nuSTORM as a Muon Collider Demonstrator

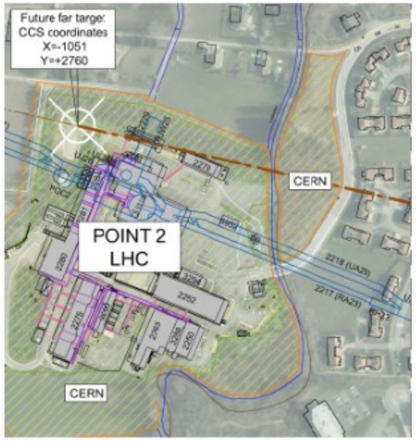
C. T. Rogers
ISIS
Rutherford Appleton Laboratory

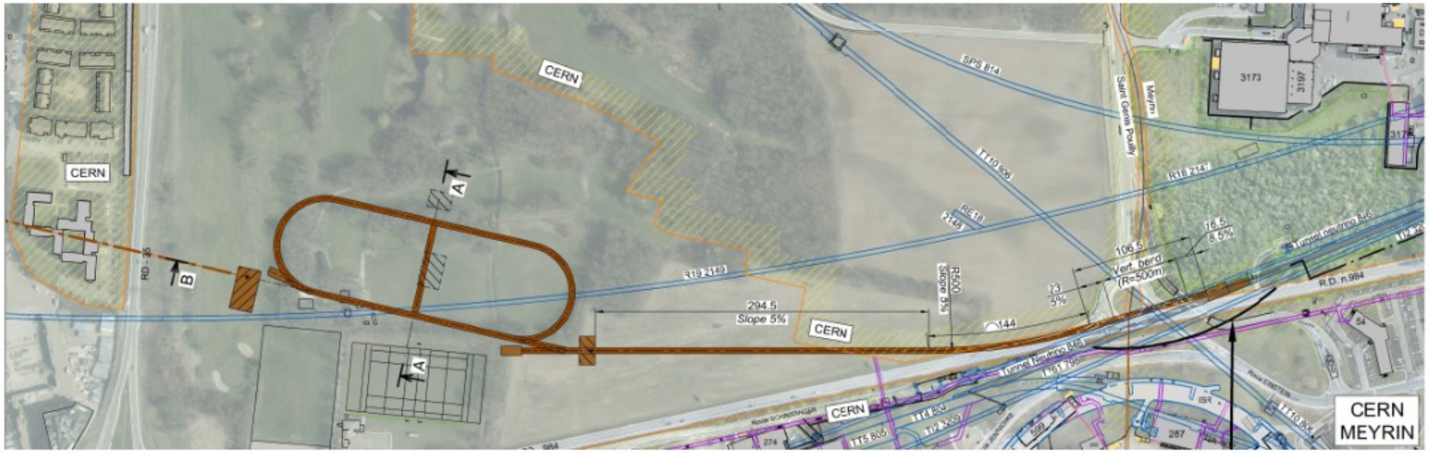
NuSTORM accelerator challenges

- nuSTORM facility is a unique facility for
  - High muon rate
  - Well-characterised neutrino beam
- Several applications
  - Measurement neutrino scattering cross sections
  - Search for sterile neutrinos and other BSM physics
  - Provide a technology test-bed for the muon collider
- What is the nuSTORM facility?
- What is the physics reach?
- How can it provide a test-bed for the muon collider?

nuSTORM facility

- What is the nuSTORM facility?





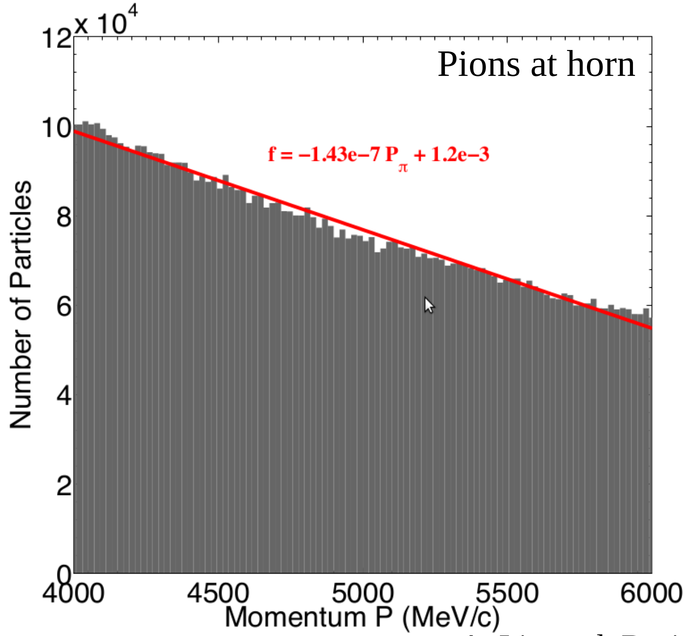
nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

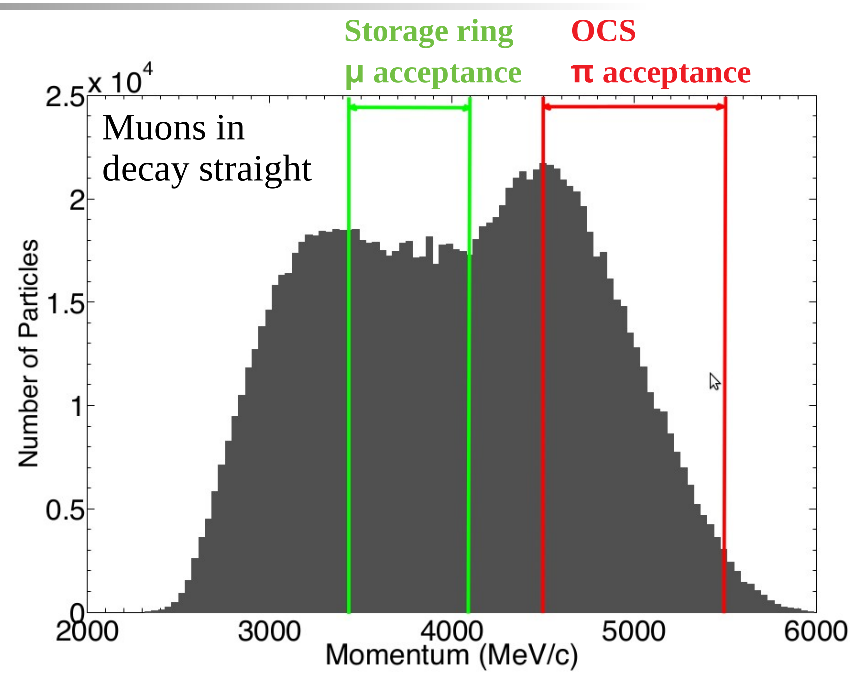
- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - Option for conventional FODO ring or high aperture FFA ring

Target and Pion Transport Line

- Conventional 250 kW target horn
- Pion transport line
  - Proton beam dump
  - Momentum selection
  - Active handling

Stochastic Muon Capture



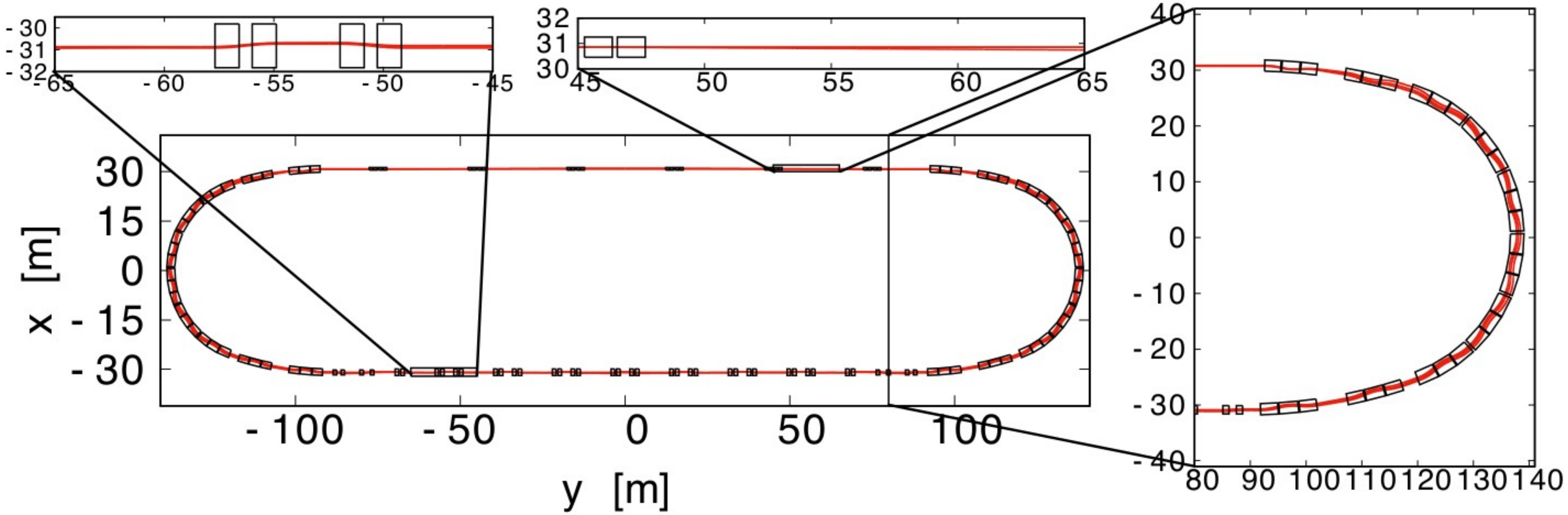


A. Liu et al, Design and Simulation of the nuSTORM Pion Beamline, NIM A, 2015
D. Adey et al, Overview of the Neutrinos from Stored Muons Facility – nuSTORM, JINST, 2017

- Pions injected into the decay ring
- Capture muons that decay backwards in pion CoM frame
- Undecayed pions and forwards muons diverted into muon test area
  - Extraction line at end of first decay straight

Storage Ring

nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

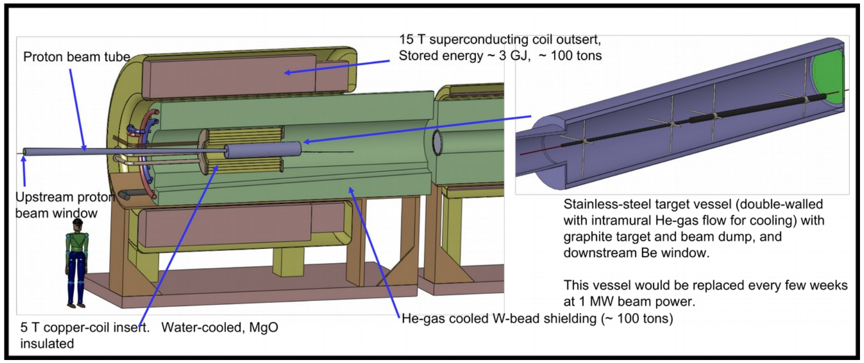


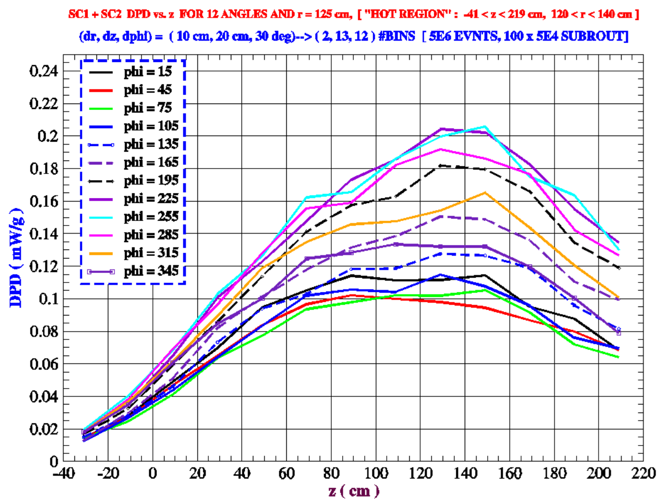
- Storage ring technologies:
  - Conventional FoDo ring
  - High acceptance FFA ring

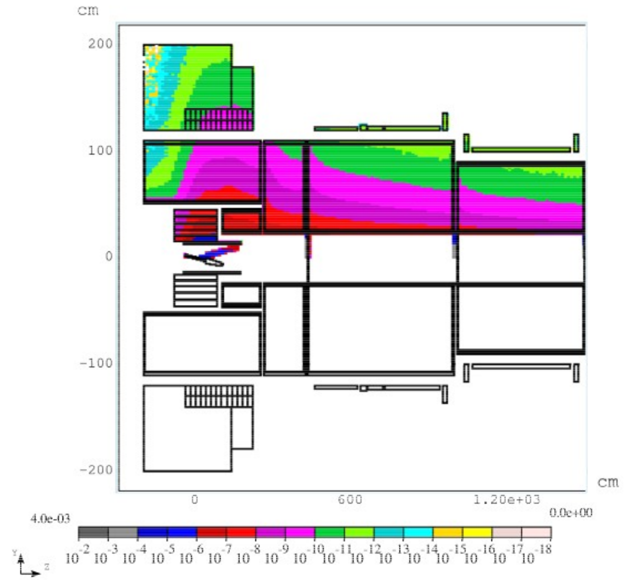
Muon Collider Technical Challenges

- Target Station
  - High-field solenoid in high radiation environment
  - Target lifetime and radiation damage
- Cooling
  - Rapid cooling in muon lifetime
- Acceleration and Collider
  - Rapid acceleration in muon lifetime
  - Neutrino radiation management

Target



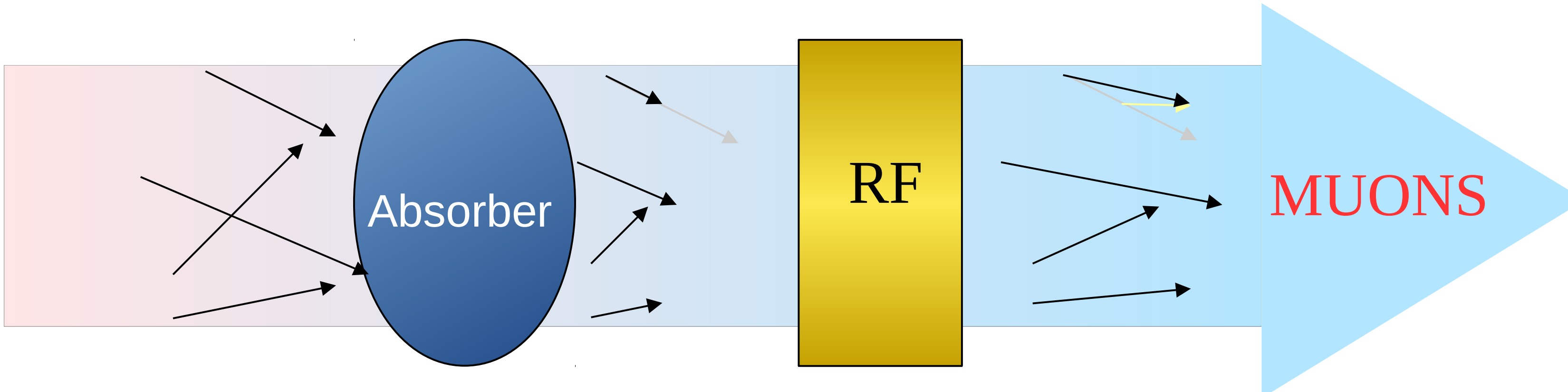




- Power deposition on target is an issue
  - Radiation damage to target material
  - Heat load on target and cryogenic cooling requirement

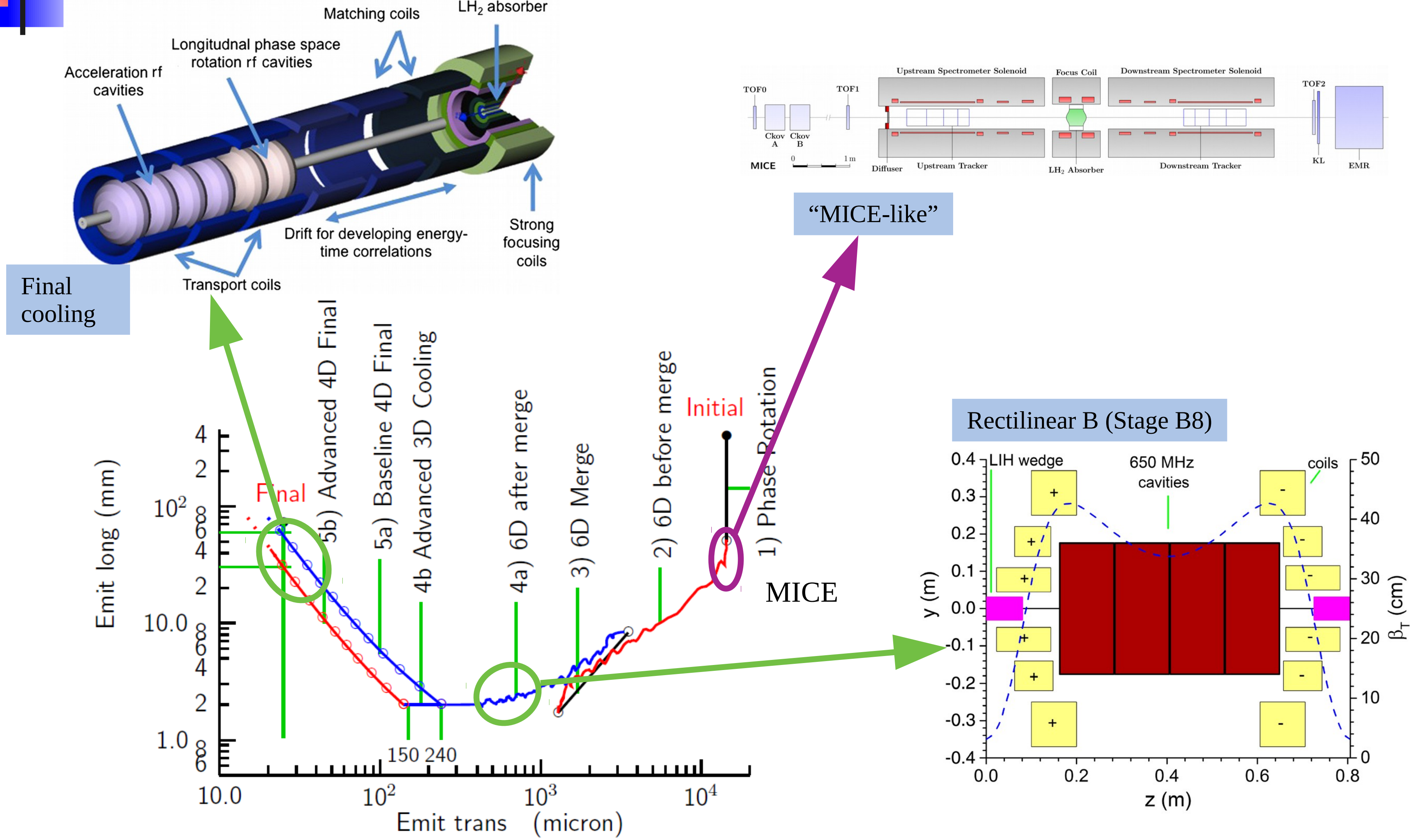
Energy deposition in the target System of a Muon Collider/Neutrino Factory,
K. McDonald et al, IPAC14

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

Muon Cooling

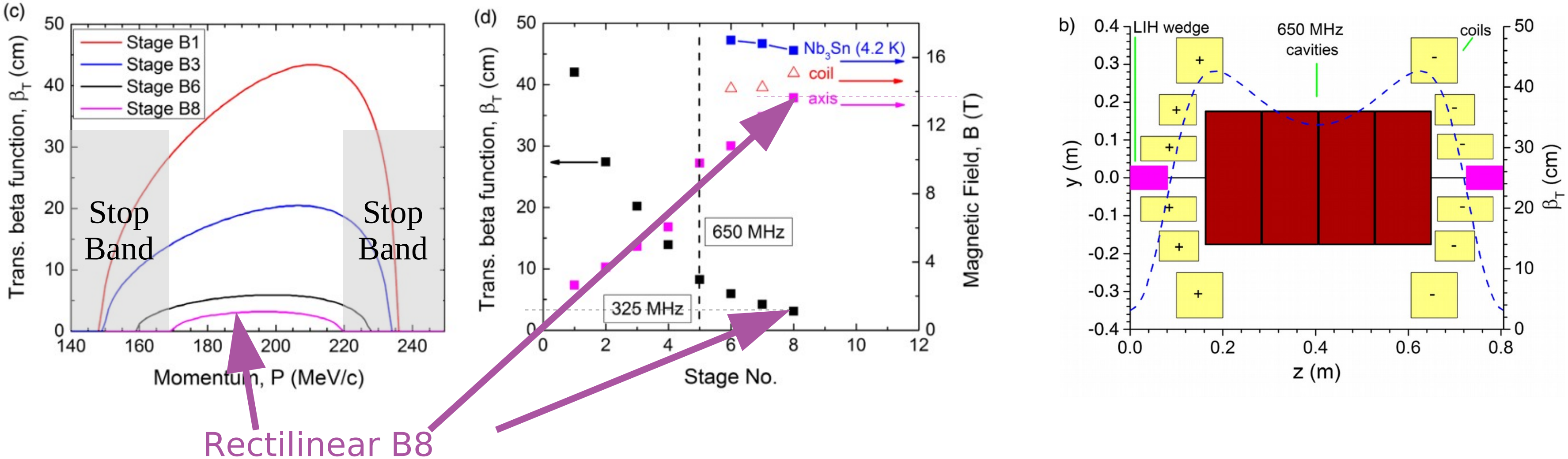


Cooling Risks

Rectilinear B	Performance does not match simulation, for example because energy straggling is underestimated, alignments can't be achieved, etc	3	Reduced performance	2	Literature review on straggling; simulation study of impact on uncertainty in straggling distribution	Further experimental measurements of energy straggling may be necessary. Integration test of cooling apparatus.
	RF voltage cannot be achieved, for example because gradients are found to be above break down limit	3	Back off on RF requirements	2		Proof of breakdown suppression with a "production" cavity and a reasonable production run of several cavities, including realistic magnetic fields
	Magnetic field strength cannot be achieved	3	Back off on magnet requirements	3	Design of magnets is required including e.g. force calculations, support design	Prototyping of magnets. Demonstration of QPS system in a reasonable magnet line.
	Radiation load on the magnets is too high due to regular beam losses and muon decay	2	Back off on magnet requirements and add extra shielding	1		
	Heat load on the absorber is challenging to manage	1	Split the beam?	3	Further simulation and design work	
	Beam loading of RF cavities					
	Space charge					
Final Cooling	Performance does not match requirements	4	Reduced performance	3	Further optimisation of the cooling channel design. Alternative concepts such as frictional cooling should be considered	Further experimental measurements of energy straggling may be necessary. Integration test of cooling apparatus.
	RF voltage cannot be achieved, for example because gradients are found to be above break down limit	3	Back off on RF requirements	2		Proof of breakdown suppression with a "production" cavity and a reasonable production run of several cavities, including realistic magnetic fields
	Magnetic field strength cannot be achieved	3	Back off on magnet requirements	3	Design of magnets is required including e.g. force calculations, support design	Prototyping of magnets. Demonstration of QPS system in a reasonable magnet line.
	Radiation load on the magnets is too high due to regular beam losses and muon decay	3	Back off on magnet requirements and add extra shielding	3	Calculations; radiation shielding for high field magnets	
	Heat load on the absorber is challenging to manage	1	Split the beam?	3	Further simulation and design work	
	Beam loading of RF cavities					
	Space charge					

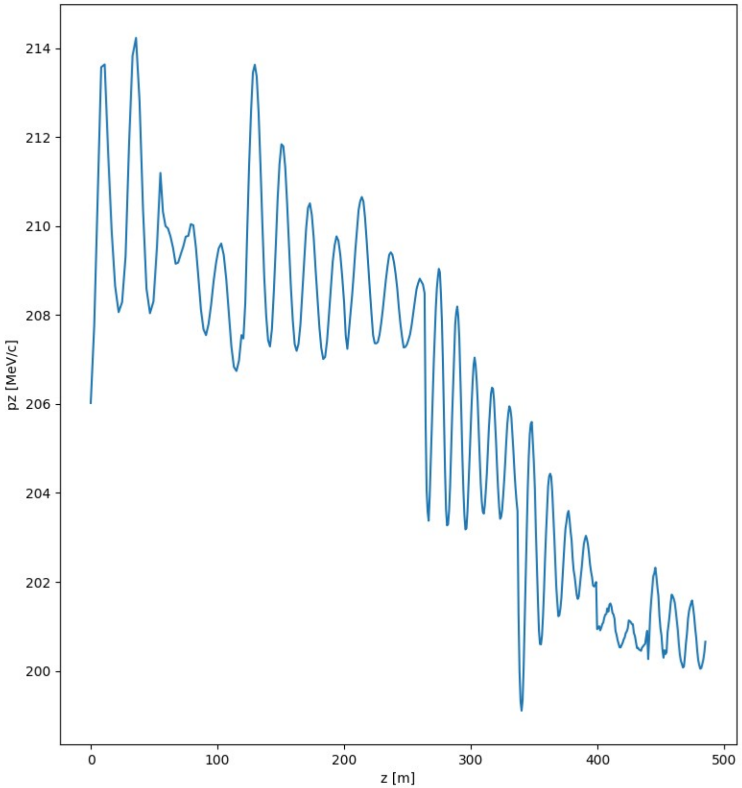
- Principle risks are at the low emittance end of the cooling channel
  - Extremely high magnetic field
  - More intense beam

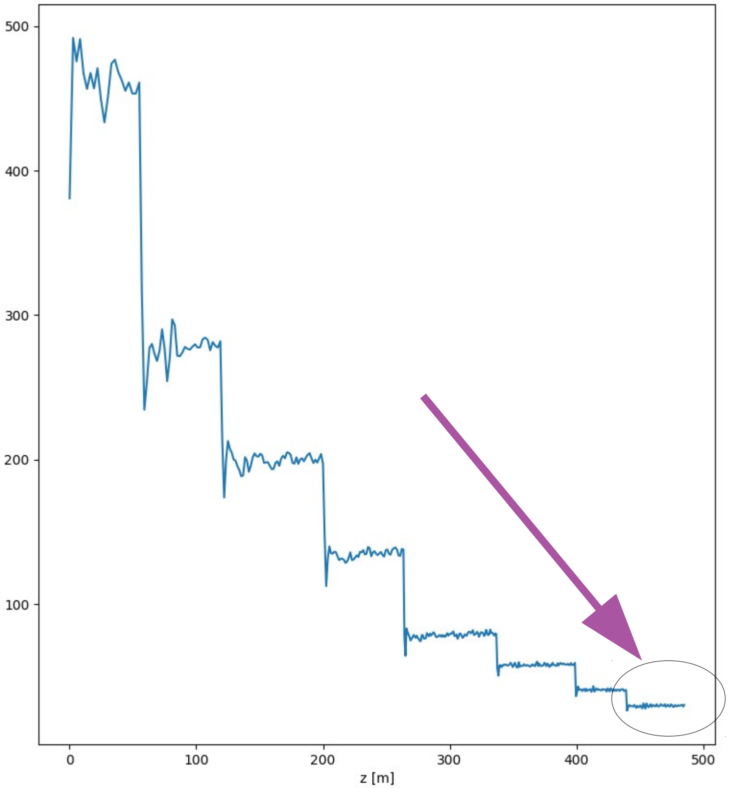
Rectilinear B8 (Stratakis et al)



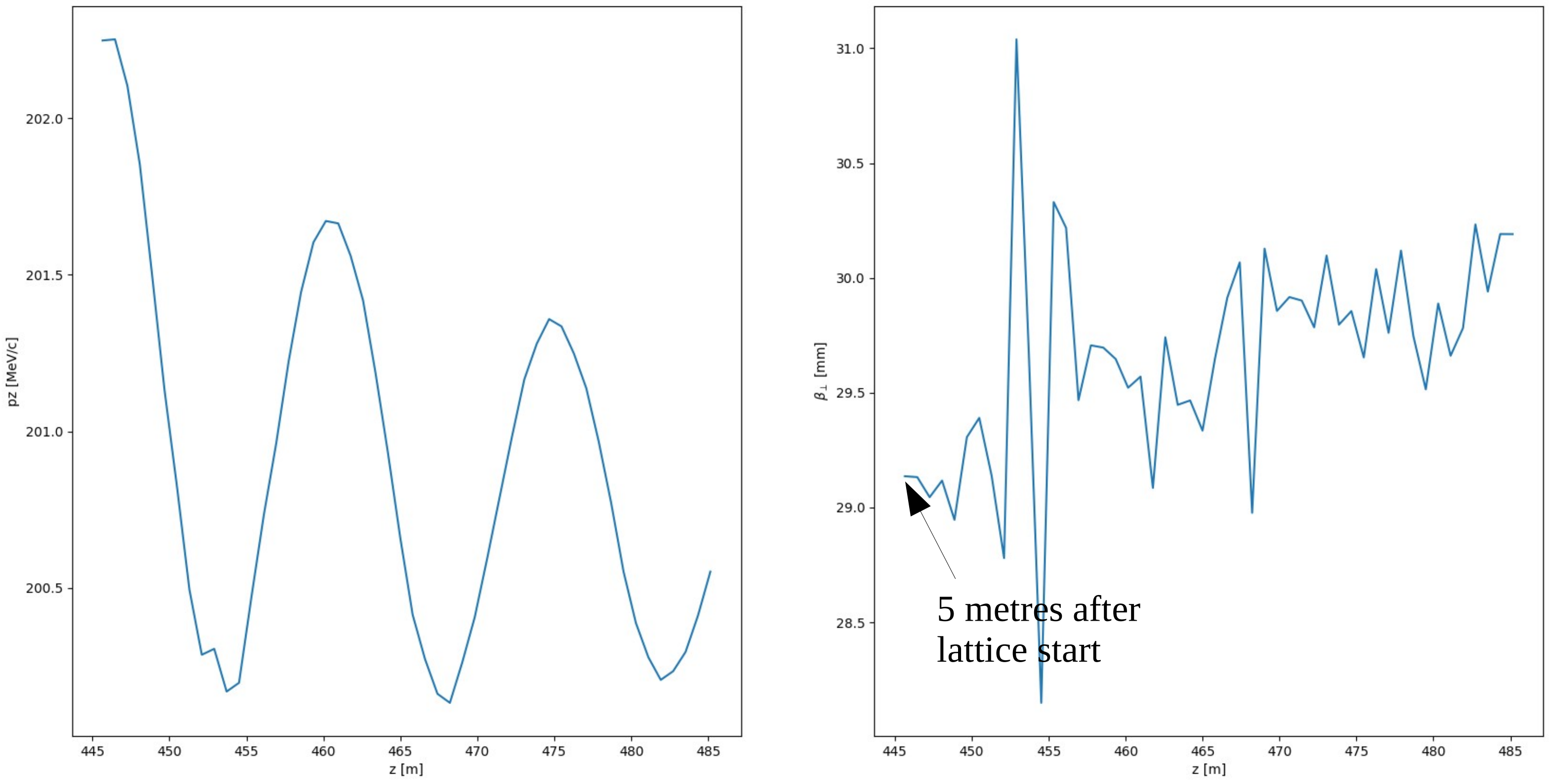
- Challenges
  - Maintaining adequate acceptance between stop bands
  - Dispersion and closed orbit control
  - Successful RF operation and suppression of RF breakdown
  - Magnet engineering
  - Integration of magnet with RF and absorber
  - Day-to-day operation
- Also intensity/collective effects
 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

Rectilinear B8



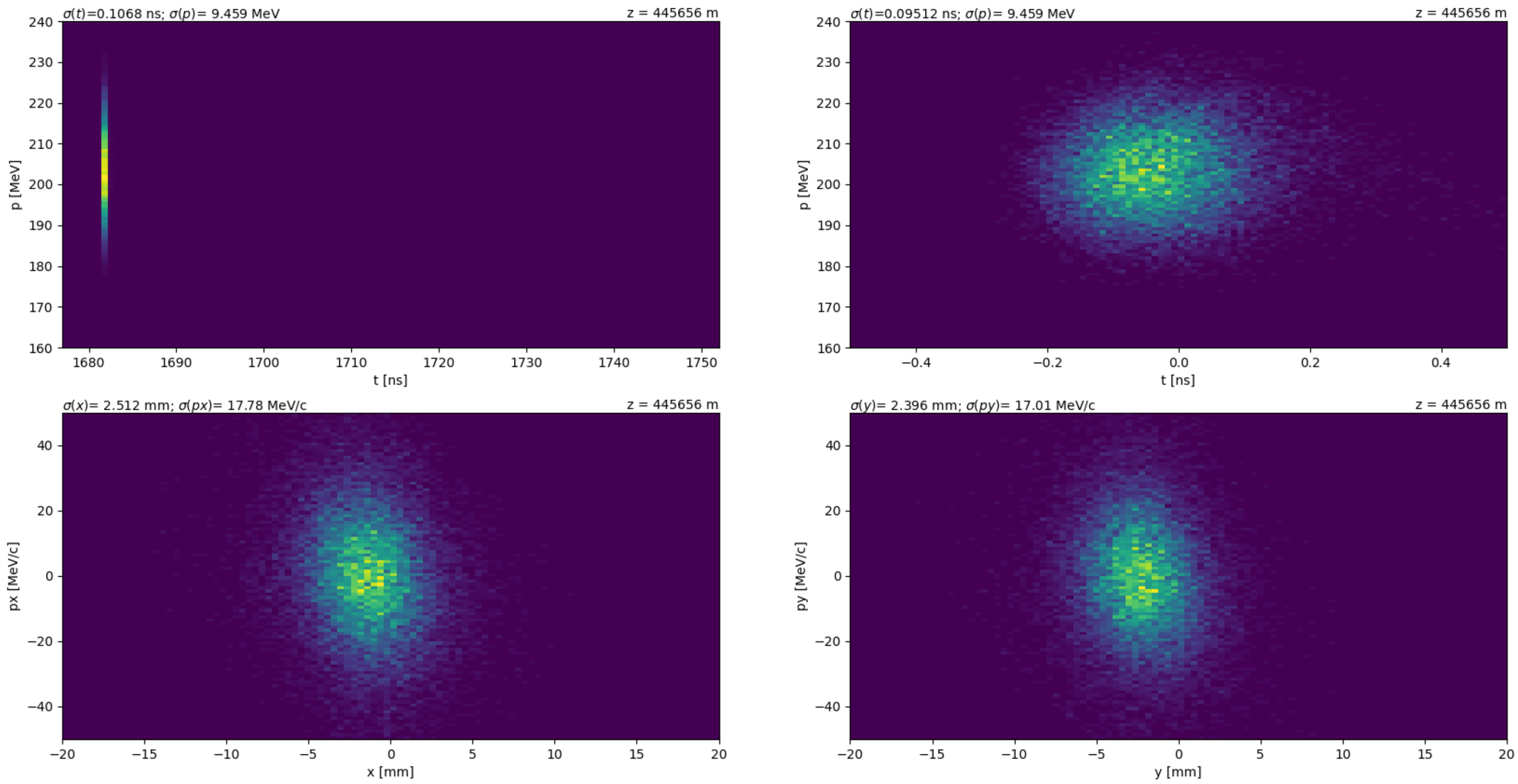


Rectilinear B8



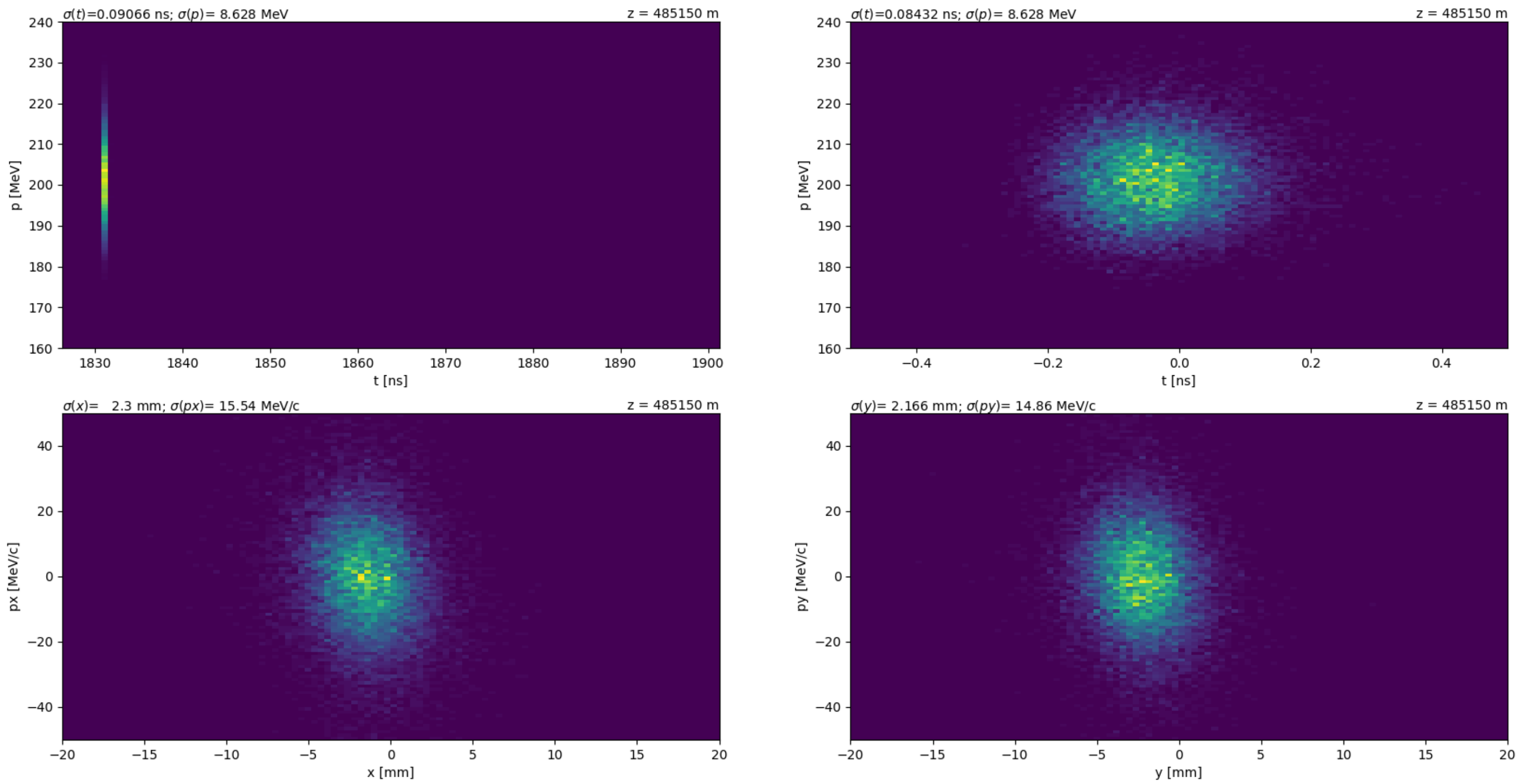
Science & Technology Facilities Council
ISIS Neutron and Muon Source

Rectilinear B8



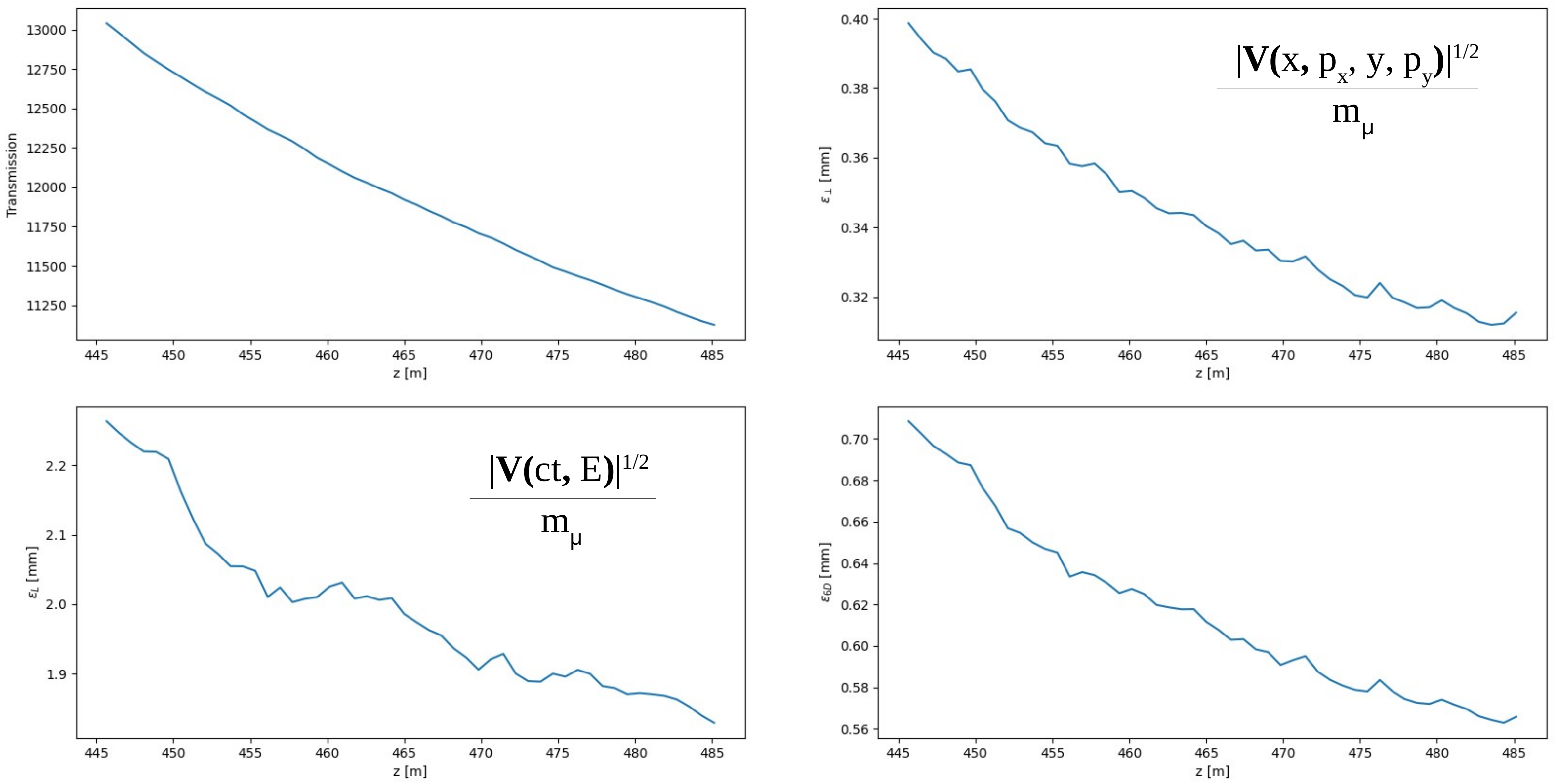
Science & Technology Facilities Council
ISIS Neutron and Muon Source

Rectilinear B8



Science & Technology Facilities Council
ISIS Neutron and Muon Source

Rectilinear B8



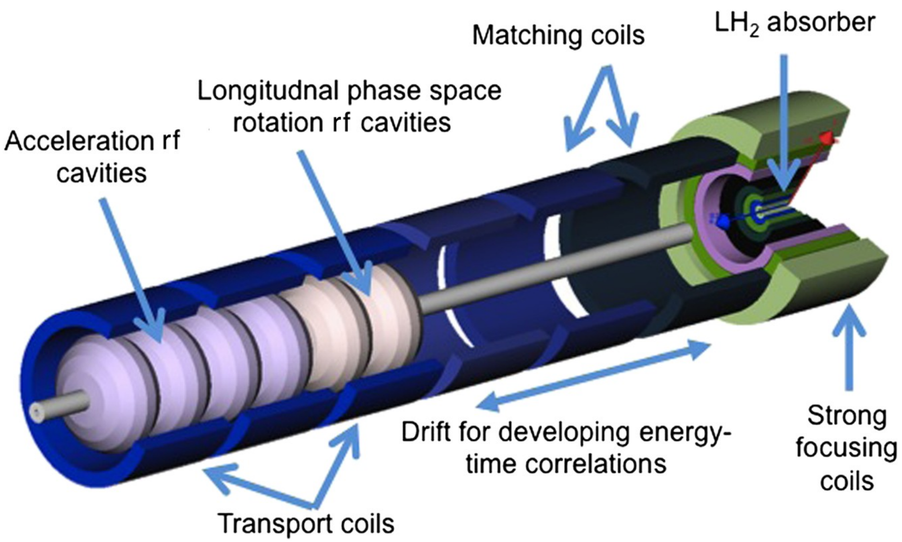
Science & Technology Facilities Council
ISIS Neutron and Muon Source

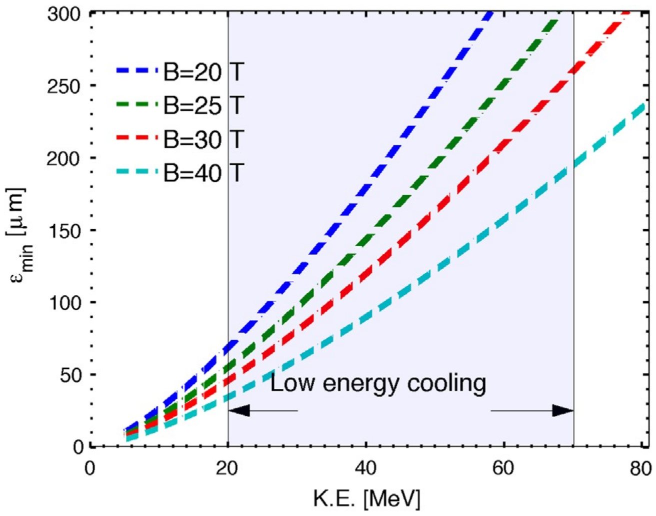
Rectilinear B8

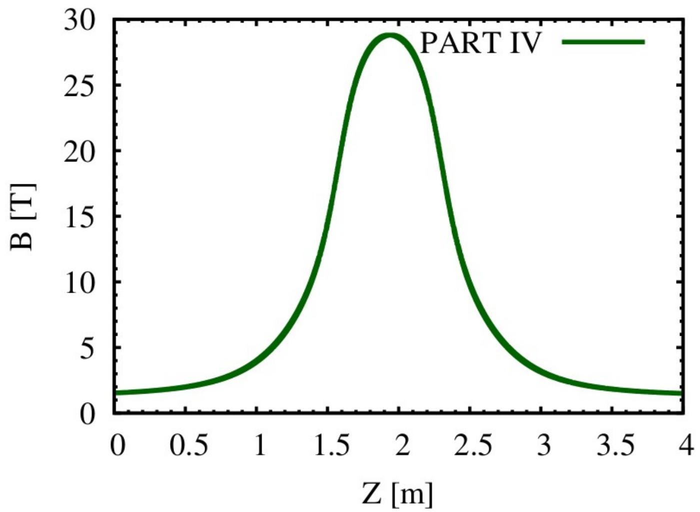
	Upstream		Downstream	
	Focus	1.5 T	Focus	1.5 T
Transverse Emittance [mm]	0.4		0.32	
Transverse Beta [mm]	29	890	29	890
sigma(x) [mm]	2.5	13.7	2.3	12.3
Sigma(px) [MeV/c]	17.8	3.1	15.5	2.8
Mean momentum [MeV/c]	200		200	
Longitudinal Emittance [mm]	2.2		1.8	
sigma(t) [ns]	0.095		0.084	
sigma(E) [MeV]	9.5		8.6	

- Beam parameters upstream and downstream of 40 m cooling channel (50 cells)
  - “Focus” is at the focus of the rectilinear channel
  - 1.5 T is in a uniform 1.5 T solenoid
  - Might imagine matching beam in/out of rectilinear for diagnostics/etc

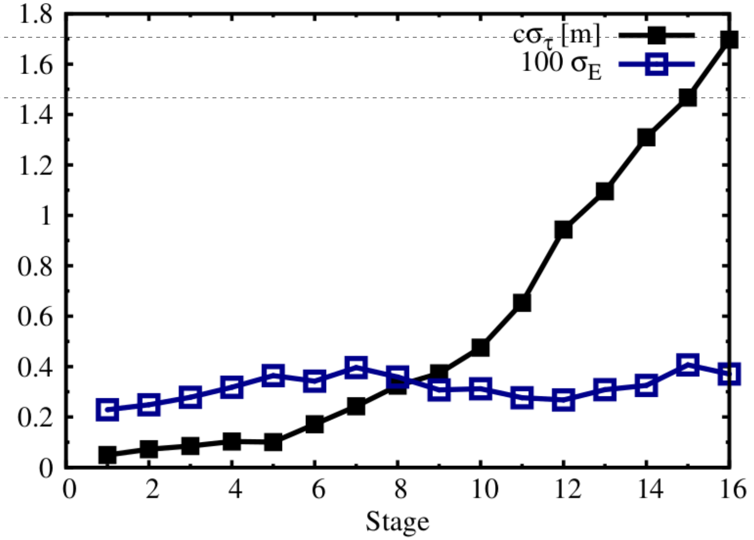
Final cooling (Sayed et al)

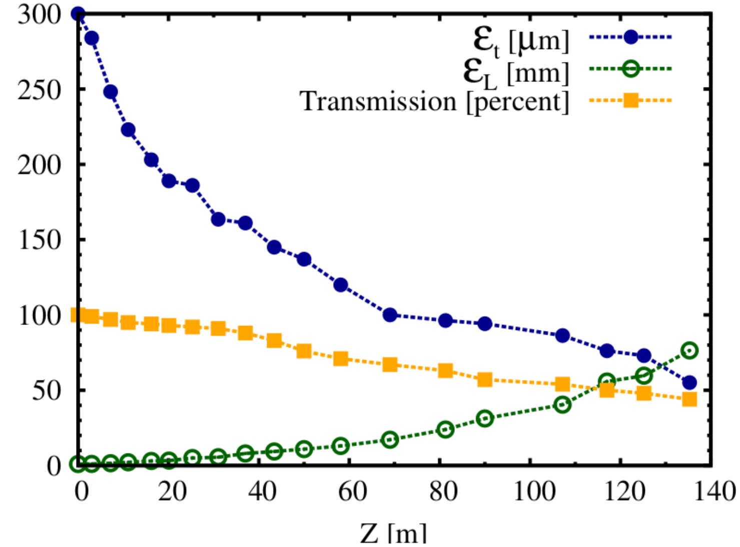


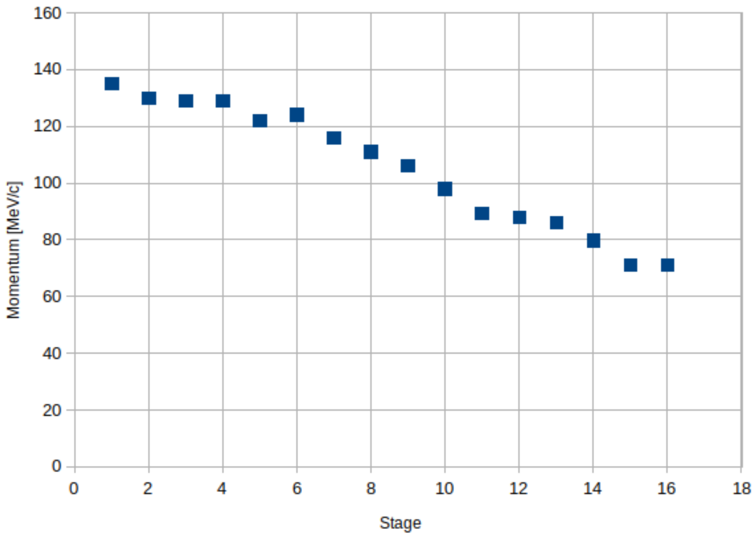


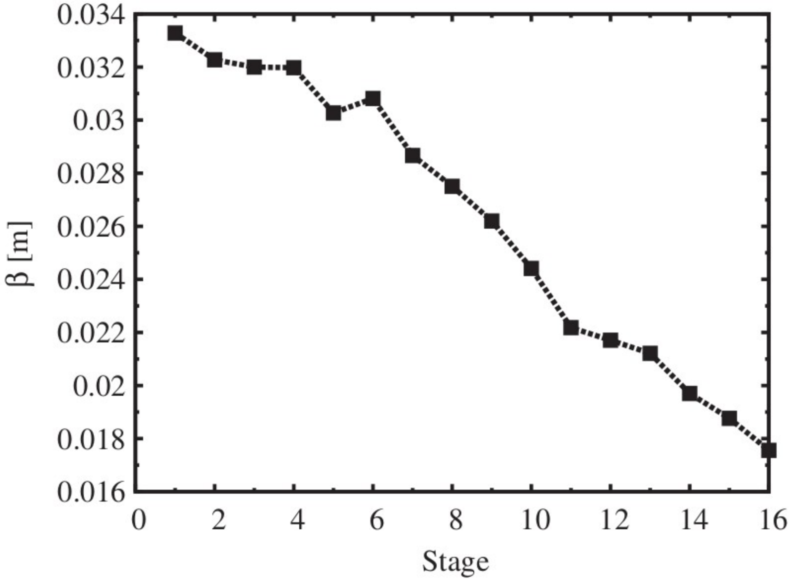


Final cooling









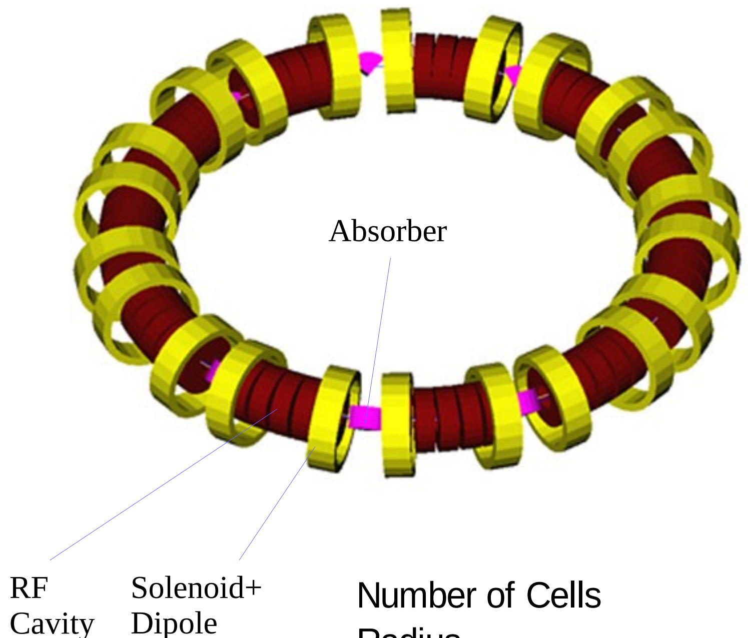
Final Cooling - Summary

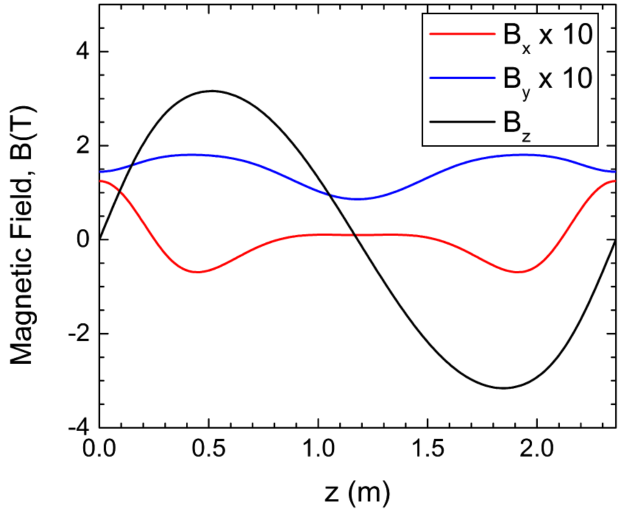
	Upstream		Downstream	
	Focus	1.5 T	Focus	1.5 T
Transverse Emittance [mm]	0.072		0.055	
Transverse Beta [mm]	18	320	18	320
sigma(x) [mm]	1.4	5.8	1.2	5.1
sigma(px) [MeV/c]	5.5	1.3	4.8	1.1
Mean momentum [MeV/c]	71		71	
Longitudinal Emittance [mm]	53		62	
sigma(t) [ns]	4.9		5.7	
sigma(E) [MeV]	3.8		3.8	

- Beam parameters upstream and downstream of single cooling cell
  - "Focus" is at the (high field) focus of the solenoid
  - 1.5 T is in a uniform 1.5 T solenoid

Solenoid Cooling Ring (Muons)

R, Palmer et al, Phys. Rev. ST Accel. Beams 8, 061003 (2005)





(b)

Number of Cells	12	Abs thickness	28 cm
Radius	5 m	Abs material	liquid H2
Energy	250 MeV	Voltage/turn	~120 MV
Solenoid field	2.8 T	RF phase	25 degrees
Dipole field	0.15 T	RF freq	201 MHz

Solenoid Cooling Ring (Muons)

	Upstream Focus	Downstream Focus
Transverse Emittance [mm]	12	3.3
Transverse Beta [mm]	400	400
sigma(x) [mm]	50	26
Sigma(px) [MeV/c]	25	13
Mean momentum [MeV/c]	200	200
Longitudinal Emittance [mm]	18.4	4.8
sigma(t) [ns]	0.805	0.411
sigma(E) [MeV]	8.05	4.1

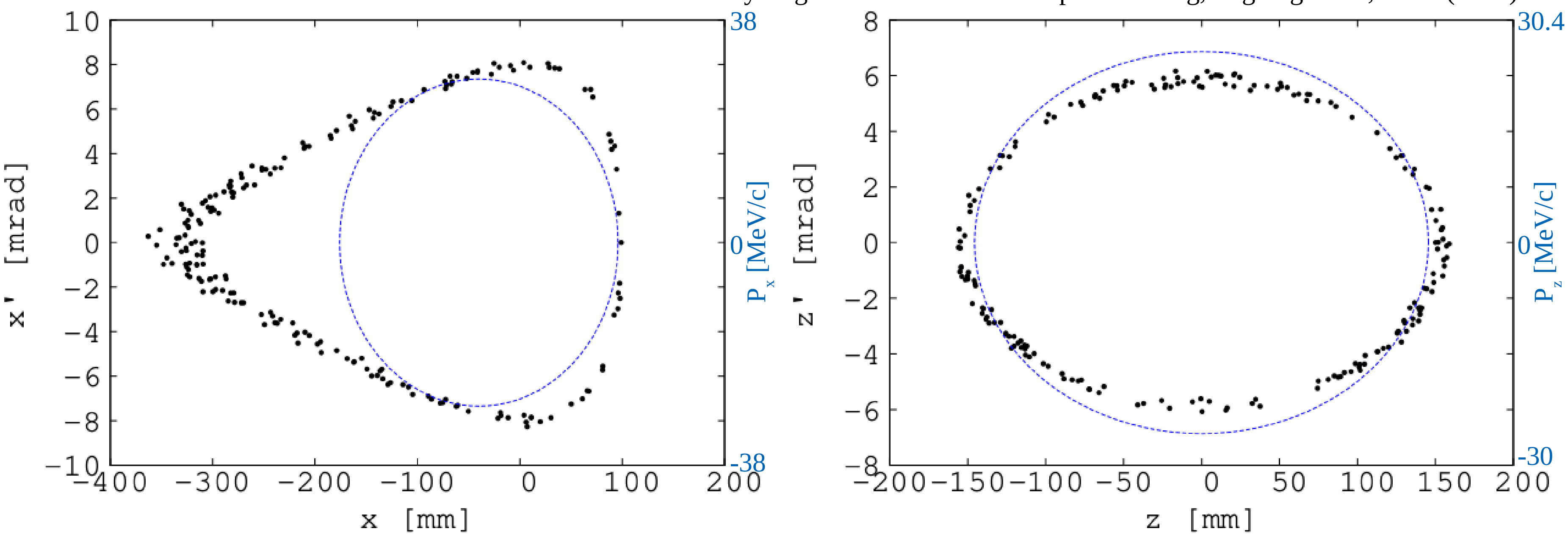
- More MICE-like
- Consider pion stochastic injection like nuSTORM?
- No need to extract
  - But not like a "realistic" muon collider cooling ring
- Would need to design low emittance cooling option

Input beam

- Bring beam energy down by low-Z energy absorber
- Generate transverse distribution by collimation
- Longitudinal distribution not so straight forward
  - (Solenoid) chicane to generate dispersion + collimators?
  - RF kickers to generate time structure?
- Need to leave enough muons that they can be measured!

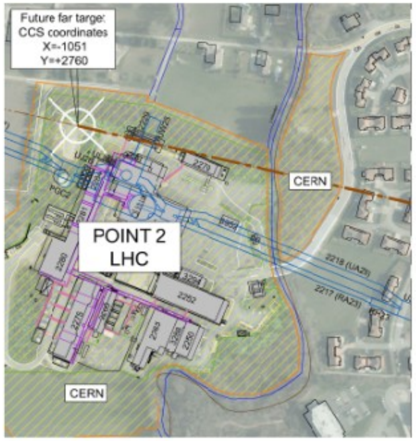
Storage Ring Phase Space

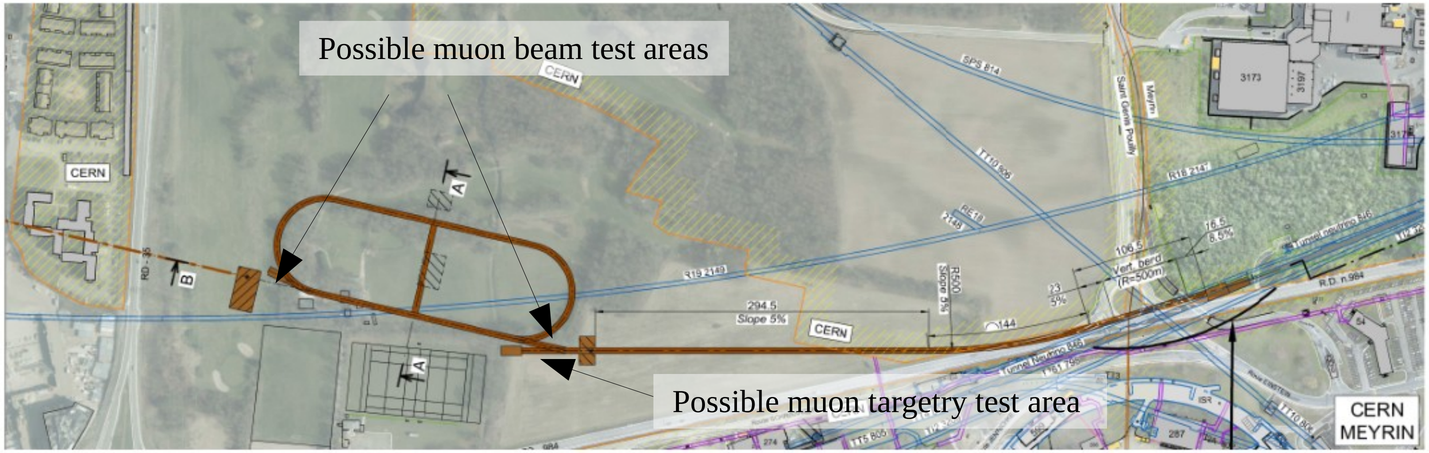
Racetrack FFAG muon decay ring for nuSTORM with triplet focusing, Lagrange et al, J.Inst (2018)

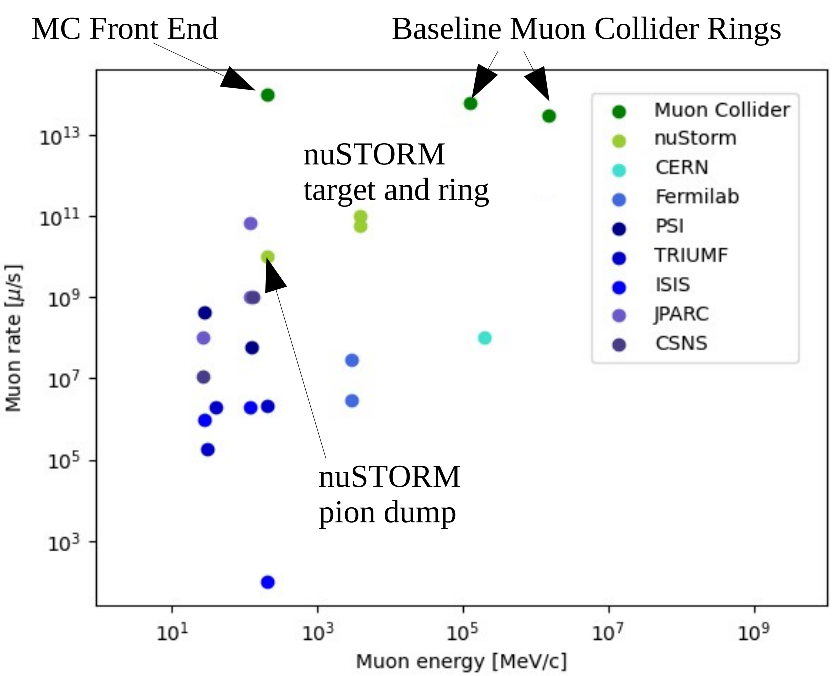


- Muon phase space in the nuSTORM storage ring
  - Central momentum 3.8 GeV/c

Survey of Muon Beamlines







- NuSTORM would make an excellent facility
  - One of the highest current high energy muon beams
  - Deal with routine issues
    - E.g. routine operation of equipment in presence of muon decays
- Target/irradiation test area
- Muon beam physics tests

Discussion

- Few options for ionisation cooling tests considered
- Worth thinking about how we can make the beams
  - Probably intensity limit is ruled out – for muons at least
  - Do we build a proton test facility elsewhere?