Demonstrator Layout – Requirements from Beam Optics

International MUON Collider Collaboration

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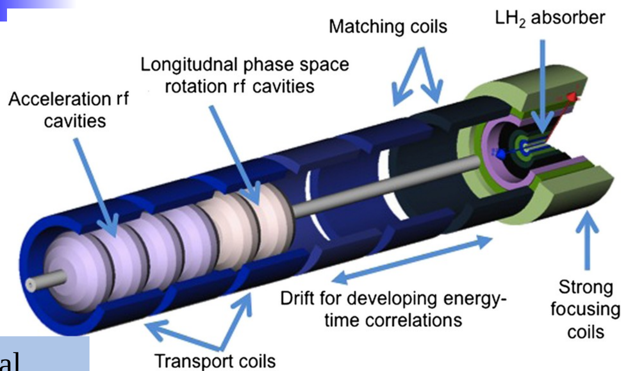
Science & Technology Facilities Council ISIS

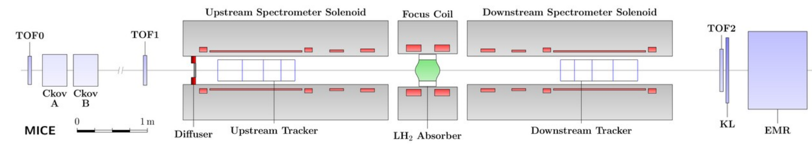
Muon Cooling Demonstrator

- Ionisation cooling is a key technology for the Muon Collider
  - It is entirely novel
  - Proof of principle “MICE” in 2020
  - But only a single cooling element
- Now need to deliver a demonstration of 6D ionisation cooling
  - Demonstrate full capability
  - Sufficient emittance reduction to convince that we can deliver the full cooling channel

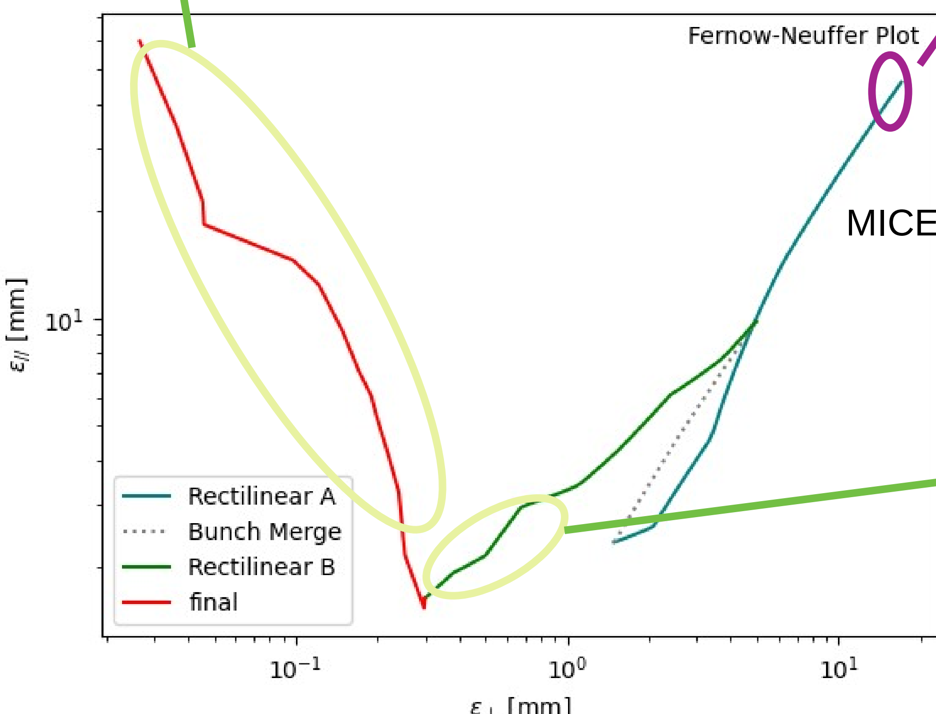
Cooling for a Muon Collider



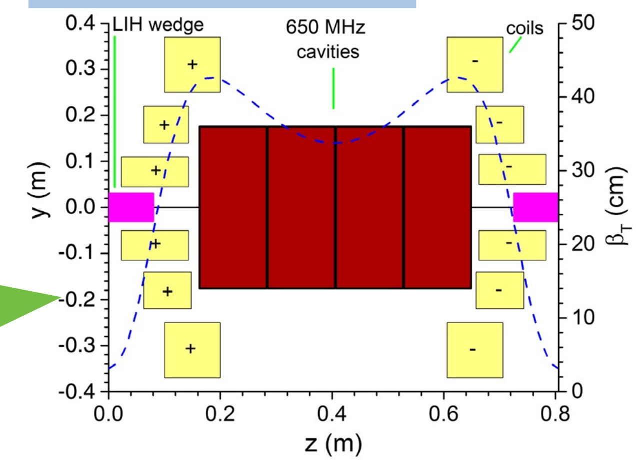
Final cooling



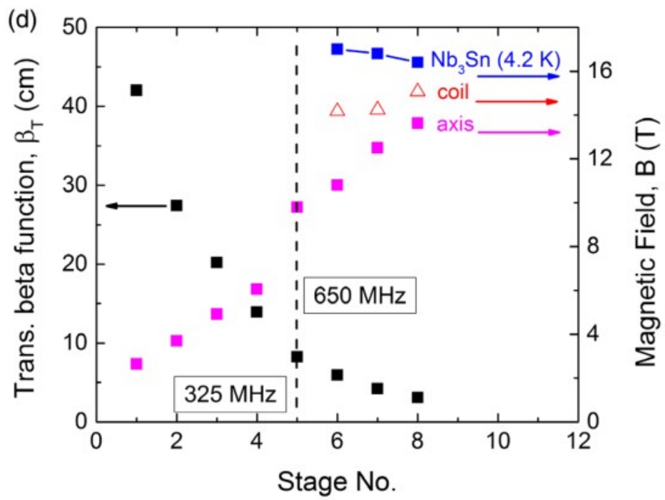
"MICE-like"

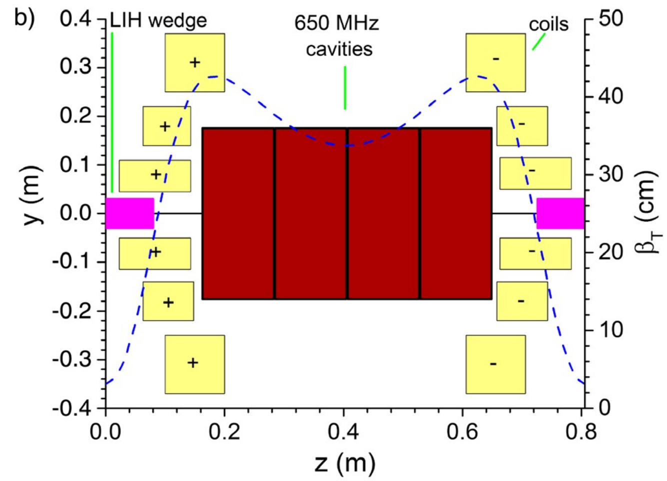


Rectilinear B (Stage B8)



Rectilinear Lattice (Stratakis et al)

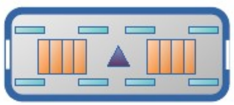




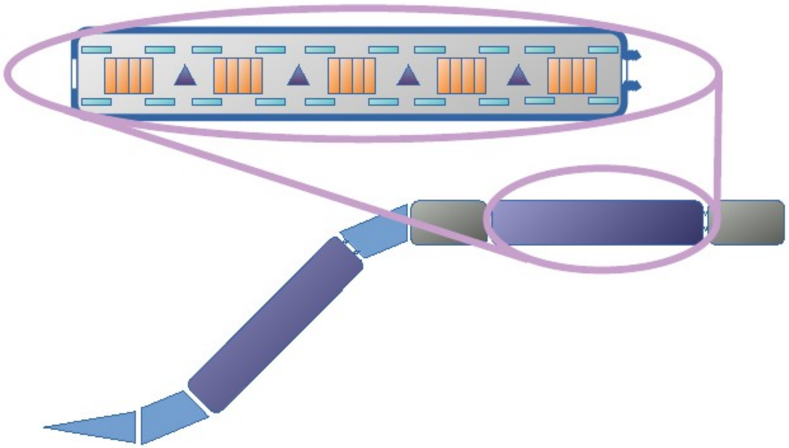
- Challenges
  - Dispersion and closed orbit control for 6D cooling
  - Successful RF operation and suppression of RF breakdown
  - Maintaining adequate acceptance between stop bands
  - Magnet engineering
  - Integration of magnet with RF and absorber
  - Day-to-day operation and instrumentation
- Also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

R&D Programme

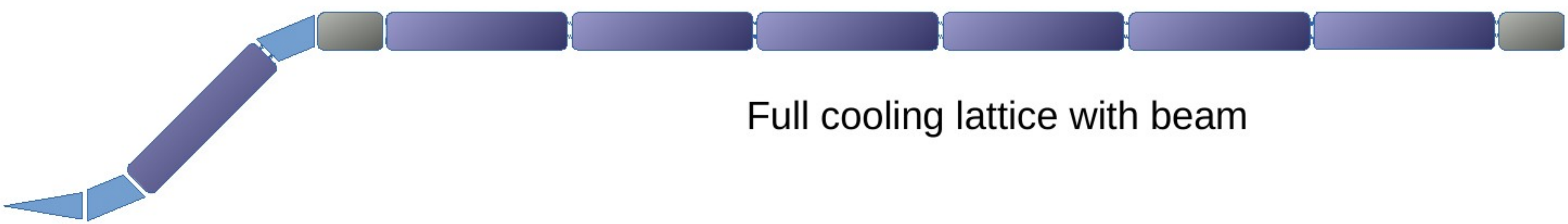
RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



Prototype of a cooling vacuum vessel to test magnet, absorber and RF integration

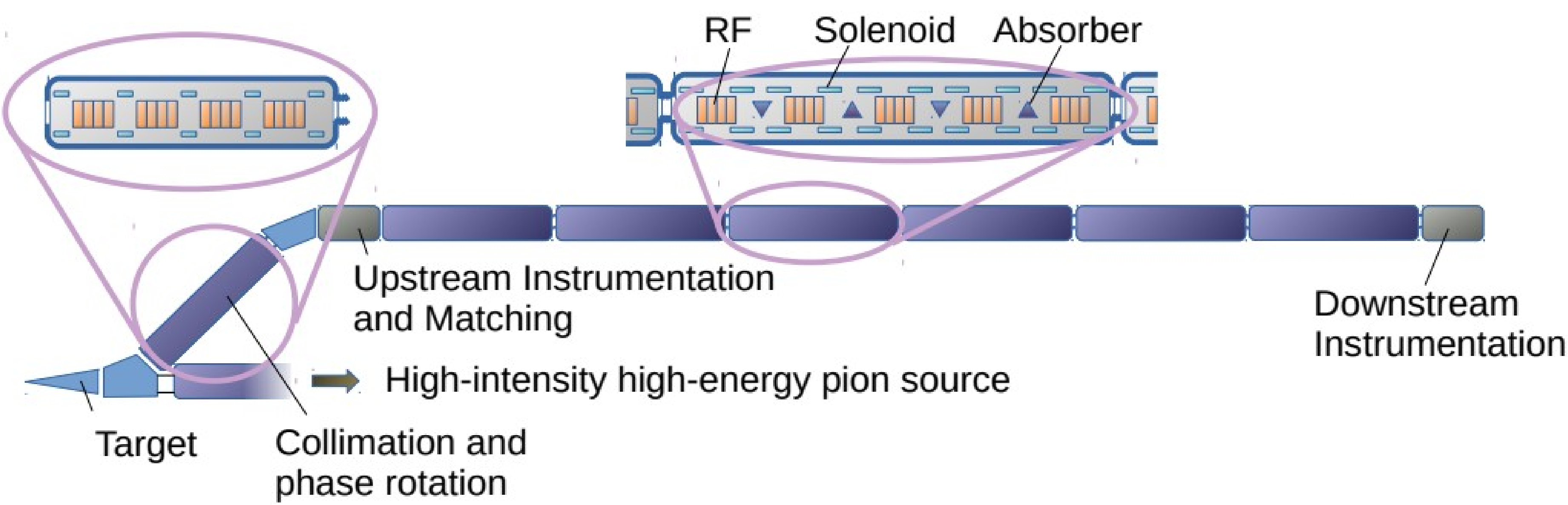


Full cooling vacuum vessel with beam

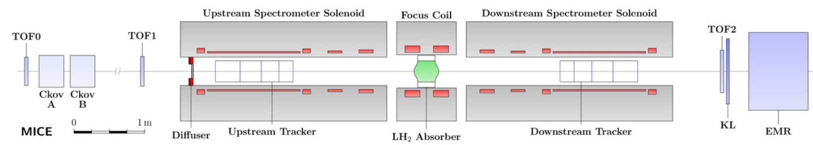


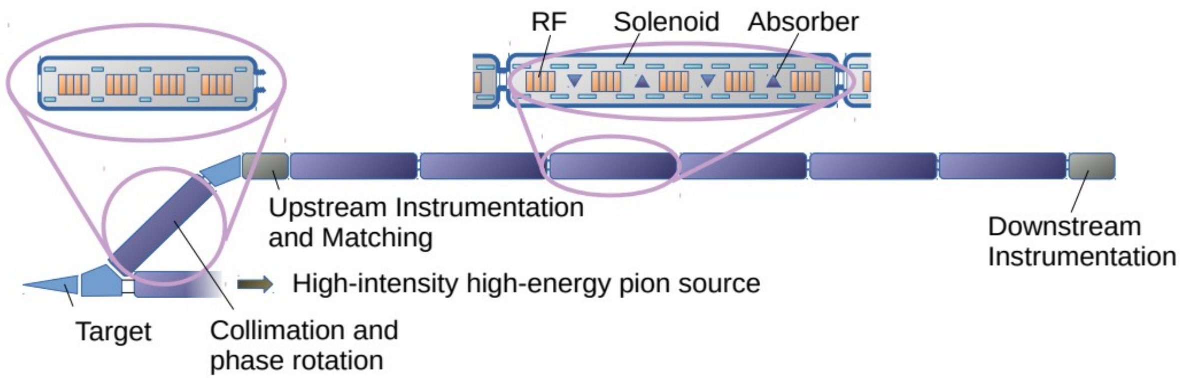
Full cooling lattice with beam

Layout


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

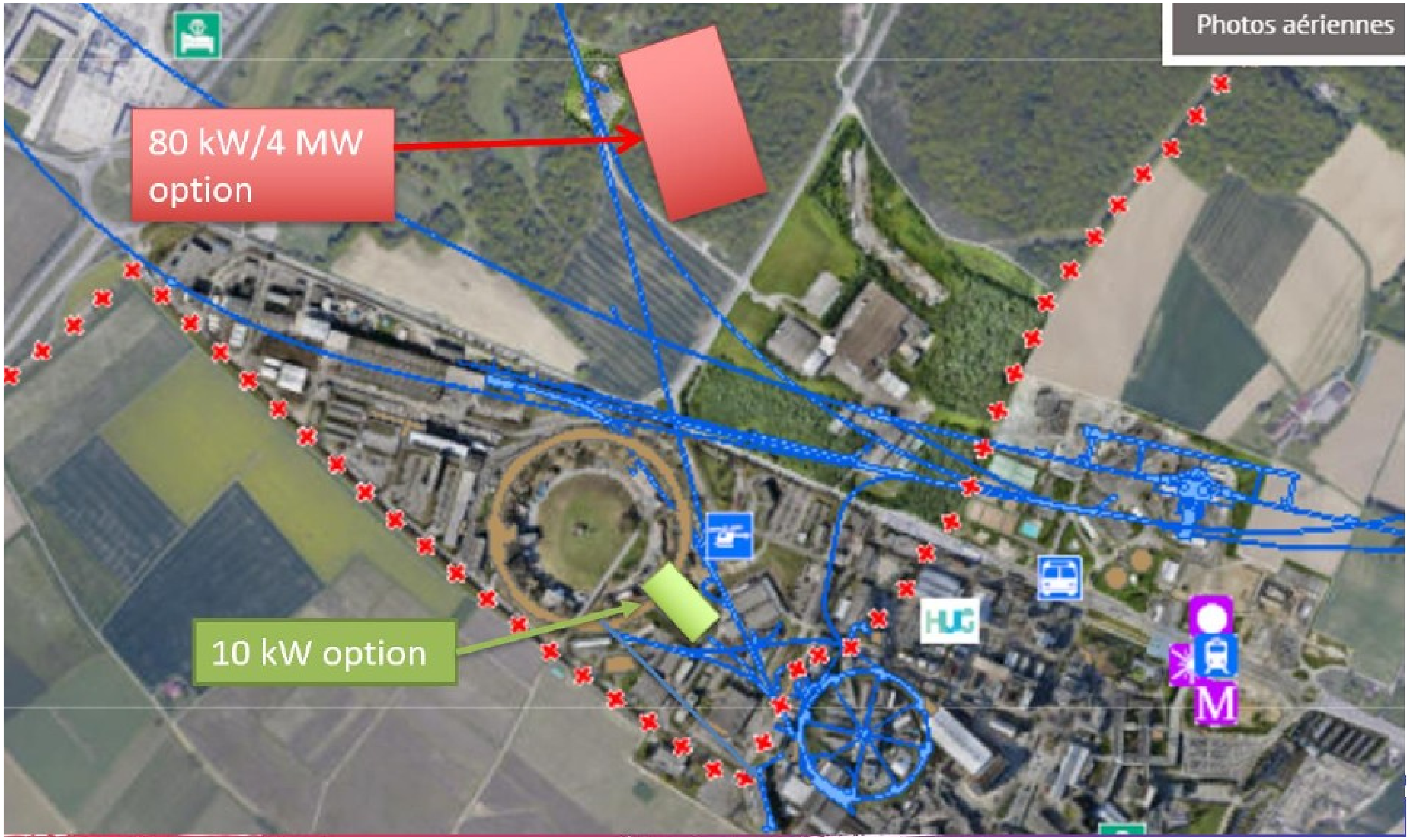
Comparison with Existing Data





	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

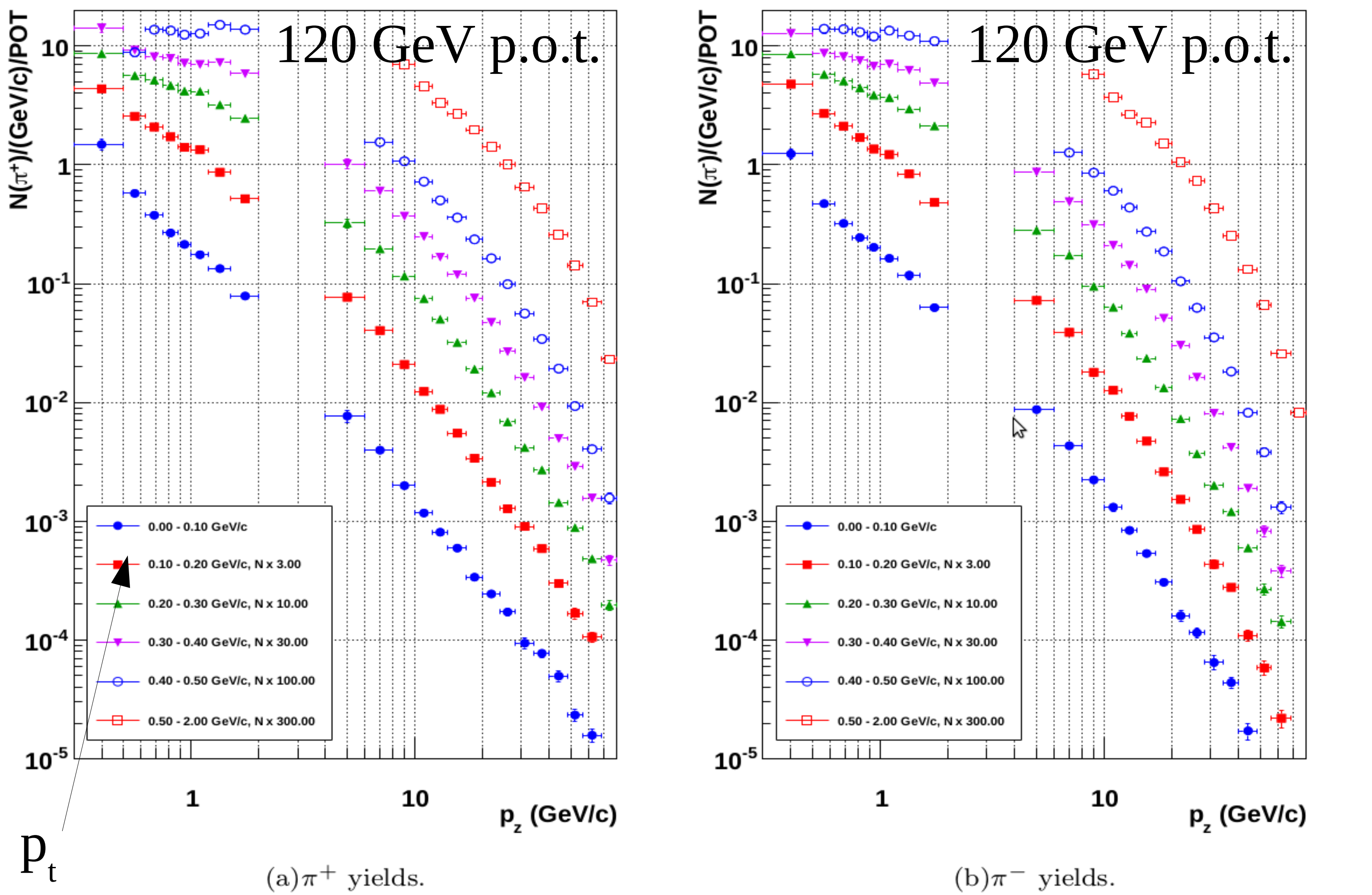
CERN Siting Options



- C/O Roberto Losito

NuMI beam

Paley et al, Measurement of charged pion production yields off the NuMI target, PRD vol 90, 2014



(a)π^+ yields. (b)π^- yields.

Assume (Vaguely worded in nuSTORM feasibility study):

SPS provides O(1e13) p.o.t. in 450 ns pulse comprising 4 bunches?

Expected muon yield

Invoke ***magic collimator fairies***

For rectilinear cooling B8:

- $\sigma(t) = 0.1$ ns
- $\sigma(p) = 0.010$ GeV/c
- $\sigma(p_x) = 0.010$ MeV/c
- $\sigma(x) = 3$ mm

Selection:

- *factor 0.01 pz selection*
- *factor 1 pt selection*
- *factor 0.01? position selection*

Per single RF bucket:

- *0.1 ns/450 ns = factor 0.0002 time selection*

Adding up all RF buckets in the pulse

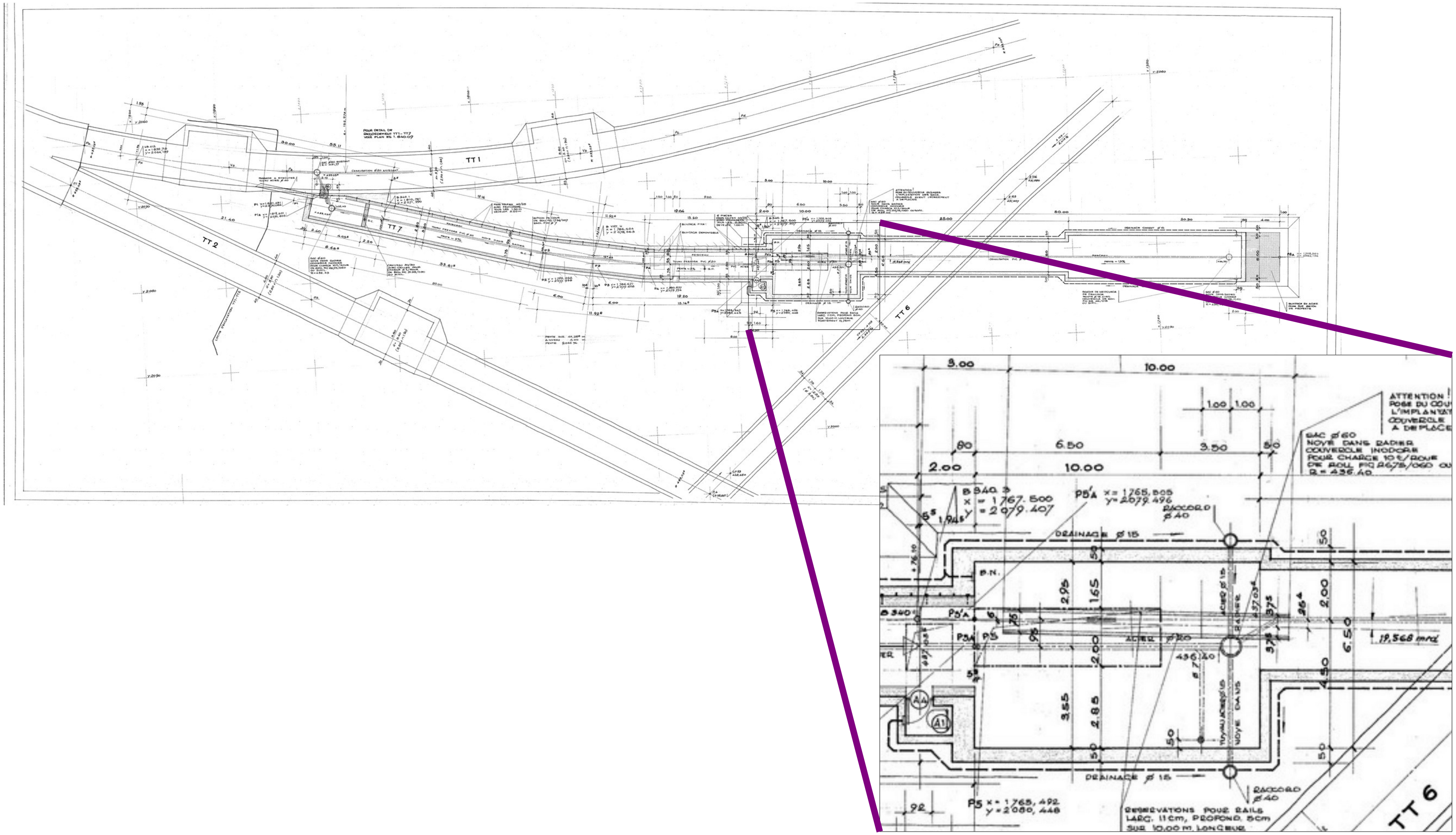
- *0.1 ns*650 MHz = factor 0.065 time selection*

Yields

- ***2e5 muons per RF bucket***
- ***5e8 muons in all RF buckets in a pulse***

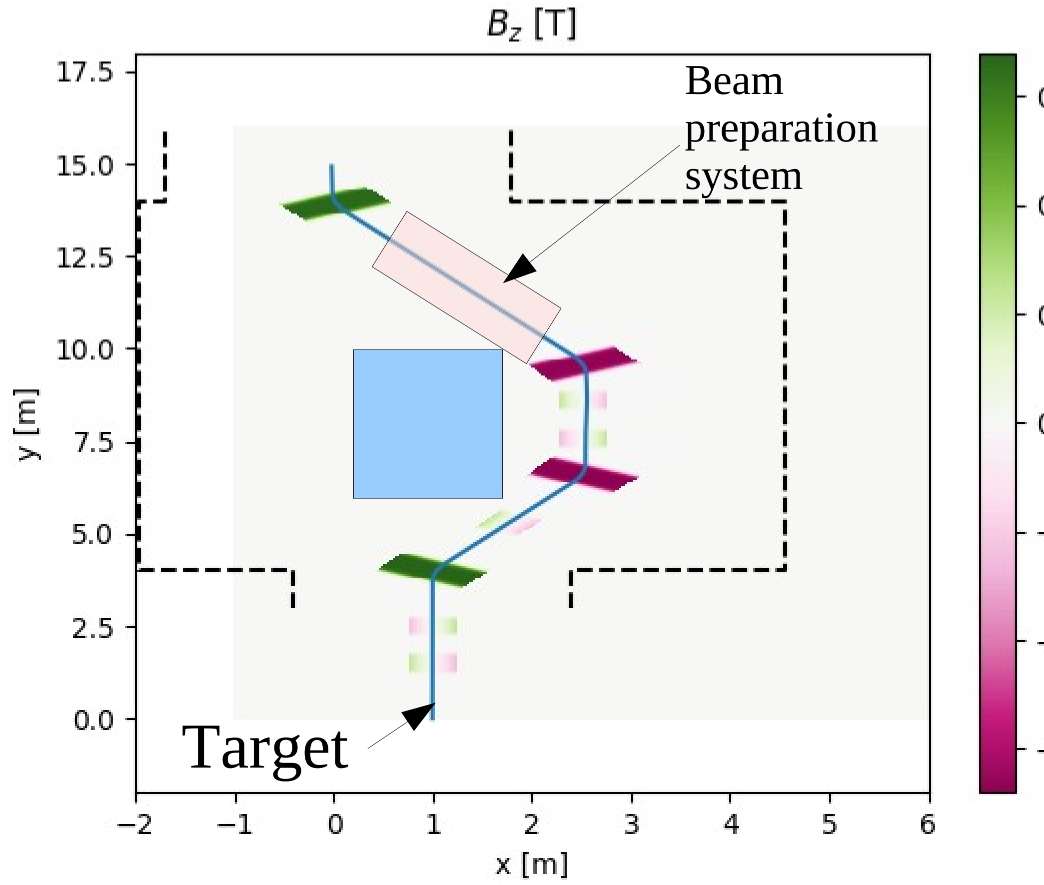
Will lower energy protons help? The number of p.o.t. is probably the same

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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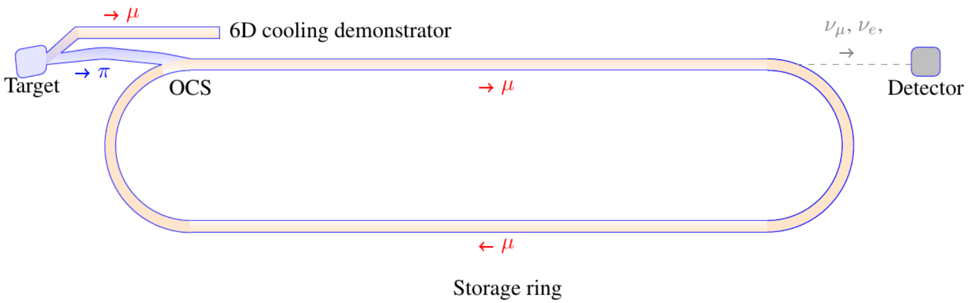
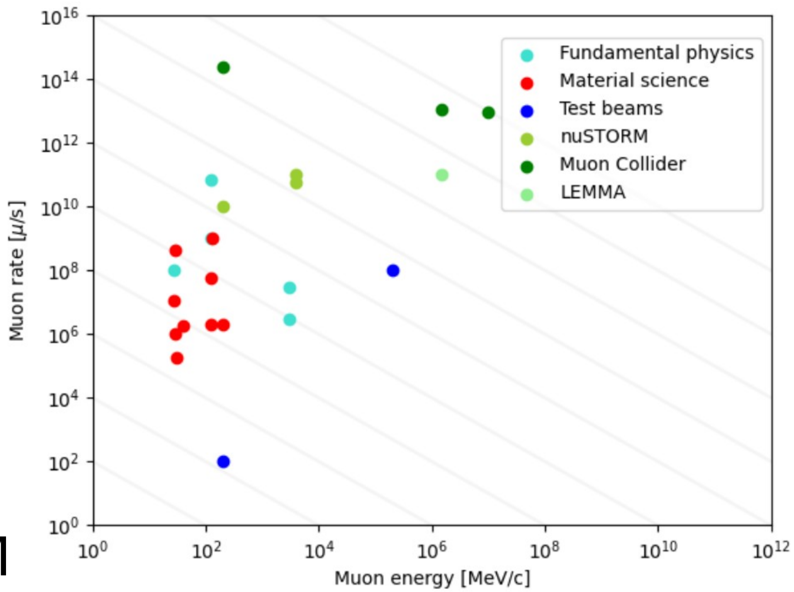
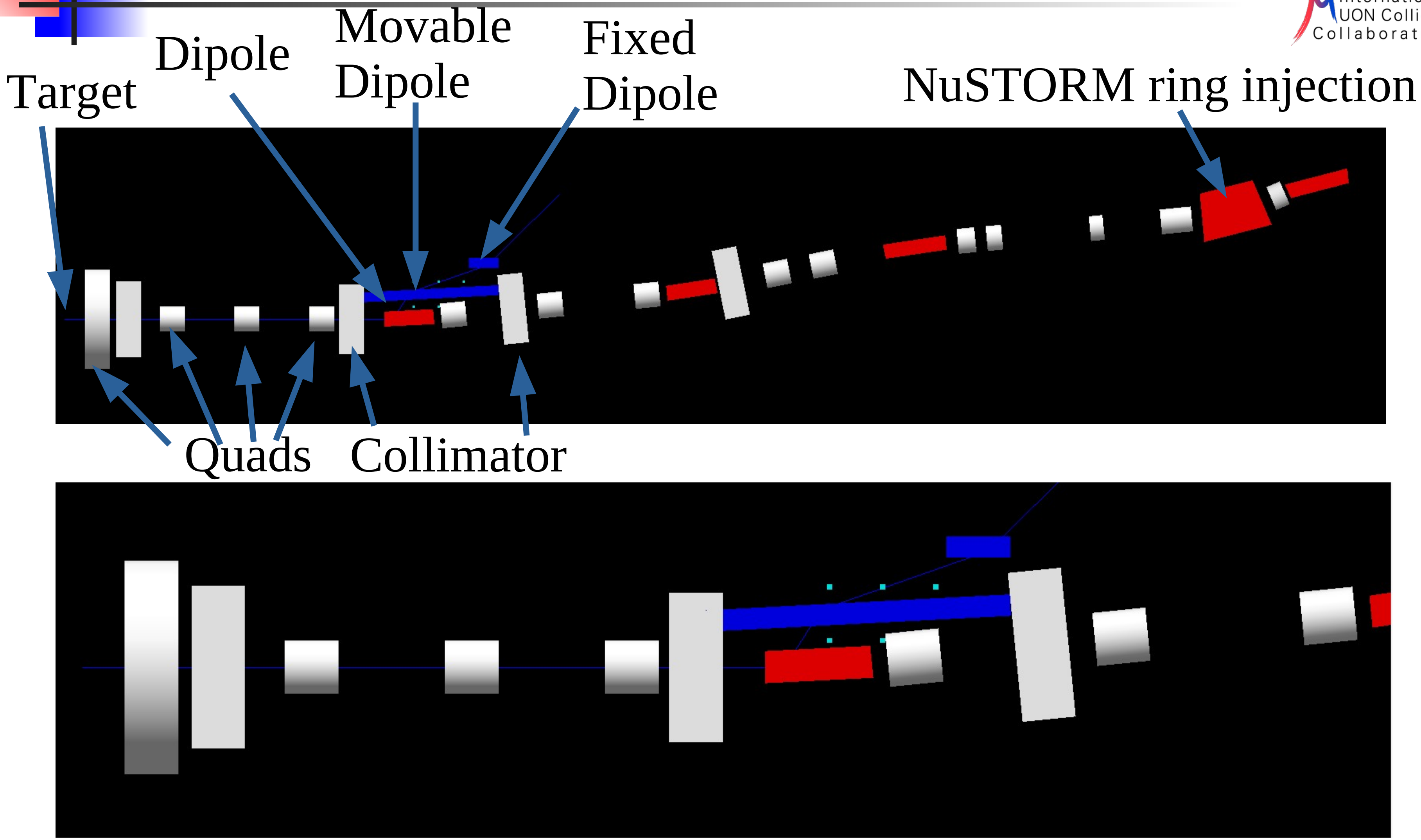
nuSTORM





- 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



NuSTORM layout – c/o Jaroslaw Pasternak et al

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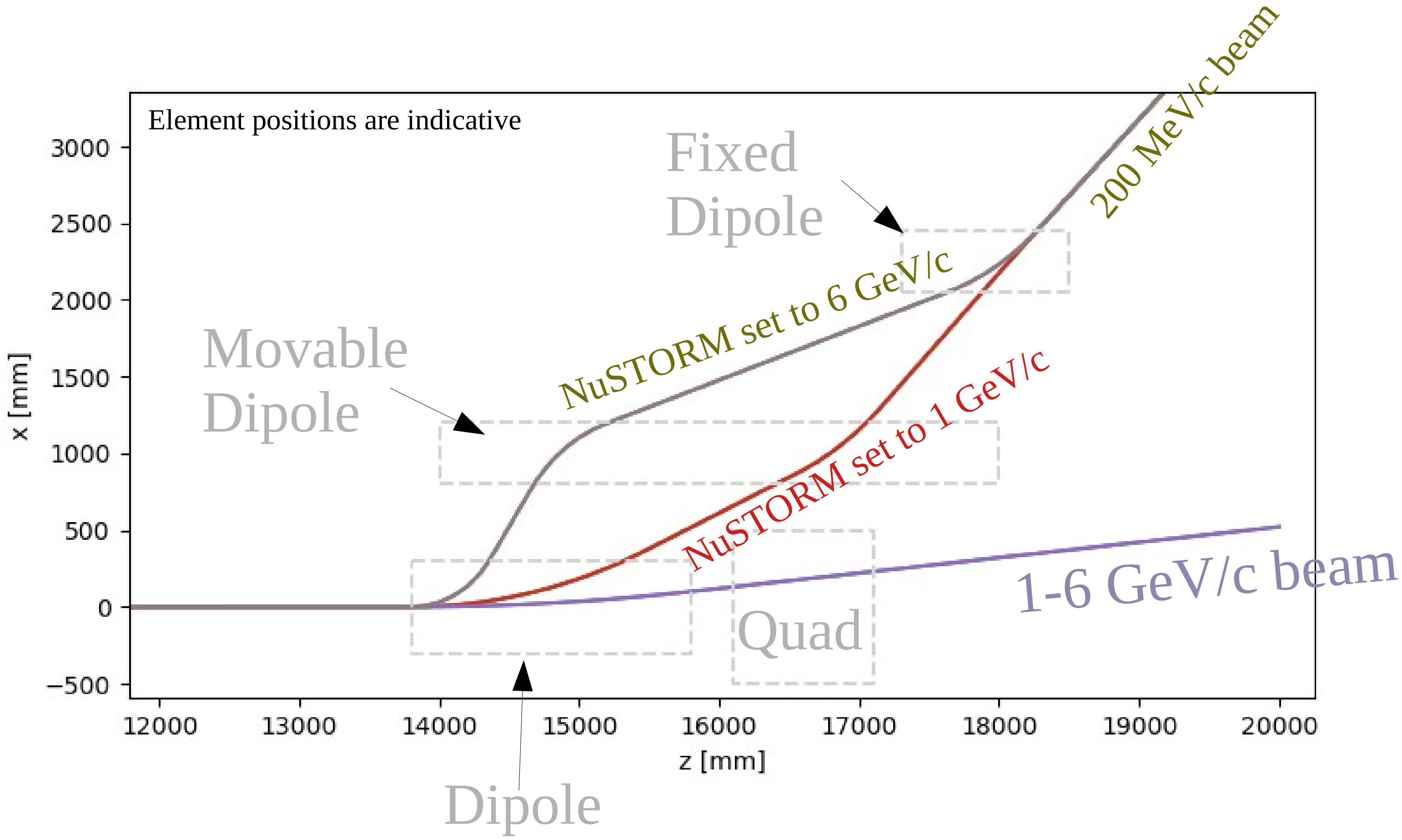
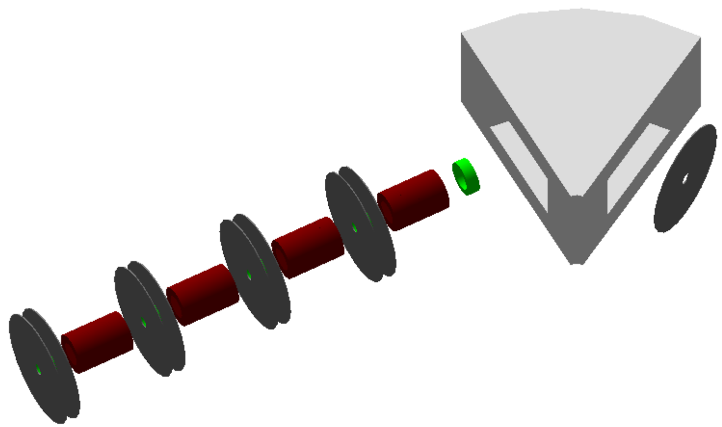
Layout – nuSTORM (2)



Beam preparation system

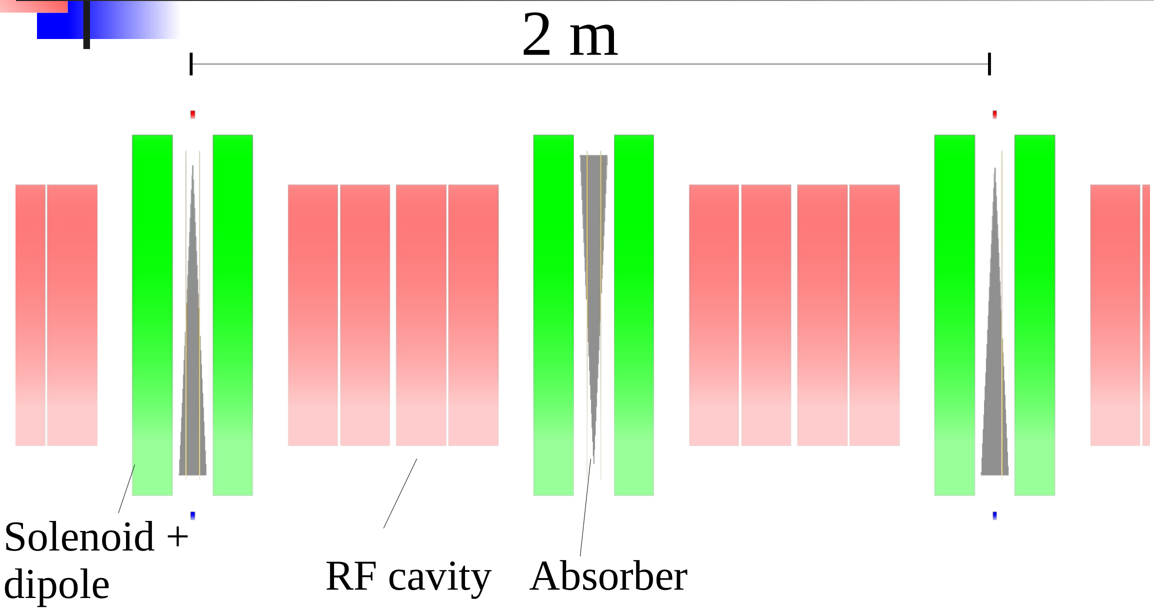
- ~ 100 ps pulsed muon beams don't exist
  - Muons have only rarely been accelerated in conventional RF cavity
  - Low emittance muon beam challenging to achieve
- Need to consider a system to prepare the muon beam
  - Assume momentum collimation in switchyard
  - Transverse collimation
  - Longitudinal phase rotation



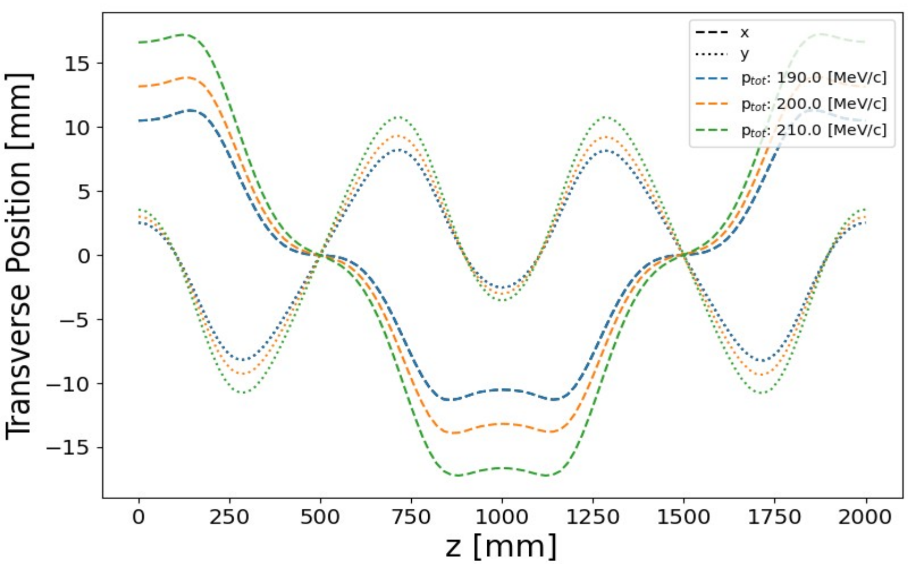
Beam Preparation System

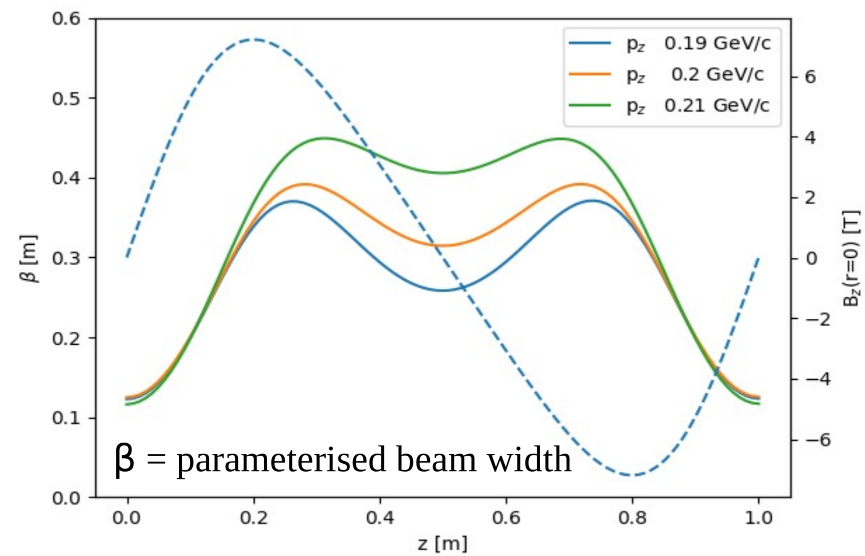
Parameter	Value
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

Preliminary Cooling Cell Concept



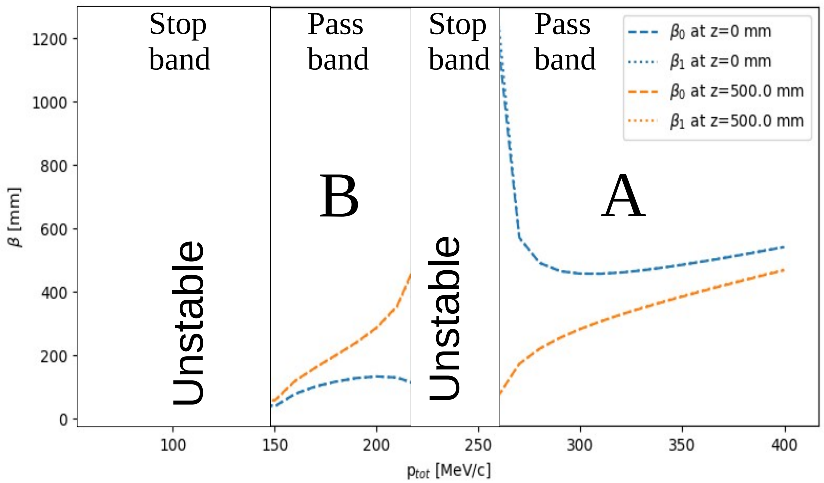
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

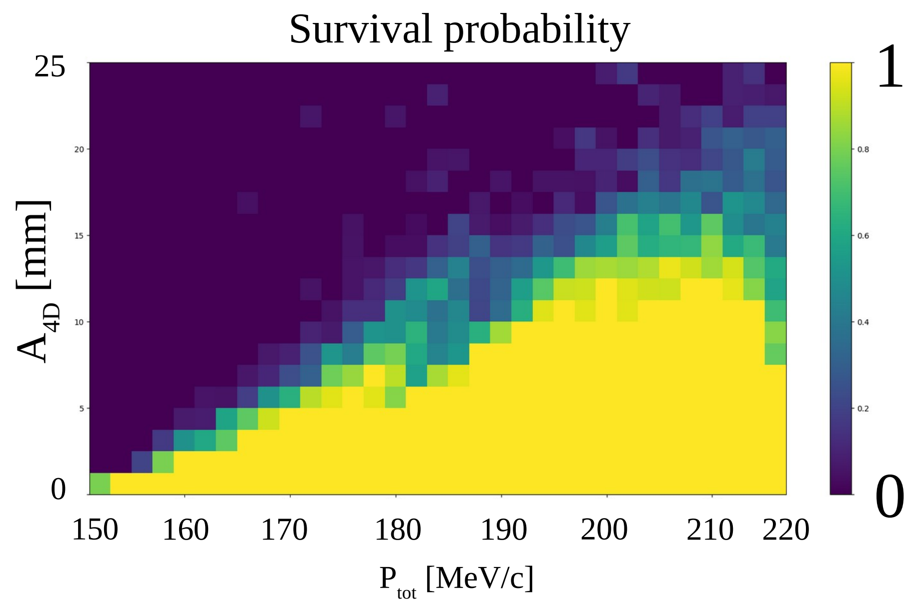




Optics vs momentum

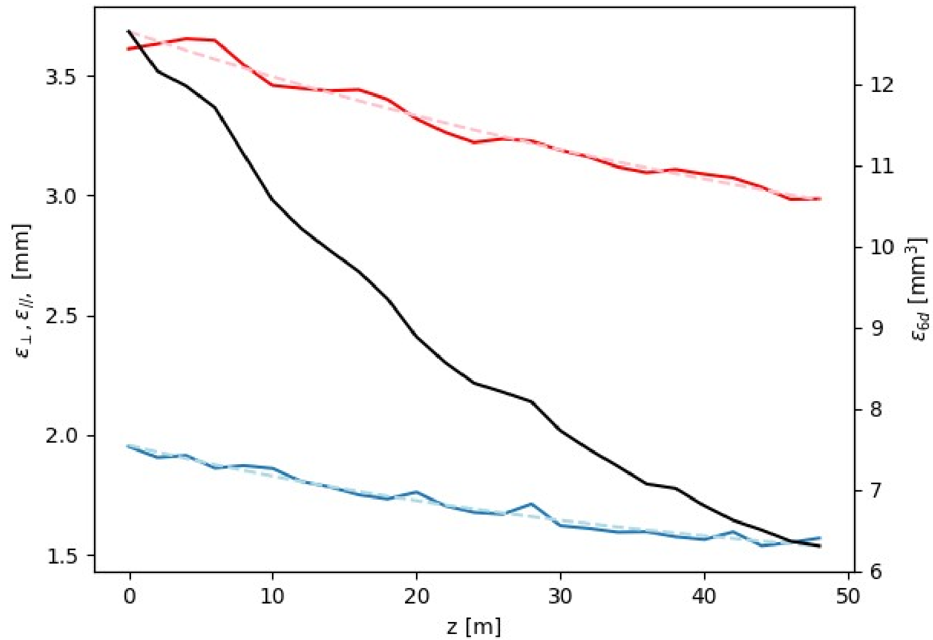
- Operation in area **A**
  - High dynamic aperture
  - Larger β
  - Larger emittances
- Operation in area **B**
  - Lower dynamic aperture
  - Smaller β
  - Lower emittances
- Lattice operates in area **B**
  - May wish to check out area A also





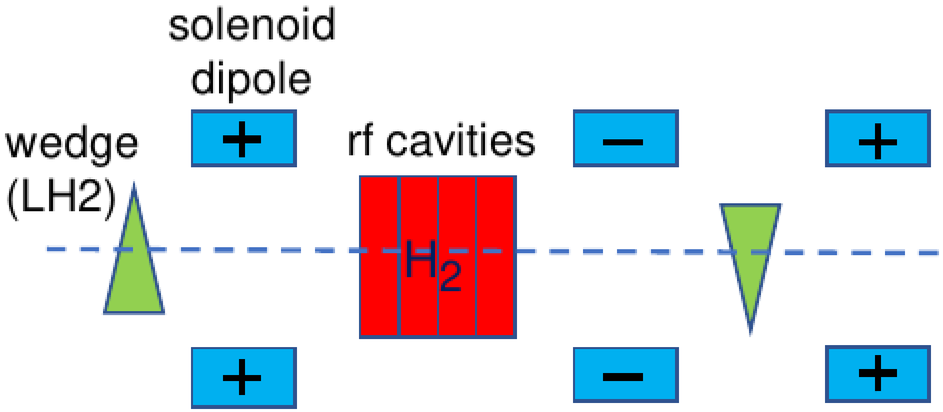
Be RF & LiH Performance

- 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

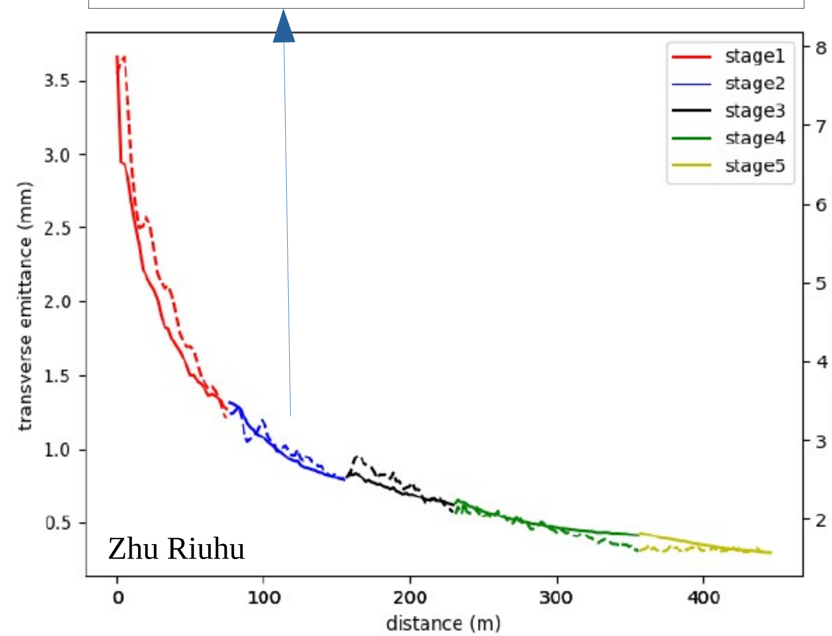


Transmission losses	2.00%
Decay losses	4.00%
Trans ε in	1.95 mm
Trans ε out	1.57 mm
Long ε in	3.61 mm
Long ε out	2.99 mm
6D ε in	12.7 mm^3
6D ε out	6.3 mm^3

lH2 Performance (Zhu Riuhu, IMP CAS)



Losses	8%
Trans ε in	1.3 mm
Trans ε out	0.8 mm
Long ε in	3.3 mm
Long ε out	2.5 mm
6D ε in	5.3 mm^3
6D ε out	1.5 mm^3



- Look at lH_2
  - Improved performance
- Considering both Be/vacuum or High Pressure gas insulation
- Next
  - Consider spreading H2 in whole lattice
  - Consider effect of pressure windows at start/end

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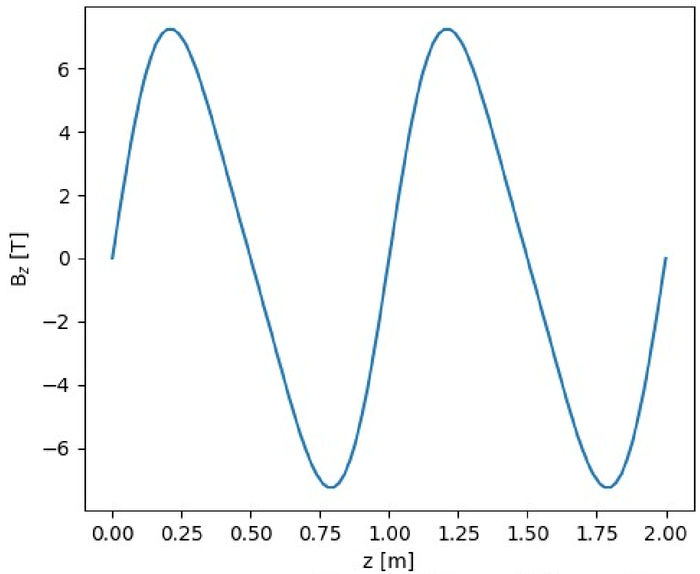
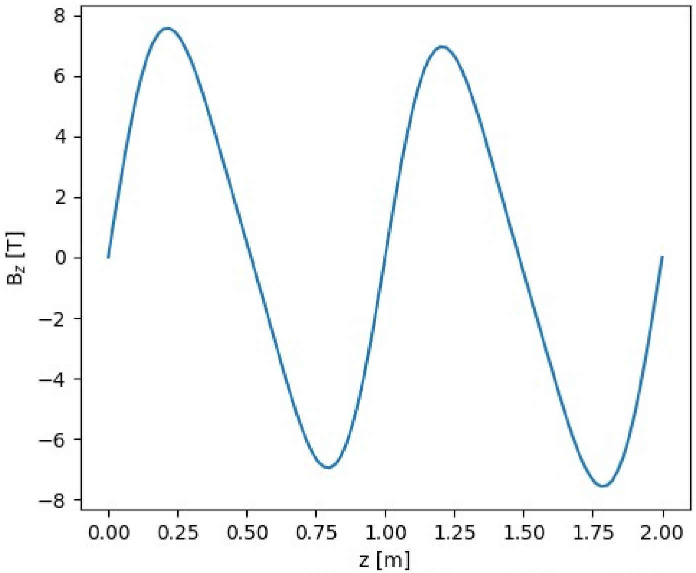
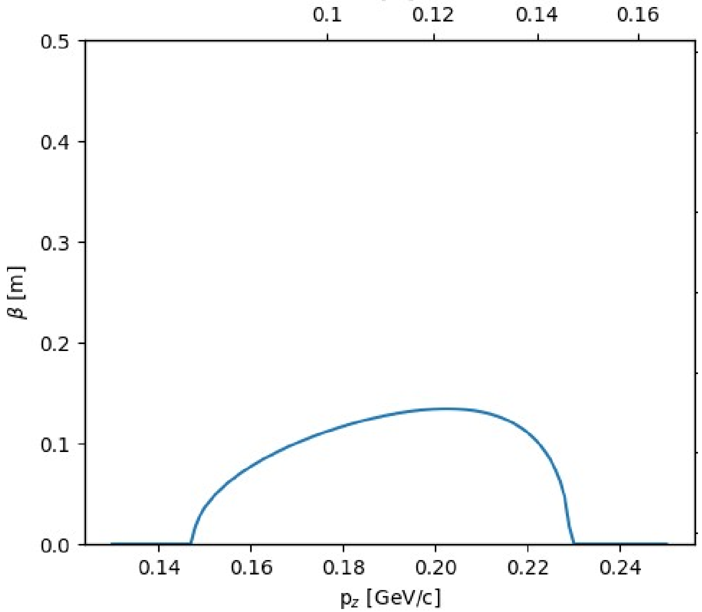
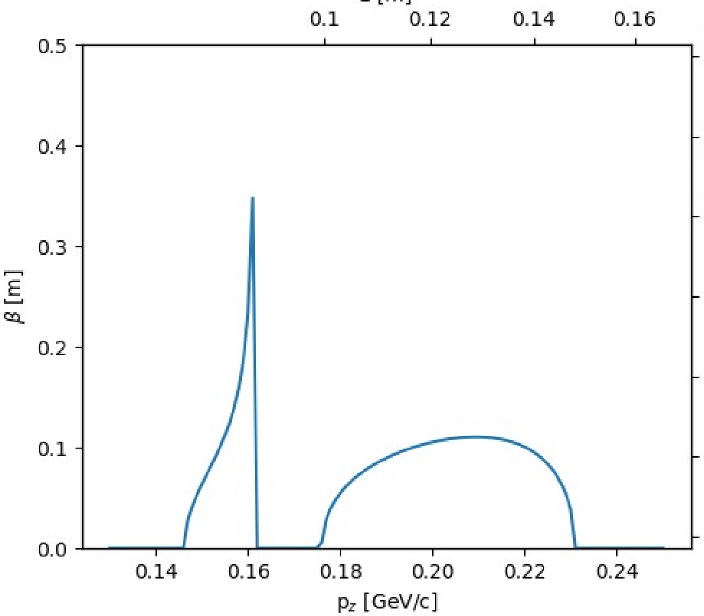
Tolerance study









Tolerances

- Looked at solenoid errors in demonstrator lattice
  - Baseline has
  - $B(z, r=0) = b_k \sin(2\pi\ \ k\ \ z)$
- Tolerances, assuming 1 % dilution of beta is tolerable
  - $b_1=1 \rightarrow$ 0.2 T vs 7 T nominal
  - $b_2=2 \rightarrow$ 0.02 T vs 1 T nominal
  - $b_3=3 \rightarrow$ 0.5 T vs 0 T nominal
  - $b_{0.5}=0.5 \rightarrow$ 0.02 T vs 0 T nominal
- May wish to consider structure of vacuum vessels to avoid systematic effects (e.g. k=0.5 issue)

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!
  - Working on initial transport line and integration with nuSTORM
- Aim is to deliver a design by 2026
  - In time for next European strategy update