Muon beams and colliders

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Why Muons?

- **Messengers to high energy**
  - Muon magnetic moment → BSM
  - Charged lepton flavour violation → BSM
- **Exquisite neutrino source**
  - Precise measurement of muon beam possible
  - Detailed understanding of muon decay
  - Well-controlled and tunable neutrino beams
- **Direct applications** for muon beams
  - Muon spin resonance spectroscopy (muSR)
  - Muon x-ray spectroscopy
- **Next-generation collider**
  - **Compact** collider compared to protons
    - Fundamental particle – energy not spread over constituent quarks
  - **Higher energy** compared to electrons
    - High mass particle – not susceptible to synchrotron radiation
- Possible to **advance particle physics by decades**

International Perspective

High-priority future initiatives

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

g. Belle II, LHCb, and Mu2e (*pursue quantum imprints of new phenomena*, section 5.2).

2.3

The Path to 10 TeV pCM

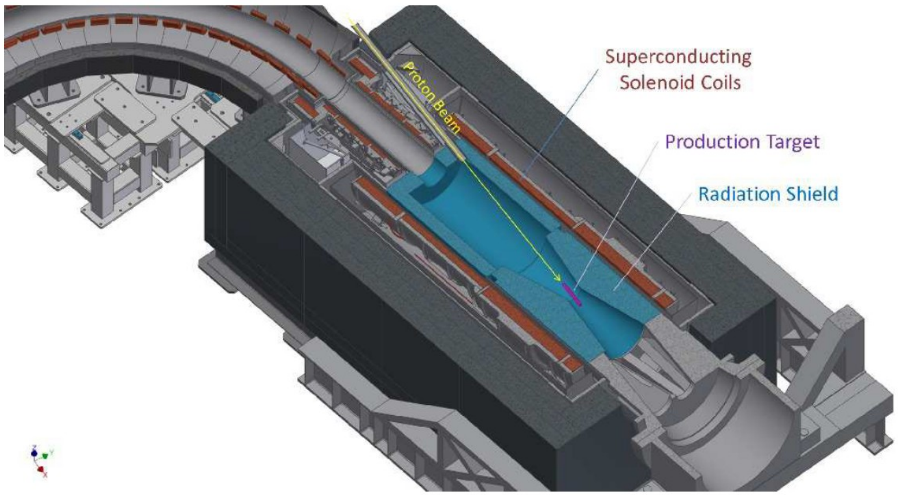
Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

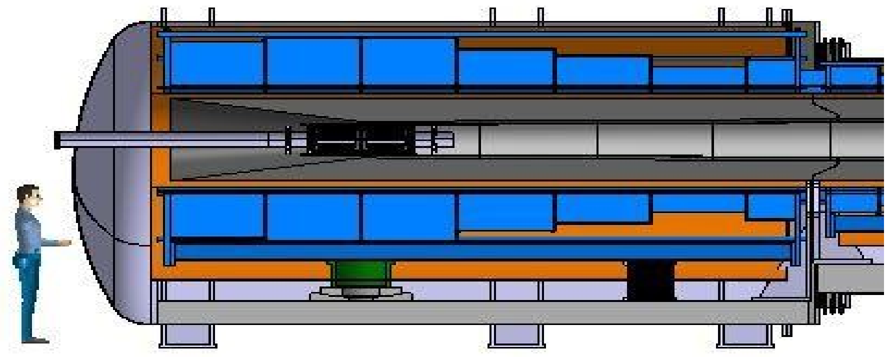
Challenges

- Muon production
  - Produced as a secondary beam
  - Difficult to make a high-quality muon beam
- Muon Lifetime
  - Muons decay!
  - Lifetime is about 660 metres/c – but time dilation
  - Acceleration → RF voltage ~0.1-1 MV/m for time dilation to win*
- Secondary particles
  - Muons decay!
    - At TeV-scale collider neutrino showers need to be managed
    - At TeV-scale collider, decay electrons make noise in detector
    - All manageable
  - For many (most) applications, the decays are the product

*Towards a muon collider, EPJC 83, 2023

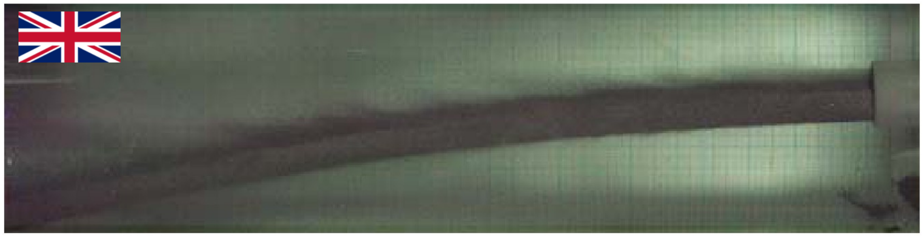
Muon Production

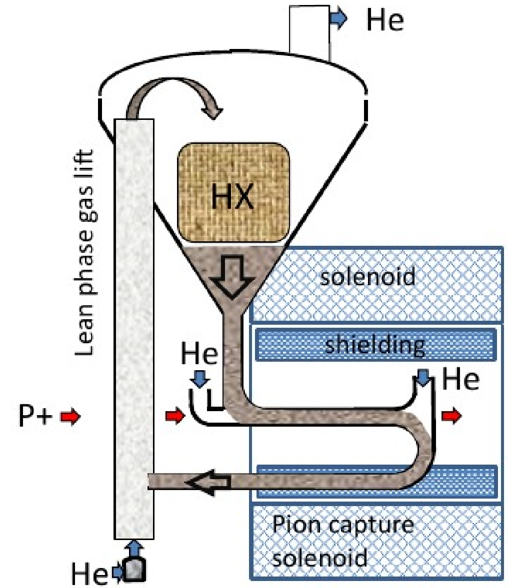


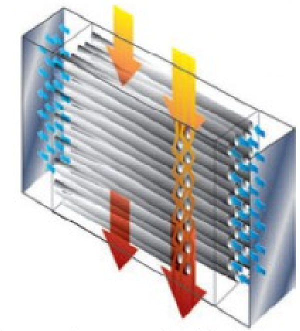


- Protons on target → pions → muons
  - ISIS → parasitic graphite plate
  - COMET → graphite (phase I), tungsten (phase II) + solenoid
  - Mu2e → tungsten + solenoid
  - PSI → rotating graphite disk
  - Muon collider → graphite rod + solenoid

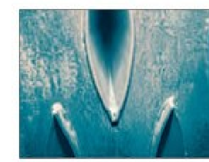
Muon Target





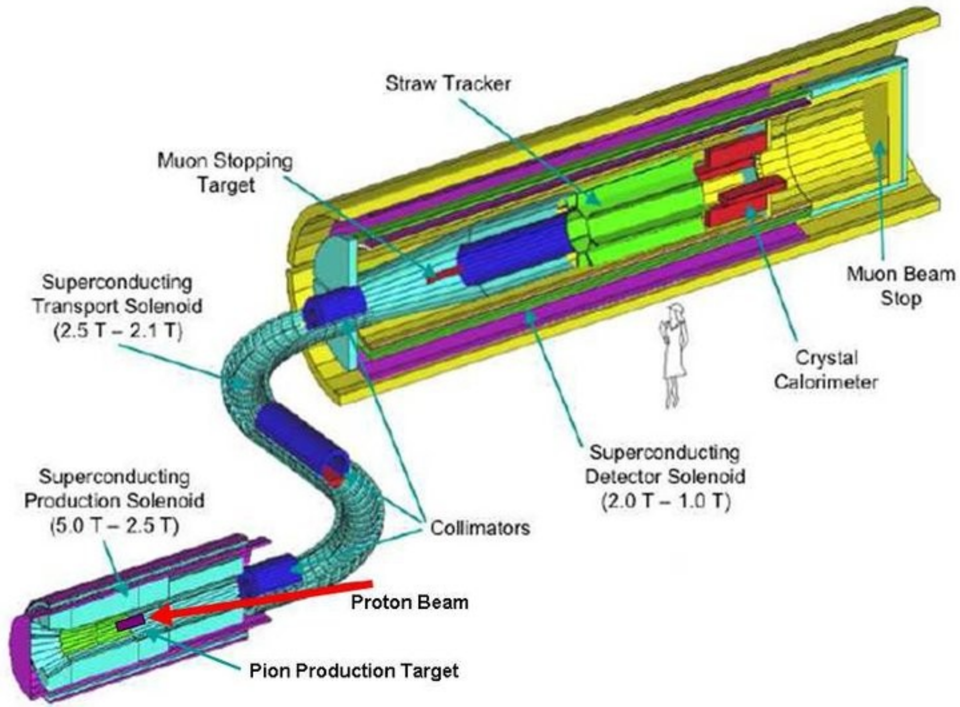


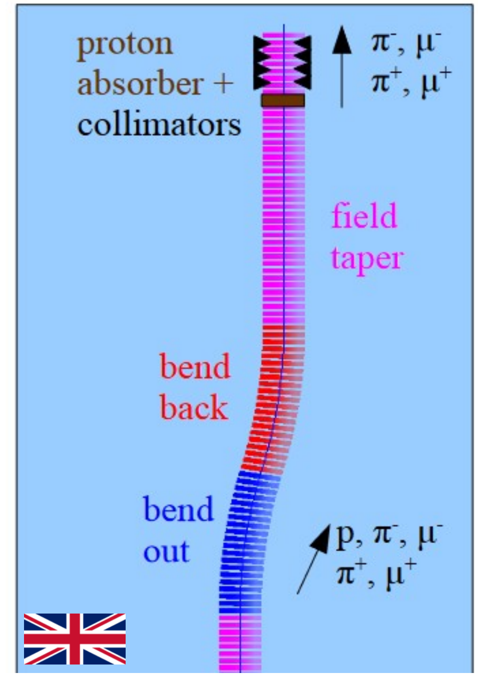
Example gravity fed granular flow heat exchanger



- Mu2e phase 2
  - Considering moving target
  - Rotating disk (e.g. PSI) not compatible with solenoid
    - Doesn't scale terribly well with power
  - Bearings on conveyor tube considered
- UK: fluidised Tungsten powder
  - Scales very well with power/heat load
  - Good candidate for muon collider
  - Interesting for neutron production
  - Builds on UK leadership in neutrino targetry

Capture

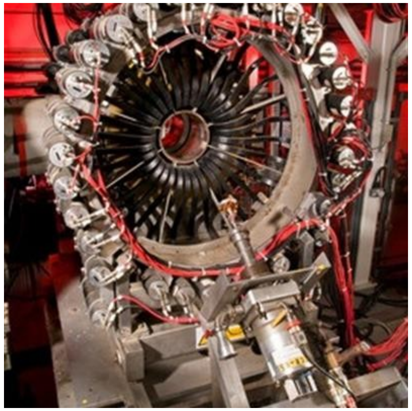


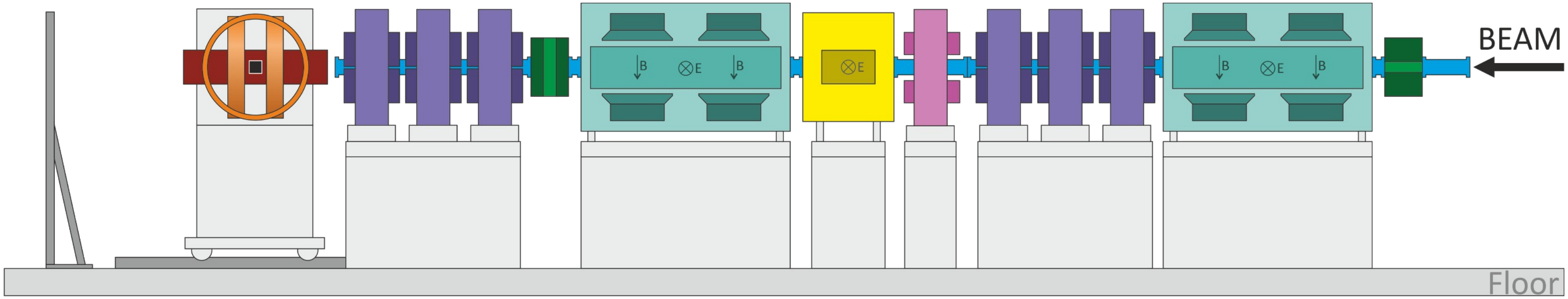


- Solenoid focusing plays a big part
  - Excellent acceptance over a large momentum range
- Chicane to collimate momentum
  - Hard bend in mu2e → narrow momentum band and bg rejection
  - Soft bend in muon collider → much broader band acceptance
    - UK-led design
  - Cooling for muon collider does the momentum "selection"

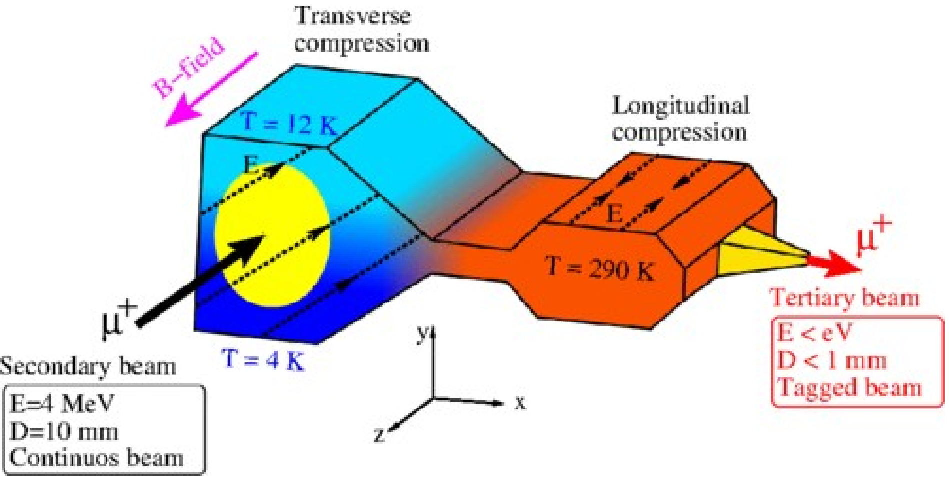
ISIS SuperMuSR

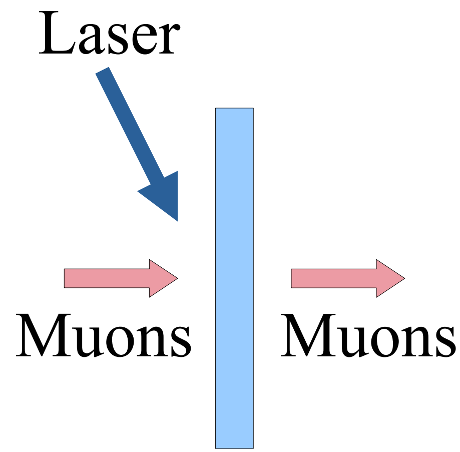
- Note ISIS muSR is quite different
  - Quadrupole focusing
  - Spin rotation
  - Chopper (short muon pulse critical)
- Strong interest in muon cooling techniques





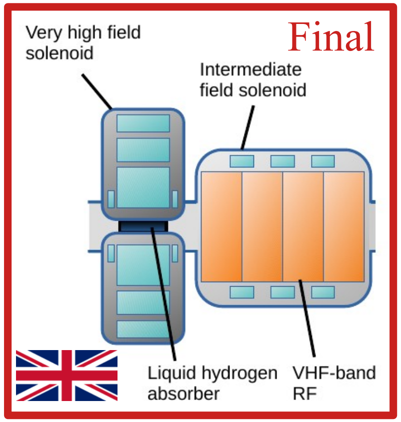
Sub-MeV muon cooling

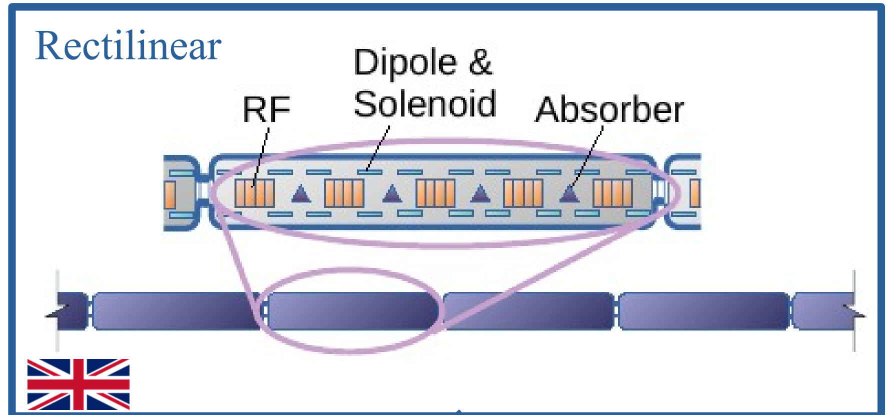


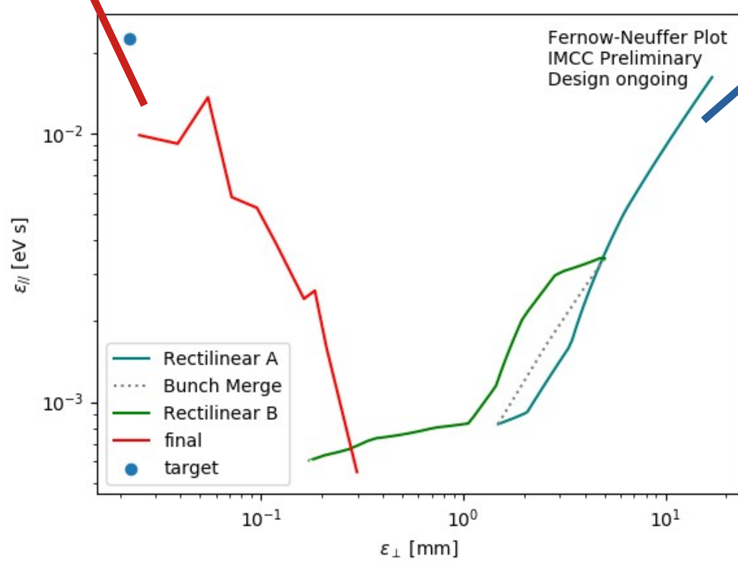


- Muon cooling → reduce muon beam size in phase space
- PSI Scheme
  - Modified Wien filter for transverse compression
  - Frictional cooling for longitudinal compression
- JPARC scheme
  - Stop muons in thin film and capture
  - Ionise with laser and reaccelerate
- Frictional cooling techniques under investigation at ISIS

Ionisation Cooling (~100s MeV)



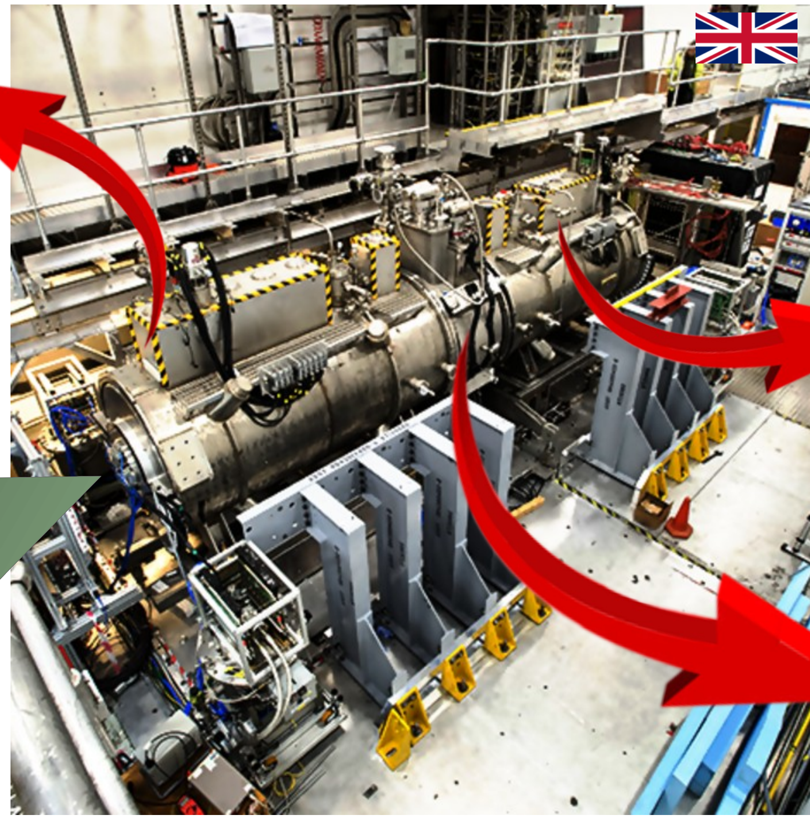




MICE - Experimental set up @ RAL

Measure muon position and momentum upstream

Beam



Measure muon position and momentum downstream

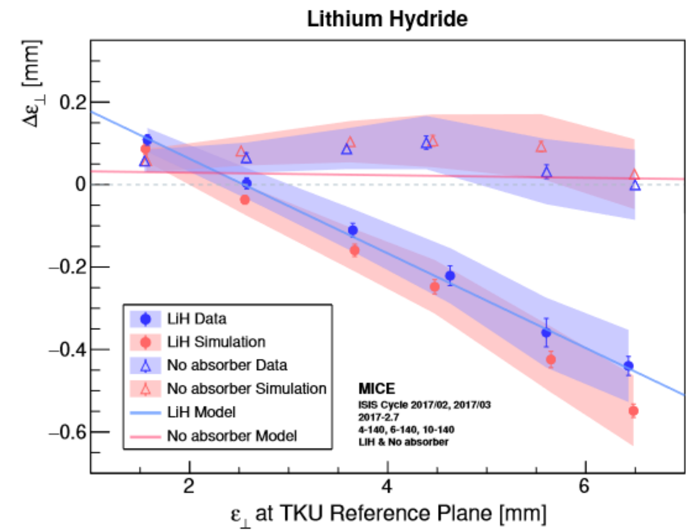
Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

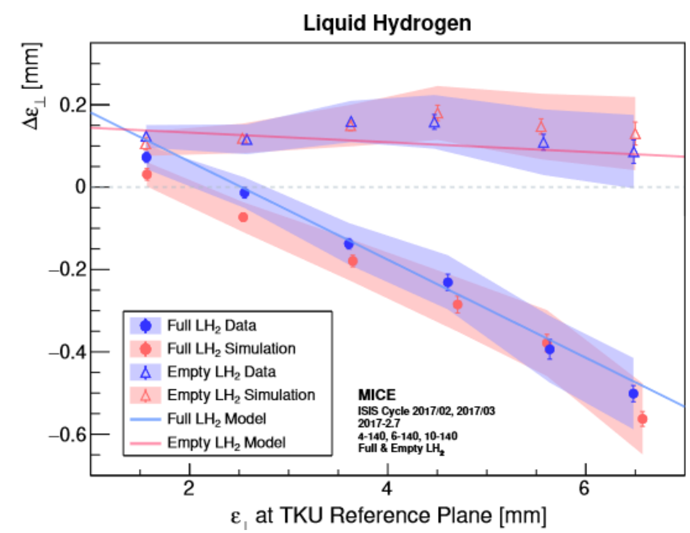
Emittance reduction

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

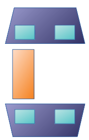
Nature Physics, Transverse emittance reduction in muon beams by ionization cooling, 2024

Nature, Demonstrator of cooling by the MICE experiment, 2020

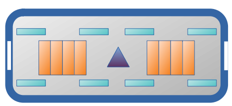




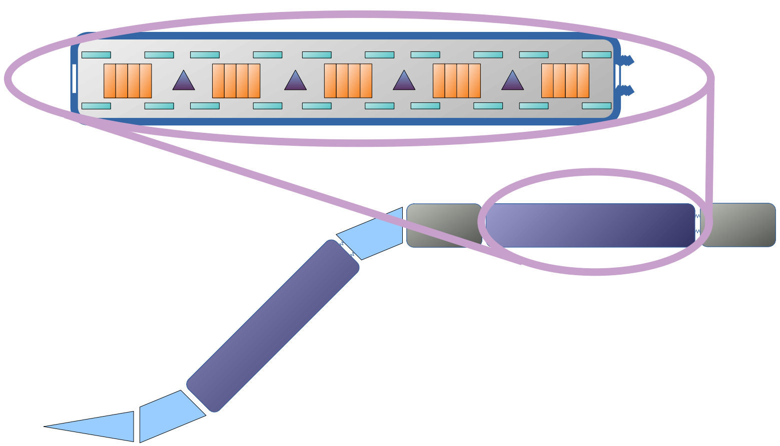
6D Cooling demonstrator



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



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



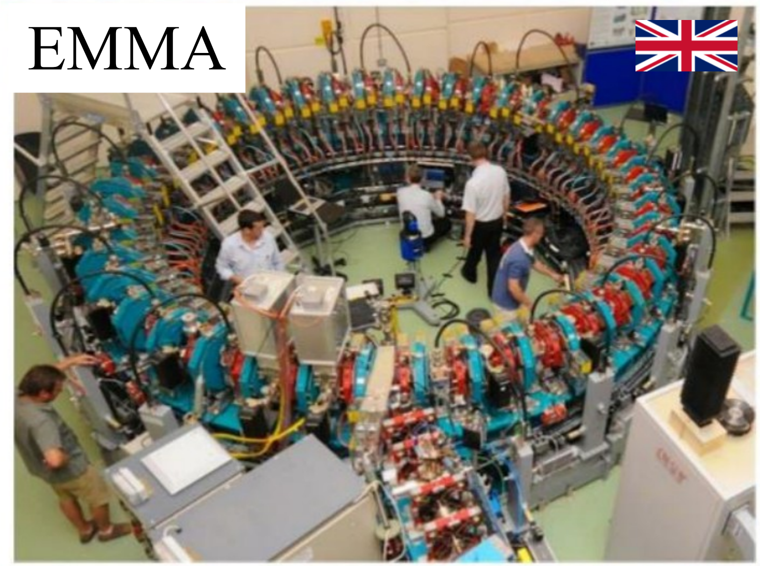
Rectilinear cooling vacuum vessel with beam

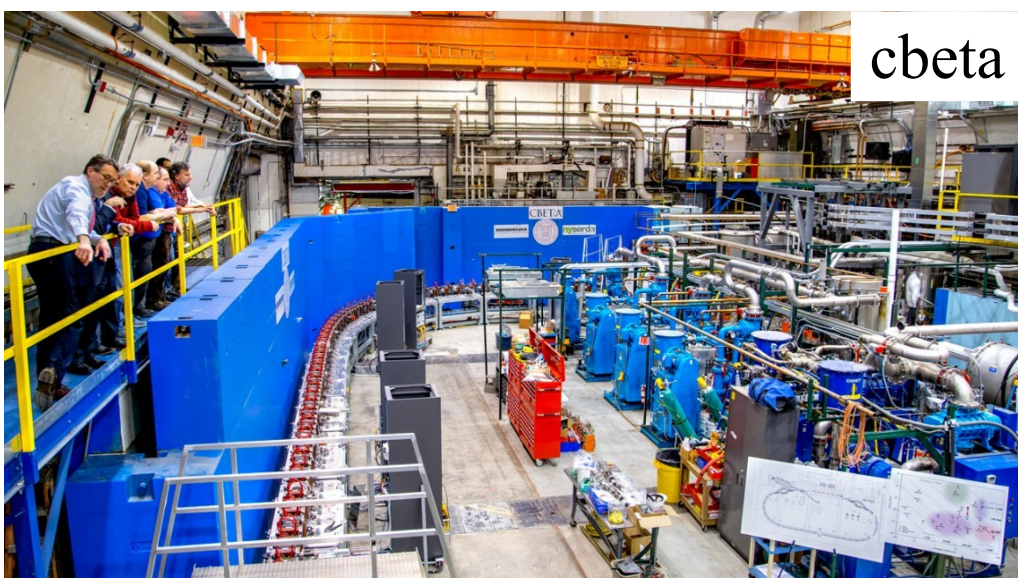
Rectilinear cooling lattice with beam

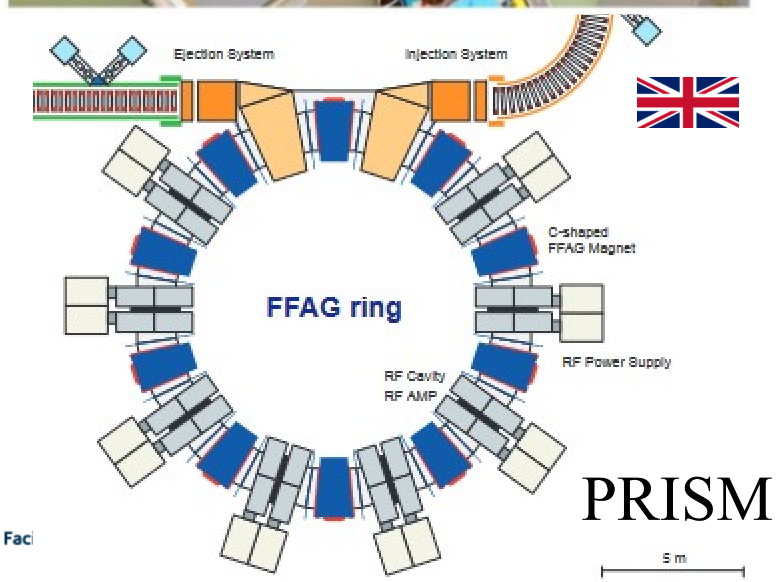
https://indico.fnal.gov/event/64984/

Muon Storage & Acceleration

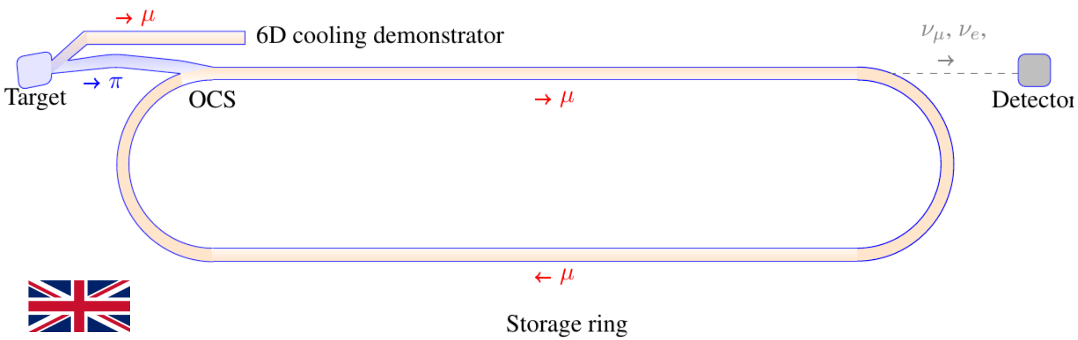
- Muon PRISM FFA
  - US → Advanced muon facility
  - COMET upgrade
- Rapid acceleration
  - GeV scale acceleration → ring or dogbone-shaped FFAs
- UK world leader in FFA technology

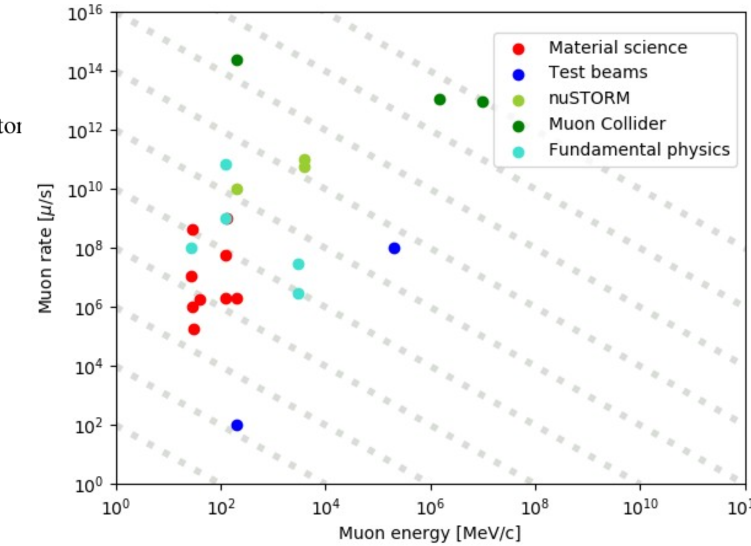






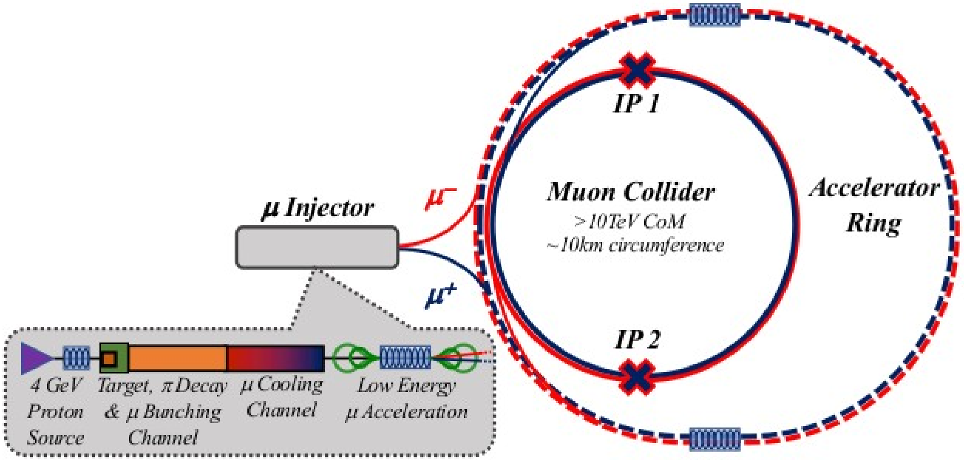
nuSTORM

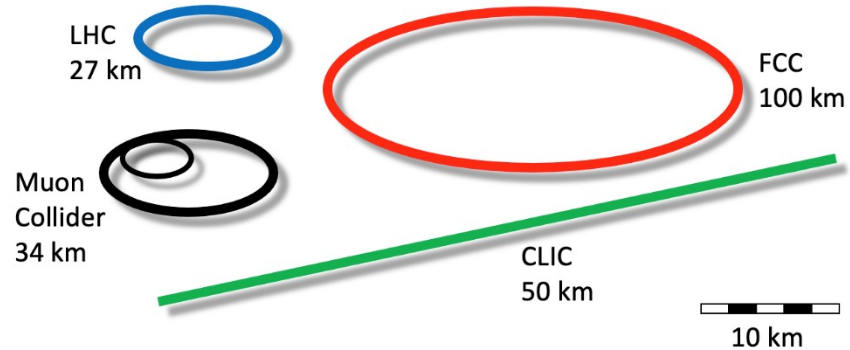




- NuSTORM → "next scale" muon facility
  - FFA-based storage ring (no acceleration)
  - Muon production target and pion handling
  - Possibly shared with cooling demonstrator
- Aim to measure neutrino-nucleus cross-sections
  - E.g. reduce neutrino oscillation experiment resolutions
  - Nuclear physics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

Muon Collider

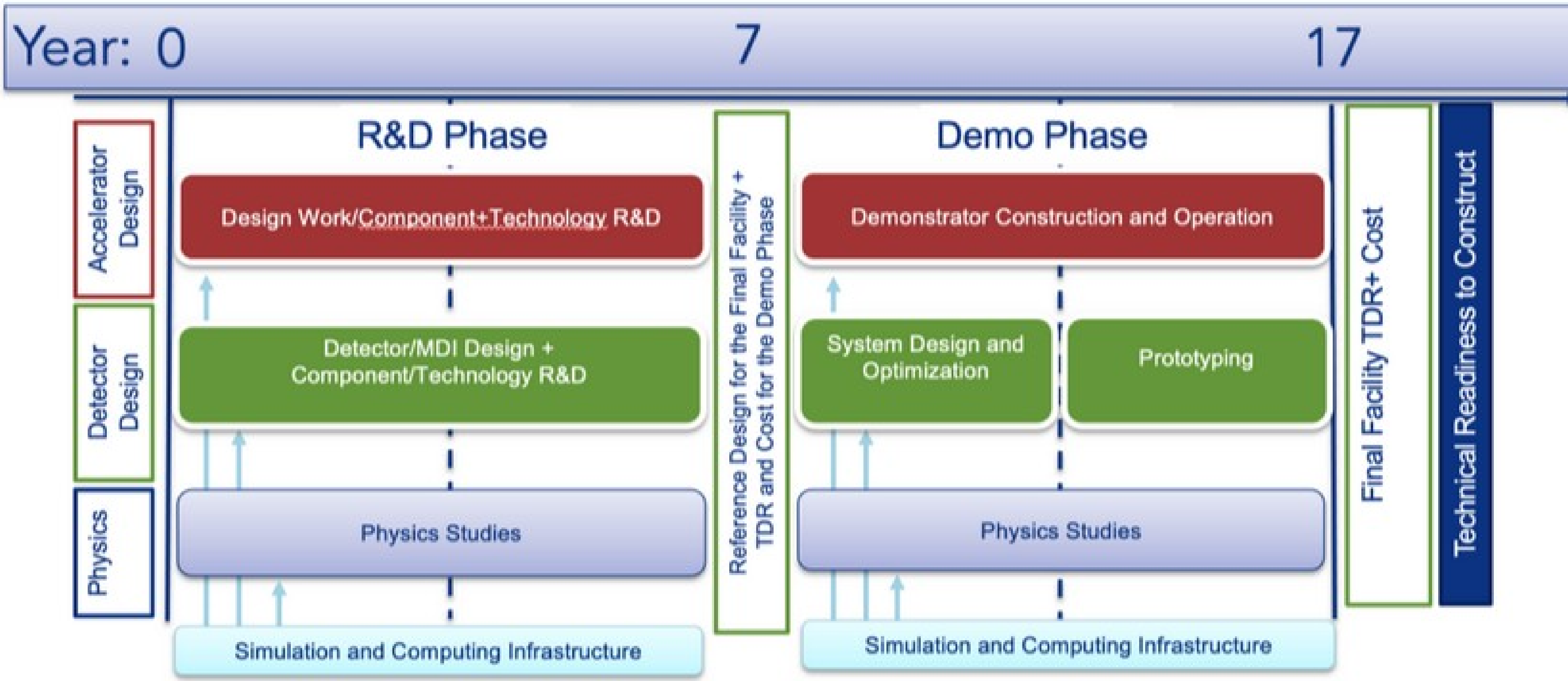




- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions

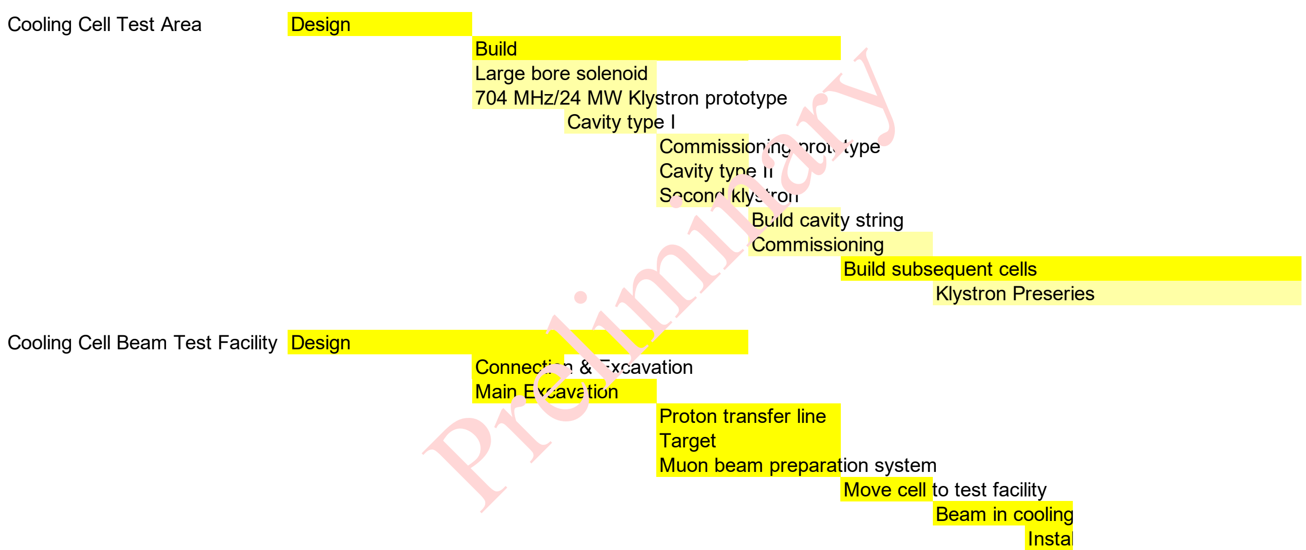
- UK has overall leadership in the facility design
- UK has leadership in muon production WP

Muon Collider - Time Scale



Science & Technology Facilities Council
ISIS

Muon Collider - Time Scale



- Requires full support of major lab
  - Demonstrator & cooling hardware is critical path
  - Cannot start until/unless serious funding starts
  - Need to develop R&D pipeline to make timings
- UK funding is CG + small amount of EU

Muon Beams - Institutes

- Not including physics & detectors!

ROYAL HOLLOWAY UNIVERSITY OF LONDON

University of Southampton

Lancaster University

University of Strathclyde Glasgow

University of HUDDERSFIELD

WARWICK THE UNIVERSITY OF WARWICK

UNIVERSITY OF OXFORD

THE UNIVERSITY of MANCHESTER

Imperial College London

UKRI Science and Technology Facilities Council

Science & Technology Facilities Council ISIS

Final Word

- Muon beams
  - Window onto new physics at energy scales beyond collider
  - Very interesting technology with direct applications
  - Strong UK leadership in many areas
  - New technologies coming online may be transformative
    - UK must be competitive here!
- The muon collider
  - Far higher energy than e^+e^- colliders
  - Far smaller footprint than equivalent proton colliders
  - Many technical challenges
    - All are manageable with current or near-to-current technologies
    - Must demonstrate practical solutions