STATUS OF NEUTRINO FACTORY AND MUON COLLIDER R&D†

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Abstract

A significant worldwide R&D effort is presently directed toward solving the technical challenges of producing, cooling, accelerating, storing, and eventually colliding beams of muons. Its primary thrust is toward issues critical to a Neutrino Factory, for which R&D efforts are under way in the U.S., via the Neutrino Factory and Muon Collider Collaboration (MC); in Europe, centered at CERN; and in Japan, at KEK. Under study and experimental development are production targets handling intense proton beams (1–4 MW), phase rotation systems to reduce beam energy spread, cooling channels to reduce transverse beam emittance for the acceleration system, and storage rings where muon decays in a long straight section provide a neutrino beam for a long-baseline (3000 km) experiment. Critical experimental activities include development of very high gradient normal conducting RF (NCRF) and superconducting RF (SCRF) cavities, high-power liquid-hydrogen absorbers, and high-field superconducting solenoids. Components and instrumentation that tolerate the intense decay products of the muon beam are being developed for testing. For a high-luminosity collider, muons must be cooled longitudinally as well as transversely, requiring an emittance exchange scheme. In addition to the experimental R&D effort, sophisticated theoretical and simulation tools are needed for the design. Here, the goals, present status, and future R&D plans in these areas will be described.

1 INTRODUCTION

In the past several years, worldwide interest has developed in the possibility of constructing a Neutrino Factory based on a muon storage ring. In addition to having a strong physics program in its own right, a Neutrino Factory serves as a crucial first step toward a possible Muon Collider. The main "players" in this endeavor are in Japan (KEK and Osaka), in Europe (CERN and RAL), and in the U.S. (as represented by the MC, whose sponsoring institutions are BNL, FNAL, and LBNL).

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Good communication and cooperation exist among the three geographical regions. There is an annual meeting, the "NuFact" workshop, that was held at Lyon ('99), at Monterey ('00), and at Tsukuba ('01), and is scheduled for London in 2002.

Though most of the recent effort has focused on Neutrino Factory R&D topics, the MC has maintained activities aimed at a Muon Collider, such as emittance exchange workshops [1] and a Higgs Factory workshop [2]. Two Neutrino Factory "Feasibility Studies" have been completed by the MC, the first sponsored with FNAL [3] and the second sponsored with BNL [4]. These studies have established that a Neutrino Factory is technically feasible (assuming component specifications are met). They have also pointed out that a scientifically-productive staged approach to a full facility is possible. Over the course of the two studies, the design performance was improved by a factor of six and the cost was reduced by 25% [4], both encouraging trends.

2 NEUTRINO FACTORY INGREDIENTS

Since a Neutrino Factory is not a "standard" accelerator complex, it is worth listing the systems that are needed. The scheme described here is dominated by two features of muon production—the very large transverse emittance and very large momentum spread with which they are created, and their very short lifetime. The systems we employ are (see Fig. 1):

- Proton Driver (to provide primary beam on a production target)
- Target and Capture (to create pions and capture them in a solenoidal channel)
- Phase Rotation (an induction linac or RF channel to exchange ΔE and Δt)
- Cooling (to reduce the transverse beam emittance with ionization cooling)
- Acceleration (to take the beam from 200 MeV to 20–50 GeV)
- Storage Ring (to store muons for about 500 turns in a ring having a long straight section aimed at a detector far away)

For a Muon Collider, the acceleration system must be significantly increased, and the storage ring becomes a collider ring with low β*.

Though this seems like a lot of hardware, it has been shown in the two Feasibility Studies [3,4] that a Neutrino

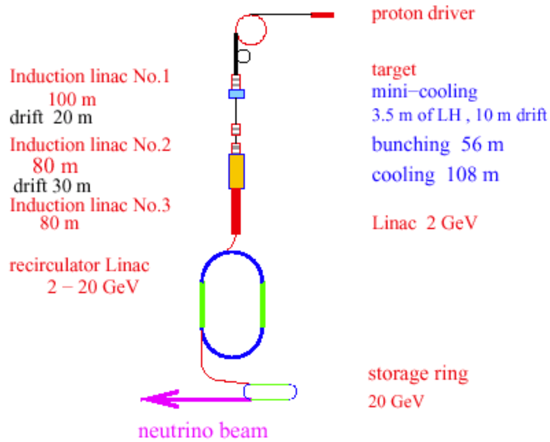

Figure 1: Layout of Neutrino Factory.

Factory footprint is a reasonable size—it would fit easily on either the BNL or FNAL site.

3 R&D PROGRAM OVERVIEW

The R&D program worldwide has several main components:

- Targetry (to demonstrate performance of key concepts, i.e., lifetime, yields, component performance)
- Cooling and Phase Rotation (to demonstrate performance of required components and study cooling effects via experiments, theory, and simulations)
- Acceleration (to demonstrate performance of required components)
- Proton Driver (to develop designs and test required non-standard components)
- Theory and Simulations (to carry out simulations of cooling and to develop theoretical and analytical tools to understand the results)

4 R&D PROGRAM

4.1 Targetry

This year saw the completion of the A3 beamline at BNL and the first beam tests of target samples. Both solid (C) and liquid-metal (Hg) targets were tested [5]. Figure 2 shows a carbon rod mounted in the target box with strain gauges attached. Simulations of the expected pressure waves induced by the beam showed good qualitative agreement with measured results. A mercury trough and a jet target were also tested. Though the Hg is dispersed by the beam pulse, measured droplet velocities are consistent with predictions, an encouraging result. The interaction of the Hg jet with a magnetic field was also tested in a 13-T magnet at Grenoble. The field had the effect of damping some of the jet surface instability. Ultimately, a pulsed 20-T magnet will be added to the setup in the A3 line to study its effects under realistic conditions.

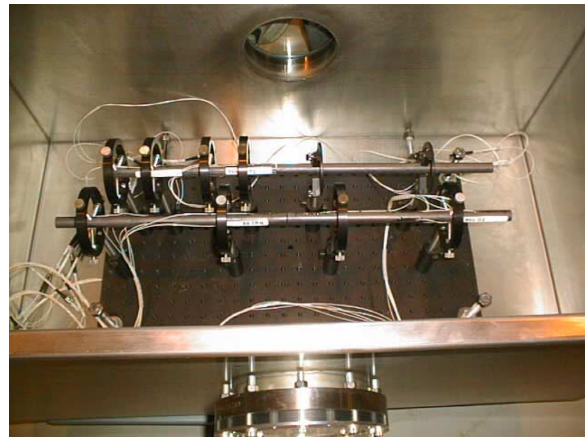

Figure 2: Carbon target rod mounted in E951 target box.

In addition to the standard target configurations, studies are being done on more novel configurations that might serve as initial implementations, such as a rotating band target [6] or a granular target of Ta pellets [7].

4.2 Cooling and Phase Rotation

There are two approaches to phase rotation that are being studied. In the U.S. scheme, a series of three induction linacs, separated by drifts, is used to perform non-distorting phase rotation [4]. The transport line includes internal 1.25-T superconducting solenoids to maintain the optics. The configuration employed is illustrated in Fig. 3. The European scheme uses high-gradient low-frequency RF cavities to accomplish the same thing. Prototypes of both systems will be fabricated.

Ionization cooling, while conceptually straightforward, places difficult demands on component performance. A cooling channel is simply a series of absorbers

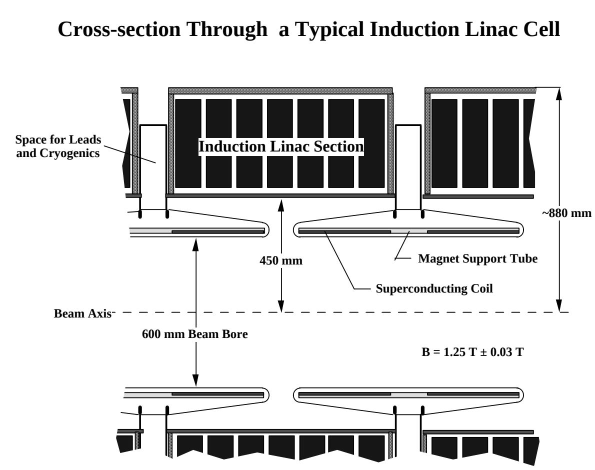

Figure 3: Cross section through induction linac cell.

interspersed with high-gradient normal-conducting RF cavities. Muons lose energy in the absorbers by *dE/dx* and the cavities restore only the longitudinal component, thus reducing the transverse emittance. (The cooling process is analogous to the synchrotron radiation damping process in an electron storage ring—only the energy loss process is different.) Analogous to the quantum excitation of synchrotron radiation, ionization cooling has a "heating" effect as well: multiple scattering in the absorbers. To mitigate this, we use strong solenoids to create a small beta function (hence large beam divergence) at the absorber, and we use a low-*Z* absorber material, LH_2.

Here too, the different groups are studying different implementations. In the European scheme, RF cavities of 44 and 88 MHz are employed. Due to their large physical size, the solenoids are placed on the bore tube of the specially designed cavities, as shown in Fig. 4. The MC scheme [4] is based on 201.25-MHz RF cavities, whose iris is closed with thin Be foils (a grid of thin tubes is also being investigated). In this case, the cavity dimensions are small enough that solenoid coils can fit outside the cavity, as shown in Fig. 5.

The MC R&D program has begun with tests of 805-MHz components. These can be viewed as quarter-scale models of the 201.25-MHz devices, or alternatively as components for a later Muon Collider. The Lab G test area at FNAL is now operational, and the first cavity, an open-cell design, is being processed now to test its gradient limits [8]. A second test cavity, having Be windows, is presently being tuned to its final frequency, and will be tested in Lab G later this summer. Low-power tests of window deflection have given encouraging results thus far [9].

The MC has plans for testing LH_2 absorbers at FNAL this year [10]. Two designs are being studied, one with an external heat exchanger, and the other with an internal heat exchanger. The latter is being designed together with KEK, using U.S.-Japan funds. The aluminum windows required for the absorbers must be very thin. A prototype window with an integral flange has been successfully machined from a solid block of material, and has achieved

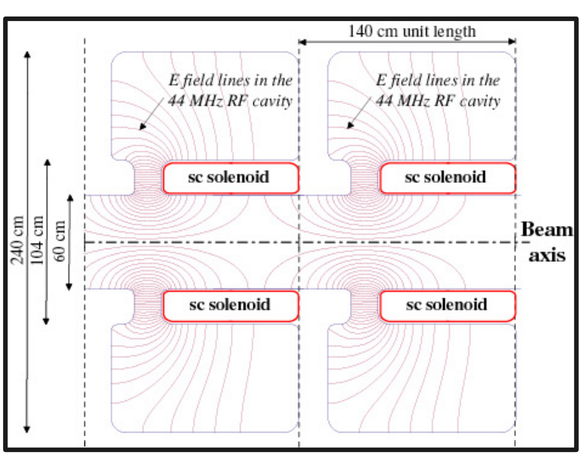

Figure 4: CERN RF cavity solenoid layout.

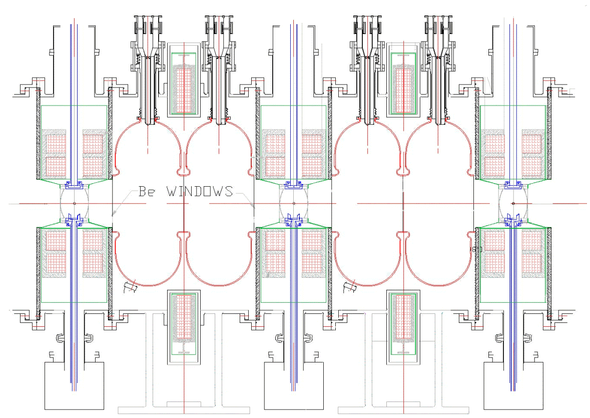

Figure 5: Lattice 2 cooling cell layout for MC scheme.

its desired profile and a minimum thickness of 125 μm.

A new area, at the end of the FNAL proton linac, is being readied for testing absorbers. The linac test area will have access to a high-power 201.25-MHz RF source, so the prototype cavity, when ready next year, will be tested there. The test area will ultimately have access to a beam of 400 MeV protons for beam tests of cooling channel components.

At CERN, an 88-MHz cavity (see Fig. 6) is being readied for high-power testing. Plans call for reaching 4 MV/m (with no associated solenoid) this year; testing with a solenoid is anticipated about a year from now.

The Japanese scheme uses large acceptance Fixed-Field Alternating Gradient (FFAG) rings to capture and accelerate the muon beam, thus bypassing the need for cooling. This approach has potential merit for a Neutrino Factory, though it is less obvious how to extrapolate it to the requirements of a Muon Collider.

In addition to the component R&D described above, there is an experiment on muon multiple scattering "MUSCAT" being carried out at TRIUMF [11]. This experiment is mainly a European initiative, though some MC members are involved. Results from an engineering

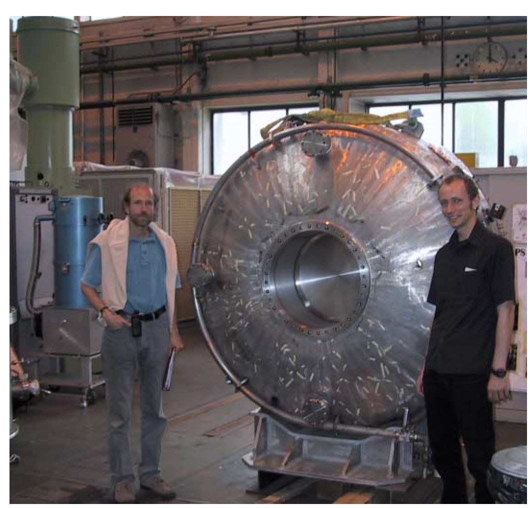

Figure 6: CERN 88 MHz test cavity.

run on a Be target were encouraging, and plans for testing LH_2 are well along.

At a more preliminary stage are plans to mount a Cooling Demonstration Experiment. This international effort is being organized by a Steering Committee having members from all three geographical regions. The aim of the experiment is twofold:

- to show that we can design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
- to place it in a muon beam and measure its performance, i.e., validate that it performs as predicted by simulations

The intention of the Steering Committee is to make the key technical decisions by December 2001, to prepare a complete proposal by June 2002, and to commence the experiment in 2004. The success of this endeavor will clearly give a great boost to the fortunes of a Neutrino Factory proposal somewhere in the world.

4.3 Acceleration

The main hardware activity of the MC in this area is to develop a high-gradient SCRF cavity at 201.25-MHz [12]. Cornell is leading the design effort, and CERN is in the process of fabricating a cavity of the Cornell design for testing. Design specifications for this cavity call for a gradient of 15–17 MV/m.

As mentioned earlier, the KEK approach to a Neutrino Factory is based on using a cascaded series of FFAG rings. A proof-of-principle FFAG has been successfully operated and there are plans to build a 150 MeV ring. There are many attractive features to this approach, most notably the large transverse and longitudinal acceptance of an FFAG. The difficulties with injection and extraction, and the need for high-gradient RF systems at very low frequency are the R&D challenges.

4.4 Proton Driver

The most intensive effort on Proton Driver R&D is taking place at CERN. They have adopted a novel scheme based on a 2.2 GeV superconducting proton linac that will provide a 4-MW proton beam. One motivation for this approach is the availability of all of the SCRF cavities released when LEP was decommissioned. In addition to its benefit to a future Neutrino Factory, such a powerful proton beam would help the programs at LHC, CNGS, and ISOLDE.

The European activities on the Proton Driver include chopper and RFQ development, beam dynamics studies, and SCRF development needed to accommodate the low-velocity beam (β = 0.5–0.8, as opposed to the fully relativistic beams for which the LEP cavities were optimized). A prototype cavity designed for $\beta = 0.7$ is shown in Fig. 7. Because the linac will operate at 50 Hz, it was necessary to verify that the cw LEP power source could handle pulsed operation. This has already been successfully demonstrated.

In the U.S., both FNAL and BNL have plans for a high-power (1–4 MW) Proton Driver. In the former case, a new rapid-cycling booster synchrotron has been designed, and in the latter case plans exist for upgrading the existing AGS complex. R&D on a high-gradient low frequency (0.5–1 MV/m at 7.5 MHz) cavity loaded with Finemet is planned.

4.5 Production Experiments

One R&D task that should not be ignored is the validation of the particle production codes, e.g., MARS [13], used for predicting Neutrino Factory target performance. This is particularly true for the CERN case, since the proton beam energy, 2.2 GeV, is relatively low. With this in mind, the HARP experiment has been mounted at CERN to measure particle yields over a range of beam energies from 2–16 GeV. The experiment will study various target materials and thicknesses to optimize a target configuration for physics experiments.

A corresponding experiment, E907, has been approved at FNAL with similar goals but focusing on the higher energies appropriate to the FNAL Proton Driver or AGS specifications.

Figure 7: Prototype cavity optimized for $\beta = 0.7$.

4.6 Beam Simulations and Theory

The activity here focuses on several aspects:

- carrying out complete end-to-end simulations, including error effects
- developing analytic tools for understanding front-end performance
- developing concepts for emittance exchange (longitudinal → transverse)

Considerable progress has been made in the past few years, as evidenced by the performance increases between Study-I and Study-II. There is ongoing effort to improve the performance/cost ratio for a Neutrino Factory, for example by exploring alternative phase rotation methods that could avoid the induction linacs, or examining the consequences of using a higher frequency RF system in the cooling channel.

Studies of emittance exchange are ongoing. A workshop on this topic was held in September 2000 at BNL [1]. A second workshop is scheduled for October 2001 at LBNL. One concept that has attracted interest is the cooling ring suggested by Balbekov [14], which would provide 6D cooling if a practical implementation scheme can be arrived at.

5 SUMMARY

In this paper we have described the many R&D activities under way in support of designing a Neutrino Factory, and ultimately a Muon Collider. The worldwide program is vigorous and healthy and is truly international in scope. It is interesting to note that this activity is really a grass-roots effort of both particle and accelerator physicists. Considerable progress has been made in the past few years, and the next few years will provide many new results if the funding to pursue the planned activities is forthcoming.

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