Accelerators for future neutrino facilities: strengths and challenges

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Abstract. Several different ideas have been put forward for future neutrino facilities, including a high-power conventional neutrino beam (a "Superbeam" facility), a Beta Beam facility based on stored beta-unstable ion beams, and a Neutrino Factory based on stored muon beams. Each of these has its advantages and disadvantages, and these are described here. After briefly describing the physics context, the various options will be described and their respective strengths and challenges indicated. The supporting R&D programs will be briefly discussed and a few specific technical questions for each facility will be outlined.

1. Introduction

Since the discovery of neutrino oscillations, there has been considerable interest in the possibility of generating intense beams of accelerator-produced neutrinos. Such a facility may be capable of observing CP violation in the lepton sector, a phenomenon that could explain the survival of matter in the universe.

Over the years, a number of schemes for producing the required neutrino beams have been proposed. These are:

- a "Superbeam" facility based on the decays of an intense pion beam
- a "Beta Beam" facility based on the decays of a stored beam of beta-unstable ions
- a "Neutrino Factory" based on the decays of a stored beam of muons

The latter facility could also serve as a precursor to an eventual Muon Collider.

All of the proposed approaches have their advantages and disadvantages. The various choices are being compared on an equal footing in the EUROnu study [1], which should be enlightening for the community. Suffice it to say here that all of the facilities would be challenging and expensive.

After briefly mentioning the physics context for these facilities, we describe each of them. We then discuss the strengths of each approach, its technical challenges, and some of the approaches to managing the challenges. Finally, we mention the main topics of the worldwide R&D programs now in place.

2. Physics Context

The Superbeam facility provides muon neutrinos or anti-neutrinos via the process $\pi \rightarrow \mu + \nu_\mu$. The polarity of the focusing horn determines the sign of the pions, and thus whether neutrinos or anti-neutrinos are delivered to the detector. Because the initial pion beam is impure, the purity of the neutrino beam is not more than ~98%.

The Beta Beam facility gives pure beams of electron neutrinos or anti-neutrinos via decays such as

$$^{6}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + \mathrm{e}^{-} + \overline{\nu_{\mathrm{e}}} \text{ or}$$
$$^{18}\mathrm{Ne} \rightarrow {}^{18}\mathrm{F} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \quad .$$

These decays, which correspond to the present baseline configuration of the Beta Beam facility, produce low energy neutrinos.

The Neutrino Factory beams, which are generated from the decays of muons, produce equal amounts of both muon and electron neutrinos

$$\mu^{-} \rightarrow \mathrm{e}^{-}\overline{\nu_{\mathrm{e}}}\,\nu_{\mu} \text{ or}$$
$$\mu^{+} \rightarrow \mathrm{e}^{+}\nu_{\mathrm{e}}\overline{\nu_{\mu}} \quad .$$

In the baseline scenario, with 25 GeV muons, the neutrinos are produced at high energy, above the tau threshold.

Electron neutrinos are the most favorable for doing the science, because the oscillations from ν_e to ν_μ gives easily detectable "wrong-sign" muons. Note that the Superbeam does not produce electron neutrinos.

3. Description of Facilities

3.1. Superbeam

A Superbeam facility is basically a higher power version of today's neutrino beam facilities, that is, the approach is evolutionary rather than revolutionary. Nonetheless, increasing the beam power to 4 MW is a big step forward and does result in challenges as will be discussed below. A schematic of the EUROnu baseline Superbeam design, which would take a neutrino beam from CERN to a detector at Fréjus, is shown in Fig. 1. It is based on a 5 GeV, 4 MW proton beam from a high-power version of the CERN SPL [2].

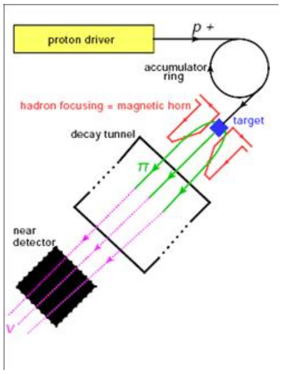

Figure 1. Schematic of CERN Superbeam layout.

3.2. Beta Beam

The baseline Beta Beam includes a number of systems—a proton driver, an ISOL target, an ion source, an acceleration system comprising a linac, a rapid cycling synchrotron (RCS), and two existing CERN accelerators (the PS and SPS), and finally a 6.9 km circumference decay ring with a 2.5 km straight section aimed at the detector. As noted earlier, the baseline scheme uses ^{6}He and ^{18}Ne ions to produce the neutrinos. This is referred to as the "low-*Q*" scenario. An alternative high-*Q* scenario, based on ^{8}Li and ^{8}B beams, is also under study. This latter concept would offer higher energy neutrino beams, but at the cost of a more complicated production scheme. To take advantage of the higher neutrino energy, a longer detector distance is required, so the high-*Q* scheme uses Gran Sasso as the detector location. Figure 2 shows the schematic layout of the Beta Beam facility illustrating both the low-*Q* and high-*Q* schemes.

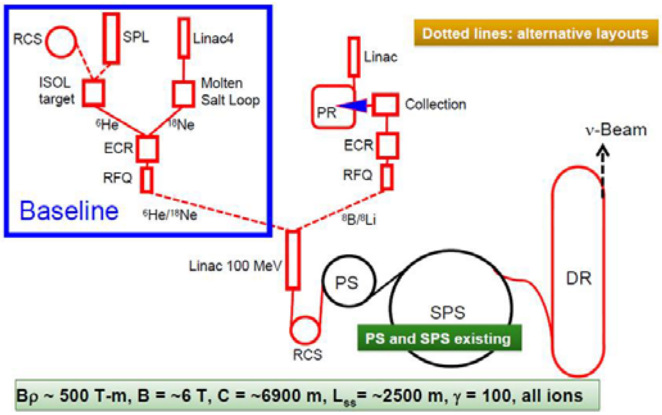

Figure 2. Beta Beam facility layout showing both the low-*Q* baseline and high-*Q* alternative configurations.

3.3. Neutrino Factory

Like the Beta Beam facility, a Neutrino Factory (Fig. 3) comprises a number of systems. These include [3]:

- a proton driver to give 4 MW of 5–15 GeV protons on a production target
- a target, capture and decay section where pions are produced, captured, and decay to muons
- a bunching and phase rotation section to reduce the energy spread of the beam
- an ionization cooling section to reduce the transverse emittance of the muon beam
- an acceleration section to increase the muon energy from 130 MeV to 25 GeV using a linac, recirculating linear accelerators (RLAs), and a non-scaling, fixed-field alternating gradient (FFAG) accelerator
- a pair of decay rings, with long straight sections aimed at the detector sites, where the muons circulate for ~1000 turns

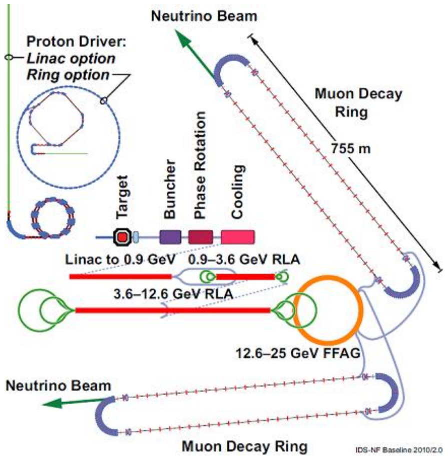

Figure 3. Neutrino Factory baseline layout.

An alternative design for a 4 GeV Neutrino Factory (Fig. 4) is also being explored [4]. This scenario is motivated by the following considerations:

- the expectation of reduced facility cost compared with the baseline design
- a neutrino energy well matched to the Fermilab to Homestake Mine distance
- a detector concept—the totally active scintillator detector (TASD)—capable of the required performance at the chosen energy

The main ingredients for the low-energy scenario are the same as those outlined for the baseline device, but there are fewer items on account of the lower energy (less acceleration, smaller decay ring, and a single detector).

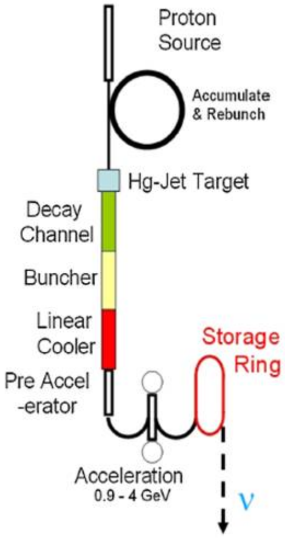

Figure 4. Schematic layout of low-energy Neutrino Factory.

3.4. Common Aspects

A common feature of all future neutrino facilities is the need for a substantially increased quantity of data. This leads to the requirements for intense particle sources and very large detectors. Both of these represent major technical challenges that extend the state-of-the-art by factors of 5–10.

All current approaches to providing the required neutrino intensities rest on producing secondary, or even tertiary, beams.

4. Strengths

For the Superbeam, its main strength compared with the other potential approaches is that it is closest to today’s technology. For this reason, it is likely to be the least expensive of the three alternatives, though it nevertheless will be expensive.

For the Beta Beam, its main strengths are that it *i*) takes advantage of existing CERN infrastructure; *ii*) offers potential synergy with nuclear physics interests in isotope production; and *iii*) provides a clean beam[1] having only electron neutrinos.

The main strength of a Neutrino Factory is that it has the most experimental sensitivity, and thus the best physics reach of the three options. In this facility, both electron and muon neutrinos are produced simultaneously, and in equal proportions. The Neutrino Factory also offers a strong synergy with intense muon and/or Muon Collider programs should either or both of these be of interest to the scientific community.

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[1] However, the Beta Beam facility must be used in combination with a Superbeam to fully elucidate the physics.

5. Technical Challenges and Mitigations

5.1. Superbeam

The challenges in this case are related mainly to the intensity requirement. In particular, one needs:

- a target capable of handling 4 MW of protons
- a horn capable of handling 4 MW of protons and operating at a 50 Hz repetition rate
- good charge selection (for beam purity)

A particular constraint for this facility is that the target and focusing horn must be in close proximity. Spatial constraints favor a solid, or possibly a powder-jet target. Materials compatibility issues make the Hg-jet target (favored by the Neutrino Factory community) impractical. Cooling of the horn in a crowded area is not easy, though solutions exist. The high radiation environment makes repairs challenging in this region, though it is inevitable that repairs (or component replacement) will be needed. A remote handling system is clearly mandatory.

The proposed approach to deal with these challenges is illustrated in Fig. 5. The idea is to use four horns and four targets, all sharing a common decay pipe. With this approach, each target must handle a more tractable 1 MW of beam power, and the individual horns can pulse at 12.5 Hz rather 50 Hz. Although the beam delivery system gets more complex, the benefits of relaxing the power and repetition rate make this a good trade-off. To simplify the design, each horn is designed as a single optimized device, with no reflector. The favored target concept, shown in Fig. 6, is a so-called "pebble bed" system using Ti spheres with aggressive cooling.

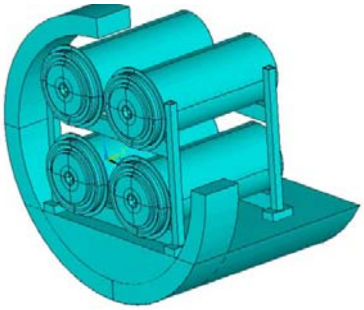

Figure 5. Four-horn target system for Superbeam facility.

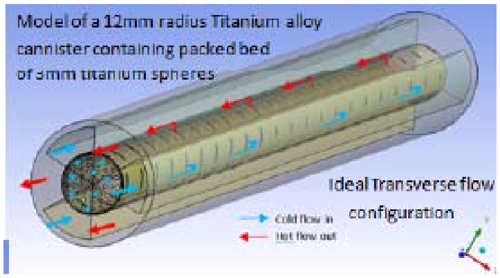

Figure 6. Schematic of pebble bed target showing cooling concept.

5.2. Beta Beam

The primary technical challenge for the Beta Beam facility is to produce the desired ion species at the required intensities. "Production" in this context includes not only the initial production of the unstable nuclei, but transporting them to an ion source, ionizing them to a useful charge state, and bunching them in a form suitable for further acceleration and transport. At present ^{6}He production looks acceptable and ^{18}Ne appears challenging, but probably possible with the ^{19}F(p,2n) reaction.

Unfortunately, the higher-*Z* species will typically exit the ion source in multiple charge states, reducing the overall efficiency of the process for a given charge state choice.

For the high-*Q* isotopes, a new production concept using a production ring and reverse kinematics has been explored [5]. Unfortunately, due to the wider decay cone for the high-*Q* isotopes, an additional factor of 5 in intensity is needed. Present estimates suggest that the required gas target thickness in the production ring would be about 10^4 times that of any existing target, which does not seem promising. A possible workaround involving forward kinematics and a liquid-lithium thin film target is being considered.

Another technical issue that is now being assessed is that of collective effects. Initial estimates [6] indicate that transverse mode coupling will limit intensities in the decay ring (and possibly in the SPS), exacerbated by the relatively low duty factor (0.5%) required. Work to understand this issue is in progress. It may be possible to modify the decay ring parameters to avoid this limitation.

Finally, the Beta Beam baseline scenario, with $\gamma = 100$ and a very short ring-to-detector distance do not appear optimal for the science program. Beams with $\gamma = 350$ and a longer detector distance are preferred. This scenario would require an upgrade of the SPS, which has not been seriously studied yet, as it is not in CERN's plans at present.

5.3. Neutrino Factory

The primary challenges for a Neutrino Factory are related to the difficulties in creating an intense, accelerator quality muon beam. Muons are produced as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$), a process that results in a beam with a large energy spread and large transverse phase space. Thus, some form of emittance cooling is required. The intensity requirement is high, demanding a target that can tolerate up to 4 MW of protons—and a proton driver that can provide such intensity in short (1–3 ns) bunches. Finally, the muon has a very short lifetime (2.2 μs at rest), which means that all beam manipulations must be rapid. In particular, the only cooling method deemed fast enough for muons is the presently untested technique of ionization cooling [7].

To accommodate the high-intensity proton beam, the favored concept is a free Hg-jet target in a 20-T solenoidal field. The specified jet velocity of 20 m/s is such that a new, undisturbed target is re-established in time to receive the next beam pulse at a 50 Hz rate. The shielding required to operate a 20-T hybrid magnet in such a high radiation environment is daunting, but appears manageable.

Though it came as somewhat of a surprise, the operation of high-gradient normal conducting rf cavities in a magnetic field has not turned out to be straightforward. Experiments at 805- and 201-MHz have shown substantial degradation of maximum gradient with even a few-T of axial field. It is known [8] that gas-filled cavities do not suffer a loss in gradient in a magnetic field, but their behavior with an intense beam of ionizing radiation must be studied. Such studies are just getting under way. Initial indications [9] are that the passage of the beam results in severe beam loading in the cavity, but its onset may be slow enough that the cavities will be functional in the Neutrino Factory parameter regime.

6. R&D Activities

To address the challenges described in Section 5, worldwide R&D efforts are under way. Of most interest here are the work of the EUROnu study [1] and those of the IDS-NF [10] and Muon Accelerator Program, MAP [11].

6.1. Superbeam

The main R&D activity has focused on target and horn. These represent the most difficult technical challenges. An optimized horn has been designed, but needs to be fabricated and tested with its power supply. Cooling and fatigue damage are issues to examine. Testing the device in a high radiation area is worthwhile, but may not be practical. A pebble-bed target is the favored design. A scale model of this needs to be built and tested with a heat source comparable to what the real beam would provide.

6.2. Beta Beam

The main items to study here—all of which are in progress—are ion production, collective effects, and beam-loss issues. The R&D effort here has suffered somewhat by being understaffed, and more help would be of great benefit. More detailed study of the implications of the heavy ion transport in the existing CERN machines (PS and SPS) is warranted. It is likely that some modifications to existing facilities will be needed and these need to be assessed and discussed in the context of future CERN plans.

6.3. Neutrino Factory

For the Neutrino Factory, the primary R&D topics are the target, ionization cooling, and the issue of how to improve the rf gradient in the presence of an axial magnetic field. The "target" R&D involves the entire target facility, including Hg circulation and cooling, superconducting magnet design and shielding, remote handling, and safety issues. Ionization cooling R&D must focus on completing the MICE experiment [12] at Rutherford Appleton Laboratory, including an analysis of the results in sufficient detail to confirm the basic understanding of the cooling process. Finally, the degradation in maximum gradient for cavities in an axial magnetic field must be understood and cures or at least mitigation strategies developed.

7. Questions to Consider

In the spirit of having a workshop, a few questions are listed here that could be topics of discussion for this or a future meeting.

For the Superbeam group:

- Is the layout of the proton beam transport compatible with horn repair or replacement?

For the Beta Beam group:

- Given the complications of producing and capturing ^{8}Li and ^{8}B, and the need for five times higher intensity for these isotopes compared with ^{6}He and ^{18}Ne, is the cost-benefit ratio for this option really favorable?
- Are there limitations (either technical or operational) in the baseline CERN-based scenario that are severe enough to justify consideration of a "green-field" site?

For the Neutrino Factory group:

- What combination of proton beam energy and bunch length is the best compromise for integrated muon beam intensity?
- Is the rf R&D plan sufficiently well focused or too broad?

For all of the groups:

- What is the time frame to complete the work necessary to request funding to build a facility?

8. Summary

As should be clear from this paper, substantial progress is being made toward the designs of accelerator-based neutrino facilities to study CP violation in the lepton sector. While there are technical challenges in all cases, these challenges are being understood and overcome by means of vigorous international R&D programs. Experiments play a critical role in this endeavor and must be a substantial part of the overall R&D effort.

The work being carried out extends the state-of-the-art in accelerator science. Examples include high-power targets, new beam cooling techniques, ion source development, and rapid acceleration techniques.

Acknowledgments

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References

[1] See http://www.euronu.org/

[2] Gerigk F (ed.), "Conceptual design of the SPL II – a high-power superconducting H^- linac at CERN," CERN 2006-006 (2006); see http://cdsweb.cern.ch/record/975366/files/CERN-2006-006.pdf

[3] The IDS-NF Collaboration Interim design report, see https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-020-v1.0.pdf.

[4] Li T "The low energy neutrino factory," https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-012-v1.0.pdf

[5] Benedetto E "Ionization cooling in a low-energy ion ring with internal target for beta beams production," in Proc. 2010 International Particle Accelerator Conf., Kyoto, Japan, May 23–28, 2010, p. 849

[6] Hansen C and Rumolo G "Collective effect studies of the beta beam decay ring," see http://heplnv135.pp.rl.ac.uk/joomla/index.php?option=com_docman&task=doc_download&gid=59&Itemid=5

[7] Neuffer D 1983 *Part. Accel.* **14**, 75

[8] BastaniNejad M *et al*. "Studies of breakdown in a pressurized rf cavity," EPAC'08, Genoa, June 2008, MOPP080, p. 736; see http://www.JACoW.org

[9] Yonehara K "Progress of high pressure rf cavity test," https://indico.fnal.gov/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=4661

[10] See https://www.ids-nf.org/wiki/FrontPage

[11] See http://map.fnal.gov/

[12] See http://mice.iit.edu/