Demonstrators for the Muon Collider

International
MUON Collider
Collaboration

C. T. Rogers
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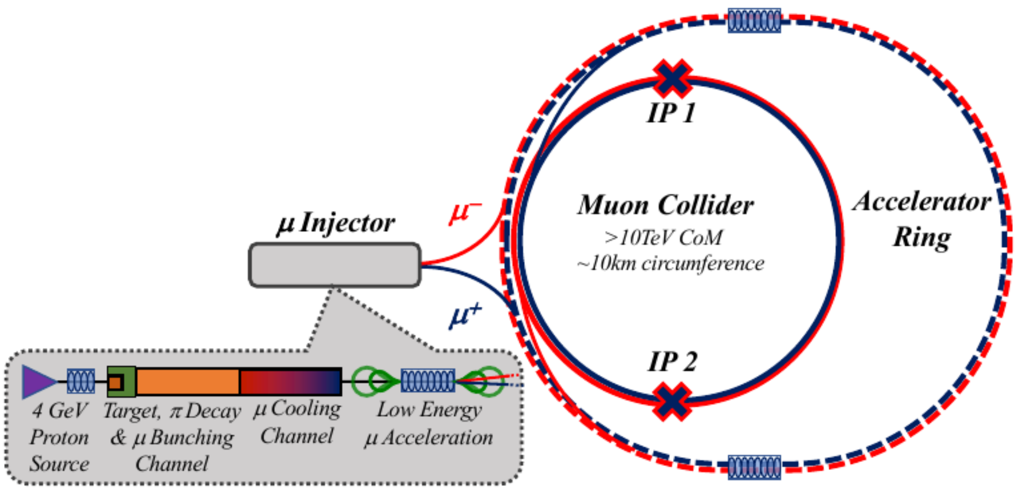
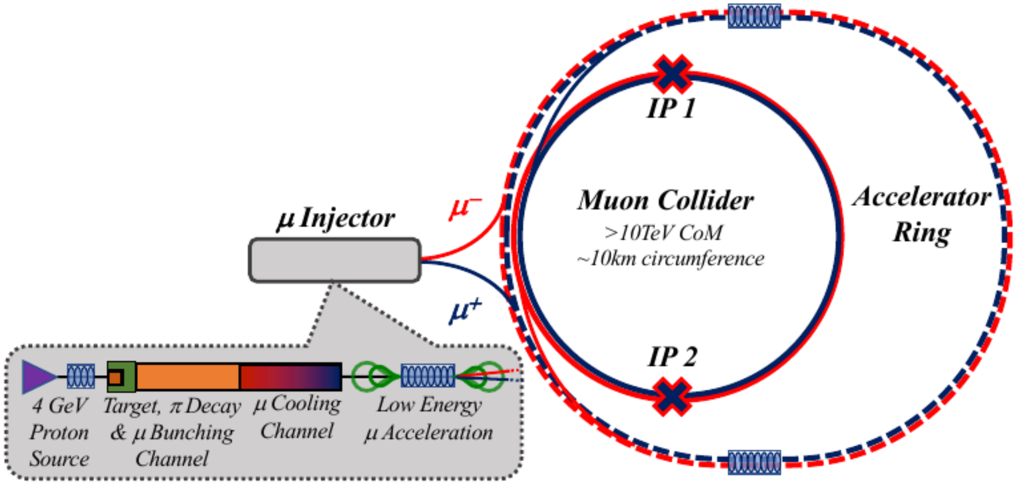
Science & Technology Facilities Council
ISIS

Muon collider



- Muon collider has excellent potential to explore 10 TeV energy scale
  - Highlight of European strategy and Snowmass
  - International Muon Collider Collaboration
  - Growing international collaboration
- Developing a baseline
  - Understand technical issues and R&D programme

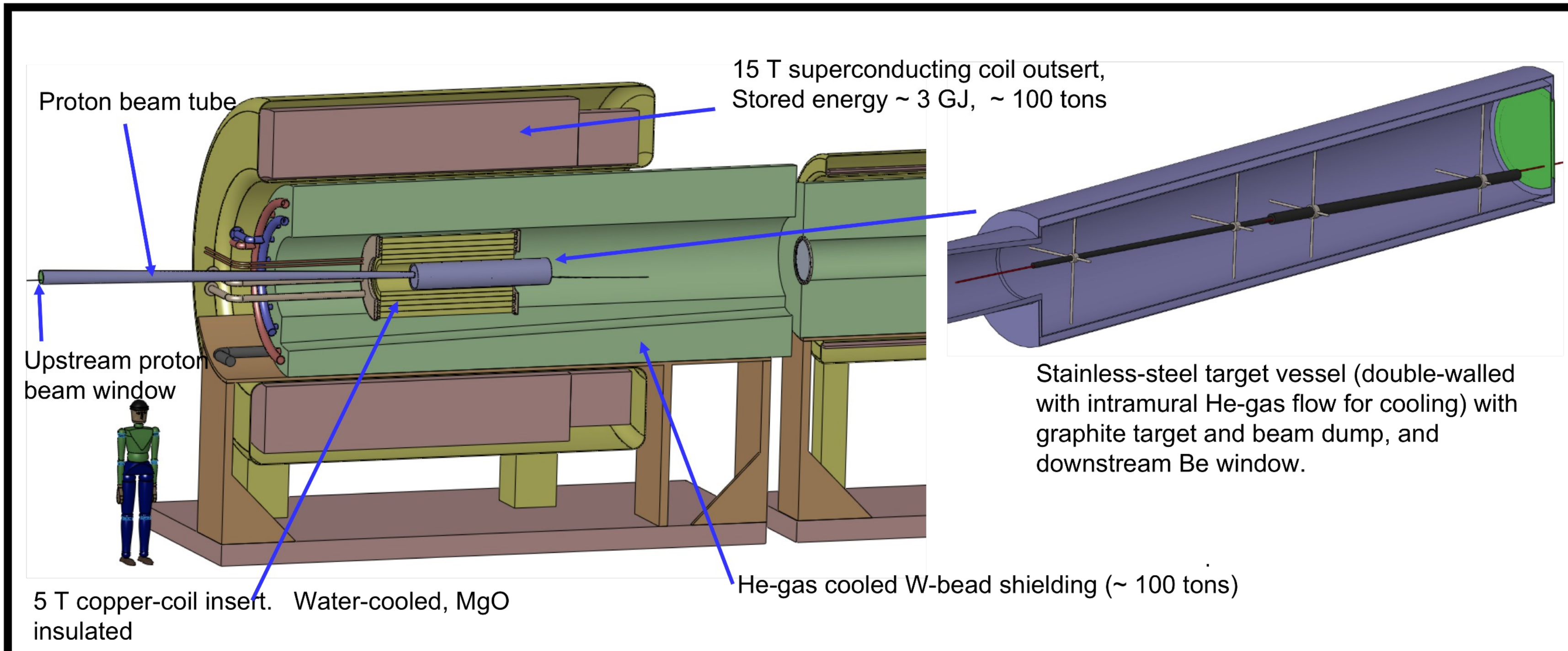
Muon collider



- 2 MW 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
- Technical challenges, but reachable parameters for all technologies
  - R&D programme required
  - Beam tests for ionisation cooling and targetry

Muon Collider Target

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

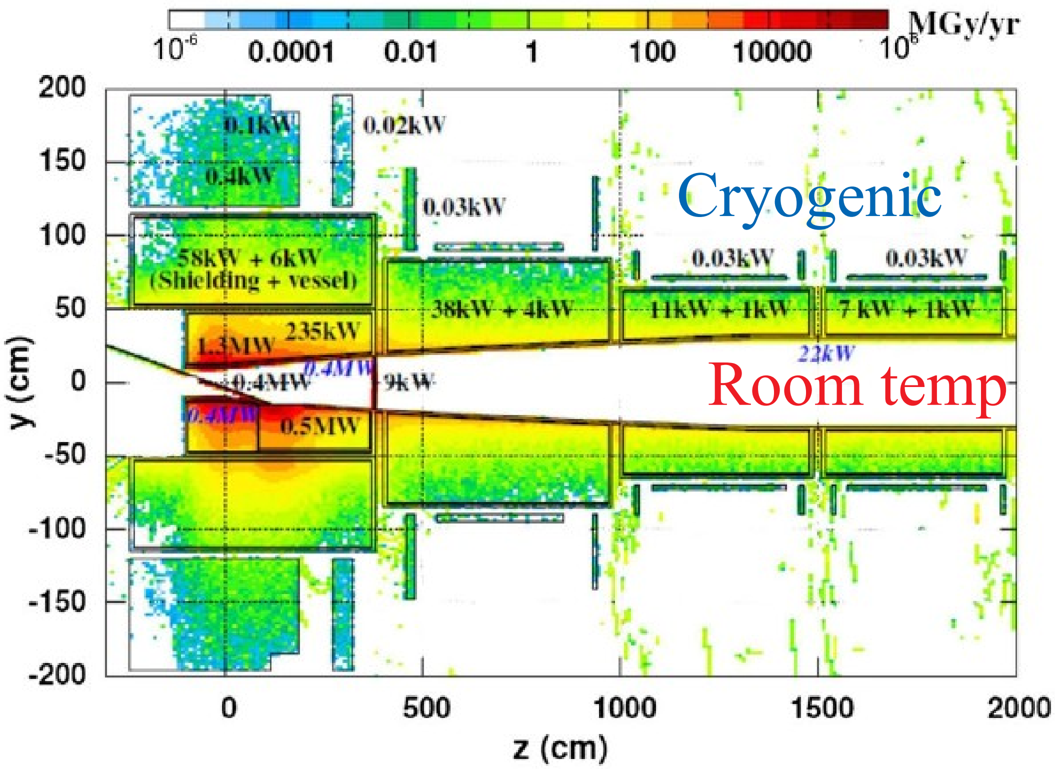


- Protons on target → pions → muons
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Energy deposition on solenoid
- Challenge: Solid target lifetime

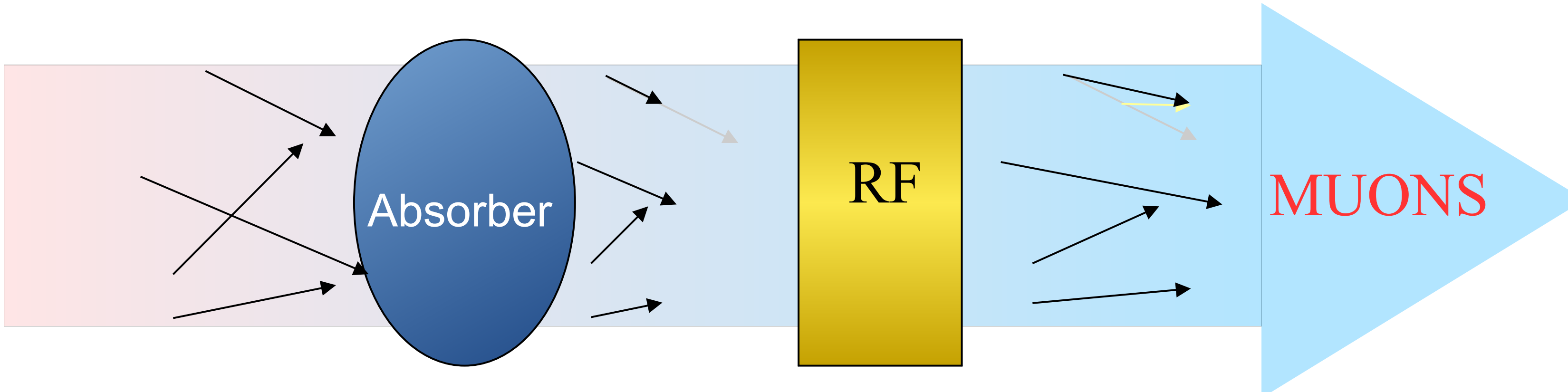
Target radiation load

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

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

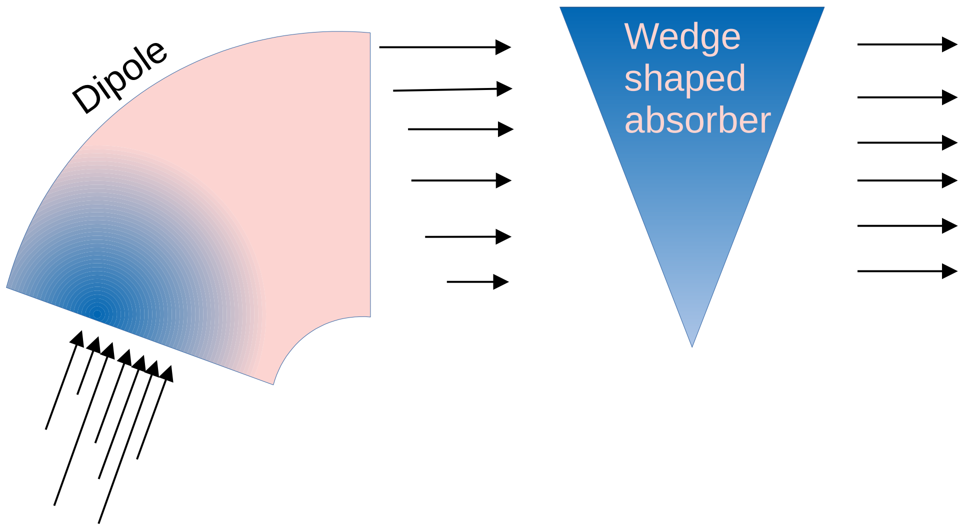


Ionisation Cooling



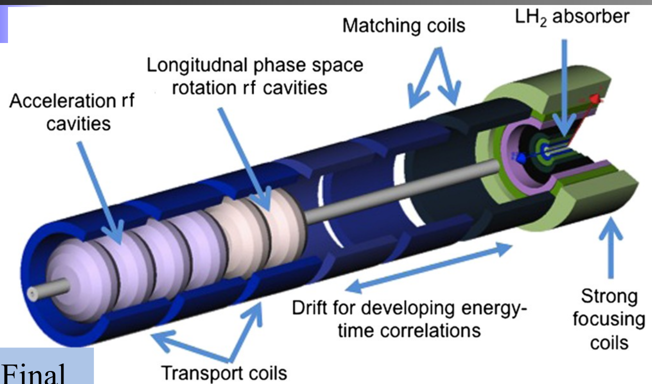
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS completely cancels the cooling

Emittance exchange

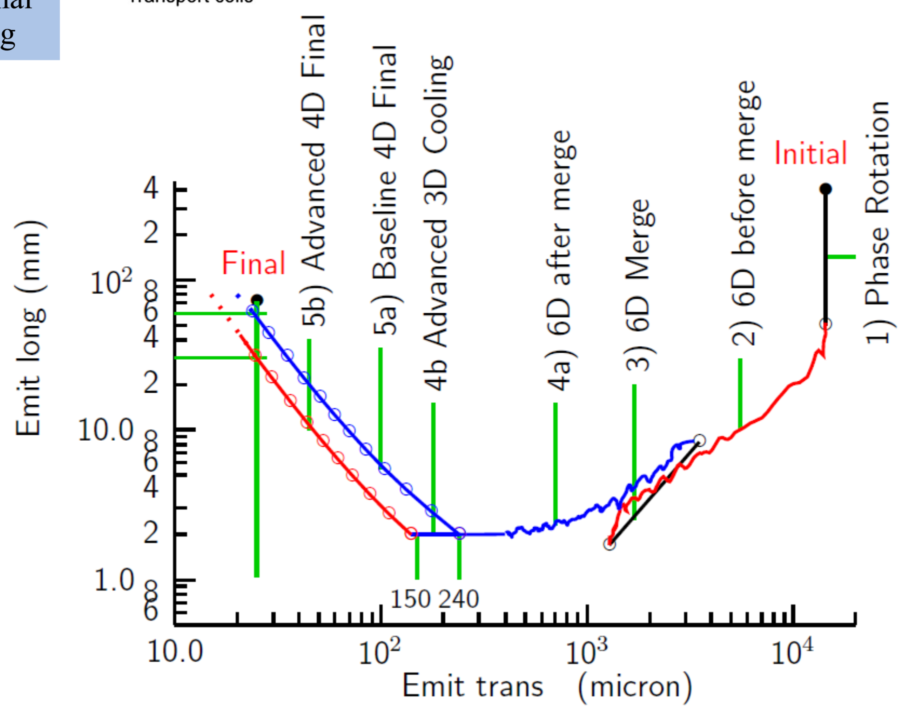


- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge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

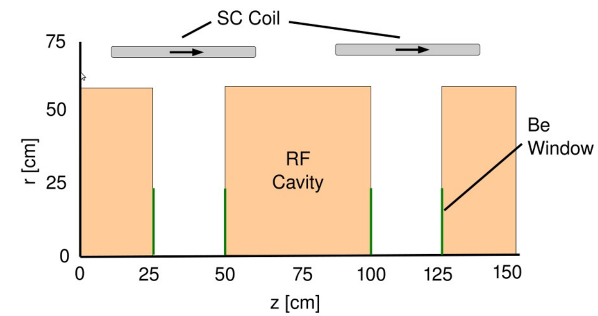
Muon Cooling



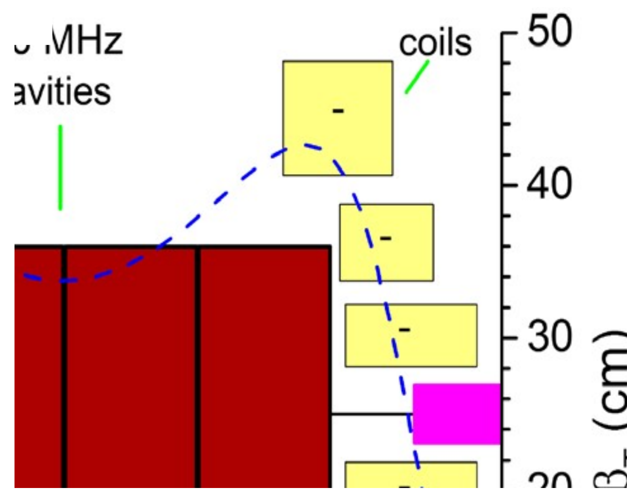
4D Final cooling



Phase rotation



6D cooling



Existing R&D

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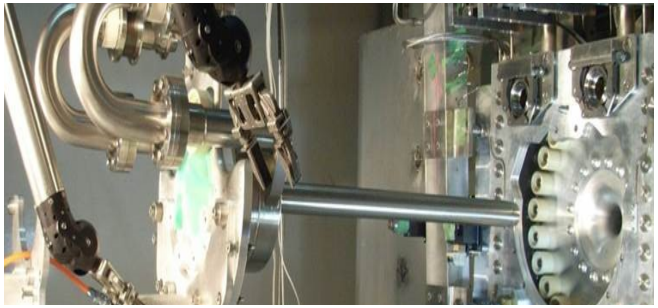
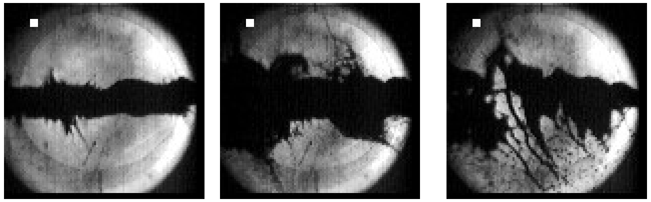
Muon Accelerator R&D

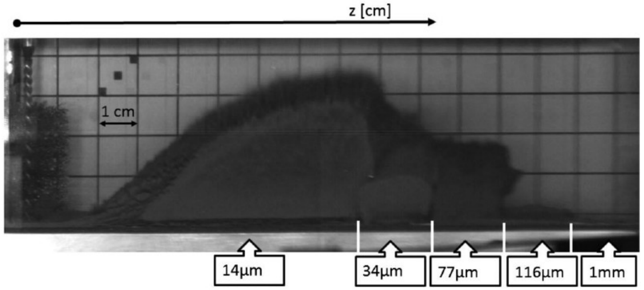
- Targetry
  - Static tungsten powder bed demonstrated with beam
  - Liquid metal target demonstrated in solenoid field and with beam
- MUCOOL
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic field
- MICE
  - Demonstration of ionisation cooling

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
    - Production liquid metal target at SNS
    - Offline tests
- None of these tests include integration with SC magnet







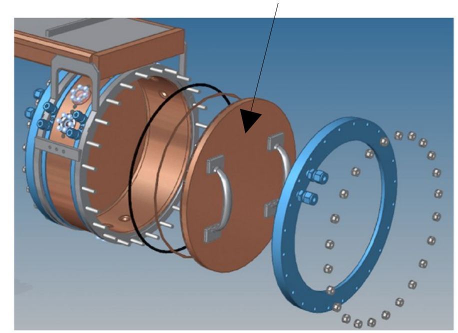
Cavity R&D

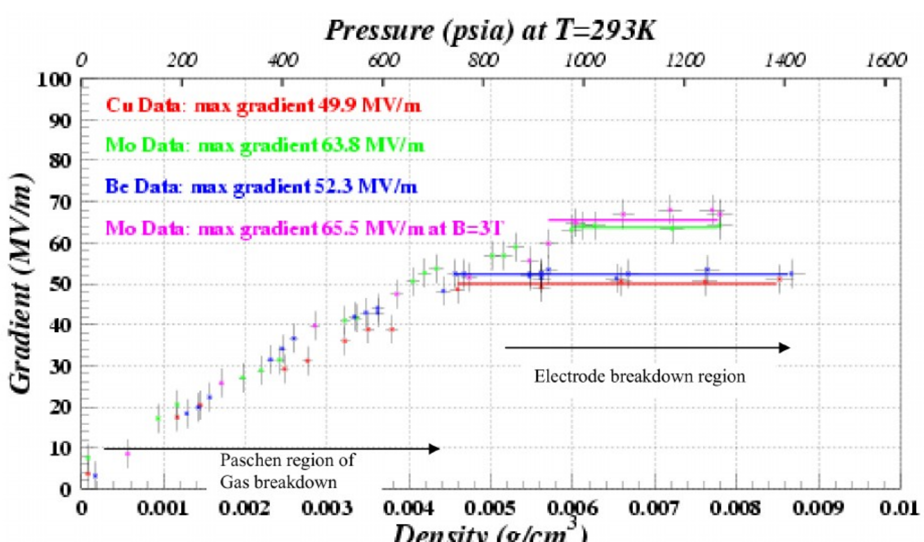
- Cooling requires strong B-field overlapping RF
  - B-field → sparking in RF cavities
- Two technologies have demonstrated mitigation:

Bowring et al, PRAB 23 072001, 2020

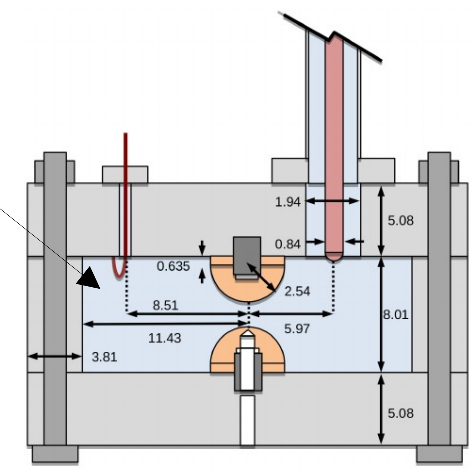
Material	B-field (T)	E-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

Changeable Cu/Be walls





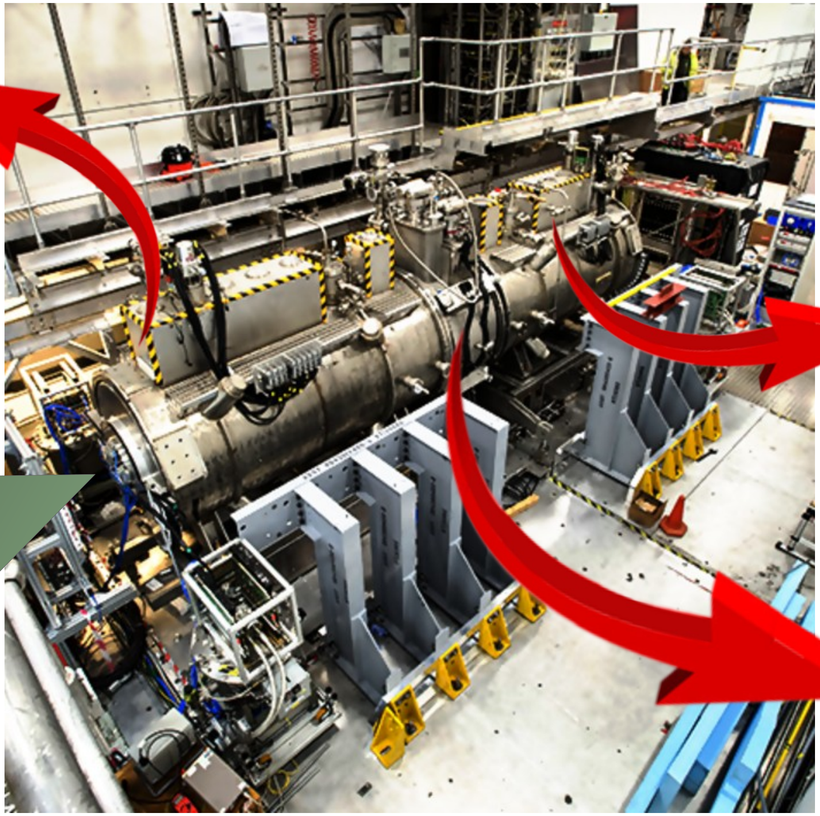
High Pressure gas



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

Beam

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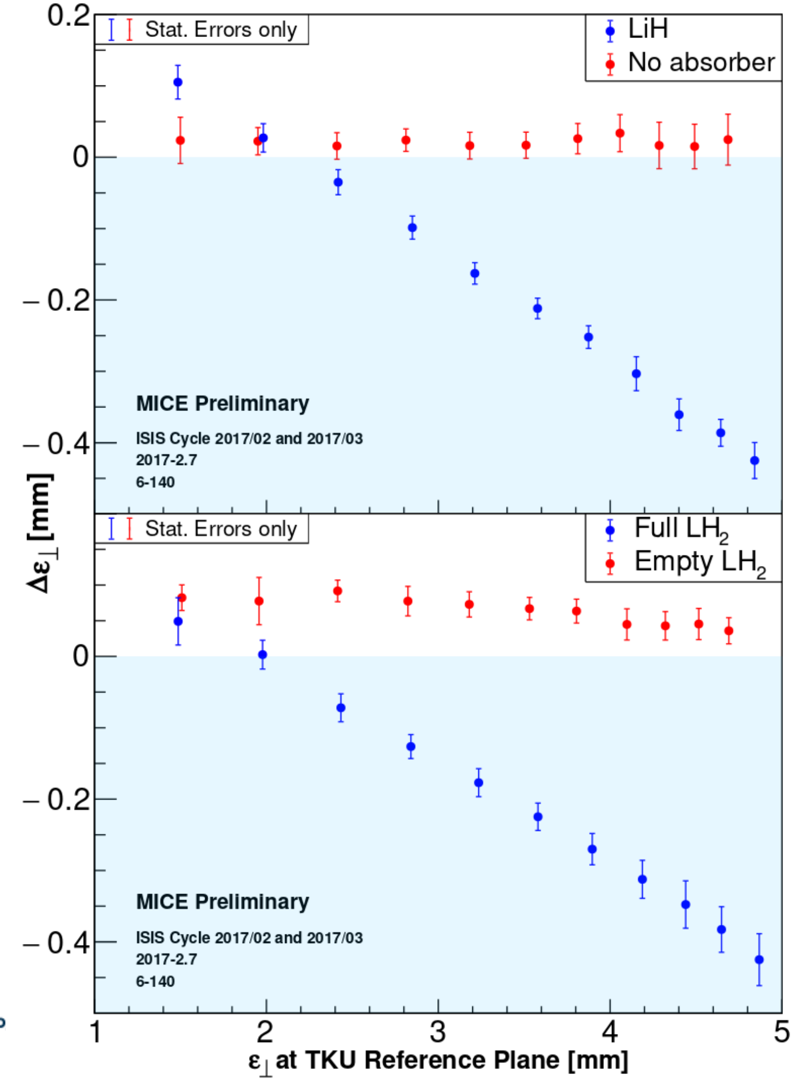
Emittance reduction

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



The Muon Collider – Future R&D

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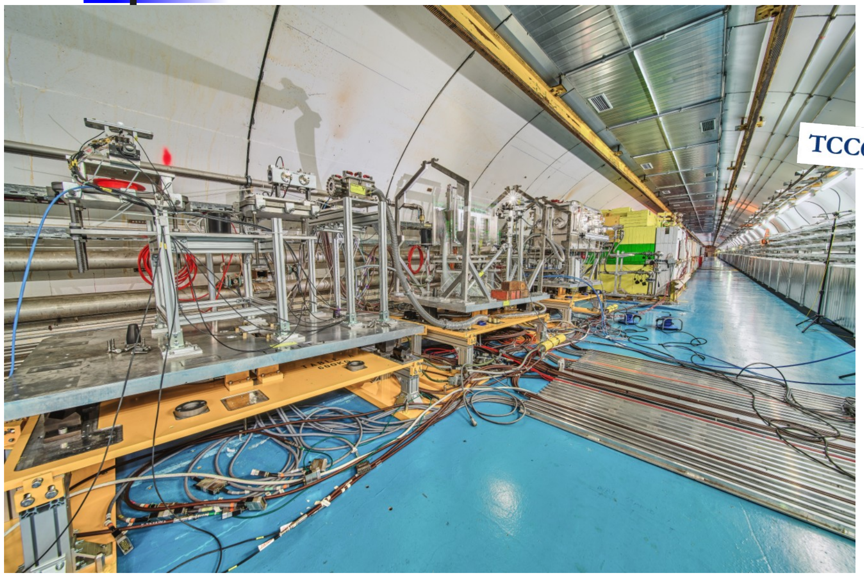
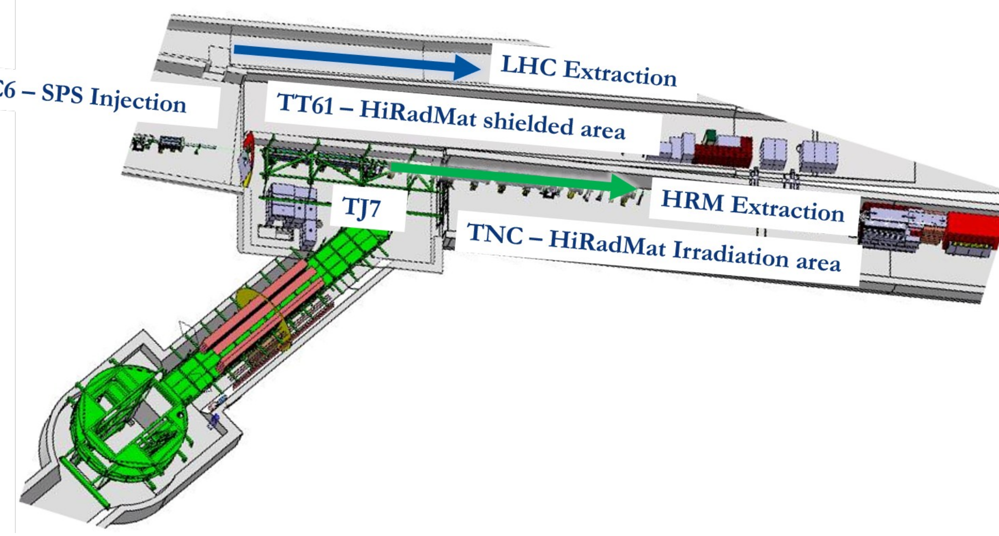
Targetry - HiRadMat





- 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

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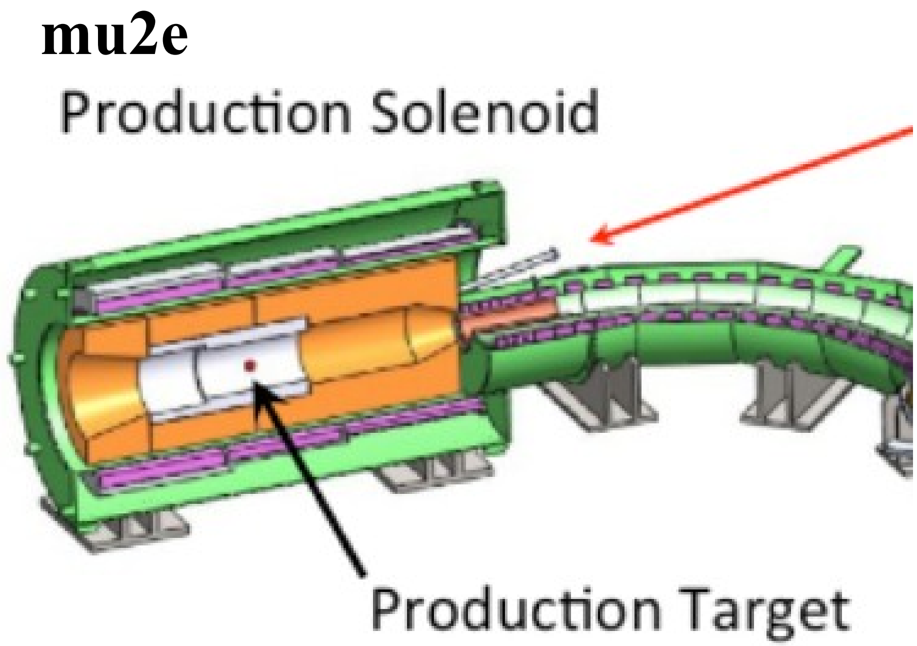
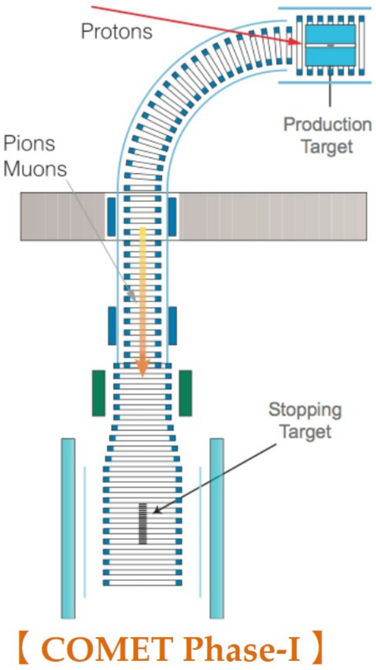
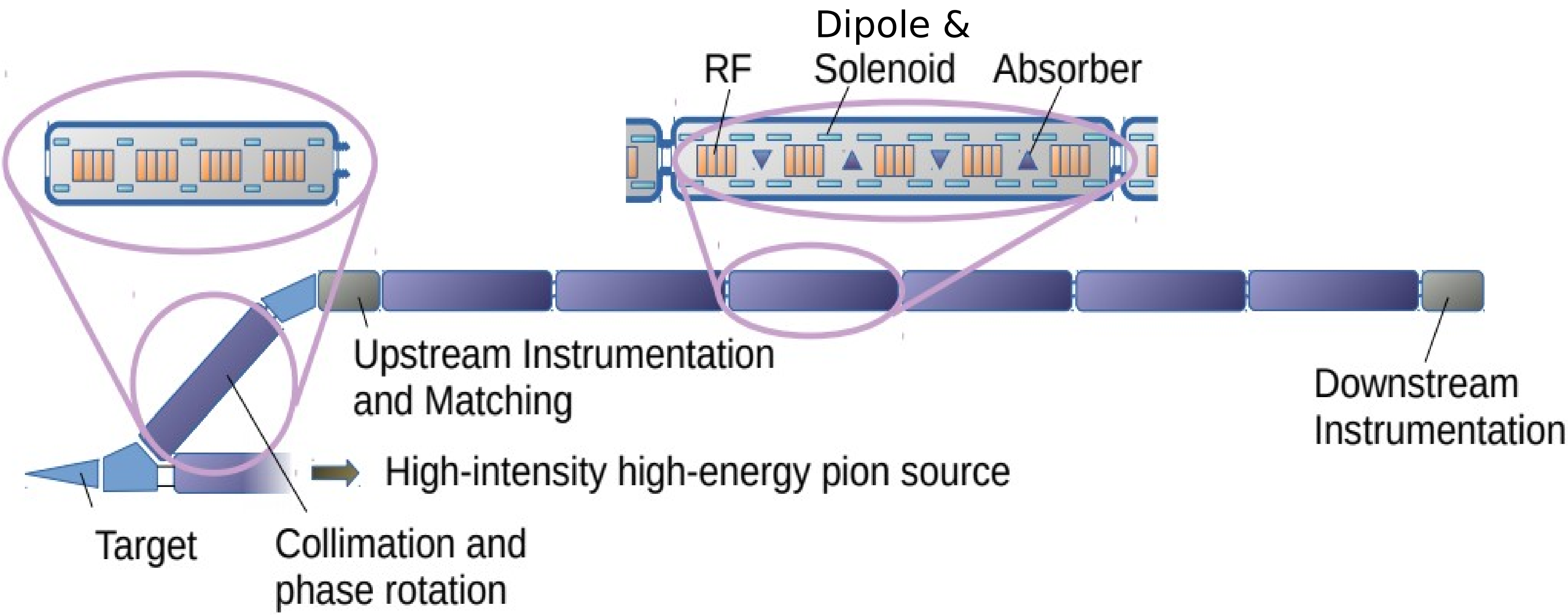
Synergy with cLFV





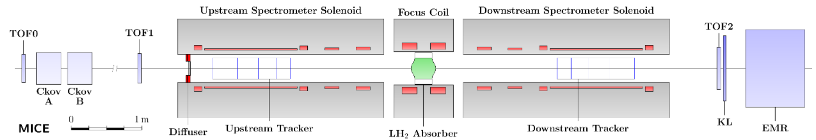
- Muon-to-electron conversion experiments
  - Look for rare decay processes
- Under construction now
- R&D for phase II in progress
- Target station similar to MC target
  - But lower power, lower field
- Strong synergy between the programmes here

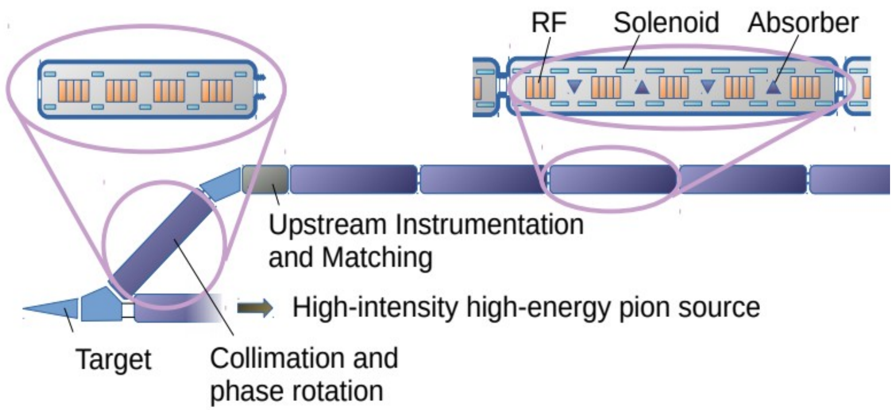
Cooling Demonstrator



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

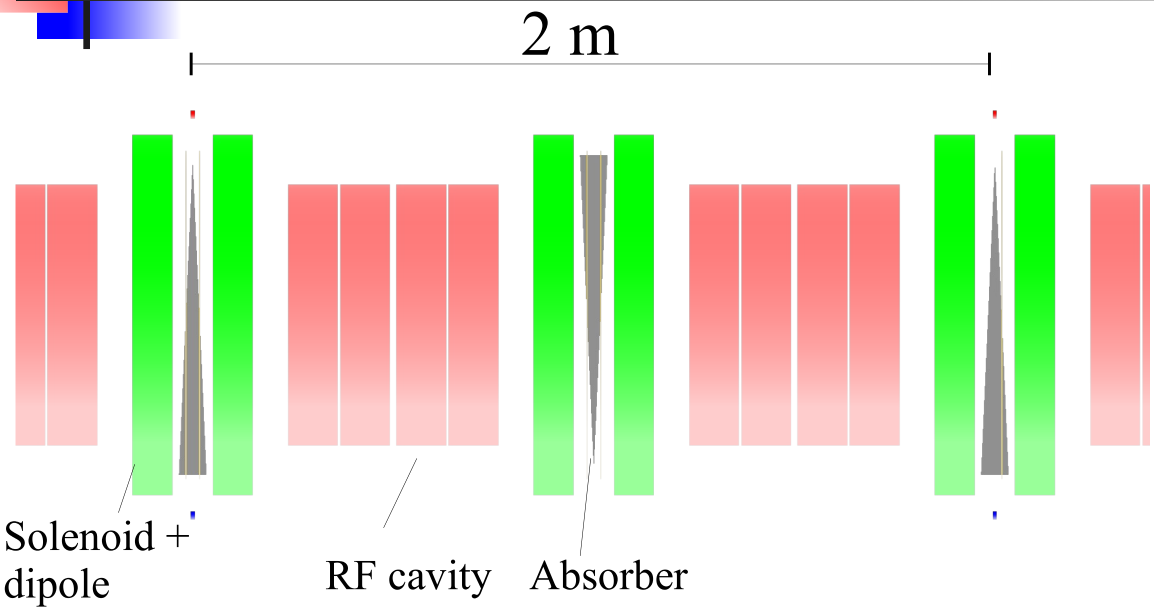
Comparison with MICE



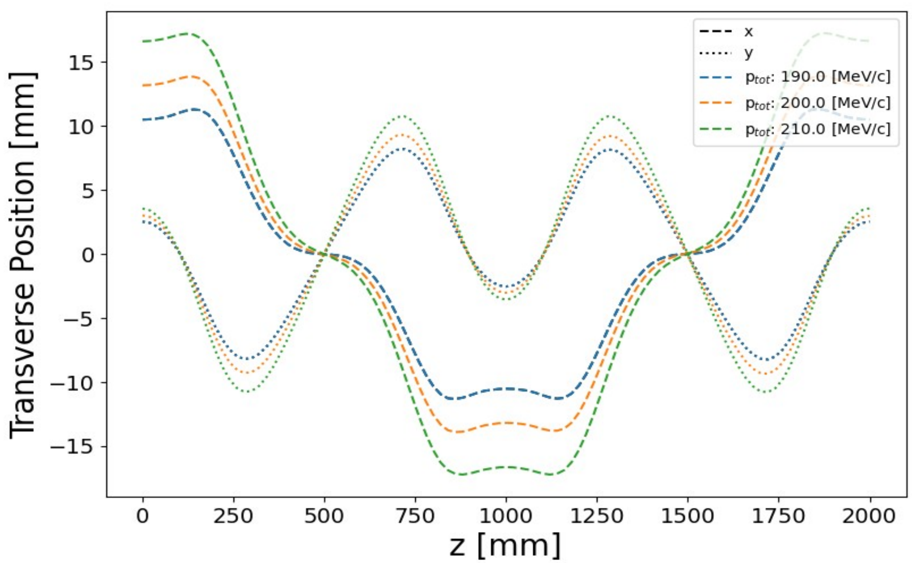


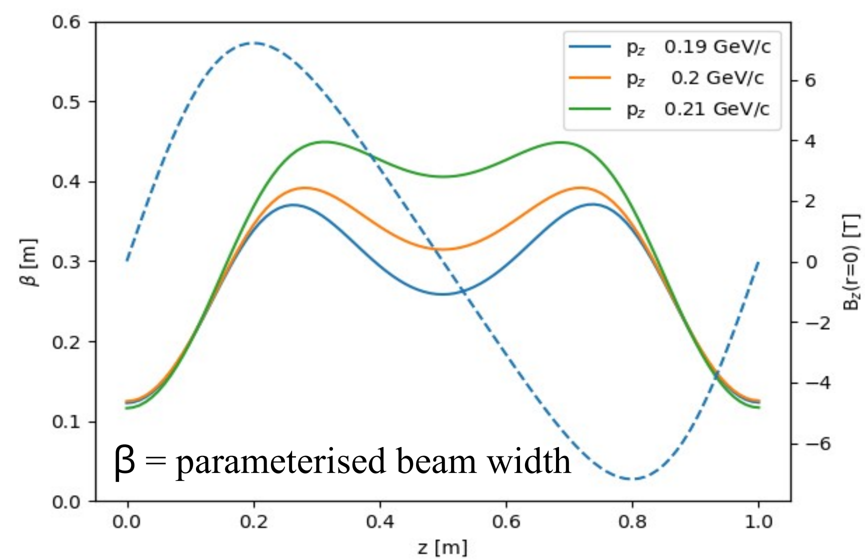
	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Preliminary Cooling Cell Concept



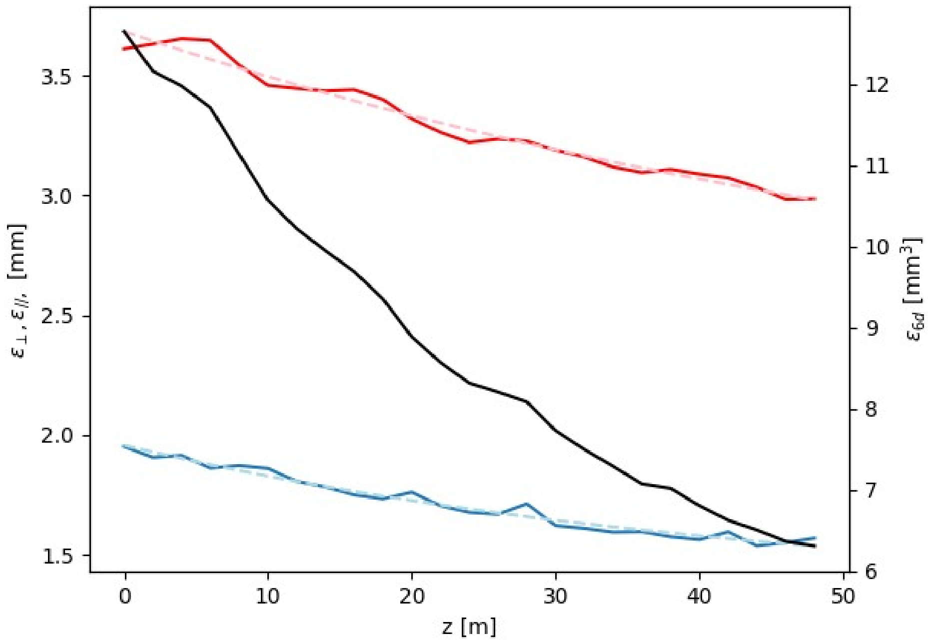
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





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

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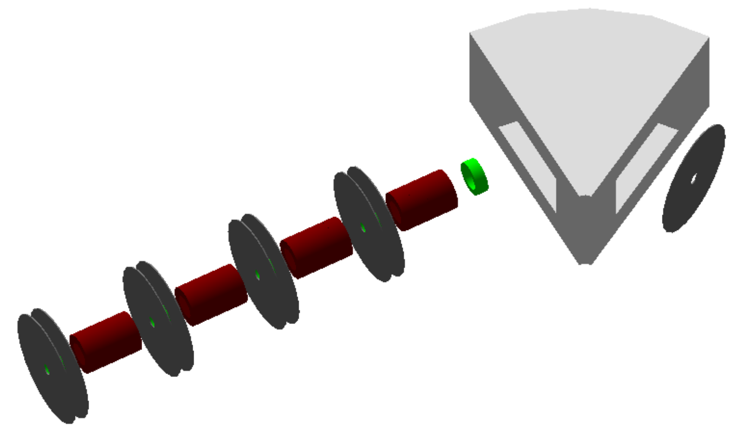
Beam preparation system

- Incident muon beam:
  - 100 ps pulses of muons
  - Mean P = 200 MeV/c
  - RMS p ~ 10 MeV/c
  - RMS x′ ~ 0.05
  - RMS x ~ 20 mm
- Need to consider a system to prepare the muon beam
  - Assume momentum collimation in switchyard
  - Transverse collimation
  - Longitudinal phase rotation

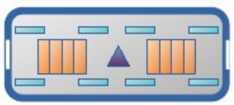


Beam Preparation System

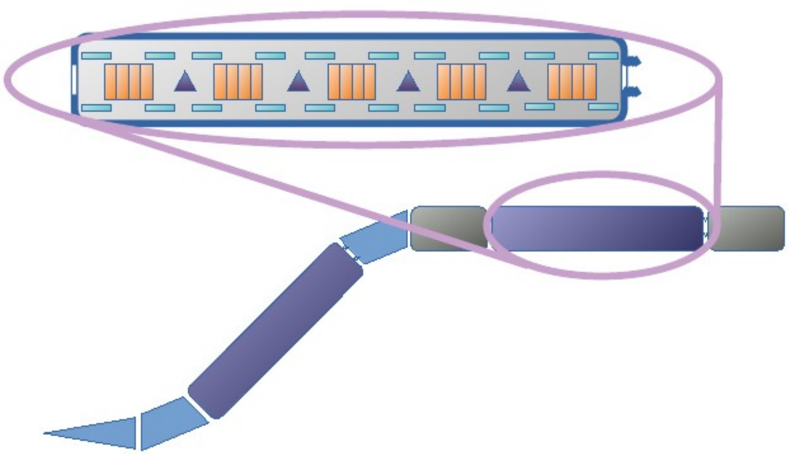
Parameter	Value
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

Demonstrator Programme

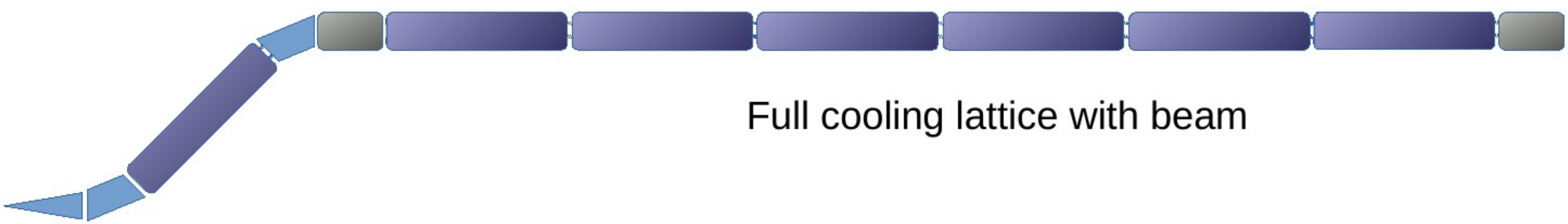
RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



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



Full cooling vacuum vessel with beam



Full cooling lattice with beam

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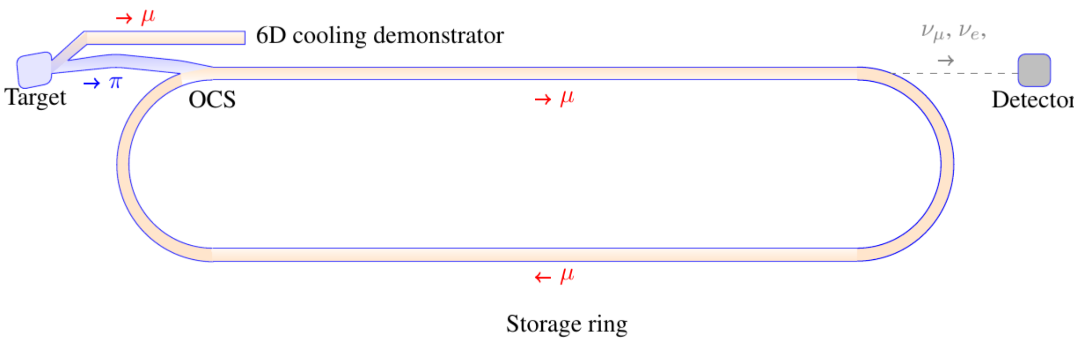
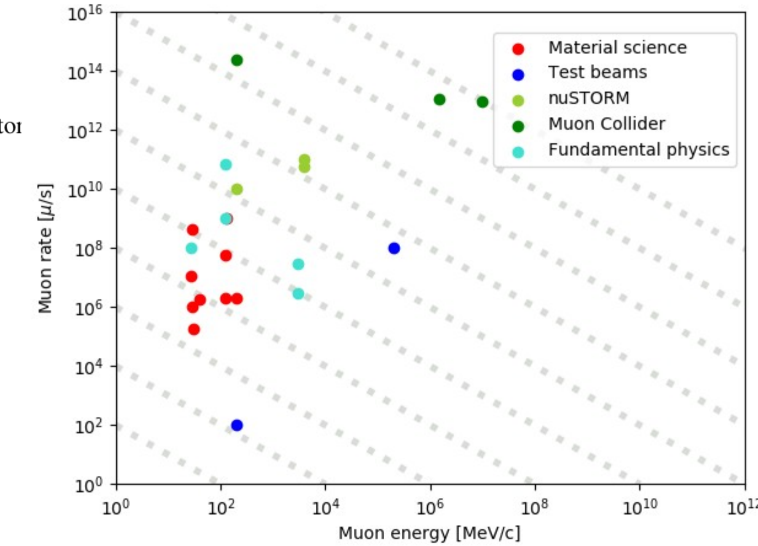
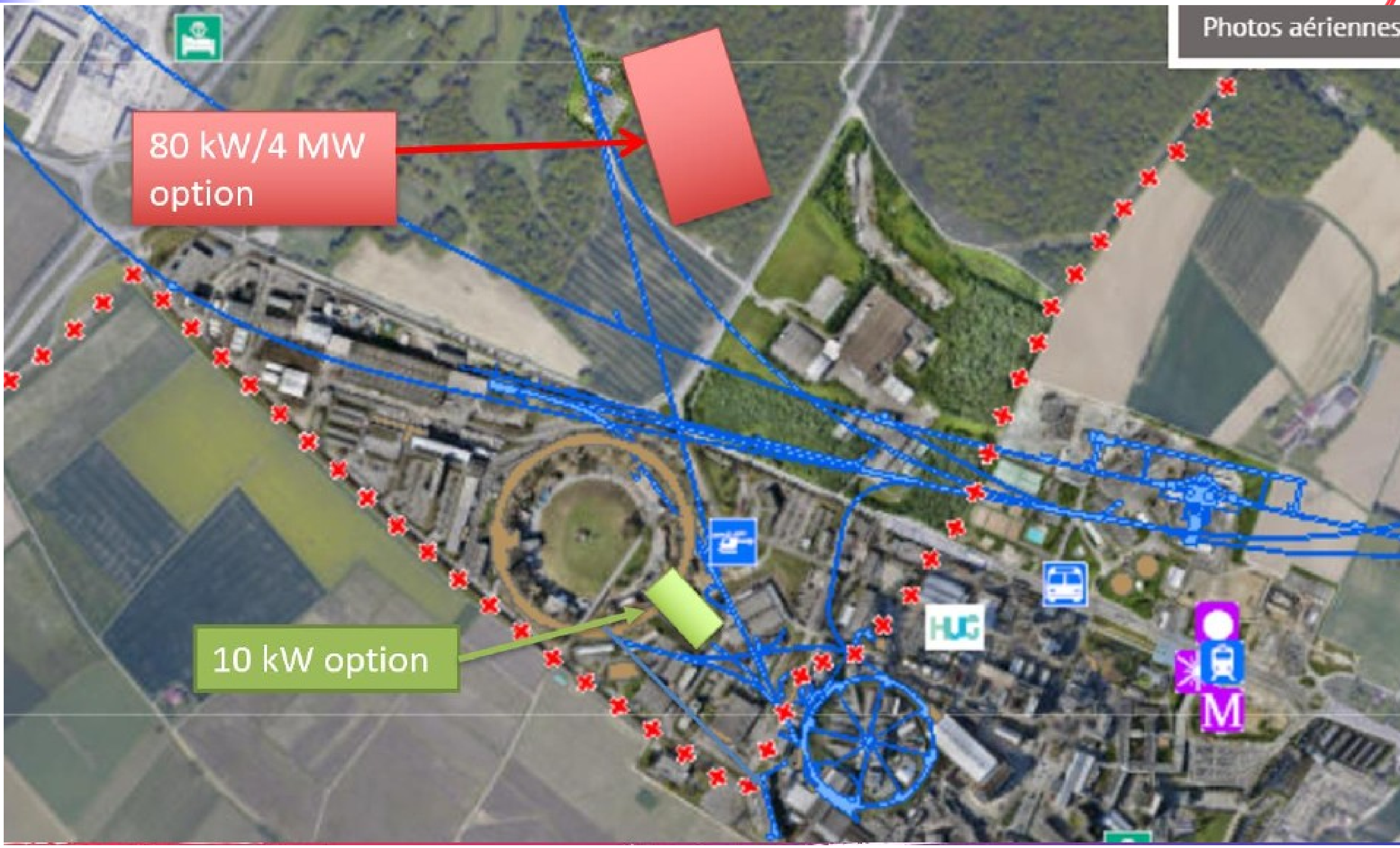
Synergy with nuSTORM





- 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

CERN Siting Options

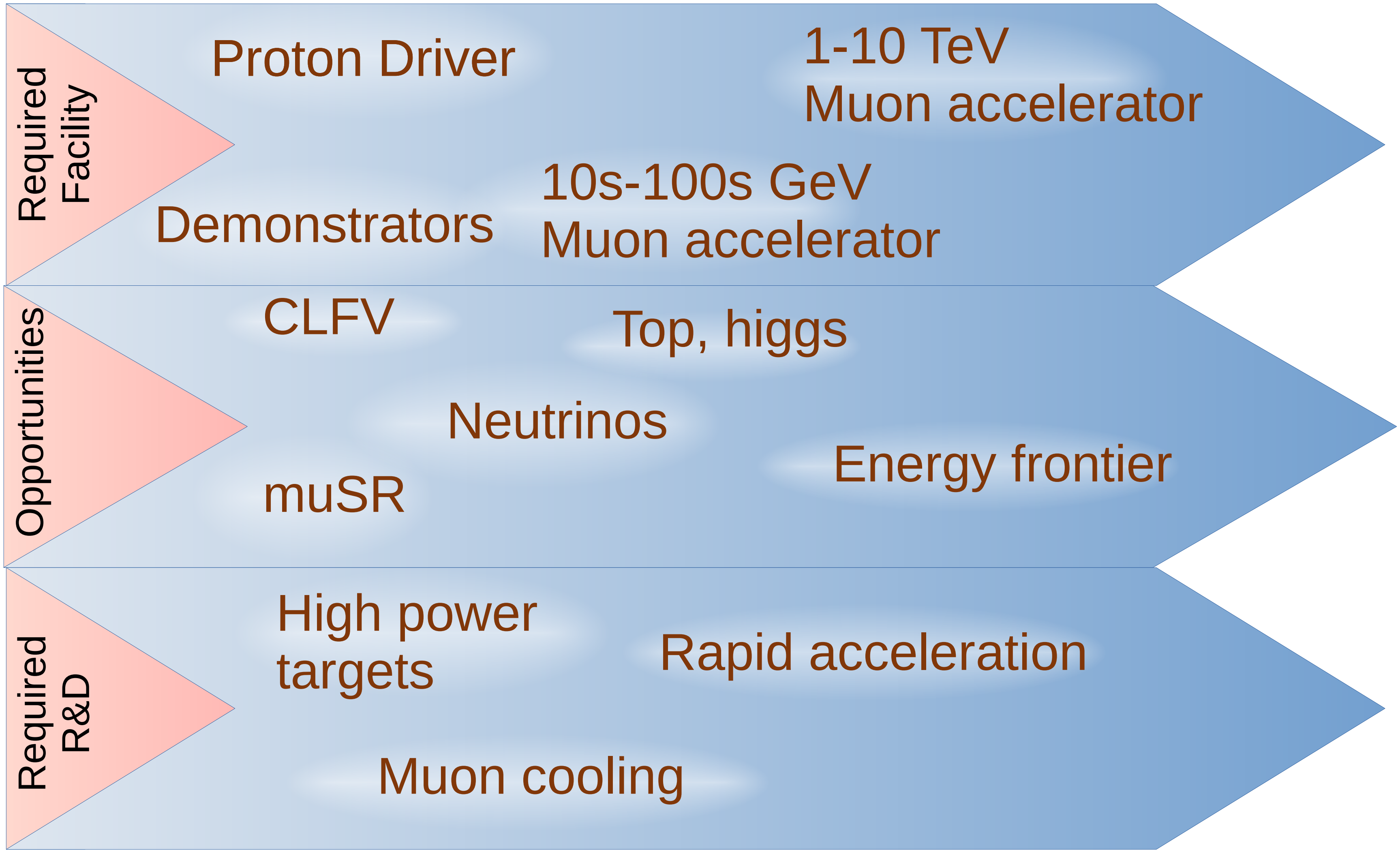


- Site options in **other laboratories/regions** are **welcome!**

Summary

Muon Collider R&D Roadmap

International MUON Collider Collaboration



Science & Technology Facilities Council ISIS

Conclusions

- Muon collider will be the premiere muon facility for 21st century
- Technically challenging
  - This is a good thing!
  - Would yield an entirely novel type of facility
- We need **your** help!
  - The entire muon beams community can help!
  - Opportunity to **drive muon beam technologies for all** applications