Shielded RF Lattice for the Muon Front End

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Shielded RF Lattice

- I wanted to remind folks of the work that has been done on this lattice
  - Last major update at NuFact ~ 6 months ago
  - Worth reminding
- Summarise more recent work that I have done since then
  - Add a few new things since christmas or so
- Quite a lot of slides - apologies
  - I've tried to break it up a bit

Part 1 - Shielded Lattice Baseline Thoughts

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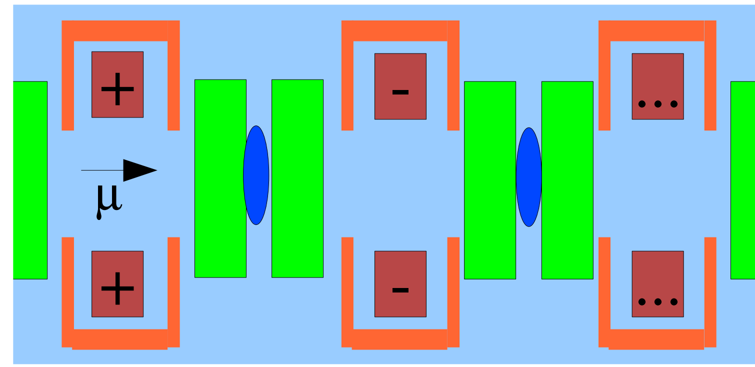
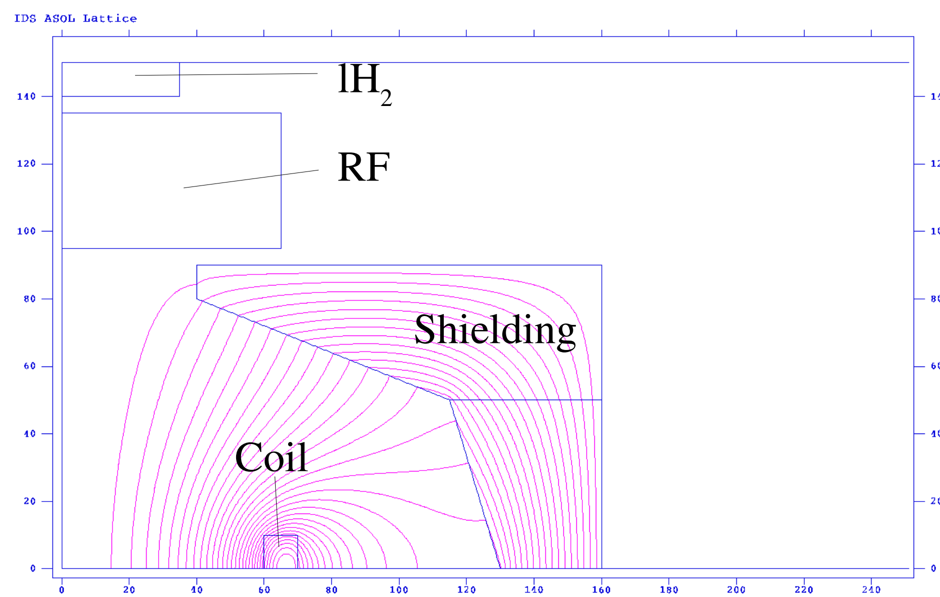
RF Problem

- Neutrino Factory baseline front end has RF in 2 T B-fields
  - Experiment indicates this will not work
    - Many caveats
  - Available RF voltage may be significantly reduced
    - Major technical risk
- Several schemes to overcome this
  - Fancy RF cavities (new materials, liquid N_2 cooling...)
  - Magnetic Insulation
  - High pressure gas to insulate RF cavities
- These are multi-million $, >5 year R&D plans that may not work
  - Probably necessary for Muon Collider
- For a Neutrino Factory, can we do something simpler?
  - Adapt lattices to keep RF cavities in low fields - “Shielded RF”
- For this talk I concentrate on the cooling section
  - Stronger B-fields, higher RF voltages, more constraints on lattice

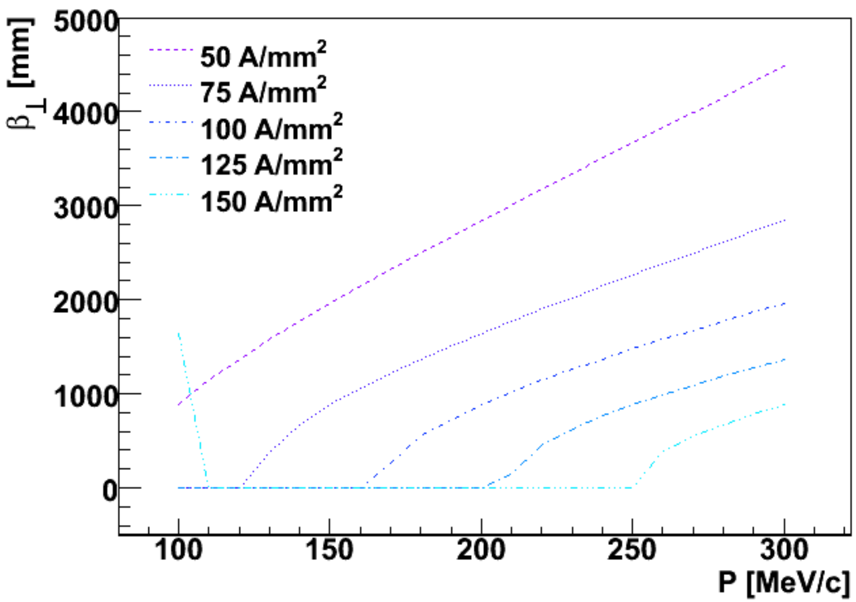
Shielded RF

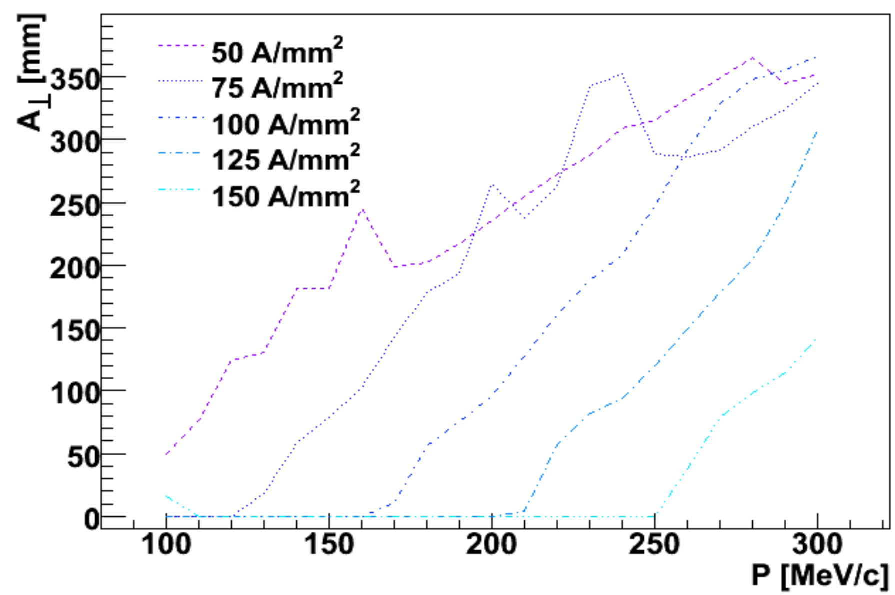
- Increase cell length to remove RF from fringe fields
  - Add shielding using iron or bucking coils
- Look at cooling section
  - This is where the RF is most limited
  - This is where optics are most demanding
- How well can we cool in this shielded scenario?
- How well can we optimise the cooling lattice?
- Try to keep RF cavities in < 0.1 T fields
- Liquid Hydrogen absorbers





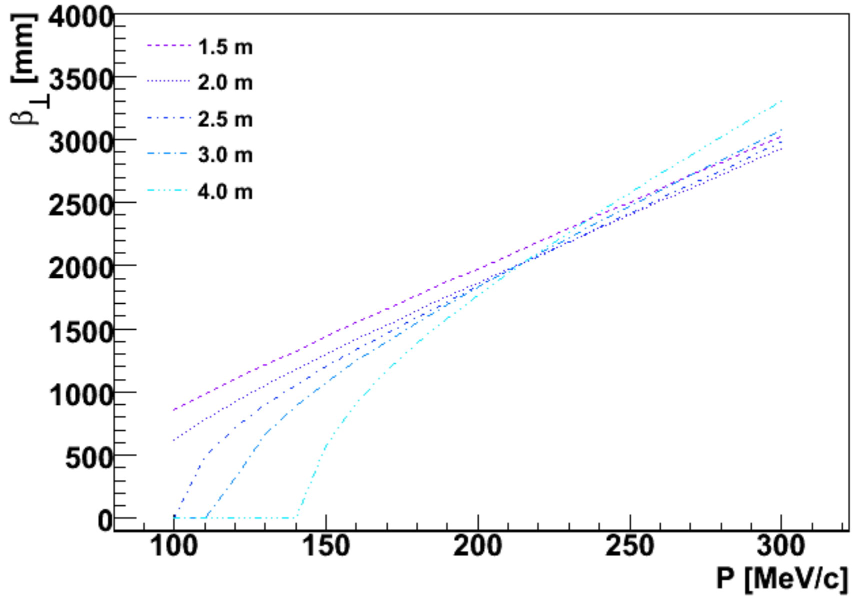
Lattice quality





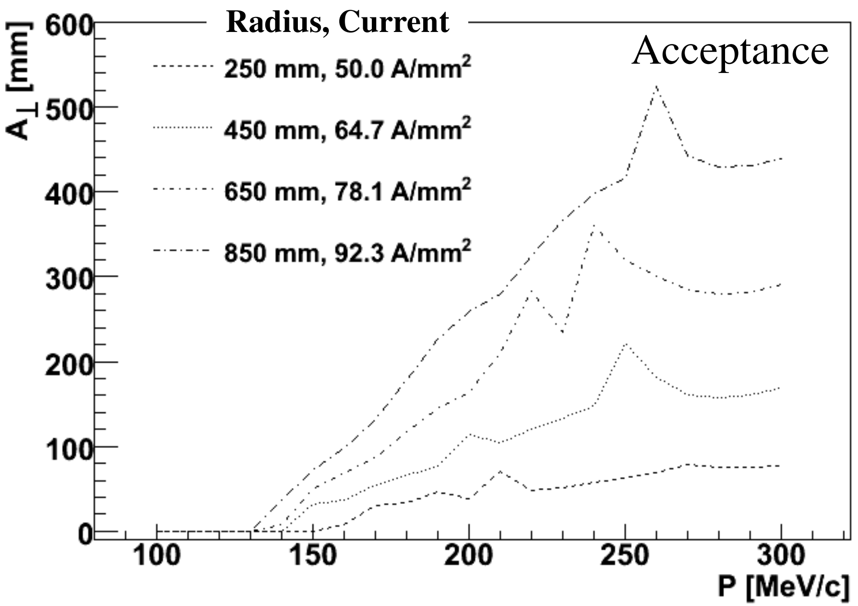
- Two criteria for lattice quality
- β function => how tightly focussed the beam is at the absorber
  - Determines how much cooling we get
  - Require good β function over a large momentum range
- Acceptance => the beam emittance that makes it through the lattice
  - Determines how much beam we get through
- Scale as ~ $\langle B_z^2 \rangle / p$

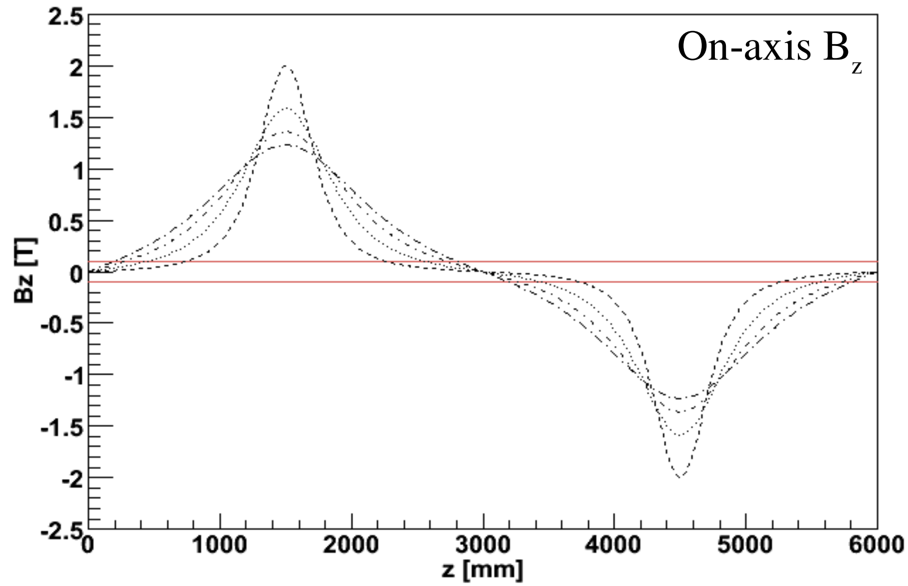
β vs Cell Length



- We want tight focussing on the absorbers for good cooling performance
  - Tight focussing => more cooling
  - Aim for β <~ 1500 mm over ~150 - 300 MeV/c (liquid Hydrogen)
- As cell length gets longer dβ/dp gets worse
  - Making it hard to contain a beam with a large momentum spread
- Keep cell as short as possible
  - To keep B_z off RF, need to reduce solenoid fringe field

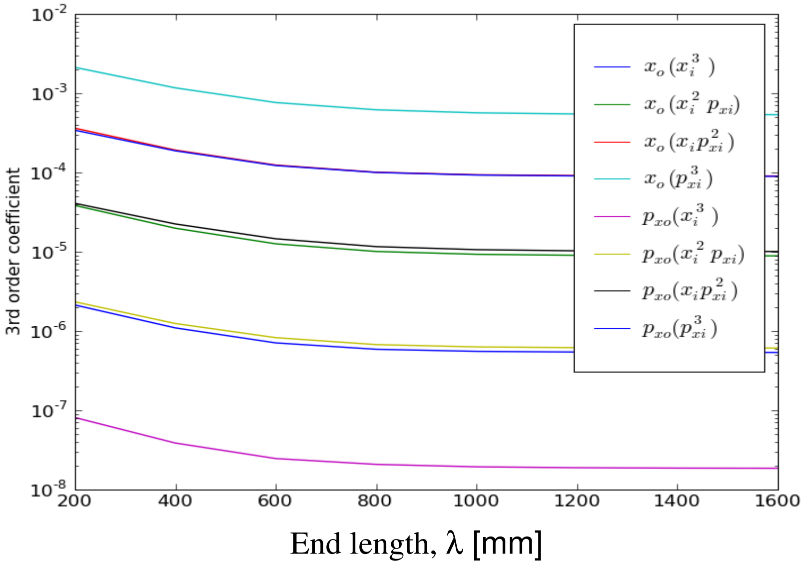
Dynamic Aperture vs Radius

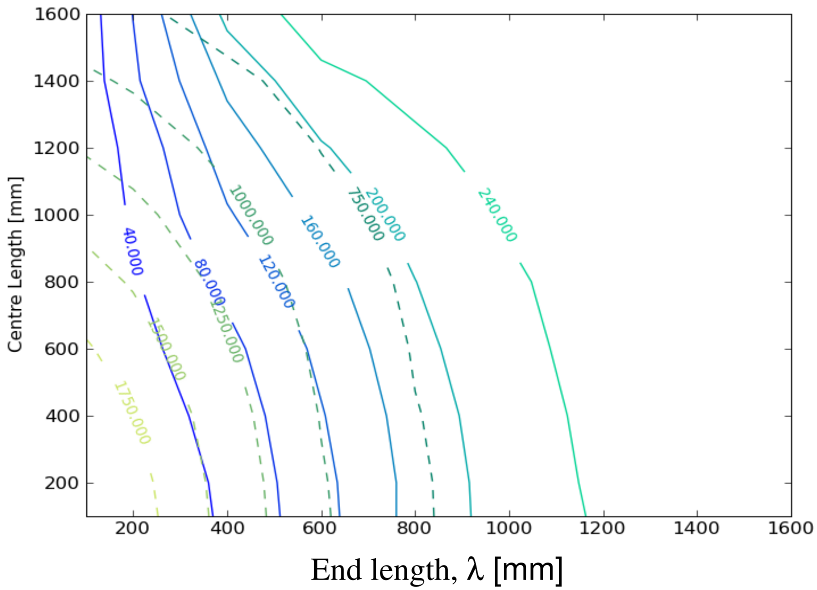




- Reducing radius of coil reduces lattice acceptance
  - Aim for acceptances >~ 100 mm
  - Naively “expect” that reducing coil radius decreases acceptance
  - “Particles travel through region of poor field quality near the coils”
- In solenoid, optics is uniquely defined by on-axis field
  - So any attempt to curtail the fields is like reducing the coil radius
  - What does “poor field quality” really mean?

Non-Linear Terms

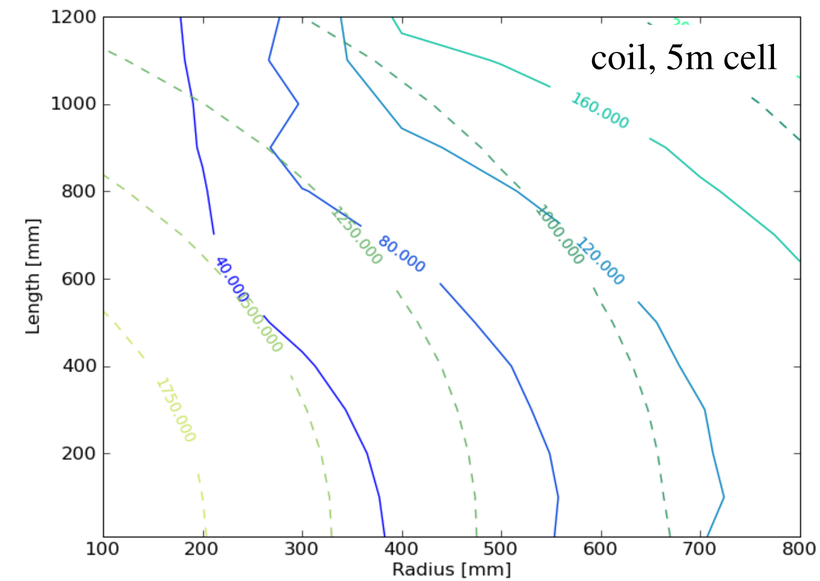


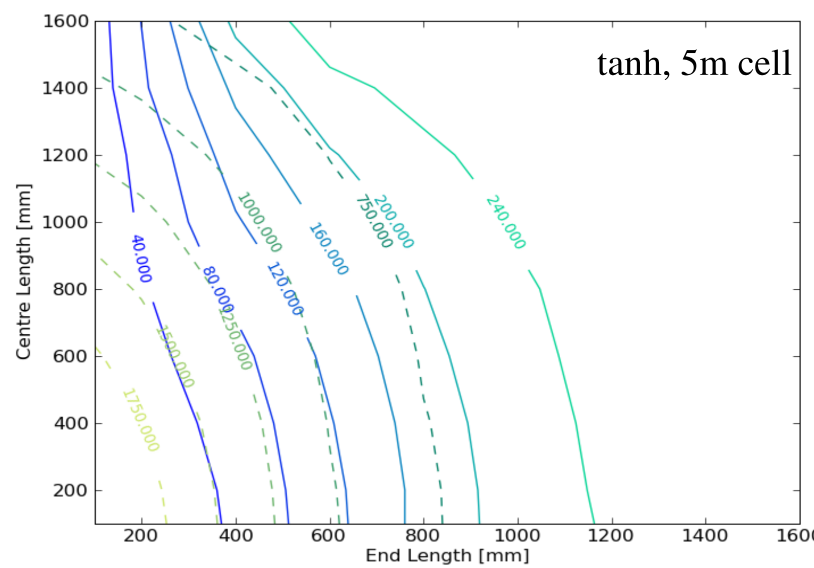


- Non-linear terms => $x_{out} = a_{ij}\, x_{in}^{i} p_{in}^{j}$
- 2nd order terms have i+j=2
  - Purely chromatic, can be ignored
- 3rd order terms have i+j=3
  - Increase by order of magnitude in short fringe field
  - In theory go as d^2B_z/dz^2
- For very short fringe fields 3rd order terms become large
  - d^2B_z/dz^2 becomes large
  - e.g. consider tanh model for $B_z(r=0)$
  - $B_z = \tanh[(z-z_0)/\lambda] + \tanh[(z-z_0)/\lambda]$
- Introducing bucking coils etc is equivalent to reducing coil radius
  - Not helpful

Coil Length

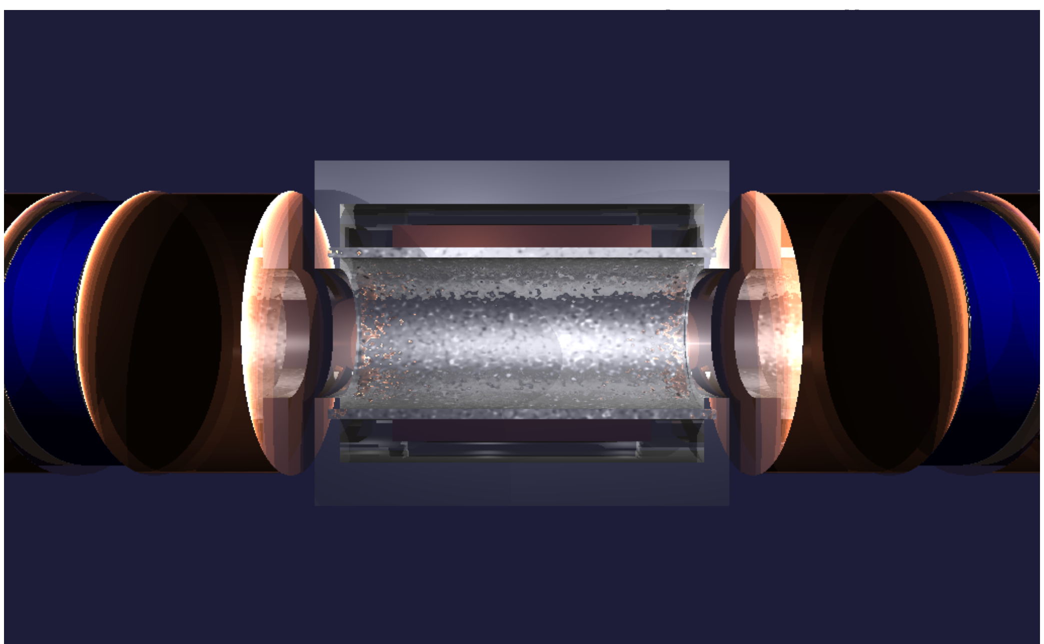
- Can we make progress by tweaking coil length?
  - Long coil needs lower B_z to keep $\langle B_z^2 \rangle$ constant => more space
  - But field extent is longer => less space
- These effects ~cancel
  - Dashed line = field free length
    - $B_z < 0.5$ T (assume shielding for rest)
    - Per 2.5 m half-cell
  - Full line = acceptance at 200 MeV
- Are there practical reasons that influence coil length?
  - Longer => Lower B_z
  - Longer => Lower current densities
  - Longer => More hardware required

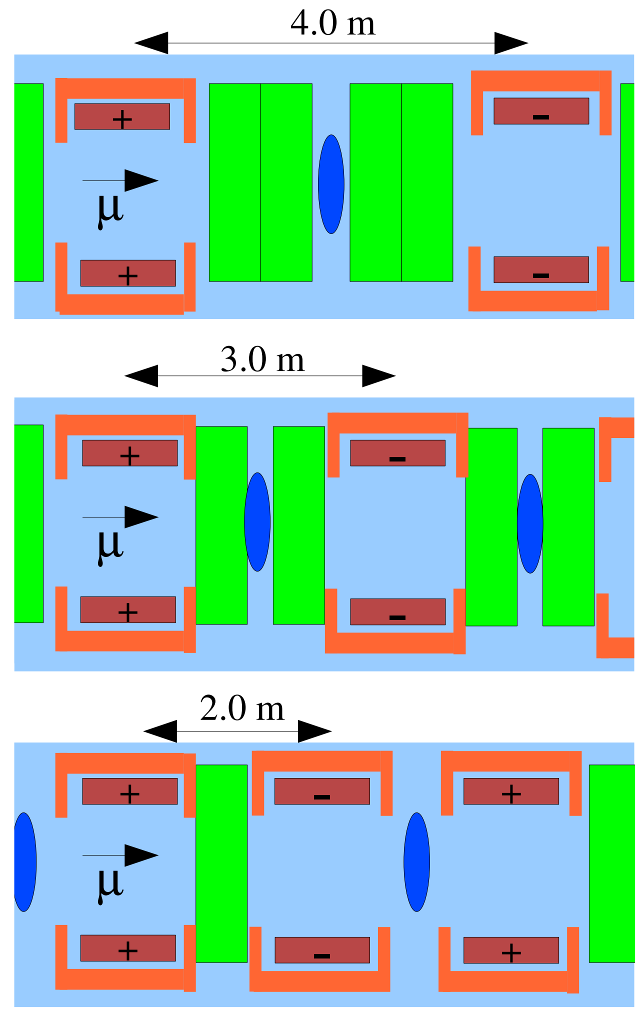




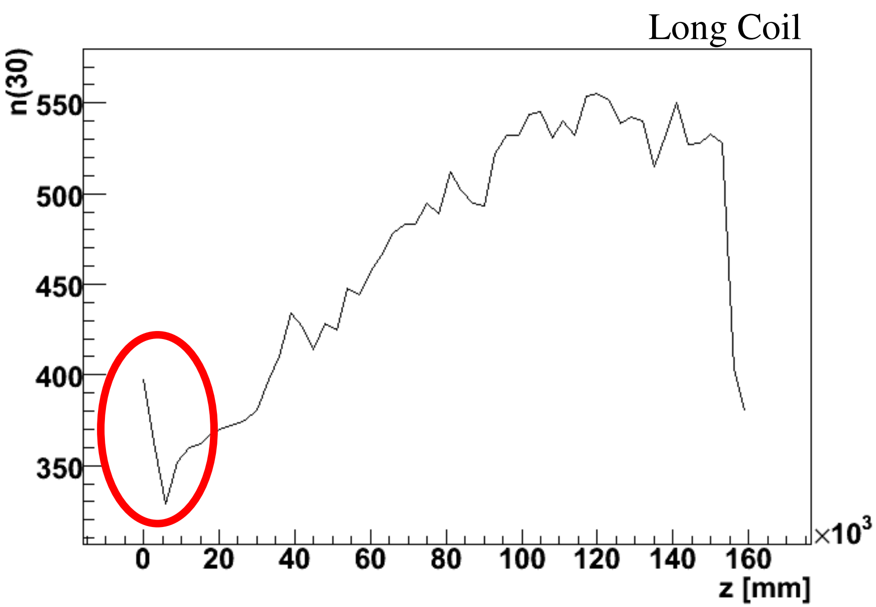
Lattice Choice

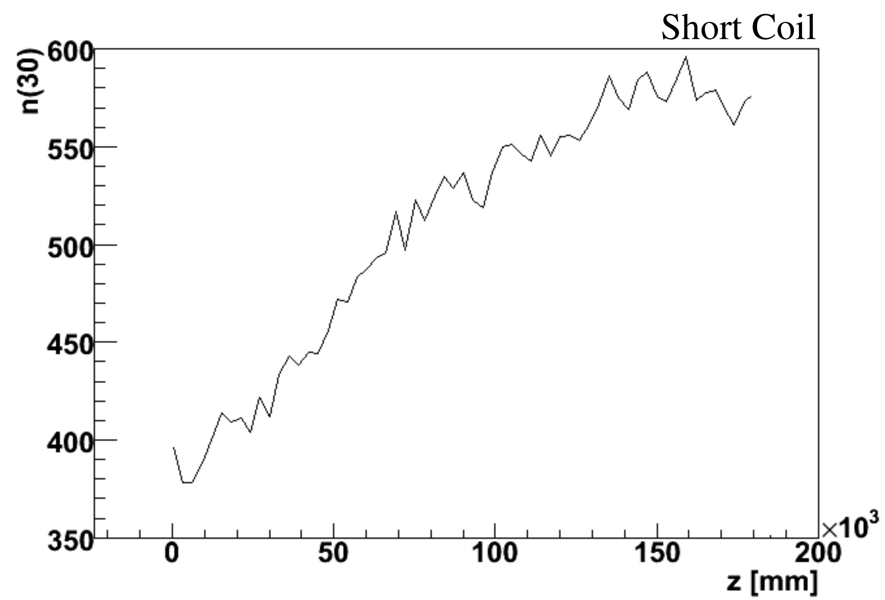
- In light of this - what lattice?
- Try 4 m, 6 m or 8 m cell
  - Longer cells have worse optics
  - Longer cells have better RF packing fraction
    - 1/8, 1/3, 1/2 respectively
- Try long coil or short coil





Long Coil Versus Short Coil

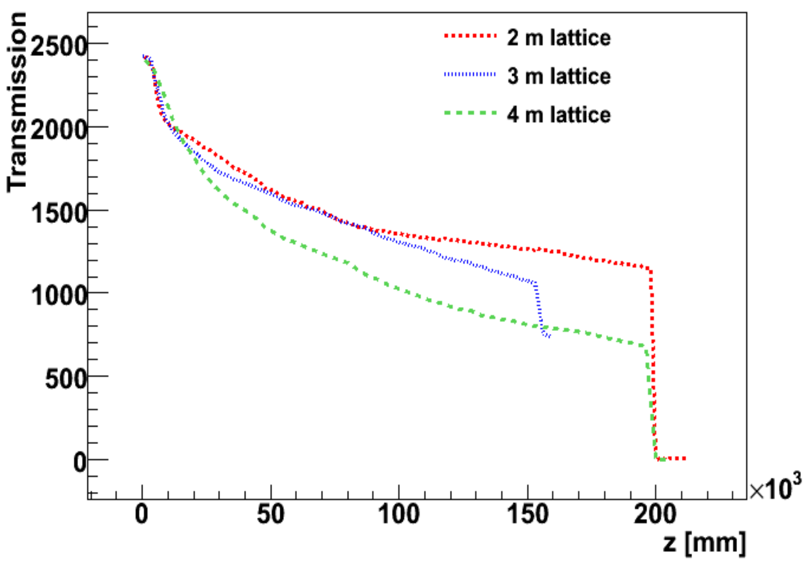


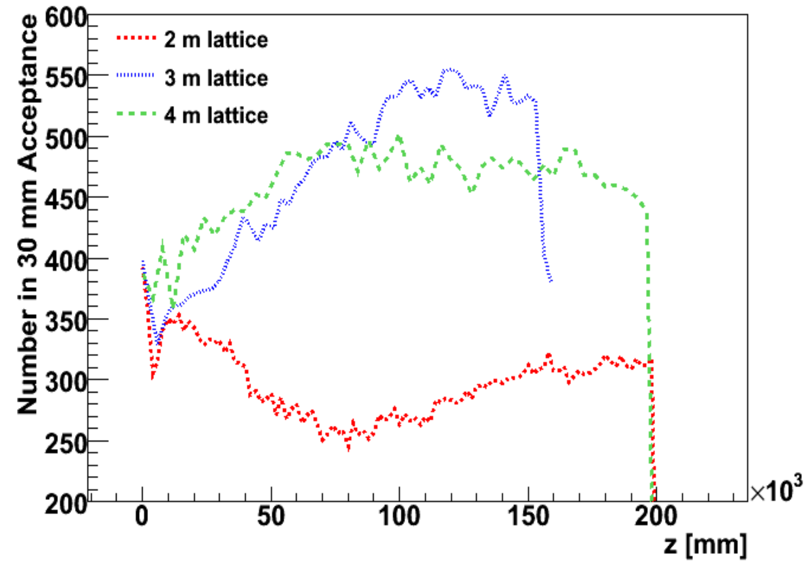


- Compare long coil with short coil
  - 3 m cell, 30° RF phase
  - Count number of muons in accelerator acceptance
    - 30 mm transverse, 100 - 300 MeV/c momentum bite
  - Short coil does a bit better
  - ~52% compared to ~42%
  - Probably means my “long coil” is too low radius
  - Perhaps initial mismatch is a problem

Cell Length

- Cell length optimisation
  - Simulated using long coil option
  - Race between RF packing fraction and β function
  - Higher RF packing => quicker cooling
  - Shorter lattice => lower β function (better equilibrium emittance)
- 3m lattice is optimal
  - Worry about initial beam loss
  - Nb low statistics
  - Get ~ 40 % with long coil (a bit more optimisation is possible)
- Case for beta tapering?





Lower B-Field Lattices

- Cooling channels with RF in high magnetic fields is tough
  - High, unknown technical risk for the Neutrino Factory
  - Solutions with >5 year, multi-million $ R&D programmes which may not work (impatient!)
- It is possible to build a cooling channel that keeps RF cavities away from strong fields
  - Reduced cooling performance compared with baseline
  - 3 m lattice preferred
  - It's all a bit marginal - it can be built, but worry about reality
- Bucked coil lattice is equivalent to reducing coil radius
  - Spherical aberrations drastically reduce transverse acceptance
  - Not much progress to be made here

Part 2 - Simulation Details

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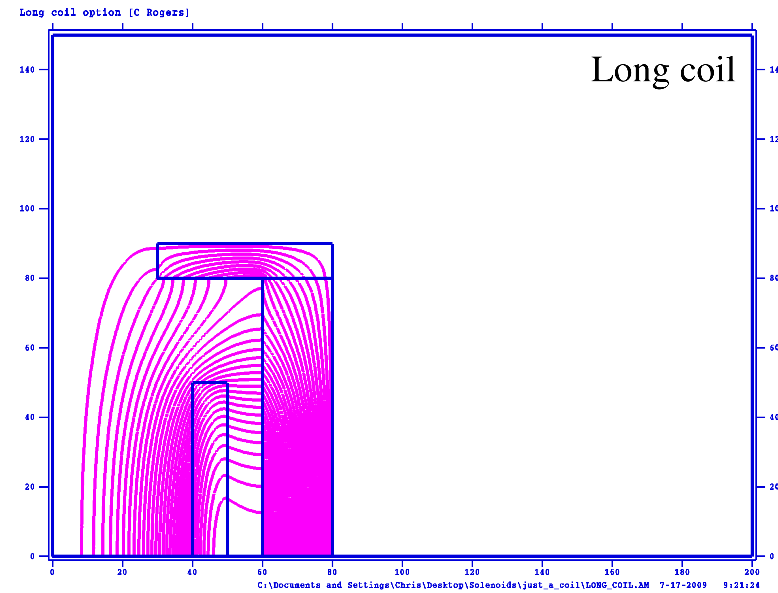
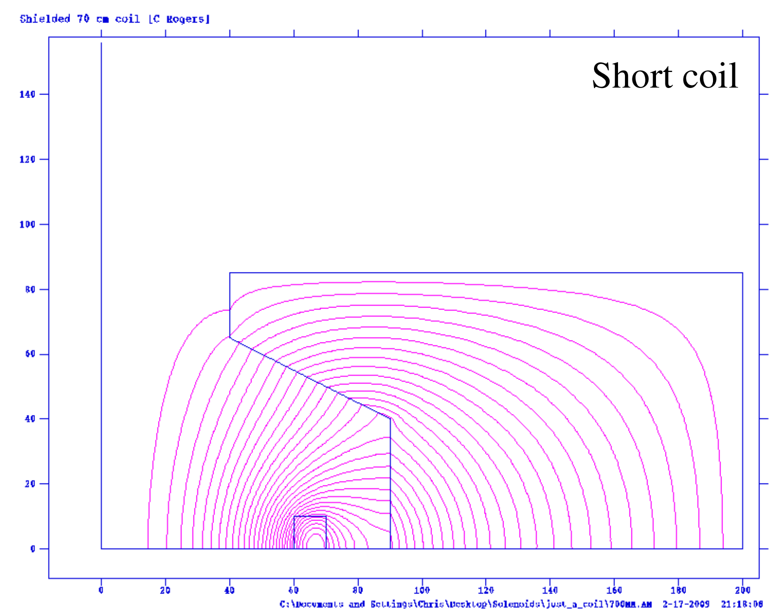
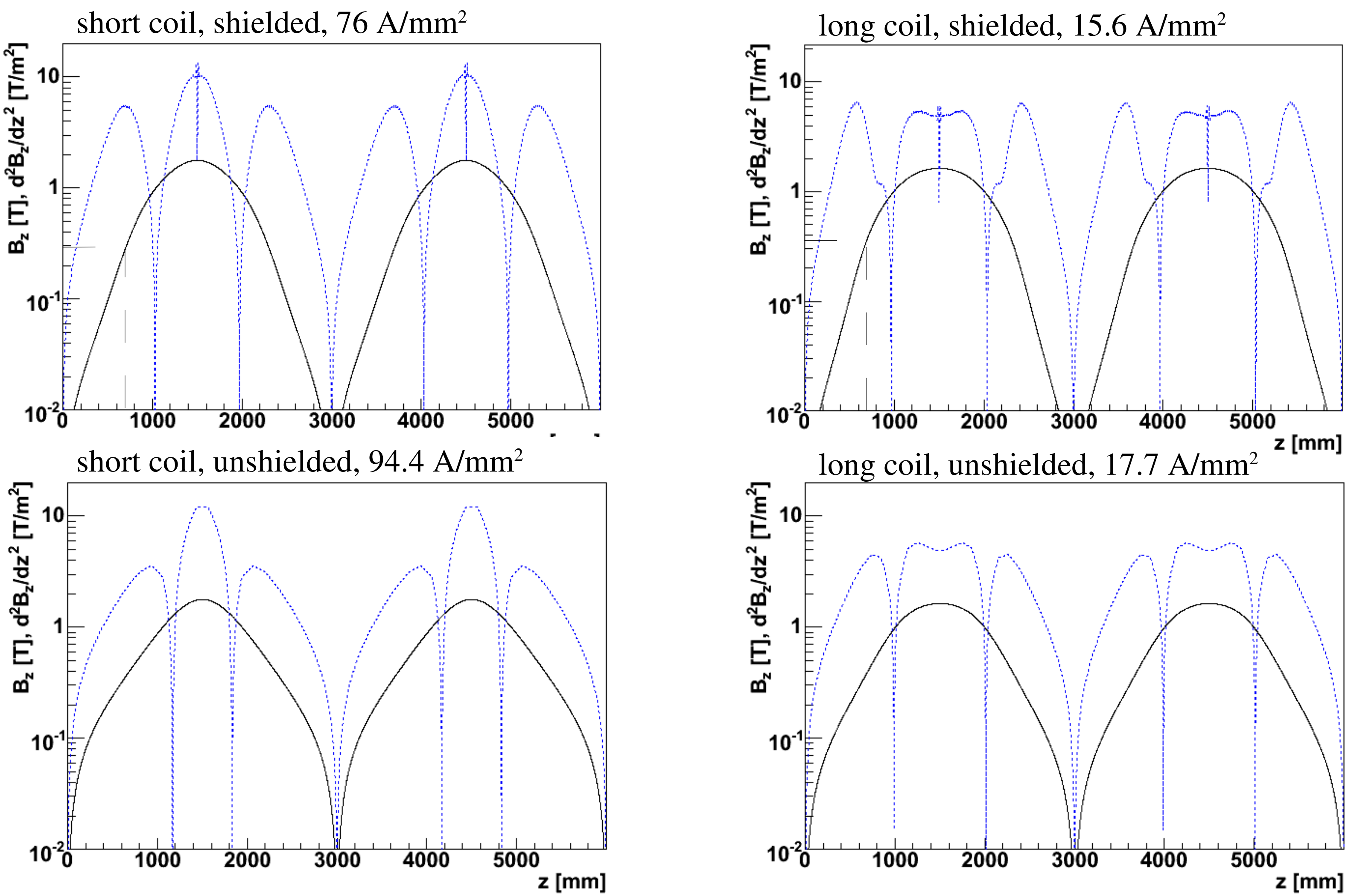
Coils and Shielding

- Assume iron shielding on coils
  - Makes handling magnets harder
    - e.g. 14 tonnes Fe (long coil)
  - Lower currents required on coils
  - Reduces fringe field on RF
  - Shield tunnel from intense fields
    - Stray iron does not affect beam
    - Stray fields do not affect hardware
    - Stray fields do not affect personnel
- Compare long coil or short coil
- Long coil may be preferable
  - Less shielding
  - Lower current densities
    - Normal conducting possible?
  - More conductor



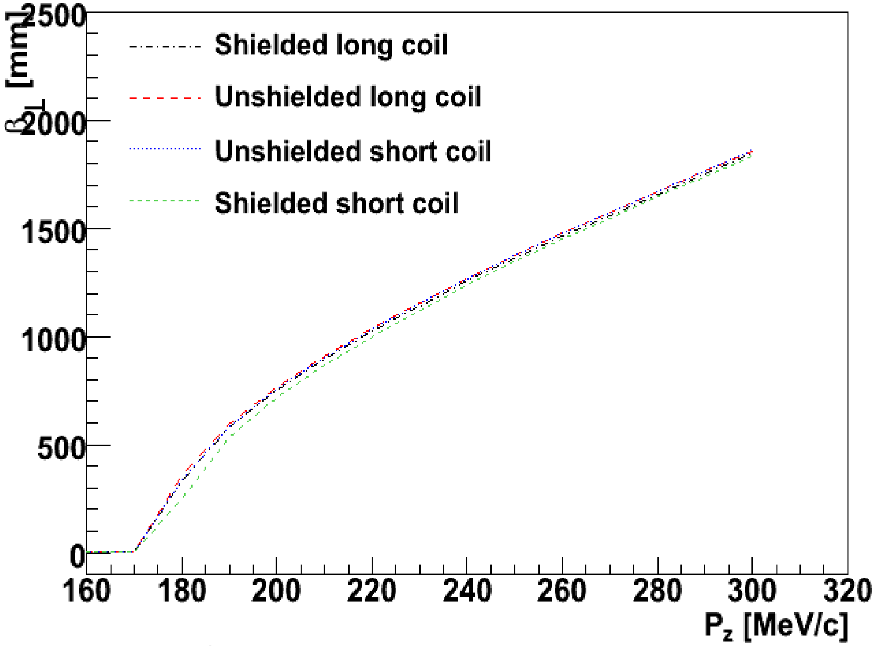


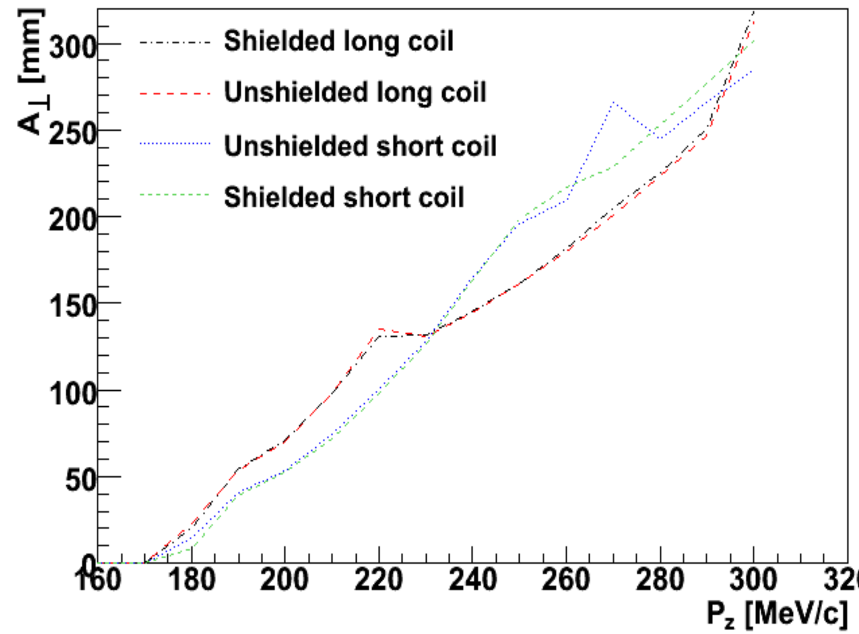
Shielded vs Unshielded Fields



- Shielding introduces slightly higher field 2nd derivative (blue)
- Reduces absolute field value (black) noticeably at fringes

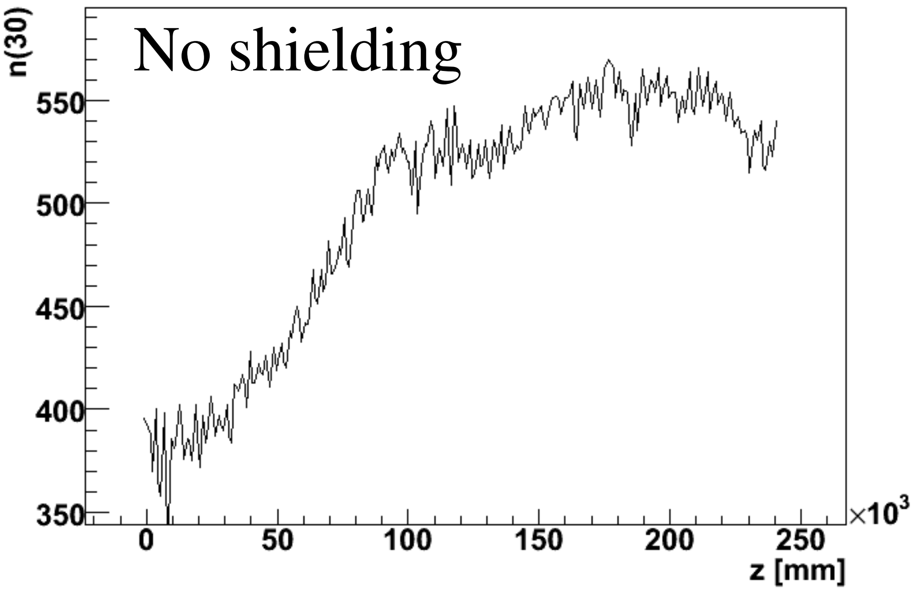
Shielded vs Unshielded Optics

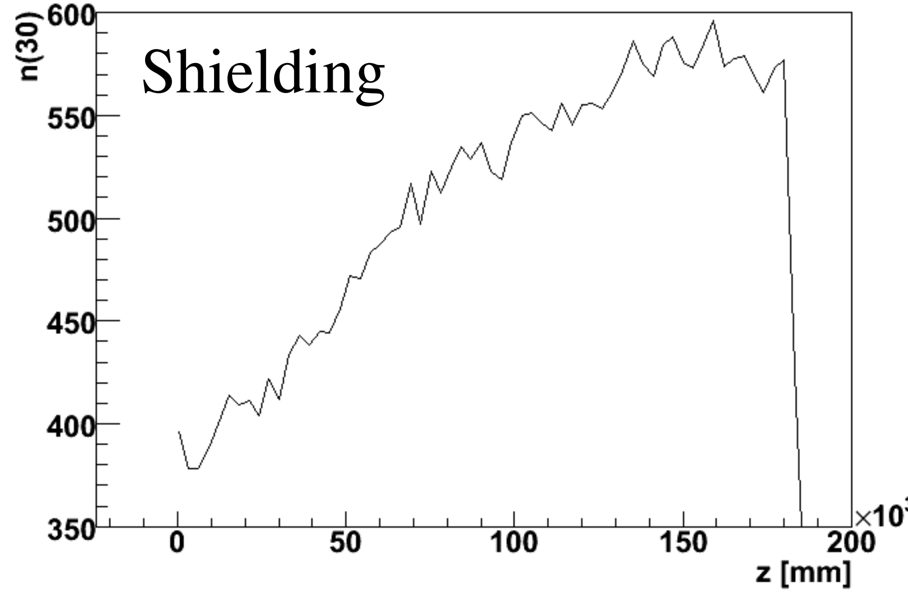




- β at absorber unaffected by presence of shielding, coil length
  - $\langle B_z^2 \rangle$ = same for all lattices
- Acceptance is slightly affected by short vs long coil
  - Can improve short coil acceptance by increasing coil radius
  - Probably of order accuracy of acceptance calculation routines
- Acceptance is ~unaffected by this weak shielding of fringe field tails

Cooling Performance

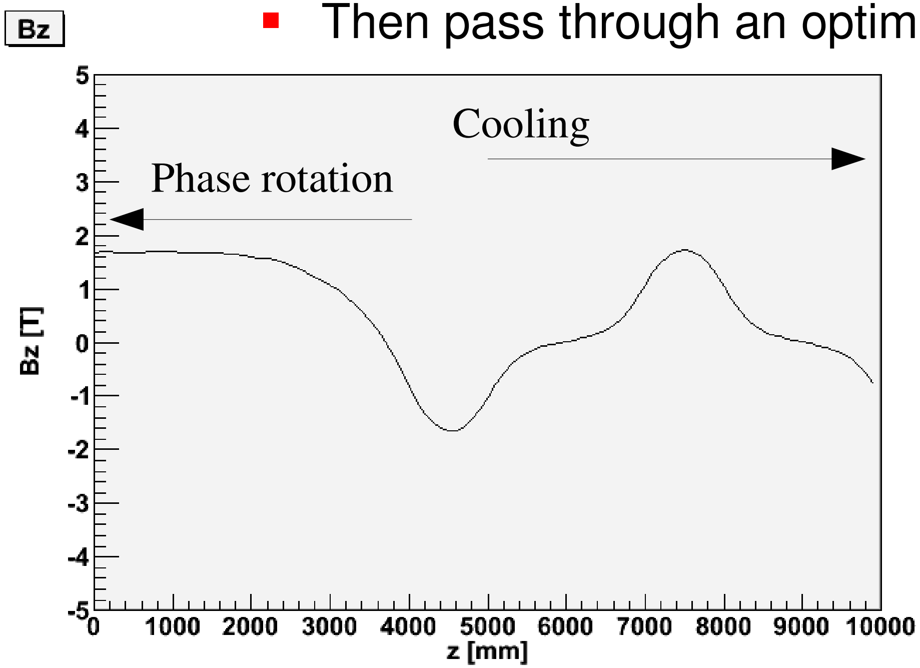


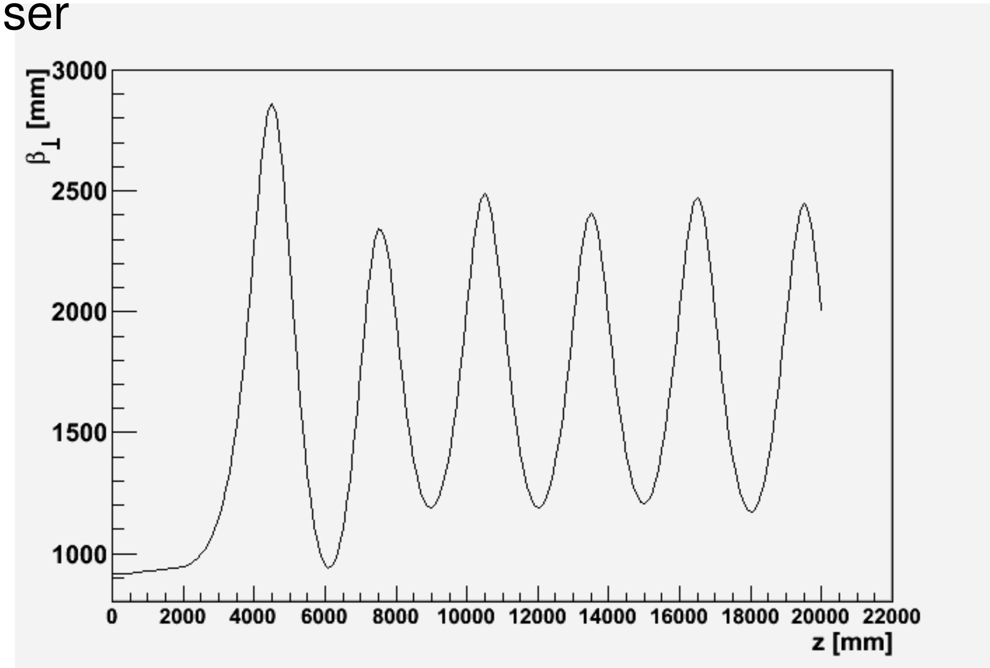


- Transmission into momentum bite 100-300 MeV/c and acceptance of 30 mm
- Shielding gets increase of ~ 52% (better than no-shielding!)
- No-shielding gets increase of ~ 45%

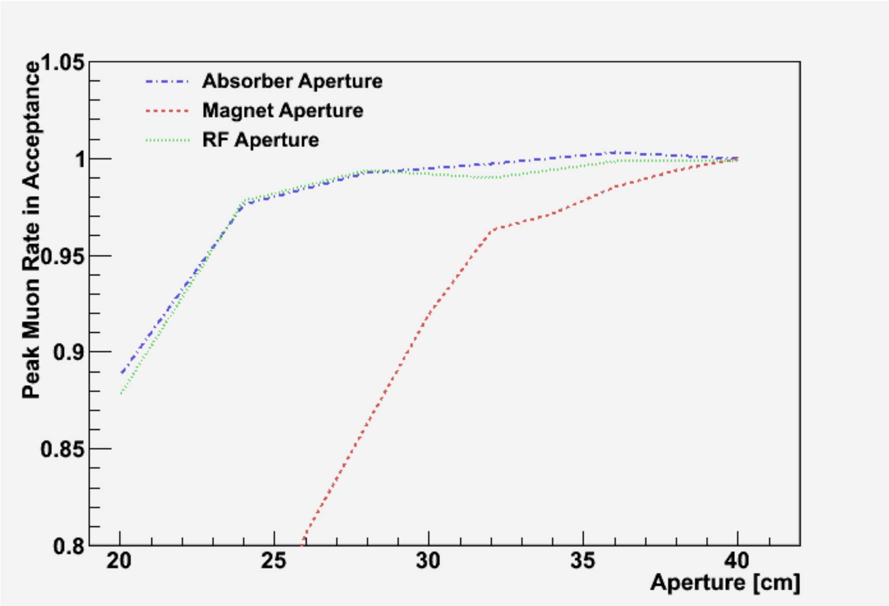
Transverse Matching

- Try using beam directly from simulation
  - p63a lattice http://www.astec.ac.uk/groups/beams/users/rogers/Front_End/Beams_and_Lattices/FrontEnd_FS2A_ICOOL_p63a-2010-02-02/
  - Linear matching using derivatives to generate transfer maps
    - Vary last coil of phase rotation and first coils of cooling
    - Not quite perfect but beam is pretty rough
  - Then pass through an optimiser



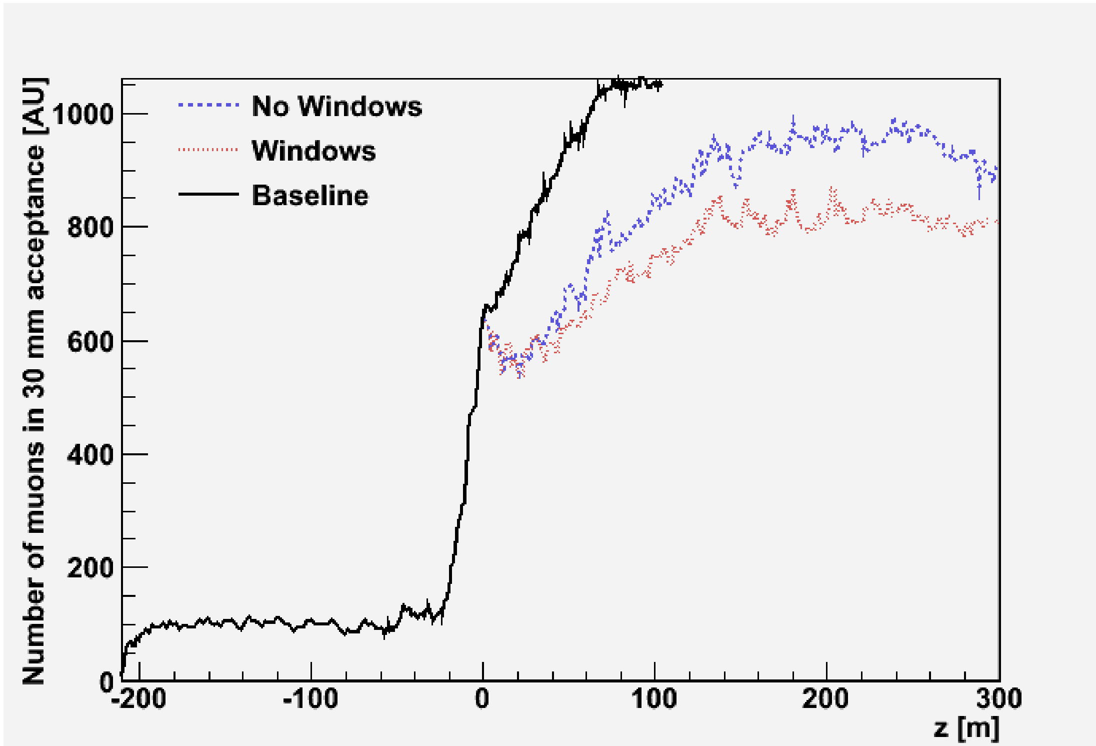


Apertures



- Change in muon rate vs aperture determines
  - How much space we can get for magnets
  - Thickness of windows

Windows



- Windows knock the improvement in rate quite a bit
  - I use ~minimum thicknesses from MICE lattice
  - Rather optimistic
    - Bigger apertures => thicker windows
  - Still quite damaging to muon rate

Part 3 - Higher Momentum Optimisation

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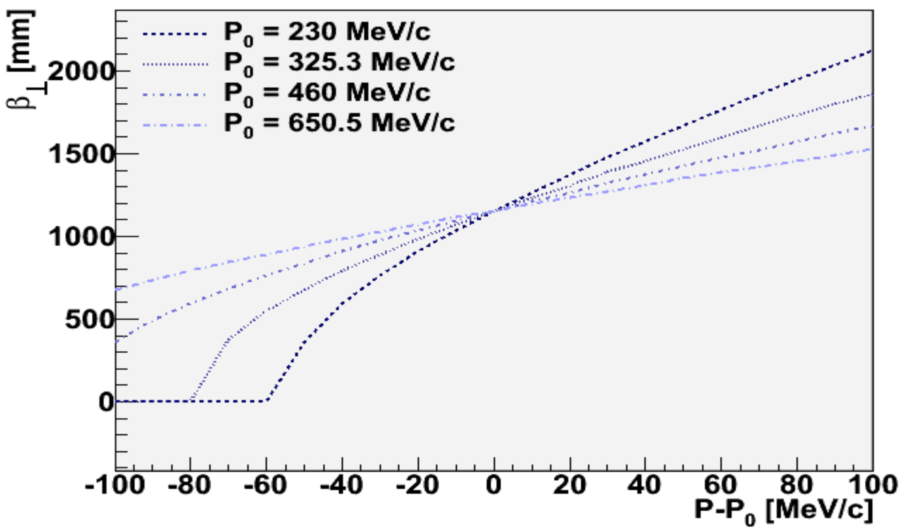
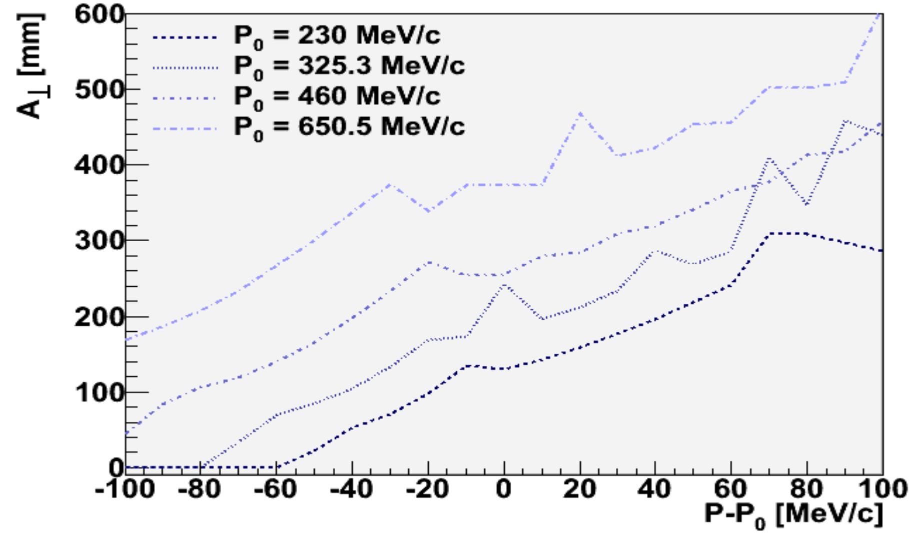
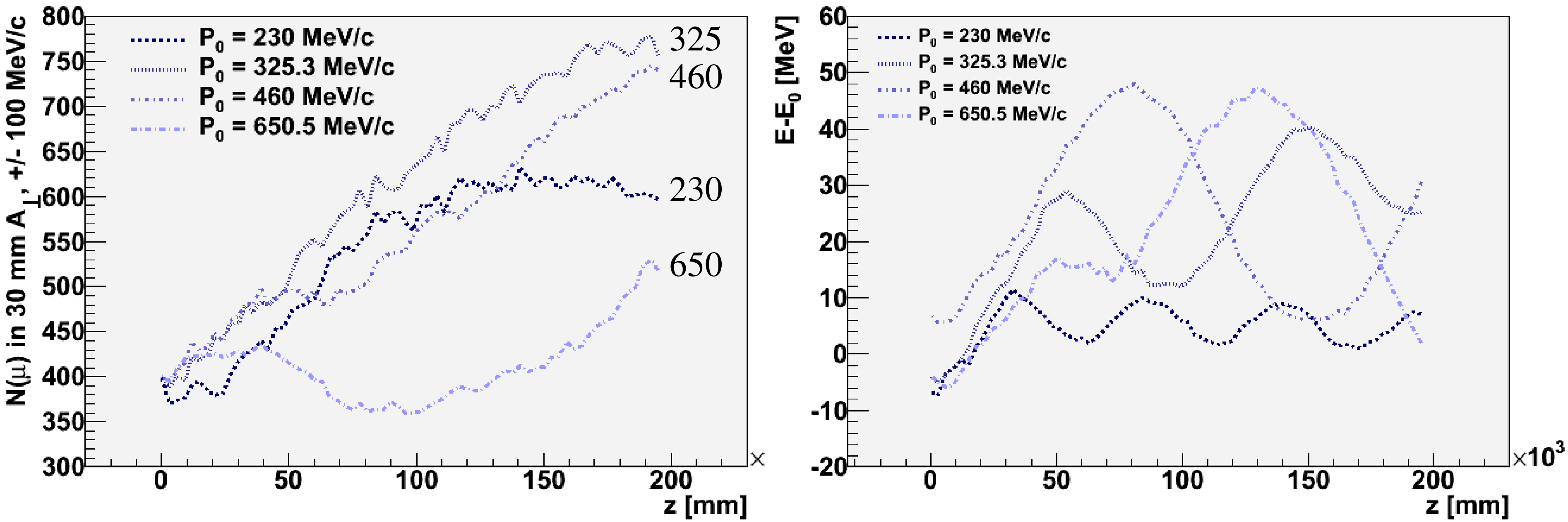
Improved Acceptance





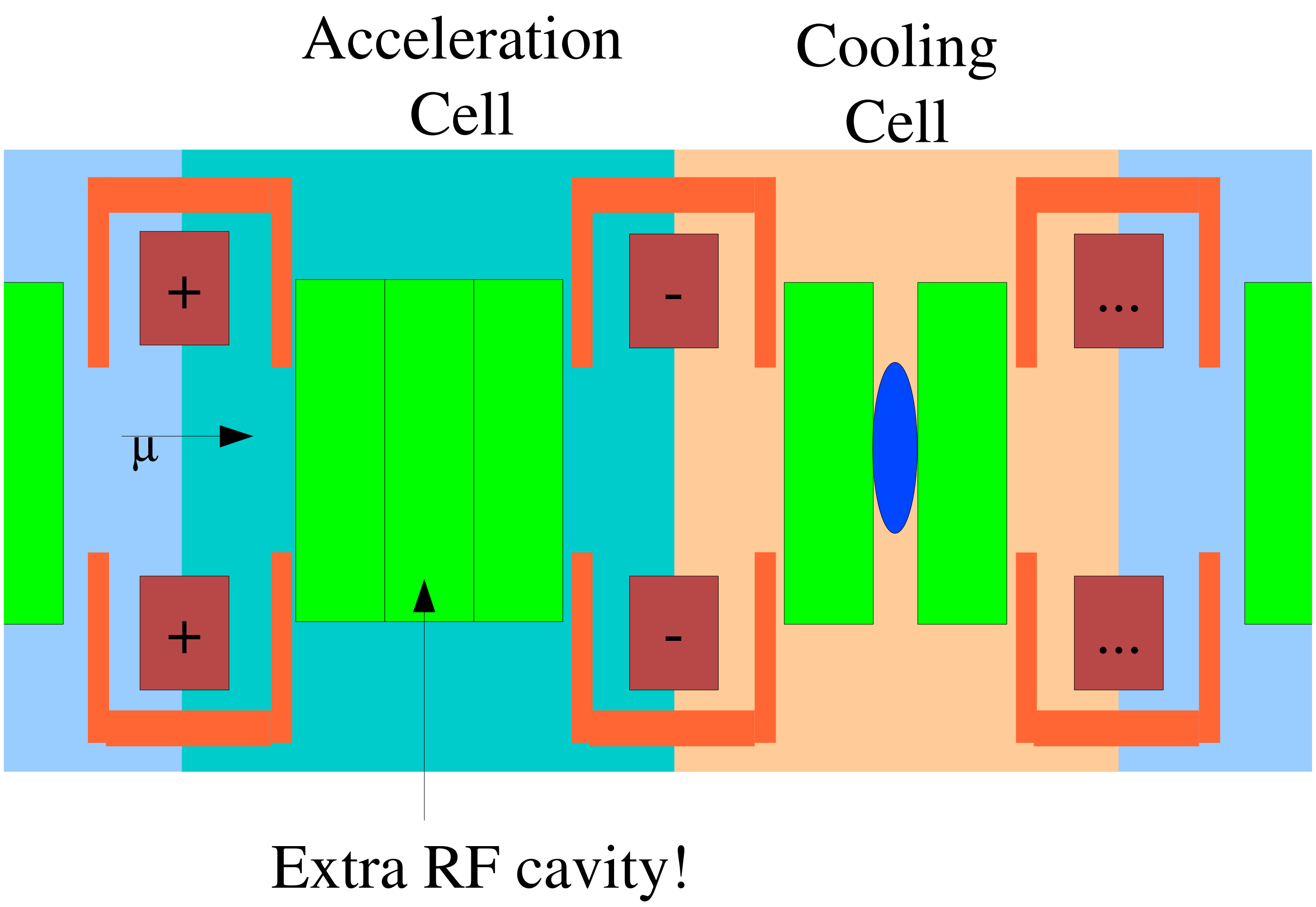
- Momentum acceptance goes proportional to p
  - i.e. $\beta(\delta p/p)$ is constant as p increases
- Transverse acceptance gets larger at higher momenta (~p?)
  - Geometric emittance effect
- Overall expect better transmission at higher momenta
  - And/or possible to move to smaller β function
- Increase RF phase - “adiabatic taper”
- But cooling length goes as $\delta p/p$

Naive simulation

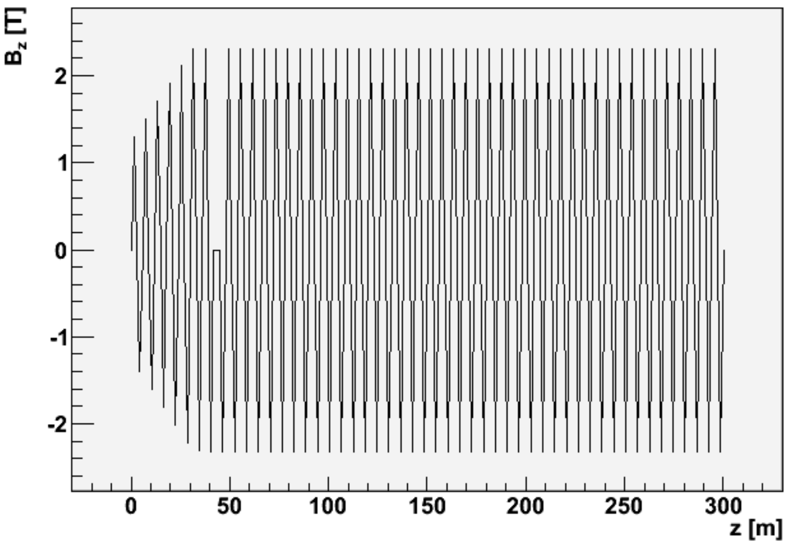


- Give my input beam a momentum kick
  - How does the n(z) go?
  - Longitudinal mismatch!

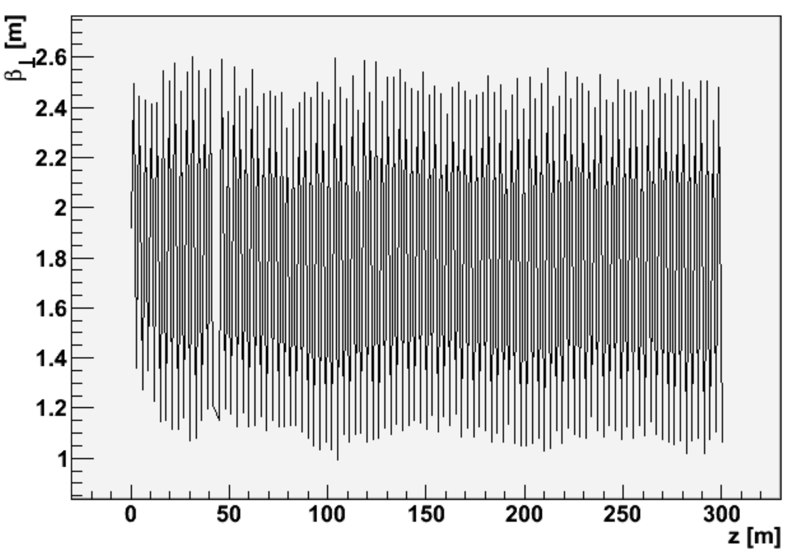
Introduce "acceleration cell"

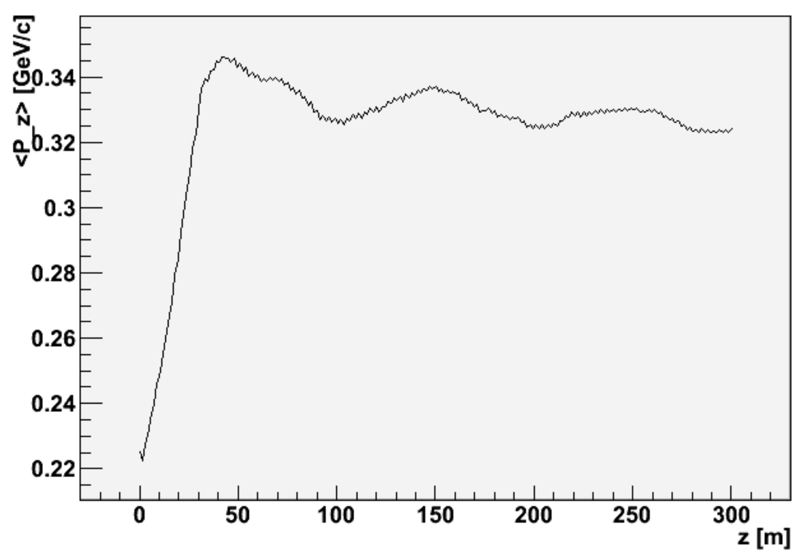


Higher Momentum Beam

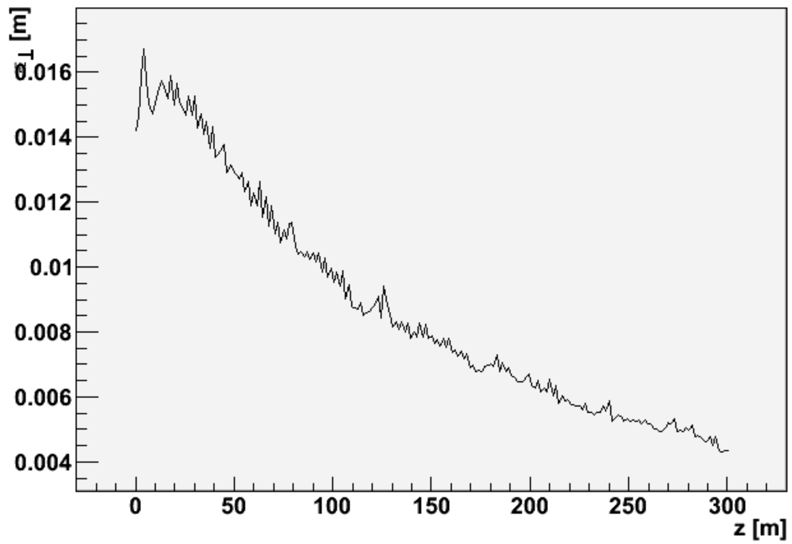


- Try accelerating the beam for real
- Bring magnetic field up “adiabatically”
  - Trying to taper β function a bit
  - Matched β starts at ~1.5 m and ends at ~1.1 m
  - Slight β beating, probably related to momentum bouncing around

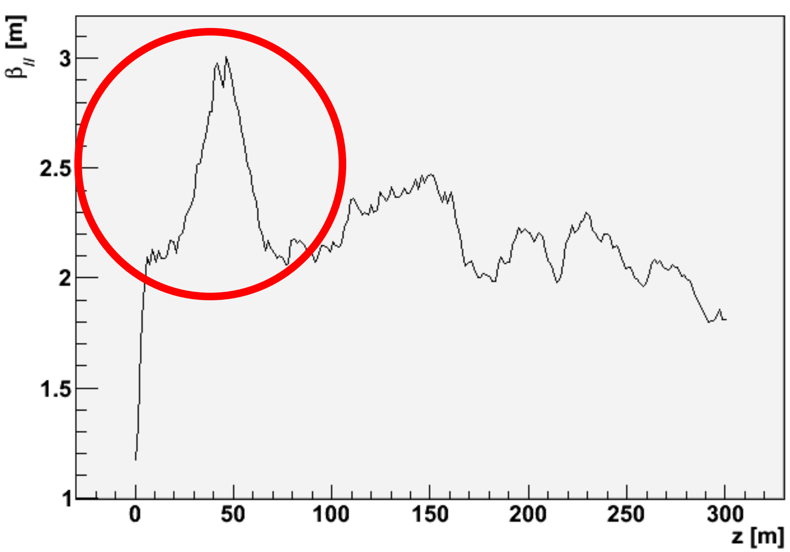


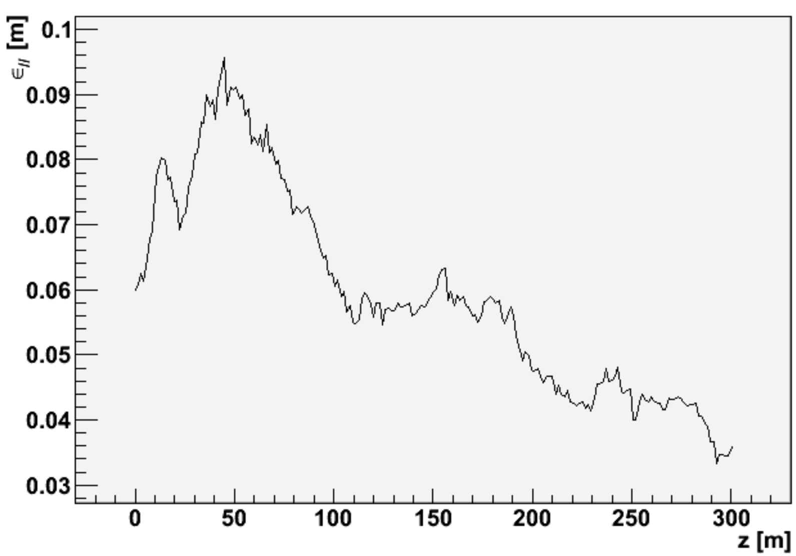


Emittances etc

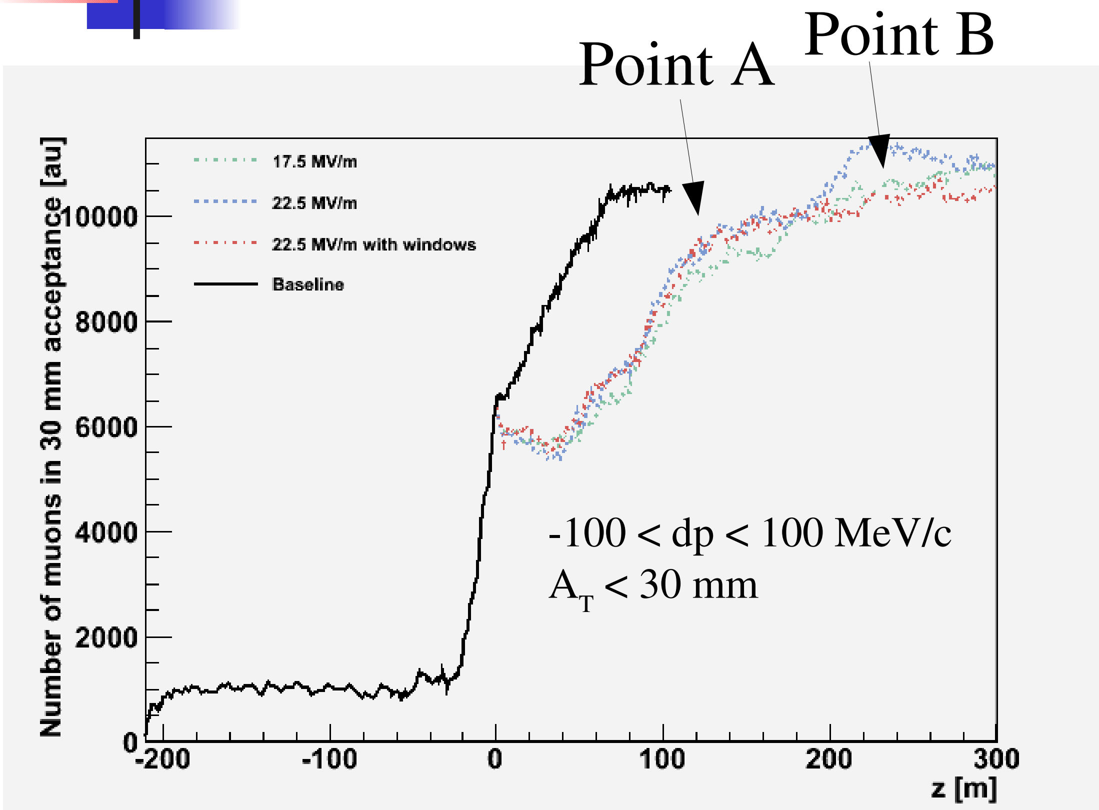


- Some longitudinal mismatch
  - Bit of longitudinal emittance growth
- Transverse looks ok
  - Note in this case I've assumed a transverse matching
  - Massaged my beam to give this match





Higher Momentum Beam



- Fairly large transmission losses
  - >~ 50%
- Most of the remaining beam is inside the 30 mm acceptance
- Getting increase in rate of ~ 70 %
  - But with more hardware
  - Performance quite similar to baseline
- If I stop at point A - I use roughly the same amount of hardware as the baseline (RF packing fraction ~ 1/2 that of the baseline)
  - And lose a few muons
- I can recover baseline performance if I go to Point B
  - But those last few muons are expensive!

Part 4 - Hardware Inventory

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RF Cavities

	Baseline	Long Coil	Accelerated 1	Accelerated 2
RF Cavities				
Number	~80	~120	~210	~210
Peak Field	15.500	19.000	17.5-12.5*	22.5-17.5**
Length	50.000	50.000	50.000	50.000
Frequency	201.250	201.250	201.250	201.250
Phase	40.000	30.000	20-40*	20-40*

* RF ramps down linearly from 17.5 to 12.5 MV/m in 10 acceleration cells and from 20 to 40 degrees phase. Subsequently RF operates at 17.5 MV/m and 40 degree phase. Note I am going to "Point B" here.

** RF ramps down linearly from 22.5 to 17.5 MV/m in 10 acceleration cells and from 20 to 40 degrees phase. Subsequently RF operates at 22.5 MV/m and 40 degree phase. Note I am going to "Point B" here.

Coils

	Baseline	Long Coil	Accelerated 1	Accelerated 2
Coils				
Number	~80	~60	~100	~100
Peak Field	2.783	1.633	1.295-2.312**	1.295-2.312**
Superconductor Volume	0.060	0.283	0.283	0.283
Current Density	106.667	17.660	14.0 to 25.0**	14.0 to 25.0**
Inner Radius	0.350	0.400	0.400	0.400
Radial Thickness	0.150	0.100	0.100	0.100
Length	0.150	1.000	1.000	1.000
Iron shield mass	N/A	14 T	N/A	N/A

** Coil peak field ramps linearly from 1.3 to 2.3 T in 10 acceleration cells. Subsequently peak fields are all 2.3 T

Absorbers

	Baseline	Long Coil	Accelerated 1	Accelerated 2
Absorbers				
Number	~75	~60	~100	~100
Absorber Thickness	1.000	25.000	25.000	25.000
Absorber Material	LiH	lH2	lH2	lH2
Window Thickness	0.025	0.300	0.000	0.000
Window Material	Be	Al	Al	Al

Part 5 - Advantages, Disadvantages

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Heat Load and Radiation

- ~ 40 W/m beam power is lost into the walls in this lattice
  - O(Similar) for baseline front end
  - + radiation from RF cavities?
- Total heat being dumped in superconductors may be significant
  - Can the baseline magnets be shielded? Not much room!
- What about activation?
  - Leptons, probably ok
- Note that long coil option can be built with more relaxed < 30 A/mm^2 current densities
  - May get worse if a bucking coil is used for shielding
  - May get better if iron is used for shielding

Continuous solenoid

- Continous solenoid scares me
  - I guess NF front end would be >> longest solenoid in the world
- What happens if quench protection system (or something) fails catastrophically?
  - cf LHC
  - Do we destroy entire front end and target solenoid?
- Having some 'fire breaks' in the magnetic field might be a good thing

Vacuum, Diagnostics

- Need to look at services
  - Vacuum system
  - Diagnostics
  - Needs space!

Magnet Shielding

- We will probably want to shield all the magnets
  - Stray iron, physicists, etc, outside the magnets can not steer the beam
  - Equipment in the same tunnel is not bathed in moderate magnetic field
  - Can lower the stored energy in the magnet - maybe
  - Stray iron won't move around the hall when the magnets are switched on
  - Physicists' credit cards, etc, less likely to get wiped

Absorbers

- Liquid Hydrogen absorber may be challenging
  - Windows
    - Fragile
    - Effect of RF cavities?
  - Safety issue
- Some issues need to be addressed for LiH absorber
  - Cooling
    - Heat load from muons
    - Heat load from RF
  - Some safety issues

Phase Rotation

- I have not touched the phase rotation part of the lattice
- Some RF cavities here have ~ high peak fields and sit in strong magnetic fields
- I may be able to do better by capturing at a higher momentum
  - Rather than having this rather aggressive section of acceleration
- I would like to try to improve the longitudinal match
  - Initial study makes it look non-trivial

Part 6 - Conclusions

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Conclusions

- It is possible to compete with the baseline lattice using RF cavities that do not sit in strong magnetic fields
- But it looks moderately expensive
  - Either in muon rate
  - Or in RF cavity power supplies
  - (Or both)
- I would like to try to improve things back in the phase rotation system
- I would like to do a high stats study
- I need to look more closely into how much shielding I can really get away with
- The baseline design may be challenging to build
  - I think this long chain of coupled solenoids will bite us!

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Appendix - Code Comparison

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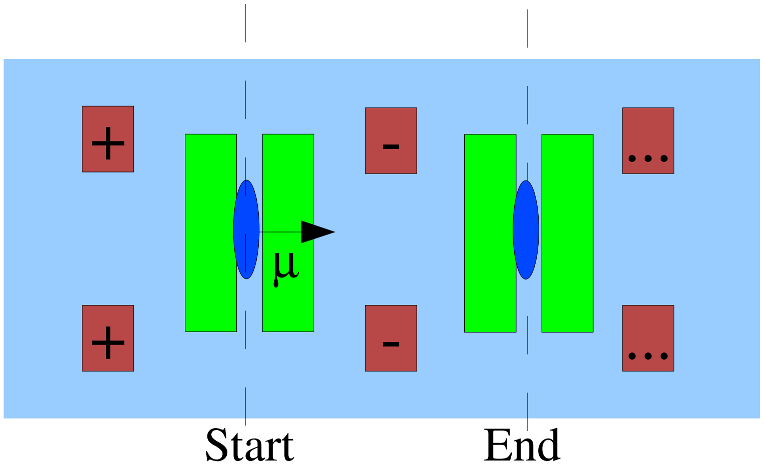
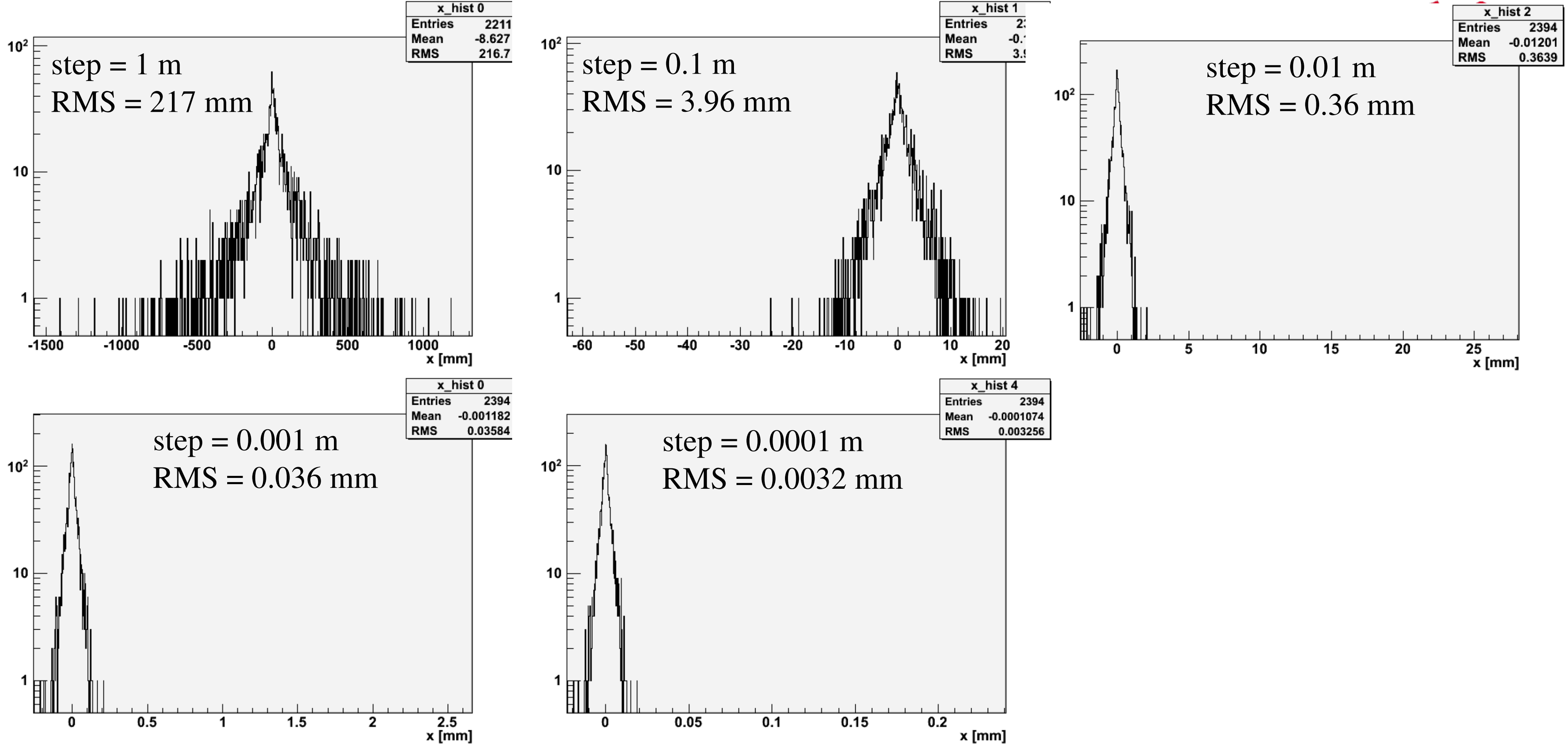
G4MICE and ICOOL

- G4MICE
  - Written for MICE experiment
  - Based on G4 physics model
    - Tracking
    - Physics processes
  - Adds field maps for multipoles, solenoids, rf cavities
  - Plus some beam optics, mapping, analysis routines
  - Last time I did a detailed study of the tracking was ~ 3 years ago
  - Tracking by integration of Lorentz force with 4th order RK
- ICOOL
  - Written for simulation of cooling for Nu Factory and Mu Collider
  - Internal physics and tracking routines
  - Many different field models
  - “Well known” by community

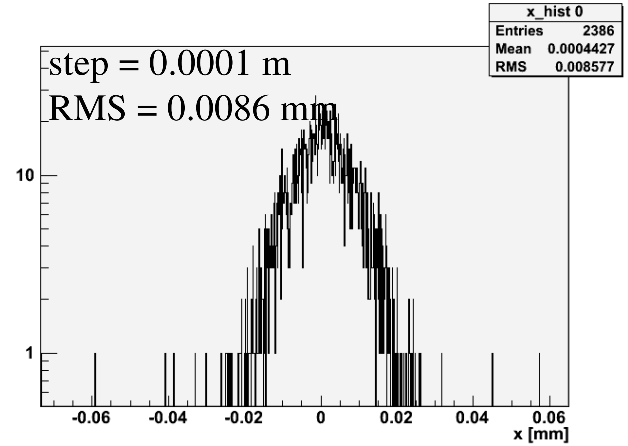
Cell Model

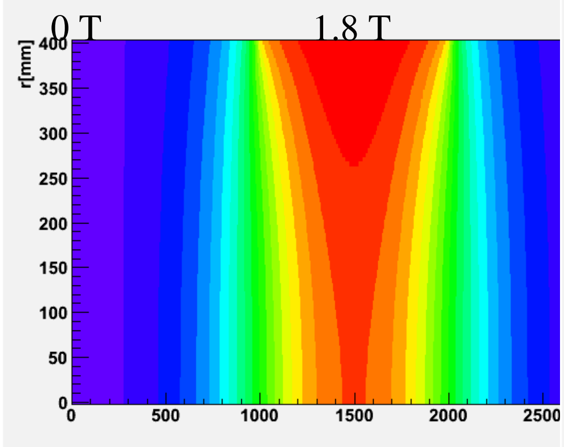


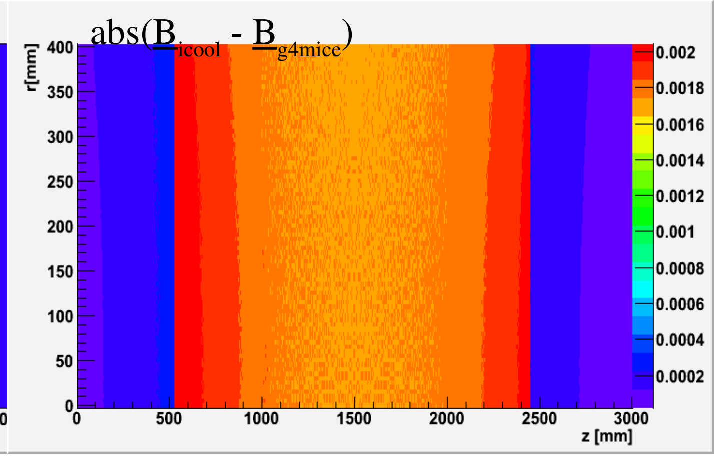
- 3 m cell
  - Start with just magnets
  - Then add pillbox cavities
  - First look at rf field maps also
    - Not in most of my simulations, but will want it sometime
  - Ambition to add Parmila solenoid field maps
  - Then add lH2
  - Don't look at windows yet
    - But will want this also soon
    - Presume if we have lH2 that's “good enough”



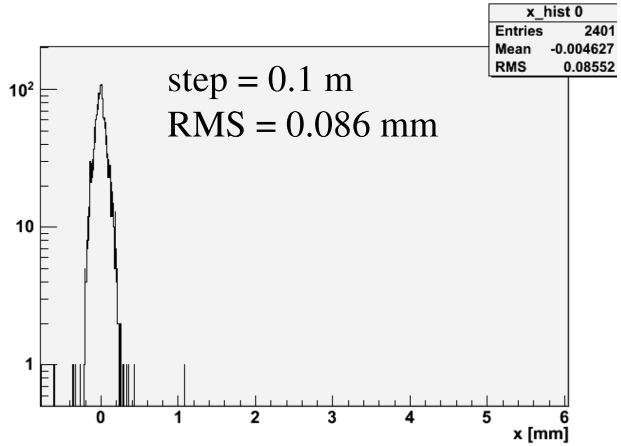
- ICOOL, magnetic field only
  - x(step) - x(1e-5) [mm], where step is step size in tracking
  - BiLinear interpolation from a field map
    - Grid spacing 5 mm in r and 1 mm in z
  - Disable dynamic step size allocation

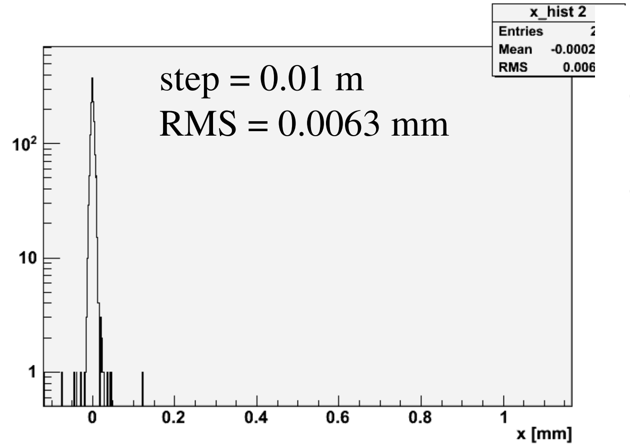


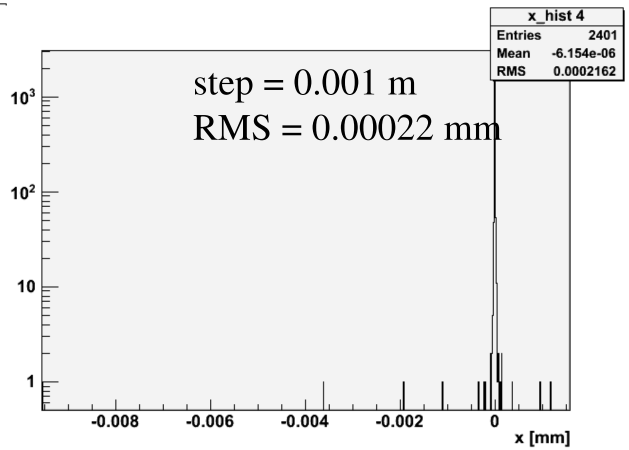




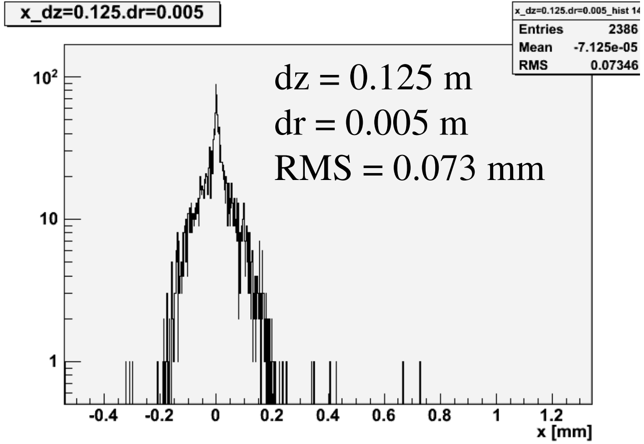
- Use ICOOL field map in G4MICE
  - Compare tracking in ICOOL step=1e-5 m with G4MICE step=1e-4 m
  - Compare G4MICE field map with ICOOL

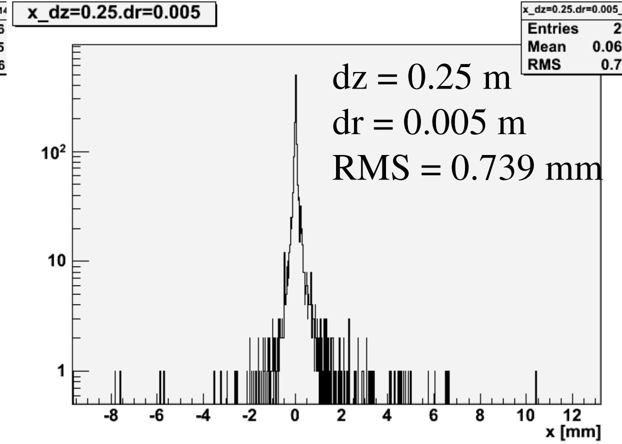


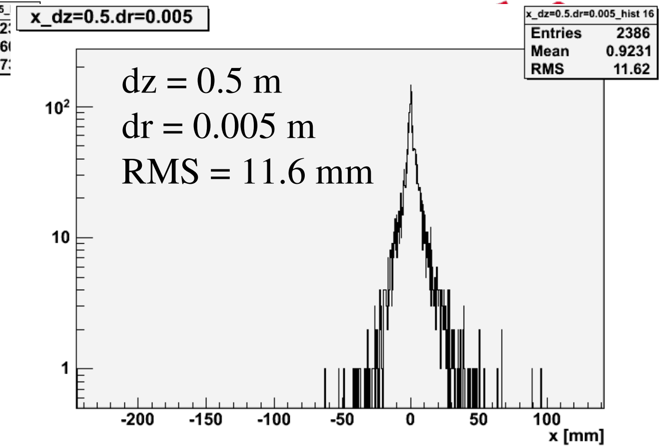


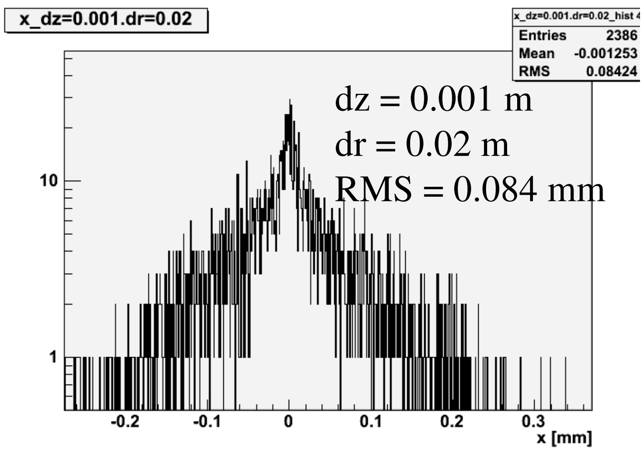


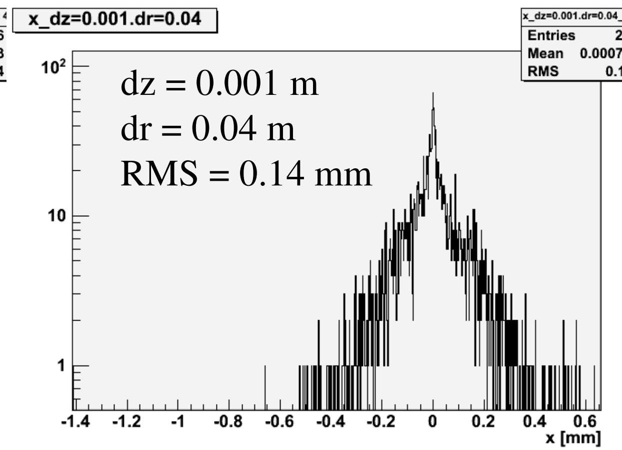
- Use G4MICE field map, all BiLinear interpolation
  - Tracking in ICOOL with ICOOL field map, step size 1e-5 m
  - Compare with tracking in G4MICE with G4MICE field map

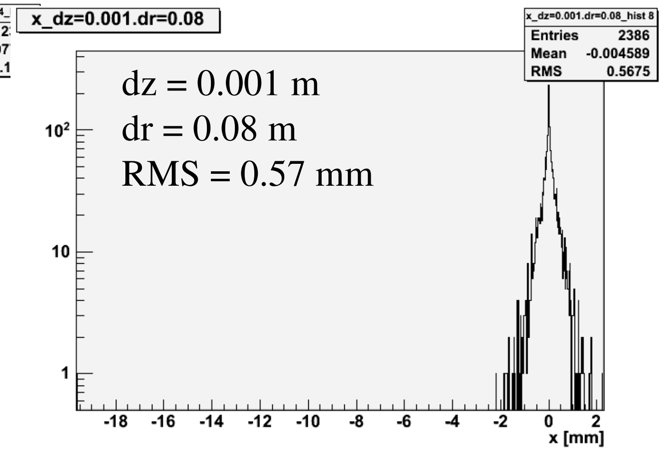




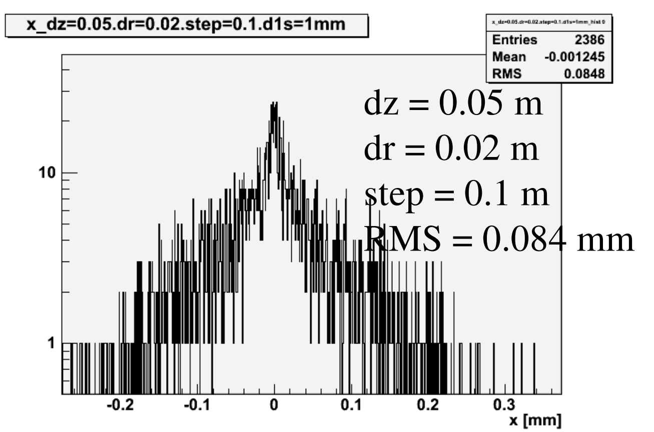


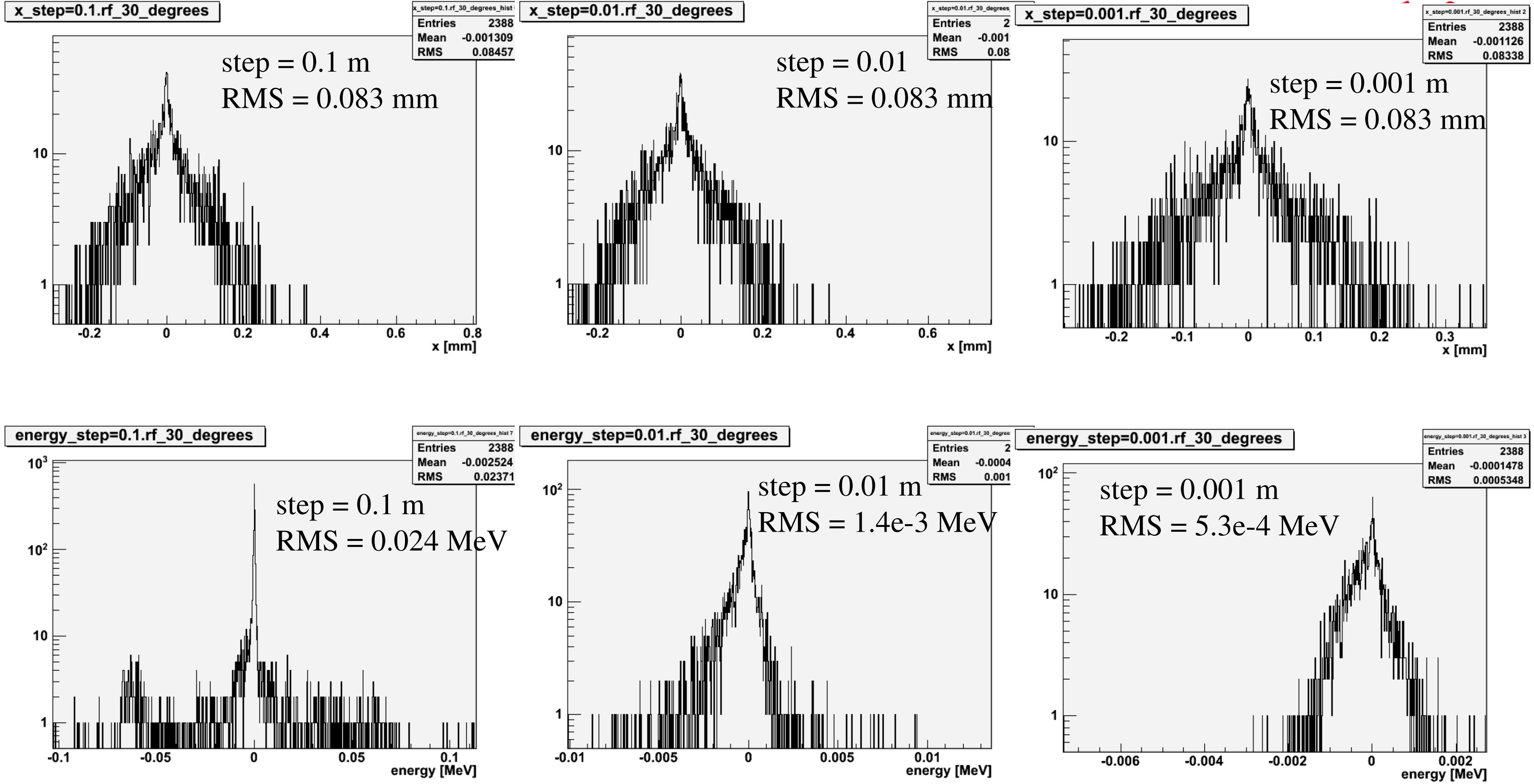




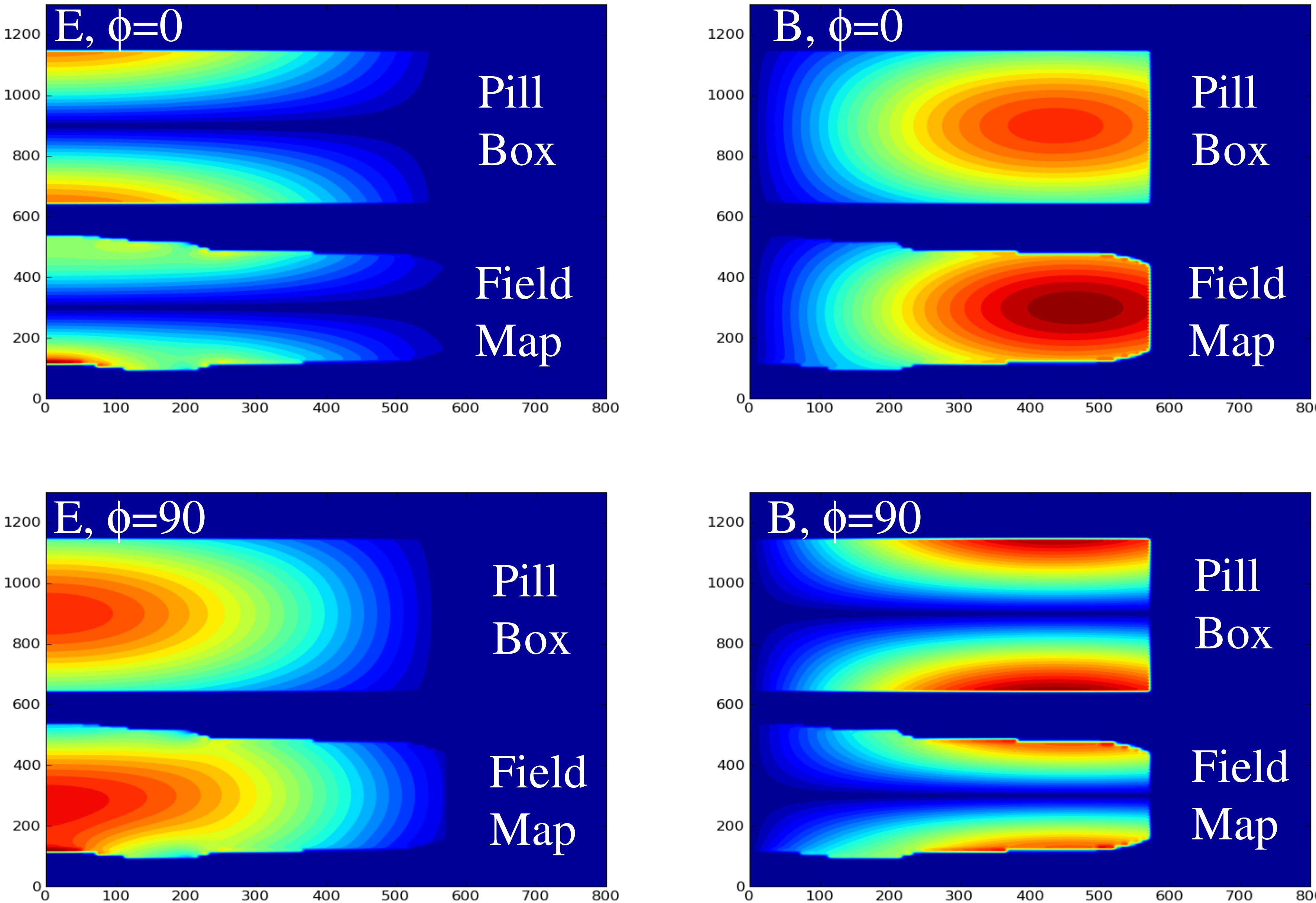


- Choose grid size for magnetic field map
  - Quite a hard cut-off as z grid size changes
  - Gradual cut-off for radial grid size
- Choose dz = 0.05 m, dr = 0.02 m, step=0.1 m
  - Enable dynamic step size allocation
  - Nominal error 1 mm





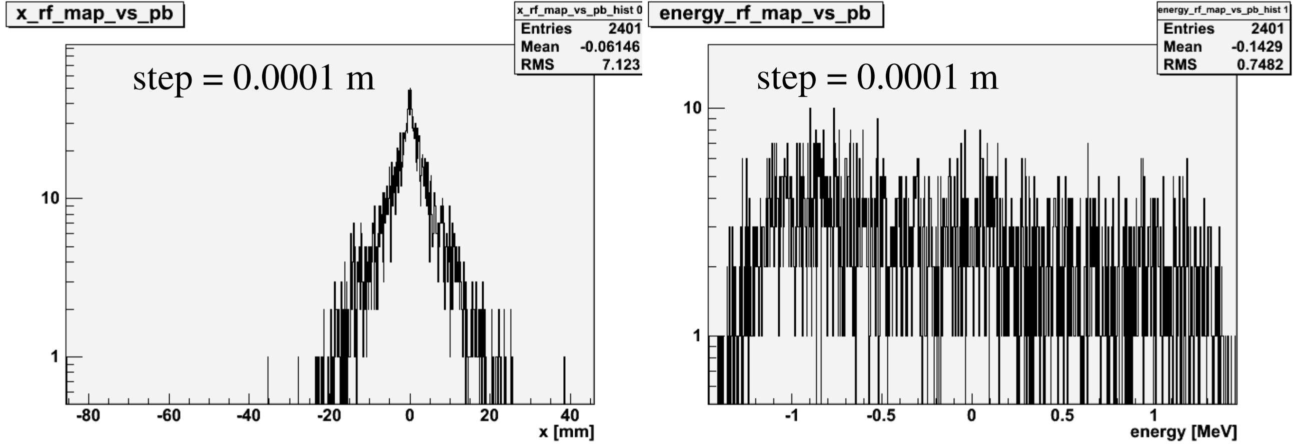
- Introduce RF cavity
  - Analytical model for pill box
  - Compare ICOOL step size 1e-4 with G4MICE
  - x limited by magnetic field map size
  - 0.1 m step size still ok

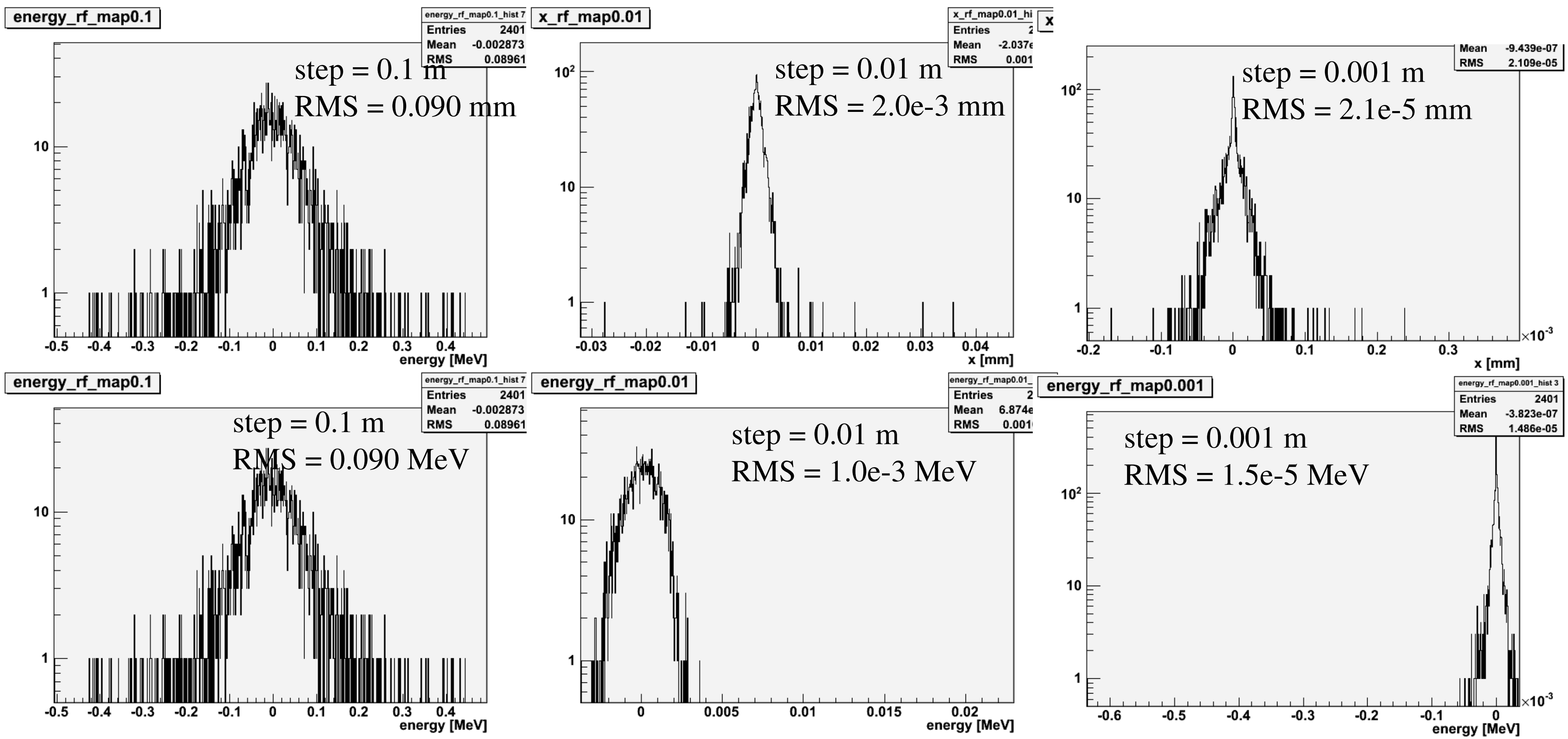


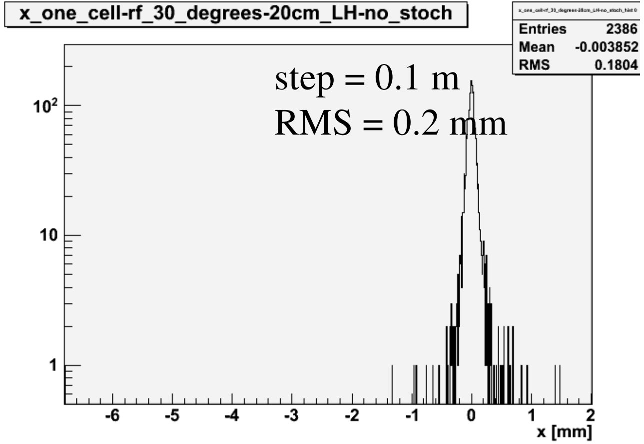
Absolute value of field seen by particle travelling at c

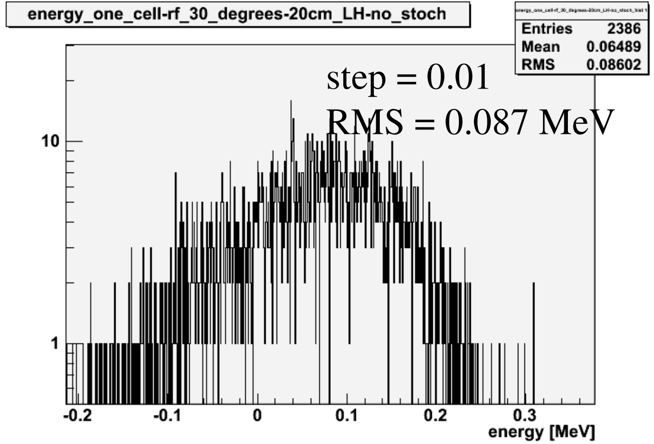
Peak E-Field = 17.5 MV/m, peak B-field ~ 20 mT

- Introduce RF field map from superfish
  - Compare with pillbox
  - Look for self-consistency

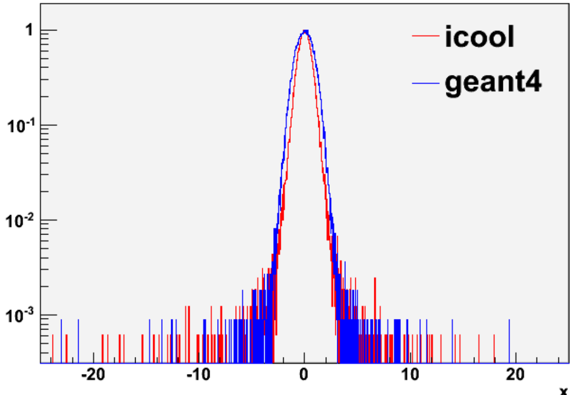


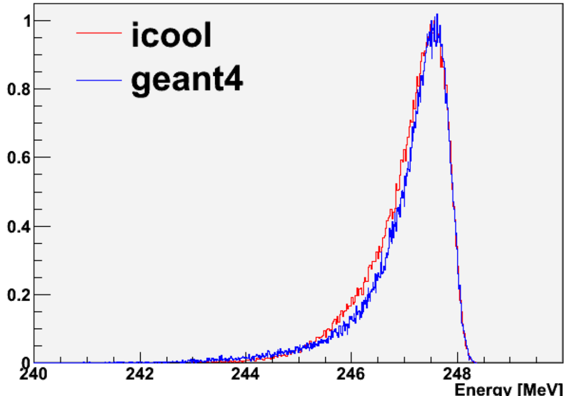






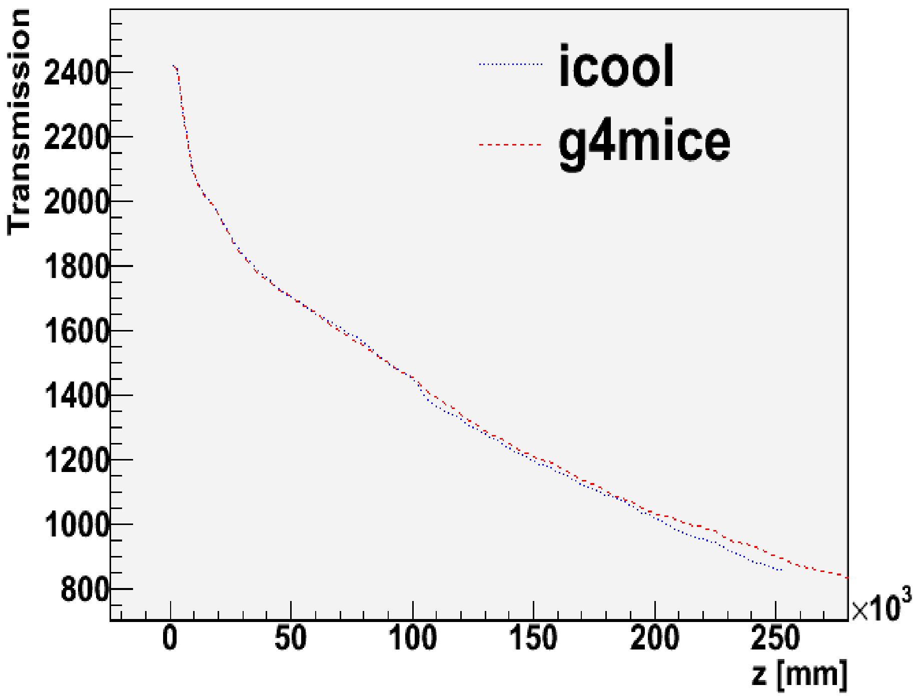
- Now add liquid Hydrogen
  - Stochastics switched off!
  - Look at difference between G4MICE tracking and ICOOL



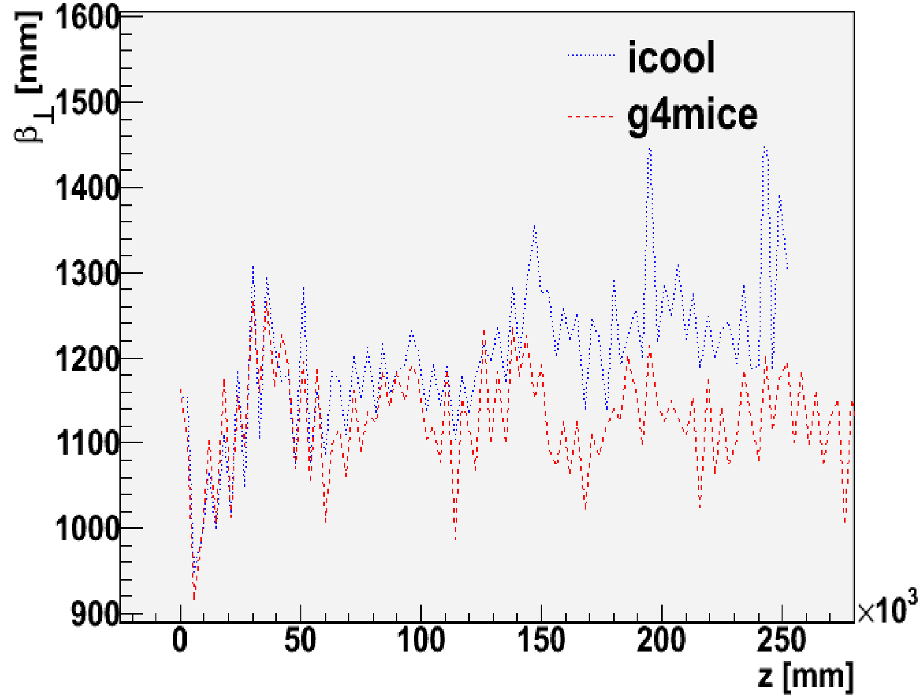


- Switch on stochastics
  - Track through 20 cm of lH2 in field map
  - Look at distributions before and after lH2
  - 1e5 muons with initial p=230 MeV/c, no transverse

Cooling Lattice



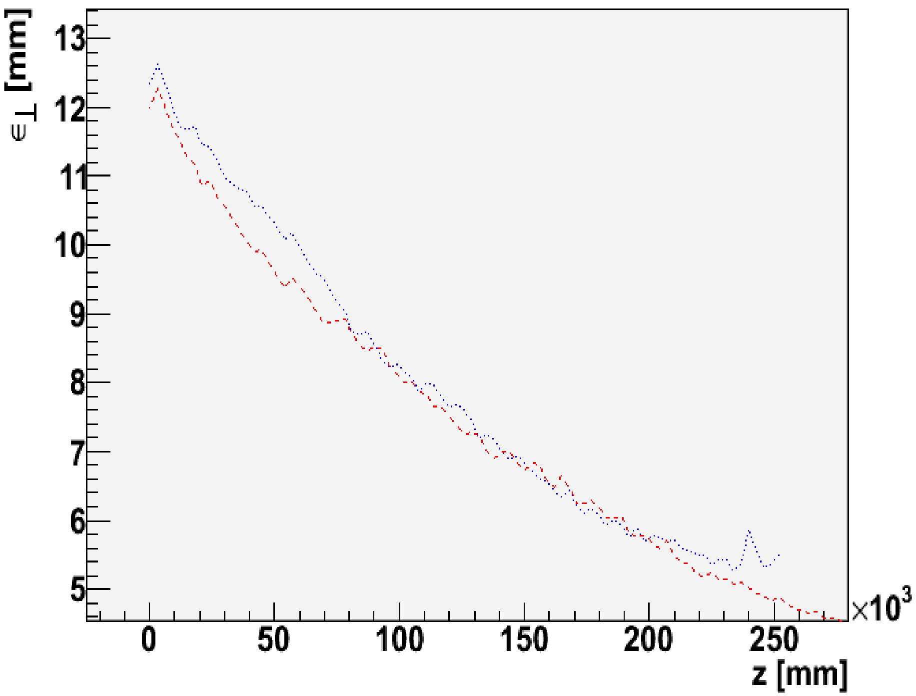
Total Transmission

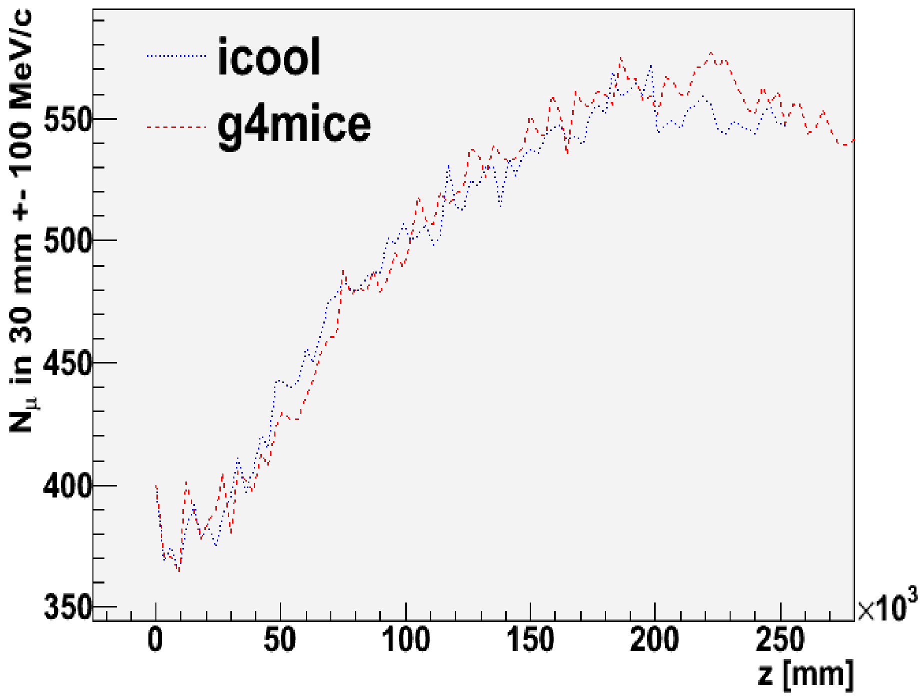


Transverse beta within

- transverse amplitude < 30 mm
- momentum 130 < p < 330 MeV/c

Cooling performance





Transverse emittance of muons
- that are transmitted to z=250 m
- momentum 130 < p < 330 MeV/c

Transmission within
- transverse amplitude < 30 mm
- momentum 130 < p < 330 MeV/c

Conclusions

- Simulation codes compare well
- For identical field models, tracking in G4MICE is convergent on tracking in ICOOL
- Physics processes in lH2 look similar
- Simulated cooling channel performance is similar for the two codes