6D Cooling

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Topical Workshop
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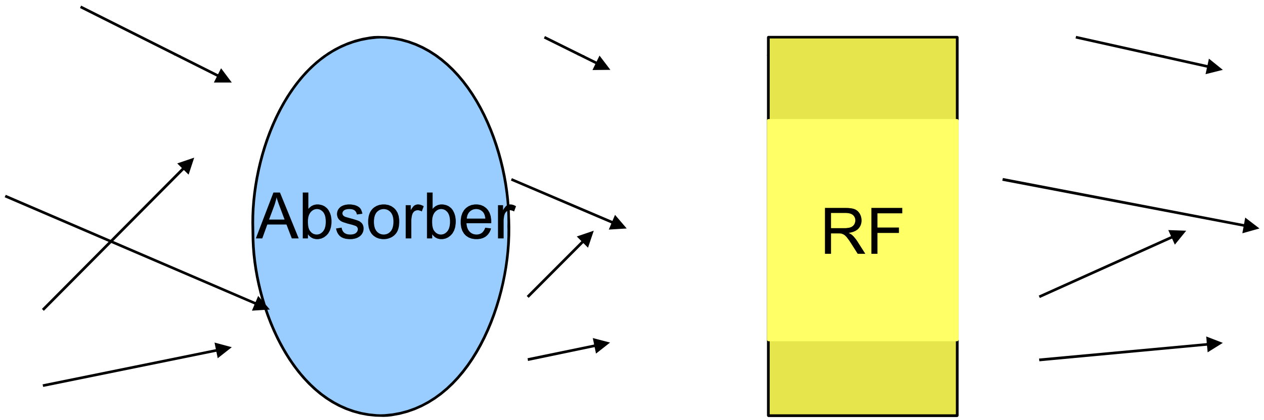
Overview

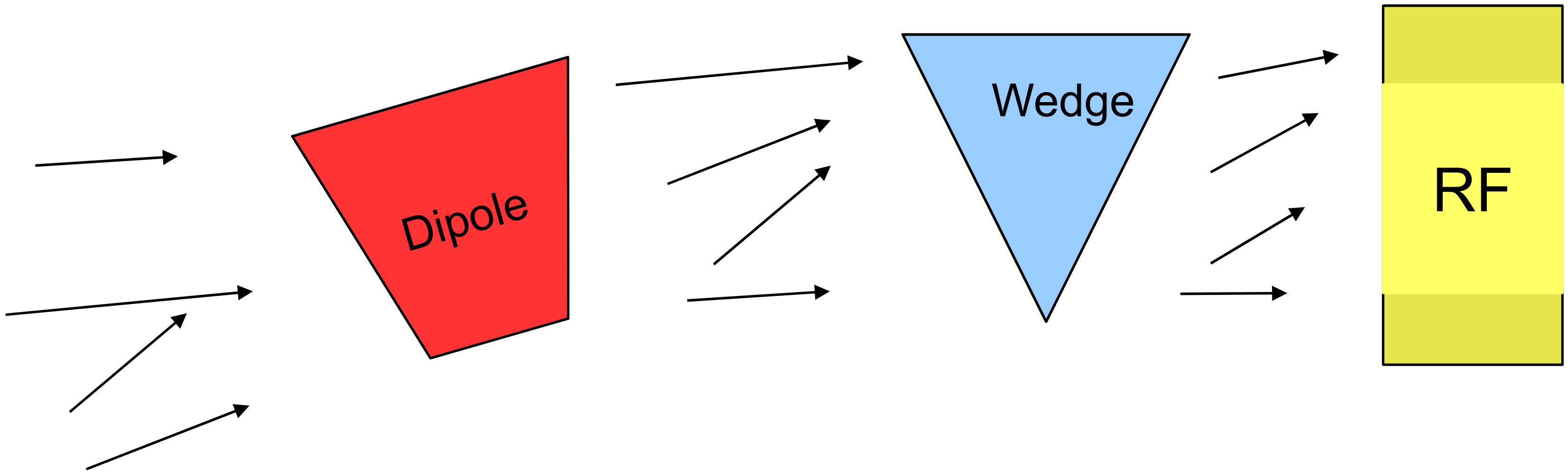
- 6D Ionisation cooling principle
- Cooling menagerie
  - RFoFo ring
  - Guggenheim for Muon Collider
  - Dogbone
  - Alternate ring geometry
  - Dual kicker scheme
  - Not helical cooling/MANX (covered earlier)
- 6D cooling measurement?
- I will talk more about problems than solutions
- Some repetition
  - I follow the experts
  - Present a more European perspective

4D Ionisation Cooling



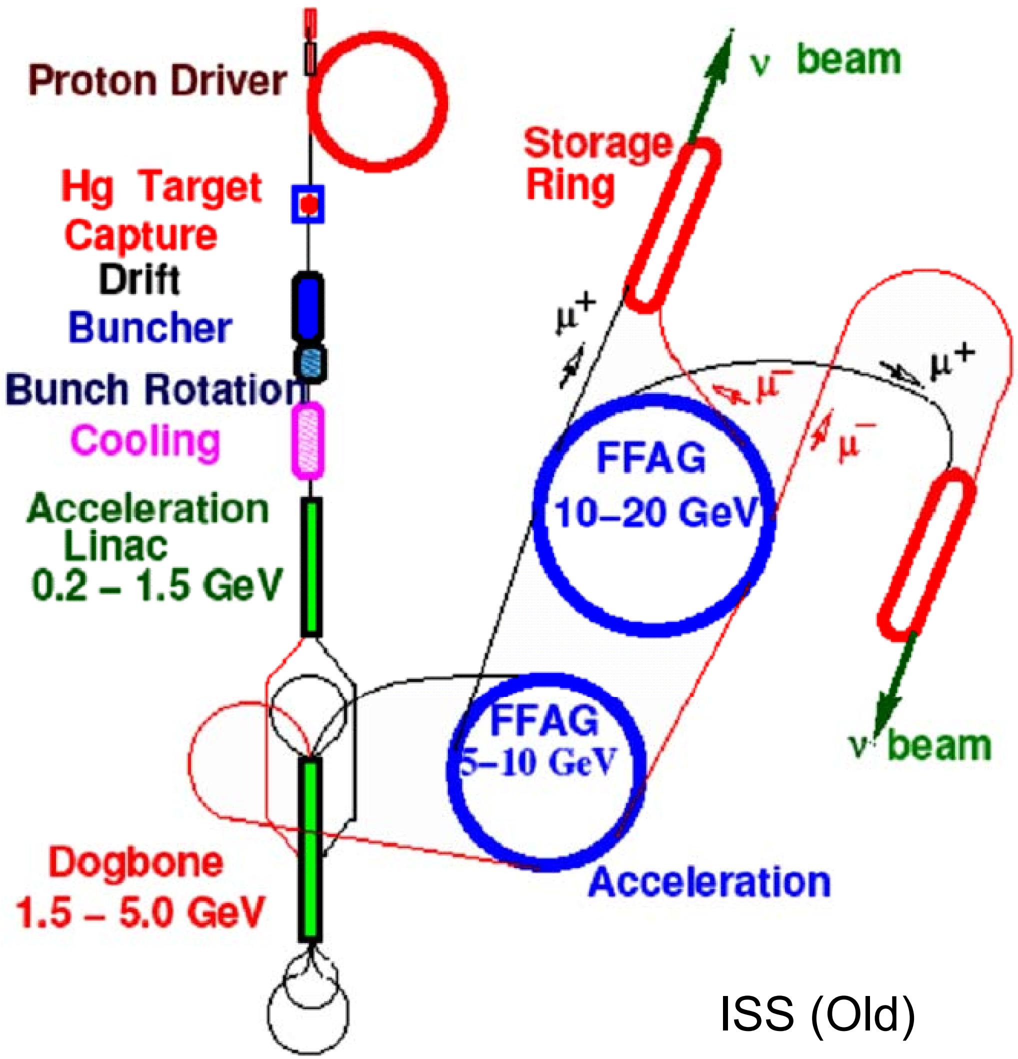
- 4D (transverse) cooling achieved by ionisation energy loss
  - Neuffer Note 1983 + rich literature subsequently
  - Absorber removes momentum
  - RF cavity replaces momentum only in longitudinal direction
  - Reduces phase space volume (emittance) of muon beam
- Stochastic effects ruin cooling
  - Multiple Coulomb Scattering increases transverse phase space volume
  - Energy straggling increases longitudinal phase space volume

Emittance Exchange

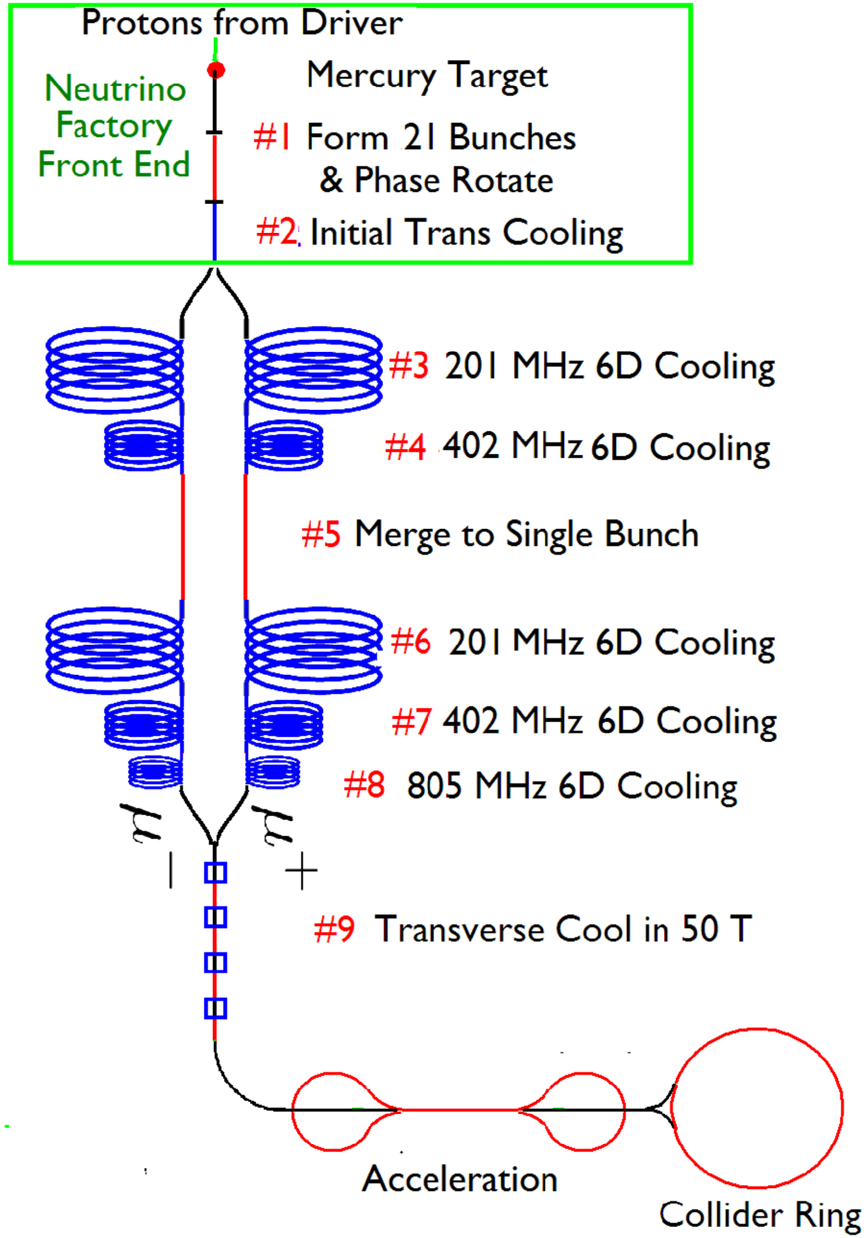


- Emittance exchange takes emittance from longitudinal phase space to transverse
  - Higher energy muons take larger radius path
  - Wedge takes more energy from large radius muons
- This is a shear in x-E phase space
  - Does not cool the beam (to 1st order)
  - But together with transverse cooling provides 6D cooling

NF/MC designs



ISS (Old)

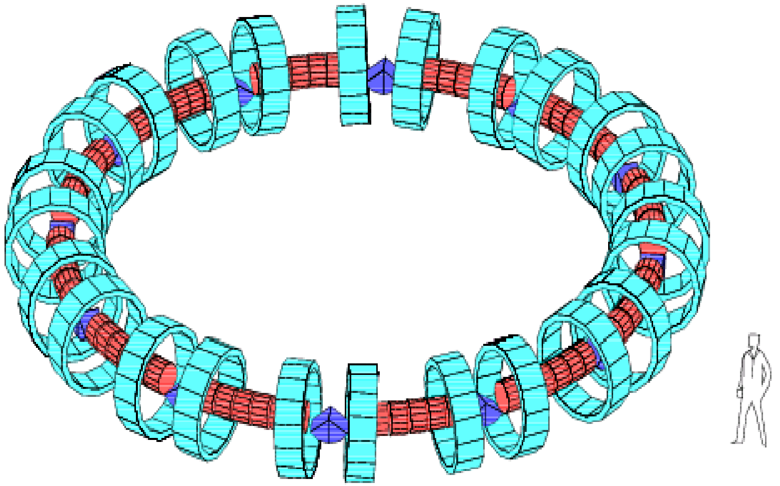


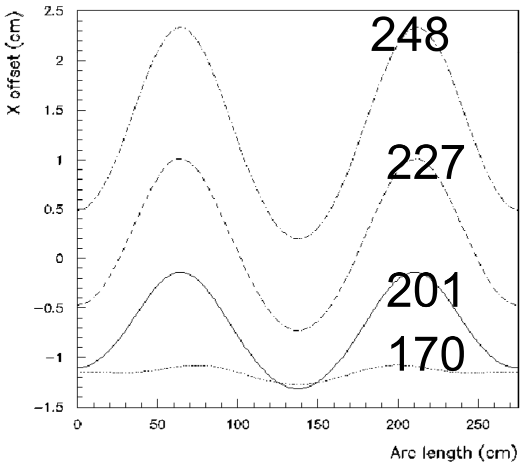
The Challenge

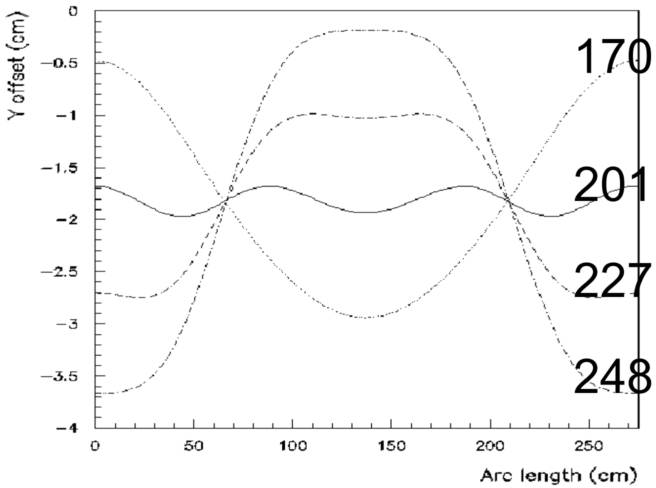
- Designing muon cooling channels is a challenge
  - Higher emittance => harder
- Balance between
  - Beam blow up from non-linearities
  - Beam falling out of RF bucket
  - Focussing to reduce the impact of multiple scattering
  - Decay losses (at lower emittance)
  - ...
- 6D cooling allows us to initially catch muons falling out of the RF bucket
  - Provide an improvement for the NF front end
- And get down to very low emittances

Ring Cooler

Palmer et al, MUC-314, 2005

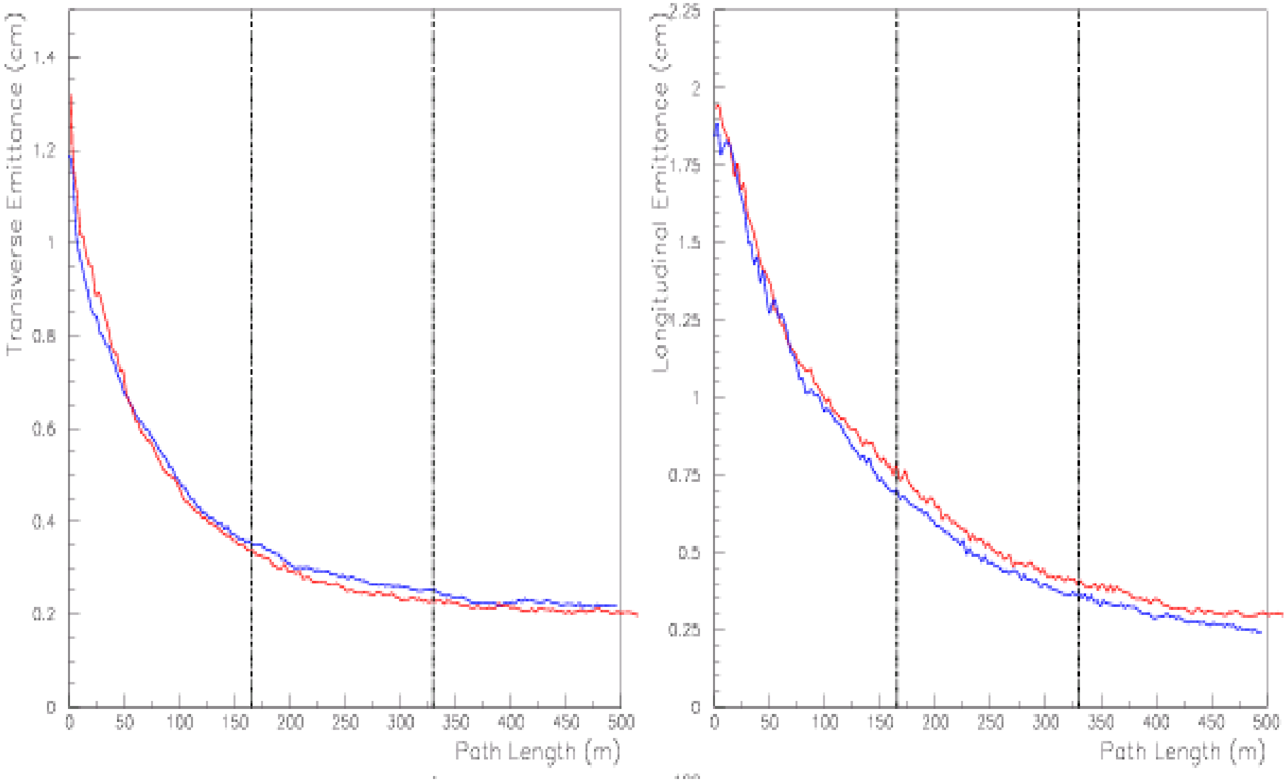






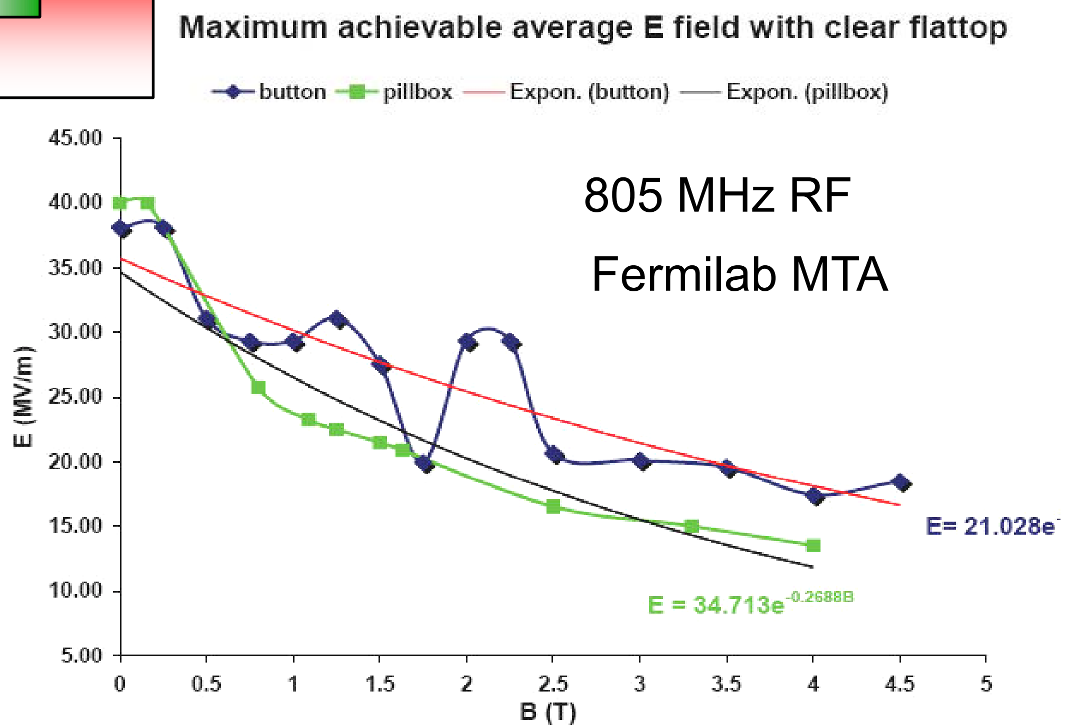
- RFoFo cooler makes bending field using tilted coils
  - Ring circumference 33 m
- Solenoidal field makes dispersion function a 2D vector
  - Show closed orbits at a number of different momenta
  - Point absorber wedge in direction of dispersion function to get the emittance exchange
    - Higher momentum muons go through thicker part of the wedge

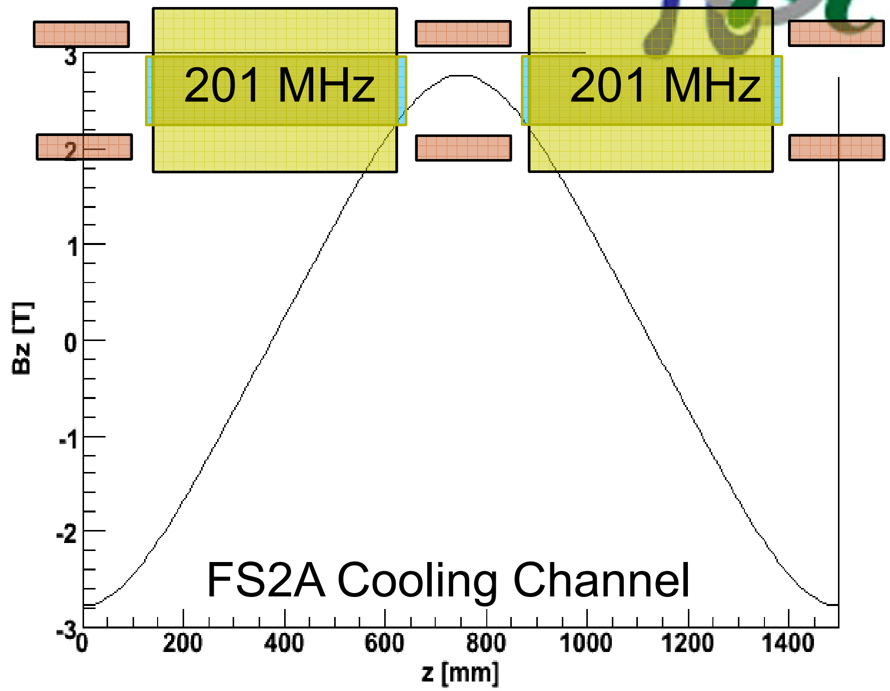
Performance



- Improves number of muons into small acceptance by ~100s
- But injection is highly challenging
- Heat load on absorbers is demanding
- RF breaks down in high Bz

B-Induced Breakdown in RF



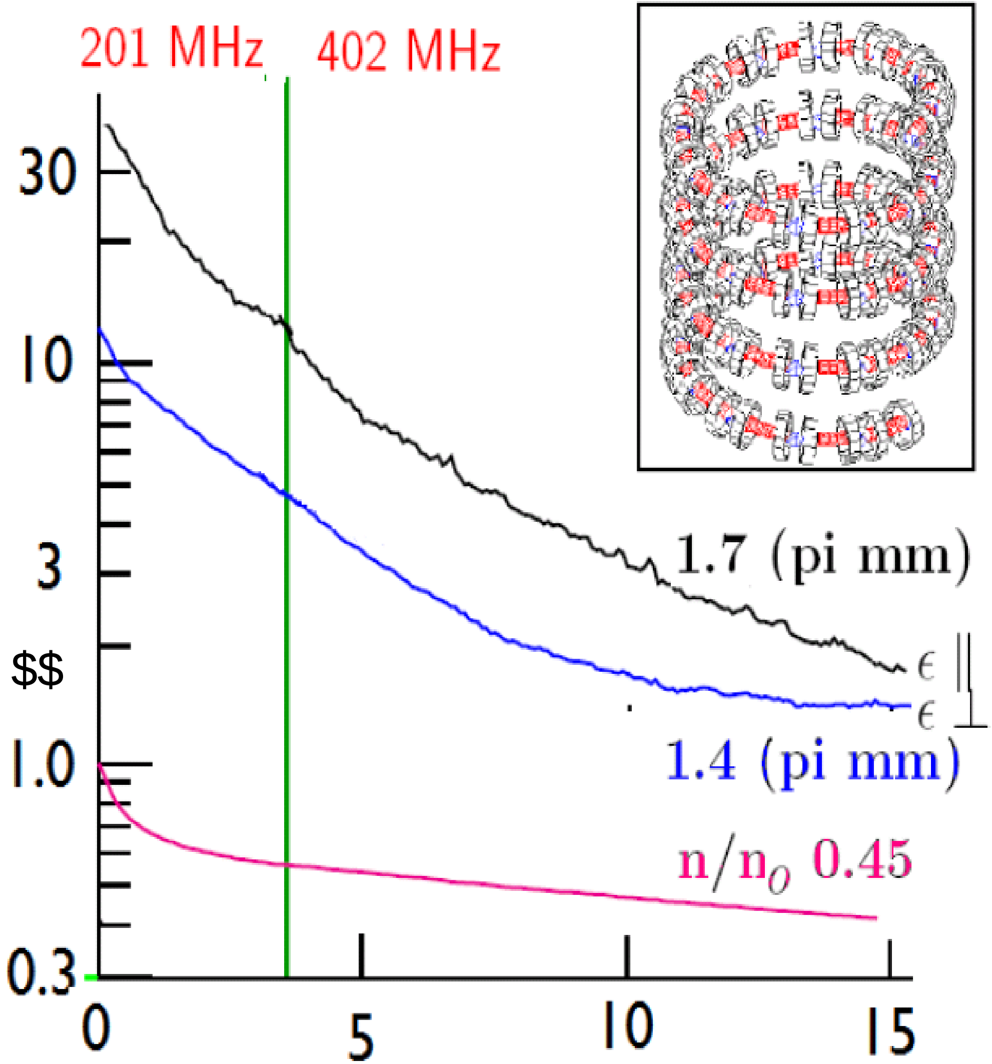


- In most designs, solenoid field overlaps cavities
  - Solenoids have extended fringe fields
- But this magnetic field induces breakdown in the RF cavities
  - Reduces peak achievable gradient by factor ~2
  - May make many of the designs I am going to talk about non-physical
- Investigations underway in the Fermilab Muon Test Area

Guggenheim Cooler

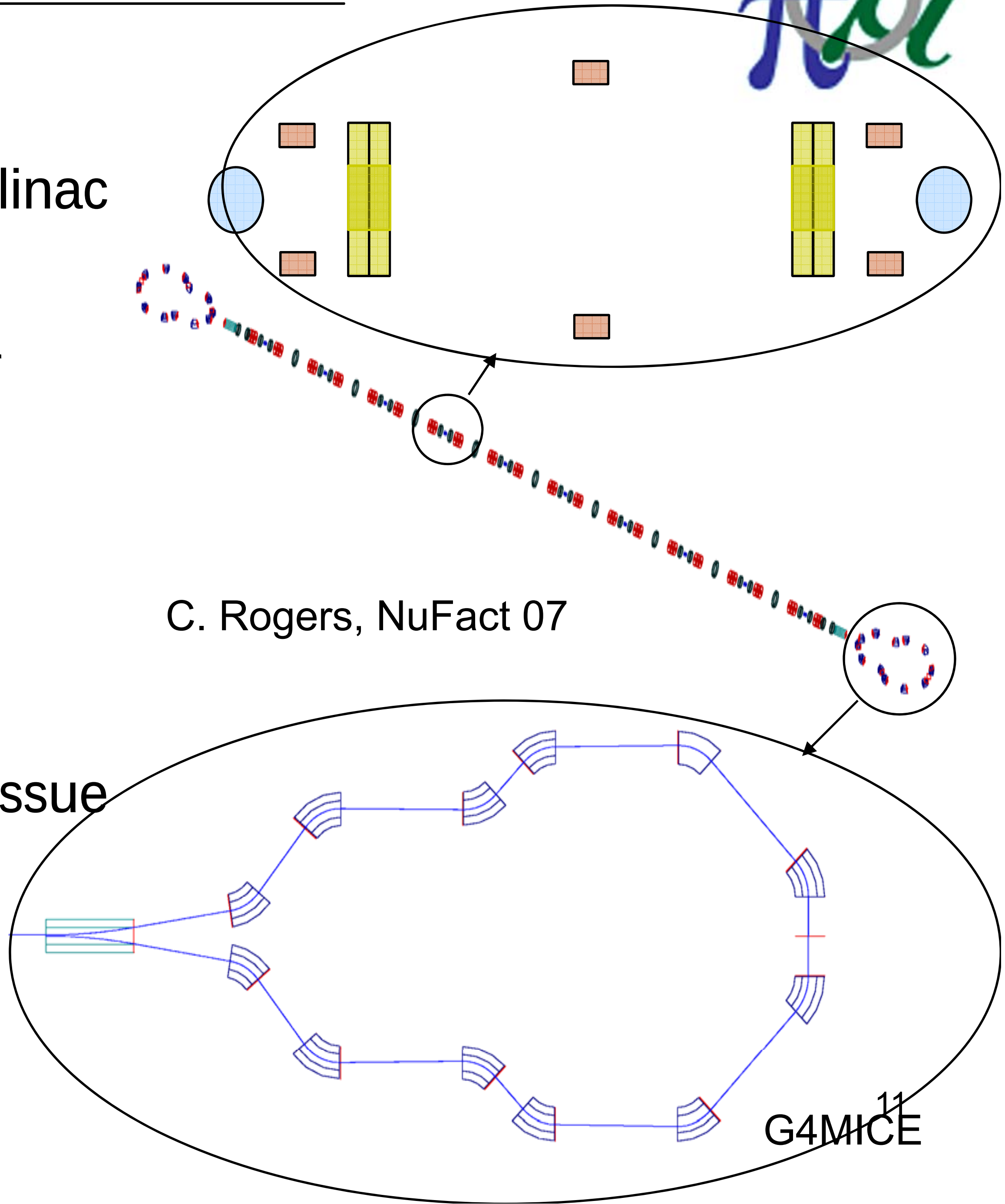
Palmer et al, MUC-519, 2007

- Pull ring out into a helix
  - Solve absorber heating
  - Solve kicker issue
- Need B-shielding between floors
  - Not a show-stopper
- Leaves RF sitting in high Bz
- Performance comparable to ring
  - But need to buy **much** more hardware $$
  - Need one for each sign
  - Can taper beta function

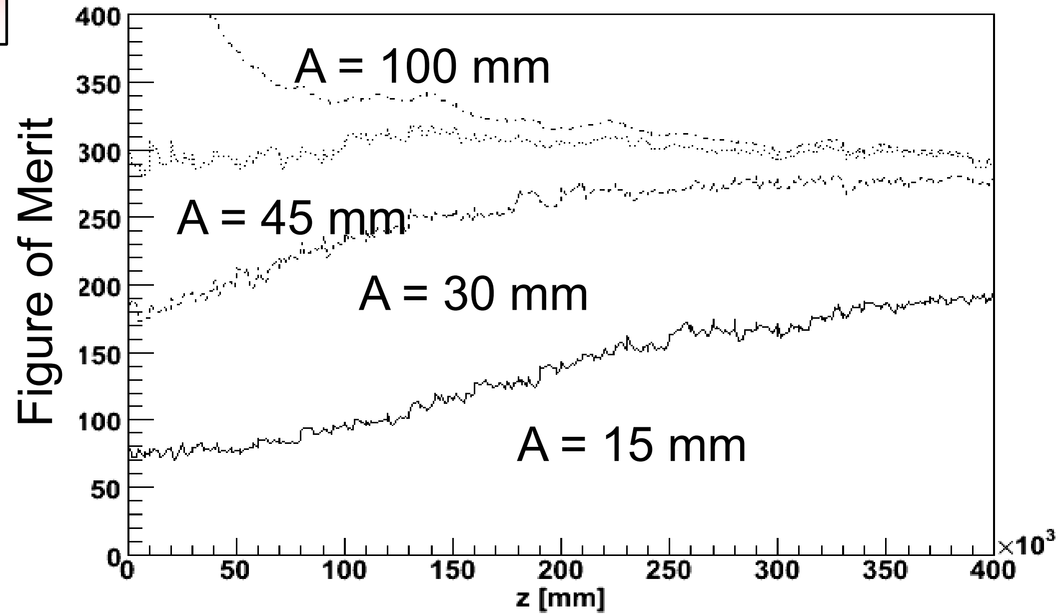


Dogbone Cooler

- Recirculate muons through a linac
  - Linear cooling in the straight
  - Place wedges in the recirculator
- Kicker is feasible
  - 0.08 T
  - 2 m long
  - 200 m rise “time”
- Absorber heating may be an issue
  - But tractable
- B-field <~ 0.6 T in RF cavity



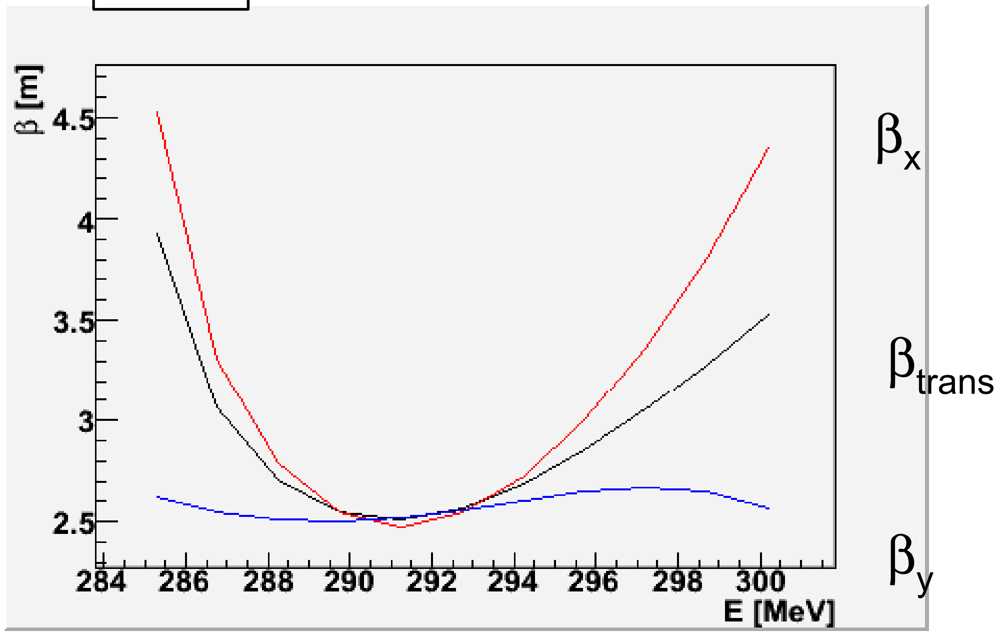
Linear Cooling Performance

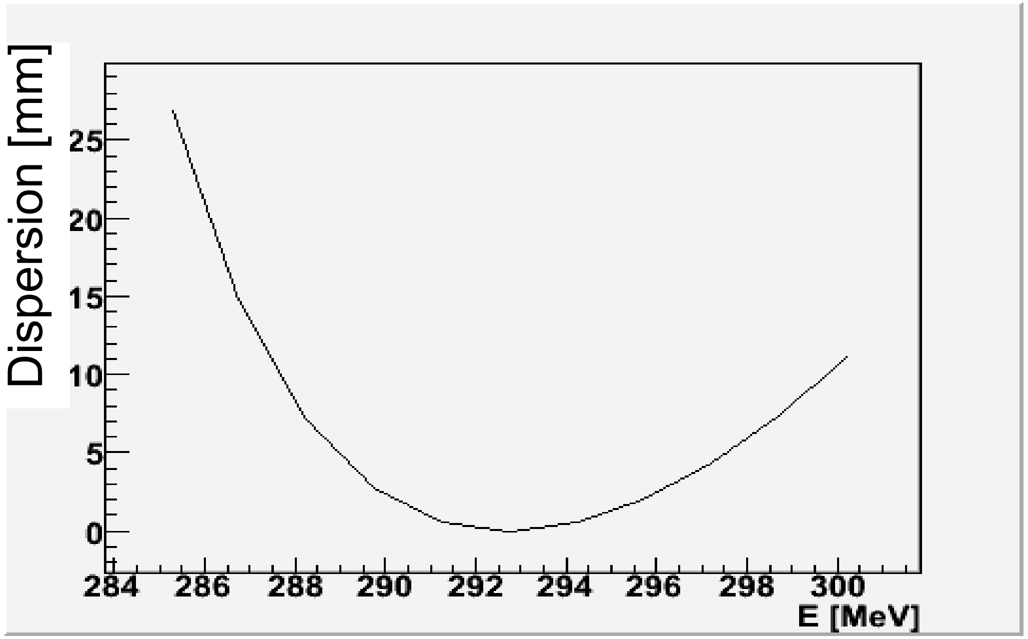


Length [m]	Figure of Merit
80	1.24
160	1.40
240	1.50
400	1.56

- Figure of merit is increase of number of muons in 30 mm transverse acceptance and 150 mm longitudinal acceptance
  - Baseline had a figure of merit of 1.7
- Cooling performance for long, straight cooling channel only
  - NOTE that this does not include any recirculator...
  - Limited statistics

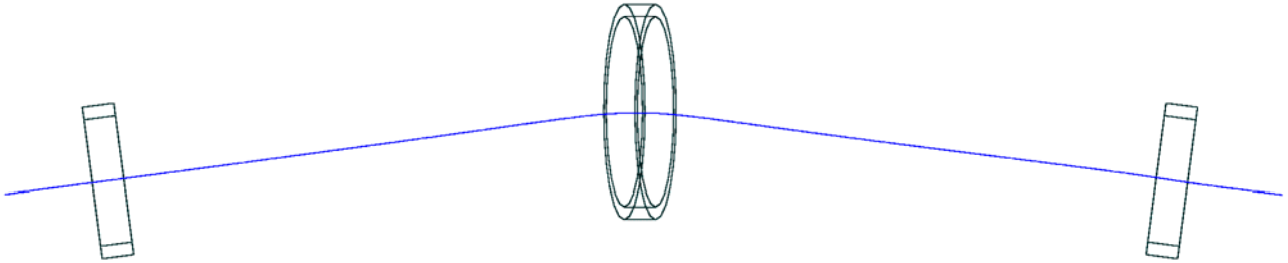
Chromatic aberration



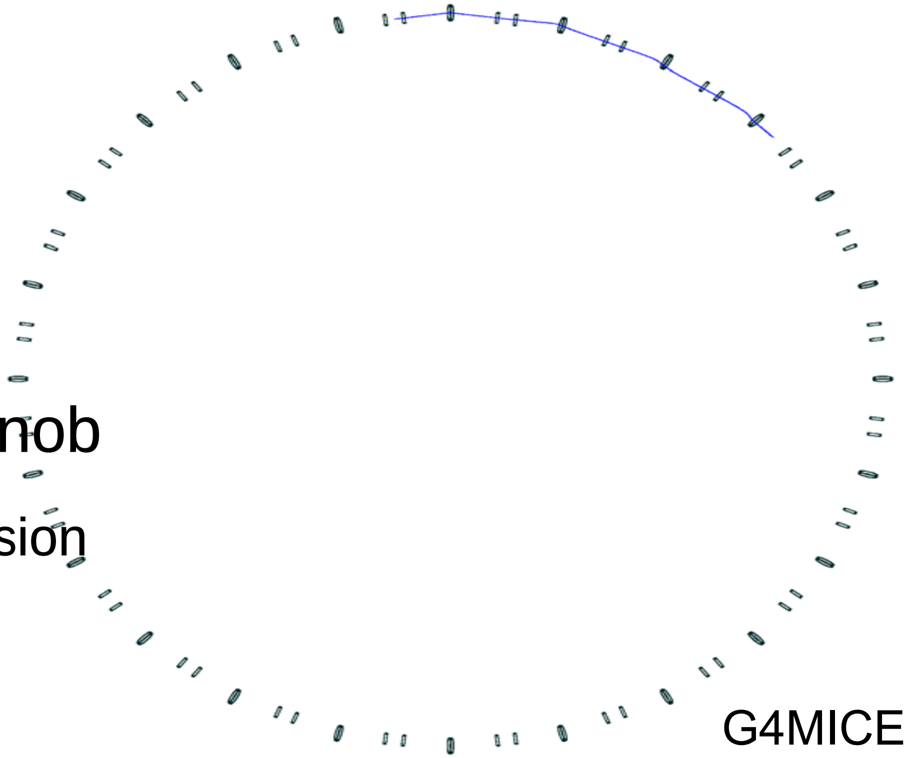


- Large chromatic aberrations
  - Compare with e.g. solenoid channel where lattice was very monochromatic over ~ 30 MeV range
  - This is **after correction with sextupoles**
  - β_x and D is parabolic with momentum => octupoles?
  - Can't put wedges in until this is fixed
  - (A lesson for Neutrino Factory transmission lines?)

Alternate Ring Geometry



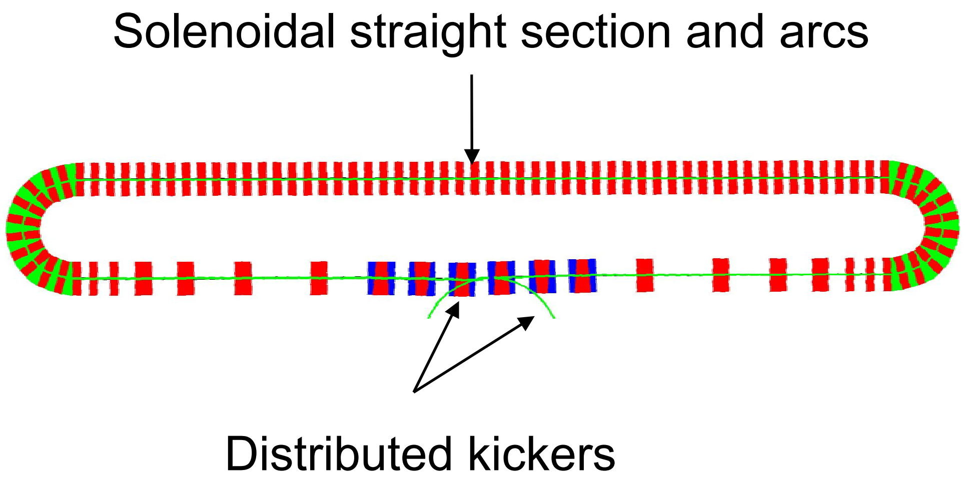
- Use a larger diameter ring?
  - Move RF out of fields
  - Make kicker easier
  - Still worry about absorber heating
- Three coil lattice gives an extra knob
  - Reverse bend to force higher dispersion
  - Try to moderate non-linearities
  - Work in progress

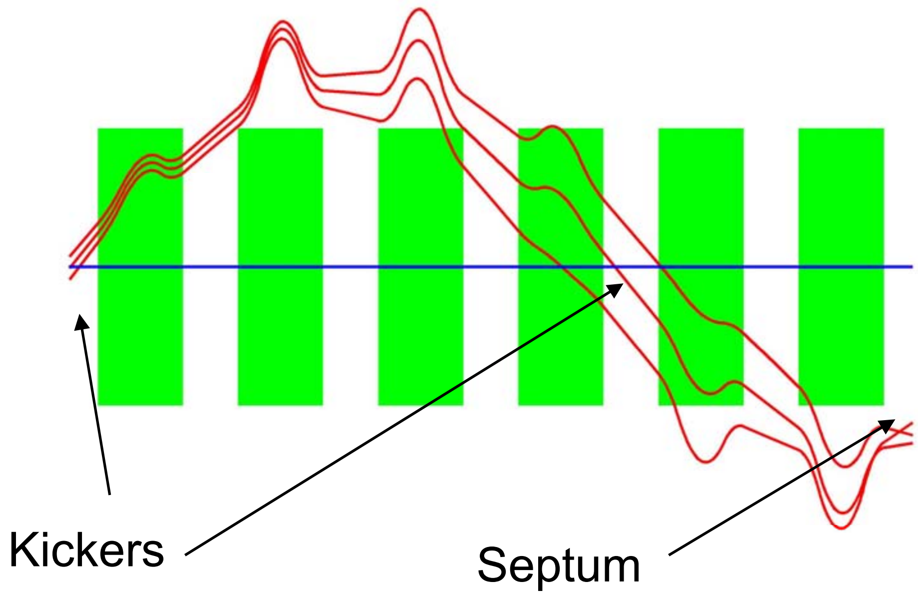


G4MICE

Distributed Kicker

V. Pasternak, NuFact 2007



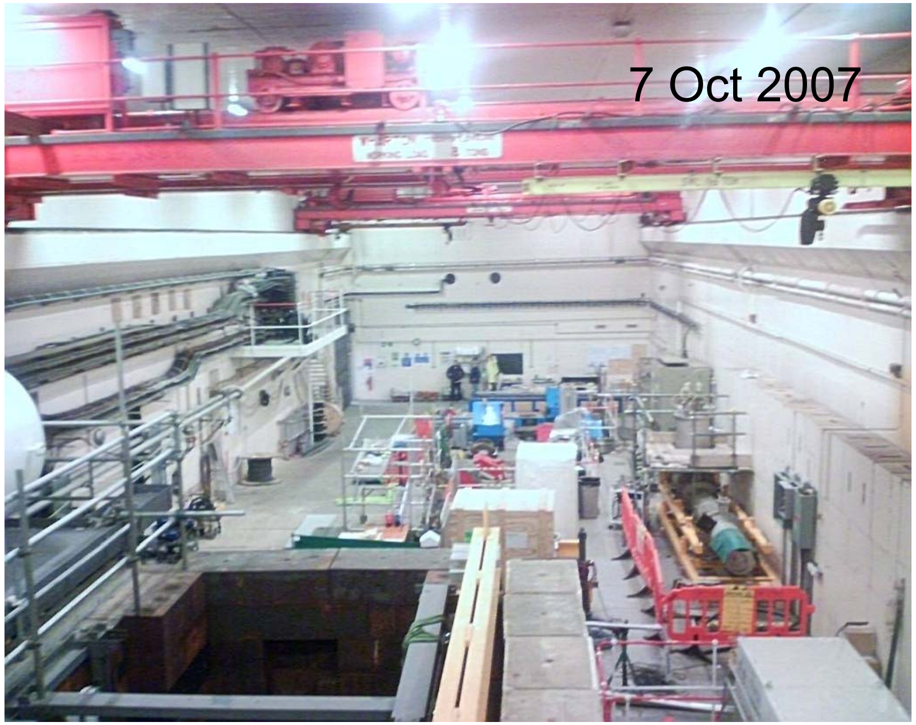


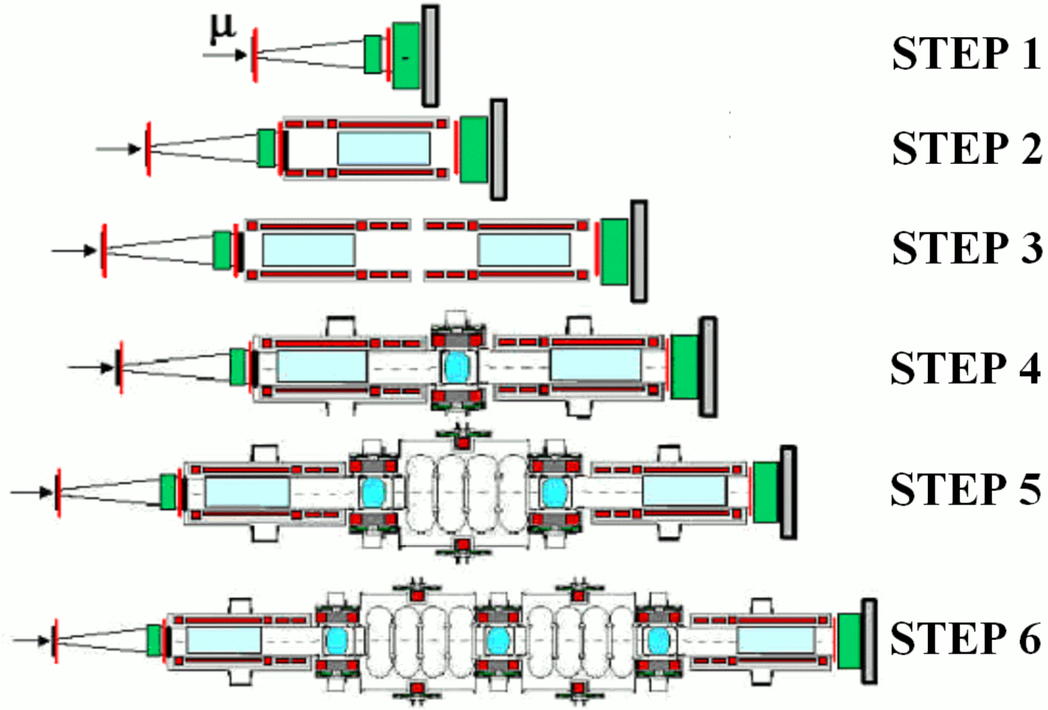
- Use two combined kickers
  - Kick once
  - Beam rotates through 180 deg phase advance in x phase space
  - Kick again
- Issues with chromatic aberrations

Simulation Codes

- Menagerie of simulation codes used
  - ICOOL
  - G4MICE
    - Simulates accelerators as well!
    - Solenoids
    - RF field maps
    - Arbitrary order ntupoles + fringe fields
    - Much more...
  - G4Beamline
  - COSY
  - Muon1
  - MUC_GEANT
  - ...
- Each has advantages and disadvantages
- A significant synergy between NuFact and MC

MICE 4D Cooling PoP

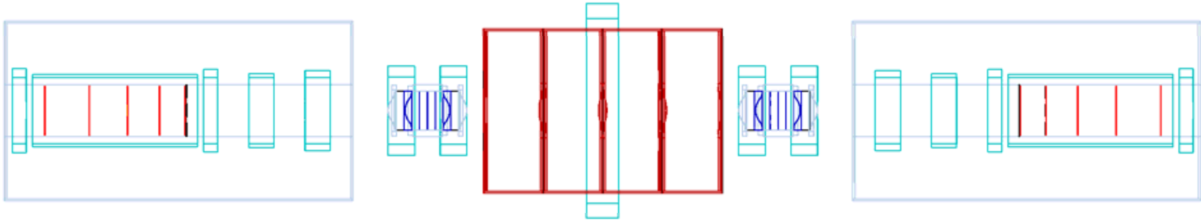




- MICE - Muon Ionisation Cooling Experiment
  - Proof of principle muon ionisation cooling cell
  - Under construction at Rutherford Appleton Laboratory
  - Muon beam line commissioning starts January 2008 (3 months time)
  - Detector testing and construction ongoing

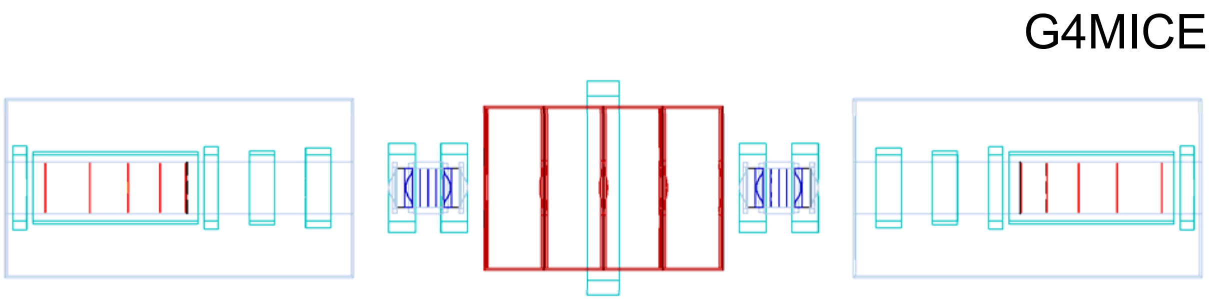
Emittance Exchange in MICE

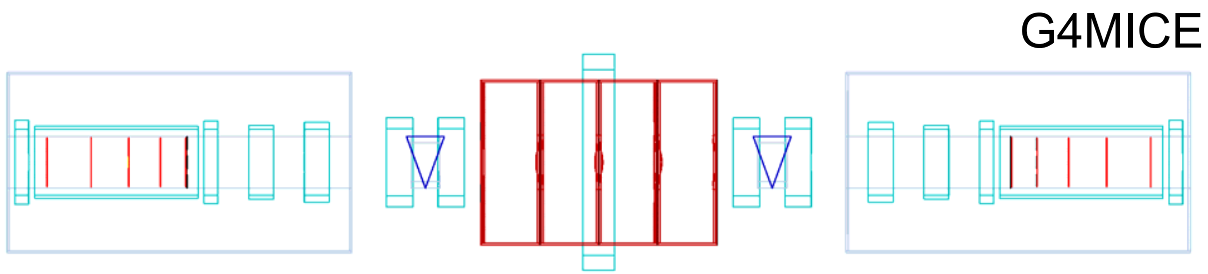
G4MICE



- How would one measure emittance exchange?
  - Build a cell of a cooling ring?
    - Expensive
    - Manpower-consuming
    - Nice to demonstrate emittance exchange but not much beyond what is demonstrated by MICE
- Is it possible to use existing MICE infrastructure?
  - Perhaps followed by custom hardware
- First look at MICE Step 5
  - Allows demonstration of emittance exchange and reacceleration

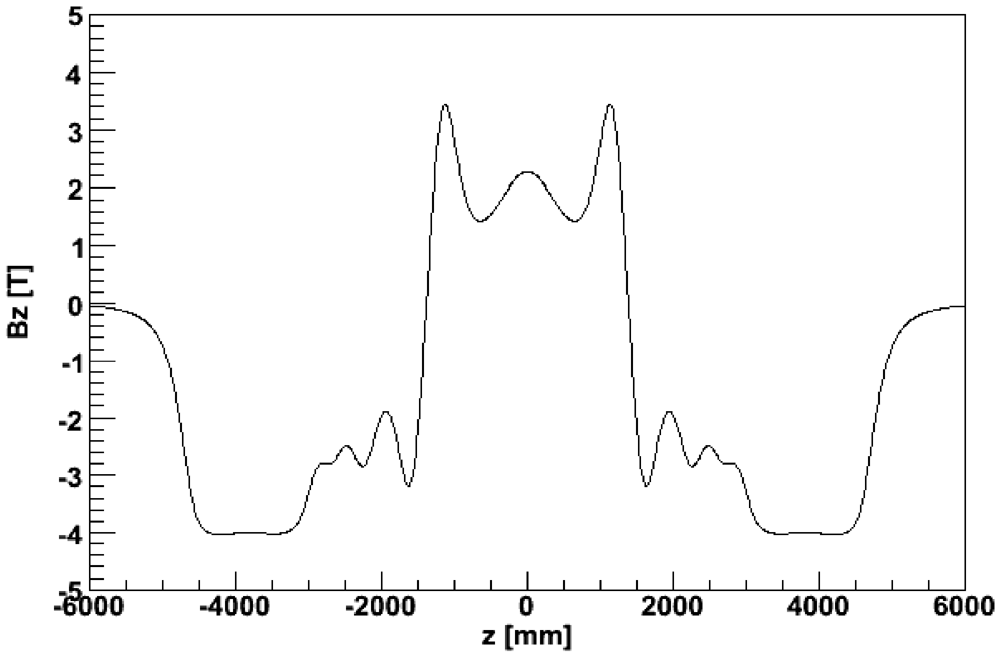
Emittance Exchange in MICE

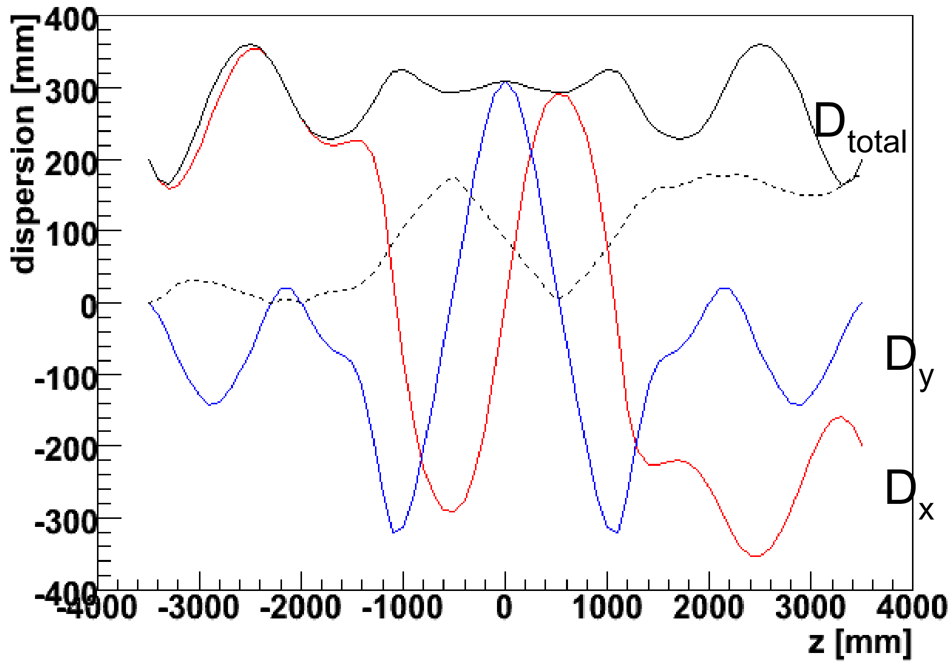




- Replace MICE absorbers with (plastic?) wedges?
  - “Easy”, Cheap

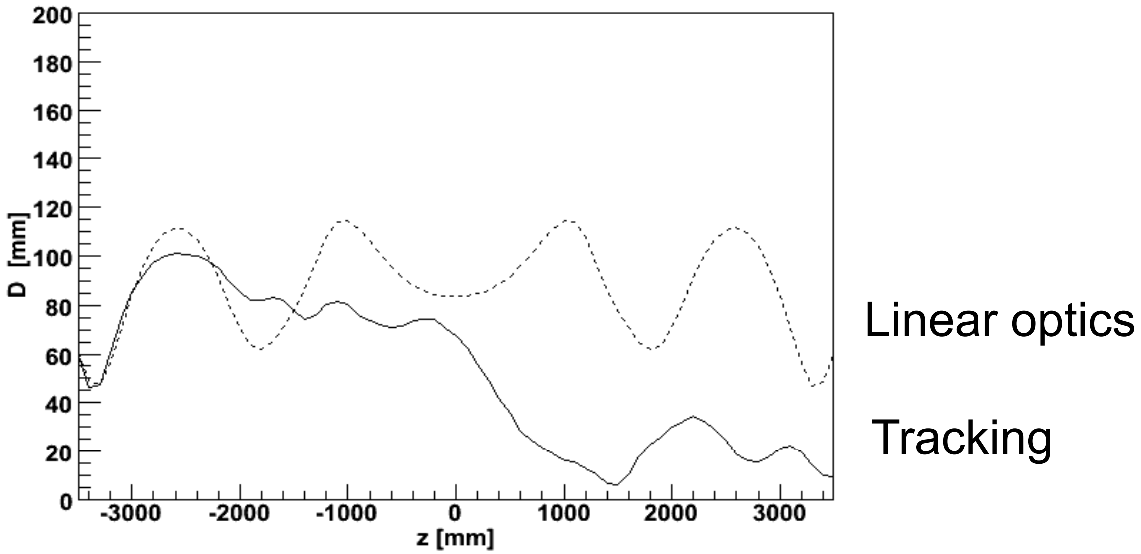
Dispersion through MICE





- Introduce a dispersive beam into MICE
  - Need to select (statistically weight) muons going into MICE
    - MICE beamline has no ability to control dispersion
  - Algorithms now exist for beam selection in 6D phase space
- Dispersion is a 2D vector in solenoids
  - Choose D to have magnitude periodic

But…



- At typical MICE emittances dispersion gets eaten by non-linearities
  - Looks difficult to transport dispersive beam through MICE
  - Would a non-flipping lattice be more forgiving?
  - Would it be worth looking at Step IV (one absorber, no RF)?
  - A subject for further work…

Another R&D Issue

- At very high B-field, models for multiple scattering fail
  - I think only reference is [P Lebrun, MUCOOL note 30, 1999]
  - Field effects trajectory of muons on the scale of multiple scattering interaction length
  - Leads to improvement in cooling
  - This becomes effective at ~ 10 T
- This can be simulated using ELMS-like tool
  - But is not yet simulated in most tracking codes (AFAIK)
- Would we want to verify such simulations with experiment
  - Max field in MICE ~ 4T
  - Is MICE sensitive to this?
- This perhaps needs looking at again as an issue

Cooling Menagerie

- There exists a menagerie of 6D cooling channel designs
- I have only covered a subset
- But transport of high emittance beams (e.g. NuFact beams) is challenging
  - Even more so in a ring
- Getting them to cool adds to difficulties!
  - But progress is being made
- Some experimental ideas