Examination of How to Put RF into the HCC

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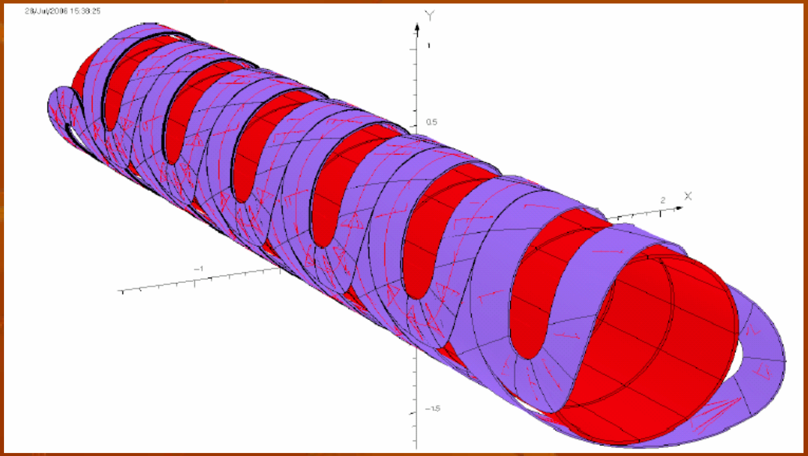
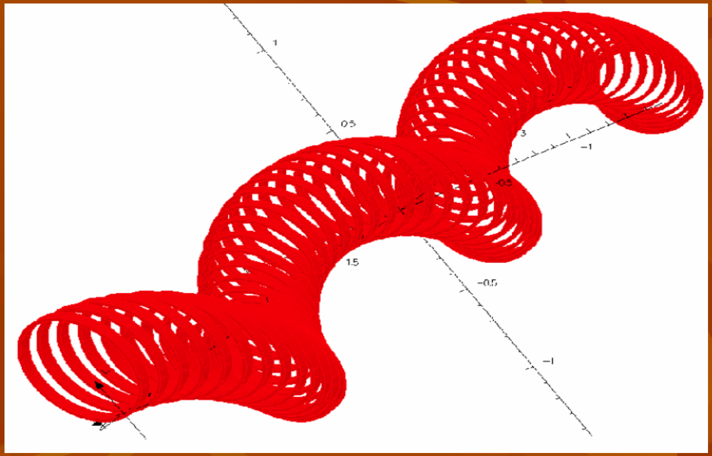
Parameters That Describe the HCC

parameter	λ	κ	Bz	bd	bq	bs	f	Inner d of coil	Maximum b	E	rf phase
unit	m		T	T	T/m	T/m2	GHz	cm	Snake | Slinky	MV/m	degree
1st HCC	1.6	1.0	-4.3	1.0	-0.2	0.5	0.4	50.0	12.0 | 6.0	16.4	140.0
2nd HCC	1.0	1.0	-6.8	1.5	-0.3	1.4	0.8	30.0	17.0 | 8.0	16.4	140.0
3rd HCC	0.5	1.0	-13.6	3.1	-0.6	3.8	1.6	15.0	34.0 | 17.0	16.4	140.0





The RF Must Replace the dE/dx Energy Losses

- For a 250 MeV/c μ in a 400 atm H_2 gas (at 273° K) dE/dx=1.43 MeV/cm along its path.
- If our HCC has κ=1 and if we choose the RF phase to be 140°, we need the peak RF gradient to be 31.4 MV/m.
  - This should be achievable in the pressurized H_2 gas for 200 or 400 MHz cavities.
  - This is a substantial amount of RF and it does not allow for much free space without RF without compromise.

Constraints Imposed by RF

- Limited space for RF:
  - Must use RF along the entire channel to use 400 atm H_2 gas.
- Thermal Isolation Issues:
  - NbTi, $NbSn_3$ and HTS would be best used at 4.3°K to achieve the necessary current densities that we would like.
  - Pressurized H_2 gas must be above critical temperature of 33°K.
  - If N_2 is used to cool RF cavities, they would be at 77ºK.
    - Can H_2 be used to cool RF cavities? We would like the cavities to be gas filled to prevent breakdown.
- Structural isolation from coil Lorentz forces.
- Structural support of RF cavity walls.
- Space to bring in RF services, eg wave guides for RF power.
- For the purposes of this study we have assumed that we would allow 3 cm around the coils for the above.
  - It appears that a 5 cm clearance around the coils is more appropriate.

Spatial Constraints for RF in HCC

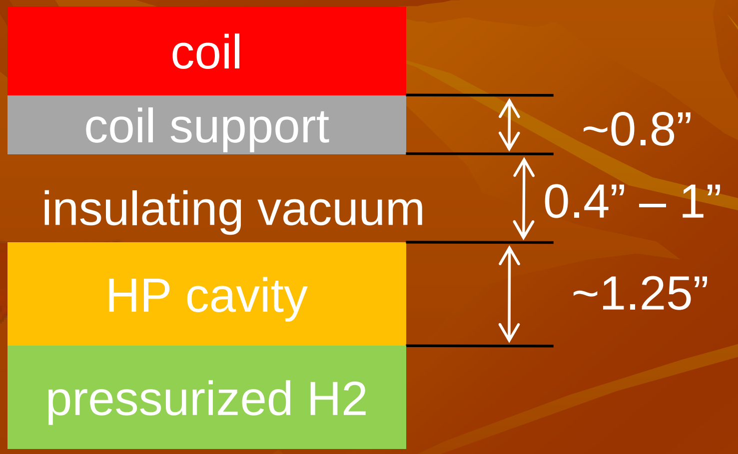
How to include RF?

1. RF inside coils?
2. RF in between coils?
3. RF and HCC separate?

How much space is needed in between? (1, 2)

How to match? (3)

Requires about 3 cm to separate RF cavity from the the coil.



From A. Jansson

A Jansson, K Yonehara, V Kashikin, M Lamm, J Theilacker, A Klebaner, D Sun, A Lee, G Romanov, D Broemmelsiek, G Kutznetsov, A Shemyakin, …

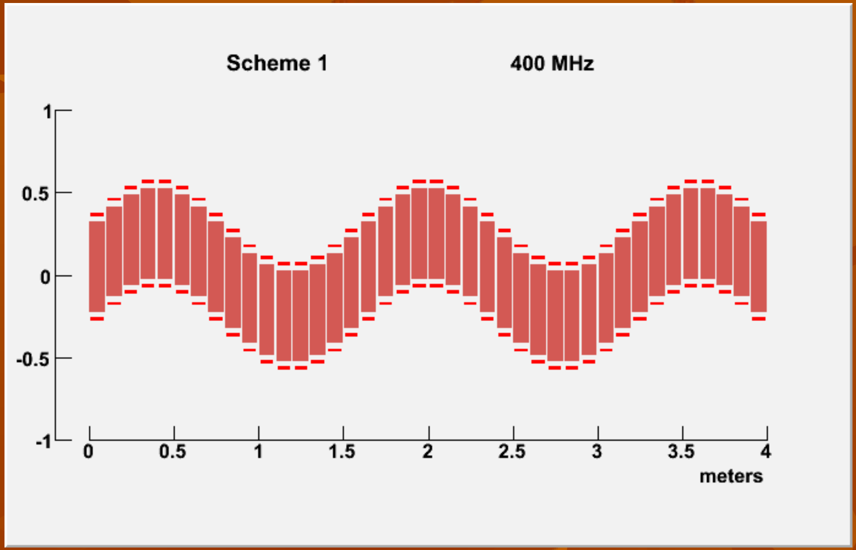
Schemes to Include RF

- There are (at least) four scenarios that we have been looking into.
- Each of these schemes has both advantages and disadvantages.
  - These include cooling effectiveness, space requirements and ease of engineering.
- These schemes are
  1. RF cavities inside coil rings.
  2. RF interleaved between coil rings.
  3. Sequences of HCC Cooling sections free of RF followed by blocks of RF cavities.
  4. A traveling wave scheme.

Scheme 1: Cavities Inside Coils

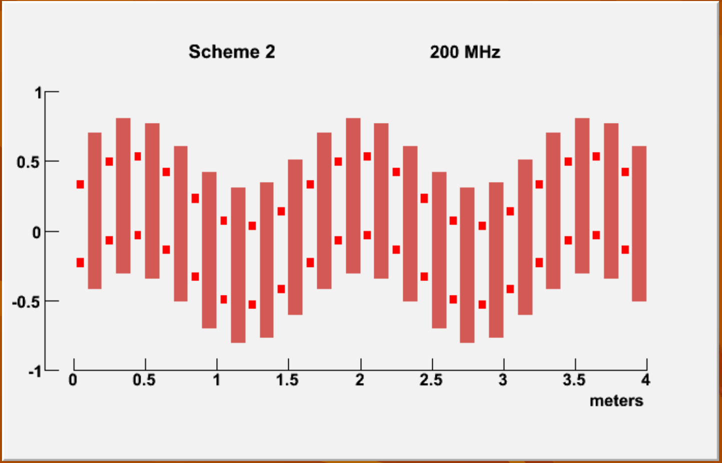
- This scheme makes effective use of space by placing RF along the entire helical trajectory.
- The frequency of the RF cavities is limited by the coil radius:
  - The pillbox cavity radius for 400 MHz with 400 atm H_2 gas would be 27.2 cm. This is slightly larger than the segment 1 (MANX) coil radius.
  - We also need a clearance for cryogenic isolation around the coils.
  - We also need space for wave guides and structural support of the cavities.
- The figure illustrates a cartoon showing this arrangement. The dimensions are in meters and there is a clearance of 2 cm for the thermal isolation of the coils.

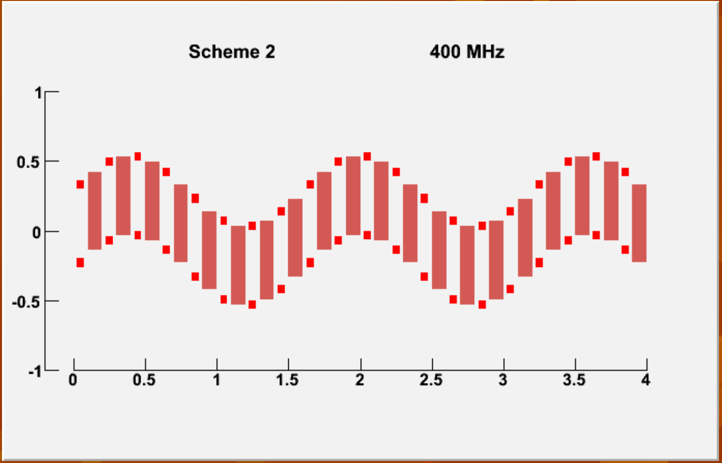
$$f = \frac{2.405c}{2\pi\sqrt{\mu\varepsilon}R}$$



Scheme 2: Cavities Between the Coils

- The field in this scheme is generated by 8 coil rings per period. (Half as many as scheme 1).
  - I will show that the field field generated is sufficiently similar.
  - Each coil now has to carry twice the current and has to be shorter to allow a thermal clearance to the cavities. The radial extent of the coils is larger in this scheme.
    - The Lorentz forces on the coils are twice as large.
- This scheme allows sufficient access to the cavities for wave guides, etc.
  - One can consider using 200 MHz cavities.
- In order to use 31.4 MV/m cavities the H_2 gas pressure would be reduced to 200 atm and consequently the channel would be twice as long to produce the same muon cooling.





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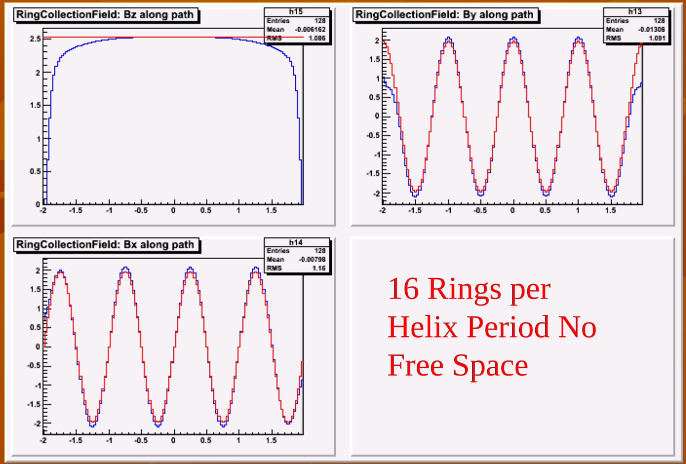
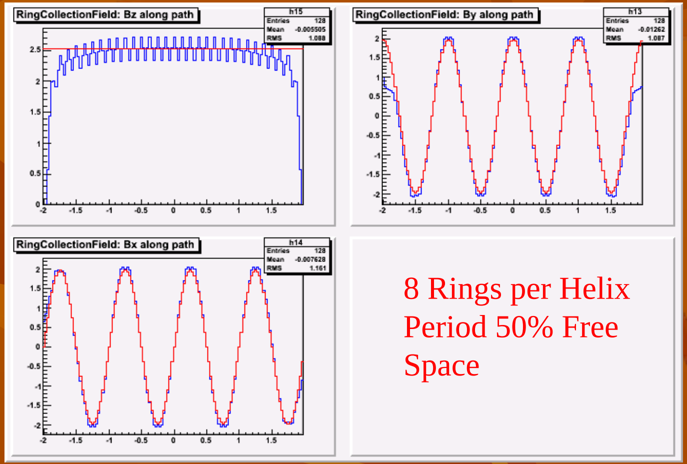
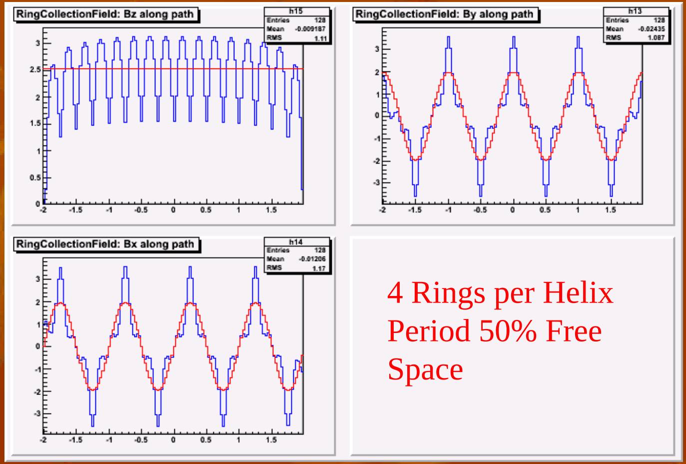
A Field Comparison



16 Rings per Helix Period No Free Space



8 Rings per Helix Period 50% Free Space



4 Rings per Helix Period 50% Free Space

- The figures show a comparison of the *slinky* field with the analytic fields given by:
- Analytic Expressions for Helical Dipole Fields:

$$b_\phi = 2b_d I_1(k\rho)\cos\psi / k\rho$$

$$b_\rho = 2b_d I_1'(k\rho)\sin\psi$$

$$b_z = -k\rho b_\phi$$

Analytic Expressions for Helical Quadrupole Fields:

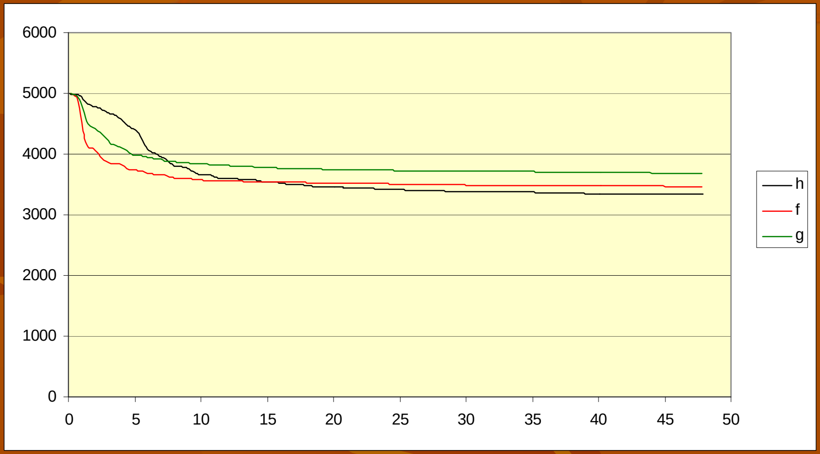
$$b_\phi = b_q I_2(2k\rho)\cos 2(\psi-\psi_2)/k^2\rho$$

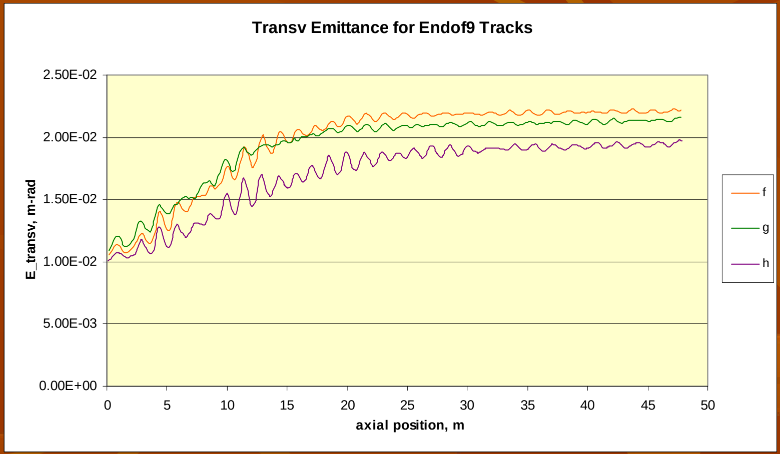
$$b_\rho = \frac{b_q}{k} I_2'(2k\rho)\sin 2(\psi-\psi_2)$$

$$b_z = -k\rho b_\phi$$

Transmission in a Long Channel

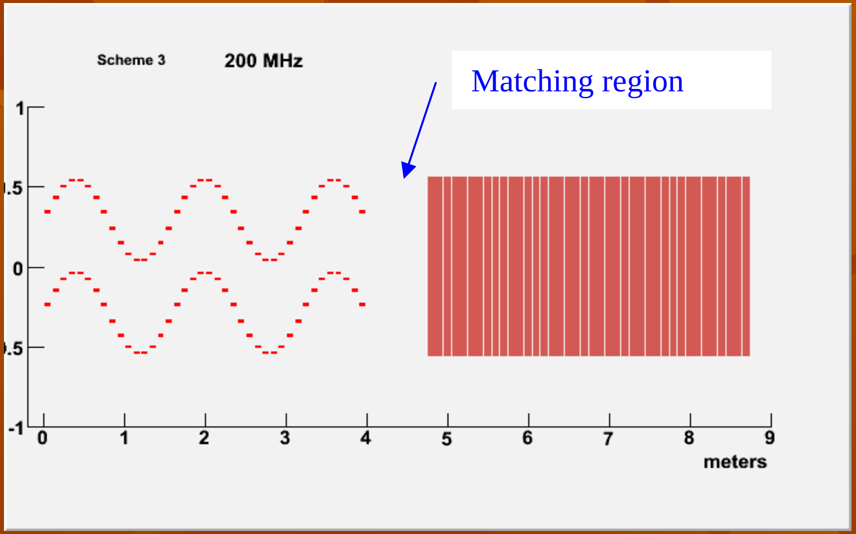
- Parameters correspond to segment 1 (MANX-like).
- The top figure shows the transmission along 50 m vacuum helical channel.
  - Black curve shows channel with closely packed rings with 16 rings per period.
  - The Red (Green) curve shows interleaved channel with 8 rings per period with NbTi (Nb_3Sn).
- The lower figure shows the transverse emittance along the channel.
  - This is a measure of the field quality, since cooling is not expected to occur in the vacuum.





Scheme 3: Blocks of RF Cavities

- This scheme is favored from an RF engineering point of view.
  - Thermal isolation between the cavities and coils is not an issue.
- Both the magnetic and RF parts of the channel will be filled with pressurized H_2.
  - Since the cavities will only occupy approximately half of the length, the H_2 gas pressure will likely be ~200 atm. The channel will need to be twice as long to achieve the same muon cooling.
- The length of the individual cavity banks and HCC magnetic chains is dependent on the tolerated energy loss swing. It is also dependent on how many matching sections that we can tolerate.



Scheme 3, cont.

- This scheme requires matching from the HCC to the RF cavities and back.
  - The scheme that Katsuya had used from a solenoid to the HCC required 1.5 λ periods. (Need for entrance and exit).
- There must be lower field solenoids around the RF cavities to hold the beam together in that region.
- I do not believe that we have successfully simulated the cooling in this scheme. We must establish that it works.
  - Does it work as well as scheme 1 or 2? Both for cooling efficiency and for minimization of losses.

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Scheme 4: Traveling Wave

- This is Katsuya's idea and it seems attractive. (More work needs to be done).
- Hydrogen has a permittivity. For H_2 gas at 400 atm ε=1.1015
  - This means that phase velocity is 0.953c.
- A muon with 325 MeV/c would have a velocity of 0.951c which would match the phase velocity.
- If we removed the cavity windows and the cavities are sufficiently close to each other, the accelerating field lines would follow the reference orbit. This would give a gain in gradient of $\sqrt{2}$

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Realizing the Coils

- The coils in segments 1 and 2 could be realized with either NbTi or Nb_3Sn superconductor.
  - We will use at NbTi in this study.
- Segment 3 will require HTS or an HTS/Nb_3Sn combination.
  - The HTS/Nb_3Sn combination will use extent. This is being studied by Mauricio Lopes.
- In this study we have chosen to have J_{EFF} to be 1/3 $J_{Critical}$.
  - This allows for a reasonable Cu/SC ratio to be used to stabilize the conductor.
  - The radial extent of the coil is increased to achieve the desired J_{EFF}.
- The field parameters can change in this picture.
  - May need additional global solenoid field to permit the flexibility to achieve the desired B_{SOL}, B_{DIPOLE}, without adjusting λ.

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How to Realize the Coils

Segment	***Scheme***	***R_{IN}***	***R_{OUT}***	***L_{CELL}***	***L_{COIL}***	***L_{CAVITY}***	***Rings per Period***	***Conductor Type***
		cm	cm	Cm	cm	cm		
1	Nominal	24.9	25.1	10	10	0	16	
1	0	30.5	30.7	10	10	0	16	
1	1	30.5	32.5	10	7.5	10	16	NbTi
1	2	30.5	36.5	20	5	10	8	NbTi
1	3	30.5	32.5	20	5	10	8	Nb_3Sn
2	Nominal	15.9	16.1	6.25	6.25	0	16	
2	1	16	19.25	6.25	4.25	6.25	16	NbTi
2	2	16	24.8	12.5	3.125	6.25	8	NbTi

Segment	***Scheme***	***Current Density***	***Current***	***B_S Solenoid***	***B_Φ Dipole***	***dB_Φ/dr Quad***	***d^2B_Φ/dr^2 Sex***
		amp/mm^2	Amp-turns	Tesla	Tesla	Tesla/m	Tesla/m^2
1	Nominal	2361	4722	4.473	1.417	-0.0133	0.000398
1	0	2361	4722	4.626	1.292	-0.0099	0.000316
1	1	315	4722	4.620	1.275	-0.0094	0.000222
1	2	315	9444	4.721	1.195	-0.0102	0.000499
1	3	944	9444	4.702	1.239	-0.0111	0.000763
2	Nominal	3554	4443	6.800	2.122	-0.0314	0.001556
2	1	323	8885	7.111	1.857	-0.0249	0.003022
2	2	322	4443	6.897	2.073	-0.0278	0.001378

Possible Ramifications for MANX

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- The MANX channel has the same HCC parameters as segment 1.
- Rather than create the MANX HCC channel with 72 closely packed rings, one could build a two period lattice with just 16 "scheme 2" type rings spaced appropriately.
  - This would use the same total amount of superconductor, however since it involves fewer rings there is likely to be cost savings.
  - MANX phase I would be a demonstration of muon cooling and not involve RF.
- For MANX phase II, one could insert, say, two pillbox 400 MHz cavities, between the first conductor rings.
  - This would address the engineering issues of putting RF into a MANX-like channel.
  - It would be desirable to instrument the MANX channel with fiber planes inside the cryostat to observe the effect of the RF on the single particle tracks.

Conclusions

- Including RF into the HCC will be challenging, but not impossible.
- We have examined several concepts that look promising. Each has advantages and disadvantages associated to it.
  - More serious engineering needs to be completed for each of these concepts.