Cooling with a Reduced Gradient

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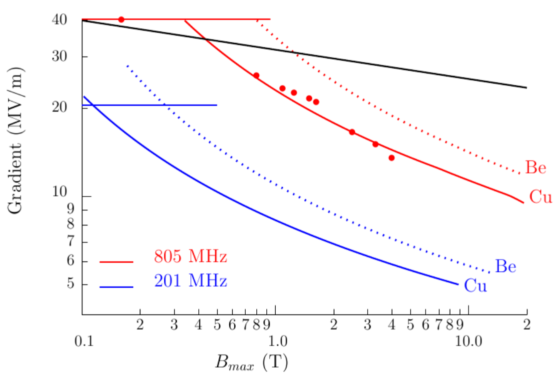
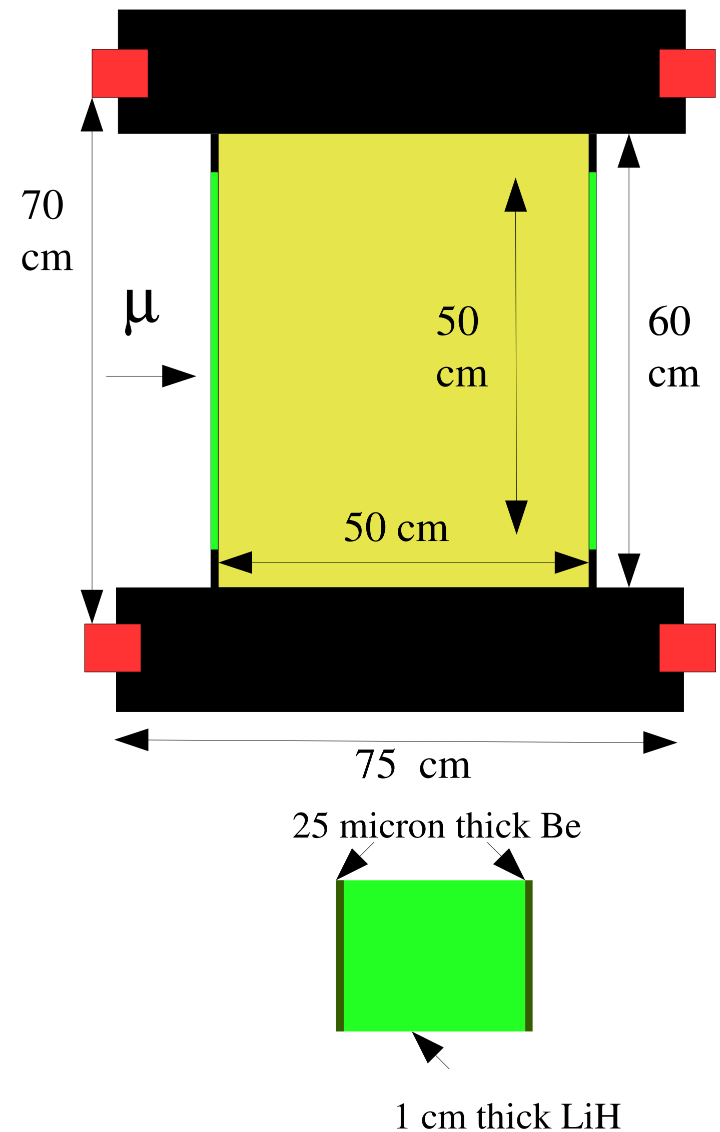
Cooling with Reduced Gradient

- Baseline Neutrino Factory cooling channel requires
  - 15.25 MV/m
  - 200 MHz RF
  - In ~2.4 T field
- It looks like this is tough to achieve
  - Kilpatrick Limit is at 17 MV/m
  - But 2.4T field limits what can really be done
  - Simulations shown at NuFact08 indicate can only get ~7 MV/m
- First: what is the difference in cooling performance between G4MICE and ICOOL?
  - I like to simulate in a code I know well
  - So I've done a comparison between the two
- Second: How well can the FS2A cooling channel cope with a reduced gradient?



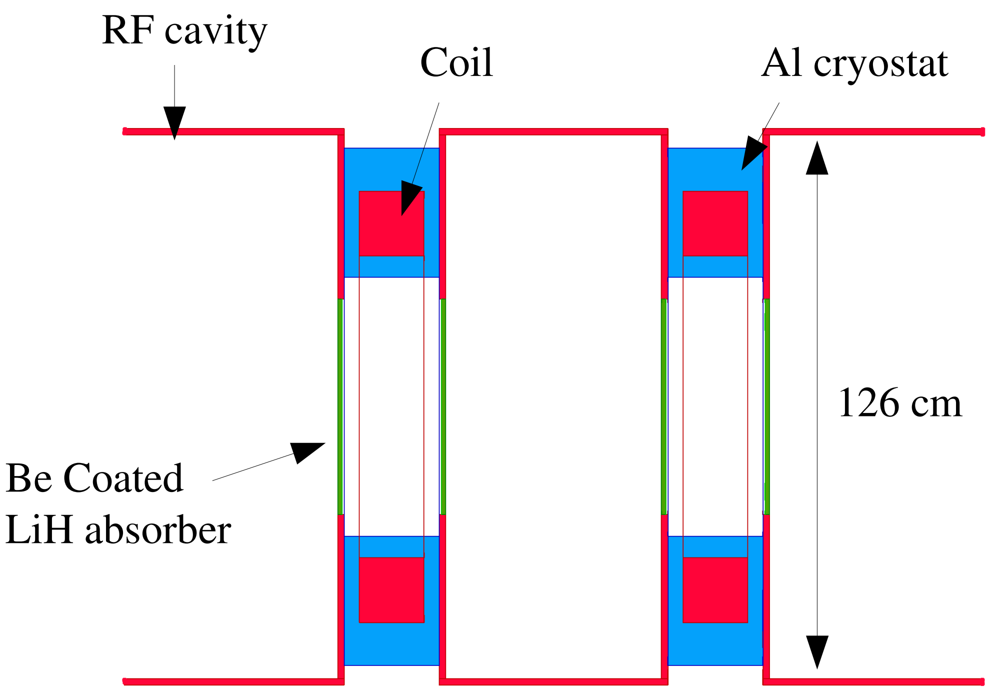
Simulation in ICOOL

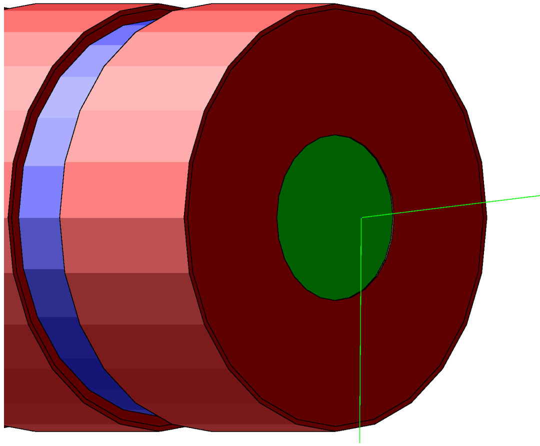
- Simulated using deck c/o ISS website
- ICOOL geometry model shown right
  - Black areas kill particles that touch it
  - Green areas are absorber windows
    - 1 cm LiH coated on each side with 25 micron Be
  - Gold area is filled with pill box rf field
    - 200 MHz
    - 15.25 MV/m peak field
    - 40 degree phase
  - Red area is a coil
    - 150 mm x 150 mm thickness x length
    - 106.667 A/mm² current density
  - Muons travel from left to right
  - Repeats every 75 cm
    - Adjacent cells have opposite solenoid polarity

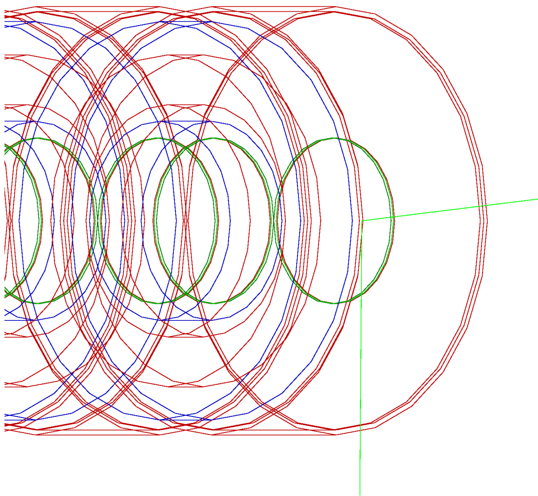


Simulation in G4MICE

- G4MICE geometry model shown
  - Fundamentally the same
  - I use real materials rather than apertures
  - Full cavity aperture

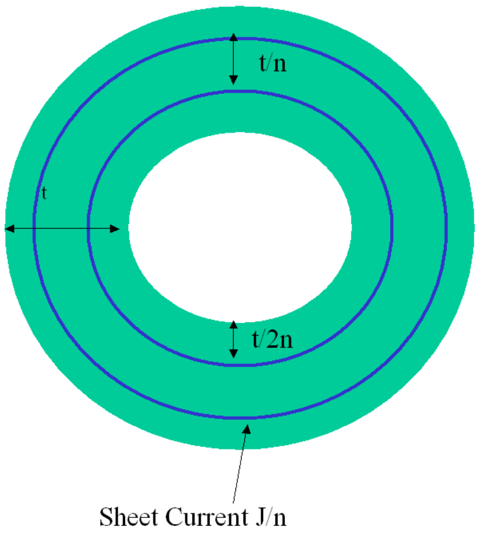




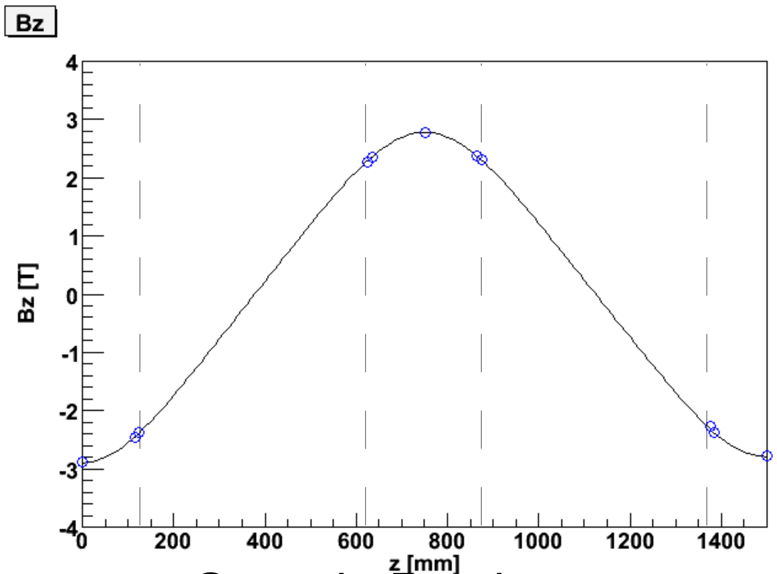


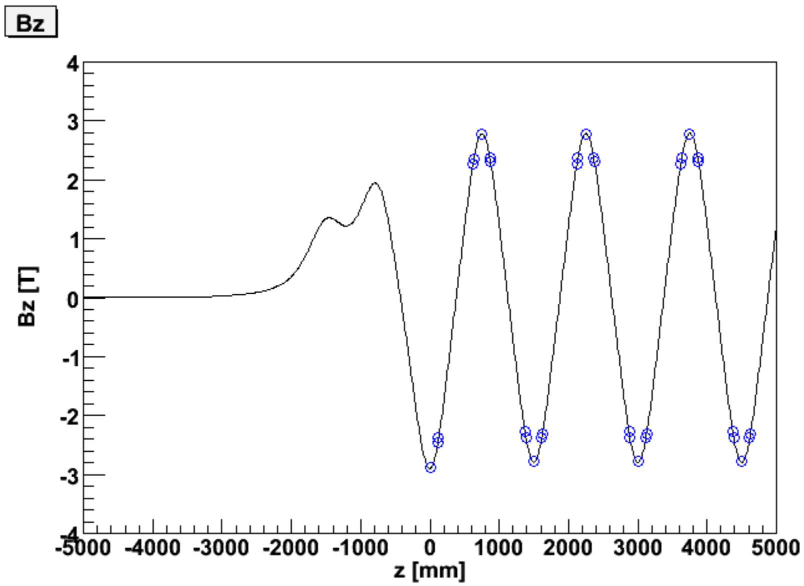
Solenoid model

- Both codes use same solenoid model
  - Obtain field by adding from a number of infinitely thin sheets
  - Write field onto a rectangular grid
  - When tracking interpolate off the grid
  - Assume cylindrical symmetry with $B_\phi = 0$
- In G4MICE, interpolation is Linear-Cubic
  - Linear in r, cubic in z
  - Other models exist
- In ICOOL, interpolation is Bi-Cubic
  - Cubic in r, cubic in z
  - Other models exist



Simulated on axis field

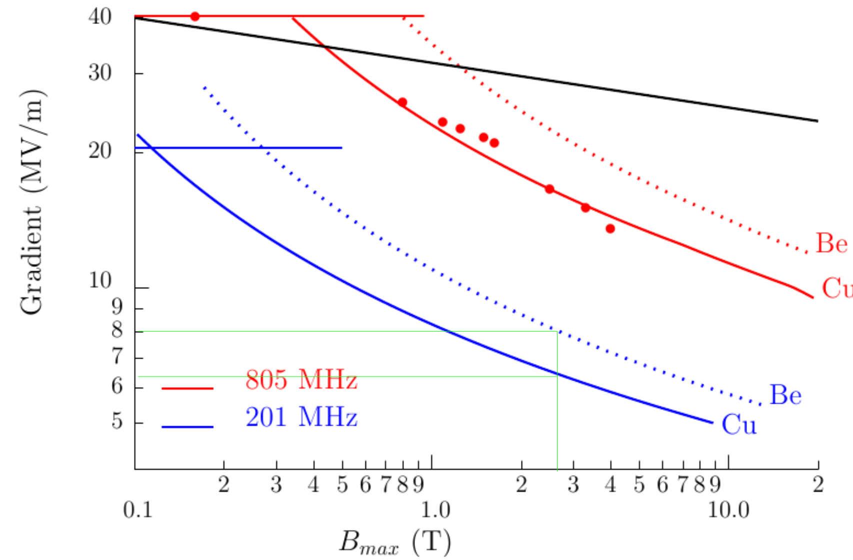




- On-axis Bz shown
  - (left) for one magnet field period
  - (right) including matching section – beam starts from 0
- Compare codes
  - ICOOL (circles)
  - G4MICE (line)
  - Dashed line is approximate position of RF cavity windows
  - ~ 2.4 T field at RF cavity windows

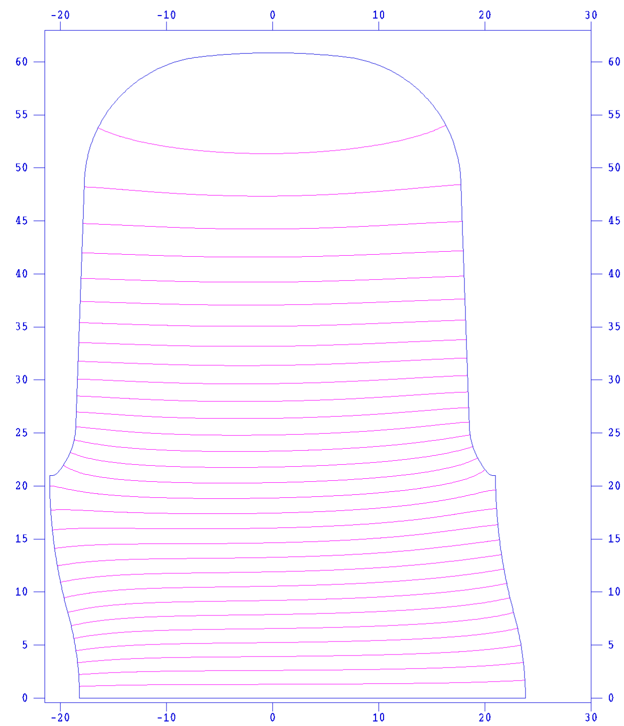
B-field vs RF field

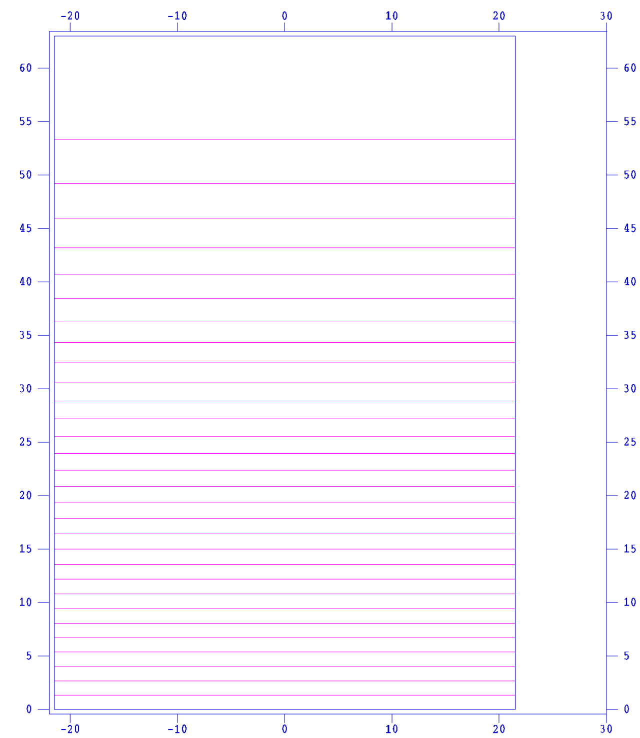
- R. Palmer showed simulation + model for RF breakdown in B-fields at NuFact 08
  - cf arXiv:0809.1633 (acc-ph)
  - Electron beamlets fire across RF cavity at breakdown
  - Focussed by B-fields on opposite wall which turns to a plasma
  - Leads to breakdown
  - Under this model, absorber windows on lH_2 would possibly melt



- Show simulated and measured (points) peak achievable field vs Bz
  - Some parameters based on fit to 805 MHz data
  - Green line is (approx) on-axis field at RF window
  - Peak achievable field gradient is of order 6-8 MV/m
    - If you believe the simulations!

RF field model





- Both simulations use TM010 pillbox mode for acceleration
  - Bessel function in *r* with a sinusoidal dependence on *t*
- In reality the world is more complicated
  - Consider model of 43 cm MICE 200 MHz rf cavity
  - Previous studies show not much effect on cooling performance

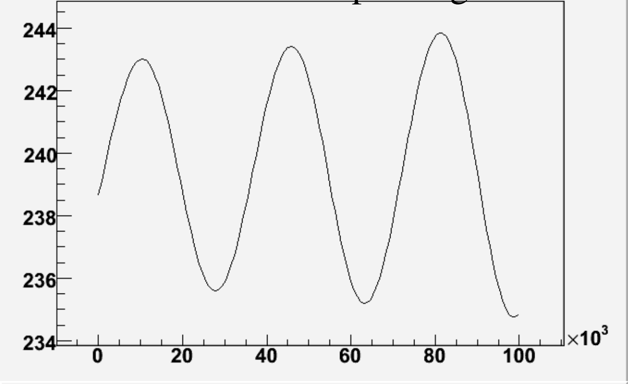
Phasing model

- Phasing is slightly difficult
- Aim is to get RF cavities to pulse as the bunch travels through
- In ICOOL this is done by firing a particle with constant velocity and no transverse momentum along the cooling channel
  - Record when it passes each cavity and pulse accordingly
  - Other models exist (but I couldn't get them to work)
- In G4MICE either (a)
  - fire the particle with constant velocity as in ICOOL
- Or (b)
  1) fire a particle and let it accelerate in RF and decelerate in material
  2) at each RF cavity record the time and energy gain of the reference particle
  3) set cavity phase to the time the particle passed cavity centre
  4) set peak field to give the particle appropriate energy gain
  5) repeat until the phase and peak field fall within some tolerance

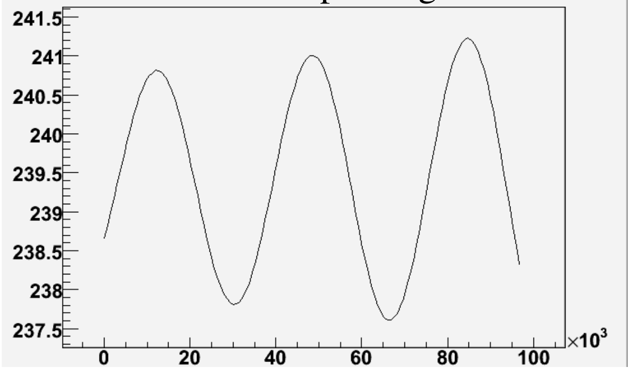
Reference energy

- Phasing with constant velocity particle introduces a jitter into the RF bucket
  - RF bucket is usually defined around a reference trajectory
  - Generate “true” reference trajectory
    - Fire a muon with no stochastic processes
  - “True” reference trajectory sometimes arrives earlier than constant velocity particle, sometimes later
    - So energy changes from cell to cell
- Perhaps gives some emittance growth?
  - Not easy to treat analytically
- Jitter seems to be bigger in G4MICE
  - See comments on material model

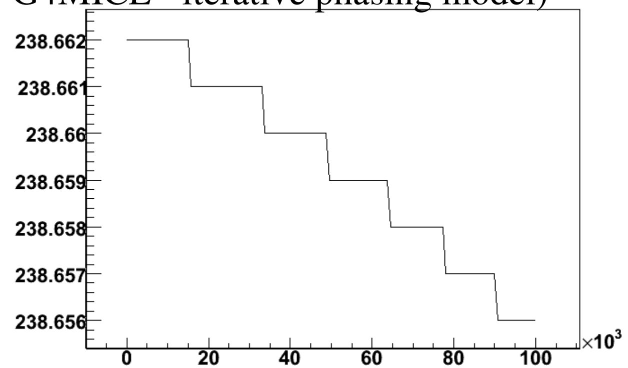
G4MICE – constant v phasing model



ICOOL - constant v phasing model



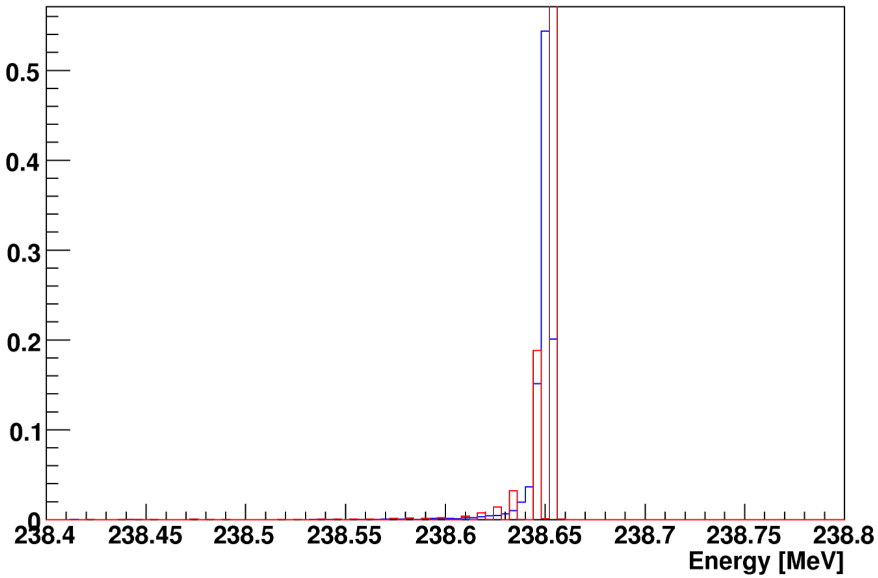
G4MICE - iterative phasing model)

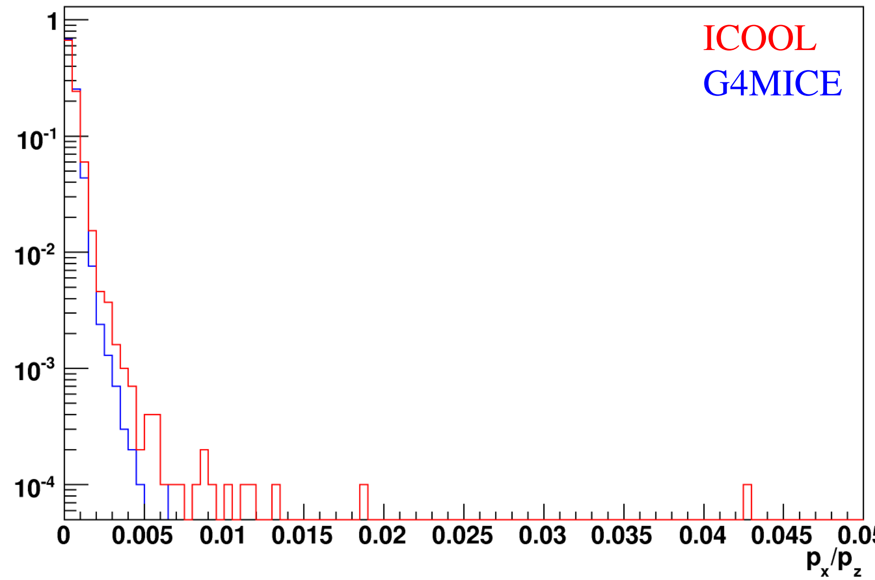


Material Model

- Cooling performance is crucially dependent on material model
  - FS2A cooling channel has 1 m of LiH over 75 m channel
  - Total energy loss ~ 180 MeV over 75 m channel
  - In next few slides I show comparison of energy loss and multiple scattering distributions in ICOOL and Geant4.8.2
- ICOOL model (I don't know the details)
  - dE/dx with density effect
  - Bethe version of Moliere scattering model with Rutherford limit
  - Vavilov energy straggling distribution
  - Nb not necessarily the best ICOOL models (but what the deck came with)
- GEANT4.8.2 models
  - Complicated!
  - http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual
- PDG models
  - Calculate using mean energy (E_in + E_out)/2.
  - Use pdg formulae and material constants

Beryllium

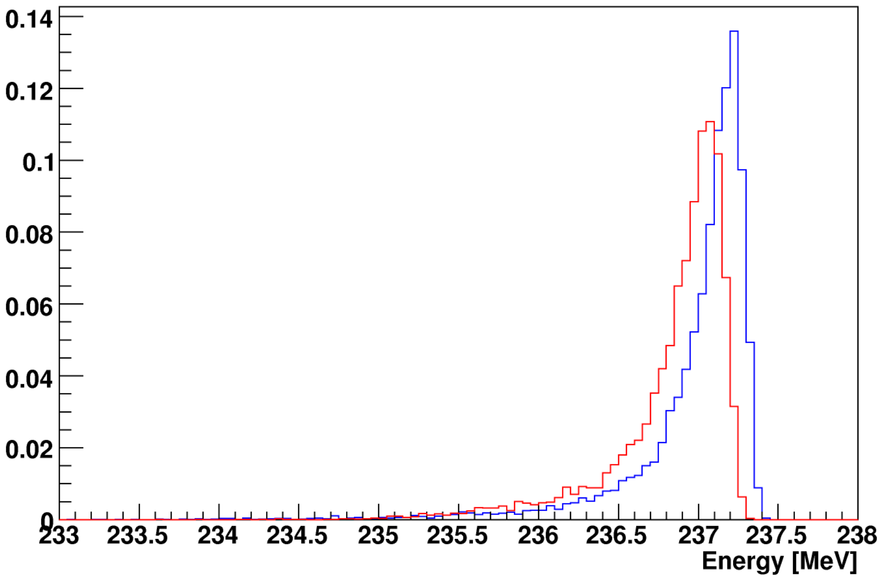


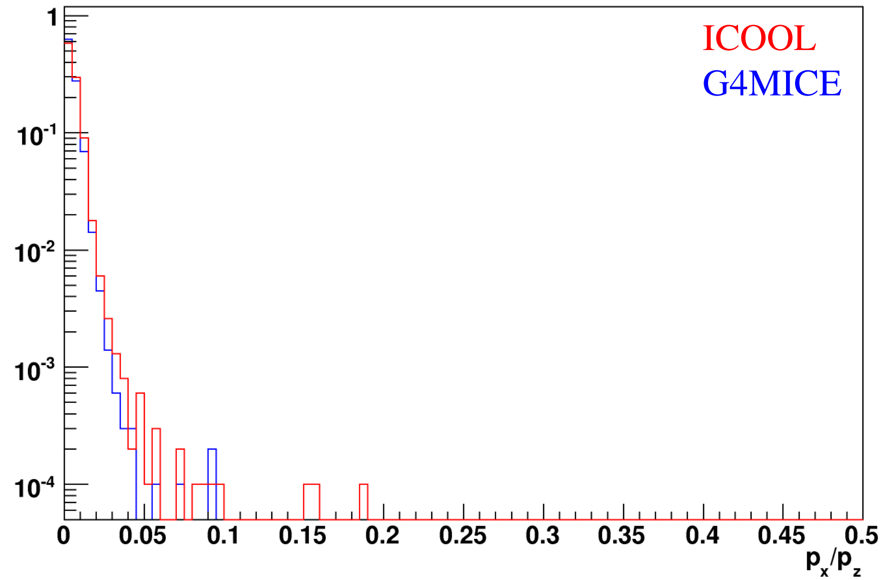


- 25 microns Beryllium
  - Note dE histogram limited by number of decimal places in output(!)
  - 10000 events @ 238.662 MeV in sample
    - E = 238.662 MeV => pz = 214 MeV/c

Be	*ICOOL*	*G4MICE*	*PDG*
Final Mean E [MeV]	238.648	238.649	238.599
Final RMS E [MeV]	0.0121	0.0139	?
Final RMS x'	0.000720	0.000372	0.000380

Lithium Hydride

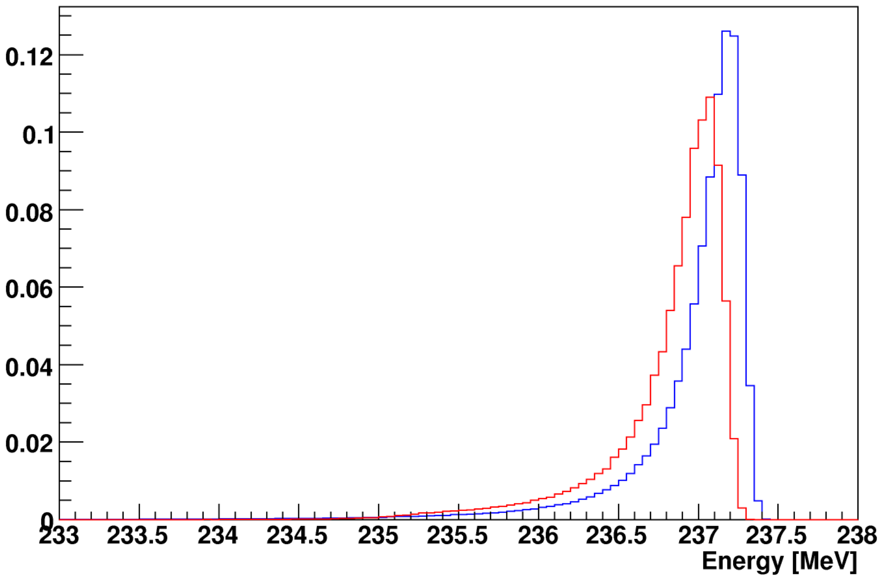


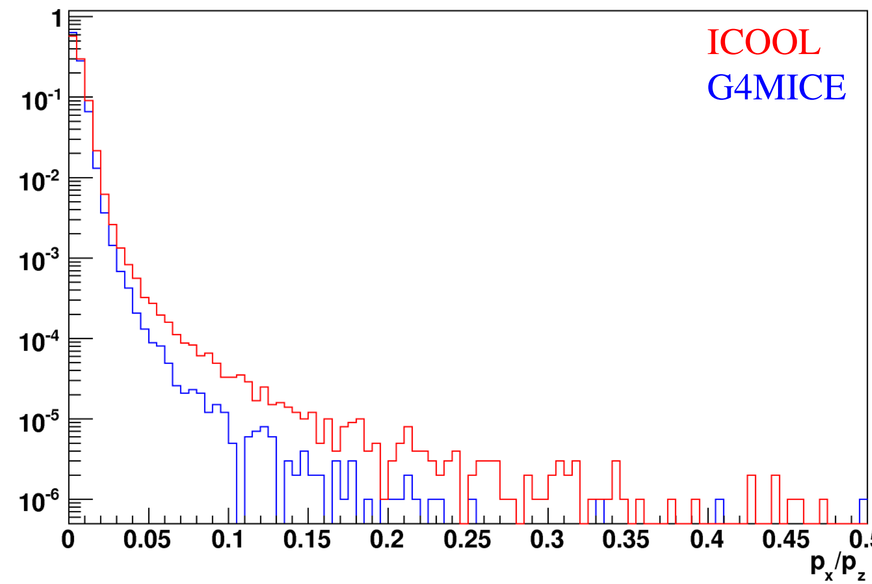


- 1 cm LiH
  - 10000 events in histogram

LiH	*ICOOL*	*G4MICE*	*PDG*
Final Mean E [MeV]	236.839	236.98	236.952
Final RMS E [MeV]	0.382	0.424	?
Final RMS x'	0.00782	0.00633	0.00597

Full absorber





- Beryllium and Lithium Hydride
  - 1000000 events
  - Difference between G4 and ICOOL
    - ~10% dE; ~10% σ(E); ~30% σ(x')

Full Window	*ICOOL*	*G4MICE*
Final Mean E [MeV]	236.813	236.963
Final RMS E [MeV]	0.396846	0.432488
Final RMS x'	0.0060284	0.0043362

Material Model - Comments

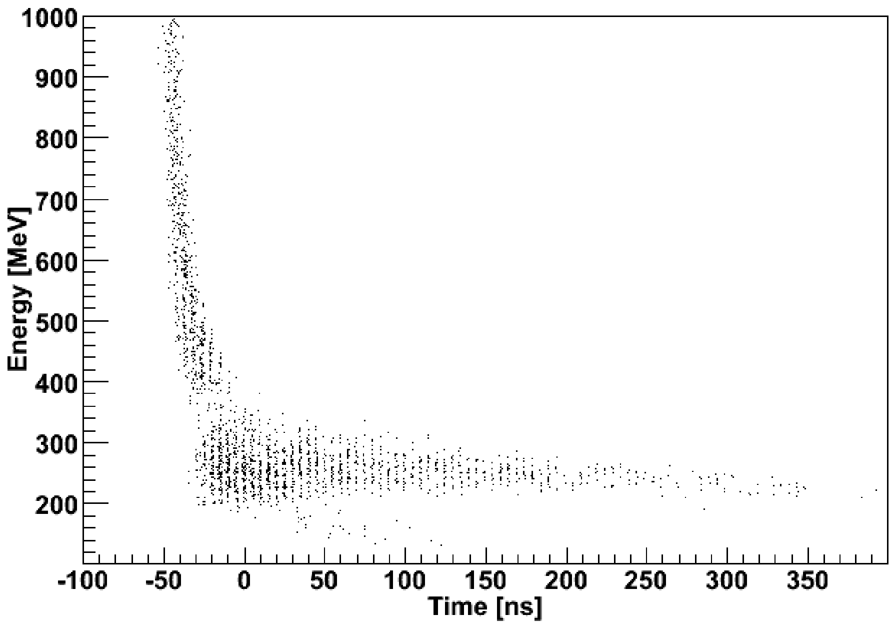
- G4.8.2 estimates significantly less energy loss and multiple scatter compared with ICOOL
  - G4 seems to agree better with PDG values
  - Other models are available in ICOOL
    - In this talk I use the ones that came with the deck
    - It may be instructive to use different models in future
  - It would be interesting to compare with MuScat
  - Could this be caused by different definition of LiH?
    - I think LiH comes with varying amounts of H and varying density
    - More like an alloy than a compound
    - G4 uses PDG values for LiH

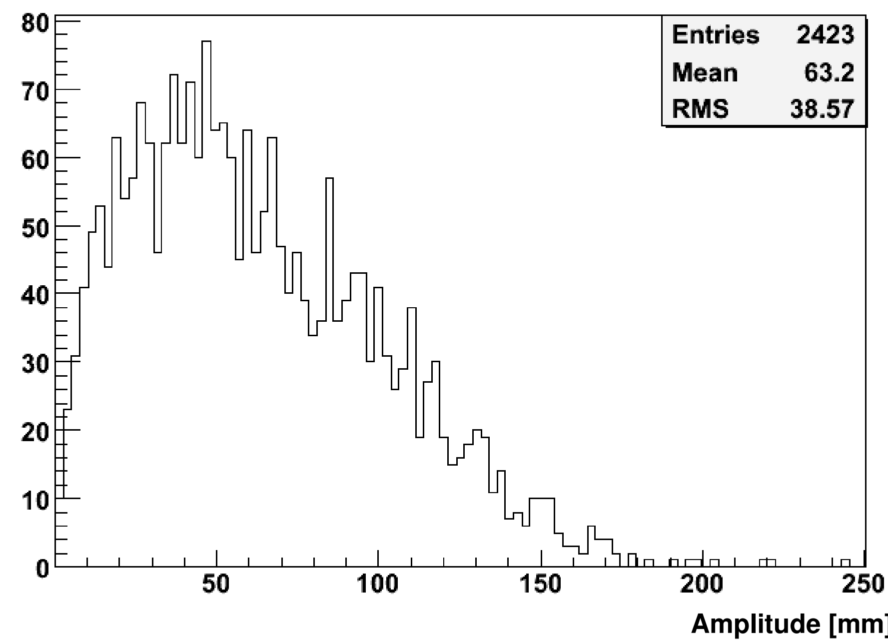
Simulation in G4MICE

- Movie

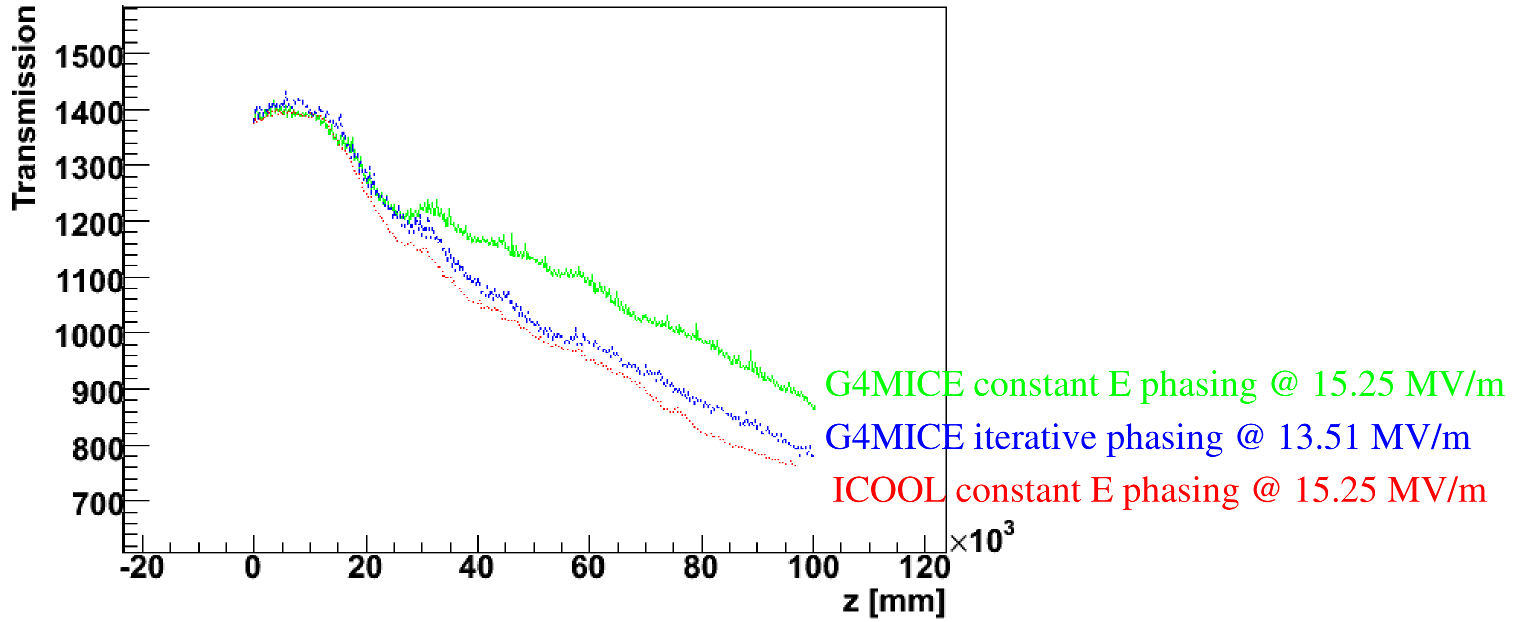
Simulation – Input Beam

- Input beam is generated from icool
  - Simulate muons from target through phase rotation
  - Write to input beam at end of matching into cooling channel
- Large energy spread at front of bunch
- ~16 mm RMS emittance
  - <amplitude>/4



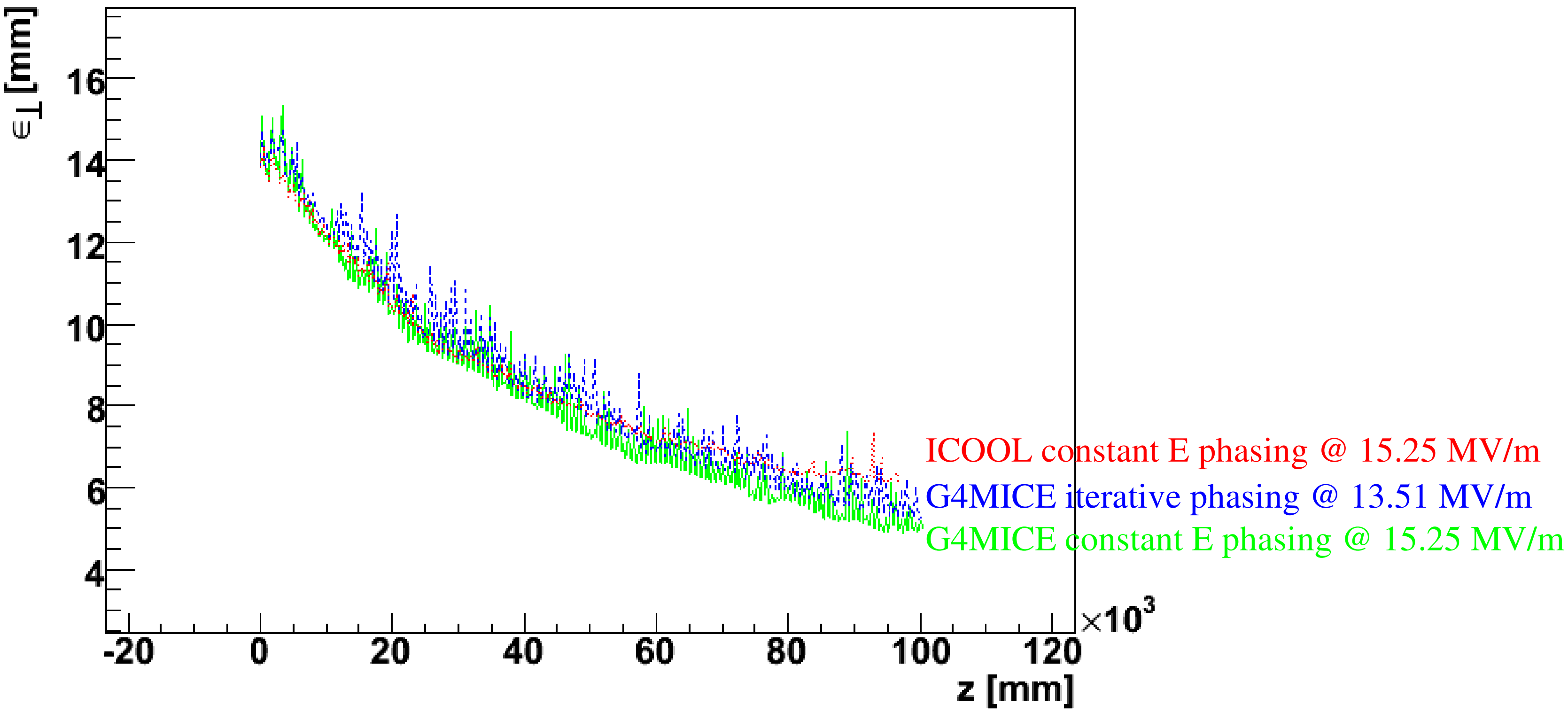


Transmission



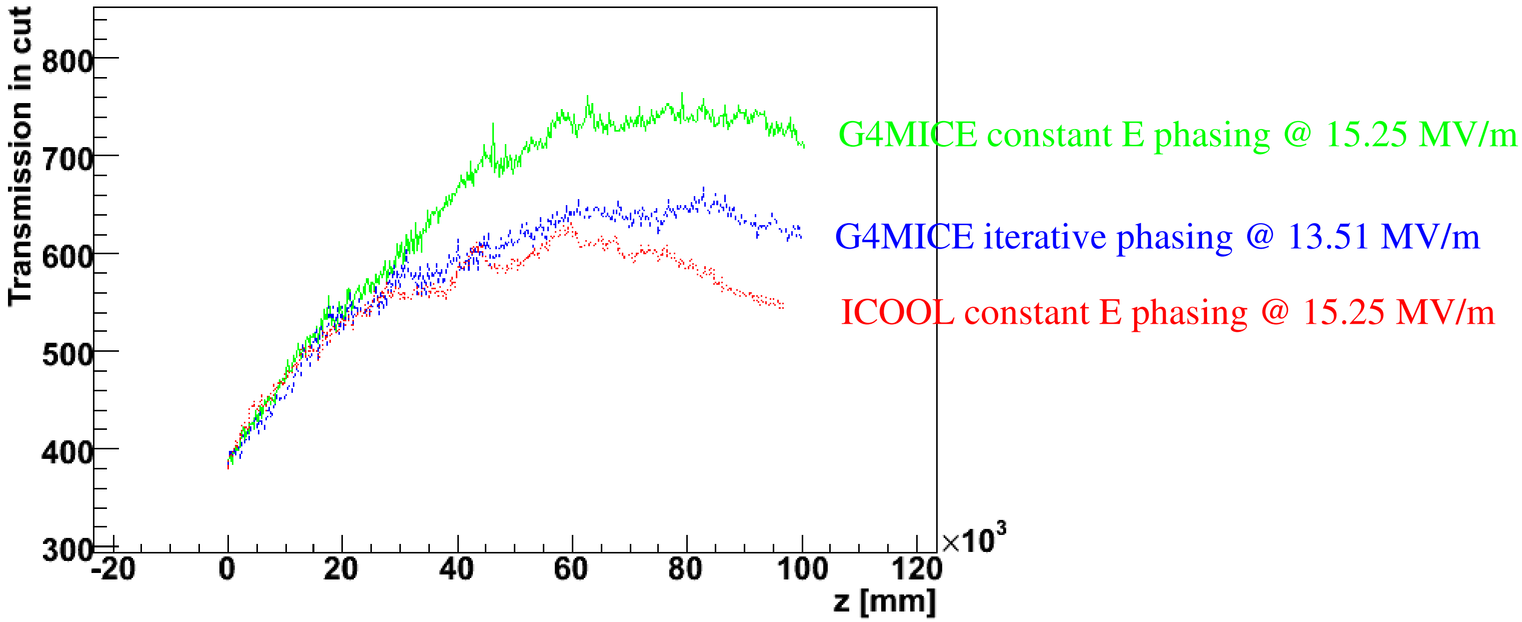
- Transmission of muons with 150 MeV < E < 300 MeV
- Transmission is better in G4MICE
  - Surprisingly, constant energy phasing does significantly better
    - Higher RF field => enhance the bucket size
    - Misphasing => lower the energy gain
    - Sort of like operating at lower phase
  - I would like to check this result

Emittance



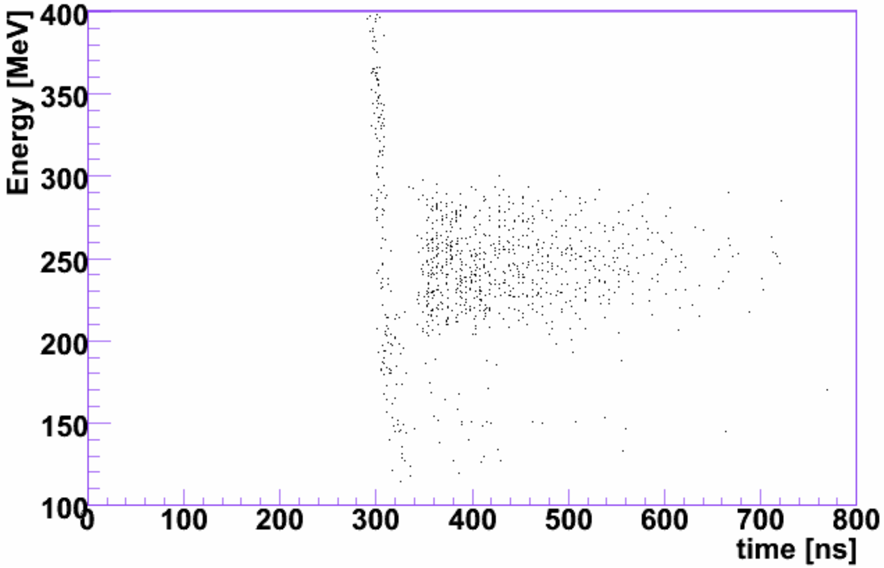
- Cooling performance is better in G4MICE
  - After cut 150 MeV < E < 300 MeV
  - ICOOL appears to be reaching equilibrium emittance after ~ 80 m
  - G4MICE is still cooling (just) after ~ 100 m

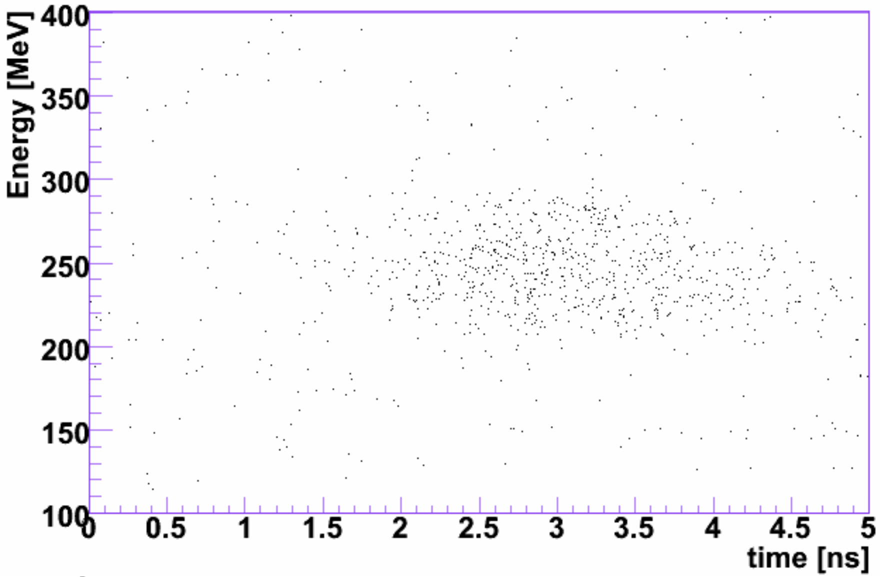
Transmission in Cut



- Plot number of muons in 30 mm acceptance
  - Also cut on 150 < E < 300 MeV
    - Note this is a wider energy acceptance than FS2A
    - In FS2A they use cut of 100 < p < 300 MeV/c
- Shows number of muons that would make it into an accelerator chain
  - Initially 383 muons in this cut
- G4MICE with the constant energy phasing model does very well

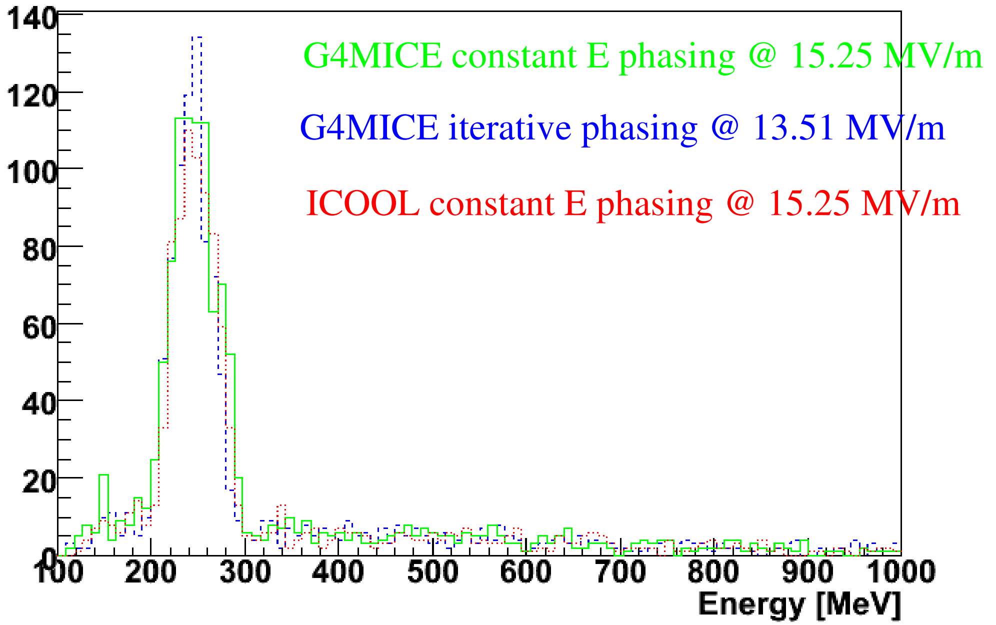
t-E Distributions @ 100 m





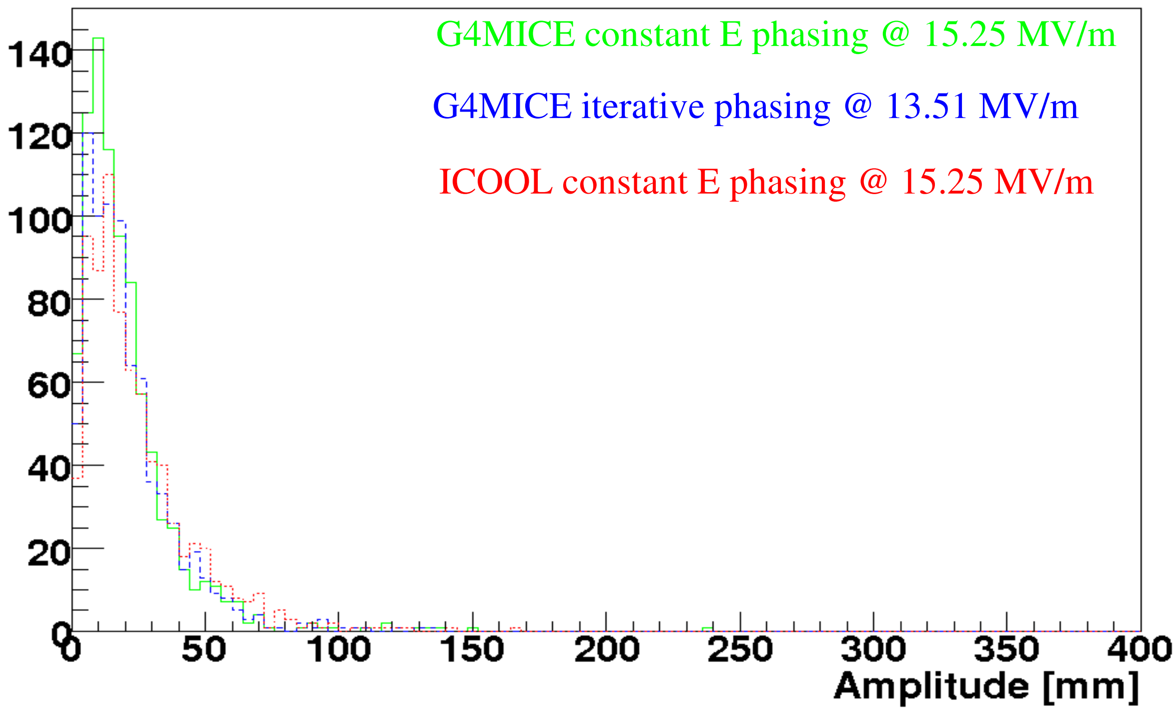
- Energy-time distributions for G4MICE constant energy phasing
  - In left hand plot I put everything between 0 and 5 ns
  - This shows the RF bucket

E Distributions @ 100 m



- Iterative phasing seems to produce a smaller energy spread
  - Indicates RF bucket is thinner

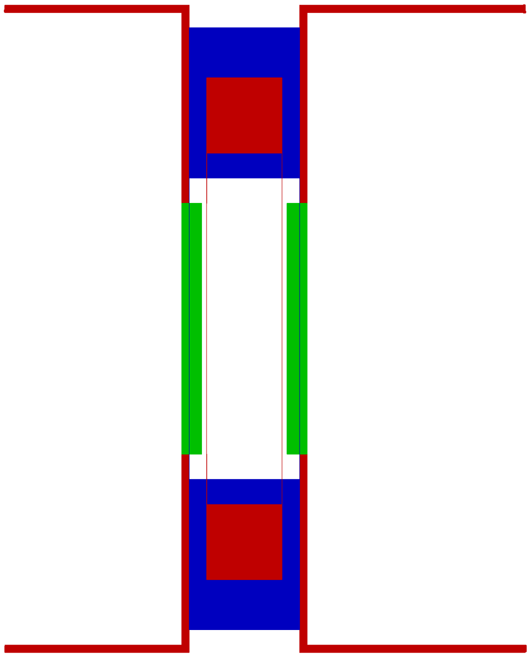
Amplitudes @ 100 m



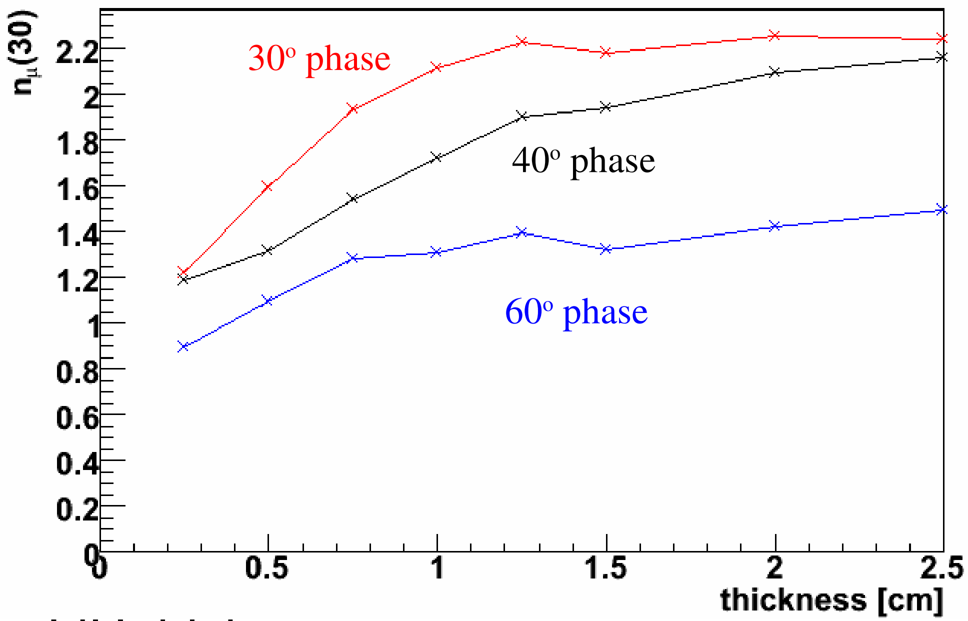
- Amplitudes after energy cut 150 MeV < E < 300 MeV

Changing RF Voltage

- Study effect of changing the peak RF voltage on the cavity
  - Keep all cavities at same voltage
  - Vary RF phase and Lithium Hydride thickness
    - Aim is to keep the energy loss from material the same as energy gain from cavity
  - Need G4MICE phasing model now
    - Here can set energy gain independent of RF phase
    - G4MICE figures out the appropriate peak field
- As I change LiH thickness, stretch material into vacuum region
  - Keep material out of RF cavity

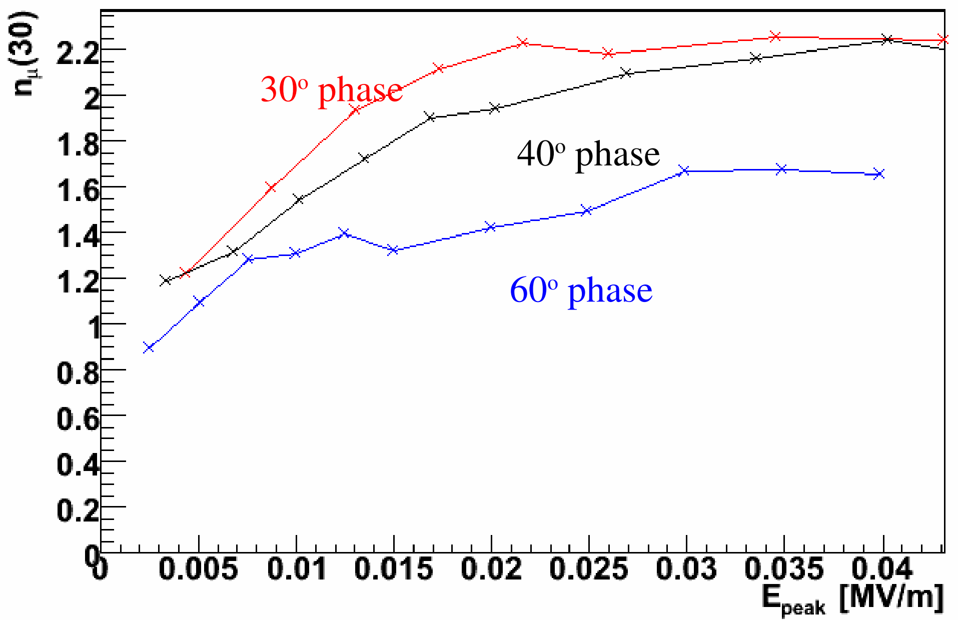


Transmission vs Thickness



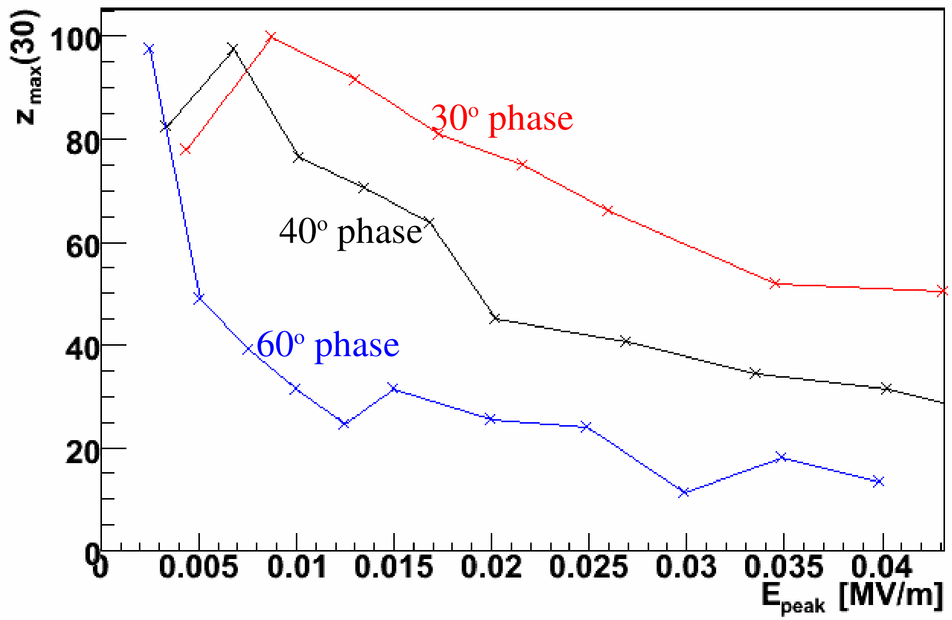
- First I adjust LiH thickness
  - Set peak field to give ref particle constant energy
  - Plot *(peak number of muons inside cut)/(input number in cut)*
    - Cut is on 150 < E < 300 MeV and Amp < 30 mm (excluding tails)
  - Cooling performance vs LiH thickness
- Improved transmission at lower phase
  - RF bucket is larger
  - Peak field is greater to keep energy gain the same

Cooling vs Peak Field



- The same plot but now x-axis is the peak field required to get the appropriate thickness
  - Phasing RF at 30° gives a superior performance than RF at 40°
  - Difference is quite significant
    - 20% on the number of muons i.e. 2 years of running(!)
  - At 15 MV/m best performance is ~ factor 2.1 in number of muons
  - At 7 MV/m best performance is ~ factor 1.45 in number of muons
  - Wider energy acceptance may have an effect

Length vs Peak Voltage



- I now plot the position in the cooling channel where the maximum was observed against peak voltage
  - Tells us how long the cooling channel would need to be
- Caveats:
  - Quite flat top => errors are large
  - Cooling channel was 100 m long so not possible to get anything longer

Study 2A Cooling Channel

- It seems ICOOL seriously under-estimates the Study 2A cooling channel performance
  - It looks like ICOOL material model does not agree with the PDG
  - Need to delve deeper into ICOOL's LiH models
  - It looks like ICOOL phasing model does not help
- The FS2A cooling channel copes well with a reduced gradient
  - Optimal cooling channel increases rate by ~ factor 2.1 in muons at 15 MV/m
  - At 7 MV/m a factor ~1.5 in muons is still possible
  - I use a wider acceptance in energy than Study 2A
- ICOOL studies suggest the increase is ~ factor 1.7
  - Difference in material processes between G4 and ICOOL
    - Need detailed comparison with experiment
  - Difference in phasing model between G4MICE and ICOOL
    - How big is this effect?
  - Difference in energy cut