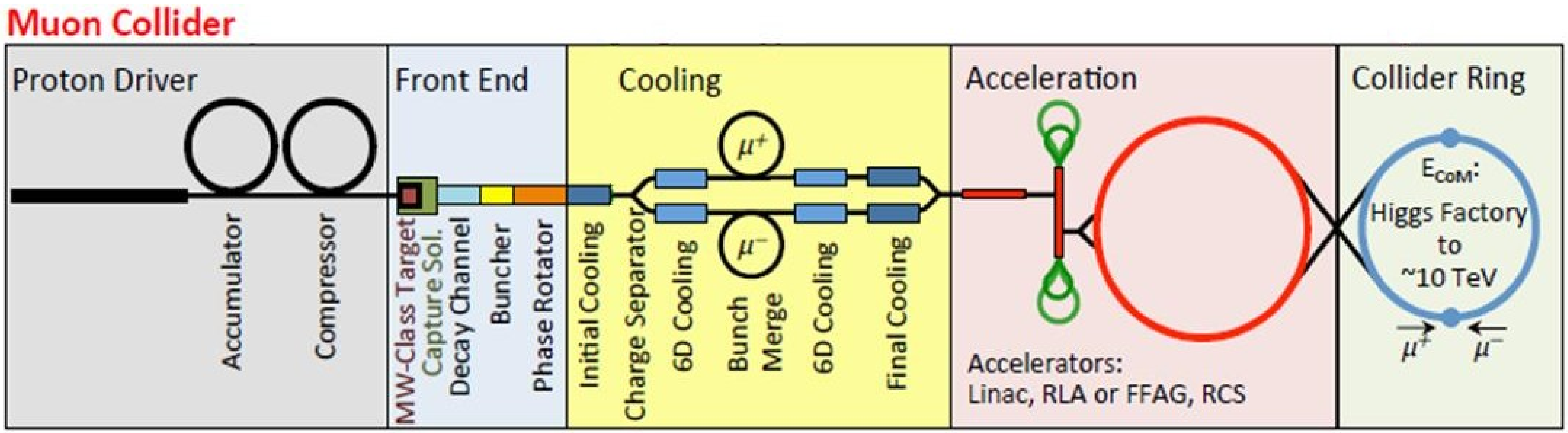
Ionisation Cooling and Demonstrator

C. T. Rogers
ISIS
Rutherford Appleton Laboratory

Muon Collider Facility

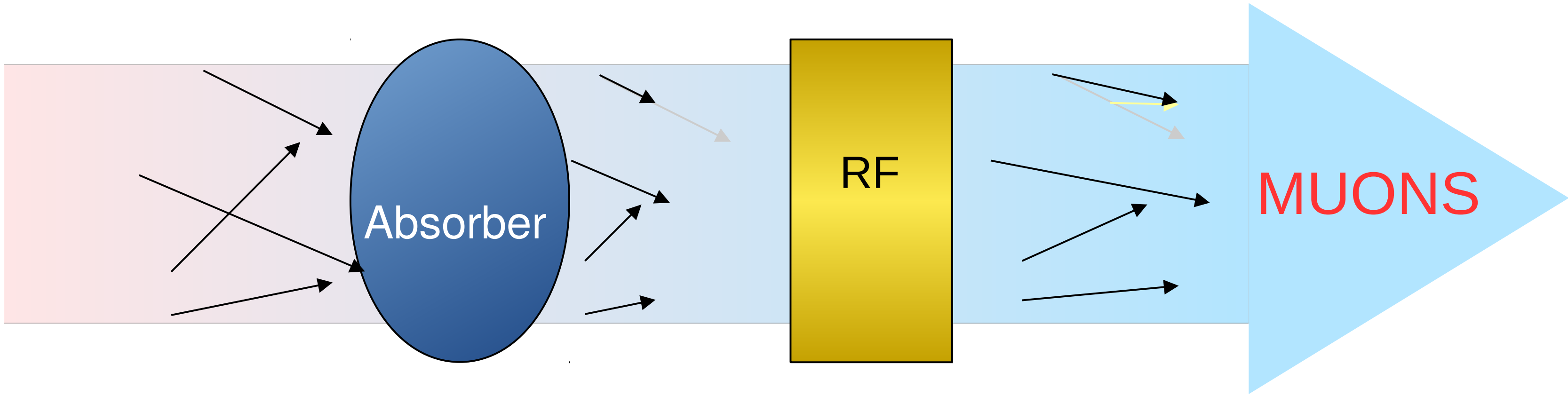


- Reminder – muon source:
  - Protons on target in high-field solenoid → pions, muons et al.
  - Clean up beam impurities
  - Capture muons longitudinally
  - Separate into positive and negative muons
  - Transverse and longitudinal “6D rectilinear cooling”
  - Bunch merge
  - More 6D rectilinear cooling
  - Transverse-only “final cooling”

Cooling priorities

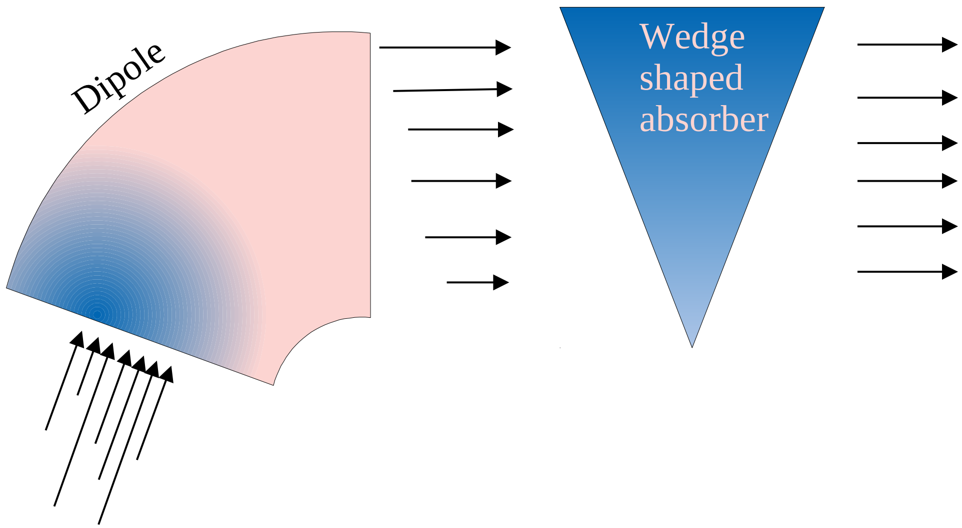
- Two areas identified as high priority
  - 6D cooling → seek to demonstrate experimentally
  - Final cooling → drives facility performance
- UK has leadership
  - Neutrino factory studies
  - MICE
- In particular, seek to deliver
  - 6D cooling
    - Leads to demonstrator facility design
  - Frictional cooling
    - Potential to tie in to ISIS muon production

4D Ionisation Cooling



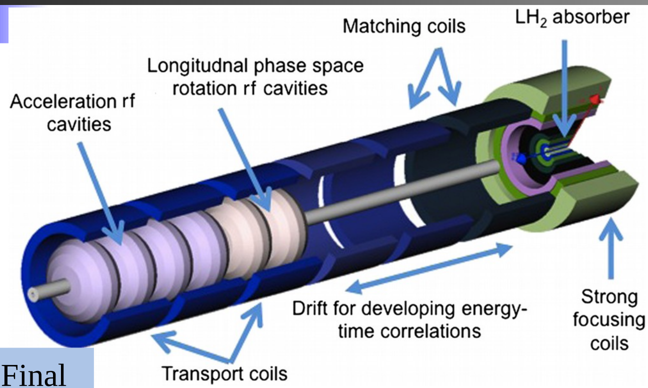
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate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

6D Ionisation Cooling

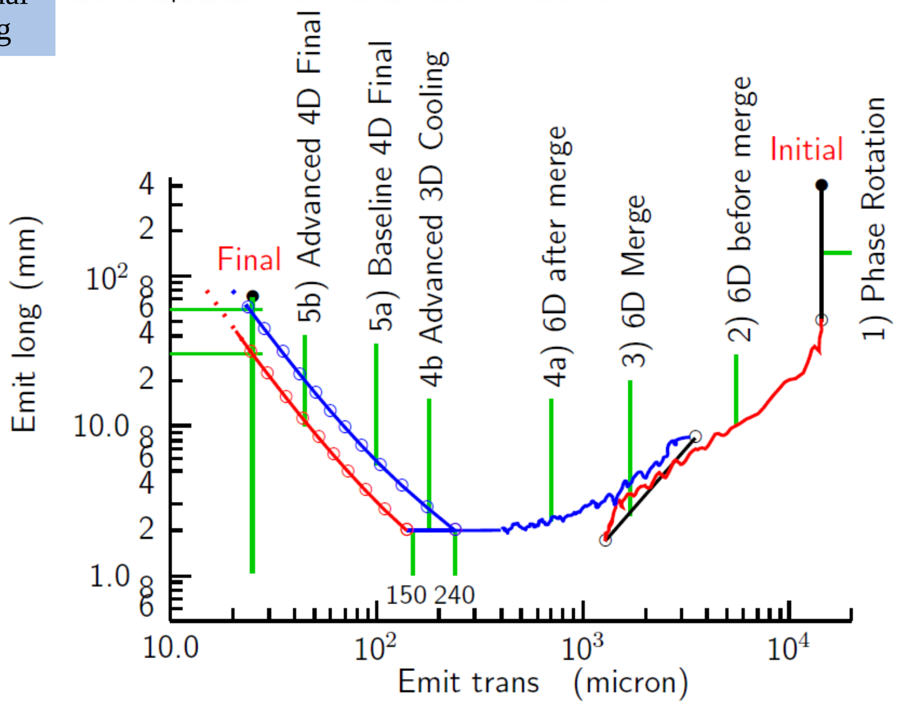


- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves wider with energy-position correlation
- Beam goes through wedge shaped absorber
  - Beam leaves wider without energy-position correlation
  - High transverse emittance and low longitudinal emittance

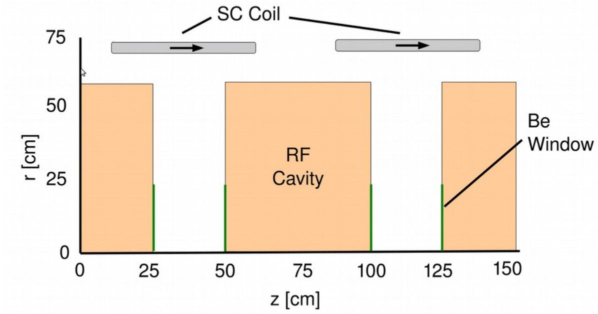
Muon Cooling



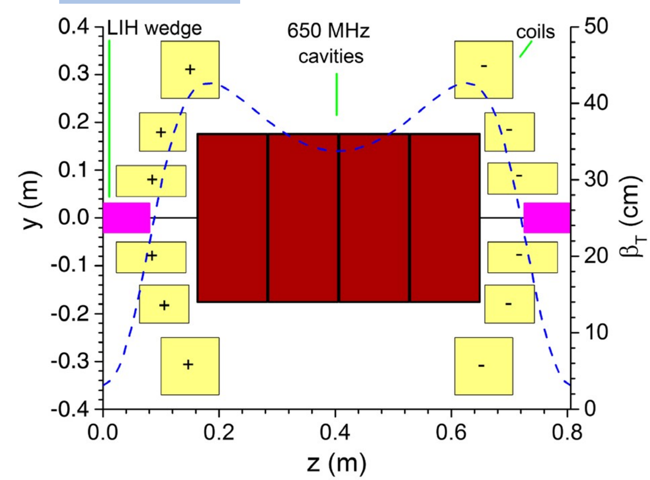
4D Final cooling



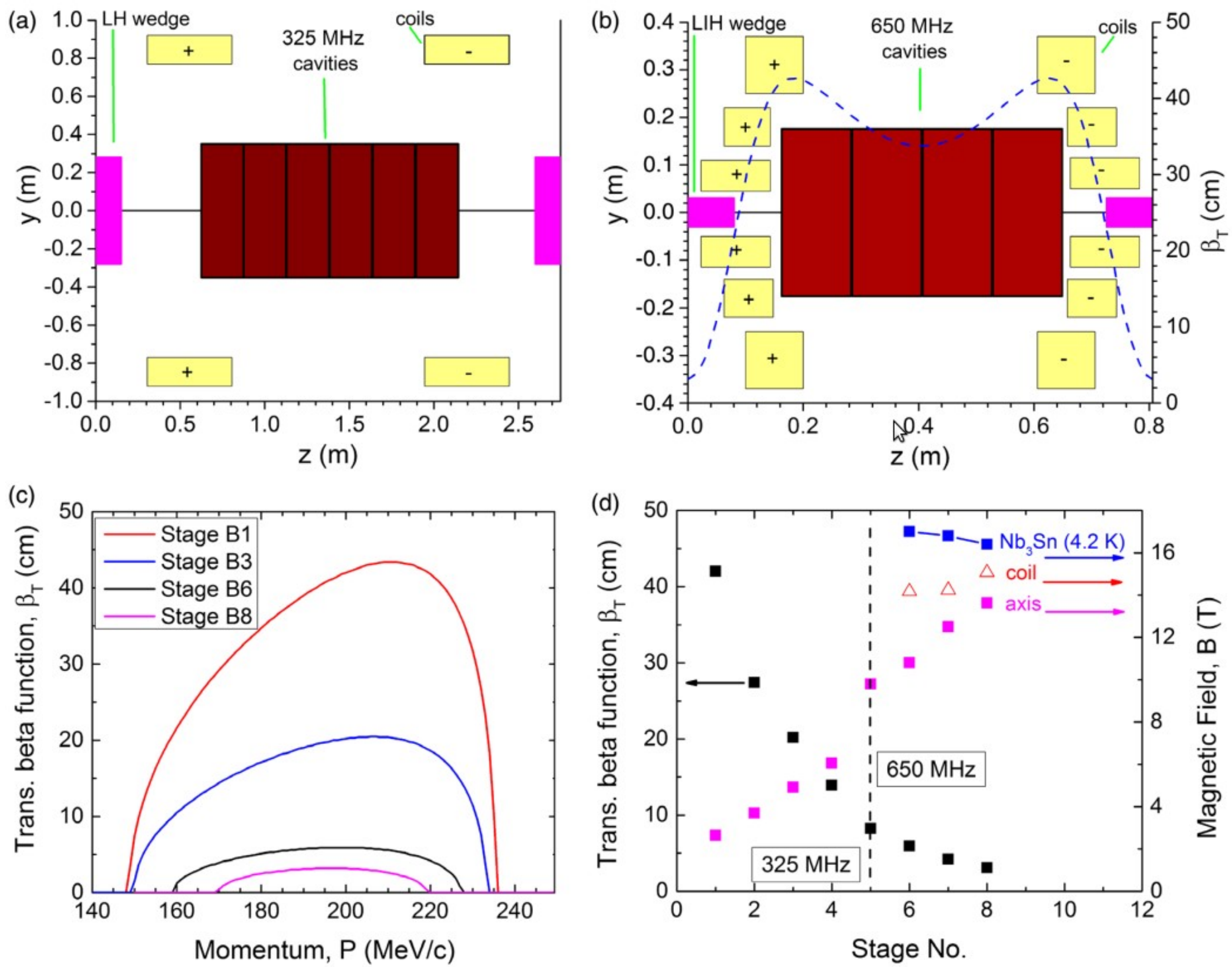
Phase rotation



6D cooling



6D Cooling (MAP)



- Needs integration with the overall muon source scheme
- Needs further optimisation (e.g. matching not well-done)

Cooling Demonstrator - Aims

- Headlines
  - Demonstrate 6D Cooling
  - Demonstrate reacceleration
  - Demonstrate cooling at low emittance
- Other things to look at:
  - Engineering integration
  - Demonstrate high-gradient RF cavity in magnetic field
  - Beam optics understanding
  - Integration of high-field magnets and short cells
  - Absorber infrastructure, potentially lH2
  - Matching into cooling cells
  - Vacuum
  - Alignment and correction
- To support this
  - Target and collimation work
  - Beam diagnostics with potentially low muon rate

Cooling Demonstrator - Studies

- Starting to do optics layout
  - Collimation system
    - Consider compatibility with nuSTORM
  - Cooling

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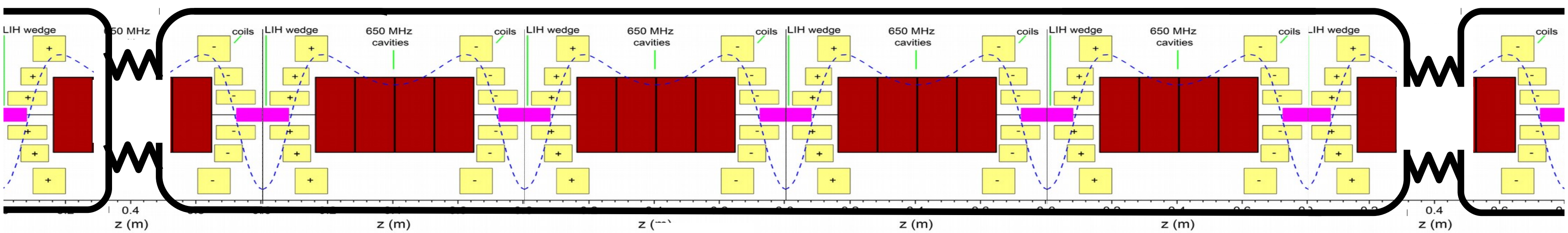
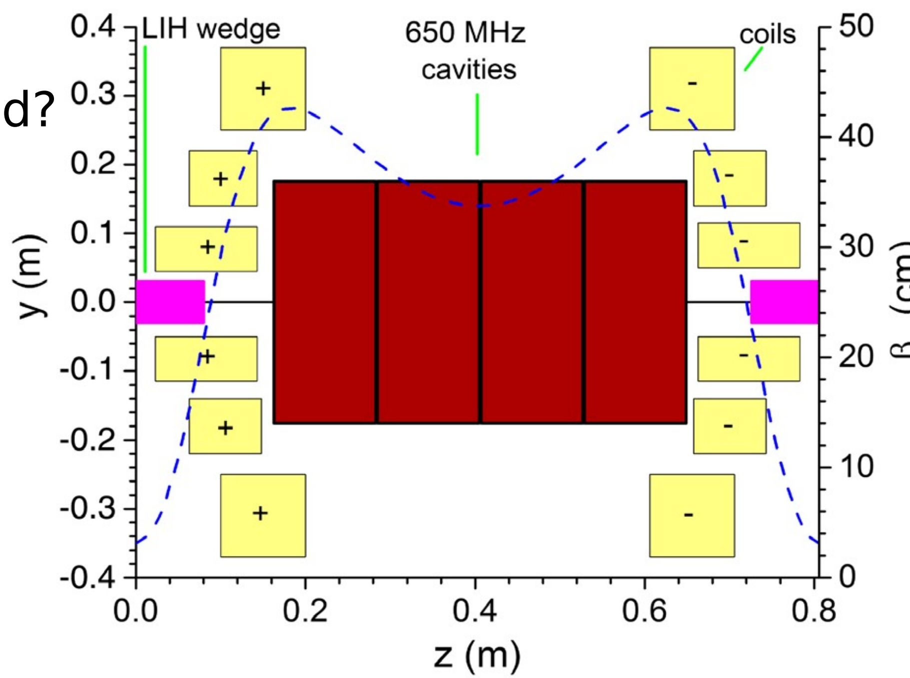
Cooling channel concept

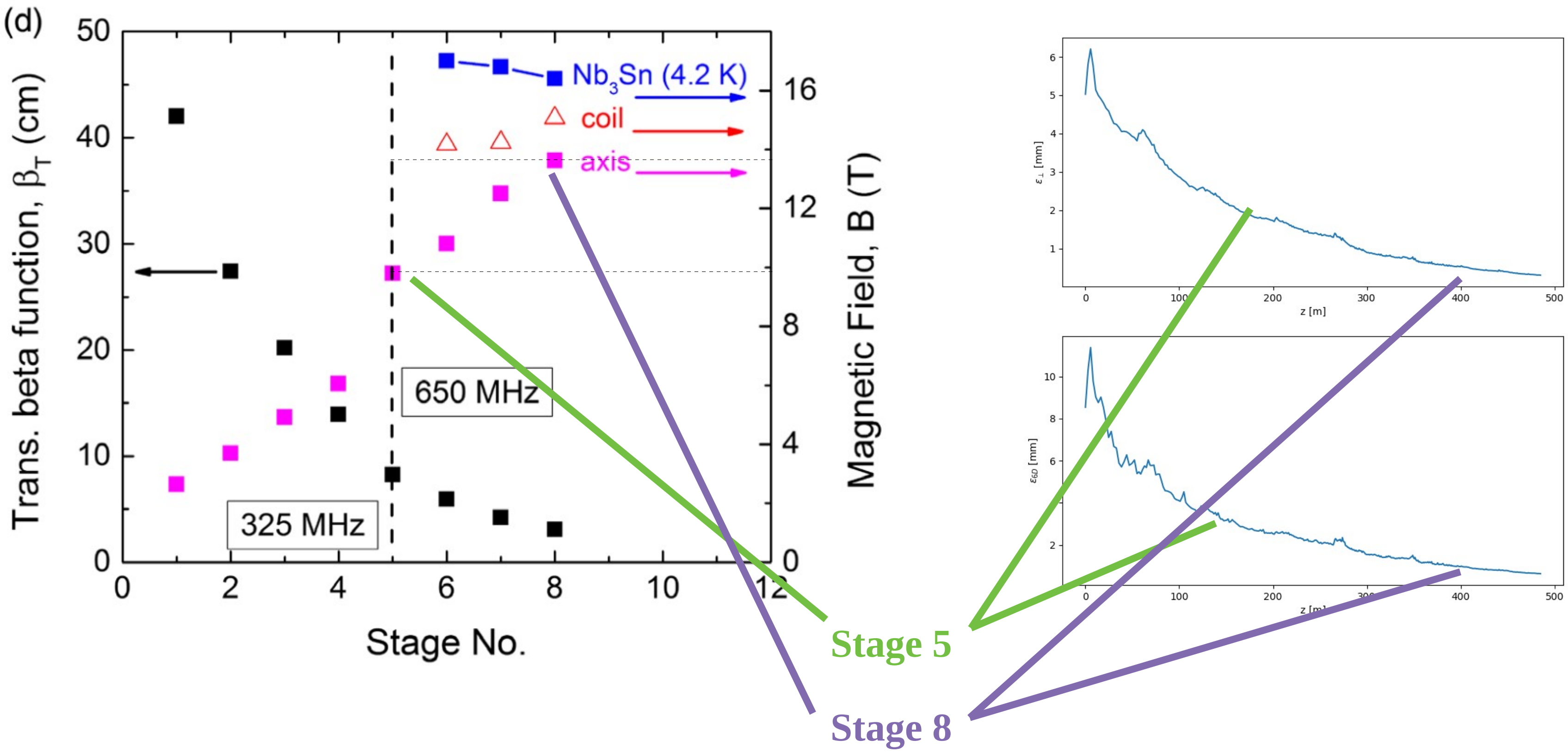


- Ongoing discussion:
  - What should be the peak field?
  - Lowest emittance @ 13 T
  - ~9 T may be cheaper
    - It is an MRI field
  - Needs consideration
- Plan for ~ 10 cryostats
  - Each containing ~ 5 cells
- Lattice well-established
  - Needs optimisation
  - Needs modification/engineering



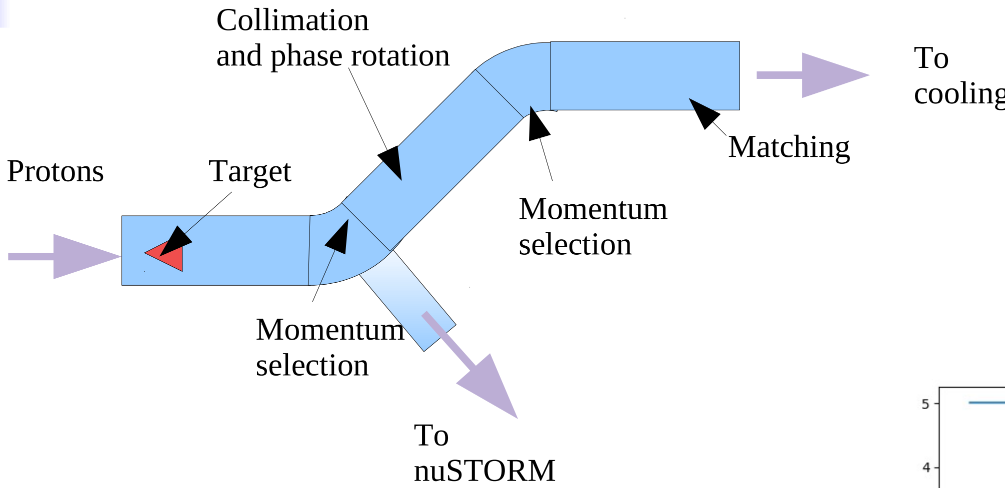
D. Stratakis et al

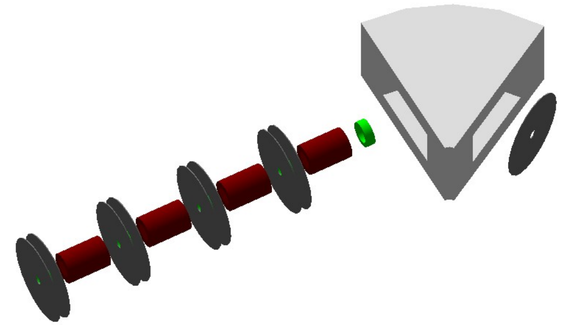
6D Cooling performance



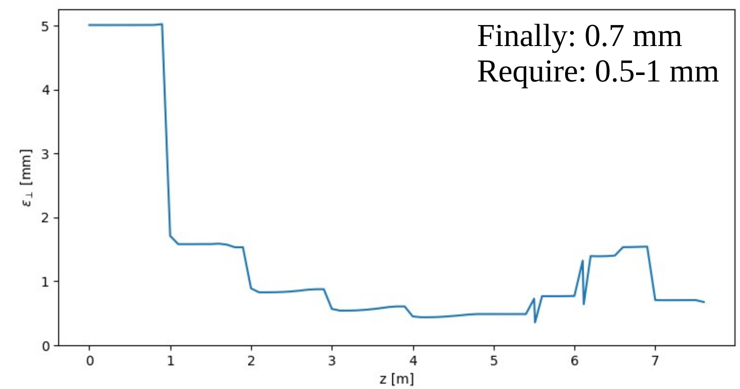
- Collimation system requirement
  - Emittance ~ 0.5 – 2 mm transverse
  - Emittance ~ 2 – 4 mm longitudinal (650 MHz RF)
- Matching (not studied yet)

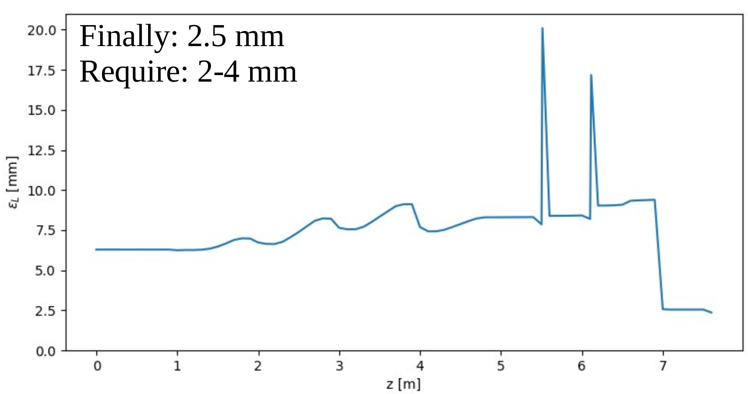
Collimation System Layout





- Concept
  - Dipole to do a first momentum selection
  - Collimation and RF to do phase rotation
  - Second dipole to do a second momentum selection





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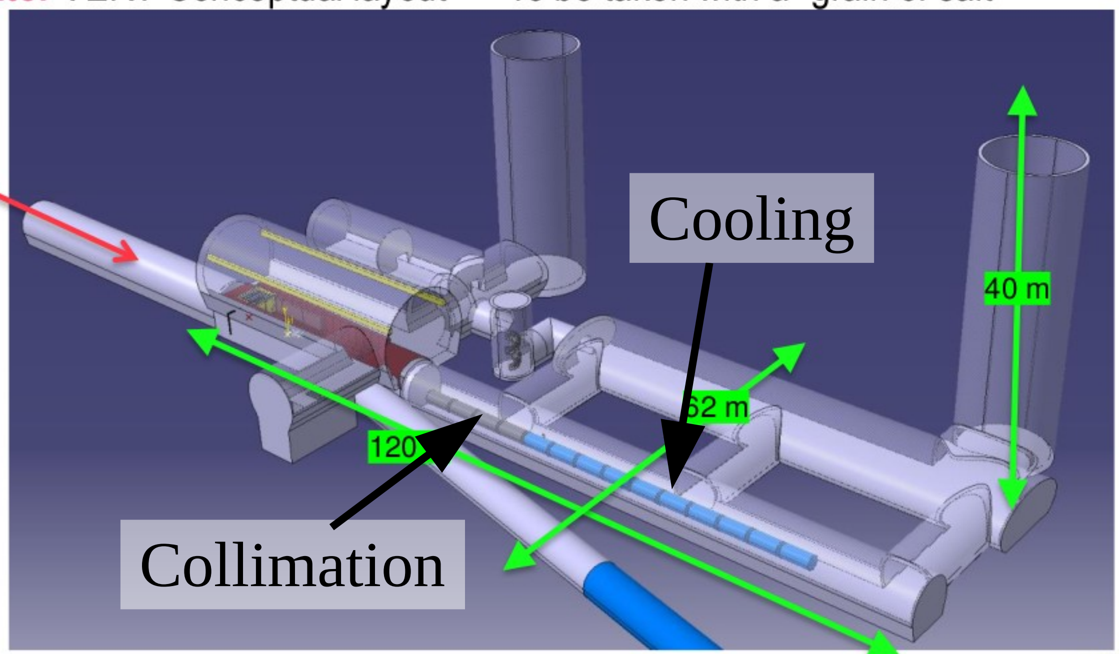
Overall layout - Rui Ximenes (CERN)

International MUON Collider Collaboration

Issues:
Large cavern
Challenge to deliver services
Near-surface solution under investigation

MUC Demonstrator VERY Conceptual layout → To be taken with a “grain of salt”

CERN TT10 branch



Indicative dimensions. Model is very flexible at this stage

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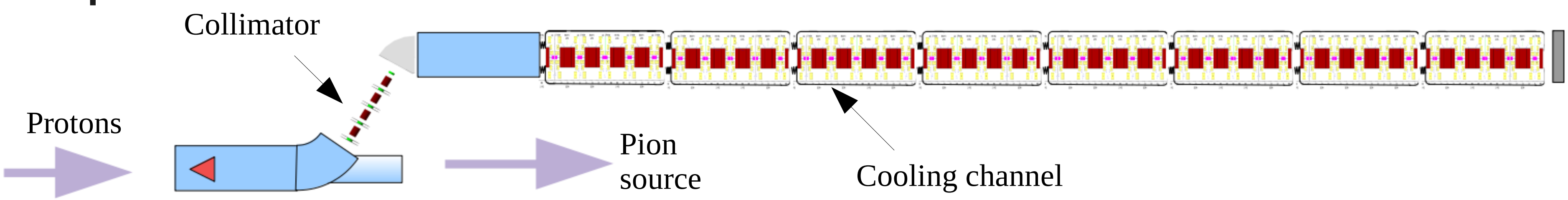
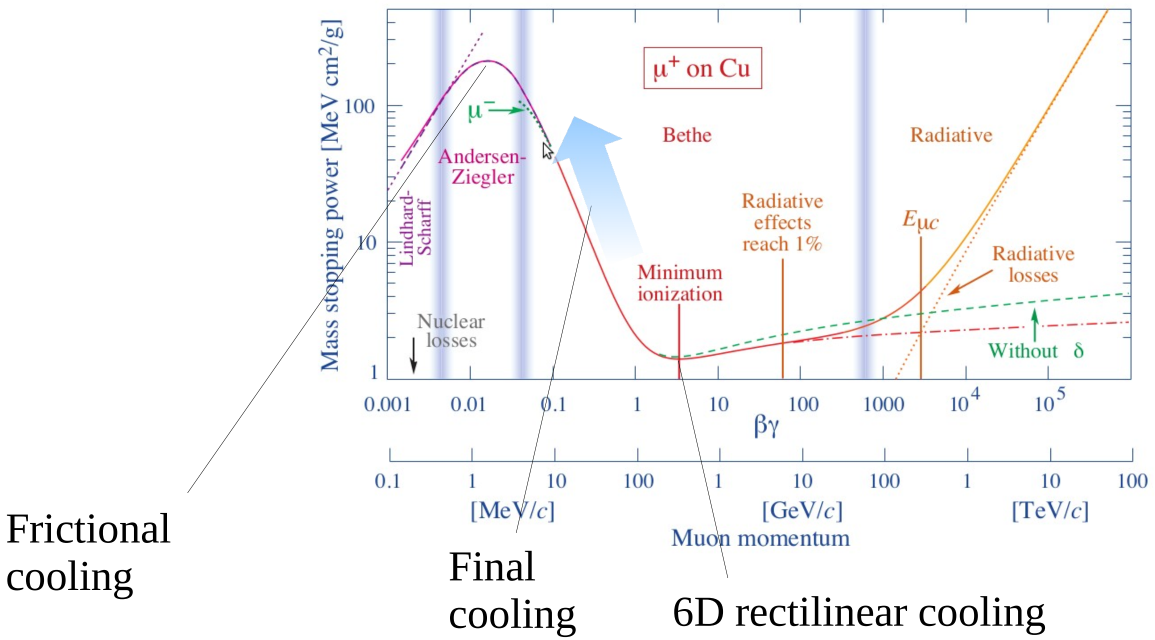
Plans



- Hope to deliver baseline layout and performance estimates
- Look at options
  - How much can we test different optics?
  - How much can we test different hardware (absorbers, etc)?
  - Diagnostics (INFN)
- RF test stand (Saclay)
  - Demonstrate high RF gradient in magnetic fields
  - Saclay has RF power but needs large bore magnet
    - Potential to use MICE focus coil magnet?
- Prototype cooling test stand

Frictional Cooling



- Final cooling scheme works at low energy
  - More focusing → better transverse cooling
  - Longitudinal emittance growth → heating
- Frictional cooling can get better focusing without emittance growth
- Frictional cooling can be valuable for muon production at ISIS

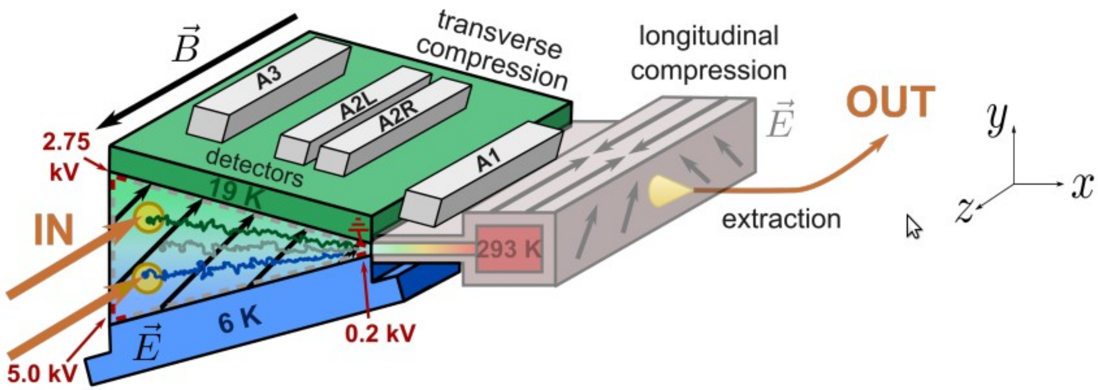
Frictional Cooling

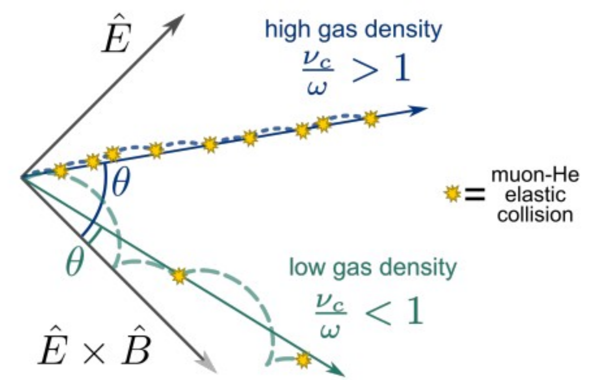
- Advantages
  - Reduction in energy spread appears naturally
  - Extremely strong focussing available even for conventional magnet fields

$$\varepsilon_{N,\min} \cong \frac{\beta_T (E_s)^2}{2 g_t \beta m_\mu c^2 L_R \left(dE_\mu / ds\right)}$$

- Challenges
  - Energy acceptance – less than 1 MeV
  - Manage time spread of beam
    - Non-relativistic
  - Any scheme must maintain transverse acceptance
  - Manage muon decays
- Previously looked at in terms of muon collider – but not in combination with full cooling scheme (as far as I can tell)
  - This would make a good “final cooling” system

PSI scheme





- Transverse emittance reduction arrangement
  - In vacuum → cycloidal motion
  - In material → motion towards middle of device
- PSI planning to implement this scheme for their muon beamline
  - ISIS muons also interested
- Note other schemes have been proposed

Taqqu, PRL, 2006
Papa et al, PRL, 2014
Papa et al, PRL, 2020

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Frictional Cooling

- Open questions (muon collider)
  - Does the PSI scheme yield sufficient acceptance?
  - Can it be adapted to increase acceptance?
  - Can it give a short pulse of muons suitable for reacceleration?
- Open questions (ISIS)
  - Is the efficiency good enough?
  - Does it generate too long pulse for ISIS?
- We should investigate
  - We should exploit the synergy!

Conclusions

- Fantastic opportunities in the muon cooling area
- Take leadership for the muon cooling demonstrator
  - Deliver optics layout
  - Participate in RF test programme
    - Loan of MICE focus coil would be a cheap way to contribute
  - Eventually, help build prototype demonstrator cells
  - Can share a muon source with nuSTORM
- Develop frictional cooling
  - Great opportunity to work with ISIS
  - Can be a “game changer” for the muon collider