ISBN: 978-3-95450-216-5 doi:10.18429/JACoW-eeFACT2018-MOYBA04

REPORT FROM ARIES MUON COLLIDER WORKSHOP IN PADUA*

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Abstract

Several novel concepts could help the muon collider become a reality. These concepts include parametric ionization cooling, low-emittance muon production by positron annihilation (LEMMA scheme), production of low-emittance muon or positron beams using the Gamma Factory concept, and strategies to upgrade large accelerator complexes, like the LHC or the FCC, into a highest-energy muon collider. The muon collider workshop organized by ARIES APEC at Padua in July 2018 gathered the international community in order to review the recent progress and to formulate a common R&D strategy. Several important conclusions and recommendations were drawn.

INTRODUCTION

On 2–3 July 2018 a Muon Collider workshop at the University of Padua attracted 78 experts from Europe and the US, as illustrated in Figs. 1 and 2. This exciting and forward-looking workshop was the second event organized in the frame of the EU co-funded ARIES Work Package 6.6 (WP6.6), after the Photon Beams workshop in 2017 [1].

Figure 1: Some participants of the ARIES WP6 workshop on Muon Colliders, Padua, 2-3 July 2018.

More specifically, the muon collider workshop was organized by ARIES WP6.6 coordinators Marco Zanetti (INFN Padova) and Frank Zimmermann (CERN), together with the newly established European Muon Collider Study Group, chaired by Nadia Pastrone (INFN Torino). ARIES is an integrating activity co-funded by the European Commission in the HORIZON 2020 Research and Innovation programme under grant agreement no 730871. Work Package 6 "Accelerator Performance and Concepts" (APeC) contains a Task 6.6, which looks at far-future concepts.

Figure 2: Snapshots from the ARIES WP6 workshop on Muon Colliders, including Alex Bogacz, Carlo Rubbia, Rolland Johnson, Mark Palmer, Manuela Boscolo, Marco Zanetti, Pantaleo Raimondi, and Jean-Pierre Delahaye.

ADVANCED PROTON-DRIVEN SCHEMES

Setting the stage, Carlo Rubbia, from CERN and INFN, the recipient of the 1984 Nobel Prize for Physics and a life-long Member of the Senate of the Italian Republic, called for an initial experiment to demonstrate muon cooling and the particular merits of parametric ionization cooling [2]; see Fig. 3. He pointed out that the first muon facility would comprise a ring at the scale of the PS, and hinted at the ESS as being the ideal place for a muon-beam facility in Europe.

Figure 3: Recognizing the muon collider as a project of reasonable cost and of reasonably fast construction, Nobel laureate Carlo Rubbia admonished the audience to focus on scientific work instead of PowerPoint studies.

* This work was supported by the European Commission under the HORIZON 2020 project ARIES no. 730871.
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BNL's Mark Palmer summarized the results of the past Muon Accelerator Program (MAP) studies in the US [3] (Fig. 4). He reported the designs of the facilities NuSTORM [4, 5], and NuMAX [6], which are short- and long-baseline options, respectively, with remarkably attractive capabilities for precision physics. A later multi-TeV muon collider would fit on the FNAL site. Mark also discussed alternative options for a muon collider in the LHC tunnel. The MAP study had considered 10 T dipoles, or about 1000 turns decay time. Echoing Carlo Rubbia, Mark Palmer's recommended strategy was to build NuSTORM and to pursue an advanced-cooling demonstration. The full physics performance and achievable resolution need to be further analyzed. The preferred scenario is a programme which culminates in a muon collider and which does exciting science all along the way.

Figure 4: BNL's Mark Palmer recommended construction of NuSTORM and pursuit of an advanced-cooling demonstration.

Ken Long from Imperial College London reported the excellent results of the first muon ionization cooling experiment (MICE) [5, 7]. A novel emittance measurement technique, which had to be developed for MICE, achieved a percent level precision.

At the workshop a general consensus emerged that the next steps forward should include the design and implementation of a 6D cooling experiment, and the establishment of a particle-physics programme based on high-intensity, high-energy muon beam, e.g. NuSTORM, presented in detail by Jaroslav Pasternak, also from Imperial College. Scott Berg of BNL pointed out that the matching problem for multiple cooling cells still ought to be addressed.

ALTERNATIVE NOVEL SCHEMES

In addition to the classical muon production approach where high-intensity proton beams are shot on a target for pion generation, with subsequent muon ionization cooling, three alternative novel schemes are recently being explored, under the names "muon photocathode", "Gamma Factory," and "LEMMA".

Camilla Curatolo, from INFN Padua discussed a "muon photocathode" [8, 9], which could be realized in hadron-photon collisions using a free electron laser (FEL). To study such a scheme she developed a dedicated event generator. For an FCC-based example, the normalized emittance would be less than 1 micron. The proton-gamma luminosity could be $10^{38}/\mathrm{cm}^2/\mathrm{s}$. Muon accumulation and muon polarization are to be considered.

Witek Krasny, from LPNHE Paris and CERN, introduced the "Gamma Factory," where partially-stripped heavy ion (PSI) beams at high energy are collided with laser or FEL pulses [10, 11]. The basic idea underlying the Gamma factory is to replace the electron beam, traditionally used for laser Compton backscattering light sources, by a PSI beam, as is illustrated in Fig. 5. The PSI beam allows for a resonant interaction with much higher cross section and with significantly higher photon energies than an electron-based Compton source. A Gamma Factory could allow for the production of huge rates of polarized muons or positrons. For example, an FCC-based Gamma Factory could provide more than 10^{17} positrons per second. A successful proof-of-principle experiment at the LHC in summer 2018 has demonstrated an excellent lifetime of the partially stripped heavy-ion beams at top energy, which represents an important milestone towards the realization of a first Gamma Factory; see Fig. 6. Witek Krasny highlighted three specific scenarios for producing polarized leptons using the Gamma Factory concept, and the associated ongoing SPS experiments. A breakthrough scheme with Pb^{+79} ions will avoid the double excitation of electrons into the continuum.

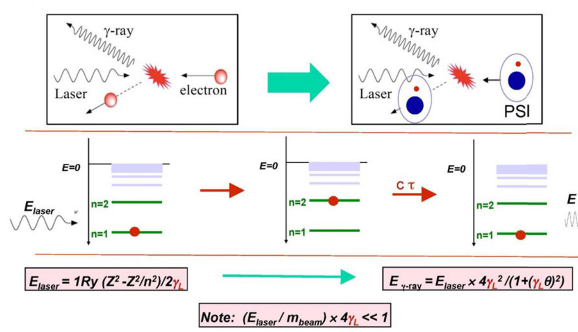

Figure 5: Concept of the "Gamma Factory" where Lorentz-boosted laser photons collide, and interact resonantly, with a PSI beam circulating in the LHC or FCC-hh. The resonant laser-PSI interaction excites atomic (ionic) transitions. The photons emitted when excited ions, nearly instantly, decay back into their ground state are once again Lorentz boosted, yielding photon energies of up to a few hundred MeV.

Manuela Boscolo from INFN Frascati presented the Low EMittance Muon Accelerator (LEMMA) scheme, which she had first proposed together with Pantaleo Raimondi (ESRF) and Mario Antonelli (INFN) [12, 13]. At LEMMA, positrons

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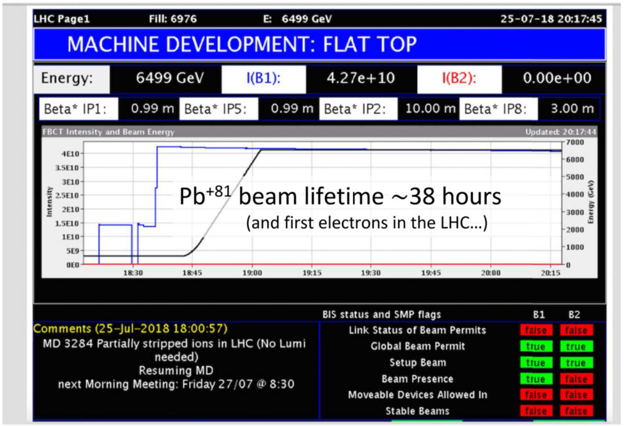

Figure 6: Gamma Factory proof-of-principle experiment at the LHC in July 2018. A Pb^{+81} beam was injected and accelerated to top energy, where the beam lifetime, limited by stripping off the residual gas, was about 38 hours. This experiment also saw the first electrons in the LHC. Dima Budker from the University of Mainz (the son of the inventor of the muon collider) called this experiment "one of the main scientific advances in the whole of physics this year".

of about 45 GeV energy, circulating in a storage ring, annihilate with electrons at rest in a thin internal target, which results in muon production just above threshold, and, hence, with a low transverse emittance. The LEMMA scheme and the classical proton-driven muon production scheme with ionization cooling are compared in Fig. 7.

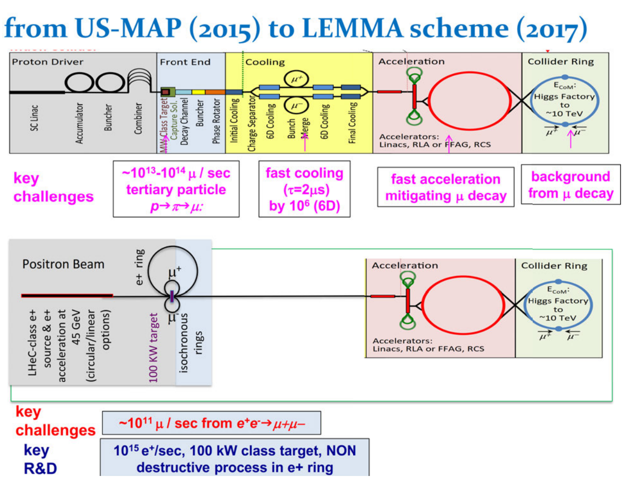

Figure 7: Comparison of US-MAP scheme for a muon collider, based on proton driver and ionization cooling, and the novel LEMMA scheme based on a positron storage ring with e^+e^- annihilation on a thin internal target (M. Boscolo, P. Raimondi, et al.). Key challenges for the two alternative approaches are also indicated.

The LEMMA positron beam loses several tens of MW energy passing through the target, made e.g. from beryllium, carbon, or hydrogen. About 200 kW of this power is deposited inside the target. Target survival is an open question. Liquid targets or rotating targets are among the options proposed. The workshop participants agreed on the need for experimental target tests. Oscar Blanco from INFN-LNF reported on the LEMMA muon accumulator ring. He pointed out that the muon beam emittance is limited by multiple scattering in the annihilation target. Citing Daniel Schulte of CERN, he also showed that for a 3 mm Be target the minimum normalized emittance is 600 nm, significantly larger than the 40 nm emittance previously assumed. Simone Liuzzo of ESRF explained that, for LEMMA, more than 120 MW of synchrotron radiation are emitted in a 6.2 km positron ring. For a 27 km ring the synchrotron-radiation power drops below 30 MW. Frank Zimmermann of CERN pointed out that this power would become even lower if the 100 km FCC-ee ring is employed. Serendipitously, the latter ring, thanks to its Z-pole running mode, already offers the right beam energy for low-emittance muon production through annihilation. Intriguingly, Francesco Collamati, from INFN Roma, showed that the abundant bremsstrahlung photons which are equally emitted from the target can be used to generate more positrons, leading to a self-amplification of the positron beam, which could solve the challenge of generating positrons at the rate required for LEMMA. Susanna Guiducci from INFN-LNF reviewed the state of the art in positron sources, which would be an integral part of LEMMA.

MUON ACCELERATION

Daniel Schulte of CERN discussed the potential use for muon-collider R&D of an experimental programme using electron beams from the CERN SPS, with a CLIC-like injector [14]. He underlined that plasma acceleration is a perfect match for muons, which typically are of low intensity and fairly large emittance. He argued that "if it is not suitable here, plasma acceleration probably cannot be used for any other type of collider".

Scott Berg of BNL and Alex Bogacz from JLAB discussed more conventional options for muon acceleration [15–17], including the FFA accelerator prototype CBETA [18] under construction at Cornell (see also the recent first ever experimental demonstration of muon radiofrequency acceleration at J-PARC [19]).

HIGH-ENERGY MUON COLLIDERS

In an exceptional remote presentation of this workshop, David Neuffer of FNAL, presented the fascinating option of a 14 TeV muon collider in LHC tunnel, which could be a cost-effective approach for reaching the ten-TeV scale in lepton collisions [20]. The proposal is illustrated in Fig. 8. Upon request, he also detailed the three fundamental laws of beam physics.

Daniel Kaplan of IIT reviewed limits from neutrino radiation [21]. Concerning the next steps, he recalled that "you don't get tenure by saving government money".

Frank Zimmermann, of CERN, sketched a possible upgrade of the FCC lepton and hadron-collider complex to a high-energy muon collider, using a combination of Gamma

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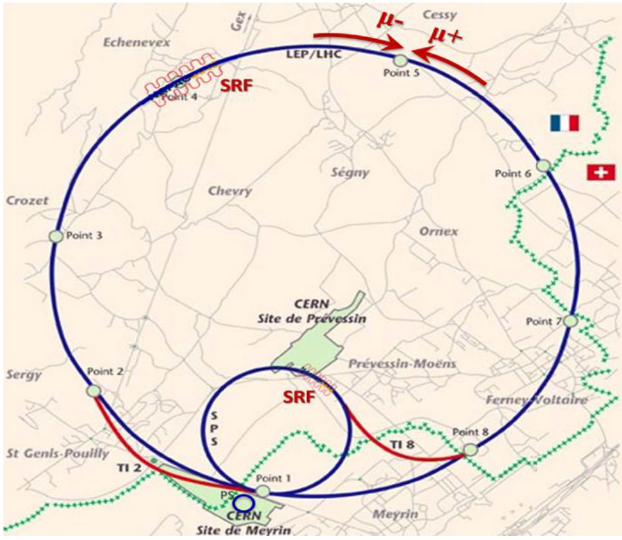

Figure 8: A 14 TeV muon collider in the LHC tunnel, based on short high-field magnets operating at a constant field of 16 T, and pulsed ±3.8 T SC magnets and an SRF system providing more than 10 GV accelerating voltage (D. Neuffer and V. Shiltsev).

Factory and LEMMA concepts [22,23] – Fig. 9. He showed that for various reasons and in view of the scaling laws – which call for a ring of large circumference and with high magnetic field – the FCC appears to be the ideal basis for constructing a future 100 TeV muon collider.

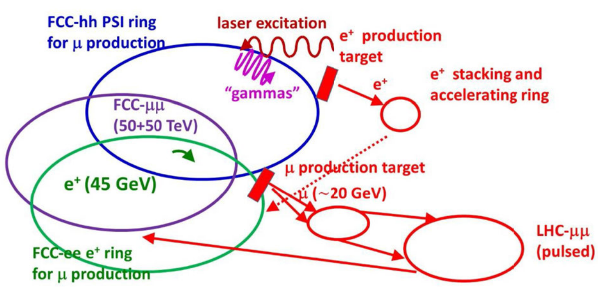

Figure 9: A 100 TeV muon collider, "FCC-$\mu\mu$", in one of the FCC-hh rings, with e+ production from a Gamma Factory using partially stripped ion beams circulating in the other FCC-hh ring, and with LEMMA type muon production from a positron beam stored in one of the 45 GeV FCC-ee rings; this concept would enable an FCC physics program extending over more than 100 years (Frank Zimmermann).

CERN's Jean-Pierre Delahaye compared the performance of several proposed future lepton colliders, introducing two figures of merit, the luminosity per construction cost and the luminosity per electrical power. This was an exciting update to an earlier similar study [24]. He showed that, with regard to both figures-of-merit, the FCC-ee was the best of all options, while the values of the muon collider extended all across the figure-of-merit plane from the worst (muon Higgs factory) to among the best (multi-TeV muon collider) – see Fig. 10.

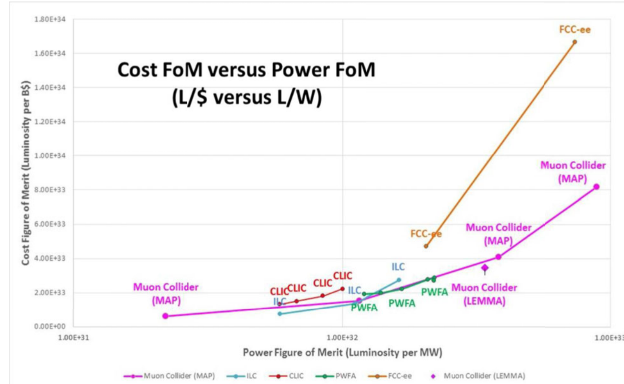

Figure 10: Cost-figure-of-merit versus power-figure-of-merit for future lepton colliders (Jean-Pierre Delahaye).

Alain Blondel from the University of Geneva pointed out that luminosity measurement techniques for muon colliders still need to be worked out. Mario Greco from Roma Tre emphasized the importance of QED radiative effects for a precision study of the Higgs pole line shape and the signal-to-background ratio, both at a Higgs-factory muon collider and at the FCC-ee.

CONCLUSIONS

At the workshop, a general consensus was reached that the steps forward should include: (1) the design and implementation of a 6D cooling experiment; (2) LEMMA target tests; (3) the Gamma Factory development; (4) the establishment of particle-physics programme based on high-intensity, high-energy muon beam, e.g. NuSTORM.

At the end of the workshop, Nadia Pastrone, from INFN Torino, the coordinator of the European muon collider study group, drew some enthusiastic conclusions and discussed the muon-collider input to the 2019/20 European Strategy Update.

More details and all presentations can be found on the indico web site of the Muon Collider workshop [25].

ACKNOWLEDGEMENT

We thank G. Arduini and M. Giovannozzi for a careful reading of the manuscript.

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