Recent progress in Design of Helical Cooling Channel

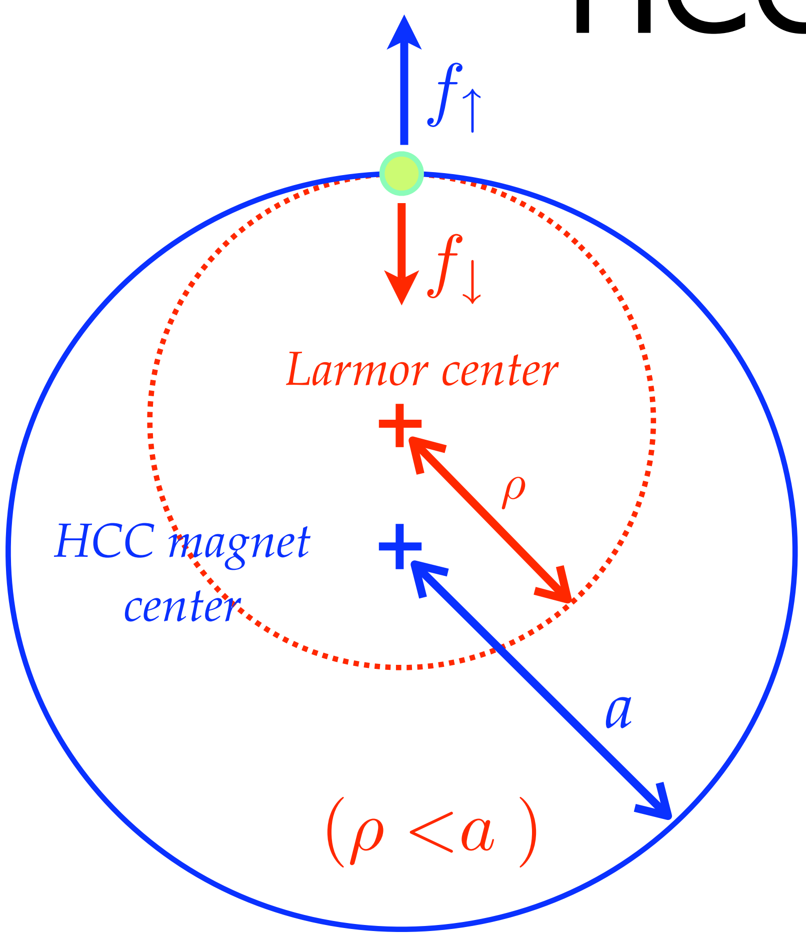
K. Yonehara

MC Design Workshop
12/10/08

To-Do List in HCC design work

- Design Realistic HCC
  - Design realistic RF cavity — In this presentation
    - Continuous RF structure in this presentation
  - Design realistic HCC magnet — In this presentation
  - Phase space matching — Under investigation
  - Cryogenics — Under investigation
  - Mechanical analysis — Some pieces have been done
Not covered in this presentation
- Safety Requirements — Under investigation
  - High pressurized window for hydrogen safety

HCC design parameters



Projectile in transverse (x-y) plane

Larmor motion in pure solenoid

$$f_\downarrow = -\frac{e}{m_\mu} p_\varphi \cdot b_z$$

$$\rho = \frac{p_\varphi}{b_z}$$

Radial equation of motion with helical dipole

$$f = f_\uparrow + f_\downarrow$$
$$= \frac{e}{m_\mu}\left(p_z b_\varphi - p_\varphi b_z\right)$$

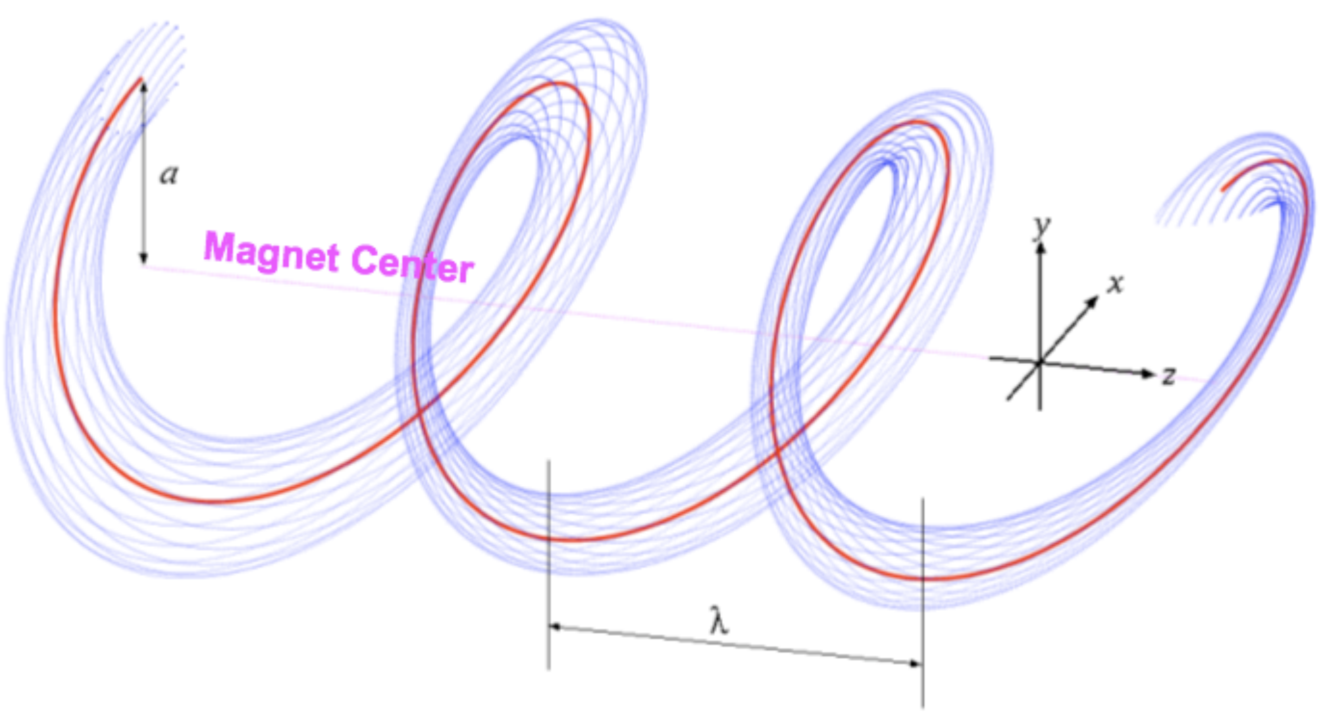
$k = \dfrac{2\pi}{\lambda}$ HCC wavenumber

$\kappa = ka = \dfrac{p_\perp}{p_z}$ HCC pitch

Equation of motion for reference particle

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left(b_z - \frac{1+\kappa^2}{\kappa} b_\varphi\right)$$

Introduction of field gradient in bϕ generates dispersion function



Particle motion in helical magnet

Beam parameters

Dispersion factor

$$\widehat{D}^{-1} = \left(\frac{a}{p} \frac{dp}{da} \right) = \frac{\kappa^2 + (1-\kappa^2)q}{1+\kappa^2} + g$$

$$g = -\frac{(1+\kappa^2)^{3/2}}{pk^2} \frac{\delta b_\varphi}{\delta a}$$

$$q = \frac{k_c}{k} - 1 = \frac{(1+\kappa^2)^{3/2}}{kp\kappa} b_\varphi = \frac{a}{\rho} - 1$$

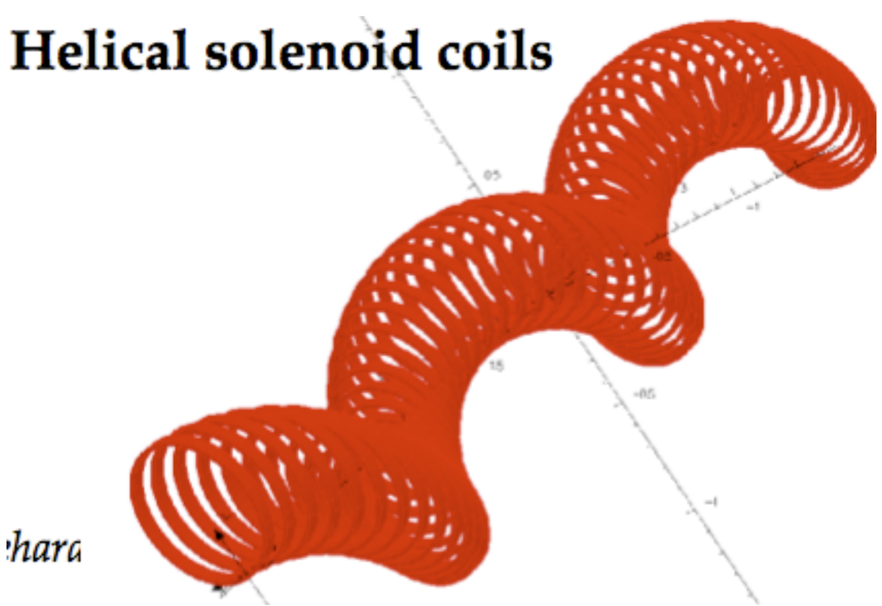
$\widehat{D}, q$ are independently fixed from cooling scheme

Stability condition is determined from betatron motion in HCC

$$0 < \left(\frac{2q+\kappa^2}{1+\kappa^2} - \widehat{D}^{-1} \right) \widehat{D}^{-1} < \frac{1}{4} \left(1 + \frac{q^2}{1+\kappa^2} \right)^2$$

Eqs. (3.18) to (3.24) in Slava & Rol's paper (PRSTAB 8, 041002 (2005))

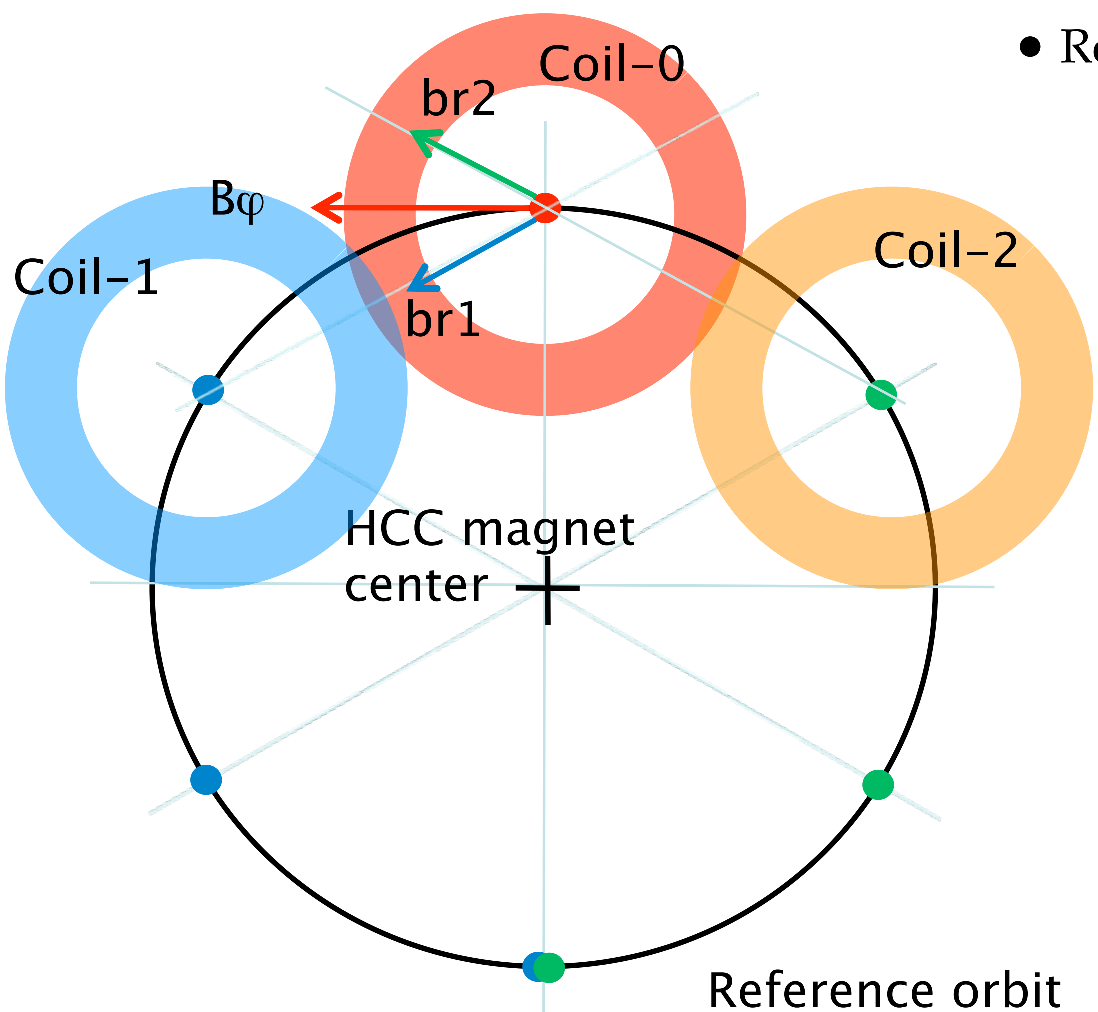
Geometric limit in current HCC design



- Consider continuous RF structure inside HCC
- HCC field is generated by HS
- Field parameters in HS has a geometric restriction
- From past HS design study: HS coil radius ~ Helix radius (a)
- It makes a lower limit of pill-box type RF frequency

  Example: $\lambda = 1$ m, $\varkappa = 1.0$, $a = 0.16$ m

  $\rightarrow$ pillbox RF frequency ~ 800 MHz
- High freq RF structure destroys the longitudinal phase space stability
- Hence, no cooling in high freq RF channel
- Furthermore, additional space between coil and RF cell is needed for thermal isolation, pressure barrier, etc
- Required minimum gap = 80 mm



- Need to adjust (Bz, b, b') on red dot (Coil-0 center)
- Blue dot and green dot are centers of upstream (Coil-1) and downstream (Coil-2) HS coils
- Coil-1 and Coil-2 generate br1 and br2 on red dot
- Br on red dot is zero by sum of br1 and br2 but those generate Bφ
- Bz and Bφ are tuned by the location of HS coil
- b' is tuned by bore of the HS coil

  $\rightarrow$ Optimum HS coil radius for cooling ~ Helix radius (a)

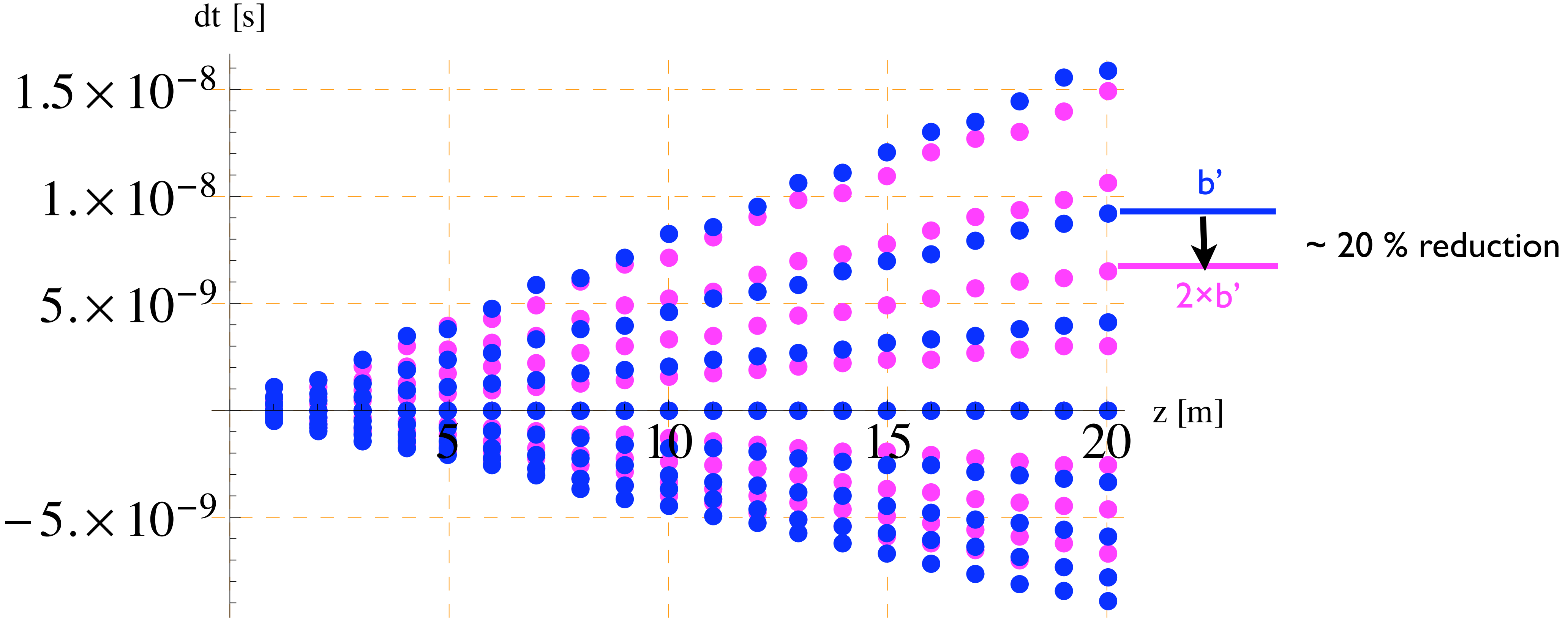
Tune time of flight by varying b’

Phase slip factor

$$\eta = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right)$$

Y. Derbenev & R. Johnson, PRSTAB 8, 0410020 (2005), Eq. (3.52)

Adjusting dispersion to adjust time of flight



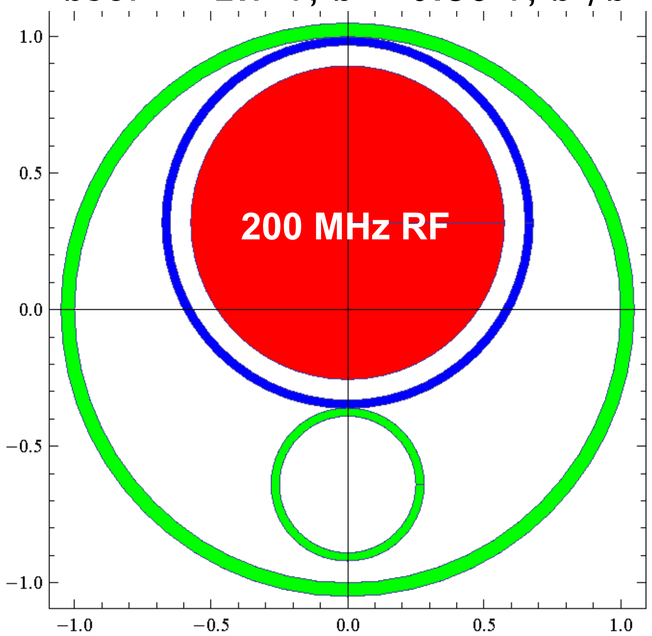
- Need to reduce time spread to use higher frequency RF cell
- Time spread can be reduced by applying higher b’
- Estimated reduction of time of flight is ~15 % with double b’
- Numerical simulation shows more than the expected value

Increment of b’ by adding correction magnets

Old design

λ=2.0 m, κ=1.0
Primary HS:
Inner R = 650 mm, Outer R = 680 mm
Current density = -69 A/mm2
Correction HS:
Inner R = 250 mm, Outer R = 280 mm
Current density = 414 A/mm2
Solenoid:
Inner R = 1000 mm, Outer R = 1050 mm
Current density = -11 A/mm2

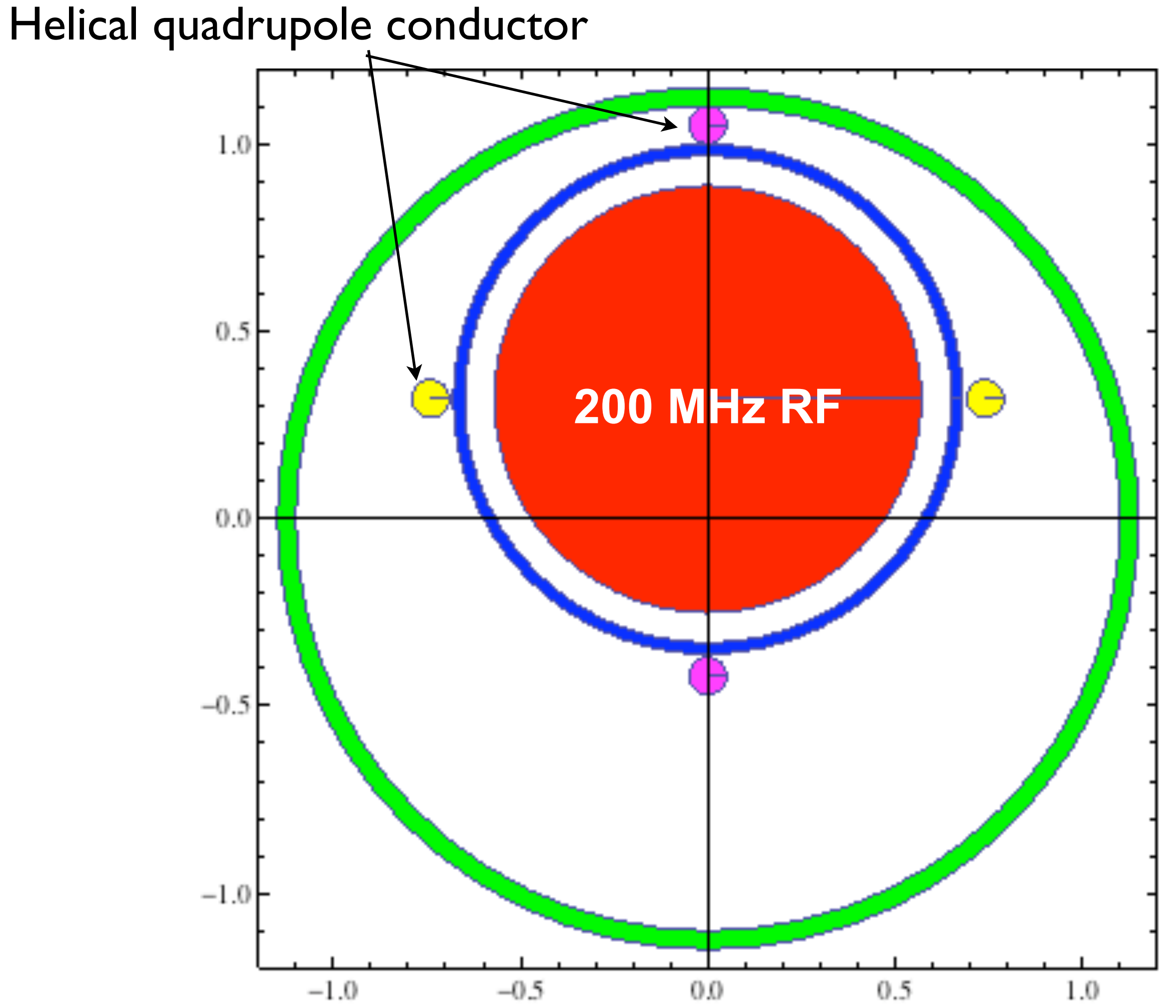
bsol = -2.7 T, b = 0.86 T, b’/b = -0.84



OR

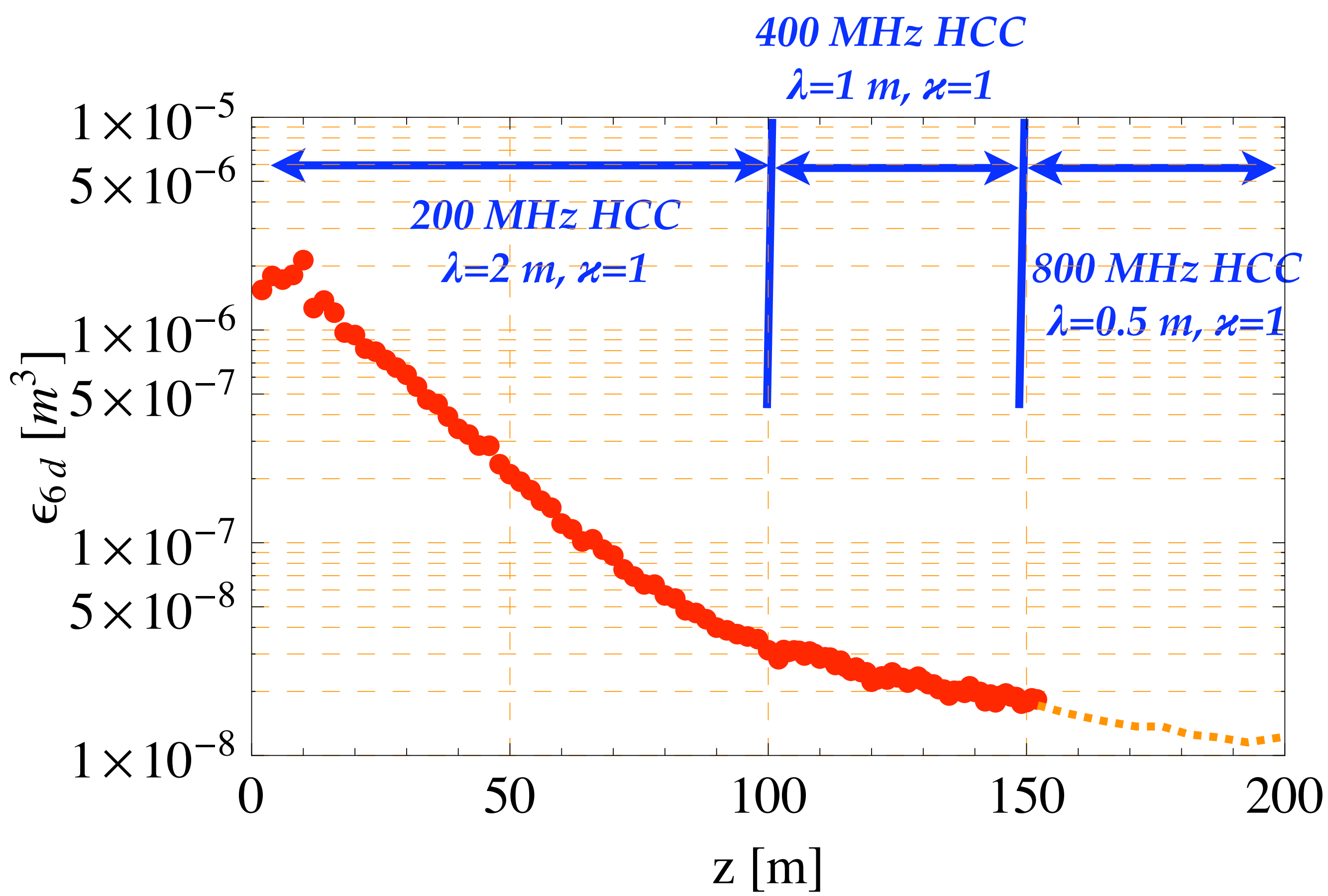
New design

Introduce helical quadrupole conductors to generate optimum field gradient



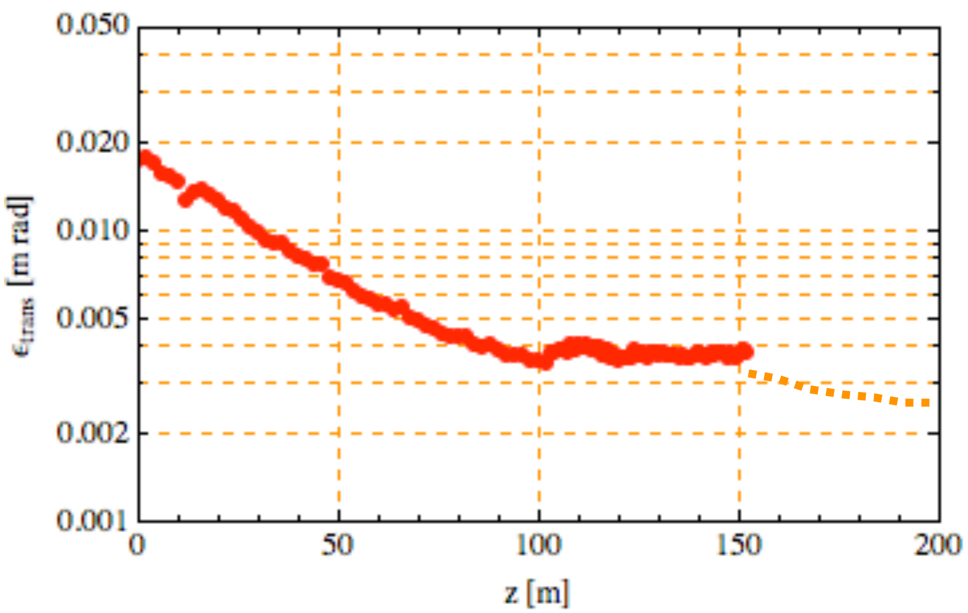
A new design generates optimum field more effectively

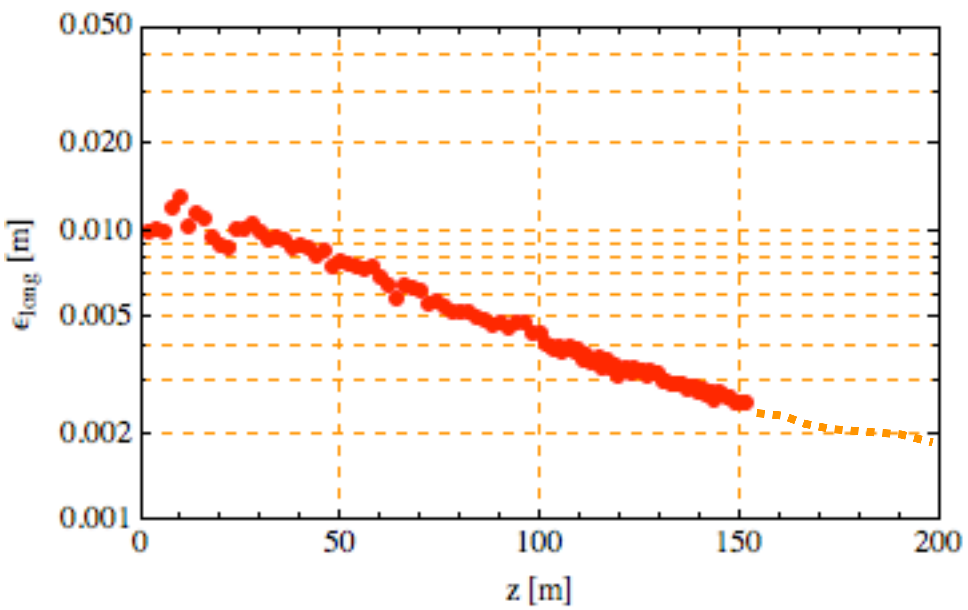
Cooling simulation result



Series of HCC

- Matching for 3rd HCC has not been made yet
- Emittance in 3rd HCC (dashed orange line) is obtained from independent simulation result
- Transmission efficiency = 70 % up to end of 2nd HCC
- Multiple set of HCC field at intermediate section for phase space matching
- Optimization is required in 800 MHz HCC





Realistic RF structure in HCC

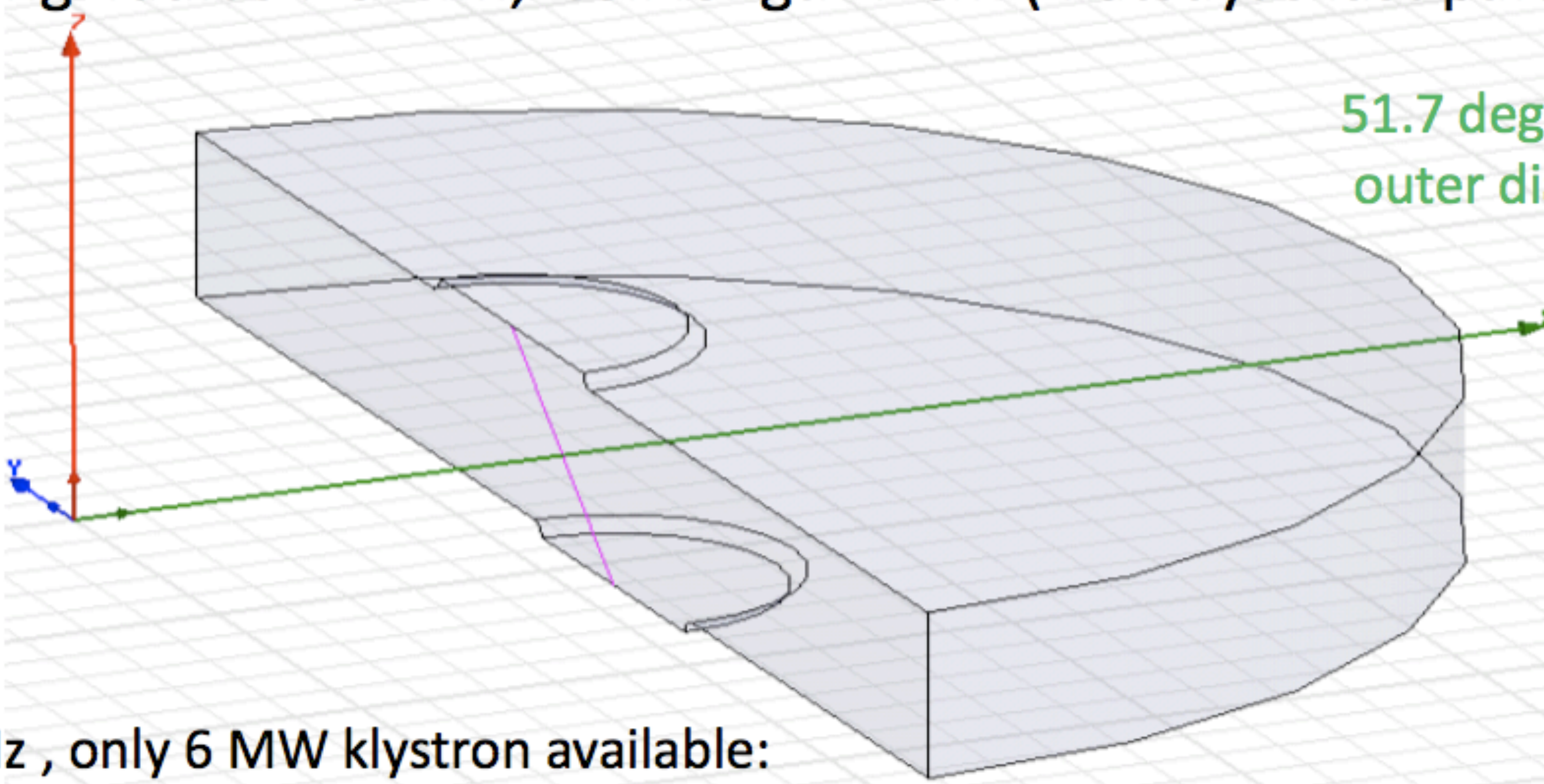
- HCC Simulation has been done by using normal pillbox RF cavity
- Acceleration field directs parallel to solenoidal magnetic field
- Key points to design realistic RF for HCC
  - Lower frequency RF is preferable for beam stability
  - How to transmit RF power into HCC RF?
  - What is RF power?
  - Mechanical structure

Traveling wave RF structure in HCC (I)

- No window required
- Less number of power coupler

Lars Thorndahl

Another difficult case: 100 mm diam. coupling and beam aperture, iris rounding radius : 5 mm, cell length 7 cm (Katsuyas last parameter)



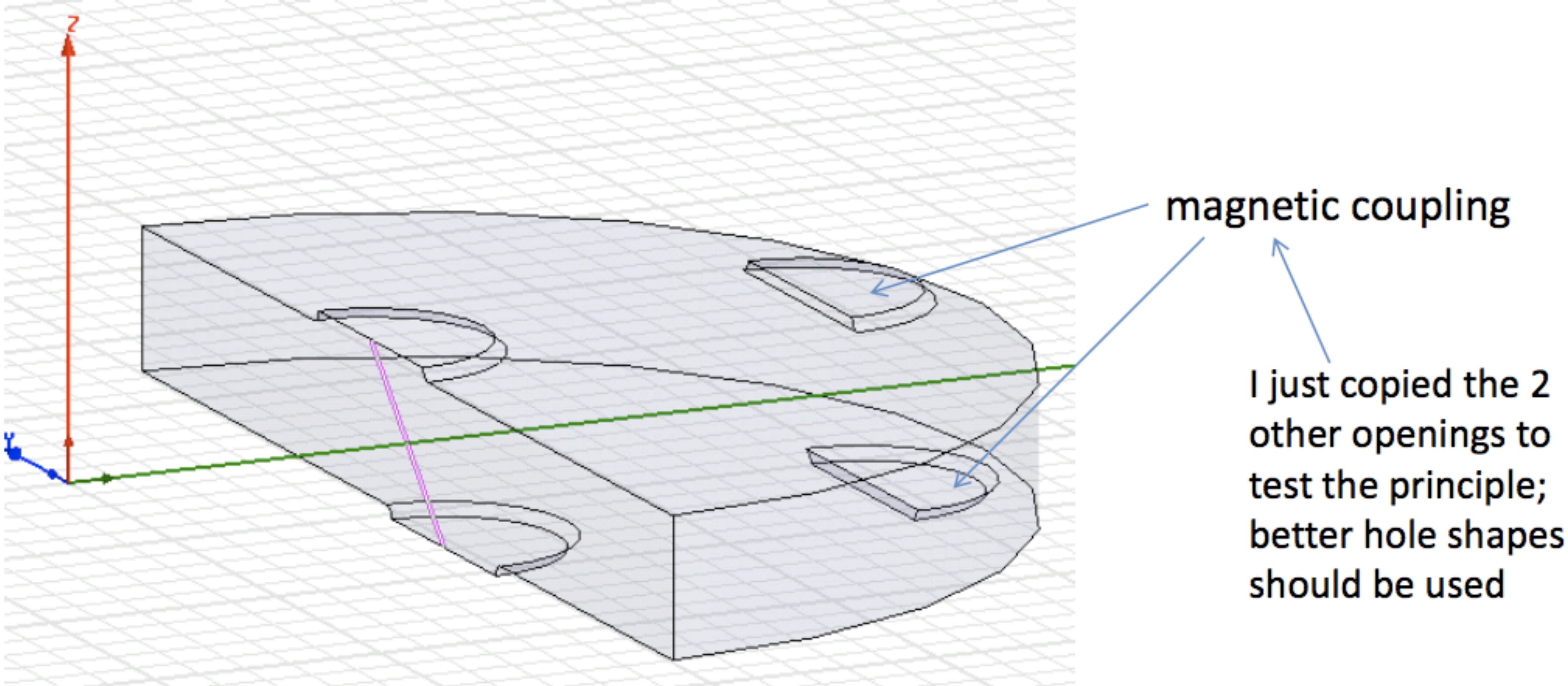
416 MHz , only 6 MW klystron available:

betagroup = +0.0064, Grad. =12 MV/m, P= 121.2 MW, E-enhancement = 2.3,
W = 4.3 J/cell , Q = 18 300 (Cu room temp.) , 614 kW peak dissipation/cell

Scaled to 800 MHz, all dimensions halved (klystron 24 MW available):
Grad. 12 MV/m, P= 30.6 MW, Q = 13200 , 217 kW peak dissipation/cell

Traveling wave RF structure in HCC (II)

Additional coupling ports for backward wave: a handle to reduce the group velocity



betagroup =0.00023 , 4.67 MW, grad. = 12MV/m, W = 4.6 J/cell, Q=14 500, Enhancement = 2.3, f= 0.393 GHz

By introducing backward magnetic coupling we can reduce the transmitted power requirement even in presence of a large beam aperture. The fill time is increased and Ez will , due to attenuation, decrease more with cell number. Above case is a first attempt. Here the magnetic coupling is somewhat excessive!

Traveling wave RF structure in HCC (III)

An extreme case: we reduce the group velocity to zero (by proper adjustment of the magnetic coupling) and obtain standing wave cells with non-zero beam apertures. The cells would be fed individually.

The cell geometry is a function of the specified phase advance/cell.

The interest of the geometry is that the beam core need not traverse any Be foil or grid (but the E-enhancement problem remains).

Furthermore, for the case of the obstructing full-aperture grid with small leaks, causing systematic forward coupling into neighboring cells, we have now the indication that the leaks can be compensated by magnetic backward coupling.

Traveling wave RF structure in HCC (IV)

Back to the geometry of slide 2 and 0.393 GHz:

The energy density is reduced by factor 1/e in Q/omega = 5.8 e-6 seconds due to wall dissipation.

During that time only 5.8e-6 x 3e8 x betagroup/cell length = 6 cells will be filled.

We could consider larger beam apertures and different iris roundings. Perhaps we can get away with an enhancement not much worse than 2.3.

What is the max. surface field acceptable?

Latest news from Mohammad (10/10/08) : estimated max. acceptable enhancement factor: 2.

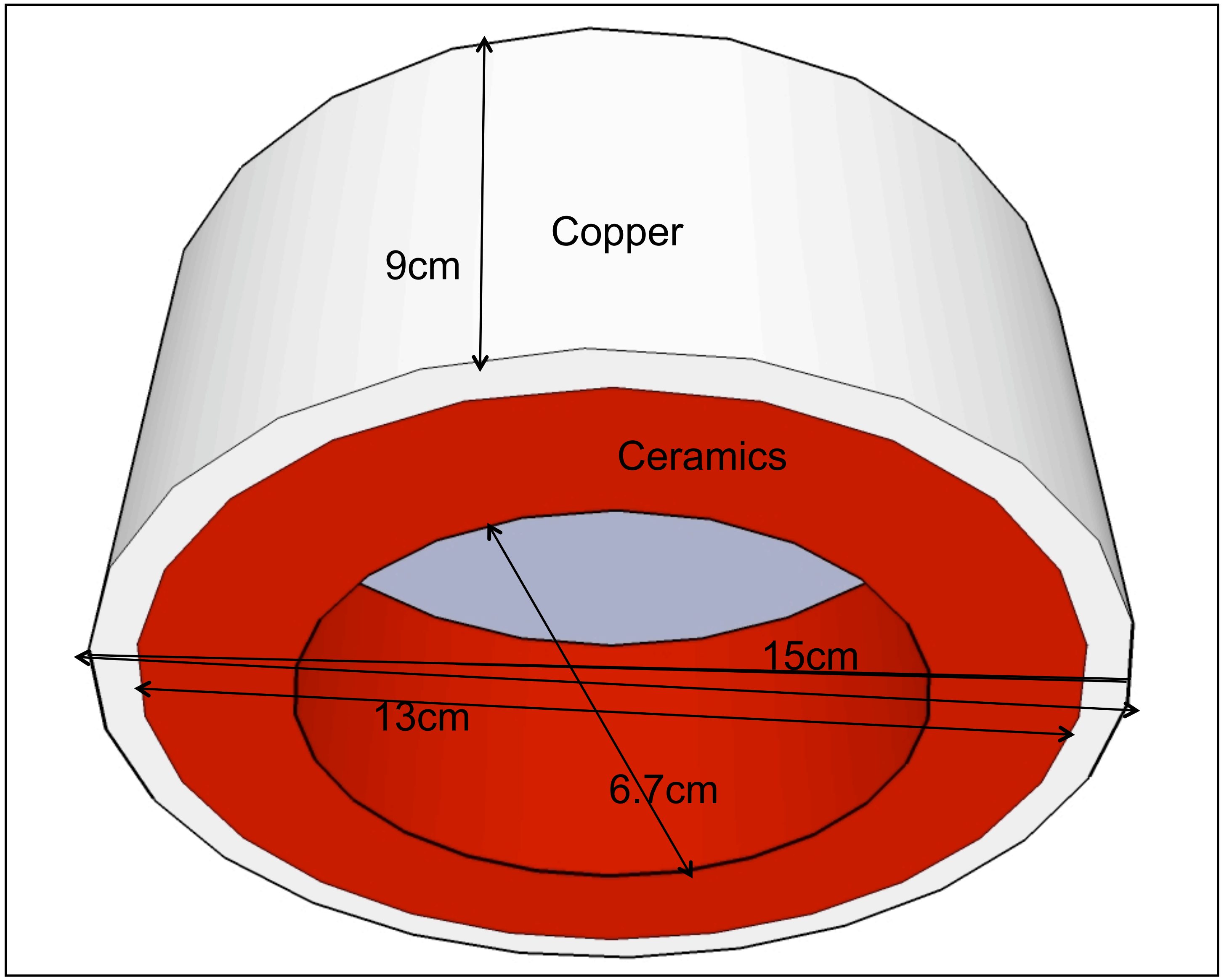
Traveling wave RF structure in HCC (V)

Summary

- No window is needed in traveling wave RF
- May reduce the number of power couplers
- Need to reduce RF power
  - Make low resistive RF cell
  - Use longer RF cell
- Adjust coupling hole to obtain ideal RF structure

Compact dielectric RF for HCC

- Reduce transverse size of RF cell
- Milorad will present this idea more detail



Conclusion

- Investigated realistic HCC design
- Large bore HCC magnet up to 3rd cooling stage can be made with present SC technology
  - Obtained phase space evolution in realistic HCC
  - Need further optimization of final HCC stage
- Studied realistic RF structure in HCC
  - Traveling wave RF structure
    - Very high RF power will be required
    - Need to investigate to reduce power
  - Compact dielectric RF structure
    - Further study is needed