REVIEW OF REQUIRED PROOF-OF-PRINCIPLE EXPERIMENTS TOWARDS A MUON COLLIDER

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Abstract

The HEP scientific community is, at present, exploring different scenario concerning the post LHC era. In fact, after the Higgs boson discovery, the future facility will require not only to improve the LHC and HL-LHC physics programs but also to continue the search for phenomena beyond the Standard Model into an extended energy domain. In this framework ideas and proposals, together with the results obtained in accelerator research, introduce a scenario where the feasibility of a multi-TeV muon collider should be explored.

This article will describe the advantages provided by the muon collider scheme. The proposed schemes will be shortly illustrated. The very important recent results obtained in proof-of-principle experiments will be subsequently described. Finally, for each scheme, the future possible directions for proof-of-principle experiments to demonstrate the muon collider feasibility will be presented.

INTRODUCTION

The future challenges in the high energy colliders frontier, cannot be decoupled from the luminosity requirements keeping as fundamental constraint the necessity to build and operate the facility with a reasonable construction and operation budget. In this context a high energy muon collider should represent a true opportunity. In this framework a still-in-progress physics case has been elaborated [1] and this has been recently taken into account in the input for the European Strategy for Particle Physics Update 2020 in the Physics Briefing Book [2].

Different considerations make the muon collider option very attractive. First of all, the center of mass energy can be considerably reduced in respect to the p-p configuration where a significant fraction of the proton-beams energy in the interaction point is carried away by the partons contribution. Furthermore, the leptonic nature of the muons also assure a direct exploitation with a significant noise reduction, resulting in foster the muon potential not only as high energy but also as a precision collider. On the other side this solution presents definite advantages with respect to the e^+e^- configuration, mainly due to the about 200 mass scaling factor. This strongly relaxes the constraints in synchrotron radiation power emission and in the beamstrahlung effect that represent one of the main performance limitations respectively for the circular and linear lepton collider options. Finally, the luminosity parameter for the high energy configuration is linearly dependent from the energy at constant beam power, when compared to the constant behaviour of the linear collider option.

A final definitive assessment of the luminosity requirement should be delivered in a CDR phase where an extensive investigation of the physics channels should be carried out. Nevertheless, basic considerations allow to fix a luminosity target of 2 10^{34}cm^{-2}s^{-1} at 3 TeV [3].

The undeniable advantages represented by the muon collider option are nevertheless challenged by the main limitation given by the muon 2.2 µs at rest lifetime, rather short in a collider perspective. This is an important limiting factor namely at the muon production. In fact, muons bunches are produced with a very large 6D emittance and a limited number of particles per bunch limited by the primary beam power and the target technology. To provide a collider design matching the luminosity requirements, any applicable cooling technique needs, thereby, to show unprecedented efficiency to guarantee the emittance shrinking with a very fast process immediately after the production. This will permit the subsequent beam shaping, transport and post acceleration phases. Different techniques should also be envisaged to recombine muon bunches before a final cooling stage, to benefit of the luminosity quadratic dependence on the single bunch intensity. All these considerations underline the crucial aspect of the source design for the muon collider option. To provide a reliable design of a muon source integrating all the production, shaping, cooling and recombination phases represented for years the true challenge and it resulted in an important and long R&D effort sustained by the community. In this framework it is important to underline the muon collider R&D strong synergies with the neutrino physics programs.

MUON COLLIDER SCHEMES

At present there are two main proposed scenarios for a muon collider facility the difference being essentially in the muon source design. The first has been elaborated in the framework of the US Muon Accelerator program (MAP) and it consider the muons as tertiary particles in the decays of the pions created by an intense proton beam interacting a heavy material target. The second, the LEMMA scheme, takes into account the process $e^+e^-\rightarrow\mu^+\mu^-$ just above threshold for the muon generation considering a high energy positron beam impinging on a target. After the peculiar phases of bunch generation and emittance shaping associated to the specific production process, similar technical and design issues for the two schemes are found in the post acceleration stage. At the end, depending on the beam emittances, different collider ring design requirements are also considered.

MAP: THE PROTON DRIVEN SCHEME

The Muon Accelerator Program [4] started in 2011 to develop the conceptual designs and to face all the technological R&D challenges associated to the Muon Colliders and Neutrino Factories. To establish the program priorities a baseline scheme was proposed [5]. The collider layout takes into account five different stages. The first includes

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the production and shaping of the high intensity primary proton beam. The second stage takes into account the generation of the muon bunches by means of the pion production in a MW class target and the front end section consiting in a decay channel for the muon production and a first longitudinal capture section. The third stage envisages the muon beam 6D emittance decrease by ionization cooling and the bunches recombination. A post cooling channel is foreseen after the recombination due to the subsequent Liouville emittance enhancement of this phase. The fourth and the fifth stages take into consideration, respectively, different design proposals for the post acceleration process and the injection and the beam storage in the collider ring. The MAP program has reached a high maturity level by systematically determining and carrying out different proof-of-principle experiments and techonological programs. Among them it is important to highlight the important progresses obtained thanks to the MICE, EMMA and CBETA facilities.

MICE: The Ionization Cooling Demonstrator

One of the most important part of the MAP proposed layout is given by the ionization cooling section, that has to assure the availability of high brightness muon bunches. This is a classical cooling mechanism where the particles lose energy in many degrees of freedom through ionization, in an appropriate material absorber, and restore it in one degree of freedom thanks to a RF post-acceleration. The final emittance budget is the result of the equilibrium between the ionization energy losses cooling mechanism and the heating process given by the multiple scattering in the absorber medium. To assure also the longitudinal muon beam cooling, different solutions are proposed to implement an emittance exchange mechanism by correlating the transverse to the longitudinal dimensions and inserting wedge shaped absorbers. In this framework it was essential, as first proof-of-principle experiment to validate the efficiency of the ionization cooling mechanism in a real 4D cooling channel with a muon beam. At this scope the MICE international collaboration [6] implemented a muon transverse cooling demonstrator at RAL. The apparatus consists in an absorber section inserted in a tight focusing twelve superconductive solenoids lattice, where the 4T spectrometer and the 3.5T on-axis field magnet allow for, respectively, the momentum measurements and the achievement of a small β function (430 mm) at the absorber location to increase the cooling efficiency. As far as the absorbers cooling performance is concerned, low atomic number materials with a large radiation length / rate of energy loss ratio, like liquid-hydrogen (LH) and lithium hydride (LiH), were chosen. The muons phase space was reconstructed before and after the cooling section by TOF and Cerenkov counters measuring the particles' velocities and by five planar scintillating-fibre stations trackers determining the muon positions and momentum. A 140 MeV/c muon beam with a normalised emittance varying from 4 to 10 mm was delivered extracting the ISIS synchrotron beam on a target.

To evaluate the effective cooling efficiency of the channel different analysis were performed comparing the upstream and downstream phase space in presence or absence of the absorbers effect. A recent outstanding publication [7] provided the first transverse ionization cooling demonstration observing the increasing of the downstream small amplitude particles and the beam phase density increase.

EMMA and CBETA: Post Acceleration Schemes.

The short muons lifetime demands another innovation effort in the muon collider post acceleration system design. Indeed, this phase duration has to be minimized to avoid relevant muon decay losses. Due to the difficulty to provide very fast high field ramping magnets one of the most promising solutions was to explore non-scaling FFGA systems whose characteristics allows fast acceleration.

A first proof-of principle experiment, the EMMA electron ring, was studied and built in Daresbury. It aimed to demonstrate, in the 10-20 MeV range, the possibility to obtain a reduced momentum compaction and hence a smaller orbit excursion, in respect to the scaling systems, with a non-scaling design and by operating fixed frequency accelerating cavities (asynchronous or serpentine acceleration), [8]. This allows reducing the elements complexity since linear magnetic fields can be associated to small orbit oscillations so increasing the dynamic aperture. Furthermore, it shows that CW operation is possible in the context of the future application to the muon acceleration. Forty-two identical cells containing offset quadrupole doublets provide the EMMA ring beam optics and the bending force [9]. To take into account the fast ramping needed for the muon bunches a RF system consisting of nineteen single-cell normal-conducting cavities, and resulting in an energy increase of more than 1 MeV per turn, was integrated [10].

Finally, it was demonstrated a stable acceleration in a serpentine channel from 12 to 18 MeV in six turns with a reduced orbit shift and where different integer H&V tunes were crossed throughout the acceleration without increasing the beam oscillations amplitude [11].

Another important proof-of-principle concept was recently demonstrated with the results obtained in the CBETA facility in Cornell, a SC Linac ERL with four accelerating passes at 42, 78, 114 and 150 MeV but integrated in a single Fixed Field Alternating Linear Gradient (FFA-LG) return beam line [12]. The different energy beams are merged by a 4 arms beam spreader. The single pass acceleration is assured by six SRF1.3 GHz 7-cell cavities cryomodules, with a 12,5 MeV/cryomodule energy gain, around the double of what is necessary for the 42 MeV pass. The ERL efficiency is estimated at 99.9%. The return loop is based on 214 permanent magnets divided in quadrupoles and combined-function gradient magnets using a variant of the circular Halbach design. The line is based on doublet cells with a focusing quadrupole and one defocusing-bending quadrupole allowing for a maximum transverse displacement of less than 46.6 mm. Recently CBETA announced the first successful eight pass (4 accelerating and 4 decelerating to demonstrate energy recovery) operation becoming, therefore, the first 4 pass ERL based on the innovative single permanent magnet return line [13].

Outstanding R&D Programs

The MAP's technological challenges related to the muon collider project require different R&D programs that, for their innovation content, can be considered as veritable proof-of principle experiments. Among others it is important to stress the test of high gradient cavities under strong magnetic fields, representing the technology core of the ionization cooling cells. Different 800 MHz class cavities (Q_0 value ranging from 1.5 ÷ 3 10^4) were tested in 5T solenoidal field [14], achieving peak surface fields of the order of 20MV/m corresponding to accelerating gradients of more than 50 MV/m. In parallel the realization and commissioning of the MICE 201 MHz cavity was carried out. For the so-call Helical Cooling Channel, it was also important to demonstrate the feasibility of pressurized high gradient cavities. Measurements were performed under 30-100 Atm pressure of pure hydrogen, nitrogen and helium, or with a SF6 doping, demonstrating gradient up to 60 MV/m in the hydrogen case. In the same pressure range a proton beam test was also successful achieving 50MV/m in a 3T field for a RF pulse length of 40µs [15]. The reach of very high magnetic fields, providing a small beta function in the cooling channel, was explored by the NHMFL R&D program on high field HTS magnets with YBCO-coated tape conductors and Bi-2212 round wires that succeeded in demonstrating a field on-axis higher than 30T [16]. As far as the Bi 2212 cables are concerned it must be highlighted that, a recent publication, illustrates the stable operation at wire current density of 1000 A/mm^2 [17]. The requirements for very high power targets, namely in the framework of the neutrino program, were addressed in the CERN MERIT proof-of-principle experiments where an 8 MW at 70Hz Hg jet target was successfully tested [18].

Future Perspectives

The undeniable success of the different over mentioned experimental programs results in a strong maturity of the MAP proposed scheme that could move into a CDR phase. Therefore, following the 4D cooling demonstration accomplishment, the future step forward should be represented by the full test of a 6D cooling cell. The cell will have to be redesign taking into account the achieved results on the different components technology, starting from the high magnet field to the cavities accelerating gradients. An emittance exchange configuration should be integrated to assure the test of the longitudinal cooling. A subsequent engineering phase should allow the realization of a cell prototype to be commissioned and finally tested on a muon (or proton) beam line as a true proof-of-principle experiment. The extension of the results of this experiment to a full 6D cooling line should confirm the theoretical possibility to attain the final required emittance before the post acceleration phase in a linear cooling channel, as a first fundamental step. The subsequent step should be represented by the measurement of the cooling efficiency of the full 6D cooling line. Even if the final baseline design takes into account a linear channel, it would be extremely interesting to set up a test facility based on one of the proposed circular systems, like the RFOFO [19] or the Dipole-Solenoid rings [20] that can represent a true validation at a reasonable cost and effort. The first system is based on a focusing-drift-focusing lattice with axial field polarity inversion in the middle of the cell. In this configuration the dispersion, the acceleration and the energy loss in a single hydrogen wedge are taken into account in each cell. The second one is composed of modules consisting of a straight section and an arc. The former is dispersion-free and takes into account the injection, the extraction and RF cavities drifts. The latter introduce the 6D cooling necessary dispersion for the energy-loss wedge absorbers.

A proof of principle experiment, in this context, should ambitiously consider the realization of a full facility based on these designs where, also in this case, all the recent technology results should be integrated in the rings lattice.

A separate context is represented by the possibility to have a proof-of-principle facility to demonstrate the Parametric-resonance Ionization Cooling concept [21]. This is supposed to be effective for the final 6D cooling stage of a high-luminosity muon collider allowing a cooling efficiency increase of one order of magnitude in respect to the conventional ionization cooling alone. The PIC technique scheme takes into account a ring with a cooling channel where a half-integer parametric resonance is induced. This converts the usual periodical elliptical phase-space trajectories into a hyperbolic shape, therefore, reducing the geometrical oscillations amplitudes and increasing the angular ones. The damping mechanism, introduced by the absorbers at the focal points, avoid the resonant instability growth reaching an equilibrium. The consequent beam size reduction in the absorbers location results in an effective cooling efficiency gain. Due to this very particular beam dynamics the PIC scheme proof-of-principle validation should be carried out in a dedicated facility.

Finally, it is important to point out that there are still some fundamental R&D programs, working on the performance of a component, to be carried out in the MAP framework. Among others a very important role is played by the development of the 400Hz - 2T fast ramping cycling magnets for the post acceleration phase [22]

LEMMA: THE POSITRON DRIVEN SCHEME

In the past years another muon collider basic scheme, LEMMA, has been proposed [23]. In this context the primary beam is made of 45 GeV positrons impinging on a target, interacting with the material electrons and consequently creating a secondary beam of muons pairs at threshold. The attractive characteristics of the γ-boosted muon bunches are a reduced emittance and a longer lifetime at creation. The drawback of this design is the very low production cross section in a collider framework. To profit of the luminosity quadratic dependence on the bunch population it is therefore necessary to introduce a bunch recombination scheme not increasing the bunch emittance. This is taken into account by recirculating in two separate rings the μ^+–μ^- beams. After one turn they are focalized with a new positron bunch on the production target so overlapping the generated pairs with the recirculated particles. This allows to bypass the Liouville theorem constraint by stacking the new generated muons in the existing bunches phase space, but taking into account the heating given by the multiple scattering in the target. After N cycles the bunches are extracted for the post acceleration process. The reduced emittance of the LEMMA design allows to integrate very small β^* IP regions in the collider, so drastically reducing the bunch intensity at constant luminosity and consequently the radiation and the background problems associated with the muons decay.

To face all the technological and design challenges of the LEMMA proposal a global design process has started recently [24] where different schemes have been proposed. The more robust considers a complex cycles succession involving a Positron Source (PS) with a Damping Ring (DR), a Positron Accumulator ring (PR), two Muons Accumulator rings (MA) and different linear accelerating systems. After a first injection of 1000 positrons bunches in the PR and their subsequent cooling the positron bunches are extracted for the first muon recirculated production cycle. All the production phase has to last less than 300μs to take into account the muon population exponential decay and, at the end, the muon bunches are extracted and send to the post acceleration complex. Following the muon production, the spent positron bunches are re-injected, with a certain efficiency, in the PR to cool down the large energy spread acquired in the target by Bremsstrahlung emission. In 10 ms the positrons are subsequently spilled out and sent, depending on the final design, either into the DR where the lost positrons population is recovered by stacking from the PS or towards an embedded positron source to generate positrons bunches with an efficiency greater than unity. This slow spill process allows also to envisage reasonable average and peak positron currents in the accelerating or decelerating linear systems. After that the positron bunch intensity and emittances have been recovered it is possible to start a new muon generation phase.

Future Perspectives

Being relatively recent the LEMMA scheme has not reached the same design maturity of MAP. A first proof-of-principle experiment has been realised in a CERN test beam, to assess the produced emittance by positrons annihilations [25]. The results showed a 20% dissymmetry in the μ^+– μ^- phase space distributions but a good agreement with the simulated values. Another proposal, in the framework of the CERN UA9 program, aims at exploring the recombination of bunches in a curved crystal and measuring its efficiency. Other experimental tests or R&D are not precisely identified by the determination of their final outcomes, but on the other side, the possibility to work with an established feasibility scheme allows to individuate the different programs topics. A first proposal should concern the possibility to measure the beam dynamics, and so the beam lifetime, in a lepton storage ring under an energy spread dominated regime given by the insertion of a target. Also if performed at a lower energy this test should confirm the reliability of the simulations results.

As far as the R&D programs are concerned one of the most important field to explore is the availability of high power targets capable to minimize the thermo-mechanical stress effects. Both the muon and the positron sources should benefit from extensive R&D programs exploring also innovative ideas as the utilization of liquid Hydrogen pellet targets, the evaluation of rotating or pendulum targets, both in amorphous or in granular configuration, and the design of shockwave impedance matching systems. On the other side the requirements of manipulating in the linear systems very intense positron beams in short periods would require a dedicated project on high gradient - hundreds mA class SC cavities. Finally, a more ambitious program should be imagined with the realization and the test of the muon recombination ring, one of the most critical systems of the whole scheme.

GAMMA FACTORY: AN ALTERNATIVE PROPOSAL

In the framework of the gamma factory activity at CERN [26] the proposal to utilize the high energy photons to produce muons pairs in a target was made. In this proposal the high energy gammas are created by Compton backscattering when very high energy ions beams collide with a laser pulse. This muon source should provide also relatively low emittances beams but requiring a very high gamma flux. At present the gamma based muon collider has not been integrated in a scheme, so it is in a very preliminary conceptual phase. Nevertheless, an important proof-of-principle experiment will be represented by the measurements planned at CERN [27] that will characterize the flux and the spectrum of the backscattered photons.

CONCLUSION

For many years the muon collider community has demonstrated creativity in proposing innovative solutions and in defining advanced R&D programs to explore its feasibility. These programs successes, in some case, represented a true breakthrough in the accelerator physics fields. The MAP program achieved a strong maturity to move to the CDR phase and its possible proof-of-principle experiments should be dedicated to the 6D cooling cell and its efficiency definition. Further ambitious program can be envisaged to test a cooling line by realising a dedicated facility that should consider also innovative proposal like the PIC resonance cooling. The LEMMA scheme has to go through a phase of definition of possible proof-of-principle experiments, especially in the domain of the targets for the high intensity positrons sources and of the energy spread dominated beam dynamics. The gamma factory proposal has already an established program to demonstrate the source performance.

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