Neutrino Factory Downstream Systems

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Abstract
We describe the Neutrino Factory accelerator systems downstream from the target and capture area. These include the bunching and phase rotation, cooling, acceleration, and decay ring systems. We also briefly discuss the R&D program under way to develop these systems, and indicate areas where help from CERN would be invaluable.

1 Introduction

A muon-based Neutrino Factory (NF) will be a powerful tool for the experimentalists. Design and performance estimates for such a facility have been ongoing for about 10 years. This effort is fully international, and includes The Neutrino Factory and Muon Collider Collaboration in the U.S., the UK Neutrino Factory group and Work Package 3 of the EUROnu Design Study in Europe, and the Japan Neutrino Factory Working Group in Asia.

Here, we will consider the Neutrino Factory systems downstream of the target and capture region, namely the bunching, phase rotation, cooling, acceleration, and decay ring systems. The upstream systems are covered in the paper by Kirk [1].

2 Muon Accelerator Description

2.1 Advantages

Muon-based facilities can address several of the key outstanding particle physics questions that can be addressed with accelerator-based experiments. In the neutrino sector, the neutrino beam is derived from the decays of either μ^+ or μ^- circulating in a decay ring. The kinematics of such decays is well known, and there are minimal hadronic uncertainties in the spectrum and flux. The neutrino beam contains high-energy electron neutrinos, above the τ production threshold, so this channel can be observed in the experiments. Oscillations from $\nu_e \rightarrow \nu_\mu$ give rise to easily detectable "wrong-sign" muons (i.e., muons whose sign is opposite to that of the circulating beam in the decay ring).

At the energy frontier, the fact that the muon is a point particle means that the full beam energy is available for particle production. Moreover, because the muon mass is much greater than that of the electron, a Muon Collider has almost no synchrotron radiation. This results in a narrower energy spread at the interaction point than occurs at an electron–positron collider, and it permits a circular Muon Collider that uses its expensive rf equipment more efficiently and has a small footprint that can fit on an existing laboratory site.

2.2 Challenges

There are two main challenges associated with producing a muon beam:

1) muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$)

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2) muons have a very short lifetime, 2.2 μs at rest

The first challenge results in a low production rate, and thus requires a multi-MW proton source, and a target capable of handling this power. Moreover, the production process gives rise to a beam with a very large energy spread and transverse emittance. This, in turn, means that solenoidal focusing is preferred for the initial portions of the facility (since solenoids focus in both planes simultaneously), that some form of emittance cooling is needed, and that a high-acceptance acceleration system and decay ring are required.

The second challenge means that rapid beam manipulations are mandatory. This implies that the presently untested ionization cooling technique is needed to reduce the beam emittance, which creates a need for high-gradient rf cavities that can operate in a strong solenoidal field. It also implies the need for a rapid acceleration system after the cooling channel. There is an additional aspect of the rapid decay of muons that affects the facility design. Decay electrons emitted by the beam in the muon decay ring create a large heat load in the mid-plane of the superconducting magnets.

2.3 Ingredients of a Neutrino Factory

A NF comprises a number of sections, including the proton driver, the target, capture, and decay section, the bunching and phase rotation section, the cooling section, the acceleration section, and finally the decay ring. Figure 1 shows the layout representing the baseline NF design of the International Design Study of a Neutrino Factory (IDS-NF) [2]. In what follows we describe the downstream systems, starting from the bunching and phase rotation.

2.3.1 Bunching and Phase Rotation

Because the beam from the upstream target and capture section is unsuitable for the downstream accelerators, it must be "conditioned" before it can be transported further. The conditioning involves a rotation in longitudinal phase space to reduce the energy spread and creation of a 201-MHz bunch train suitable for capture in the cooling and acceleration systems to follow. The task is accomplished with a series of rf cavities whose frequencies decrease from about 325 to 201 MHz along the channel in a prescribed way. Optimization of the length and performance of this section is in progress.

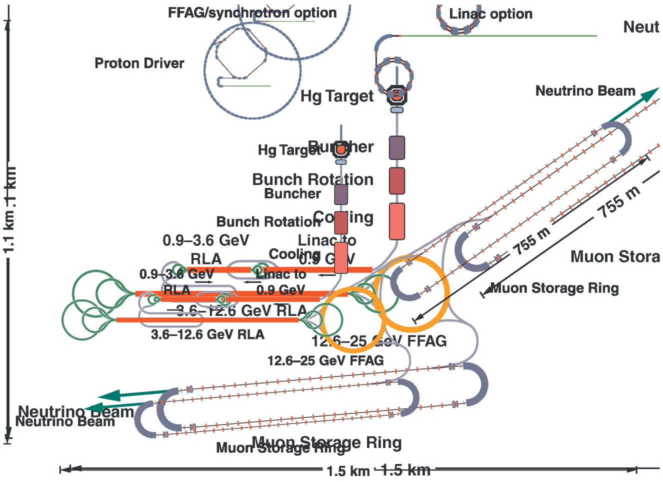

Fig. 1: Schematic layout of NF.

2.3.2 Ionization Cooling

As part of the International Scoping Study of a Neutrino Factory [3], the performance of the various cooling channel designs was compared. As a result of that comparison, the so-called “Feasibility Study 2” (FS2) channel [4] was found to perform the best. When coupled with a proton driver providing 4 MW of 5–15 GeV protons (in 2 ns bunches), this channel, illustrated schematically in Fig. 2, meets the requirement of 10^{21} useful muon decays per 10^7 s year. The channel transmits both muon signs simultaneously, interleaved at different phases of the 201-MHz rf system. It is worth noting that the actual implementation of such a channel, such as that being built for the Muon Ionization Cooling Experiment (MICE) [5], is considerably more complicated than the simple “physicist’s view” illustrated in Fig. 2.

2.3.3 Acceleration

The baseline scheme adopted for the IDS-NF (see Fig. 3) comprises a pre-acceleration linac that increases the beam energy to 0.9 GeV. This is followed by a pair of “dog-bone” Recirculating Linear Accelerators (RLAs) that raise the energy from 0.9–3.6 GeV and from 3.6–12.6 GeV, respectively. The last stage of acceleration, from 12.6–25 GeV, is provided by a non-scaling Fixed-Field, Alternating Gradient (FFAG) ring. Optics for the linac, the RLAs, the required injection chicanes, and the transfer lines have been completed [6].

The last system, the non-scaling FFAG ring, presents several technical challenges. First, there is a strong coupling between the longitudinal and transverse dynamics that is important for the emittance values of interest to a muon FFAG. Different amplitude particles have different flight paths and thus different flight times. The result is that large-amplitude particles slip out of phase with the rf and are not fully accelerated. Using sextupoles to effect a partial chromatic correction has been shown [7] to ameliorate the problem and appears workable.

The second challenge concerns injection and extraction into the densely packed FFAG ring. Progress on this topic has recently been reported by Pasternack [8], though the kicker and septum magnet specifications remain daunting.

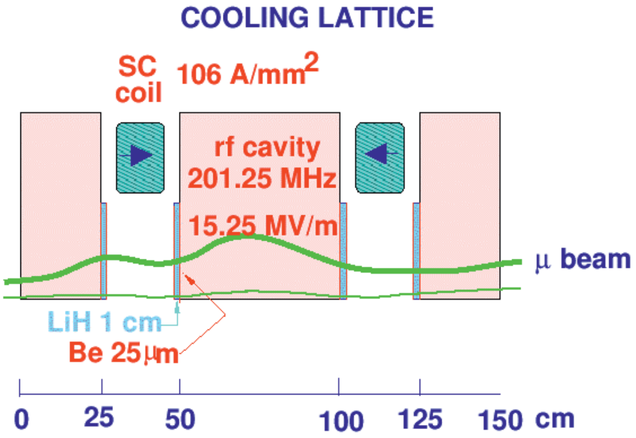

Fig. 2: Schematic of FS2 cooling channel.

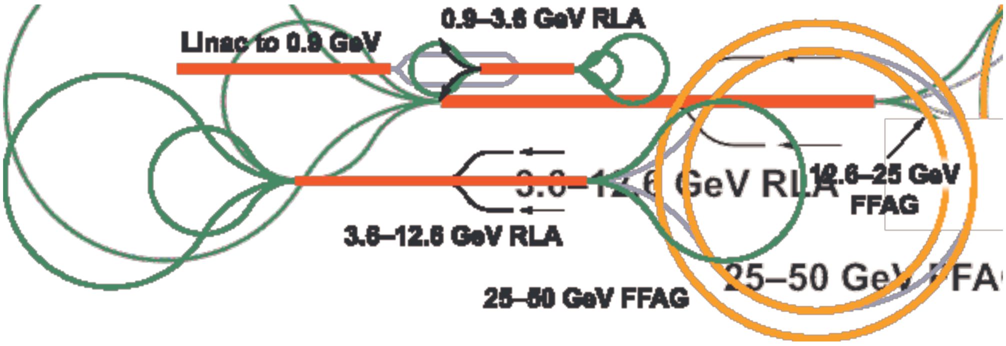

Fig. 3: Schematic of IDS-NF baseline acceleration system.

2.3.3.1 Racetrack Ring

As suggested by the name, a racetrack ring has two long straight section that can be aimed at a single detector site. If there are two baselines, there are two independent rings. The facility could be operated with one muon species in each ring, with the two species interchanged periodically, or it could be operated with both species counter-rotating in each ring. Although it is likely to be more expensive, this configuration is very flexible compared with the triangle case (see Section 2.3.3.2), in the sense that it can be used for two detector sites with no spatial constraints, and can be used with the full beam even if only one detector is operating. For these reasons, it has been adopted as the IDS-NF baseline [2,3].

2.3.3.2 Triangle Ring

In this configuration [3], two rings would be stacked side-by-side in a single tunnel, with one ring storing each muon sign. A typical layout is shown in Fig. 4. Two detectors can be illuminated with interleaved trains of positive and negative muon decay products. In terms of the percentage of circumference available for decays, the triangle ring is somewhat more efficient than the racetrack design. However, its geometry constrains the locations of the two baselines. If the two sites are in the same direction from the ring, or if only a single site is used, the racetrack is preferred.

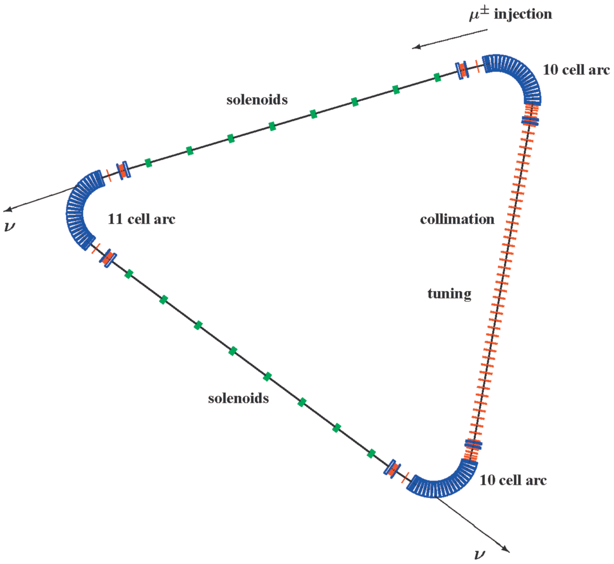

Fig. 4: Schematic of NF triangle ring.

3 R&D Program

A substantial R&D program is now under way to validate the various design choices for a NF. Broadly, the program can be separated into three categories:

- Simulations
- Component Development
- System Tests

This program is being carried out worldwide, managed via loose, but effective, international coordination.

Simulations include studies and optimization of the accelerator design. At present, this activity is being carried out under the auspices of the IDS-NF. Component development includes the development of rf cavities, magnets, and liquid-hydrogen absorbers suitable for use in a NF. The key issue at present is the degradation in maximum gradient observed for room-temperature cavities immersed in a strong axial magnetic field. Finally, system tests involve proof-of-concept tests to validate the overall performance and cost of critical subsystems. Because such tests require substantial resources, they are typically carried out by means of international collaborations.

3.1 Overview of Technical Issues

Each R&D category has its own issues to examine. In the simulations area, the main tasks include optimization of the subsystem designs and eventually end-to-end tracking of the entire facility. For component development, the critical R&D topics include development of normal conducting rf cavities capable of operating in a strong axial magnetic field, development of low-frequency superconducting rf (SRF) cavities, development of fast, wide aperture kicker magnets for the FFAG ring, and development of decay ring magnets that can tolerate the high mid-plane heat load resulting from muon decay electrons. System tests include the recently completed MERcury Intense Target (MERIT) experiment at CERN [9], the Muon Ionization Cooling Experiment (MICE) [5], presently under way at RAL, and the non-scaling FFAG experiment EMMA [10], under way at Daresbury Laboratory. At some future time, a 6D cooling experiment to serve as proof-of-concept for a Muon Collider cooling channel will undoubtedly be carried out.

3.2 IDS-NF

The goal of the IDS-NF program is to deliver, in a 2013 time frame, a Reference Design Report (RDR) for a NF. In the RDR, the physics performance of the facility will be detailed, and the specification of each of the required accelerator, diagnostics, and detector systems will be defined. A cost estimate for the facility described in the RDR will be included in the document. The present baseline NF design shown in Fig. 1 is a result of this design effort. The EU contributes strongly to this effort via its EUROnu design study program.

3.3 Normal Conducting RF

As mentioned earlier, the main challenge for operation of a NF cooling channel (and also the bunching and phase rotation sections) is the operation of rf cavities in a strong solenoidal focusing field. As shown in Ref. [11], for vacuum rf cavities the maximum stable gradient decreases as the magnetic field is increased. Interestingly, an rf cavity filled with high-pressure hydrogen gas shows no such degradation [12]. Present plans call for investigating different materials, such as beryllium, for the vacuum cavities, and measuring the response of a cavity filled with high-pressure hydrogen to an intense beam of ionizing radiation.

3.4 MICE

The MICE experiment [5], now under way at RAL, aims to design, engineer, fabricate, and test with muons, a section of a realistic NF cooling channel. Detailed comparisons with simulation codes will be made to validate the codes as a design tool for an eventual facility. The cooling channel components are being fabricated now, and are already providing information on both the cost and complexity of a muon cooling channel.

3.5 EMMA

EMMA, being fabricated at Daresbury Laboratory in the UK as a primarily UK effort, will test an electron model of a non-scaling FFAG ring. This represents the first test of such a device and will serve to demonstrate the feasibility of the concept. While it is not designed to be a scale model of a muon FFAG, the EMMA ring will serve to investigate longitudinal dynamics, transmission, emittance growth, and the influence of resonances on the beam. As shown in Fig. 5, the components are mostly fabricated and are now being installed. Commissioning is anticipated to commence early in 2010.

4 Possibilities for CERN Participation

There are many areas where expertise from CERN could—and hopefully will—make substantial and necessary contributions to the R&D program outlined in this paper. We list these below:

1. *Target facility design*. CERN staff have experience in making estimates of the shielding needed for a 4-MW target facility. They also have the necessary skills to explore the safety and environmental aspects of the proposed mercury-jet target and beam dump system. Developing a robust target facility design from a safety perspective would greatly benefit from CERN involvement, both in defining the requirements and in preparing a design to satisfy them.
2. *Proton driver design*. The design of this portion of the NF facility is expected to be site dependent. CERN could develop a site-specific design based on the SPL operating at 4 MW with ~2 ns bunches.
3. *Engineering and costing of key components*. CERN engineering staff, especially those completing the LHC project, are world experts in normal conducting and superconducting rf systems, cryogenic systems, superconducting magnets, and fast kicker magnets. All these components are needed for the NF design.

Fig. 5: EMMA accelerator components installed on a girder.

It is worth noting that CERN staff made key contributions to both the NF design and the design of the MICE experiment in the "early days." The intellectual effort provided then is greatly missed and is badly needed.

In the longer term, CERN participation in an international 6D cooling experiment for a MC would be of great value to the scientific community. A Muon Collider is a larger and more complicated facility than a Neutrino Factory, and its construction would surely be carried out as an international endeavor .

5 Summary

R&D toward both a NF and a MC is making steady progress, with strong EU contributions in many areas. MERIT has established the ability of a mercury jet to tolerate 4 MW of protons. MICE is progressing toward a demonstration of muon ionization cooling in a few years, and EMMA will begin commissioning shortly. In order to develop realistic technical designs and their corresponding cost estimates, CERN help in component engineering and cost estimating will be critical. Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—and challenging—goal to pursue. It seems only natural that CERN, representing the premier particle physics laboratory in the world, would play a significant role in such a program.

Acknowledgments

I am grateful for the continued R&D efforts of my colleagues in the Neutrino Factory and Muon Collider Collaboration and the IDS-NF whose work has resulted in the design and R&D progress summarized here.

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