Muon-accelerator based facilities: opportunities for science

Scientific opportunities

The discovery of the Higgs boson has completed the Standard Model but left unanswered questions related to a deeper understanding of the origin of electroweak-symmetry breaking. Neutrino oscillations, which imply neutrino mass and mixing, show that the Standard Model is not the whole story. The LHC experiments seek evidence for new phenomena by which the patterns and features of the Standard Model may be explained. The mysteries associated with neutrino masses are being addressed by experiments around the world that exploit accelerator-based, solar, atmospheric, reactor, radioactive and cosmological sources of neutrinos. Together, the LHC and its upgrades, the DUNE and Hyper-K long-baseline neutrino experiments, the short-baseline neutrino programme and the study of extremely rare processes provide an exceptional discovery platform for the next decade.

To go beyond the capability provided by the LHC, its upgrades and the next generation of accelerator-based neutrino experiments will require innovation in detectors and new particle-acceleration techniques.

Experiments served by muon beams have made, and continue to make, seminal contributions to the development of the electroweak Standard Model, the Quark Parton Model and QCD. Detailed study of the properties of the muon and its decay allow stringent constraints to be placed on phenomena beyond those described by the Standard Model. Muon beams are essential in the search for charged-lepton-flavour violation (cLFV). Advances in technique have led to the preparation of ground-breaking cLFV-search experiments at FNAL, J-PARC and PSI. Muon beams are also exploited in the study of the magnetic and dynamic properties of materials.

Over the past ten to fifteen years an extensive R&D programme encompassing detailed design studies, component development and system-level proof-of-principal experiments has demonstrated that high-brightness muon beams have the potential to:

- Offer a path towards improved experiments on cLFV with unprecedented sensitivity;
- Revolutionise the study of the neutrino by providing neutrino beams for which the flavour composition and energy spectrum are known precisely; and
- Provide a route to very high energy lepton-antilepton collisions.

Discussion of the scientific potential of muon beams; CERN 18^{th} November 2015

A meeting to discuss the scientific potential of muon beams was held at CERN on the 18^{th} November 2015 [1]. 95 people attended the meeting [2]. Invited presentations reviewed: the status of searches for cLFV and the plans for the next-generation experiments COMET, mu2e and g-2; the unique opportunities presented by neutrino beams derived from muon decay; and the benefits of muon accelerators for the energy-frontier lepton-antilepton-collider programme. The status of the technology R&D programme was also reviewed and the scientific programme that could be served by the incremental development of muon-accelerator capability was discussed. Additional contributions covered the advantages of neutrino beams generated from pion decay in a magnetic transport channel, cold muon beams produced through e^+e^- annihilation, the use of the ESS as a source of conventional, and muon-based neutrino beams, the Chinese muon-beam-development programme and the use of lasers to create cold muon beams. These presentations enriched and enhanced the discussion.

The consensus of the meeting was that the wealth of opportunity offered by facilities based on high-brightness muon beams is sufficient to justify an internationally-coherent programme to review and quantify the potential scientific impact and to identify the incremental technology-development programme that is required to deliver the necessary capabilities. The steps by which it is recommended that this programme be established are presented below.

Recommendations

Over the next two years, through an appropriate series of plenary and working-group meetings, determine the scope of the physics programme that can be addressed through the incremental development of current facilities and the staged implementation of specific capabilities. Further, determine the technology R&D programme that must be carried out in parallel to the physics programme to allow the subsequent increments in capability to be delivered.

When determining the incremental development of the programme consider:

1. Low-energy muon beams:
   (a) Improved and higher sensitivity experiments on cLFV through the golden channels $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$;
   (b) Measurements of muon properties such as the anomalous magnetic moment a_μ or the electric dipole moment d_μ;
   (c) Muon cooling and phase rotation to achieve muon beams of unprecedented brightness for low energy muon physics;
   (d) High-intensity, high-brightness sources of muonium, revisiting of muonic atom spectroscopy and a measurement of atomic parity violation in muonic atoms;
2. Neutrinos from stored muon beams:
   (a) The precision with which $\overset{(-)}{\nu}_e N$ and $\overset{(-)}{\nu}_\mu$ scattering processes can be measured and the potential for these measurements to:
      - Enhance the reach of present and future accelerator-based neutrino experiments as well as experiments that exploit atmospheric or astrophysical sources of neutrinos; and
      - Calibrate the response of neutrino detectors using neutrinos by muons confined within a storage ring;
   (b) The technology development and prototyping programme necessary to achieve the neutrino-scattering programme; ; and
   (c) If appropriate, the development of a proposal for a facility able to perform an experimental program of significant interest to the neutrino-oscillation community ; and
3. Energy frontier $\mu^+\mu^-$ collider:
   (a) The physics potential and conceptual design of a Higgs Factory and the investigation of a possible demonstrator facility;
   (b) The physics potential, conceptual design and incremental development of a multi-TeV muon collider;
   (c) The specification and conceptual design of a 6D cooling demonstration to follow on from the MICE 4D ionization cooling proof of principle; and
   (d) If appropriate, the construction of system-demonstration experiments beyond MICE, MERIT, MuCool and the component development carried out by the US Muon Accelerator Programme;
4. Sources of resource to execute the development programme including Horizon 2020, national funding agencies and national laboratories.

The programme must be capable of incremental development and exploit the synergies that exist between its various aspects as is the case, for example, for the ionization-cooling and demonstrator programmes (1c, 2b, 2c, 3c and 3d).

References

[1] "Discussion of the scientific potential of muon beams." https://indico.cern.ch/event/450863/, 2015.

[2] "Discussion of the scientific potential of muon beams: participants." https://indico.cern.ch/event/450863/registrations/participants, 2015.