A Demonstrator for Muon Cooling

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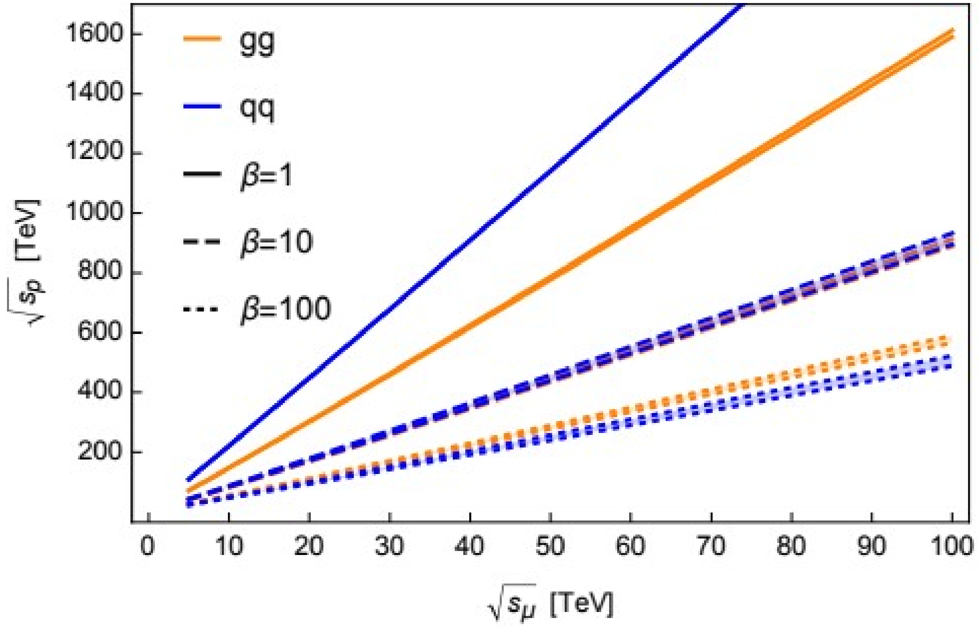
Muon collider

- Significant interest in the Muon Collider as an Energy Frontier Facility
- Needs ionisation cooling
- Transverse cooling at high emittance demonstrated by MICE
- Now need to follow up with 6D cooling at lower emittance
- What could such a Demonstrator look like?
- Where could it be sited?
- How does it fit into the muon – and neutrino – programme?

Muon collider



- Muon collider has enormous potential
  - Muons are fundamental particles → energy *per parton* >> proton beam at same energy
  - Muons are high mass → recirculate muons without synchrotron radiation
- Compared to other energy frontier colliders
  - Luminosity increases as E^2 → great potential at multi TeV scale
  - Compact
  - Low wall-plug power

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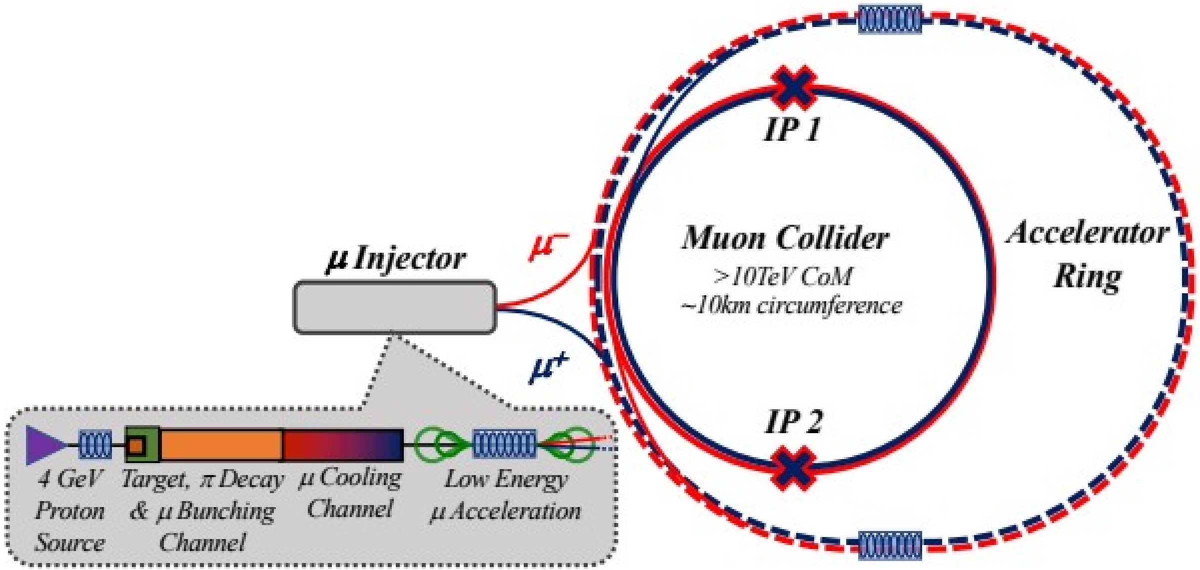
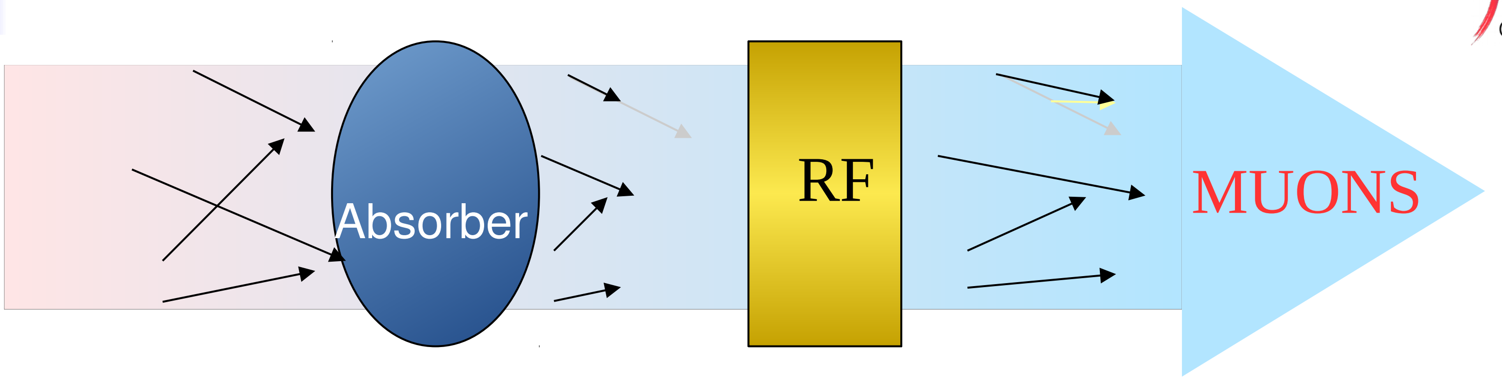
Muon collider facility



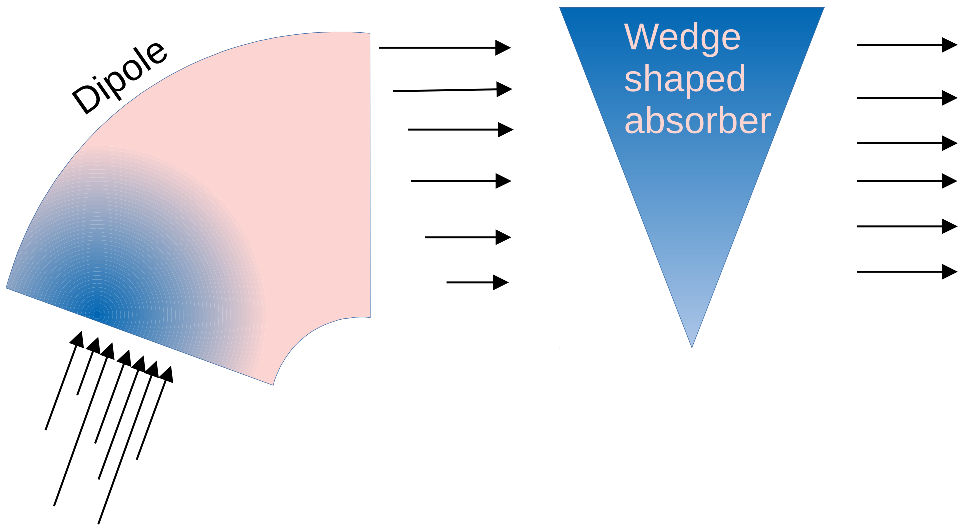
- Proton driver → target
- Cooling
- Acceleration + collisions
- Cooling on time scale of muon lifetime is challenging
  - Ionisation cooling is proposed technique
  - 4D cooling demonstrated by MICE
  - Now need to go to the next step – but how?

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 parallel
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing → low β
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS cancels the cooling
- Verified by the Muon Ionisation Cooling Experiment (MICE)

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 dipole 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
- Tests done at Fermilab

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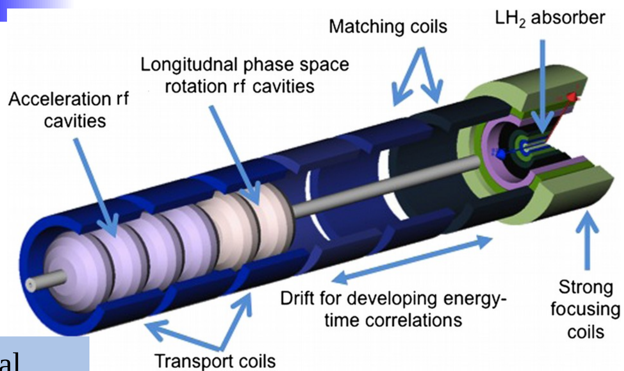
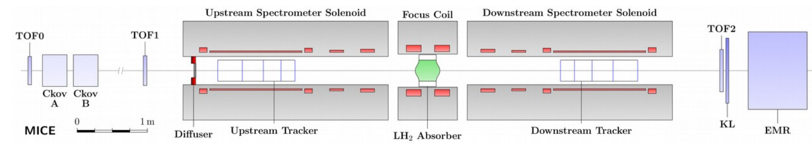
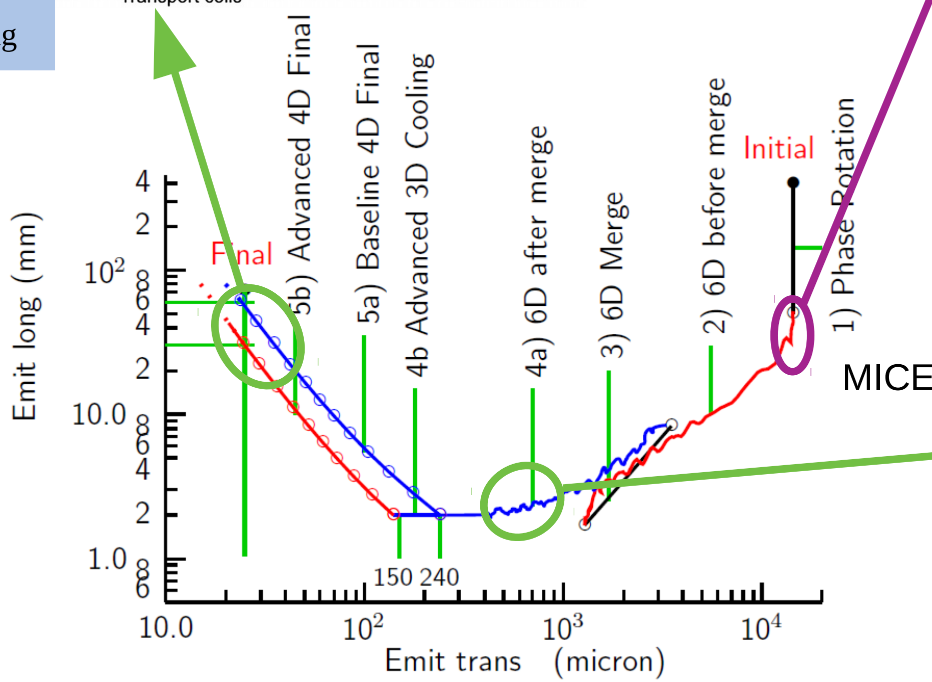
Cooling for a Muon Collider



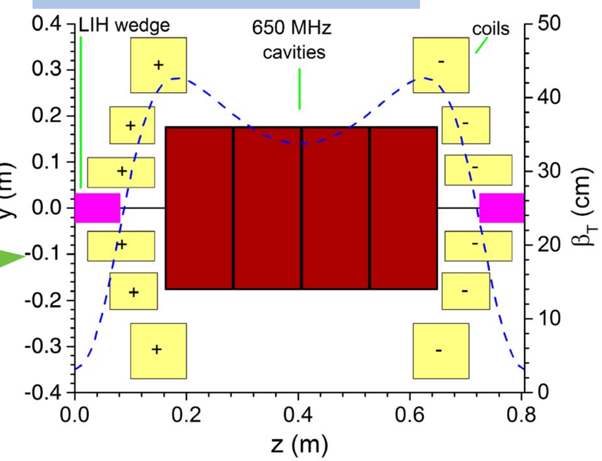
Final cooling



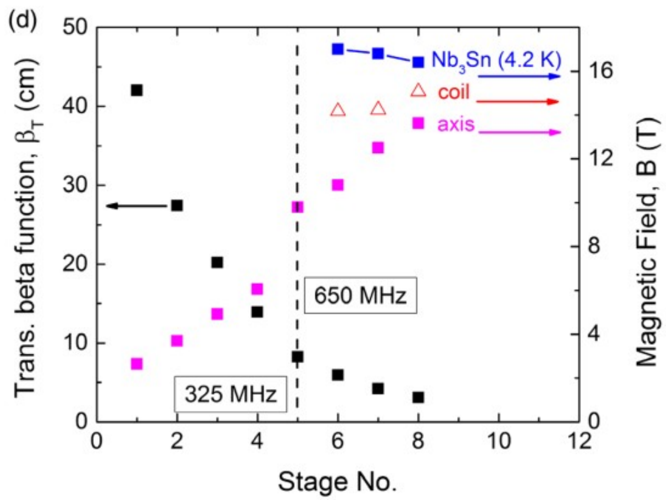
"MICE-like"

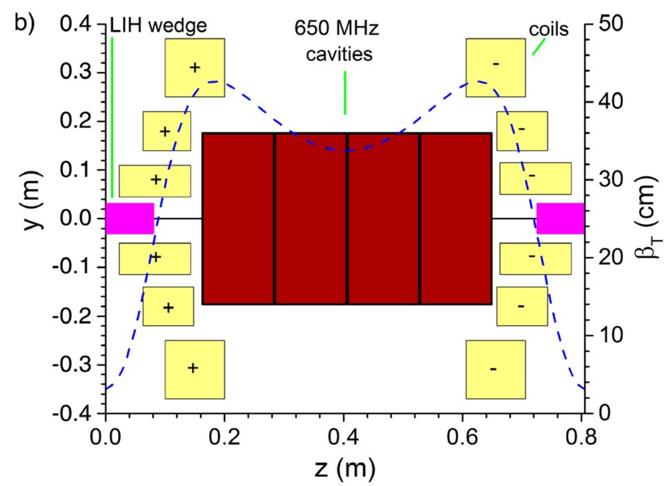


Rectilinear B (Stage B8)



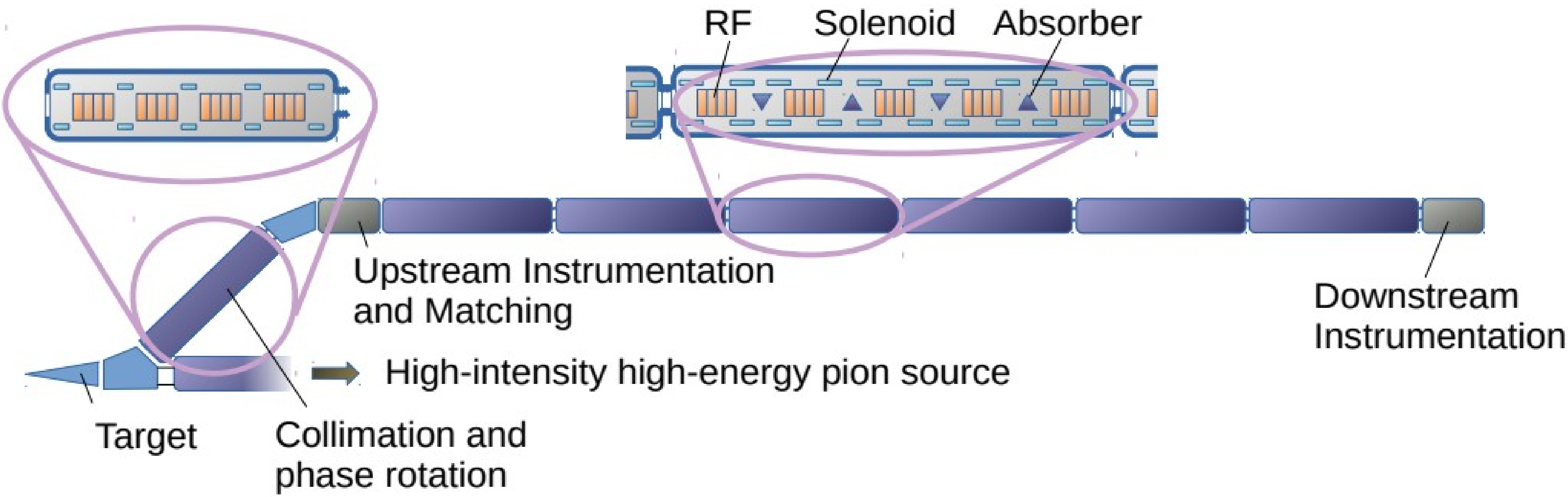
Rectilinear Lattice (Stratakis et al)





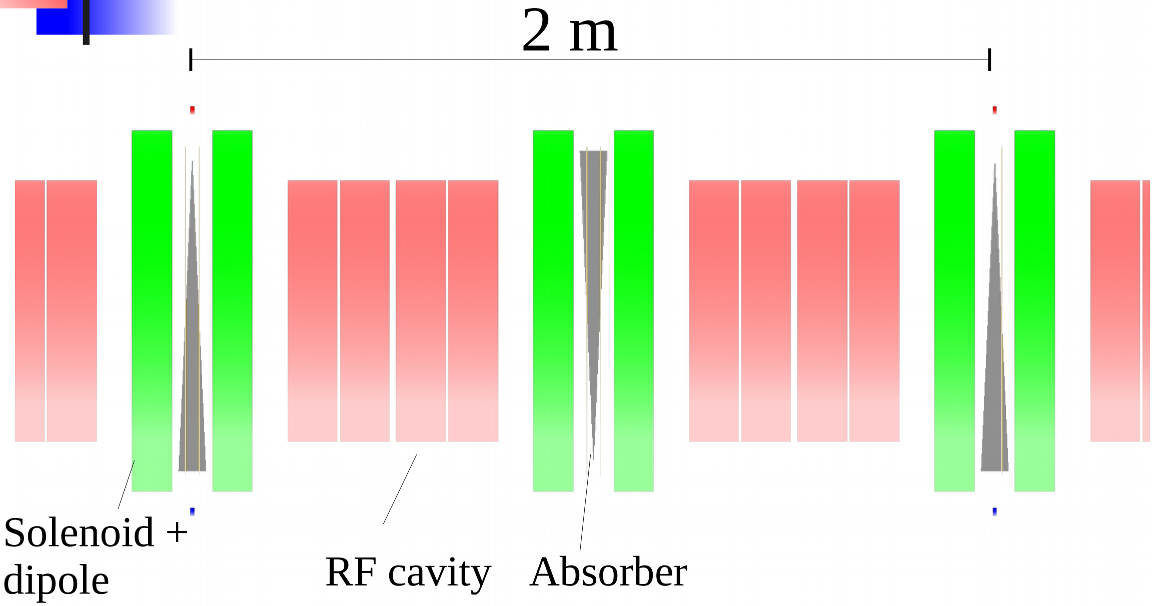
- Challenges
  - Dispersion and closed orbit control for 6D cooling
  - Successful RF operation and suppression of RF breakdown
  - Maintaining adequate acceptance between stop bands
  - Magnet engineering
  - Integration of magnet with RF and absorber
  - Day-to-day operation and instrumentation
- Also intensity/collective effects → proton beam test?
  - Space charge, beam loading, absorber/RF window heating
  - Decay radiation load on magnets

Layout

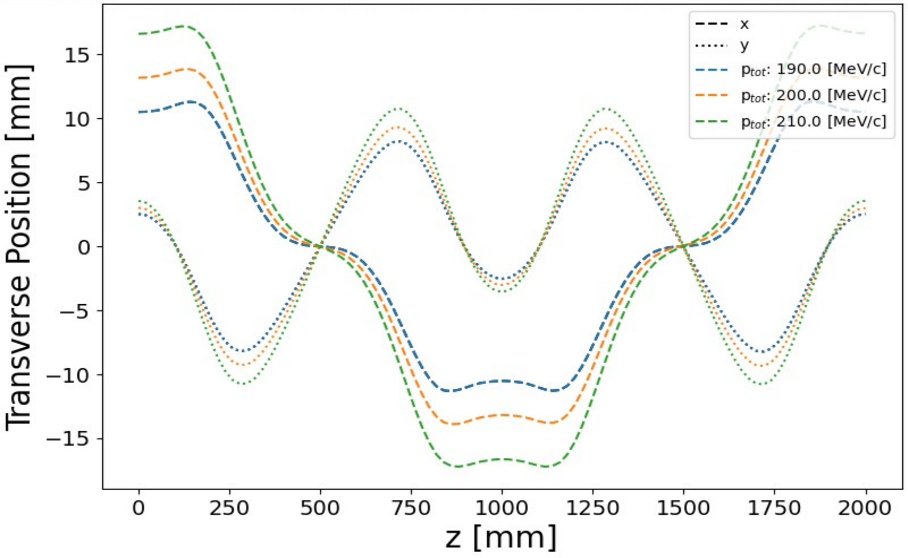


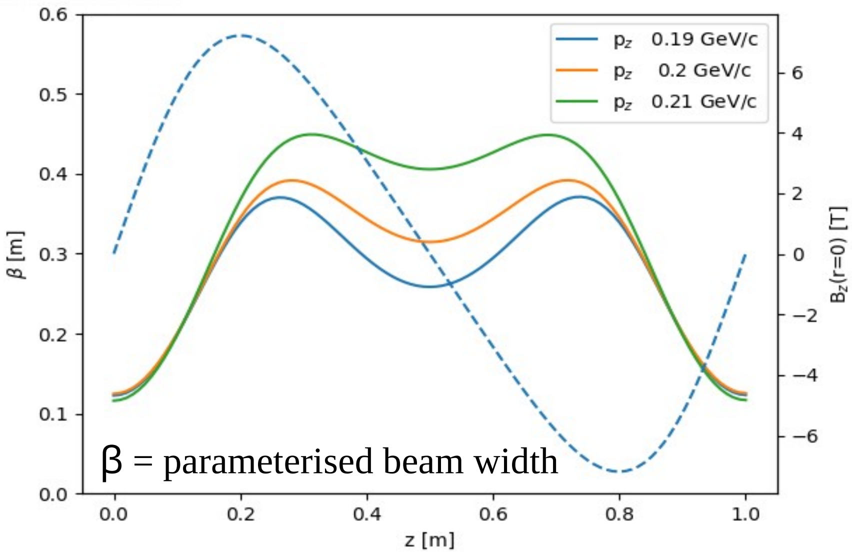
RF
Solenoid
Absorber
Upstream Instrumentation and Matching
Downstream Instrumentation
High-intensity high-energy pion source
Target
Collimation and phase rotation

Preliminary Cooling Cell Concept



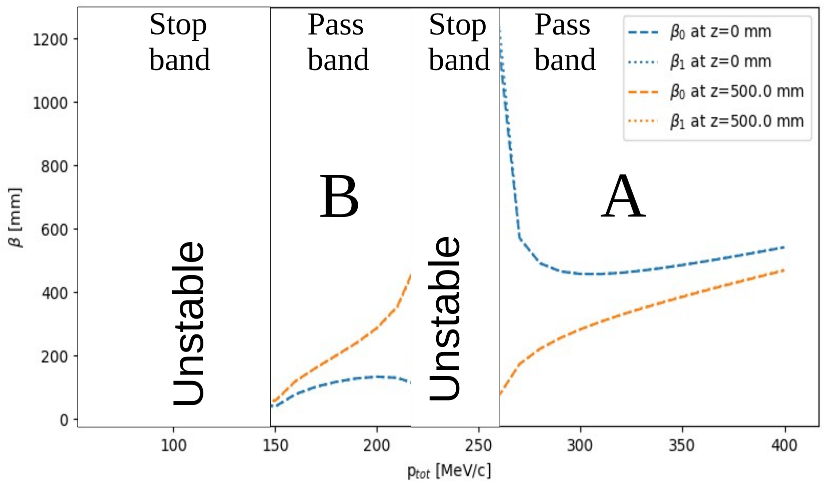
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

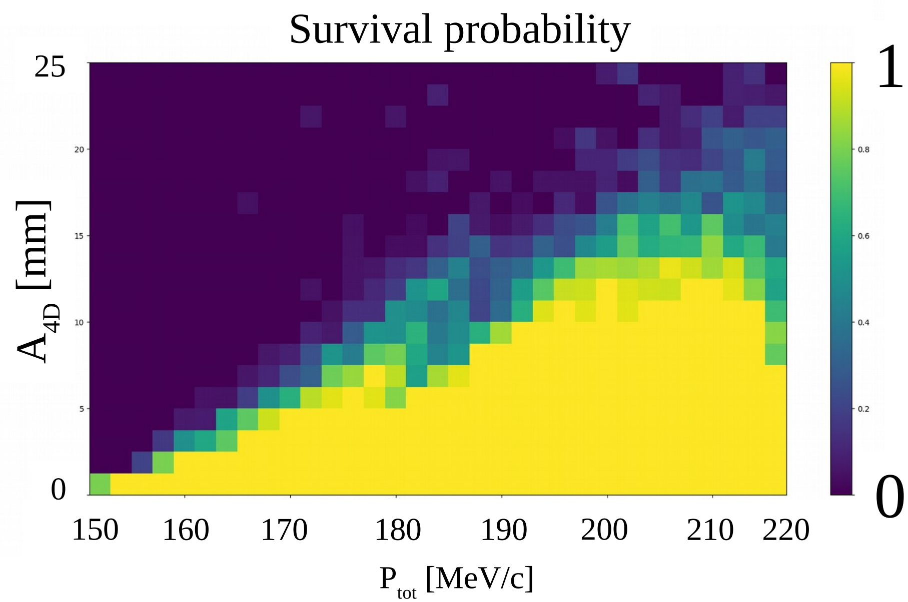




Optics vs momentum

- Operation in area **A**
  - High dynamic aperture
  - Larger β
  - Larger emittances
- Operation in area **B**
  - Lower dynamic aperture
  - Smaller β
  - Lower emittances
- Lattice operates in area **B**
  - May wish to check out area A also





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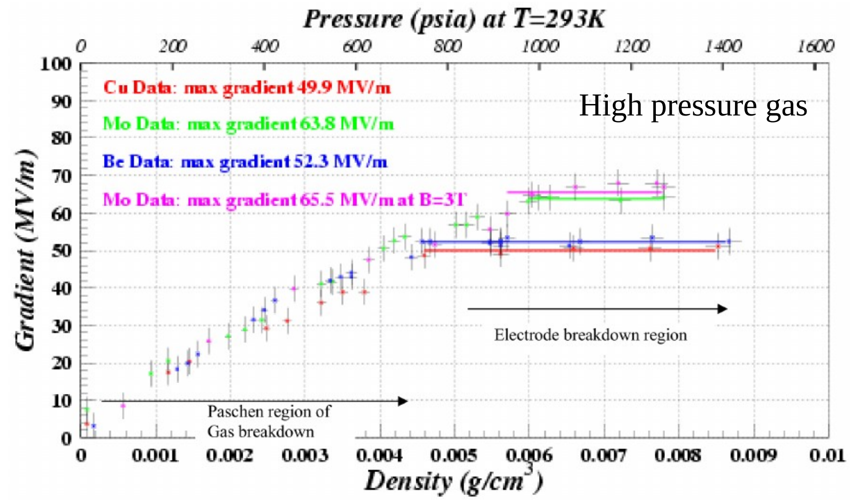
Integration issue: RF

- B-fields reduce RF Safe Operating Gradient (SOG)
  - e^- emitted from copper
  - B-field focuses on far wall
  - Induces sparks
- Muon cooling needs high RF gradient + B-field
- Two routes demonstrated
  - Either: Beryllium window resistant to damage
  - Or: High-pressure gas absorbs spark
- Other ideas
  - Operate at lN2 temperature
  - Short RF pulse to limit heating

Window material	B-field (T)	SOG (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$
Be/Cu	0	43.9 ± 0.5
Be/Cu	3	10.1 ± 0.1

Bowring et al



Yonehara et al

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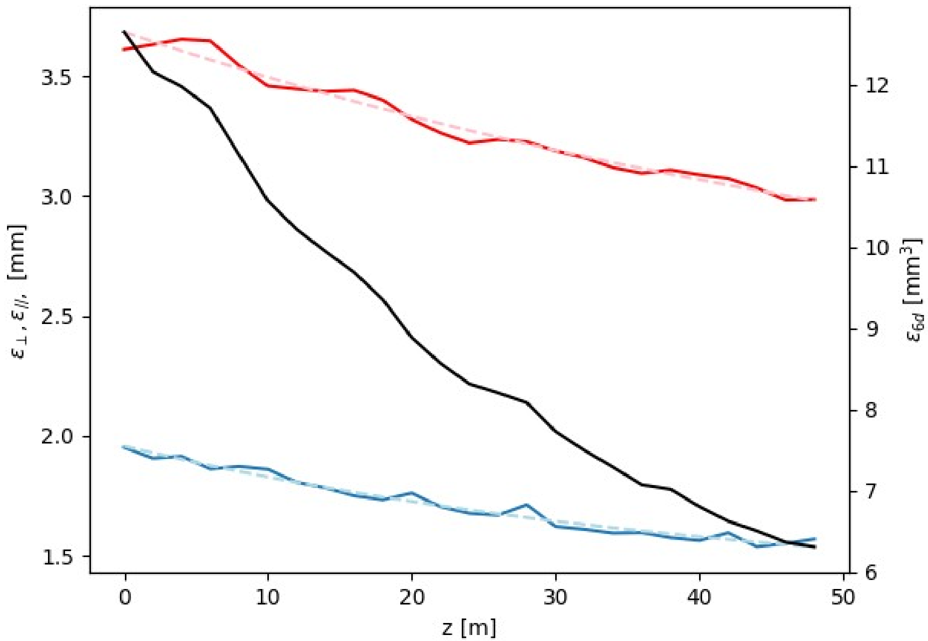
Performance

- Good cooling performance
  - Transverse and longitudinal emittance reduced by ~ 20 %
  - Approx factor two reduction in 6D emittance
- Optimisation ongoing
- Assumes perfect matching for now



Transmission losses	2.00%
Decay losses	4.00%
Trans ε in	1.95 mm
Trans ε out	1.57 mm
Long ε in	3.61 mm
Long ε out	2.99 mm
6D ε in	12.7 mm^3
6D ε out	6.3 mm^3

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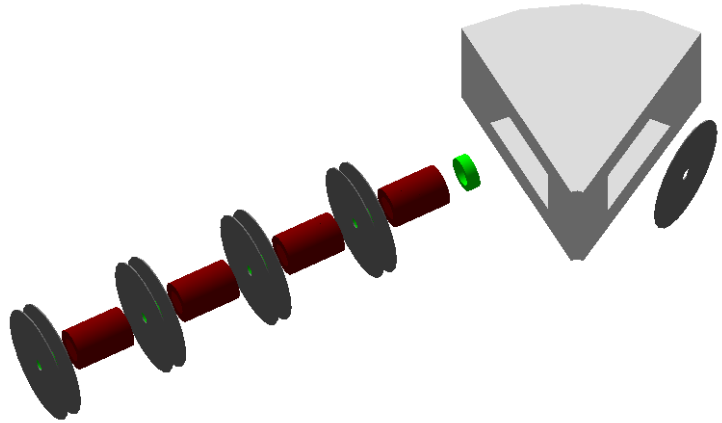
Beam preparation system

- ~ 100 ps pulsed muon beams don't exist
  - Muons have never been accelerated in conventional RF cavity
  - Low emittance muon beam challenging to achieve
- Need to consider a system to prepare the muon beam
  - Assume momentum collimation in switchyard
  - Transverse collimation
  - Longitudinal phase rotation



Beam Preparation System

Parameter	Value
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

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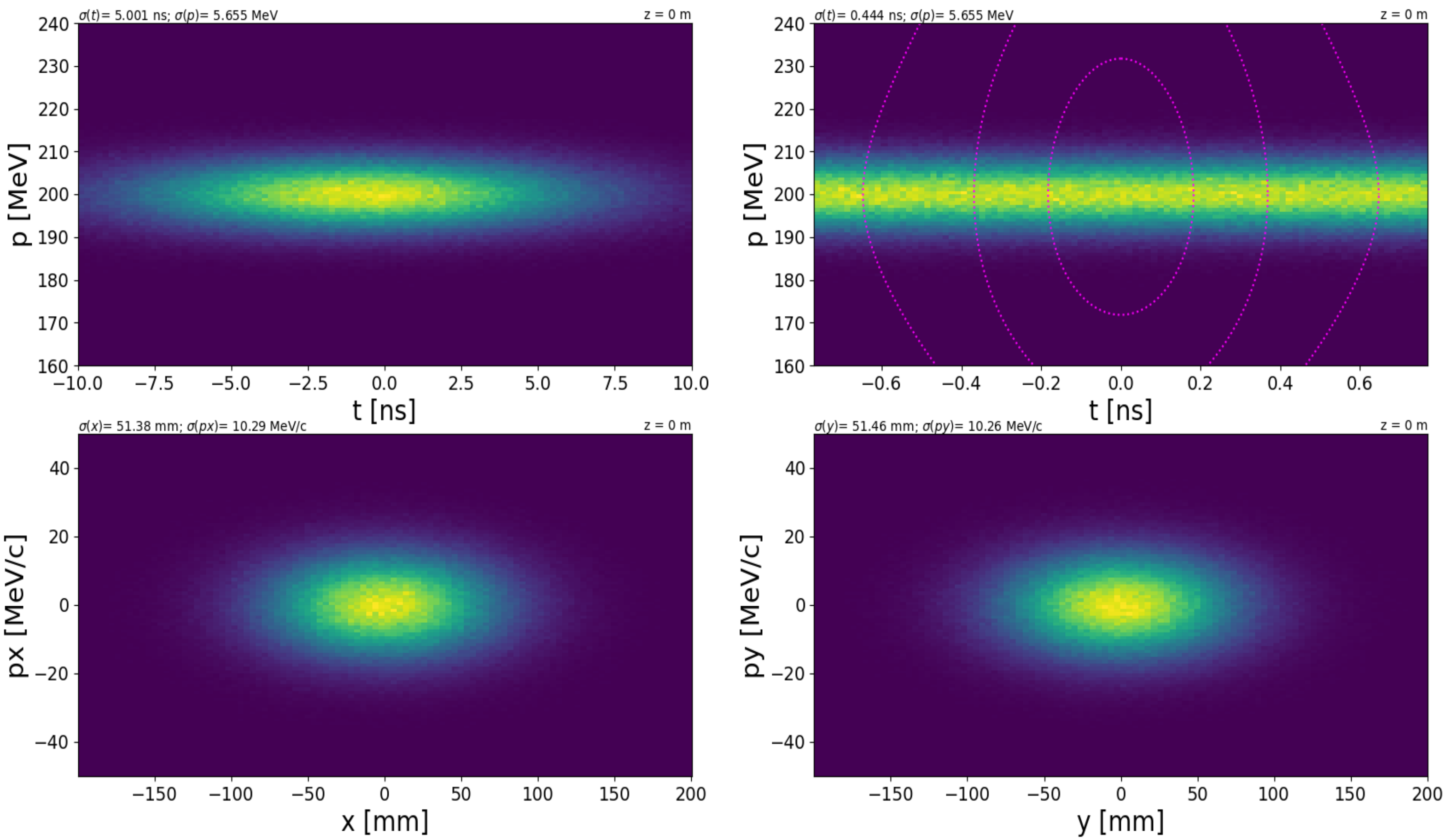
Beam preparation system



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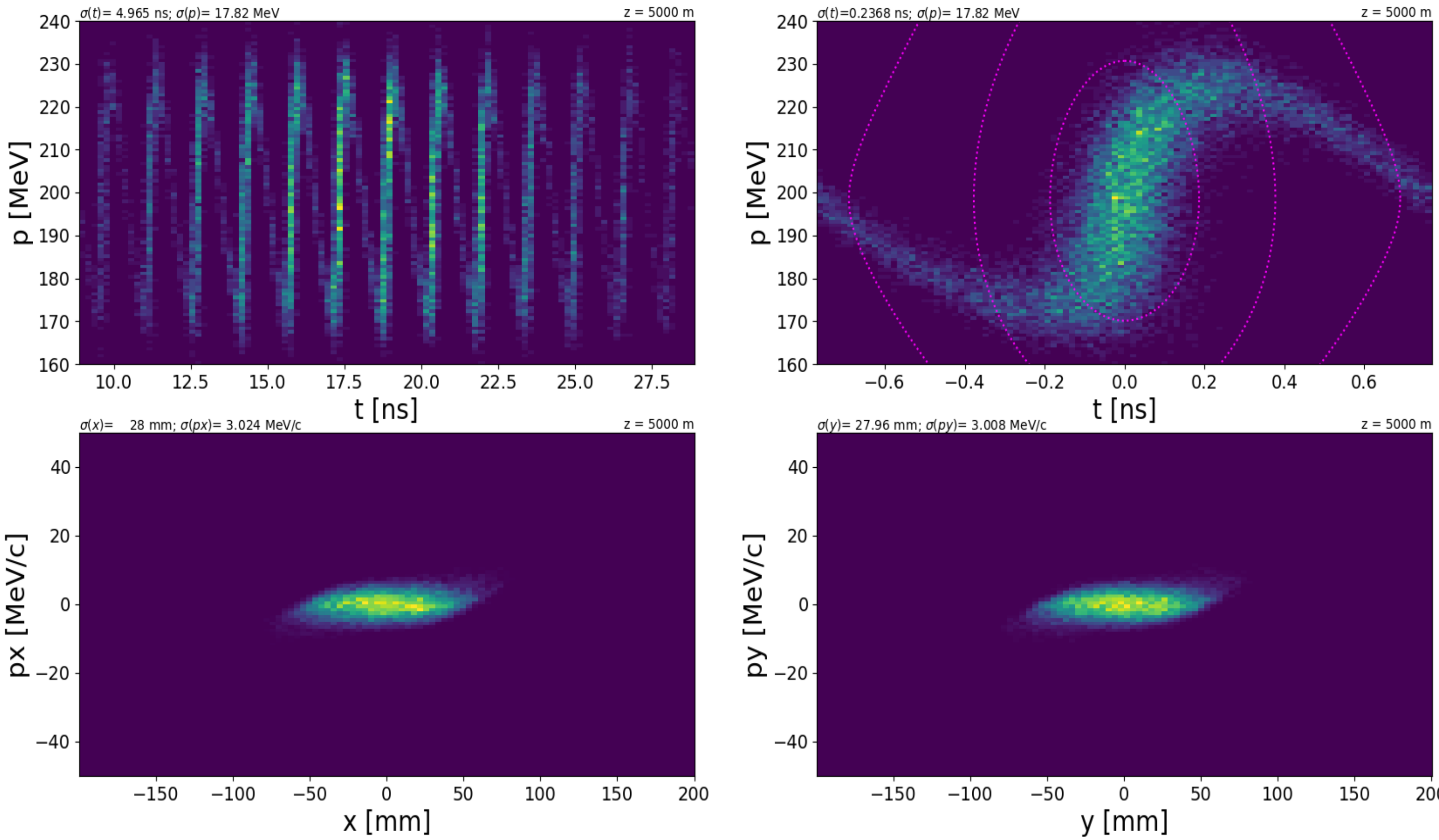
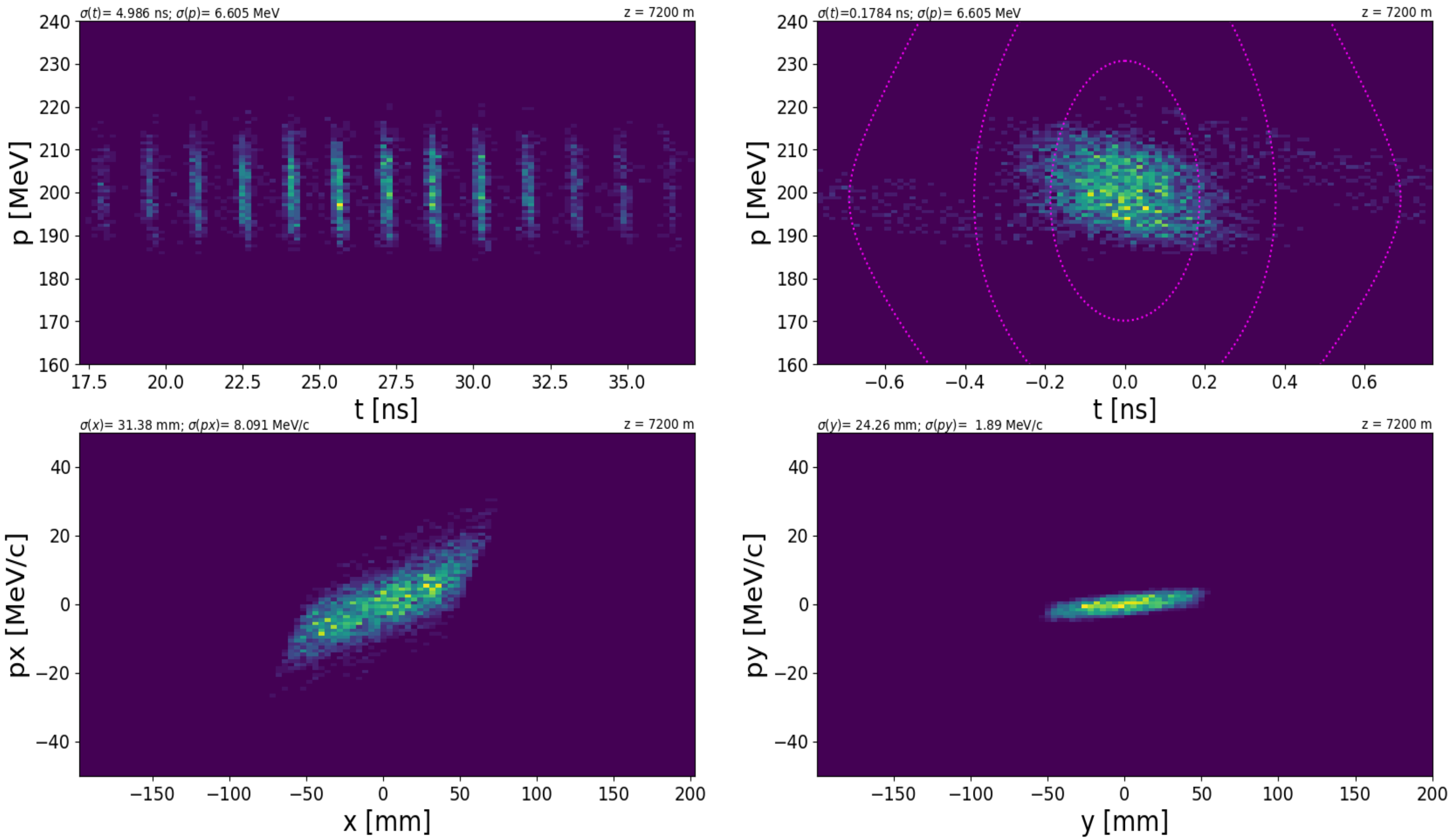
Beam preparation system



Beam preparation system



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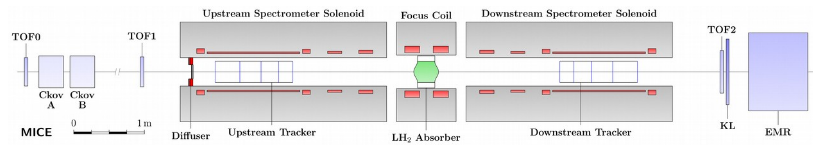
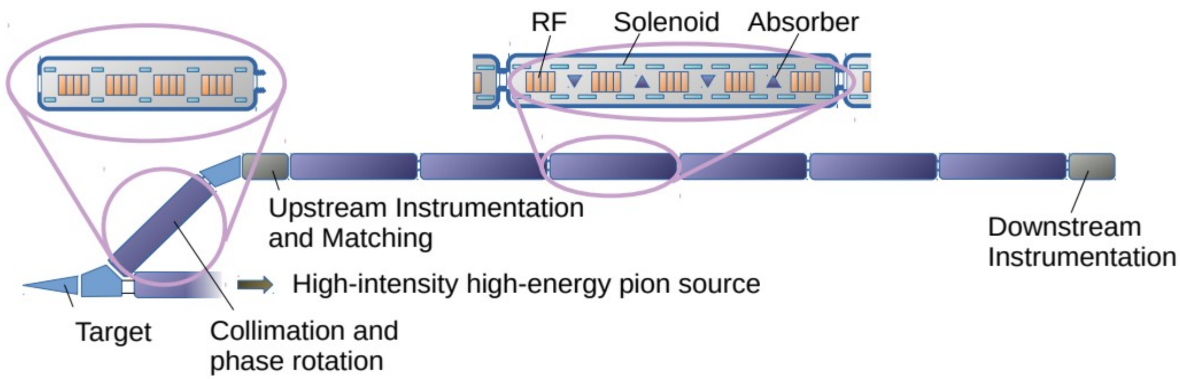
Comparison with MICE

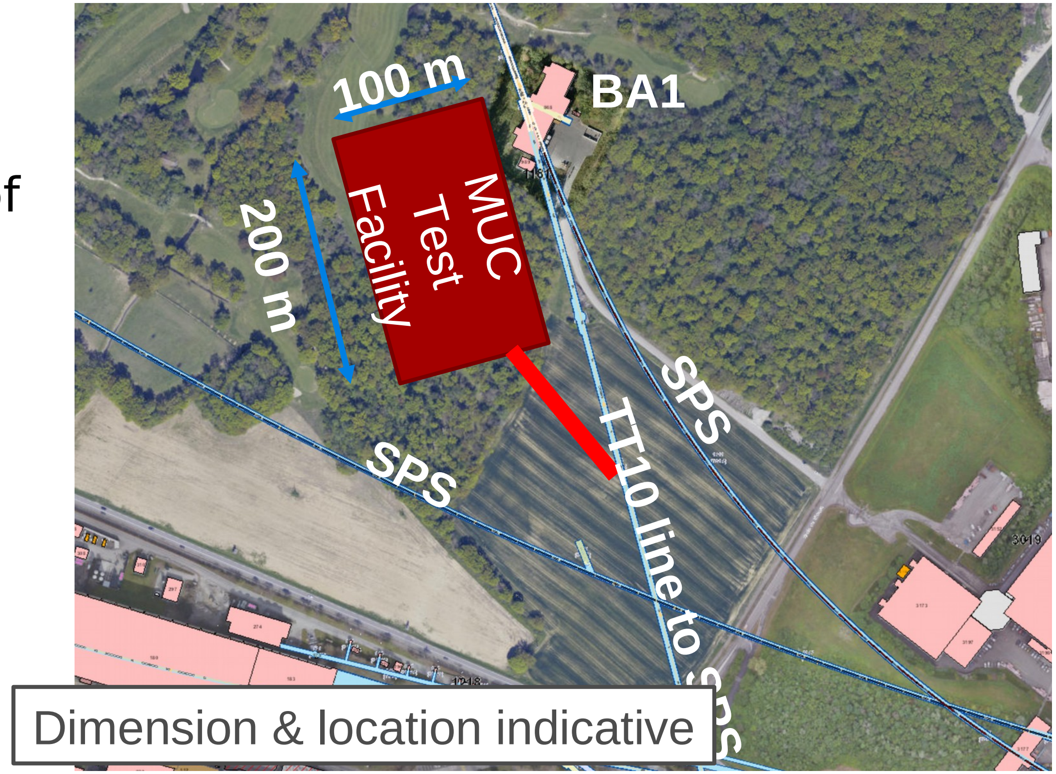




	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Siting

- Two potential sites identified
- New site
  - Advantageous for use of pion beam
  - Points towards North Area
- Existing tunnel
  - Limited beam power possible
  - Leverage existing infrastructure



Calviani et al

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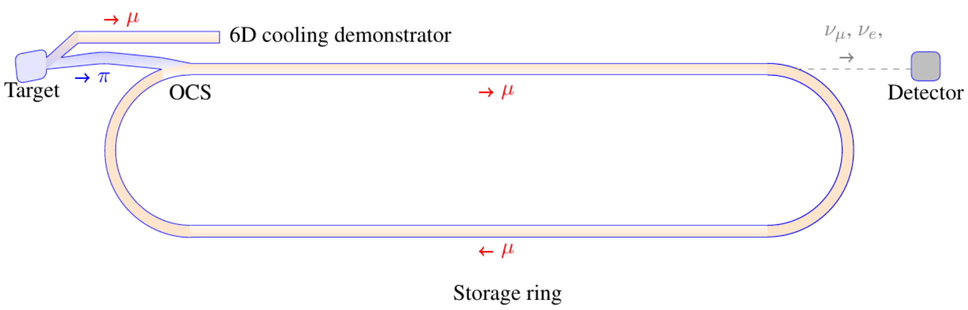
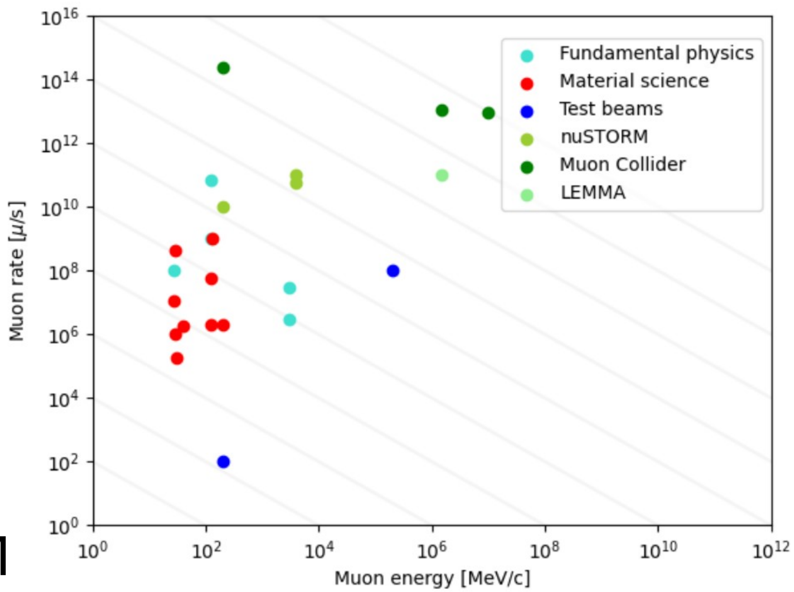
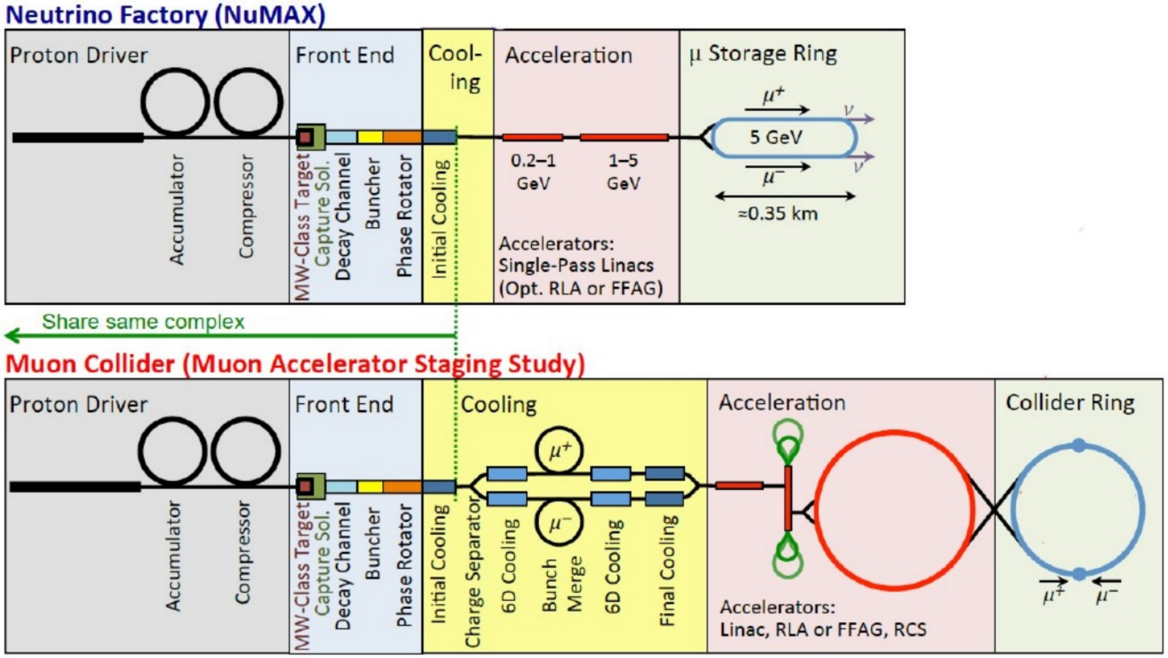
nuSTORM





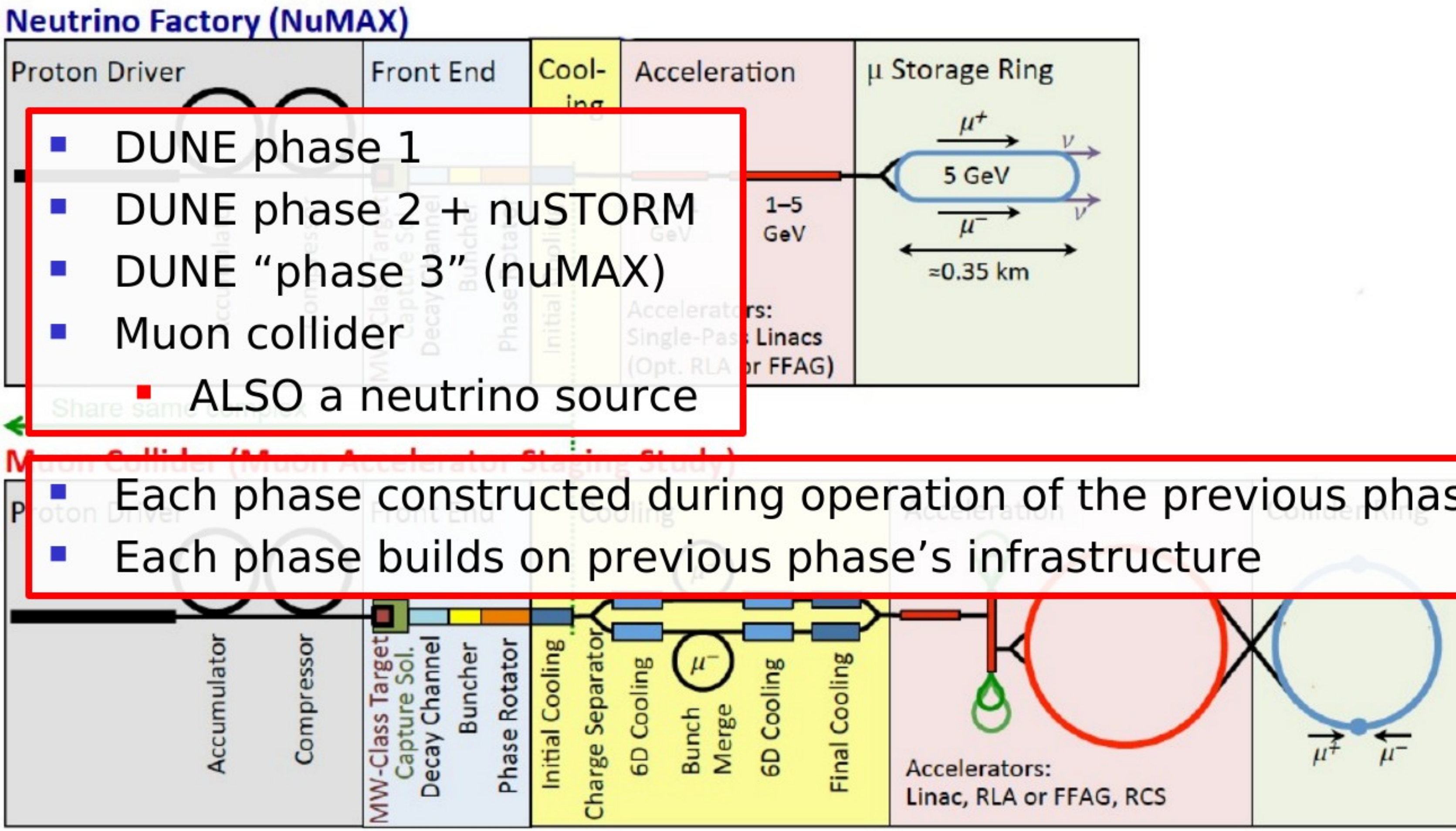
- New site compatible with nuSTORM
  - Measurement of neutrino scattering cross sections
  - Beyond Standard Model physics programme
  - Muon beam test area for Demonstrator
- Demonstration of highest-current high-energy muon beam facility
  - Pion beam handling
  - Target concepts can be tested
  - FFA storage ring → rapid acceleration concepts

Muon-Based Neutrino Factory



- DUNE phase II is systematics-limited
  - How can neutrino community progress?
- One option is neutrino factory
  - Pure, well-characterised neutrino beam
  - Great sensitivity to oscillation parameters
  - High sensitivity to BSM physics
  - Upgradeable to muon collider

Potential path to muon collider



- DUNE phase 1
- DUNE phase 2 + nuSTORM
- DUNE “phase 3” (nuMAX)
- Muon collider
  - ALSO a neutrino source

- Each phase constructed during operation of the previous phase
- Each phase builds on previous phase’s infrastructure

Outlook

- Growing interest in the muon collider
  - High Priority Initiative in European strategy for particle physics
    - Same level as e.g. high field dipole programme
    - Highlighted in European strategy for particle physics accelerator R&D roadmap
    - Muon collider grant issued by EU
  - Strong recommendation to develop a design by Snowmass Energy Frontier
- Demonstration of cooling is a key technology requirement
  - Demonstrator lattice proposed
  - Beam preparation system considered
  - Optimisation and further studies ongoing
- Compatible with nuSTORM
- Aim is to deliver a design by 2026
  - In time for next European strategy update