Katsuya Yonehara
Accelerator Physics Center, Fermilab

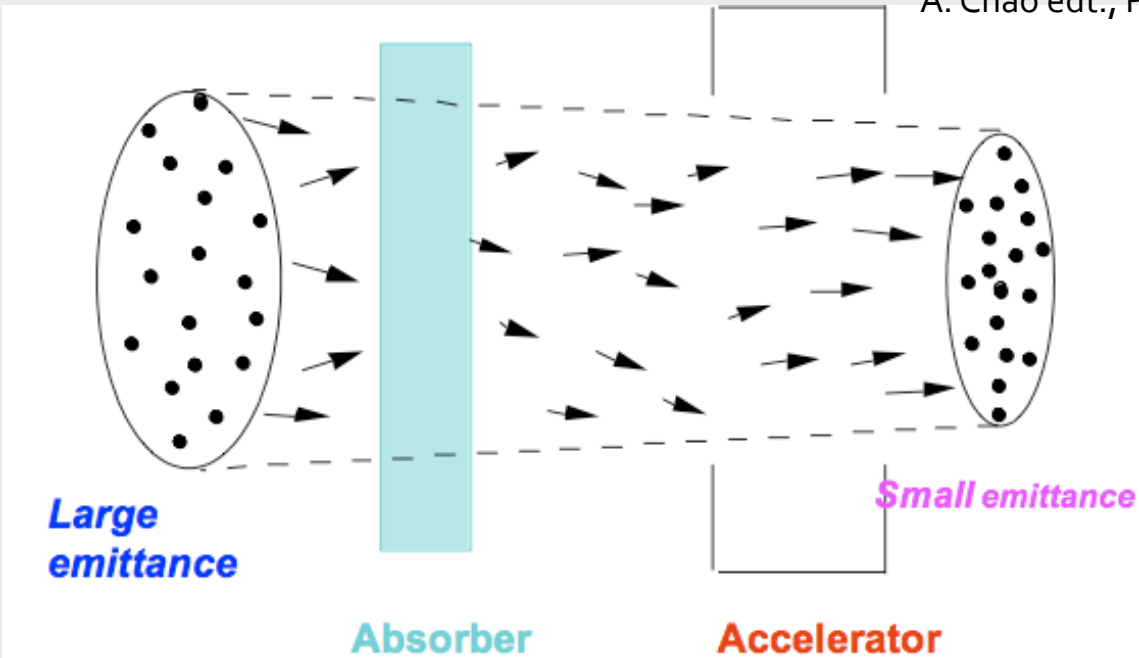
Apply Helical Cooling Channel for Higgs Factory

Outline of my talk

- Review past helical cooling channel simulation effort
- Discuss what we are working now to realize the helical beam element
- Discuss new beam element for Higgs Factory

Concept of an Ionization Cooling Channel

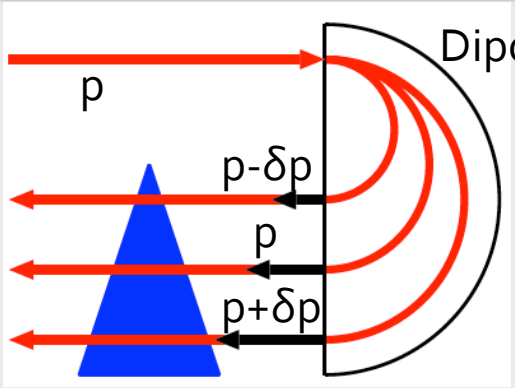
More detail, please see
A. Chao edt., Physics and Engineering



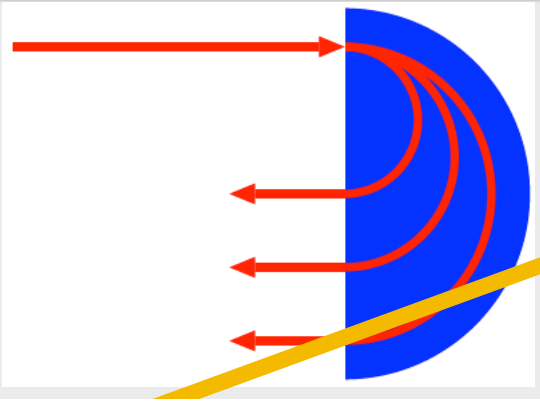
Emittance evolution $$\frac{d\varepsilon_n}{dz} = \beta\gamma\frac{d\varepsilon}{dz} + \varepsilon\frac{d\beta\gamma}{dz}$$

Cooling Heating

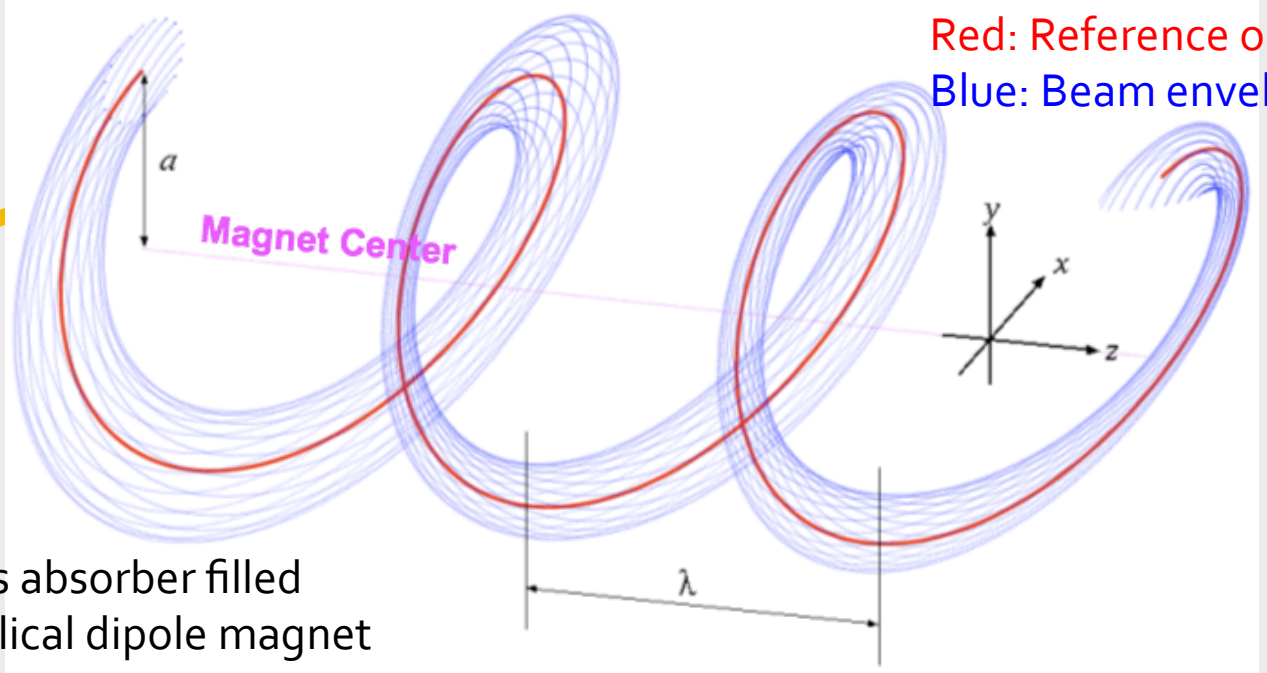
Concept of Emittance Exchange



Wedge absorber

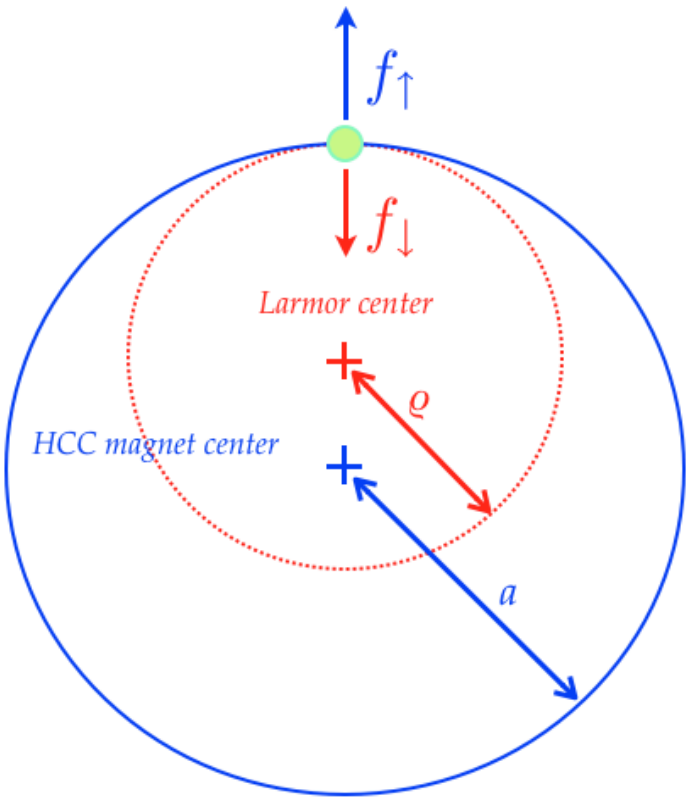


Homogeneous absorber filled dipole magnet



Homogeneous absorber filled continuous helical dipole magnet

Basic particle dynamics in HCC (Helical Cooling Channel)



Larmor motion

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

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

Radial equation of motion with helical dipole

$$f = f_\uparrow + f_\downarrow$$

$$= \frac{e}{m_\mu}\left(p_z b_\varphi - p_\varphi b_z\right)$$

$$f = \gamma m r'' - \gamma m r \omega^2$$

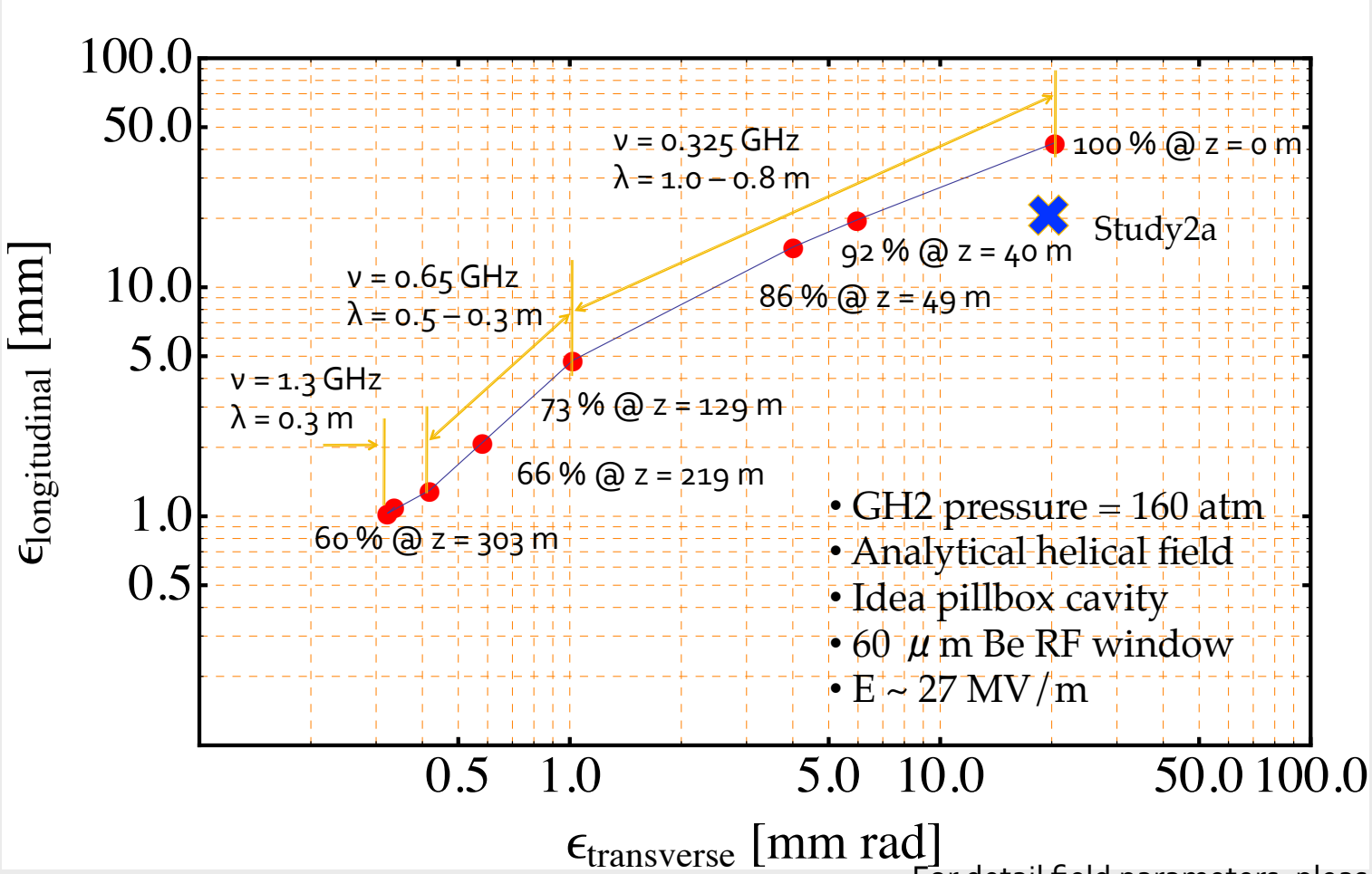
$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left(b_z - \frac{1+\kappa^2}{\kappa} b_\varphi\right)$$

Ya Derbenev & R.P. Johnson, PRSTAB 8 041002 (2005)

Homogeneous Cooling Material Filled Helical Cooling Channel

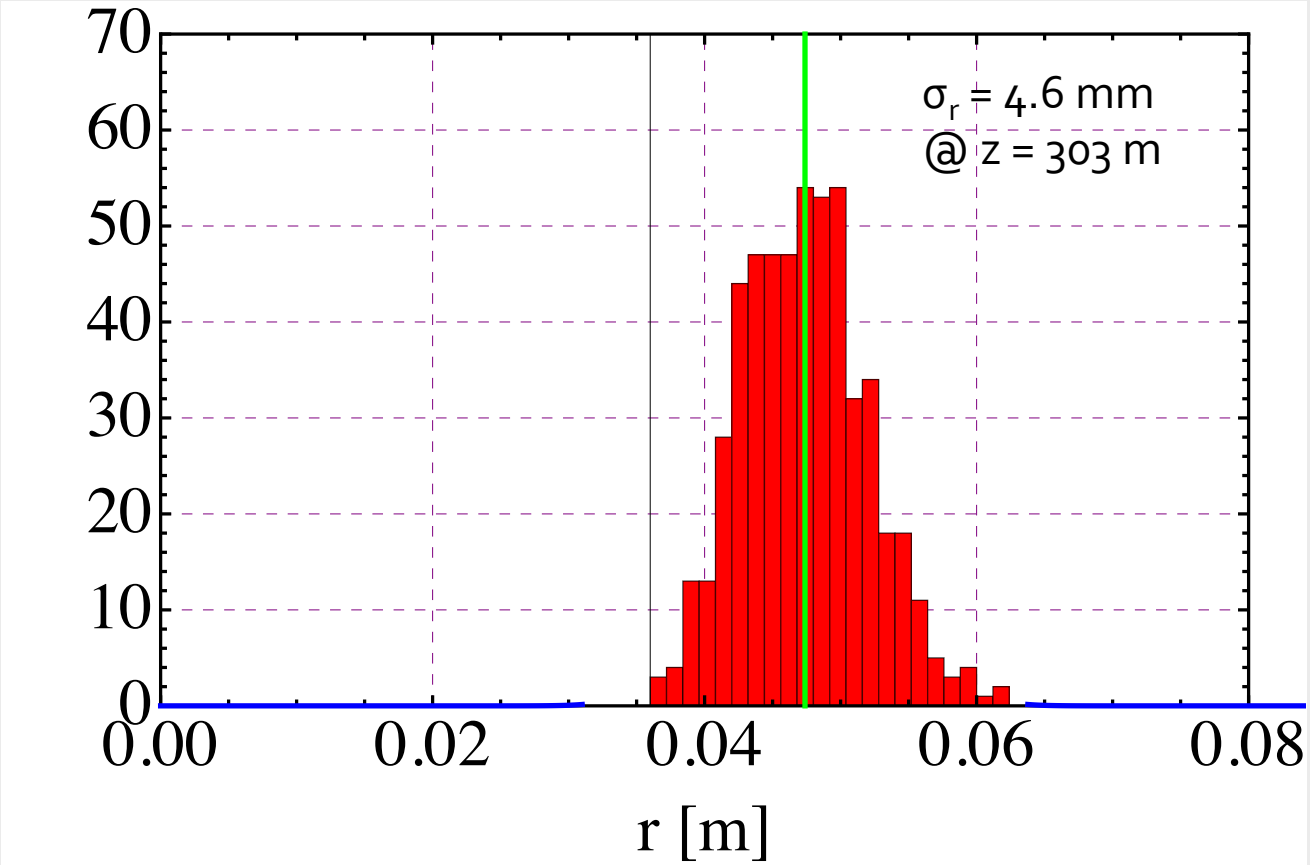
- Advantage: A continuous magnet structure
  - Fast cooling
  - Single pass
    - No critical injection & extraction issue
    - No heating absorber issue
  - No beam resonance
  - Etc…
- Challenge: Require technological development
  - Need state of the art technology
  - Some critical device will be discussed in this talk

Helical Cooling Channel Simulation



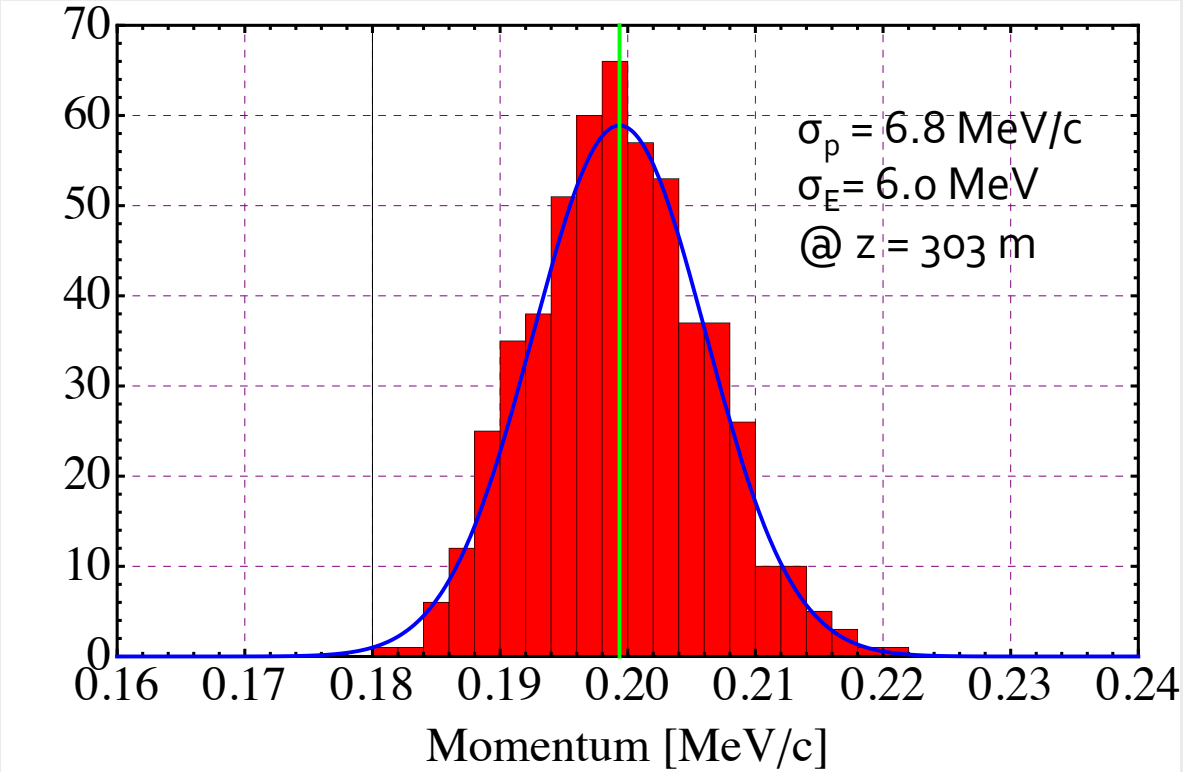
For detail field parameters, please see K. Yonehara et al., IPAC 2010, MOPD076

Radial Distribution in Final HCC



- Beam size is small enough to fit in 1.3 GHz SRF (DA 10 cm)

Final Momentum/Energy distribution from HCC Simulation



- Population in δE = [-1/3 σ, 1/3 σ] = 4 MeV is 26 %
- Possible improvement:

  Phase rotation, more longitudinal cooling, etc

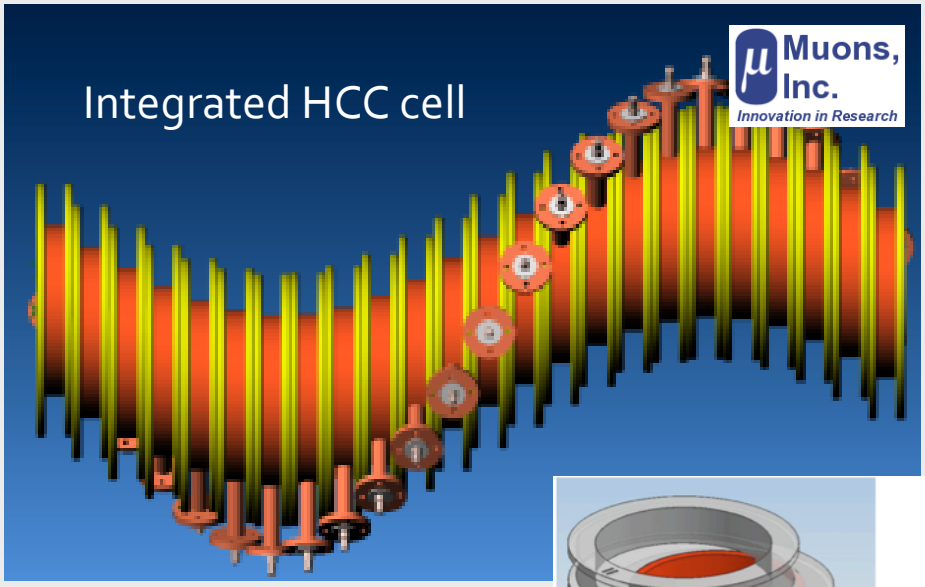
Considerable HCC Simulation Efforts

- Improve final longitudinal emittance
  - Tapering momentum along with HCC length makes better cooling because of larger energy loss rate (dE/dx)
  - Increase helical field strength to realize low beta function
  - Design E-t phase rotation
- Design a matching section
  - Connect straight section to HCC
  - Transport beam with RF frequency shift

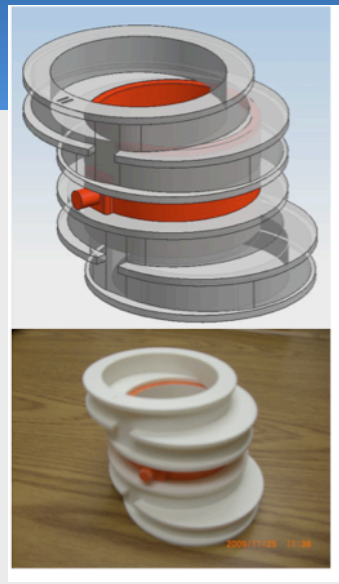
Use fast & powerful computer to optimize HCC

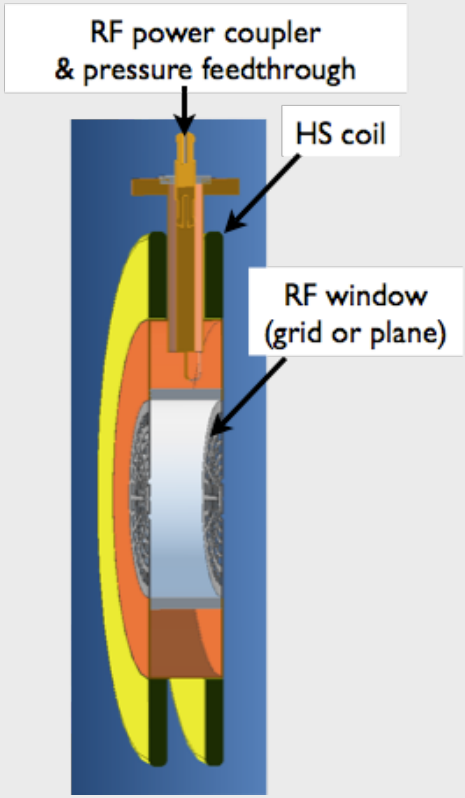
→ NERSC is almost ready to go! (Goal D&S effort in FY13)

Develope HCC beam element



Assemble HCC cell

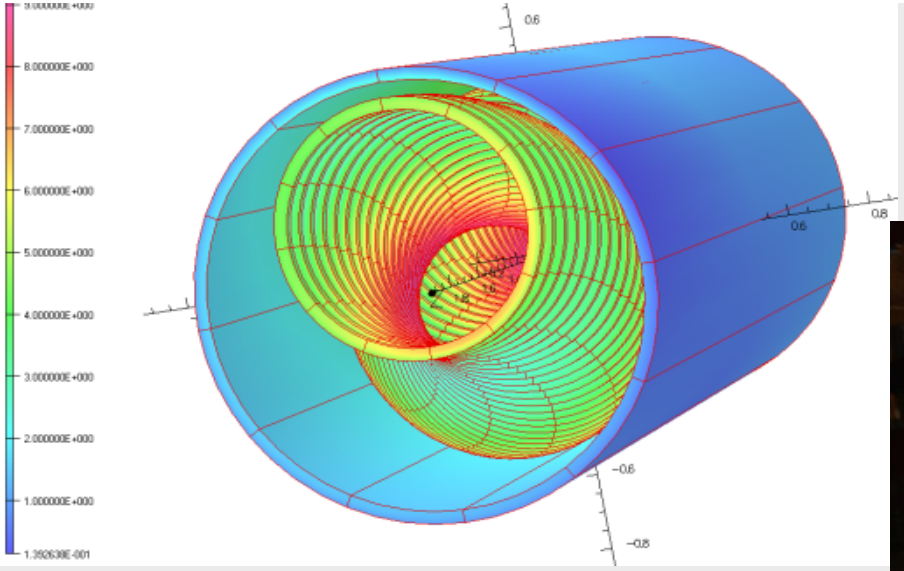


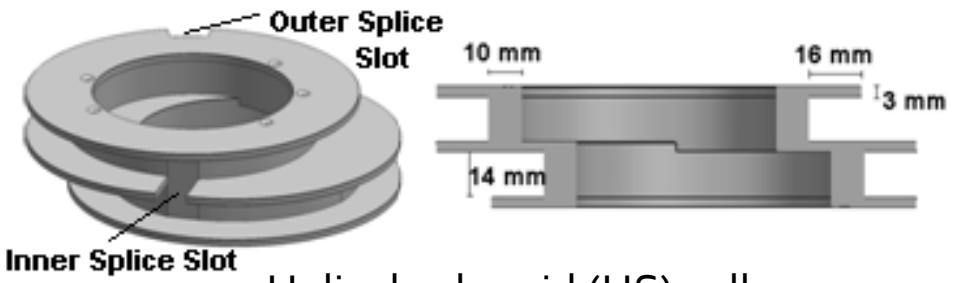


HCC cell

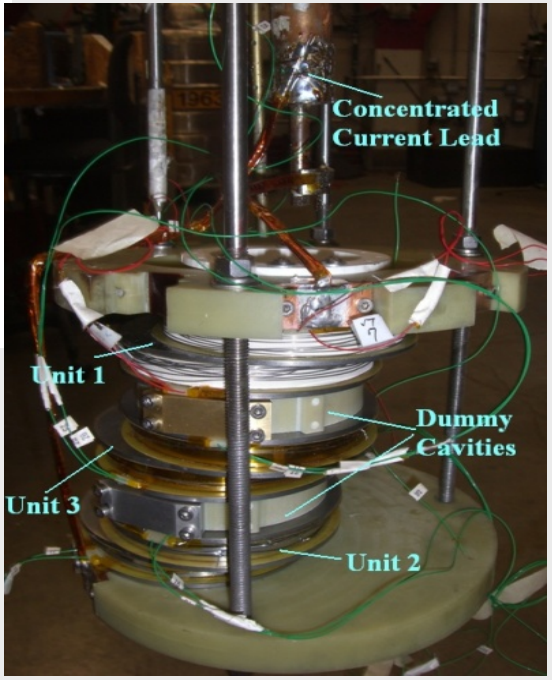
HCC magnet R&D

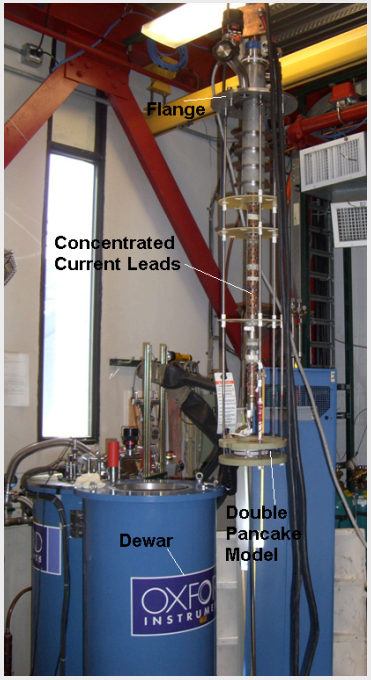
HCC magnet consists of helical solenoid (HS) coil and a straight solenoid





Helical solenoid (HS) cell



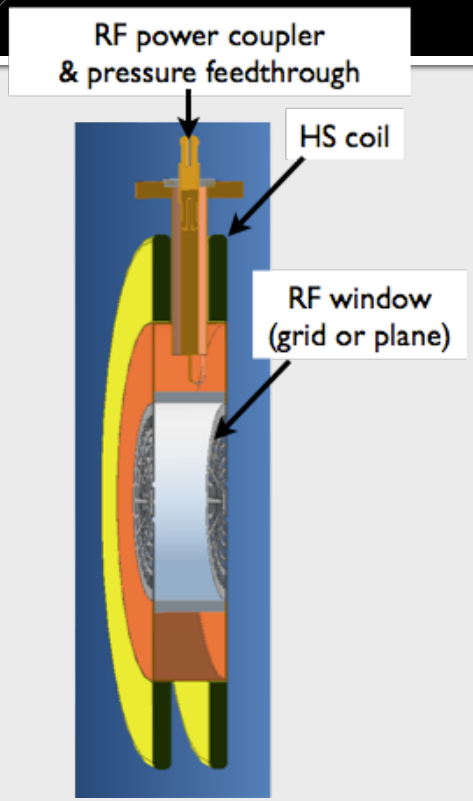


- Made NbTi, $NbSn_3$ & YBCO HS coils
- Experimentally verified simulation
- Development of winding HS coil
- Design mechanical support
- Development of quench protection

G. Flanagan et al., IPAC 2012, THPPD041

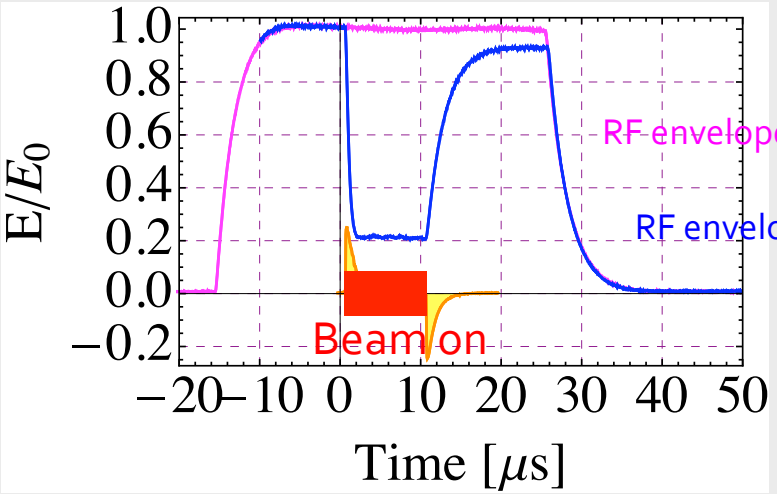
HCC RF cavity R&D

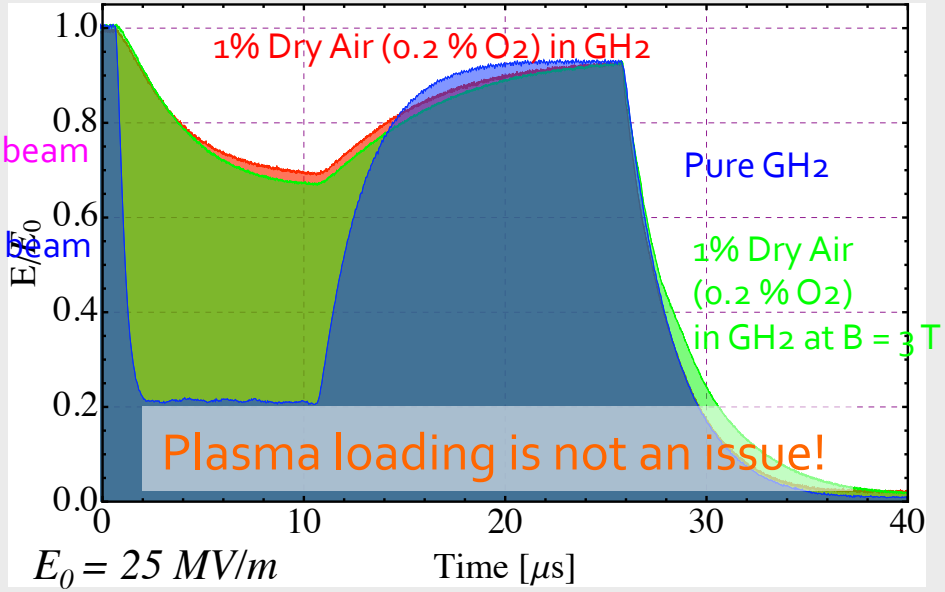
- Most crucial device for HCC
- HCC needs a continuous cooling material
- Continuous HCC RF system is considered
- Proposed hydrogen gas filled RF cavity
  - Gas acts as a beam cooling material
  - Gas also suppresses an RF electric breakdown
- Proposed dielectric loaded RF cavity
  - Compact



Plasma loading effect in gas filled RF cavity (Feasibility test)

- Beam generates an ion pair in a gas filled RF cavity during ionization (cooling) process
- Electron is so light that it consumes much RF power (plasma loading effect)
- Electron is removed by a small amount of electronegative gas





Produce Polarized Muon Beam

- Studying polarized muon beam becomes important especially for Higgs Factory
- In fact, muon spin is oriented in pion decay because of parity violation
- However, the angular distribution is isotropic, overall muon polarization is zero
- Fortunately, bunched muon beam preserves polarization since ToF of muons has a memory of orientation of pion decay
- Polarization is useful to calibrate kinetic energy and increase Higgs production (figure of merit $\propto p^2$)

Spin Exchange Process

Pair particle Muon spin

$$\uparrow\downarrow = |\uparrow\downarrow\rangle$$

Polarization $$p = \frac{(\uparrow\uparrow + \downarrow\uparrow) - (\uparrow\downarrow + \downarrow\downarrow)}{\uparrow\uparrow + \downarrow\uparrow + \uparrow\downarrow + \downarrow\downarrow}$$

$$\mu + p \rightarrow \mu H \quad p = \frac{(\uparrow\uparrow + \downarrow\uparrow) - (\uparrow\downarrow + \downarrow\downarrow)}{\uparrow\uparrow + \downarrow\uparrow + \uparrow\downarrow + \downarrow\downarrow} = 0$$

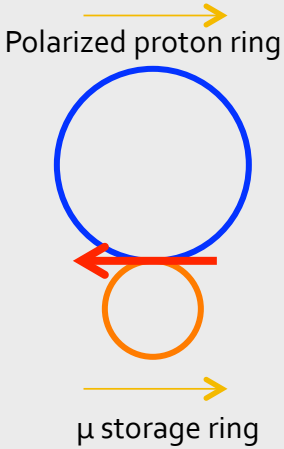
$$\mu + \vec{p} \rightarrow \mu \vec{H} \quad p = \frac{(\uparrow\uparrow + \downarrow\uparrow) - (\uparrow\downarrow + \downarrow\downarrow)}{\uparrow\uparrow + \downarrow\uparrow + \uparrow\downarrow + \downarrow\downarrow} = \frac{(\uparrow\uparrow + \downarrow\uparrow) - \uparrow\downarrow}{\uparrow\uparrow + \downarrow\uparrow + \uparrow\downarrow} = \frac{1}{3}$$

$\uparrow\downarrow = \downarrow\uparrow$ Hyperfine coupling (A=44.2 GHz)

- Full spin transfer possible by using RF field in zero-crossing B field
- Polarization becomes 100 %

Relative-Speed Zero Proton Beam

- Intense polarized proton beam is under study (electron-heavy ion collider)
- No relativistic energy required
  - β will be 0.7~0.9
- No long straight section needs
  - Depend on the cross section of muonium production rate
  - 1 meter is enough for hyperfine interaction
- Cold proton beam even cool down muon phase space (analogy of electron cooling)
- Proton cooling may improve 36 times faster cooling than electron in energy transfer process



Summary

- Evaluated HCC for Higgs Factory
  - Final transverse emittance looks fine
  - Need more optimization to obtain low longitudinal emittance (factor three cooling)
- Developed HCC beam element
  - R&D of helical solenoid coil goes very well
  - R&D of high pressure gas filled cavity seems to be feasible
  - Next step: Dielectric loaded RF test
- Discussed spin-exchange process to make a polarized muon beam
  - Need serious theoretical investigation