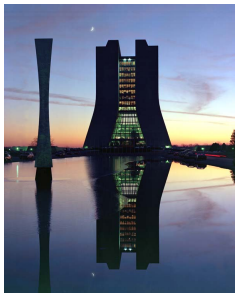
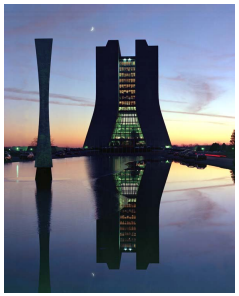


Progress of HCC Design and Simulation

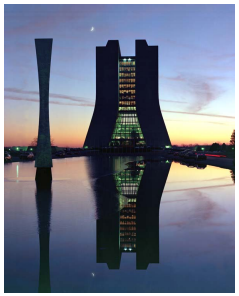
K. Yonehara

APC, Fermilab



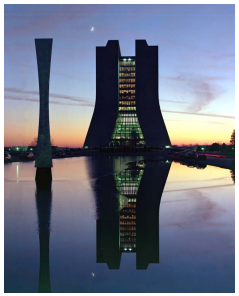
Contents

- Current working item since MAP DOE meeting
- Highlights in current activities
- Deliverable plan



List of Current Working Item since MAP DOE '14

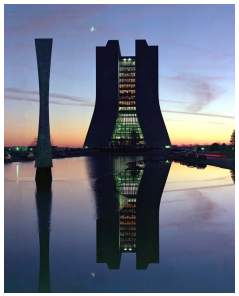
Item	Description
Design Cooling Elements	• Update initial cooling channel (see Yuri's talk) • Update initial matching section (see Cary's poster) • Resume helical bunch merge system (see Amy's talk)
Machine Develop ment	• Prepare dielectric loaded gas-filled RF cavity test (see Ben's talk) • Investigate gas-plasma chemistry (plan to submit to PRSTAB) (see Ben's poster) • Develop HCC magnet design (see Mauricio's talk) • Develop double layered Nb3Sn winding technology (see Mauricio's talk) • Study various HS coil configurations (see Steve's talk) • Design RF window (see Alvin's talk) • Study beam loading effect (see Alvin's talk)
HCC Theory	• Muon beam dynamics interacting with gas-plasma (see Moses' poster) • Theoretical investigation of helical cooling channel in terms of the generic cooling theory • Translate HCC theory to the generic cooling theory • Optimize emittance evolution



Highlights in currently working items (I)

Three Highest Priority Items in Cooling Simulation Effort

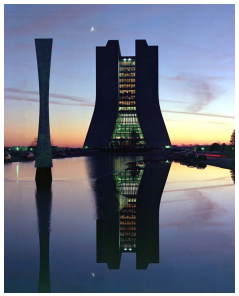
- Initial FOFO Snake Cooling
  - Evaluated the channel with the same initial muon beam distribution as Valeri's rectilinear channel
  - Published the result (MAP-doc-4377)
  - See Yuri's talk for detail
- Match-In Channel Muons, Inc. Innovation in Research
  - Improve transmission efficiency 60 → 80 %
  - Tune more parameter spaces to make better transmission
  - See Cary's poster for detail
- Helical Bunch Merge Channel Muons, Inc. Innovation in Research
  - Update the optics to fit to the present MAP IBS beam parameter
  - See Amy's talk for detail



Highlights in currently working items (II)

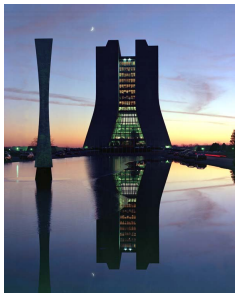
Another Highest Priority Items in Experimental & Design Efforts

- HCC magnet design and status of double layered Nb3Sn
  - See Mauricio's talk
- Study various HS configurations
  - See Steve Kahn's talk
- Dielectric Loaded HPRF cavity test
  - The test cavity is ready for low power sample measurement
  - We also plan to have a beam test
  - See Ben's talk
- RF window study
  - Estimate required thickness to mitigate thermal expansion and Lorentz Force Detuning (LFD) effects
  - See Alvin's talk
- Beam loading effect
  - Estimate HOM + fundamental mode wake fields in the cavity
  - See Alvin's talk
- Gas-Plasma simulation
  - Influence gas-plasma motion on beam dynamics
  - See Moses' poster



Study HCC from theoretical aspects

- Translate HCC theory into generic cooling theory
  - Systematic way to study HCC
    - Evaluate non-linear dynamics, e.g. Space charge effect & Plasma lens, etc
    - Estimate cooling performance including with RF window, beam diagnostic material, spacing, etc
  - Compare HCC with VCC from analytical point view
    - Import/Export key concept
- Optimize HCC
  - Modulate optics to reach goal emittance
    - <u>Maximize transmission efficiency</u>
    - <u>Optics parameters should be bound by practical engineering parameters</u>



Translate HCC theory into generic cooling theory

Emittance evolution

$$\varepsilon_r(s) = \left(\varepsilon_{r,0} - \varepsilon_{r,eq}\right)\exp\left(-\Lambda_r s\right) + \varepsilon_{r,eq}$$

Equilibrium emittance

$$\varepsilon_{T,eq} = \frac{\beta_T \left(13.6\ MeV\right)^2}{2 m_\mu \beta g_T X_0 \langle dE/ds \rangle}$$

$$\varepsilon_{L,eq} = \frac{m_e c^2 \gamma^2 \beta \left(1 - \beta^2/2\right)\beta_L}{2 m_\mu g_L \left(\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2\right)}$$

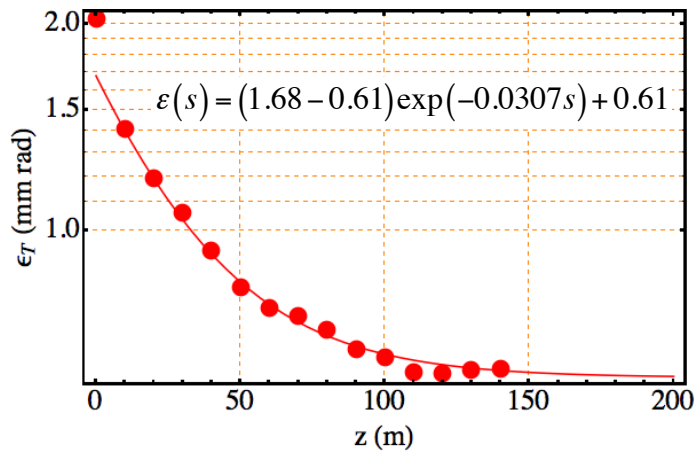
Cooling decrements

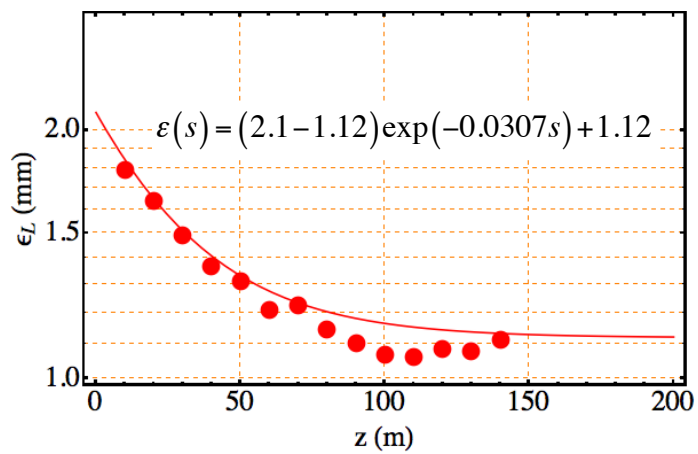
$$\Lambda_T = \frac{g_T}{\beta^2 E}\frac{dE}{ds}$$

$$\Lambda_L = \frac{g_L}{\beta^2 E}\frac{dE}{ds}$$

g_T and g_L are the function of dispersion

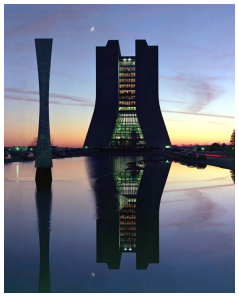
λ = 0.5 m, ν = 650 MHz, Gas Pressure = 160 atm
E = 20 MV/m, RF window thickness = 60 μm, 10 RF cells / λ





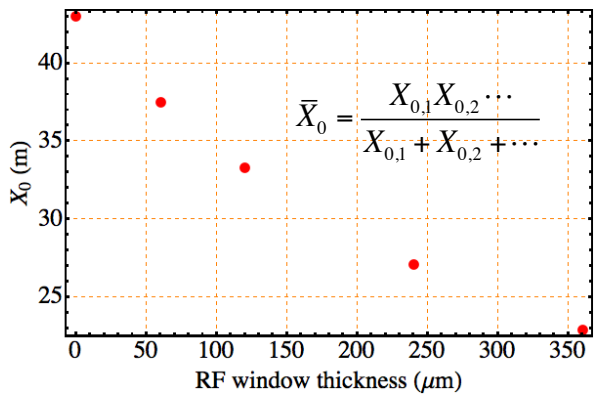
Solid line is the prediction (NOT fitting!)

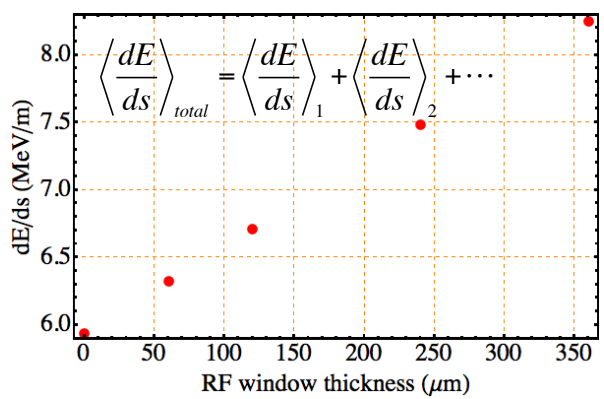
Go to Appendix to see detail analytic formulae



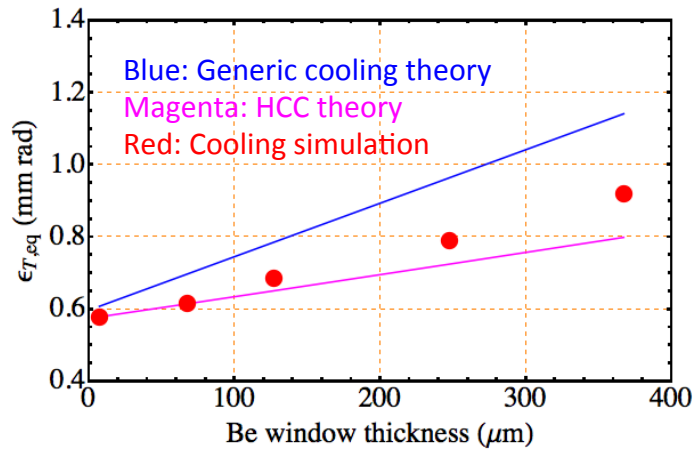
Equilibrium emittance vs RF window

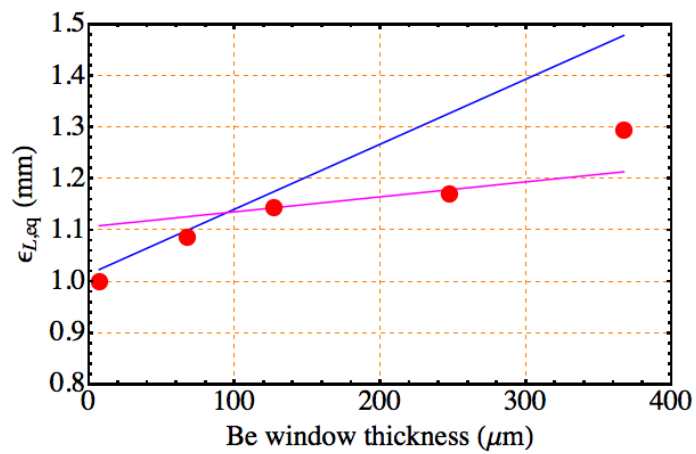
Modify radiation length and dE/dx to involve RF window dependence

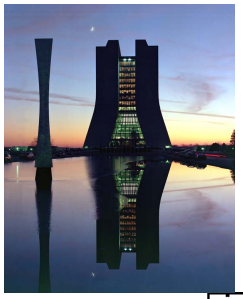




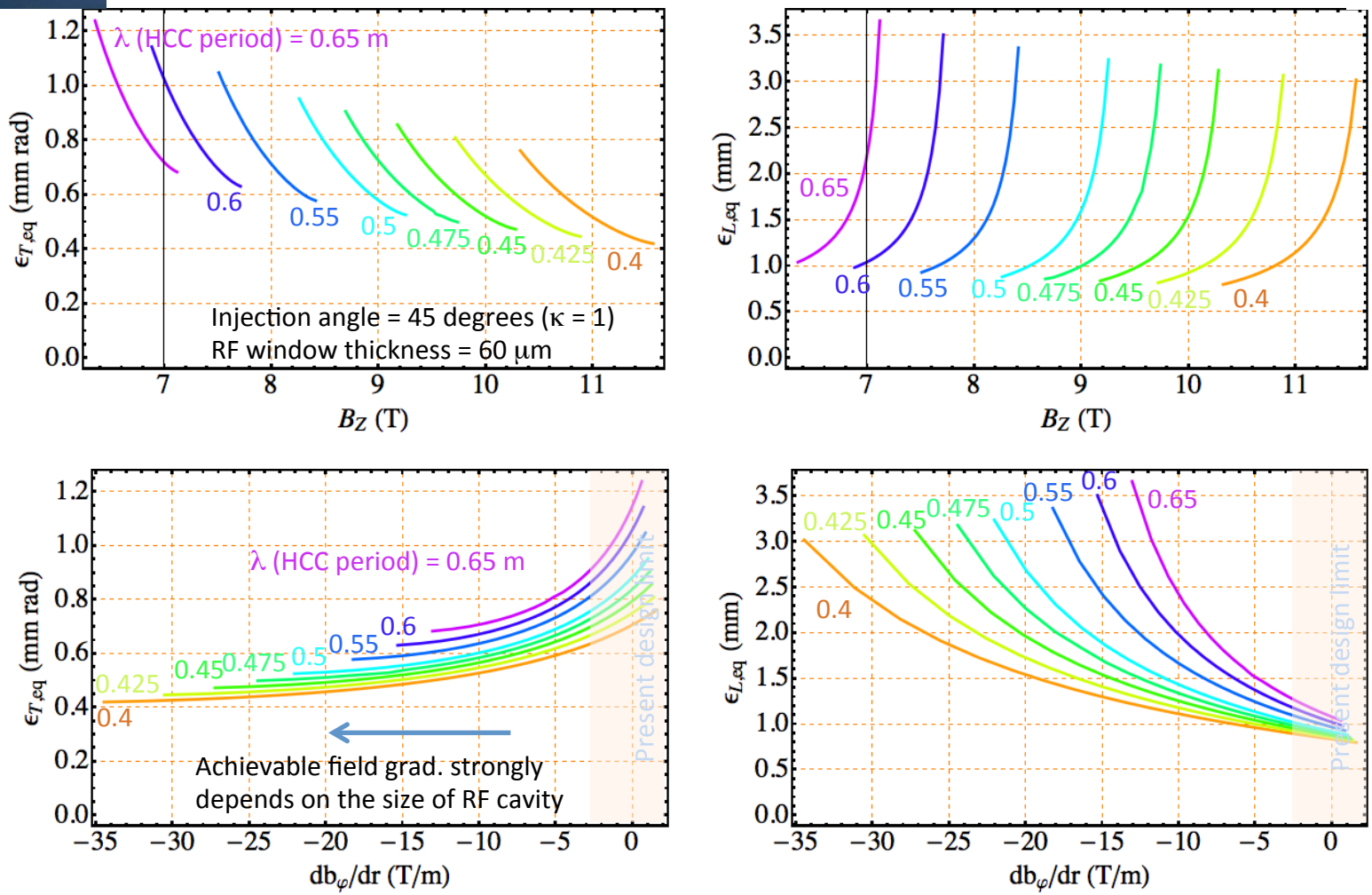
Equilibrium emittances in a 650 MHz HCC



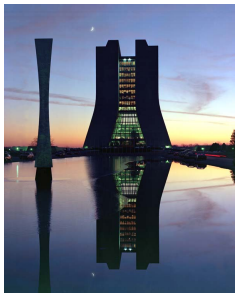




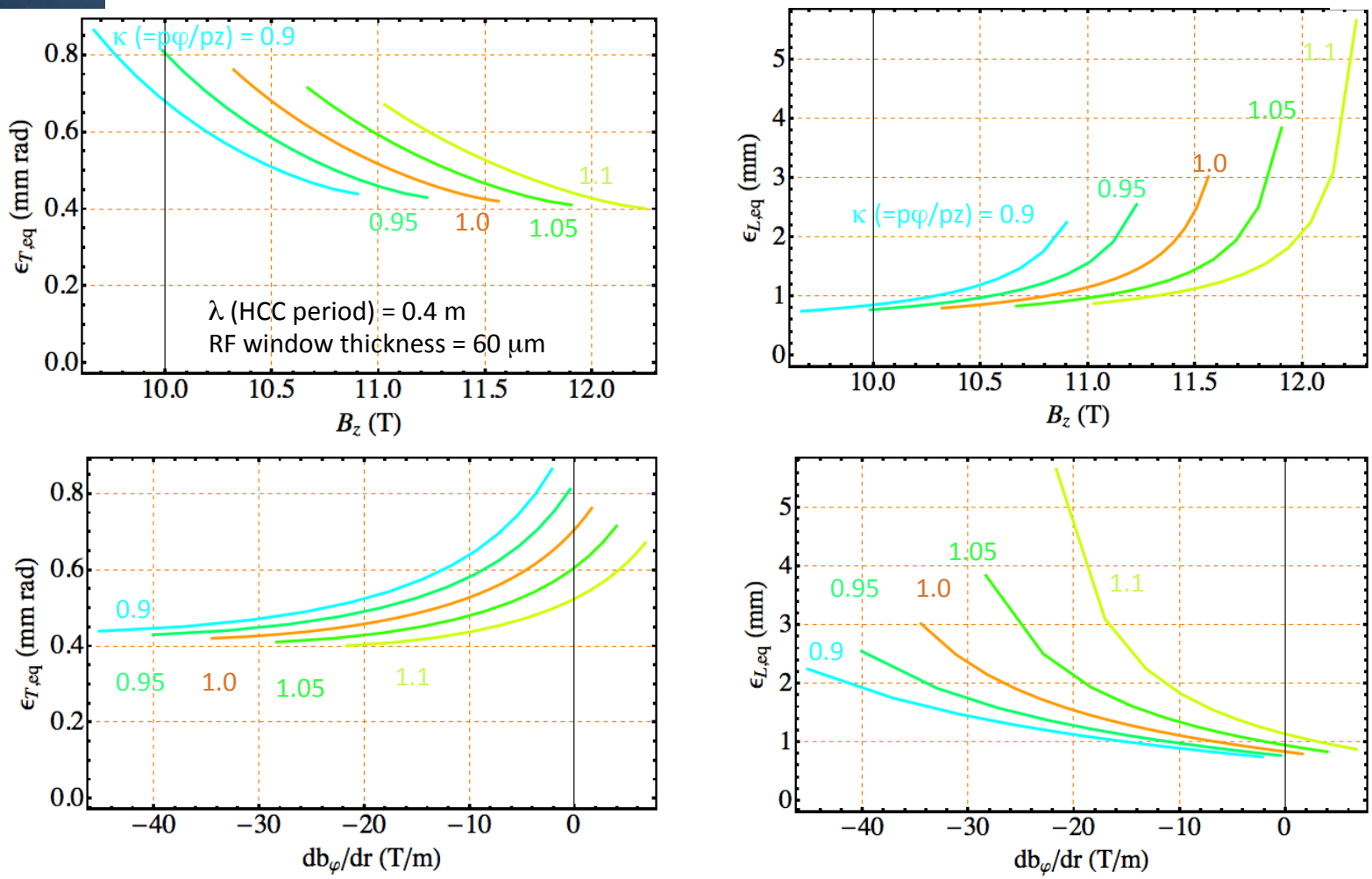
Equilibrium Emittance in B space

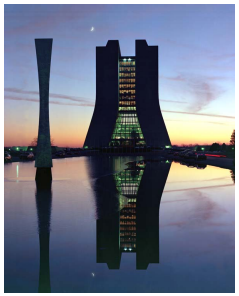


Hardest requirement in HCC magnet design is making huge field gradient to reach low trans. emit.
However, low long. emit. can be made in low field grad. → <u>It is a clue of a new cooling scenario</u>

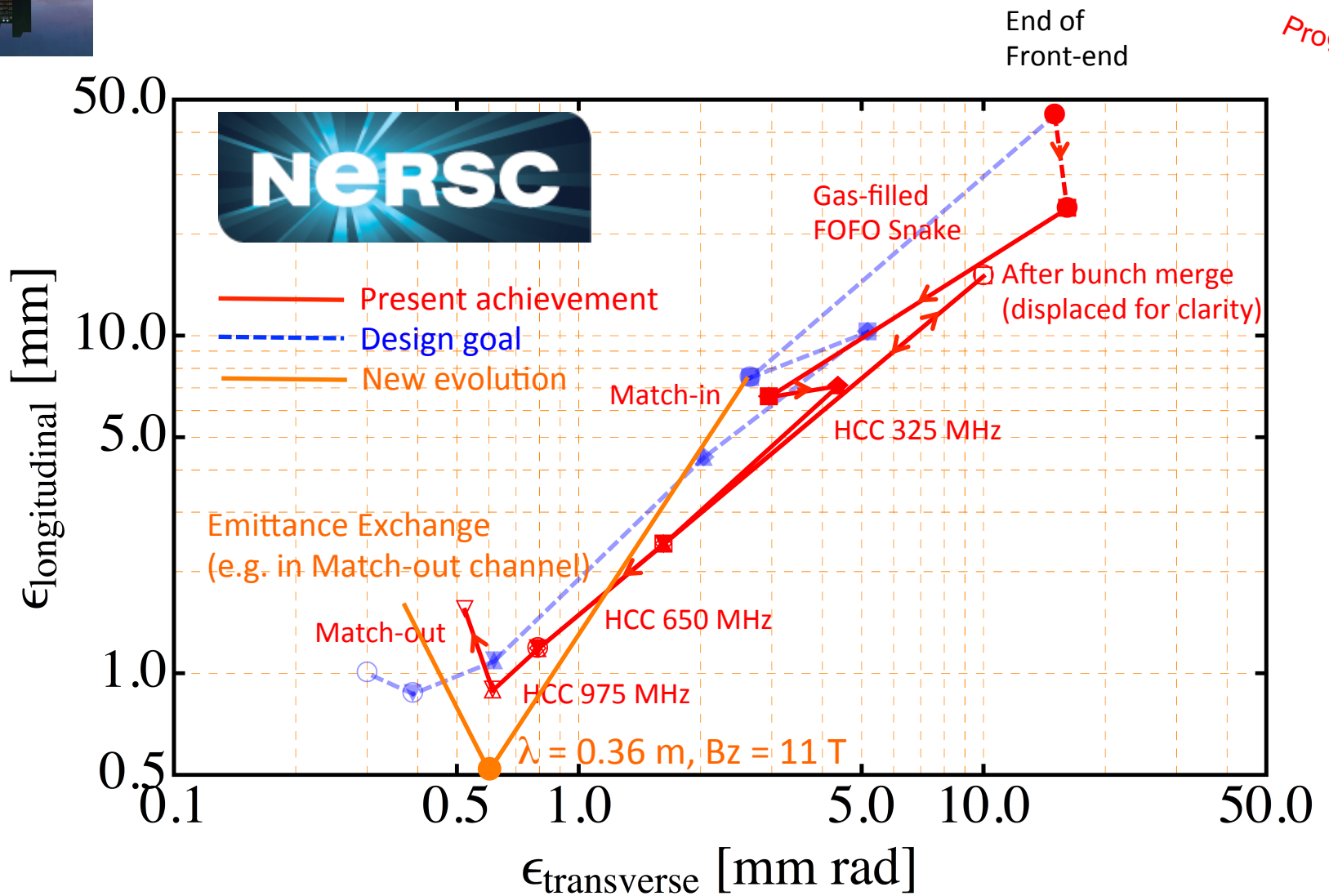


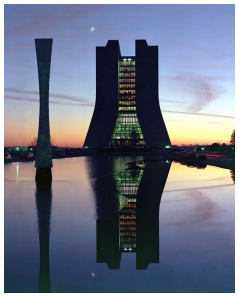
Equilibrium Emittance with various kappas





Possible cooling scenario

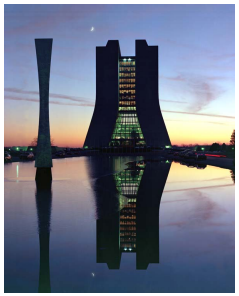




Plan by September 2014

- Technology Development
  - RF
    - DL HPRF cavity test
    - RF window study
  - Magnet
    - Design HS coil based on double layered Nb3Sn test result
  - Design/Consider beam diagnostic system
- Design and Simulation
  - Initial cooling channel, match-in, and helical bunch merge channel
  - Smooth λ HCC to maximize transmission efficiency
    - Current goal length 200 m
- Critical item in cooling physics
  - Study wake field effect
  - Beam dynamics with plasma motion

APPENDIX



Present Gas-Filled RF 6D Helical Cooling Channel Design Working Group

Supported by MAP & SBIR/STTR & Lee Teng Internship program

Original: 9/14/13
Modified: 2/07/13

[1]Fermilab
[2]Muons, Inc.
[3]Jlab
[4]IIT
[5]BNL
[6]STONY BROOK

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R. Johnson[2]
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C. Ankenbrandt[2]
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Y. Alexahin[1]

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J. Tompkins[1]
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HCC RF system
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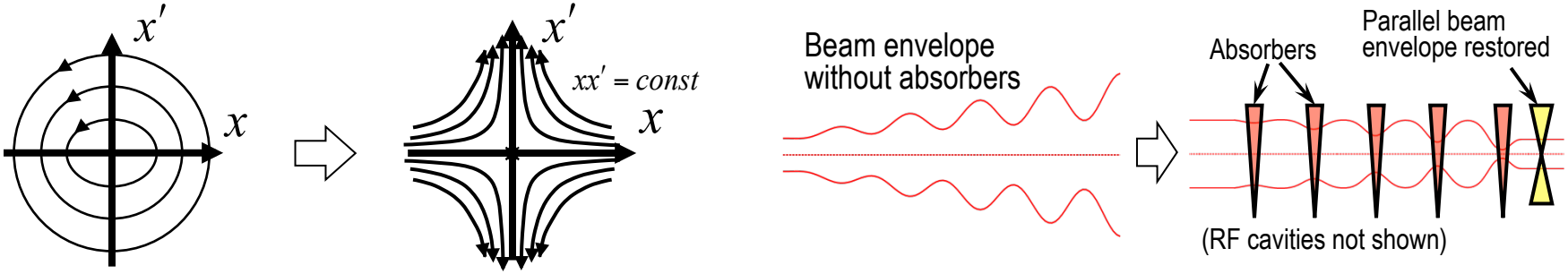
B. Freemire[1,4]
Y. Torun[4]
K. Yonehara[1]
R. Samulyak[5,6]
K. Yu[6]

Muons, Inc.
Innovation in Research

SKEW PARAMETRIC IONIZATION COOLING CHANNEL

PIC Concept

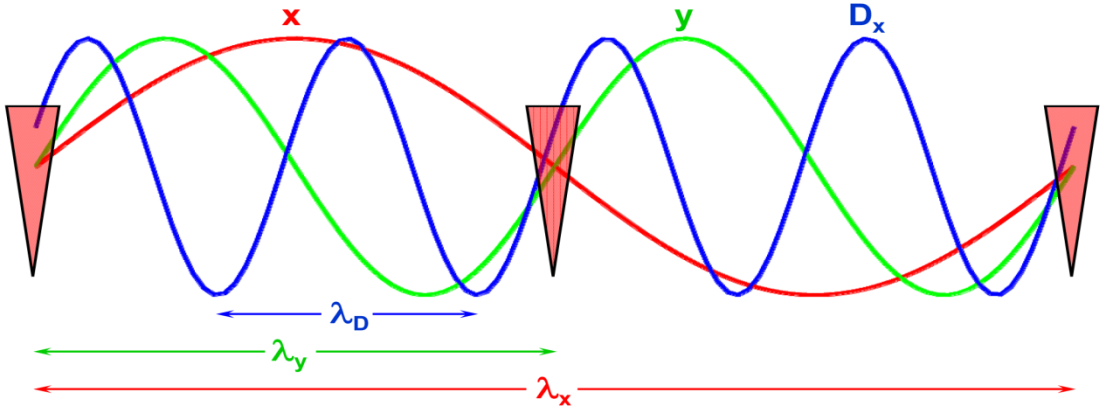
- **Half-integer resonances with simultaneous focusing in both planes**
  - Absorber limits angular spread at the focal points



  - An order of magnitude smaller transverse emittance than in conventional case

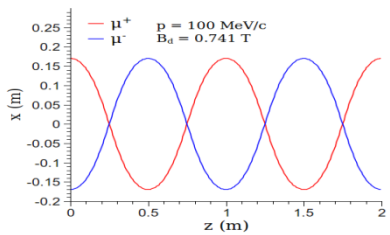
$$\varepsilon_{\perp}^{n} = \frac{\sqrt{3}}{4\beta}(Z+1)\frac{m_e}{m_\mu}w$$

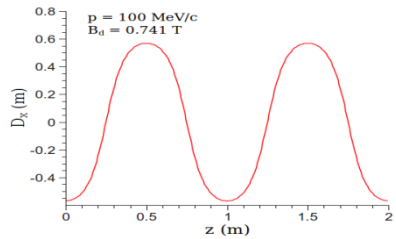
- **Correlated optics**



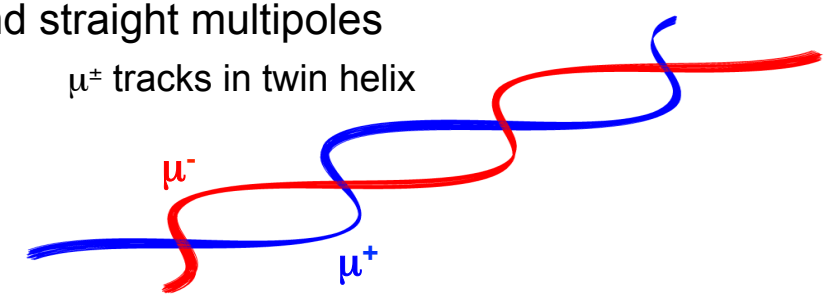
PIC Developments

- **Twin-helix channel with correlated optics**
  - Superposition of pairs of helical harmonics and straight multipoles

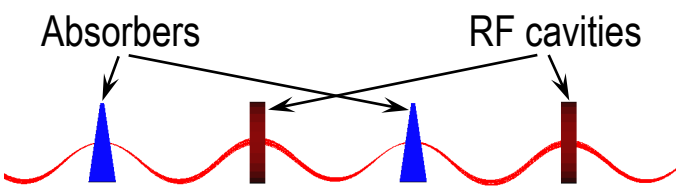


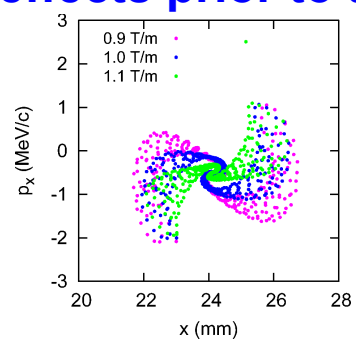


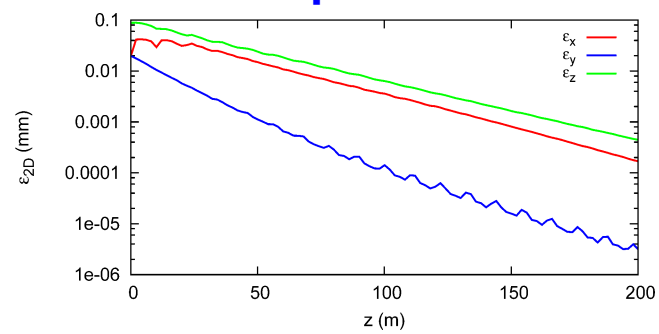
μ± tracks in twin helix



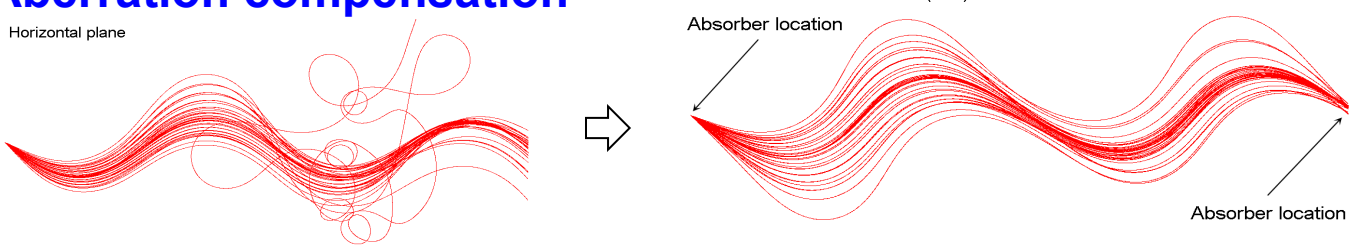
- **Simulations ignoring stochastic effects prior to aberration compensation**







- **Aberration compensation**



- **Non-linear resonance issue: many correcting harmonics make motion unstable**
  - e.g. $x \sim \cos(k_1 z), \quad B_y \sim x^2 \cos(k_2 z) \sim \cos^2(k_1 z)\cos(k_2 z) \quad \Rightarrow \quad k_2,\ k_2 \pm 2k_1$ lead to many non-linear resonances in case of correlated optics making compensation very challenging

Extension to *Skew PIC* : the principles

- Plane snake orbit
- Pursuing to build correlated optics but for radial motion only
- This feature is realized by adding skew quads for strong x-y coupling
- Azimuthal motion is not correlated (a free tune subject of a design choice; tune spread is irrelevant to the radial PR)
- 2d snake-dispersion is focused periodically
- Pose weak Parametric Resonance quads to provide and control beam gradual focusing at zero dispersion points
- Beam envelope still be not axially-symmetric, thus leaving one with possibility use of multipoles to compensate for *radial* aberrations

Extension to *Skew PIC* : advantages

- 2d-dispersion is not in resonance with transverse oscillations (big release for conceptual design!)
- Ease creation of a dispersion required for chromatic compensation

  (a big advance!)
- Effective reduction of the two-dimensional task of compensation for aberration to the one-dimensional (radial) one (other big release and advance!)
- A drastic cutback in the required group of compensating multipoles

  (big simplification in design/construction/control)!
- Other advantages: intrinsic equating of 1) PR rates in two planes; 2) transverse cooling decrements
- Using thin tilted absorber plates installed at zero dispersion points) instead of "micro-wedges" (-way to control emittance exchange – *promoted by R. Palmer*):

  a critically important technical reduction! – yet a conceptual simplification
- Skew PIC is easily transformable to the succeeding REMEX (at use of method !)

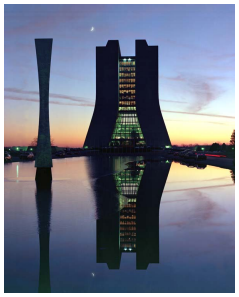
Linear SPIC concept has been proven-in-principle in basics

(compatibility of the pointed principal properties with simplecticity)

What is next

- Accomplish studying the linear SPIC dynamics and design
- Develop the non-linear Hamilton's analysis
- Utilize *compensation for aberrations theory: impose the required multipoles*
- Utilize cleaning for dangerous non-linear resonances if needed
- Implement *parametric resonance*
- Find a feasible technical concept of magnetic lattice for SPIC
- Demonstrate (in tracking) expected dynamical features in SPIC channel
- Implement an adequate RF stuff
- Study IC with G4BL
- Develop the related beam & optics control
- At success, extend SPIC to REMEX

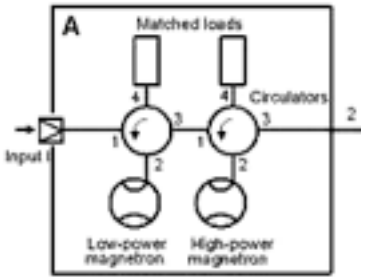
MACHINE DEVELOPMENT



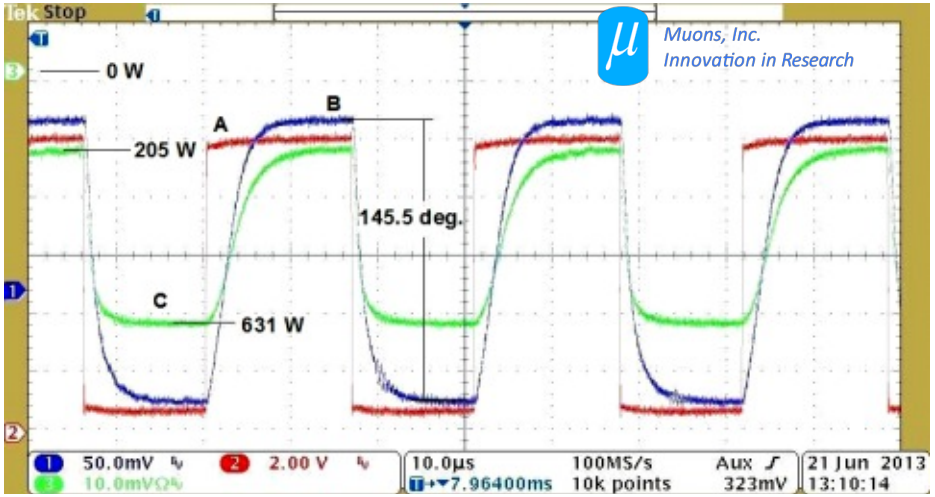
Cost Effective RF Power Source: Magnetron

G. Kazakevich

- Muons, Inc. promoted a 650 MHz magnetron for PIP-2 (a.k.a. Project-X)
- Developed and demonstrated a new method of control of magnetrons allowing extremely good stability
  - Expected phase stability less than 1 degrees
- Can make a new MW scale precisely stable RF source

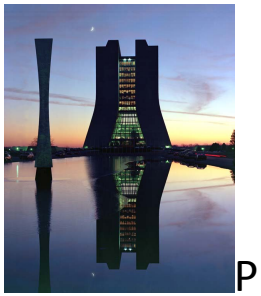


Muons, Inc.
Innovation in Research



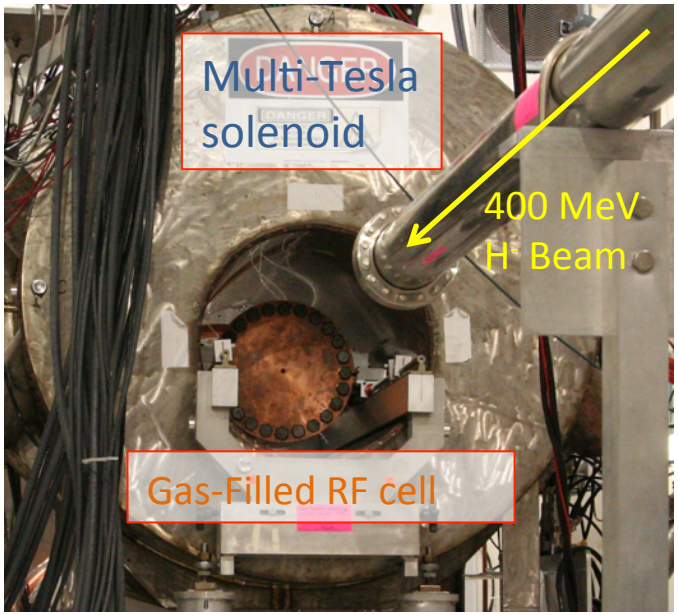
Muons, Inc.
Innovation in Research

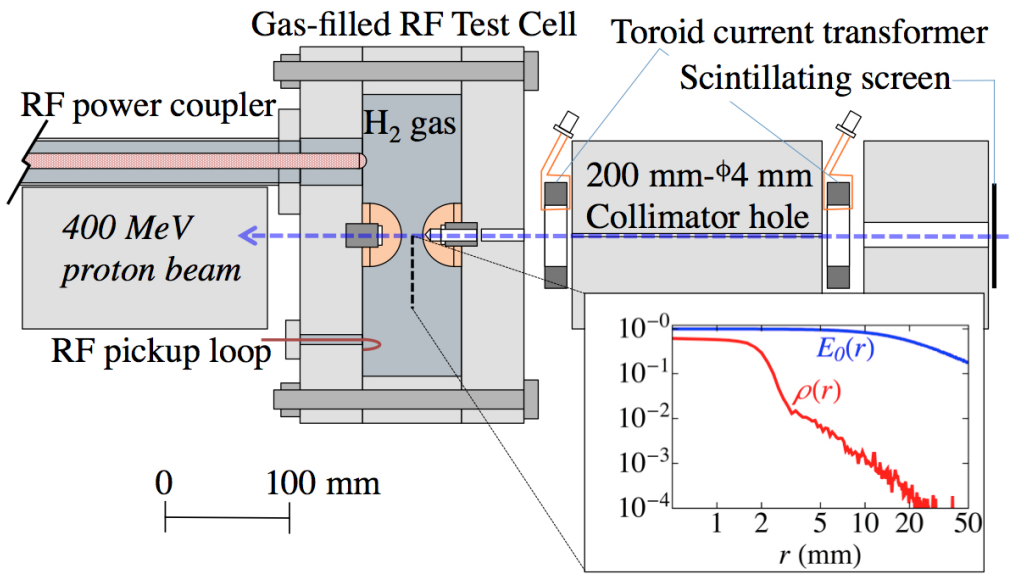
G. Kazakevich et al., NA-PAC'13, 966

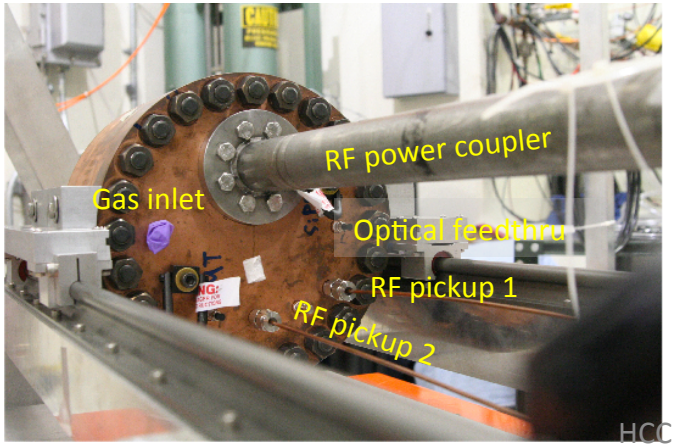


HPRF Beam Test at MTA

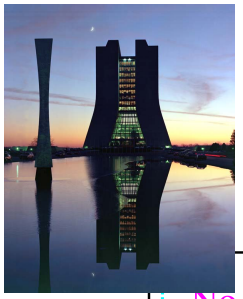
Proton beam test at MTA



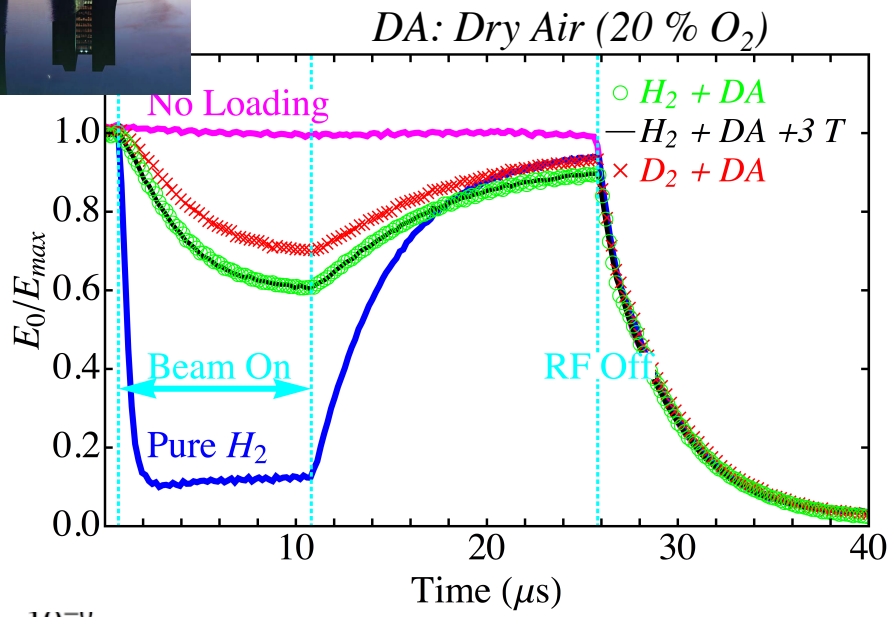




- Test H2, D2, N2, He
- SF6, Dry Air as electronegative gases
- B = 0 or 3 Tesla
- Vary peak RF E, 5 – 50 MV/m
- Vary gas pressure, 20 – 100 atm
- Vary beam intensity (Full intensity 54 mA)



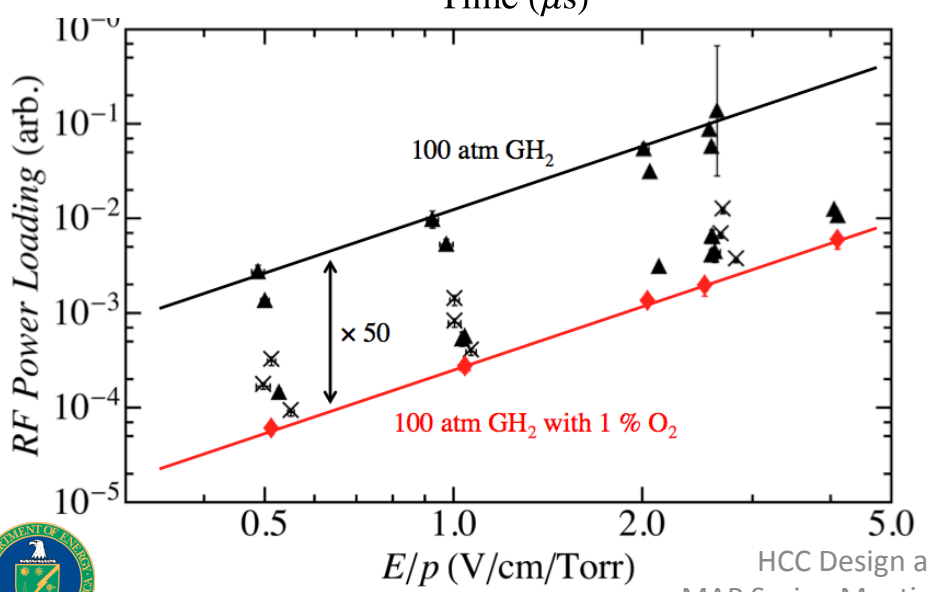
Beam-Induced Gas Plasma Experiment



M. Chung et al., PRL 111, 184802 (2013)

RF amplitude with beam-induced gas plasma

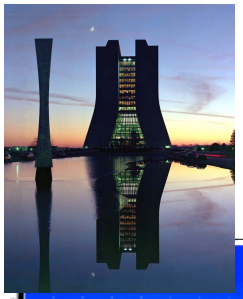
- Ionization electrons consume RF power
- A small amount of electronegative dopant (O_2) can greatly reduce the plasma loading
- No RF degradation due to magnetic field
  - ▹ e-H2 Collision frequency ≫ Larmor frequency

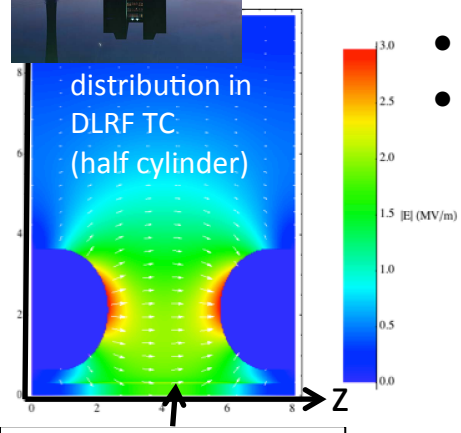


Measured plasma loading

- Measured plasma loading effect is 0 ~ 70 % lower than expected in pure H_2 gas
  - ▹ Density effect
- Plasma loading is 50 times lower by adding 1 % O2

Dielectric Loaded Gas-Filled RF Test





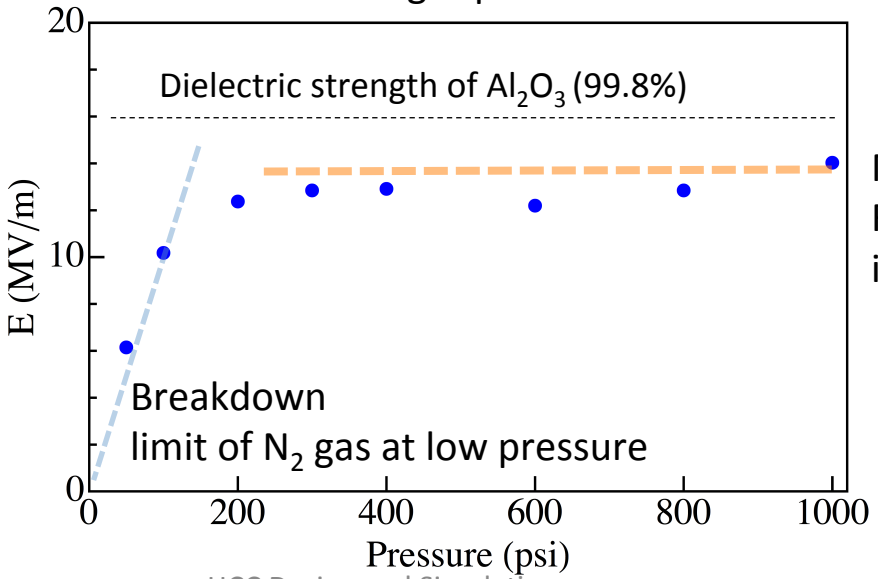
Alumina sample

- Compact RF cavity is required for a short-length 6D cooling c
- Dielectric loaded gas-filled RF cavity is proposed
  - Increase RF capacitance by adding dielectric material to shrink the cavity size → Verified
  - Gas can suppress the surface breakdown of dielectric material → Verified

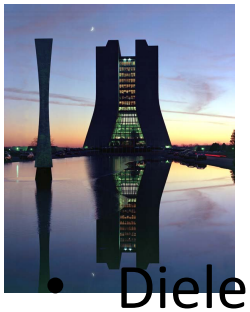
L. Nash et al.,IPAC'13

HPRF test cell

Measured maximum available RF gradient in an Al_2O_3 (Alumina) loaded gas-filled RF test cell as a function of N2 gas pressure



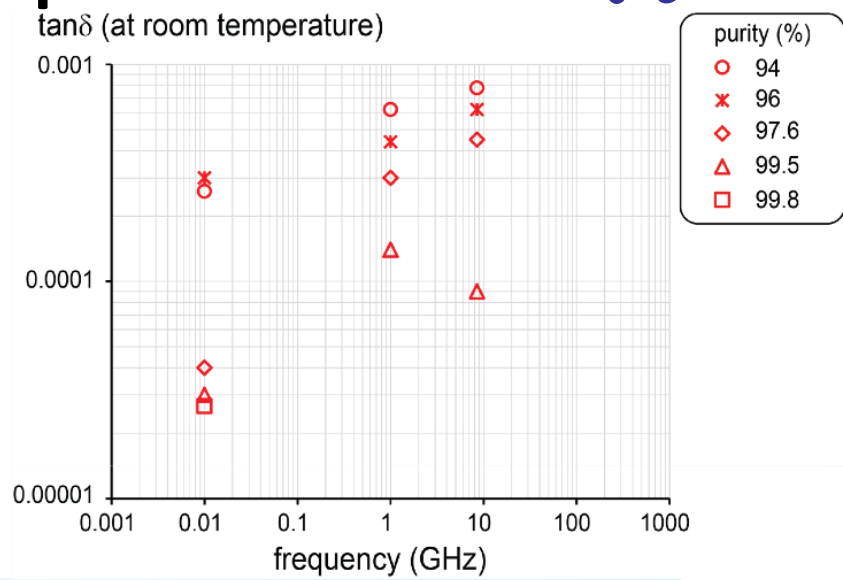
Maximum surface RF field 14 MV/m in this test

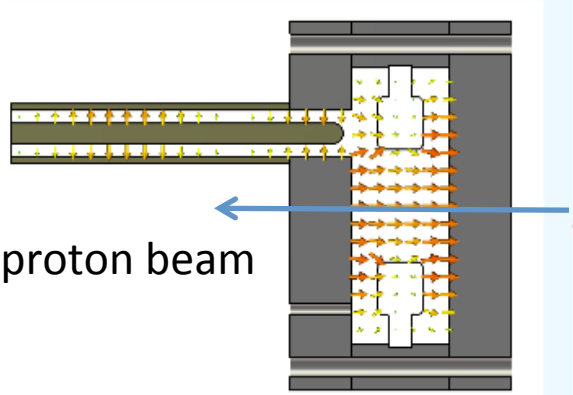


Future HRRF experiment

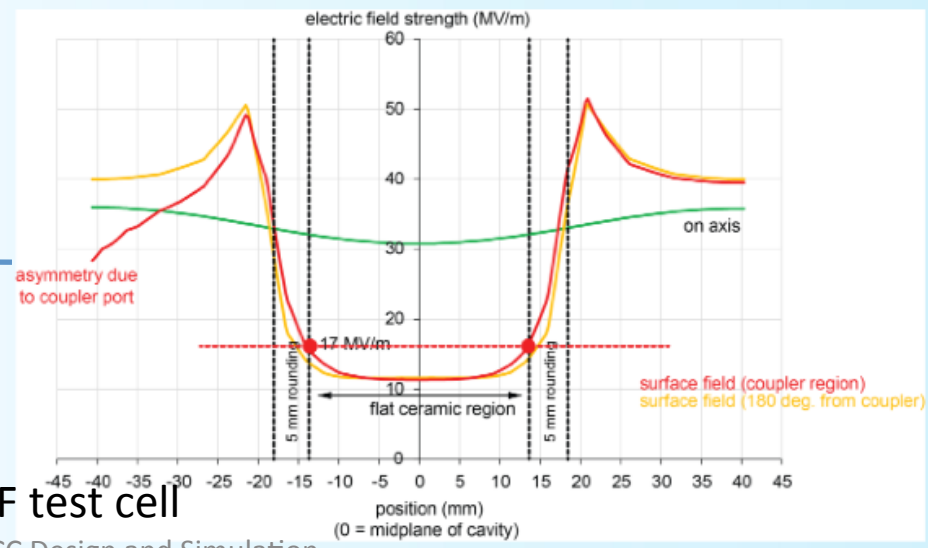
- Dielectric loaded gas-filled RF test
  - Dielectric material sample test
  - Beam test
  - Cold RF test
- RF window test

Wesgo Alumina grade (purity)	AL500 (94 %)	AL600 (96 %)	AL300 (97.6%)	AL995 (99.5%)	AL998 (99.8%)
Dielectric Strength (MV/m)	25.6	26.6	43.3	31.5	≥ 17

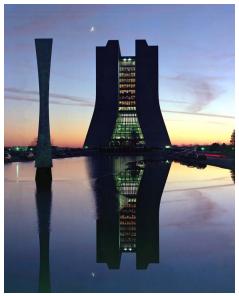




MTA proton beam



Dielectric loaded RF test cell

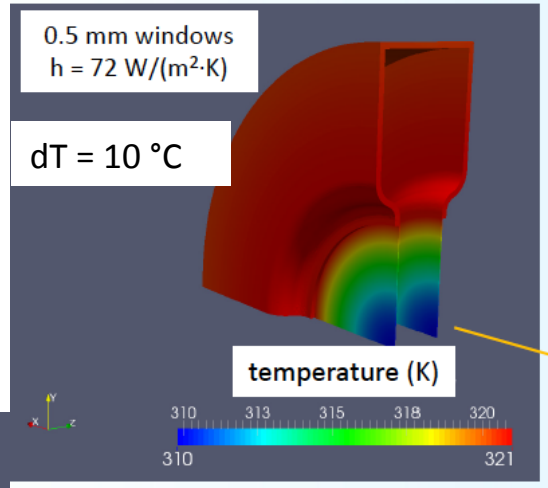


Thermal calculation of RF Window in Gas-Filled RF Cell

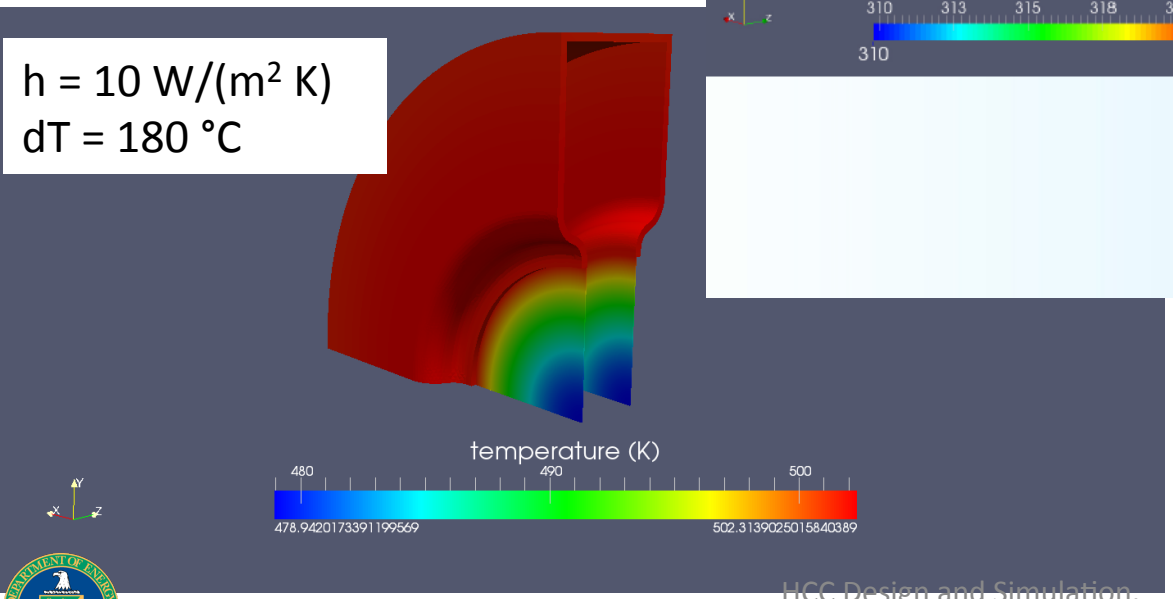
F. Marhauser

E = 24 MV/m

160 atm GH2



1 atm Air



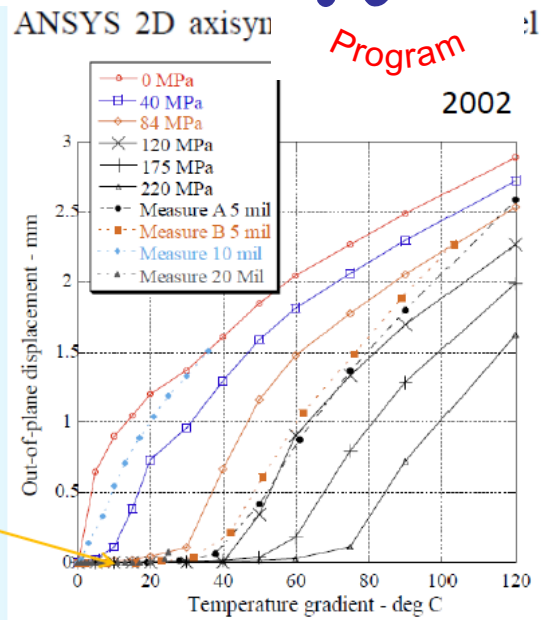


Figure 3: Thermal gradient and out-of-plane displacement. Experimental and ANSYS data.

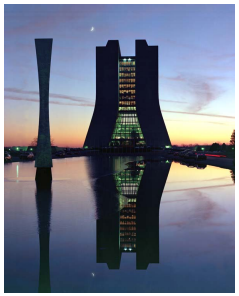
Proceedings of EPAC 2002, Paris, France

MECHANICAL AND THERMAL ANALYSIS OF BERYLLIUM WINDOWS FOR RF CAVITIES IN A MUON COOLING CHANNEL *

Derun Li, A. Ladran, D. Lozano, R. Rimmer, LBNL, Berkeley, CA.
One Cyclotron Road, Berkeley, CA 94720

- Thermal gradient is worse in a vacuum RF than 1 atm Air
- While dense gas acts as a coolant thus, significantly reduces temp. rise on the window

GENERIC COOLING FORMULAE



Key formulae in generic cooling and HCC theories

Transverse beta tune in HCC

$$Q^2 = Q_\pm^2 \equiv R \pm \sqrt{R^2 - G}$$

Average transverse beta function

$$\bar{\beta}_{T,HCC} \equiv \sqrt{\beta_+ \beta_-} \qquad \text{where } \beta_\pm = \frac{1}{kQ_\pm} = \frac{\lambda}{2\pi Q_\pm}$$

Longitudinal beta function in HCC

$$\beta_L = \sqrt{\frac{m_\mu c}{\eta \omega e V'}} \frac{1+\sin(\phi_s)}{1-\sin(\phi_s)}$$

Equilibrium emittances

$$\varepsilon_{T,eq} = \frac{\beta^3 \gamma E \beta_T \, d\langle \theta_{rms}^2 \rangle / ds}{g_T \langle dE/ds \rangle} = \frac{\beta_T (13.6\ MeV)^2}{2 m_\mu \beta g_T X_0 \langle dE/ds \rangle}$$

$$\varepsilon_{L,eq} = \frac{\beta^3 \gamma E \beta_L \, d\langle (\delta p/p)_{rms}^2 \rangle / ds}{g_L \langle dE/ds \rangle} = \frac{m_e c^2 \gamma^2 \beta (1-\beta^2/2) \beta_L}{2 m_\mu g_L \left(\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 \right)}$$

$$R = \frac{1}{2}\left(1 + \frac{q^2}{1+\kappa^2}\right)$$

$$\hat{D} = \frac{p}{a}\frac{da}{dp}$$

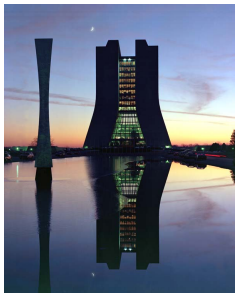
$$q = \sqrt{\frac{1+\kappa^2 - 1/2\,\kappa^2 \hat{D}}{1 + 1/2\,\kappa^2 \frac{\hat{D}}{1+\kappa^2}}}$$

$$G = \left(\frac{2q+\kappa^2}{1+\kappa^2} - \hat{D}^{-1} \right) \hat{D}^{-1}$$

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

$$g_L \to g_{L,0} + \delta g_L, \quad g_{T(=x,y)} \to 1 - \frac{\delta g_L}{2}$$

$$\delta g_L = \frac{\kappa^2}{1+\kappa^2}\hat{D}$$



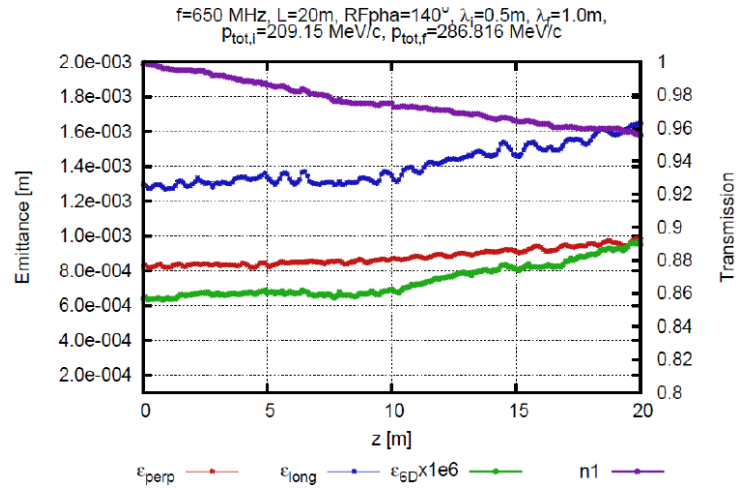
Emittance growth in accelerating helical channel in helical bunch merge channel

Emittance evolution

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2 E}\left\langle \frac{dE}{ds} \right\rangle \varepsilon_n + \frac{\beta\gamma}{2}\left(\beta_n(s)\sigma_n^2\right)$$

Vary beta function as a function of channel length (s)

$$\beta_n \rightarrow \beta_{n,0}\left(1 + \frac{d\lambda}{ds}\frac{s}{\lambda_0}\right)$$

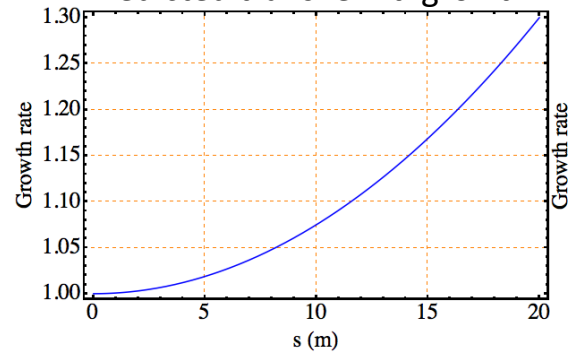


Predicted emittance growth

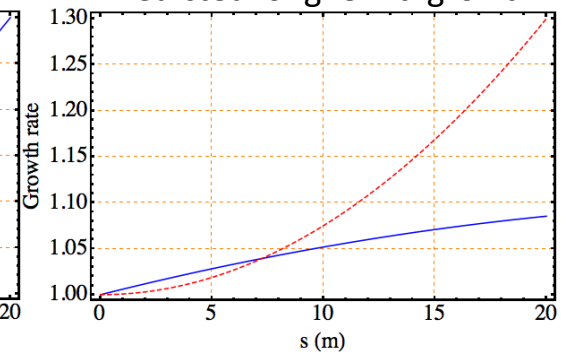
$$\varepsilon_T(s) \approx \varepsilon_0 + \frac{\sigma^2 \beta_{n,0}\, d\lambda/ds}{\lambda_0}\frac{s^2}{2!} \approx \varepsilon_0\left(1 + \frac{\Lambda\, d\lambda/ds}{2\lambda_0}s^2\right)$$

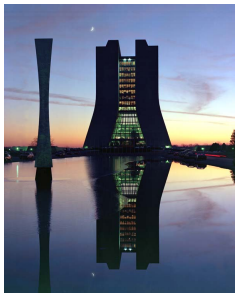
$$\varepsilon_L = \varepsilon_0 + \left(\sigma^2\beta_L - \varepsilon_0\Lambda\right)s - \left(\sigma^2\beta_L - \varepsilon_0\Lambda\right)\frac{\Lambda}{2}s^2$$

Predicted trans. emit. growth



Predicted long. emit. growth





Study Admittance

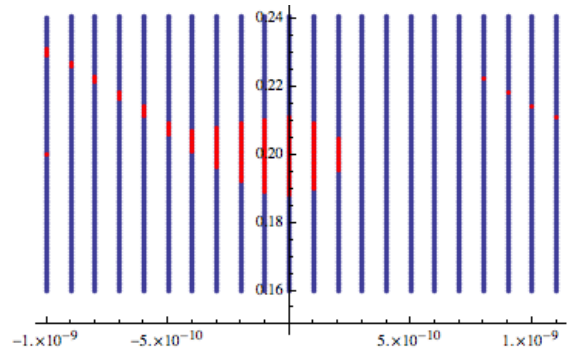
Longitudinal beta function

$$\beta_L = \sqrt{\frac{m_\mu c}{\eta \omega e V'}} \frac{1+\sin(\phi_s)}{1-\sin(\phi_s)}$$

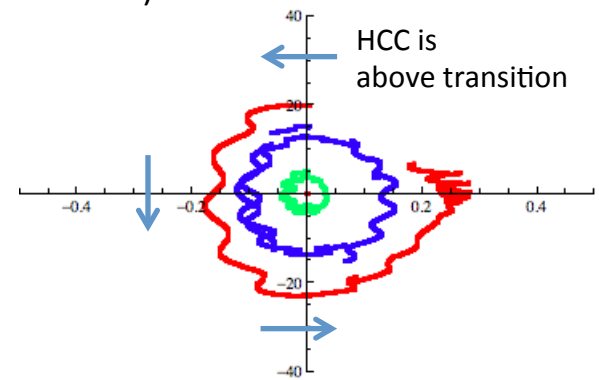
Phase slip factor

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

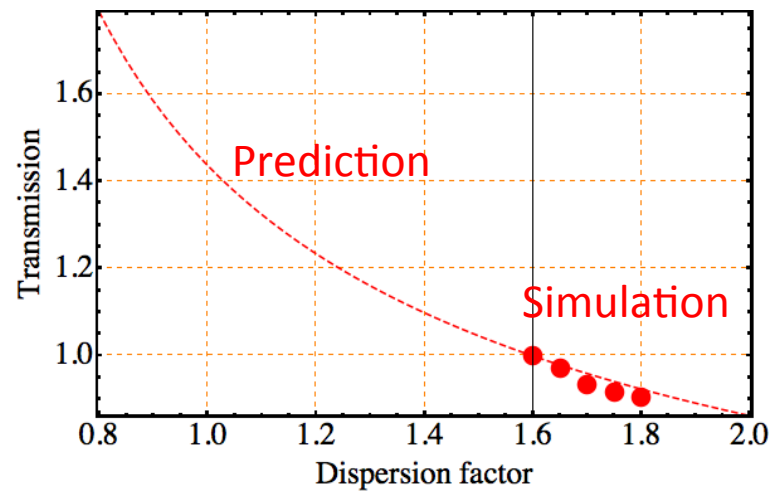
Initial longitudinal beam phase space
(Red: accepted particles, Blue: lost in 20 m HCC)

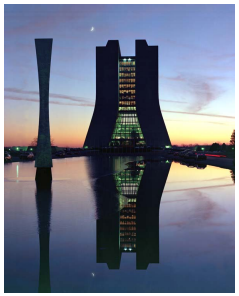


Separatrix



Lower dispersion makes longer longitudinal beta function
→ Larger longitudinal acceptance





Study transverse acceptance

Transverse beta function

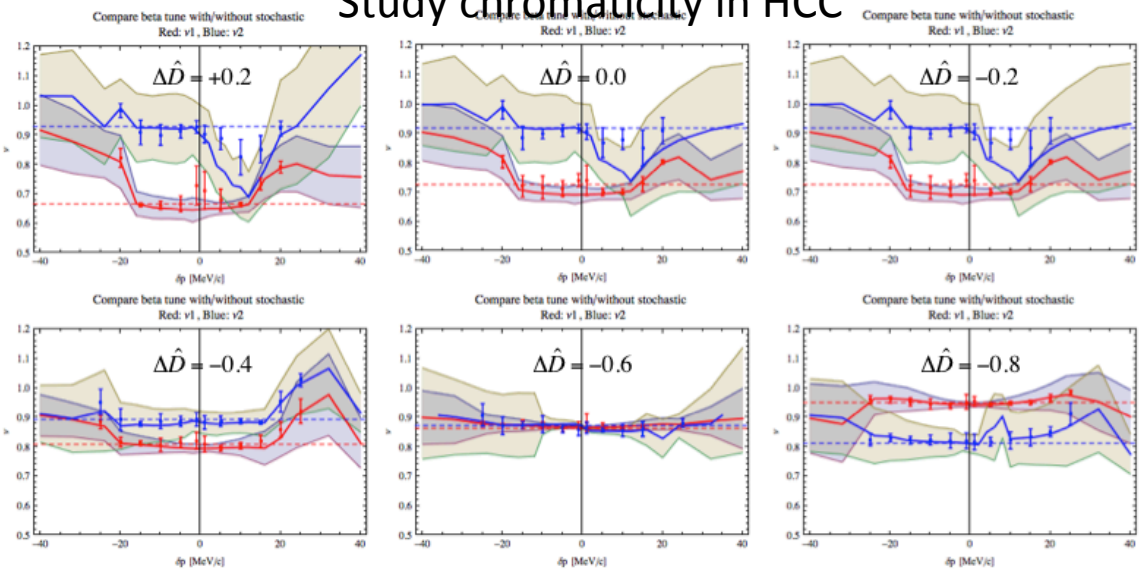
$$Q^2 = Q_\pm^2 \equiv R \pm \sqrt{R^2 - G}$$

$$\beta_\pm = \frac{1}{kQ_\pm} = \frac{\lambda}{2\pi Q_\pm}$$

$$\bar{\beta}_{T,HCC} \equiv \sqrt{\beta_+ \beta_-}$$

Lower dispersion makes longer transverse beta function
→ Larger transverse acceptance

Study chromaticity in HCC



Higher order dispersion function

$$D(p) = \frac{p}{dp} dr \rightarrow \frac{dr}{dp}\left(p_0 + \frac{dp}{ds}s + \frac{1}{2!}\frac{d^2p}{ds^2}s^2 + \frac{1}{3!}\frac{d^3p}{ds^3}s^3 + O(s^4)\right)$$

$$D_0 = \left(\frac{dr}{dp}\right)p_0 = 2a\frac{1+\kappa^2}{\kappa^2}\left(1 - \frac{2\hat{\beta}^2}{3}\right)$$

$$D_1 = \frac{dr}{dp}\frac{\partial p}{\partial s}s = \left(\frac{dr}{dp}p_0\right)\frac{s}{p_0}\frac{dp}{ds} = D_0\frac{s}{p_0}\frac{dp}{ds}$$

$$D_2 = \frac{1}{2!}\left(\frac{dr}{dp}\right)\frac{\partial^2 p}{\partial s^2}s^2 = \frac{1}{2!}\left(\frac{dr}{dp}p_0\right)\frac{s^2}{p_0}\frac{dp}{ds}\frac{d}{dp}\left(\frac{dp}{ds}\right) = \frac{1}{2}D_0\frac{s^2}{p_0}\frac{dp}{ds}\frac{d}{dp}\left(\frac{dp}{ds}\right)$$

$$D_3 = \frac{1}{6}D_0\frac{s^3}{p_0}\left(\frac{dp}{ds}\right)^2\frac{d^2}{dp^2}\left(\frac{dp}{ds}\right)$$