An R&D Programme for Muon Beams in the UK

*The UK Muon Beams Collaboration**

DRAFT - FOR DISCUSSION

1 Muon Beams R&D Landscape

The 2020 Update of the European Strategy for Particle Physics recommended that muon beam R&D should be considered a High-Priority Future Initiative due to the excellent potential for physics studies at a muon collider. The update noted the importance of a programme of experimentation to determine neutrino cross sections, such as the programme that could be delivered by the Neutrinos from Stored Muons experiment (nuSTORM). The exploration of flavour and fundamental symmetries, such as those that can be delivered by muon to electron conversion experiments, were noted as Essential Scientific Activities. In the European Strategy for Particle Physics - Accelerator R&D Roadmap, muon beam R&D towards delivery of a Muon Collider was highlighted as a key priority for Europe. A particular need for development and construction of a Muon Cooling Demonstrator was highlighted along with the potential to share key infrastructure with nuSTORM. In the US, muon collider R&D was highlighted as a key recommendation by the Energy Frontier of the Snowmass Summer study.

STFC's Particle Physics Advisory Panel recommended that muon collider R&D be performed concentrating on medium-term projects such as nuSTORM. It also recommended that the UK should support and invest in future charged lepton flavour violation experiments.

The international Muon Collider Collaboration (iMCC) was formed by CERN in 2020. The UK has leadership in a number of technical areas, including targetry and cooling and overall leadership of the facility design. iMCC submitted a successful proposal to Horizon Europe, of which the UK was a principal beneficiary.

The UK has previously had a world-leading programme in muon beam physics studies. The UK hosted the international Muon Ionization Cooling Experiment (MICE) to demonstrate muon cooling; constructed the Electron Model for Many Applications (EMMA) to demonstrate fast acceleration using a Fixed Field Alternating Gradient accelerator (FFA) and suitable for muons; led a number of studies to develop high power pion targetry suitable for a multi-MW beam comprising very short proton bunches; and is constructing pion-production targets for T2K and DUNE. The UK also led design studies such as the Neutrino Factory International Design Study. ISIS is designing a FFA-based proton accelerator as part of its upgrade study. A FFA is foreseen to provide acceleration to high energy in ITRF/LhARA phase 2 which also has applications for muon beams. The UK has leadership in the nuSTORM facility design, which would enable definitive neutrino cross section measurements.

The ISIS muon beam line provides the world's most intense source of pulsed muons for condensed matter research. ISIS muon group operates some of the world's leading muon spectrometers for material sciences. ISIS is currently upgrading the muon suite as part of its Endeavour programme. A dedicated muon target station and associated muon beam lines and instruments is under study as an option for ISIS2. Novel muon cooling schemes to deliver high-brightness, low-energy muon beams for material studies and fundamental physics have been developed by PSI and proposed by JPARC.

2 The Muon Collider

Circular muon colliders have the potential to reach centre-of-mass energies of tens of TeV with high luminosity. Muons are point-like particles, so the entire beam energy is available to produce short-distance reactions, which allows direct searches for new particles over a wide range of unexplored masses. A muon collider also allows accurate tests of the Standard Model to be performed at extremely high energy, offering great opportunities to detect new physics indirectly and to confirm and to characterise direct discoveries. Furthermore, by exploiting the copious rate for vector boson fusion and vector boson scattering processes, the muon collider provides the opportunity to probe the finest details of the electroweak symmetry breaking mechanism.

A baseline muon collider scheme was developed in the US and demonstrated a practical end-to-end facility design. This scheme has been adopted by the iMCC. In the baseline scheme, protons are fired onto a target

*chris.rogers@stfc.ac.uk

	Muon production	Muon cooling	Novel acceleration
Muon collider	X	X	X
Muon cooling demonstrator	X	X	
ISIS2	X	X	X
ITRF/LhARA			X
Muon to electron conversion	X	X	
nuSTORM	X		X

Tab. 1: The relevance of each programme topic to a particular project is highlighted with an X.

producing pions. The pions decay radioactively to muons and the muon beam is prepared using a challenging muon cooling scheme. The muons are then accelerated rapidly to extremely high energies where they collide. Unlike other energy frontier facilities, the footprint of the muon collider is small enough to fit on the site of existing facilities such as the CERN complex. Owing to the small footprint and lower beam power demands compared to equivalent facilities, the muon collider may well have a lower wall-plug power demand, but further R&D is needed to make a solid estimate.

Key technology development is required in order to realise the muon collider:

- A high-power proton driver, similar to the one foreseen for ISIS upgrades but with the addition of a compressor to deliver very short proton bunches;
- Pion production targetry, similar in concept to that required for muon-to-electron experiments but operating with significantly higher magnetic field and proton beam power;
- Muon cooling, comprising cells that are similar in concept to that developed for MICE but with a number of extra capabilities;
- Very rapid acceleration, far faster than that available in Rapid Cycling Synchrotrons such as ISIS;
- A compact collider ring.

3 Proposed Programme

We propose a programme of R&D that will yield physics results and improved UK research infrastructures, support UK leadership of other major European research infrastructures and lead to delivery of the muon collider as the next European collider facility, following the LHC end-of-life. The programme comprises:

- Muon production: Muons are produced by firing protons on a target. Solenoids can be used to collect high yields and purer muon beams. However the muon current available is limited by effects of radiation impacting the solenoid and radiation effects in the target itself. Novel solutions for target and shielding design are required to deliver a satisfactory muon yield for the next generation of muon to electron conversion experiments and ultimately the muon collider. Proper integration of a target horn into a muon/pion capture channel is essential for nuSTORM and may act as a risk mitigation for the muon collider.
- Muon cooling and high-gradient RF Development: Muon cooling may be used to enhance the brightness of muons impinging upon experiments downstream of the target. Large RF gradients are required in high-field magnets, which can induce breakdown. Mitigation of this effect requires further study. Development of muon cooling at 100s of MeV is required to develop the Muon Cooling Demonstrator that has been proposed for the muon collider. Novel beam cooling schemes at $<$ 100 MeV may enable much more efficient muon beam production which may be beneficial for low energy muon beam experiments.
- Novel acceleration: FFAs are expected to improve the efficiency of proton drivers and muon acceleration and enable complex longitudinal adjustments to the beam to be made, for example the bunch compression required for muon production in the proton driver. An FFA-style storage ring for nuSTORM yields a large improvement in neutrino flux. Studies are required to design and refine suitable FFAs. Additionally, studies are required on the machine detector interface in FFA-style lattice and more conventional lattices in order to study stability issues and the effect of muon decay products on the particle physics detector.

Authors

UPDATE

References

[1] European Strategy Group, 2020 Update of the European strategy particle physics. CERN-ESU-015 (2020).

[2] M. Bogomilov et al. Demonstration of cooling by the Muon Ionization Cooling Experiment. Nature 578, 53–59 (2020).

[3] S. Machida et al, Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA. Nature Phys 8, 243–247 (2012).

[4] S. Machida, Applications of vertical excursion FFAs (vFFA) and novel optics, Letter of Interest to Snowmass21 (2020).

[5] C.C. Ahdida et al, nuSTORM at CERN: Feasibility Study, CERN-PBC-REPORT-2019-003, 2019.

[6] D. Schulte, International Muon Collider Collaboration, Submission to Snowmass21 (2020).

[7] Muon Collider Collaboration, Issues and mitigations for advanced muon ionization cooling, Letter of Interest to Snowmass21 (2020).

[8] B. King, Potential hazards from neutrino radiation at muon colliders, PAC99 (1999).