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Author
Zisman, Michael S.

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PROTON BEAM REQUIREMENTS FOR A NEUTRINO FACTORY AND MUON COLLIDER*

MICHAEL S. ZISMAN

Accelerator & Fusion Research Division, Lawrence Berkeley National Laboratory Berkeley, CA 94720 U.S.A.

Both a Neutrino Factory and a Muon Collider place stringent demands on the proton beam used to generate the desired beam of muons. Here we discuss the advantages and challenges of muon accelerators and the rationale behind the requirements on proton beam energy, intensity, bunch length, and repetition rate. Example proton driver configurations that have been considered in recent years are also briefly indicated.

1. Introduction

Design and performance evaluations for a Neutrino Factory (NF) and a Muon Collider (MC) have been ongoing for more than a decade. In the case of a Neutrino Factory, the effort is fully international and includes the Neutrino Factory and Muon Collider Collaboration (NFMCC) in the U.S., the UK Neutrino Factory group and the EUROnu design study in Europe, and the Japan Neutrino Factory Working Group in Asia.

Here we focus on the requirements such facilities place on the proton beam parameters, including power, energy, bunch length, repetition rate and bunch train structure.

2. Muon Accelerator Advantages

The interest in muon accelerators is based on their ability to address several of the outstanding particle physics questions that require accelerator facilities. In the neutrino sector the neutrinos result from the decays of either μ^+ or μ^- circulating in a decay ring. These decays produce high-energy electron neutrinos or anti-neutrinos. The kinematics of this decay process are well understood, so there are minimal uncertainties in the spectrum and flux. Moreover, the neutrinos are produced at high energies, above the tau threshold.

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Studies [1] indicate that a muon-based NF would have unmatched sensitivity for CP violation, determination of the mass hierarchy, and deviations from unitarity.

At the energy frontier, the fact that the muon is a point particle means that the full beam energy is available for particle production. The heavier mass of the muon compared with that of the electron means that synchrotron radiation is negligible. This allows the use of a circular collider, which makes much more efficient use of the expensive rf equipment, and also nearly eliminates the energy spread at the interaction point arising from beamstrahlung.

3. Muon Beam Challenges

Despite the advantages of muon beams described in Section 2, they are not easily created. There are two main challenges:

1. muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
2. muons have a short lifetime (2.2 μs at rest)

The first issue means that production rates are low. A multi-MW proton source is needed to give the desired number of muons, along with a production target that can handle this power level. Because of the production mechanism, the muons are created with a large beam emittance and a large energy spread. Solenoidal focusing, which operates in both planes simultaneously, is needed to maintain the beam, and emittance cooling is required to produce beam suitable for downstream accelerator systems. Even with such cooling, a large acceptance and rapid acceleration system is needed to bring the muons to the desired energy.

The short lifetime means that all beam manipulations must be rapid, requiring (in the cooling channel) high-gradient rf cavities operating in a strong solenoidal field. In addition, the decay electrons from stored muons in either the NF decay ring or MC collider ring result in a substantial heat load in the mid-plane of the superconducting magnets.

4. Proton Beam Requirements

As indicated in Fig. 1, the present vision is that the NF and MC could share a common front end. For this reason, the NF requirements generally represent those of the MC as well. There are a few differences, however. In particular, a MC prefers a lower repetition rate than does a NF (10–15 Hz compared with ~50 Hz), and the MC prefers a single bunch (or at least a short bunch train), whereas a NF has no a stringent requirement on the bunch train length. Table 1 summarizes the NF proton driver parameters obtained during the ISS [2].

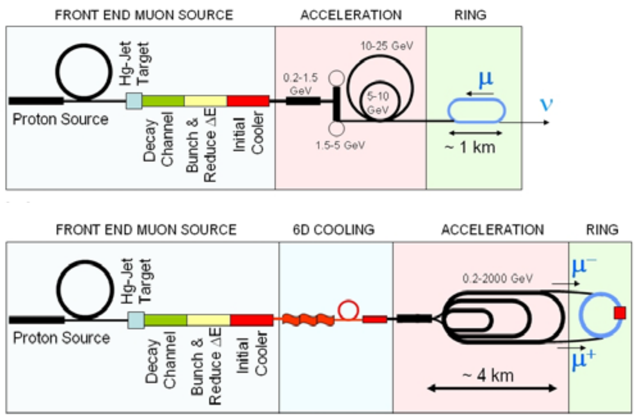

Fig. 1. (top) NF systems (schematic); (bottom) MC systems (schematic). The front end muon source could be the same for both facilities.

Table 1. Proton driver requirements for a Neutrino Factory.

Parameter	Value
Average beam power (MW)	4
Pulse repetition frequency (Hz)	50[a)]
Proton energy (GeV)	10 ± 5
Proton rms bunch length (ns)	2 ± 1
No. of proton bunches	3 or 5
Sequential extraction delay (μs)	≥ 17
Pulse duration, liquid-Hg target (μs)	≤ 40
Pulse duration, solid target (ms)	≥ 20

[a)]For a Muon Collider a lower repetition rate, 10–15 Hz, is required.

For either the MC or NF, the target comprises a free Hg jet within a 20-T solenoid. A tapered series of solenoids brings the field smoothly down to 1.75 T for further transport into the downstream phase rotation and cooling sections. The MERIT experiment [3] serves as a proof-of-principle for the target concept.

4.1. *Beam Energy*

The muons captured by the downstream channel are low energy, with kinetic energies in the range of about 100–300 MeV. Initial studies with MARS14 [2] indicated that the proton energy range for optimal production was 6–11 GeV for

μ^- and 9–19 GeV for μ^+. The ISS adopted 10 ± 5 GeV as the range that represented these results. Below 5 GeV, a steep fall-off in production was predicted. More recent production estimates using MARS15 suggested an even narrower optimum energy range, with a peak at 8 GeV and a fall-off by about a factor of two beyond about 40 GeV. The steep fall-off at low energies remained. At the NuFact09 workshop, Strait [4] looked at the HARP data for particles within the NF/MC energy acceptance in the low-energy regime. As indicated in Fig. 2, the data do not show evidence of the steep fall-off at low energy predicted by MARS.

4.2. *Bunch Length*

When evaluated after the cooling channel, there is a preference for short proton bunches. Below an rms proton bunch length of 1 ns, there is no loss in transmission, whereas a bunch length of 3 ns results in a 10% loss in intensity. For this reason, the ISS [2] and the follow-on IDS-NF [5] adopted an rms bunch length requirement of 2 ± 1 ns, as listed in Table 1. For a linac solution, downstream accumulator and compressor rings would provide this structure.

4.3. *Repetition Rate*

For the baseline Hg-jet target, the maximum repetition rate is limited by disruption of the target material. At high magnetic fields, the disruption length is reduced, and is typically about 0.2 m at the intensities of interest to a NF. For a jet velocity of 15 m/s, the disruption recovers in about 15 ms, which would permit a repetition rate of 70 Hz. Present NF designs call for a repetition rate of about 50 Hz.

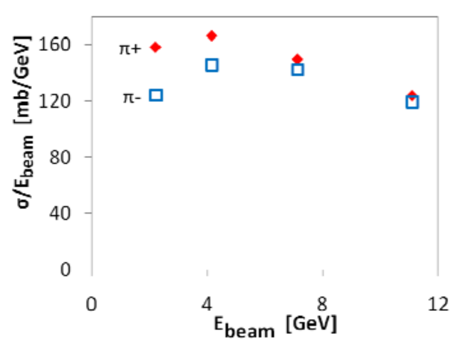

Fig. 2. HARP results in the acceptance of relevance to a NF or MC.

The minimum repetition rate will be limited by the space-charge tune shift in the compressor ring, which will define how short a bunch the ring can deliver. For the MC, where fewer bunches are desirable, it may be necessary to provide a workaround, e.g., using multiple bunches in the compressor ring with separate transport lines that serve as "delay lines" to deliver the separately extracted bunches to the target simultaneously.

4.4. *Bunch Train Length*

As mentioned earlier, the NF does not have a strong constraint on the length of the 201-MHz bunch train, and trains of up to ~70 bunches have been considered. To make the front end more compatible with the MC, Neuffer [6] has developed a shorter bunching and phase rotation section that reduces the bunch train length to ~20 bunches. This is helpful, but will not obviate the need for some form of further bunch merging to obtain a single muon bunch of each charge in the collider ring.

5. Implementation Schemes

There are a number of ways to provide the required proton parameters, and the choice of which approach to adopt is thus a site-specific one.

Rees and Prior [2] have developed a 10 GeV system with a 180 MeV linac followed by a 3-GeV rapid cycling synchrotron and a 10 GeV non-scaling FFAG ring. J-PARC [7] has already successfully commissioned a proton source with a linac followed by two RCS rings, the first providing 3 GeV and the second up to 50 GeV. Fermilab's Project X [8] has considered several different configurations. Their initial configuration was based on an 8 GeV pulsed superconducting linac. Other variants, e.g., an 8 GeV CW linac and a lower energy linac followed by an RCS to reach 8 GeV, have also been explored. A 5 GeV superconducting linac (the SPL [9]) is being discussed at CERN.

6. Summary

As of today, the proton beam requirements for either a NF or a MC are reasonably well understood. These include a beam energy of 5–15 GeV, a beam power of ~4 MW, a bunch length at the target of 1–3 ns, and a repetition rate of 10–50 Hz. These parameters are considered to be achievable, and there are several approaches that should be able to deliver them. Because the requirements for the two types of facility are very similar, it is expected that a single implementation can satisfy either one.

It is worth noting that the facility to house a 4 MW target and beam dump is a substantial one, and requires a significant amount of engineering to develop. Radiation shielding, equipment and air activation, and remote handling and repair are just some of the issues that must be addressed to develop a 4 MW target hall. In practice, it would be prudent to consider designing for even higher beam power to allow for future upgrades.

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