INTERACTION OF MUON BEAM WITH PLASMA DEVELOPED DURING IONIZATION COOLING

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IPAC12

Particle Accelerators/Colliders

Frontiers in particle accelerators/colliders:

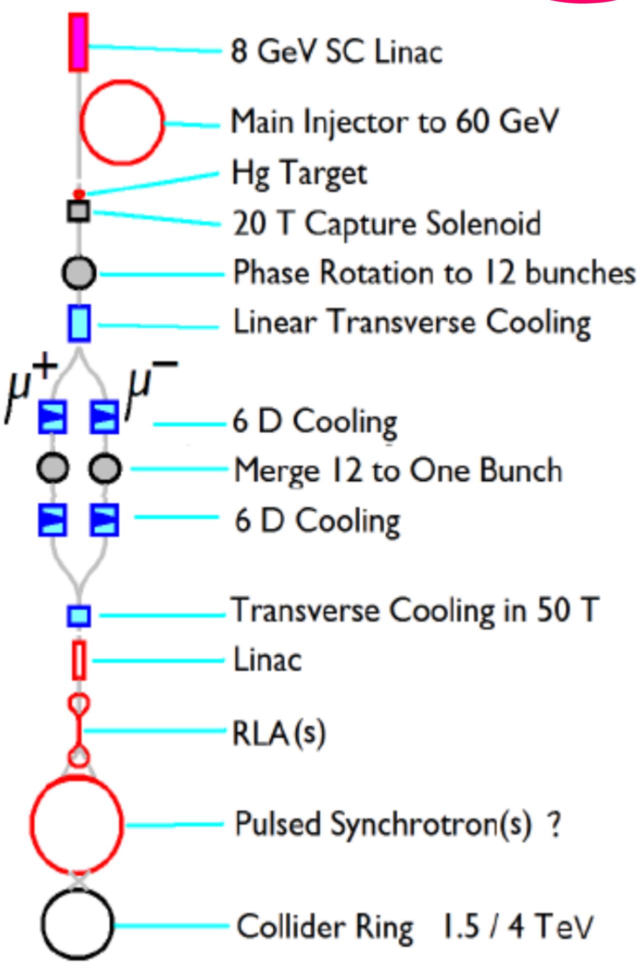
- **ILC:** e^+e^- machine (~ 31 km, E ~ 1 TeV, L ~ 2 x 10^{34} cm^{-2} s^{-1})
- **CLIC:** e^+e^- machine (~ 51 km, E ~ 3 TeV, L ~ 2 x 10^{34} cm^{-2} s^{-1})
- **Muon Collider:** $\mu^+\mu^-$ machine (~ 2 km diameter, E ~ 3 TeV,
  L ~ 4 x 10^{34} cm^{-2} s^{-1})
- **Plasma Wakefield accelerator** (PWFA) --- SLAC, UCLA, ANL
(Beam produced plasma and Laser produced plasma)
- **Dielectric Wakefield accelerator** (DWA) --- SLAC, ANL
- **THz Radiation Technology** --- SLAC, ANL

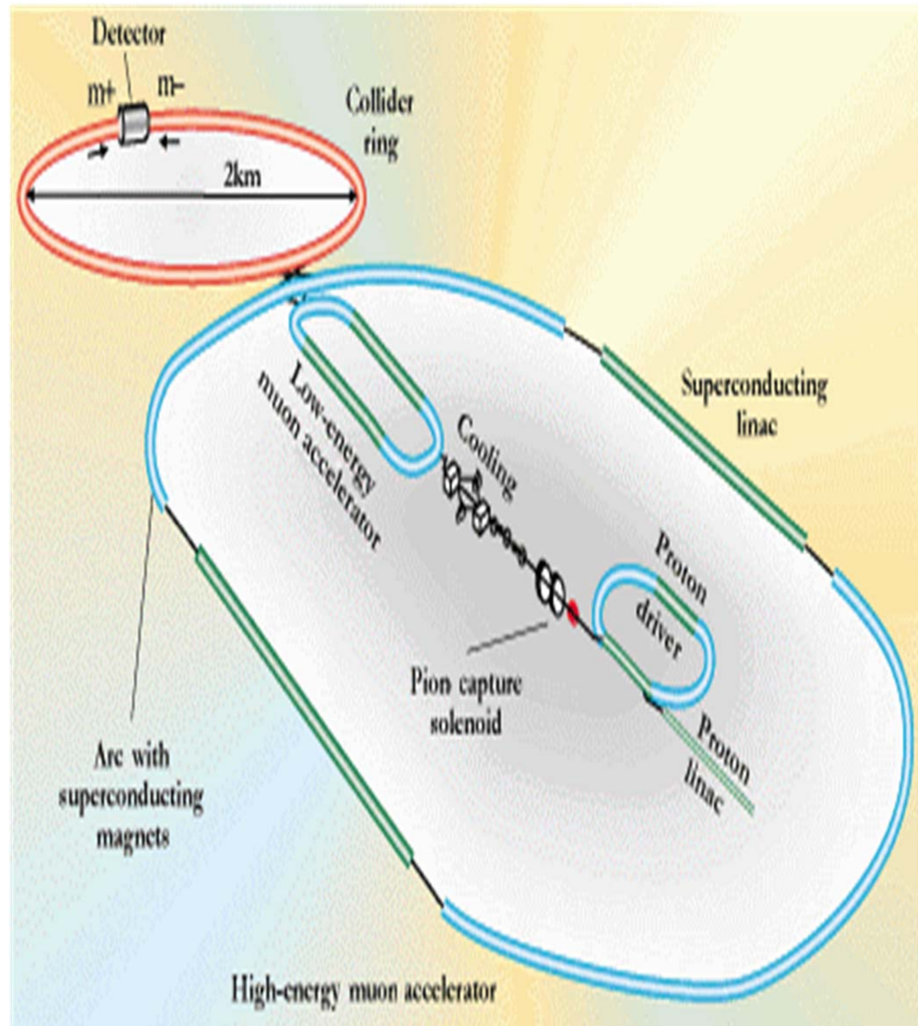
Muon Collider has unique feature !

$m_\mu \sim 207 m_e$ => low synchrotron radiation, small energy spread at IP

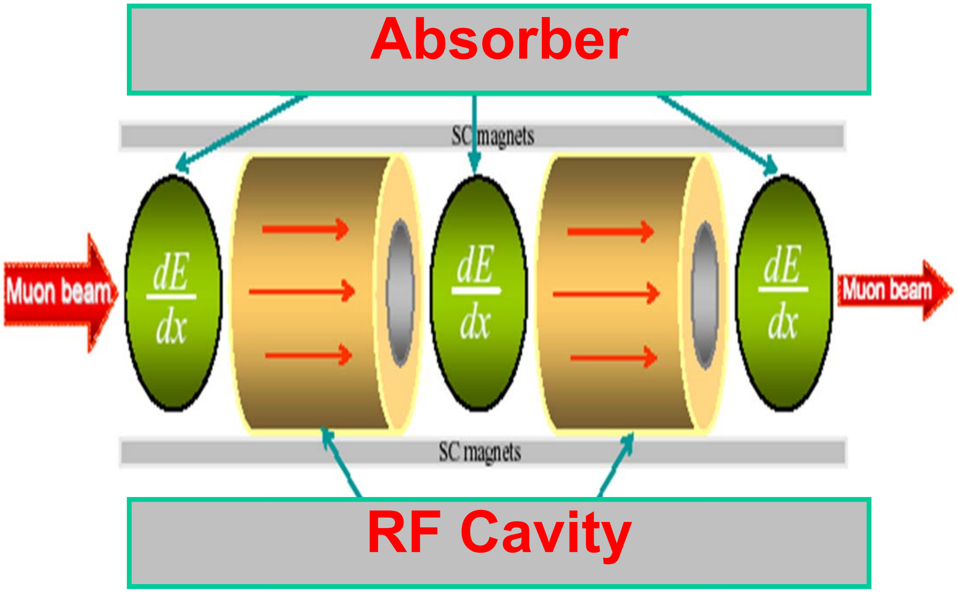
$\mu^+ - \mu^-$ Collider

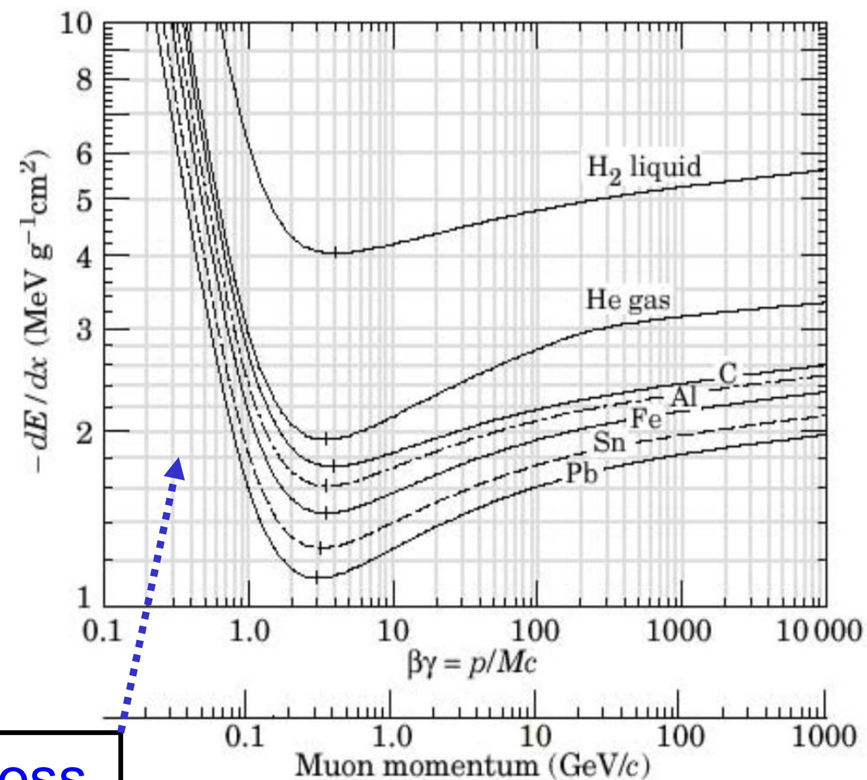
$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_\mu}{\sigma_x \sigma_y}$$





Ionization Cooling Principle





Ionization Energy Loss

Balance between cooling and heating gives normalized emittance:

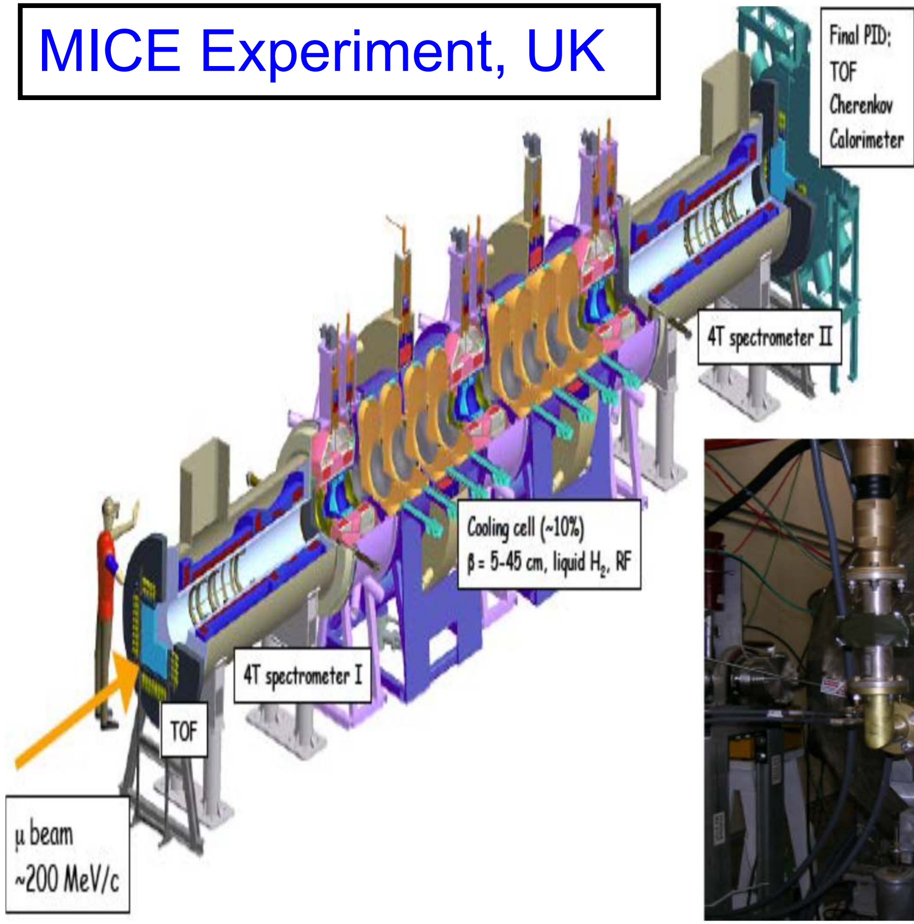
$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

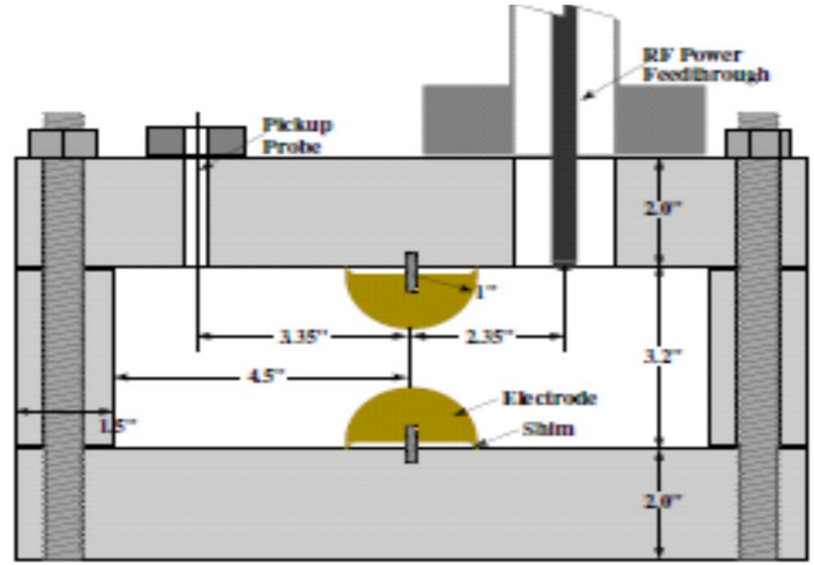
Cooling (dE/ds) **Heating** (Coulomb Interaction)

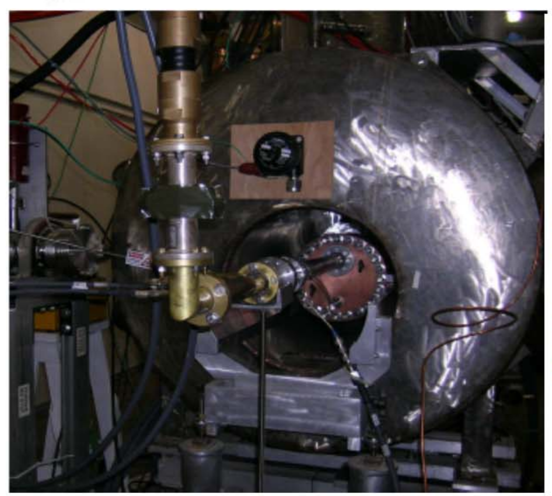
$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta\, m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

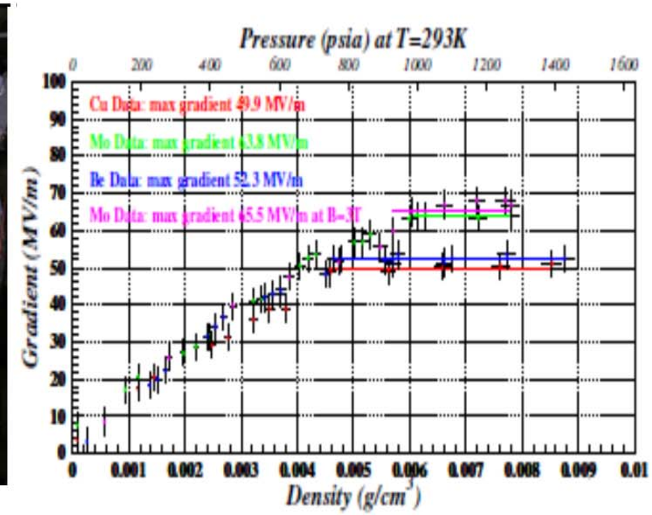
Muon Ionization Cooling – A Quick Look

MICE Experiment, UK









Efforts at Fermilab

Motivation

Important questions during the process of ionization cooling:

- How does the electron concentration of an absorbing material (e.g. 10^{29} m^{-3} for Li) interact with the incoming μ-beam ?
- How does the high density of ionization developed in the process of cooling affects the incoming beam ?

A realistic model should take into account the complete process, the ionization of medium due to incoming beam and its interaction. However, modeling the ionization of a medium at very high pressure (~ 10 – 100 atm) is complex (fluid + PIC code).

To study the collective effects in beam interaction with dense ionized medium, it is justified to assume that plasma has been formed by several bunches passed through the absorber. This model can address the above questions.

Motivation -- Cont'd

Important effects need to study:

- The excitation of plasma wave and wakefields for μ^- and μ^+ beam propagating inside plasma.
- Effects of various densities of plasma on incoming beam.
- Effects of external magnetic field.

XOOPIC

2-D self-consistent EM PIC code (FDTD), developed by Plasma Theory and Simulation group, UC Berkeley.

- **2-dimensional spatial grid**
  - Cartesian (x,y) or cylindrically symmetric (r,z)
  - Non-uniform grids in both dimensions
- **Plasma and beam emission / interaction**
  - Boundary interactions (absorption, reflection)
  - Secondary emission from boundaries
  - Monte Carlo scattering between species; ionization
  - Time-dependent current injection
  - Tunneling ionization

MKS Units

Distance -- meter

Time -- second

E-field -- V/m

H-field – A/m

Energy -- Joule

- **Space charge physics**
- **Full EM field solver**
  - Electromagnetic Problems
  - Wakefields -- PWFA and LWFA
- **Supports MPI implementation for distributed computing**
- **Application:** Microwave devices, Plasma sources, Beam optics, Laser/beam plasma interaction, Accelerators.

Parameters of Study

Beam:

Shape: Gaussian

Particle: muons (μ^-, μ^+)

N_b = number of beam particles = 1×10^{12} per bunch

r_b = bunch radius = 3 mm

L_b = bunch Length = 40 mm

P = reference momentum = 200 MeV/c

m_μ = rest mass of muon = 105.7 MeV/c^2

β = 0.88

Υ = 2.1

τ_p = pulse length = 151 ps

E_{tot} = 226 MeV

Q_b = total charge = 160 nC

n_b = peak beam density ~ 10^{18} m^{-3}

ω_{pb} = plasma frequency of beam ~ 10^9 rad/s ($\sqrt{(ne^2/\varepsilon_0 m)}$)

Plasma: Li

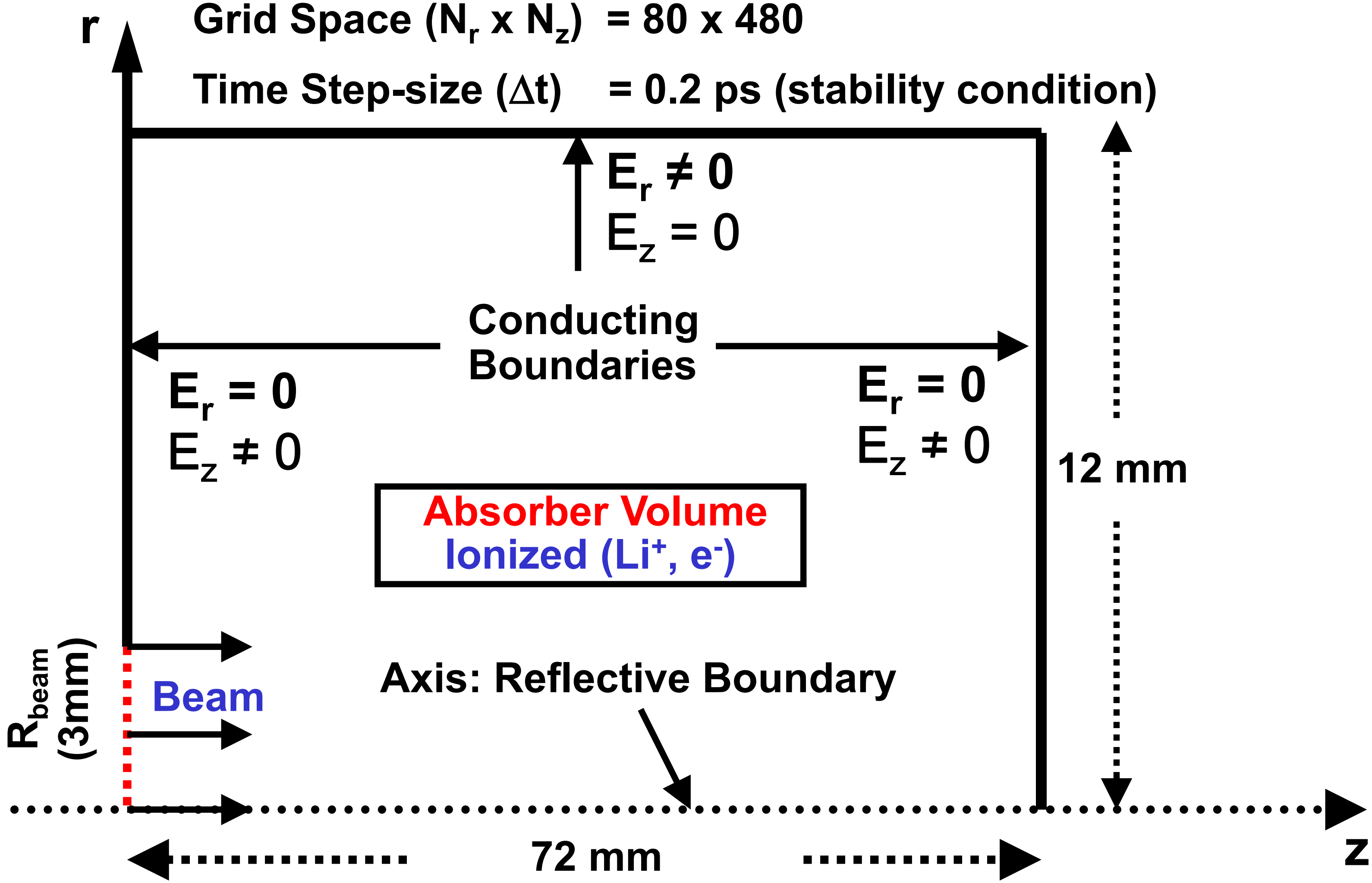
Density varies in the simulations (10^{16} – 10^{22} m^{-3})

Simulation Setup

2D Cylindrical Symmetry

Grid Space (N_r x N_z) = 80 x 480

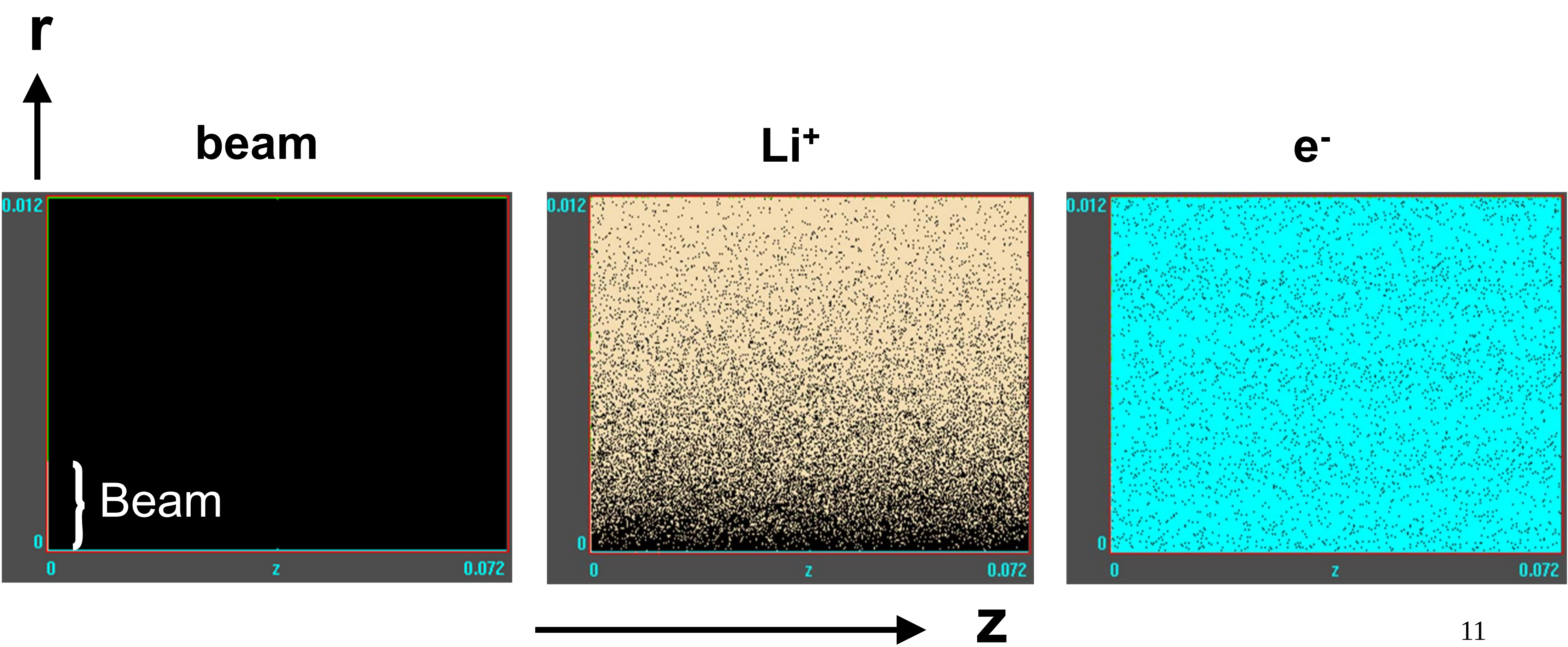
Time Step-size (Δt) = 0.2 ps (stability condition)



XOOPIC Simulation Setup at Time t = 0

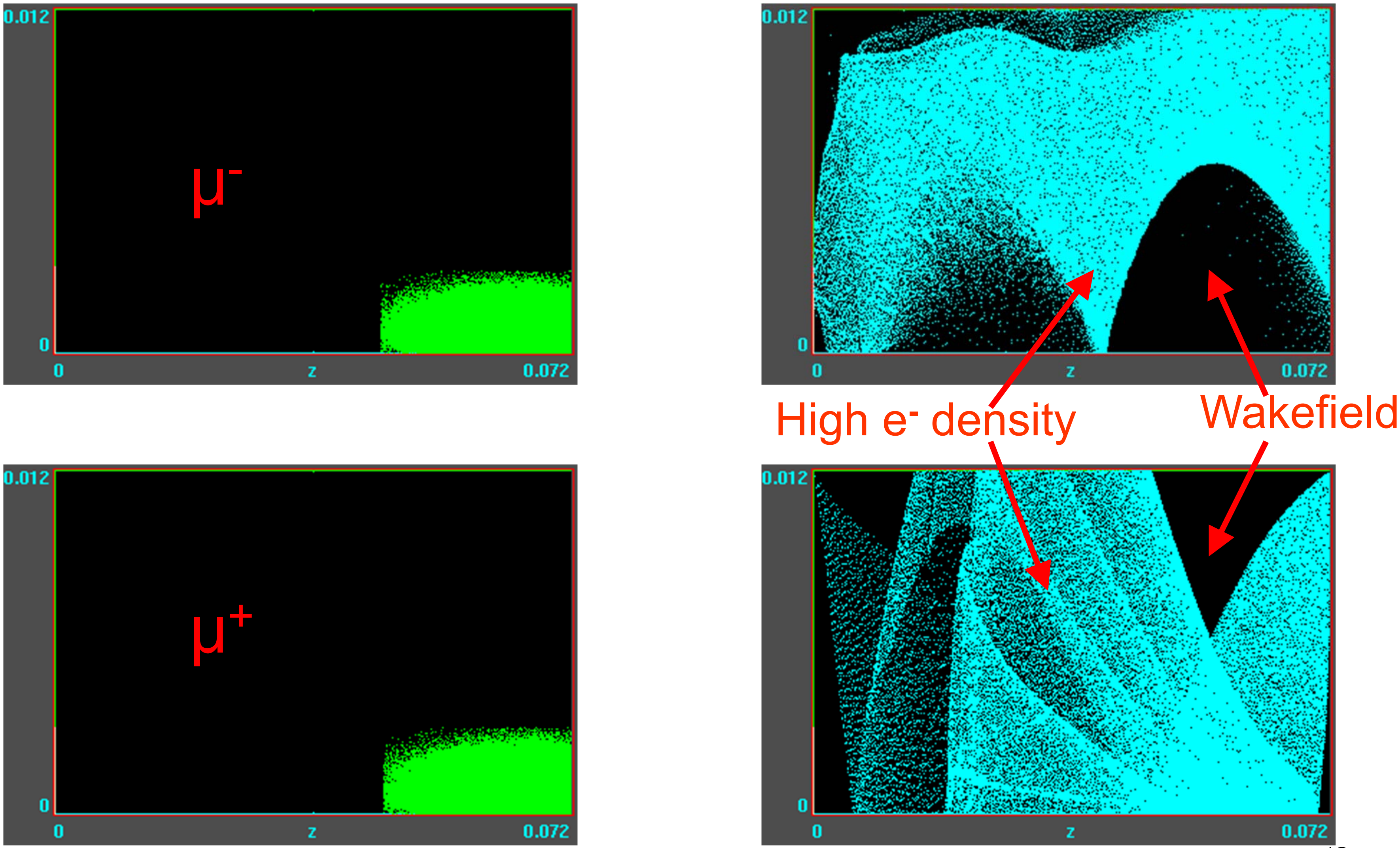
- Muon beam enters the cold lithium plasma.
- Plasma ions are modeled as a stationary uniform background.
- Plasma electrons are modeled with uniformly distributed particles with zero initial velocity.

$$n_b \sim 10^{18}\ m^{-3}\ ,\ \ n_{pe} \sim 10^{18}\ m^{-3}$$



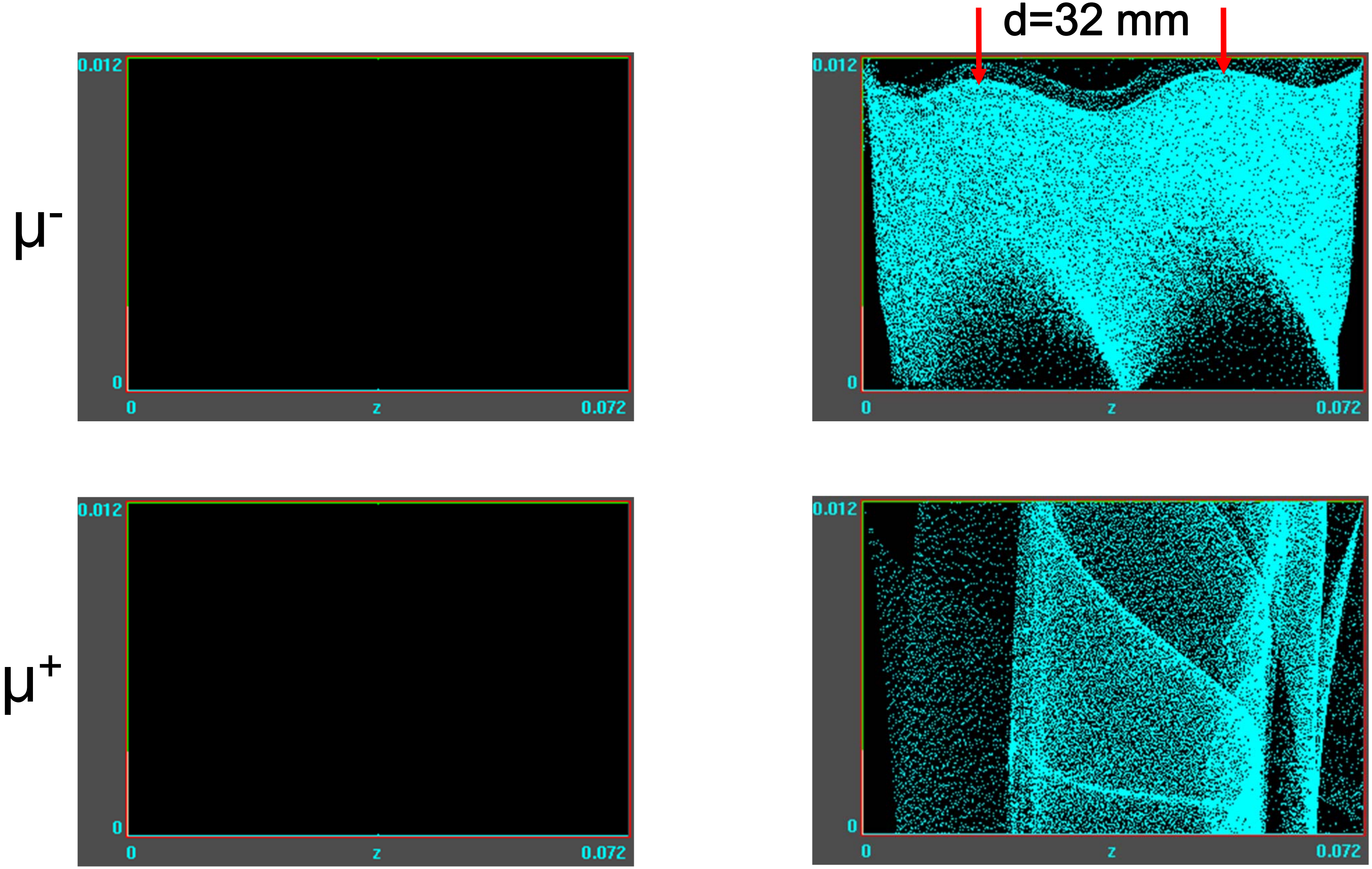
Plasma Wakefield Excitation by μ^- & μ^+ Beam

Time snapshot, pulse head @ 80 mm



Muon Beam **Electron Plasma**

Evolution of μ^- - μ^+ beam in e^- Plasma

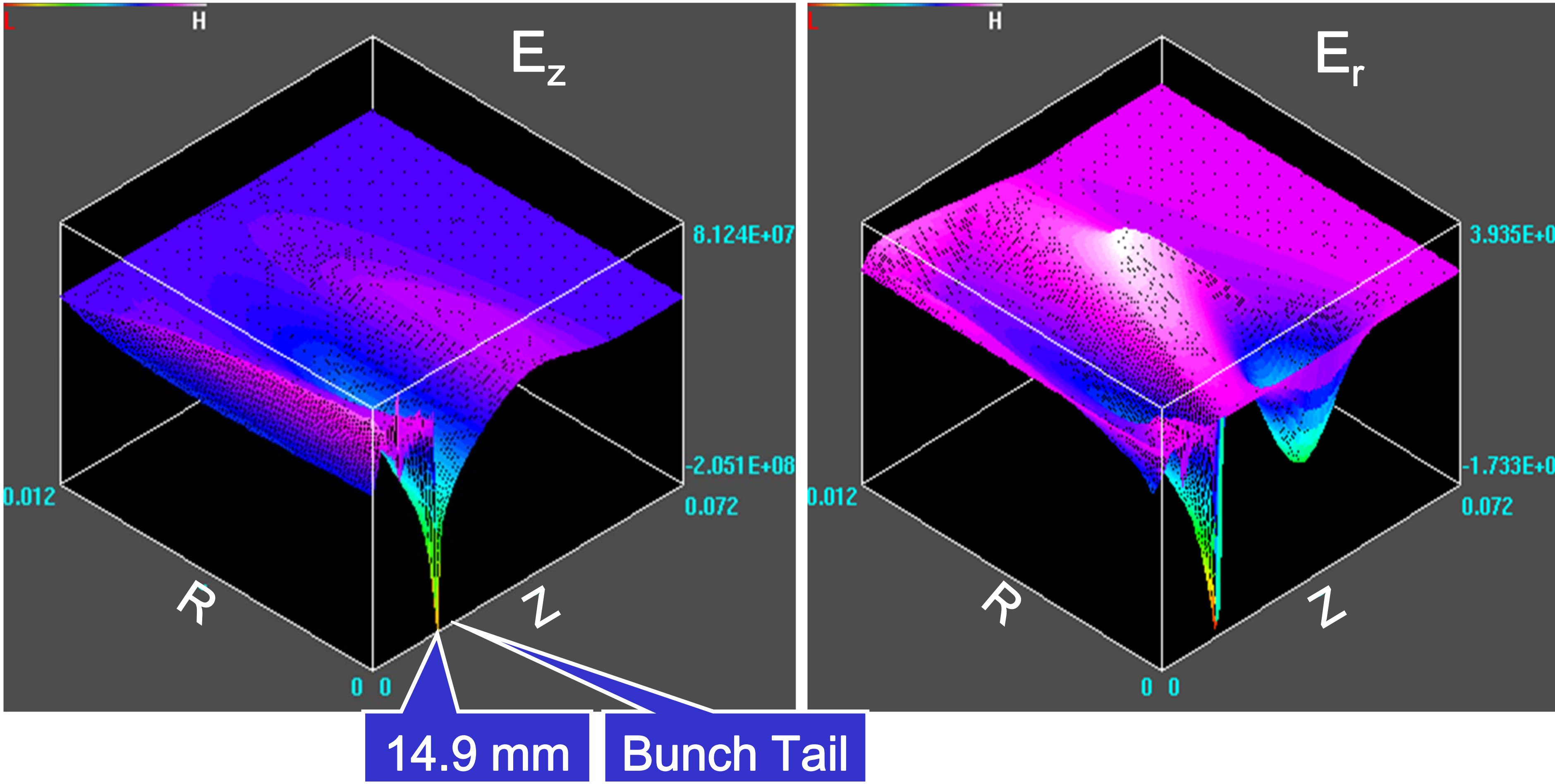


wavelength of plasma wave = 32 mm for $n_e = 10^{18}$ m^{-3}

Plasma wave is excited, however, not dangerous

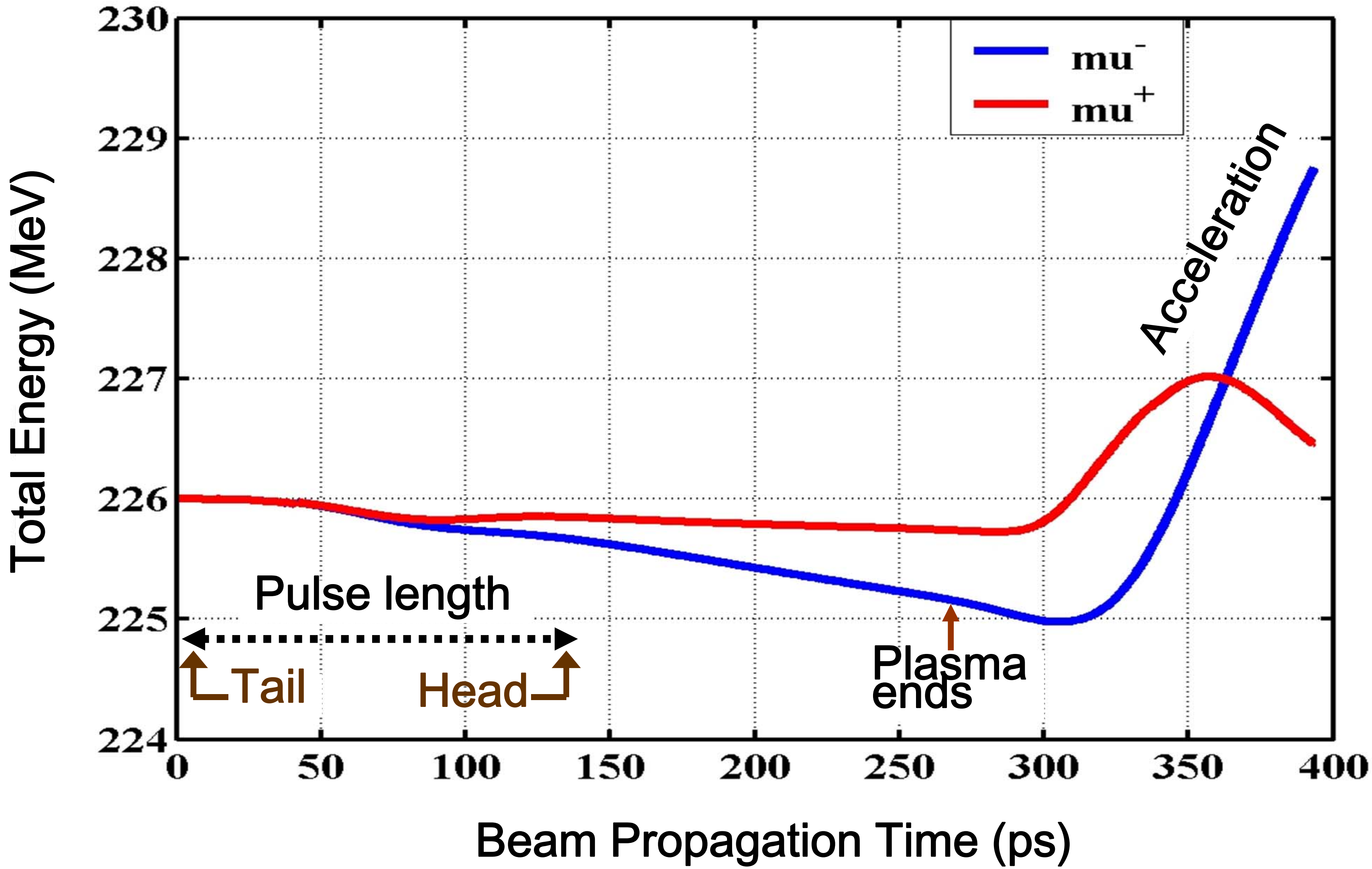
3-D Wake E-field Structures for μ⁻

Snapshot @ t = 210 ps (~ 55.4 mm)   Beam-length = 40 mm



Bunch head generates strong negative wakefield -- acceleration & compression

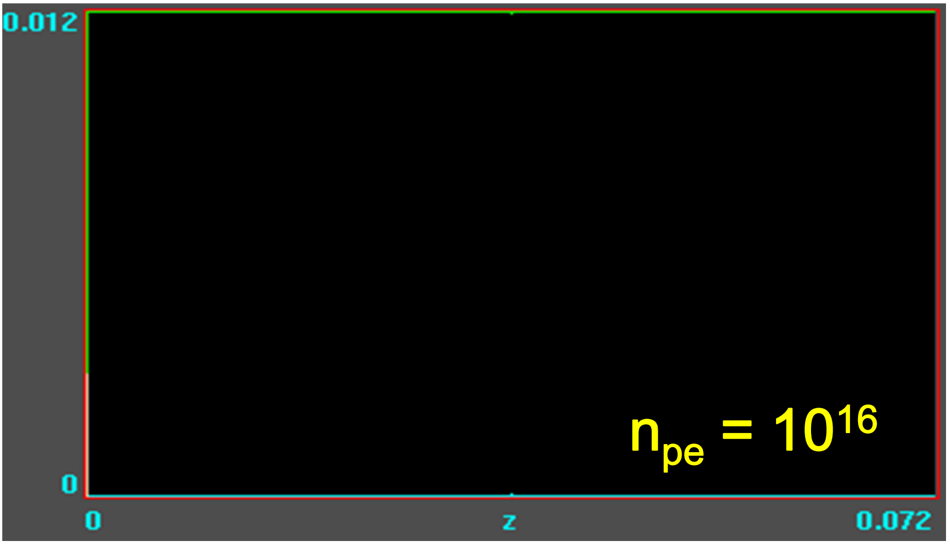
Total Energy of μ⁻ and μ⁺ Beam



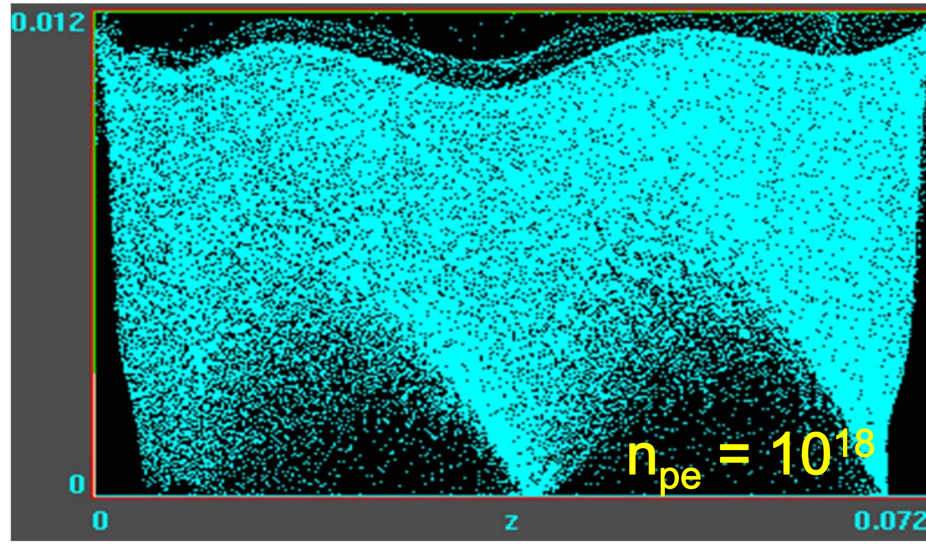
Collective Effects
for
μ^- Beam in Plasma

Effects of Plasma Density for $n_b = 10^{18}$

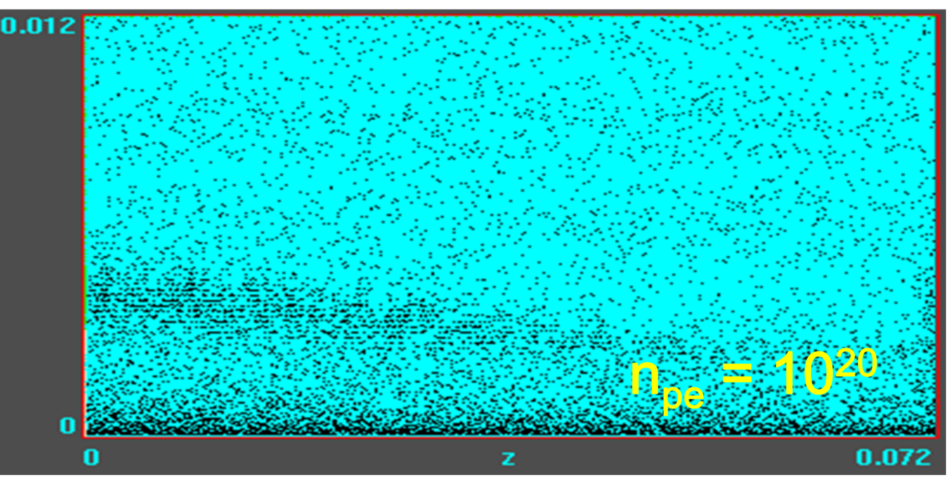
Plasma Wiped out



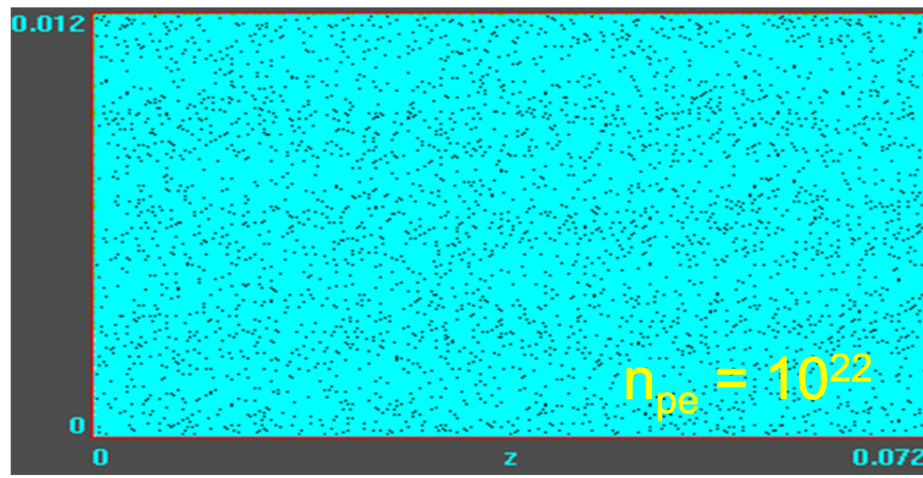
Strong Wakefield



Weak Wakefield



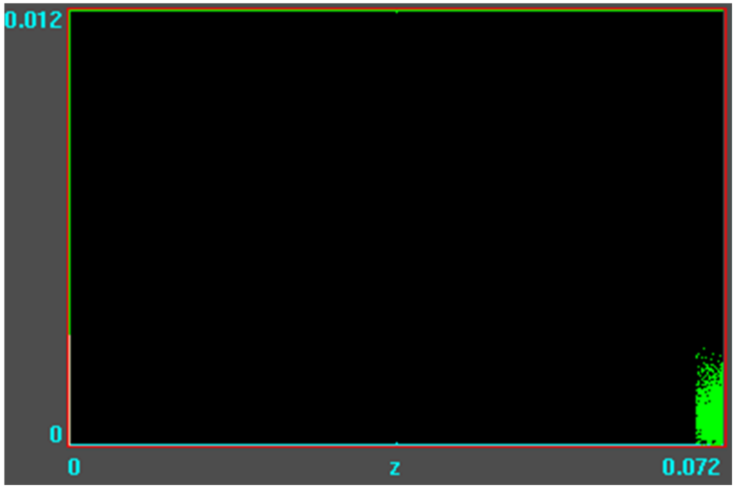
Unaffected



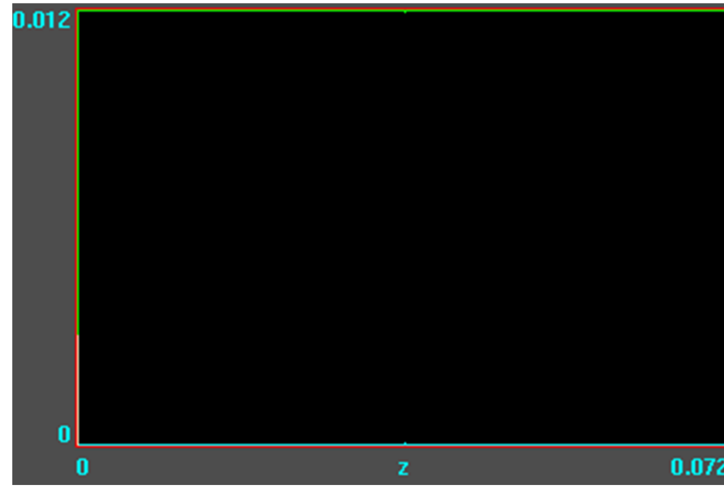
Evolution of μ^- beam in Under and Over Dense Plasma

Beam Window

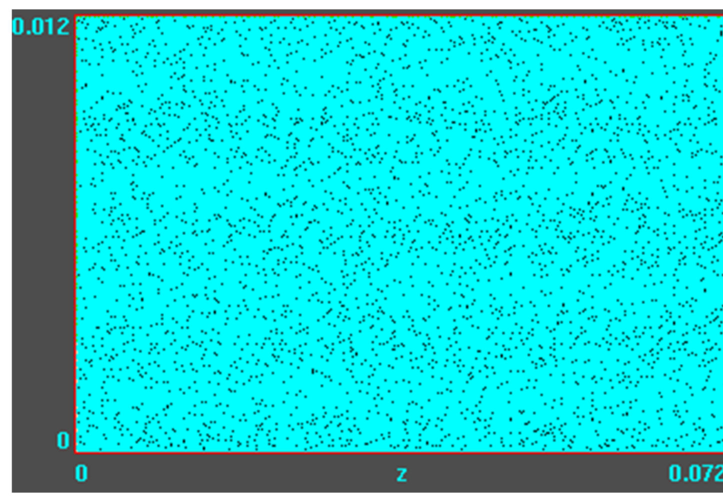
Plasma Window



$n_b=10^{18}$
$n_{pe}=10^{16}$

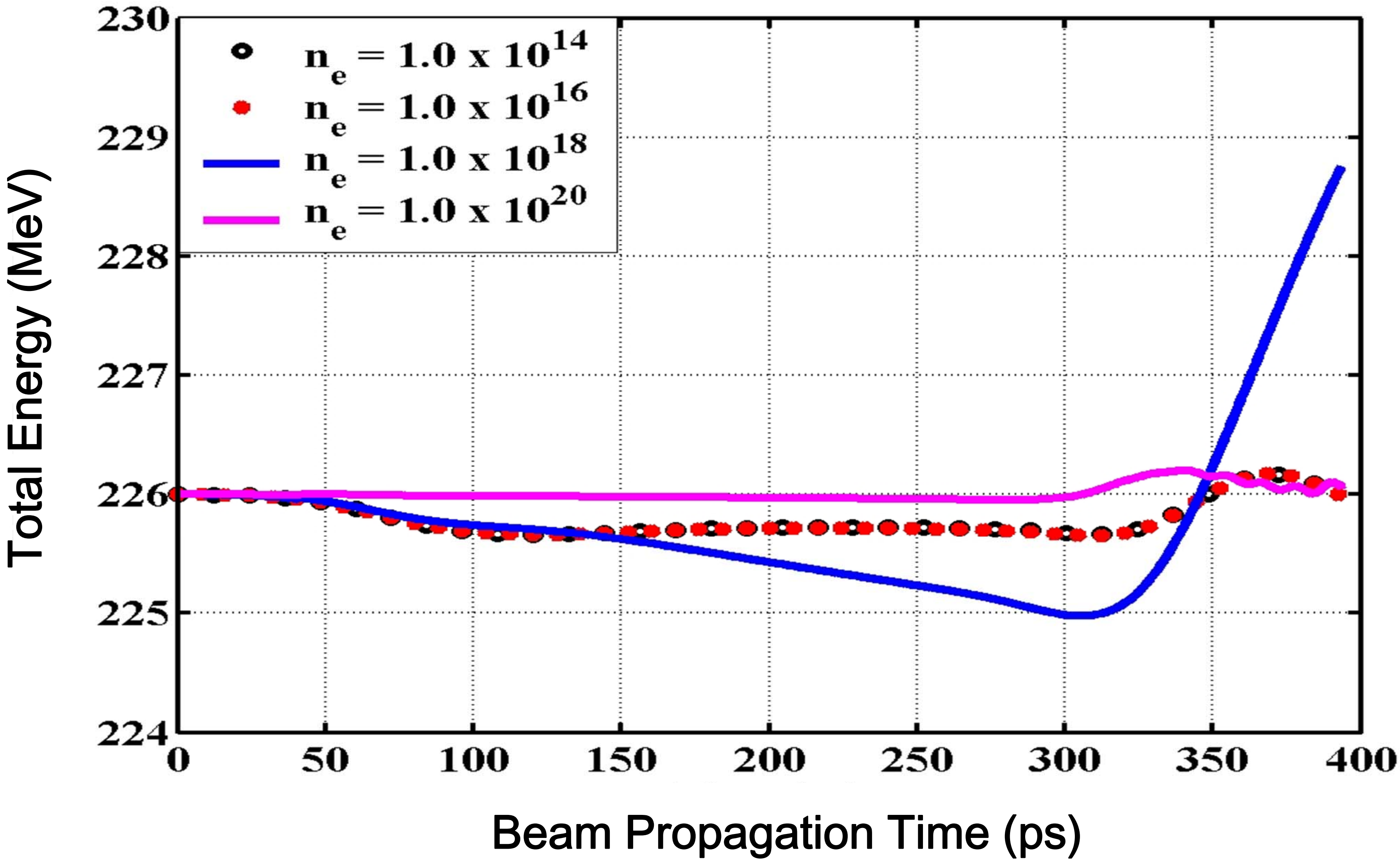


$n_b=10^{18}$
$n_{pe}=10^{22}$



Under dense plasma Wiped out, over dense plasma unaffected

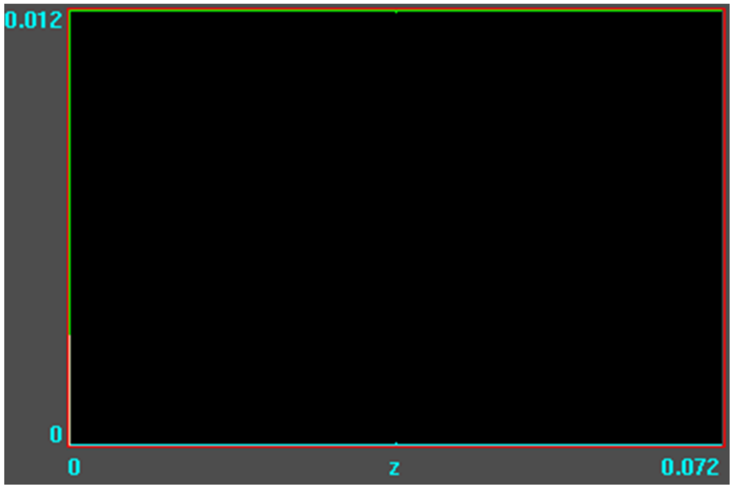
E_{tot} of Beam in Different Plasma Density



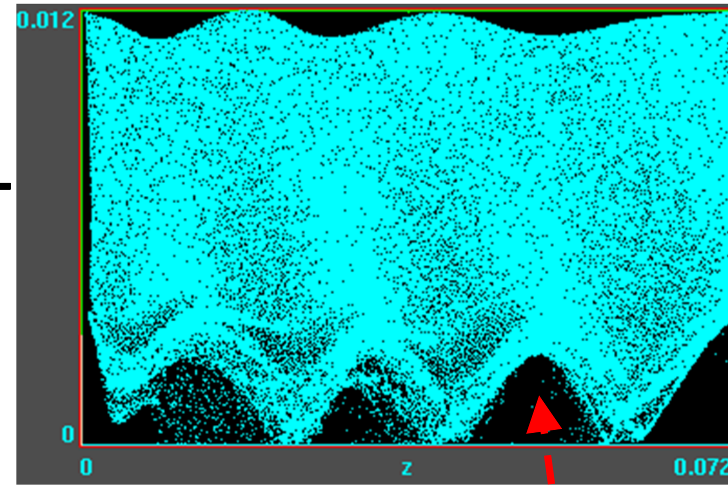
Beam and plasma of almost equal density have strong interaction

Effects of Magnetic field (B_z) -- Movie

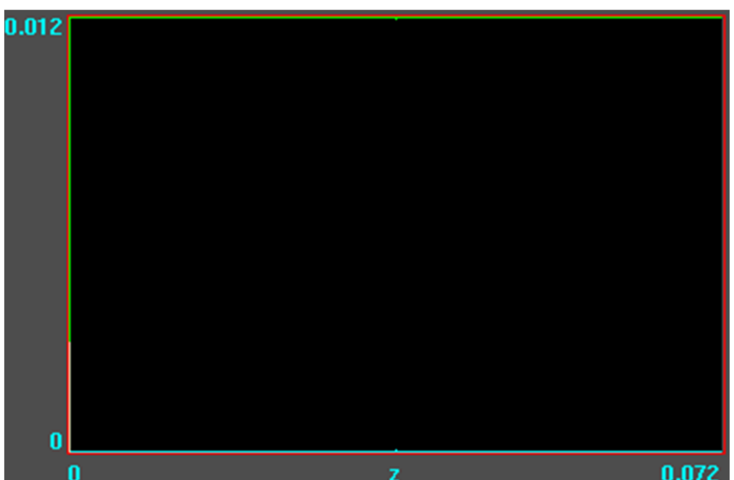
For μ collider, cooling channel is placed in a strong B-field



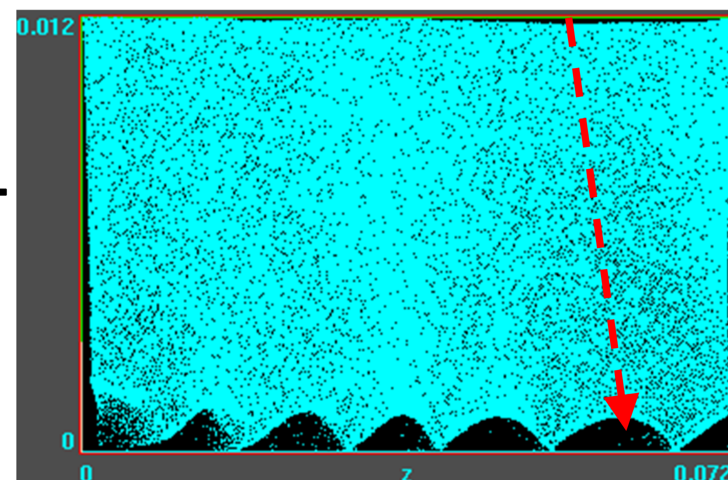
B_z=.5 T



$n_b \sim 10^{18}$, $n_{pe} \sim 10^{18}$



B_z=1 T



Magnetic field suppresses the strength of wakefield

Conclusions

- Particle-in-cell simulations of beam interaction with plasma reveal detailed wakefield structures which depend on beam and plasma densities, applied field strength, polarity of beam particle, etc

- Plasma wakefield excitation important when peak density of beam is comparable with plasma density, consistent with the other plasma wakefield accelerator simulations --- **polarization of medium and wakefield does not stop beam**

- Negatively charged beam experiences net acceleration. However, acceleration is weak for positively charged beam. These results are consistent with SLAC and Max Planck Institute wakefield accelerator simulation results. **Wakefield due to μ^+ is weaker than μ^-**

- External magnetic field can suppress wakefield which in turn may prevent longitudinal emittance increase

- Present simulations reveal that **collective effects are not important** for the present design parameters

Thanks for your Attention