OPTIMIZED SOLENOID BASED CAPTURE MECHANISM FOR A MUON COLLIDER/NEUTRINO FACTORY TARGET SYSTEM

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MAP COLLABORATION MEETING FERMILAB 2013

Muon Accelerator Program

BROOKHAVEN
NATIONAL LABORATORY

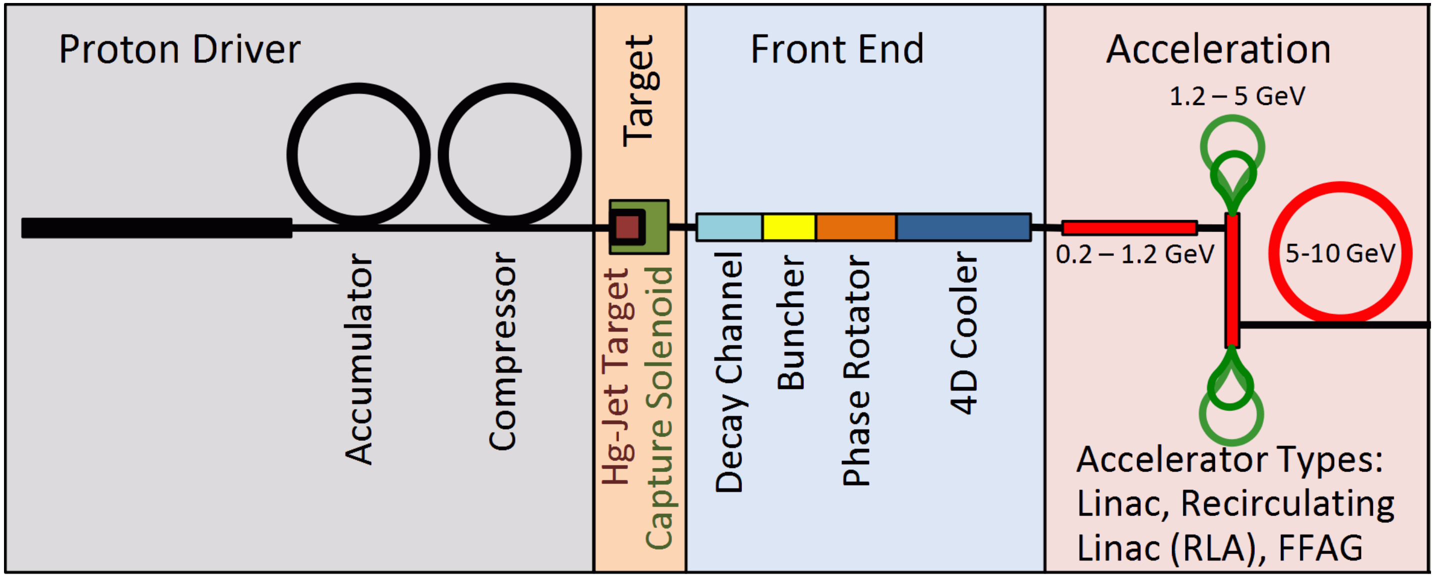
INTRODUCTION & LAYOUT

Muon Capture in Target & Front END

- Capture Solenoid Field Study:
  - Optimizing quantity: Muon (Pions) count – transverse capture
    - Target Solenoid peak field
    - Final end field
  - Optimizing quality: Muon (Pions) longitudinal phase space (transverse-longitudinal coupling) – transverse-longitudinal capture
    - Taper field profile

- Optimizing the time of flight of incident beam (Buncher-Rotator RF phase)
- Transverse focusing field in decay-channel-buncher-rotator
- Match to ionization cooling channel for every end field case 1.5 T → 3.5 T
- Performance of front end as a function of proton bunch length
- Realistic Coil Design & performance optimization

MUON COLLIDER/NEUTRINO FACTORY LAYOUT

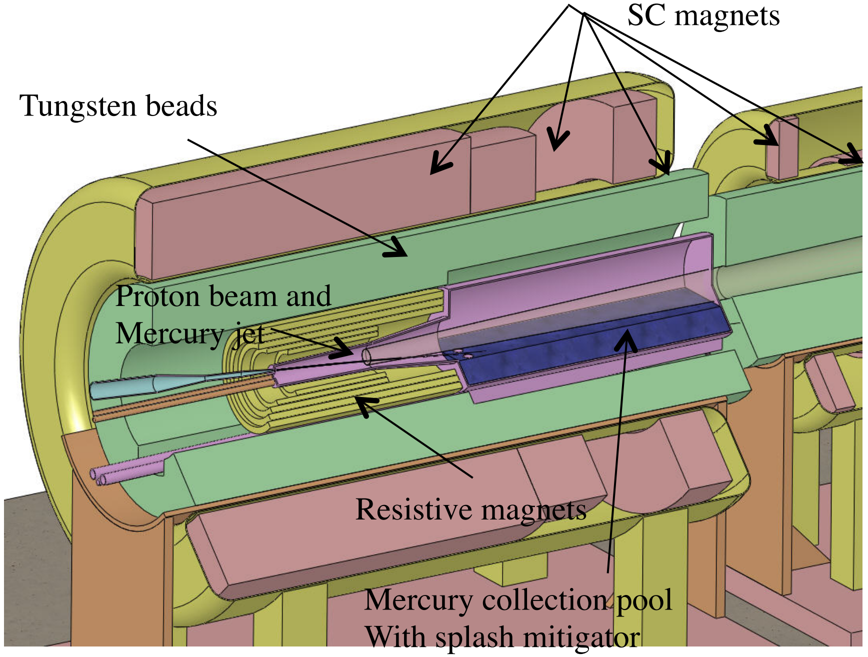


Target System Solenoid:
Capture μ± of energies ~ 100-400 MeV from a 4-MW proton beam (E ~ 8 GeV).

TARGET SYSTEM CURRENT BASELINE DESIGN

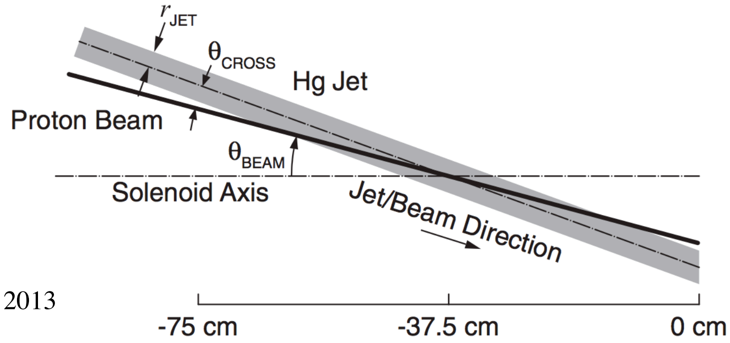
- Production of 10^{14} μ/s from 10^{15} p/s (≈ 4 MW proton beam)
- Proton beam readily tilted with respect to magnetic axis.
- Shielding of the superconducting magnets from radiation is a major issue.

- Hg Target
- Proton Beam
  - E=8 GeV
- Solenoid Field
  - IDS120h → 20 T peak field at target position (Z=-37.5)
  - Aperture at Target R=7.5 cm - End aperture R = 30 cm
  - Fixed Field Z = 15 m → Bz=1.5 T



5-T copper magnet insert; 10-T Nb3Sn coil + 5-T NbTi outsert.
Desirable to eliminate the copper magnet (or replace by a 20-T HTS insert).

- Production: Muons within energy KE cut 40-180 MeV end of decay channel
  - $N_{\mu+\pi+\varkappa}/N_P=0.3\text{-}0.4$



TAPERED TARGET SOLENOID OPTIMIZATION

Inverse-Cubic Taper

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

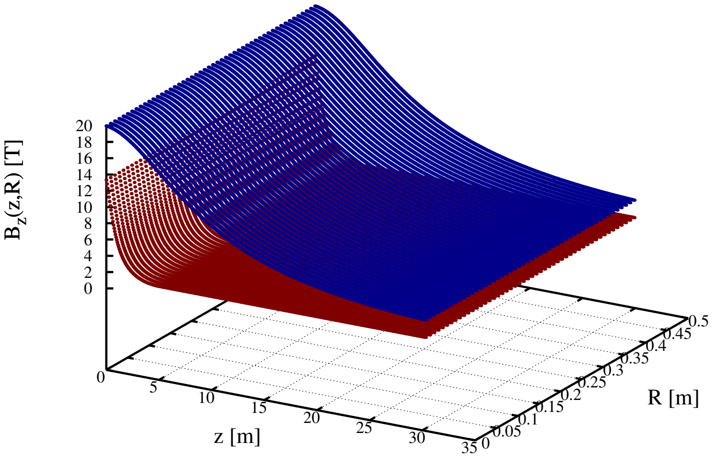
$$a1 = -\frac{B_1'}{pB_1} \qquad a_2 = 3\frac{(B_1/B_2)^{1/p}-1}{(z_2-z_1)^2} - \frac{2a_1}{z_2-z_1} \qquad a_3 = -2\frac{(B_1/B_2)^{1/p}-1}{(z_2-z_1)^3} + \frac{a_1}{(z_2-z_1)^2}$$

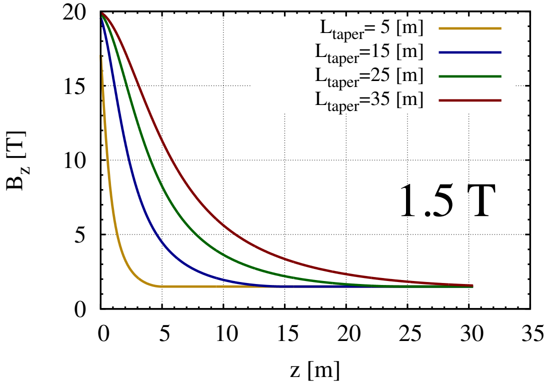
Off-axis field approximation

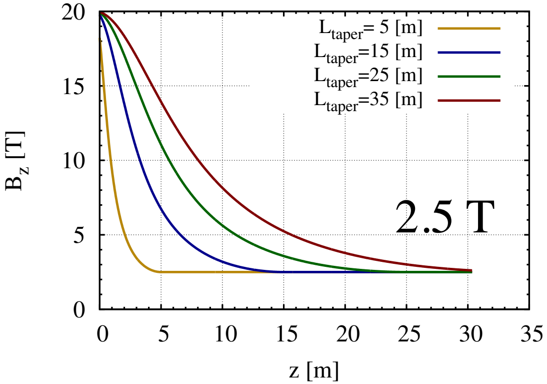
$$B_r(r,z) = \sum_n (-1)^{n+1} \frac{a_0^{(2n+1)}(z)}{(n+1)(n!)^2}\left(\frac{r}{2}\right)^{2n+1}$$

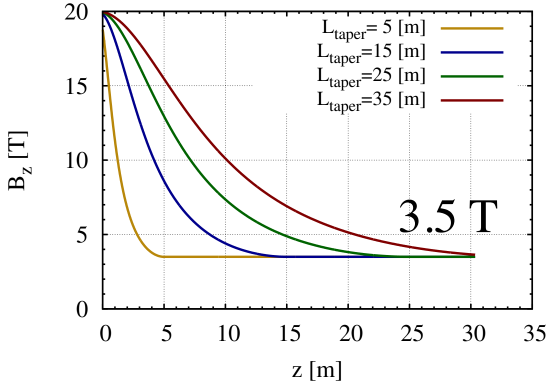
$$B_z(r,z) = \sum_n (-1)^n \frac{a_0^{(2n)}(z)}{(n!)^2}\left(\frac{r}{2}\right)^{2n}$$

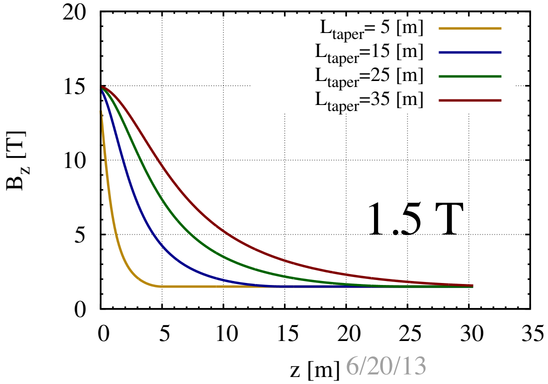
$$a_0^{(n)} = \frac{d^n a_0}{dz^n} = \frac{d^n B_z(0,z)}{dz^n}$$

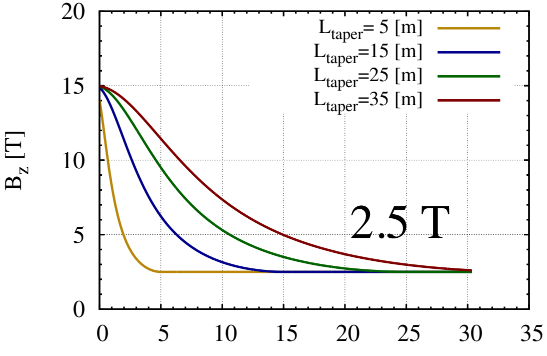


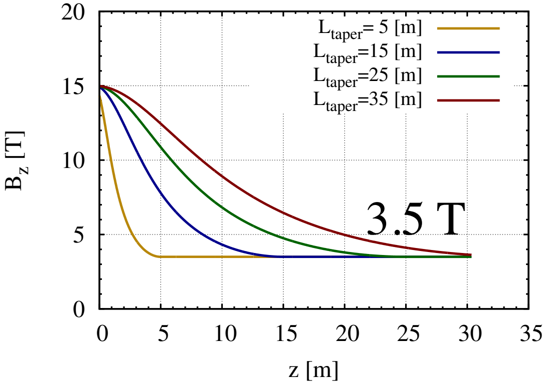






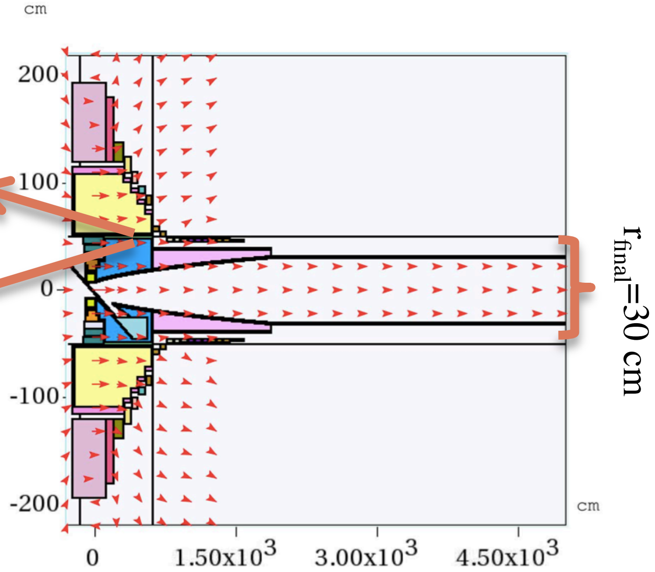






MARS SIMULATIONS & TRANSMISSION

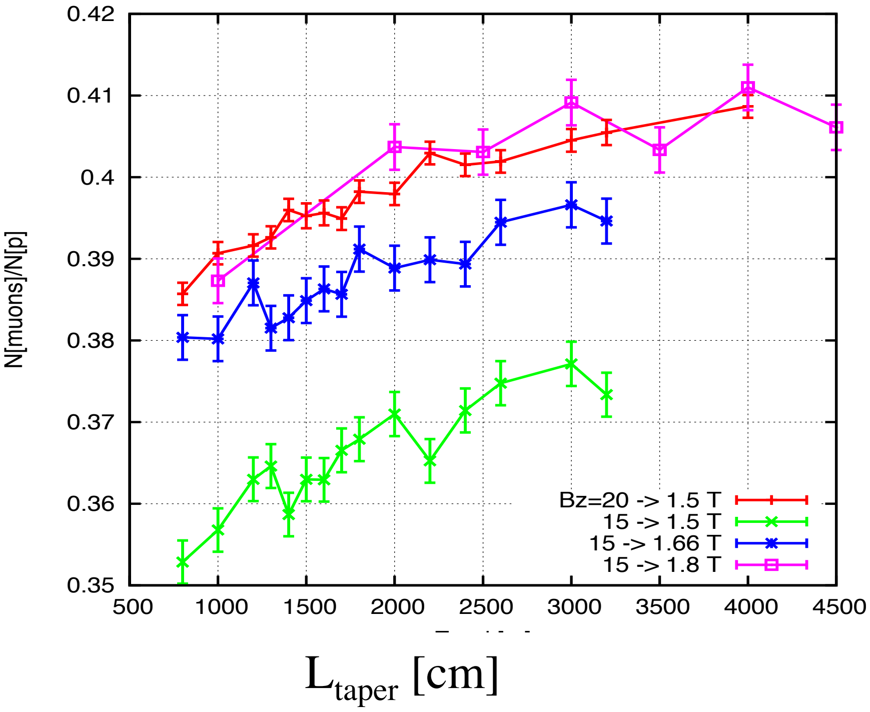
MARS1510 Simulation:
Counting muons at 50 m with K.E. 80-140 MeV



R_{ini}=7.5-10 cm

B_i=20-15 T

r_{final}=30 cm

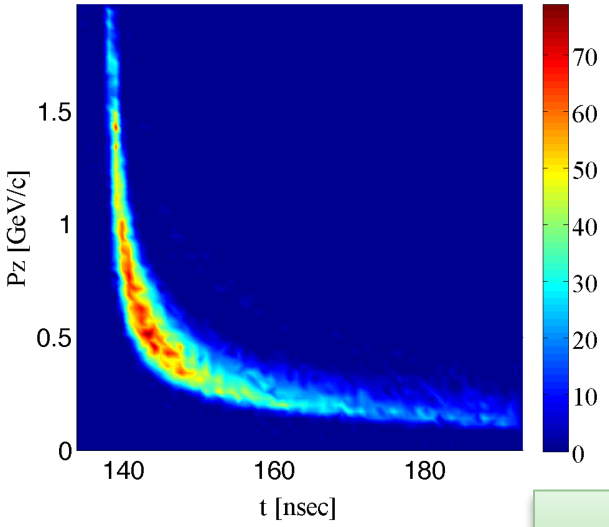


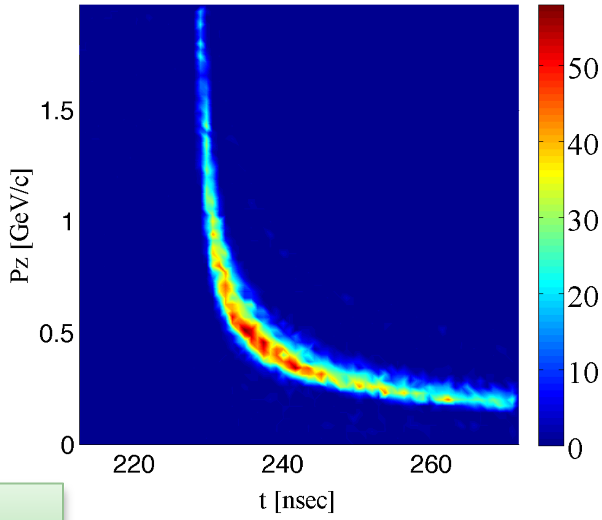
LONGITUDINAL PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

End of taper

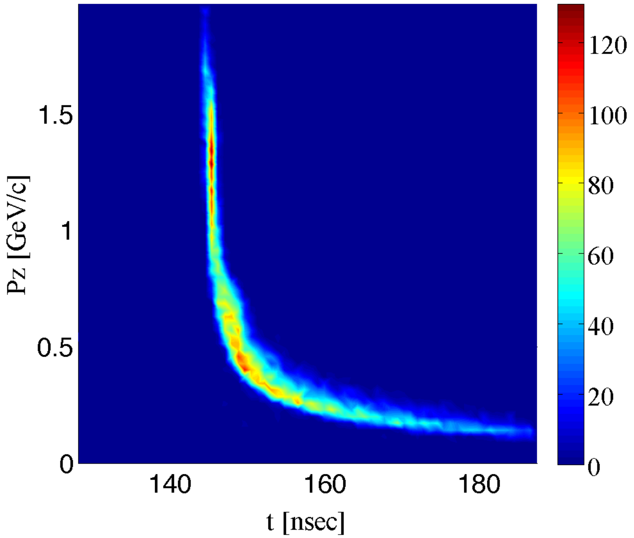
Long adiabatic taper 40 m

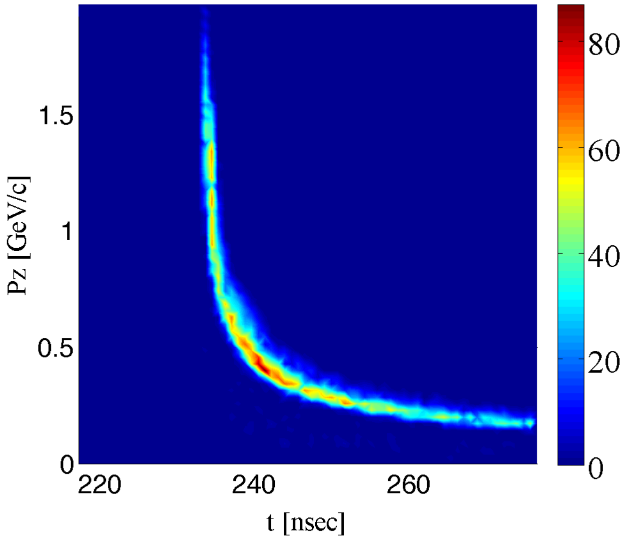
End of Decay





Short taper 4 m



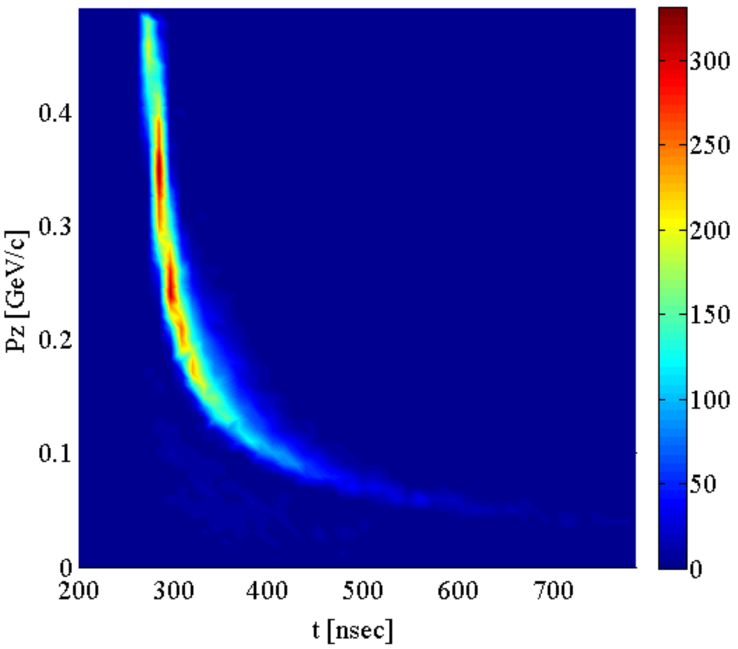


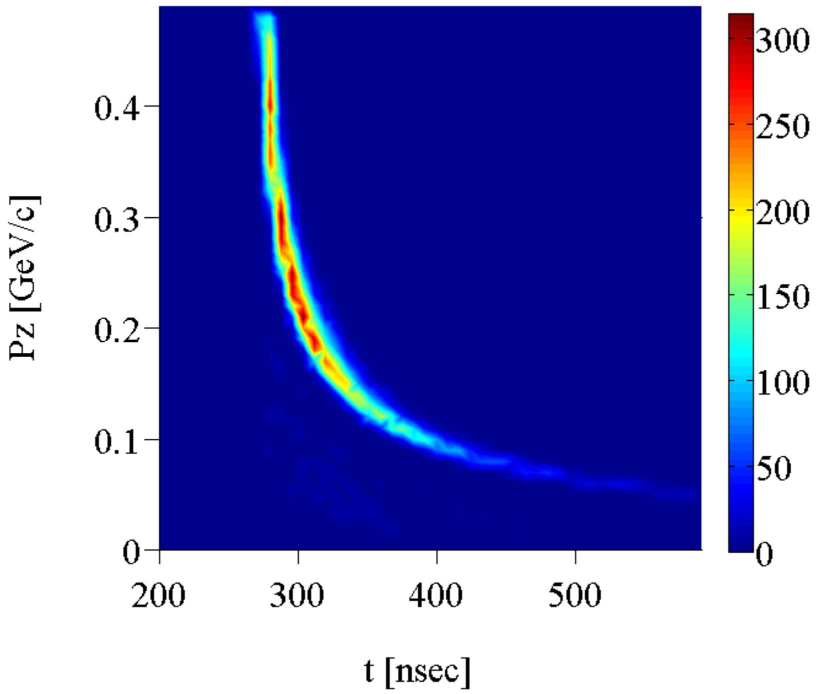
PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

T-Pz Correlations at end of decay channel

Long Solenoid taper:
- More particles
- More dispersed (misses the buncher acceptance windows)

Short Solenoid taper:
more condensed distributions that fits more particles within the buncher acceptance windows

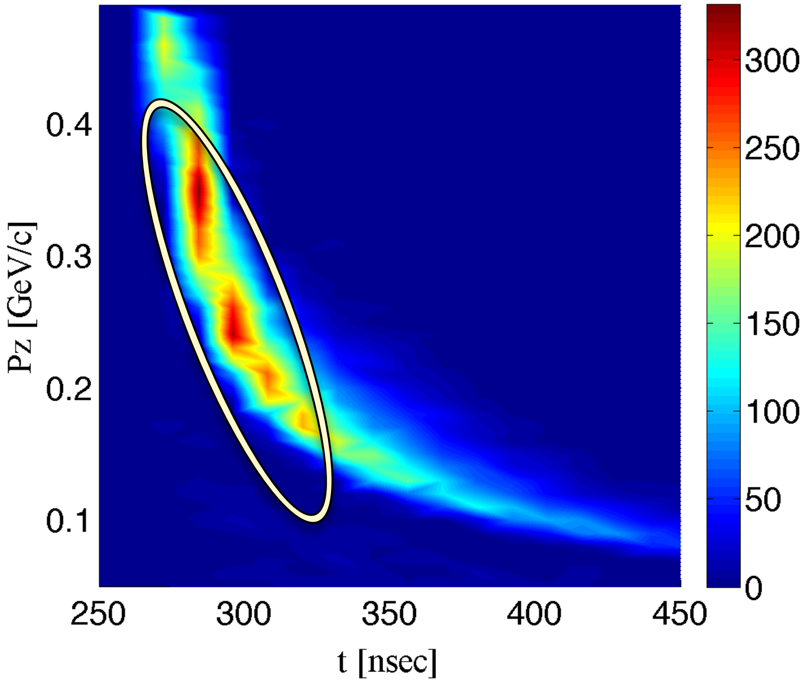

Long Taper


Short Taper

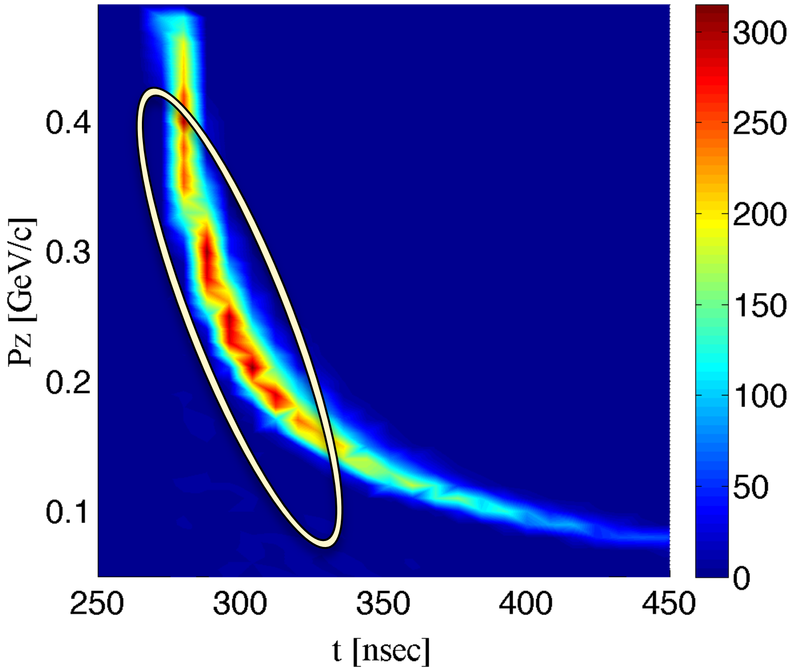
PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

T-Pz phase space at end of decay channel

Long Taper 40 m



Short Taper 4 m



Long Solenoid taper:

- More particles
- More dispersed (misses the buncher acceptance windows)

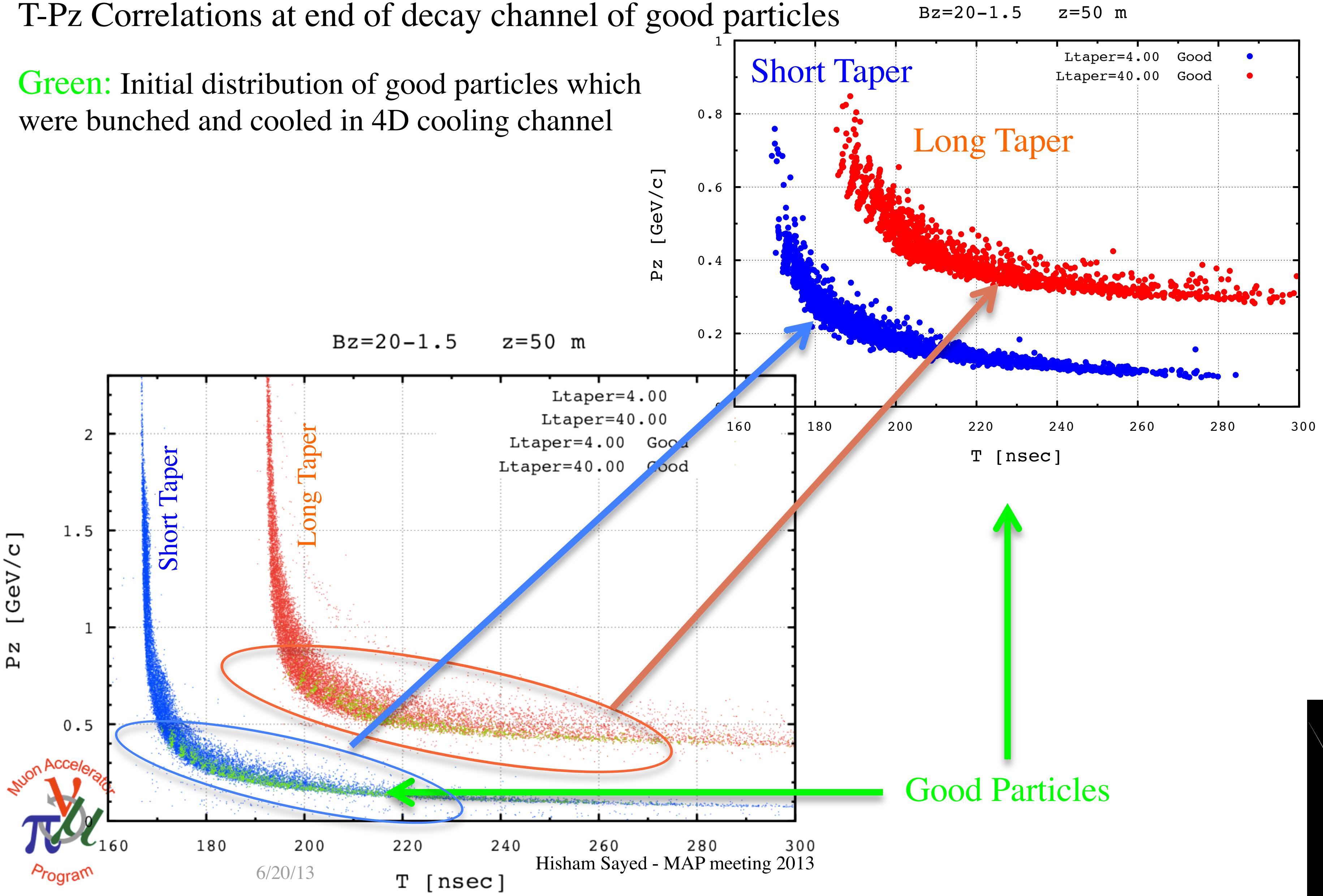
Short Solenoid taper:

- Higher density t-pz distribution
- Fits more particles within the acceptance of buncher/rotator

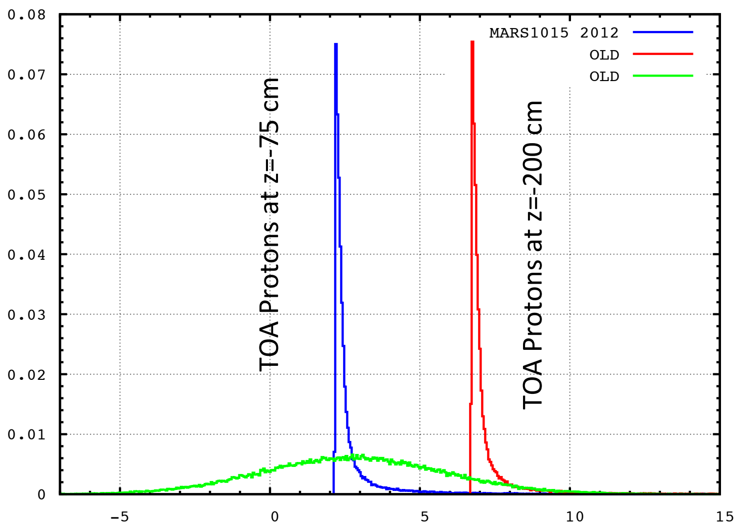
PHASE SPACE - SHORT VERSUS LONG TAPER

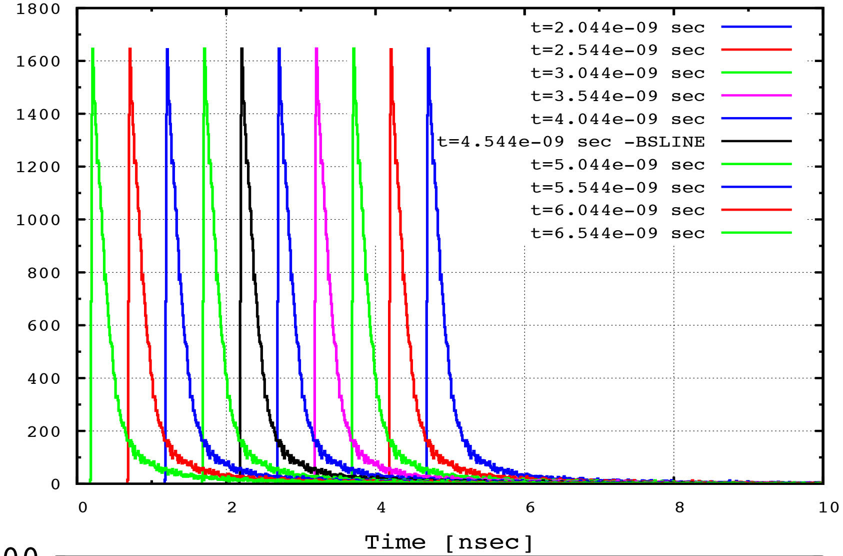
T-Pz Correlations at end of decay channel of good particles

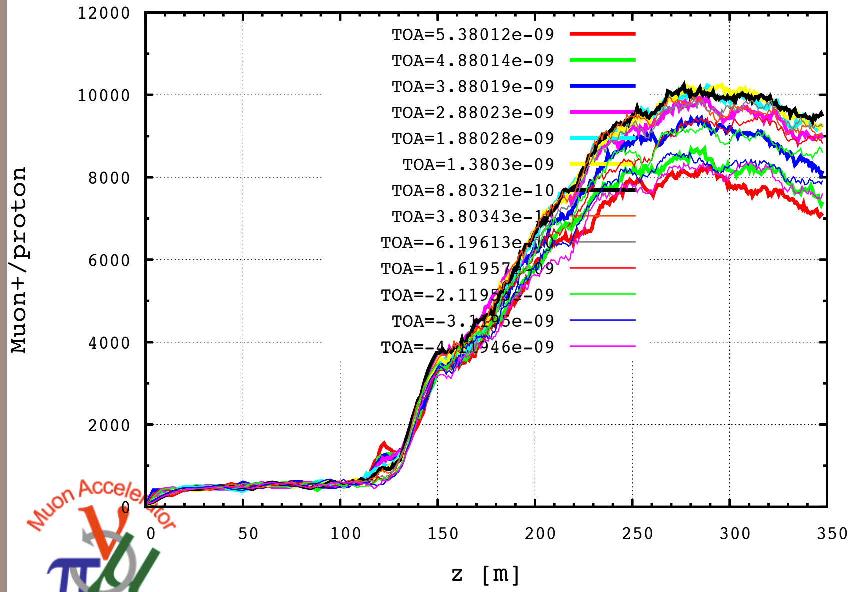
Green: Initial distribution of good particles which were bunched and cooled in 4D cooling channel

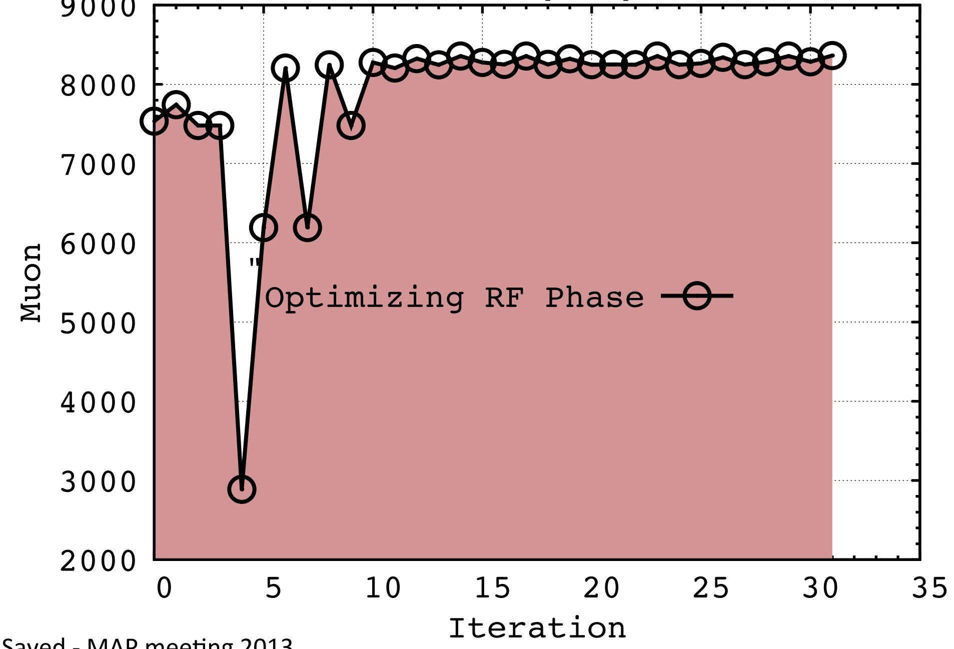


PERFORMANCE DEPENDENCE ON TIME OF FLIGHT (RF PHASE)



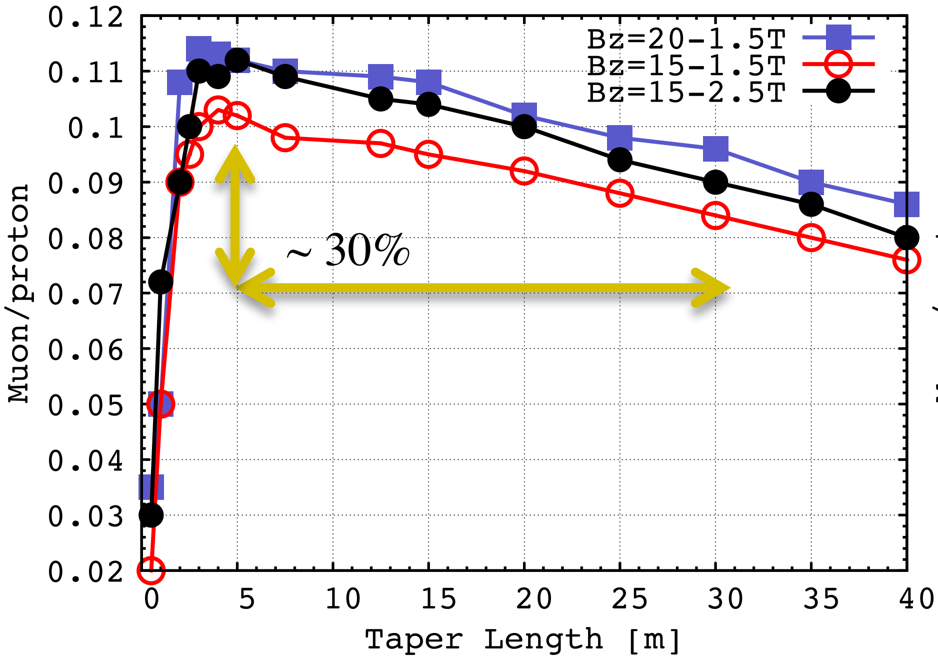




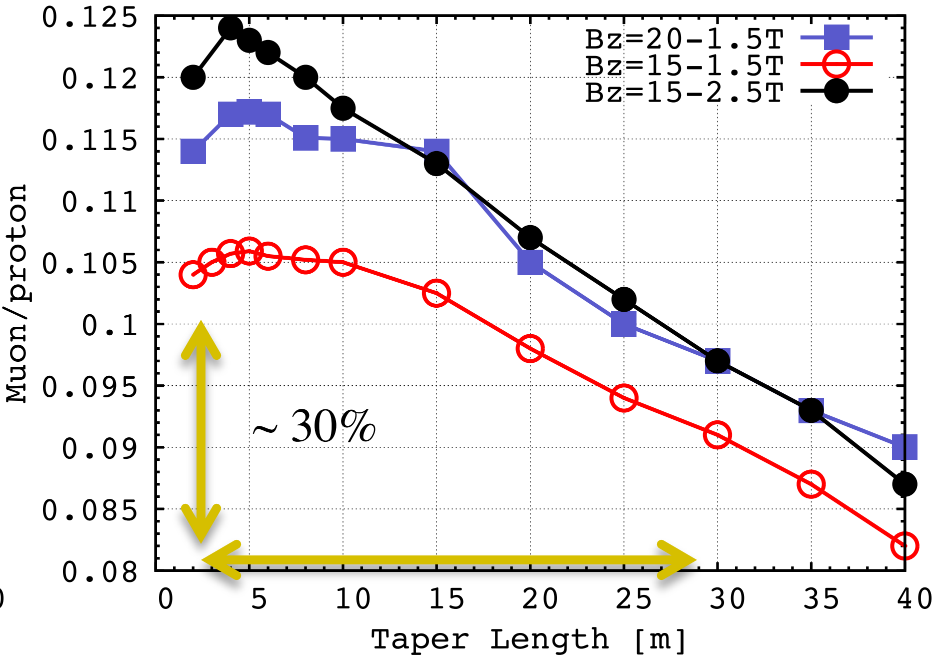


FRONT END PERFORMANCE

Using baseline cooling section
(140 cooling cell)

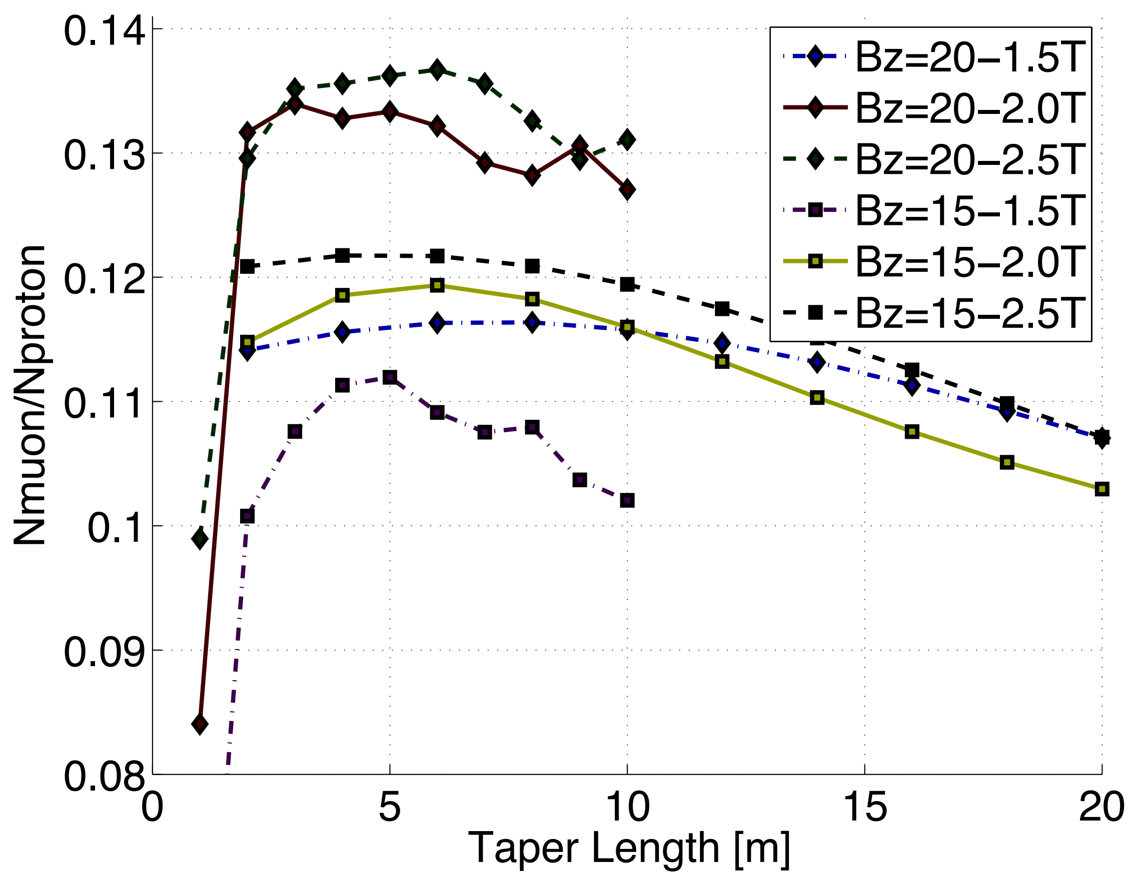


Using longer cooling section
(200 Cooling cell)



High statistics tracking of Muons through the front end

FRONT END PERFORMANCE

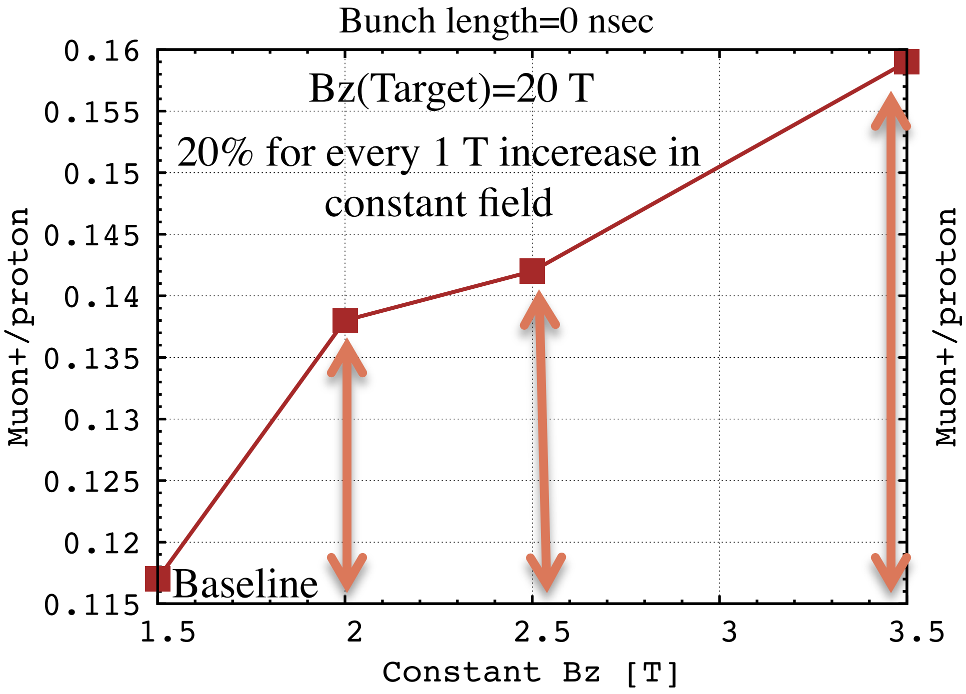


Using longer cooling section
(200 Cooling cell)

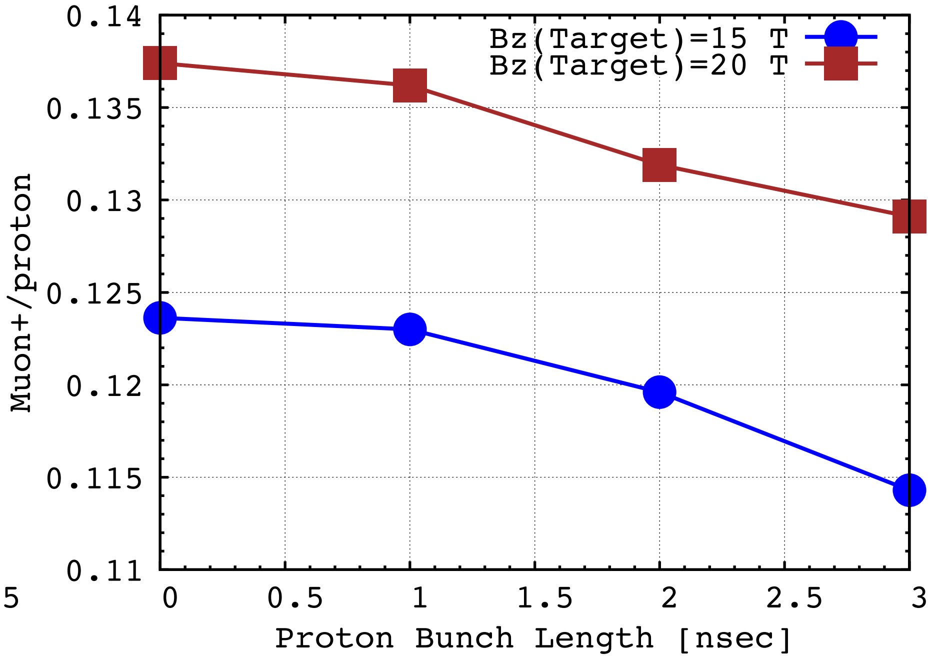
High statistics tracking of Muons through the front end

MUON YIELD VERSUS END FIELD & BUNCH LENGTH

Muon yield versus end field



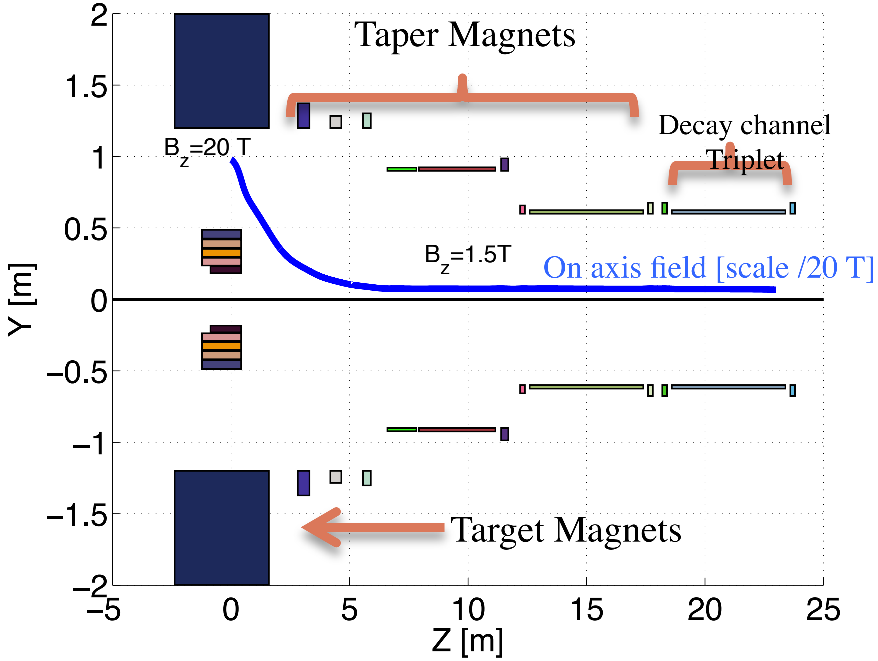
Muon yield versus Proton Bunch Length



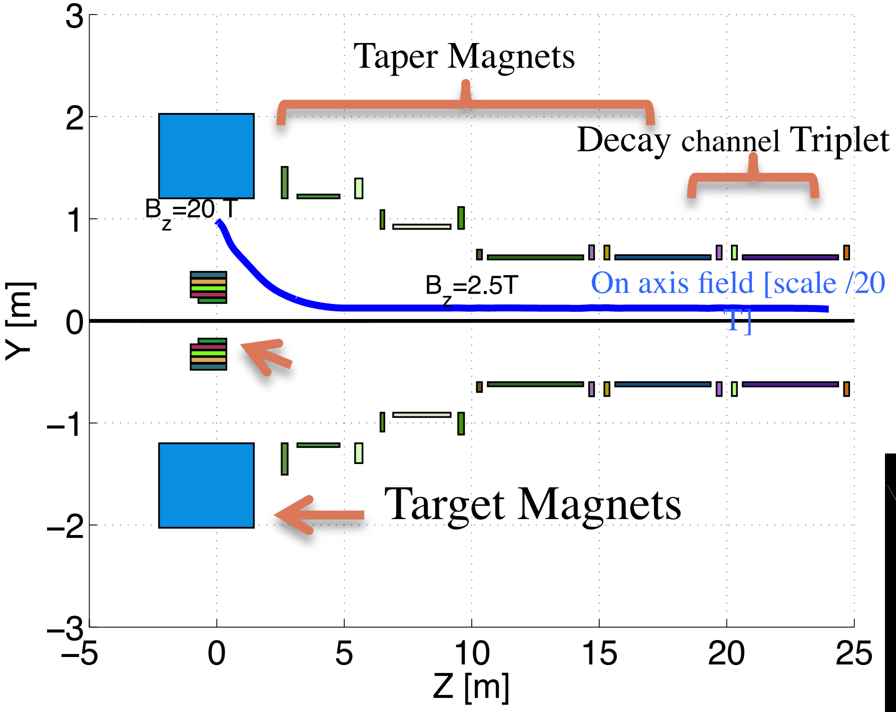
Performance of FE as function of Constant solenoid filed in Decay Channel – Buncher – Rotator (matched to +/- 2.8 T ionization cooling channel)

~ 3% loss per 1 nsec increase in bunch length

NEW SHORT TARGET CAPTURE REALISTIC MAGNET (WEGGEL)



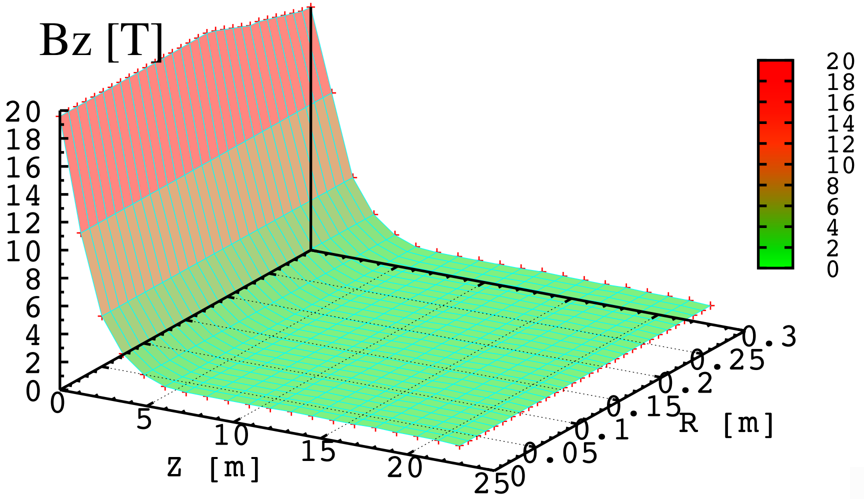
Muon Target Capture Magnet
Short Taper length =7 m- B=20-1.5 T



Muon Target Capture Magnet
Short Taper length =5 m- B=20-2.5 T

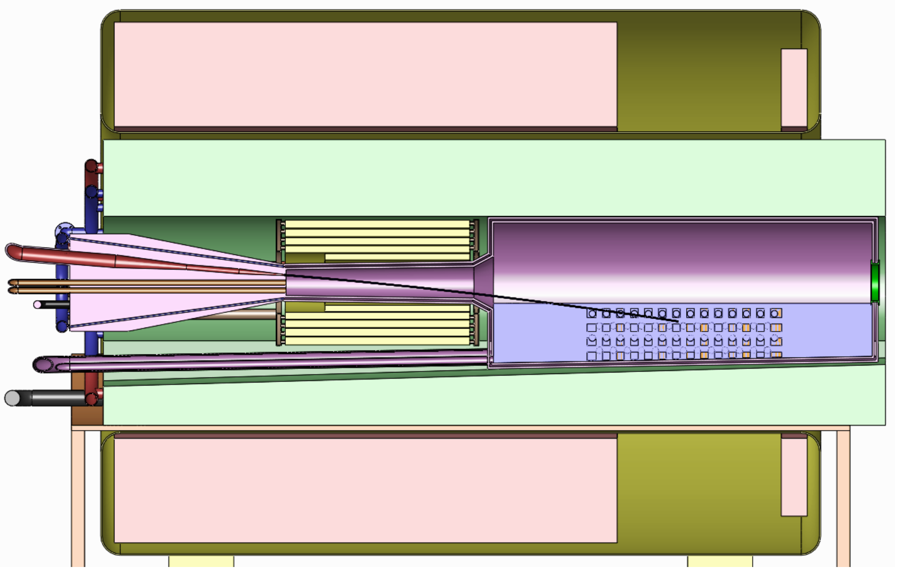
NEW SHORT TARGET CAPTURE MAGNET (WEGGEL)

Muon Target Short Taper Magnet taper length =7 m- B=20-1.5 & 2.5 T



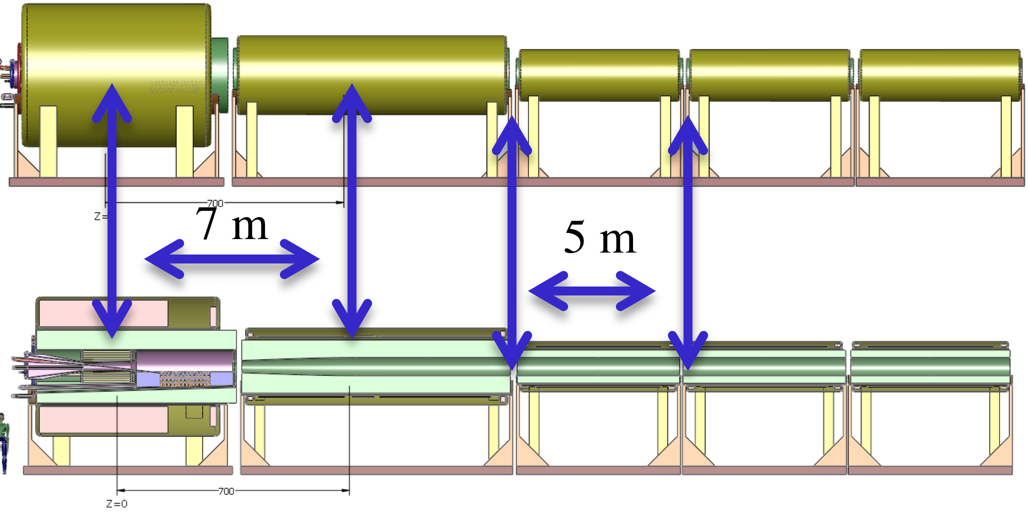
Target SC Magnets Field Map calculated from realistic coils

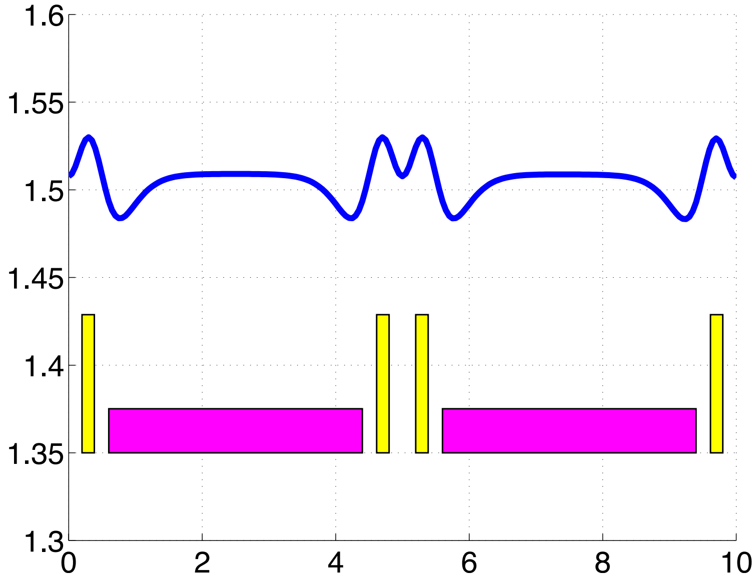
Engineering (V. Grave)
IDS120_20-1.5T7m2+5 Cryo 1



NEW DECAY CHANNEL REALISTIC MAGNET (WEGGEL)

- ➢The pions produced in the target decay to muons in a Decay Channel (50 m)
- ➢Three superconducting coils (5-m-long) Bz(r=0) ~ 1.5 or 2.5 T solenoid field.
- ➢Suppress stop bands in the momentum transmission.





Axial-field profile of two Decay-Channel modules

IDS120L20-1.5T 7m

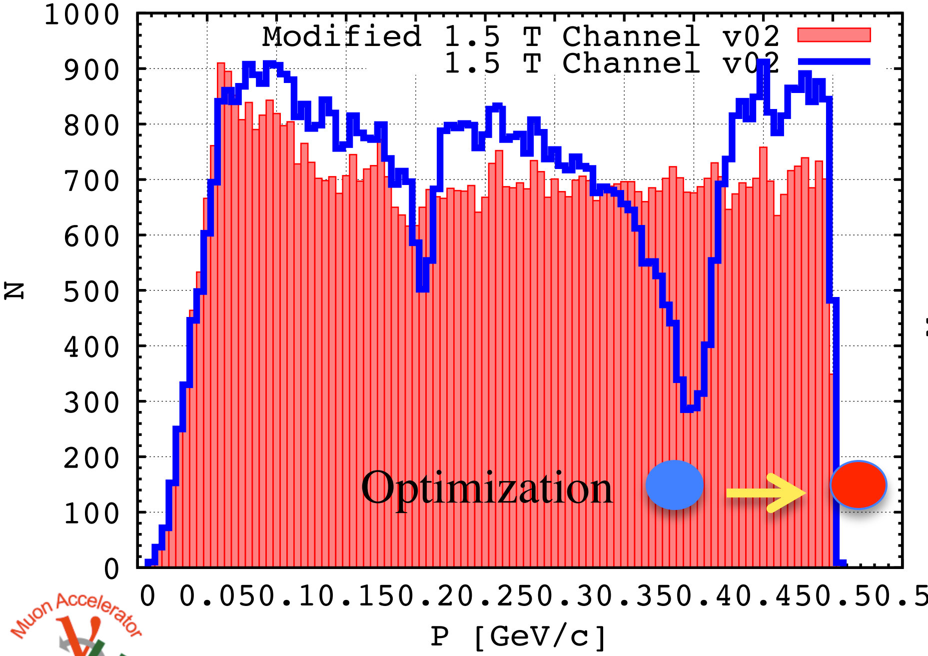
Magnet	Length [m]	Inner R [m]	Outer R [m]	J [A/mm^2]
1	0.19	0.6	0.68	47.18
2	3.8	0.6	0.63	40.00
3	0.19	0.6	0.68	47.18

REALISTIC COIL BASED DECAY CHANNEL SOLENOID STOP BAND STUDY

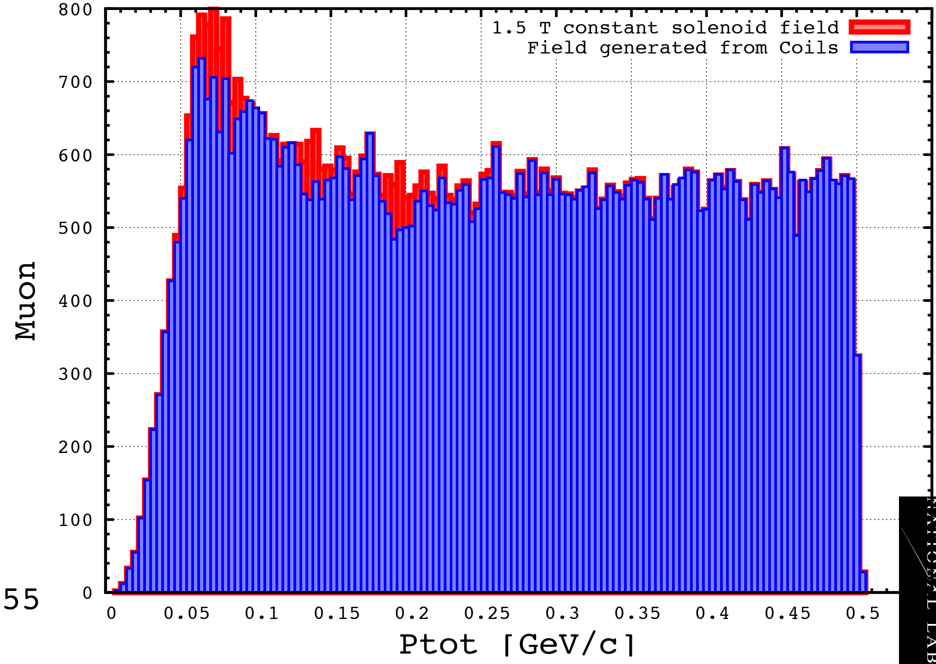
Suppression of stop bands in the Decay Channel:
Tracking muons through decay channel 10 cells (50 m) optimize magnet design for best performance

Transmission:	
Constant 1.5 Solenoid Field	%67
IDS120L20to1.5T7m	%62
Modified IDS120L20to1.5T7m	%66

IDS120L20to1.5T7m



IDS120L20to1.5T7m



CONCLUSION & SUMMARY

1- Target Solenoid parameters that affect the particle Capture & Transmission at target or after cooling

Initial peak Field – Taper length – End Field

2- Impact:

Short taper preserves the longitudinal phase-space → muons can be captured efficiently in the buncher-phase rotation sections and more muons at the end of cooling.

The maximum yield requires taper length of 7-5 m for all cases (20-15T) (1.5-3.5T) for any bunch length.

3- Final constant end field increases the yield by 20% for every 1 T increase in the field beyond the 1.5 T baseline

4- Initial proton bunch length influence the muon/proton yield at the end of the cooling channel

~ 3% reduction per 1 nsec increase in bunch length.

5- Realistic Coil design.