# The UK Muon Beams Programme and the Muon Collider

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# Muon Collider

- Multi-TeV muon collider provides outstanding physics
  - Muons are fundamental particles – unlike protons
    - **10 TeV $\mu^+\mu^-$ has comparable physics to 100 TeV pp**
  - Muons can be accelerated to high energy
    - **~No synchrotron radiation**, ring accelerators are possible
  - Exquisite **non-collider physics programme**
  - Phased R&D programme with physics on the way
    - **$\mu^+\mu^-$ can be ready by 2040s**
- **Strong international support**
  - Strong potential as the post-DUNE US programme
  - Highly ranked in the European Strategy
  - Horizon Europe project (**highest score** by a CERN project)
- **UK has strong – and growing – collaboration**
  - 14 UK institutes
  - Deputy Study Leader, steering board rep and WP leadership

# Physics Reach

- Paradigm shift in the study of collider physics
  - Study of the **microscopic nature of the Higgs** boson
    - Higgs coupling structure
    - Rare/new decays
    - H-coupled top partners
    - Other Higgs bosons?
  - **Testing** unverified predictions of the **SM**
    - precision Yukawa couplings, HHH and WWHH in double-Higgs production
    - HHHH final states
  - Explore the last vestiges of **WIMP dark matter** (targeting >1 TeV)
  - Observe **new QFT regime**
    - Broken EWSM & observable EW “color”
  - Excellent **non-collider physics programme**
    - Muon decay products → high-brightness multi-TeV neutrino beam
    - Proton beam dump and low energy pion/muon beams
- Opportunity for novel R&D and **physics on the way**
  - Precision neutrino beams e.g. nuSTORM
  - Charged lepton flavour violation experiments
  - Many non-HEP applications

https://arxiv.org/abs/2303.08533

# International Perspective - Europe

- 2020 Update to the European Strategy
  - FCC-ee given strong support → excellent physics programme
  - Bright Muon Beams listed as “High Priority Initiative”
  - International Muon Collider Collaboration formed (IMCC)
- Muon collider → backup in case FCC-ee does not go ahead
  - CepC decision in 2025-26
  - European funding not guaranteed
- 2022 Accelerator R&D Roadmap
  - Muon collider facility design reviewed by independent team
    - Developed tentative baseline parameter set
    - **No showstoppers** – design is fundamentally sound
    - Need to understand **cost** and **power** requirements

| Parameter | Symbol | Unit | Target value | | |
|---|---|---|---|---|---|
| Centre-of-mass energy | $E_{cm}$ | TeV | 3 | 10 | 14 |
| Luminosity | $\mathcal{L}$ | $1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ | 2 | 20 | 40 |
| Collider circumference | $C_{coll}$ | km | 4.5 | 10 | 14 |
| Muons/bunch | $N_{\pm}$ | $1 \times 10^{12}$ | 2.2 | 1.8 | 1.8 |
| Repetition rate | $f_r$ | Hz | 5 | 5 | 5 |
| Total beam power | $P_{-} + P_{+}$ | MW | 5.3 | 14 | 20 |
| Longitudinal emittance | $\varepsilon_l$ | MeV m | 7.5 | 7.5 | 7.5 |
| Transverse emittance | $\varepsilon_{\perp}$ | µm | 25 | 25 | 25 |
| IP bunch length | $\sigma_z$ | mm | 5 | 1.5 | 1.1 |
| IP beta-function | $\beta^*_{\perp}$ | mm | 5 | 1.5 | 1.1 |
| IP beam size | $\sigma_{\perp}$ | µm | 3 | 0.9 | 0.6 |

# International Perspective - US

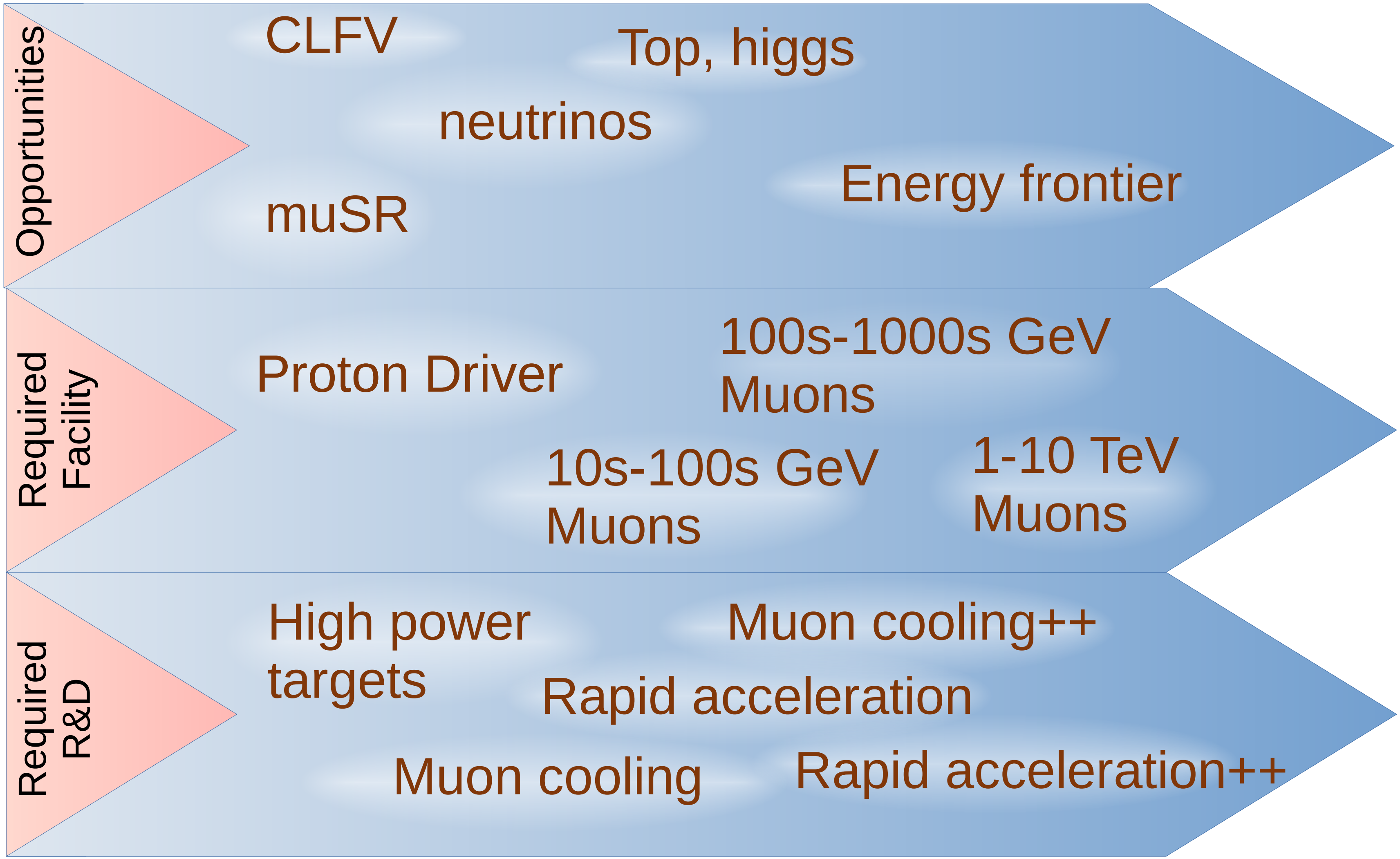
- Very strong support for muon collider in US
  - Highly ranked recommendation from Snowmass21
  - Discussed as **baseline for Fermilab** post-DUNE
- US planning to join IMCC
  - Assess European and US resources, once we know the P5 outcome
- All pending P5

# UK Collaboration

International MUON Collider Collaboration

- About 10 PhDs, 3 PDRAs and supervision
  - Based on EU grant and **tiny amount** of **UK funding**
    - Major beneficiary of EU grant
  - Spread over facility and detector

# R&D Path

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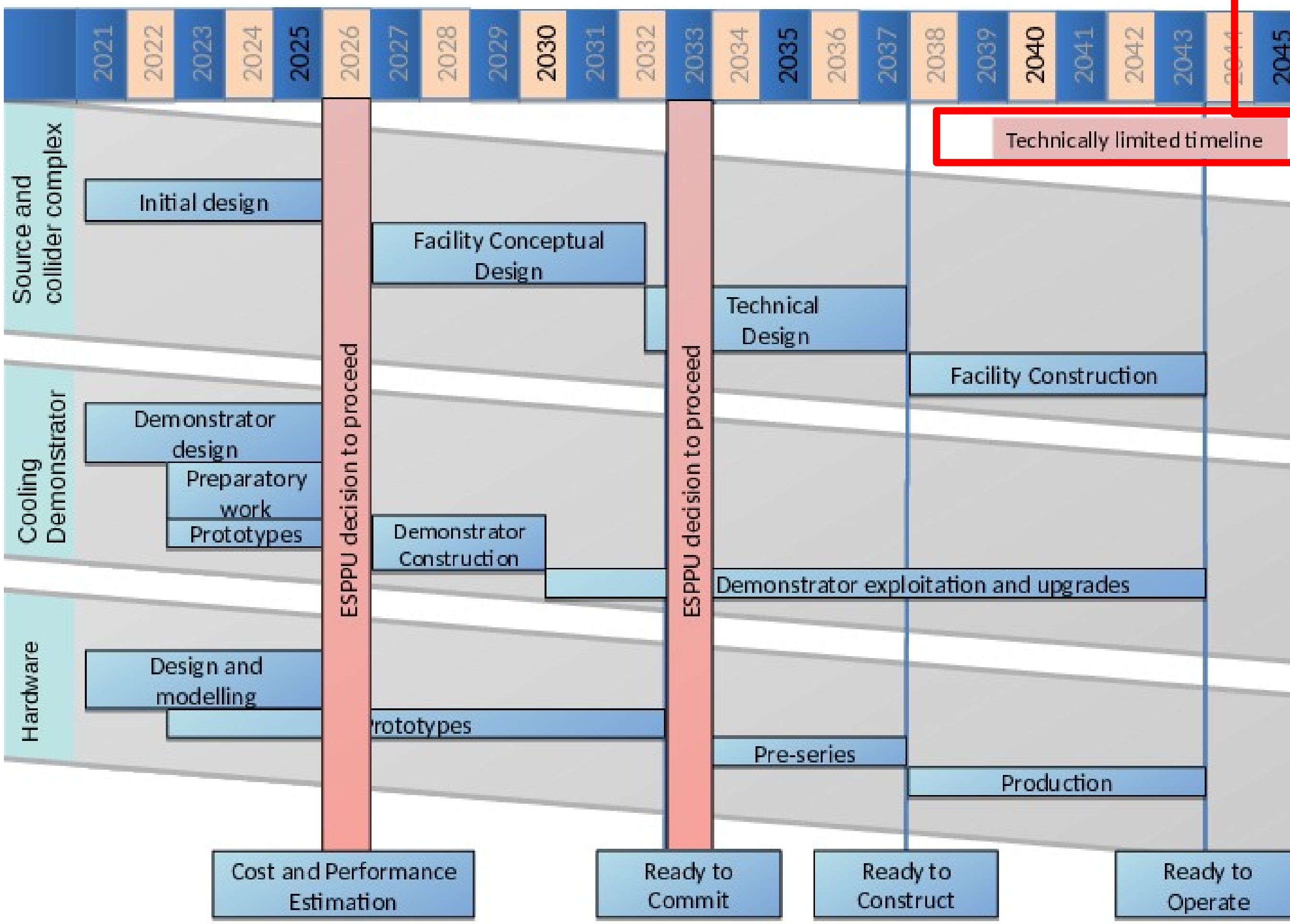
# Detector/Physics Interests

- Detector challenges comparable to HL-LHC
- Ongoing studies in physics performance
  - Di-Higgs
  - NP in Flavour
  - Collider physics performance/MDI
- Tracker
  - 4D tracking and readout
  - TDAQ
  - Tracking performance studies
  - Synergy with ISIS/muSR
- Non-collider physics
  - NuSTORM physics performance
  - non-collider physics opportunities with collider R&D (e.g. heavy neutral leptons in νSTORM)

# Facility Interests

- Proton driver & acceleration
  - Synergy with ISIS/proton source
- High power targetry
  - Synergy with CLFV, neutrinos, ISIS/neutron spallation/muSR
- Ionisation cooling
  - Synergy with ISIS/muSR
  - Muon cooling demonstrator will be built late 2020s
- Machine-Detector Interface
  - Synergy with linear colliders
- Building on major accelerator experiments sited in UK
  - EMMA
  - MICE
- Building on UK expertise from ISIS, and elsewhere

# Timeline




- Timeline prepared by LDG panel (mostly $e^+e^-$ people)

# Final Thought

- **Muon beams** are **essential** for next generation of particle physics experiments
- **Muon collider** would be an **exquisite machine** with an **awesome physics case** and **ready by 2045**
- **UK** is **world-leader** in muon beam tech
- Europe is now catching up
  - CERN is putting in significant effort
  - Italy is coming in with a lot of resource
  - Germany, France, Switzerland, Austria, Sweden, others joining
- US is likely to rejoin in next few months
  - A lot of expertise – and resource - here
- **Investment is needed now** for UK to maintain leadership
  - UK programme has approximately 0 UK funding
  - We are a major beneficiary of the EU grant
  - **PPAP** can **help** to get **accelerator funding** from STFC
  - UK should support detector R&D
  - Strengthen UK in other aspects of the muon beams programme

# Backup

International
MUON Collider
Collaboration

MuCol

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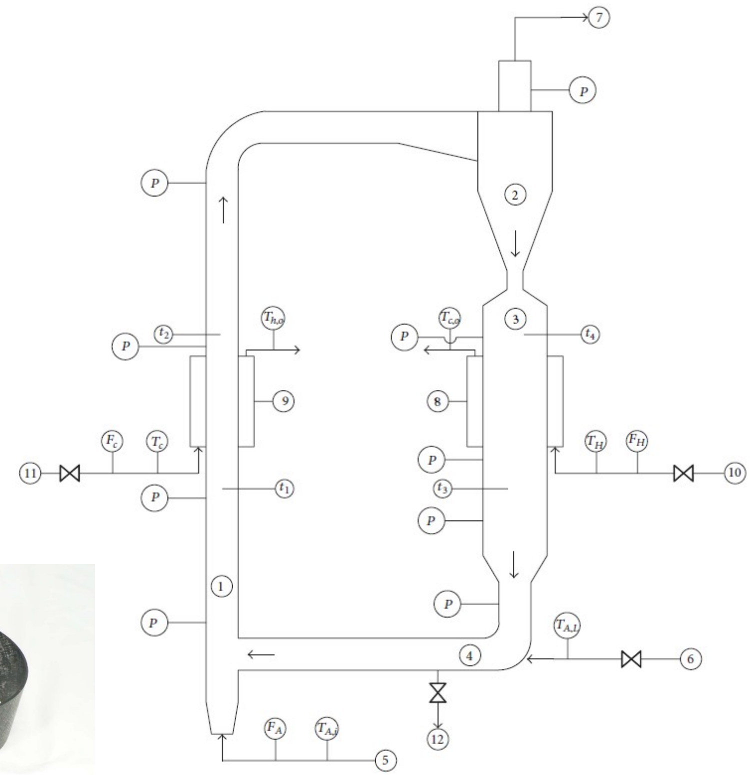
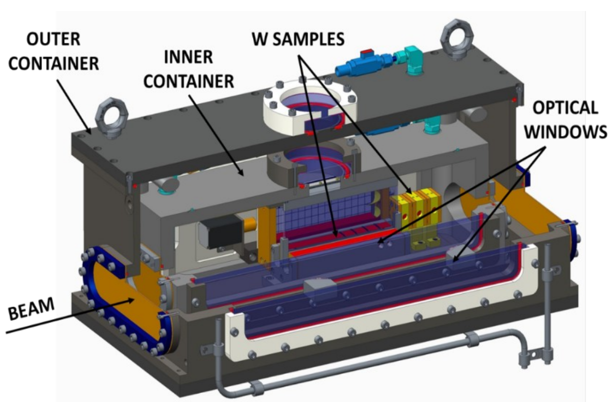
# Target

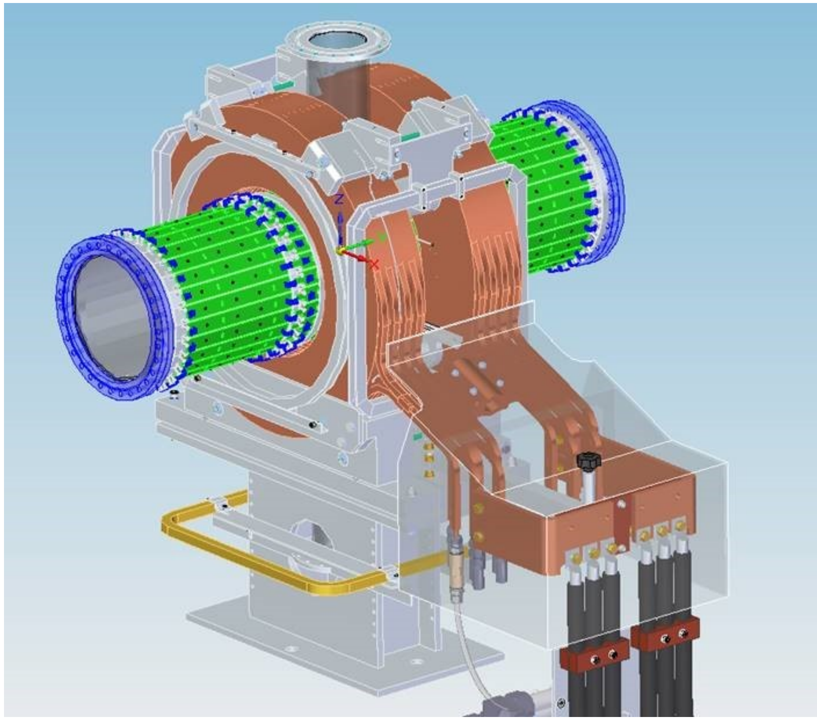
- Design and construction of prototype pneumatically conveyed granular tungsten Circulating Fluidized Bed (CFB) with no additional moving parts in the primary circuit.
- Incorporate SiC-SiC composite and other candidate materials in CFB for erosion studies
- Carry out pulsed in-beam test of granular tungsten at CERN’s HiRadMat facility to measure interactions with pipe wall



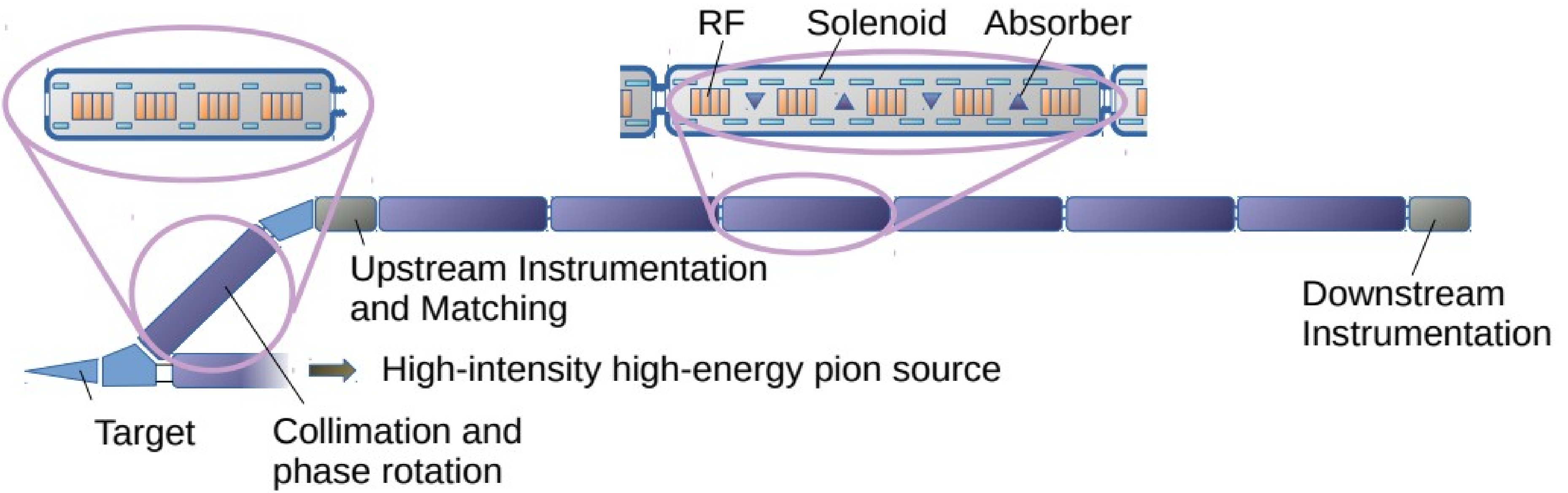



# muSR

- Edge effects on scintillators, SiPM mounting, and wrapping leading to worst-case 12-33% dead volume
  - Best case might be 4.5-13% dead volume
  - Today’s MuSR is roughly 15% dead volume
- Counting rate of SiPMs is slightly worse than individual PMTs – need digitisers to claw this back
- Getting the counting rate for full beam will be at the limit of what is feasible

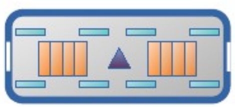


# Demonstrator

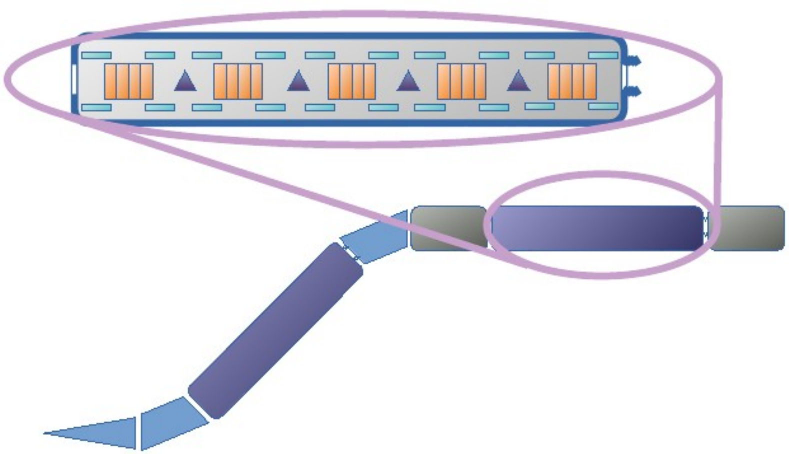


# R&D Path

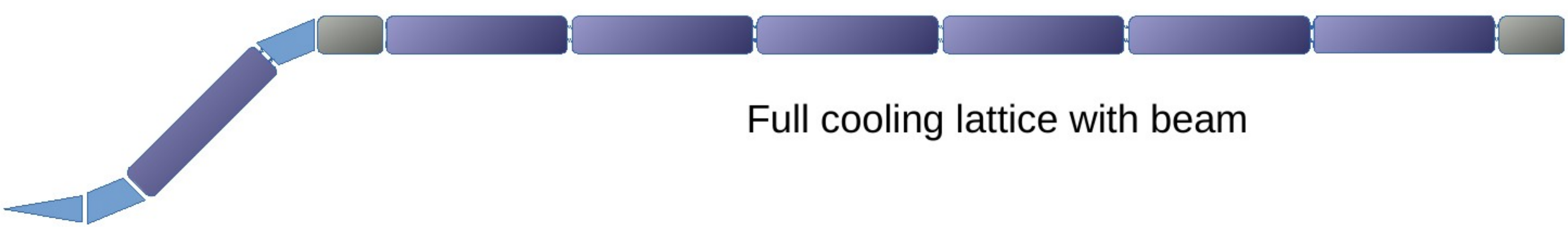
RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



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

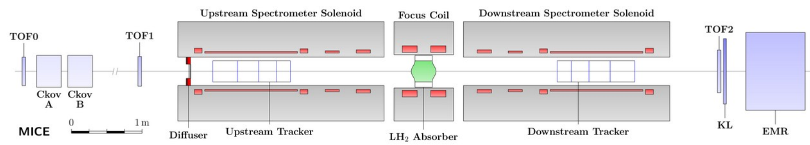


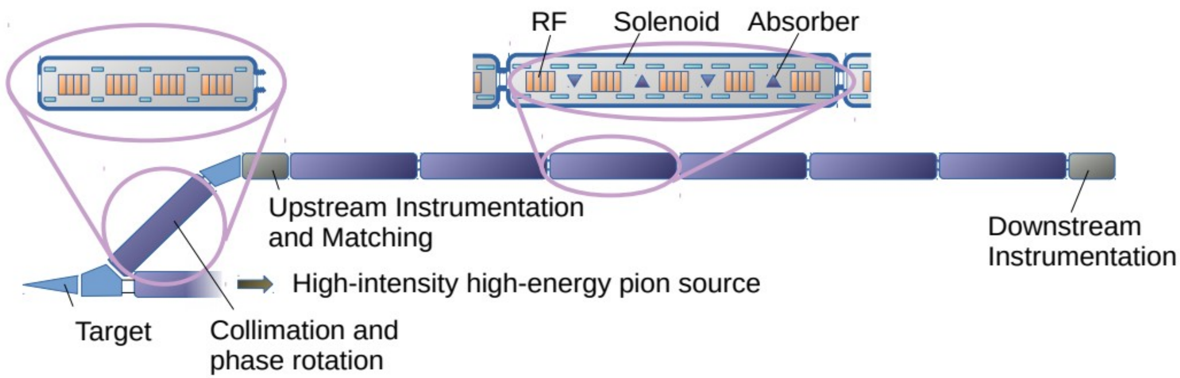
Full cooling vacuum vessel with beam



Full cooling lattice with beam

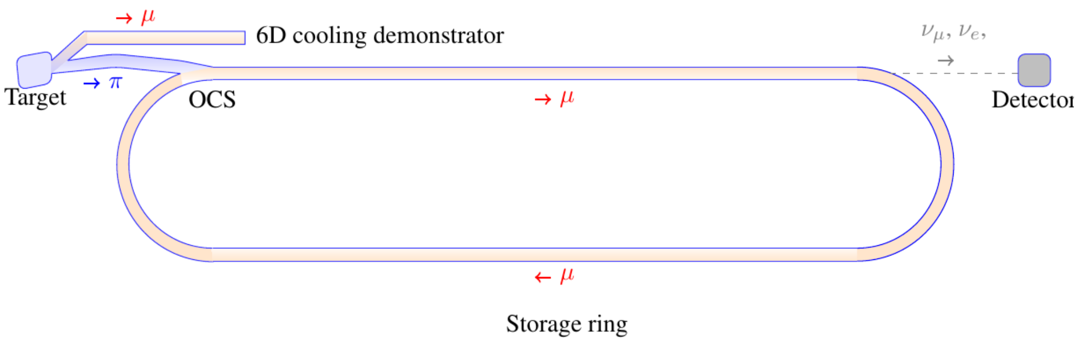
# Comparison with MICE

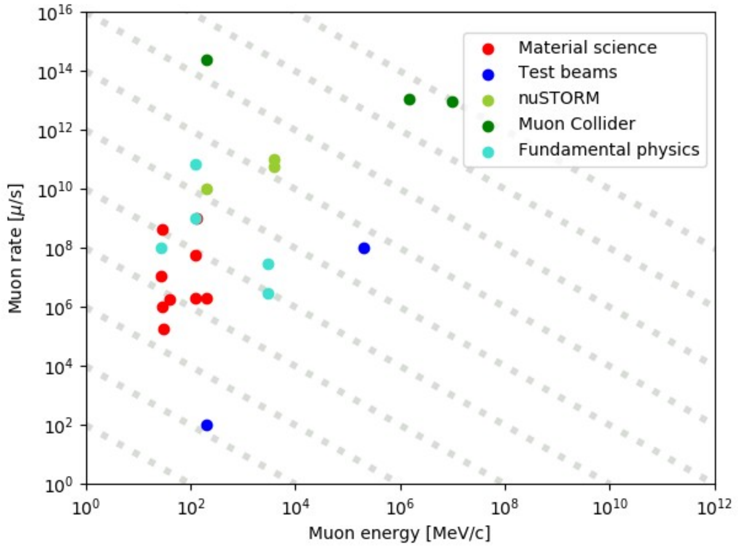



| | MICE | Demonstrator |
|---|---|---|
| **Cooling type** | 4D cooling | 6D cooling |
| **Absorber #** | Single absorber | Many absorbers |
| **Cooling cell** | Cooling cell section | Many cooling cells |
| **Acceleration** | No reacceleration | Reacceleration |
| **Beam** | Single particle | Bunched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

# 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

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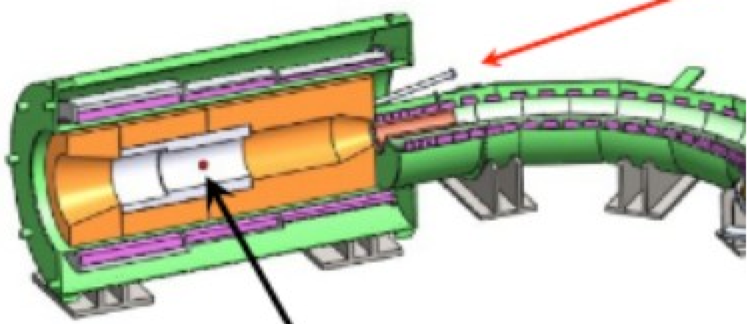
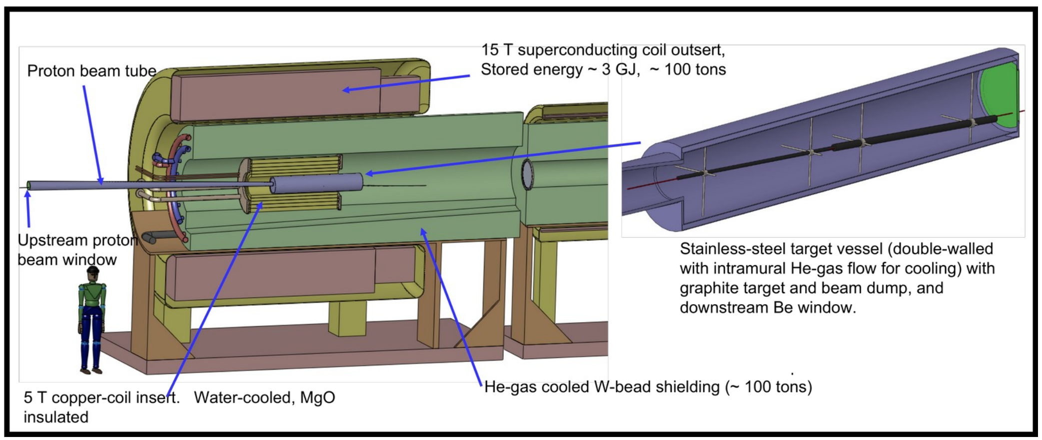
International MUON Collider

# Synergy with mu2e




- 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
- Build collaboration