

Neutrino Factory R&D in the U.S.

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Abstract. We report here on the technical progress and R&D plans of the U.S. Neutrino Factory and Muon Collider Collaboration. Programs in targetry, cooling, acceleration, and simulations are covered. U.S. activities in support of the international Muon Ionization Cooling Experiment (MICE) are also described.

INTRODUCTION

An R&D program aimed at the production, acceleration, and storage of intense muon beams is under way in the U.S. under the auspices of the Neutrino Factory and Muon Collider Collaboration (MC). This program is supported from several sources, including the U.S. Department of Energy, the National Science Foundation, and the State of Illinois Board of Higher Education. The program described here is both complemented and enhanced by the corresponding R&D programs carried out in Europe and Japan.

The MC is attacking the R&D issues associated with intense muon beams on a broad front. This paper describes current activities and plans in the areas of targetry, cooling, acceleration, and simulations, along with an update on the effort aimed at preparing for MICE [1].

R&D PROGRAM PROGRESS

Targetry

There has been a great deal of progress in the targetry program over the last several years. Initial beam tests of both solid and liquid targets were completed at the AGS, using a 24 GeV extracted proton beam. These tests were done at a typical intensity of about 4×10^{12} protons per pulse (compared with a design intensity of 1.6×10^{13} protons per pulse). Results of this work have been reported previously [2] and will not

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be covered here. Unfortunately, we are unable to get beam time in 2003 or 2004—a major impediment to rapid progress in this area.

We have continued tests of carbon target sublimation rates at ORNL. Earlier tests in vacuum indicated a target lifetime of the order of one month at a beam power of 1.5 MW [3]. We are preparing the apparatus required to repeat these tests in a helium atmosphere. It is expected that the presence of helium will reduce the sublimation rate, thereby giving a longer target lifetime at a given beam power. Whether this will extend the operating range of a carbon target up to 4 MW remains to be seen.

Other tests to determine the properties of candidate solid-target materials have also been carried out at BNL [4]. Samples of Super-Invar and Inconel were irradiated with a 200 MeV proton beam, after which we looked for changes in mechanical properties (tensile strength and coefficient of thermal expansion, CTE). Comparison of the CTE changes of the two materials is shown in Fig. 1. Although Super-Invar has a low CTE prior to irradiation, the CTE increases by a factor of about five after irradiation. Inconel has an initially higher CTE, but shows little sensitivity to radiation dose.

To improve our knowledge of target behavior with a high intensity beam, we are carrying out bunch-merging tests at the AGS. Figure 2 shows a longitudinal profile of the beam during the bunch-merging process. Two bunches from an $h = 12$ rf system are transferred to an $h = 6$ system. To date, we have demonstrated an extracted bunch intensity of 1×10^{13} protons per pulse. In Fig. 2 there are clearly visible residual oscillations after the bunches merge, so there is work remaining to optimize the process. Nonetheless, the technique is clearly workable and shows good potential for delivering the required intensity of 1.6×10^{13} protons per pulse.

Open questions for the Hg-jet target concept include:

- Injection of the jet into a 20-T solenoidal field
- Nonlinear dynamics of the jet at full proton intensity

To address these issues, the MC has undertaken a number of R&D activities. We have designed a test magnet that can operate at a field level up to about 15 T, we are designing a Hg-jet system capable of providing the required 20–30 m/s jet velocity, and we are continuing our simulation effort to predict and interpret the effects we observe experimentally. An engineering study of the proposed magnet has been completed. The concept we intend to explore is illustrated in Fig. 3. Although

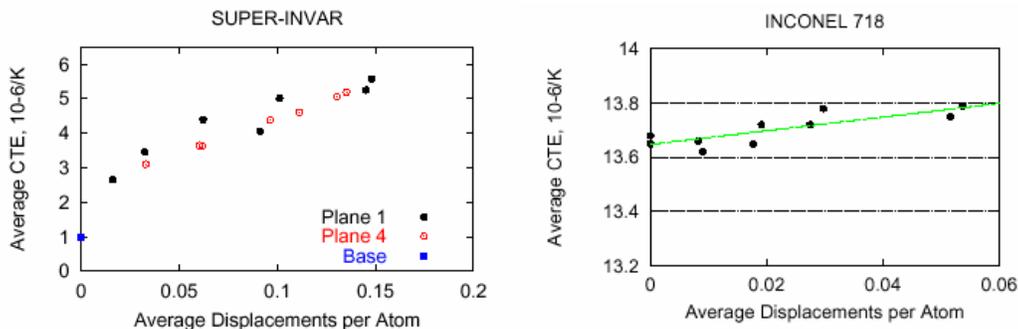


FIGURE 1. CTE changes for Super-Invar (left) and Inconel (right) as a function of radiation dose. Note the very different vertical scales in the two plots.

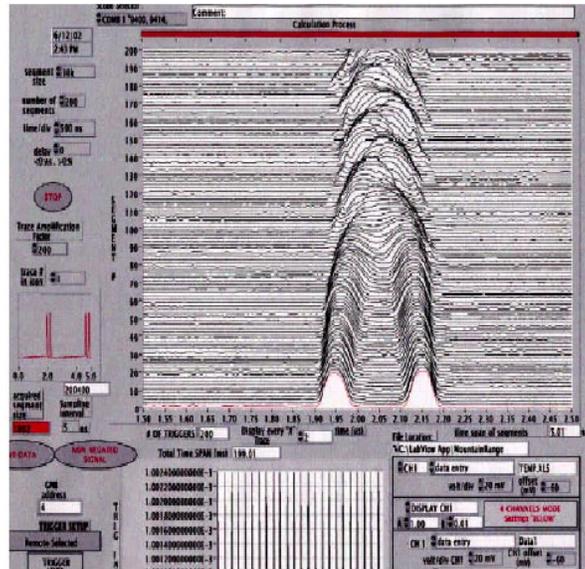


FIGURE 2. Merging of two $h = 12$ bunches into one $h = 6$ bunch at the AGS.

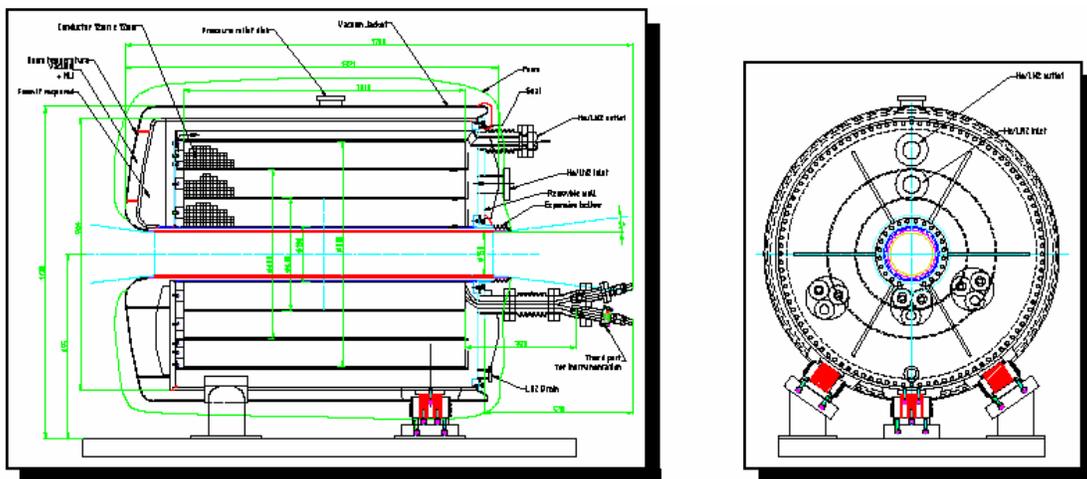


FIGURE 3. Side view (left) and end view (right) of the proposed targetry test magnet. The magnet is designed with three nested coils to provide the required field. It will be operated at cryogenic temperatures for power efficiency reasons, though it will not be superconducting.

consideration was initially given to using hydrogen coolant at the highest field level, the present plan is to use LN_2 and operate with a larger power supply.¹

Cooling

This activity (“MUCOOL”) includes the hardware R&D on rf cavities, absorbers, and solenoids.

¹After evaluating the safety implications of the H_2 system, which show up as additional costs, it appears more cost-effective to avoid hydrogen.

Most of our rf work to date has been done with 805-MHz cavity structures. These serve essentially as quarter-scale models of the cavities we intend to use for a cooling channel. A 201-MHz cavity has been designed [5] and is now under construction. The main question we are addressing is what limits the achievable operating gradient in the cavity. In particular, we are studying breakdown phenomena and dark currents.

Development work on liquid-hydrogen absorbers is being done at several Illinois universities, supported by the Illinois Consortium for Accelerator Research (ICAR), as well as at KEK, supported by U.S.–Japan funds. Much progress has been made in the past few years on the development and testing of large, but very thin, aluminum windows. Due to the proximity of the liquid-hydrogen absorber to the rf cavities and superconducting magnets of a cooling channel, consideration of safety requirements is important. This activity is well along, with solutions being developed to permit testing in the MUCOOL Test Area (MTA) at Fermilab and also to permit operation of a segment of cooling channel beam line for MICE.

Development work for the required superconducting solenoids is also ongoing, with the main goals being to reduce costs and increase reliability.

Cavity R&D

Recent tests have made use of an 805-MHz pillbox cavity [6] having replaceable windows (or possibly grid tubes) to terminate the electric field. Using windows or grids significantly enhances the shunt impedance of the cavity, thereby reducing the power needed to achieve high-gradient operation. These tests are carried out in Lab G at Fermilab, where there exists a 5 T solenoid (provided by the MC) with a bore size sufficient to accommodate the cavity.

In initial tests without a solenoidal field, the cavity (with copper windows) reached an accelerating gradient of 34 MV/m. After the field was turned on, the performance was poorer. The maximum gradient was only 18 MV/m and the radiation levels were much higher. We inferred that the field increased the likelihood of physical damage to the cavity. We did see some evidence for “healing” by reprocessing the cavity without the solenoid, but performance never recovered fully. When the cavity was disassembled in December 2002, we noted significant pitting of the copper window, along with copper dust at the bottom of the cavity.

Next, we installed beryllium windows, coated with a thin layer of TiN to prevent multipactoring. As before, we saw no conditioning problems without a magnetic field. This indicates that the “parallel-plate” geometry is not an intrinsic problem. After conditioning with magnetic field, we again observed a degradation in performance, though not as severe as with the copper windows. Upon opening the cavity for visual inspection, we found no damage to the Be window, but there was sputtered copper on the window surface. The implication is that it is material from the cavity body that is migrating. We will explore the possibility of coatings that might mitigate this effect. Even with the sputtered copper coating, the beryllium windows produced lower backgrounds under comparable conditions, as shown in Fig. 4.

We have completed our design work on a 201-MHz test cavity and begun fabrication. This cavity, which will accommodate either Be windows or an alternative

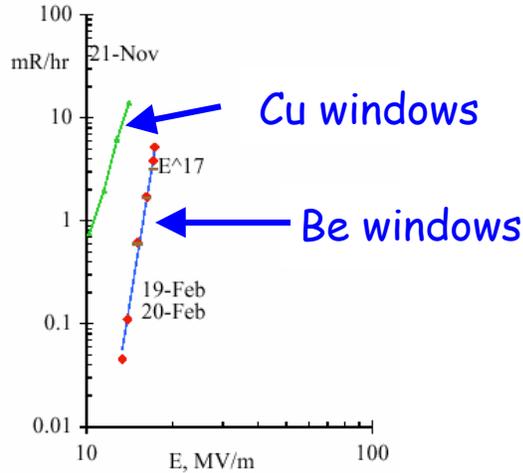


FIGURE 4. Comparison of radiation levels in 805 MHz pillbox cavity produced when using Cu and Be windows.

grid-tube electric field termination, is expected to be available for testing in about one year.

The ideal cavity window would be perfectly conducting, transparent to the muon beam, and mechanically stiff enough to resist changes to the cavity resonant frequency. Our initial concept was to use flat, pre-stressed Be foils. In practice, however, we found it difficult to maintain sufficient flatness to avoid detuning the cavity frequency, even at the smaller dimensions appropriate to the 805-MHz cavity. In addition, the Be window frame had to be very thick to support the pre-stress, making the windows costly.

We have recently adopted a new concept [5], based on a pre-curved window that bows predictably. With proper design, the stresses in the window remain quite low as the foil heats. We are testing various means to manufacture the required shape. One approach, involving clamping in a graphite die and then brazing the window to a frame, is shown in Fig. 5.

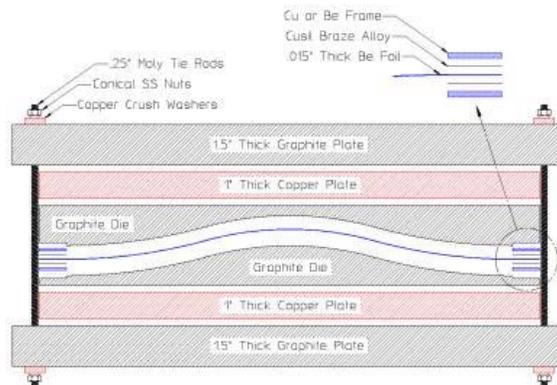


FIGURE 5. Graphite die and clamping arrangement for producing curved Be cavity windows.

Absorber R&D

The absorber program has been very successful in developing thin aluminum windows suitable for absorber use [7]. A new stronger (hence thinner) shape has been developed and will be tested next. The new design involves a double curvature, of the type shown in Fig. 5.² The first absorber will be filled with liquid hydrogen later this year. The test will be done in the newly-constructed MUCOOL Test Area (MTA) at Fermilab, which is expected to be ready for beneficial occupancy in October, 2003.

Acceleration R&D

The hardware program in acceleration involves the fabrication and testing of 201-MHz superconducting cavities for a recirculating linear accelerator (RLA). This work, carried out at Cornell under NSF sponsorship, has made good progress. Figure 6 shows the prototype cavity being readied for testing in a vertical dewar. The focus of the effort is to achieve a high design gradient of 16 MV/m. After being returned to CERN once for recleaning, the cavity reached 11 MV/m [8]. This is an encouraging first effort. Still to be done are the design and testing of ancillary items, such as the input coupler, higher-order-mode damper, and tuner.

Simulations

In the past year, the MC has formed a separate group to concentrate on emittance exchange, i.e., on 6D cooling. Cooling rings [9, 10] look particularly attractive, due to their potential for significant cost reduction. While the cooling process itself looks promising, issues remain. First, the ability to inject into (or extract from) a cooling ring appears difficult, and, second, it is not yet clear how to incorporate the beam from a cooling ring into the “standard” Neutrino Factory scenarios.³



FIGURE 6. Prototype 201 MHz superconducting cavity being readied for testing in a vertical dewar at Cornell.

² The idea for the rf cavity window shape referred to earlier was based on this new absorber window concept.

³ The small circumference of a ring precludes the relatively long bunch train for which present Neutrino Factory scenarios are optimized. However, a cooling ring does lend itself well to a Muon Collider scenario, where only one bunch of muons of each sign is required.

In addition to the more or less standard solenoid-based approaches, we continue to investigate alternatives such as quadrupole-based cooling ring systems [11].

We have also continued to look at the possibilities for utilizing an enhanced version of acceleration hardware. In particular, we are investigating [12] the idea of applying the FFAG (fixed-field, alternating gradient) principle to the design of the RLA arcs. This may permit a simpler and less costly approach to the RLA, in which there is only one FFAG arc on each side rather than a different arc for each pass. Another scheme being looked at is that of very rapidly cycling synchrotrons [13]. To be competitive with the other approaches, the cycle rate must be in the kHz range. This would require very special magnet designs.

Preparations for Study III

In the previous MC-sponsored feasibility studies, we focused mainly on feasibility and performance. In the next such study, we envision developing improved approaches that maintain the performance while giving a more cost-optimized design. Among the ideas we are considering are: improved bunching and phase rotation; 6D cooling (via rings or otherwise); and FFAG acceleration

Our expectation is that Study III will be a “world” study, sponsored by a non-U.S. institution. Participants would come from all three geographical regions—EU, Japan, and U.S. An international organizing group for Study III, now being formed, will become responsible for the organization and execution of the study.

MICE ACTIVITIES

The MICE technical proposal was submitted to RAL in January 2003, and subjected to review by an international panel in February 2003. The review panel subsequently “strongly recommended” approval of the project to RAL management.

The U.S. team for MICE has already submitted a funding proposal to NSF, and hopes to get a response early in 2004. The involvement of the U.S. team will be in the areas of rf cavities and coupling coils, along with contributions to the tracker detector, software development, and experimental simulations.

R&D PLANS

We have developed detailed R&D plans for all of the MC programs. These are briefly mentioned here. The targetry group will fabricate a 15 T magnet to utilize at the AGS or another facility. The cooling group will fabricate and test a 201-MHz cavity at high gradient (≈ 17 MV/m), and will fabricate and test liquid-hydrogen absorbers (first convection cooled, then externally cooled forced-flow type) with all safety aspects. Development of a full prototype of a 201 MHz SCRF cavity module will be pursued by the acceleration group. The simulation group will develop scenarios for use of cooling rings, with the eventual goal of developing a fully engineered cooling ring concept. They will also participate in Study III as part of the “world team.”

SUMMARY

The U.S. muon beam program continues to make excellent technical progress on all fronts, despite budgetary problems that make this difficult. We have established good working relationships with our colleagues worldwide, and believe that the muon community serves as a good model for how to work together on large international projects. We are part of a strong international effort for MICE and anticipate obtaining funding for this activity soon. In the meantime, the MUCOOL program of the MC is developing components that serve as prototypes for those needed in MICE. We continue our strong simulation effort, with the intention to participate fully in a World Design Study for a Neutrino Factory in about one year.

ACKNOWLEDGMENTS

The progress reported here is the result of the dedicated work of the 130 members of the MC. I thank them for the high quality of their efforts and the enthusiasm with which they carry them out. Working with such a group is a real privilege.

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