Demonstrators for the Muon Collider

International
MUON Collider
Collaboration

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Science & Technology Facilities Council
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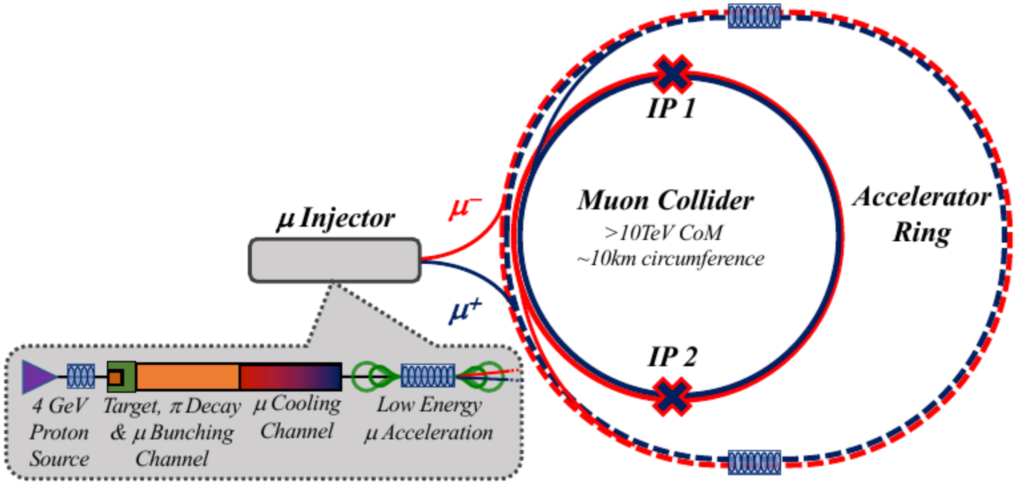
Muon collider

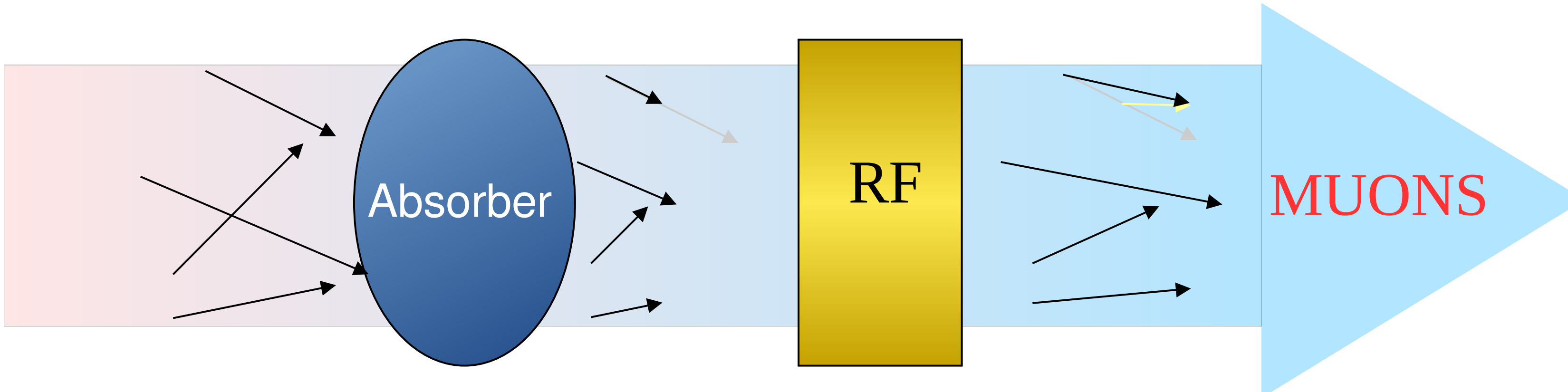


- Muon collider has excellent potential to explore 10 TeV energy scale
  - Highlight of European strategy and Snowmass
  - IMCC - growing international collaboration
- Protons on target → produce pions
- Muon ionisation cooling to reduce the beam size
- Rapid acceleration
  - Magnet ramp O(10) times faster than rapid cycling proton sources
- Collider ring
  - As short as possible to ensure most collisions before decay
  - Mitigate weak neutron showering caused by decay neutrinos

Demonstrators

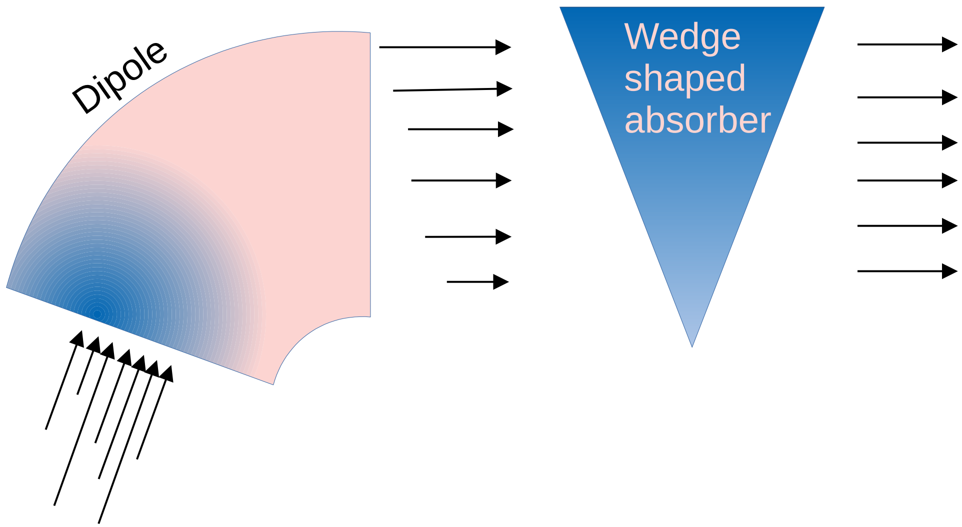
- Following technologies need stand-alone tests
  - Operation of RF in magnetic fields for ionisation cooling
  - Fast ramping RCS dipoles
  - High field magnets for small collider ring
  - Movable collider ring equipment to smear out neutron shower
- Following technologies need beam tests
  - Target in solenoid field
  - **Ionisation cooling technologies**
- For this discussion the focus is on ionisation cooling technologies
  - Component designs
  - Overview of previous R&D
  - Plan for demonstrators
  - Possible applications
  - Topics for the workshop

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

Emittance exchange

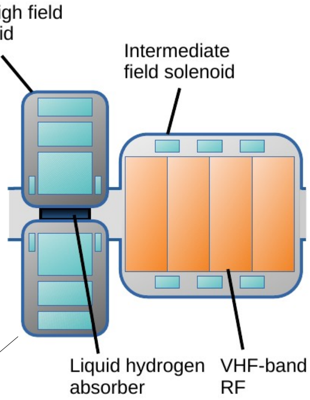


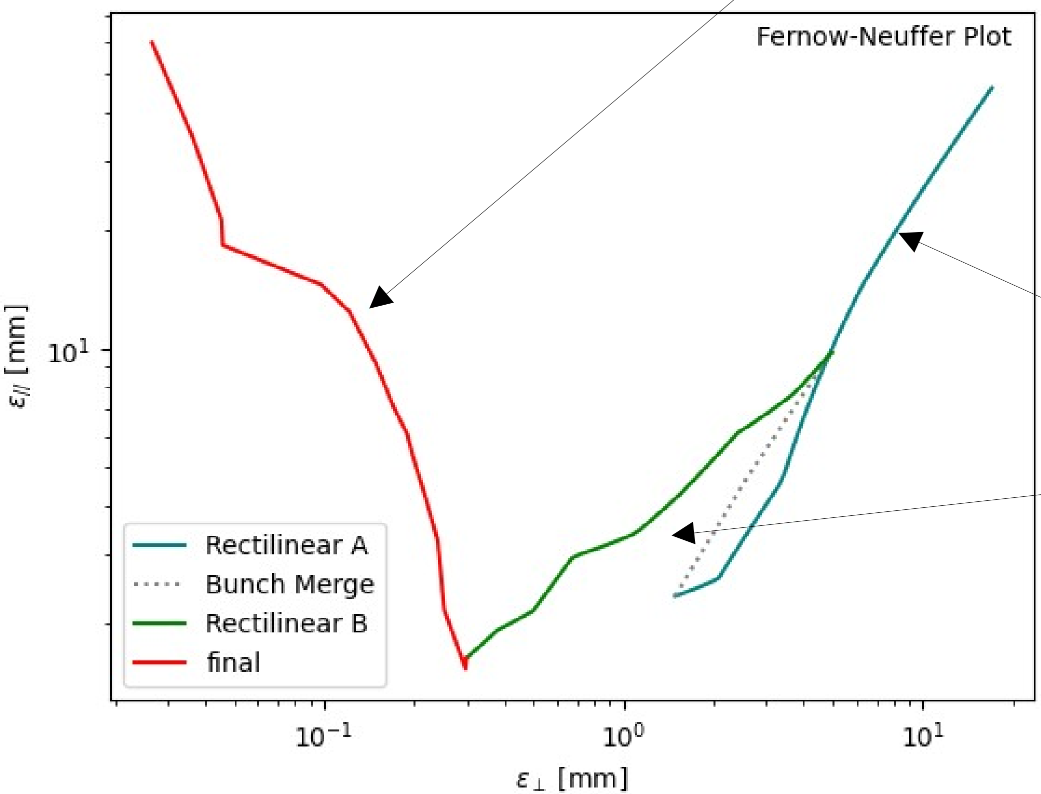
- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge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

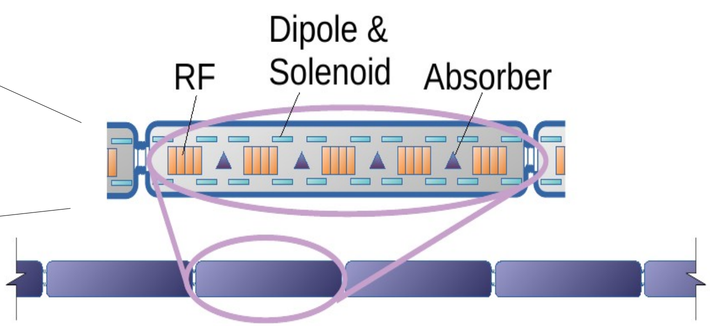
Muon Cooling

Sayed et al, PRSTAB 18, 2015
Fol et al, IPAC22

4D Final cooling







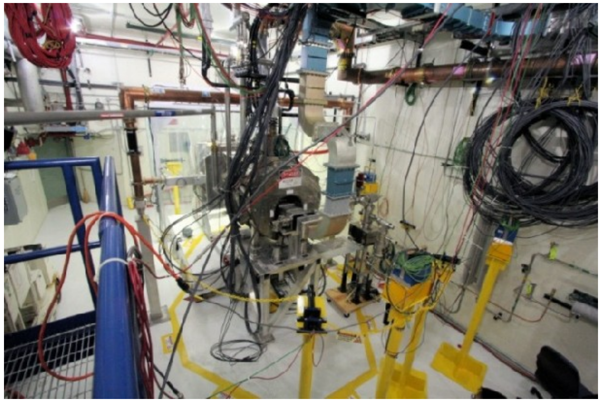
Stratakis et al, PRSTAB 18, 2015
Zhu et al, COOL23

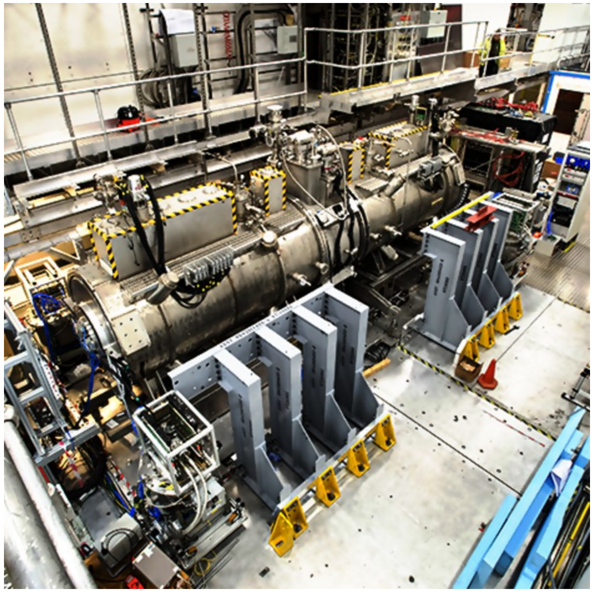
Rectilinear cooling

es Council

Muon Accelerator R&D

- Targetry
  - Static tungsten powder bed demonstrated with beam
  - Liquid metal target demonstrated in solenoid field and with beam
- EMMA (& CBeta)
  - Demonstrated fast acceleration in FFAs
- **MUCOOL**
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic field
- **MICE** demonstration of ionisation cooling





MUCOOL Cavity R&D

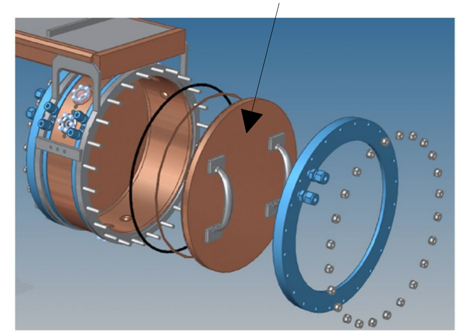
- Cooling requires strong B-field overlapping RF
  - B-field → sparking in RF cavities
- Two technologies have demonstrated mitigation:

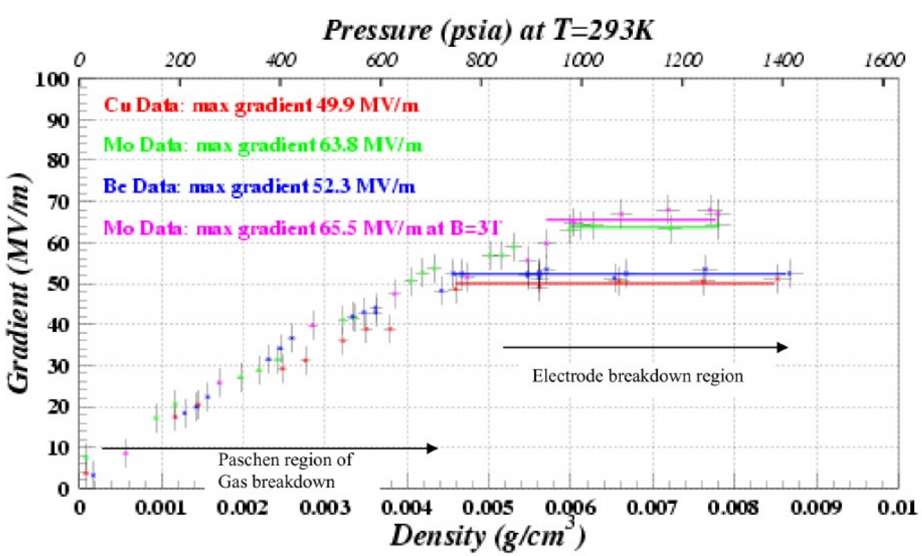
Bowring et al, PRAB 23 072001, 2020

Material	B-field (T)	E-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

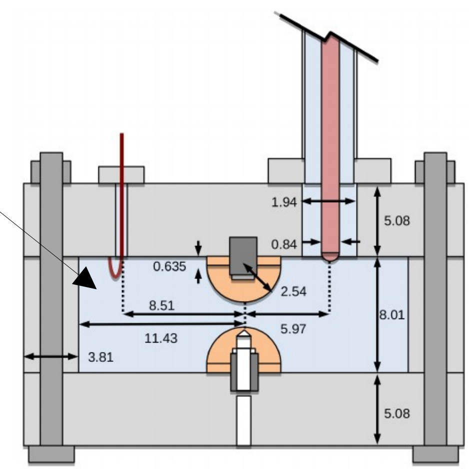
Double vs Cu cavity in 0 T

Changeable Cu/Be walls





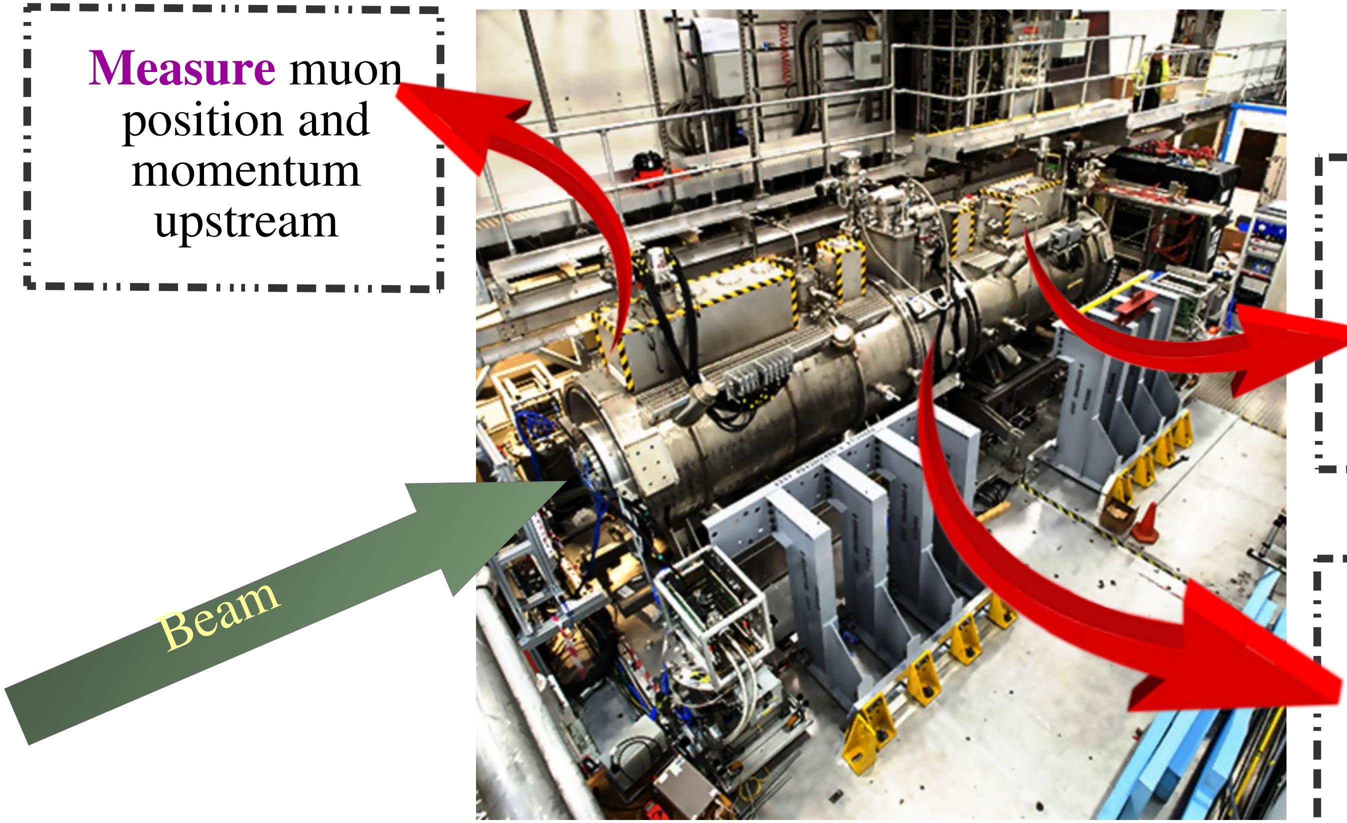
High Pressure gas



Freemire et al, JINST 13 P01029, 2018

MICE - Experimental set up

Measure muon position and momentum upstream



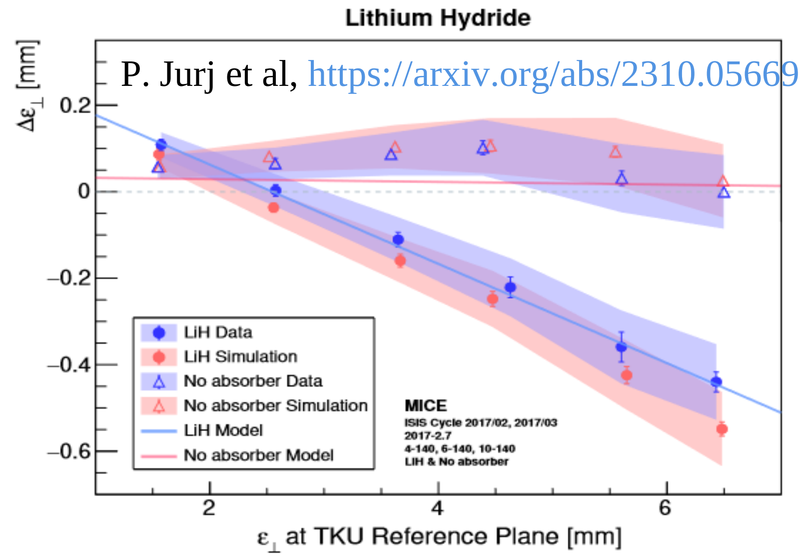
Measure muon position and momentum downstream

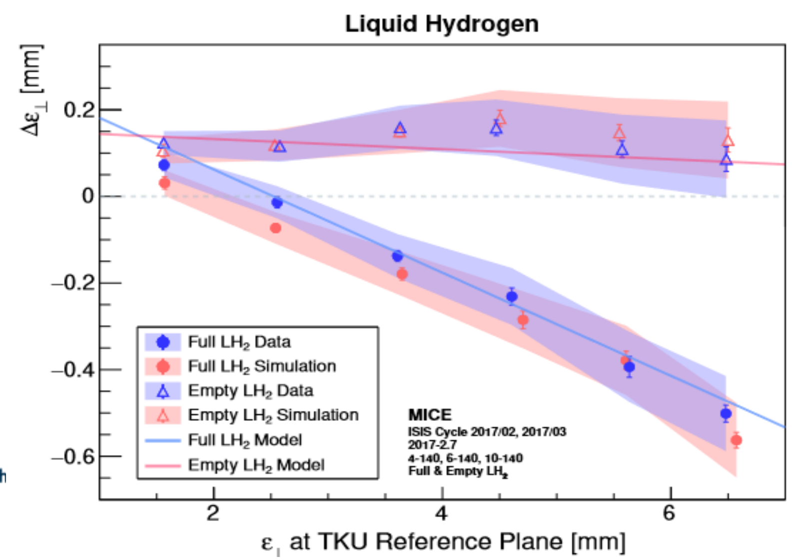
Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

Emittance reduction

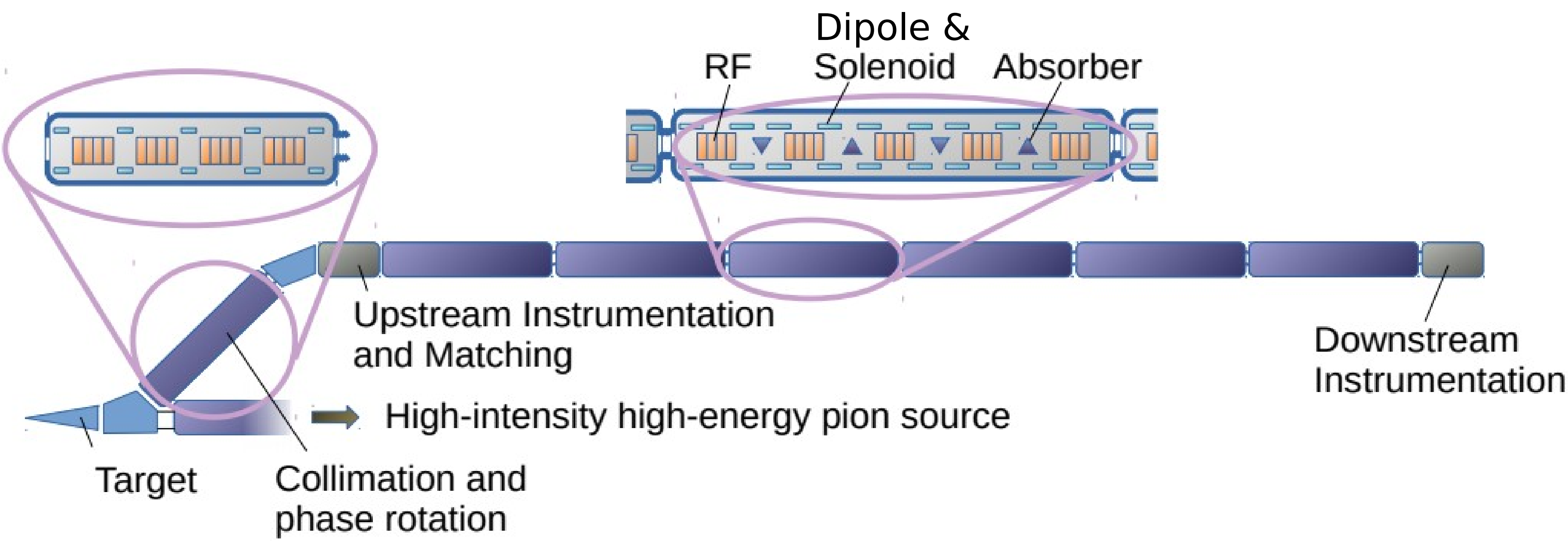
- When absorber installed:
  - Cooling above equilibrium emittance
  - Heating below equilibrium emittance
- When no absorber installed
  - Optical heating
  - Clear heating from Al window

P. Jurj et al, https://arxiv.org/abs/2310.05669



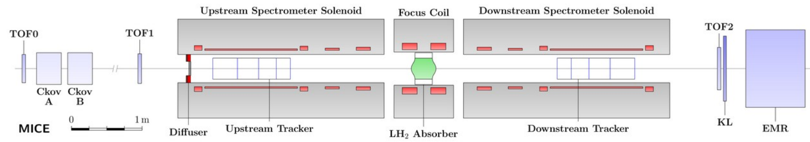


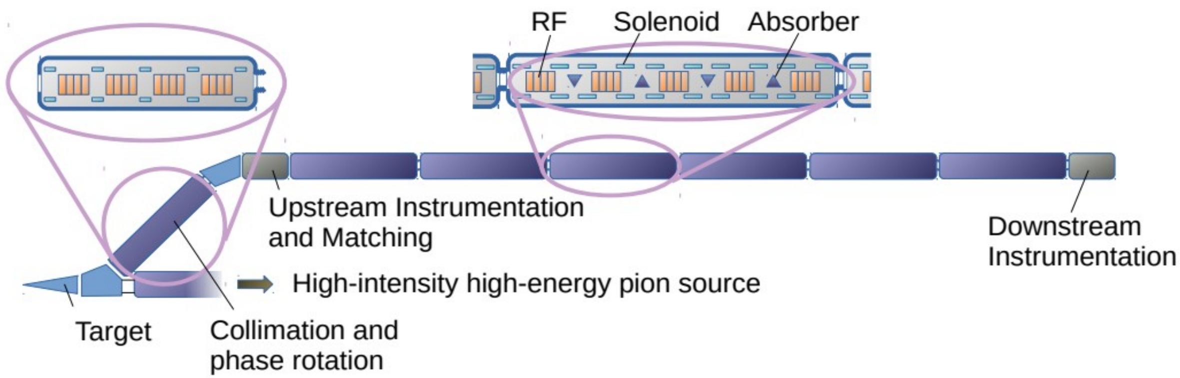
Cooling Demonstrator



- Build on MICE
  - Longitudinal and transverse cooling
  - Re-acceleration
  - Chaining together multiple cells
  - Routine operation

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

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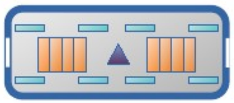
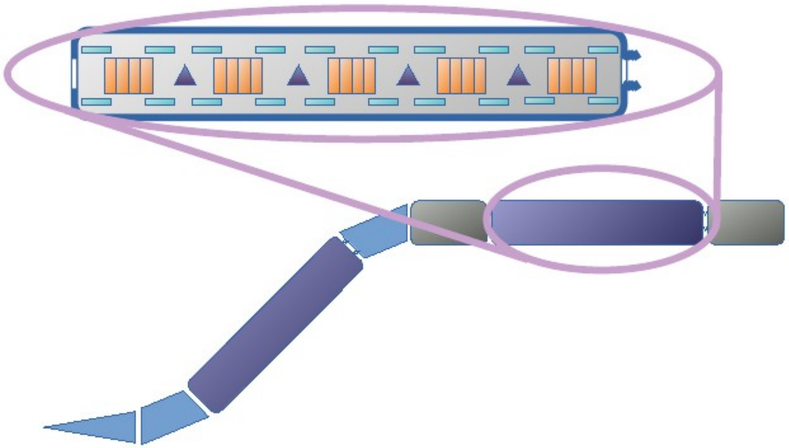
Demonstrator Programme

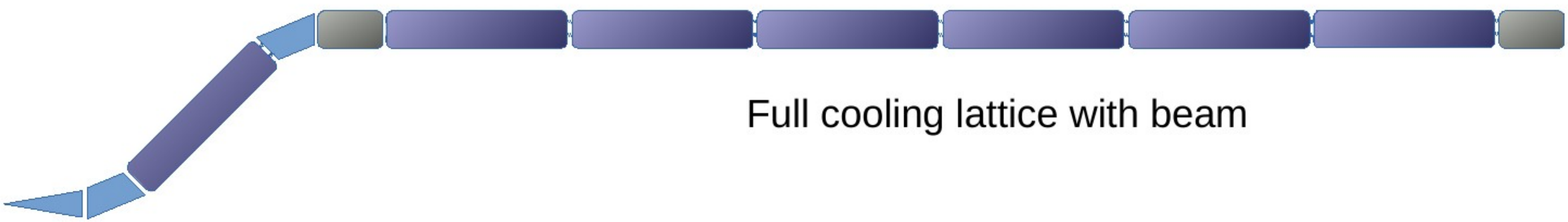
RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



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



Full cooling vacuum vessel with beam



Full cooling lattice with beam

Later…

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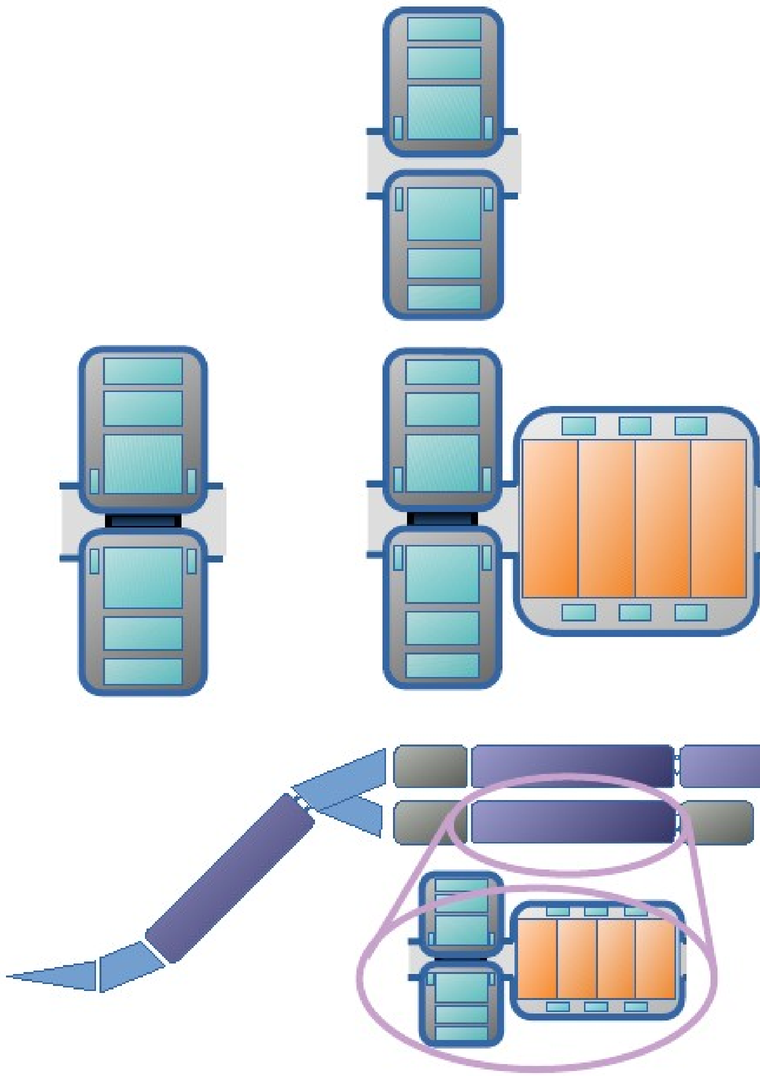

Prototype final cooling magnet

Final cooling test including integration of cooling equipment

Rectilinear cooling lattice with beam

Final cooling cell with beam

Workshop charge

Muon Cooling Demonstrator Workshop

High-energy muon colliders combine cutting edge discovery potential with precision measurements. Because muons are point-like particles they can achieve comparable physics to protons at much lower centre-of-mass energies. Due to the muon's high mass, synchrotron radiation production is suppressed compared to electrons. This makes a high energy muon collider an excellent candidate for discovery at the energy frontier. The International Muon Collider Collaboration (IMCC) is charged by CERN to deliver an assessment of the potential for a muon collider to be a future collider facility and the required R&D to deliver such a facility. The IMCC is supported by the EU MuCol study. The Particle Physics Project Prioritisation Panel has identified the muon collider as an important future possibility for the US particle physics community.

One of the key challenges in development of the muon collider is delivery of a high brightness muon beam, which is essential to produce sufficient luminosity. Ionisation cooling is the technique that is planned to increase beam brightness. The ionisation cooling technique has been demonstrated in principle by the Muon Ionisation Cooling Experiment. However, a number of questions remain that must be answered in order to prove that the technique can be applied in practice. The IMCC foresees a Muon Cooling Demonstrator and associated development programme that must be executed in order to deliver the muon collider.

In this workshop we will:

- Review the progress on design of the muon cooling Demonstrator.
- Identify potential host sites and associated timelines within which the Demonstrator could be deployed.
- Identify associated science programmes that could be synergistic with the development, construction and operation of the Demonstrator.

Comments on the Charge

- Identify potential host sites and associated timelines within which the Demonstrator could be deployed.

  - Potential host sites:
    - The RF test programme may be a separate site to the main demonstrator
    - Other equipment tests/development is valuable
      - E.g. solenoids, beam instrumentation, absorbers
    - Early timeline considerations are valuable – when will the sites become available, any constraints from e.g. existing operations
    - Not looking anywhere near formal approvals, rather expression of scientific interest

Comments on the Charge

International MUON Collider Collaboration

- Identify associated science programmes that could be synergistic with the development, construction and operation of the Demonstrator.
  - Associated science programmes
    - Directly associated i.e. sharing beam or equipment
    - Indirectly associated e.g. potential applications and parallel developments of the technologies
    - Other approaches to muon cooling are also interesting

Our Task

- Today:
  - Settle on a date
  - Consider important topics
  - Consider how we break the topics down to a block agenda

* Introduction to the cooling demonstrator
* Fermilab requirements/constraints
* Dates proposal
* Important topics to cover & block agenda
* Discussion

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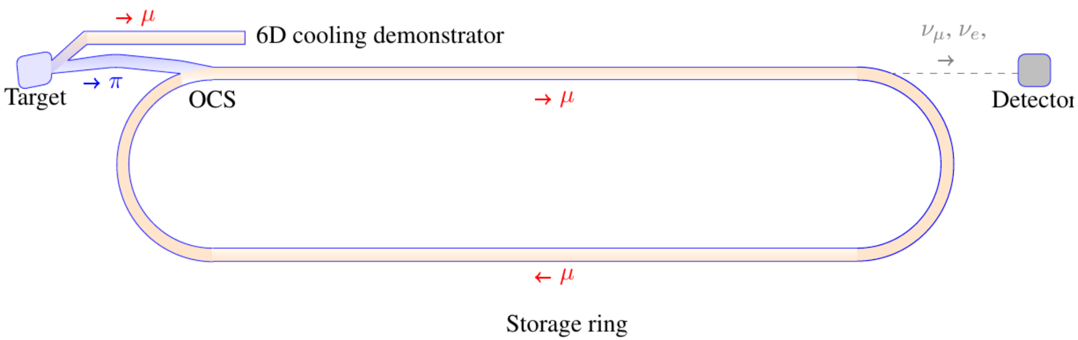
Other Material

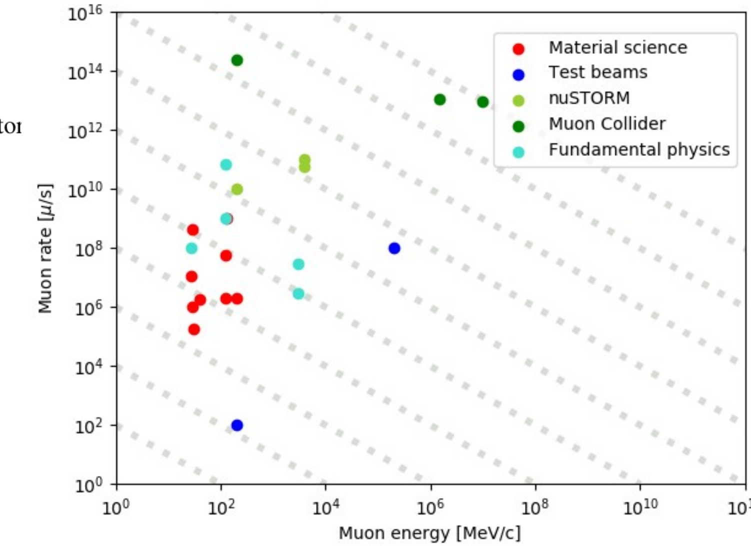
Conclusions

- Muon collider is an excellent candidate for post-LHC era
- Technically challenging
  - This is a good thing!
  - Would yield an entirely novel type of facility
- Beam tests are required
  - Solenoid-focused target
  - In particular ionisation cooling
  - Demonstrator is an excellent candidate facility
- Can support an excellent physics programme on the way

Synergy with nuSTORM

International MUON Collider

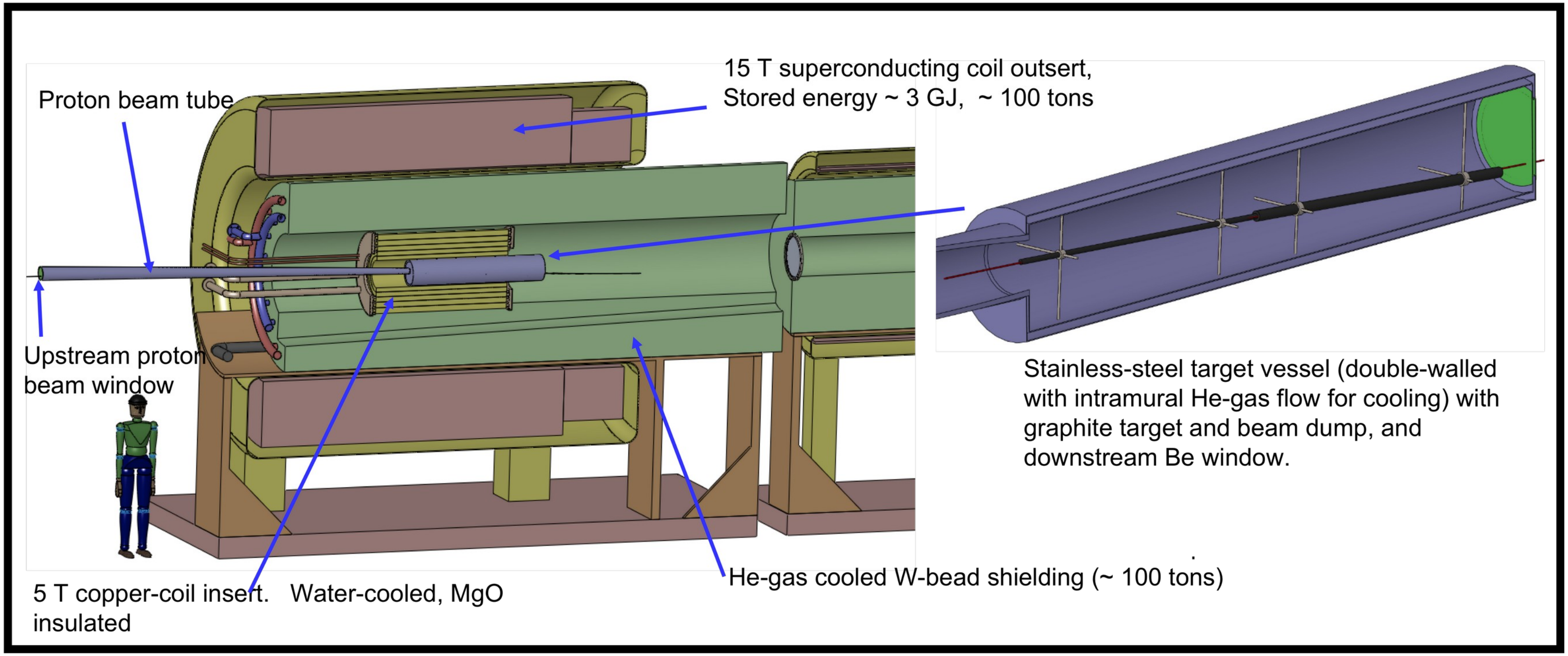




- NuSTORM → “next scale” muon facility
  - FFA-based storage ring (no acceleration)
  - Muon production target and pion handling
  - Possibly shared with cooling demonstrator
- Aim to measure neutrino-nucleus cross-sections
  - E.g. reduce neutrino oscillation experiment resolutions
  - Nuclear physics studies
  - Sensitivity to Beyond Standard Model physics

MC Target

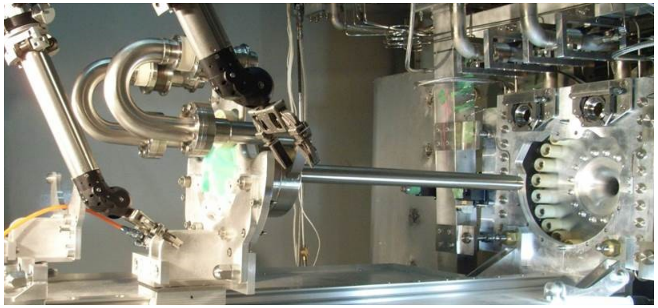
X. Ding et al, Carbon and Mercury target system for muon colliders and neutrino factories, IPAC16

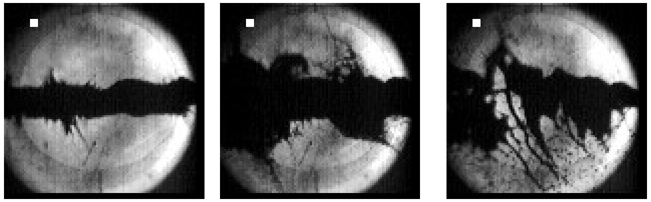


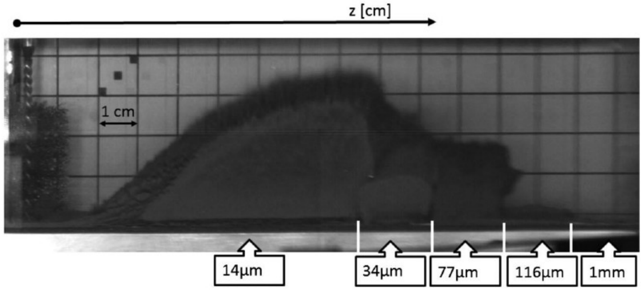
- Protons on target → pions → muons
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Energy deposition on solenoid
- Challenge: Solid target lifetime

Target R&D

- Graphite target "work horse" of pion production world
  - Long target may reduce pion yield, especially at high energy
  - Radiation damage may limit available beam power
- Investigating back-up options
  - Tungsten powder
  - Liquid metal targets
  - Experiments done
    - Online using CERN proton source
    - Offline



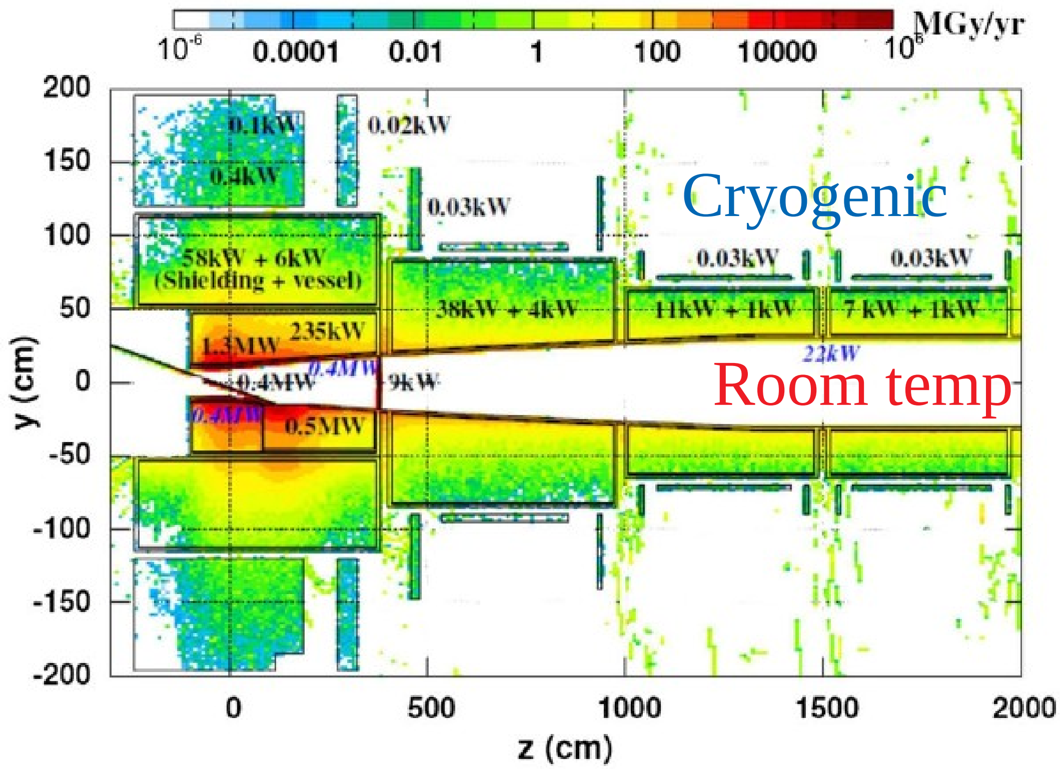




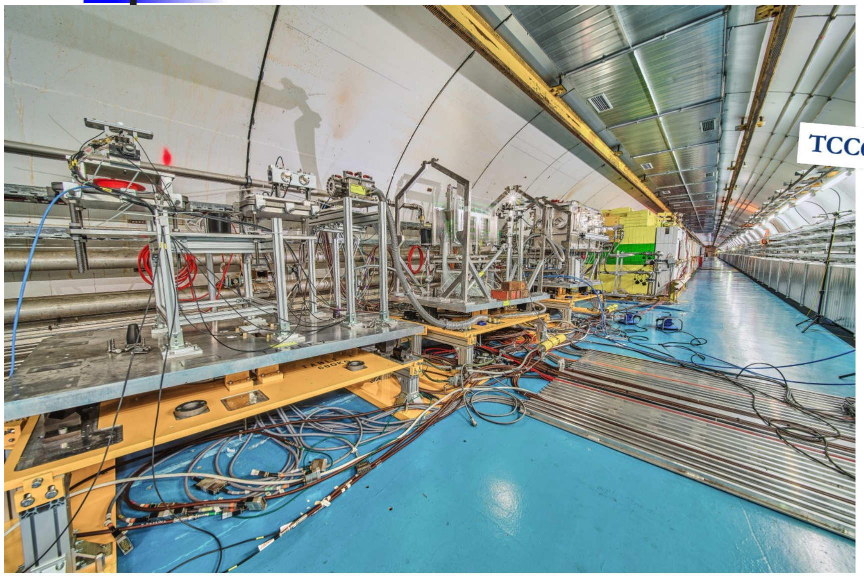
Target radiation load

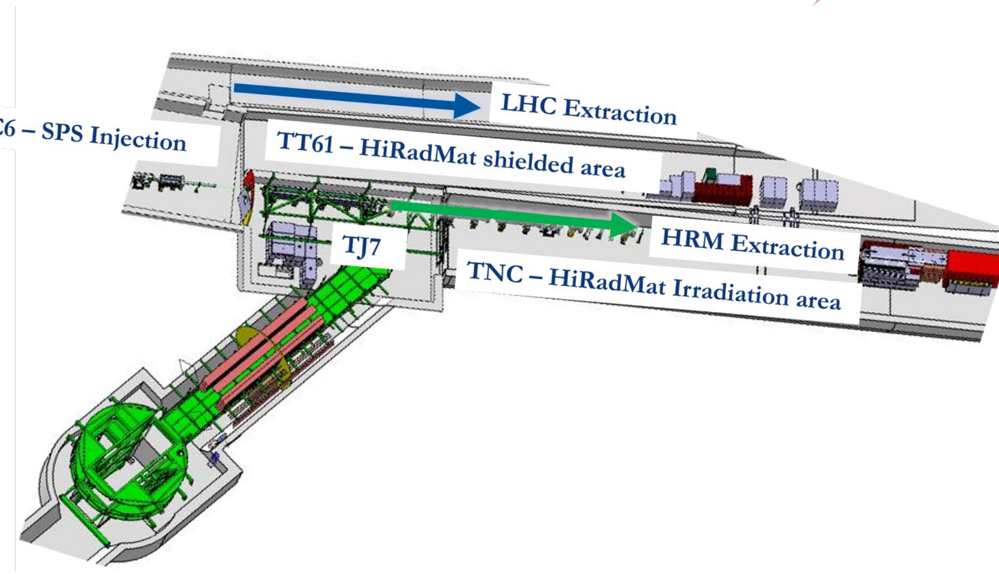
- Radiation load significant issue
  - Degrades insulation/glue
  - Requires more cooling
    - 1 kW heat → O(200) kW electricity
- Shield at room temperature
- Magnet at superconducting temperature
  - HTS → warmer, more efficient

Neutrino factory, Bogomilov et al, PRSTAB 17 (2014)



Targetry - HiRadMat

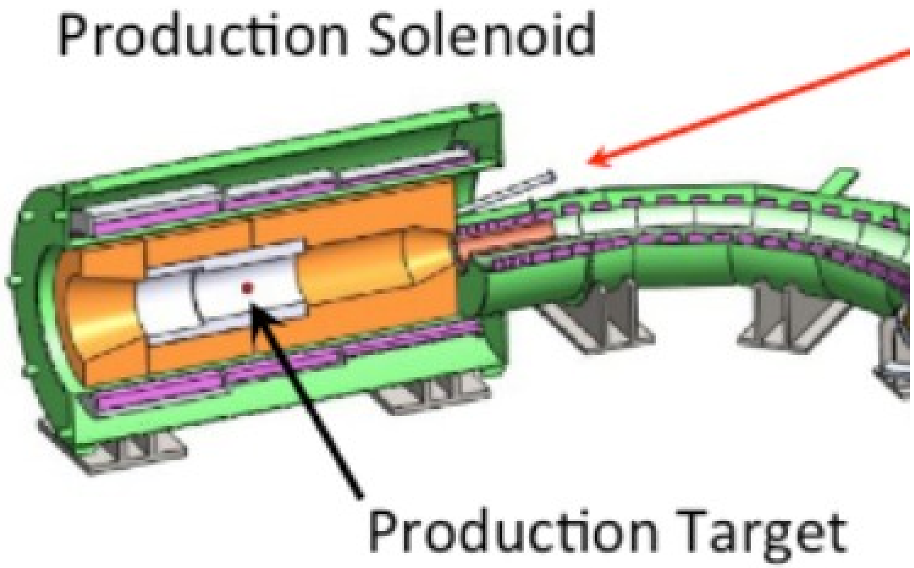


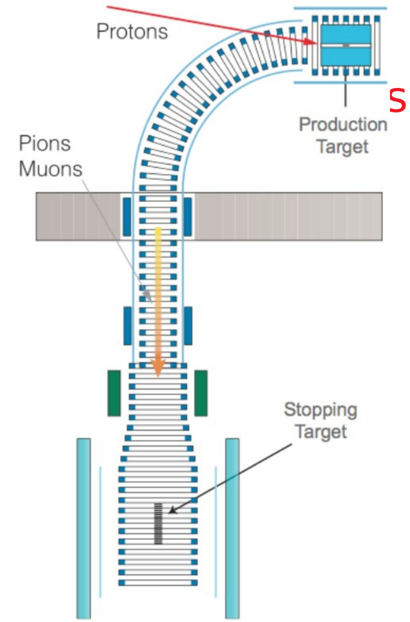


- HiRadMat facility at CERN
  - Study of effect of high instantaneous beam power
    - Up to 2.4 MJ proton pulse over 8 microseconds
  - Used in previous tests
- Irradiation facilities

Synergy with cLFV

mu2e

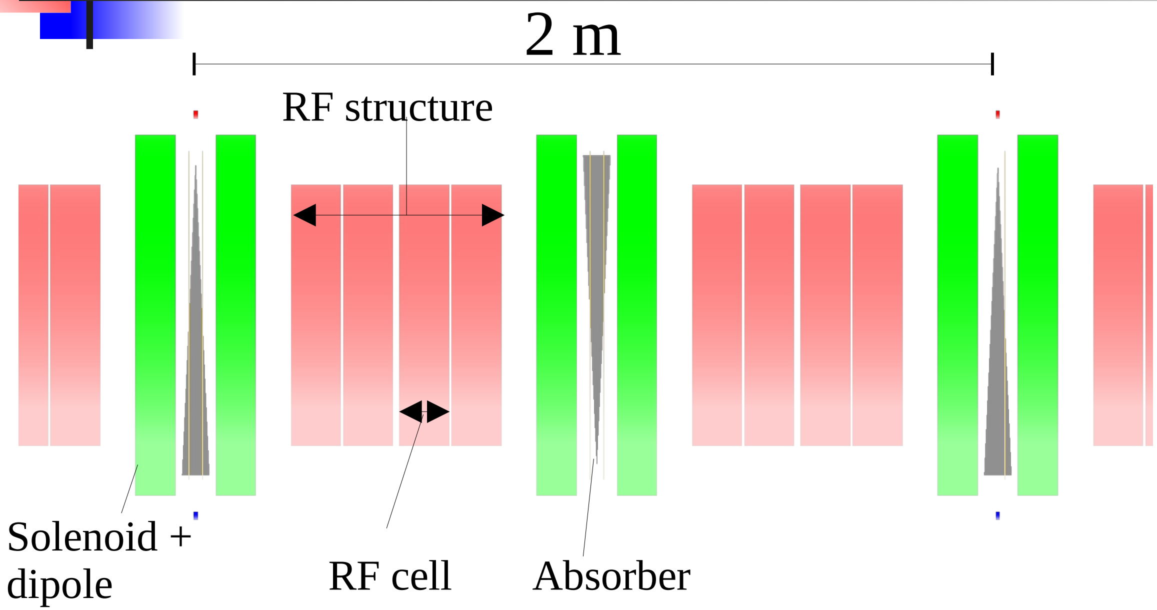




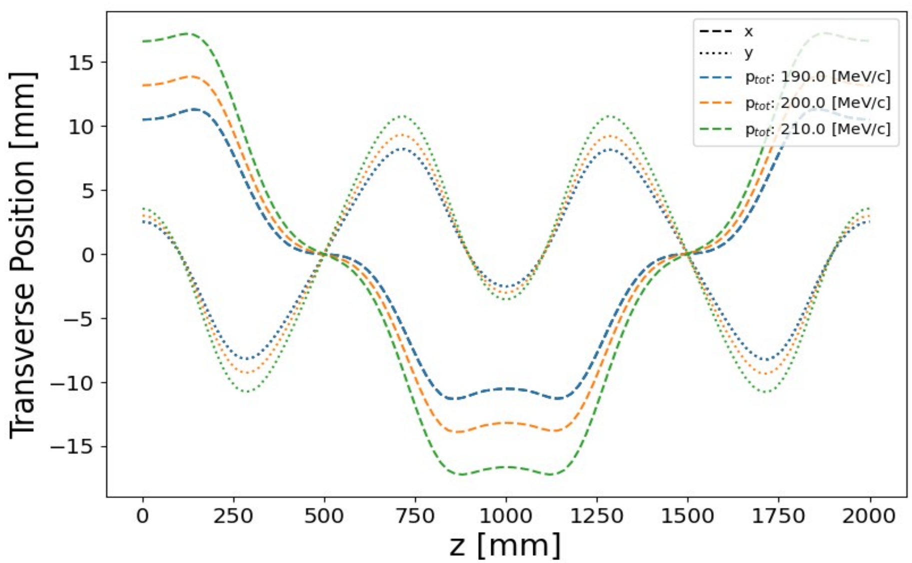
【 COMET Phase-I 】

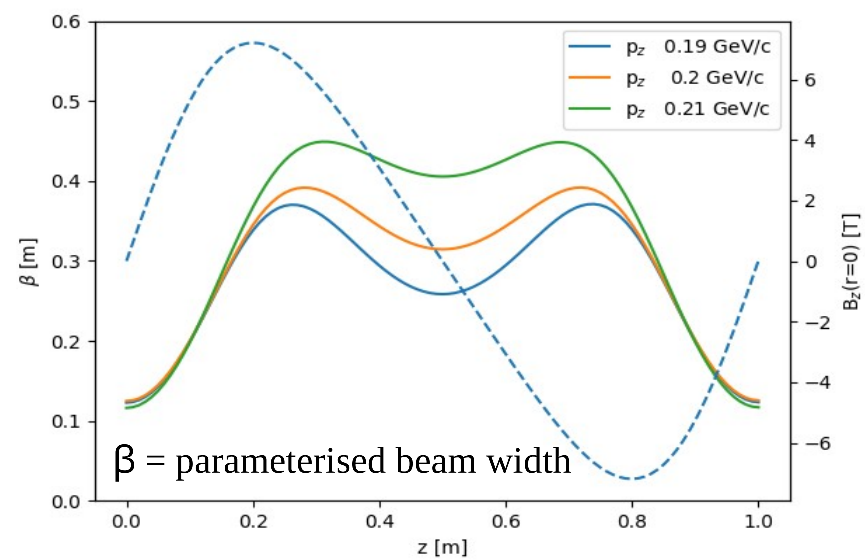
- Muon-to-electron conversion experiments
  - Look for rare decay processes
- Under construction now
- R&D for phase II in progress
- Target station similar to MC target
  - But lower power, lower field
- Excellent opportunity to test ideas on target station

Preliminary Cooling Cell Concept



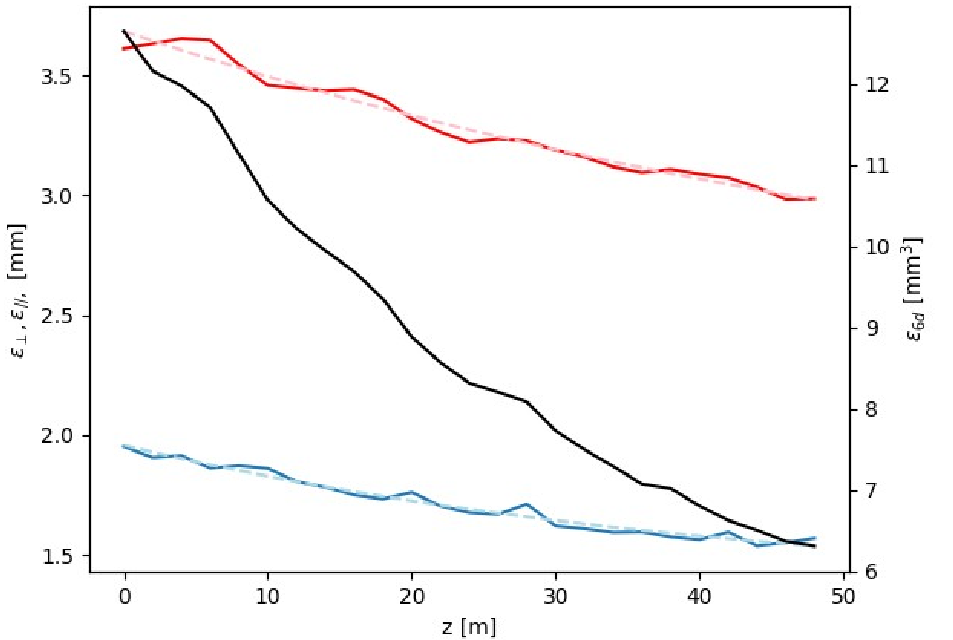
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





Performance

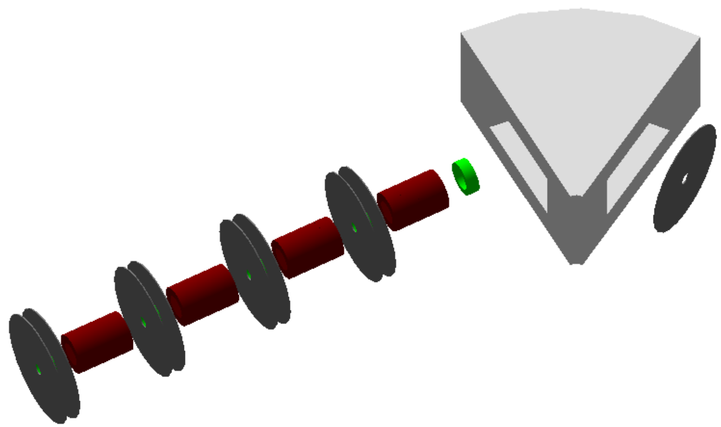
- Good cooling performance
  - Transverse and longitudinal emittance reduced by ~ 20 %
  - Approx factor two reduction in 6D emittance
- Optimisation ongoing
- Assumes perfect matching for now



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

Beam preparation system

- ~ 100 ps pulsed muon beams don't exist
  - Muons have only rarely been accelerated
  - 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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R&D Roadmap

International MUON Collider Collaboration

Opportunities
- CLFV
- Top, higgs
- Neutrinos
- muSR
- Energy frontier

Required Facility
- Proton Driver
- 1-10 TeV Muon accelerator
- Demonstrators
- 10s-100s GeV Muon accelerator

Required R&D
- High power targets
- Rapid acceleration
- Muon cooling

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