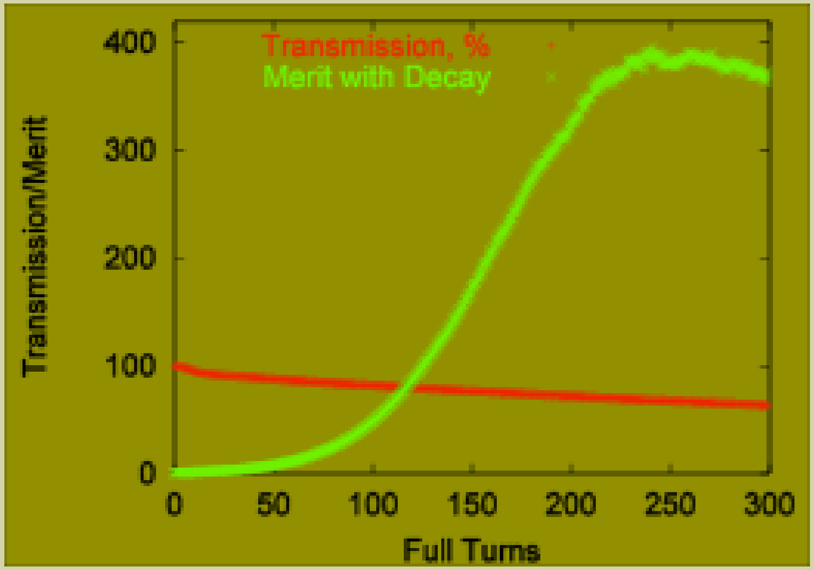
Dispersion = 60 to 64 cm

Circumference = 3.91 m

6-Dipole High-Field Ring Performance



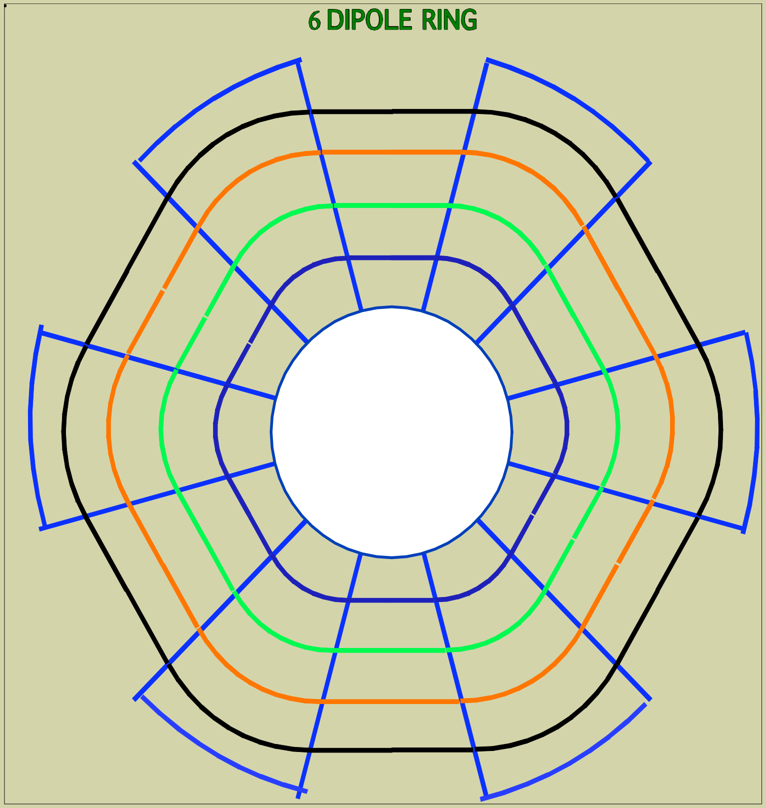
- B = 5.2T
- Po = 250 MeV/c
- 100 Atmospheres H_2



Rings to demonstrate cooling

- 1.8T conventional magnets
- 200 MHz RF cavities
- Compressed H2 gas
- Number of dipoles and harmonic number chosen for best performance

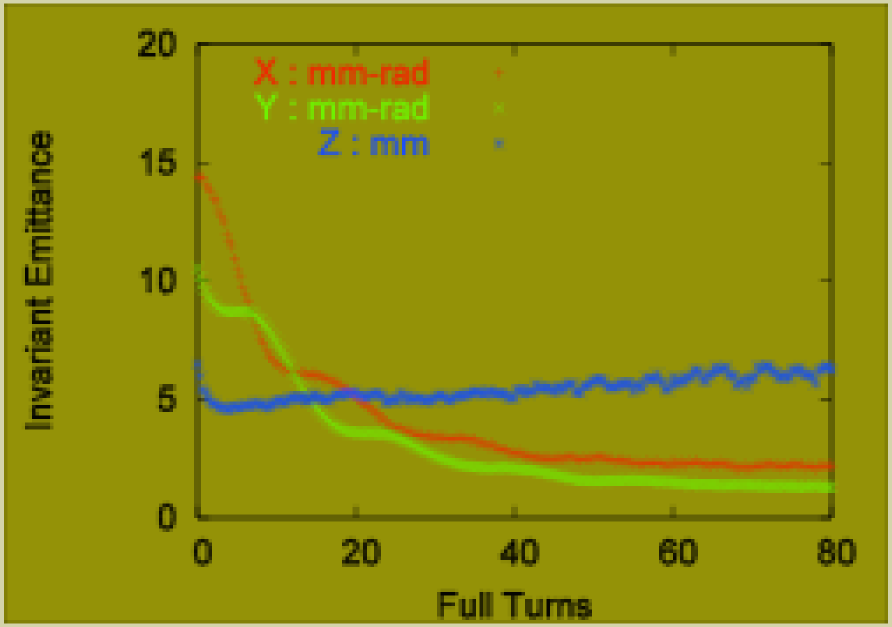
1.8T Dipoles and 200 MHz Closed Orbits for 6 Cell Demonstration Ring



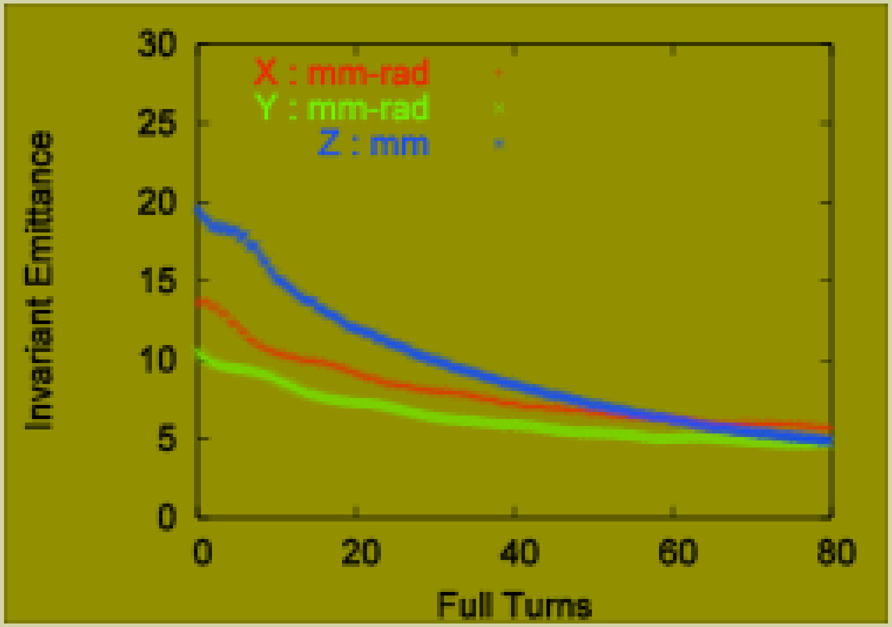
- Fix the closed orbits for a 1.8T dipole such that the total path length of the muons is a harmonic of 200 MHz.
- Then:
- Harmonic 2
  - Circumference = 1.76 m
  - P_0 = 77 MeV/c
- Harmonic 3
  - Circumference = 3.76 m
  - P_0 = 165 MeV/c
- Harmonic 4
  - Circumference = 5.45 m
  - P_0 = 240 MeV/c

6-Sector Ring, 1.8 T Dipoles

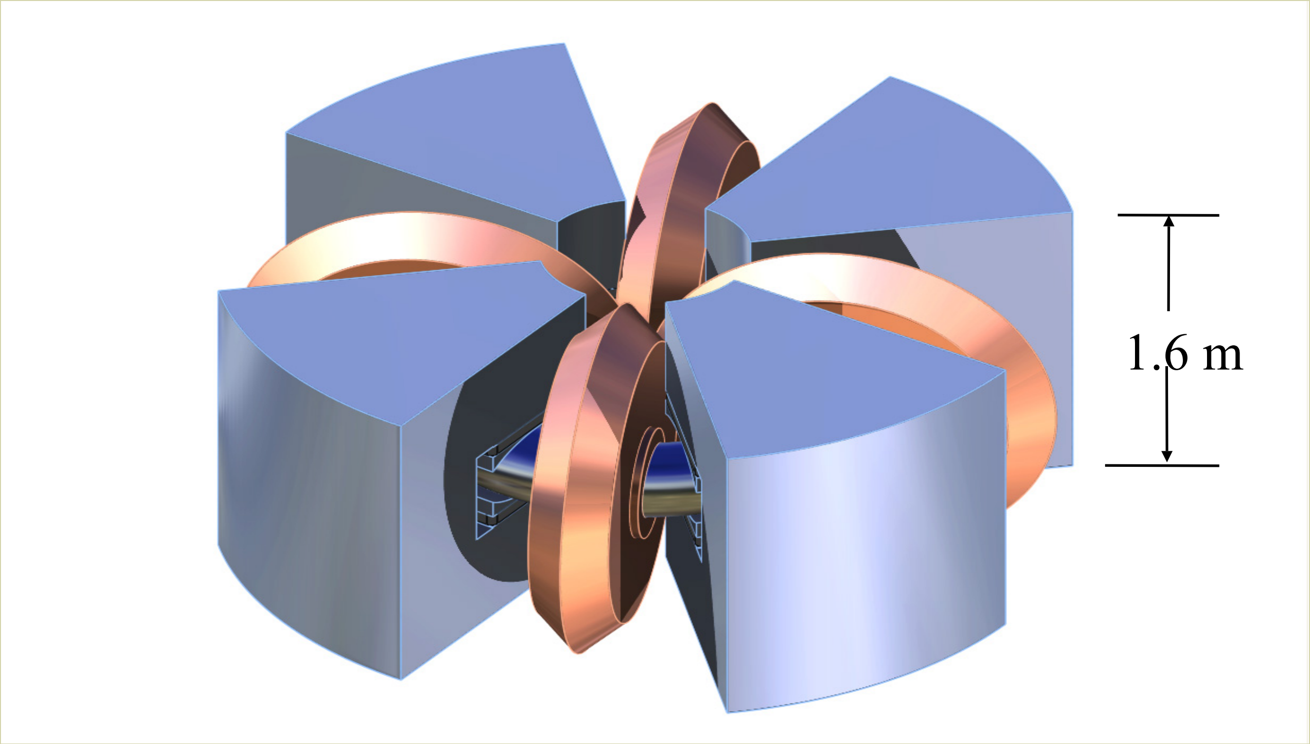
- Harmonic 2



- Harmonic 3



Small Muon Ring for a Cooling Demonstration



- A compact ring with edge focusing dipole magnets.
- The beam enclosure filled with high-pressure hydrogen gas to serve as the energy loss absorber.
- RF cavities to restore the longitudinal energy loss.

Demonstration Ring Design Parameters

- Pressurized H_2 gas filled ring.
  - The gas is the absorber.
    - 40 Atm @ 300° K
    - 10 Atm @ 77° K
- Four Weak focusing dipoles
  - Dipoles use edge focusing.
  - Iron yokes for flux return.
    - Nominal dipole field of 1.8 T
    - 2.3 T would be possible with Vanadium Permendur.
- RF cavities in the drift region between magnets to replace energy loss in gas.
  - Using 201.25 MHz cavities.
  - 10 MV/m gradient.

Parameter	Value
Dipole Field	1.8 T
Number of Cells	4
Reference Momentum	172.12 MeV/c
Ring Circumference	3.81 m
X Aperture	±20 cm
Y Aperture	±10 cm
P_z Acceptance	±10 MeV/c
Minimum β_X	38 cm
Maximum β_X	92 cm
Minimum β_Y	54 cm
Maximum β_Y	66 cm
Hydrogen Gas Pressure	40 Atm @ 300º K
RF Gradient	10 MV/m
RF Frequency	201.25 MHz
Total RF Length	1.2 m
Total Orbit Turns	100

Table 1: Parameters that describe the muon cooling ring.

Quadrant Geometry of 4- Cell Ring

Definitions:

$\lambda = \rho \,/\, Rc$

$\sigma = (1+\lambda^2+2\lambda\cos\theta)^{1/2}$

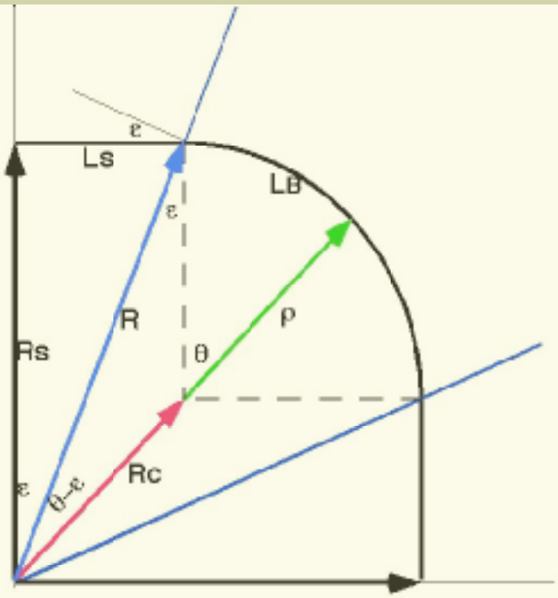
$R = Rc\ \ \sigma$

$\varepsilon\ =\ \sin^{-1}(\sin\theta\,/\sigma)$

$Rs = R\cos\varepsilon$

$Ls = R\sin\varepsilon$

$LB = \rho\,\theta$

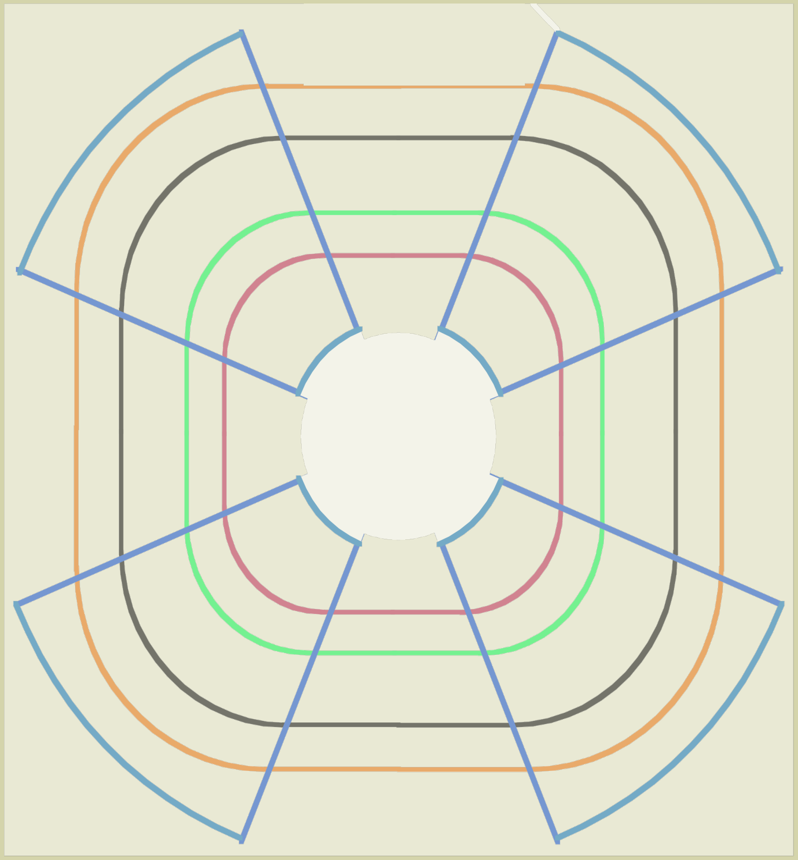


$\lambda\ = 1$

$\theta = \pi/4$

$\varepsilon = \pi/8$

1.8T Dipoles and 200 MHz Closed Orbits for 4 Cell Demonstration Ring

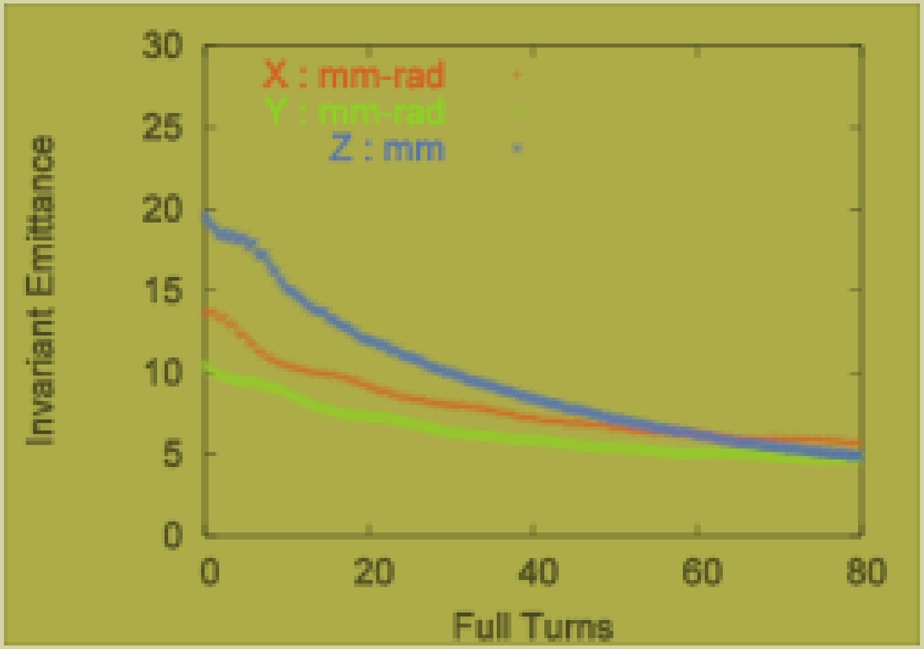


Fix the closed orbits for a 1.8T dipole ring such that the total path length is a harmonic of 200 MHz.

Then:

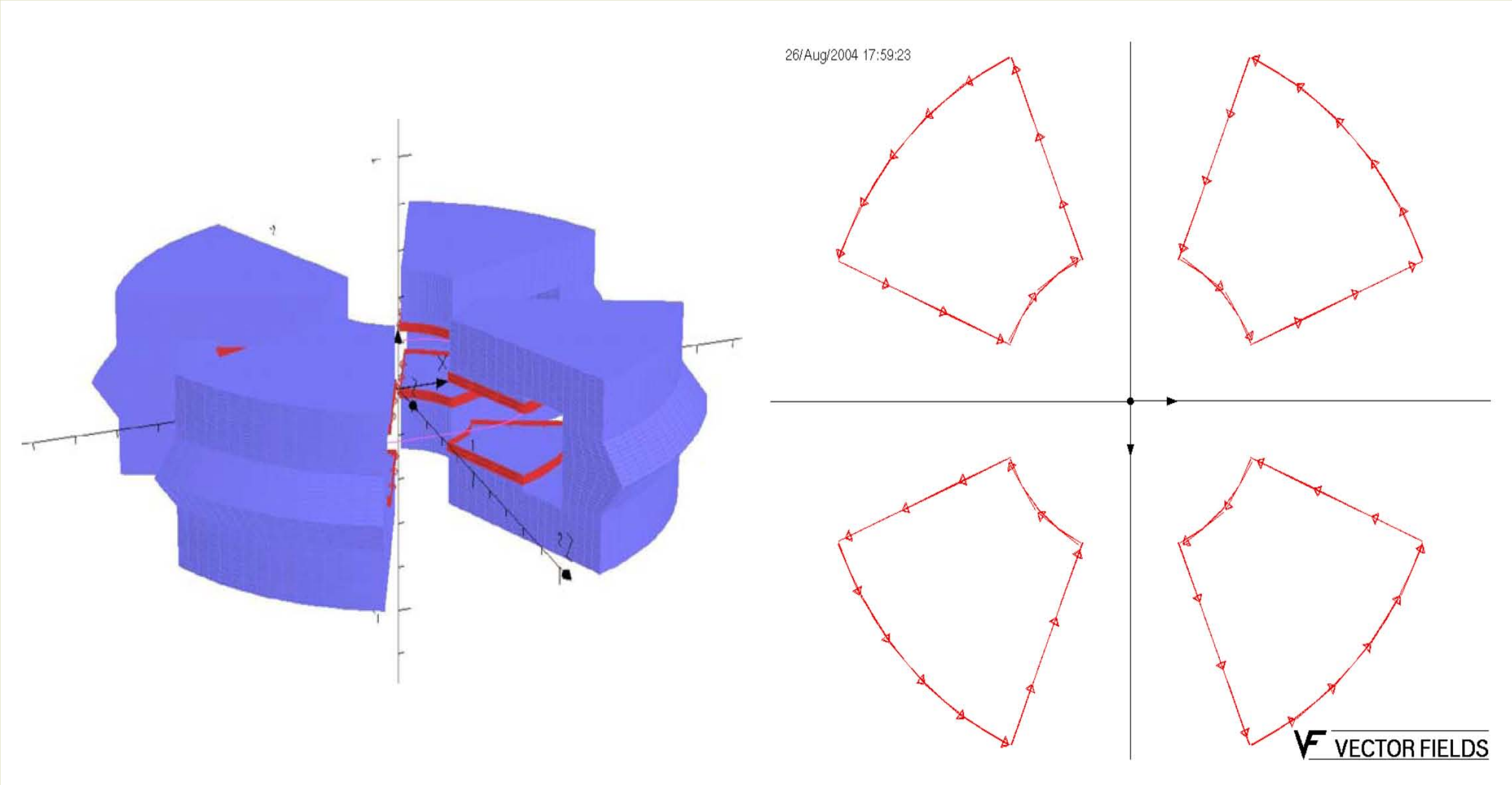
- Harmonic 2
  - Circumference = 1.76 m
  - P_0 = 77 MeV/c
- Harmonic 3
  - Circumference = 3.76 m
  - P_0 = 165 MeV/c
- Harmonic 4
  - Circumference = 5.45 m
  - P_0 = 240 MeV/c

4 Sector Ring, 1.8 T Dipoles

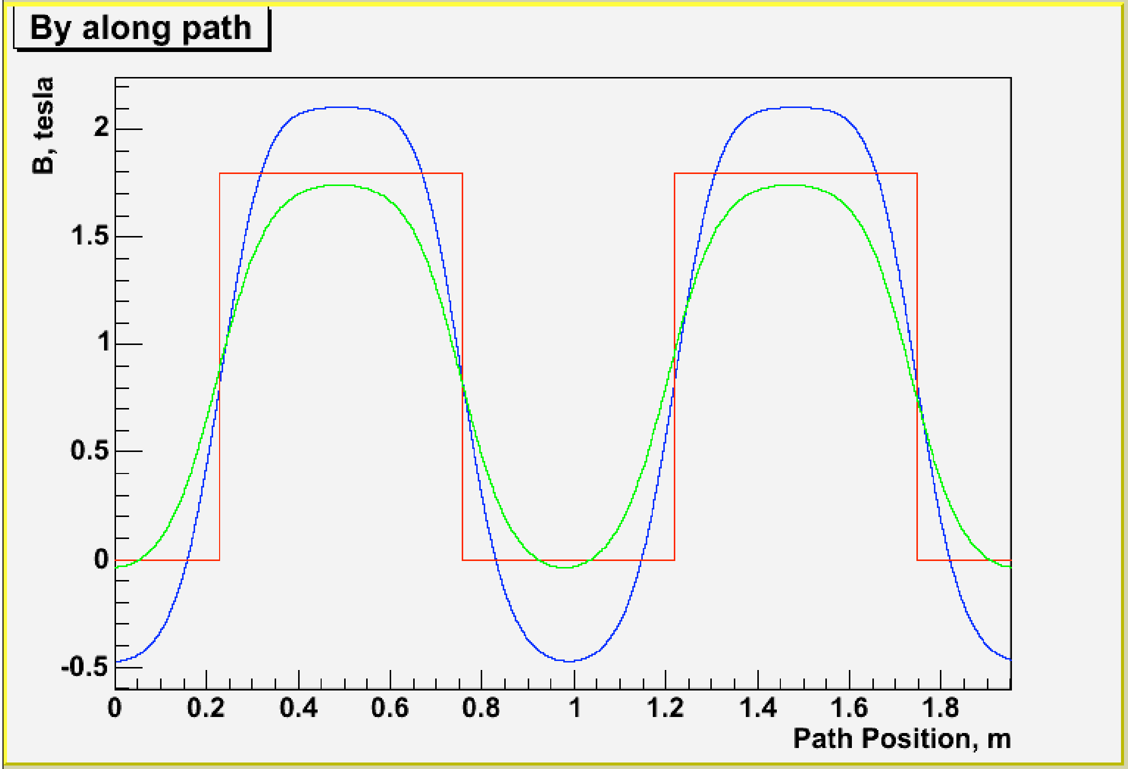


- Harmonic 3
- 40 Atmosphere H_2
- Total Merit without decay is 20

Modeling the fields of the ring



B_y Field Along the Closed Orbit Path



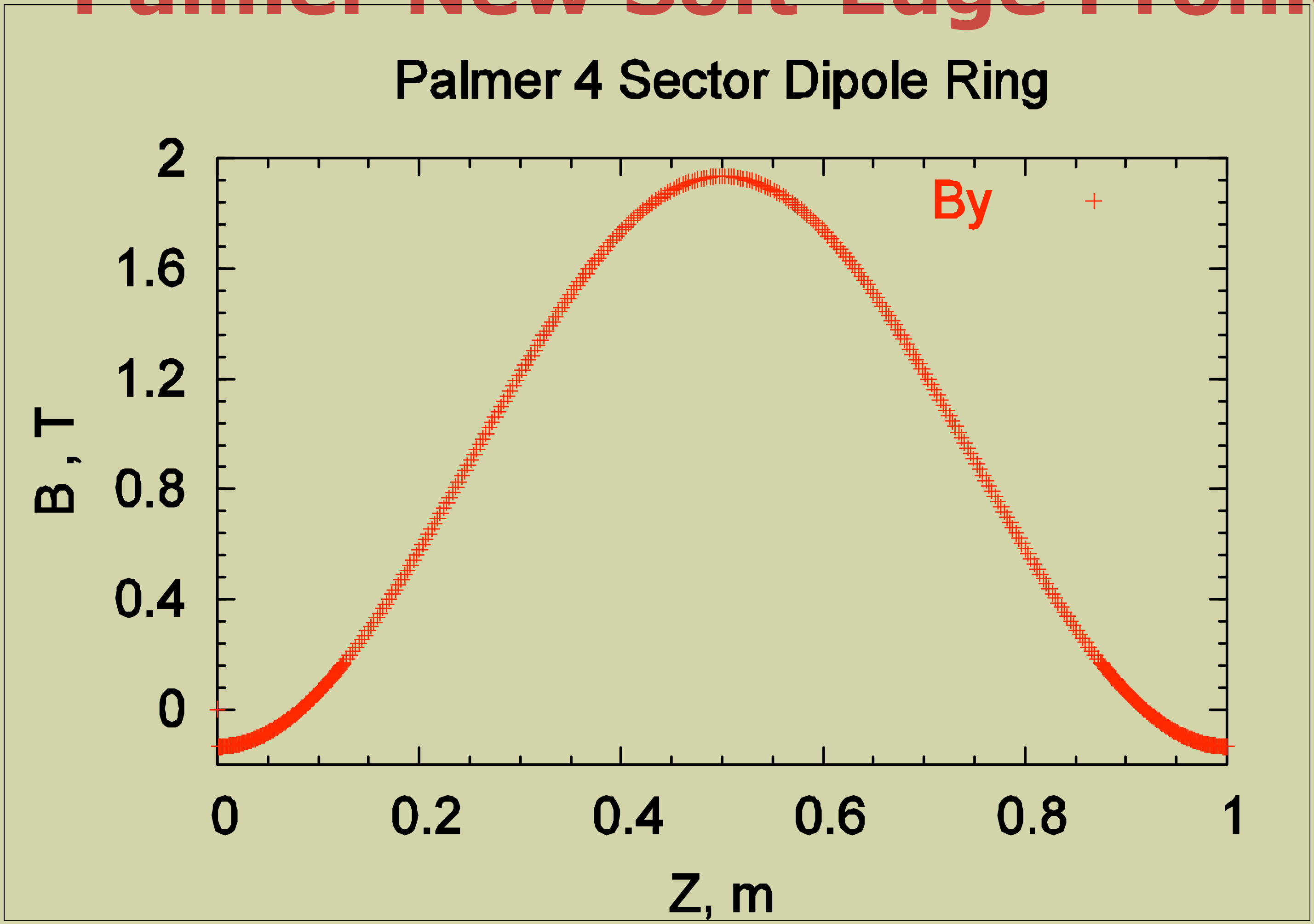
Coils only—No Iron

Coils plus Iron

Constant Hardedge Field

- Since coil only field has large negative field between the magnets, it must have larger field in the magnet to give the same integrated bend.

Palmer New Soft-Edge Profile



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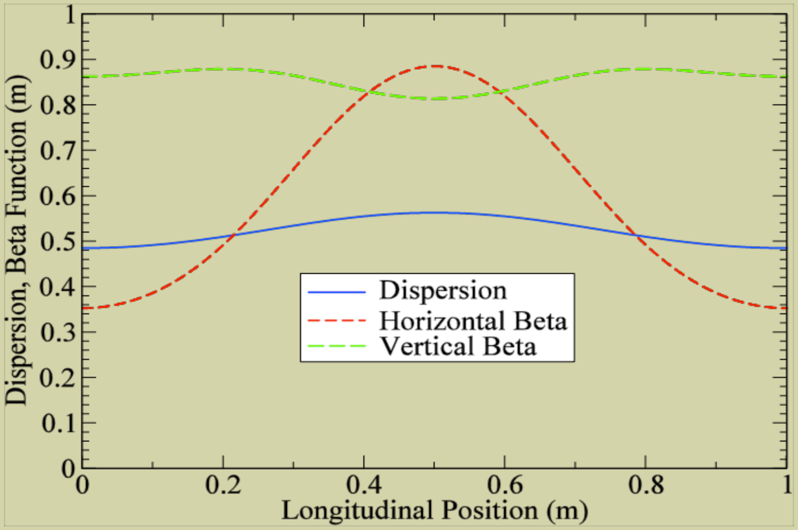
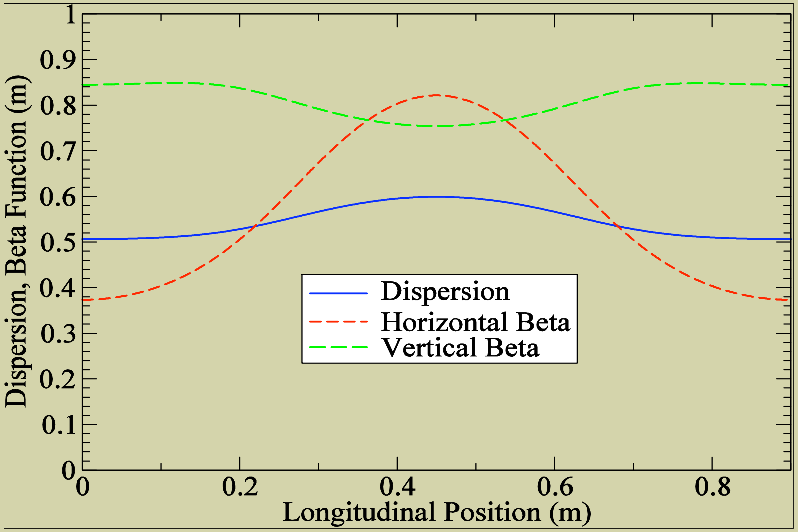
Lattice Parameters

Calculations by Scott Berg



Palmer Lattice with Quadrupole



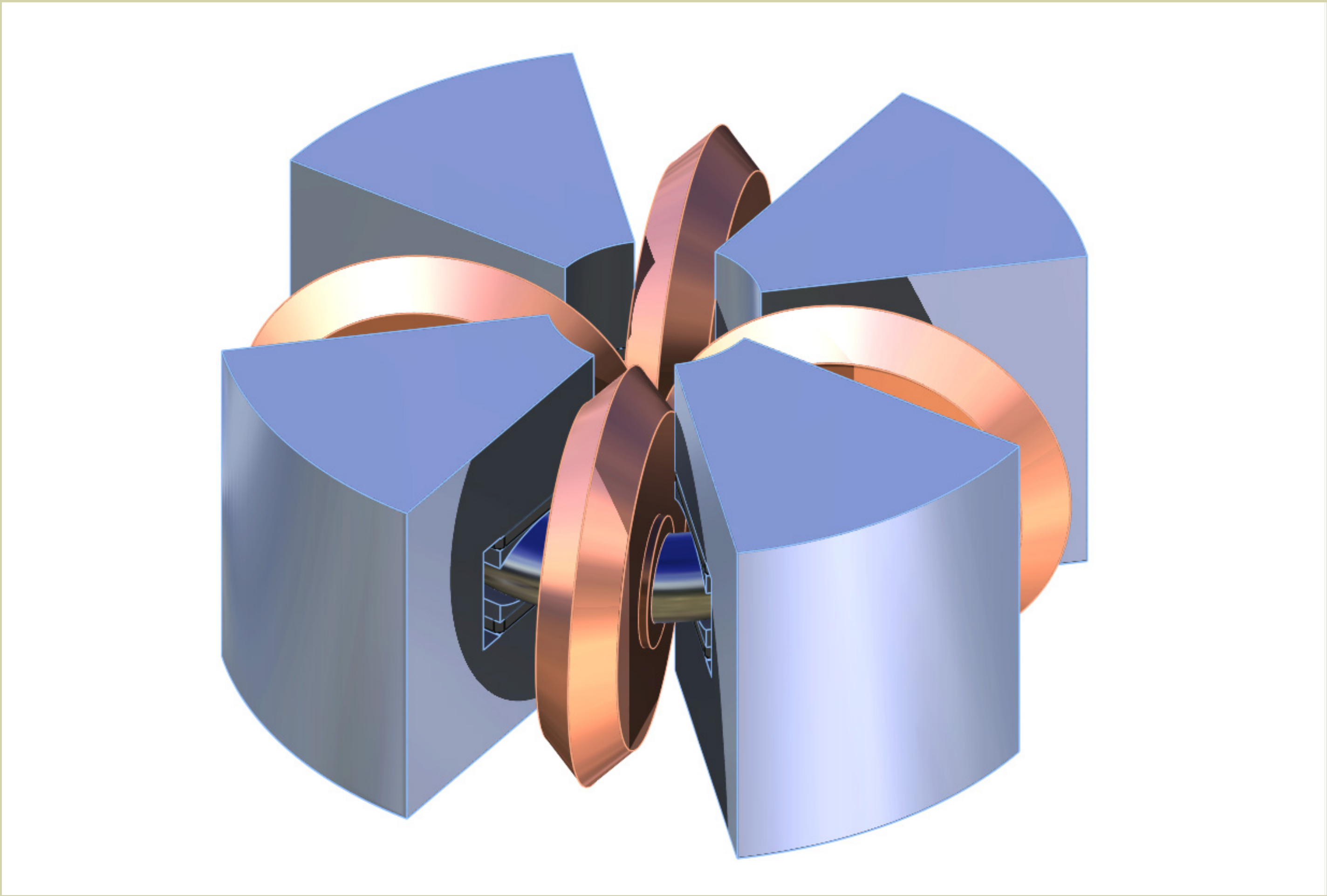
Kahn II lattice with Iron

Summary

- Quad-dipole rings with LiH absorbers gave poor cooling except with very high fields.
- Dipole-only rings were more compact and gave better cooling.
- Further progress was made with rings with scaling lattices filled with compressed hydrogen gas.
- A small sector focused machine was designed to demonstrate the principle of 6-D ionization cooling of muons.

Additional slides

Dipoles and RF Cavities of Demonstration Cooling Ring



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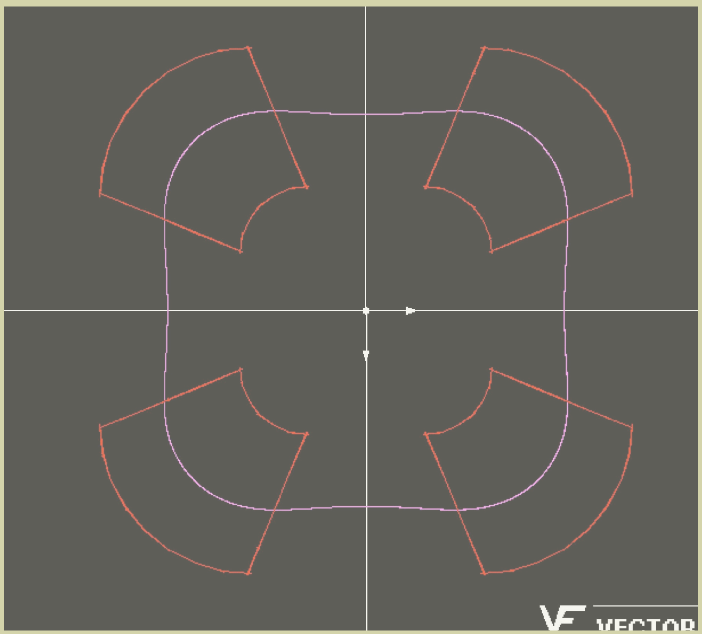
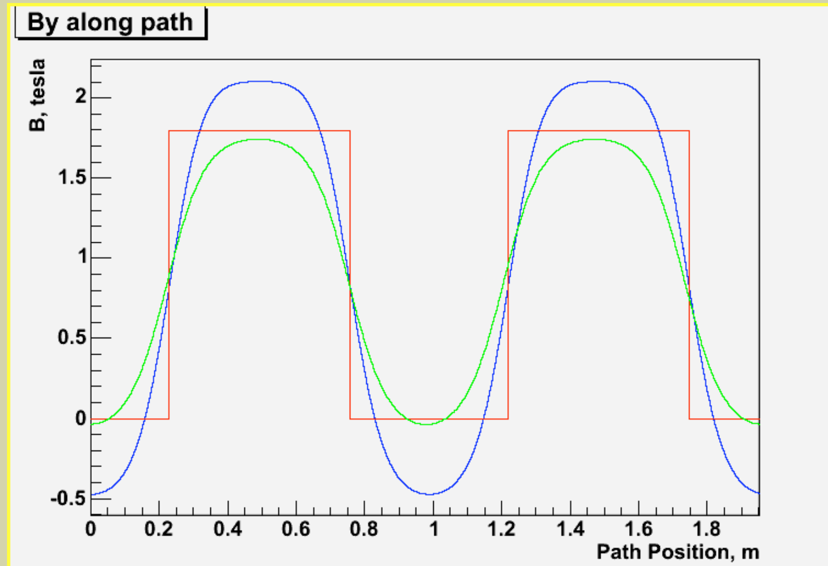
Tosca Results

Fields generated by thin wire coils on the edges of the pole faces





Coils only—No Iron

Coils plus Iron

Constant Hardedge Field