CONCEPTUAL DESIGN OF THE MUON COOLING CHANNEL MAGNET SYSTEM TO INCORPORATE RF CAVITIES

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May 28, 2014

Introduction

- A helical cooling channel with a pressurized H_2 gas absorber imbedded in a magnetic channel that provides solenoid, helical dipole and helical quadrupole fields has shown promise in providing 6D cooling of the muon phase space.
- Muons traversing the cooling channel will lose energy in the H_2 gas, which must be replaced using RF cavities. A substantial fraction of the channel length must be filled with these cavities.
- The magnetic field necessary to hold the beam on the helical path is represented by helical harmonics:

Dipole Term:

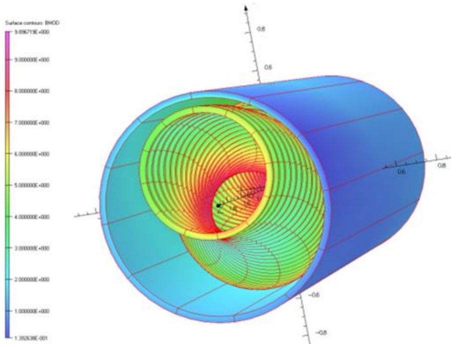
$$B_\varphi = 2b_d I_1(k\rho)\frac{\cos\vartheta}{k\rho}$$
$$B_\rho = 2b_d I'_1(k\rho)\sin\vartheta$$
$$B_z = -k\rho B_\varphi$$

Quadrupole Term:

$$B_\varphi = \frac{b_q}{k} I_2(2k\rho)\frac{\cos 2(\vartheta-\vartheta_2)}{k^2\rho}$$
$$B_\rho = \frac{b_q}{k} I'_2(2k\rho)\sin 2(\vartheta-\vartheta_2)$$
$$B_z = -k\rho B_\varphi$$

An Implementation of the Helical Cooling Channel

- The helical harmonic magnet components are difficult to implement directly with helical multipole fields outside a solenoid since the $I_n(nk\rho)$ Bessel functions grow exponentially with radius producing very large fields on the coils.
- The most effective approach to implementing the desired field is a helical solenoid (HS) channel composed of short solenoid coils arranged in a helical pattern.
  - These short solenoid coils create an excess of B_z which must be accounted for.
- The HS channel is placed inside an external solenoid to allow for the independent setting of B_ϕ and B_z on the reference orbit. Setting the dB_ϕ/dr for optimum focusing requires an additional degree of freedom.
  - We will discuss options for dB/dr.



Constraints Imposed on Magnet System

- The inner coil radius must be large enough to contain the RF cavity plus some thermal isolation space.
  - Note that larger radius coils have less dB/dr which is needed for focusing. We will consider alternate approaches to obtain this focusing.
- The coils and cavities would be arranged into cells such that the number of cells per period would match the number of cavities per period.
  - Longer cavities will reduce the peak power losses since there are fewer walls.
    - This means fewer coils per period. The current design has ~ten cells/period.
- For the HS to provide the desired B_z for the HCC, an anti-solenoid is needed to buck the excess built-up solenoid field.

RF Cavity Parameters

- These parameters chosen from F. Marhauser's spread sheet for dielectric loaded cavities (dated 15-Jul-13).

Section	Units	1	2	3	4	5
Frequency	MHz	325	325	325	650	650
Radius	mm	280.2	280.2	280.2	140.1	140.1
Length	mm	77.3	69.0	60.7	35.7	27.3
Cavities/Period		13	13	13	13	13
Ceramic Inner Radius	mm	92	92	92	46	46

Parameters Describing the HCC Sections

Section		1	2	3	4	5	6
frequency	MHz	325	325	325	650	650	650
λ, period	m	1.0	0.9	0.8	0.5	0.4	0.3
κ, pitch		1.	1.	1.	1.	1.	1.
a, ref. orbit	cm	15.92	14.32	12.73	7.96	6.37	4.77
B, cyclotron	T	5.541	6.157	6.927	11.08	13.85	18.47
B_ϕ on ref.	T	1.289	1.432	1.611	2.577	3.222	4.296
B_z on ref.	T	4.253	4.725	5.316	8.505	10.631	14.175
dB_ϕ/dr on ref	T/m	-0.502	-0.620	-0.785	-2.010	-3.140	-5.583

The last three rows specify the field that we want to achieve. The HS channel needs to be designed to accomplish that.

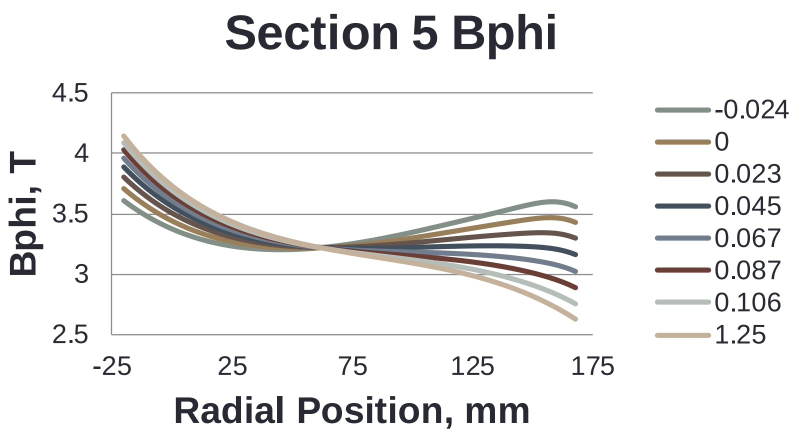
Optimizing the Field

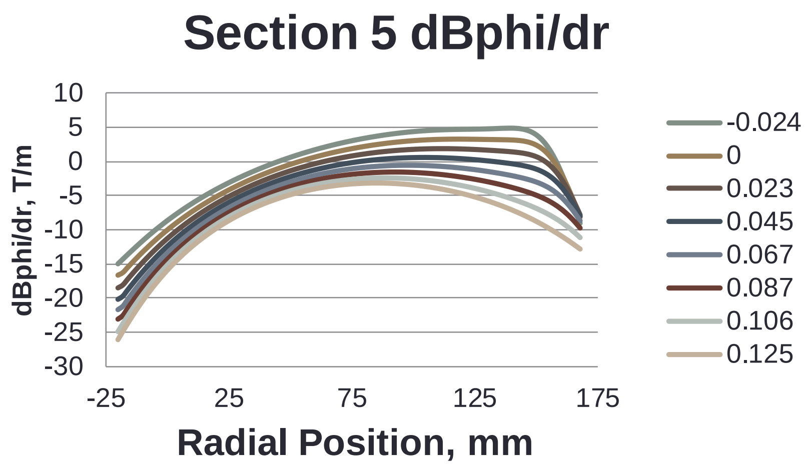
- B_ϕ and B_z can be set to the desired values by adjusting the currents in the HCC coils and the global anti-solenoid.
  - There are limits on the size of the anti-solenoid field because of cost considerations.
  - We do anticipate that the anti-solenoid fields can be made small enough that those coils can be wound with NbTi conductor.
- The field derivative, dB_ϕ/dr, which controls the focusing is more difficult to control. There are several techniques which can affect dB_ϕ/dr.

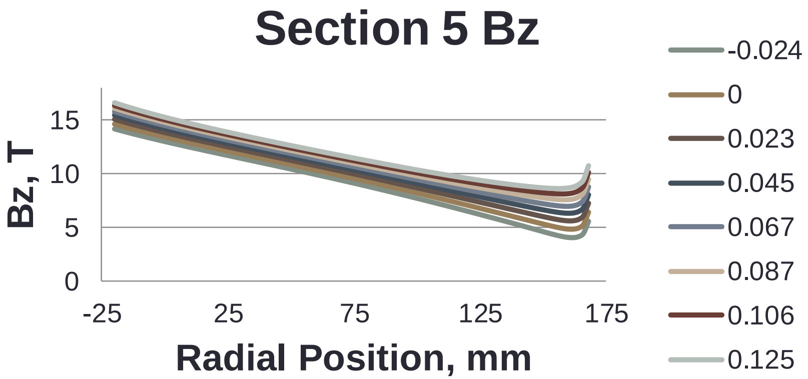
Controlling dB_ϕ/dr

- There are several techniques to be used which can affect dB_ϕ/dr. Because the coil radius is large, adjusting it provides very little field gradient.
  - Placing the reference orbit and cavities away from the coil center will generate gradient.
    - If the ref. orbit is placed toward the helix center one obtains a gradient of the proper sign.
    - This leads to larger coils which typically have larger field on the coils, which we would like to avoid.
  - Deform the coils into an elliptical shape. This has a significant effect on dB/dr and can be used to achieve the desired gradient in most cases.
  - Tilting the coils. Not only does this have a beneficial effect on dB/dr, it also produces a helical dipole.
    - This additional contribution to B_ϕ allows for a reduction of current in the coils.
    - Because the current is reduced the B_z from the HS is smaller, reducing the *anti-solenoid* required.

Field Profiles for Different Elliptical Coil Asymmetries for Section 5 of the HCC

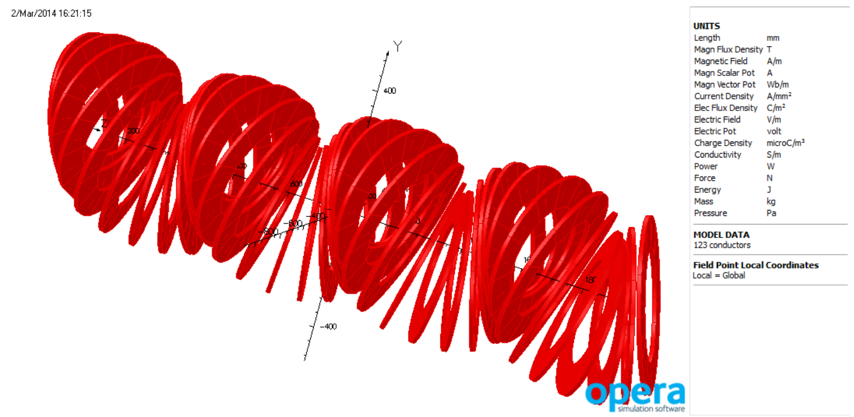


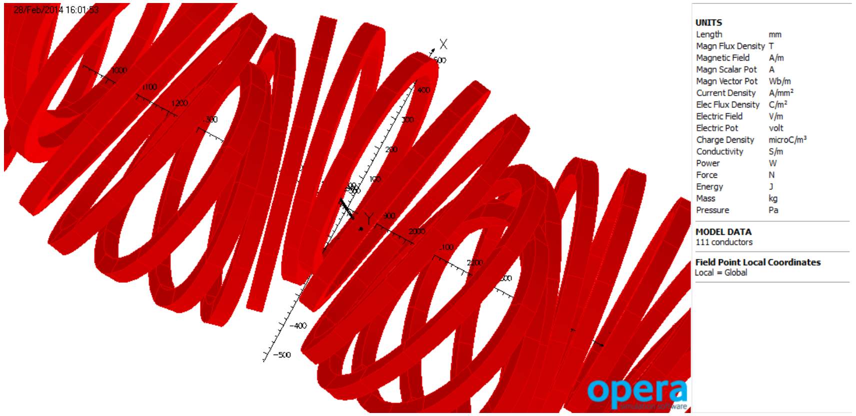




Tilting the Coils

- The upper figure shows the coil configuration for Section 4 with 300 mr coil tilt. The lower figure shows Section 2 with 250 mr coil tilt.
- It is envisioned that the limiting allowed tilt would be from 200 to 250 mr to allow space between the coils.
- To provide room to tilt the coils the coil fill factor fraction is chosen to be 50%.
    - This requires larger current densities to compensate.
    - However it allows larger free space of RF services, etc.





Representative Coil Geometries for Sections 1-5

Segment	Period	Inner Azimuthal Coil Radius	Inner Radial Coil Radius	Frequency	Current Density	Tilt Angle
	meters	mm	mm	MHz	A/mm^2	radians
1	1.0	315	315	325	215	0.2
2	0.9	370	315	325	289	0.2
3	0.8	350	275	325	304	0.25
4	0.5	225	150	650	320	0.2
5	0.4	130	110	975	347	0.2

- Note that we used both elliptical coils and tilted coils in some of these cases.
- Note that section 5 uses 975 MHz cavities instead of 650 MHz to reduce the coil radius.

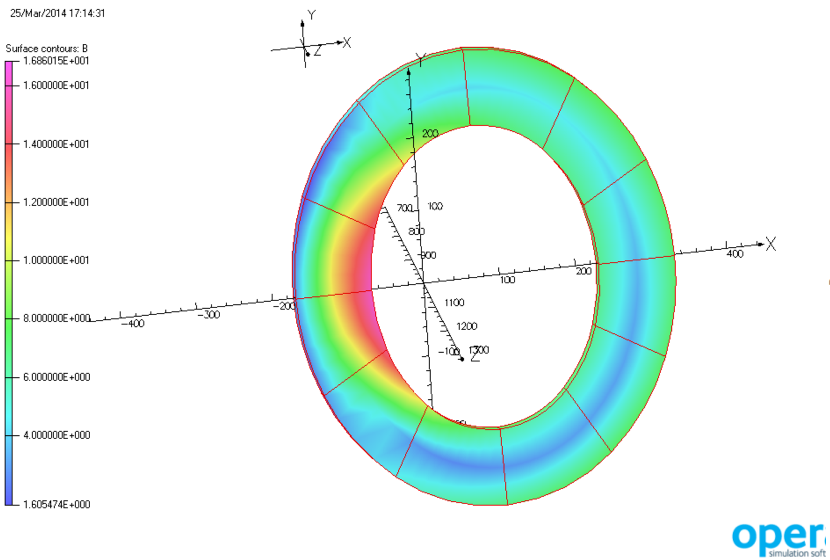
Fields Associated with these Representative Cases

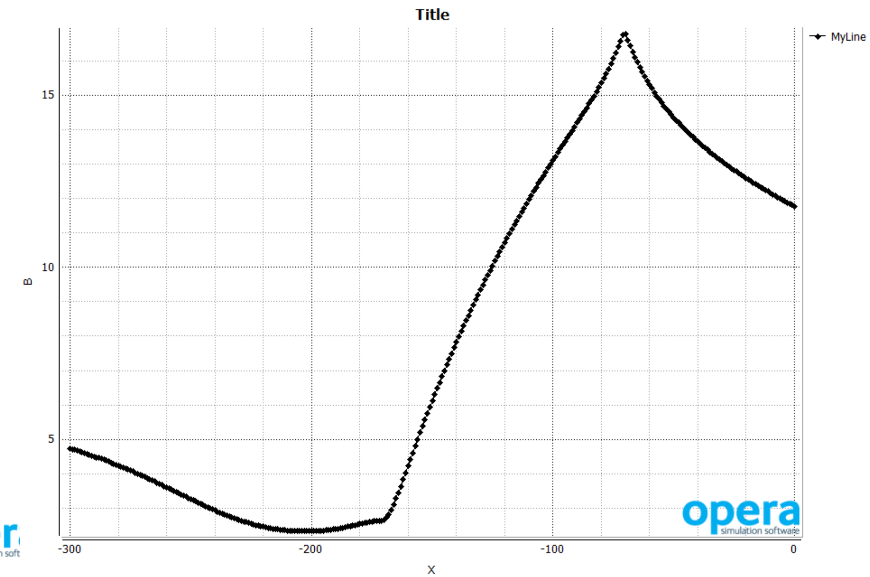
Segment	J_E,	B_ϕ	dB/dr	Anti-Solenoid	B_z at coil	B_ϕ at coil	B at coil
	A/mm^2	T	T/m	T	T	T	T
1	216	1.289	-0.609	-1.13	8.85	2.64	9.24
2	289	1.432	-0.651	-2.79	11.25	3.50	11.78
3	304	1.611	-0.677	-3.66	12.50	3.88	13.09
4	320	2.479	-2.135	-6.08	16.16	4.56	16.79
5	347	3.220	-3.129	-7.33	18.85	5.22	19.56

- The *anti-solenoid* fields are now more manageable. They could be wound with NbTi.
- The fields on the coils for section 5 are large. I will comment more.

Fields on the Coil

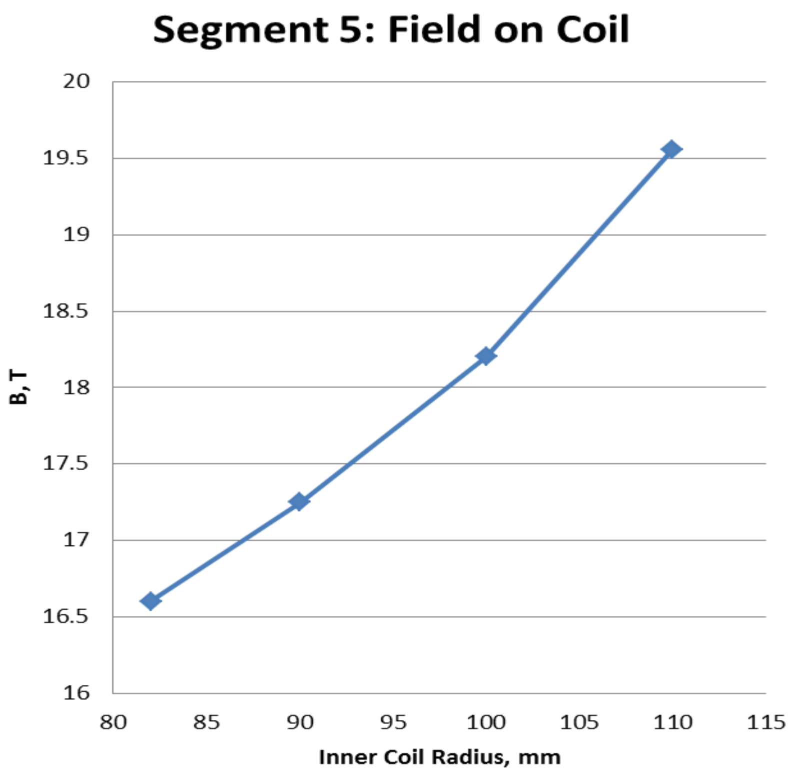
- The field on the coil will limit the current density that the coil can carry

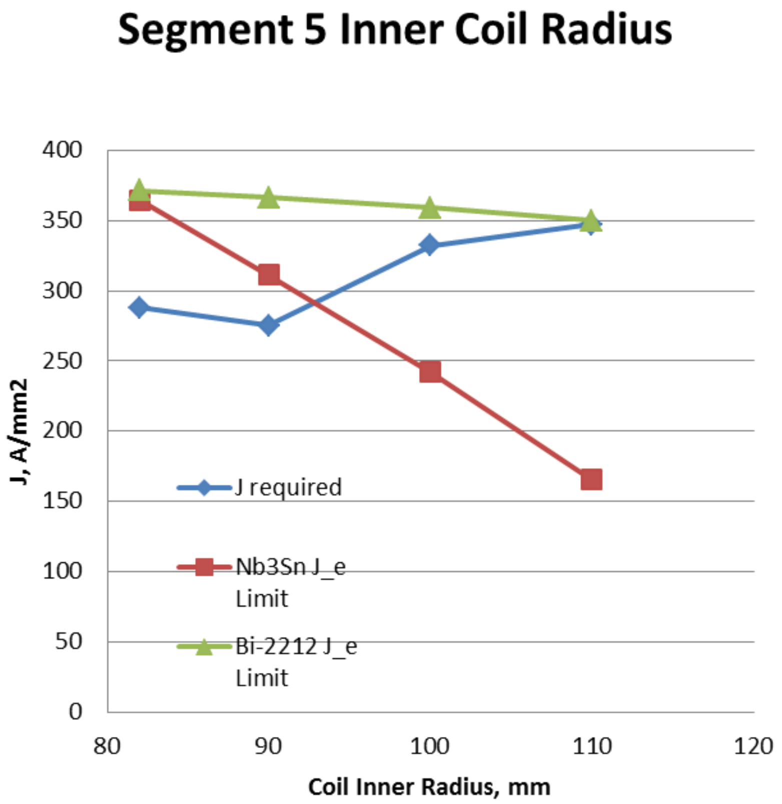




- The field on the coil is shown for section 4. The figure on the right shows the high field region is near the helix axis where the coil apertures overlap.
- The figure on the left shows |B| vs x at the coil. The peak field is on the inner coil surface with a rapid falloff within the conductor.

Section 5 is Near the Feasibility Limit





Decreasing the cavity radius requires more ceramic which increases the peak power.

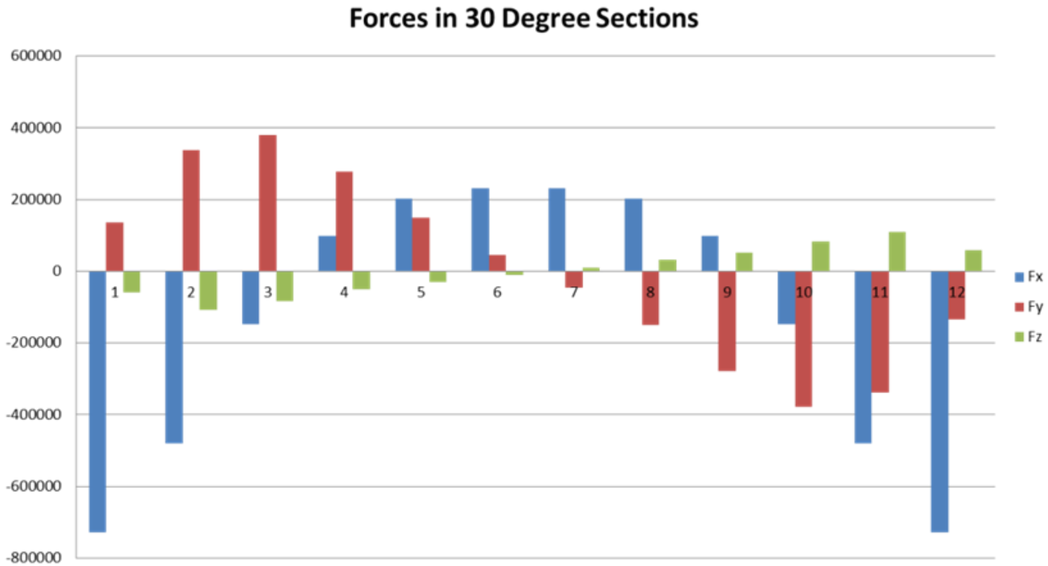
Limiting J_E is 50% of measured J_c for the conductor

Section 5 comments

- Reducing the coil radius may not be possible, because reducing the RF cavity radius would increase the peak power, since we would need more dielectric to achieve that.
- If we kept the preferred radius, we would need Bi-2212 conductor which we would like to avoid.
- The best approach may be to ease the dB_{ϕ}/dr specification. Katsuya’s presentation indicates that the cost to doing that may not be large. We plan to look into that.

Forces on Tilted Coils

- There are two issues with coil forces:
  - What are the forces between an individual coil and the HCC coil lattice.
  - What are the hoop stresses on a single coil from the HCC coil lattice.
    - This affects the conductor strain limit.



Total forces in 30° sections for the section 4 coils with 200 mr tilt.

F_x

F_y

F_z

Integrated Forces and Torques

Segment	Tilt Angle, mr	Local Horizontal Force, F_x newtons	Torque about local x-direction, τ_x N-m
3	0	-2.05×10^6	2.57×10^5
3	200	-3.18×10^6	-3.83×10^4
3	250	-2.88×10^6	-1.12×10^5
3	300	-2.67×10^6	-1.72×10^5
4	0	-1.46×10^6	8.10×10^4
4	200	-1.65×10^6	-1.57×10^4
4	300	-1.83×10^6	-6.64×10^4

Integrated forces and torques on a single coil from the other coils in the HCC. Note that F_y, F_z, τ_y, and τ_z are zero by symmetry.

Conclusions

- We have looked at how conceive of the HCC magnet channel with the desired field allowing room for RF cavities.
- In order to do this we have used elliptically shaped coils and we have tilted the coils to provide some of the helical dipole. This has allowed us to reduce the anti-solenoid required.
- This is a work in progress. We can expect modifications in the future.