Study of Helical Cooling Channels for Intense Muon Sources

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Cool'15 Workshop at JLab

Ionization cooling for muon beam

Highlights of D. Kaplan's talk

- Energy loss collision with atoms/molecules via ionization process
  - Very high collision frequency (therefore a high cooling rate) since a high density cooling media is available
  - Lost-energy is immediately recovered by RF accelerations
  - Often a large angle scattering takes place by collision with nuclei of the cooling media (i.e. multiple scattering)
  - Low Z material is ideal to minimize the large angle scattering

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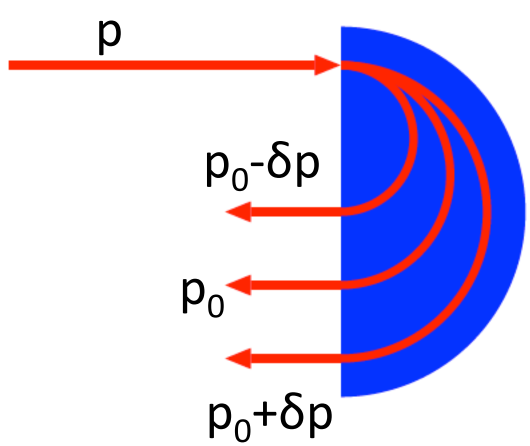
Gaseous hydrogen is the best cooling material

- High energy-loss rate (dE/dx)
- Small scattering angle via protons (long radiation length X_0)
- GH2 can also be used to suppress dark currents

→ Eliminate a RF electric breakdown due to strong magnetic fields

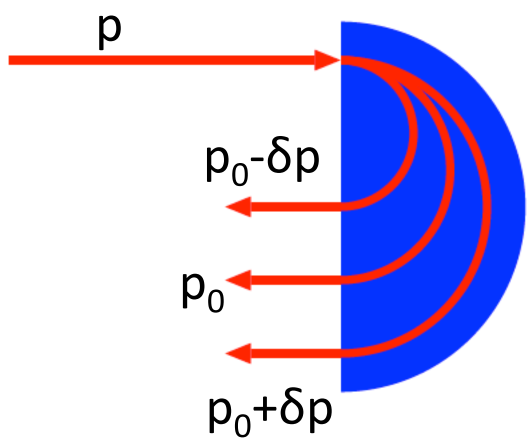
(See B. Freemire's talk)

Concept of hydrogen gas-filled Helical Cooling Channel (HCC)



Homogeneous gas
absorber in
a dipole magnet

Concept of hydrogen gas-filled Helical Cooling Channel (HCC)

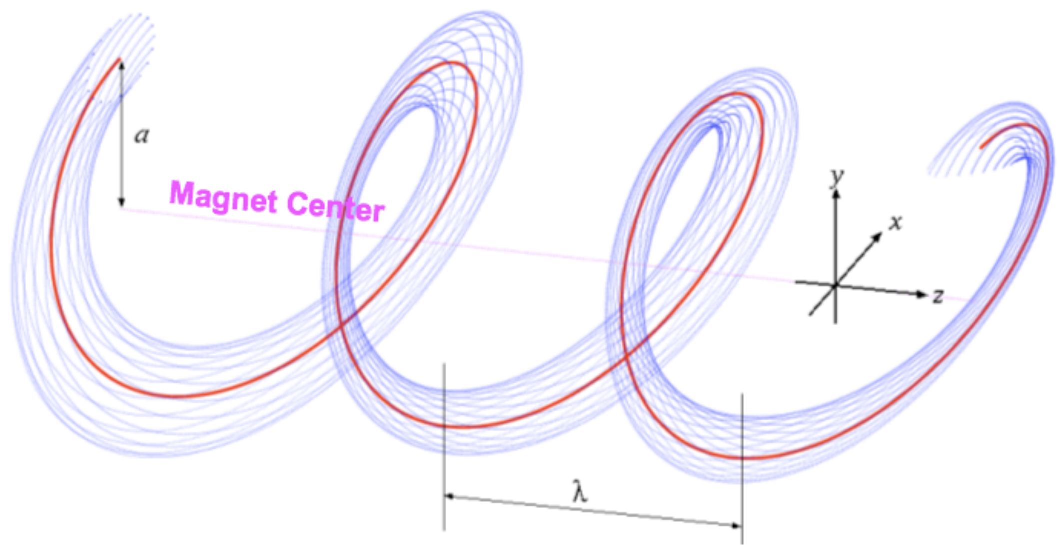


Homogeneous gas absorber in a dipole magnet

New conceptual accelerating system

Key feature:

- Dense hydrogen gas distributed homogeneously in a lattice with constant dispersion
  → Non-periodic lattice structure



Particle tracking in HCC (red: reference)

Particle motion (blue) is periodic due to the solenoid and helical dipole magnetic fields

Complete linear theory: Ya.S. Derbenev & R.P. Johnson, PRSTAB 8 041002 (2005)

Linear beam parameter in HCC

- Betatron tune: $Q^2 = Q_\pm^2 \equiv R \pm \sqrt{R^2 - G}$ where $R^2 \geq G$ is a stability condition

Equation of motion for a reference particle

$$f_{central} = \frac{e}{m}(b \cdot p_z - B_z \cdot p_\perp)$$

$$B_z = b_z + \kappa b$$

$$p = \frac{(b_z + \kappa b)(1+\kappa^2)^{1/2}}{k(q+1)}$$

k and q are a geometry parameter

$$\kappa = \frac{p_\perp}{p_z} = \frac{2\pi a}{\lambda} = ka, \quad q = \frac{b(1+\kappa^2)}{\kappa(b_z + \kappa b)}$$

R and G are given by q, k, and $\hat{D}$

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

- Dispersion factor:

$$\hat{D}^{-1} = \left(\frac{p}{a}\frac{da}{dp}\right)^{-1} = g + \frac{\kappa^2 + (1-\kappa^2)q}{1+\kappa^2}, \qquad b' \equiv \frac{db}{da} = \frac{gpk}{(1+\kappa^2)^{3/2}}$$

- Beta function:

$$\beta_\pm = \frac{1}{kQ_\pm} = \frac{\lambda}{2\pi Q_\pm}, \quad \beta_L = \sqrt{\frac{m_\mu c}{\eta\omega eV'}\frac{1+\sin(\phi_s)}{1-\sin(\phi_s)}}$$

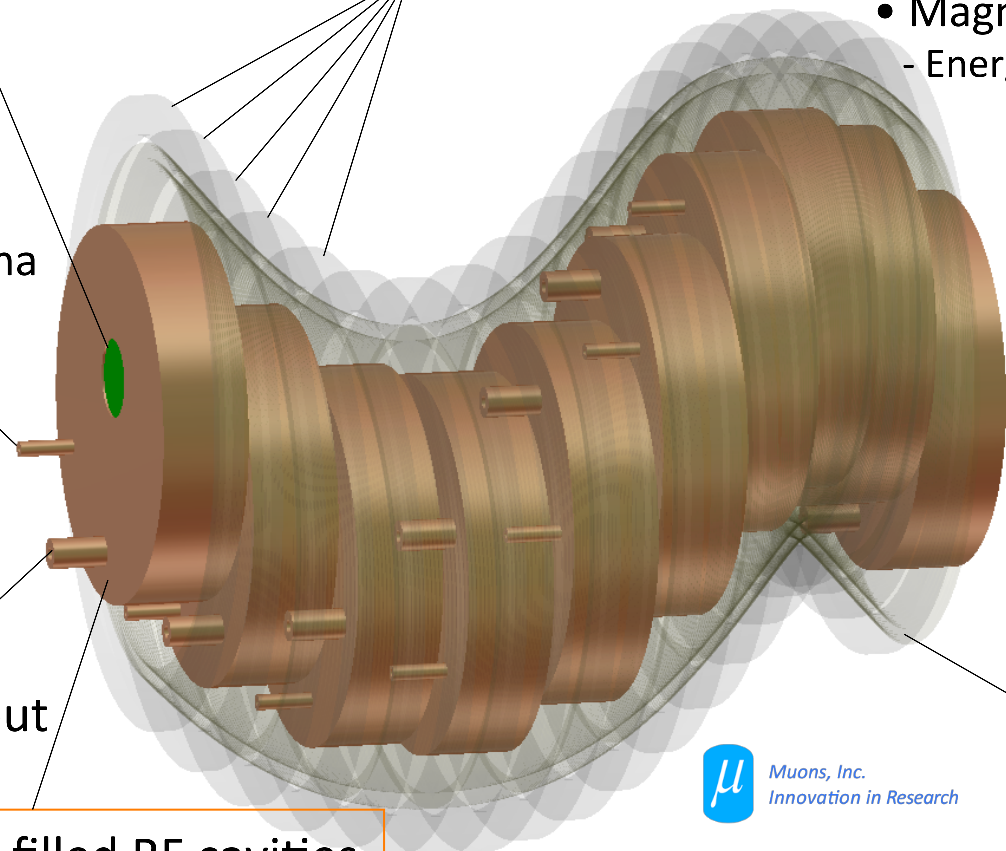
Phase slip factor

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

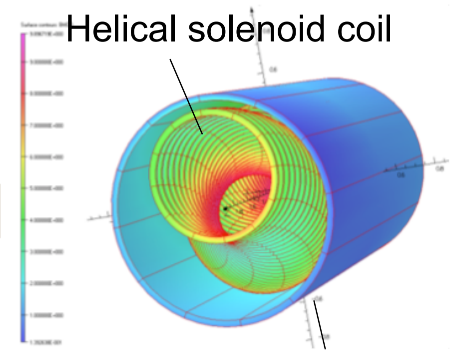
Note: HCC has a positive slip factor

Design concept of helical beam element

Innovative helical beam element
- Hydrogen gas filled RF cavity
- Helical solenoid coil
- Magnetron
  - Energy efficient RF power source



Helical magnet



Validate HCC theory with numerical simulation

Emittance evolution

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

Equilibrium emittance

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

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

Cooling rate (decrement)

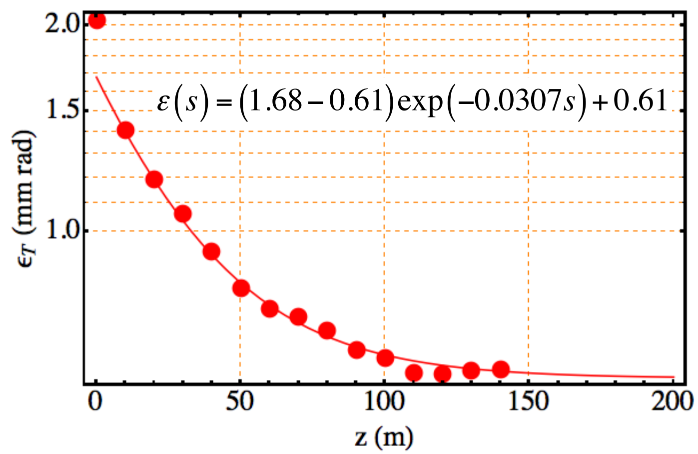
$$\Lambda_T = \frac{g_T}{\beta^2 E} \frac{dE}{ds}$$

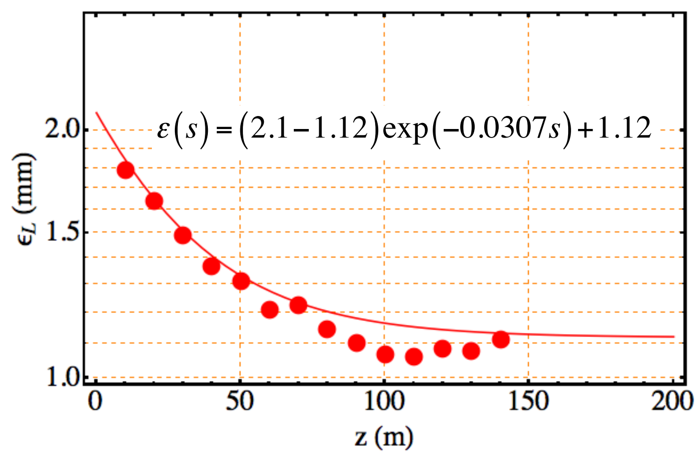
$$\Lambda_L = \frac{g_L}{\beta^2 E} \frac{dE}{ds}$$

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

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

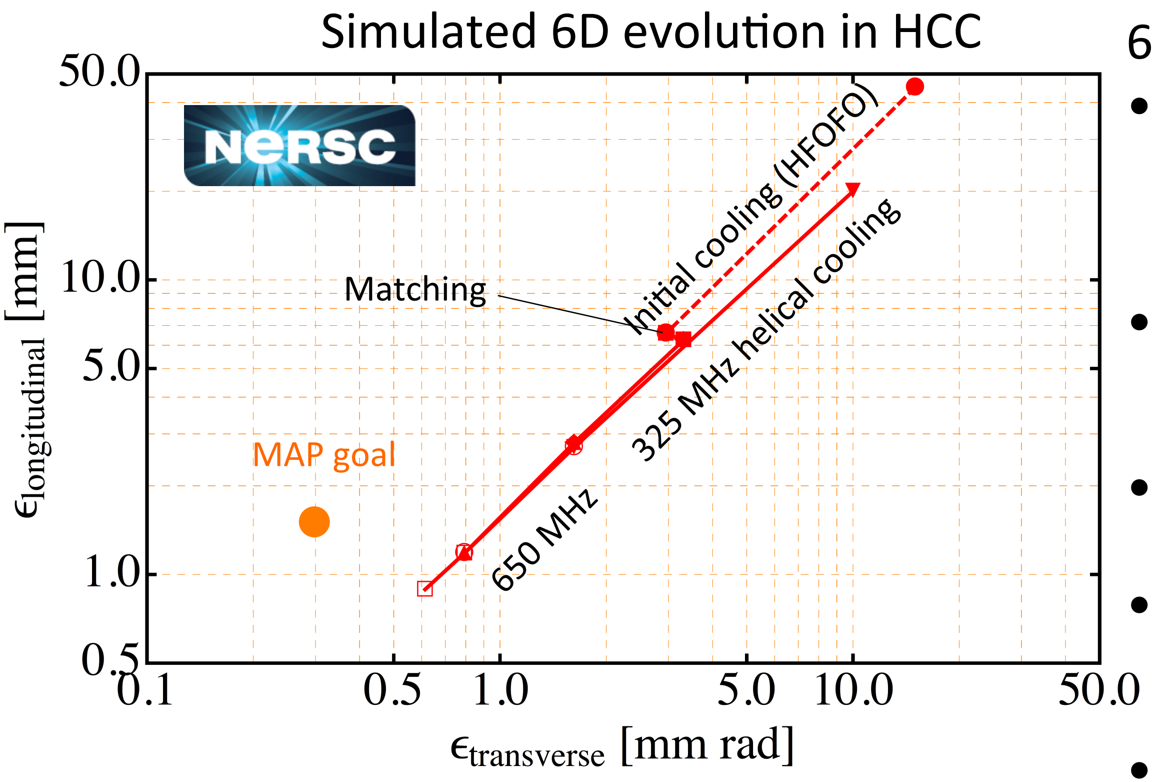
l = 0.5 m, n = 650 MHz, Gas Pressure = 160 atm @ 300 K
E = 20 MV/m, RF window thickness = 60 mm, 10 RF cells / l





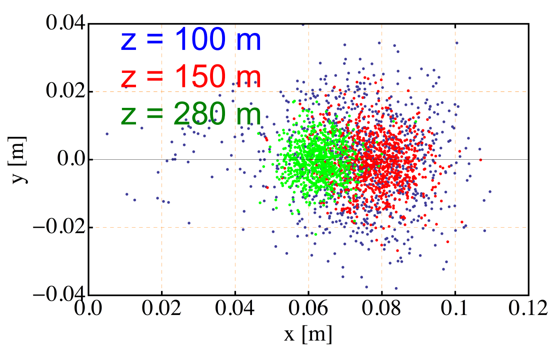
Solid line is the prediction
(Not a fitting curve!)

Six-dimensional phase space evolution in helical cooling channel for muon collider scheme



6D HCC

- RF parameter
  - E_{peak} = 20 MV/m
  - n = 325 & 650 MHz
  - 60 mm thick Be window
- Gas pressure
  - 160 atm at 300 K
  - 43 atm at 80 K
- Magnetic fields
  - B_z = 4 – 12 Tesla
- Equilibrium emittance
  - e_T = 0.6 mm (goal: 0.3 mm)
  - e_L = 0.9 mm (goal: 1.5 mm)
- Transmission (one cooling path)
  - 60 %
- Channel length (one cooling path)
  - 280 m



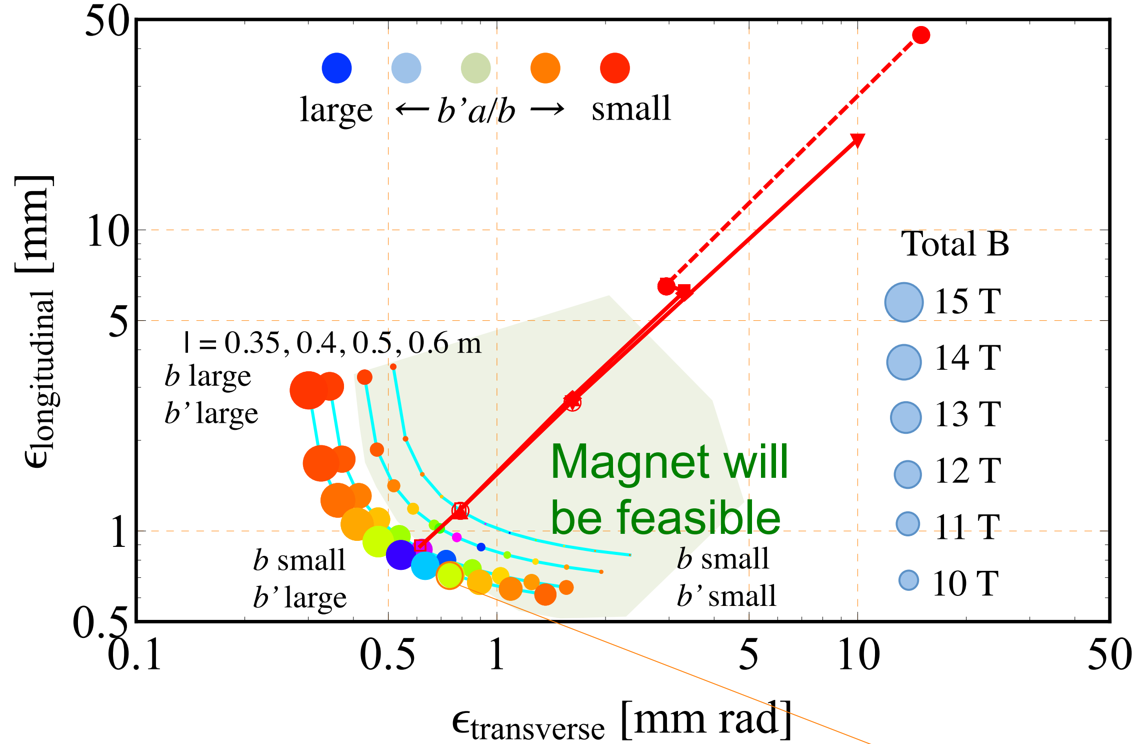
z = 100 m
z = 150 m
z = 280 m (ΔE = ±4 MeV ~ Γ_{Higgs})

Equilibrium emittance was limited by the magnetic field strength

Variable cooling rate and equilibrium emittance by tuning helical lattice

To overcome equilibrium emittance limit…

Feasibility of helical magnet vs achievable equilibrium emittance



- Shorter *l* generates lower emittance
- Shorter *l* requires stronger *B*
- Equal cooling decrements require large *b'a/b*
- Lower longitudinal emittance requires lower *b'a/b*
- Space charge is not important
  - → Longitudinal space charge focuses for positive η
  - → Transverse space charge is neutralized by gas-plasma (see next slide)
- For example, it will be possible to reach e_t = 0.75 mm and e_l = 0.75 mm at a total B = 12 T and *l* = 0.35 m

Longitudinal enhance cooling will be applied for a Higgs factory

Matching and Low Energy Bunch Merging based on HCC

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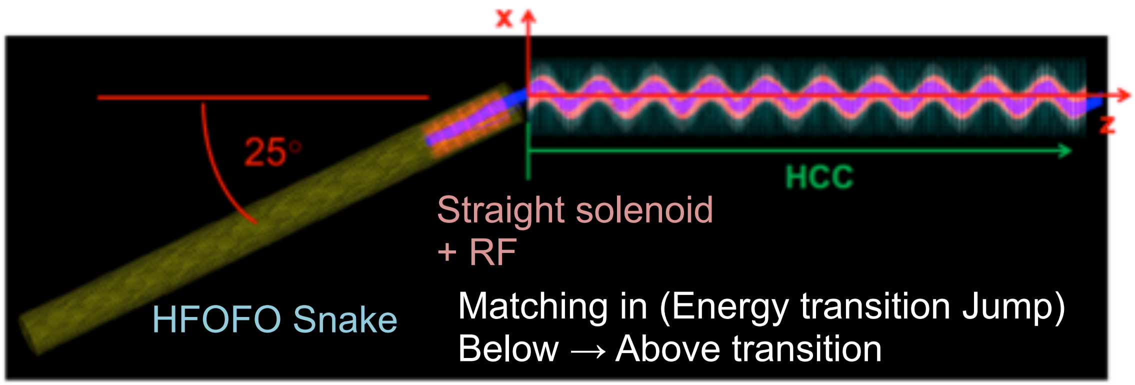
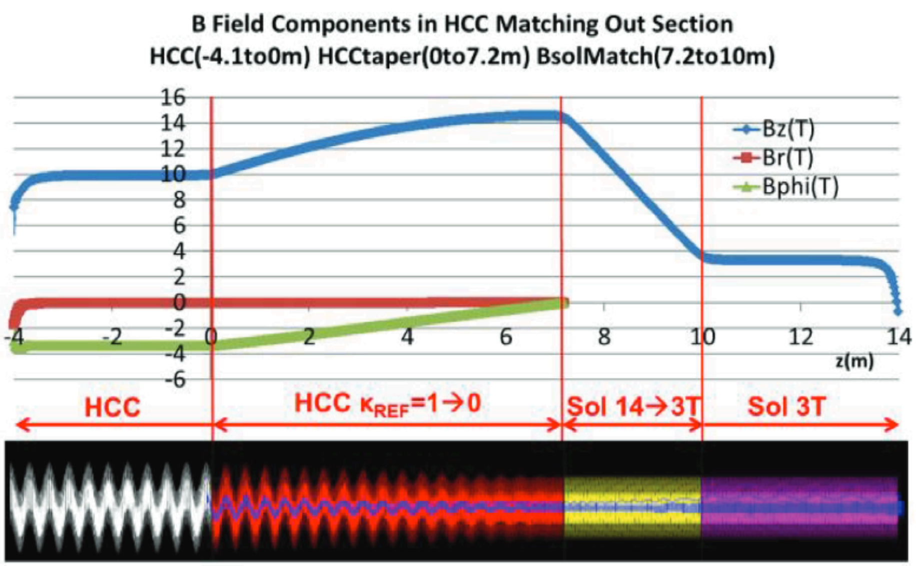
Innovation in Research

NERSC





Matching and Low Energy Bunch Merging based on HCC

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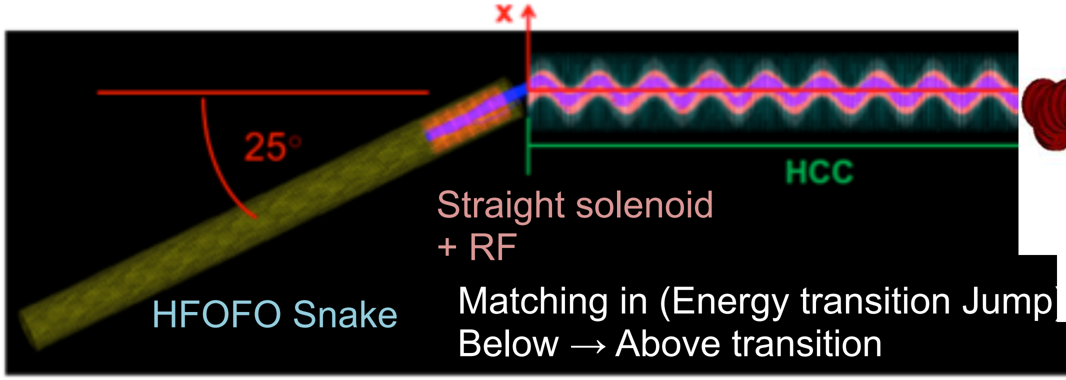
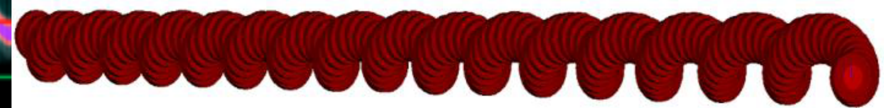
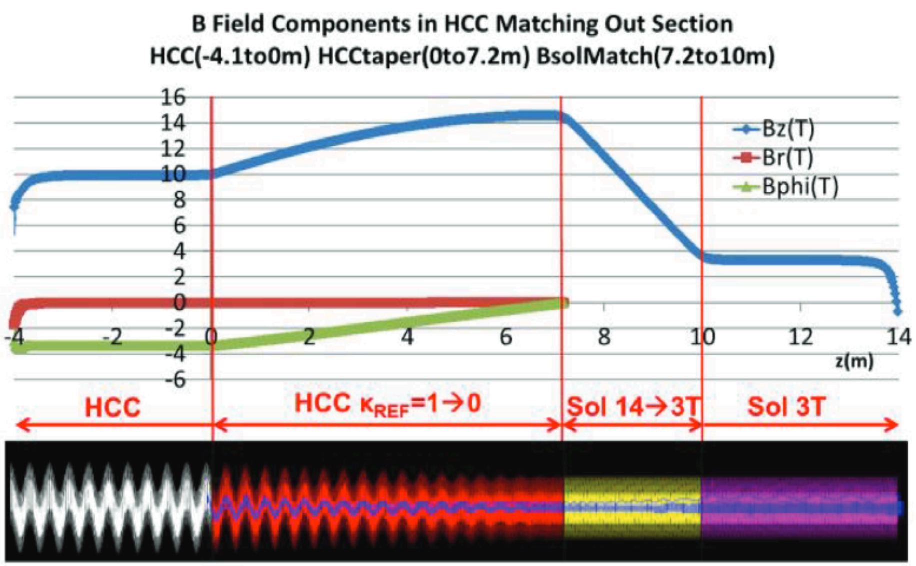


Helical bunch merge channel
= Accelerator + Isochronous channel
Transmission ~90 % in 120 m



Helical accelerator for b = 1 channel



Phase space in a helical bunch merge chann

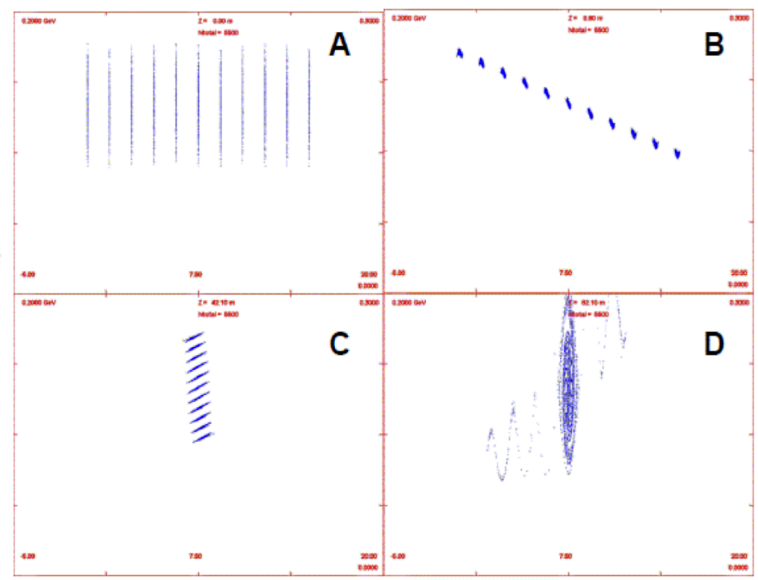
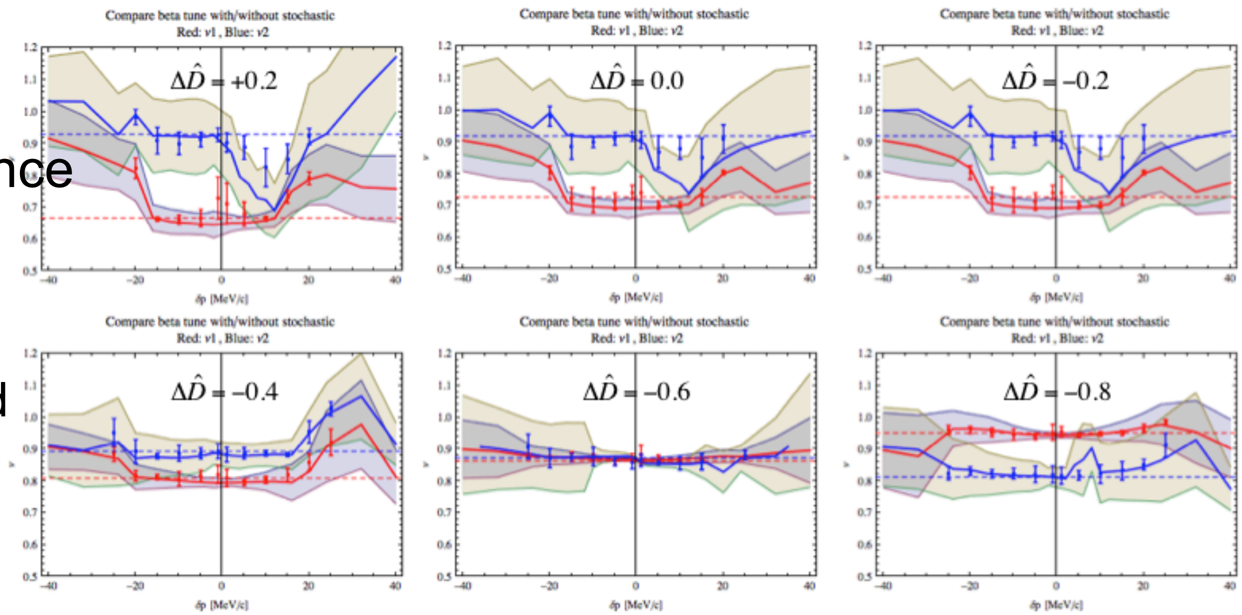


Figure 4: Overview of bunch recombiner with initial quasi-isochronous bunch formation.

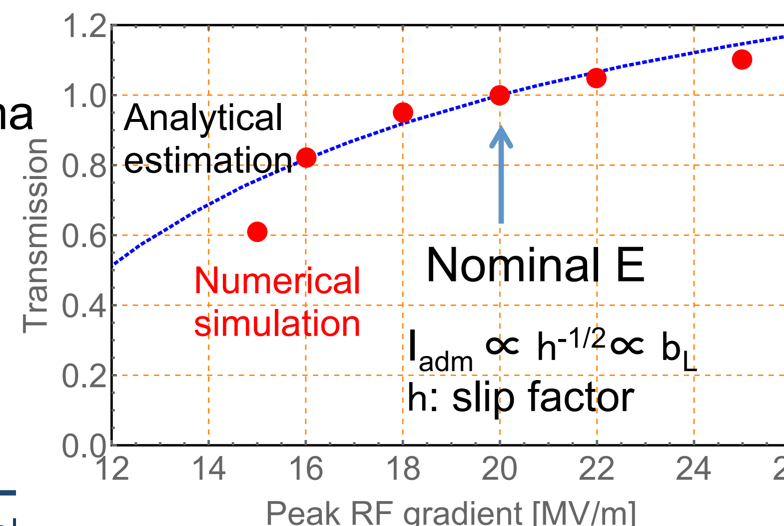
Acceptance in non-linear fields

Chromaticity in HCC

Study transverse acceptance
- Added helical sextupole component to compensate a chromaticity
- Transmission was improved by 10 %

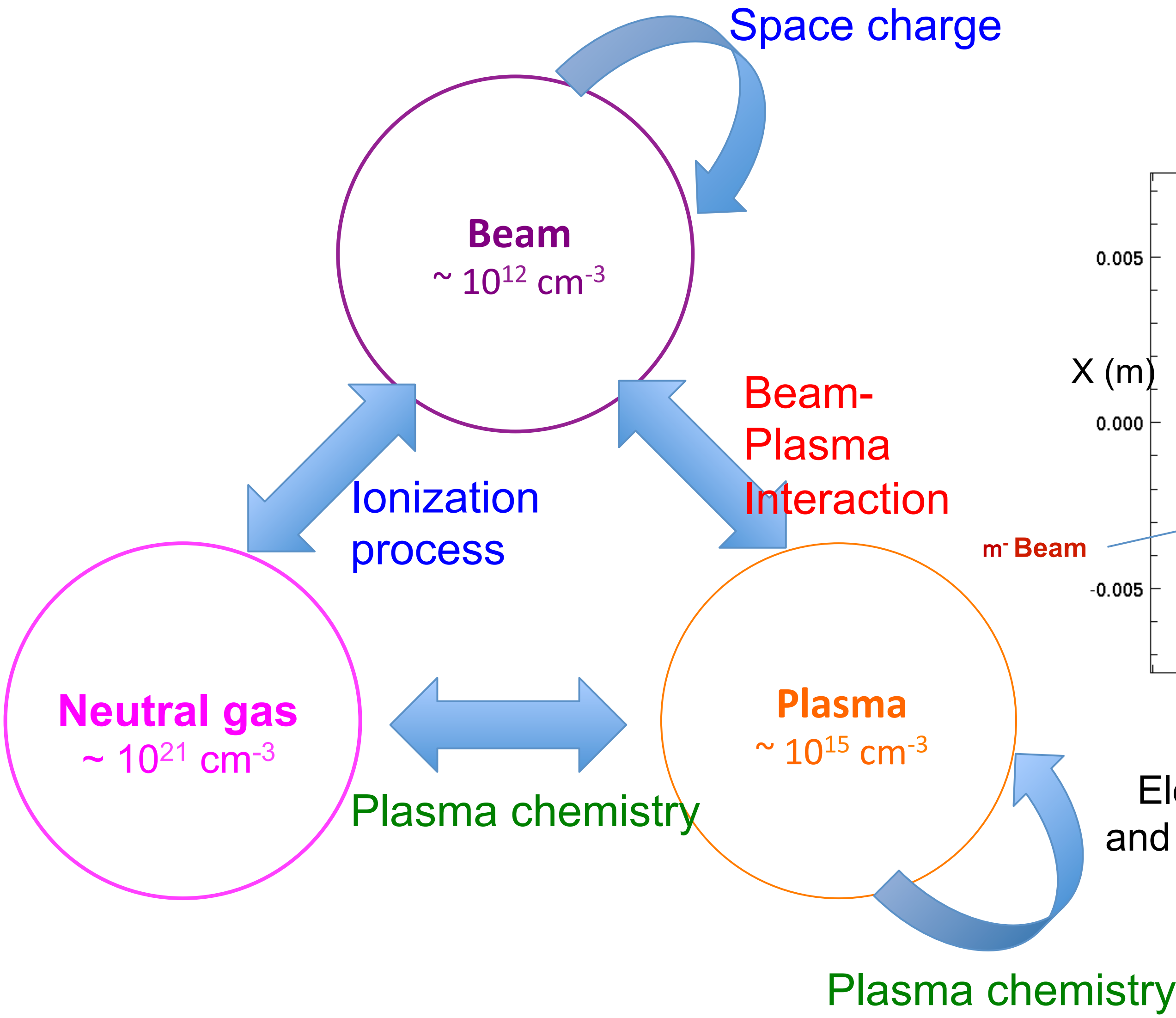


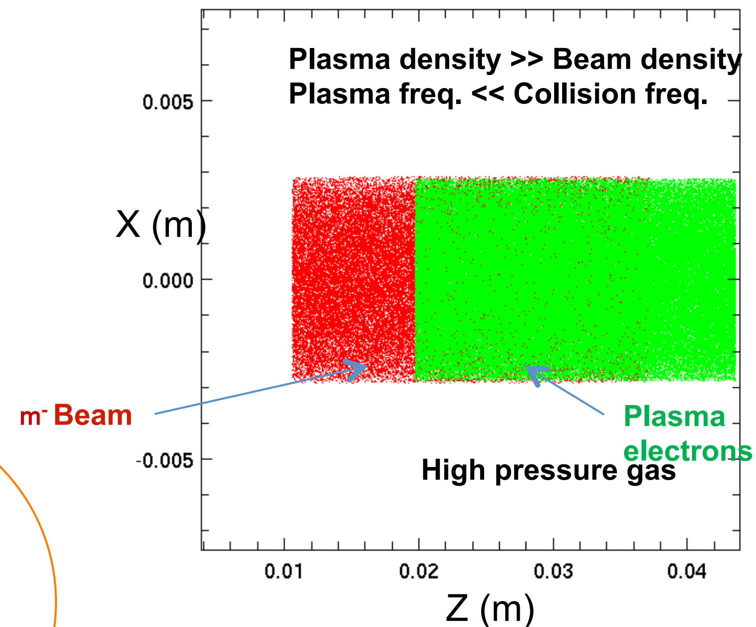
Study longitudinal acceptance
- RF power is consumed by beam-induced plasma
- RF gradient drops by 20 % for the 21st bunch
- Numerical study agrees well with the prediction except for E = 15 MV/m



Space Charge Neutralization and Plasma Lens

Beam-plasma interaction in gas-filled RF cavities

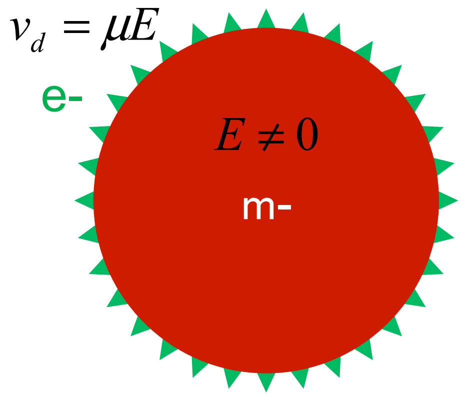




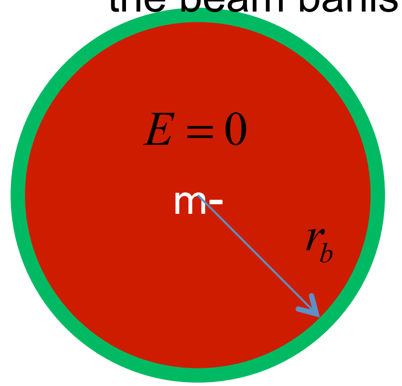
Electrons are quickly thermalized and the spatial distribution is "frozen"

Space Charge Neutralization

1. Space-charge of the muon beam pushes plasma electrons outward



2. Electron column expands slightly, making E-field inside the beam banish



3. This space-charge neutralization can change the beam dynamics

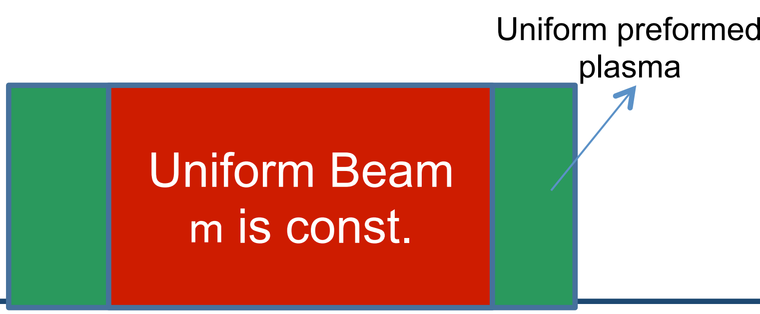
$$\boxed{\frac{d^2 r_b}{dz^2} + \left(\kappa_{sf} + \frac{\alpha K_b}{r_b^2}\right) r_b = \frac{\varepsilon_{KV}^2}{r_b^3}}$$

$$\alpha = \begin{cases} -1 & \text{for no neutralization (defocusing)} \\ \gamma^2 \beta^2 & \text{for full neutralization (focusing)} \end{cases}$$

$$K_b = \frac{2 r_e}{\gamma^3 \beta^2} \frac{N}{\sqrt{2\pi}\sigma_z}$$

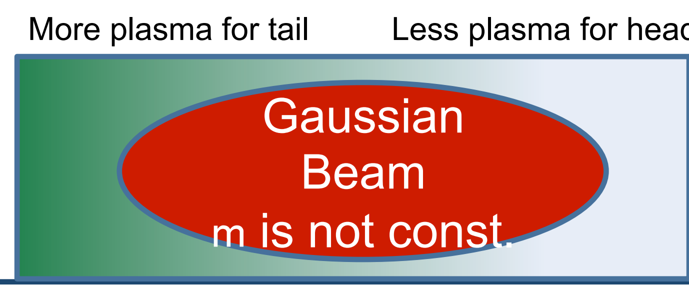
4. Analytical estimation of space-charge neutralization time for a simple configuration

$$\tau = \frac{\varepsilon_0}{(n_e / n_b)\mu |e|} < \text{typical bunch length } (\sim 100 \text{ ps})$$

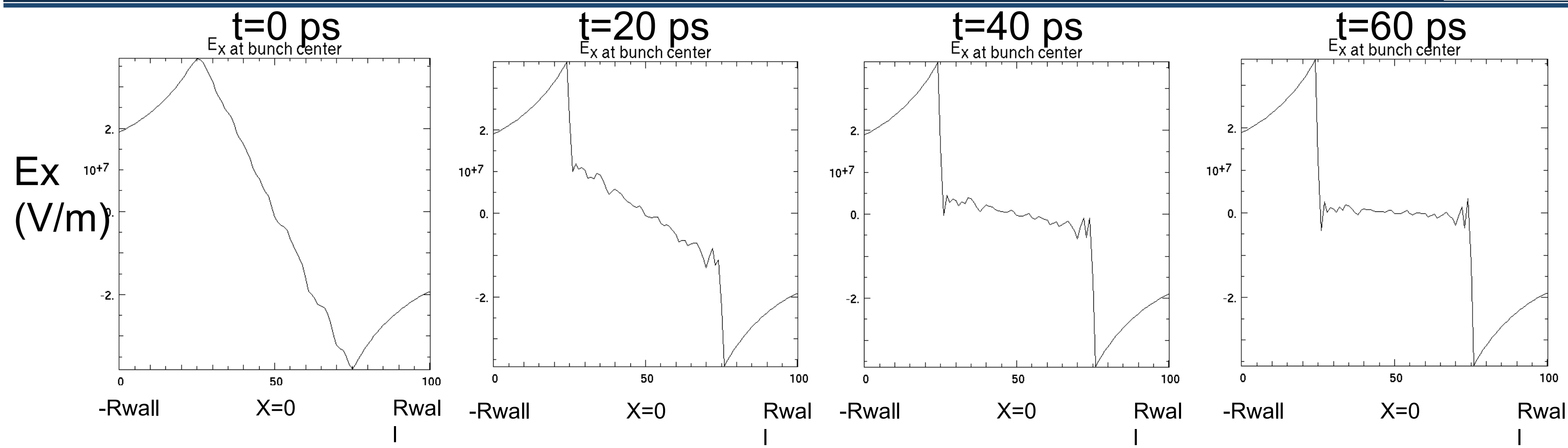


5. Good simulation is required to predict the beam dynamics in the real configuration

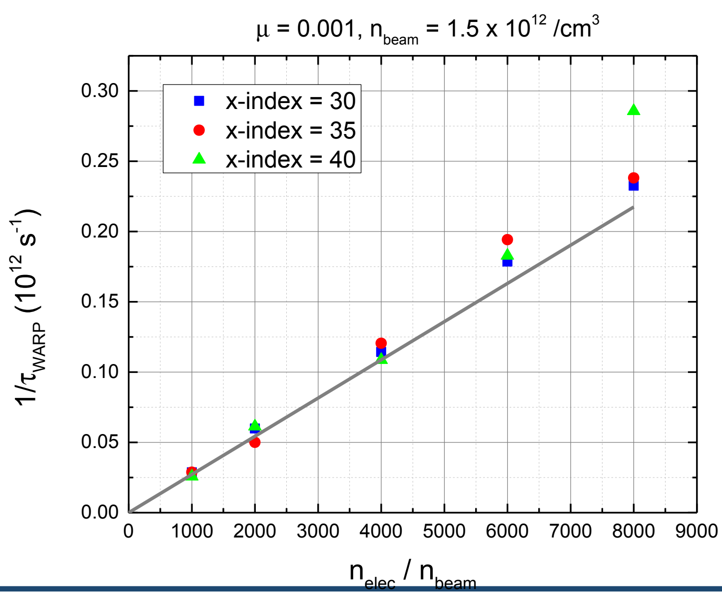
- Fermilab: WARP PIC code
- BNL: SPACE code with molecular processes

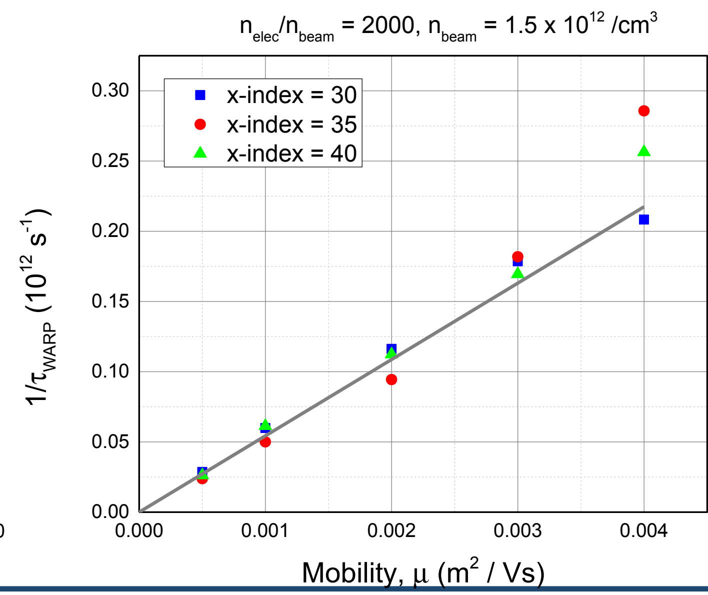


Time constant of charge neutralization

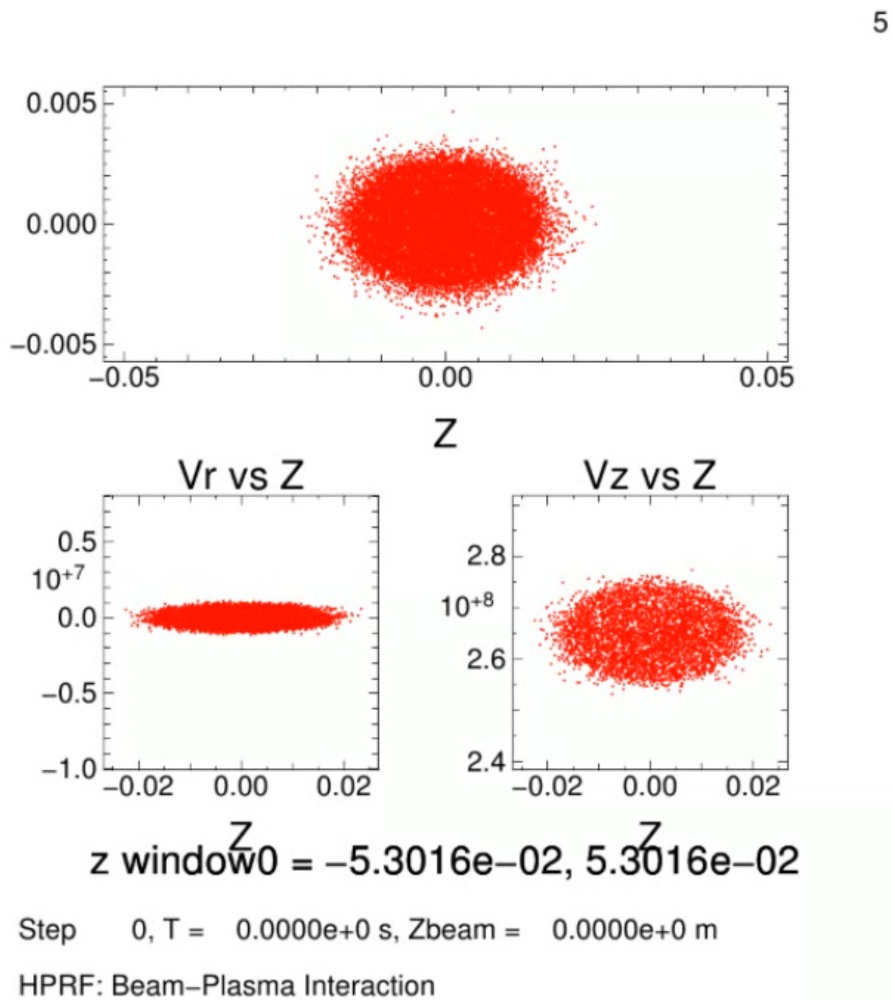


Good agreement between theory and simulation





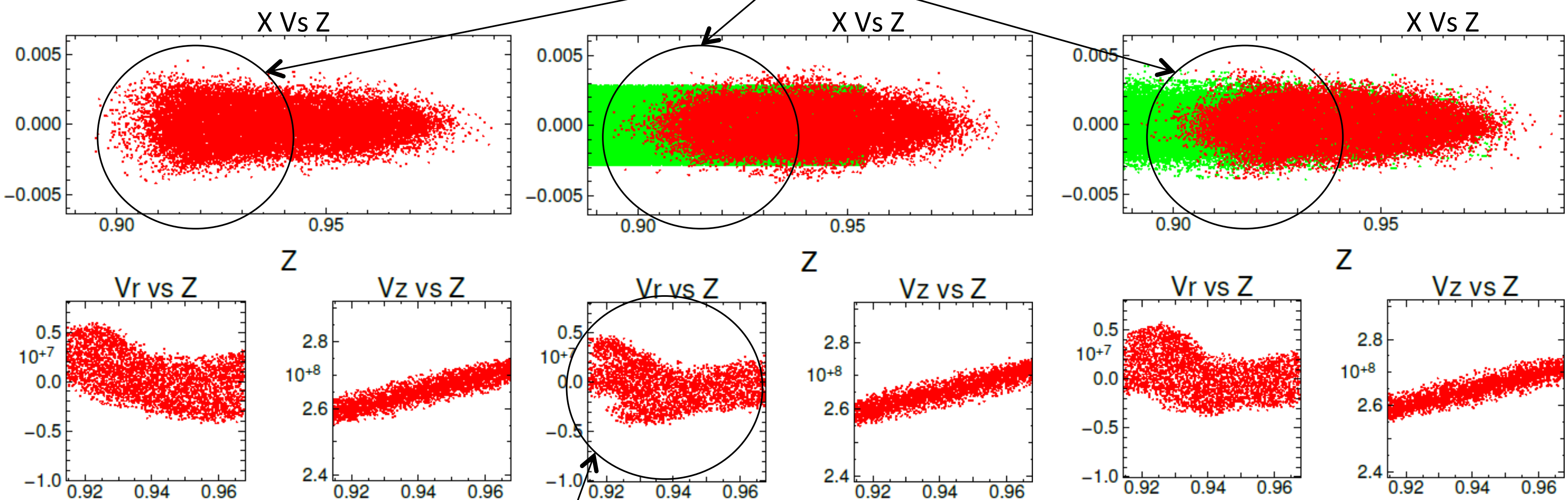
Beam-Plasma interaction



- No RF for longitudinal focusing
- No dispersion magnet
- A straight 5-T solenoid

Beam-plasma interaction in gas-filled RF cavities

Less spread in bunch tail due to charge neutralization



No plasma

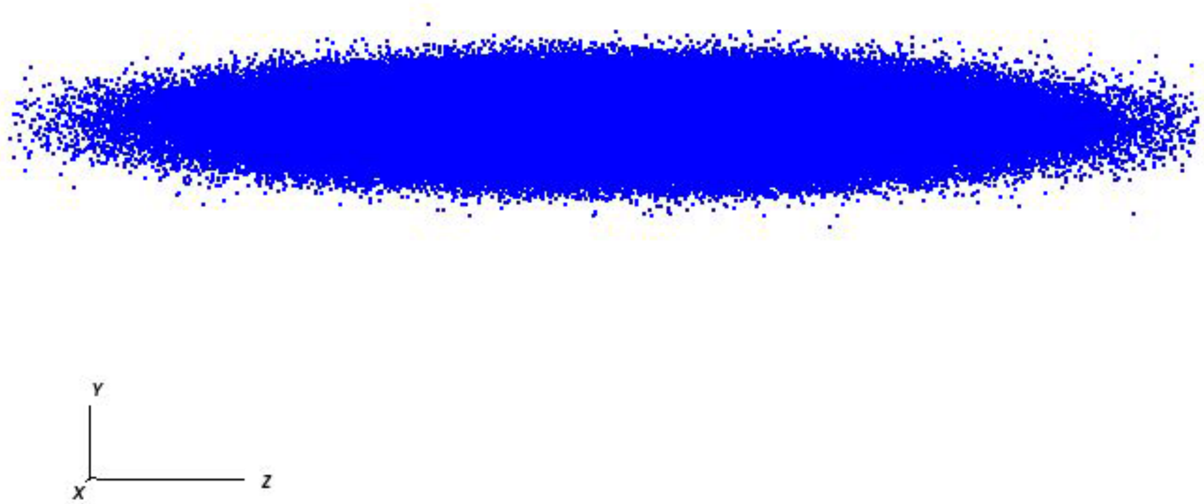
Preformed plasma

WARP added

Edge effect from uniform cylinder

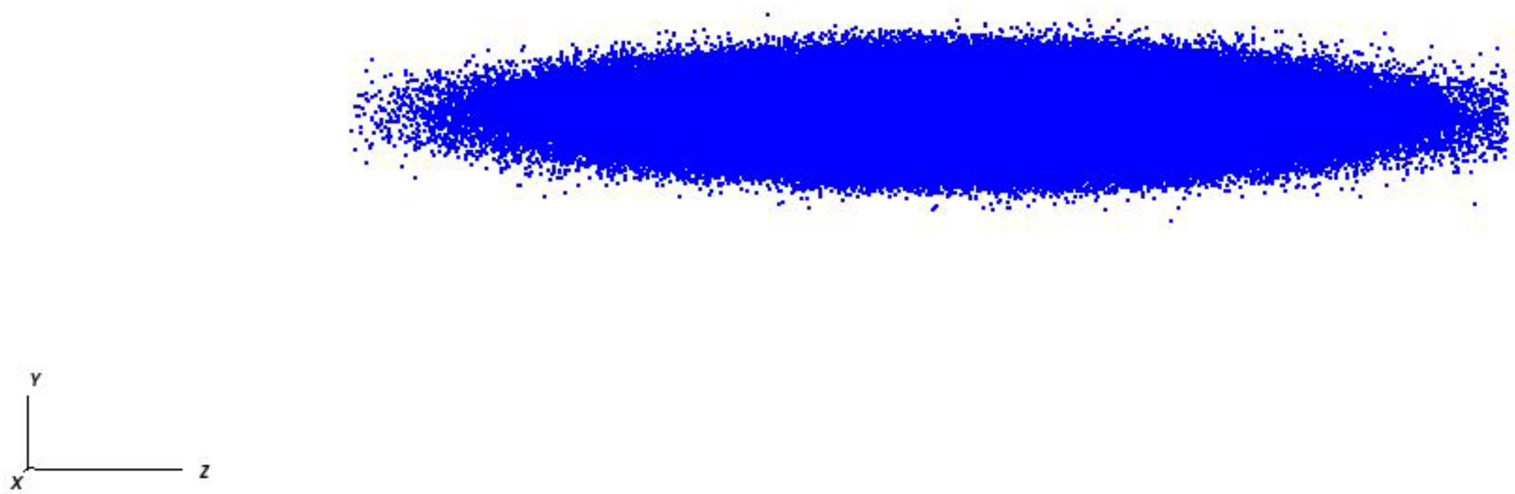
Beam-plasma interaction study in non-WARP simulation

Vacuum



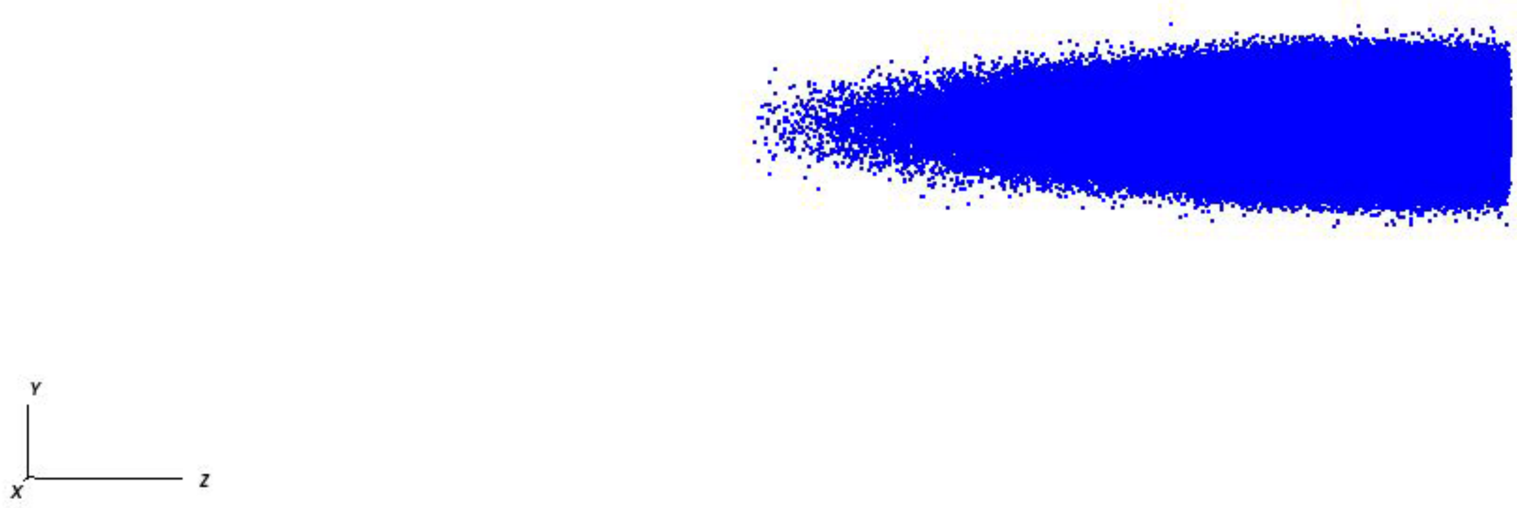
Beam-plasma interaction study in non-WARP simulation

Vacuum



Beam-plasma interaction study in non-WARP simulation

Vacuum

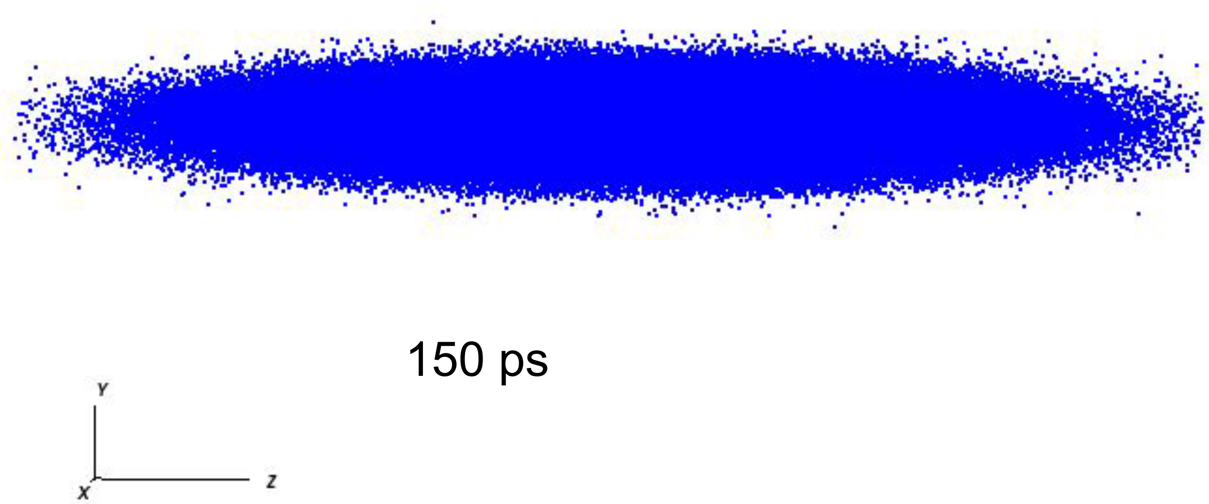


Beam-plasma interaction study in non-WARP simulation

Vacuum

Beam-plasma interaction study in non-WARP simulation

In a dense H2 gas



Beam-plasma interaction study in non-WARP simulation

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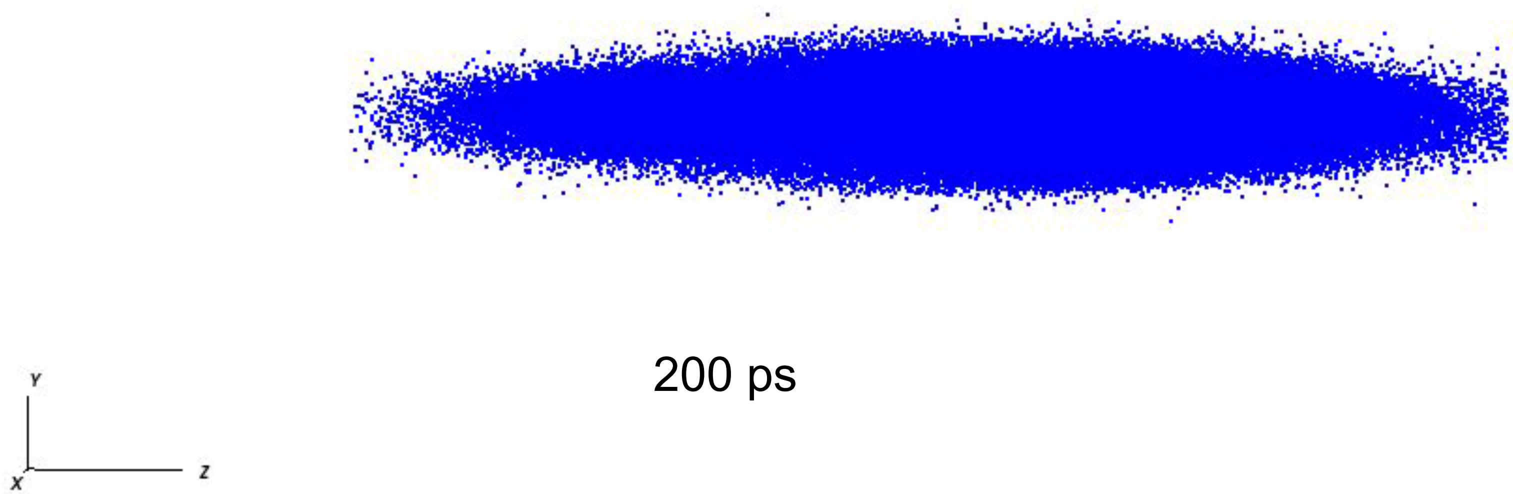
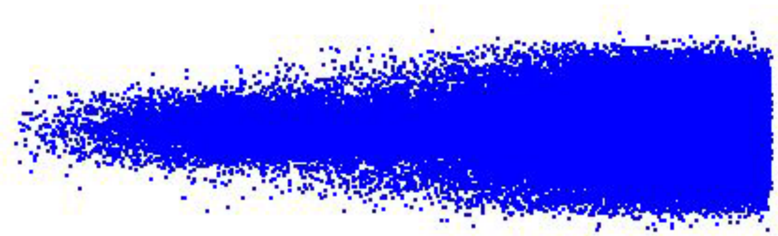


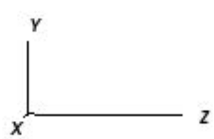
200 ps

Beam-plasma interaction study in non-WARP simulation

In a dense H2 gas

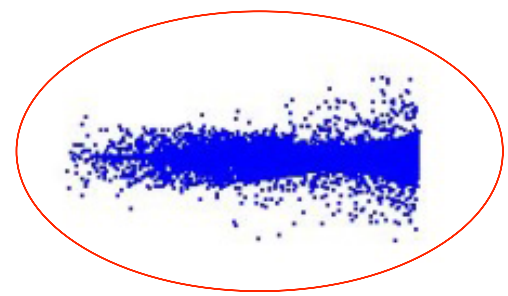


250 ps



Beam-plasma interaction study in non-WARP simulation

In a dense H2 gas



300 ps

Collaborators

6D Cooling Design & Simulation

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Helical magnet

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Summary of HCC Design Effort

- Verified helical cooling theory
  - Understood linear dynamics
  - Studied non-linear dynamics (in progress)
  - Demonstrated ability to tune the cooling lattice
    - Enhanced longitudinal cooling to overcome the field limit
- High pressure RF cavities
  - Oxygen doped high pressure RF cavities tested
  - Plasma was modeled and compared to measurement
  - High pressure RF HCC should work
- Beam-plasma interaction
  - Plasma lens effect may increase beam focusing
  - Requires re-evaluating cooling models/simulations (in progress)