DESIGN OF HIGH INTENSITY MUON SOURCES

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FRONT END DESING & OPTIMIZATION

OUTLINE

Goal : Optimize number of useful muons

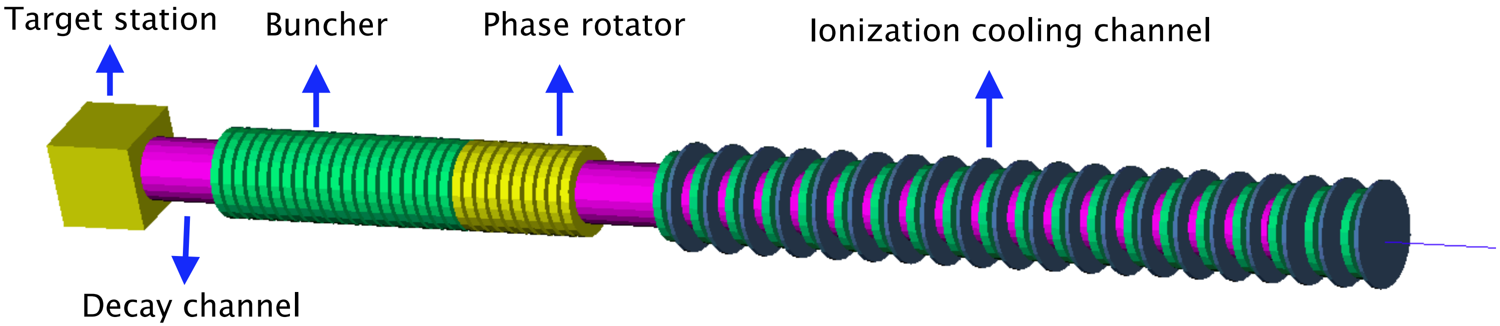
Involved systems:

- Carbon target geometry
- Capture field
- Buncher and rotator RF

1- Target geometry parameters:

Carbon target length, radius, and tilt angle to solenoid axis

2- Target Capture field: constant field length - taper length - end field



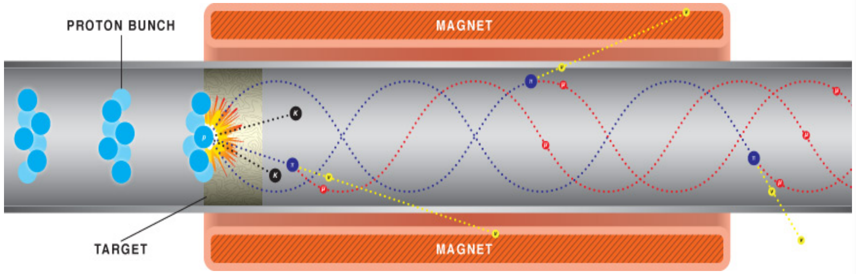
MUON BEAM PRODUCTION

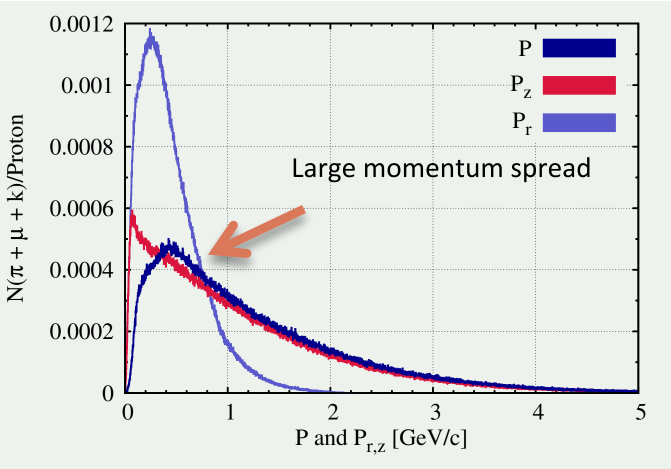
Challenges with muon beams:

- Short lifetime ~ 2 μs
- Require fast and aggressive way of reducing the muon beam transverse and longitudinal emittance to deliver the required luminosity

Production and acceleration of muon beam

High energy proton beam on Hg or graphite target

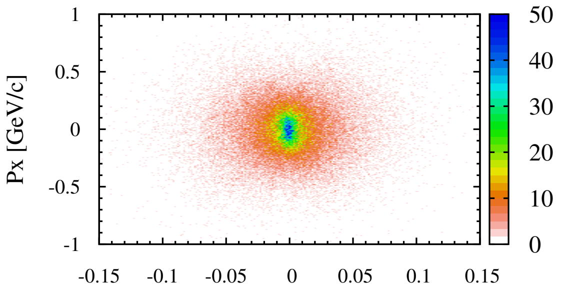




Large momentum spread

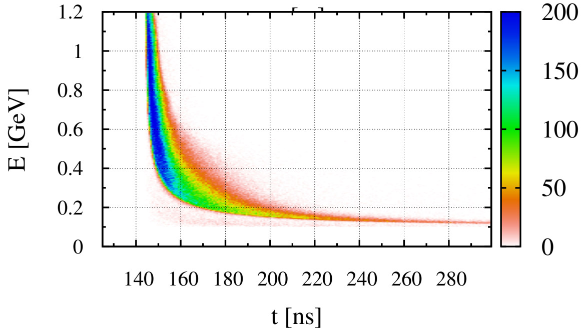
Captured pion beam has a large emittance

Pions decay into muons with even larger emittance



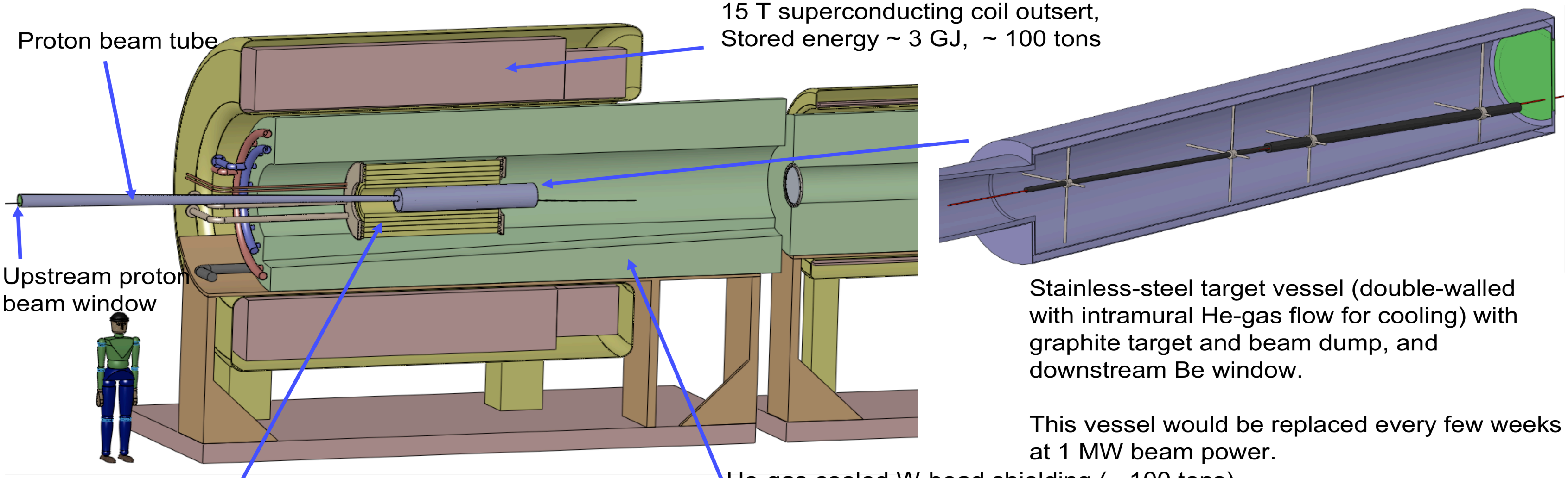
Transverse phase space

$\varepsilon_{T(rms)}$ ~ 25 mm-rad



Longitudinal phase space

HIGH POWER TARGET STATION



Proton beam tube

15 T superconducting coil outsert,
Stored energy ~ 3 GJ, ~ 100 tons

Upstream proton beam window

Stainless-steel target vessel (double-walled with intramural He-gas flow for cooling) with graphite target and beam dump, and downstream Be window.

This vessel would be replaced every few weeks at 1 MW beam power.

He-gas cooled W-bead shielding (~ 100 tons)

5 T copper-coil insert. Water-cooled, MgO insulated

http://physics.princeton.edu/mumu/target/hptw5_poster.pdf

TAPERED CAPTURE SOLENOID OPTIMIZATION

Inverse-Cubic Taper

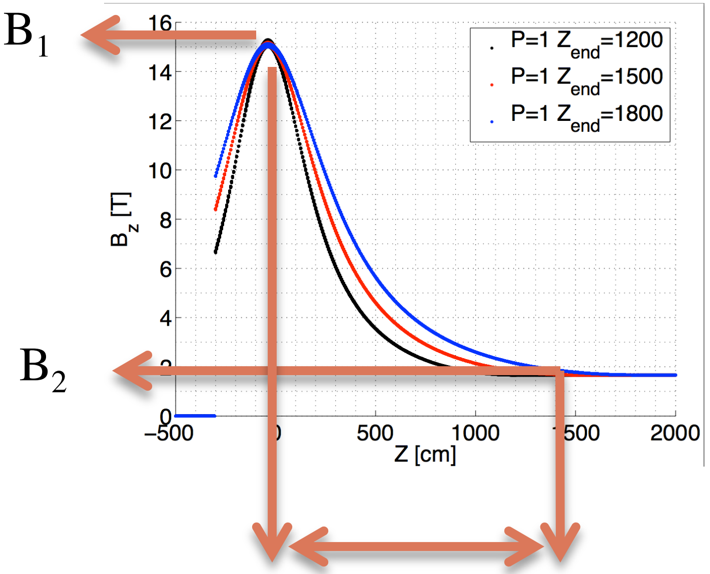
- Initial peak Field B_1
– Taper length z
– End Field B_2

$$B_z(0, z_i < z < z_f) = \frac{B_1}{[1 + a_1(z - z_1) + a_2(z - z_1)^2 + a_3(z - z_1)^3]^p}$$

$$a1 = -\frac{B_1'}{pB_1} \qquad a_2 = 3\frac{(B_1/B_2)^{1/p} - 1}{(z_2 - z_1)^2} - \frac{2a_1}{z_2 - z_1}$$

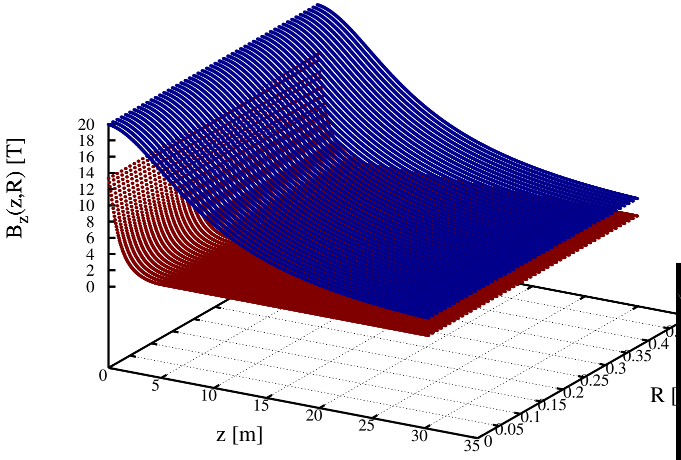
$$a_3 = -2\frac{(B_1/B_2)^{1/p} - 1}{(z_2 - z_1)^3} + \frac{a_1}{(z_2 - z_1)^2}$$

Target Solenoid on axis field



Taper Length z_1-z_2

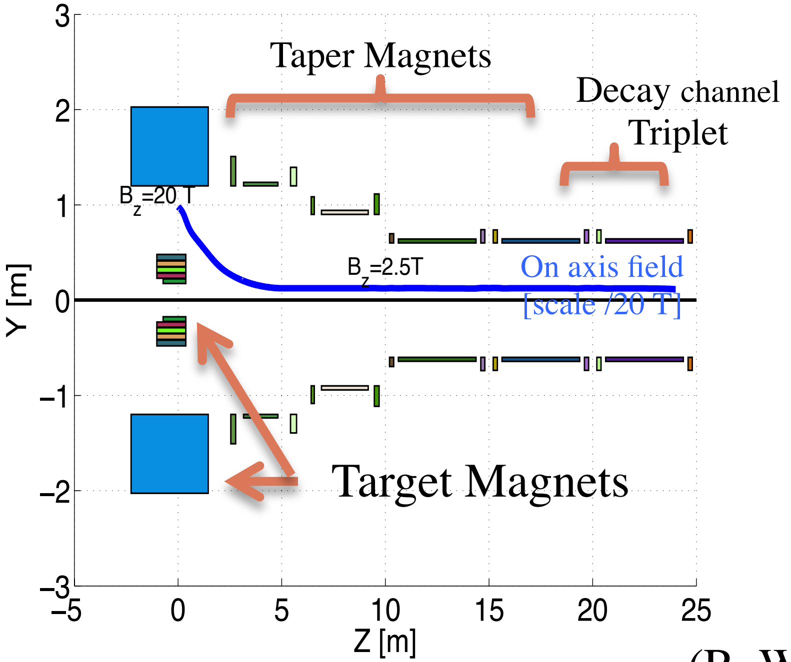
- Impact of the Peak field on the number and phase space of the captured pions
- Impact of taper length on the number and phase space of the captured pions/muons
- Impact of the end field on the number of captured muons



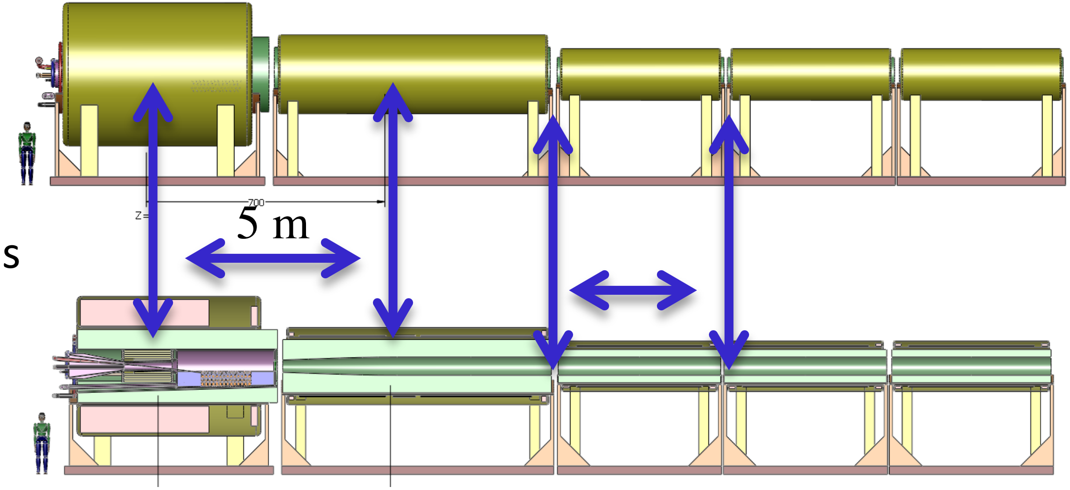
NEW SHORT TARGET CAPTURE WITH REALISTIC SUPERCONDUCTING MAGNETS

New baseline Muon Target Capture Magnet :
Short Taper length =5 m

B=20-2.0 T, 20 – 2.5 T 20 – 3.5 T



(R. Weggel)



V. Graves

CARBON TARGET GEOMETRY OPTIMIZATION

- Target geometry parameters (channel includes target + chicane+ decay channel):
  - → Carbon target length -- radius -- tilt angle to solenoid axis
  - → Proton beam size

- Objective: optmize at z=70 m

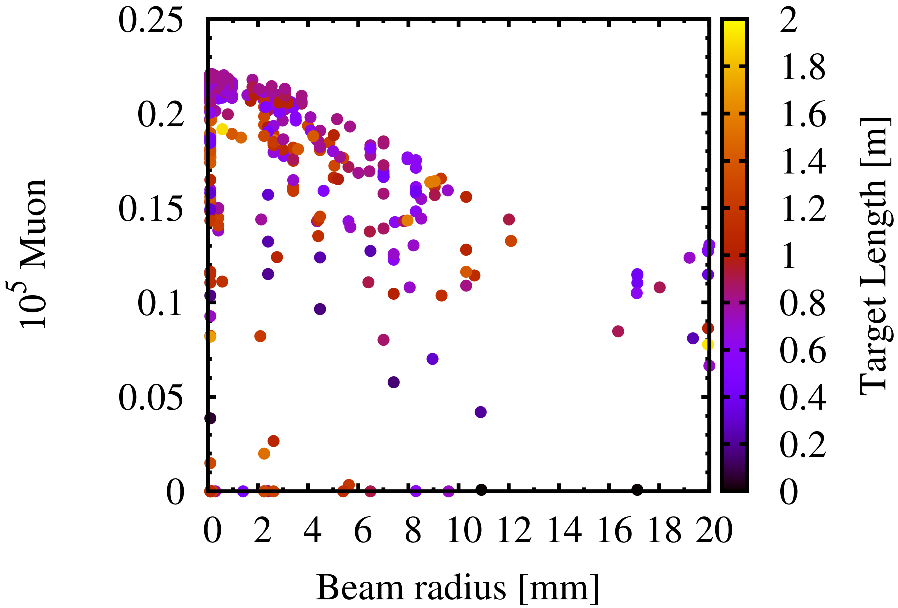
  $\Sigma\ \pi+\mu+\kappa$ within
  pz < 450 MeV/c (to compensate for the Be absorber effect)
  pt < 150 MeV/c

Initial lattice in G4Beamline – using GEANT4 physics list QGSP

- Bz=20-2.0-7.0 T over variable taper length
- Initial protons K.E. = 6.75 GeV - $\sigma_t = 2$ ns
- Tracking includes target + chicane + decay channel

- The optmization run 6 hours on 1200 cores at NERSC
- using Multiobjective – Multivariable parallel genetic algorithm

CARBON TARGET GEOMETRY OPTIMIZATION

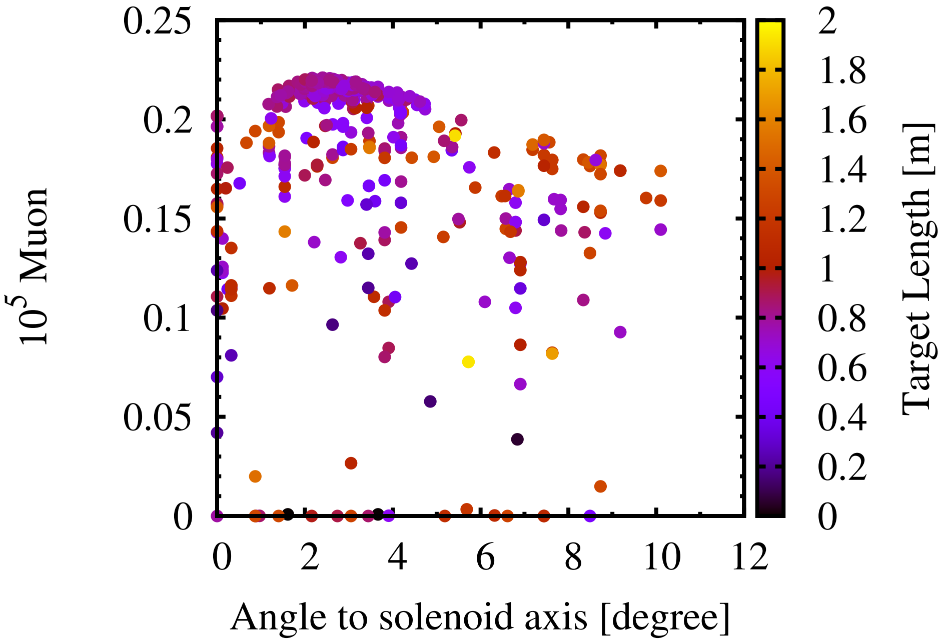


◆ Optimizing the target geomtery and proton beam parameters.

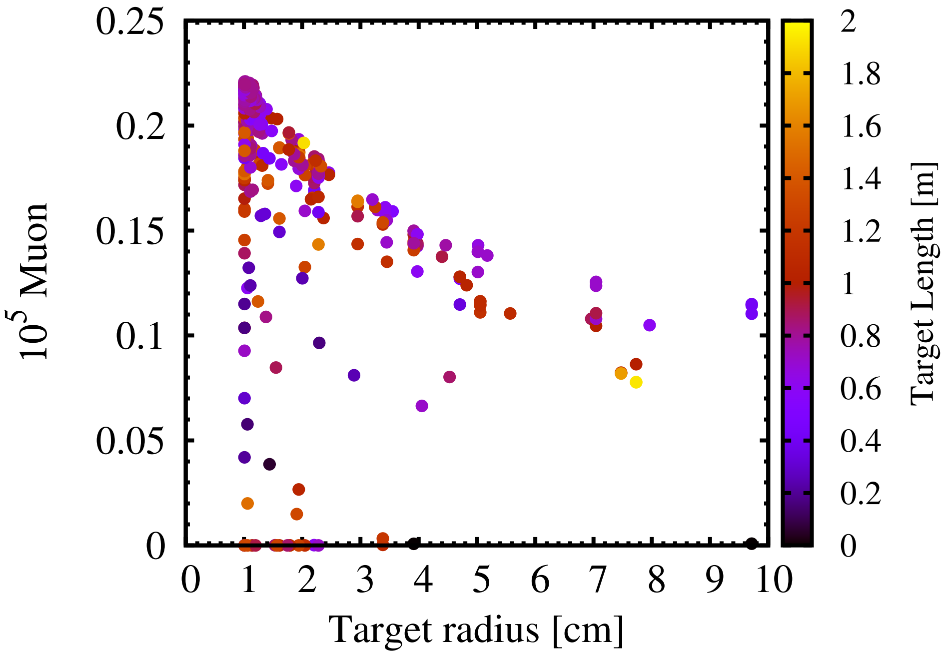
◆ Objective is the muon count at end of decay channel

Optimal working point 1-2 mm

Optimal working point 1-3 degrees



CARBON TARGET GEOMETRY OPTIMIZATION



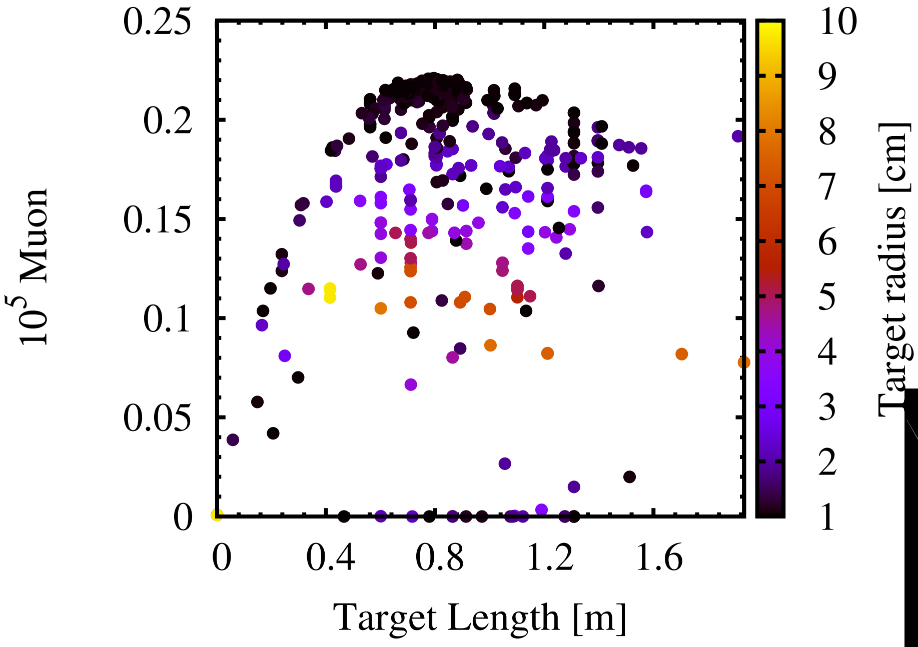
- ◆ Optimizing the target geomtery and proton beam parameters.
- ◆ Objective is the muon count at end of decay channel

Optimal working point ~ 1 cm

Optimal working point 70-90 cm

Optimal working point for C-target
- ➢ Proton beam size 1-2 mm
- ➢ C–rod Length 80 cm
- ➢ C–rod radius 1 cm

Beam + target angle to solenoid axis 2-3 degree

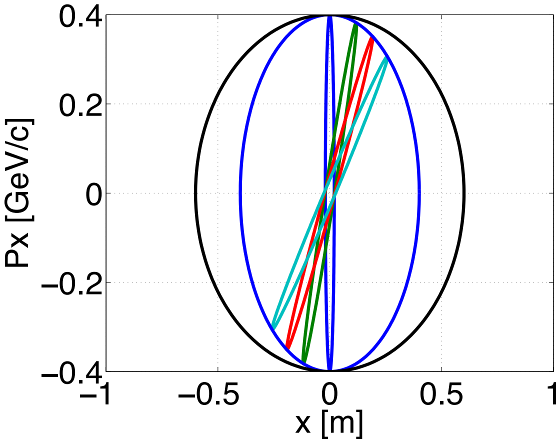


DEPENDENCE OF TRANSVERSE EMITTANCE & CAPTURE EFFICIENCY ON PEAK FILED

Emittance growth due to betatron oscillation decohenrce:

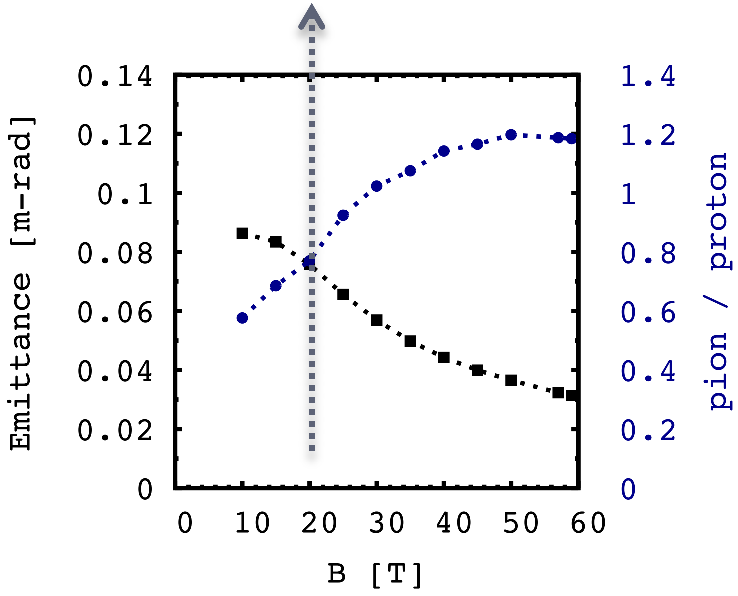
- Pions created at the target
  - Small radial extent (small transverse emittance)
  - Large spread in energy and axial point of origin
- Particles with different energy and different transverse amplitude rotate over the transverse phase space at different oscillation frequencies.

- Strong solenoid field stabilizes the emittance growth by reduction of axial extend
- The final projected transverse emittance is smaller for higher fields



$$\epsilon_\perp = \frac{2\sigma^2_{p_\perp}}{eB_z m_\pi c}$$

Limit of operation of solenoids in high radiation area

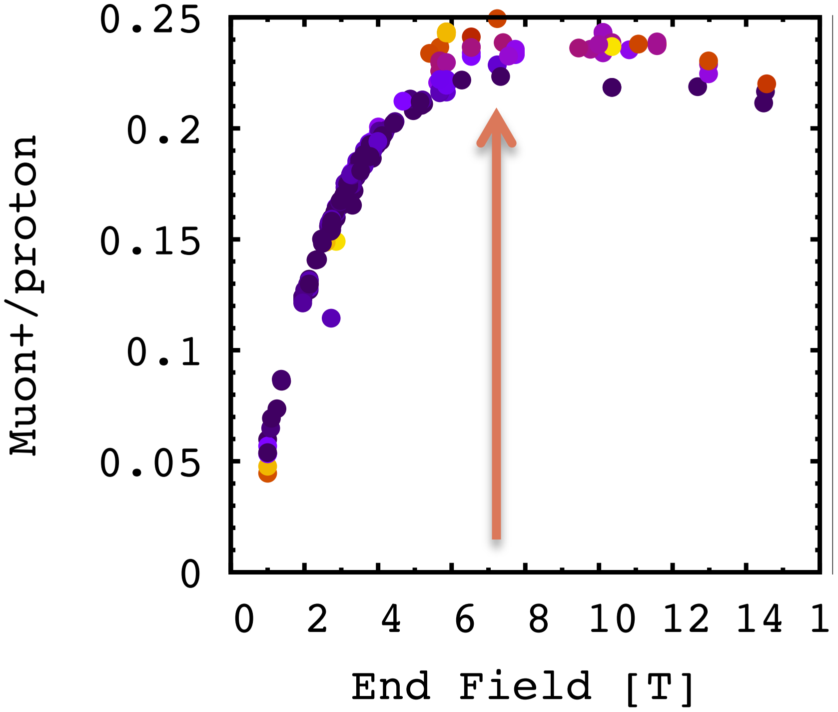


MARS Simulation of π^+ & μ^+ production from 8 GeV proton beam on Hg target.

- Emittance calculation from covariance matrix
- particle count at end of the target

CARBON TARGET GEOMETRY OPTIMIZATION

Optimization of the target end field and decay channel – (no buncher- rotator RF)
Points with differing colors have different target geometry parameters

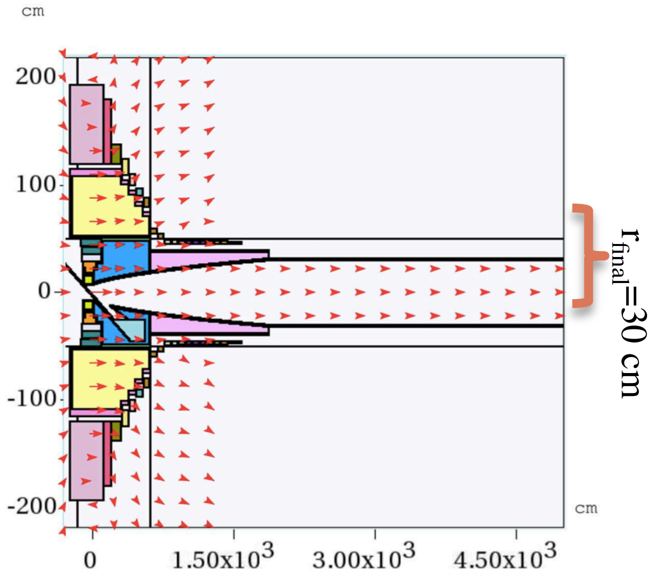


MARS SIMULATIONS & TRANSMISSION

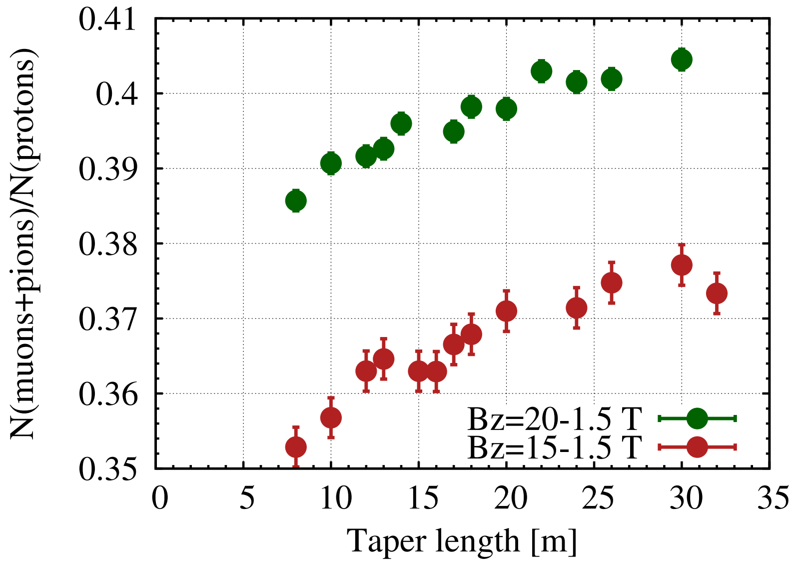
Muon count within energy cut at end of decay channel

Adiabatic condition:
length scale over which the magnetic field changes is large compared to betatron wavelength of the helical trajectory of a particle

$$\frac{2p}{eB^2}\frac{dB}{dz} << 1$$



Muon count at z=50 increases for longer solenoid taper



MARS15 Simulation:
Counting muons at 50 m with K.E. 80-140 MeV

BUNCHER AND ENERGY PHASE ROTATOR

Target: π production

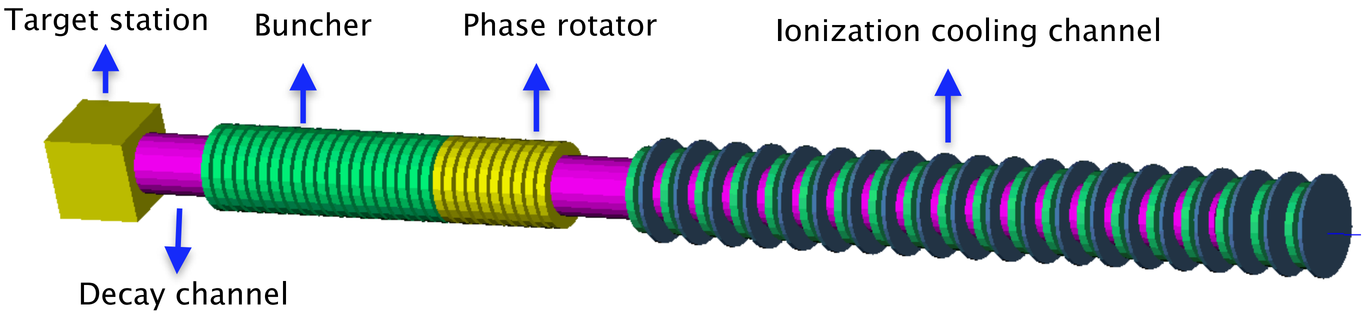
Drift: π's decay to μ's + creation of time-energy correlations

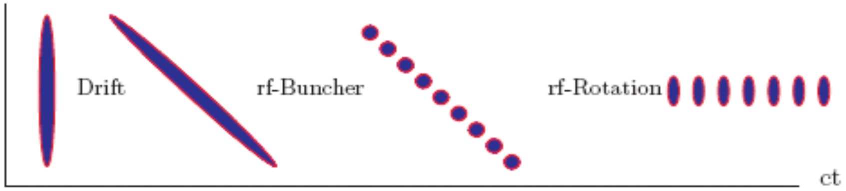
Adiabatic bunch:

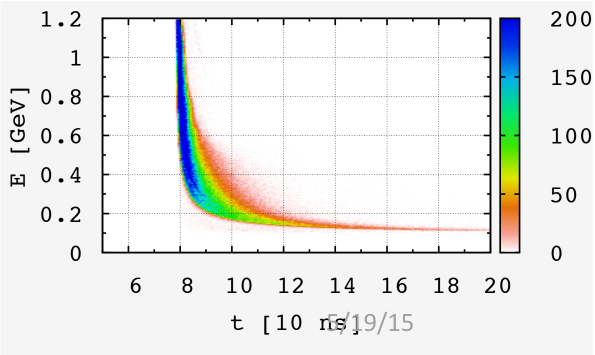
Converts the initial single short muon bunch with very large energy spread into a train of microbunches with much reduced energy spread

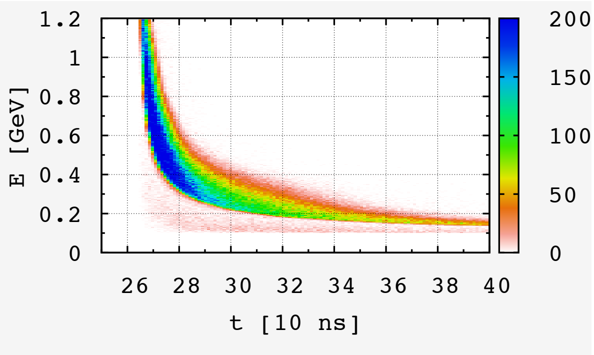
Energy phase rotatation: Align microbunches to equal energies

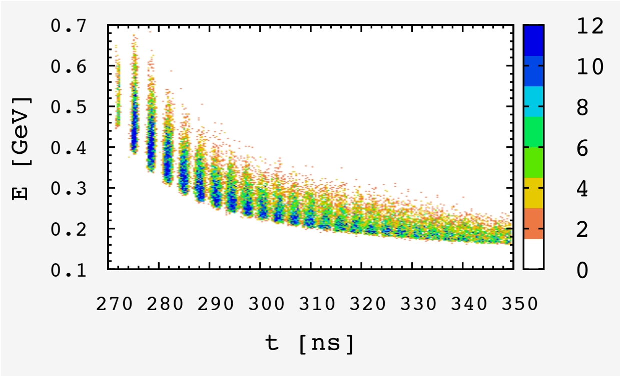
Transverse ionization cooling: RF 325 MHz











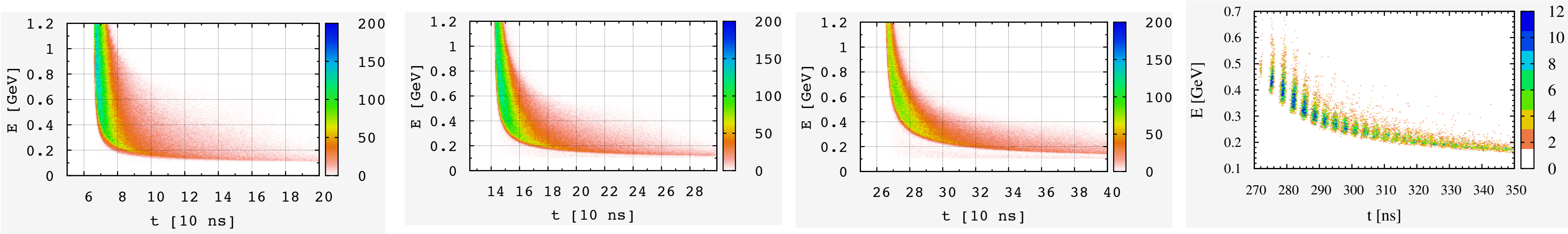
LONGITUDINAL PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

Bunch length increase in strong solenoid field:

Temporal difference between the arrival time at a position z of a particle with a nonzero transverse amplitude and that of a particle with zero transverse amplitude

$$\Delta t \approx \frac{p_\perp^2 E}{2c^2 p^3} \int_0^z \frac{B_z(z')}{B_z(0)} dz'$$

Long adiabatic taper 40 m



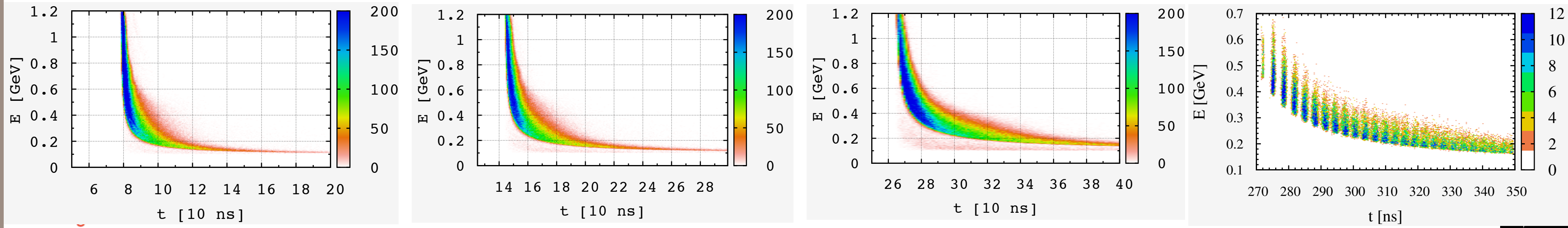
z=20 m

End of Decay z=80 m

After buncher

Short taper 4 m

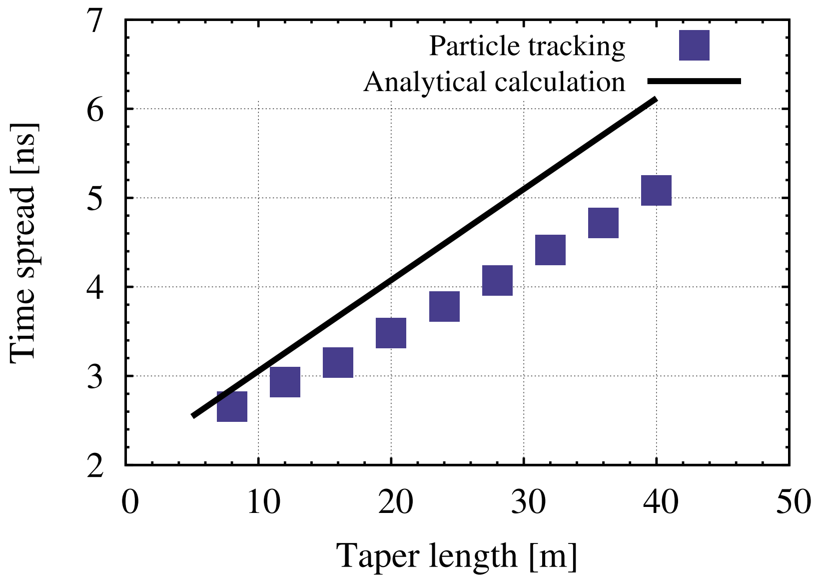
Shorter bunch length → Higher longitudinal phase space density



DEPENDENCE OF TIME SPREAD & TRANSVERSE EMITTANCE ON TAPER LENGTH

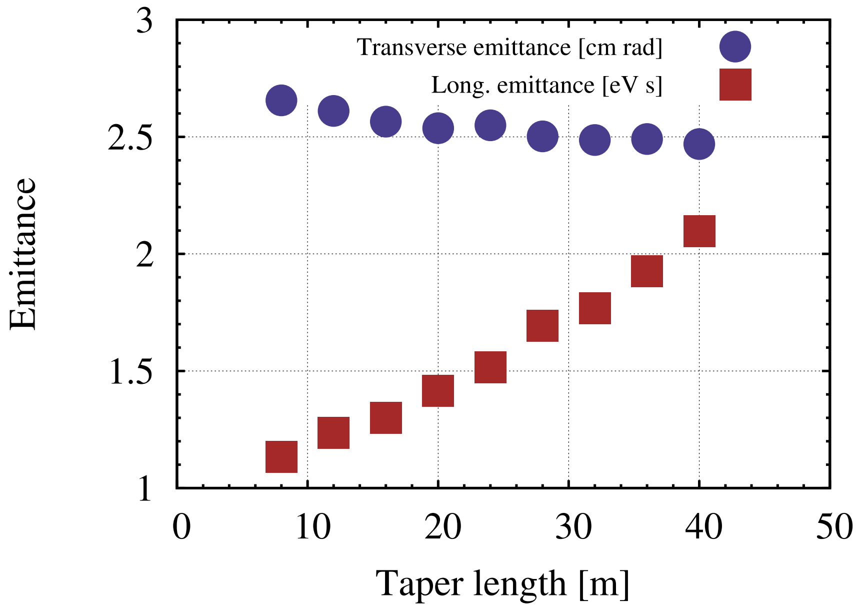
Muon beam emittance calculation was done at the end of the decay channel at z= 70 m
Initial proton bunch has pancake tempral distribution σ_t=0 ns for this calculations

Time spread dependence on taper length



Time Spread increase by 90%

Implication on projected emittance

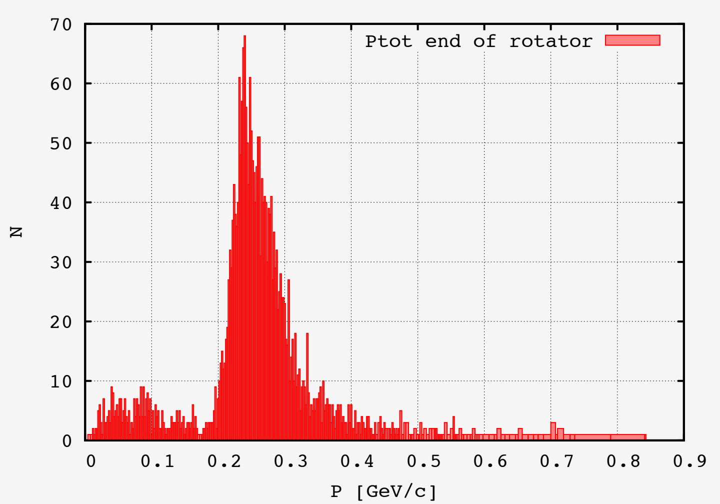


- Projected transverse emittance did not change dramatically
- Longitudnal emittance decreases more dramatically

NUMERICAL NONLINEAR GLOBAL OPTIMIZATION ALGORITHMS ON NERSC

- **Expensive objective evaluations on CRAY: (In collaboration with LBNL)**
  - High performance parallel environment: N cores > 1000
    - Run parallel evaluations of the objective functions (Parallel Evolutionary algorithms)
    - Each evaluation of the objective run in parallel to limit the cost of every evaluation (parallel Icool – G4BL , MARS .. etc.).
- **Implemented algorithm:**
  - **Parallel Differential Evolutionary Algorithms**

Momentum distribution of "useful muons" at end of phase rotator

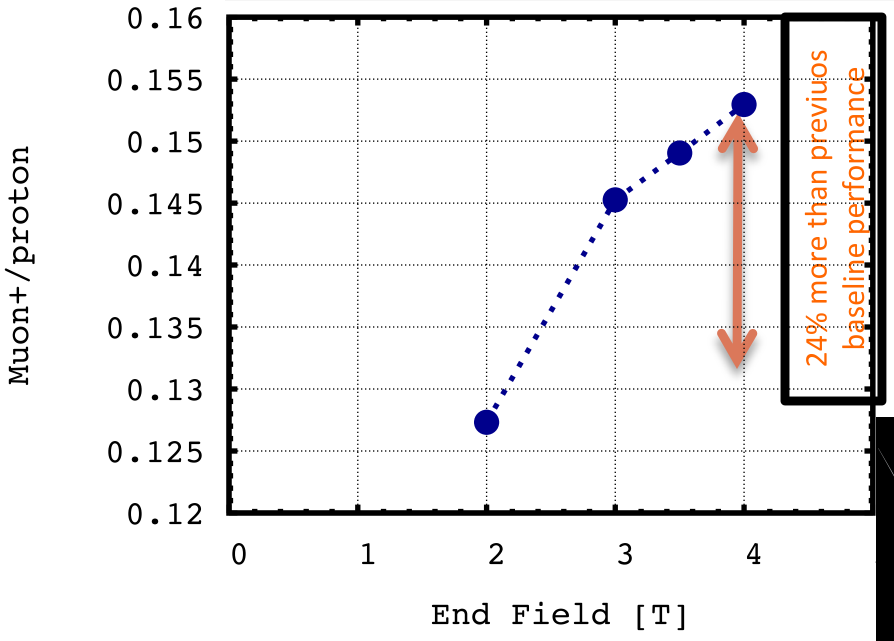


Muon Front End Global Optimization

- Multivariable optimization of the Muon Accelerator Front End:
  - Target parameters
  - Capture field parameters
  - RF modulation in buncher & rotator
  - Optimizing the broad band match to the 4D

End Field Limitations:

- Operation of RF cavities in magnetic fields

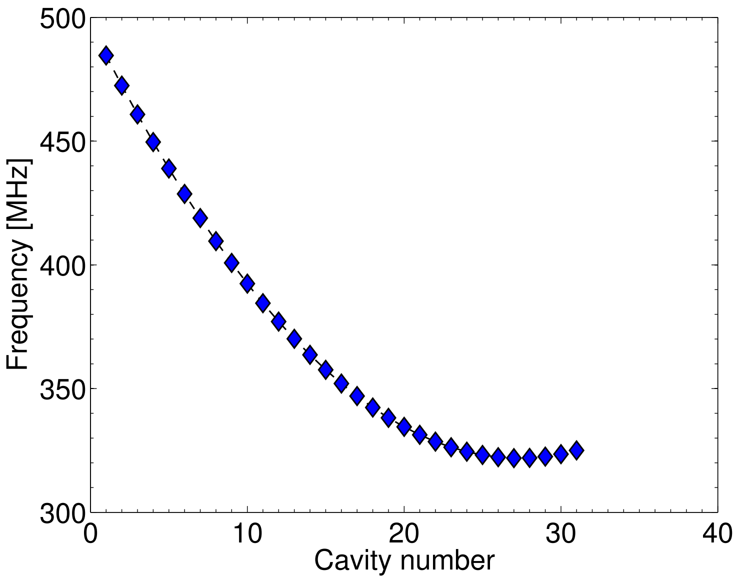


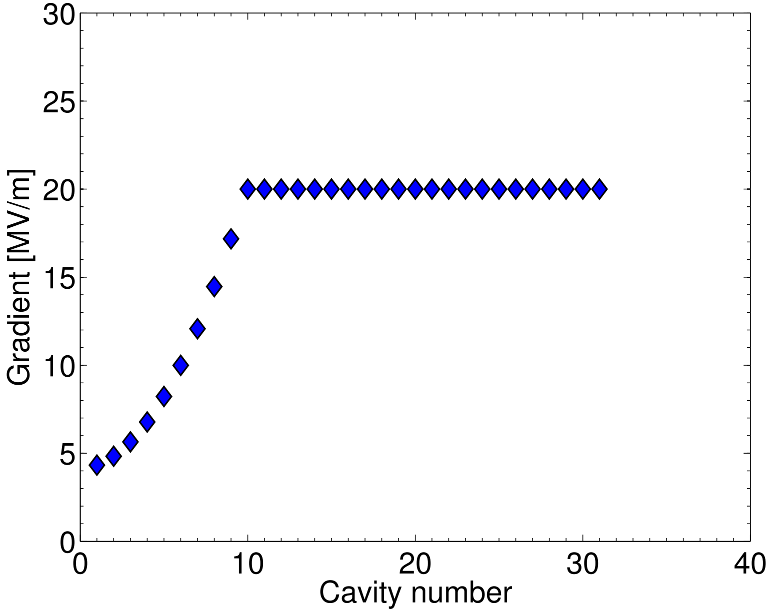
OPTIMIZING THE BUNCHER & ROTATOR RF

- Limite the number of RF frequencies to only 31
- Optimizng the RF modulation in the buncher & rotator simultaneoulsy

$$\Phi(n) = \kappa_1 \xi^2 + \kappa_2 \xi + \kappa_3$$

$$V(n) = \tau_1 \xi^2 + \tau_2 \xi + \tau_3$$

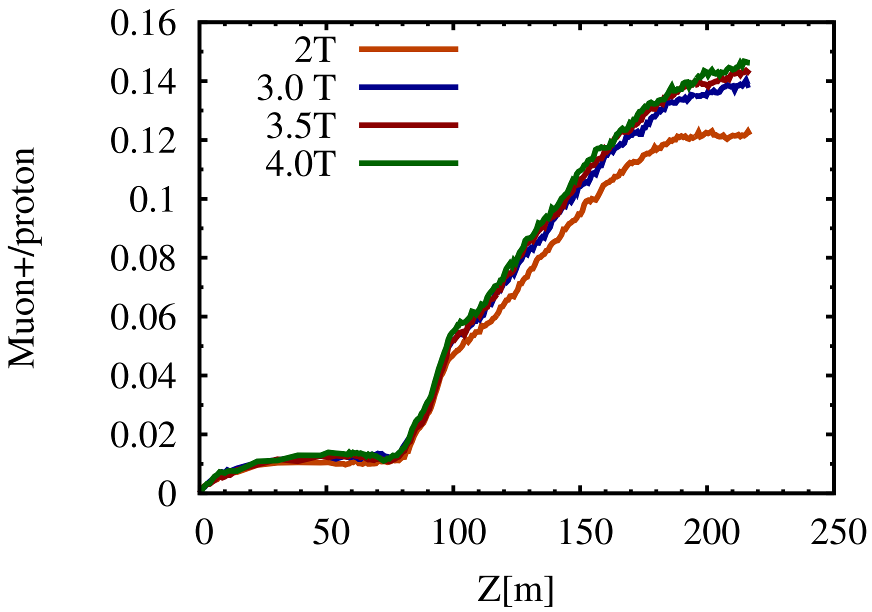




CONCLUSION & SUMMARY

Global Optmization of the Muon Accelerator Front End:

- Target geomtery
- Capture Field
- Buncher & phase roation modulation
- Longitudnal and transverse match to 4D ionization cooling channel



Longitudnal – transverse coupling plays a majore rule on the muon capture effeciency

Global Optimization of the longitudanl and transverse components of the Muon Front End simultnoulsy is required

CONCLUSION & SUMMARY

Target Parameter	Unit	Optimal Working Point
Target Rod Length	m	0.8
Target Radius	cm	1.0
Angle to solenoid axis	degree	2.4
Proton beam size	mm	0.2

Target Parameter	Unit	Optimal Working Point
Target Aperture size	cm	12.5
End Field	T	4.3
Taper Length	m	5.15

Parameter	Optimal Working Point
κ_1	0.2055×10^6
κ_2	-12.745×10^6
τ_1	0.00105×10^6
τ_2	1.6975×10^6
τ_3	-2.204×10^6