STATUS OF NEUTRION FACTORY DESIGN AND R&D*

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Abstract

Neutrino physics has become increasingly interesting to the high-energy physics community, as it may provide clues to new physics beyond the standard model. The physics potential of a Neutrino Factory—a facility to produce high-energy, high-intensity, high-brightness neutrino beams from decays of muons stored in a muon storage ring—is thus very high. There has been a global R&D effort aimed at a Neutrino Factory design that meets the physics requirements and addresses the key technologies, such as targetry, muon ionization cooling and acceleration. Tremendous progress has been made in the past few years in many aspects of accelerator technology. In this paper, we will review recent worldwide progress toward a cost-effective Neutrino Factory design, with emphasis on the associated R&D programs under the auspices of the U.S. Neutrino Factory and Muon Collider Collaboration [1].

INTRODUCTION

Neutrino physics has become increasely interesting to the high-energy-physics community, as it may provide clues to new physics beyond the standard model. A neutrino factory producing high intensity neutrinos would help to provide more precise information on neutrino oscillation parameters, examining the three-flavor mixing framework and leptonic CP violation.

A neutrino factory requires a high intensity proton beam in the energy range of 2–50 GeV. The proton beam impinges on a target of high-*Z* material. Collisions between the proton beam and the target nuclei produce a secondary pion beam that quickly decays into muons. Muons have a lifetime of ~2.2 μs and thus must be conditioned quickly before they can be injected into an accelerator. A neutrino factory is used to condition the muon beam, accelerate it rapidly to the desired energy of a few tens of GeV, and store it in a decay ring having a long straight secion oriented such that decay neutrinos produced there will hit a detector located thousands of kilometers away from the source.

A generic neutrion factory comprises a proton driver, a target followed by drift, bunching, phase rotation and cooling sections. After rapid accelerations with super-conducting recirculating linacs and FFAG (Fixed Field Alternating Gradient) rings, the muon beam is injected into a decay ring with long straight sections. Figure 1 shows a neutrino factory layout studied by the US Neutrino Factory and Muon Collider Collaboration (MC).

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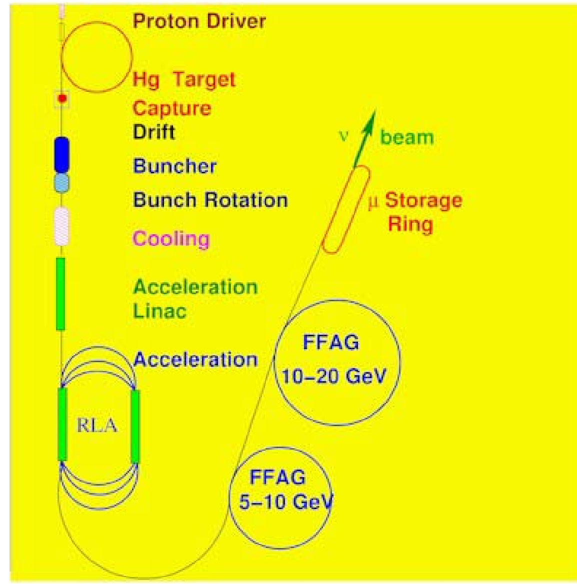

Figure 1: Layout of a generic neutrino factory studied by the MC.

Tremendous progress has been made in past years on neutrino factory design and R&D in the US. This is documented in the US feasibility studies (FS) I, II and IIa hosted by Fermilab and Brookhaven National Laboratory, respectively. FS-IIa, for instance, has kept the same performance with significant cost savings. International collaboration has been an essential part of the NF studies and has been proven to be very effective and efficient. The US R&D programs are enchanced significantly by correcponding programs in Europe and Japan.

This report focuses mainly on neutrino factory R&D actvities in the US under the auspices of the MC. The R&D activities and US responsibility for the international Muon Ionization Cooling Experiment (MICE) will be presented at the end.

R&D PROGRAMS

R&D programs are planned and coordinated through the MC. Due to a limited budget, we focus on the key technology challenges and physics issues related to multi-MW targets and intense muon beams. In addition to numerical design studies and necessary code development, we also develop and build critical hardware components for muon cooling.

Targetry

The production target is one of the key components for the realization of a neutrino factory. In order to produce intense muon beams (decayed from pions), a multi-MW target is needed. But, there is no proven target technology available yet to satisfy this requirement. There has been a

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worldwide R&D effort on developing targets that can withstand up to 4 MW power needed for a neutrino factory. Significant progress has been made on studies for both solid and liquid-mercury jet targets in the last few years [2].

Recent progress and studies include experimental studies on window material qualifications for intense proton beams and carbon target sublimation in a helium atmosphere. It was found that a carbon-carbon composite having a nearly zero coefficient of thermal expansion is largely immune to beam-induced pressure waves. A carbon target in a helium atmosphere is expected to have much lower sublimation loss, and this is being tested via an experiment program under way at ORNL. Radiation damage may be a limiting factor for a carbon target; the predicted lifetime is about 12 weeks when bombarded with a 1 MW proton beam. Reports on these studies can be found in [3].

Liquid targets, however, have potential for extension up to 4 MW, but there are many key issues regarding jet dynamics in a high field solenoid that need to be further studied. Experimental study at the AGS with about 2×10^{12} ppp showed that a mercury jet is not dispersed until long after the beam pulse has passed through the target, as shown in Figure 2. Experimental results compare favourably with simulation estimates.

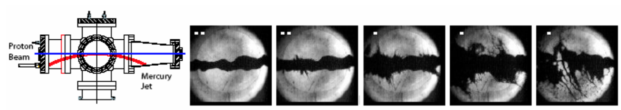

Figure 2: Disruption of a mercury jet hit with the AGS proton beam bunch containing ~ 2×10^{12} protons. Frames from left to right correspond to time steps of 0, 0.75, 2, 7, and 18 ms, respectively.

Development of a fast jet at the speed of ~ 20 m/s and testing it in a 15 T solenoid are in progress. A proposal was submitted in April 2004 to the ISOLDE and Neutrino Time-of-Flight Experiments Committee at CERN for studies of a mercury jet target system for 4 MW and 24 GeV proton beam. Participating institutions include RAL, CERN, KEK, BNL, ORNL and Princeton University. This proposal was approved in April 2005. We plan to start the target experiment in 2007. A cost-effective magnet design, a pulsed solenoid that is capable of providing up to 15 T field has been developed and construction is under way. Figure 3 shows the design for this target magnet and Figures 4 and 5 are photos taken recently during the construction phase of the coil and cryostat pressure vessel for the solenoid. To complement the experimental program, target simulation efforts are ongoing. These aim at a sufficiently detailed understanding of the processes involved to reproduce the observed experimental results both with and without a magnetic field. Fully three dimensional magneto-hydrodynamics codes are being utilized for this effort. Preliminary simulation results compare well with experimental observations.

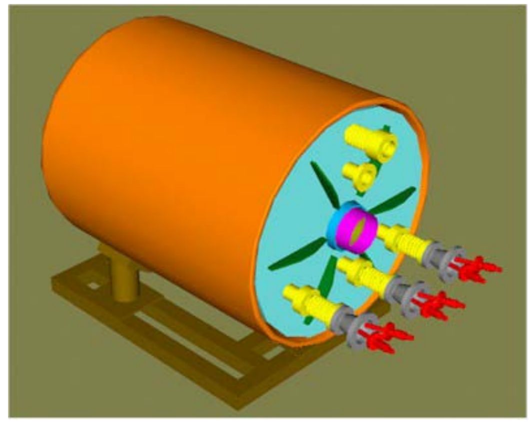

Figure 3: Design of the pulsed targetry magnet. The magnet has three nested coils that permit operation at 5, 10, and 15 T field. The magnet has a 15 cm warm bore and 1 m long beam pipe. The coils are normal conducting but cooled to liquid-nitrogen temperature to ease the requirements on the power supply.

Figure 4: Targetry magnet coils during construction phase.

Figure 5: Cryostat pressure vessel for the targetry magnet.

MUCOOL R&D Program

We have been actively pursuing hardware R&D for muon ionization cooling for years. Current programs include experimental RF studies at 805 MHz; 201 MHz prototype cavity design, fabrication and tests; absorbers and superconducting magnets. We have completed the construction of the MUCOOL Test Area (MTA), a facility for testing all hardware components of a muon cooling channel at Fermilab, but not for testing of the ionization cooling. The MTA, located at the end of the Fermilab proton linac, is designed to eventually permit beam tests of components and detectors with 400 MeV protons. Both the RF and absorber experimental programs have been moved to the MTA, RF transmission lines and a 5-T superconducting magnet are in place. Experimental RF studies using the 805 MHz and 201 MHz cavity will resume soon. Figure 6 shows the superconducting magnet and RF transmission lines in the MTA.

Figure 6: The 5-T superconducting magnet (left) and 805 and 201 MHz RF transmission lines (right) at the MTA.

Normal Conducting RF Cavity R&D

Muon cooling channels require the highest possible accelerating gradient RF cavities. These cavities are immersed in high magnetic fields needed to confine the muons. Therefore, superconducting RF is precluded. The technical challenge for an RF cavity for muon cooling is to design a cavity with high shunt impedance and operate it at the highest possible gradient in a few-Tesla magnetic field. Cooling channels for a nominal neutrino factory require accelerating gradients ~ 17 MV/m. At 201 MHz, this has not been previously achieved in such a high magnetic field. Experimental studies have indicated that peak surface field on the cavity has been a limiting effect for normal conducting cavities in terms of achieving higher accelerating gradient. To minimize the peak surface field while maintaining high shunt impedance, we have chosen a cavity design with thin beryllium (Be) foils ("windows") to terminate the conventional open beam irises by taking advantage of the muon's penetration property. The Be windows provide a nearly perfectly conducting boundary condition to RF fields while being almost transparent to muons. The cavity then resembles a closed pillbox cavity. Each cavity phase then can be adjusted independently. Initial experimental studies have been conducted at 805 MHz. An 805-MHz 6-cell open-iris structure, a pillbox cavity at 805 MHz, and a 5 T superconducting solenoid were built to study how to condition and operate these RF structures in magnetic fields. The RF structures were placed inside the warm bore of the 5-T superconducting magnet. Dark currents, x-rays and breakdown events were measured during the conditioning and operation. The accelerating gradient specified for this cavity is 30 MV/m (red line in Figure 7). We achieved 40 MV/m easily without magnetic field. In the case with the external magnetic field, we found that Be windows with a TiN-coated surface did help to suppress multipacting and were able to withstand high accelerating field without suffering surface damage. However, copper particles were found to be sputtered over the Be surface suggesting that stronger materials (than copper) or coatings on the cavity copper surface in high field areas may help. Figure 7 summarizes our experimental studies on the closed pillbox cavity. With magnetic fields, the achievable gradient decreases significantly and is a function of the magnetic field.

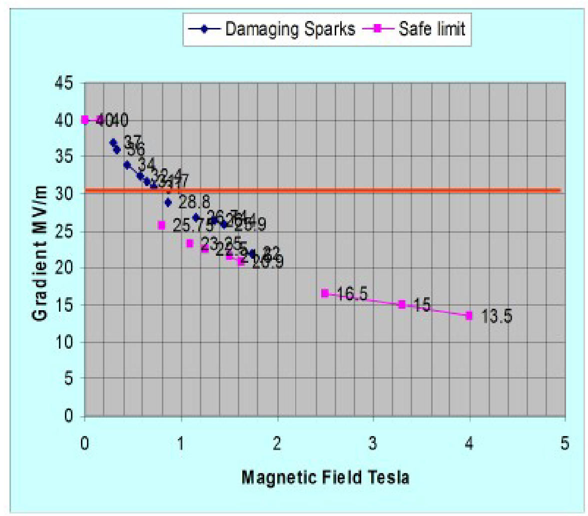

Figure 7: Experimental results of the achievable accelerating gradients for the 805-MHz pillbox cavity are plotted as a function of external magnetic field.

The 805 MHz pillbox cavity is designed to accommodate demountable windows. Tests of different window materials and coatings using this cavity are under way. More recently we modified the cavity by adding a button at the center of the window to enhance peak surface field. This allows us to study different button materials and coatings more efficiently at higher fields. In addition, we have successfully designed and fabricated two curved Be windows for the 805-MHz cavity. The curved Be windows are expected to be better than pre-tensioned windows. They are thinner, mechanically stronger, and less expensive. Two curved windows are oriented in the same direction in the cavity to minimize frequency shifts resulting from window deflection under RF heating [4].

201 MHz Prototype Cavity

We started 201-MHz cavity fabrication two years ago after optimizing the cavity geometry based on experimental study experience with the 805 MHz cavity. The optimization was mainly to minimize peak surface

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field of the cavity while facilitating the fabrication process. The cavity is nearly complete now (see Figure 8).

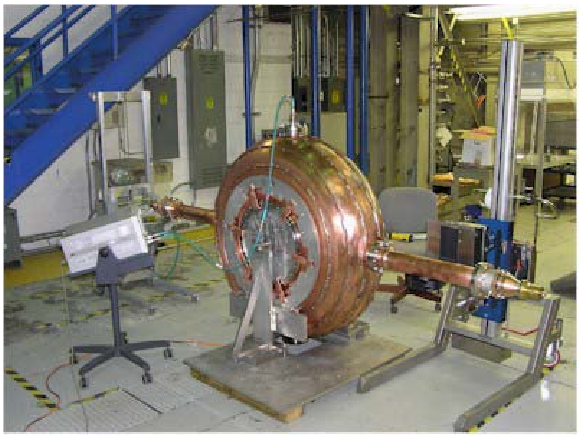

Figure 8: The 201 MHz prototype cavity with two RF couplers attached during a low power microwave measurement conducted at Jlab in March 2005.

The cavity body was e-beam welded together at the equator from two half shells formed by spinning from 6-mm copper sheets. There are four ~ 4-in. diameter ports on the equator for RF couplers, probes, and vacuum, respectively. We have developed a technique and succeeded in extruding these ports through the e-beam joints on the equator. Water cooling lines are TIG brazed to the cavity body [5]. The cavity open beam irises are terminated by curved Be windows of 420 mm diameter and 0.38 mm thickness. Figure 9 shows the first successful curved Be window with this size made by Brush-Wellman Company in California.

Figure 9: A 420 mm diameter and 0.38 mm thick curved beryllium window made by Brush Wellman Company.

We chose loop RF couplers (at critical coupling) for the cavity. The coupler design and fabrication have been completed. Ceramic RF windows (donated from Toshiba Company and designed for the 805-MHz SNS linac) are incorporated in the coupler design. The couplers are now at ORNL for high power conditioning and have reached 650 kW in travelling wave mode.

The cavity is currently at Jlab for electro polishing before shipping to the MTA in Fermilab for RF tests this summer.

Absorbers

The absorber R&D programs continue to make excellent technical progress. Liquid hydrogen is an excellent absorber for muon ionization cooling. However, it implies engineering complexity regarding the safe use of liquid hydrogen. In addition to the successful development of new thin absorber windows to contain liquid hydrogen, we have passed a safety review and were approved to fill the first absorber with liquid hydrogen at the MTA in July 2004. We have succeeded in filling the absorber with liquid hydrogen safely, demonstrated stable operation and measured the LH_2 temperature distribution in the absorber. We also measured the cooling capability with a G-He heater to a maximum of 23 W. Figure 10 shows the absorber and its cryostat.

Figure 10: The KEK LH_2 absorber and its cryostat in the MTA at Fermilab.

Acceleration

The hardware R&D program for acceleration focuses on design, construction and testing of a 201-MHz super-conducting cavity at Cornell University. The cavity was made at CERN by sputtering Nb onto a copper cavity body. We have achieved 11 MV/m (15 MV/m is the goal). Q_0 is ~ 10^{10} at low field, but decreases significantly at high field, as shown in Figure 11.

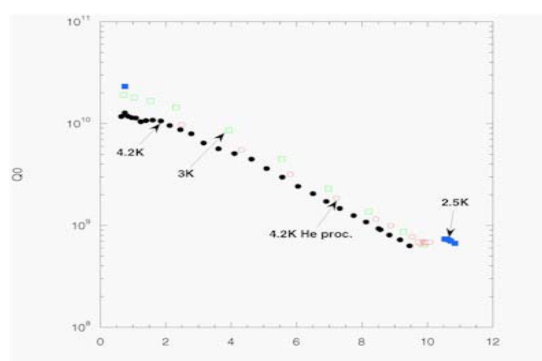

Figure 11: *Q* value deteriorates as the increase of accelerating gradients

This steeper than expected *Q*-slope is called *Q* disease, and is being studied now. Recent measurement shows the cavity performance is not affected by external magnetic field when H_{ext} <1200 Oe. We have incorporated the *Q*-slope study into a 500 MHz cavity program. Our goal is to understand and develop coating and cleaning techniques that can reduce or eliminate the *Q*-slope. We will explore cyclotron resonance coating R&D with Jlab.

Simulations

Simulation efforts are focused on intense muon beam dynamics and defining a cost effective front-end for a neutrino factory or muon collider. Simulations on FFAG and cooler ring dynamics continue. Simulation efforts also support experimental targetry programs and MICE. We continue our efforts in developing and maintaining the ICOOL code to meet the increasing simulation needs. Good agreement has been achieved between ICOOL and Geant simulations. We have made considerable progress in simplifying front-end systems while maintaining performance [6]. This includes:

- developing an RF bunching and phase rotation scheme
- developing a simplified cooling channel
- studying an FFAG scheme for final acceleration stages

As a result, the recently completed Feasibility Study (FS)-IIa for a neutrino factory has reduced the cost by 30–40% compared with FS-II. The savings break-down is summarized in Table 1.

Table 1: Cost savings in FS-IIa compared with FS-II (PD stands for proton driver and Tgt for target).

	All (M$)	No PD (M$)	No PD + Tgt (M$)
FS-II	1832	1641	1538
FS-IIa scaled (%)	67	63	60

MICE ACTIVITY

A muon ionization cooling channel is an essential component for a neutrino factory. There has to date been no experimental demonstration of muon ionization cooling. MICE is a proposed international muon cooling demonstration experiment hosted by RAL [4]. It is an important step toward the realization of a neutrino factory. Designing, building, commissioning and operating a realistic section of cooling channel and measuring its performance in various operational modes and beam conditions will allow a neutrino factory complex to be optimized. MICE has received scientific approval and funding from the UK government. Significant technical progress has been made in every aspect of MICE. Figure 12 shows the layout of the MICE cooling channel.

The MC is heavily involved in MICE; we are responsible for two RFCC modules, and windows for three absorbers. We have recently taken on the additional responsibility of providing the two spectrometer solenoids. We are working closely with UK colleagues on hardware development, instrumentation, and system integration for MICE. Component developments within MUCOOL are directly applicable to MICE.

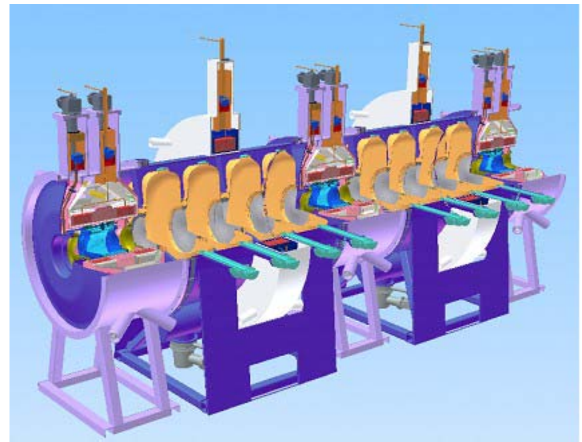

Figure 12: MICE cooling channel layout. There are two RF cavity and coupling coil (RFCC) modules and three absorber and focusing coil (AFC) modules.

SUMMARY AND R&D PLANS

We continue making excellent technical progress on all muon beam R&D activities in the US. International collaboration has played an important role in the R&D programs for a neutrino factory. It has been effective and efficient. We will continue hardware development programs and carry out the US responsibility for MICE. We will complete the required hardware fabrication for the CERN targetry experiment and resume the normal conducting RF test programs at the MTA for both 805 MHz and 201 MHz cavities. R&D for superconducting cavities for acceleration will focus on understanding the *Q*-slope and developing new or improved surface coating techniques. Using the tools developed by the MC, we will help launch and participate in the International Neutrino Factory Scoping Study [7].

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