Possible issues of RF cavities in 6D muon cooling channel

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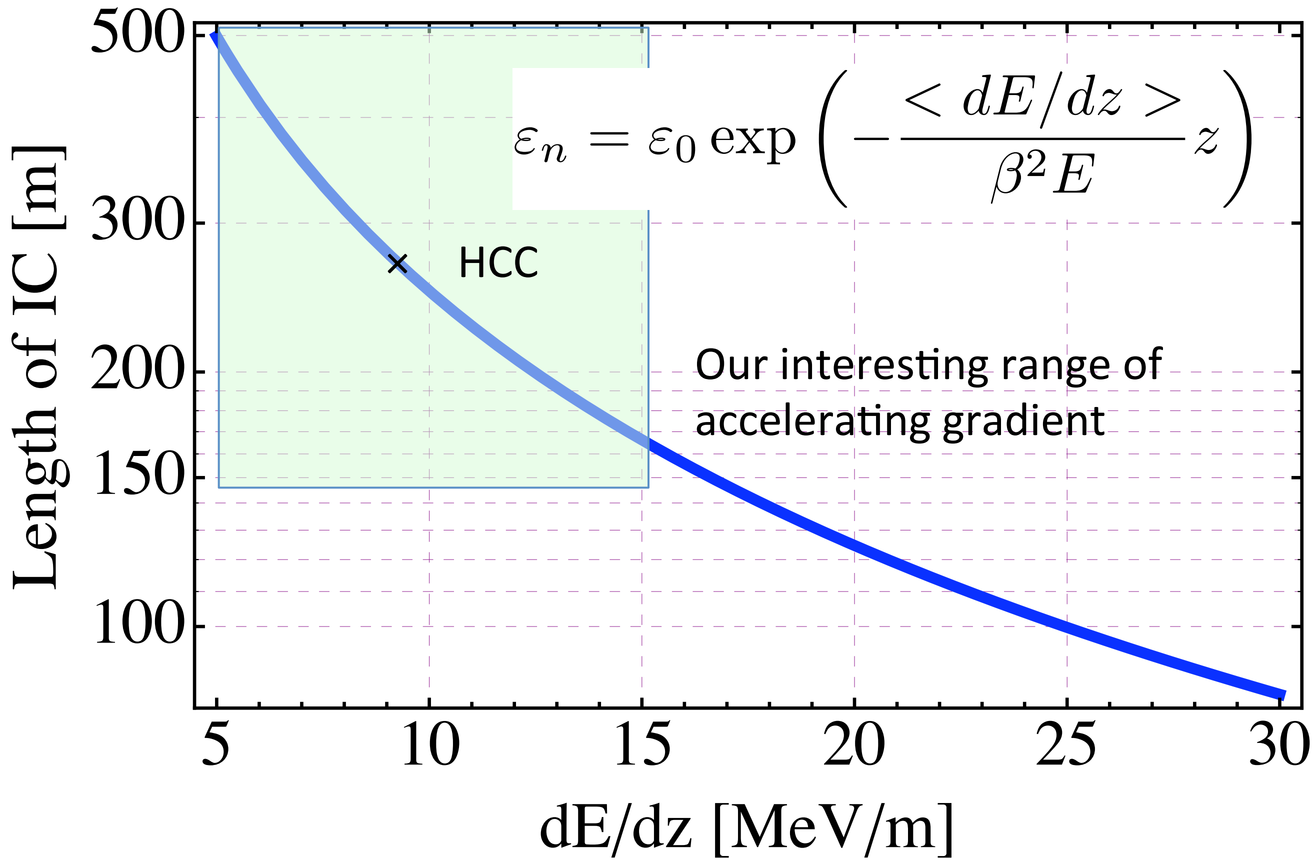
Introduction

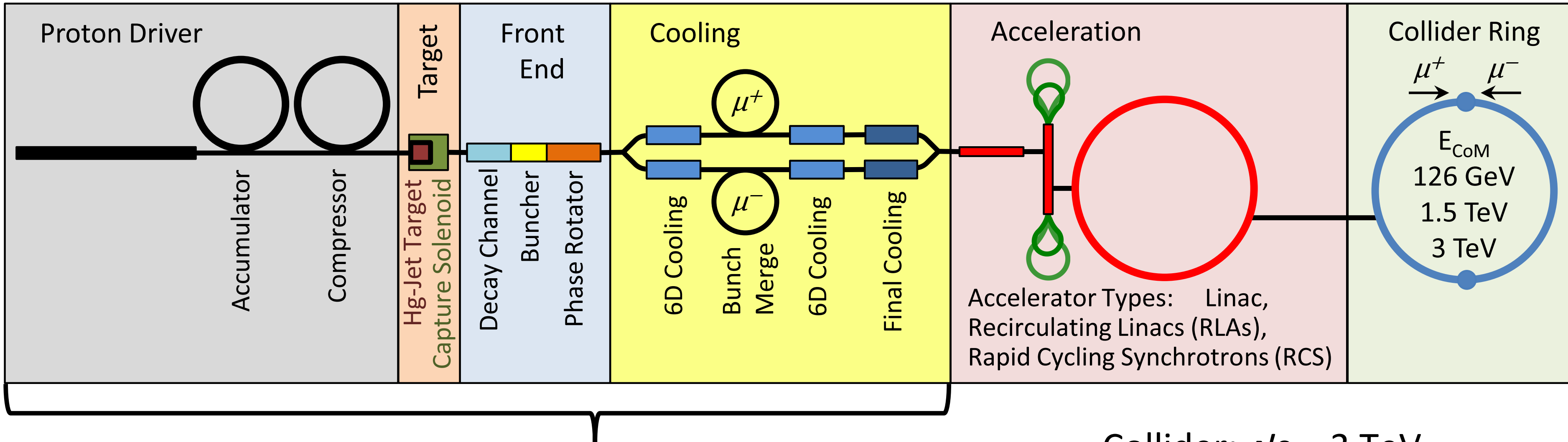
- RF operation in a multi-tesla magnetic field is crucial for all 6D cooling channel
- Here, I assume that we have a solution for a vacuum RF cavity
- What is the other considerable physics we have to address?
  - Beam loading
  - Anything else?

Cooling performance vs RF gradient

Length of IC (Ionization Cooling Channel) required 10^{-6} reduction as a function of the RF acceleration gradient



One of most crucial issues: Beam loading



Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity μ beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

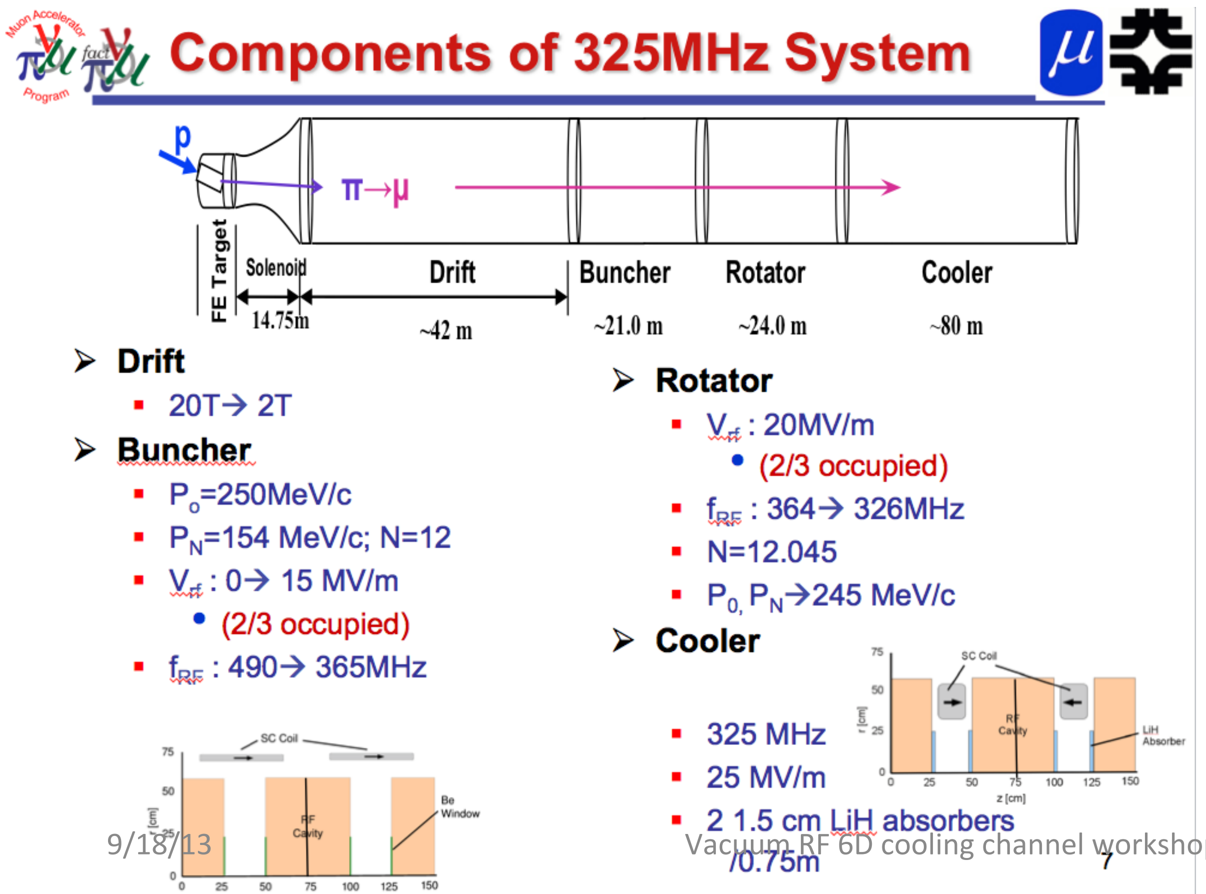
Collider: √s = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = $2\text{x}10^{12}$
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{//N}$=72 mm
β^* = 5mm
Rep. Rate = 12 Hz

$N_{\mu,\pi} > 10^{14}$ @ Target

$N_{\mu} > 3\ 10^{13}$ @ Decay channel
~ $10^{12} \times (10 \sim 20) + \alpha$ @ Buncher & Phase rotator
~ $10^{12} \times (10 \sim 20)\ /2$ @ Cooling channel (after charge separator)
~ 10^{13} @ Cooling channel (after bunch merging)

Beam loading in front end

- Alvin will give a detail talk tomorrow about a beam loading in a cooling channel
- One should look it in a front end, too

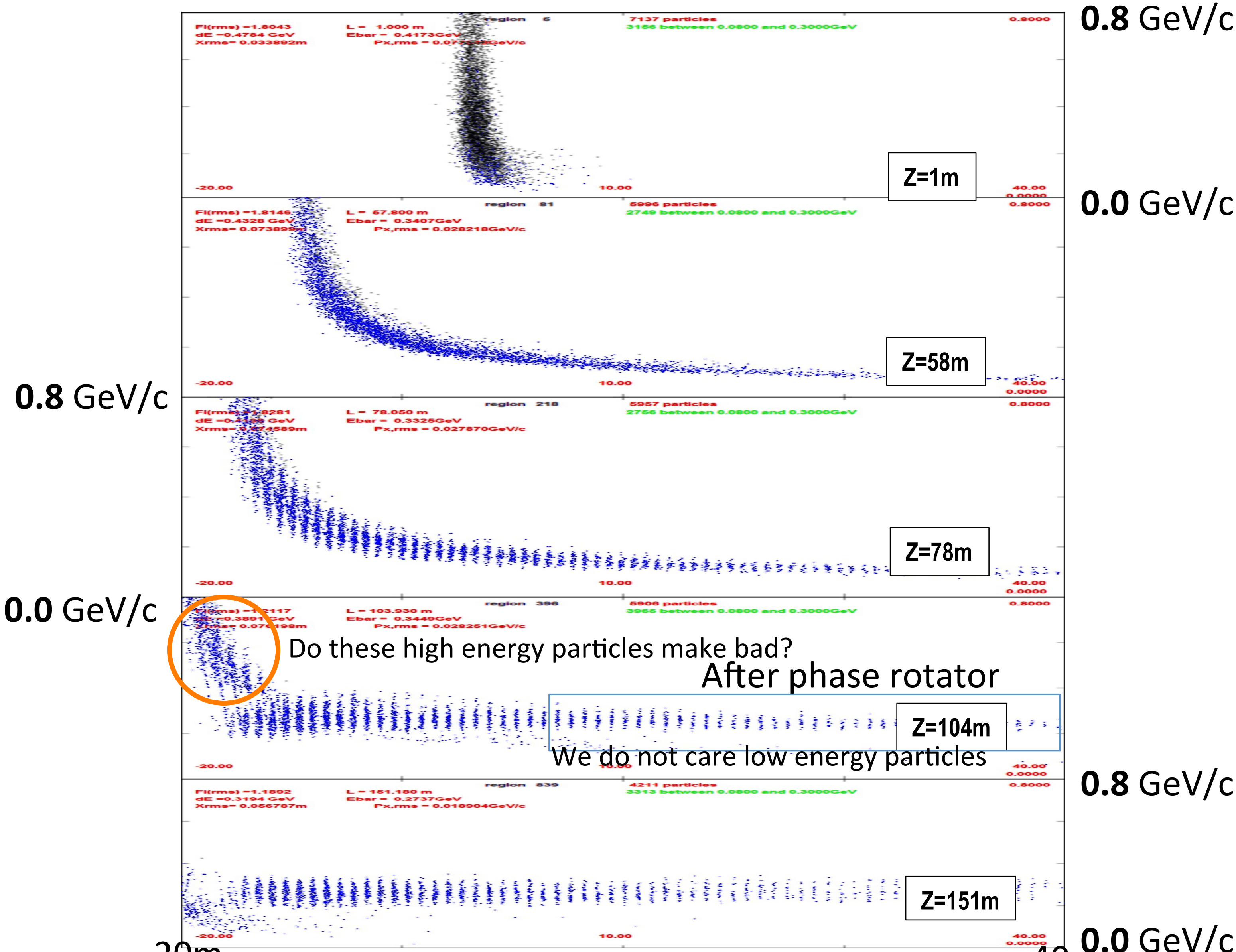


Number of bunches:
12@200 MHz channel
20@325 MHz channel
Similar bunch train length ~ 60 ns

Number of muons per bunch:
N_μ/bunch@200 MHz channel
> N_μ/bunch@325 MHz channel

Bunch gap:
t_μ/bunch@200 MHz channel
< t_μ/bunch@325 MHz channel

Bunched beam in front end

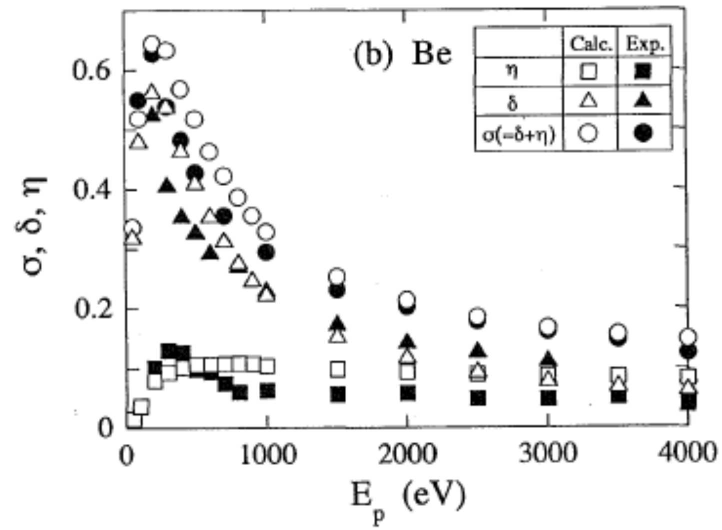


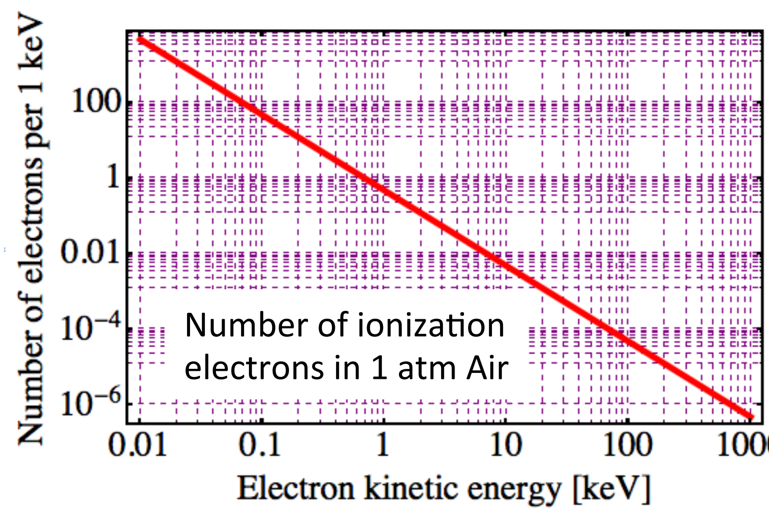
Electron cloud in RF cavities

- Electron cloud can be generated everywhere
  - Ionization electron from Be window
  - Ionization electron from residual gas
  - Surface emission electron
- What is the considerable physics process with them?

Ionization electrons from materials

- SEY of Beryllium is known
- 10^{13} muons produces
  0.15×10^{13} electrons
- Residual gas in a cavity
  (assume Air) can be estimated
- Residual gas pressure can be
  10^{-8} Torr
- $1{,}000 \times 1.3\ 10^{-11} \times 10^{13}$ electrons
  are generated from residual gas



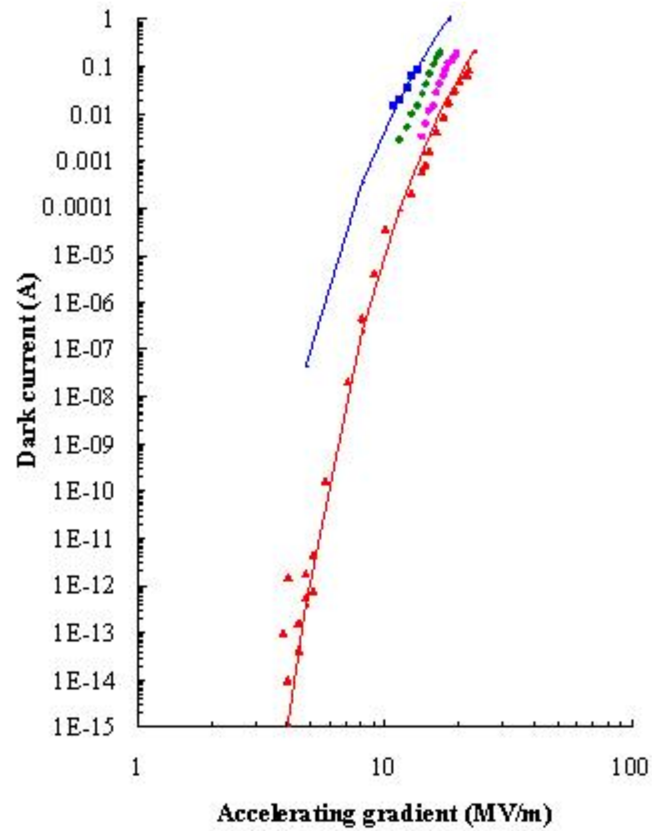


Other contributions: Field emission electrons

- Assume E=20 MV/m, then the dark current is ~ 0.1 Amps
- Assume the RF flattop is 60 ns

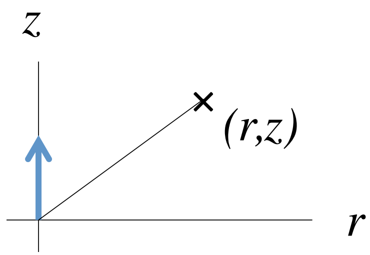
  Ne ~ 60 10^{-9} 0.1/e (at E=20 MV/m)

  ~ 4 10^{10} Electrons/one RF cycle



Overall number of electrons in a cavity will be
0.15 10^{12} + 1.3 10^{2} + 4 10^{10}
~ 0.19 10^{12} electrons/bunch
20 % of the number of muons

Beam-induced EM field (collective effect)



Induced Electric field by moving single charge particle

$$\hat{e}(\vec{r}) = -\frac{q}{4\pi\varepsilon_0}\frac{\gamma}{r^3\left(1+u_r^2\gamma^2/c\right)^{3/2}}\vec{r}$$

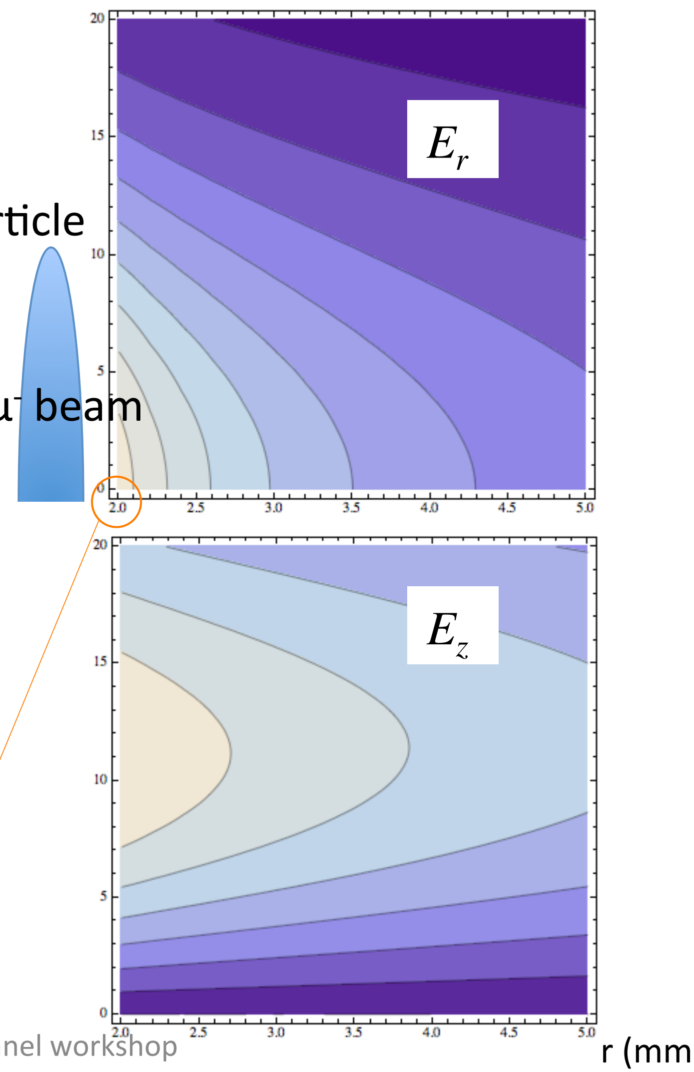
$$E_{total} = \int Q\, f(\vec{r})\sqrt{\hat{e}_r(\vec{r})^2 + \hat{e}_z(\vec{r})^2}\, d\vec{r}$$

I used the normal distribution *f(r)*

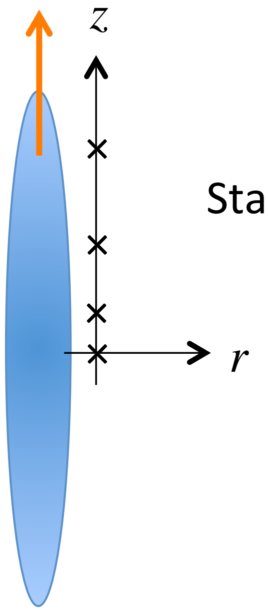
σr = 2 mm
σz = 10 mm
$N_\mu = 10^{12}$ μ/bunch

Maximum electric field is 170 MV/m

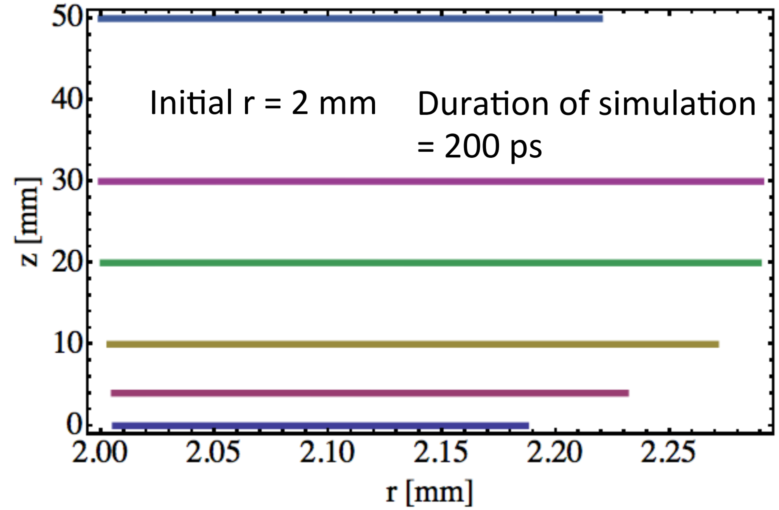
z (mm) Calculate field map with *f(r)*

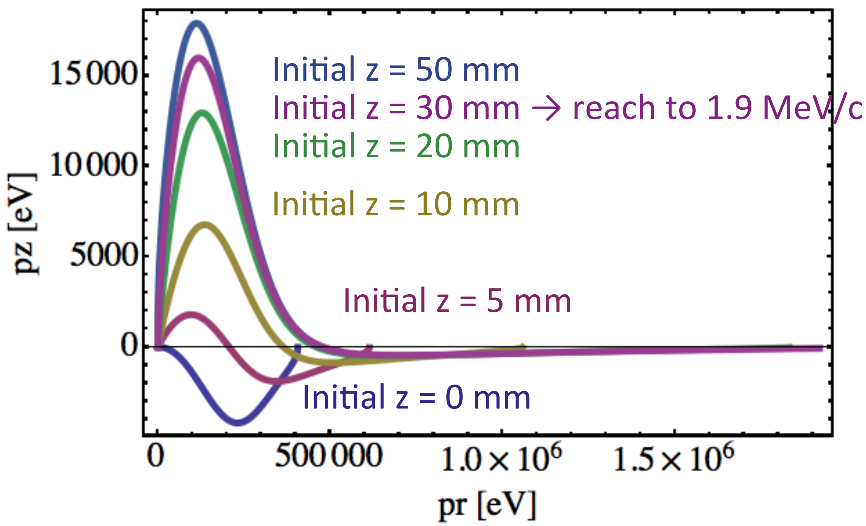


Single particle tracking with beam-induced EM fields



Start point of electrons





σr = 2 mm
σz = 10 mm
$N_\mu = 10^{12}$ μ/bunch
p = 200 MeV/c

New mechanism of beam energy consumption by an electron swarm

- Average energy consumption of free electron (within a 1 - 3σr & ±5 σz sheath) is 0.7 MeV
- If density of electron cloud is ~20 % of the number of muons per bunch, single muon can lose the kinetic energy 0.15 MeV/0.1 m from electron cloud
  - dE/dx in LH2 is 3 MeV/0.1 m
  - 5 % of additional dE/dx
  - Is it good or or bad?

Memorandum in present simulation

- Simulation only made with μ^- beam, μ^+ should be looked
- Electron motion in beam path should also be looked
  - Beam dynamics, i.e. transverse & longitudinal oscillations needs to be involved
- Simulation only calculates an induced electric field
  - Induced magnetic field and RF external field should be involved

New energy loss mechanism: Plasma Cooling (“Tollestrup” process)

- No stochastic in the beam-plasma process
  - No statistic heating
- Density of electron cloud can be controlled by putting gas in the RF cavity
  - There should be an optimum gas pressure
    - Gas generates ionization electrons
    - Gas also dumps the kinetic energy of electrons
    - Simulation effort is in progress
    - Plasma coherent motion will be dominant at some plasma density (f_{plasma} ~ beam bunch length at gas pressure 1 atm)

Summary

- Preliminary particle tracking simulation has been made to investigate the influence of electron cloud on μ^- beam
  - Result suggests that there may be a new energy loss mechanism
- Involving coulomb interaction of electron with gas is in progress
  - Gas plasma simulation for HPRF cavity project has been proposed
  - The result will be used to test the numerical simulation