GLOBAL OPTIMIZATION OF THE MUON COLLIDER/NEUTRINO FACTORY FRONT END

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FRONT END MEETING
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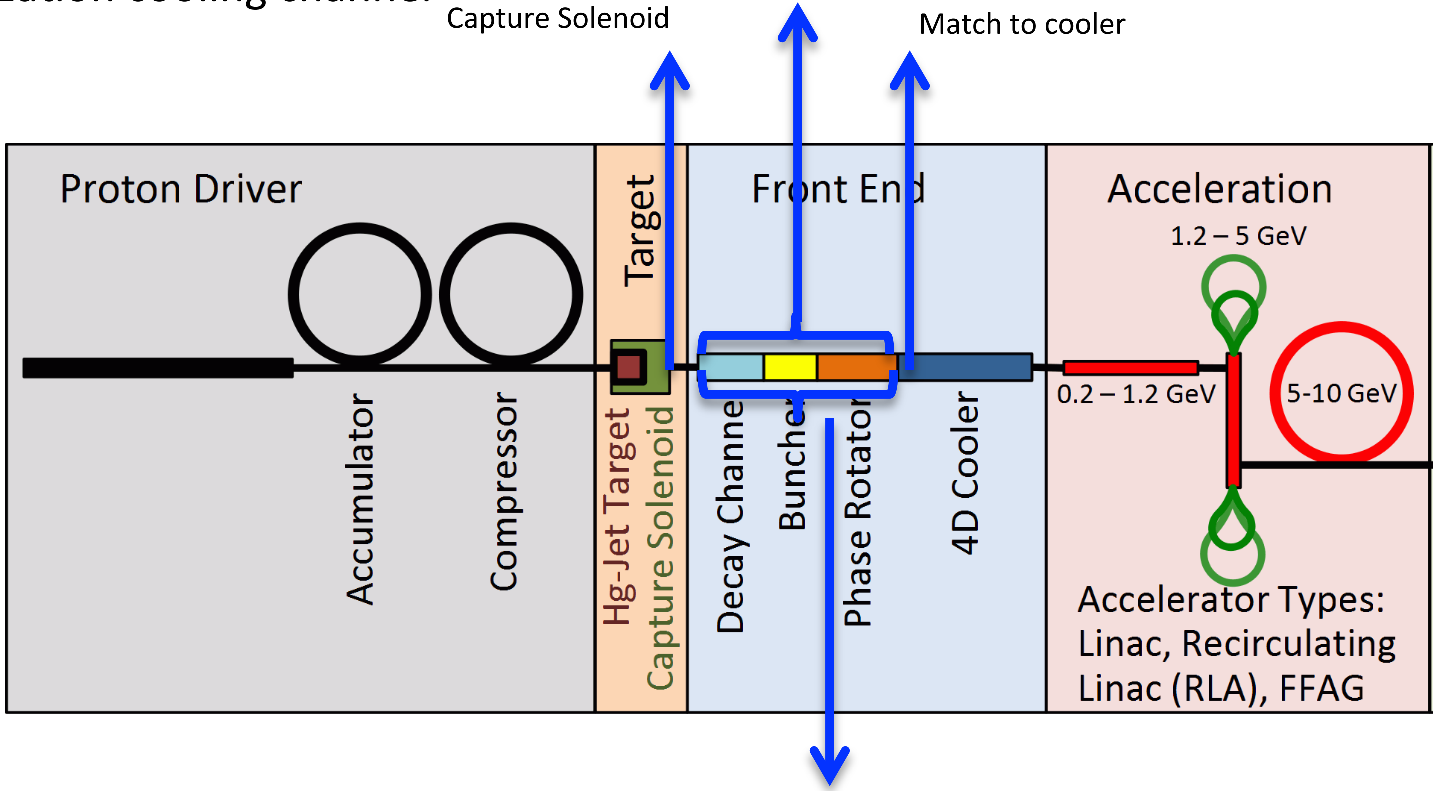
GLOBALLY OPTIMIZING MUON TARGET & FRONT END

1- Target (Captured Beam quantity & quality)
2- Decay channel
3- Buncher – Phase rotator
4- Matching to the cooling channel
5- Ionization cooling channel



Capture Solenoid

Decay channel solenoid

Match to cooler

Capturing muons in bunches

INTRODUCTION & LAYOUT

- High performance Optimization Tools on NERSC
- Target:
  - Capture Field → Muon (Pions) count – transverse capture
    → Muon (Pions) longitudinal & transverse phase space
  - Target – Proton Beam geometry (size – incident angle) pion count
- Decay Channel: → Control stop band losses (optimize realistic coil design)
- Decay Channel - Buncher – Phase rotator → Length- RF (voltage- frequency – phase)
- Transverse focusing field in decay channel-buncher-rotator
- Broadband match to ionization cooling channel for every end field case 1.5 T → 3.5 T
- Realistic Coil Design & performance optimization
- Ionization cooling channel

INTRODUCTION & LAYOUT

Parameters which effects the performance of the overall front end in every system

- 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

NUMERICAL NONLINEAR GLOBAL OPTIMIZATION ALGORITHMS

- **Global Optimization Algorithms:**

Disadvantage: Computationally expensive (requires large number of iterations to converge)
Advantage: Guarantee of finding the global optimum (without falling to the nearest local maxima/minima).

- **Expensive objective evaluations: (Tracking large number of particles)**
  - Fast converging algorithms (problem dependent)
  - High performance parallel environment:
    - 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- R. RYNE).
- **Implemented algorithms:**
  - **Parallel Differential Evolutionary Algorithms** (J. Qiang): stochastic operators iteratively improve a population of individuals (candidate solutions) according to an adaptation criterion (the objective function)

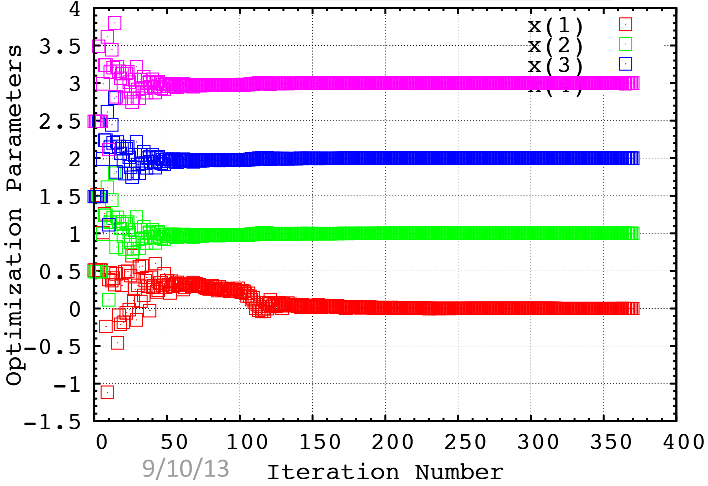
  Stochastic based optimizer – Global nonlinear optimizer which works well with problems with many local minima – Computationally expensive but running in parallel reduces the cost.

  - **Nelder-Mead:**

  Direct search method (non gradient based) – Computationally less expensive – Not a true "Global Optimizer" but can work with local minima although not guaranteed – Faster convergence with not so hard problems.

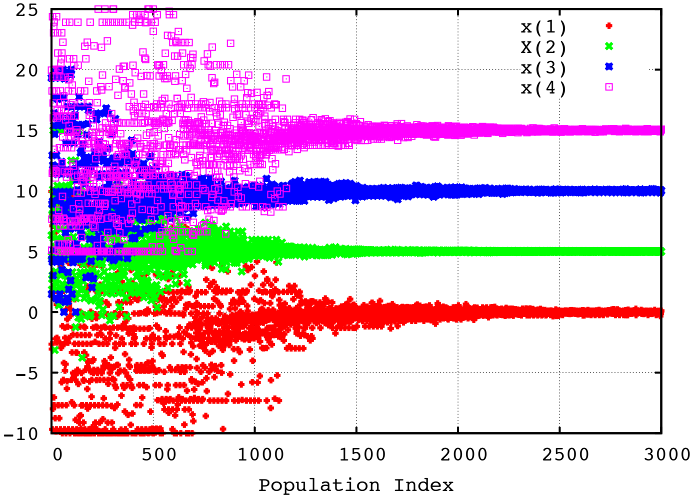
POWELL'S SINGULAR FUNCTION

Nelder-Mead



POWELL'S SINGULAR FUNCTION

Evolutionary Algorithms



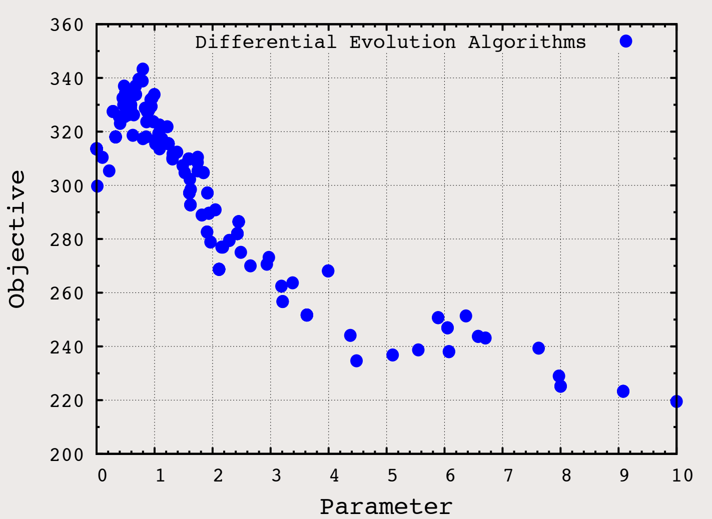
OPTIMIZING 325 MHZ BUNCHER – ROTATOR "DIFFERENTIAL EVOLUTION"

Tools:

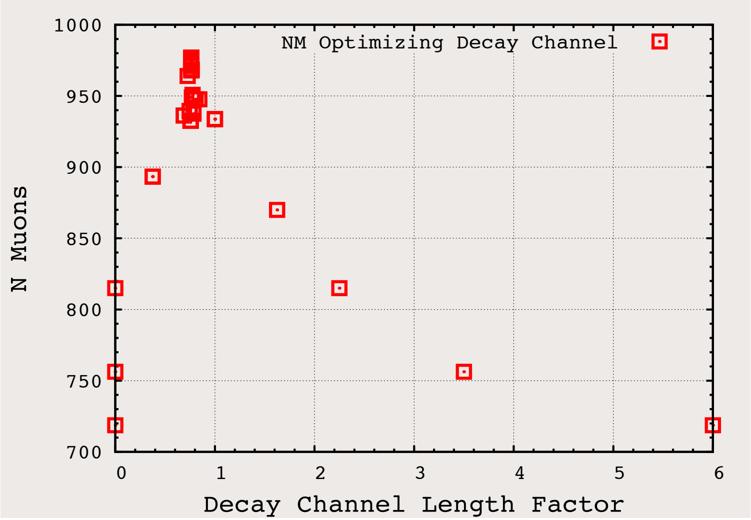
Parallel Differential evolution algorithm that works with with parallel Icool – (future includes G4BL)

Conventional optimization algorithm "Nelder-Mead" with parallel code (MPI ICOOL)

Evolutionary Algorithms



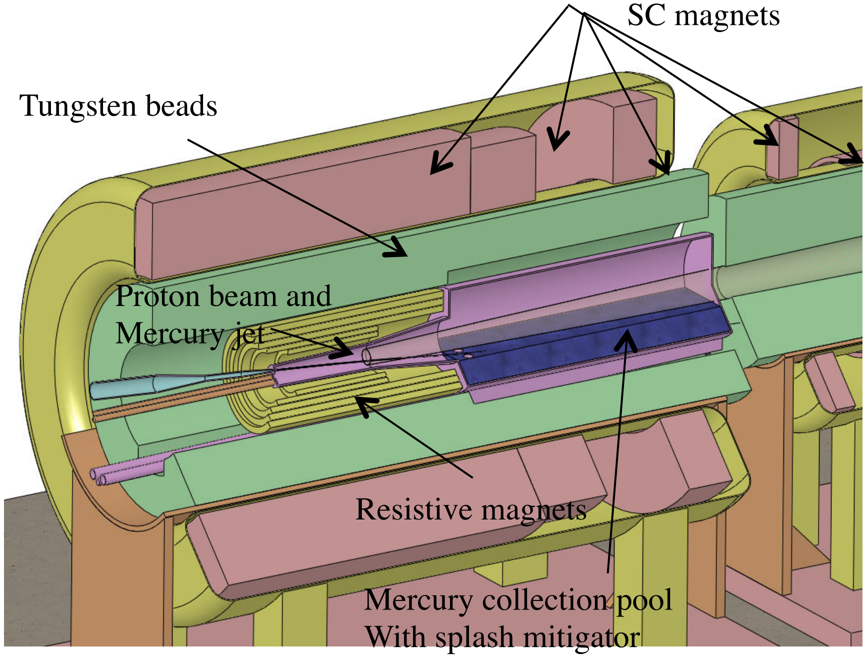
Nelder-Mead



- One parameter "decay channel length" → one objective (N muons within accelerator acceptance cuts)
- Converged after 200 icool calls (12 generations) .
- Random search in the parameter space (good for the global minima)
- More robust in case of close local minima

TARGET SYSTEM CURRENT BASELINE DESIGN

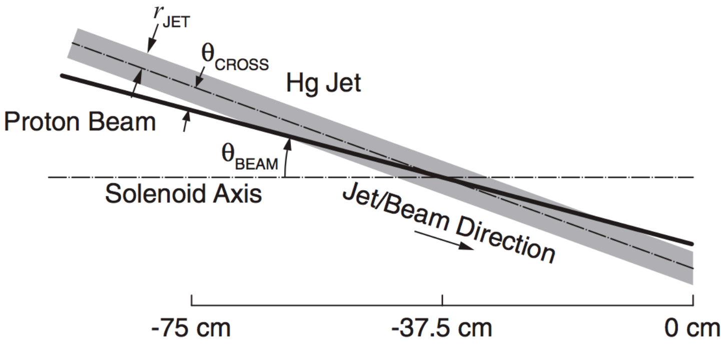
- Production of 10^{14} μ/s from 10^{15} p/s (≈ 4 MW proton beam)
- Proton beam readily tilted with respect to magnetic axis.



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).

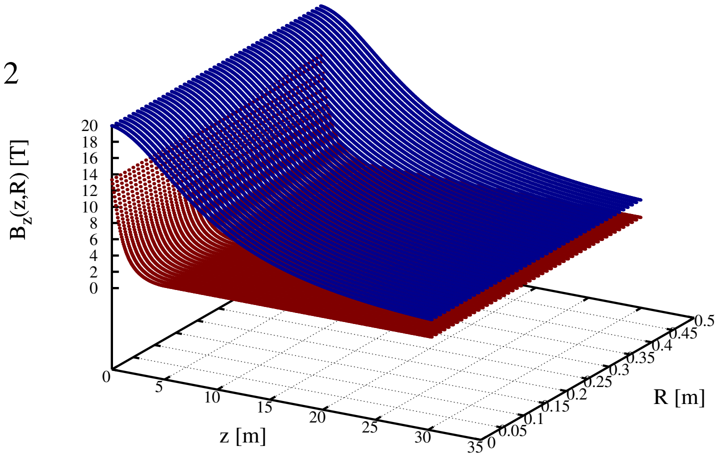
- Hg Target
- Proton Beam
  - E=8 GeV
- Solenoid Field
  - IDS120h → 20 T peak field at target position (Z=-37.5)
  - Aperture at Target R=7.5 cm - End aperture R = 30 cm
  - Fixed Field Z = 15 m → Bz=1.5 T

- Production: Muons within energy KE cut 40-180 MeV end of decay channel
  - $N_{\mu+\pi+k}/N_P=0.3\text{-}0.4$
- Beam – Target geometry optimization (X. Ding)



TAPERED TARGET SOLENOID OPTIMIZATION

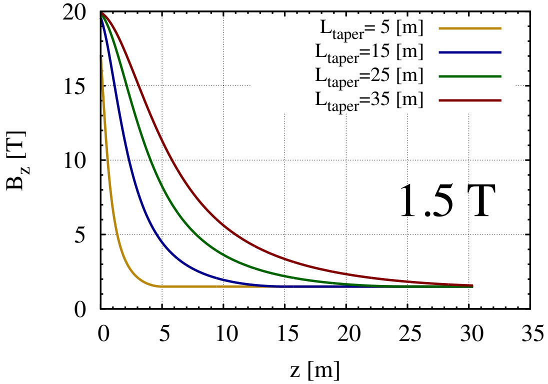
Initial peak Field B_1 – Taper length z – End Field B_2

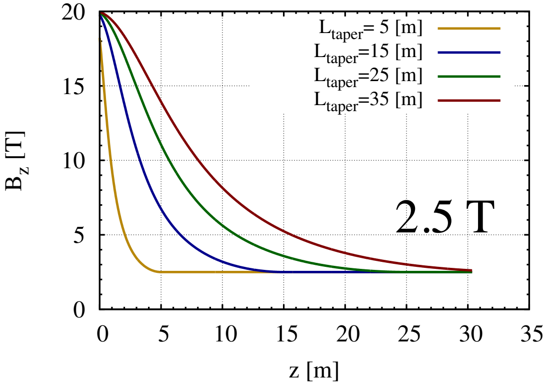


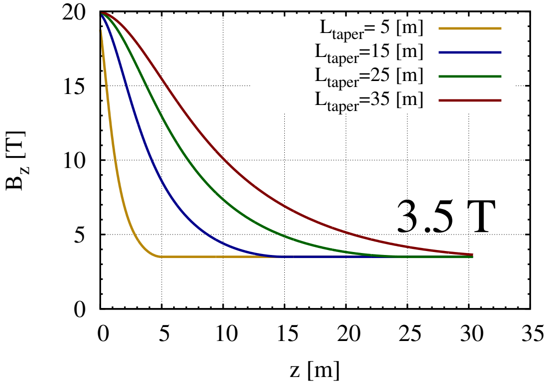
Inverse-Cubic Taper

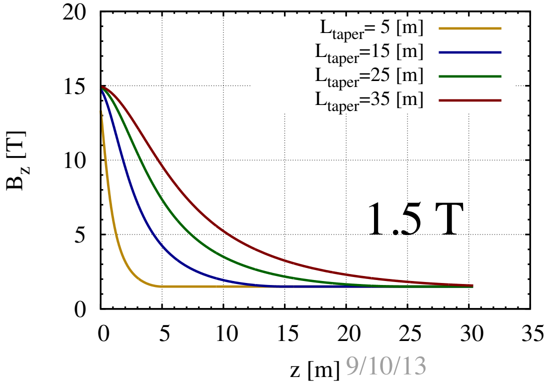
$$B_z(0, z_i < z < z_f) = \frac{B_1}{[1+a_1(z-z_1)+a_2(z-z_1)^2+a_3(z-z_1)^3]^p}$$

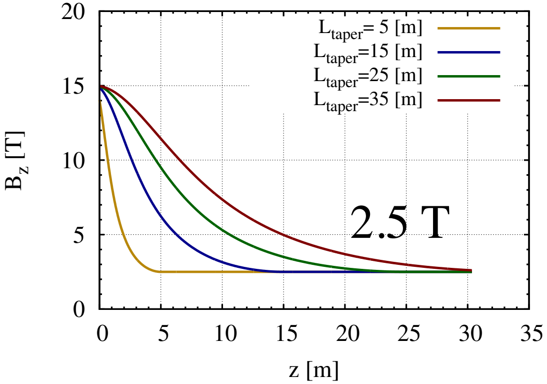
$$a1 = -\frac{B_1^{'}}{pB_1} \qquad a_2 = 3\frac{(B_1/B_2)^{1/p}-1}{(z_2-z_1)^2} - \frac{2a_1}{z_2-z_1} \qquad a_3 = -2\frac{(B_1/B_2)^{1/p}-1}{(z_2-z_1)^3}+\frac{a_1}{(z_2-z_1)^2}$$

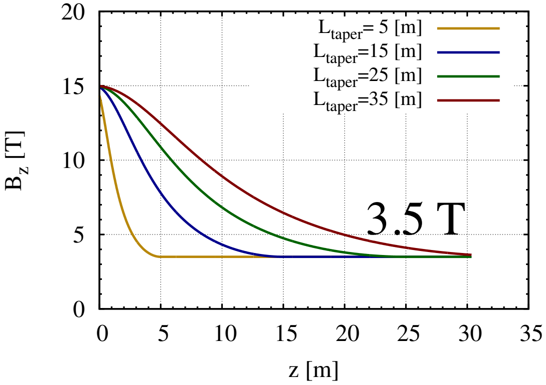










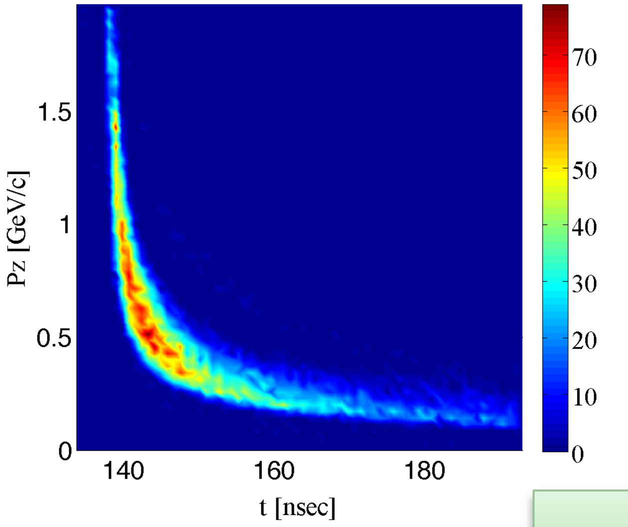


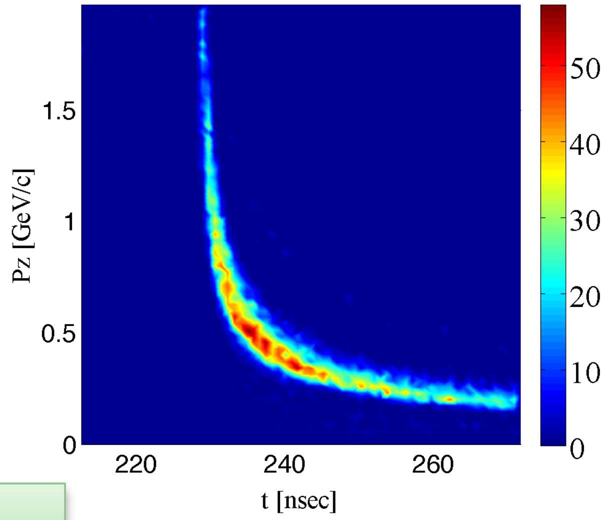
LONGITUDINAL PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

End of taper

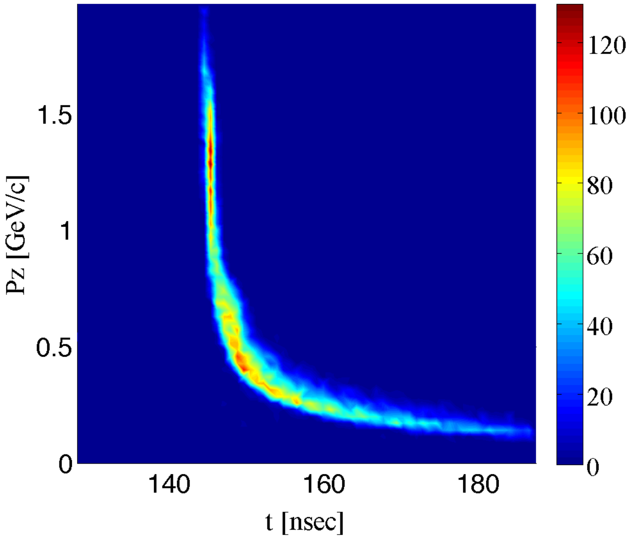
Long adiabatic taper 40 m

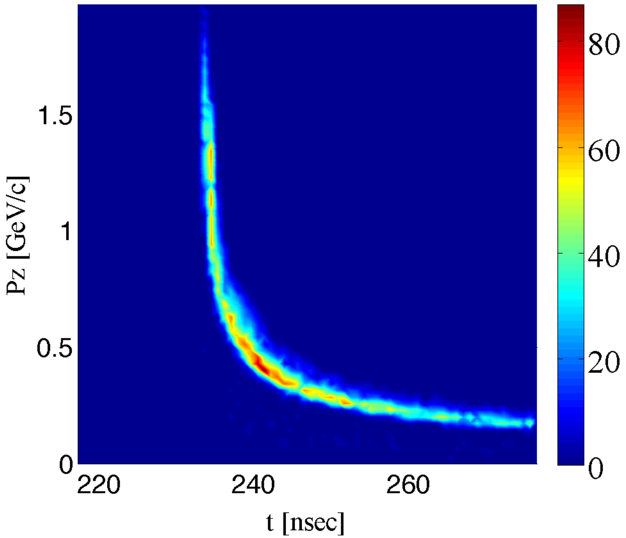
End of Decay





Short taper 4 m

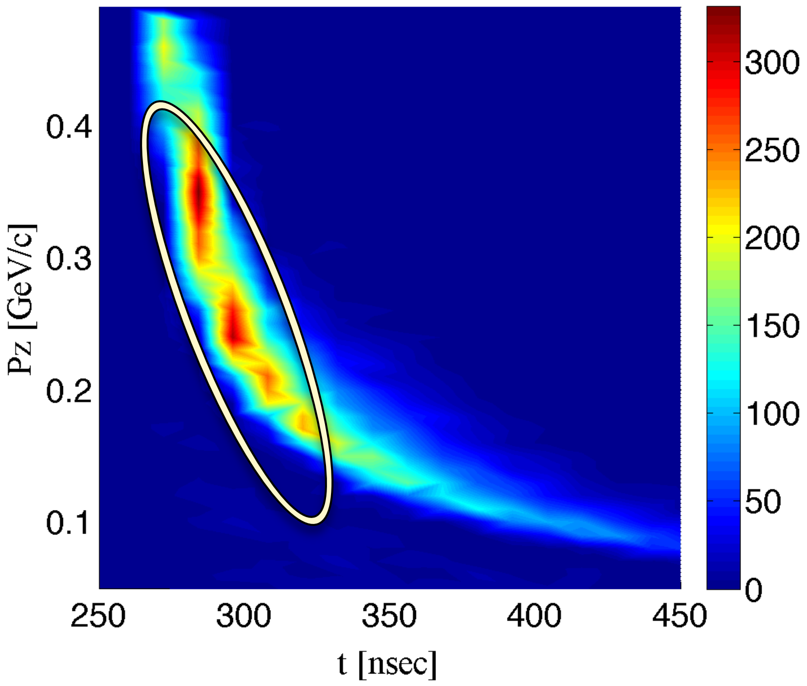




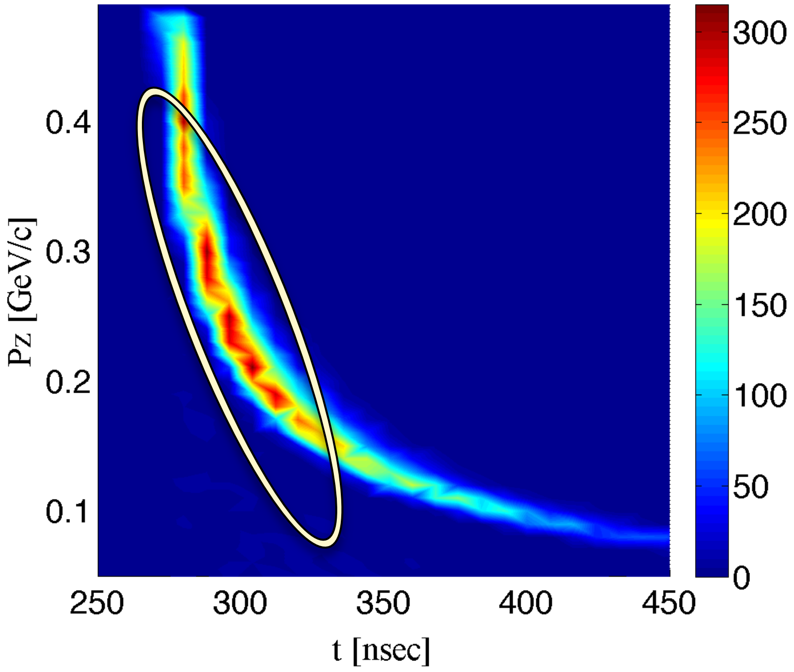
PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

Longitudinal phase space at end of decay channel

Long Taper 40 m



Short Taper 4 m



Long Solenoid taper:

- More particles
- Large time spread → large longitudinal emittance

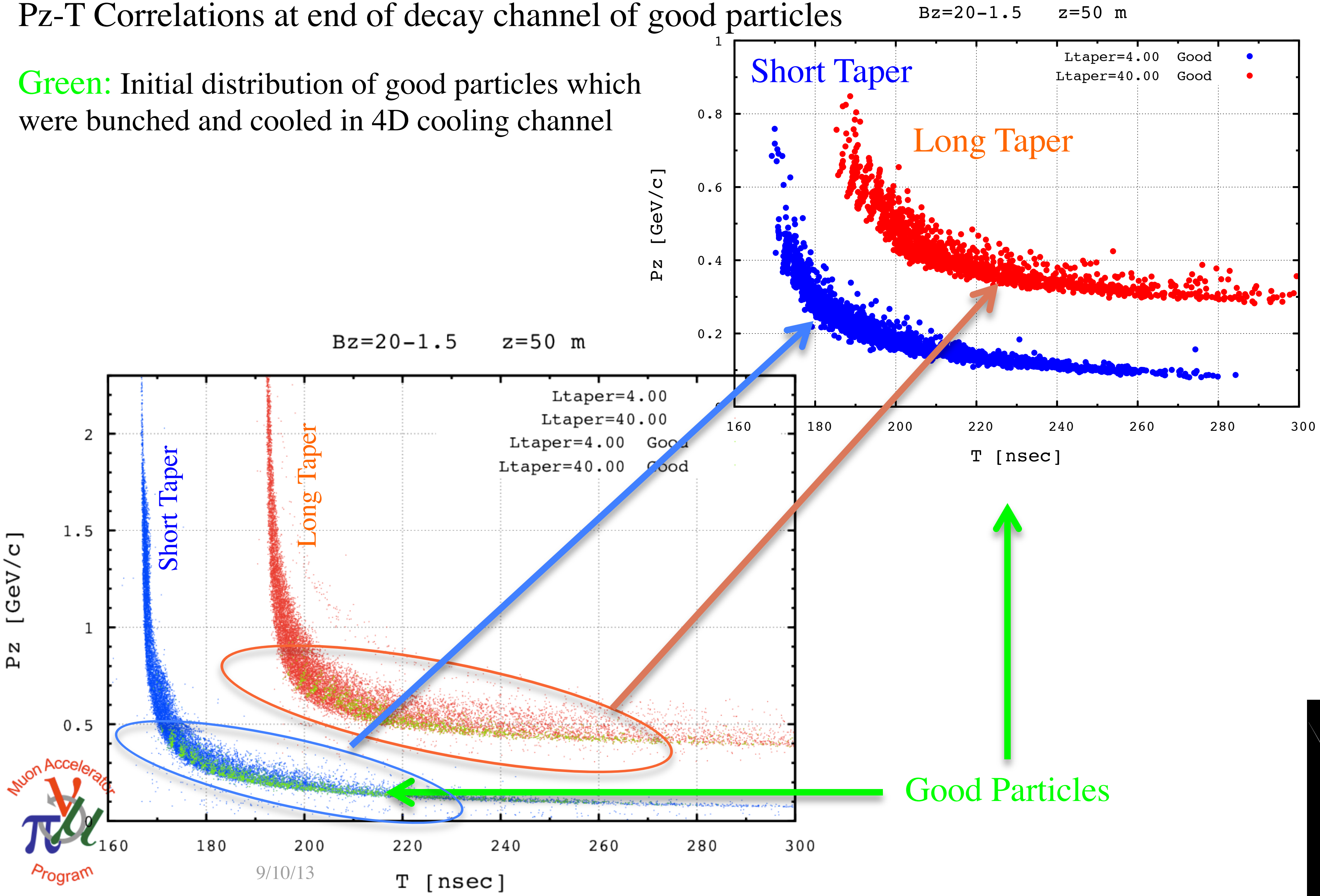
Short Solenoid taper:

- Smaller time spread → smaller longitudinal emittance
- Fits more particles within the acceptance of buncher/rotator

PHASE SPACE - SHORT VERSUS LONG TAPER

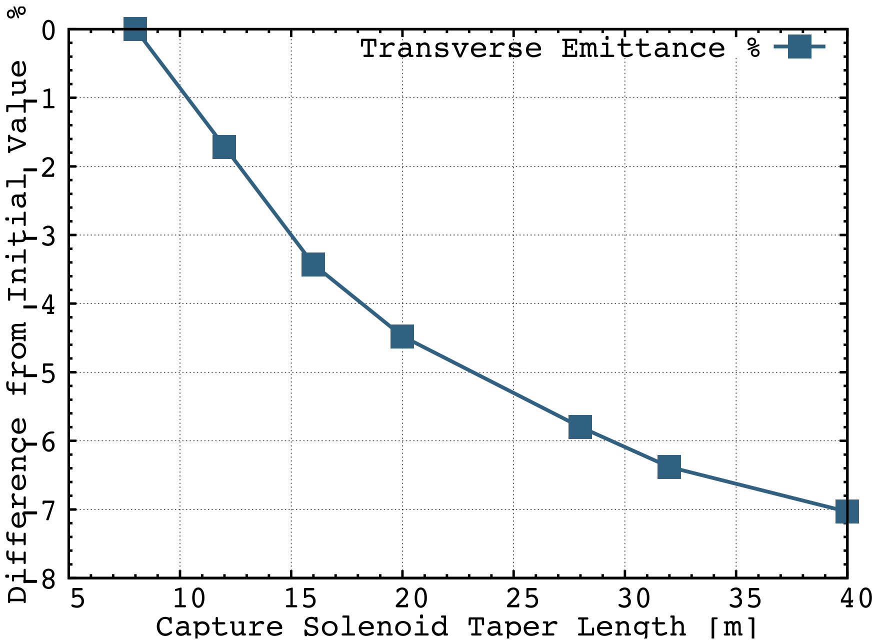
Pz-T Correlations at end of decay channel of good particles

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

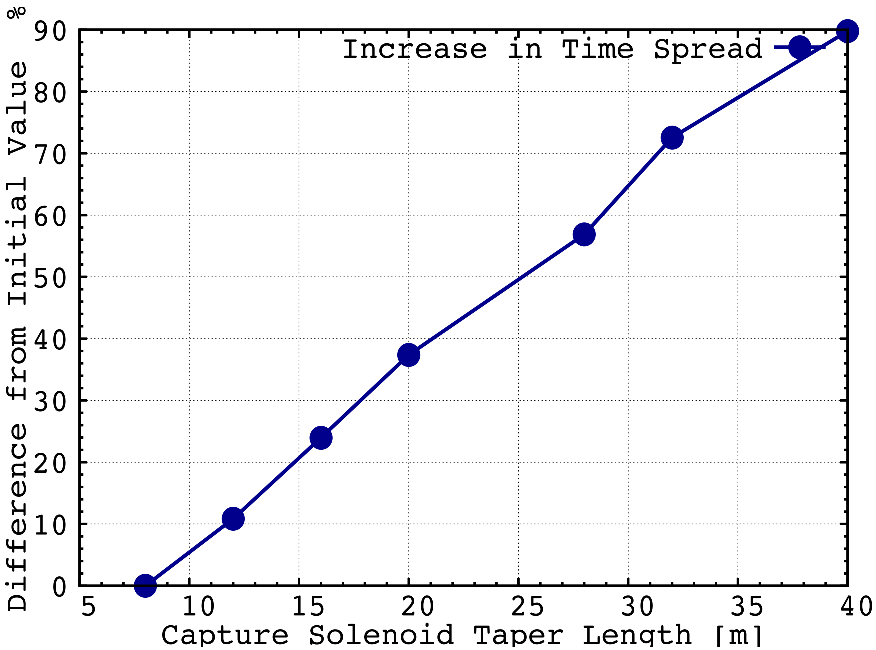


DEPENDENCE OF TIME SPREAD & TRANSVERSE EMITTANCE ON TAPER LENGTH

Transverse emittance shaped by capture solenoid



Time spread shaped by capture solenoid

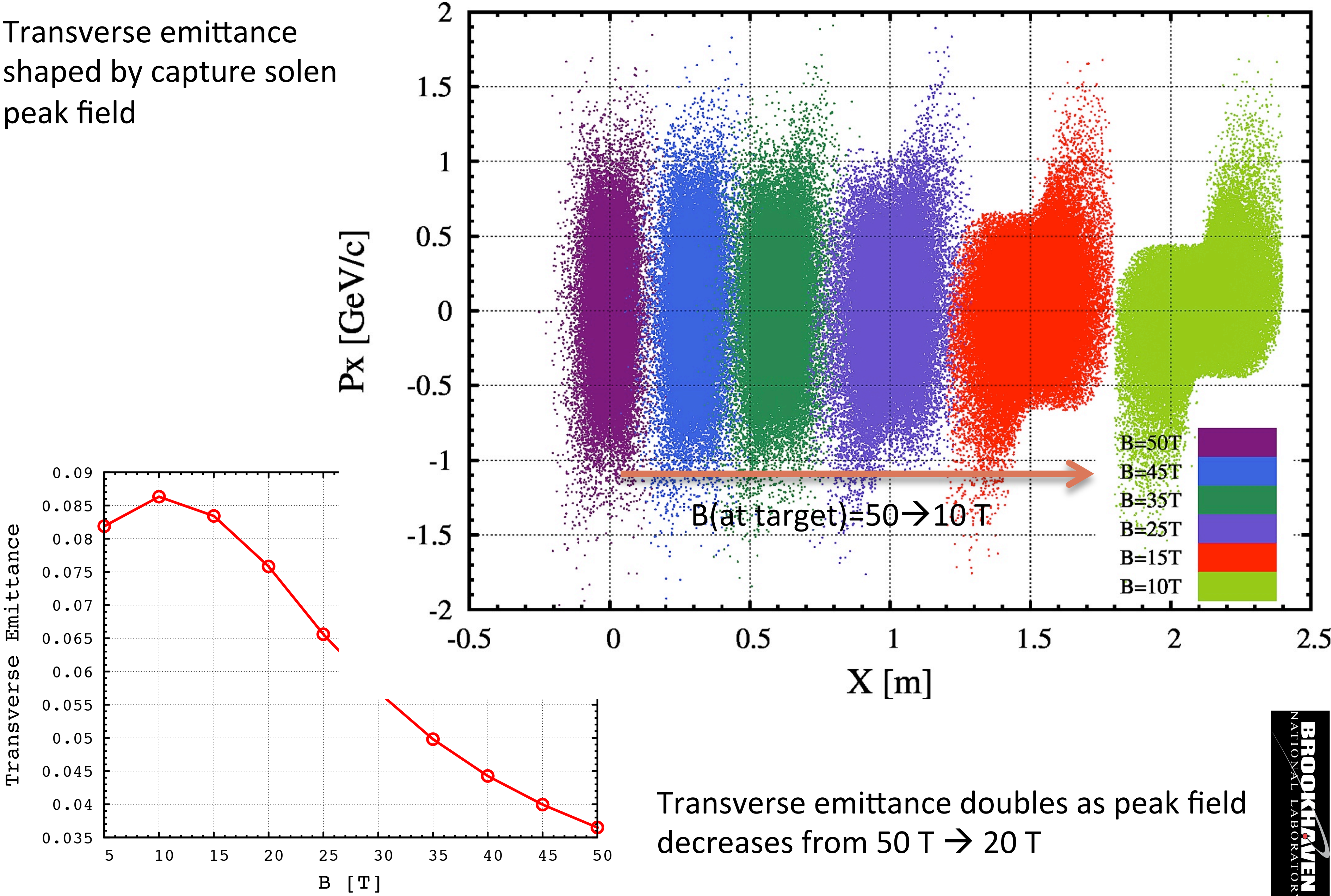


Transverse emittance decreases by 8% with solenoid taper length going 8→40 m

Time Spread increase by 90% with solenoid taper length going 8→40 m

DEPENDENCE OF TRANSVERSE EMITTANCE & CAPTURE EFFICIENCY ON PEAK FILED

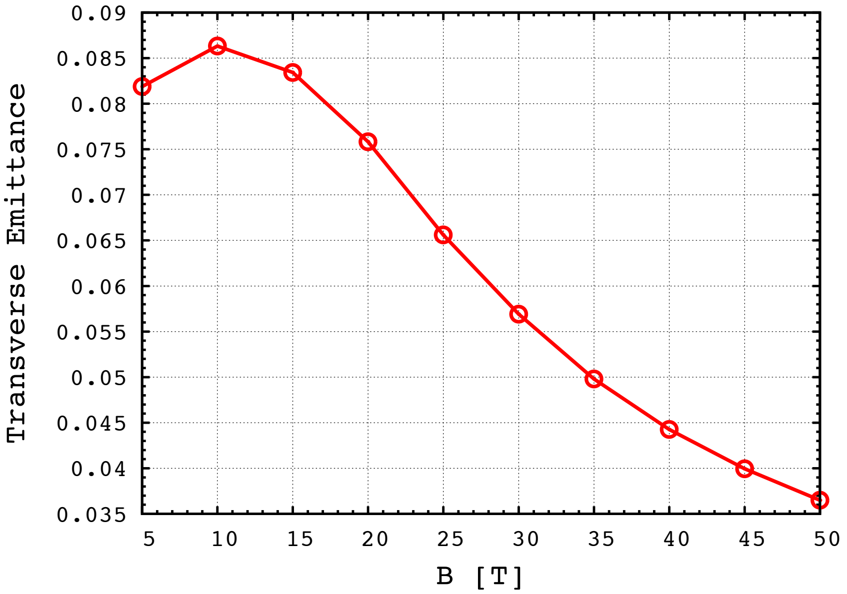
Transverse emittance shaped by capture solen peak field



Transverse emittance doubles as peak field decreases from 50 T → 20 T

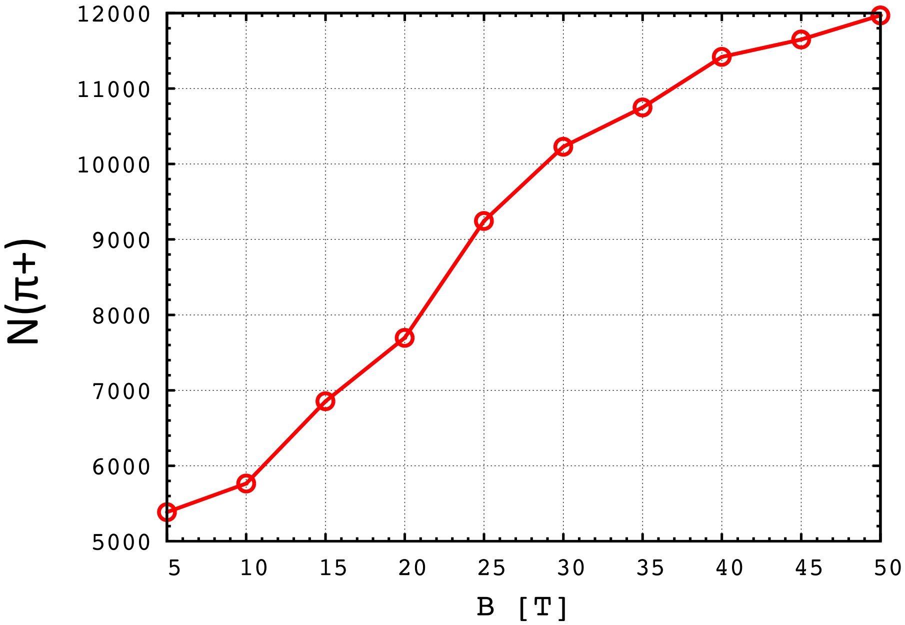
DEPENDENCE OF TRANSVERSE EMITTANCE & CAPTURE EFFICIENCY ON PEAK FILED

Transverse emittance shaped by capture solenoid



Transverse emittance doubles as peak field decreases from 50 T → 20 T

Capture efficiency dependence of peak solenoid field

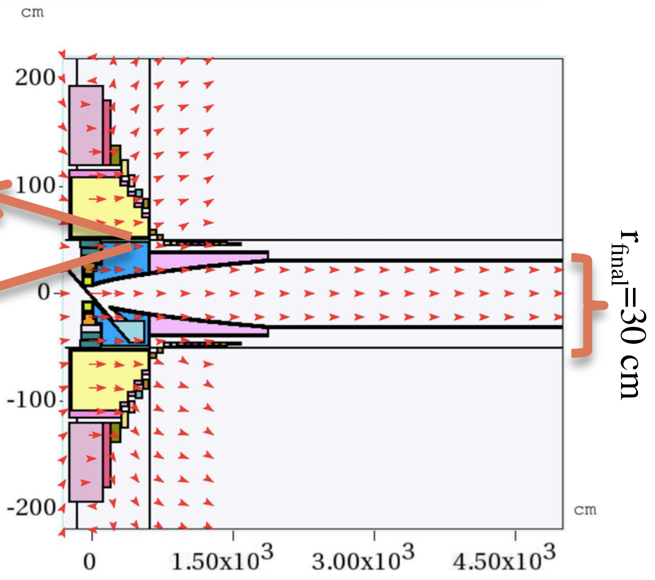


Number of pions+mu+k within transverse 6 σ cut and Pz=0.0-1.0 GeV/c

MARS SIMULATIONS & TRANSMISSION

Muon count within energy cut at end of decay channel

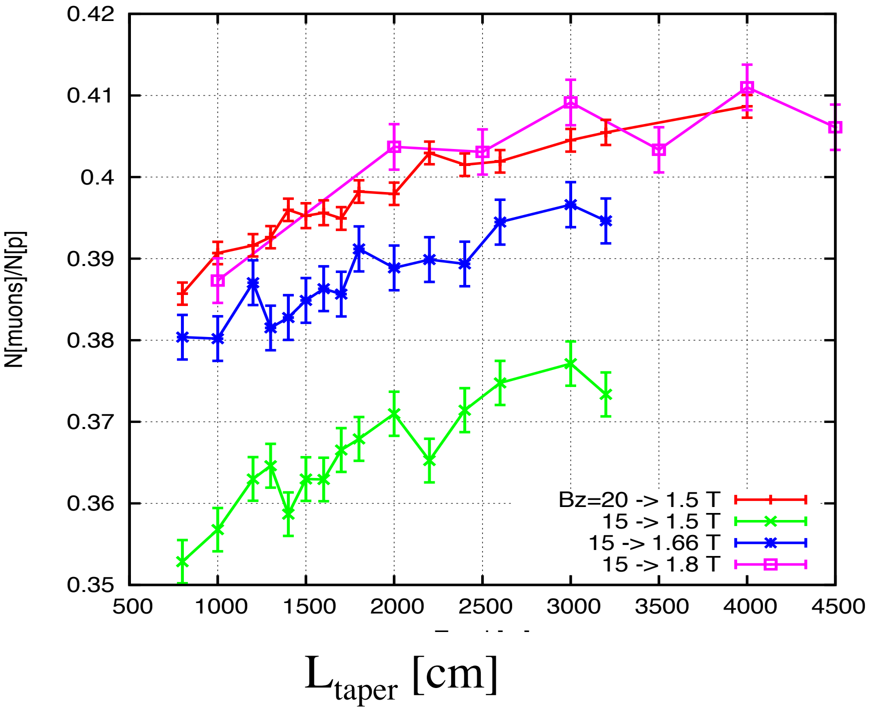
MARS15 Simulation:
Counting muons at 50 m with K.E. 80-140 MeV



R_{ini}=7.5-10 cm

B_i=20-15 T

r_{final}=30 cm



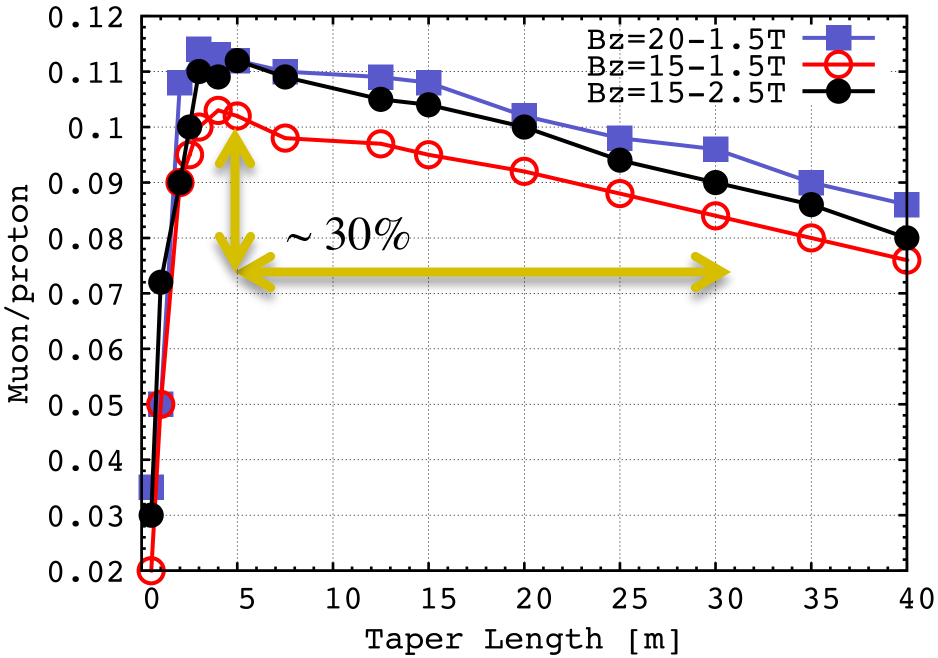
Muon count at z=50 increases for longer solenoid taper

FRONT END PERFORMANCE

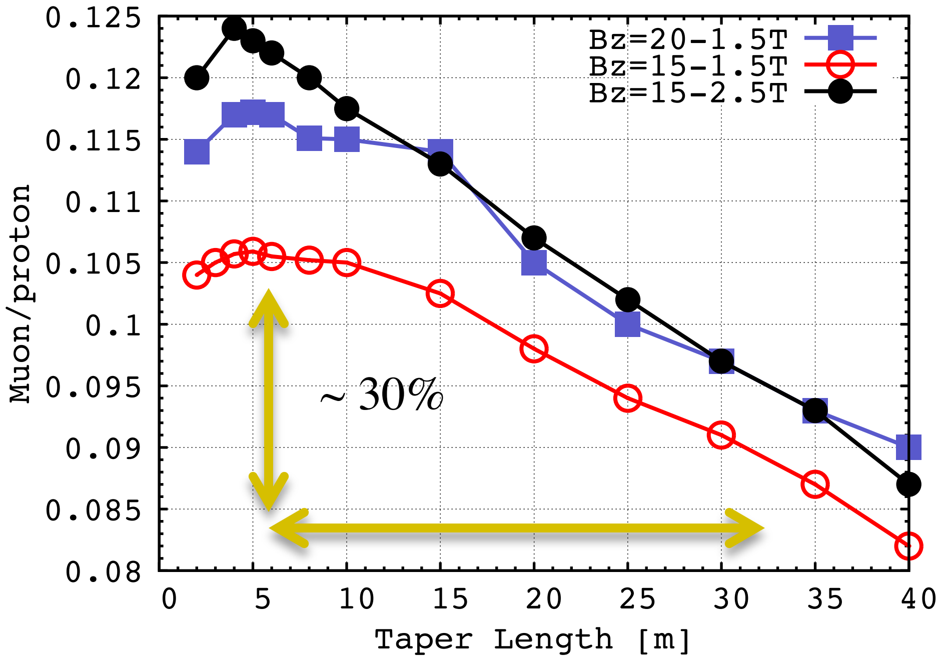
Muon count within acceleration acceptance cuts at end of ionization cooling channel

μ+ only

Before optimizing ionization cooling channel

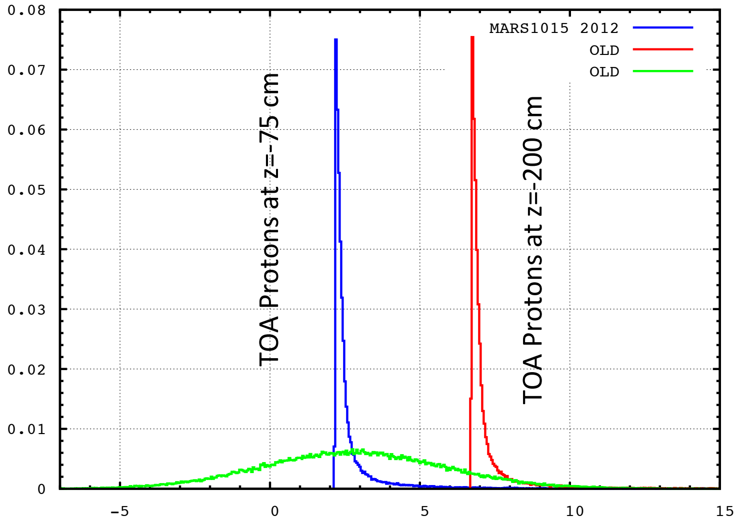


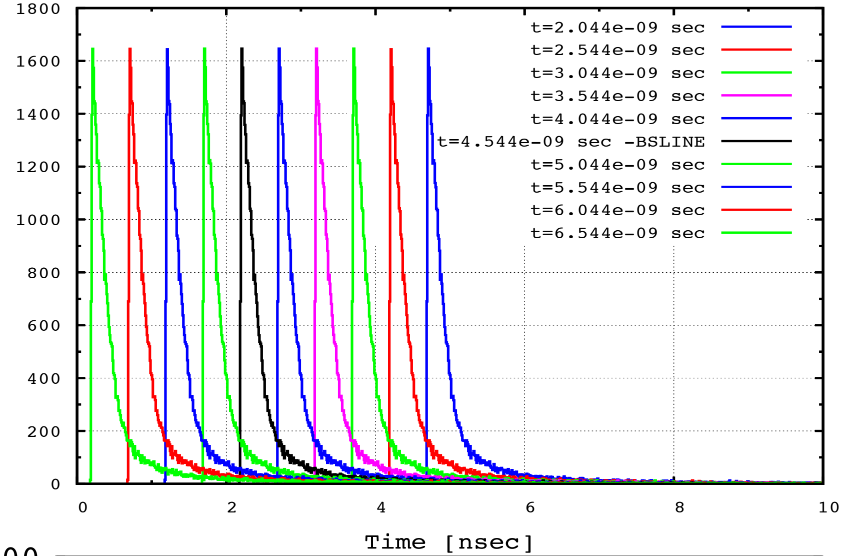
After optimizing ionization cooling channel

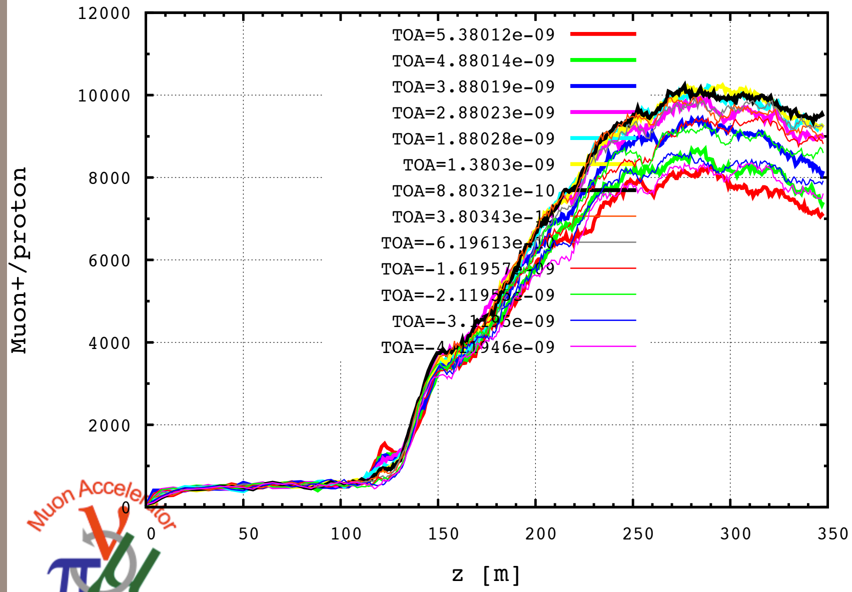


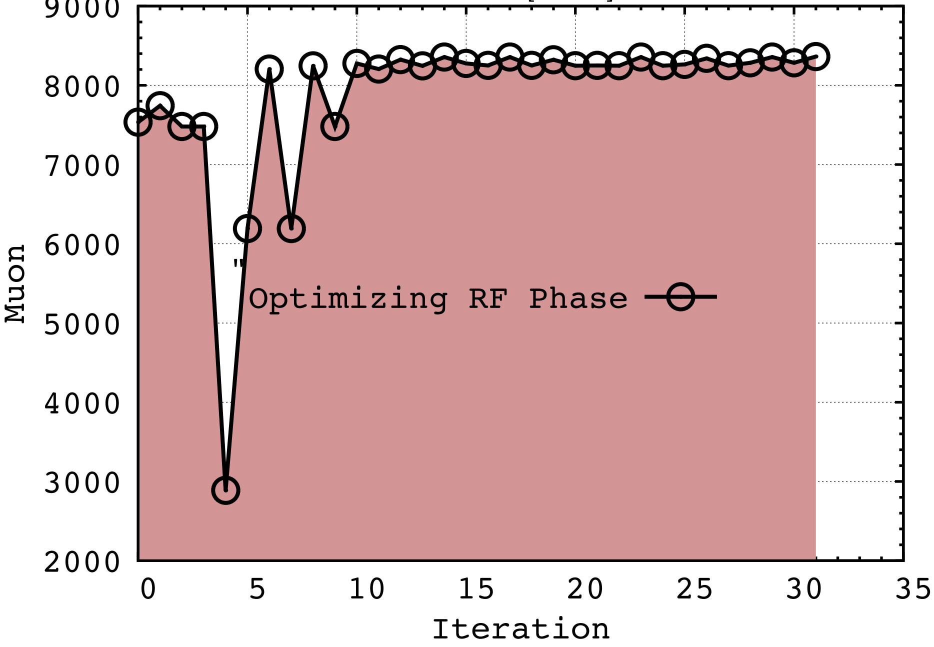
Shorter taper provide better quality muons → More muons at end of ionization cooling channel

PERFORMANCE DEPENDENCE ON TIME OF FLIGHT (RF PHASE)



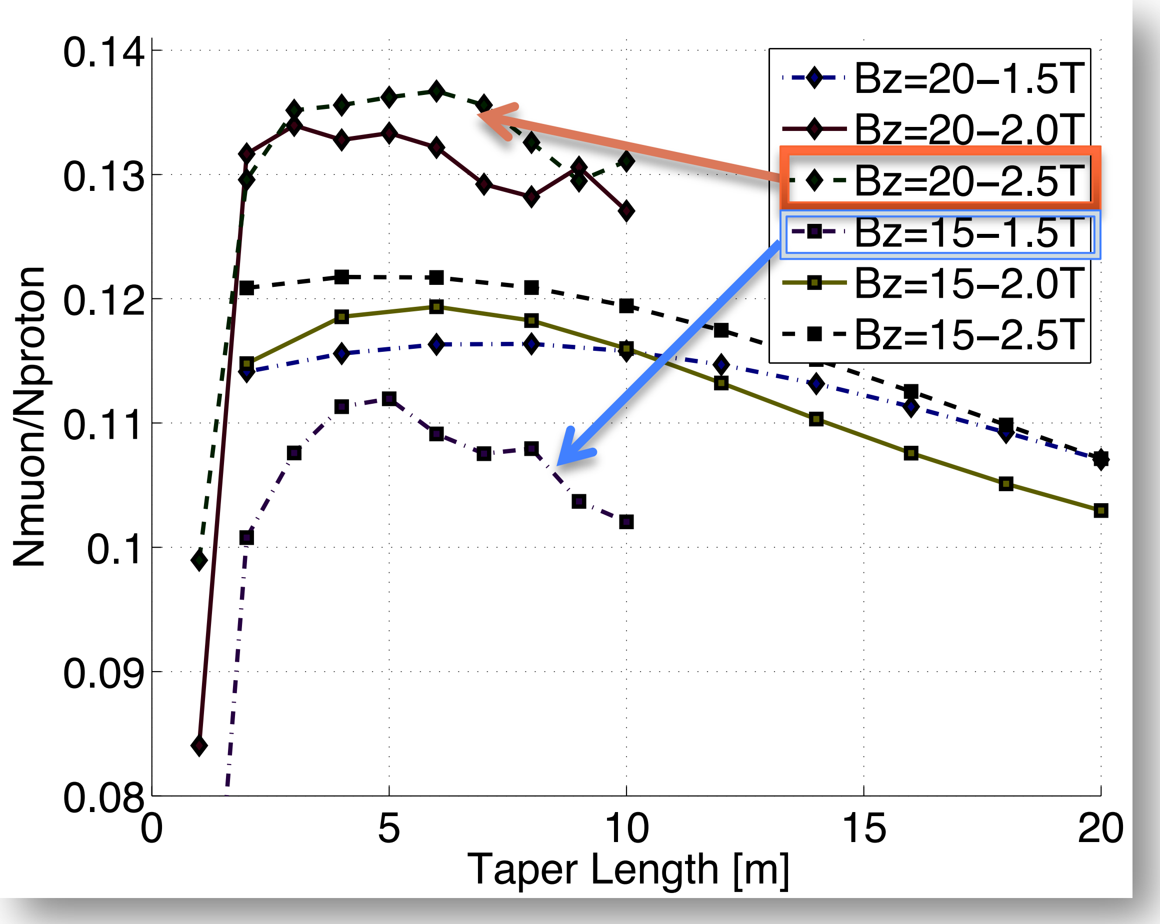






FRONT END PERFORMANCE

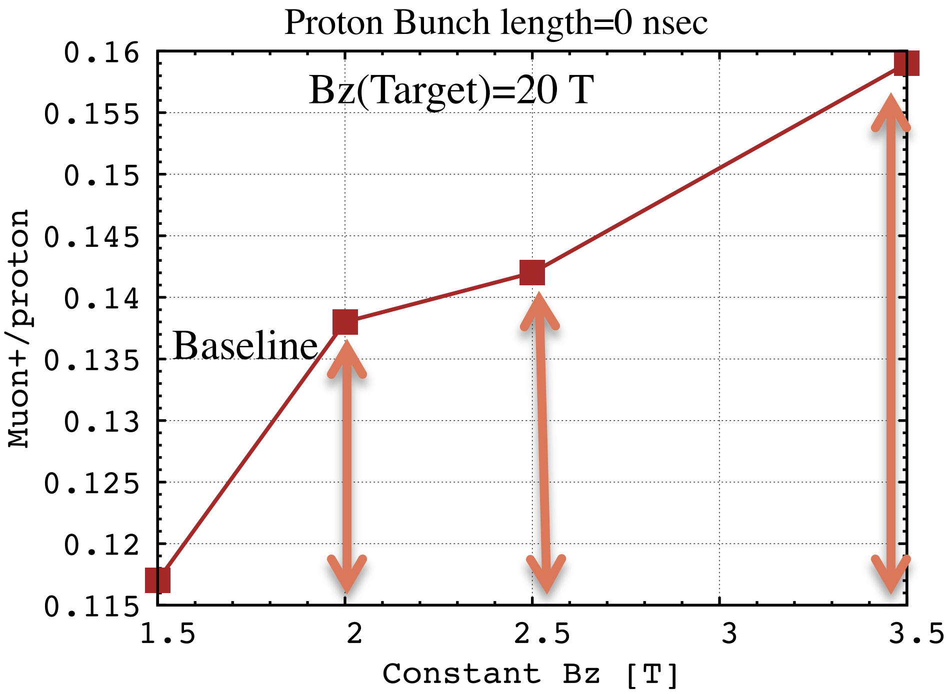
μ+ only



High statistics tracking of Muons through the front end

MUON YIELD VERSUS END FIELD

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

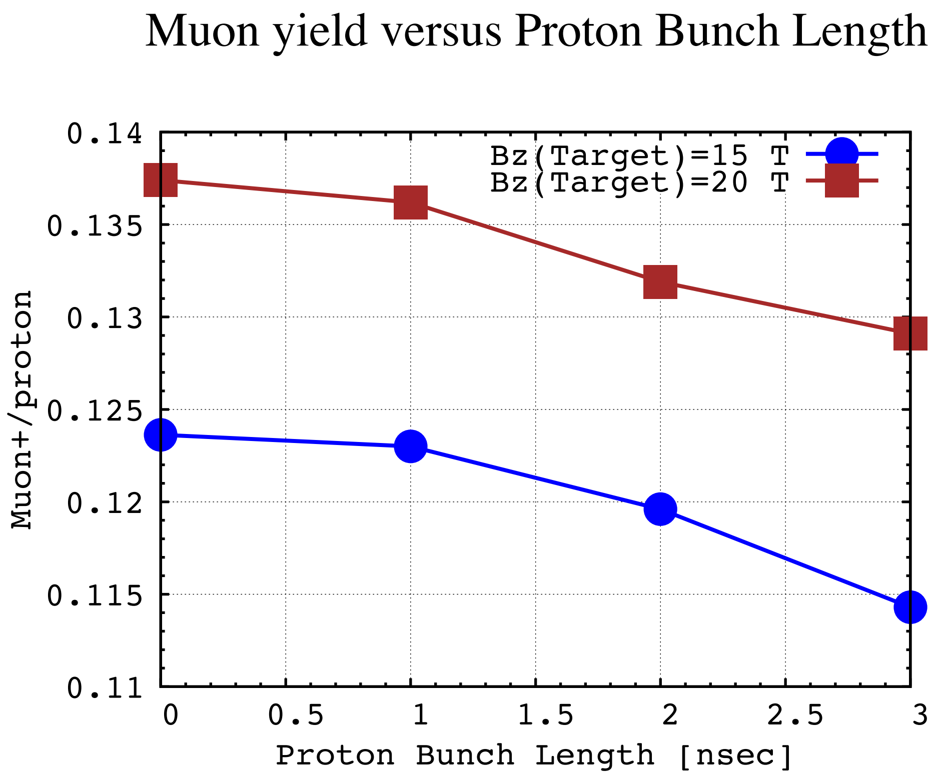


20% for every 1 T increase in constant field

μ+ only

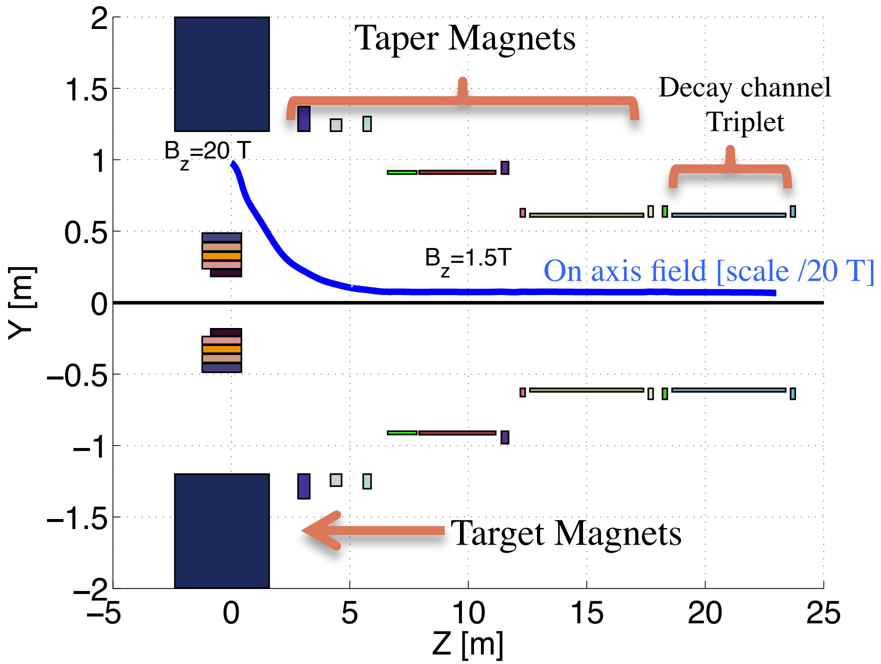
Muon yield versus end field

PROTON BUNCH LENGTH

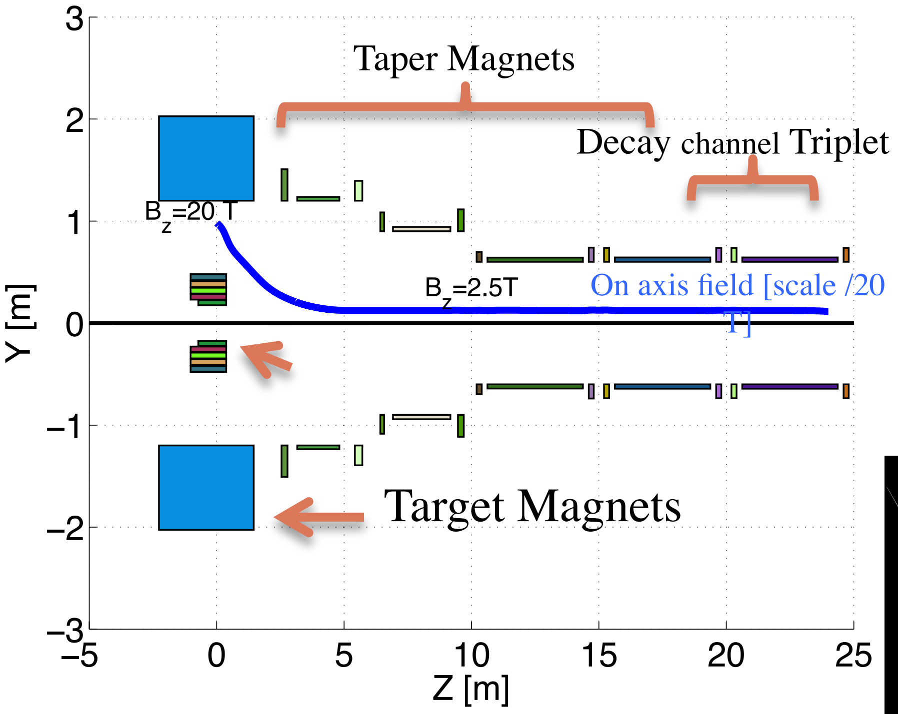


~ 3% loss per 1 nsec increase in bunch length

NEW SHORT TARGET CAPTURE REALISTIC MAGNET (WEGGEL)



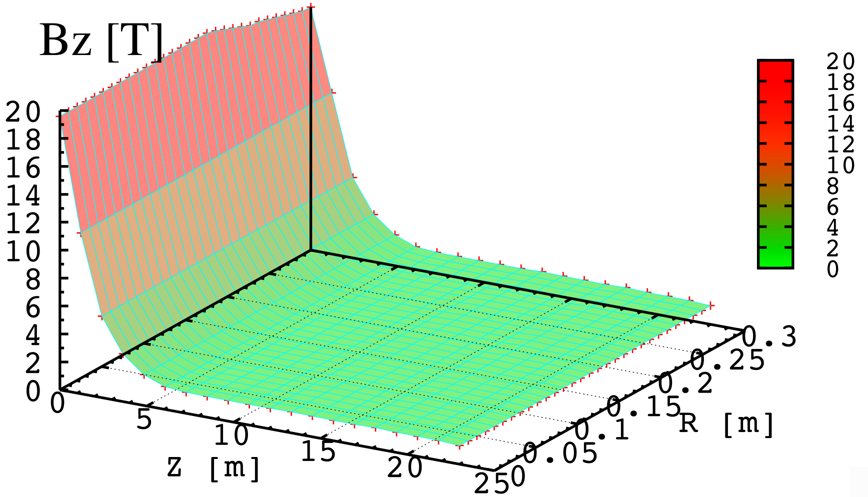
Muon Target Capture Magnet
Short Taper length =7 m- B=20-1.5 T



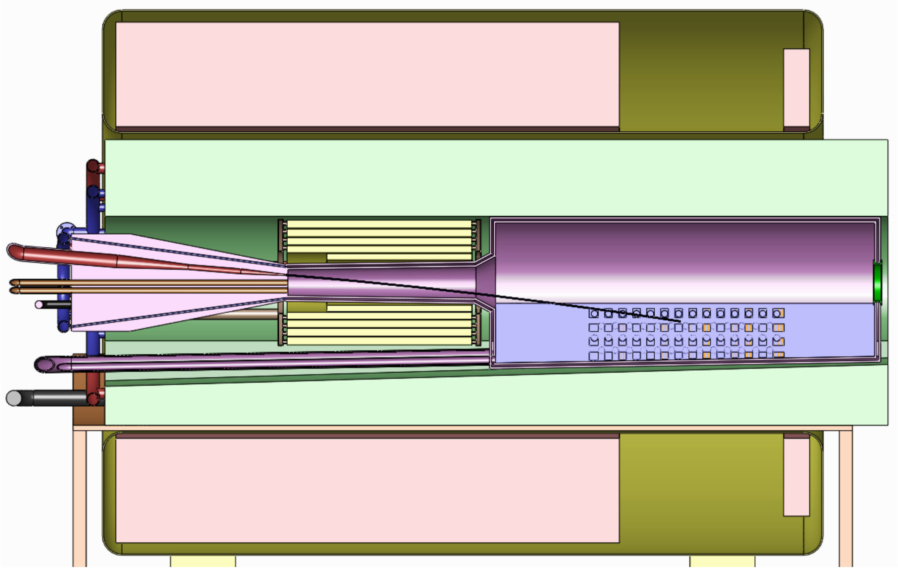
Muon Target Capture Magnet
Short Taper length =5 m- B=20-2.5 T

NEW SHORT TARGET CAPTURE MAGNET (WEGGEL)

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

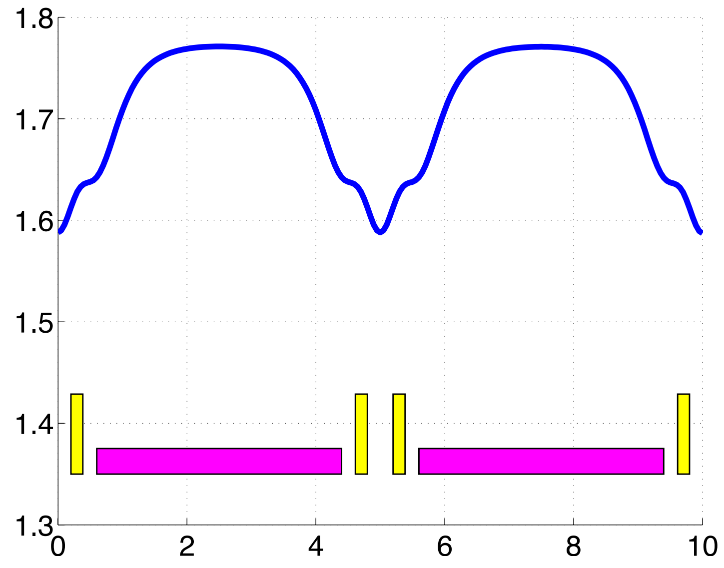


Target SC Magnets Field Map calculated from realistic coils



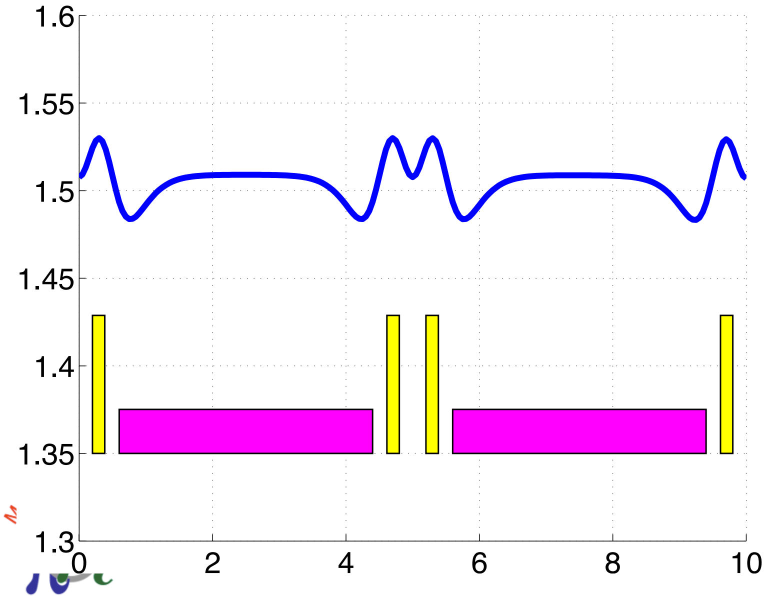
Engineering (V. Grave)
IDS120_20-1.5T7m2+5 Cryo 1

NEW DECAY CHANNEL MAGNET (WEGGEL)



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	47.18
3	0.19	0.6	0.68	47.18

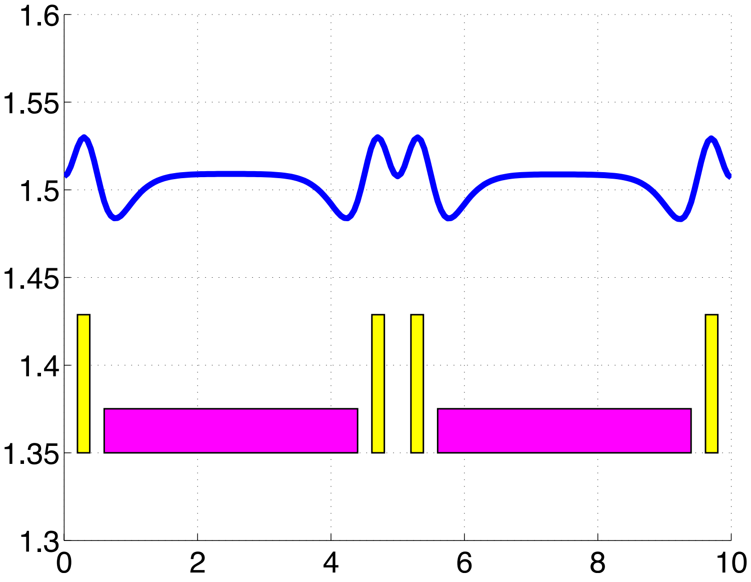


Modified - IDS120L20-1.5T 7m

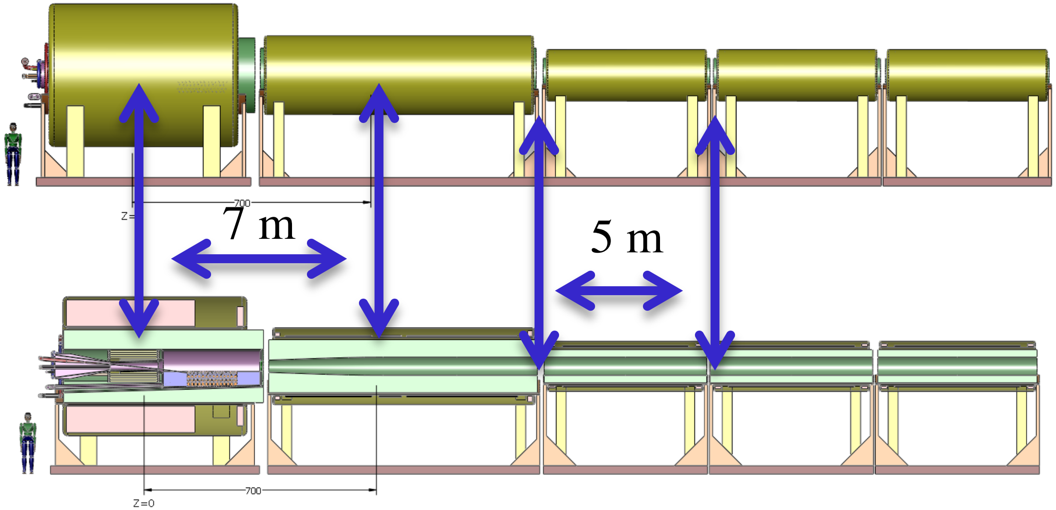
Magnet	Length [m]	Inner R [m]	Outer R [m]	J [A/mm^2]
1	0.19	0.6	0.68	47.18
2	3.8	0.6	0.63	40.00
3	0.19	0.6	0.68	47.18

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



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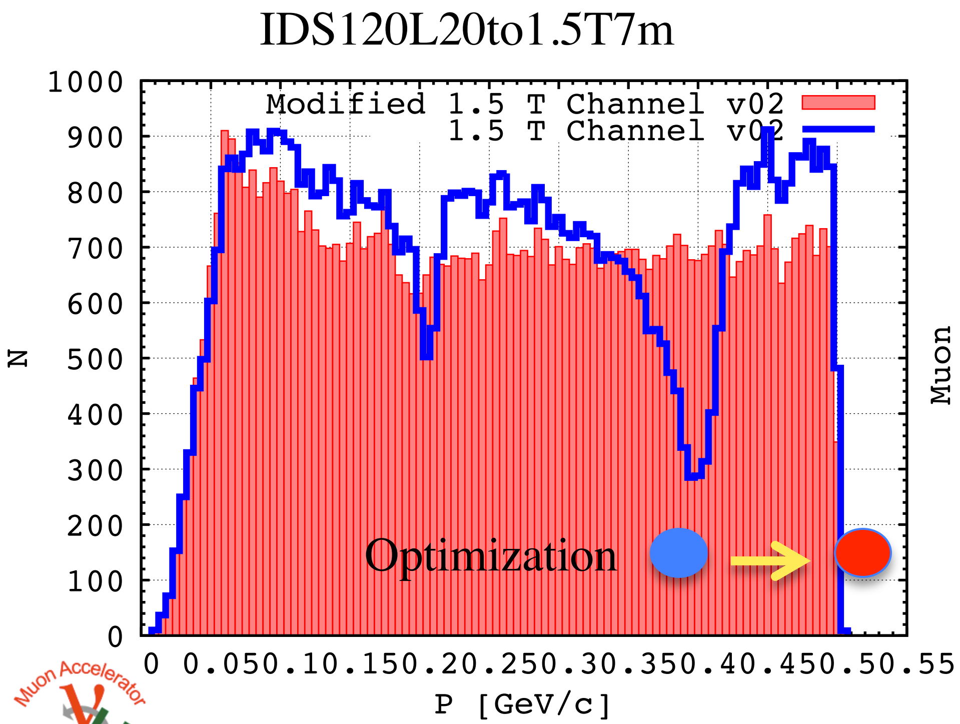
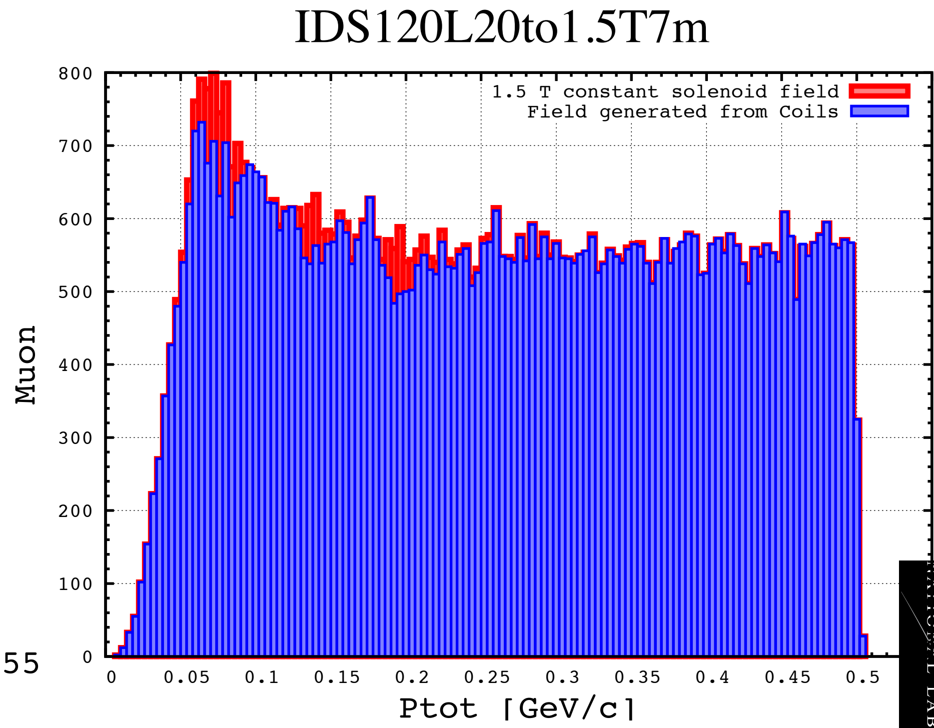
REALISTIC COIL BASED DECAY CHANNEL SOLENOID STOP BAND STUDY

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.

6- Realistic Coil design for the capture target and decay channel.

7- Open Questions : ?! Include cooling channel ? – Other items