R&D TOWARD NEUTRINO FACTORIES AND MUON COLLIDERS*

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Abstract

R&D aimed at the production, acceleration, and storage of intense muon beams is under way in the U.S., in Europe, and in Japan. Considerable progress has been made in the past few years toward the design of a "Neutrino Factory" in which a beam of 20–50 GeV μ^- or μ^+ is stored. Decay neutrinos from the beam illuminate a detector located roughly 3000 km from the ring. Here, we briefly describe the ingredients of a Neutrino Factory and then discuss the current R&D program and its results. A key concept in the design is "ionization cooling," a process whereby the muon emittance is reduced by repeated interactions with an absorber material followed by reacceleration with high-gradient rf cavities. Plans to test this concept in the Muon Ionization Cooling Experiment (MICE) are well along and are described briefly.

INTRODUCTION

Presently, there is intensive worldwide activity to design a Neutrino Factory, and ultimately to develop a Muon Collider. The former facility would provide an intense beam of electron neutrinos (or anti-neutrinos) to study neutrino oscillations and hopefully to observe, for the first time, charge-conjugation–parity (CP) violations in the lepton sector. Observation of this phenomenon would provide a window to very high energy neutrino effects, and possibly provide an explanation for the observed matter–antimatter asymmetry in the universe. The latter facility would initially facilitate the study of the Higgs boson and could ultimately provide an energy-frontier machine small enough to fit on an existing laboratory site.

In the U.S., the activities take place under the auspices of the Neutrino Factory and Muon Collider Collaboration (MC), a group of some 130 scientists and engineers drawn from national laboratories and universities. In Europe, there is a corresponding organization, the European Neutrino Group (ENG). There is also a Japanese Neutrino Factory Working Group, centered at KEK but having members from Japanese universities as well. These groups are attacking the problems of intense muon beam accelerators on a broad front, and considerable progress has been made. In this paper, the primary emphasis will be on the R&D activities of the MC, although some activities of the other groups will be mentioned.

NEUTRINO FACTORY INGREDIENTS

A schematic of a possible Neutrino Factory is shown in Fig. 1. A high-power proton beam (1–4 MW) impinges on a production target, producing pions. These are captured

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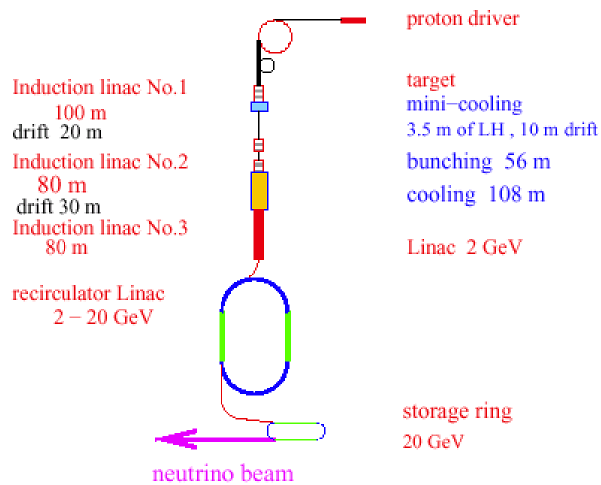

Figure 1: Schematic of Neutrino Factory layout, taken from Ref. [2].

into a solenoidal decay channel where they decay into muons. The resulting muon beam then undergoes "phase rotation," converting a beam with a large energy spread and a small time spread into a beam with a smaller energy spread and a longer time spread. The beam is then bunched into a train of 201 MHz bunches and cooled in an ionization cooling channel. These activities all take place at low muon momentum, roughly 200 MeV/c. After cooling, the muon beam is accelerated to its final energy (20–50 GeV) and stored in a ring with one or more straight sections aimed at detectors located several thousand km from the ring. Two feasibility studies of complete systems have been done [1,2], with the conclusion that such a facility is possible, albeit challenging.

Ionization Cooling

Ionization cooling is a key feature of intense muon beam facilities. This is because the production process described above results in a muon beam with very large emittance. (The short lifetime of the muon, 2.2 μs at rest, eliminates any alternative cooling schemes, such as stochastic or electron cooling.) The process, illustrated in Fig. 2, is analogous to synchrotron radiation damping. In

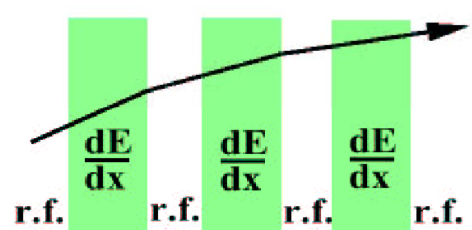

Figure 2: Schematic of ionization cooling process.

place of synchrotron radiation, ionization cooling makes use of energy loss in an absorber to decrease the particle's momentum in all dimensions; energy gain in the rf cavities restores only the longitudinal component. Repeating the process many times results in a decrease of $p_{x,y}/p_z$, and thus the transverse emittance.

There is also a heating term, analogous to the quantum excitation in the radiation damping case, resulting from multiple scattering in the absorber material. The balance between cooling and heating gives rise to an equilibrium emittance, given approximately by

$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta\, m_\mu X_0 \left|\dfrac{dE_\mu}{ds}\right|} \qquad (1)$$

where $\beta_\perp$ is the Twiss parameter at the absorber location, $\beta\ (\equiv v/c)$ is the particle velocity, m_μ is the muon mass, X_0 is the radiation length and dE_μ/ds is the energy loss per unit length in the absorber material. To reach a low emittance, strong focusing (low $\beta_\perp$), large energy loss, and large radiation length are preferred. The latter features favor H_2 as the absorber material.

R&D PROGRAM PROGRESS

Targetry

In the past few years, the MC has carried out initial beam tests at the AGS of both solid (C rod) and liquid (Hg jet) targets [3]. Unfortunately, this program has no beam time scheduled at the AGS in FY2003 and we expect none in FY2004 either. This is clearly a major impediment to further progress. Tests of C sublimation are being carried out at ORNL. Earlier work [4] indicated a target lifetime of 1 month at a beam power of 1.2 MW. We plan He atmosphere tests to see if the sublimation rate can be reduced to the level where 4 MW beam power is practical.

With regard to the Hg jet tests, the open questions concern injection into a strong solenoidal field (≈20 T) and nonlinear behavior of the jet dynamics at full proton intensity. To explore these issues, we have designed a test magnet capable of providing up to 15 T, we are designing a Hg jet system capable of the required 20–30 m/s velocity, and we have continued our simulation effort to predict and interpret our results.

In our initial beam tests, we reached an intensity of about 4×10^{12} p/pulse, compared with our design value of 16×10^{12} p/pulse. Tests of bunch merging techniques are under way, as illustrated in Fig. 3. These have already reached 10×10^{12} p/pulse, showing that the approach is workable.

Europe also has a strong program in Targetry, focusing on development of magnetic horns [5], and, in collaboration with the MC, working on Hg jet issues, such as the jet behavior in a strong magnetic field [6]. They have put considerable emphasis on developing a Superconducting Proton Linac (SPL) to serve as a proton driver. The concept being considered [7] is shown in Fig. 4. The original idea was to reutilize surplus LEP 352 MHz rf equipment, but more recent thinking has favored using a 700 MHz linac implementation.

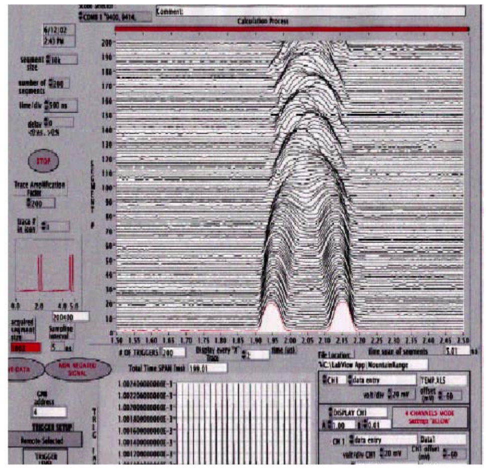

Figure 3: Demonstration of bunch merging at AGS. Two bunches on harmonic 12 are coalesced into one bunch on harmonic 6.

Cooling

This activity includes hardware R&D on cavities, absorbers, and solenoids, along with a significant simulation effort to design and optimize cooling channels.

Because the cooling channel rf system is immersed in a strong solenoidal field, the cavities must be normal conducting. To optimize the shunt impedance, we enclose the cavity ends with a conducting metal window. Our experimental rf work to date has been done at 805 MHz, that is, one-quarter scale with respect to the 201 MHz frequency intended for the cooling channel. The main issue to study is limits to the achievable gradient, i.e., breakdown and dark current phenomena.

The pillbox cavity [8] we employ for tests is shown in Fig. 5, along with its input waveguide. This cavity fits into the bore of our 5-T solenoid in Lab G at Fermilab. In the absence of a solenoidal field, and with copper windows, the cavity reached 34 MV/m, exceeding its 30 MV/m design goal. With the solenoidal field, the performance was poorer (18 MV/m) and the radiation levels from the cavity were much higher. We conclude from these tests that the presence of the magnetic field enhances physical damage to the cavity surfaces, though the detailed mechanism is uncertain. Some evidence for healing was found, in the sense that the cavity partially

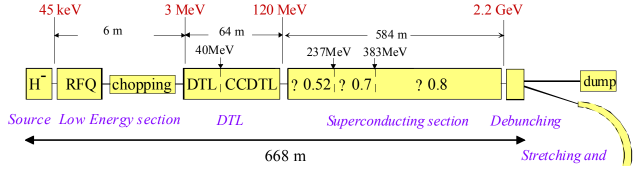

Figure 4: Diagram of proposed SPL configuration at CERN.

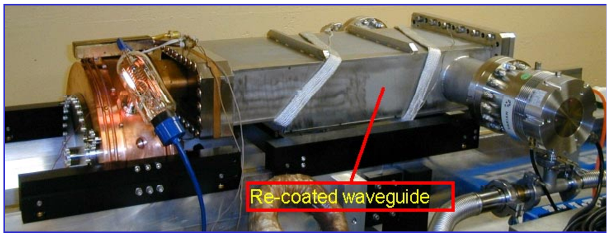

Figure 5: 805 MHz pillbox cavity used in high-power tests at Fermilab.

recovered to lower radiation levels when reprocessed without magnetic field. Inspection of the cavity after the tests showed pitting of the copper windows and copper "dust" at the bottom of the cavity.

We next replaced the copper windows with TiN-coated beryllium windows. Beryllium is the material of choice for a cooing channel because of its low Z (resulting in less multiple scattering). The conditioning went smoothly without a magnetic field, demonstrating that the parallel geometry of the windows does not result in inordinate multipactoring. After operation with magnetic fields, we again removed the windows for inspection. Figure 6 shows a section of the window and indicates that sputtered copper is present on its surface. No damage to the beryllium surface was observed, an encouraging result. This evidence suggests we need to focus more on the copper body than on the windows themselves to reach higher gradients. We plan to explore coatings of other materials that may mitigate these effects.

Even with the field present, beryllium windows produce lower backgrounds than copper windows under comparable conditions, as shown in Fig. 7.

As noted above, a crucial ingredient in the rf cavity design is the window that terminates the electric fields. Ideally, such a window would be perfectly conducting, transparent to the muon beam, and sufficiently rigid to have no effect on the cavity frequency. Our initial concept [9] was to use a thin flat window of pre-stressed beryllium foil. In practice, however, even at 805 MHz it is difficult to preserve the flatness as the window heats, and the thick frame required to support the pre-stress makes the windows expensive. For 201 MHz cavities, with correspondingly larger aperture, the approach was becoming impractical. Instead, we are now pursuing a pre-curved beryllium window that will bow predictably as it heats. The window is designed with a dual curvature, patterned after the absorber window design (see below) developed with University of Oxford.

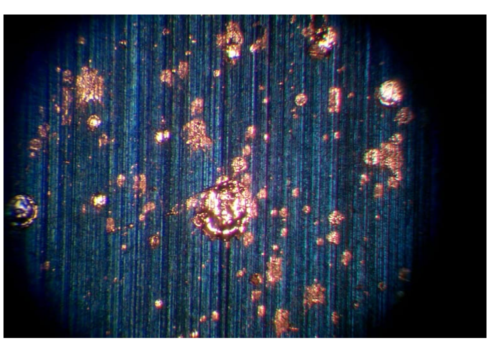

Figure 6: Be window surface showing sputtered copper.

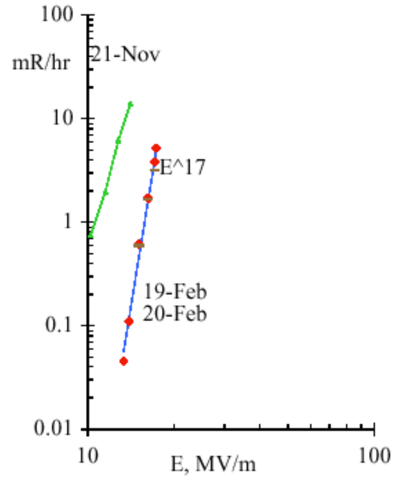

Figure 7: Background levels for copper windows (upper curve) and beryllium windows (lower curve) under identical magnetic field conditions.

As mentioned earlier, the cavity frequency envisioned for a cooling channel is 201 MHz. For the past year, we have worked on the engineering design [10] for such a cavity (see Fig. 8). Fabrication of a prototype cavity began this year and will be completed in about one year.

Thin, yet very strong, aluminum windows are needed for the liquid-hydrogen absorbers. A simple torispherical design has demonstrated the ability to support 8 atm pressure with a 340 µm window, sufficient for our needs [11]. An improved version with a double curvature (see Fig. 9) promises to be even thinner and stronger. Fabrication of the new windows is in progress, after which pressure tests will be performed to validate the predicted performance based on finite-element analysis.

An area to test absorbers and 201 MHz rf cavities is presently under construction at Fermilab. This area, which should be available in Fall 2003, is situated at the end of the 400 MeV proton linac and could ultimately be used for beam tests of cooling channel components.

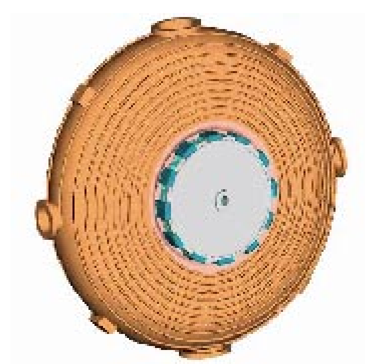

Figure 8: 201 MHz cavity for muon cooling channel.

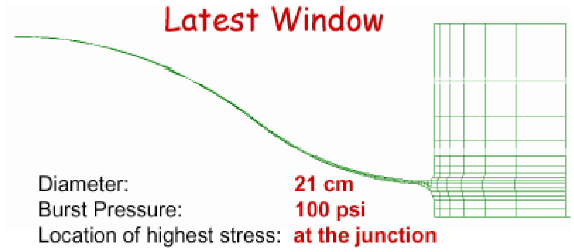

Figure 9: Improved absorber window design.

Acceleration

Although much of the R&D work for muon beams centers around cooling, there are other areas of focus. For muon acceleration, we need to develop 201 MHz superconducting cavities. While superconducting cavities at higher frequencies are by now relatively standard items, the cavity size required for 201 MHz (see Fig. 10) makes this a challenging component. The present focus [12] is to achieve high gradients, high Q, and acceptable mechanical stability. To date, the test cavity has operated at an accelerating gradient of 11 MV/m and has demonstrated a low-power Q of 10^{10}. Still needed are designs for the ancillary items required for a complete cavity module: input coupler, higher-order-mode coupler, and tuner.

In Japan, a substantial Fixed-Frequency Alternating Gradient (FFAG) accelerator development program is under way. In the Japanese Neutrino Factory scheme, a cascaded series of FFAG rings is used to capture the muon beam from the target area and bring it to its final energy of 20–50 GeV. An FFAG for 150 MeV protons has recently been completed, and is presently being commissioned. A series of FFAG workshops [13] is being held to better understand the features and potential promise of such devices.

Figure 10: 201 MHz superconducting cavity under test at Cornell.

Simulations

The focus of the simulations group in the past year has been on "emittance exchange." In this process, dispersion is introduced into the cooling channel and a variable thickness ("wedge") absorber is used to reduce the longitudinal emittance of the beam. Though this approach increases the transverse emittance, the standard cooling technique described earlier reduces this, with the result that the cooling takes place in 6D phase space. The natural way to do this is to arrange the cooling channel into a cooling ring [14,15]. Simulations of one such ring are presented in Fig. 11. We see that after some 10 turns in the 33 m circumference ring the 6D emittance is reduced by a factor of 302. Practical realization of such a ring requires full aperture injection and extraction kickers that are fast and powerful. This remains a challenging problem.

MICE ACTIVITIES

Although ionization cooling of muons is expected to be straightforward from a physics viewpoint, it has not been experimentally demonstrated. Given that a Neutrino Factory facility based on this concept will be expensive, it is clearly prudent to invest in a demonstration of this key principle. An international group has been formed, the MICE Collaboration, to propose and then carry out an experiment to study ionization cooling of muons. The group submitted a formal proposal [16] to Rutherford Appleton Laboratory (RAL) in January, 2003 and underwent a formal international review in February, 2003. The review committee has recently recommended that the experiment be approved, and we anticipate a favorable response from RAL soon. With a motivated collaboration, an enthusiastic host laboratory, and a solid experiment design, the time to carry out the experiment is now. Among other things, MICE forces us to deal with operational and cost issues early.

The MICE Collaboration has members from Europe, Japan, and the U.S. Funding requests to their agencies

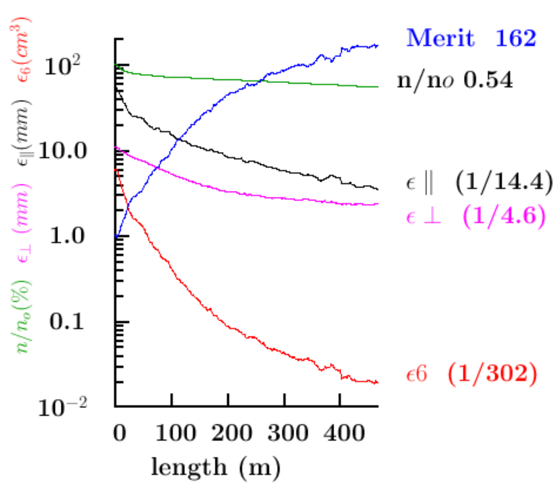

Figure 11: Simulations for RFOFO cooling ring [15].

have already been made by the UK and the U.S. groups. After formal approval by RAL, other groups will likewise make formal funding requests. It is anticipated that data taking will happen in 2007–2008.

Figure 12 illustrates the basic ingredients of MICE. The cooling channel components include liquid-hydrogen energy absorbers (capable of handling ≈100 W), 201 MHz rf cavities to restore the lost energy (capable of up to 17 MV/m), and solenoid magnets to contain the muons (capable of reaching about 5 T). In addition, the experiment provides a diffuser to create a large emittance sample, an upstream diagnostics section to define the initial emittance, and a downstream diagnostics section to measure the final emittance and provide particle identification.

R&D PLANS

In the next few years there are specific R&D plans in all technical areas.

For the Targetry program, the main item is to fabricate a 15 T test magnet and test it with beam from the AGS or elsewhere.

The Cooling program will complete fabrication of the 201 MHz high-gradient cavity and test it up to the required gradient of 17 MV/m. Liquid-hydrogen absorbers will be fabricated and tested, including all safety aspects. These tasks will be carried out in the MUCOOL Test Area at Fermilab.

Acceleration work will continue to concentrate on development of a 201 MHz superconducting rf cavity module, with the aim of reaching a gradient of 17 MV/m.

Simulation work will aim toward a well defined ring cooler concept that can be turned into a fully engineered ring design. They will also develop scenarios for incorporating a ring cooler into an end-to-end Neutrino Factory design. This may be done in the context of a "world" feasibility study of a Neutrino Factory that serves as a follow-on to the two U.S. studies done several years ago [1,2].

MICE activities will center on designing and fabricating the required beam line components and detectors. Accompanying this will be a strong software effort to develop the data acquisition, data analysis, and simulation tools needed to interpret the experimental results.

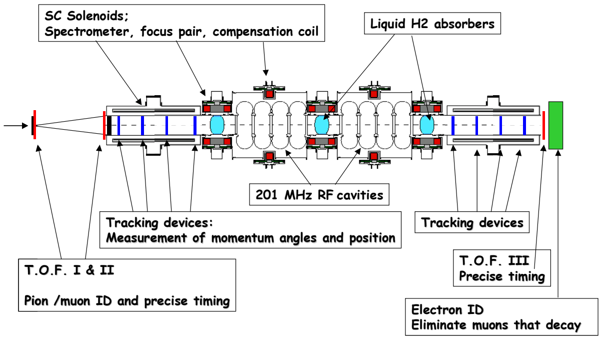

Figure 12: Schematic layout of MICE.

SUMMARY

The intense muon beam R&D program continues to make excellent progress on all fronts, due to the efforts of many dedicated scientists and engineers in Europe, Japan, and the U.S. Hardware development is continuing at a good pace and the simulation effort has made great strides in developing 6D cooling scenarios. The interaction of the R&D groups from the three regions is very positive, and serves as a model for working together on major international projects. The hardware components being developed will serve as prototypes for MICE. This key experiment, a grass-roots effort from all three regions, is expecting formal approval from RAL in the near future. If funding is made available in a timely way, this experiment could begin in a few years.

Despite the progress, it is clear that funding limitations are hampering the effort in all three regions. Restoring a healthy funding level for accelerator R&D is critical for maintaining the health of high-energy physics, and must be a priority to preserve the future of the field.

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