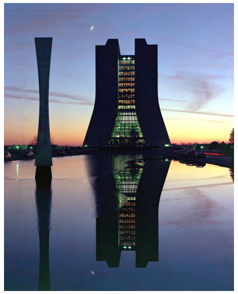


Recent progress of HCC D&S

K. Yonehara

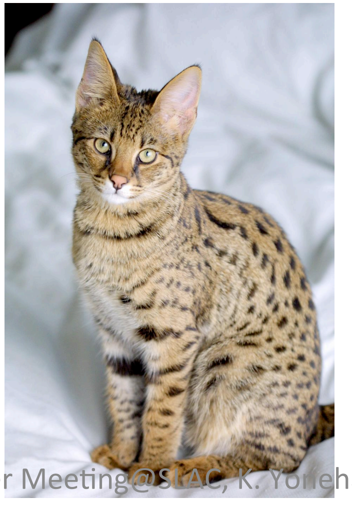
APC, Fermilab

Contents

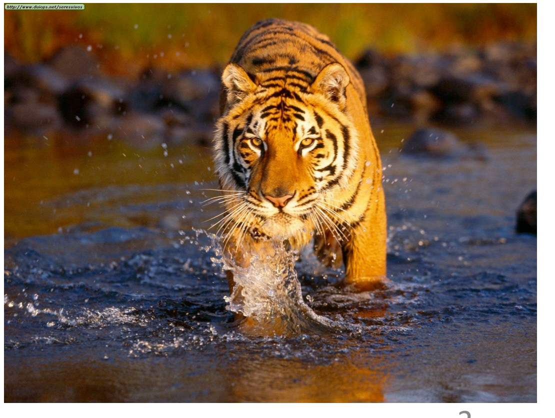
- R&D of HCC beam element
  - How to mitigate the geometry constraint?
- Re-optimizing HCC lattice
- Summary

Original beam element

Compact beam element

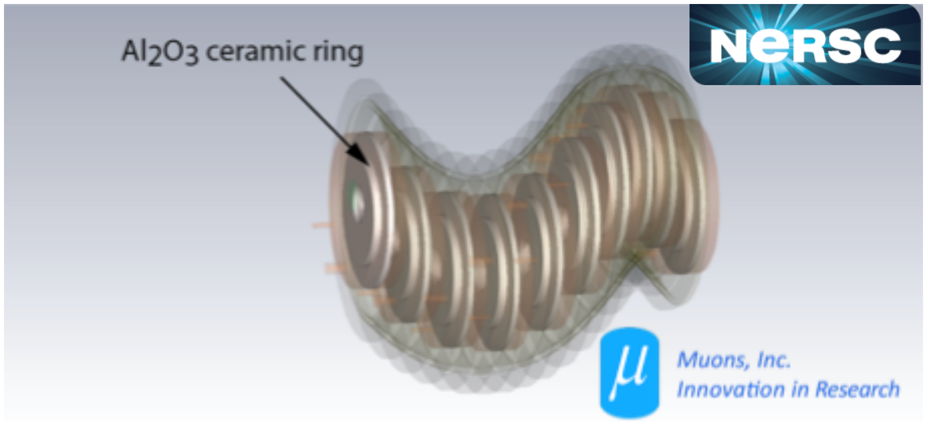


Re-optimize HCC lattice

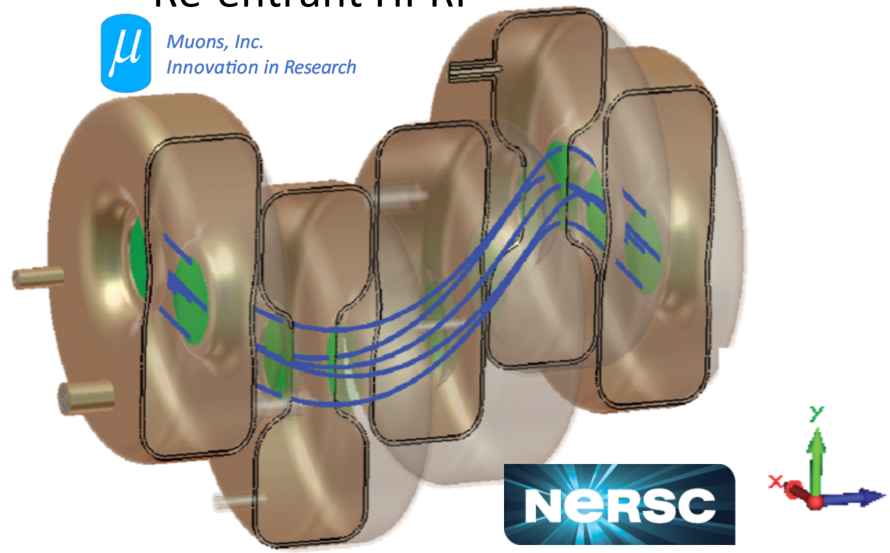


HCC RF system

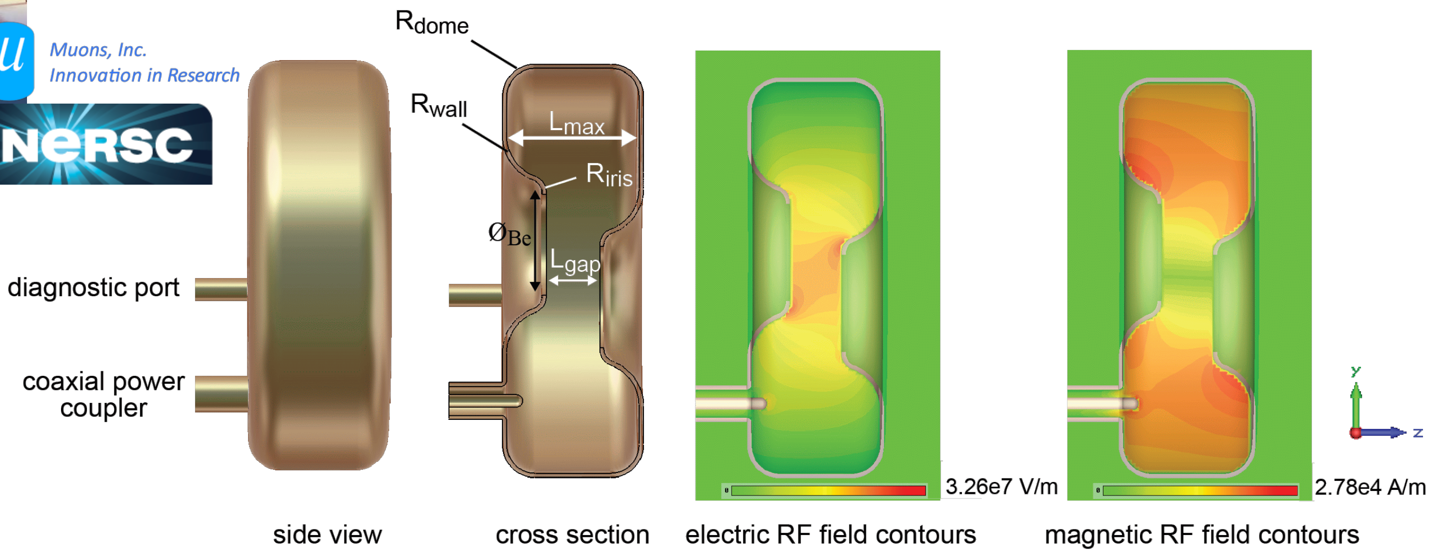
Dielectric loaded HPRF



Re-entrant HPRF



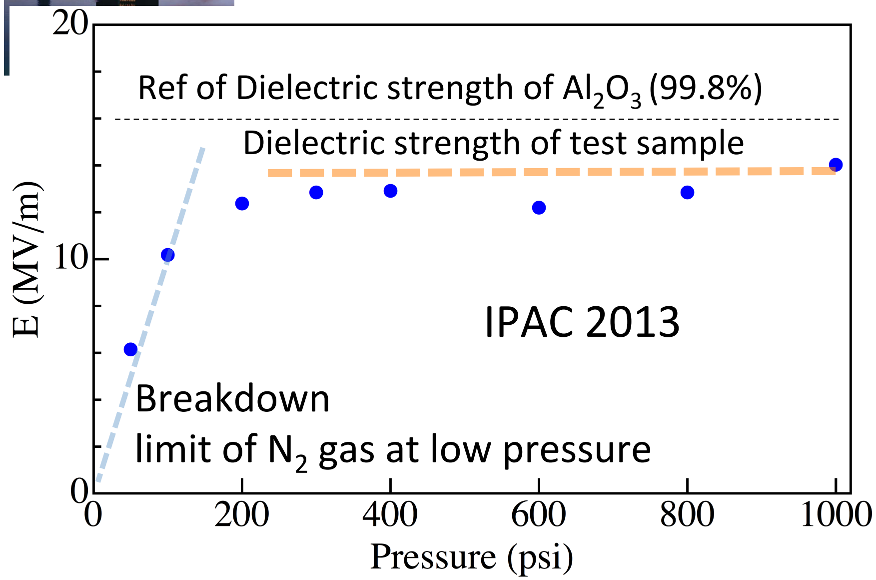
Re-entrant HPRF cavity



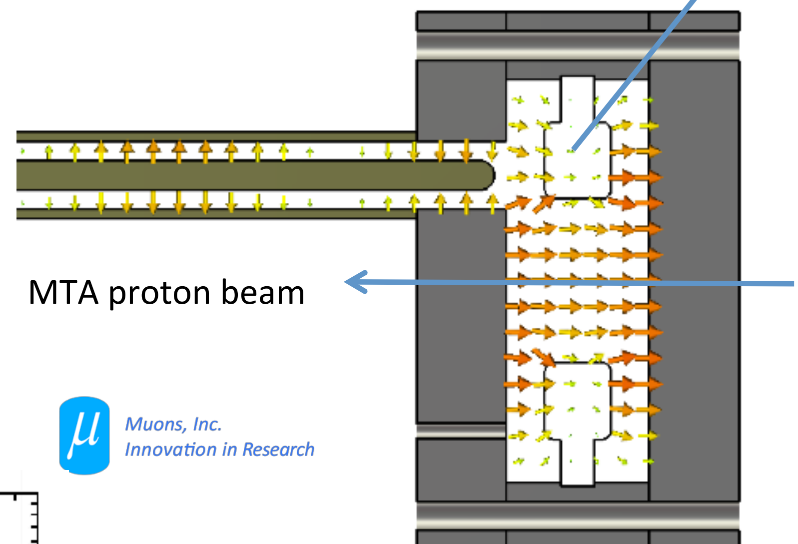
- Since huge RF power (see magnetic field above plot) can be stored in a dome the required peak power is almost factor 10 smaller than the dielectric loaded RF (4.4 MW/m @ 300 K, 325 MHz)
- However, the peak RF gradient should be higher than the DLRF
  - Accelerating gap in the re-entrant RF is 1/2 of the DLRF
  - Thus, the plasma loading in the re-entrant RF cavity becomes significant
- Real EM fields of the re-entrant RF was tested in g4bl and observed cooling
- Longitudinal matching is the current issue
  - Too strong longitudinal kick to hold particles in the RF bucket

Require more lattice tuning & test cooling simulation

Dielectric Loaded HPRF cavity



Dielectric insert



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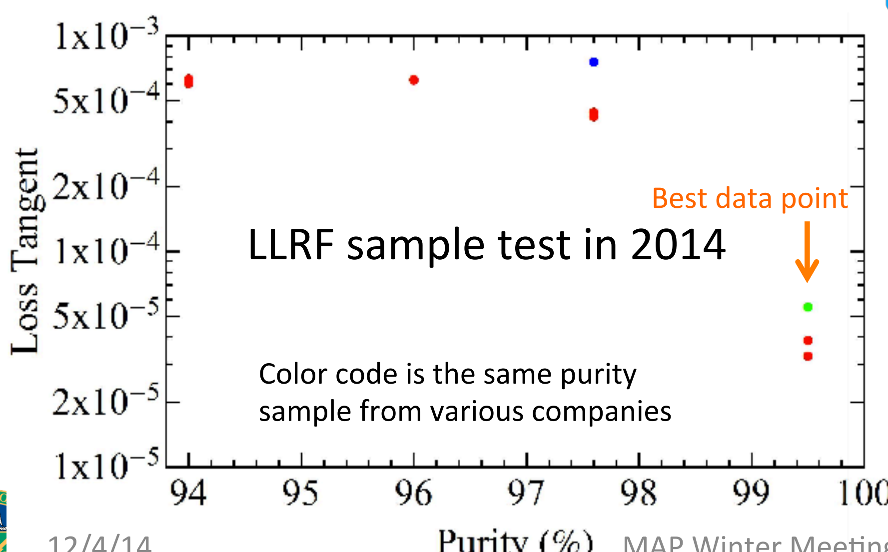
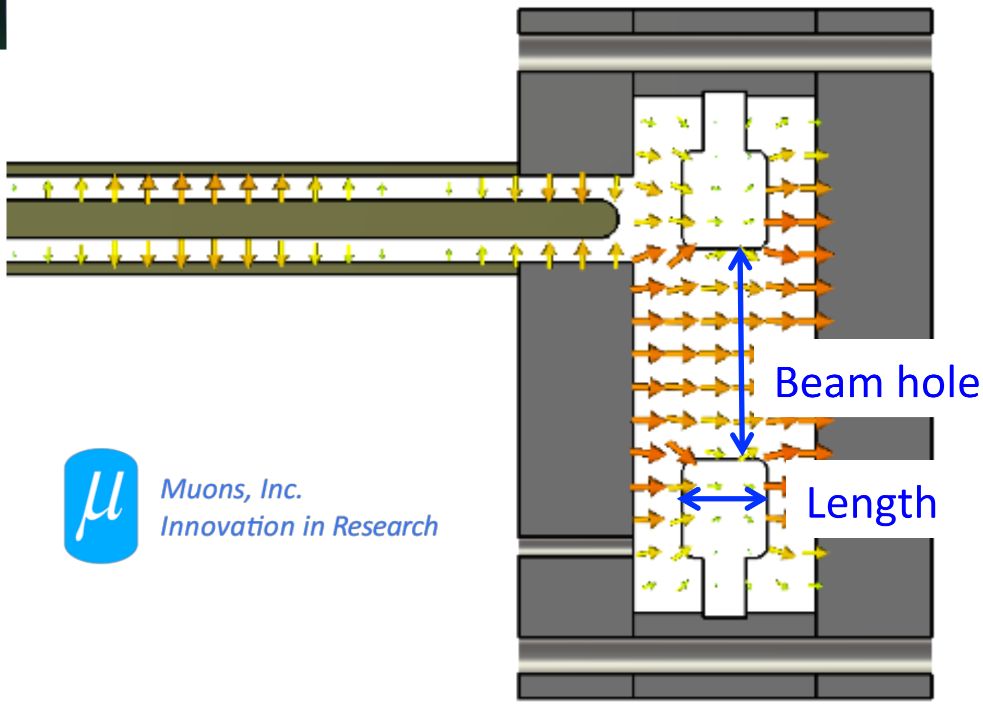
Innovation in Research



Proposed dielectric loaded HPRF test cell
Tests will be made in FY15 & 16 to observe the loss tangent and the dielectric strength at high RF power with intense beam

Test, Test, Test!

Strategy of DL HPRF test for HCC



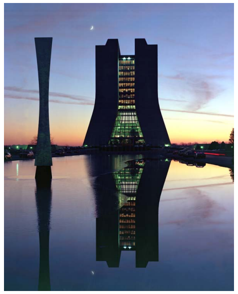
- Original design was made to reduce the risk of permanent damage of ceramics
  → We assumed to use a 99.8 % ring
  → Big tolerance for operating gradients

From recent tests,

- Obtained loss tangent of 99.5 % is twice lower than our original design
- Company spec shows that the 99.5 % is twice higher dielectric strength than 99.8 %
  → We consider a 99.5 % ring is better than the 99.8 % one

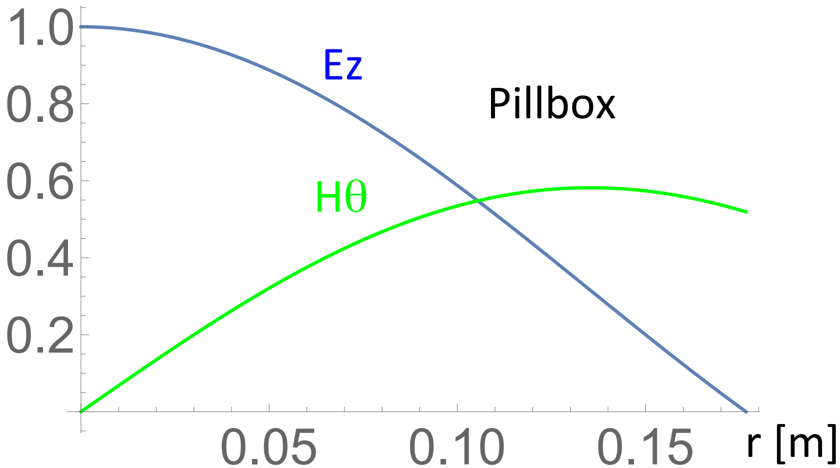
If the high power test shows that the dielectric strength of the 99.5 % sample is very high (> 20 MV/m) we can re-evaluate the insert with smaller beam hole and longer than the test sample

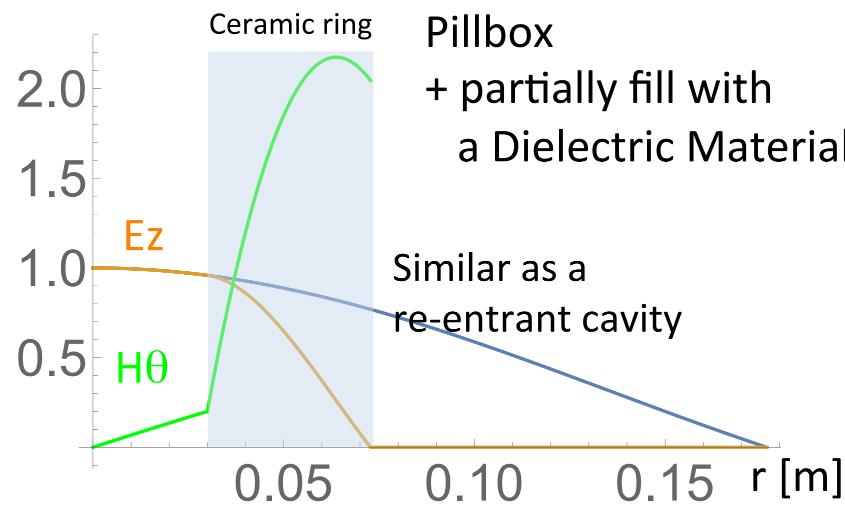
→ Allow to design a very compact cavity



Considerable advantages in DL HPRF

f = 650 MHz, E = 20 MV/m, tan δ = 0.4e-4, ε = 9.6





<u>IR = 0.177 m</u>
Q = 7,518
<u>U = 2.34 J</u>
P = 1.27 MW

<u>IR = 0.073 m</u>
Q = 5,073
<u>U = 4.17 J</u>
P = 3.36 MW

- Cavity radius of the DL HPRF is significantly small
- DL HPRF has almost twice larger stored energy than the pillbox
- Peak power is still high but getting lower at smaller beam hole

Constraint of HCC magnet

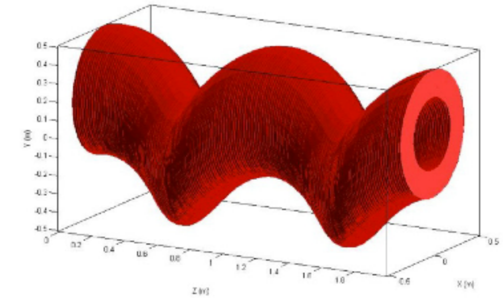
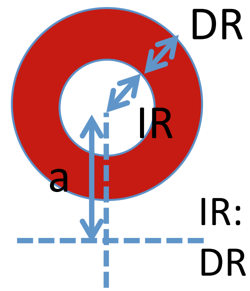
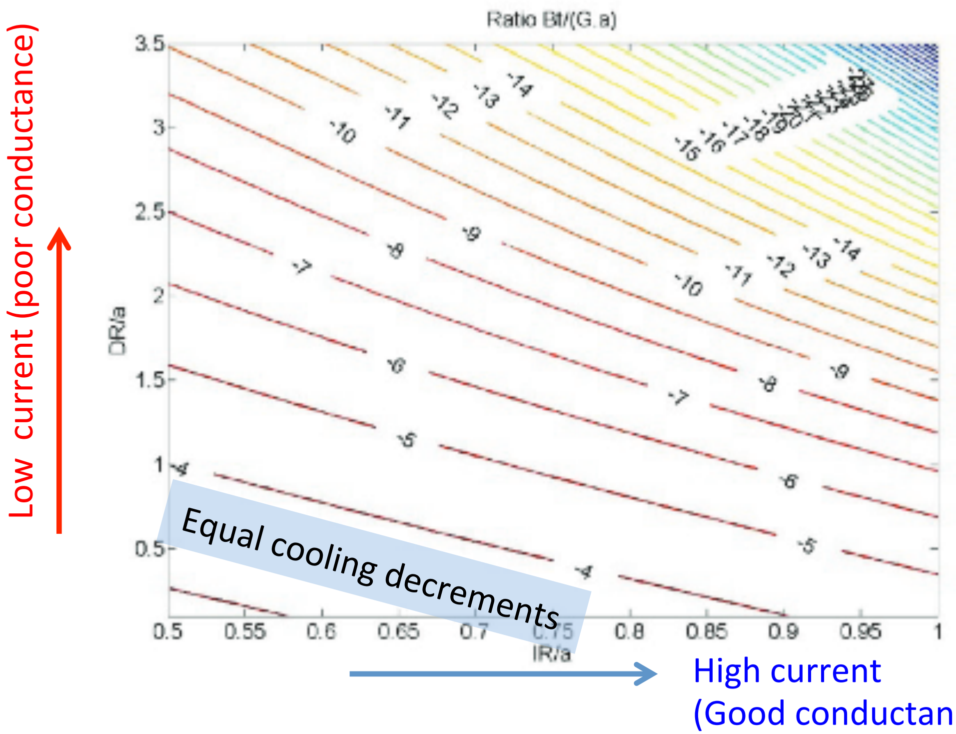


Figure 1: A helical solenoid generated with SolCalc.

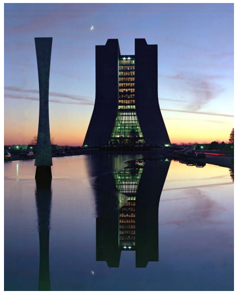


IR: inner radius
DR: coil thickness
a: Helical radius = $\kappa\ \lambda/2\ \pi$

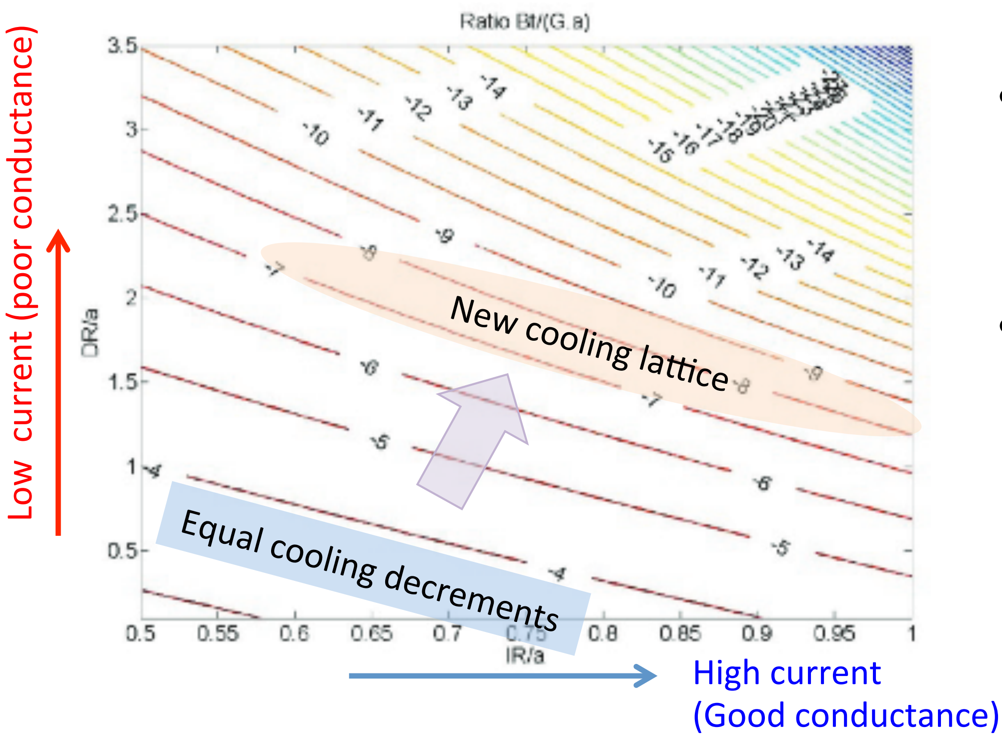
- M. Lopes made a field calculation code, SolCalc written in Matlab (IPAC'14)
- He demonstrated the limit of IR at the equal cooling decrements



- Left plot shows the correlation between the HS coil geometry and the ratio of helical dipole and field gradient
- Dispersion is determined from the strength of helical dipole and the field gradient (see next slide)
- Therefore, the cooling decrements in the HCC is determined by the coil geometry
- Maximum allowable current (conductance) is another parameters to determine the coil geometry
- Coil geometry becomes tighter (smaller IR) if higher current is needed



Propose new configuration of HCC magnet



- Relax the constraint of HCC magnet! Larger IR & thinner DR
  - → Helical dipole stronger
  - → Field gradient smaller
- What happens cooling performance in the new lattice configuration?

Emittance evolution in cooling channel

Generic emittance evolution formulae

$$\frac{d\varepsilon_n}{ds} = \varepsilon \frac{d\beta\gamma}{ds} + \beta\gamma \frac{d\varepsilon}{ds} = \varepsilon_n \frac{1}{\beta^2 E} \frac{dE}{ds} + \frac{\beta\gamma}{2}\left(\hat{\beta}_\xi \sigma_\xi^2\right)$$

$$\varepsilon_n(s) = \left(\varepsilon_{n,0} - \varepsilon_{n,equ}\right) e^{-\Lambda_\xi s} + \varepsilon_{n,equ}$$

$\varepsilon_{n,0}$; initial emittance

$$\varepsilon_{n,equ} = \frac{\beta\gamma}{2}\left(\hat{\beta}_\xi \sigma_\xi^2\right) / \left(\frac{1}{\beta^2 E}\frac{dE}{ds}\right)$$; equilibrium emittance

$$\Lambda_\xi = \left(\frac{g_\xi}{\beta^2 E}\frac{dE}{ds}\right)$$; cooling decrement

$$\varphi = \int \frac{ds}{\hat{\beta}_\xi} \rightarrow \hat{\beta}_\xi = \frac{1}{\omega \hat{Q}_\xi}$$; beta function in HCC (beta is constant)

σ_ξ^2 ; rms fraction due to stochastic process

g_ξ ; partition of cooling

Exact formulae for emittance evolution in HCC are given in Slava & Rol's PRSTAB and IPAC'14

In case of HCC,

- These formulae are still good approximation
- ε_n has a strong coupling among three orthogonal components (horizontal, vertical & longitudinal)
- The coupling is given by the dispersion

$$g_L \rightarrow g_{L,0} + \delta g_L$$

$$g_T \rightarrow 1 - \frac{\delta g_L}{2}$$

In the HCC, δg_L is given (D. Neuffer)

$$\delta g_L = \frac{\kappa^2}{1+\kappa^2}\frac{\partial\rho}{\rho}\frac{p}{\partial p} \equiv \frac{\kappa^2}{1+\kappa^2}\hat{D}$$

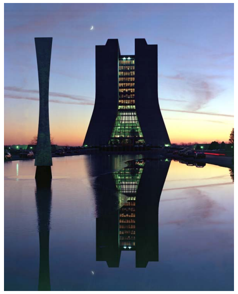
Equal cooling decrements

→ $g_L = g_T$

→ Need strong focusing (high field gradient)

In case of low field gradient…

→ $g_L > g_T$ Longitudinal enhance cooling



Equilibrium Emittance in various cooling decrements

Equal cooling decrements

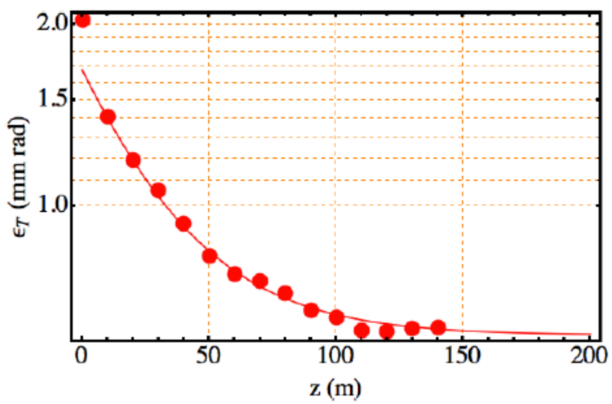


Figure 5: Estimated transverse emittance evolution. Red line is the predicted emittance evolution curve, $\varepsilon_T(s) = (1.68 - 0.62)e^{-0.0307s} + 0.62$.

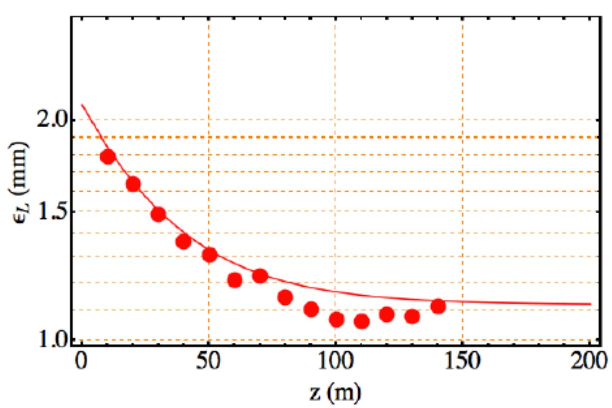
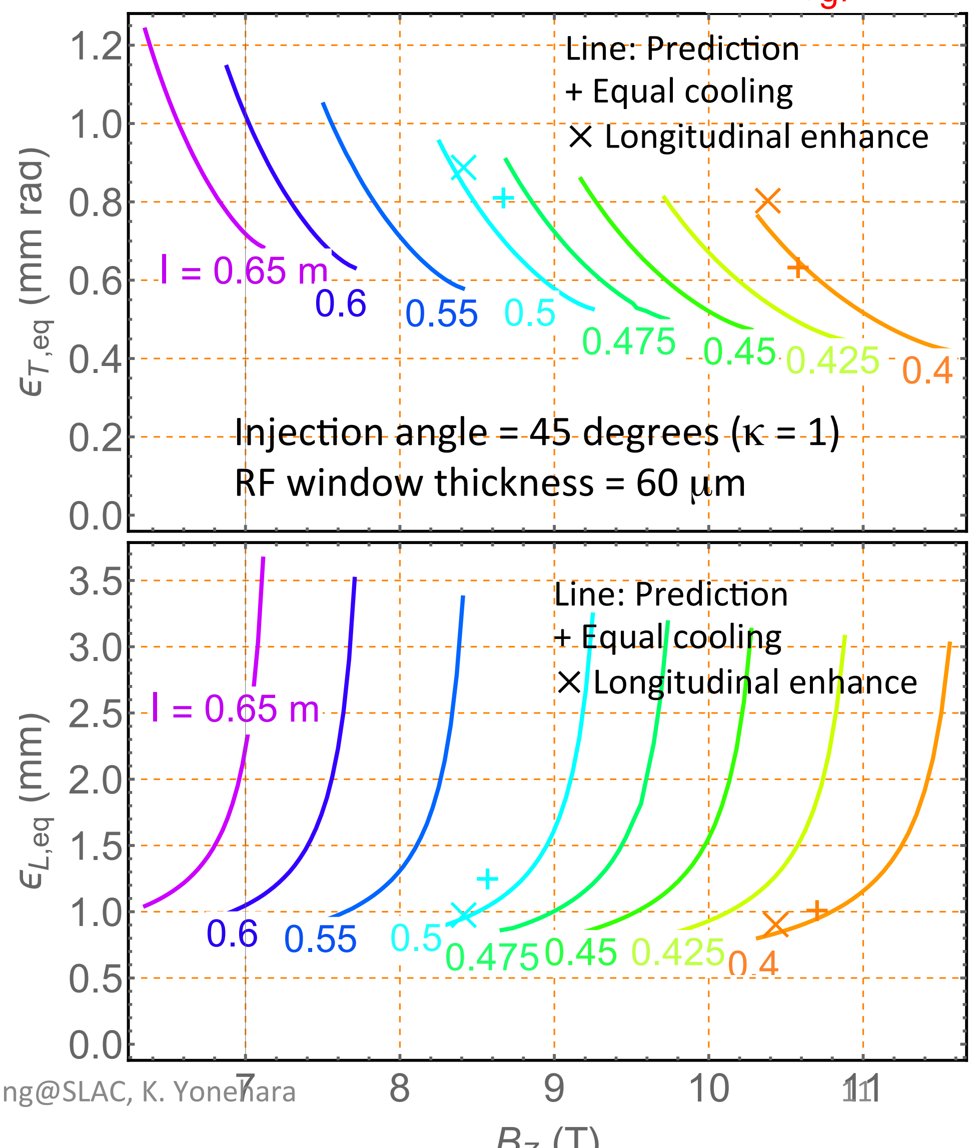
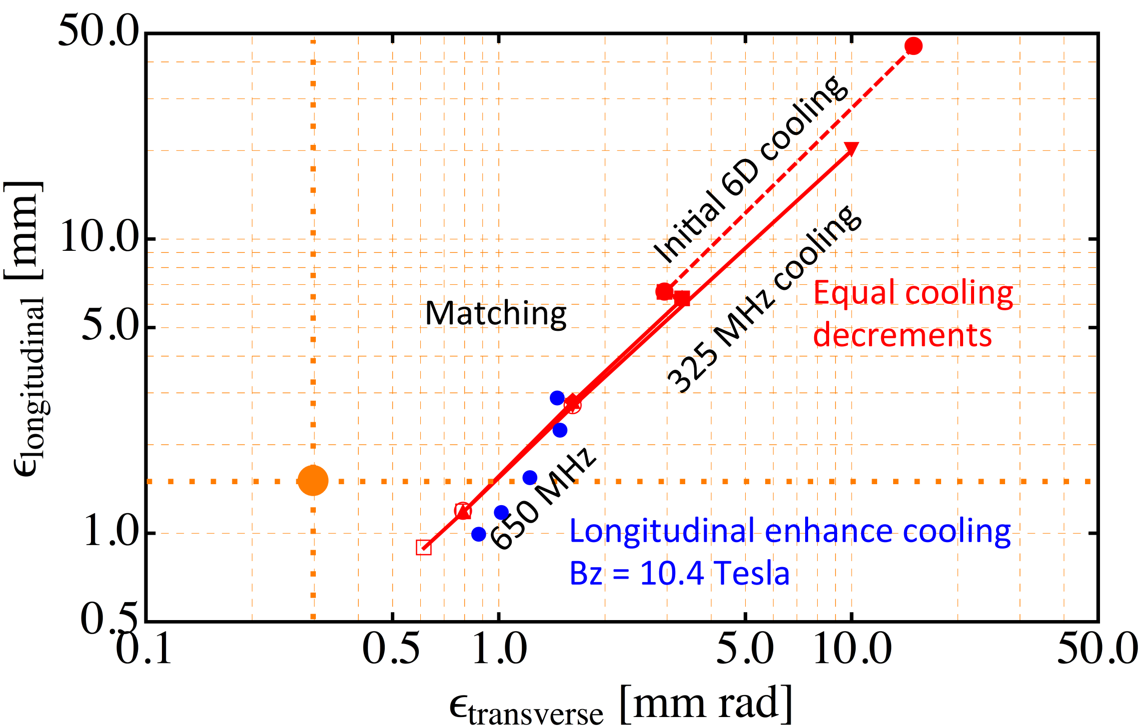


Figure 6: Estimated longitudinal emittance evolution. Red line is the predicted emittance evolution curve, $\varepsilon_L(s) = (2.1 - 1.12)e^{-0.0307s} + 1.12$.



Recent cooling result



Simulation study for longitudinal enhance cooling is just begun.
More result will be shown by next meeting.

Matching

Transmission: 56 % → 72 %

6D HCC

- RF parameter
  - E = 20 MV/m
  - ν = 325 & 650 MHz
- Gas pressure
  - 160 atm at 300 K
  - 43 atm at 80 K
- Magnetic fields
  - Bz = 4 – 12 Tesla
- Equilibrium emittance
  - ε_T = 0.6 mm (goal: 0.3 mm)
  - ε_L = 0.9 mm (goal: 1.5 mm)
- Transmission (no bunch merge)
  - ~ 60 %
- Channel length
  - 380 m → 280 m

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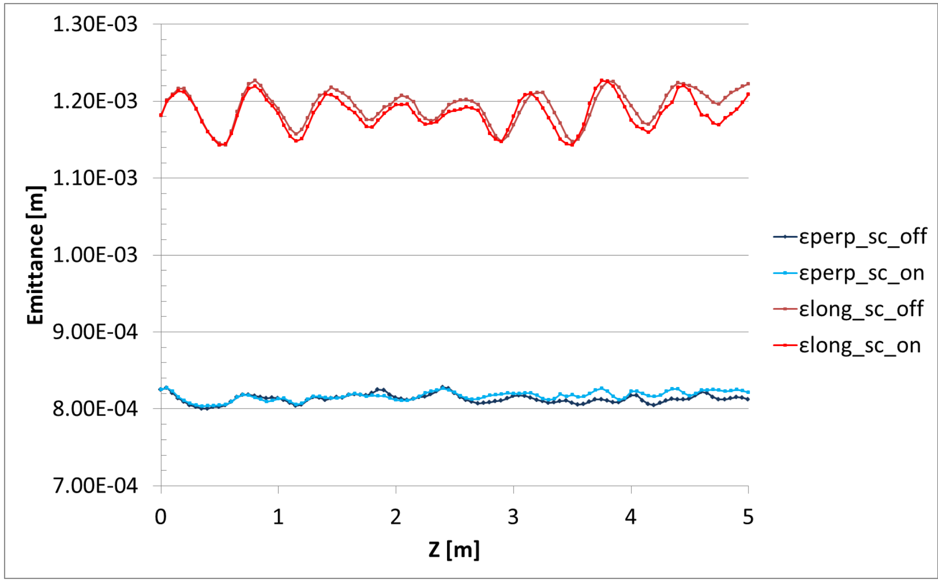
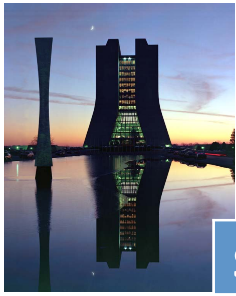
Space Charge in the HCC

- **High bunch charge (~10^{13} muons per bunch) after the bunch merge may affect emittance evolution within the HCC due to the space charge field from beam-induced plasma in the HPRF cavities**
- **G4Beamline space charge capabilities are currently limited and will require development to fully simulate effects of high-pressure hydrogen gas environment**

- **Current results:**
  - **Existing *spacechargelw* module in G4Beamline indicates no effect on emittance evolution over short HCC sections**
- **In progress:**
  - **Extension of simulations to longer HCC channel sections**
  - **G4Beamline code development to better model space charge fields from a beam-induced plasma**
  - **Increasing bunch charge to find the bunch charge limit in the HCC**

Emittance evolution in L=5m HCC section with G4Beamline *spacechargelw* module on and off
Bunch charge 1e13 μ^+ per bunch



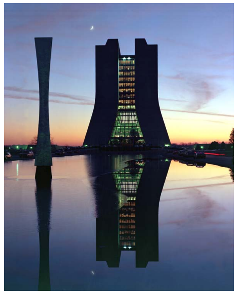


Power estimation

Section	Units	1	2	3	4
λ, period	m	1.0	0.8	0.5	0.4
β_T/β_L (equal)	m	0.20/2.1	0.16/2.1	0.098/1.5	0.079/1.5
Length	m	80	50	100	50
HS Coil R_{in}	mm	275	217	105	100
HS Coil R_{out}	mm	300	247	195	190
Coils/period		10	10	10	10
Coil Length	mm	100	80	50	40
J, curr density	A/mm^2	258.2	271.4	149.1	188.8
Anti solenoid	T	-2.49	-3.21	-8.78	-7.15
Stored B	MJ/m	4.84*	4.7	10.7	10.5
RF gradient	MV/m	20	20	20	20
RF frequency	MHz	325	325	650	650
Peak power	MJ/m	11 (36)**	11 (36)	13 (50)	13 (50)

*HS coil +Anti Sol

**77 K operation (300 K)



Summary

- Progress on HCC machine design
  - Re-evaluation & Re-optimization based on recent experimental results
- Longitudinal enhance cooling is considerable option for later 6D cooling stage
  - Significantly reduce the geometry constraint
  - HCC does not have any limit due to longitudinal space charge
- We should evaluate hydrogen safety if the gas filled channel is the solution