Shielded RF Lattice for the Muon Front End

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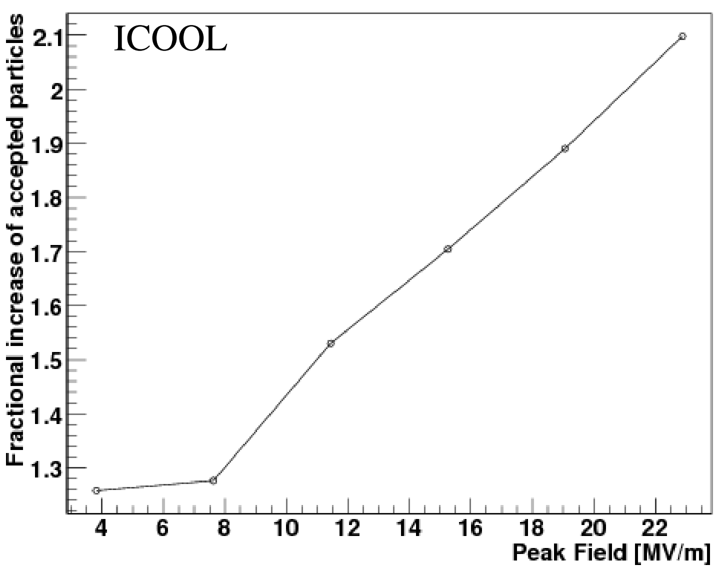
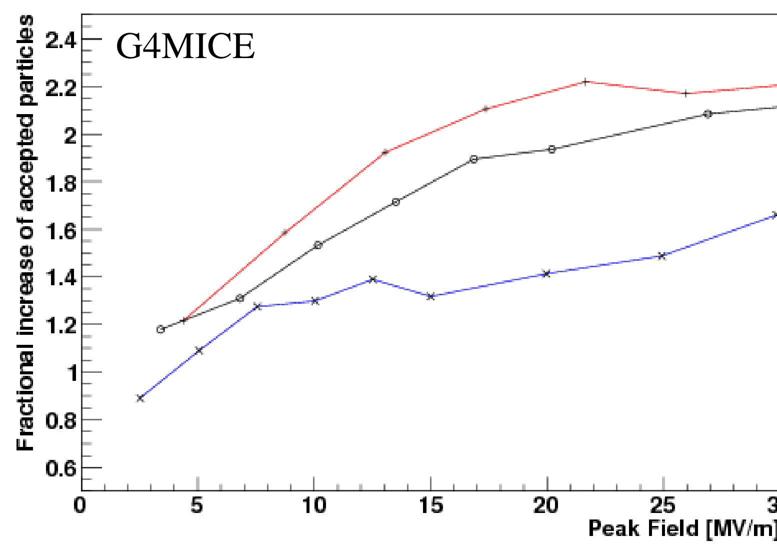
RF Problem

- 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

Problem Scope

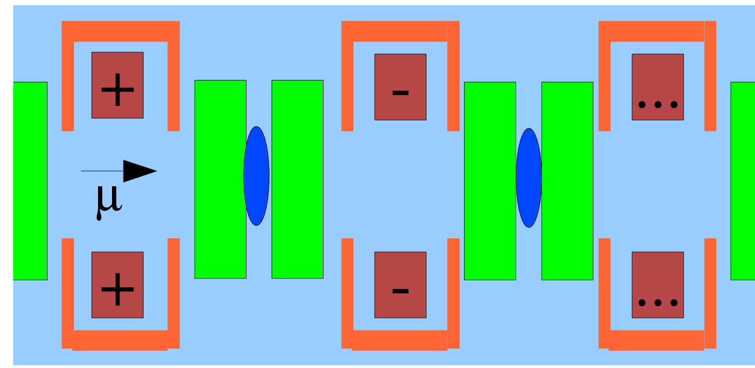
- What is the scope of the problem?
  - Baseline has RF cavities in ~ 2 T field
  - Guess peak gradient reduced factor 2-3
    - From 800 MHz studies
    - Need 200 MHz data
  - See, eg *C. Rogers and G. Prior, Cooling in Reduced RF Gradient, PAC09*
    - Also earlier study by Juan Gallardo (in ISS?)

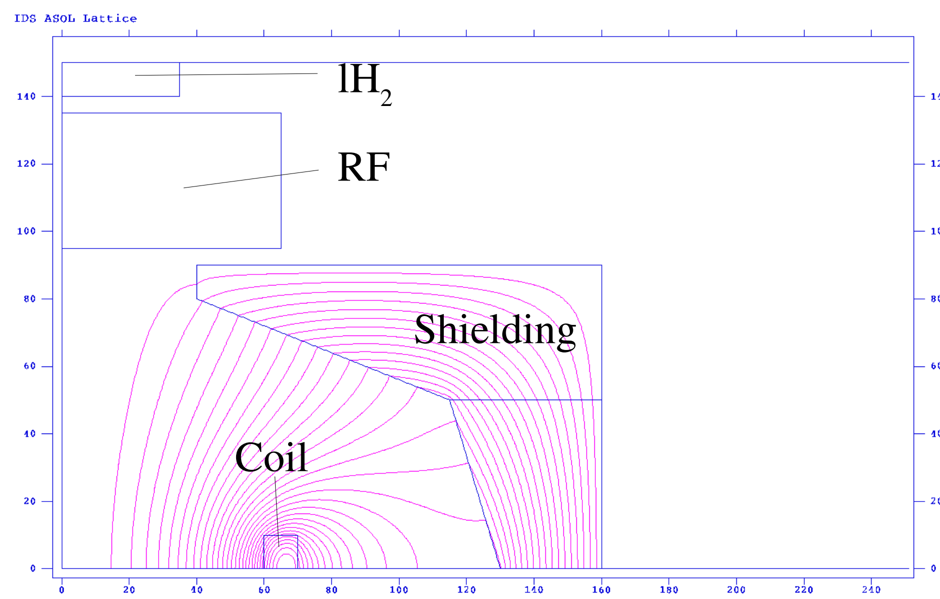




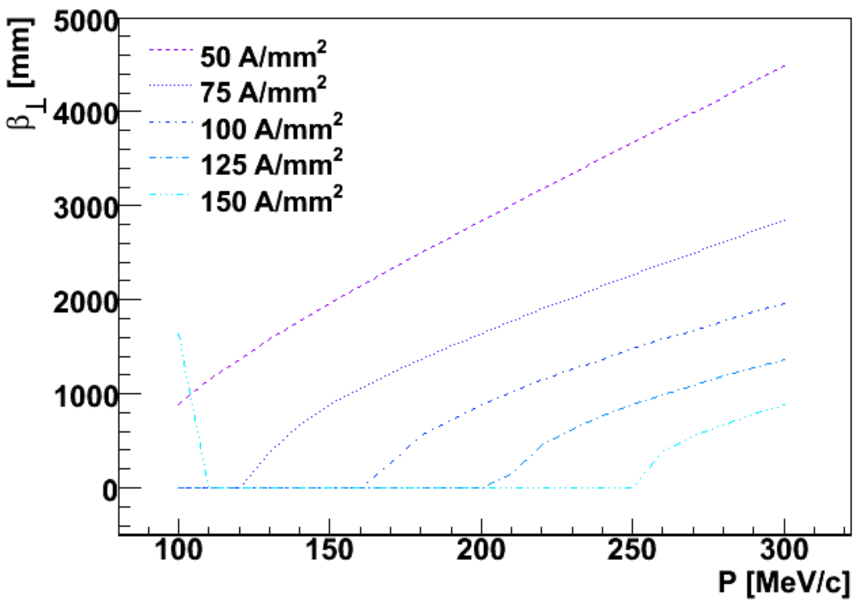
Shielded RF

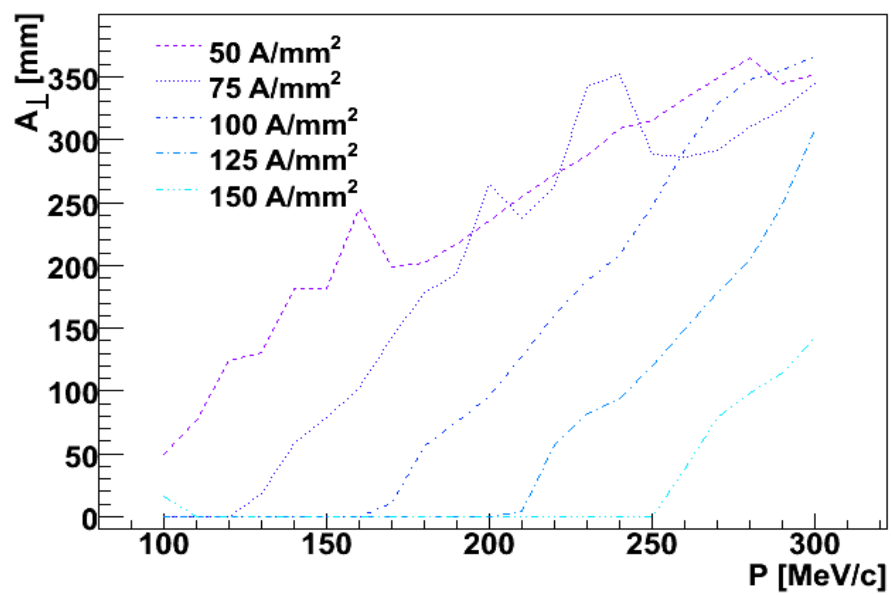
- Increase cell length to remove RF from fringe fields
  - Further shielding provided by iron
- Look at cooling section
  - This is where the RF is most limited
  - This is where optics are most demanding
- How well can we cool in this shielded scenario?
- How well can we optimise the cooling lattice?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





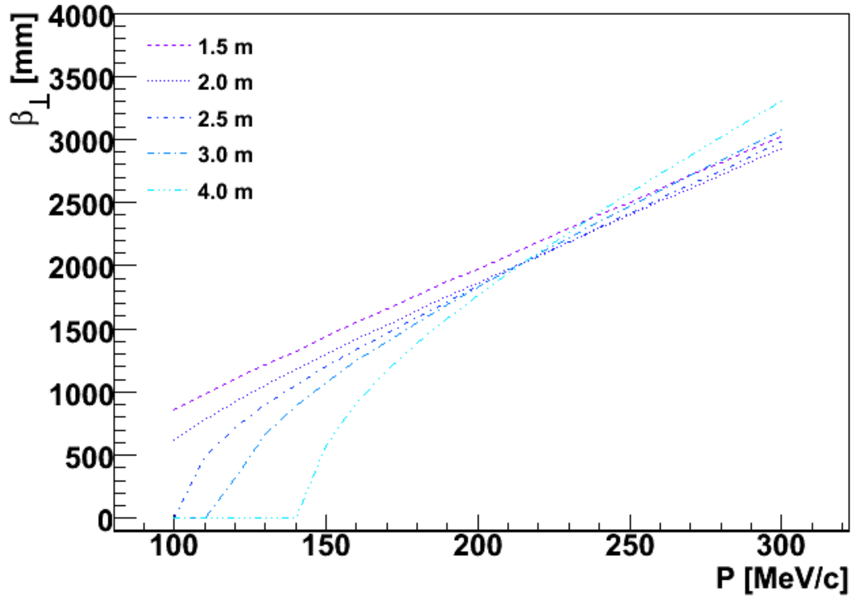
Lattice quality





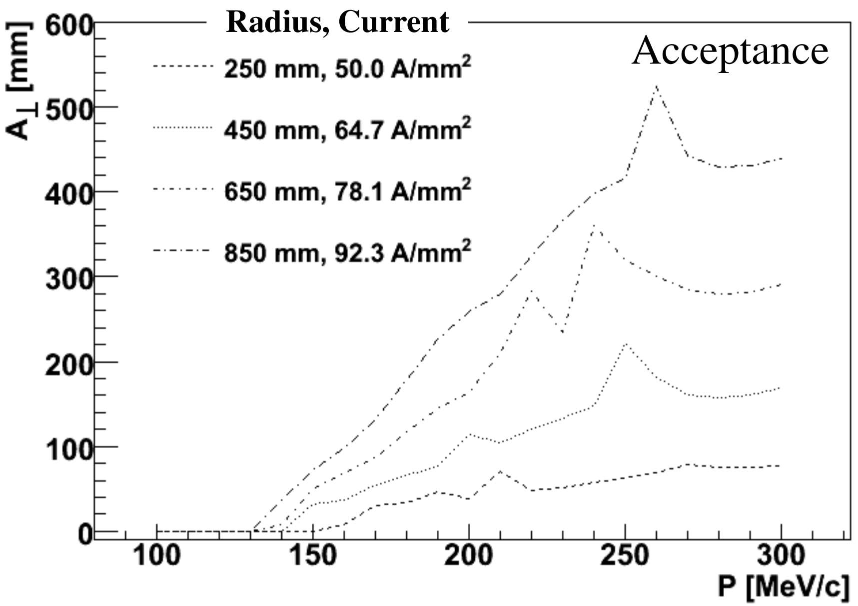
- Two criteria for lattice quality
- β function => how tightly focussed the beam is at the absorber
  - Determines how much cooling we get
  - Require good β function over a large momentum range
- Acceptance => the beam emittance that makes it through the lattice
  - Determines how much beam we get through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

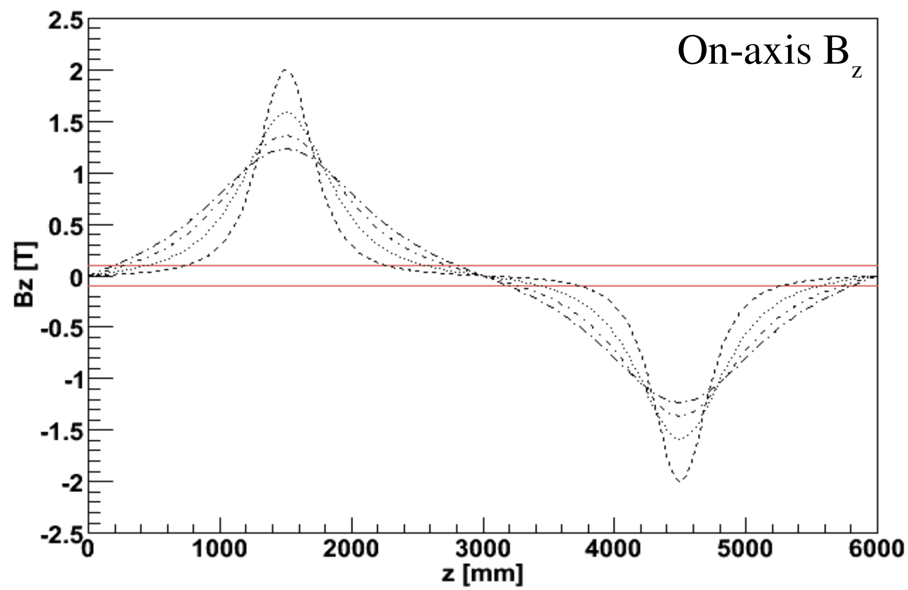
β vs Cell Length



- 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

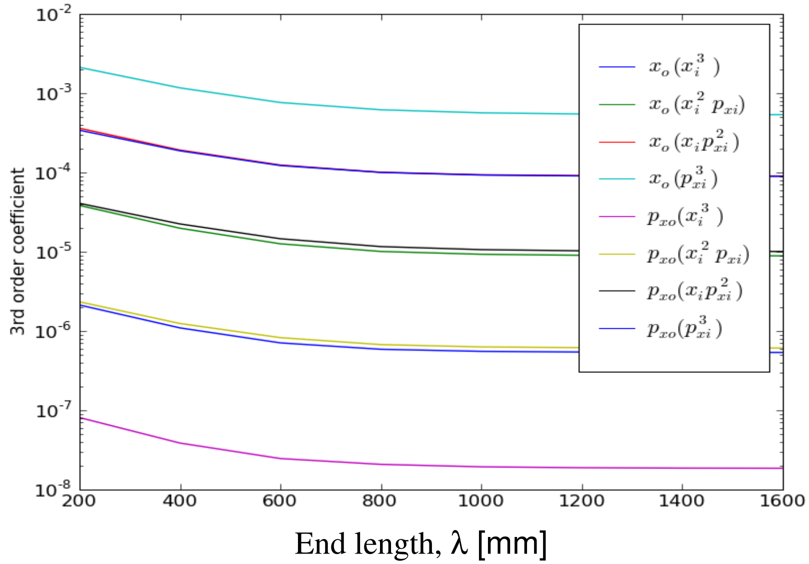
Dynamic Aperture vs Radius

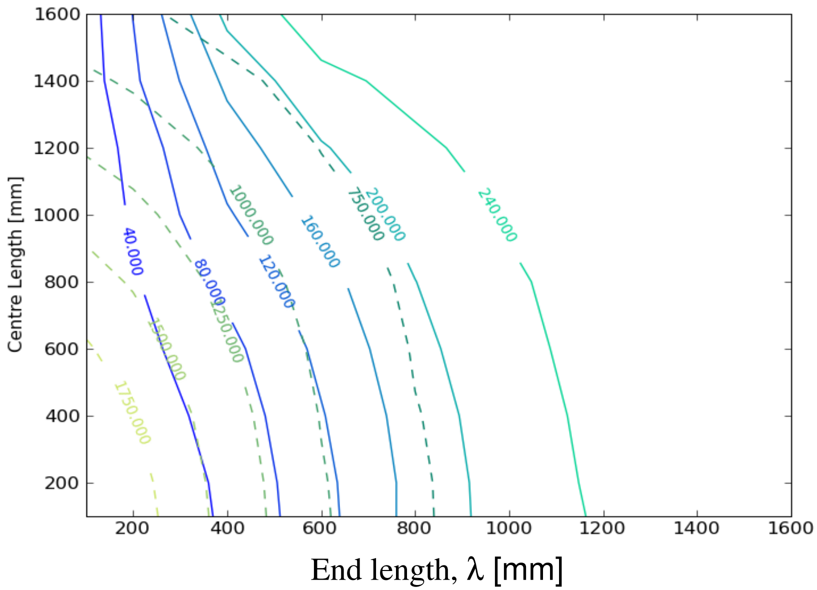




- Reducing radius of coil reduces lattice acceptance
  - Aim for acceptances >~ 100 mm
  - Naively "expect" that reducing coil radius decreases acceptance
  - "Particles travel through region of poor field quality near the coils"
- In solenoid, optics is uniquely defined by on-axis field
  - So any attempt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

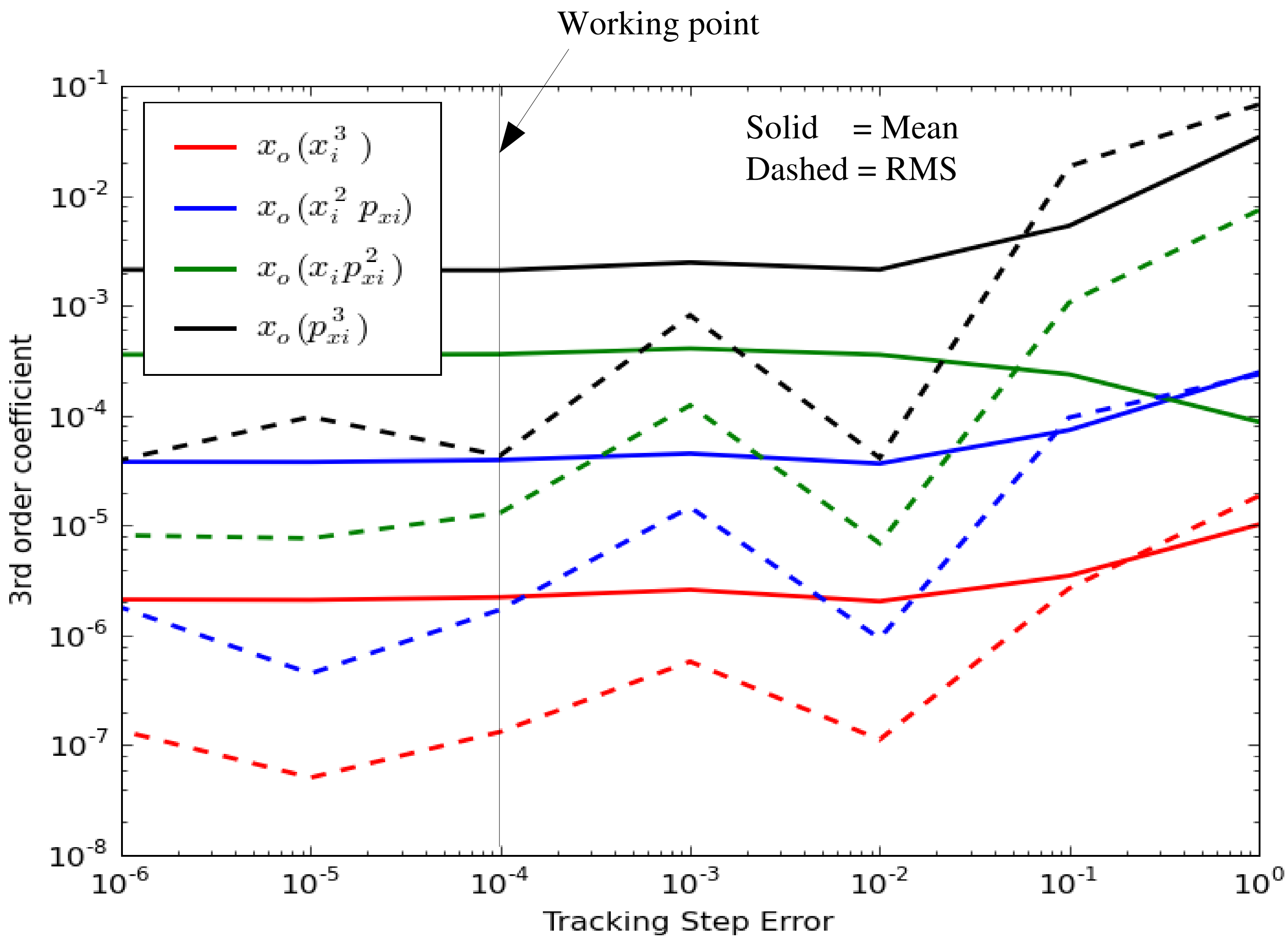
Non-Linear Terms





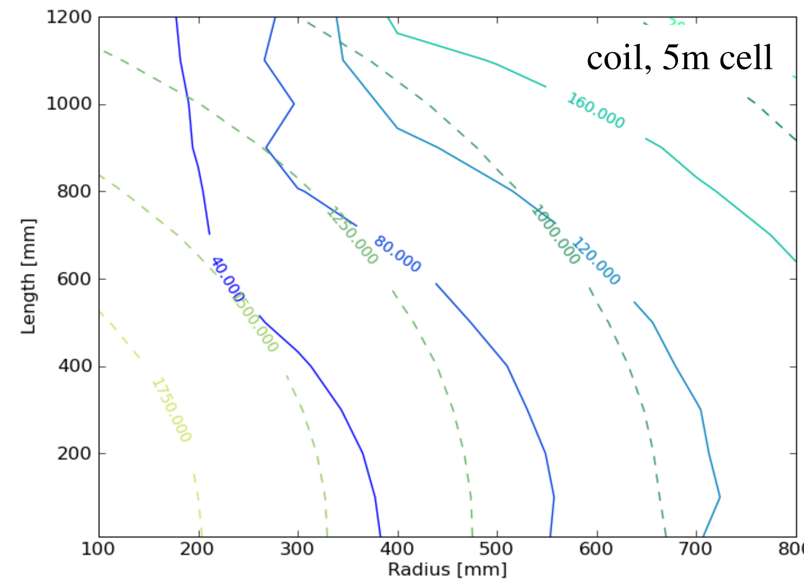
- Non-linear terms => $x_{out} = a_{ij}\ x_{in}^{\ i} p_{in}^{\ j}$
- 2nd order terms have i+j=2
  - Purely chromatic, can be ignored
- 3rd order terms have i+j=3
  - Increase by order of magnitude in short fringe field
  - In theory go as d^2B_z/dz^2
- For very short fringe fields 3rd order terms become 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

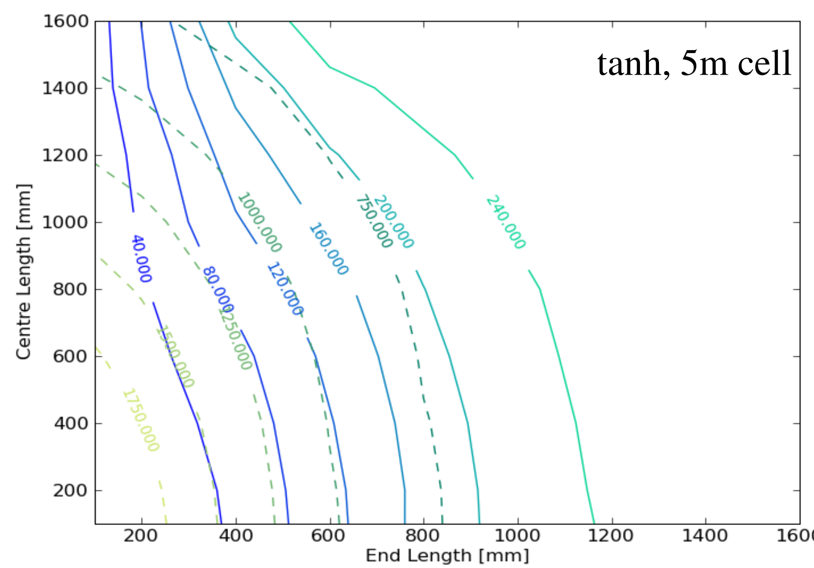
Stepping Error vs Non-Linear Term



Coil Length

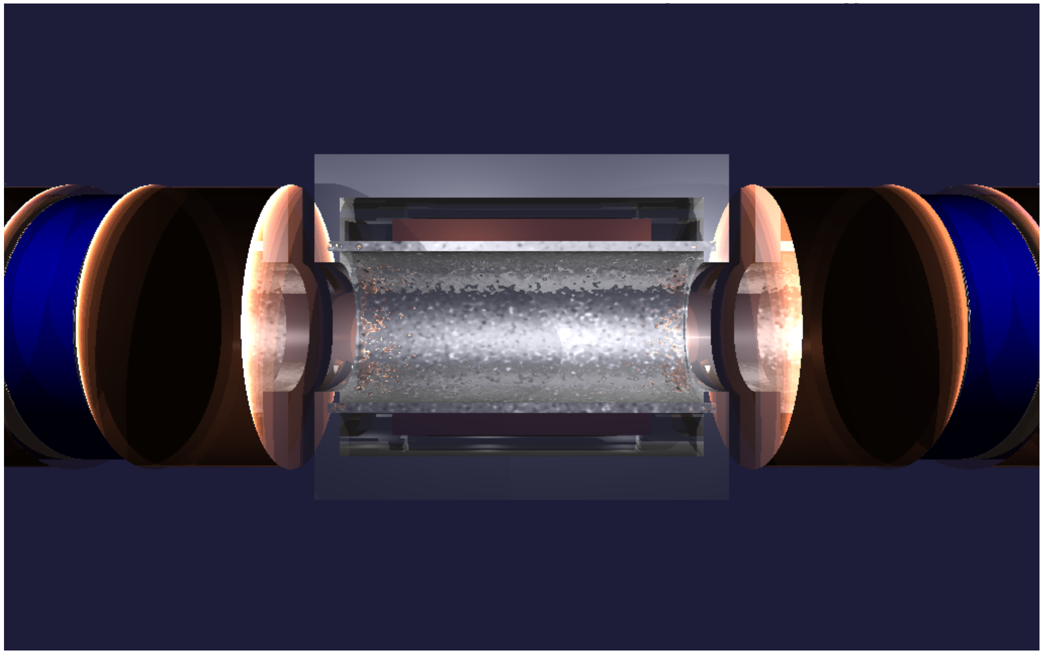
- Can we make progress by tweaking coil length?
  - Long coil needs lower B_z to keep $\langle B_z^2 \rangle$ constant => more space
  - But field extent is longer => less space
- These effects ~cancel
  - Dashed line = field free length
    - $B_z < 0.5$ T (assume shielding for rest)
    - Per 2.5 m 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

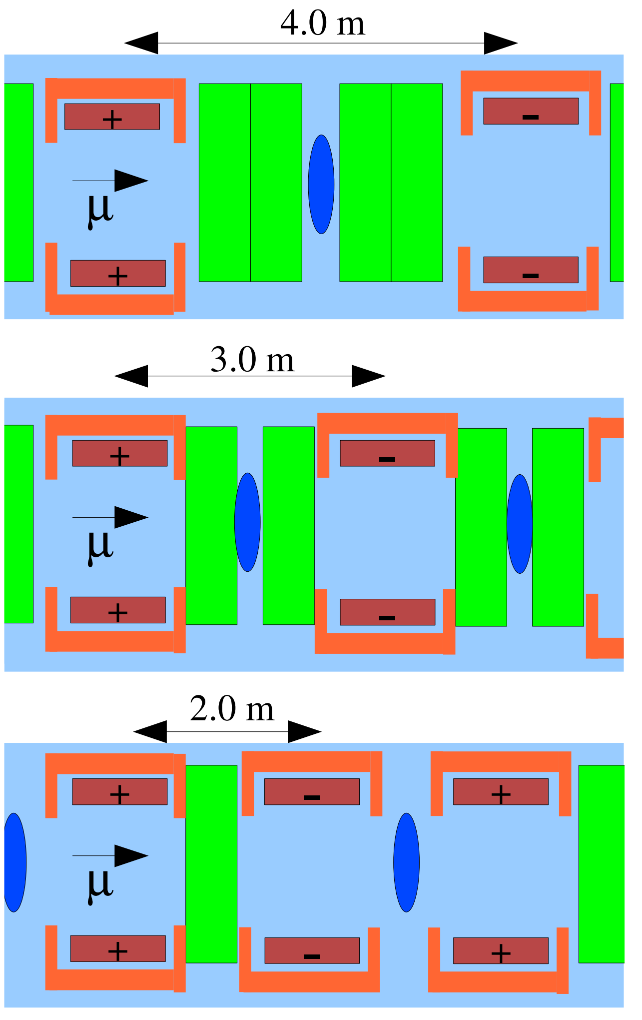




Lattice Choice

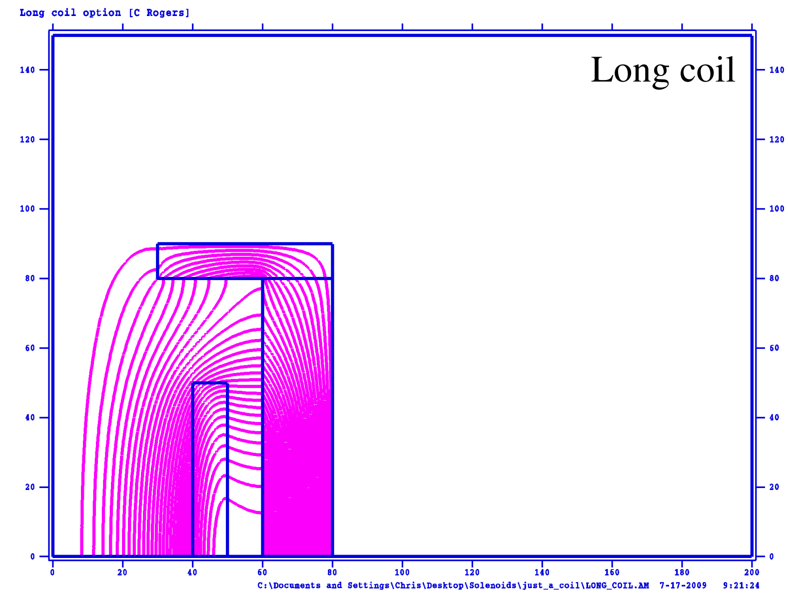
- In light of this - what lattice?
- Try 4 m, 6 m or 8 m cell
  - Longer cells have worse optics
  - Longer cells have better RF packing fraction
    - 1/8, 1/3, 1/2 respectively
- Try long coil or short coil

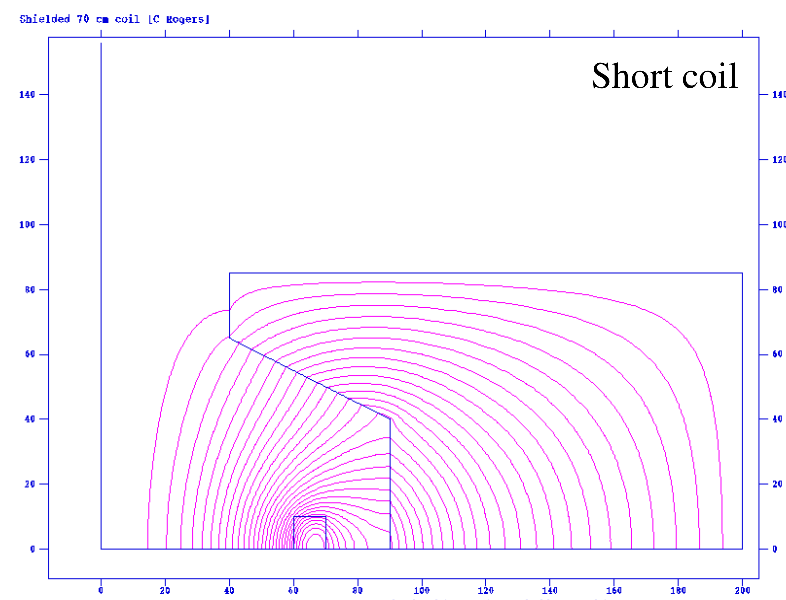




Coils and Shielding

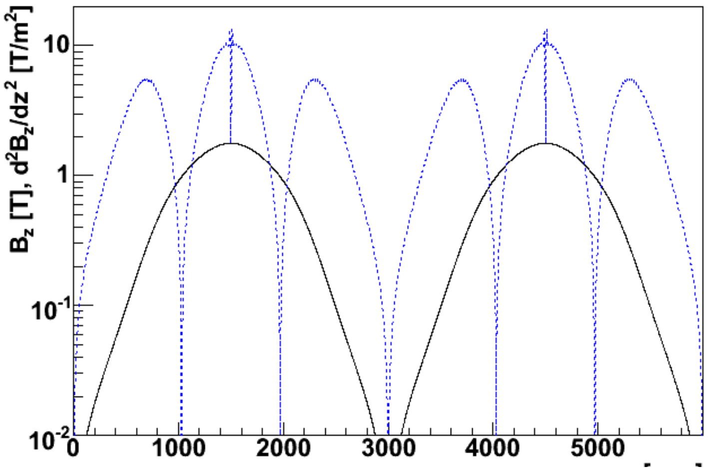
- Assume iron shielding on coils
  - Makes handling magnets harder
    - e.g. 14 tonnes Fe (long coil)
  - Lower currents required on coils
  - Reduces fringe field on RF
  - Shield tunnel from intense fields
    - Stray iron does not affect beam
    - Stray fields do not affect hardware
    - Stray 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



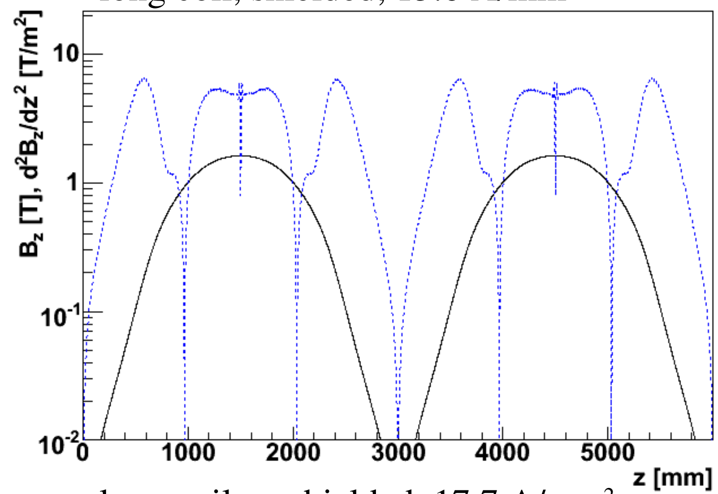


Shielded vs Unshielded Fields

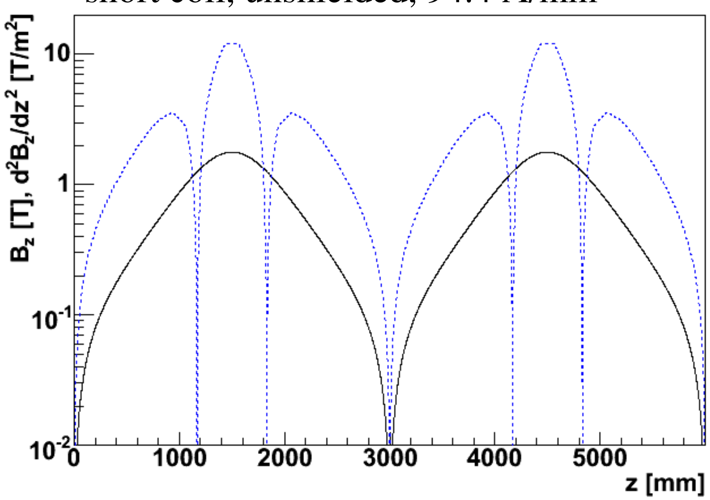
short coil, shielded, 76 A/mm²



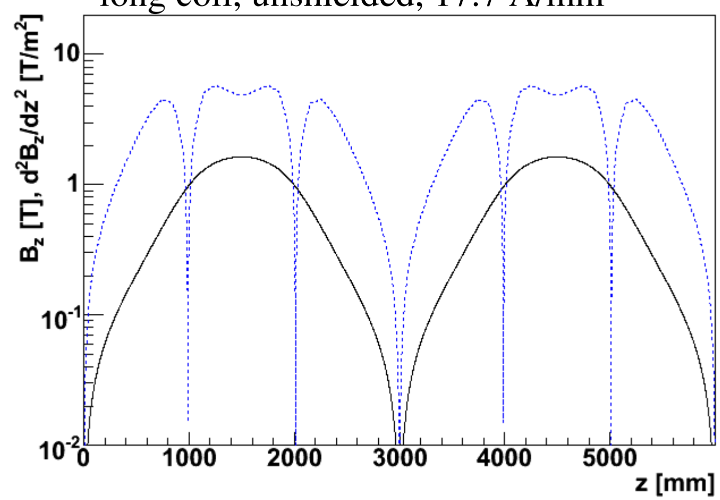
long coil, shielded, 15.6 A/mm²



short coil, unshielded, 94.4 A/mm²

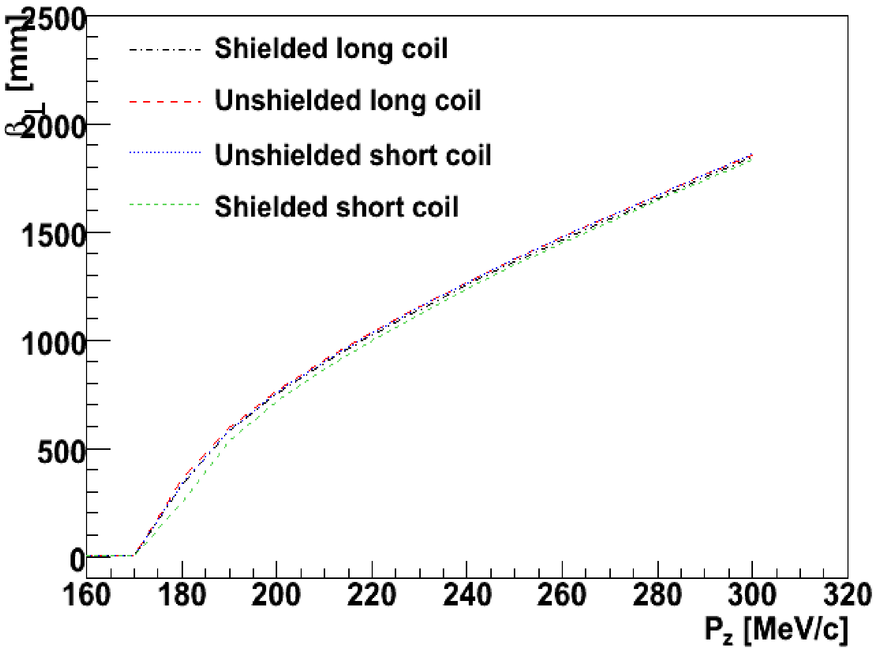


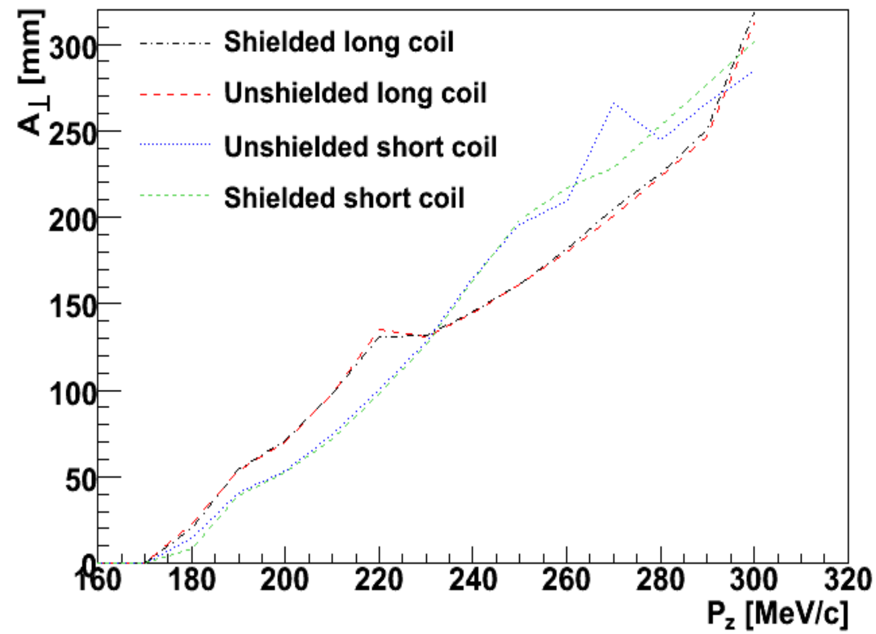
long coil, unshielded, 17.7 A/mm²



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

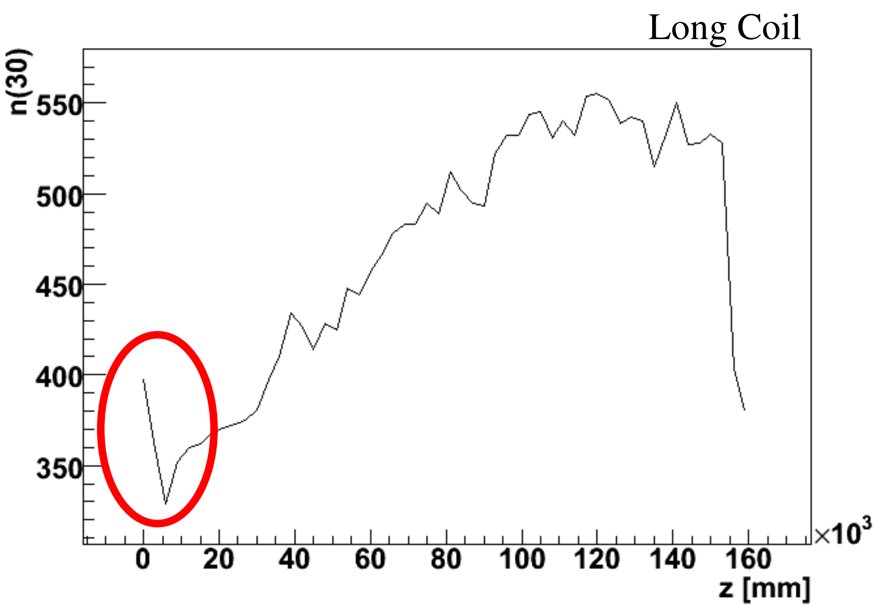
Shielded vs Unshielded Optics

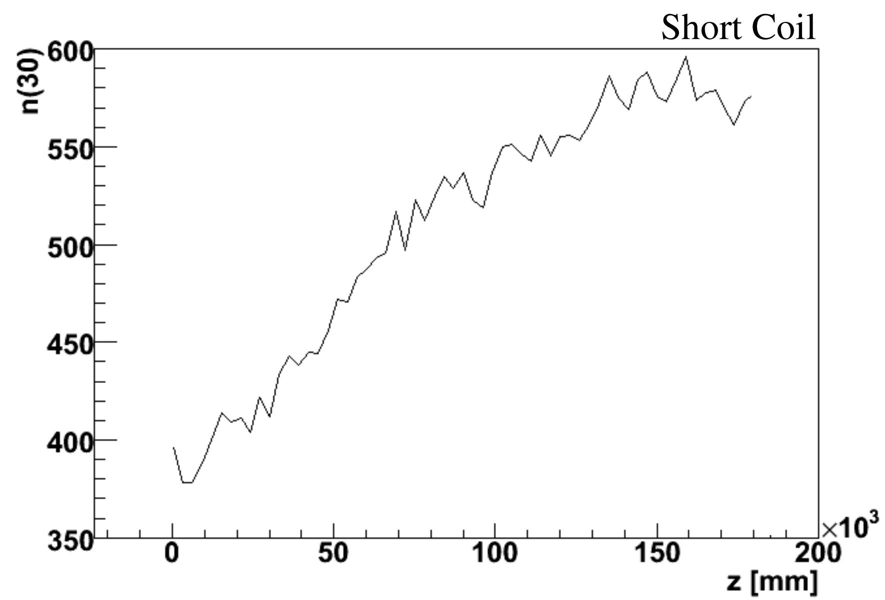




- β unaffected by presence of shielding, coil length
  - $\langle B_z^2 \rangle$ = same for all lattices
- Acceptance is slightly affected by short vs long coil
  - Can improve short coil acceptance by increasing coil radius
  - But larger coils means more shielding etc
- Acceptance is ~unaffected by shielding

Long Coil Versus Short Coil

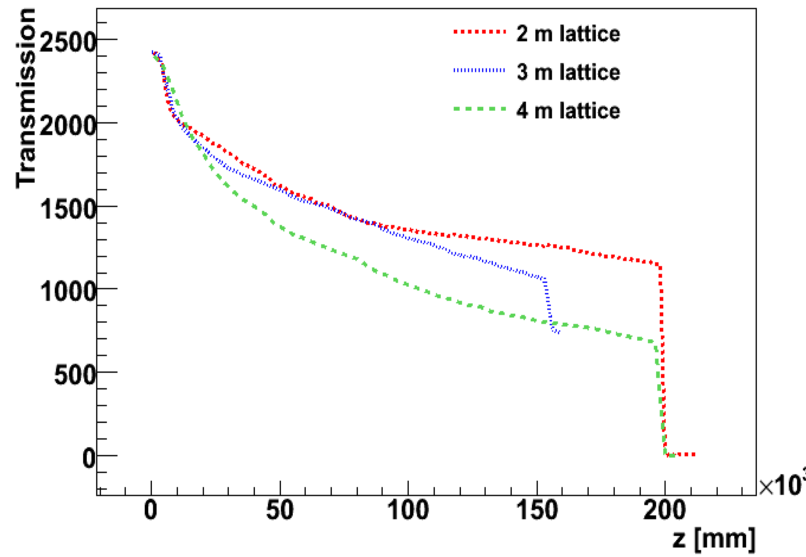


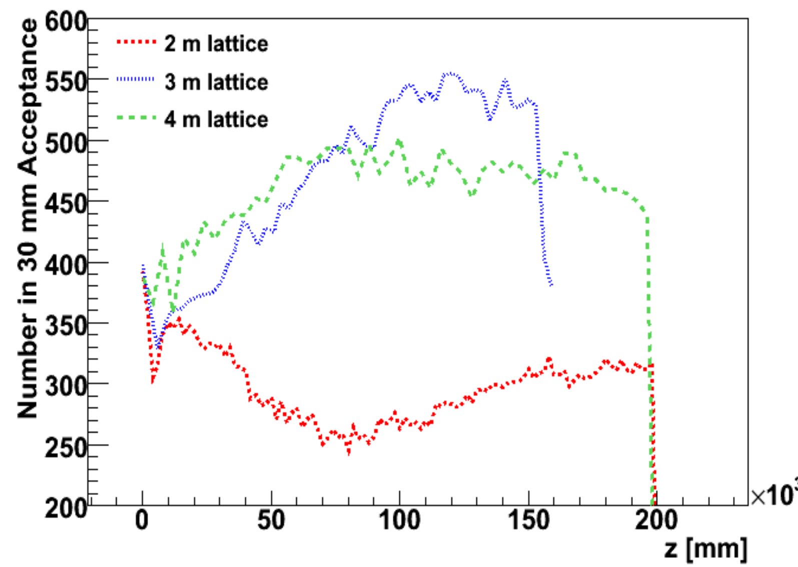


- Compare long coil with short coil
  - 3 m cell, 30° RF phase
  - Count number of muons in accelerator acceptance
    - 30 mm transverse, 100 - 300 MeV/c momentum bite
  - Short coil does a bit better
  - ~52% compared to ~42%
  - Probably means my "long coil" is too low radius
  - Perhaps initial mismatch 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
- 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
  - Need to examine effect of windows
  - Need to run with higher statistics
  - Need to compare with ICOOL
  - Beta tapering - might help
- Bucked coil lattice is equivalent to reducing coil radius
  - Spherical aberrations drastically reduce transverse acceptance
  - Not much progress to be made here