Accelerator R&D
Part I: Muon Production and Cooling

P. B. Jurj

with contributions from C. Rogers, R. Kamath and R. Zhu

Workshop on UK Contributions to Muon Collider Detector R&D

University of Birmingham, 3 Jul 2024

Funded by the European Union

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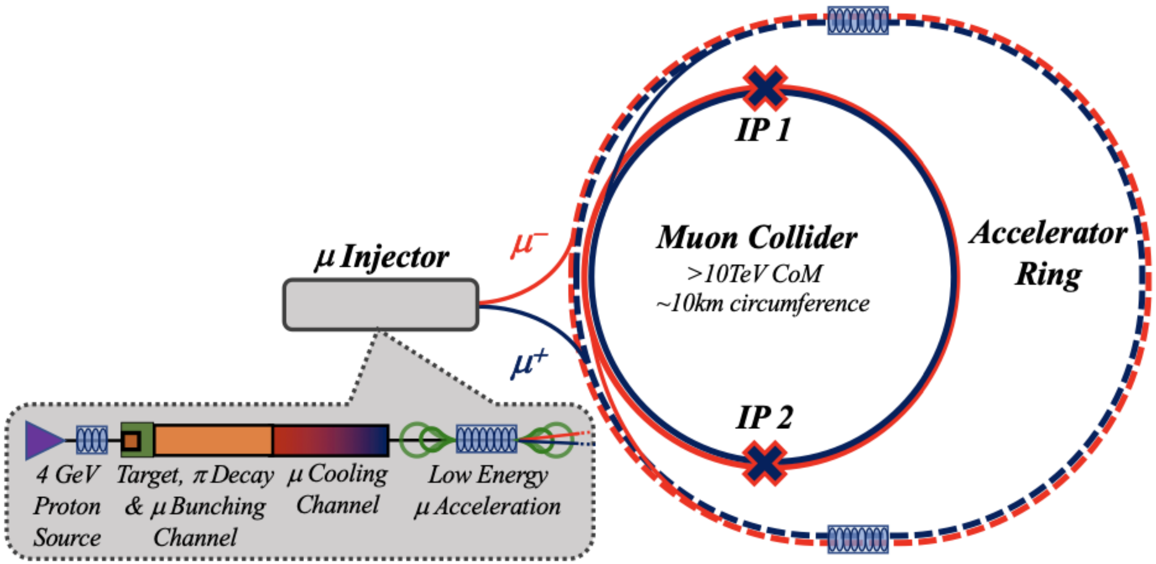
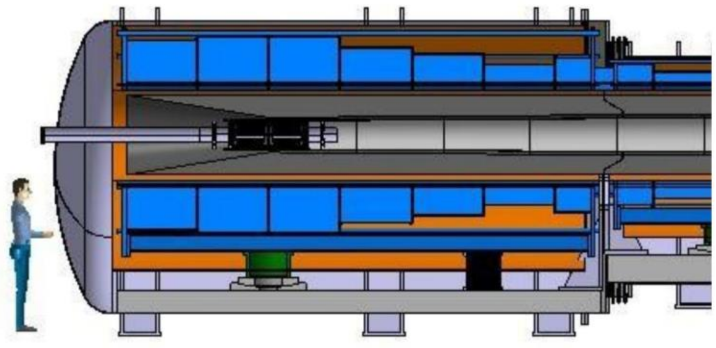
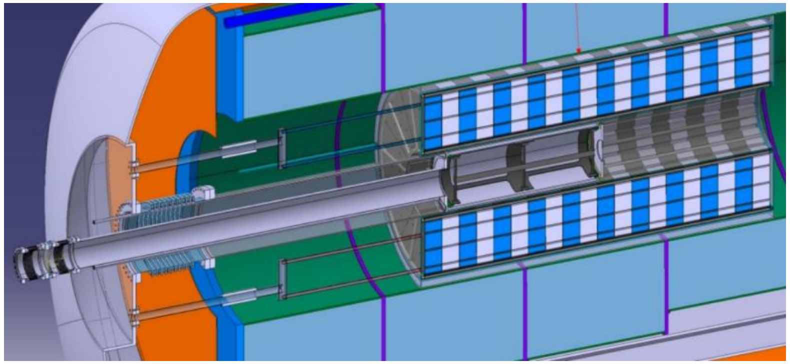
Muon Collider



- Main muon source challenges arise from muon production and cooling
- Two beam demonstration studies are considered
  - Muon cooling demonstrator
  - High-power targetry

Muon Collider Target

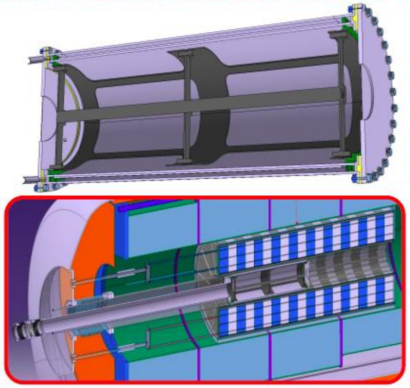




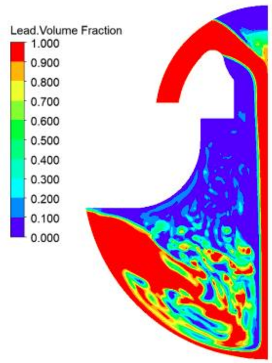
- Protons impinge on a target ⟶ pions ⟶ muons
- Very high field (~20 T) solenoid captures both pion charges
- Heavy shielding required
- Challenges
  - Lifetime of solid target and windows
  - Energy deposition and solenoid shielding

Targetry options & synergies

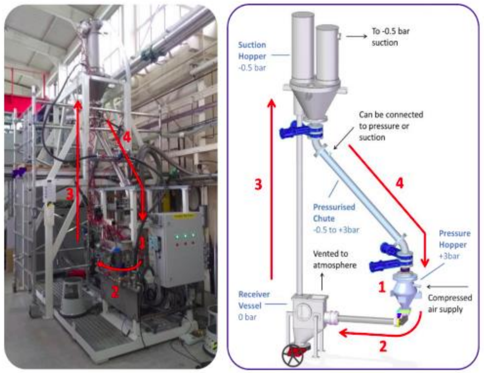
C-Target & target system
CERN
R. F. Ximenes, M. Calviani, D. Calzolari, A. Lechner, F. Saura, J. Manczak, C. Mucher et al



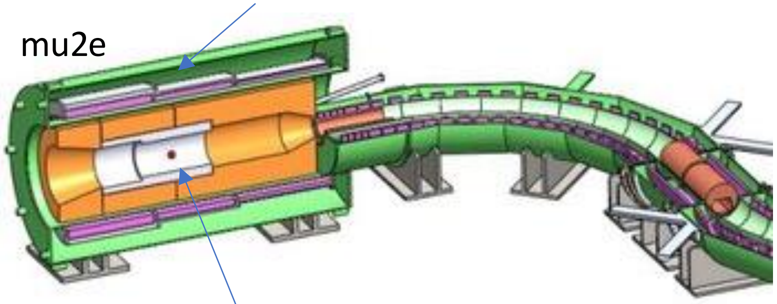
Liquid Pb Target
ENEA & CERN
C. Carrelli, M. Tarantino, I.Di Piazza, P.C. Puviani et al.



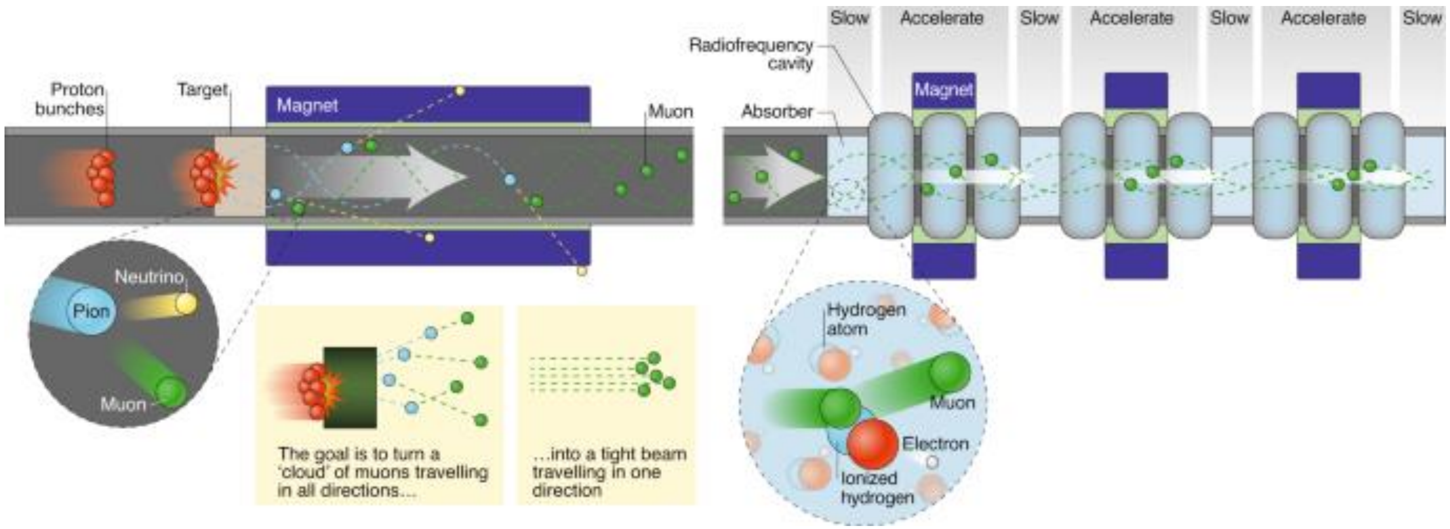
Fluidized W-Target
RAL & Warwick Uni.
C. Densham, J.J. Back, W. Bishop, D. Wilcox, et al.



- HTS cable for high field solenoids
  - Strong synergy with fusion experiments
- Muon-to-electron conversion experiments produce muons in a similar way
  - Lower proton beam power and lower magnetic field



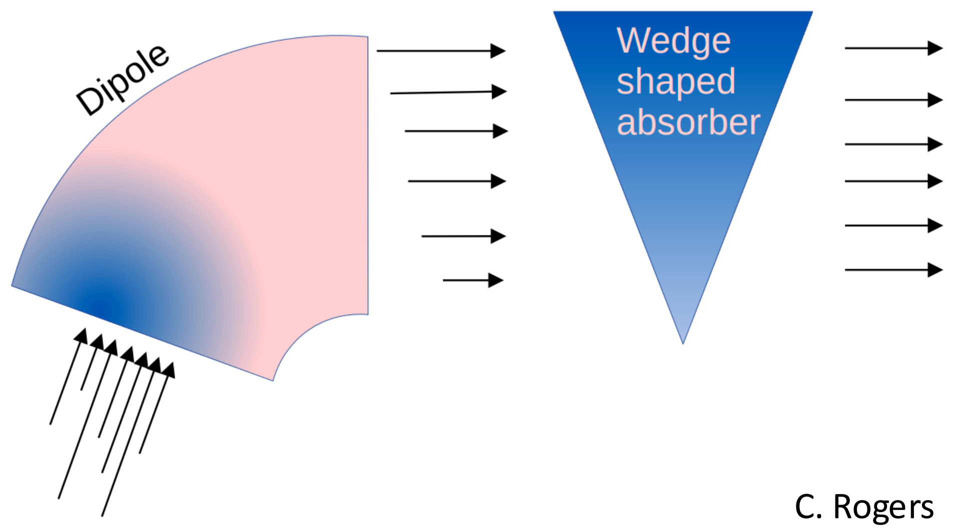
Ionization Cooling



- Beam loses energy in absorber material
  - Momentum reduced in all directions
  - Longitudinal momentum restored using RF cavities
  - Outcome: a beam with a reduced angular divergence, more parallel
- Multiple Coulomb scattering has an antagonising effect; can be mitigated
  - Tight focusing at absorber
  - Low-Z absorber materials (liquid hydrogen, lithium hydride)
- Emittance – measure of the phase-space volume occupied by the beam
  - Equilibrium emittance achieved when the two effects cancel out

Emittance exchange

- 6D cooling required for the Muon Collider
  - Must also cool the beam longitudinally
  - Can be achieved through emittance exchange



C. Rogers

Input: low transverse emittance, high longitudinal emittance → **Dipole**: induces an energy-position correlation; beam wider → **Wedge absorber**: removes energy-position correlation and momentum spread → **Output**: high transverse emittance, low longitudinal emittance

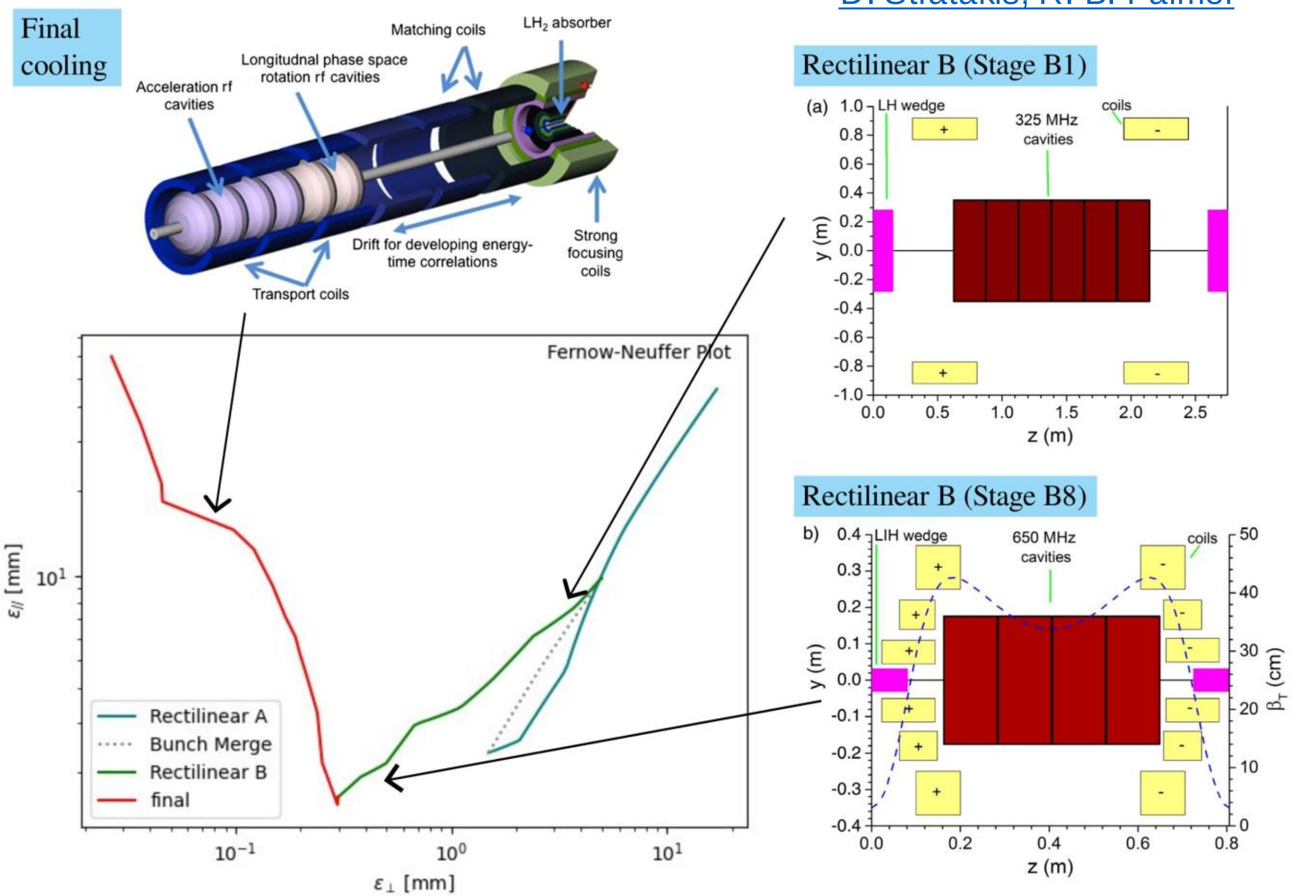
Muon Collider Cooling Scheme

Challenges:

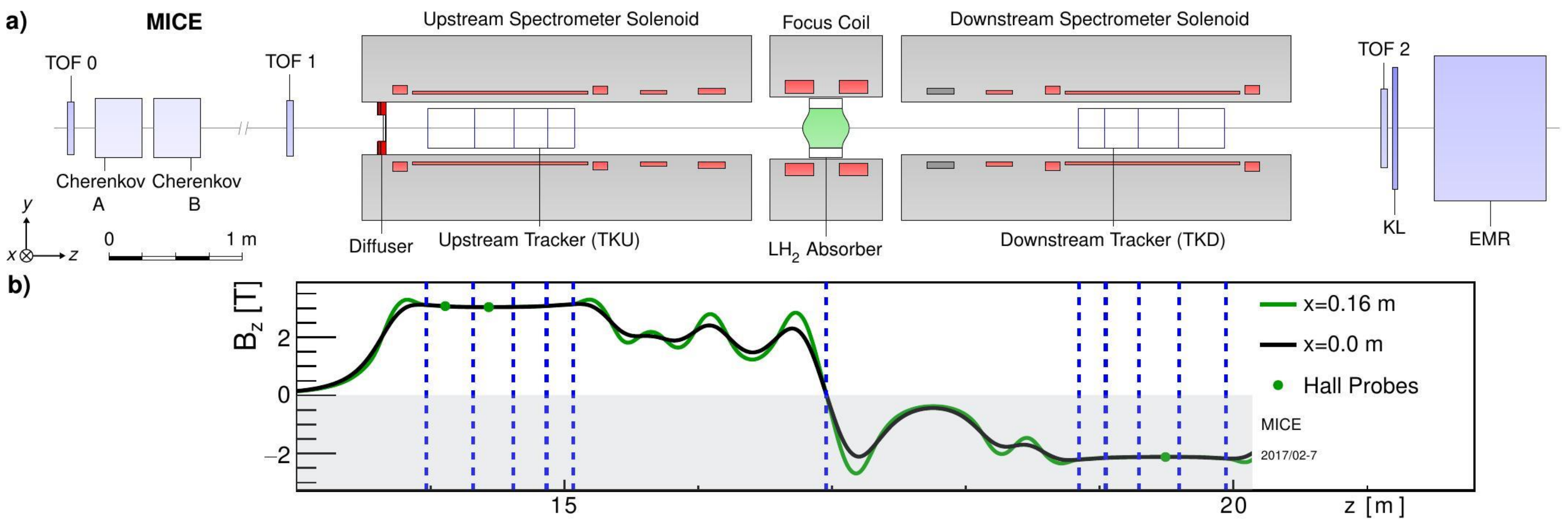
- Rectilinear cooling
  - Integration of magnets, absorbers and RF cavities in a compact lattice
  - High RF gradients in strong magnetic fields
- Final cooling
  - Very high magnetic fields required (~ 30+ T)
  - Management of longitudinal emittance growth
  - Liquid hydrogen absorber in the presence of high beam currents

H. K. Sayed, R. B. Palmer, D. Neuffer

D. Stratakis, R. B. Palmer

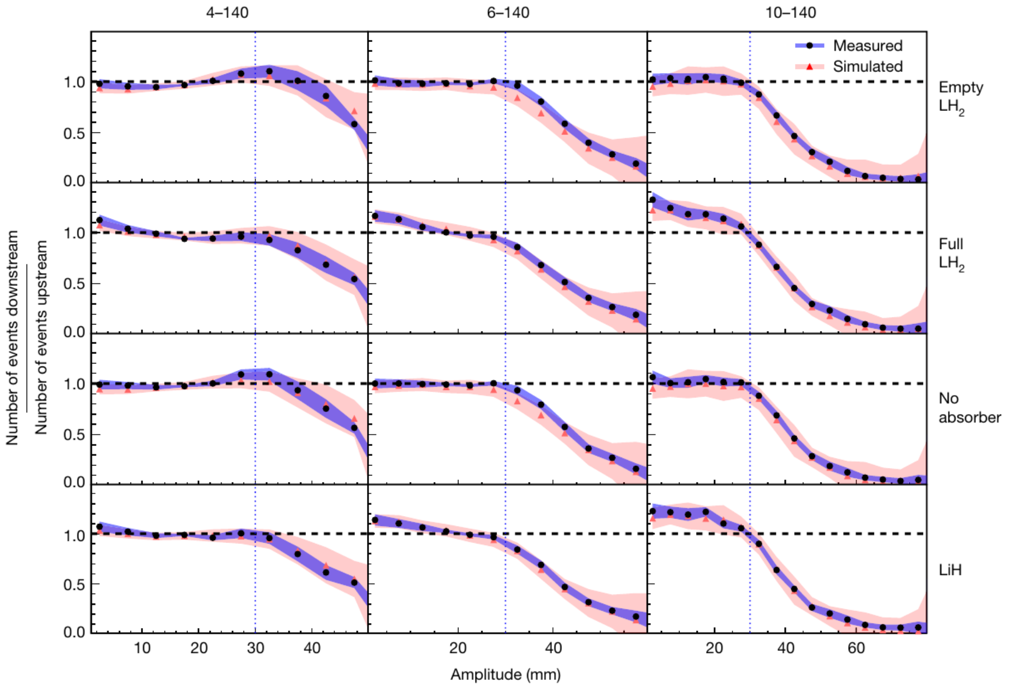


Muon Ionization Cooling Experiment (MICE)



- One cooling cell/absorber, no acceleration
- Beam measured particle by particle upstream and downstream of the absorber (lithium hydride, liquid hydrogen)

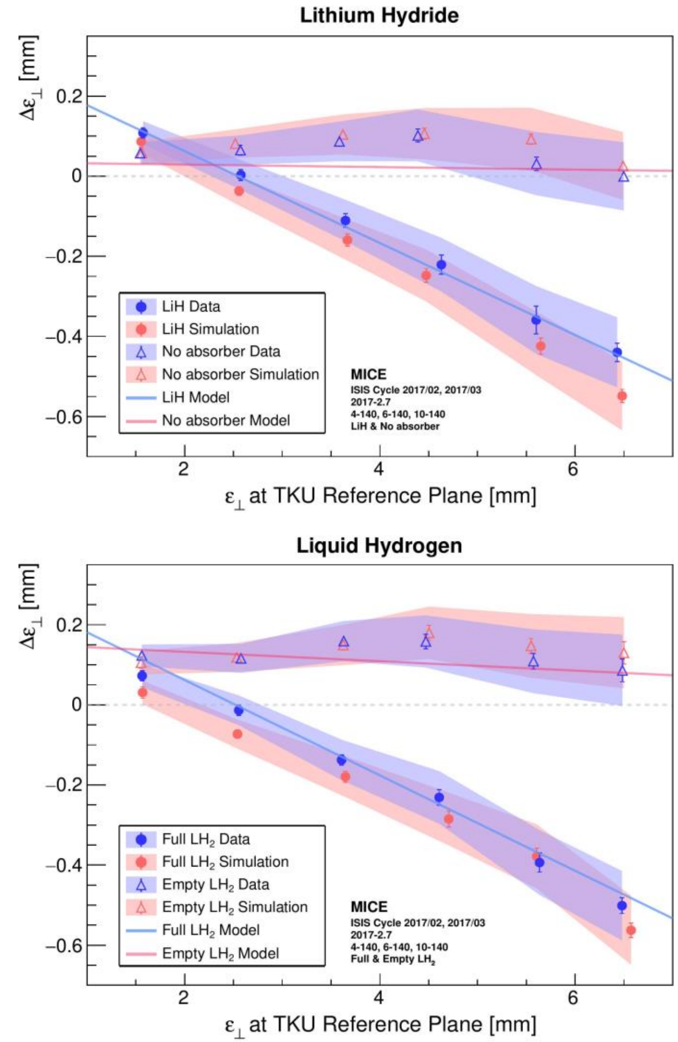
MICE results - core density increase



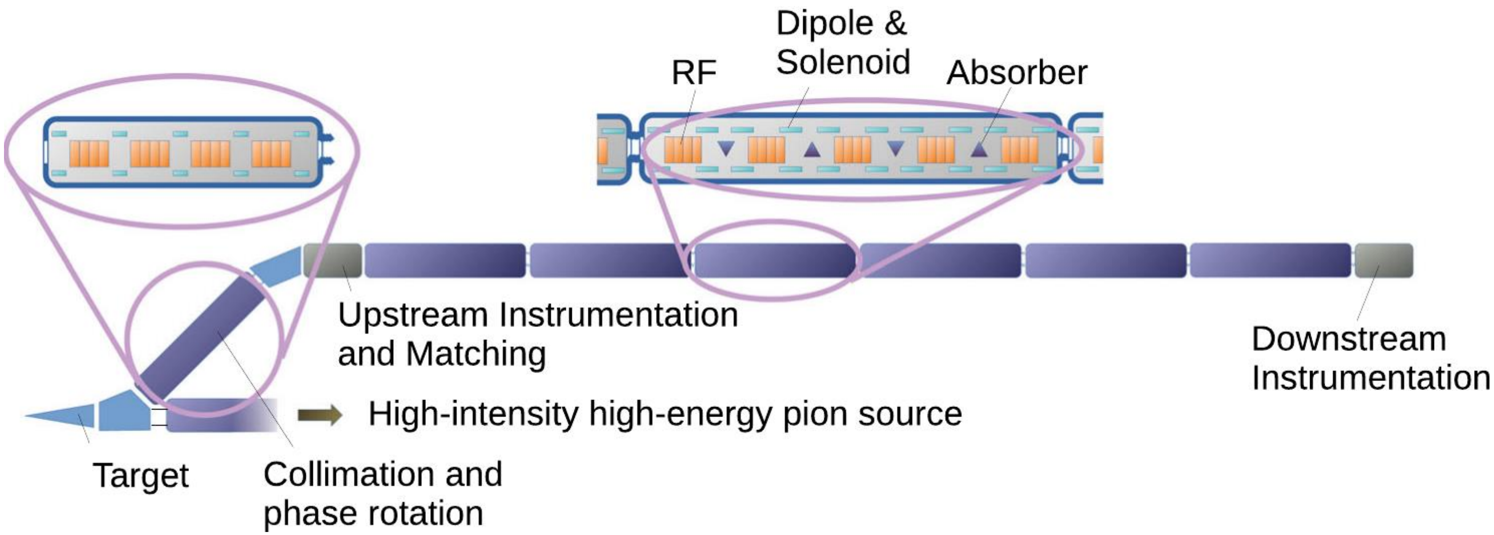
- Transverse (4D) ionization cooling demonstrated by MICE
- Amplitude - distance of muon from beam core
- When absorber present
  - Increase in the number of low-amplitude muons in the beam core
- Results published in Nature

MICE results - emittance reduction

- When absorber present:
  - Cooling above equilibrium emittance
  - Heating below equilibrium emittance
- When no absorber present:
  - Optical heating
  - Additional heating from Al windows
- Results accepted for publication in Nature Physics (arXiv)



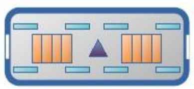
Muon Cooling Demonstrator



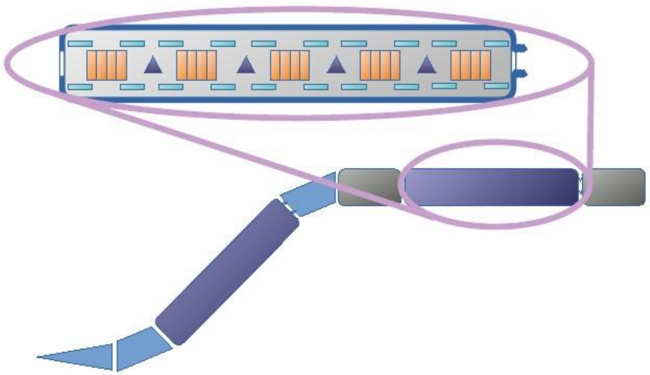
- 6D cooling
  - RF acceleration
  - Multiple cooling cell staging
  - Achieve suitable cooling performance
- Demonstrator design in progress
  - Muon source
  - Beam transport and preparation
  - Cooling lattice

Demonstrator programme

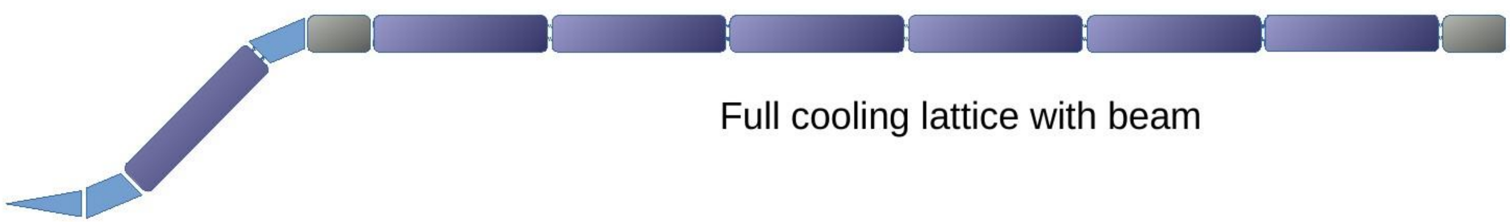
RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



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



Full cooling vacuum vessel with beam



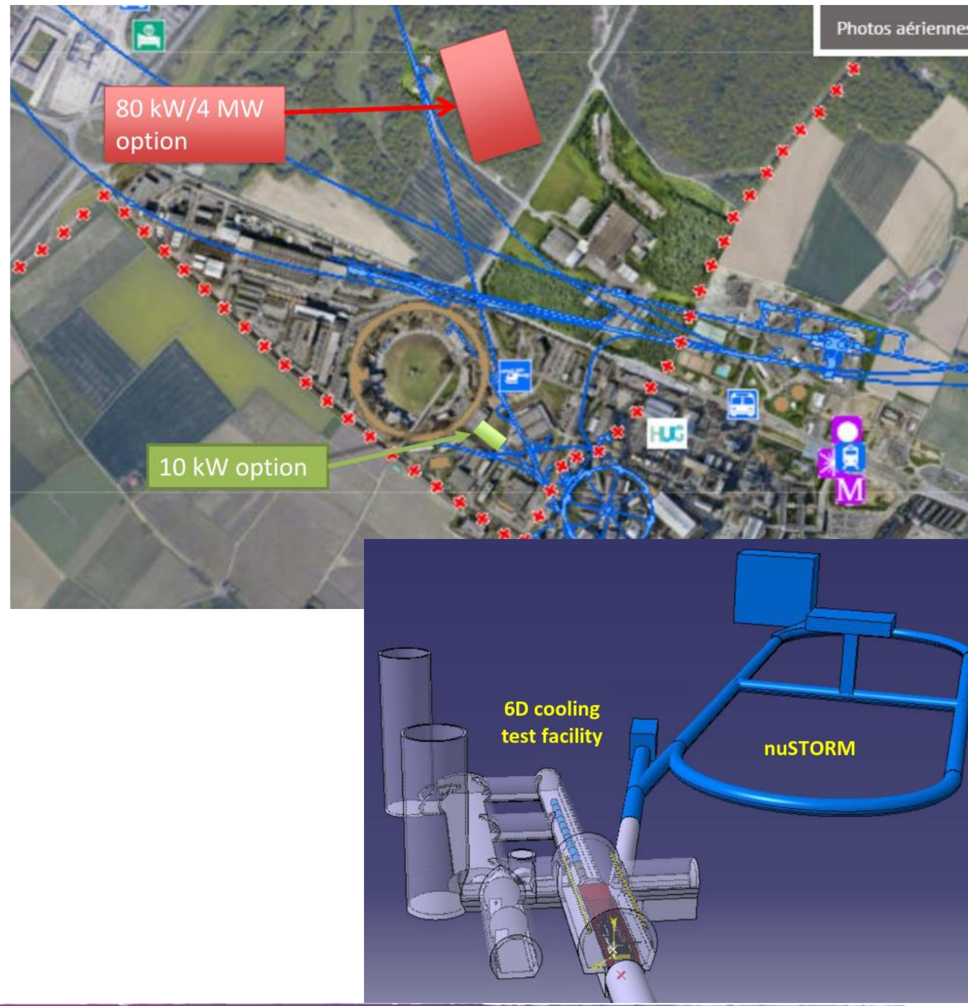
Full cooling lattice with beam

RF development

- Substantial effort done by the US Muon Accelerator Program to develop high-gradient RF cavities capable to operate in strong magnetic fields
- Two cavities developed and tested with promising results in mitigating breakdown
  - Beryllium walls (Bowring *et al*, PRAB 23 072001, 2020)
  - Insulation with high pressure gas (Freemire *et al*, JINST 13 P01029, 2018)
- A dedicated facility required to test these concepts (and others) further
  - High-gradient RF source housed within a large aperture high-field solenoid
  - Several labs considered for hosting a test stand (Daresbury, Milan, Saclay)

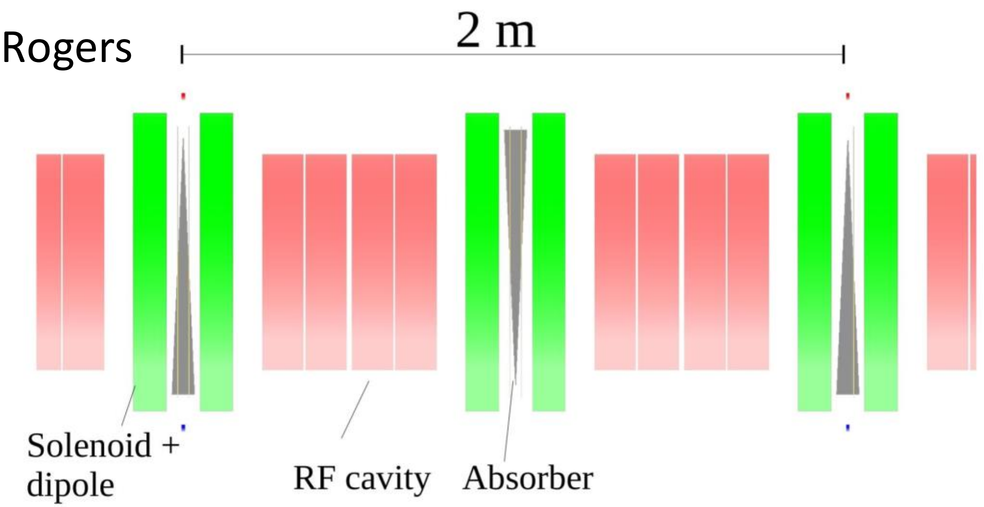
Demonstrator - Siting options at CERN

- Two siting options at CERN currently considered (non-CERN proposals welcome)
- 10 kW beam power option
  - In the TT7 extraction line
  - Proton beam from the CERN PS
  - Requires bespoke muon production and transport system design
- 80 kW/4 MW beam power option
  - Proton beam from the CERN PS or SPS
  - Pion production system could be shared with the nuSTORM facility

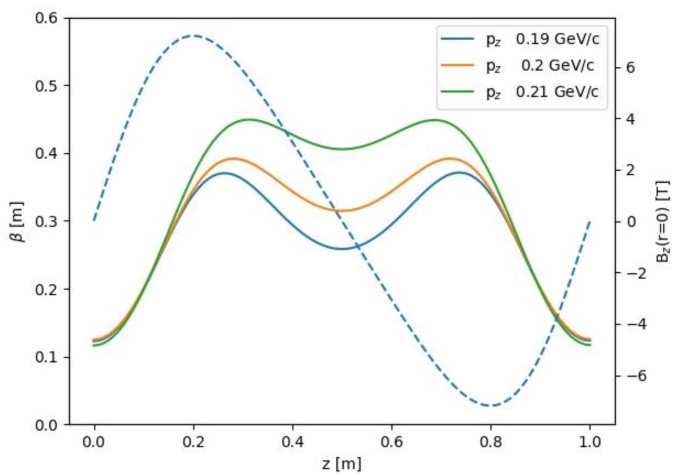


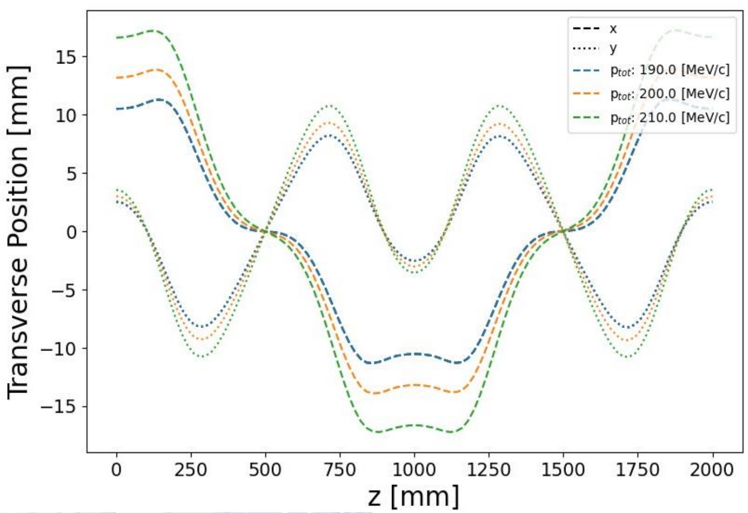
Preliminary cooling cell concept

C. Rogers



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

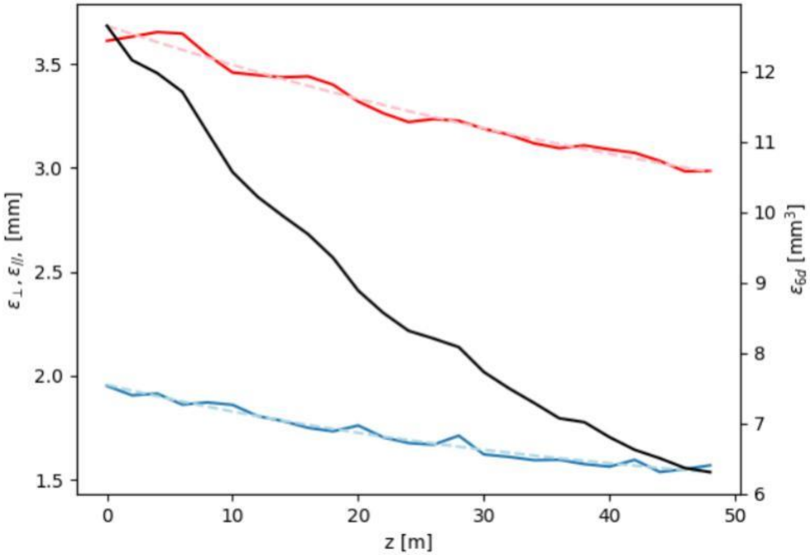




Preliminary cooling channel performance

C. Rogers

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

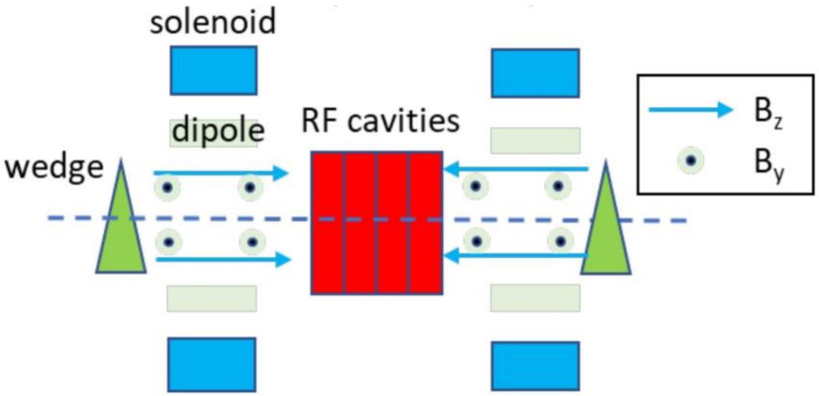


- Lithium hydride absorber
- Currently under optimisation
  - Tighter focusing could provide more cooling
  - Practical/engineering constraints incorporated iteratively

Preliminary cooling channel performance

R. Zhu

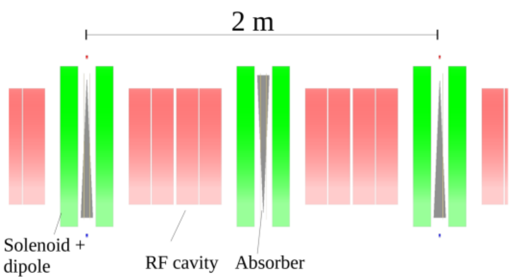
	$\varepsilon_{T,sim}$ (mm)	$\varepsilon_{L,sim}$ (mm)	$\varepsilon_{6D,sim}$ (mm^3)	Transmission
Start	5.129	9.991	262.5	
Stage 1	2.898	8.583	73.60	86.1%
Stage 2	1.974	5.852	23.49	91.1%
Stage 3	1.449	3.251	7.067	88.8%
Stage 4	1.066	2.367	2.856	91.7%
Stage 5	0.7271	2.284	1.266	91.3%
Stage 6	0.4956	2.149	0.5374	88.2%
Stage 7	0.3549	2.075	0.2734	87.7%
Stage 8	0.2690	1.891	0.1403	88.4%
Stage 9	0.1831	1.767	0.05911	82.2%
Stage 10	0.1403	1.563	0.03057	83.5%



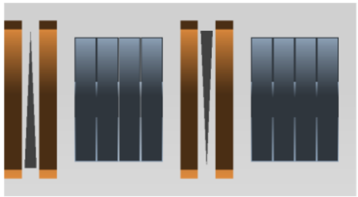
- Demonstrator cooling cell design also informed by the rectilinear cooling channel optimisation studies
- Liquid hydrogen
  - Improved performance, but higher transmission losses

Code development: BDSIM for ionization cooling

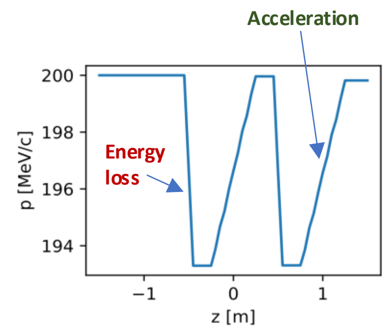
- Current muon cooling simulation studies: G4beamline
- Plan to conduct parallel cooling studies in BDSIM
  - Advance code to deliver simulations of the full cooling system (Demonstrator/Muon Collider)
  - Validate and benchmark against G4beamline
- Initial work and validation conducted using existing Cooling Demonstrator lattice designs
  - Beam optics validation (solenoids only)
  - Longitudinal acceleration
  - Transverse cooling
- Future work
  - Dipole field integration
  - Solenoid field model development
  - Full simulation validation

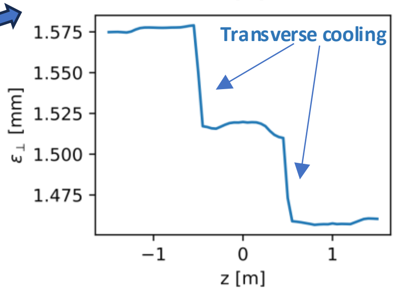


G4beamline (C. Rogers)



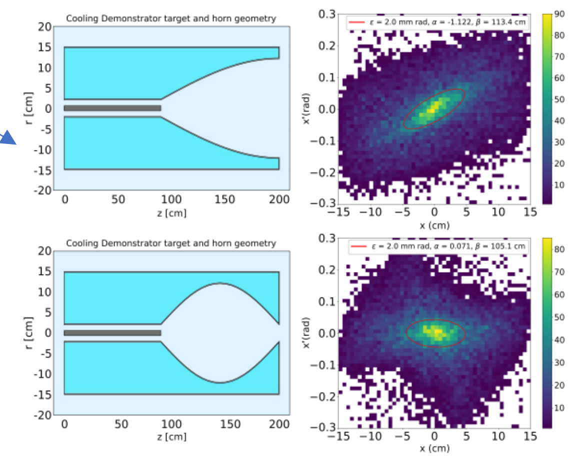
BDSIM (R.Kamath, P. Jurj)

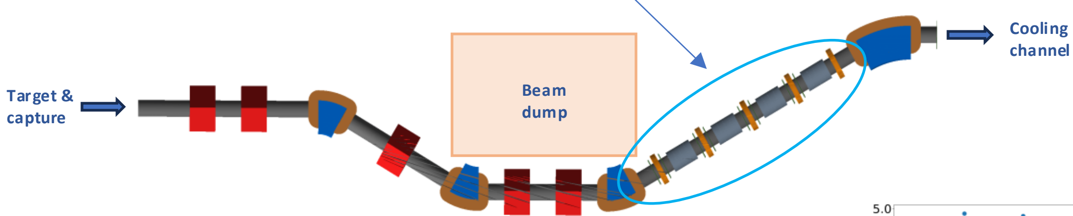


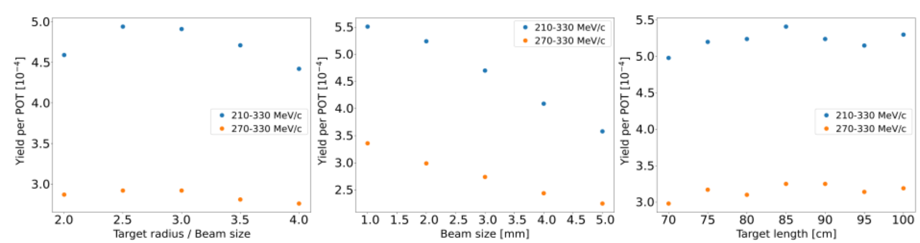


Demonstrator - Beam production and transport

- Preliminary design studies on muon production and transport for the low beam power CERN option
  1. Muon (pion) production
     - Studied feasibility of using 14 GeV protons from the CERN Proton Synchrotron
     - Target and magnetic horn parametric scans/optimization
  2. Beam transport
     - Initiated a study (BDSIM & MAD-X) to fit the transport chicane within existing tunnel (CERN TT7)
     - Chicane to include a beam preparation system, used to tune the beam transversely and longitudinally before delivery to the cooling channel







Summary

- Muon production and cooling at a Muon Collider - technically challenging
- Beam tests are essential
  - 6D ionization cooling, at a Muon Cooling Demonstrator
  - MW-class targetry in a high-field solenoid
- Opportunities for a rich physics programme

Thank you

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