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The muon collider

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Summary. — We describe the scientific motivation for a new type of accelerator, the muon collider. This accelerator would permit an energy-frontier scientific program and yet would fit on the site of an existing laboratory. Such a device is quite challenging, and requires a substantial R&D program. After describing the ingredients of the facility, the ongoing R&D activities of the Muon Accelerator Program are discussed. A possible U.S. scenario that could lead to a muon collider at Fermilab is briefly mentioned.

PACS `29.20.db` – Storage rings and colliders.

Introduction

A muon-based collider would represent a powerful addition to the experimentalist's arsenal. In the U.S., design and performance evaluations for such a facility have been ongoing for more than 10 years. Until this year, this work was carried out as a coordinated program of two organizations, the U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC) [1] and Fermilab's Muon Collider Task Force (MCTF) [2]. R&D program coordination has been managed by a coordinating committee comprising the management of the two groups.

At the behest of the U.S. Department of Energy (DOE) Office of High Energy Physics, these two groups are now being merged into a single entity, the Muon Accelerator Program (MAP). MAP will operate under the oversight of the Fermilab director. A MAP proposal has been submitted to DOE and a review is anticipated during 2010.

Motivation

Muon beam accelerators can address several of the outstanding accelerator-related particle physics questions. At the energy frontier, the fact that the muon, like the

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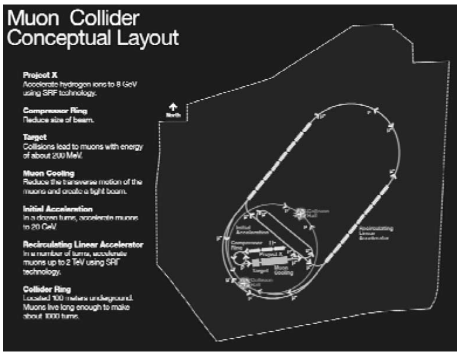

Fig. 1. – Schematic layout of muon collider on the Fermilab site.

electron, is a point particle means that the full beam energy of a muon collider is available for particle production. Because of its heavier mass compared with the electron, the muon couples strongly to the Higgs sector. Moreover, the muon emits almost no synchrotron radiation, which makes possible a circular collider that uses the expensive RF equipment efficiently and can fit on the site of an existing laboratory. Figure 1 illustrates how such an accelerator complex would fit on the Fermilab site.

A muon accelerator could also explore the neutrino sector. The high-energy neutrino beam (above the τ threshold) derived from the decay of stored muons in a ring (a "neutrino factory") has well-understood properties, with minimal hadronic uncertainties in the spectrum and flux. Oscillations from electron to muon neutrinos give rise to easily detectable "wrong-sign" muons, that is, muons whose sign is opposite to that of the stored muon beam. This channel can be observed with low background, giving the neutrino factory unmatched sensitivity for studies of charge-conjugation–parity (CP) violation, the mass hierarchy, and unitarity in the neutrino sector.

Challenges

While there are clear advantages to making use of muon beams, there are equally clear challenges. Because muons are created as a tertiary beam ($\mathrm{p} \to \pi \to \mu$), the production rate is low, necessitating a multi-MW proton source and a target that can withstand it. The production process also results in a beam with very large transverse phase space and energy spread, necessitating a mechanism for emittance cooling and, even so, a large acceptance downstream acceleration system.

The short muon lifetime ($2.2\,\mu$s at rest) is also challenging from an accelerator perspective. All beam manipulations must be very rapid, requiring high-gradient RF cavities that operate in a magnetic field (for the cooling channel), use of the presently untested ionization cooling technique, and a fast acceleration system.

Finally, the decaying muons produce an intense beam of decay electrons in the midplane of the collider ring or neutrino factory decay ring. These electrons produce a substantial heat load for the superconducting magnets and potentially create backgrounds in the collider detectors.

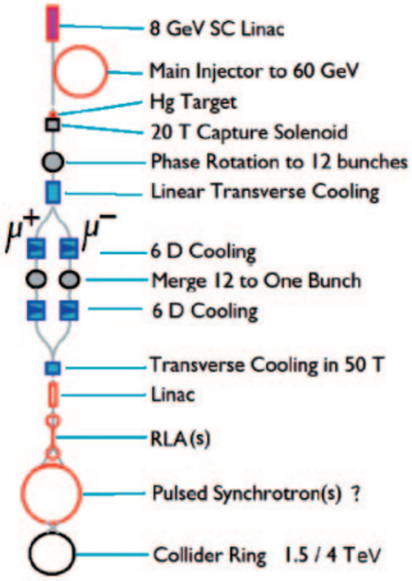

Fig. 2. – Schematic layout for muon collider.

Muon collider systems

The layout of a muon collider is illustrated schematically in fig. 2. The following systems are included:

- a 4-MW proton driver that produces the primary beam for the production target,
- a target, capture, and decay region where the pions are created, captured, and decay into muons; the MERIT experiment [3] addressed this part of the facility,
- a bunching and phase rotation section where the muons are rotated in longitudinal phase space to reduce their energy spread,
- a cooling section to reduce the transverse and longitudinal emittance of the muon beam; the MICE experiment [4] addresses the transverse cooling part of the facility,
- an acceleration section, where the muon beam energy is increased in stages from about 130 MeV to about 1 TeV,
- a collider ring where the beam is stored for ~ 500 turns.

Much of the front end of a muon collider—up to and including the transverse cooling section—is identical to what is needed for a neutrino factory. The early portion of the acceleration system is likewise identical. Because of this, the R&D program for a muon collider is largely in common with that for a neutrino factory.

Typical parameters for two muon collider scenarios are summarized in table I. The required proton driver power is about 4 MW, based on nominal transmission values. As the design is refined, this requirement will undoubtedly evolve, and could well increase.

Table I. – *Typical parameters of* 1.5 *and* 3 TeV *c.m. muon colliders.*

$\sqrt{s}$ (TeV)	1.5	3
Av. luminosity/IP (10^{34}cm^{-2} s^{-1})	0.77	3.4
Max. bending field (T)	10	14
Av. bending field in arcs (T)	6	8.4
Circumference (km)	3.1	4.5
No. of IPs	2	2
Repetition rate (Hz)	15	12
Beam-beam parameter/IP	0.087	0.087
β^* (cm)	1	0.5
Bunch length (cm)	1	0.5
No. bunches/beam	1	1
No. muons/bunch (10^{11})	20	20
Norm. trans. emit. (μm)	25	25
Beam size at IP (μm)	6	3
Energy spread (%)	0.1	0.1
Norm. long. emit. (m)	0.07	0.07
Total RF voltage (MV) at 805 MHz	77	886
μ^+ in collision/8 GeV proton	0.008	0.007
8 GeV proton beam power (MW)	4.8	4.3

Collider subsystems

Proton beam energy

Our simulations are based on pion production estimates for 8 GeV protons from the MARS15 code [5]. Recently, it has been shown [6] that the steep fall-off in pion production at low proton energy predicted by the code is inconsistent with experimental data from HARP [7]. The MARS15 code is presently being updated to account for the new data. While 8 GeV still appears to be a reasonable choice, lower proton energies, say 5 GeV, are likely to be acceptable.

Proton bunch length

The proton bunch length has a significant influence on the production rate. An rms bunch length of 1 ns is preferred, but bunch lengths of 2–3 ns are considered acceptable. This parameter presents a challenge for the proton driver, as achieving such short bunches is difficult at the proton energies and intensities required for a muon collider.

Proton repetition rate

The maximum proton beam repetition rate is limited by disruption of the Hg-jet target. This was studied by the MERIT experiment [3]. As shown in fig. 3, the target disruption length seen in MERIT was about 22 cm. If the jet velocity is 15 m/s, it takes about 15 ms to recover from the disruption. The nominal repetition rate adopted for a muon collider (see table I) is about 15 Hz, and that for a neutrino factory is 50 Hz. Both are compatible with the limit inferred from the MERIT data.

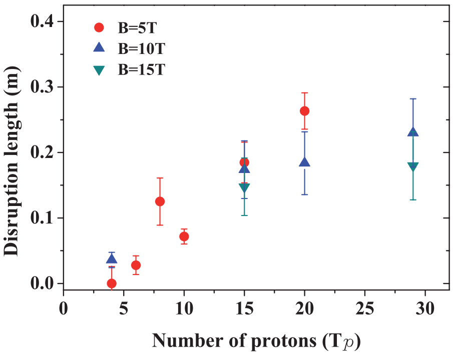

Fig. 3. – Hg target disruption length seen in the MERIT experiment.

The minimum repetition rate is limited by space-charge tune shift in the compressor ring of the proton driver. It may be possible to work around this limit to some degree by accelerating and compressing several bunches and then combining them at the target. The lower the beam energy, the more severe this limitation becomes.

Target, capture, and decay

The target, capture, and decay channel makes use of a free Hg jet contained within a tapered solenoid field, as shown in fig. 4. At the target, the solenoidal field is 20 T, falling to 1.75 T at the end of the decay channel. The channel captures low energy pions, with kinetic energies between 100 and 300 MeV.

Bunching and phase rotation

Beam from the target requires "conditioning" before it can be used in the downstream systems. The conditioning involves a rotation in longitudinal phase space (*i.e.*, trading bunch length for energy spread) and bunching the beam into 201-MHz bunches, as illustrated in the left-hand side of fig. 5. These tasks are accomplished [8] with an RF system similar to that of the cooling channel (discussed below), but having many frequencies (see right-hand side of fig. 5).

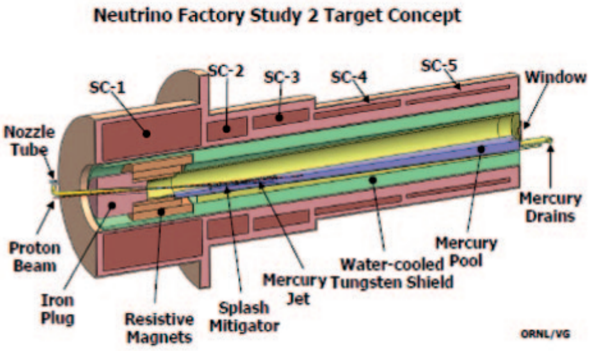

Fig. 4. – Diagram of target area showing initial portion of field taper.

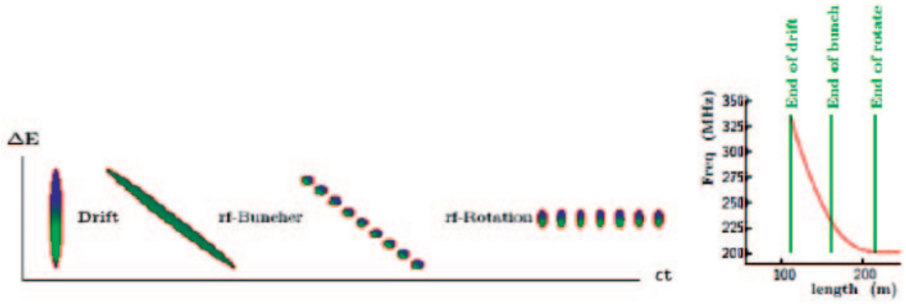

Fig. 5. – (Left) schematic of phase rotation and bunching process; (right) frequencies of RF cavities along the channel.

For a muon collider, only a few bunches are preferred, whereas a neutrino factory can accommodate more bunches. The phase rotation and bunching scheme for the collider is presently being optimized to reduce the number of bunches produced. Ultimately, the muon collider needs only a single bunch of each sign, so an additional bunch-merging operation is envisioned in the cooling channel, as indicated in fig. 2.

Ionization cooling section

This section is one of the most critical in the collider. Transverse cooling is a straightforward process, analogous to synchrotron radiation damping. In ionization cooling, the energy loss mechanism is ionization energy loss ($\mathrm{d}E/dx$) in a low-Z material, which reduces p_x, p_y, and p_z. Restoration of p_z is done with RF cavities. A number of cooling channel implementations have been investigated during the past 10 years. The current baseline design is the so-called Study 2a [9] channel, illustrated in fig. 6. This channel is able to transmit muons of both signs, interleaved at opposite phases of the RF cavities. The actual implementation of such a channel is complicated, due to the proximity of RF cavities, strong solenoids, and absorbers.

For a muon collider, we must also reduce the longitudinal phase space by means of emittance exchange. The process requires creating a dispersive section where there is a correlation between a muon's energy and its position. It is then possible to arrange

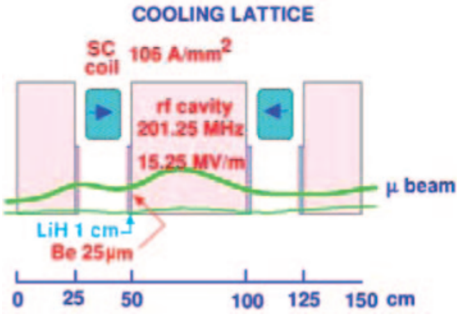

Fig. 6. – Layout of Study 2a transverse cooling channel.

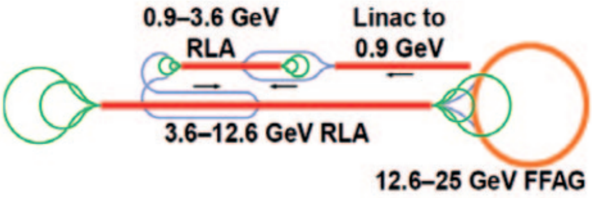

Fig. 7. – Low-energy acceleration system suitable for neutrino factory or muon collider.

for an absorber that provides more energy loss for higher energy particles than for lower energy ones, which reduces the beam energy spread.

Final cooling to an emittance of 25 μm-rad is accomplished in a linear cooling channel using very strong solenoids. Present simulations assume 50 T solenoids, which is, to say the least, on the high end of what is practical. There is no "hard edge" for this parameter, however. Lower field solenoids would work, but at the expense of the maximum luminosity of the collider.

Acceleration section

The low energy acceleration section includes a linac followed by a pair of dog-bone-shaped recirculating linear accelerators (RLAs), as illustrated in fig. 7. This system has been studied extensively [10] as part of the neutrino factory design and is capable of accommodating 30 mm-rad transverse and 150 mm longitudinal emittance, and of transmitting both muon signs.

At higher energies, a different scheme is employed. The baseline design makes use of a pair of rapid cycling synchrotrons [11], the first from 25–400 GeV, and the second from 400–750 GeV. To achieve the fast cycling rate in the lower energy RCS, the magnets must be fabricated from grain-oriented silicon steel. For the higher energy RCS, superconducting magnets are needed, but these cannot cycle rapidly. A hybrid ring has been designed (see fig. 8) with fixed-field superconducting magnets interleaved with silicon steel magnets that ramp from +1.8 T to −1.8 T in order to maintain an orbit with acceptable excursions.

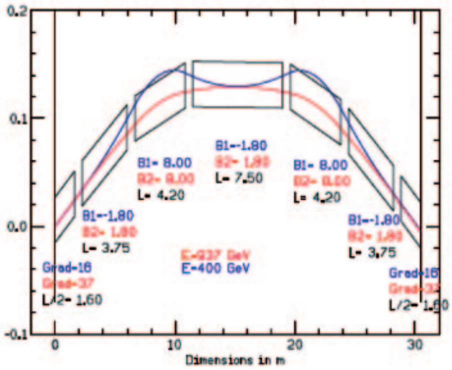

Fig. 8. – Magnet layout and beam orbits for hybrid RCS.

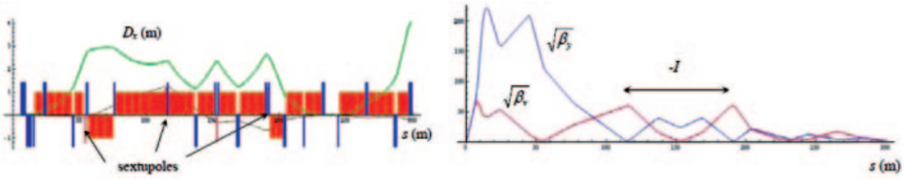

Fig. 9. – (Left) magnet layout and dispersion function for collider interaction region; (right) interaction region beta functions.

Collider ring

A lattice design for a 1.5 TeV collider is under development [12]. At the present time, the bare lattice has a dynamic aperture of 4.7σ and a momentum acceptance of 1.2%. The interaction region layout and optics are shown in fig. 9.

A key design activity is to understand the machine-detector interface. This understanding is needed to determine the ultimate physics capability of the facility and to assess and mitigate the expected backgrounds. A successful collider requires that the detector and its shielding be tightly integrated into the machine design. Help with this task from the experimental particle physics community is sorely needed.

R&D program

As mentioned earlier, a combined R&D program, MAP, has now been put in place to deliver a Design Feasibility Study (DFS) for a muon collider, technology development to support the DFS (including participation in MICE and planning for a future 6D cooling experiment), and the U.S. portion of the neutrino factory Reference Design Report being prepared under the auspices of the International Design Study for a Neutrino Factory (IDS-NF) [13]. A parallel physics and detector study for a muon collider is also being launched.

The muon collider R&D effort includes simulations, technology development, and system tests. Simulation work focuses on design and performance optimizations. Technology development includes RF cavities, magnets, and absorbers; the main focus presently is the development of high-gradient RF cavities that operate in a magnetic field. System tests are major efforts to demonstrate proof-of-principle, typically undertaken by international collaborations; both MERIT (already completed) and MICE fall in this category.

Conclusion

We have described the main features of a muon collider and indicated the scope of the supporting R&D program. A concept for the possible evolution of a muon beam accelerator complex at Fermilab is being discussed. The system would make use of the hoped-for Project X proton driver feeding the existing Recycler and Main Injector, along with a new high-power target facility, to create intense muon beams. These would be used for cooling R&D that would ultimately lead to either a muon collider, a neutrino factory, or possibly both, on the Fermilab site.

R&D toward a muon collider is making steady progress. The MERIT experiment has been completed and MICE is well under way, with all components in production. The muon collider design is also progressing well, with a promising lattice and all of the main subsystems simulated at least partially. Finalizing the system matching details and end-to-end simulations remain to be done. Development of muon based accelerator facilities offers great scientific promise and is a worthy—and challenging—goal to pursue.

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