Progress on Muon Cooling

International
MUON Collider
Collaboration

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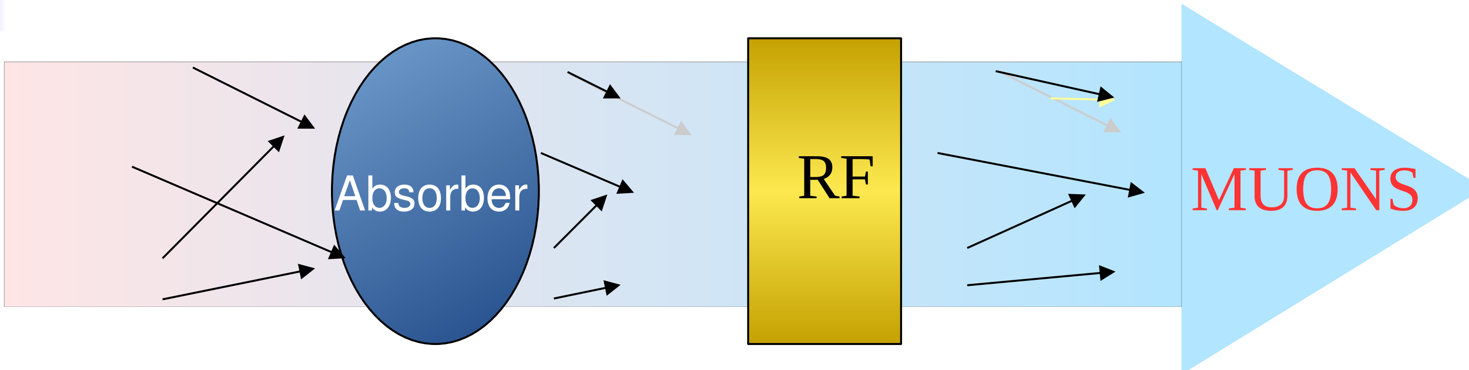
Science & Technology Facilities Council
ISIS

Progress on Muon Cooling Demonstration

- Muon production
  - Target and transverse capture
  - Beam cleaning
  - Longitudinal capture
  - Charge separation
  - First cooling
  - Bunch merge
  - Second cooling
  - Final cooling
  - Reacceleration
- Complex system
- Requires demonstration of key component – ionisation cooling
  - Focus for this talk will be ionisation cooling

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)

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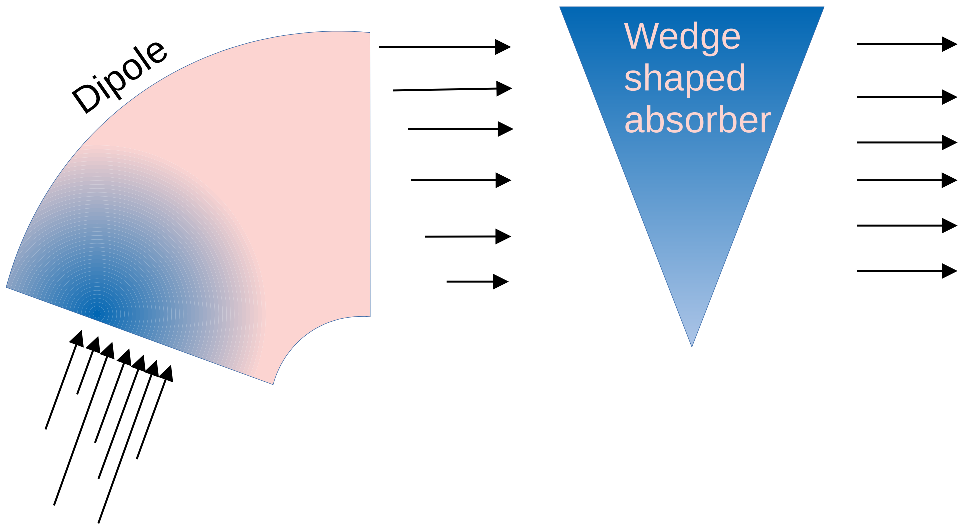
6D Ionisation Cooling



- 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

Cooling for a Muon Collider

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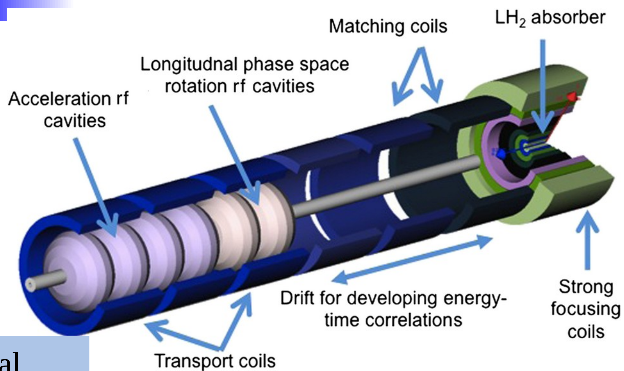
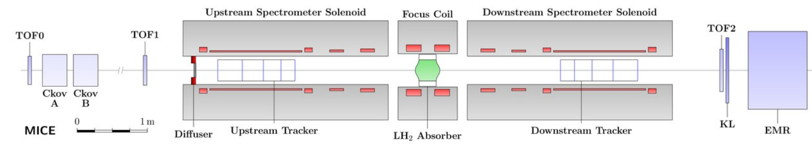
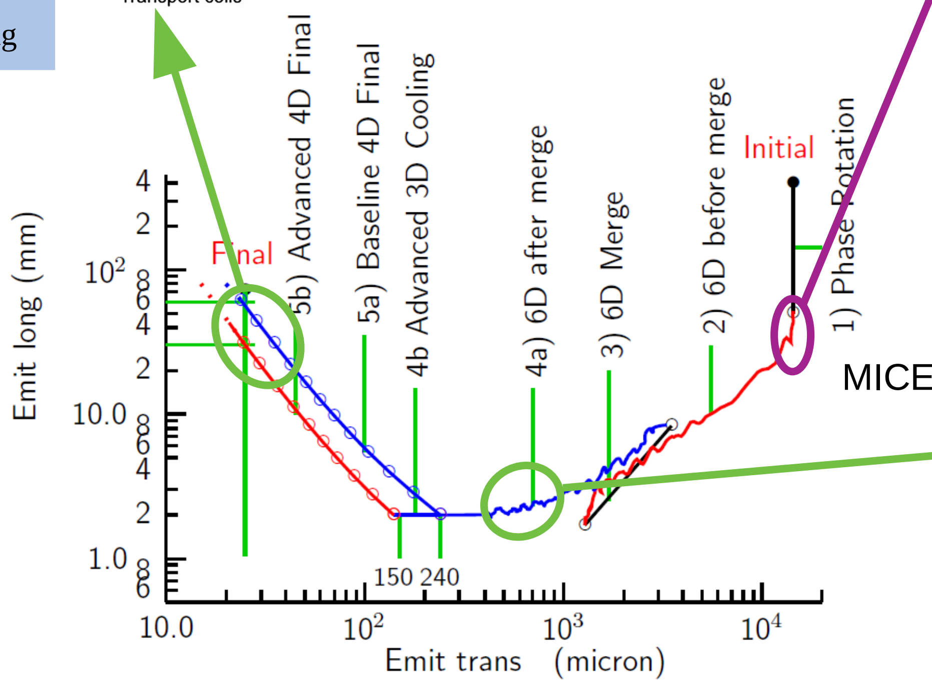


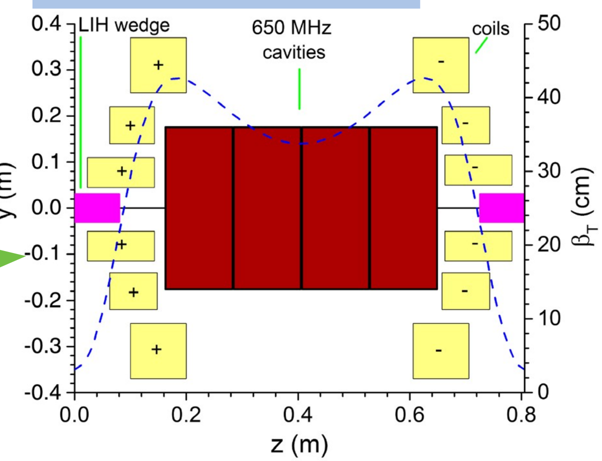
Final cooling



"MICE-like"



Rectilinear B (Stage B8)



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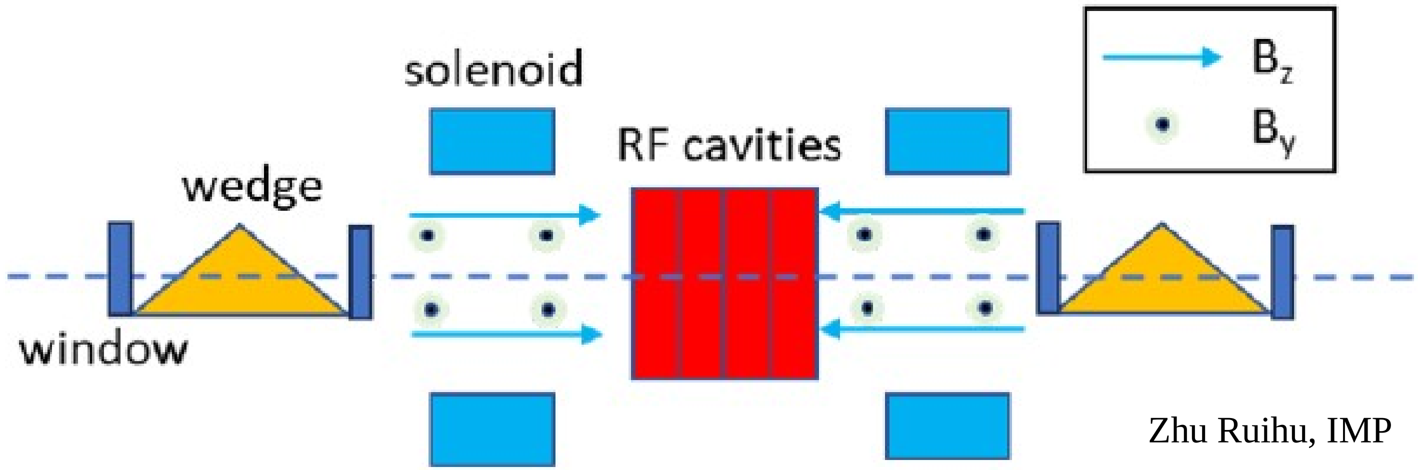
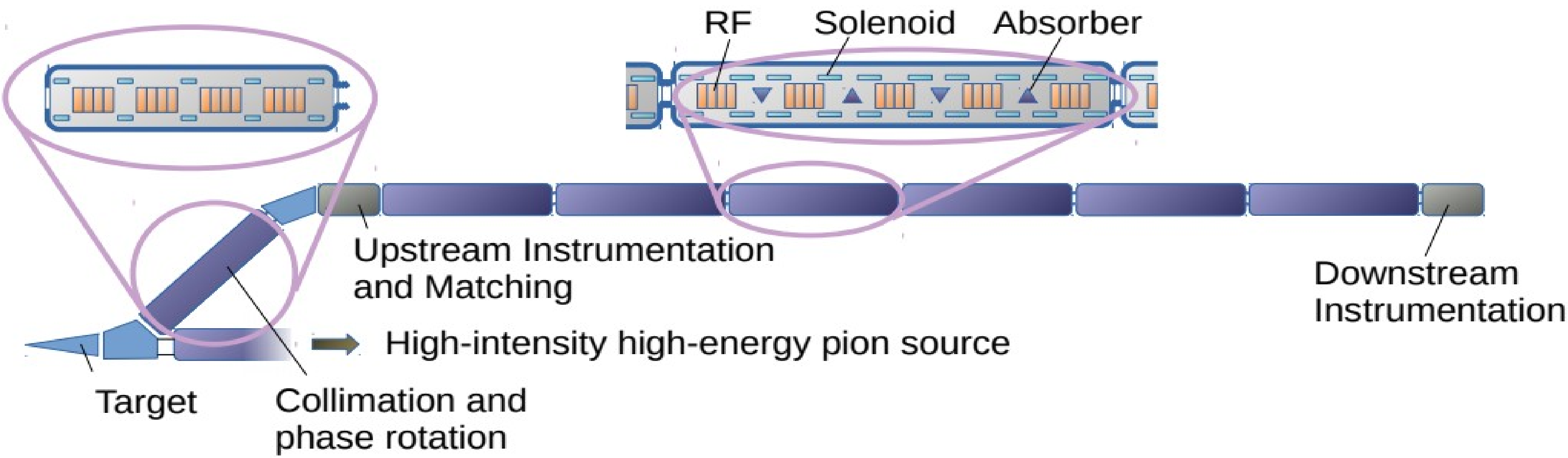
Rectilinear Lattice



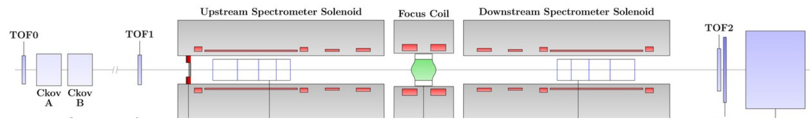
Zhu Ruihu, IMP

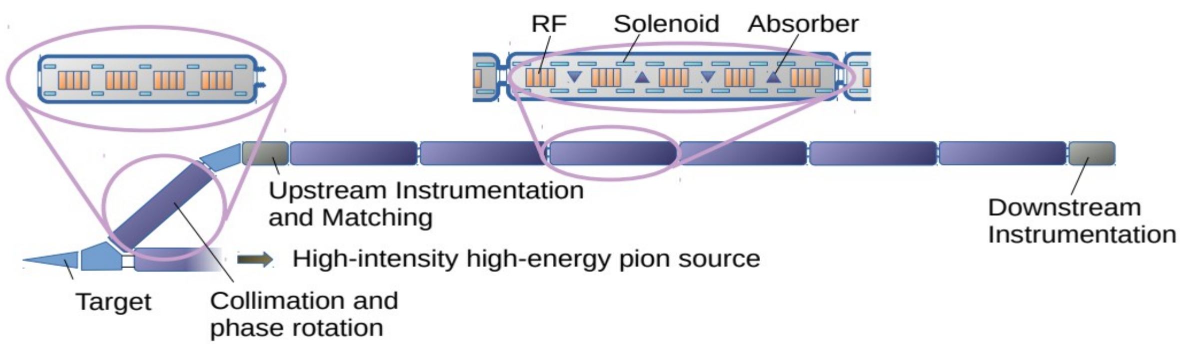
- Challenges
  - Dispersion and closed orbit control for 6D cooling
  - Successful RF operation and suppression of RF breakdown
  - Maintaining adequate acceptance between stop bands
  - Magnet engineering
  - Integration of magnet with RF and absorber
  - Day-to-day operation and instrumentation
- Also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

Demonstrator Layout



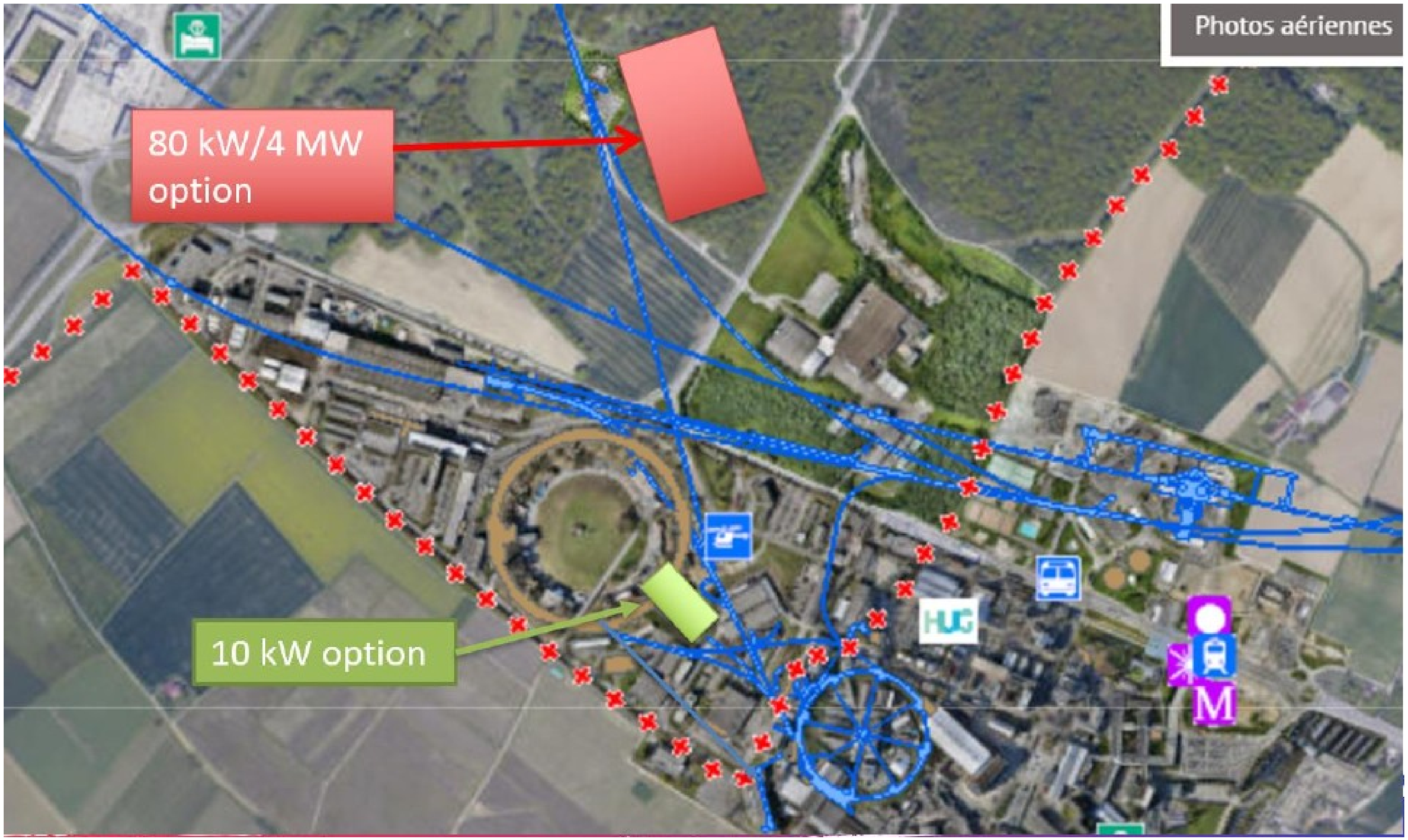
Comparison with Existing Data





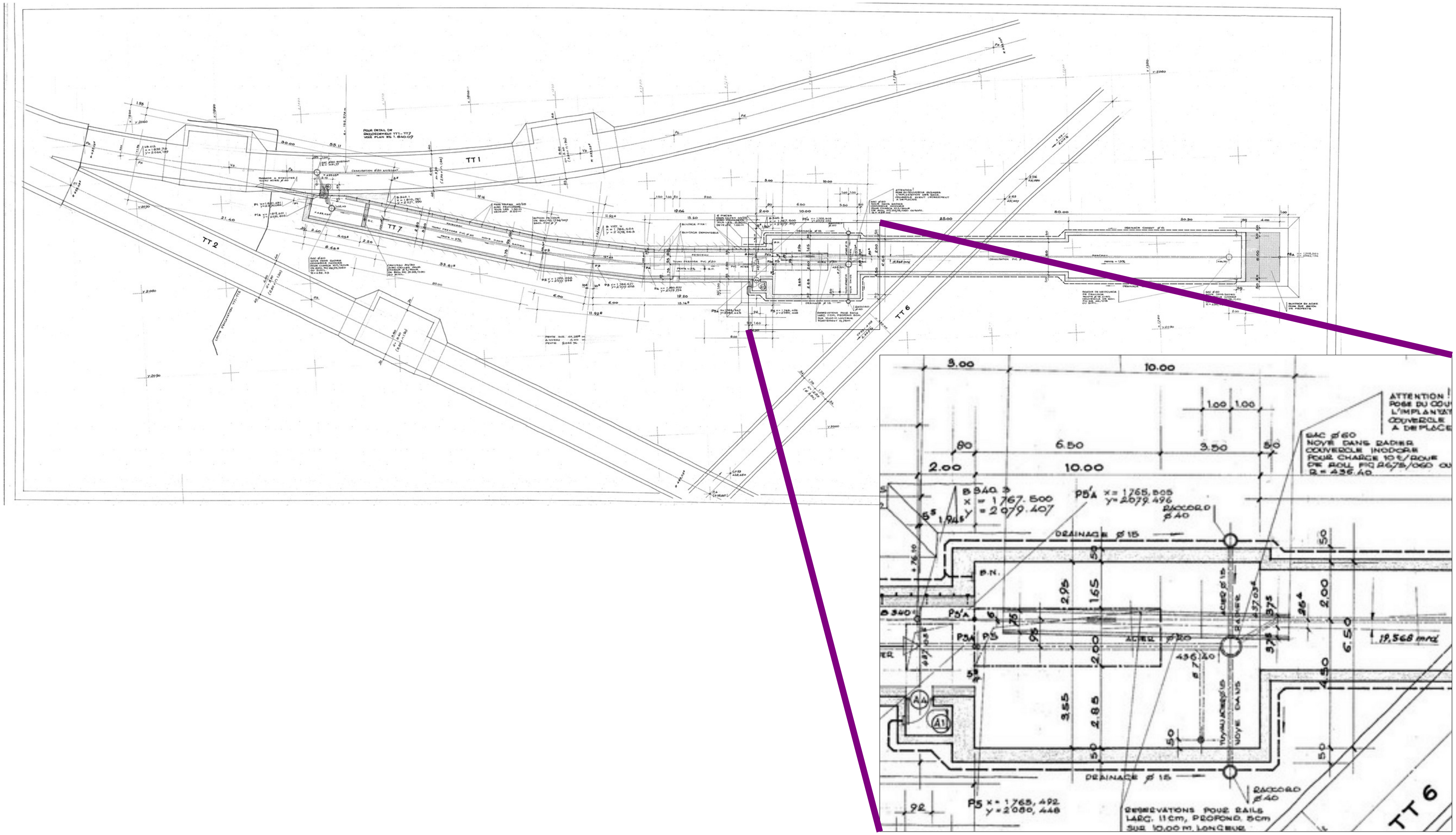
	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

CERN Siting Options



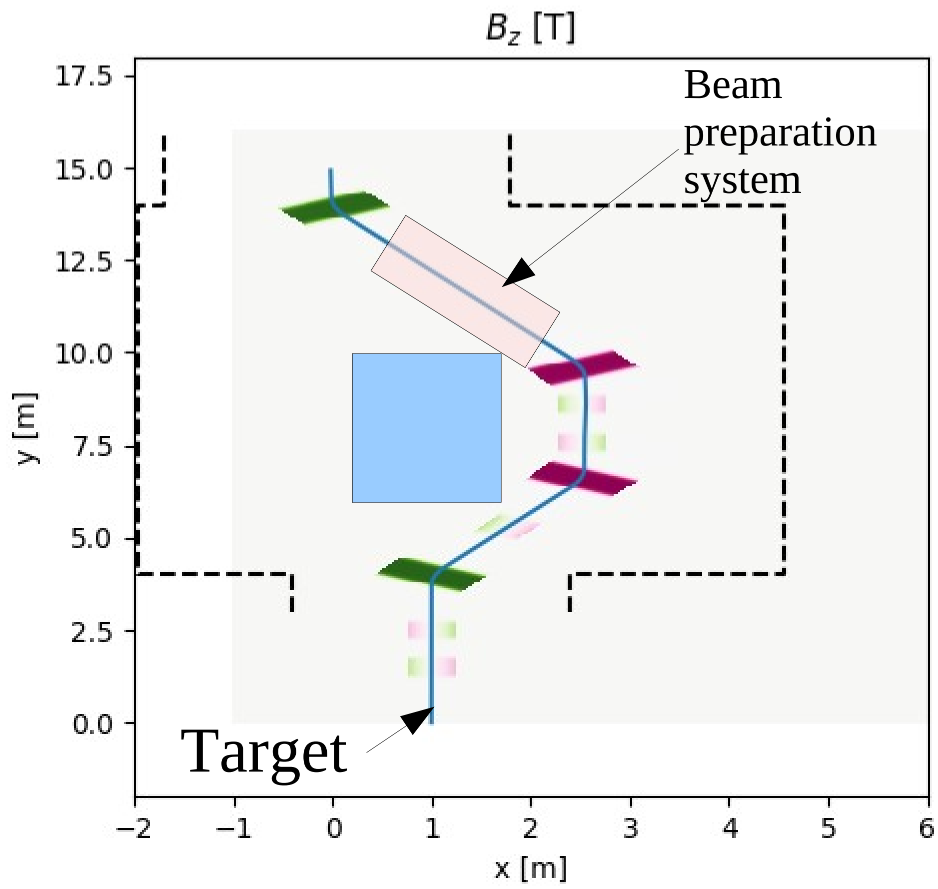
- C/O Roberto Losito

Layout – 10 kW option



Preliminary optics layout

- Preliminary optics layout seems okay
  - Still work in progress
- Dipoles
  - ~ 0.7 T, 30°
  - 0.5 m long
- Quads
  - ~ 1 T/m, TBC
  - 0.5 m long
- Approx 1.5m by 4m region for beam stop
- Followed by beam preparation system



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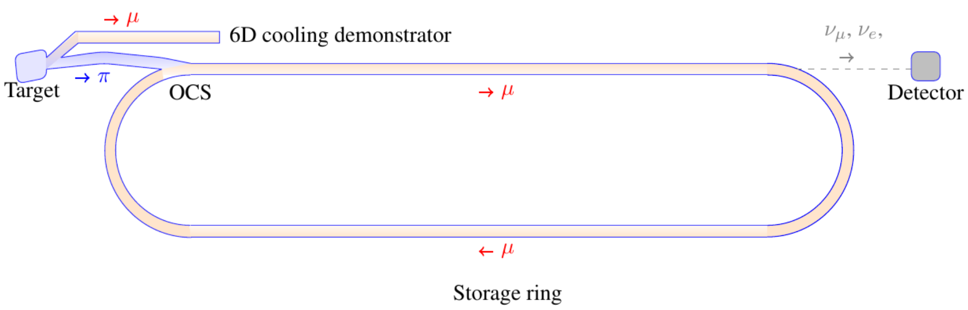
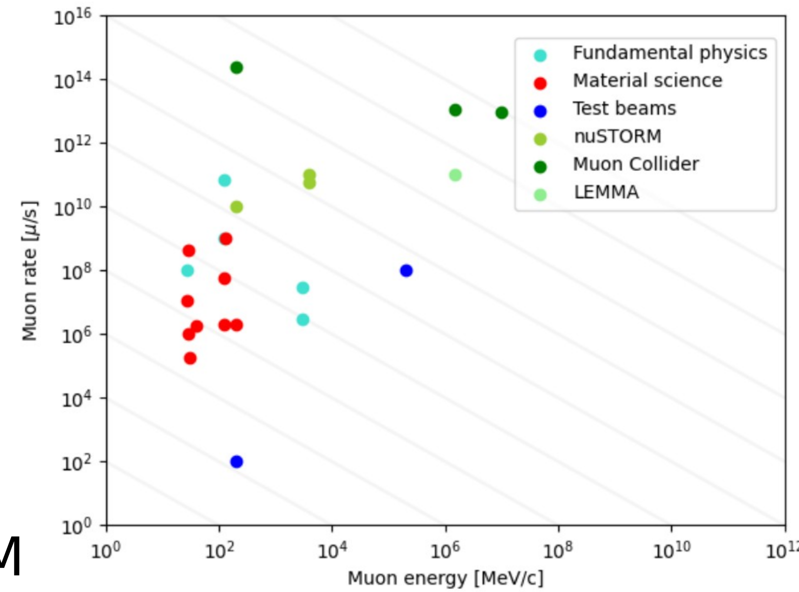
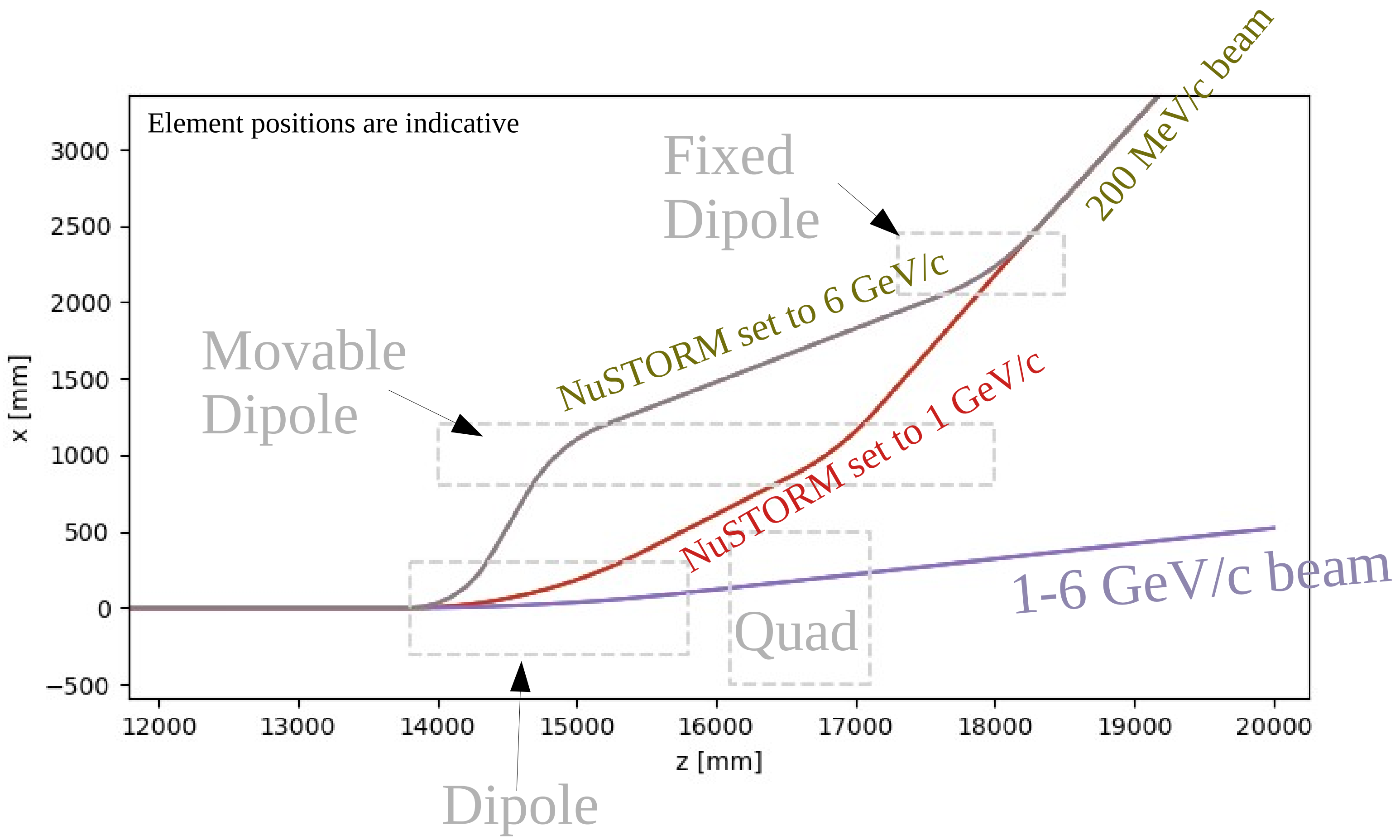
nuSTORM





- 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

Layout – nuSTORM (2)



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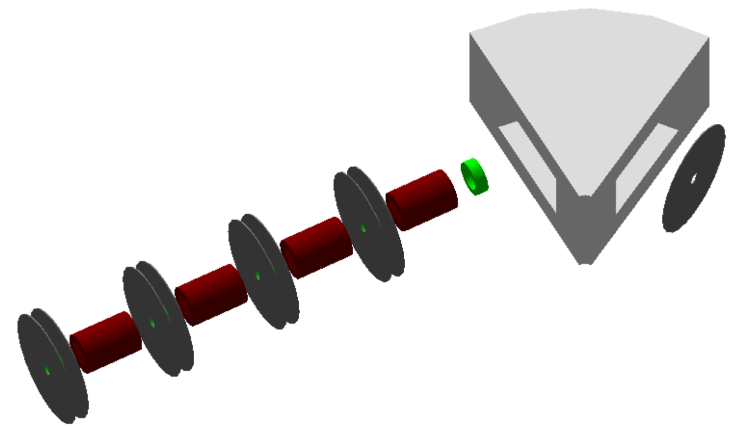
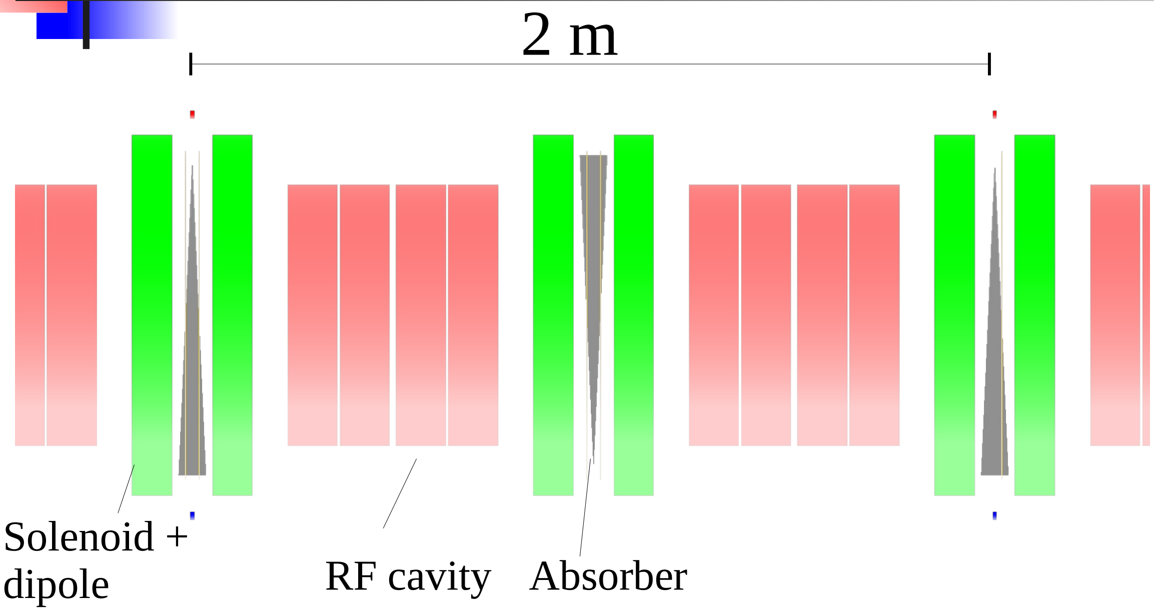
Beam preparation system

- ~ 100 ps pulsed muon beams don't exist
  - Muons have only rarely 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

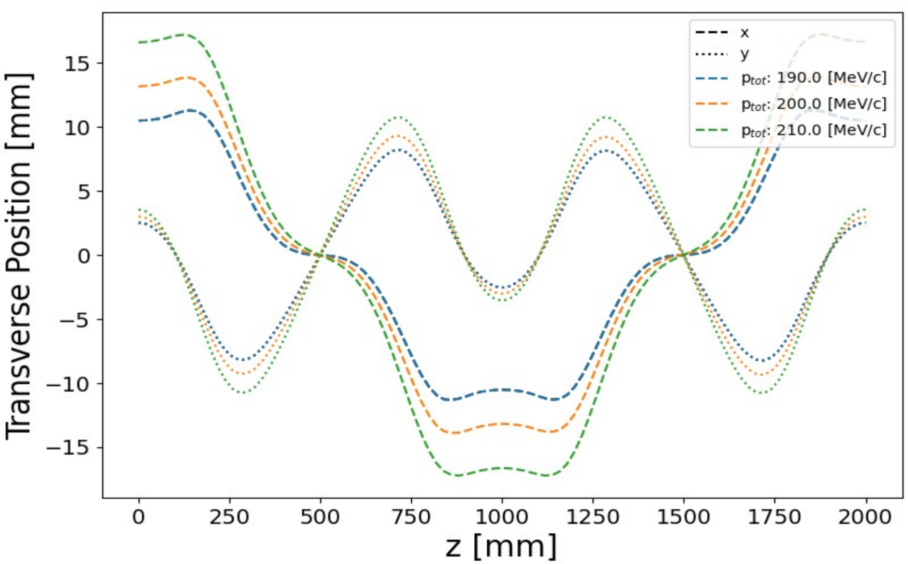


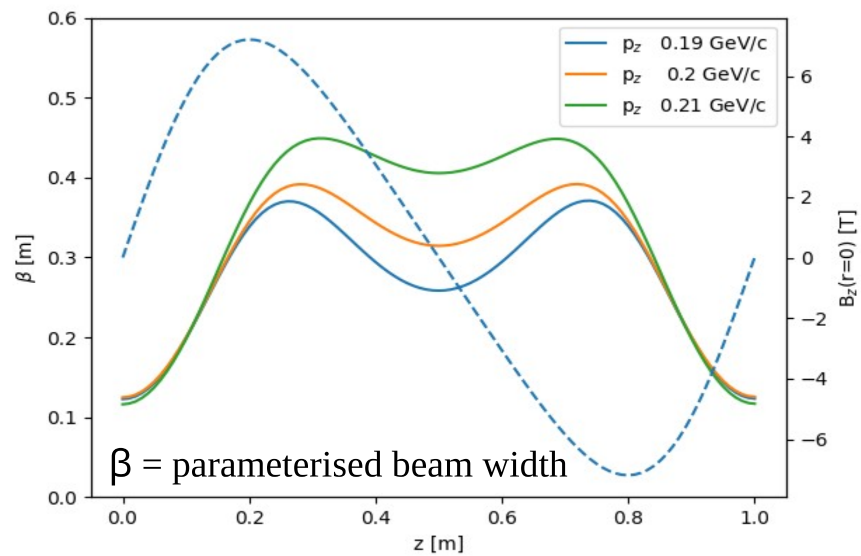
Parameter	Value
Beam Preparation System	
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T

Preliminary Cooling Cell Concept

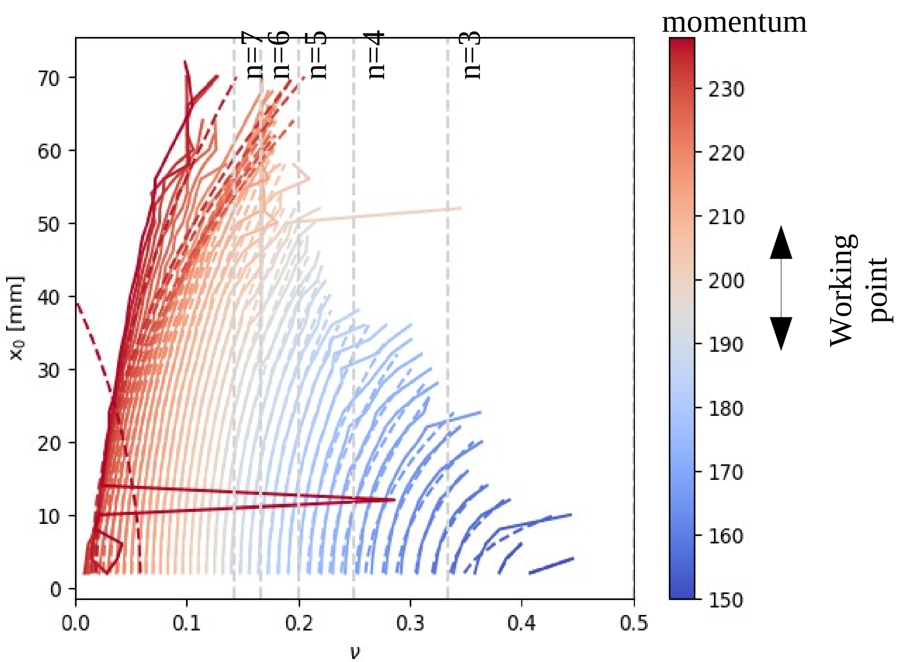


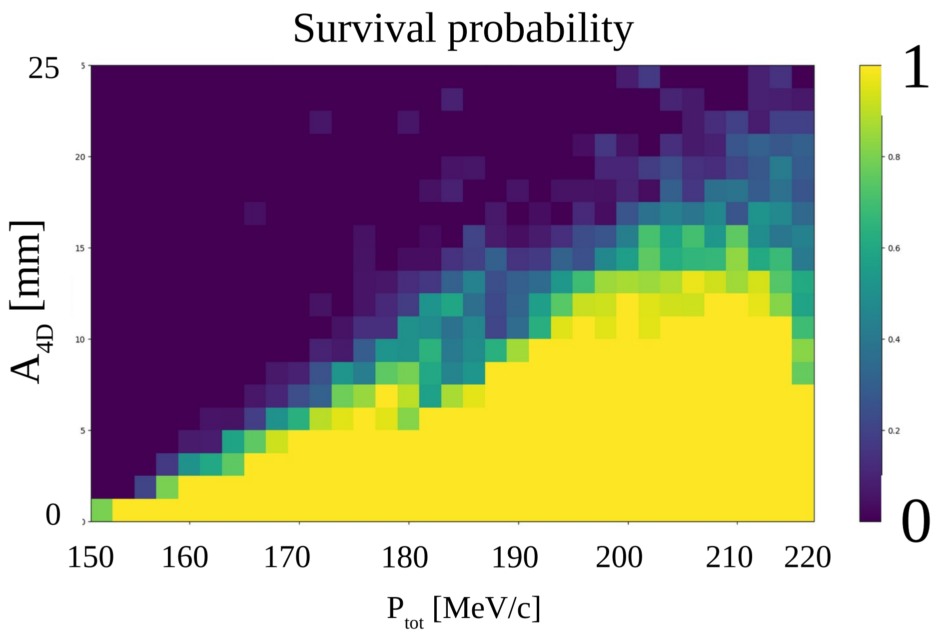
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





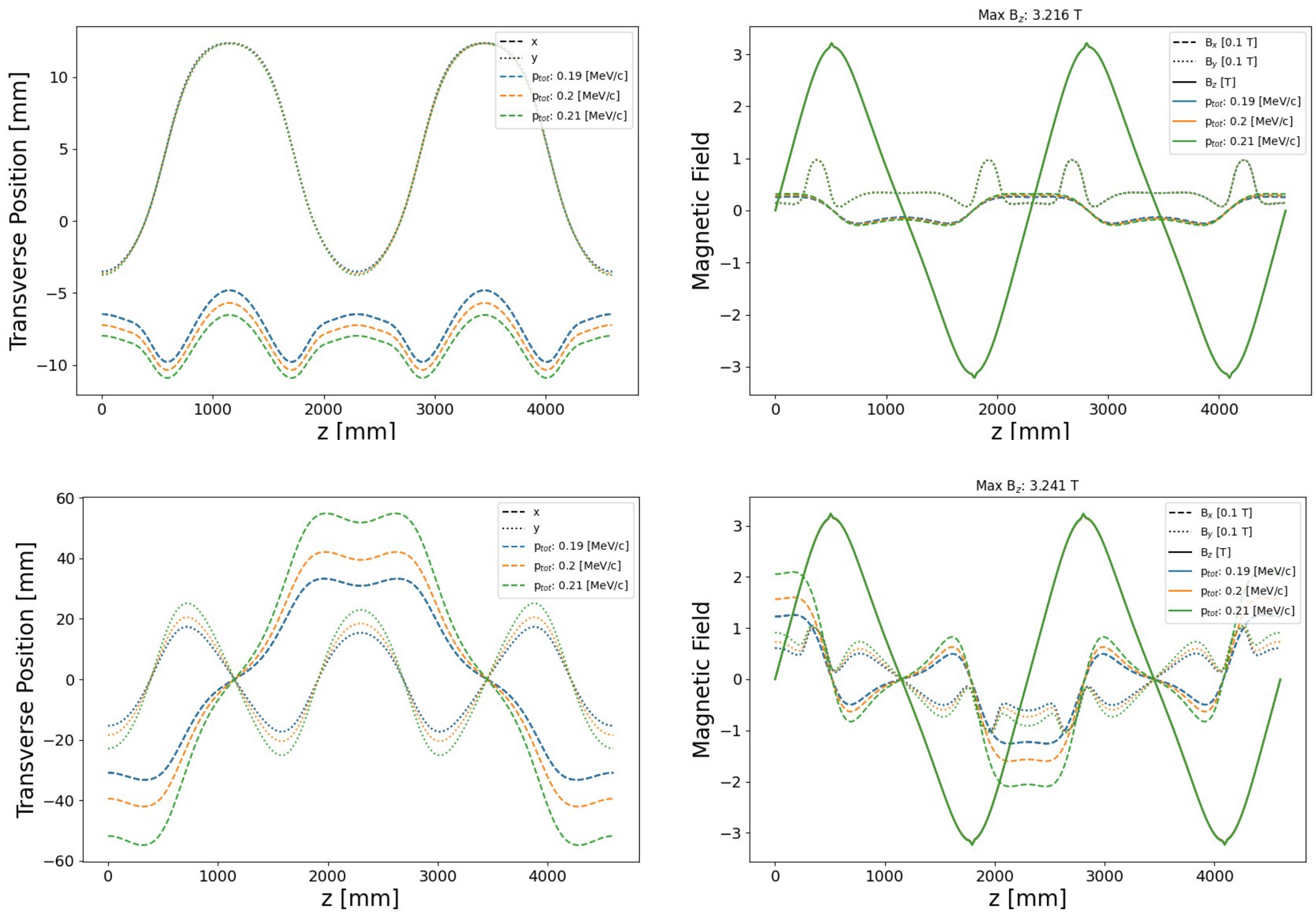
Optics vs momentum





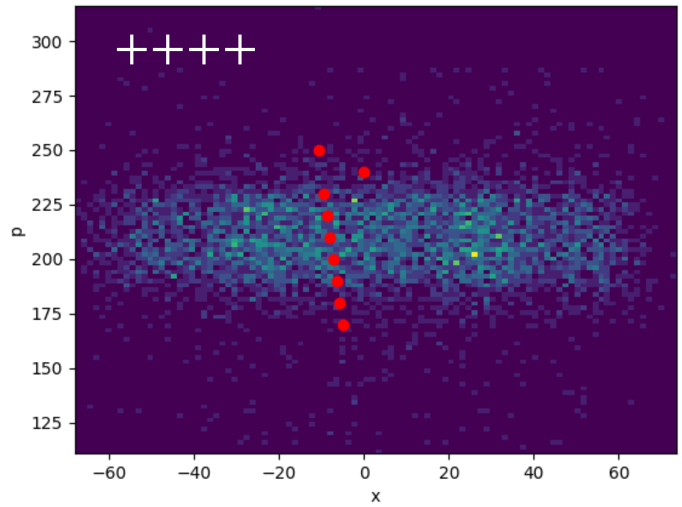
- Acceptance driven by tune consideration
  - Tune = number of focusing oscillations per magnetic cell
  - Acceptance for tune near to resonances

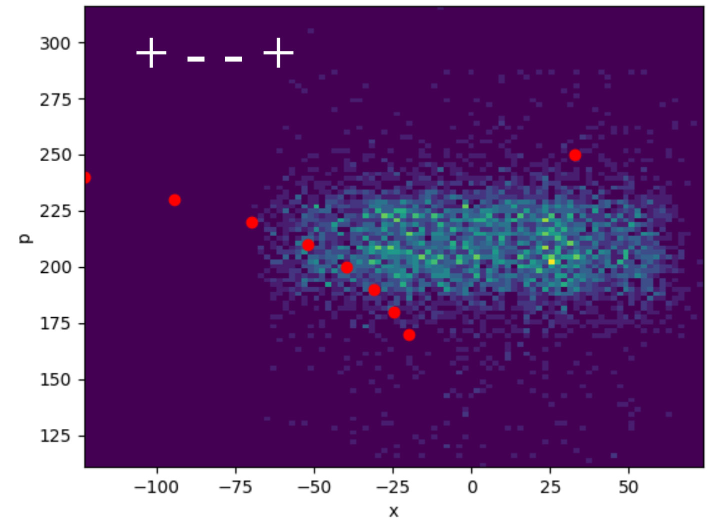
Dipole configuration



- Two possible dipole configurations
  - ++++
  - + - - +

Dipole configuration





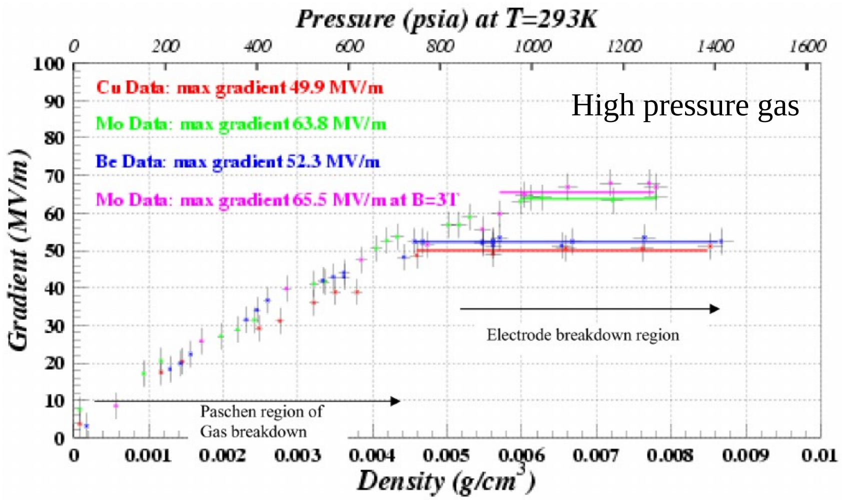
- + - - + yields much more dispersion
- Can create considerably more 6D cooling
- Cost is more non-linearity
  - Challenging to match

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

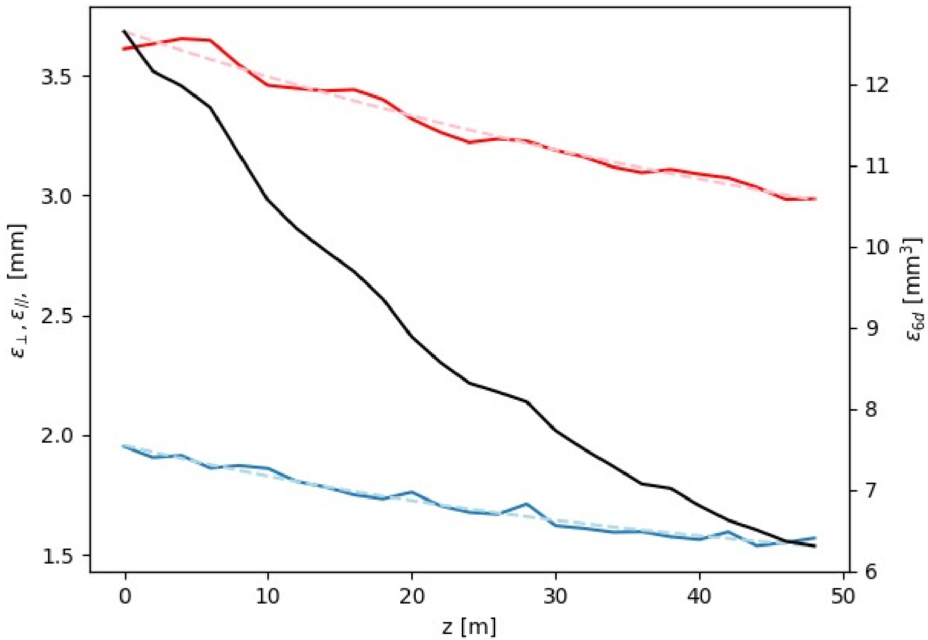
Bowring et al



Yonehara et al

Be RF & LiH Performance

- Use Beryllium for RF cavity walls
- Use LiH in absorber
- 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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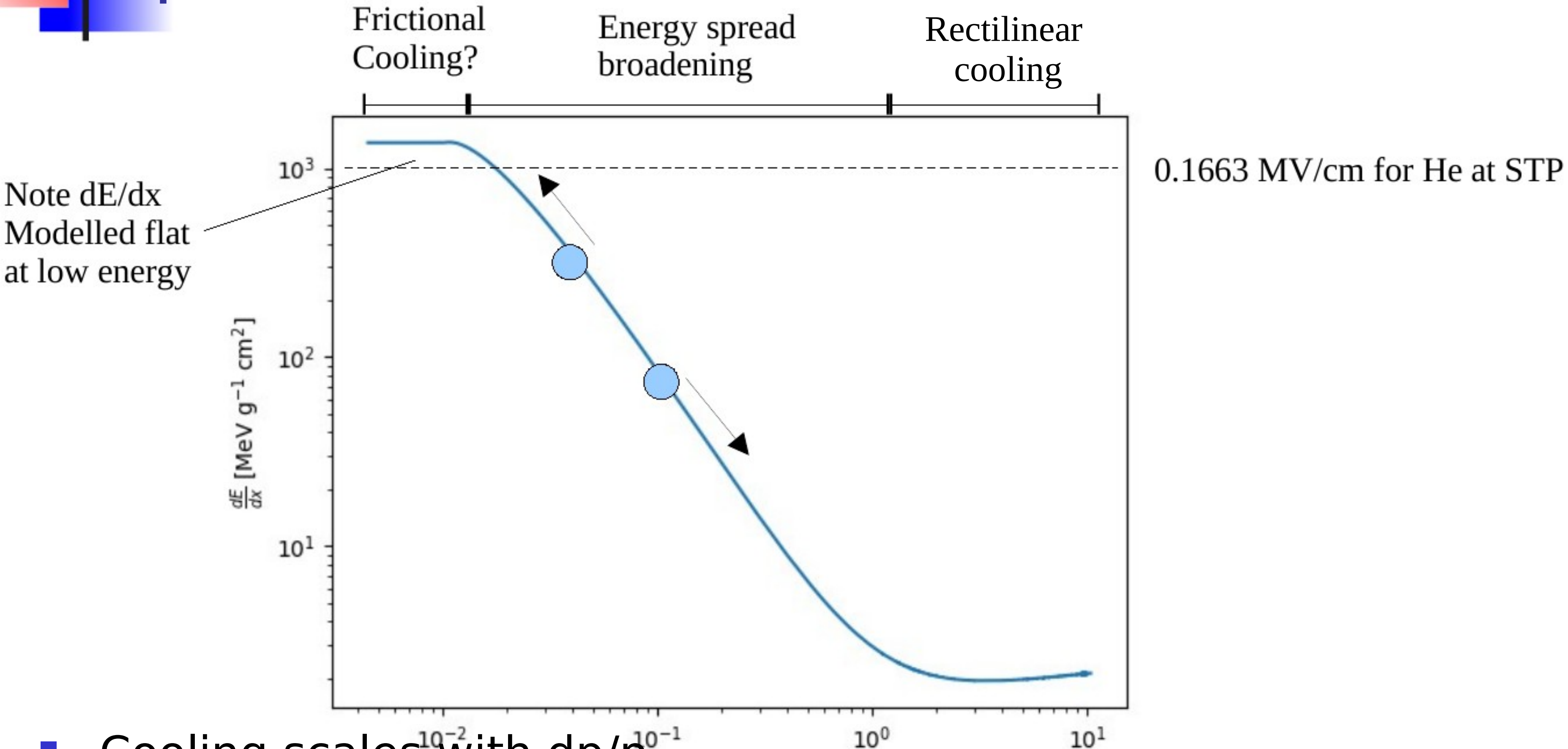
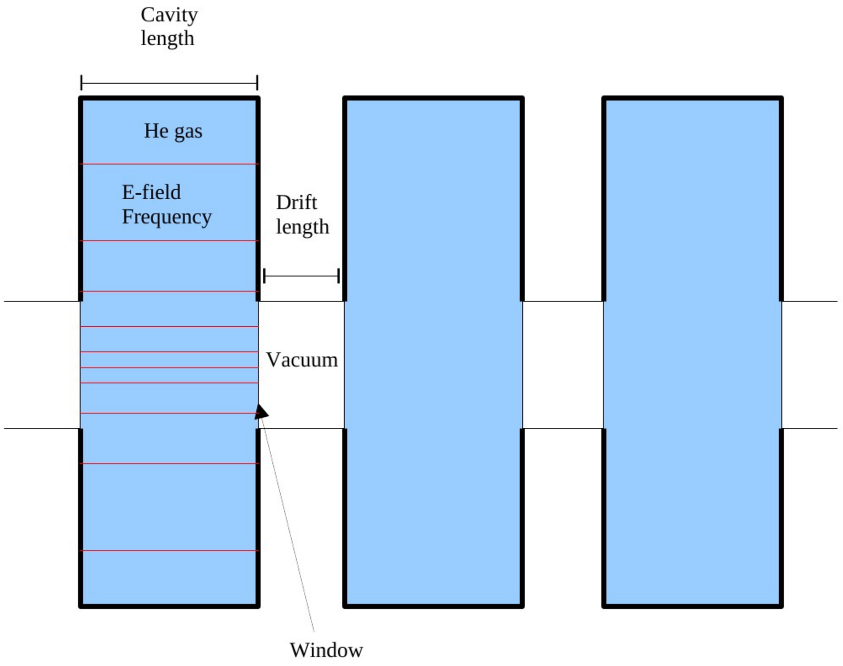
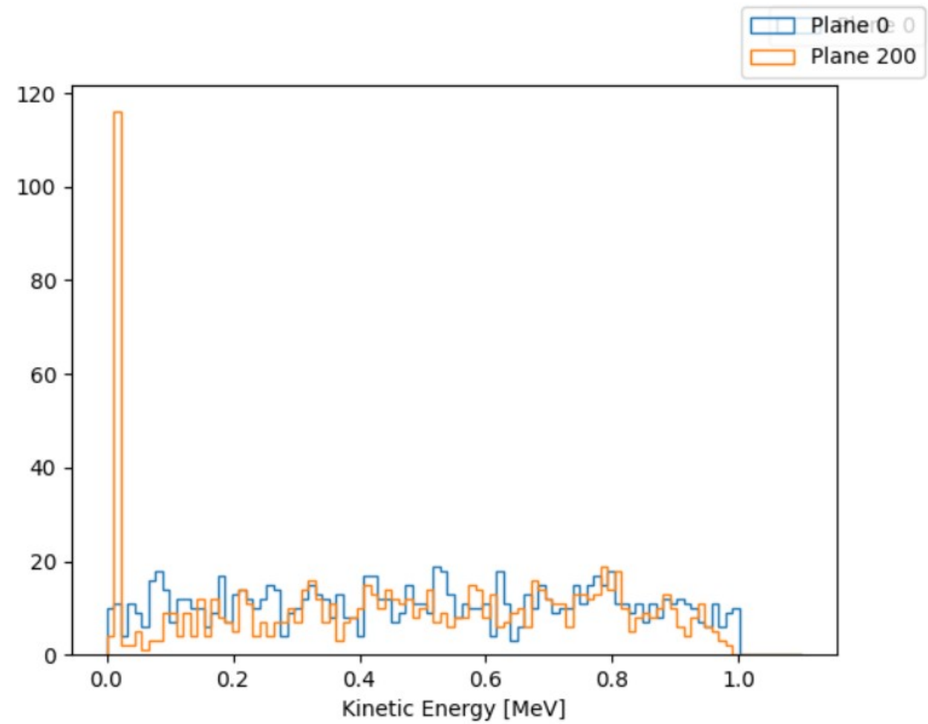
Demonstrating full cooling performance



- Cooling scales with dp/p
- Higher energy → more RF
- Lowest energy beams → muSR

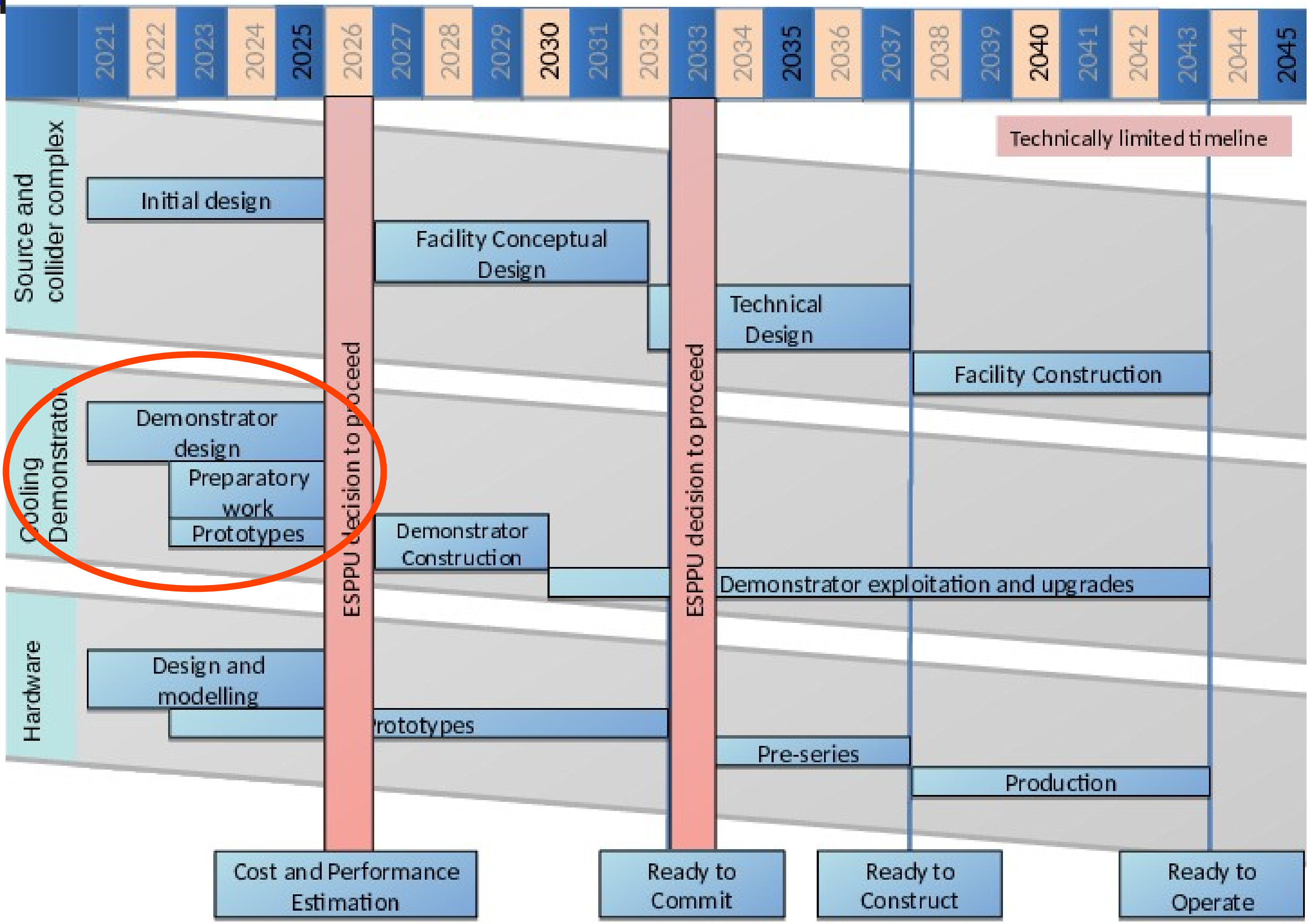
Demonstrating full cooling performance





- Longitudinal only simulation!
  - About 12 % of the muon beam ends up in the low energy bucket (assume uniform incident beam in energy)
  - After 1 metre of cooling system

Timeline



- **Assumes full effort of major lab e.g. CERN, Fermilab**

Outlook

- Demonstration of cooling is a key technology requirement for Muon Collider
  - Improved demonstrator lattice studied
  - Beam preparation system looks okay
  - Looking at layout from target to cooling system for CERN site
    - Happy to look at non-CERN sites!
- Aim is to deliver a design by 2026
  - In time for next European strategy update