Muon collider: the Low EMittance Muon Accelerator (LEMMA) approach

M. Antonelli, O. R. Blanco-Garcia, M. Boscolo, M. Iafrati, B. Ponzio, M. Ricci, M. Rotondo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

S. Hoh, D. Lucchesi, A. Paccagnella, J. Pazzini, S. Rossin, M. Zanetti

Università di Padova and INFN Sezione di Padova, Padova, Italy

G. Ballerini, C. Brizzolari, V. Mascagna, M. Prest, M. Soldani

Università degli Studi dell'Insubria e INFN Sezione di Milano Bicocca, Milan, Italy

A. Bertolin, C. Curatolo, F. Gonella, L. Sestini, S. Ventura

INFN Sezione di Padova, Padova, Italy

N. Bartosik[*]**, C. Biino, B. Kiani, N. Pastrone, M. Pelliccioni**

INFN Sezione di Torino, Turin, Italy

N. Amapane, A. Cappati, G. Cotto, O. Sans Planell

Università degli Studi di Torino e INFN Sezione di Torino, Turin, Italy

F. Anulli, M. Bauce, F. Collamati, F. Iacoangeli

INFN Sezione di Roma, Roma, Italy

L. Bandiera

INFN Sezione di Ferrara, Ferrara, Italy

G. Cavoto

Università di Roma La Sapienza and INFN Sezione di Roma, Roma, Italy

R. Di Nardo

CERN, Geneva, Switzerland

E. Vallazza

INFN Sezione di Milano Bicocca, Milan, Italy

M. Casarsa

INFN Sezione di Trieste, Trieste, Italy

A. Triossi

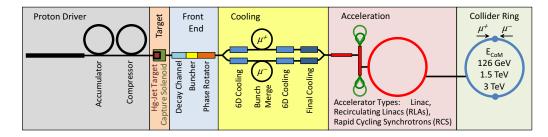*Institut Pluridisciplinaire Hubert Curien, Strasbourg, France*

This work introduces a new proposal for a low–emittance muon accelerator (LEMMA) in which muon beam is obtained from the $e^+e^- \to \mu^+\mu^-$ annihilation process with positrons at the threshold energy of 45 GeV. The experimental test beam setup implemented to validate this concept is presented together with preliminary results from the experimental data.
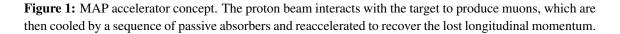
---

*Speaker.

1. Muon Collider

Active discussions are ongoing about the next possible accelerator that would best complement or even replace the LHC as the main instrument for consolidating the present knowledge of the Standard Model (SM) and searching for Beyond Standard Model (BSM) processes. The two most discussed classes of such accelerators are hadron-hadron and electron-positron colliders, possessing either very high centre-of-mass energy or very clean collision environment respectively. Given that we still do not have clear evidence for where the new physics could be found, the ideal future discovery machine should possess both high energy reach for a direct observation of potential BSM particles and capability of high-precision measurements of Standard Model processes to find deviations from SM predictions. An attractive solution in this scenario is a muon collider, which provides the same clean collision environment as electron-positron colliders, but thanks to much less synchrotron radiation from muons, allows to efficiently accelerate the beams to multi-TeV energies [2].

Figure 1: MAP accelerator concept. The proton beam interacts with the target to produce muons, which are then cooled by a sequence of passive absorbers and reaccelerated to recover the lost longitudinal momentum.
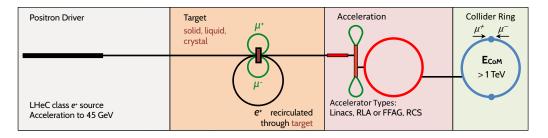
Studies of neutrino factories and muon colliders have been on-going since the 1990's in the USA within the Muon Accelerator Program (MAP) [3], where muons are produced through the decay of pions obtained from the collision of protons with a fixed target [4]. Surface muons that originate from pion decays at the material surface can be produced at a very high intensity sufficient for a muon collider, but the resulting muon beams have very large emittance, which has to be reduced before accelerating the beams to a designed collision energy. Therefore, a dedicated muon cooling section is foreseen as an intermediate step in the MAP accelerator concept, where emittance in the longitudinal and transverse planes is reduced to achieve sufficient luminosity, as shown in Fig. 1. The ionisation cooling concept in the transverse plane has been tested by the MICE experiment at the Rutherford Appleton Laboratory, finishing its program with positive results which are now public [5]. The longitudinal cooling has not yet been tested.

2. LEMMA concept

The Low EMittance Muon Accelerator (LEMMA) program [6] is studying the possibility of a muon collider with performance similar to that of MAP, but with muon beams produced already with small emittance, eliminating the need for a complex and expensive ionisation cooling system. In this scheme muons are produced from annihilation of a high intensity positron beam with

electrons in a fixed target at the centre-of-mass energy at the $e^+e^- \to \mu^+\mu^-$ production threshold, which corresponds to the positron beam energy of 45 GeV [8]. The schematic designs of the LEMMA scheme is shown in Fig. 2.

Figure 2: LEMMA accelerator concept. The beam in the positron ring (in black) interacts with the target on every turn. Muons are accumulated in the accumulator rings (in green) during less than one lifetime and then extrated for further acceleration.

A number of challanges have to be addressed before making the LEMMA concept applicable in a real Muon Collider. First, the muon production rate is limited by the small cross section of the $e^+e^- \to \mu^+\mu^-$ process: 0.1 to 1 μbarn. This implies that a very high flux of positrons is required to obtain the sufficient number of muons. A potential solution to this issue is to recirculate the positron beam through the target in a 6.3 km long ring, as shown in Fig. 2. The produced muons are stored in the two muon accumulator rings before being extracted for further acceleration.

A second challenge of the LEMMA scheme is the thermo-mechanical stress in the target material caused by the absorption of a high-intesity positron beam. Among several target options that are currently under consideration a solid beryllium (Be) target is the primary candidate providing a good balance between the muon production rate and degradation of the positron beam.

After demonstrating with initial simulation studies that the beam emittance can be kept under control in the whole accelerator chain [6, 7], the LEMMA has started to move towards experimental validation of the low emittance muon production concept. In total two testbeam campaigns were carried out in the CERN North Area using positrons from the H4 beam line in 2017 and from the H1 beam line in 2018. In the following the latest experimental setup of 2018 is described as well as first evaluation of its performance. The full documentation of the experiment and results can be found in Ref. [1].

3. Experimental setup

The experimental setup was designed to measure with high precision trajectories and momenta of the two muons as well as direction of the incoming positrons. The layout of the setup is schematically shown in Fig. 3, with a right-handed coordinate system defined by the Z axis pointing in the direction of the positron beam and X axis pointing in the μ^- direction. It starts with the positron beam passing through a plastic scintillator and a pair of silicon tracking sensors before hitting the target measuring the direction and position of the positron beam on the target. The silicon sensors are 1.9×1.9 cm^2 in size and provide 1D position measurements with a microstrip pitch of 50 μm [9]. Muon pairs produced in the target material pass through the vacuum beam pipe and

another pair of silicon sensors, one before and one after the pipe, which measure the direction of the muons before passing through the 2.01 T magnetic field created by the dipole magnet.

Figure 3: Schematic view of the LEMMA experimental setup as used in the testbeam of August-September 2018. All the components of the setup are marked in the figure except for a sequence of silicon tracking sensors (in blue) and plastic scintillators (in yellow) that were used for triggering of the data acquisition.

Downstream from the magnet the two muons diverge into two arms, which allows to reconstruct their momenta from the measured trajectories. In each arm a muon passes through three layers of Si sensors followed by a calorimeter and by two layers of Drift Tube (DT) muon chambers. Silicon microstrip sensors positioned downstream from the target vary in size from 9.3×9.3 cm^2 near the target to 18×18 cm^2 in front of the DT chambers, with spatial resolution ranging from 228 μm in the smaller sensors to 456 μm in the larger ones [10]. The silicon modules located between the magnet and calorimeters have alternating orientations to provide measurements both along the X and Y axes. Each DT chamber consists of four fixed layers of wires, providing ≤ 8 hits in the Z-X plane in each arm. The expected spatial resolution along the X axis is about 150 μm.

Positrons are expected to deposit most of their energy in the calorimeter. Any eventual leakage is to be absorbed by the iron shielding placed downstream such that only $\mu^\pm$ tracks were expected to reach the DT chambers. The calorimeter consists of the lead-glass (PbWO$_4$) section to measure the deposited energy followed by the Cherenkov section to differentiate between electron and muon tracks.

Finally a pair of plastic scintillators positioned after the 2-nd Si layer and behind the last DT chamber in each arm serve as a trigger for the data acquisition system (DAQ) by requiring a coincidense between signals from all the scintillators in both arms and the scintillator at the positron entrance point. The trigger signal was used to acquire data from the silicon sensors and calorimeters, while the DT chambers were using a completely independent trigger-less DAQ system, which acquired data from all chambers every 25 ns. The trigger signal from scintillators was shared between the two DAQ systems for synchronisation of events.

4. Analysis strategy

At the beginning of each testbeam campaign a series of calibration runs were recorded in different configurations. In particular during the last campaign of September 2018 the following calibration runs were recorded:

- e^+ beam at energies in range 16-28 GeV in steps of 2 GeV without target: for alignment of the silicon modules and calibration of the calorimeters;

- same configuration but with a reversed magnetic field direction to obtain signals in the other arm of the setup;

- μ^+ beam at energies of 22 GeV, 26 GeV and 30 GeV without target with the two opposite magnetic field directions: for alignment of the calorimeters and DT muon chambers.

The calibration runs with positron beams without target were also used to ensure that no tracks are registered by the DT chambers, as confirmed by the analysis of the recorded data.

Physics runs were recorded with the positron beam impinging on a cylindrical target in several different configurations, varying the positron beam energy as well as target material and dimensions, as summarised in Table 1.

Table 1: Configurations of physics runs taken with the positron beam and cylindrical targets during the testbeam campaign of September 2018.

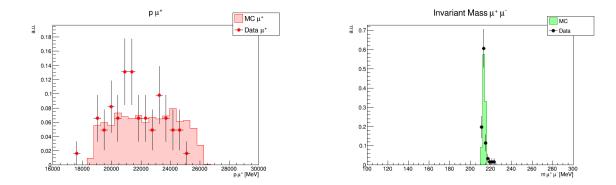| e^+ energy, GeV	Target material	Length, mm	Diameter, mm
45.0	Be	60	40
46.5	Be	60	40
49.0	Be	60	40
45.0	C	60	40
45.0	C	20	40

The process of interest in the analysis of physics runs is $e^+e^- \to \mu^+\mu^-$, which implies the presence of two reconstructed muon tracks in the DT chambers and silicon modules. The reconstruction starts from the hits in muon chambers that are fitted by straight lines and then propagated upstream towards the silicon detectors. The first assumption of muon momenta is done based on the track position in the muon chambers, which is used to propagate the tracks to the first silicon detector upstream the magnet with the circular track model. Linear extrapolation is then used to propagate the muon tracks to the silicon module next to the target. Finally all hits are fitted again to obtain the best estimate of the track momenta and angle in the bending X-Z plane. Candidate events are selected if both μ^+ and μ^- track fits converged.

5. Results

Following the reconstruction procedure described in the previous section, momenta of the two muon tracks are obtained, which are combined to calculate the invariant mass of the muon pair ($m_{\mu^+\mu^-}$), as shown in Fig. 4. The invariant mass distribution peaks at twice the muon mass, i.e. around 212 MeV, as expected from the simulation.

6. Conclusions

While a Muon Collider is a very promising option for a future high-energy collider, it has a number of challanges, one of which is the production of muon beams with very low emittance. For

Figure 4: Reconstructed momentum of the positively charged muon track (left) and invariant mass of the reconstructed muon pair (right) compared to the corresponding distributions simulated with MC. Data and simulation are normalised to unit area.

the first time the new LEMMA concept has been implemented experimentally using the CERN SPS as a positron source. Although several technical difficulties led to a limited statistical precision of this measurement, consistency with detailed simulation of the detector setup has been achieved. By using more accurate tracking devices and more efficient trigger and readout systems such a setup can be used for a study of the LEMMA scheme at high precision.

References

[1] Amapane N. et. al. *Towards a measurement of the emittance of muons produced by positron annihilation at threshold energy*, arXiv:1909.13716

[2] Zimmermann F. *Future Colliders for Particle Physics – "Big and Small"*, Nucl. Instr. Meth. A **909**, 33-37 (2018); arXiv:1801.03170

[3] Ryne R. D. et. al. *Design Concept for Muon-Based Accelerators*, WEPWA057, in proceedings of *IPAC* 2015, Richmond, VA, U.S.A.

[4] Berg F. *Development of a Next-generation High-Intensity Muon Beam at the Paul Scherrer*, LNF Mini-Workshop Series: Muon production and beam interceptors. April-19, 2018; LNF/INFN, Frascati, Italy

[5] Mohayai T. A. et. al. *First Demonstration of Ionization Cooling in MICE*, FRXGBE3, in proceedings of *IPAC* 2018, Vancouver, BC, Canada

[6] Boscolo M. et. al. *Low Emittance Muon Accelerator Studies with production from positrons on target*, Physics. Rev. Accel. Beams **21-6** (2018)

[7] Alesini D. et. al. *Positron driven muon source for a muon collider*, arXiv:1905.05747

[8] Antonelli M. et. al. *Novel Proposal for a Low Emittance Muon beam using positron beam on target*, Nucl. Instr. Meth. A **807** 101-107 (2015)

[9] Lietti D. et. al. *A microstrip silicon telescope for high performance particle tracking*, Nucl. Instr. Meth. A **729** 527-536 (2013)

[10] Barbiellini G. et. al. *The AGILE silicon tracker: testbeam results of the prototype silicon detector*, Nucl. Instr. Meth. A **490** 146-158 (2002)

5