



Cooling Status – New Ideas after MICE

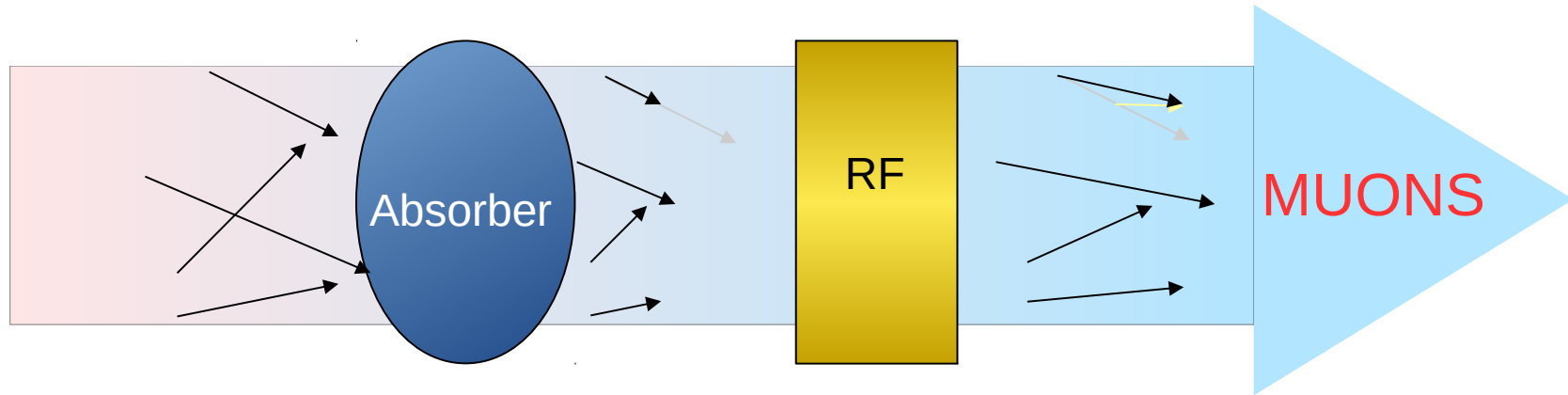
C. Rogers,
ISIS,
Rutherford Appleton Laboratory



Ionization Cooling

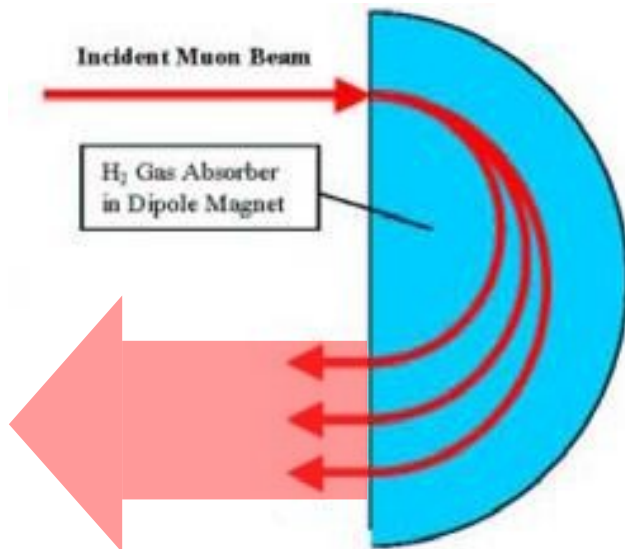
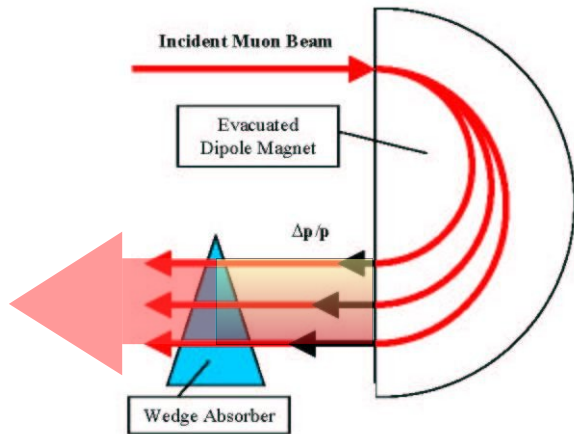
- Reminder:
 - Proton-based muon collider uses ionization cooling
 - Reduce muon beam emittance → increased luminosity
 - Key technology
- MICE has demonstrated ionization cooling
- What is left to do?
 - Lots!

Ionisation Cooling



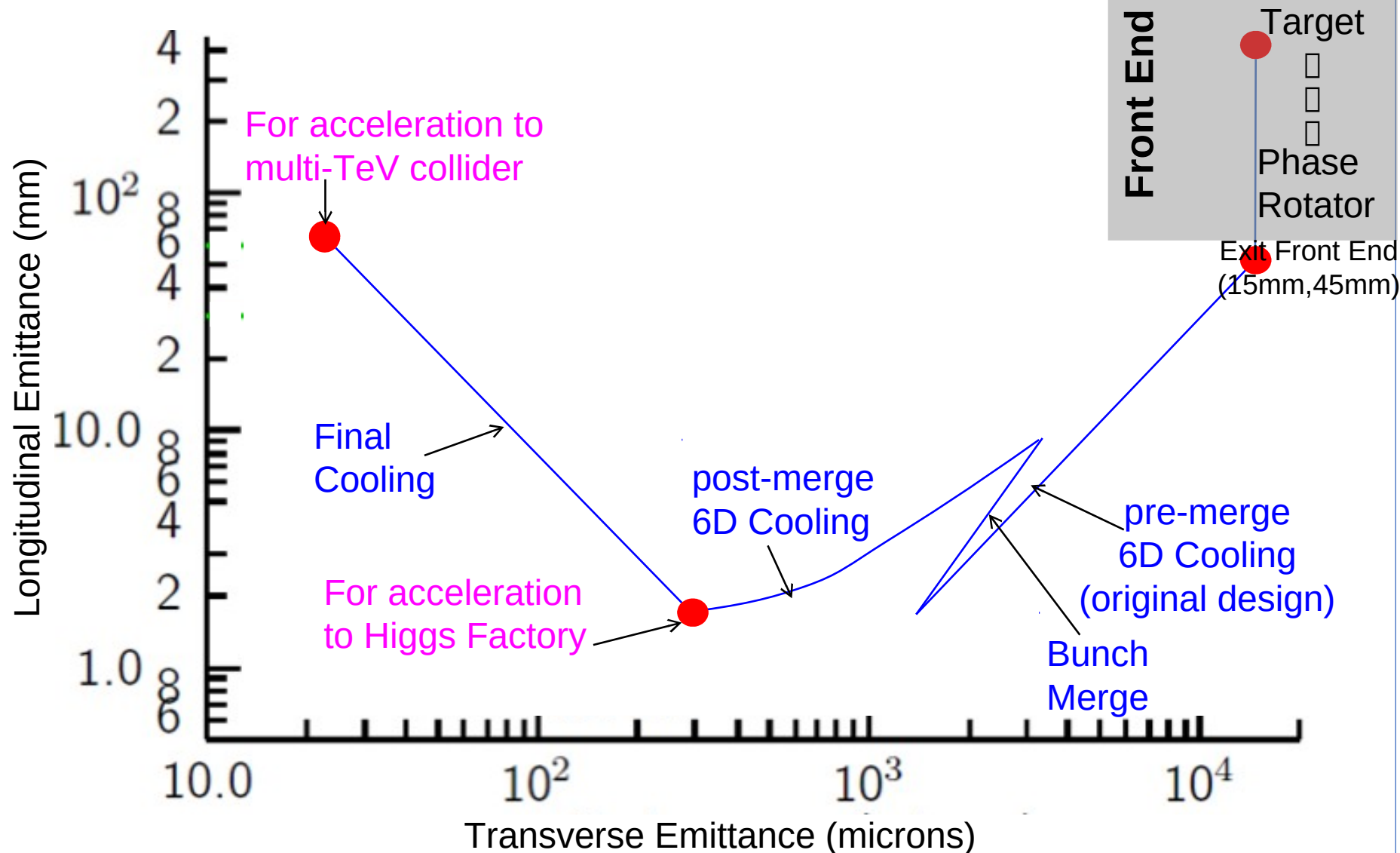
- Beam loses energy in absorbing material
 - Absorber removes momentum in all directions
 - RF cavity replaces momentum only in longitudinal direction
 - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
 - Mitigate with tight focussing
 - Mitigate with low-Z materials

Emittance Exchange

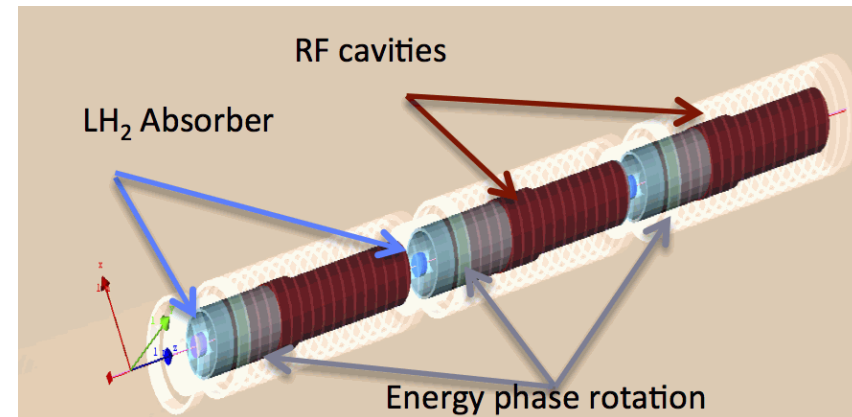
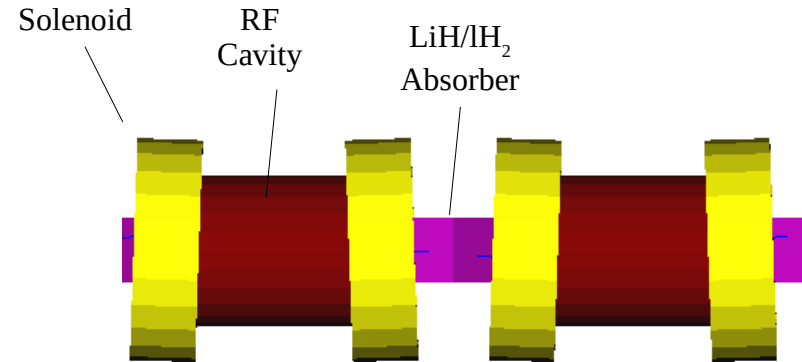
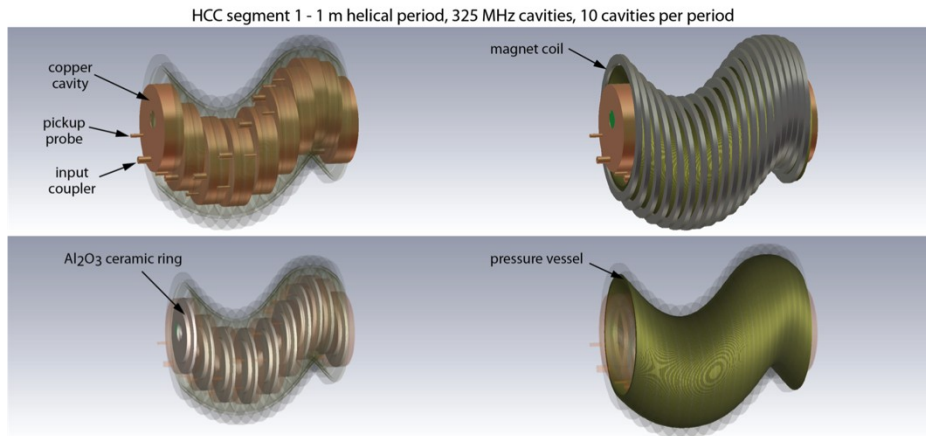


- Higher energy particles take wider orbit
- Higher energy particles pass through more material
- Higher energy particles lose more momentum
 - End up with wider beam with smaller momentum spread
- Results in “emittance exchange”
 - Emittance moves from longitudinal to transverse
- Results in reduction in longitudinal emittance and transverse emittance

Ionization Cooling



Technology



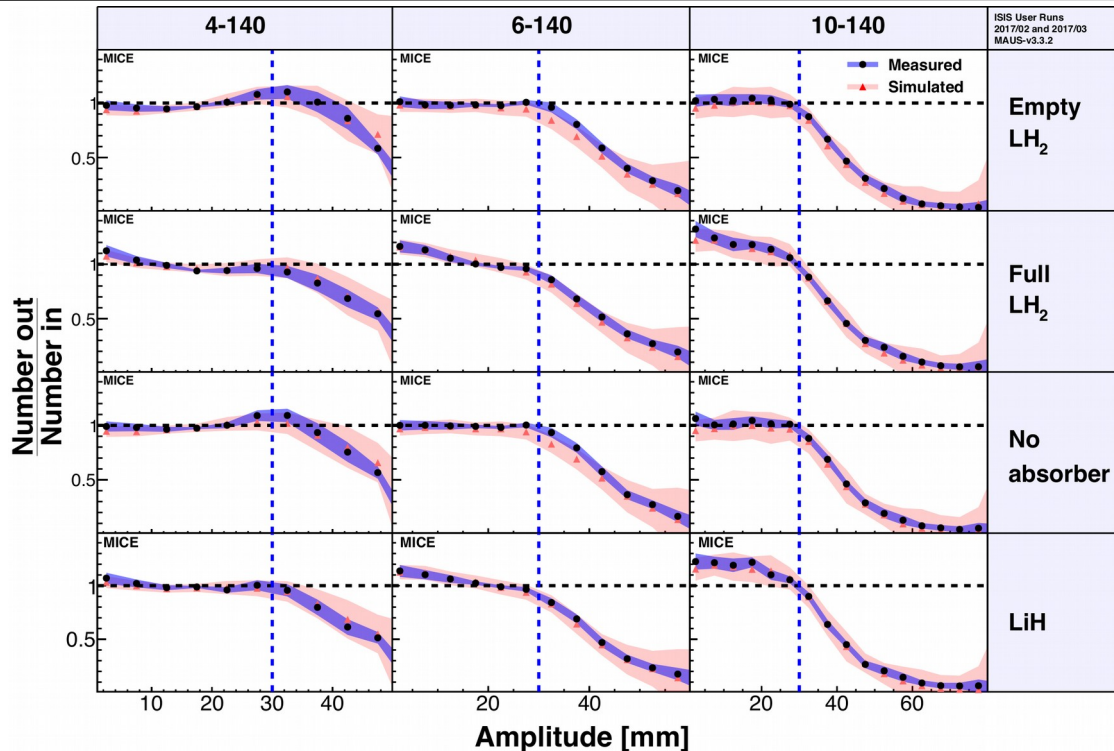
- A few different lattice technologies
 - Helical solenoid or solenoid + dipole focussing
 - Mostly few 100 MHz RF
 - Few MHz induction linac in final cooling



Potential Issues

- Cooling tests should address technical issues
 - 4D cooling
 - Focussing, multiple scattering and dE/dx
 - 6D cooling
 - Energy straggling
 - Novel optics
 - “Tilted solenoid” or “solenoid and dipole” optics
 - Helical optics
 - Bulk effects
 - Space charge
 - Absorber degradation
 - Bulk ionization of material
 - Beam-induced plasma loading in High Pressure RF
 - Specific engineering issues
 - Magnets
 - Forces
 - RF voltages
 - etc

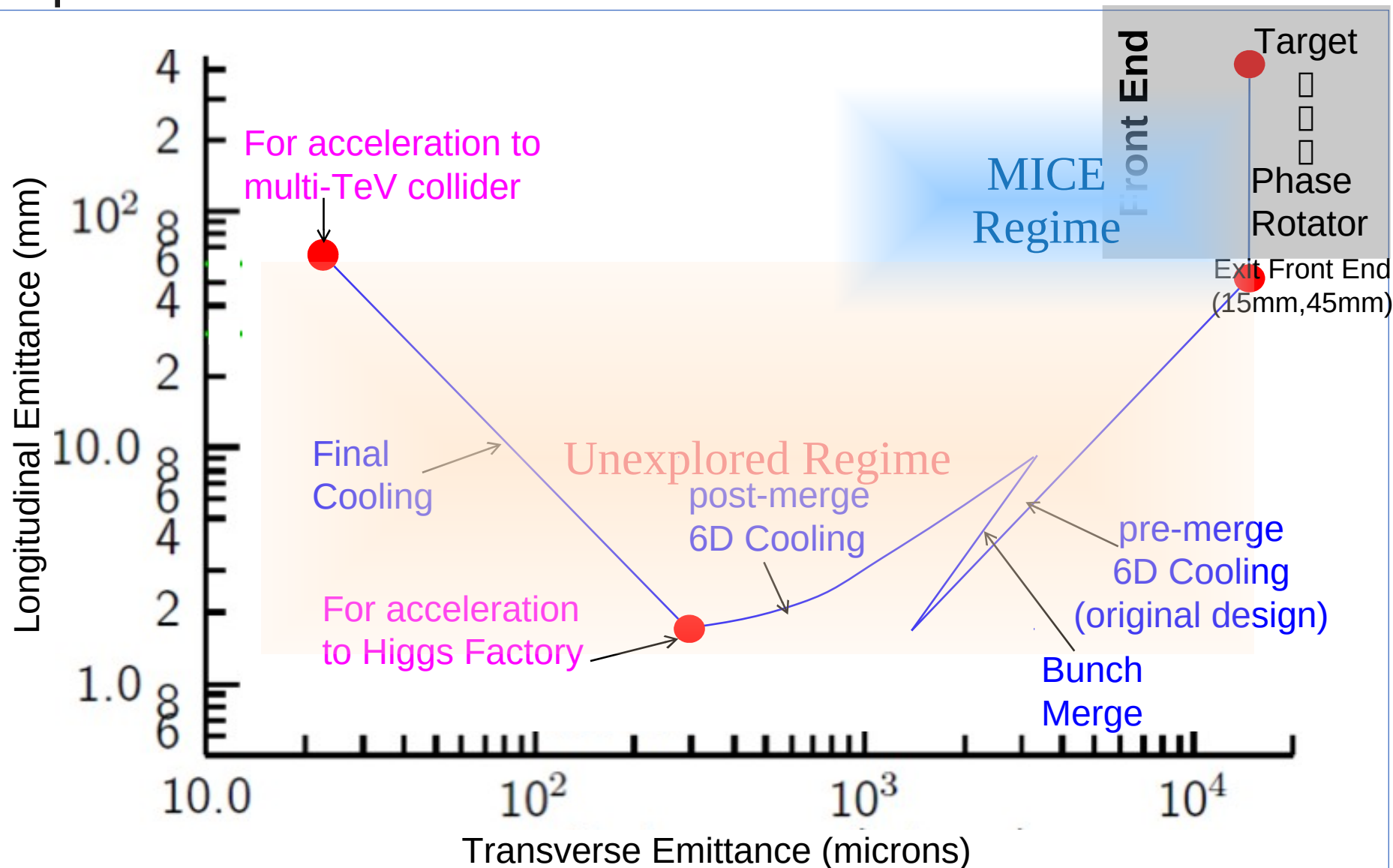
Transverse (4D) Cooling



MICE Collaboration,
Nature volume 578 (2020)

- MICE principally addressed transverse cooling
 - Cooling in regime between 1000 micron - 10000 micron
 - Optical beta $\sim 50 - 100$ cm
 - Momenta 140 - 240 MeV/c
 - Good agreement with simulation
- Some analysis ongoing, but don't expect surprises

Ionization Cooling





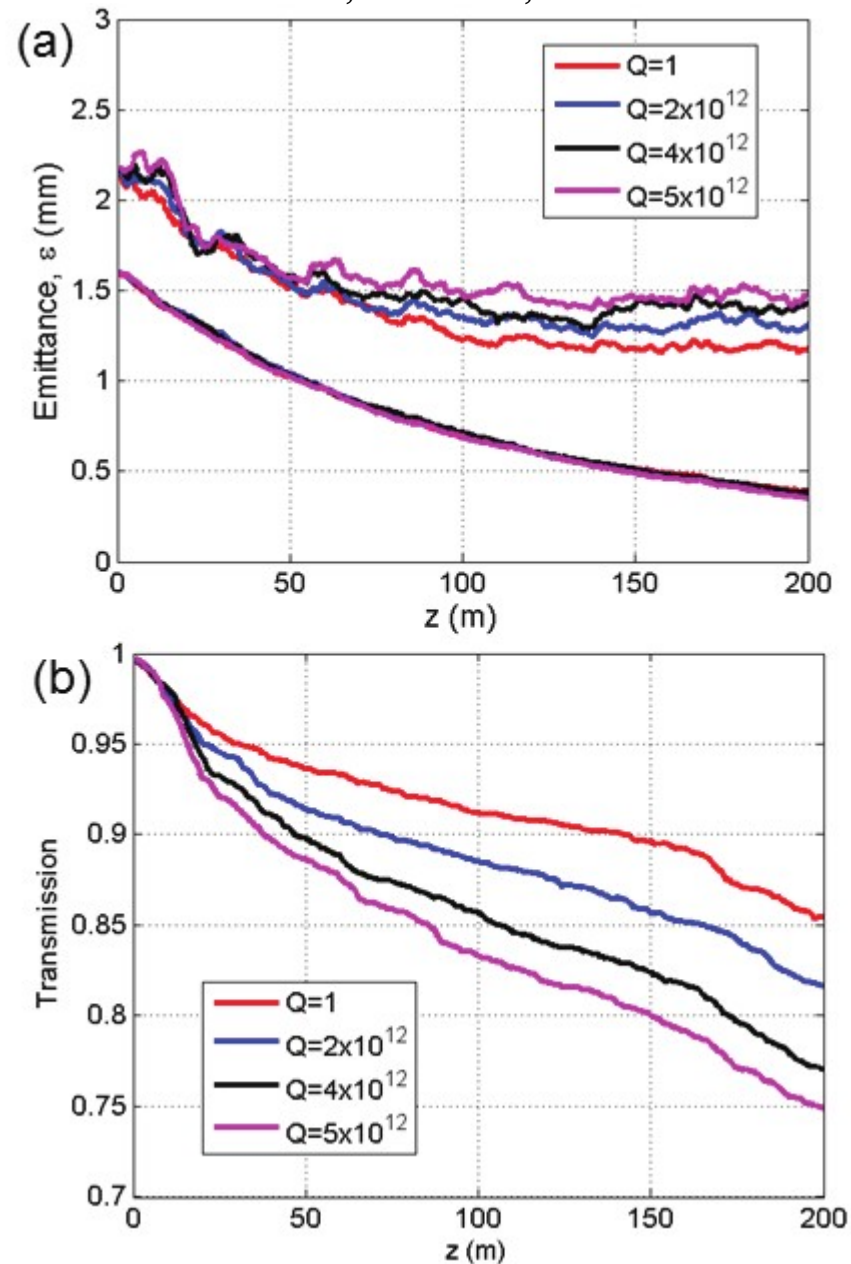
6D Cooling

- MICE did not study longitudinal cooling much
 - Wedge absorber was studied; analysis is in progress
 - Limited resolution in energy and time
 - Limited capacity to generate dispersive beams
- Physics is reasonably well understood
 - Energy loss and straggling is well known
 - Properties of RF and dispersion are well known

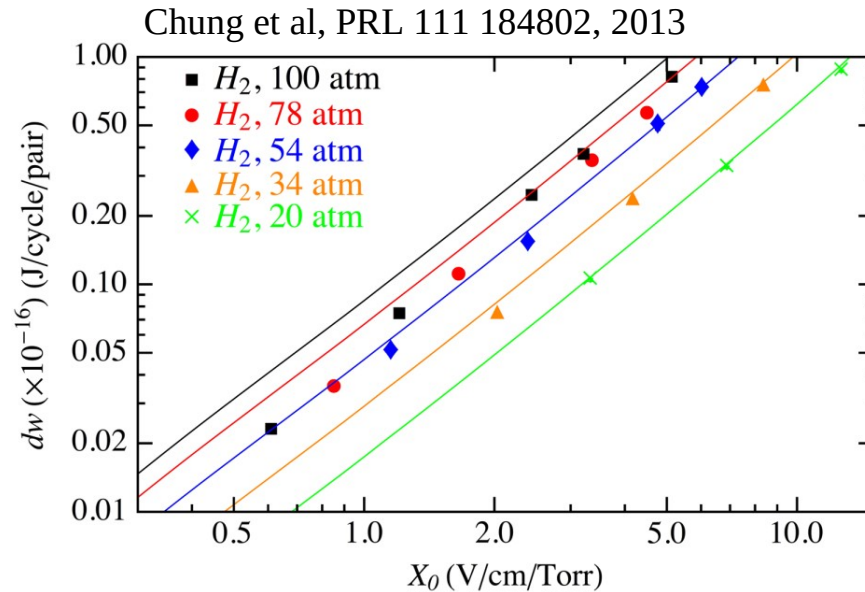
Space Charge

- Space charge
 - Space charge becomes significant for the lowest emittance beams
 - Suspect longitudinal space charge causes loss
 - Deserves more simulation
 - Supported by experiment

Stratakis et al, TUPFI088, IPAC13



Beam induced plasma loading



- Some lattices call for high pressure gas to fill RF cavities
 - Suppresses RF breakdown enabling higher RF voltages
 - Ionisation of the gas by beam; ions load the cavity
- Tested in Fermilab (2013)
 - Measured less loading (dw) than expected



Bulk ionization of material

- Beam ionizes material
- Subsequent beams perturbed by ionization “wake”
- May enhance density effect and energy loss
- Not expected to be significant for muon collider
 - But needs checking

Huang et al, TUA1MCIO02, Proc COOL09, 2009



Specific Engineering Issues

- Many proposed cooling channels are quite demanding
 - High magnetic fields
 - RF voltage
- Further hardware R&D is required
 - Magnet development
 - Engineering prototypes
 - Etc
- Likely can be done without beam

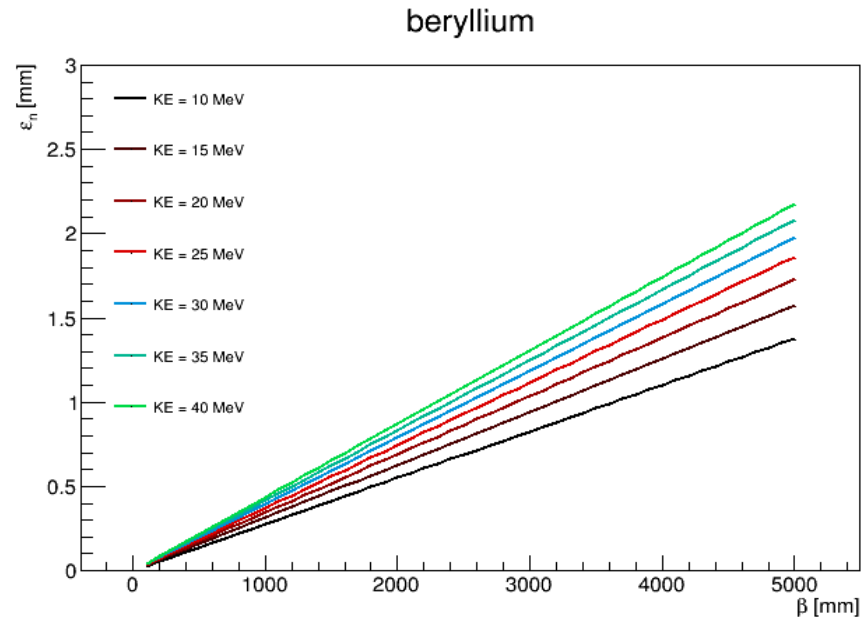


Potential Beam Tests

- Single pass (like MICE)
 - Single pass through linac and absorber
 - Aim for higher intensities than MICE
 - Aim for tighter focussing
- Recirculating (i.e. ring)
 - Higher average intensity
 - Bigger signal/easier diagnostics
- Particle Species
 - Protons
 - Intensities comparable to MC bunch intensity (10^{12} mu/bunch)
 - Different energy loss/scattering characteristics
 - Hadronic interactions
 - Muons
 - Lower intensity
 - Correct physics
 - Electrons?

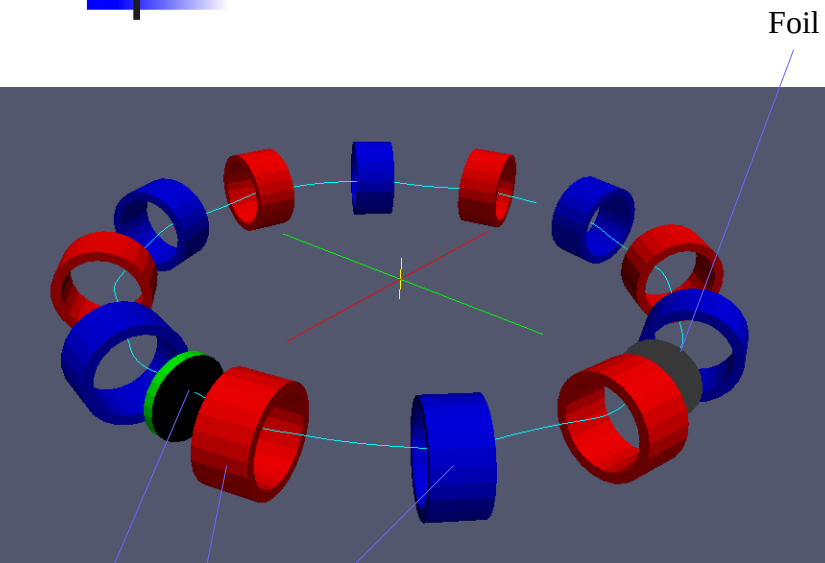
Recirculating Proton example

- Aim for a proton ring with acceptance $>$ equilibrium emittance
 - Longer beam lifetimes
- Consider transverse only
- What are the lattice properties required for transverse containment?
 - Bethe Bloch energy loss model
 - Moliere scattering model
 - Linear optics
- Desire
 - Tight focus in both planes
 - Good acceptance
- Low z foil e.g. Beryllium



Equilibrium emittance vs optical β

Solenoidal Ring



RF
Cavity

Solenoid+
Dipole

Number of Cells

Radius

Energy range

Solenoid field

Dipole field

Magnet Length

Bore Radius

12

3 m

6-15 MeV

1.6 T

0.68 T

500 mm

400 mm

Foil thickness

Foil material

Voltage/turn

RF phase

RF freq

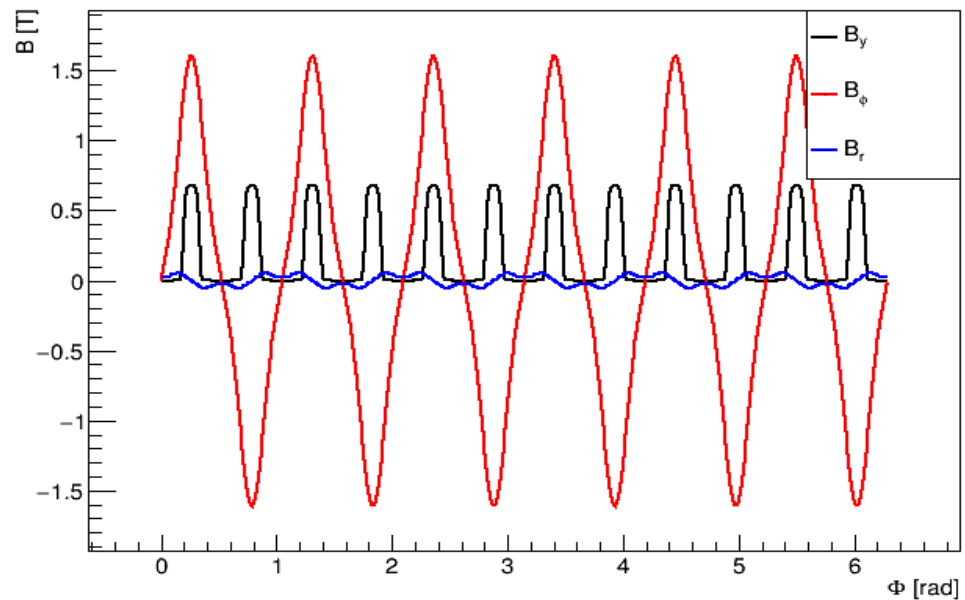
10 micron

Be

250 kV

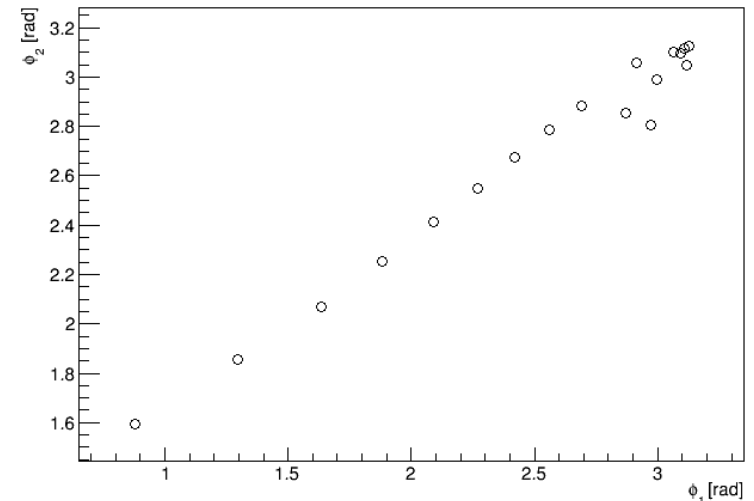
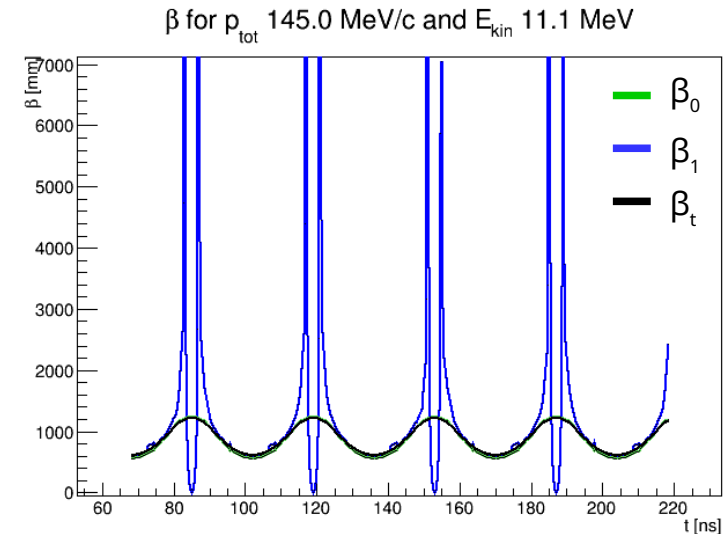
11 degrees

2.452 MHz



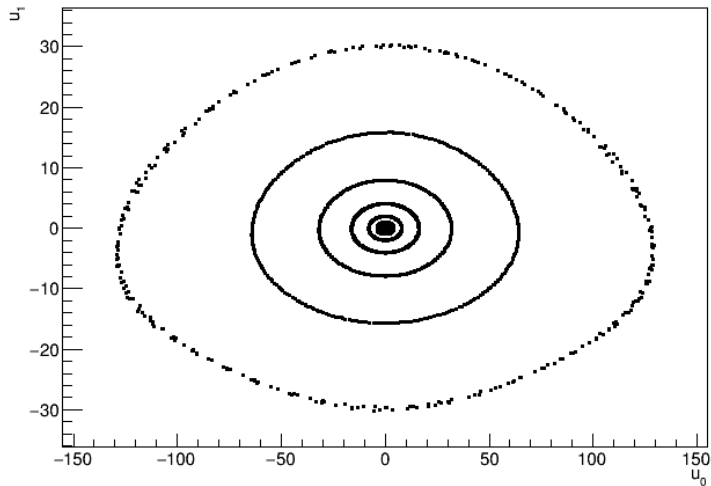
Optics

- Totally coupled optics
 - Solenoid couples x and y
 - (RF and dispersion couples time)
- Split analysis into 2D transverse eigenspaces
 - Follow Parzen formula
 - Develop beta function in the eigenspace
 - Also consider 4D beta
- Large tune spread
 - Inherent non-linearities in solenoid (and dipole) fringe field

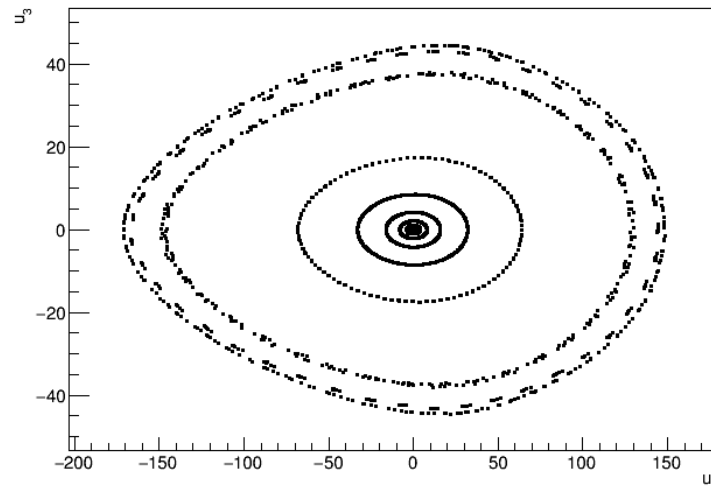


Acceptance (eigenspace)

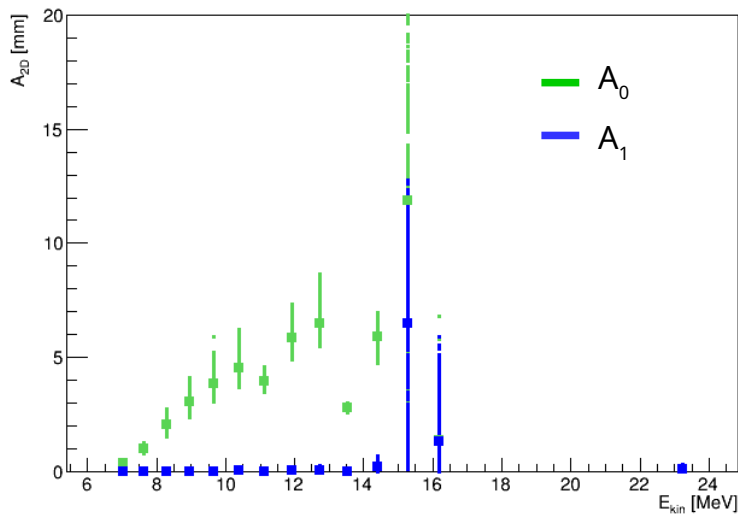
DA for eigenspace: 0 P: 145.0 MeV/c and E_x : 11.1 MeV requiring 50.0 turns



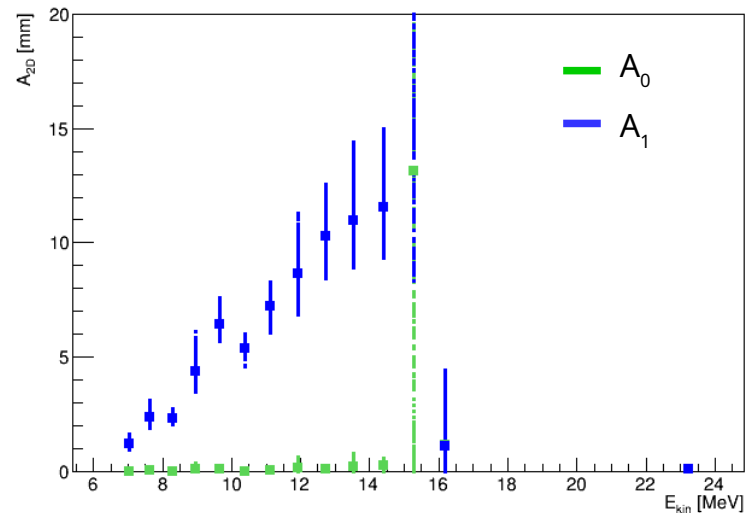
DA for eigenspace: 1 P: 145.0 MeV/c and E_x : 11.1 MeV requiring 50.0 turns



Acceptance for eigenspace 0 after 50.0 turns

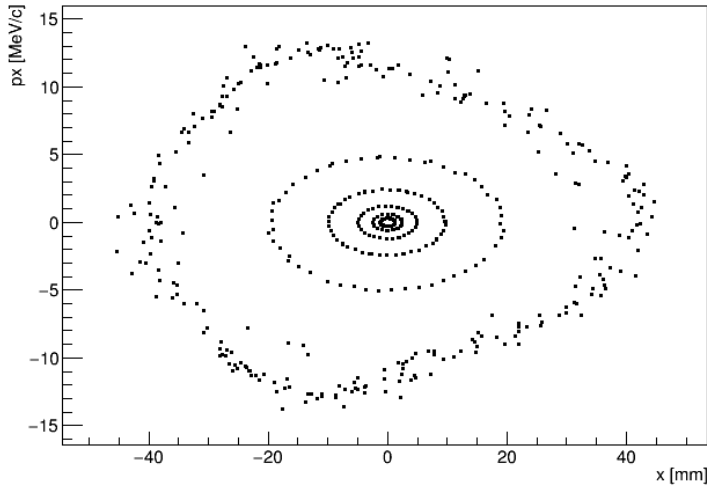


Acceptance for eigenspace 1 after 50.0 turns

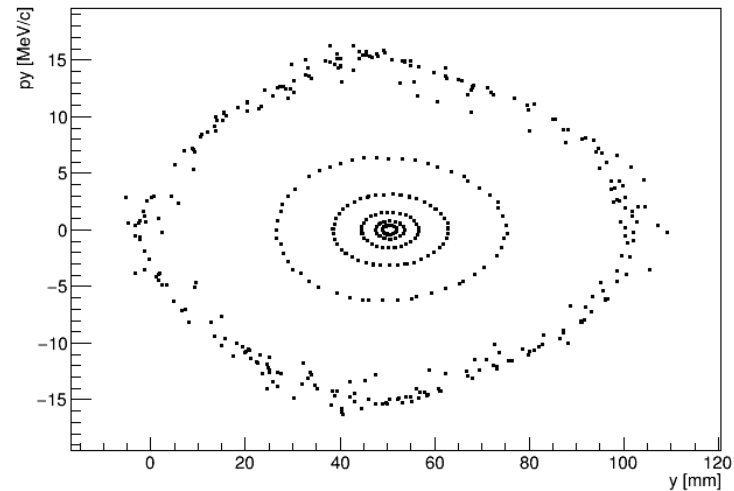


Acceptance (projected to physical space)

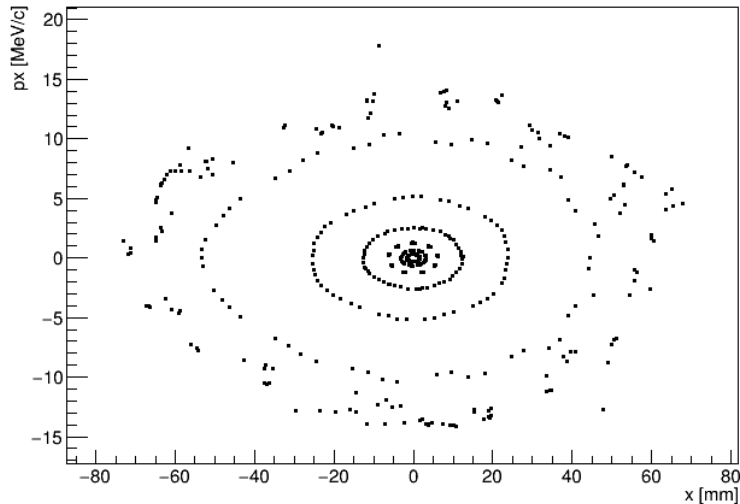
DA for eigenspace: 0 P: 145.0 MeV/c and E_k : 11.1 MeV requiring 10.0 turns



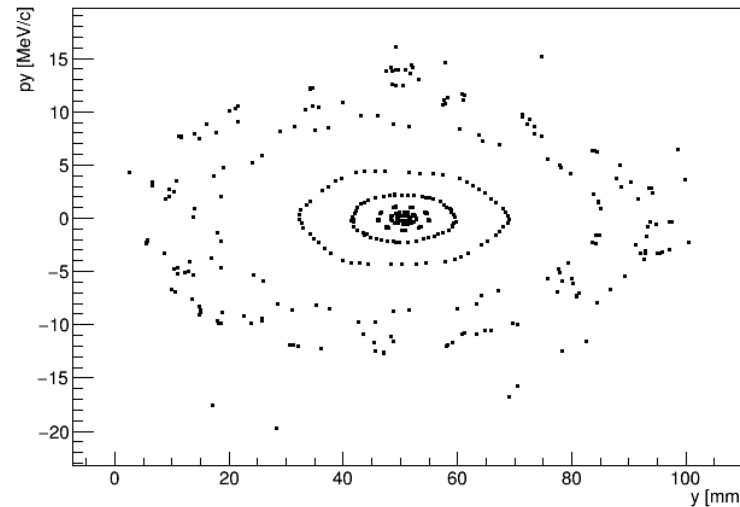
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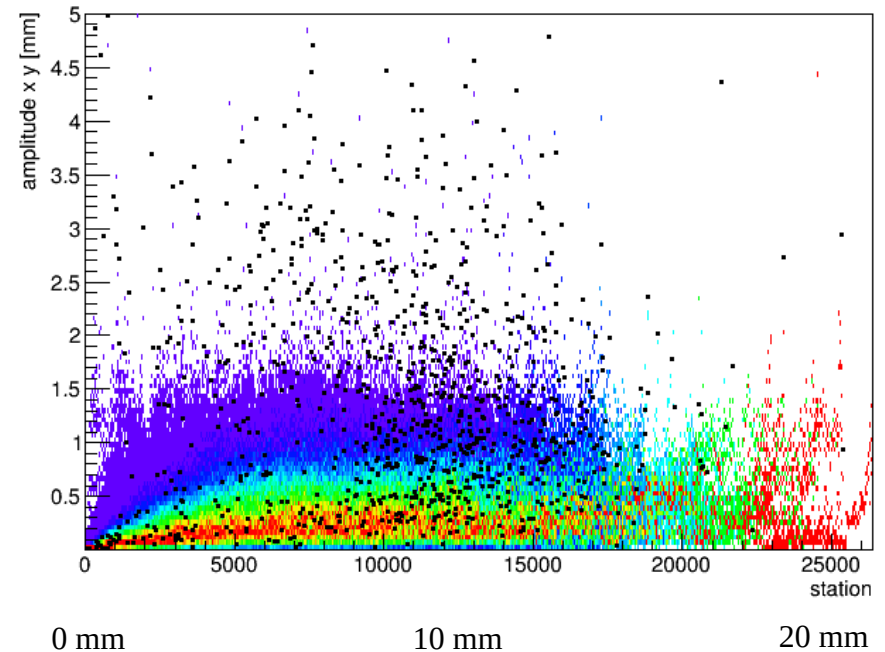
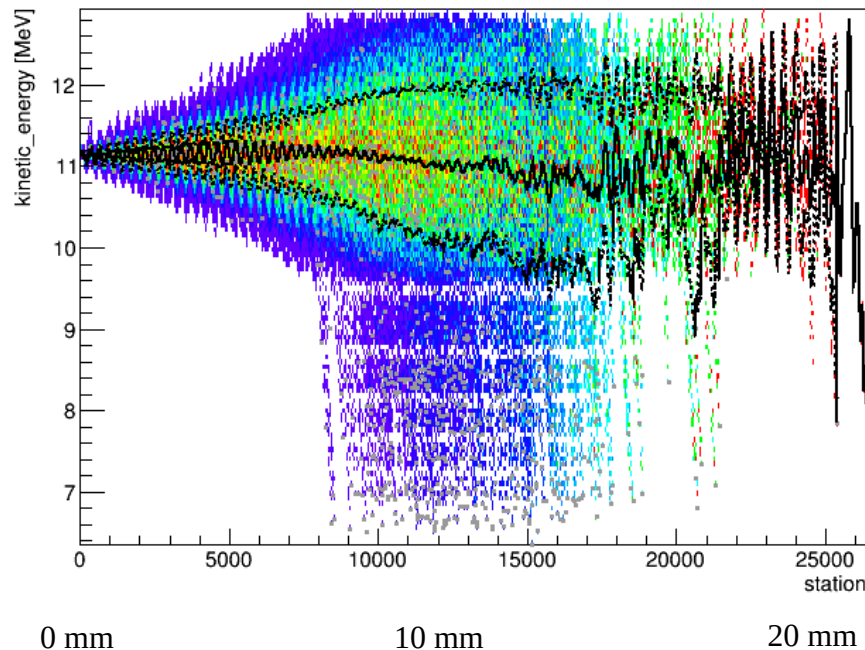
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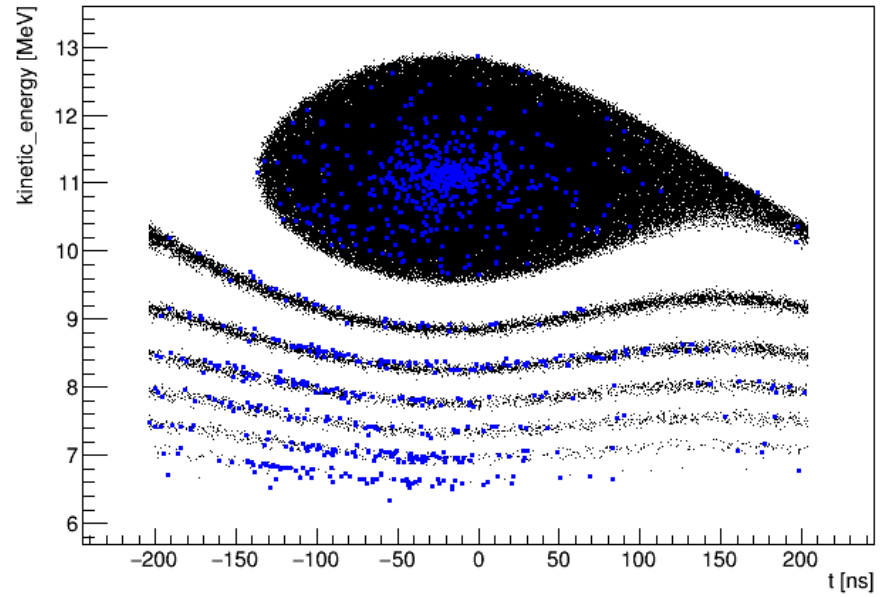
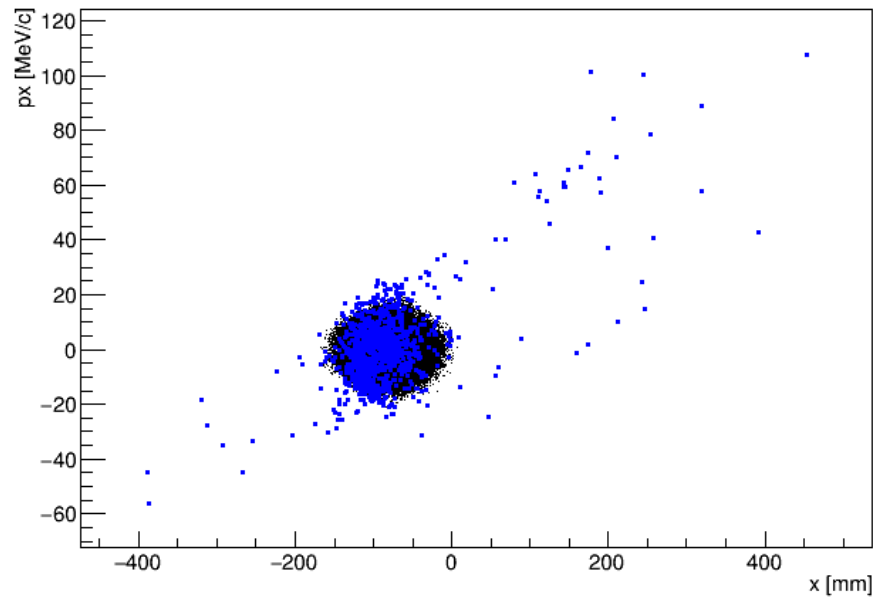


Full tracking



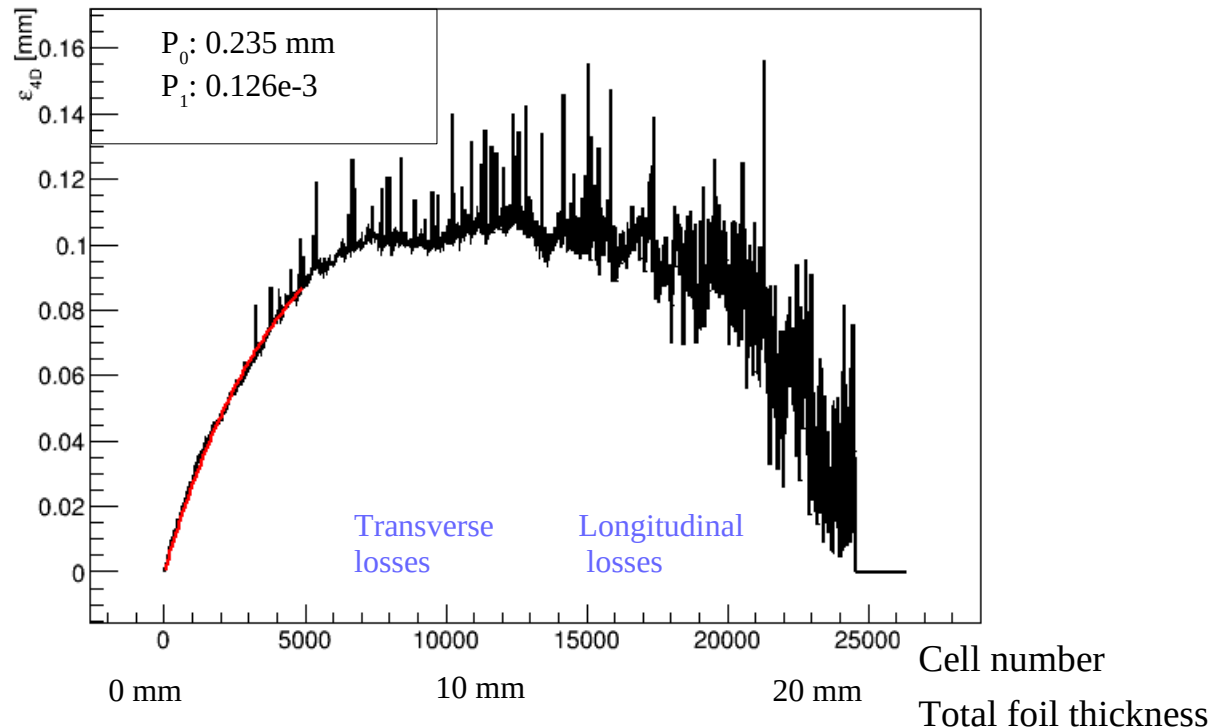
- Now add in the foil and RF
 - 12 stations = 10 micron foil and 250 kV
 - Start with 0 emittance beam (longitudinal and transverse)

Full tracking



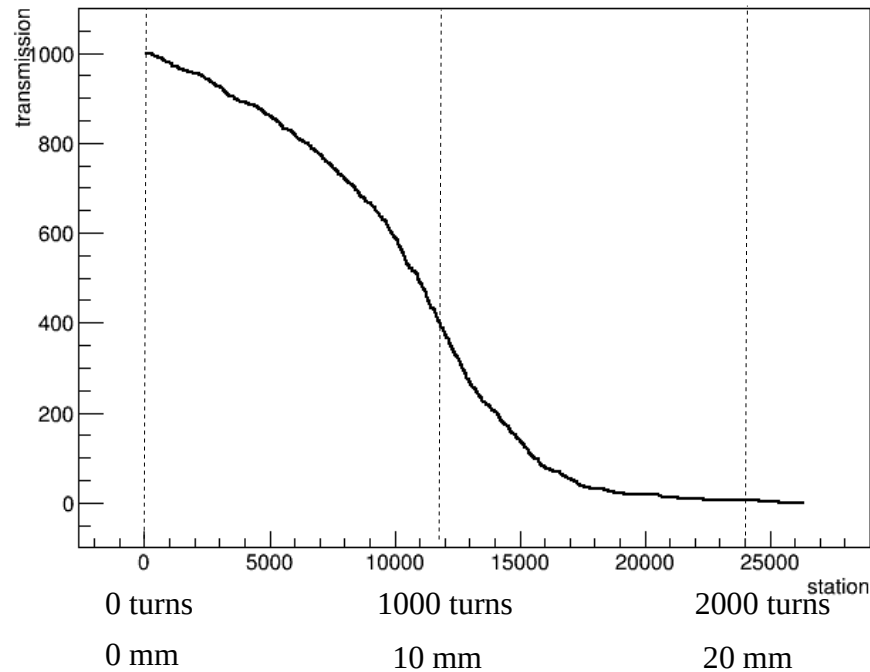
- Now add in the foil and RF
 - 12 stations = 10 micron foil and 250 kV

Transverse Emittance



- Fit to (s is station) using $\epsilon = p_0[1-\exp(p_1(s-s_0))]$
 - Associate emittance cut off to transverse loss
 - Associate emittance decay with longitudinal loss

Full tracking



- Why is there loss even at the very beginning?
 - High angle Coulomb scatters?
 - Hadronic interactions?



How well did we do?

- How well does such a ring test physics?
 - 4D and 6D cooling – okay; would be nice to get to smaller β
 - Novel optics
 - Tests “solenoid and dipole” optics
 - Does not test helical dipole optics
 - Bulk effects
 - Space charge – we should be able to get to space charge limit
 - Absorber degradation – we should be able to study windows/etc
 - Bulk ionization of material
 - spot size is $\sim 2000 \text{ mm}^2$, would like $\sim 1 \text{ mm}^2$
 - Beam-induced plasma loading in High Pressure RF
 - Can't put high pressure RF in this lattice
 - Specific engineering issues
 - Deal with in dedicated engineering prototypes



Stopping Target Proton Accelerators

- Most proton accelerators are used for secondary particle production
 - SNS, ISIS, ESS → neutron spallation (and muons)
 - PSI cyclotron, TRIUMF → muon production (and neutrons)
 - Proposals for radioisotope production
- Accelerate a very intense beam to high energies
- Stop the beam on a target
- Space charge effect is stronger at low energy
 - Accumulate beam at high energy or use CW beam
- Improve yield by using very high energy particles
- But:
 - Imprecise – all proton energies are present in target
 - Expensive – acceleration of protons to high energy requires challenging, multistage accelerators



Internal Target Model

- Recirculate protons through a thin target
 - Use RF cavities to re-energise the protons
- Precise choice of proton energy in the target
- More efficient use of protons
 - Lower currents required, fewer losses
 - Potentially large amplification of beam power
- Applications in
 - Neutron production
 - Energy amplifier
 - Isotope production
- Nice to have a shorter term goal



Conclusions

- A significant amount of work has been done to validate ionization cooling
- A few things left to check
 - But no expected physics problems
- Example test proton ring could be used to study
 - 6D cooling
 - Solenoid-dipole optics
 - Space charge effects
 - Long term stability of absorber material
- But can't study
 - Plasma loading in RF cavities filled with high pressure gas
 - Low emittance (optical beta) optics/cooling