NEUTRINO FACTORIES: THE FACILITY

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The recent results from Super-K clearly indicate the existence of neutrino oscillations and, therefore, motivate the building of a muon storage ring (20-50 GeV) that can produce a directed beam of intense neutrinos (10^{20} -10^{21} per year) for both domestic and intercontinental experiments (base line of as much as 5,000 km). Such a device requires a powerful proton source (1-4 MW), muon capture, manipulation, cooling, acceleration, and storage. The physics of the neutrino sector is discussed in the previous article; here we describe the factory itself.

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I. INTRODUCTION

The fascination of the neutrino sector, how it may be explored, and what we might learn in such a venture has been described in the previous *Comment* by Stephen Geer [1]. The need to adequately address this sector puts new, and interesting, burdens upon the accelerator builder. True, accelerators have, through the years, produced neutrinos and certainly one can imagine ever-more powerful proton accelerators that, combined with horns, can produce ever-more powerful neutrino beams. Can one design and build a facility directly oriented to this new need ? Would such a device be superior to conventional neutrino beams and would it permit one to address new areas ? The answer to both questions is “yes”, and in this *Comment* I would like to describe what form such a facility, A Neutrino Factory, might take. See Fig. 1 for a picture of a facility.

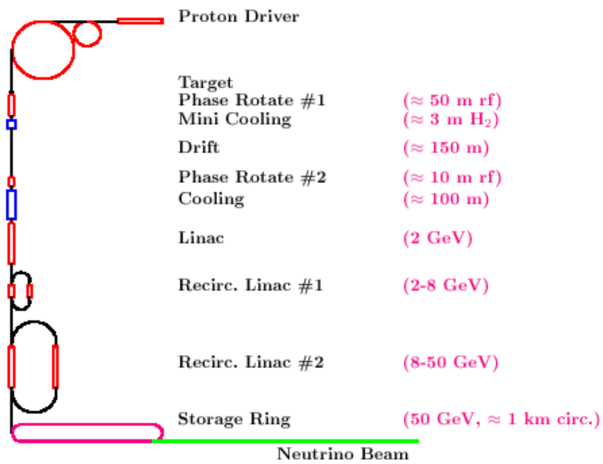

FIGURE 1 A schematic of a neutrino factory. One sees the major components: a proton driver, a target and muon capture region, a phase rotation and cooling section, an acceleration section consisting of a linac and re-circulating linacs, and a storage (decay) ring.

I will go into some detail, in this *Comment*, in describing the components of such a facility, the demands upon each component, the required R&D before undertaking construction of such a facility, and the expected performance of a Neutrino Factory. I shall, also, describe possibilities for up-grade in flux and energy.

The concept of a neutrino factory was proposed, in the mid-seventies, independently, by Kushkarev, Wojcicki, and Collins. It is fair to say, however, that the concept was first quantified by Geer in 1998 [2]. He was able to build upon the very large body of work developed in the efforts on muon colliders (See the many references and information available on the Neutrino Factory and Muon Collider Home Page [3].) The work on muon colliders, much of which is relevant to neutrino factories, may be found in the Status Report of 1999 [4] and, further details, in Ref. 7.

Subsequently, a very exhaustive feasibility study was carried out, led by N. Holtekamp and D. Finley [5]. We shall draw heavily upon this work. A good summary of neutrino factories, including the particle physics and the facility characteristics was developed by K. McDonald [6].

A Neutrino Factory design is dominated by two considerations. First, the muon decays (when at rest) in 2 microseconds. Even time dilation only extends this to a millisecond (at 50 GeV); everything must be done very fast and, therefore, many of the "tricks" that accelerator builders employ, such as adiabatic capture, can not be employed. The second consideration is that the muons are very dilute and to make a suitable beam requires manipulation of phase space and an increase of muon density, i.e., cooling, and, of course, all this needs to be done very fast (in a microsecond or so).

II. DRIVER, TARGET AND CAPTURE

The first element of a neutrino factory is a proton driver. That is, the protons produce pions which, subsequently, decay into muons. The driver must be intense, we talk of 1 to 4 MW of proton beam power, which is high, but in the same range as a spallation neutron source. The present AGS, at Brookhaven, produces 0.2 MW of proton beam power and improving the rep rate, alone, would bring it to 1.0 MW. At Fermilab there is talk of building a new booster, at 16 GeV, that satisfies the needs of a neutrino factory.

The pions are primarily produced at the $\Delta(3,3)$ resonance, as is shown in Fig. 2. Solid carbon targets may be used, although liquid mercury jets give an enhanced flux by about a factor of two (but are harder to operate). The target should be placed at a small angle both with respect to the proton drive beam and the surrounding solenoid, so as to reduce pion re-absorption. The production is not only spread over energy but also over angles. To capture as large a number of pions as one is able, a very strong magnet is put over the target region. The magnet we are considering provides 20 T, which is large, but far from the most powerful solenoid made. However, lifetime and operation in the intense radiation field are issues that result in employing smaller field strength. The captured muons are (about) 0.6 per proton.

Shortly after the target there may be an rf cavity. We don't, yet, know if this is required (although it surely increases polarization), or even possible to operate, in the radiation field about the target. A possible set up is shown in Fig.3.

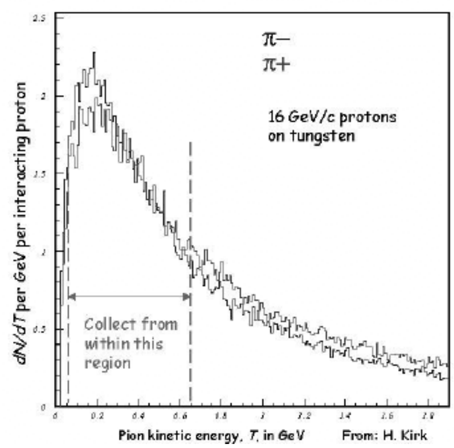

FIGURE 2 Target production of pions by a beam of protons at 16 GeV/c on tungsten. One can see the 3-3 resonance, which provides a copious number of pions.

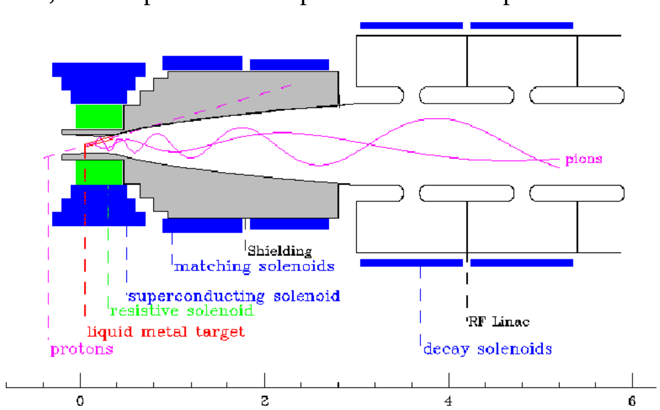

FIGURE 3 The target and capture region. Note the very powerful magnet over the target (20 T) in order to increase the capture efficiency.

Issues to be addressed in the R&D program involve survival of the target, operation of a mercury jet, operation of the rf cavity, and construction of the target solenoid.

III. PHASE ROTATION AND COOLING

The muons, resulting from pion decay, are spread in energy as shown in Fig 4. If the bunch is now allowed to drift then the higher energy muons, being faster, will move to the front of the bunch and vice-versa. In short a correlation will be developed between energy and position. At the same time, the energy spread, at any one position, will be decreased. These effects are shown in Fig. 5 (especially when compared with Fig.4.) The length of the drift region is determined by making the energy spread sufficiently small that the beam can be accepted by down-stream components. (Of course, the longer the drift the more muons are lost for their mean survival length, at the low energies considered, is only 660 m.)

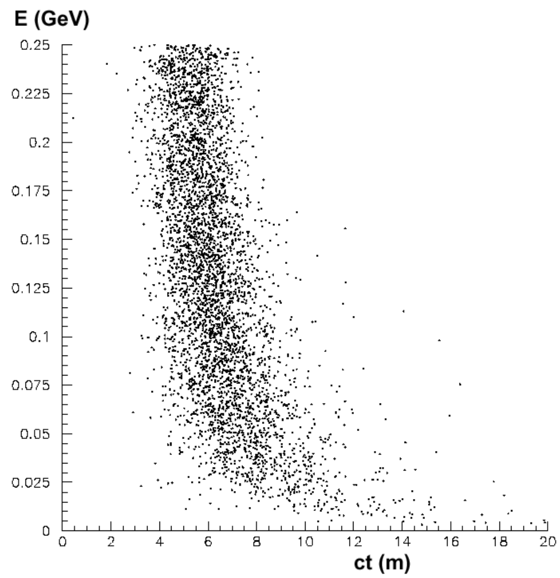

FIGURE 4 A simulation showing the distribution in energy and longitudinal position (or time) of muons just after capture.

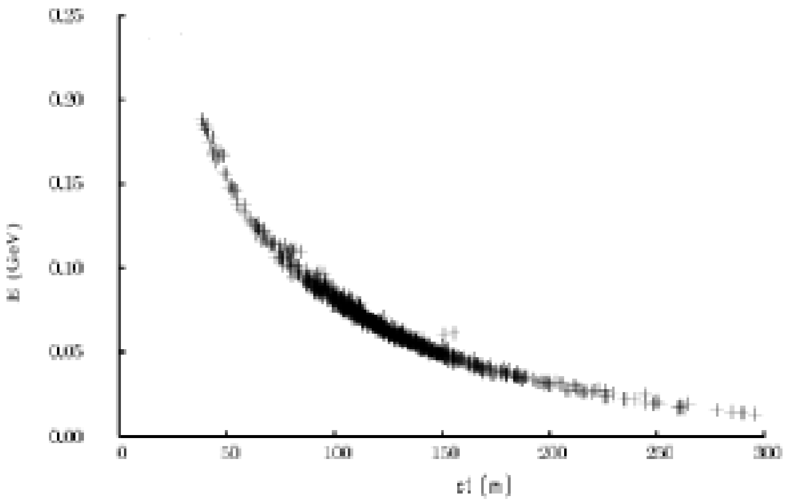

FIGURE 5 A simulation showing the distribution in energy and longitudinal position after 160 meters of drift. One notes, in comparison with Fig. 4, the greatly reduced energy spread (at any one position) and the correlation that has developed between energy and position.

The correlation between energy and position must now be removed and that can be done with an induction accelerator which, unlike rf, has a pulse length as long as the muon bunch. In Fig 6 is shown a diagram of such a unit. In combination with the drift, the muon beam can now be bunched and longitudinally accepted by the rest of the factory.

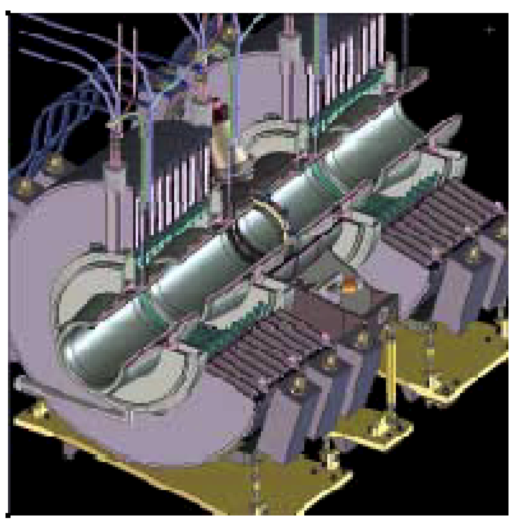

FIGURE 6 A conceptual drawing of an induction unit that might be employed in the phase rotation; i.e., the removal of the correlation between space and energy so as to produce a close to mono-energetic beam of muons.

However, the transverse size of the muon beam must still be reduced. To this end, ionization cooling is employed. The principle is shown in Fig.7. Actual realization involves design of a cooling channel and one such design is shown in Fig.8. The beam is squeezed (low beta) at the position of the absorber so as to minimize the scattering from the absorber (a “heating effect”).

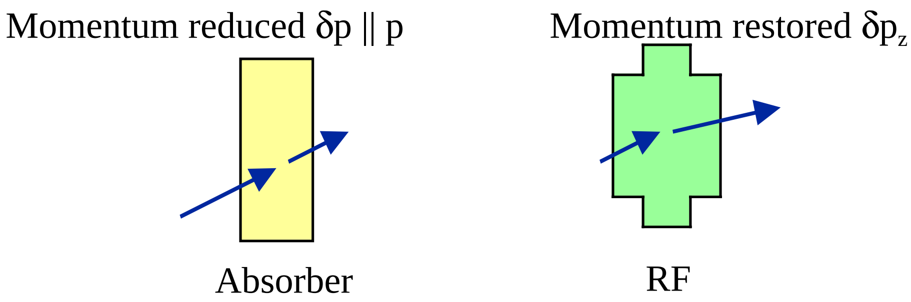

FIGURE 7 The concept of ionization cooling. Energy is lost in the absorber and replenished by the rf cavity with the net effect of reducing transverse angles; i.e., cooling the beam.

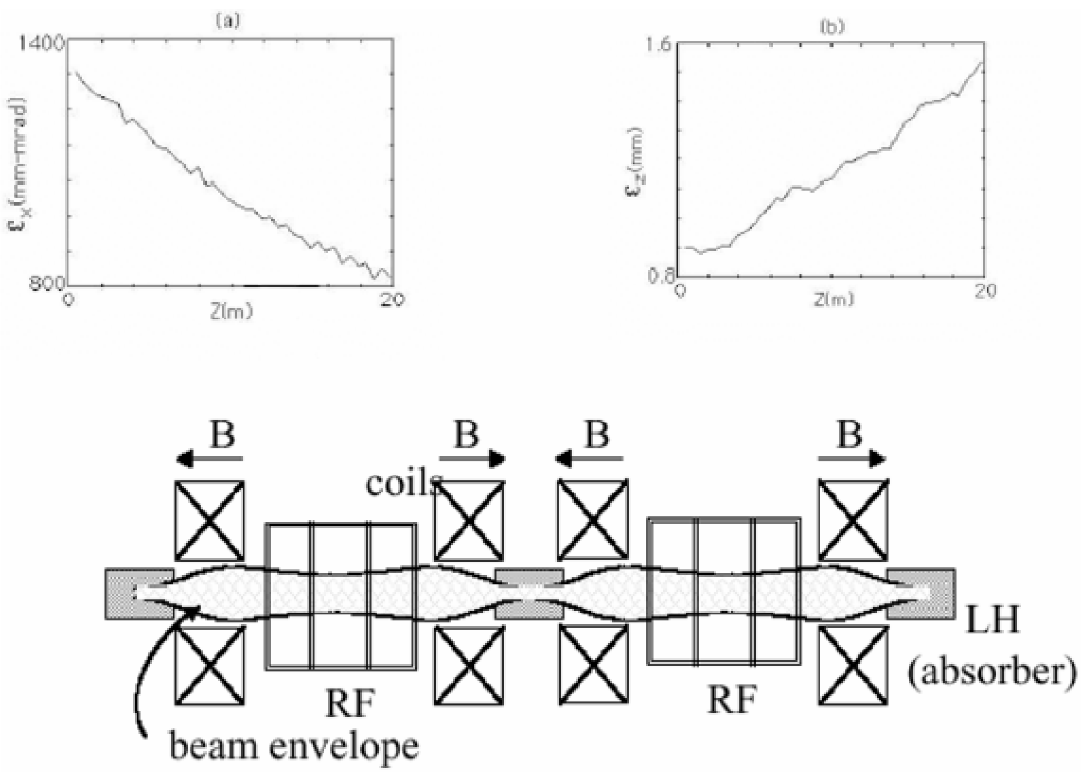

FIGURE 8 A section of a FOFO cooling channel. One sees the reversed fields which produce a low beta at the absorber while, also, preventing a growth of canonical angular momentum. The transverse emmittance is decreased, but the longitudinal emmitance grows (lower energy particles ionize better; i.e., lose more energy).

The cooling channel operates best if the rf gradient is very high. Of course the frequency must be low (200 MHz) so as to transversely accept the large muon beam and the rf must be room temperature rf because of the transport magnetic field of the surrounding solenoid. Foils of material, berilium is being considered, may be used to close off the beam pipe (muons readily go through material) and increase the cavity shunt impedance by about a factor of two. A picture of such a foil, and its performance, is shown in Fig. 9. Finally, all this must be put together, and an engineering drawing of a section of cooling channel is shown in Fig.10.

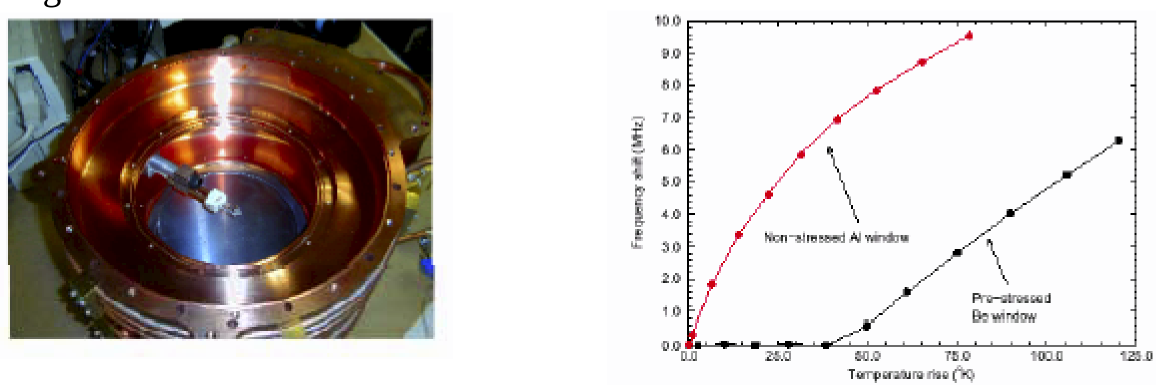

FIGURE 9 Beryllium windows can be employed on the rf cavities, with little effect on the muons, and yet increasing the cavity shunt impedance by a factor of two. Pre-stressed beryllium behaves well even when subject to rf heating.

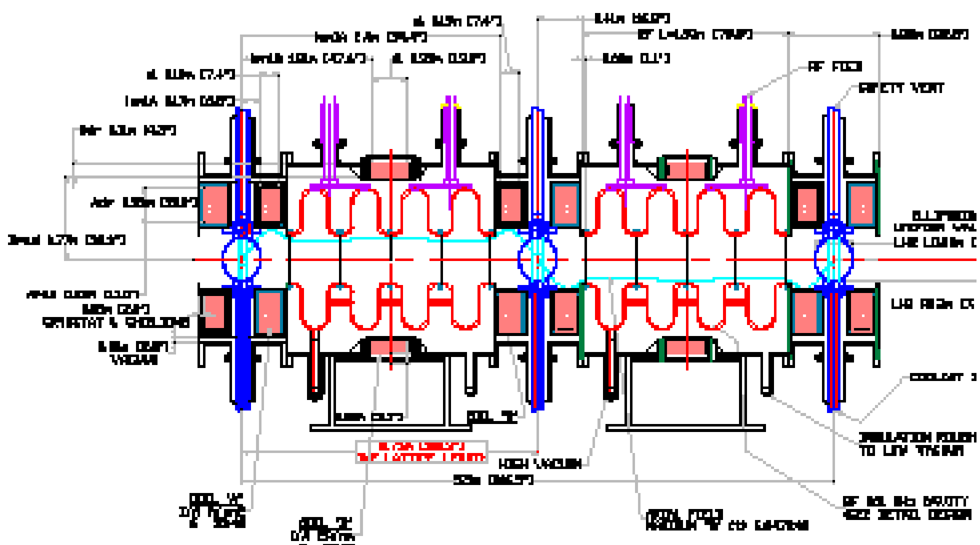

FIGURE 10 An engineering drawing of a section of cooling channel.

At this point, the number of muons per proton is (approximately) 0.1-0.2, which, with the 1-4 MW of proton driver power, gives $10^{20} – 10^{21}$ muon decays per year assuming only small losses and some decay in the rest of the complex. An R&D program would consist of making an induction unit, developing high gradient rf cavities, engineering a cooling channel and actually demonstrating cooling. This R&D program is called MUCOOL and is described on their home page [8].

IV. ACCELERATRION AND STORAGE

Once a muon beam has been developed, by the rather difficult procedures described in the previous two sections, which takes about half a kilometer, rather than a few inches (as would be the case for another lepton; namely, an electron), acceleration and storage is easy; well, at least very much simpler than producing a beam of muons.

Acceleration must be rapid, of course, and the method of choice is the use of recirculating linacs. (Other methods, such as FFAG, are being studied.) First, the beam must be accelerated in a linac so as to obtain some adiabatic damping in both transverse and longitudinal (energy- rf phase) phase space. Second, when the beam is adequately small, which occurs at about 1 GeV, it is injected into a superconducting re-circulator operating at a low frequency of 200 MHz. It appears that only four re-circulations are possible, because of the difficulty of separating large beams (despite the adiabatic damping, the beam is still large compared, say, to an electron beam). Third, the beam is extracted and then injected into a second superconducting re-circulator (operating at 400 MHz) where, perhaps, five re-circulations are now possible. Naturally, a good bit of simulation and design has been done and that can be found in Ref. 5.

An R& D program is needed on the rf superconducting cavities employed in the accelerating re-circulators. A number of types of storage rings have been considered; a triangle being particularly attractive. The rings must, of course, be properly oriented and, furthermore, slope down so that the neutrino beam will hit the detector. The simplest is a race track. A draw-back of his geometry is that only one of the neutrino beams is directed to a far detector (the other points up).

An overview of a neutrino facility, with a 50 GeV muon beam, is shown in Fig.11. As one can see, the size is modest and the facility could be staged, for example by leaving off the second re-circulator in an “entry level” device (so that the muon energy is less than 50 GeV) and leaving off some of the cooling (so the flux is reduced). Finally, in Fig.12 is shown a very futuristic concept, but not a piece of science fiction; it could be real.

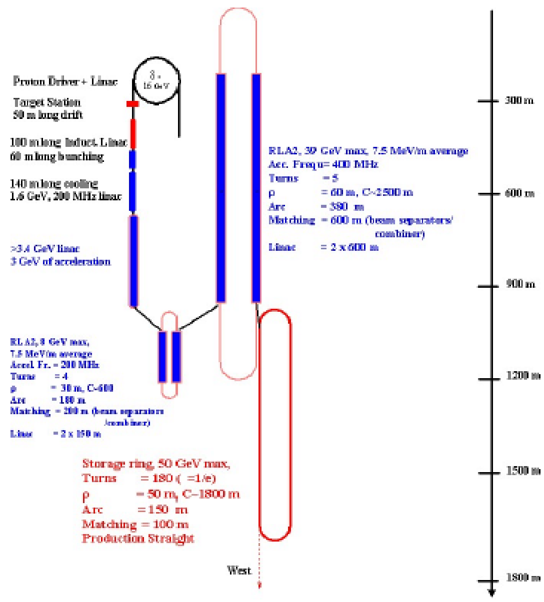

FIGURE 11 The layout, to scale, of a muon factory. The energy is 50 GeV.

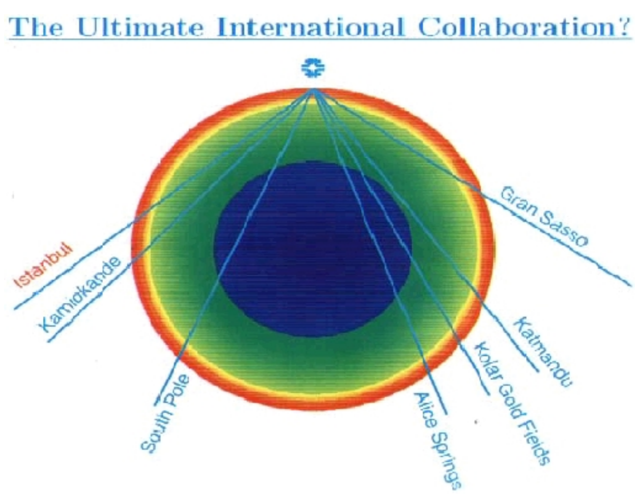

FIGURE 12 A grand view of what might, some day, be the case when neutrino beams are being sent, from Fermilab, to many different locations, so as to study intrinsic properties of neutrinos, matter effects on neutrinos, and properties of the earth.

V. CONCLUSION

We have seen that it is feasible to construct a neutrino factory. However the facility won't be cheap, both in time (many years of R&D is required before construction) and money (the facility is in the billion-dollar class).

We estimate that in a technologically limited program there would be three years of R&D before one could initiate work on writing a ZDR (Zero Design Report). The ZDR would take two years, after which one could start on a CDR (Conceptual Design Report) that would take two years more. Thus in seven years one could start construction, which would take another four years. The facility might be completed, and ready for physics studies, by 2012. Of course, unexpected accelerator physics developments, political considerations, and financial considerations could well extend the time frame.

The cost of such a facility won't be known, with any precision, before the CDR is completed in 2008. However it is clear that the facility will be in the billion-dollar range. It is interesting to consider constructing it in stages, first the driver, then an entry level facility, and then an increase in flux and energy. In this way, new regions of physics are addressed at each stage, while the cost of each stage is less than a billion dollars.

We should also note, although it is not the primary thrust of this *Comment*, that a neutrino factory is a very significant step towards a muon collider. Since muon colliders are likely to be an important element of high energy physics in the future, it is wise to advance that possibility as soon as we can, and a neutrino factory would do exactly that.

Finally, the concept is intrinsically international, and one would hope that the very significant international cooperation that we are now enjoying in the R&D phase would extend into the construction and utilization phases.

Acknowledgements

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