A Proton-Based Muon Source for a Collider at CERN

on behalf of the Muon Collider Collaboration

1 Introduction

The muon collider collaboration was formed following the publication of the 2020 Update of the European Strategy for Particle Physics in June of this year [1]. Owing to the excellent potential for physics studies at a muon collider, the strategy update recommended that muon beam R&D should be considered a high-priority future initiative.

The collaboration is investigating two options for producing muons at CERN [2]: either to fire protons onto a target to produce pions and other mesons, which decay into muons; or to fire high energy positrons onto a target near to the threshold for muon pair production [3]. This Letter of Interest gives a brief overview of plans for the proton-based source.

The muon collider collaboration plans to build upon the proton-driven source concept that was developed by the US Department of Energy funded Muon Accelerator Programme (MAP) [4]. The proton-driven muon source is briefly described below.

2 MAP Muon Source

Pions, muons and other particles are produced by firing protons onto a graphite target [5]. Liquid mercury targets were also considered [6]. The target is contained in a 20 T magnet which serves to confine both positively and negatively charged secondary particles, unlike a horn-type target. The field is tapered to a 2 T constant solenoid field.

High momentum impurities are removed from the beam by means of a chicane created using a bent solenoid field, which introduces vertical dispersion [7]. High momentum particles get proportionately more dispersion and are removed on scrapers. A reverse bend returns the surviving particles with remarkably little emittance growth despite the large transverse emittance and huge momentum spread.

Low momentum protons are removed by a thick Beryllium window [7]; low momentum protons lose much more energy than muons and electrons in the material. The window marks the end of the active handling area.

Muons are first captured longitudinally [8]. The muon beam contains all momenta up to the limit of the chicane. Fast muons migrate to the front of the bunch while slow muons migrate to the end of the bunch. RF cavities are placed successively with gradually increasing voltage to adiabatically introduce microbunches into the beam. Frequency of successive cavities is selected to match the increasing time spread in the beam. RF cavities towards the end of the section are dephased such that the earlier, faster bunches experience a decelerating gradient and the later, slower bunches experience an accelerating gradient. This is repeated until the energy of the later bunches matches the energy of the earlier bunches.

An initial 'HFoFo' ionization cooling channel, capable of cooling both muon charges, reduces the 6D emittance of the muon beam [9, 10, 11]. In this scheme, the transverse field is alternated so that the beam passes through focusses. Dipole fields introduce dispersion, with oppositely charged muons having opposite dispersion. By carefully selecting position and size of wedge-shaped absorbers, the beam is cooled in all six dimensions.

The beam is separated into positive and negative muon species by means of another solenoid chicane [12]. Positive muons have the opposite dispersion to negative muons, enabling separation.

A 'rectilinear' series of combined dipoles and solenoids with wedges cools the beam in 6D. Because the charge is separated, more dispersion and tighter focussing can be introduced with consequently more cooling [13].

The microbunches are merged longitudinally into fewer, more widely separated, microbunches by means of a phase rotation scheme using slightly dephased RF cavities [14]. The front of each set of bunches undergoes a decelerating gradient and is slowed, while the back experiences an accelerating gradient and is accelerated.

The resultant microbunches are merged transversely into 1 bunch by means of parallel transfer lines having different time delays. Each microbunch is kicked transversely into a different transfer line to get the appropriate time delay. The microbunches are brought together and stacked transversely into one bunch.

The beam then traverses another rectilinear cooling channel to further reduce its emittance [13].

A sequence of high field solenoids is used to introduce tight focussing around absorbers to further reduce the transverse emittance [15]. In order to reach very low emittances cooling is performed at low momentum, where transverse cooling is more effective at the expense of longitudinal heating.

The MAP scheme proposed acceleration a combination of conventional linacs, followed by linacs with multiple dogbone arcs to recirculate the muon beam for reuse of the accelerating equipment for acceleration to higher energies (so-called 'dogbone RLA') [16]. Following the RLAs, Rapid Cycling Synchrotrons were considered for acceleration to collision energy [17].

3 Plans

The muon collider collaboration will continue to investigate the issues surrounding the muon source. Consideration will be given to any necessary modifications to the CERN complex to provide proton beam power and structure appropriate for the muon collider. The collaboration will also note relevant proton sources beyond CERN, for example Fermilab [18].

Further evaluation of the target area will be performed to consider effects of high beam power on the target. Rotating targets [19], fluidised powder targets [20, 21] and similar concepts will be considered to mitigate any issues.

The final cooling is a priority, where further design work may yield improved luminosity. Improvements to the cooling lattice will be considered, along with novel ideas such as parametric ionisation cooling [22] or [23] emittance exchange schemes and a final cooling ring that could double the collider luminosity [24]. Issues and mitigations of ionization cooling will be studied [25].

Further studies will be made on the acceleration scheme and collider ring. The effects of neutrino radiation [26] will be re-evaluated and appropriate mitigations sought. Novel technologies will be considered such as vertical FFAs [27, 28]. The effects of electron radiation on the magnets will be considered.

A demonstrator for muon beam technologies having lower flux and energy than the muon collider will be considered.

4 Conclusions

The newly formed muon collider collaboration has begun studying options for a muon collider, including performance goals and design challenges. An initial list of key issues is expected to be ready in time for the Snowmass Process and a refined one on a two year timescale. Optimisation of the existing design and new ideas will follow.

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