RECOMMENDATIONS FROM THE INTERNATIONAL SCOPING STUDY FOR A NEUTRINO FACTORY

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Abstract

The International Scoping Study (ISS) - a one-year review set up in August 2005 - aimed to lay the foundation for a planned international design study (IDS) of a neutrino factory or superbeam facility. The ultimate goal is the generation of intense beams of neutrinos for particle physics research, from the decay of muons in a system of particle accelerators. A team of experienced physicists were charged with assessing the status of neutrino factory work at the time in order to identify a fully self-consistent and viable accelerator scenario. Additional design work was carried out, and areas for immediate study and R&D were identified. The ISS report makes recommendations for all parts of a Neutrino Factory complex, ranging from a high intensity proton driver, through muon production and acceleration, to the design and orientation of the storage rings that direct the neutrino beams through the earth to far detectors. The paper outlines the work, explains the ISS proposals, and identifies the most urgent R&D.

INTRODUCTION

The idea of generating neutrino beams from the decay of pions and kaons in long straight sections in a storage ring was first raised in the 1970s, but the predicted intensities were too low to answer many questions of interest to particle physicists. It was not until 1997 [1] that a scenario was devised that promised ultimately to generate sufficient neutrinos - set at 10^{21} a year - to probe small values of the mixing angle θ_{13} in the standard model, determine the mass hierarchy and search for CP violation in the lepton sector. The basic ideas of such a neutrino factory (NF) are shown in Figure 1. A high intensity proton source directs a beam of a few megawatts onto a pion production target. Charged pions are captured in a focussing channel at low energy; they decay to muons, whose phase space is controlled and reduced in size by ionisation cooling. The resulting muon beam is then accelerated rapidly to an energy in the range 20-50 GeV. Finally the muons are stored in designated storage rings with long straight sections, where the neutrinos produced by their decay can be directed through the earth towards the detector sites. The alternative of a neutrino superbeam from the direct decay products of a production target has also been considered, and may possibly be regarded as a first step towards a full neutrino factory. The neutrino factory itself, with enhanced muon cooling, might eventually be developed into a muon collider.

An annual NF conference was initiated in 1999 and has served as a forum for dissemination of information in all areas of study. A seminal paper by Palmer, Johnson and Keil [2] led to major design reviews, first by Fermilab in April 2000 (US Study I [3]) and then by Brookhaven, completed the following year in 2001 (US Study II [4]). US Study I demonstrated feasibility of the NF concept, while Study II considerably improved the performance through changes in the target and the muon cooling and accelerating systems. Additional studies were carried out at CERN in 1999 [5] and in Japan in 2001 (Nufact-J [6]), the Japanese study being notable for its use of very large acceptance fixed field alternating gradient (FFAG) accelerators (of the scaling type) and the absence of muon cooling. Non-scaling FFAGs were then introduced in a revised US Study known as IIa [7], but with the cooling retained.

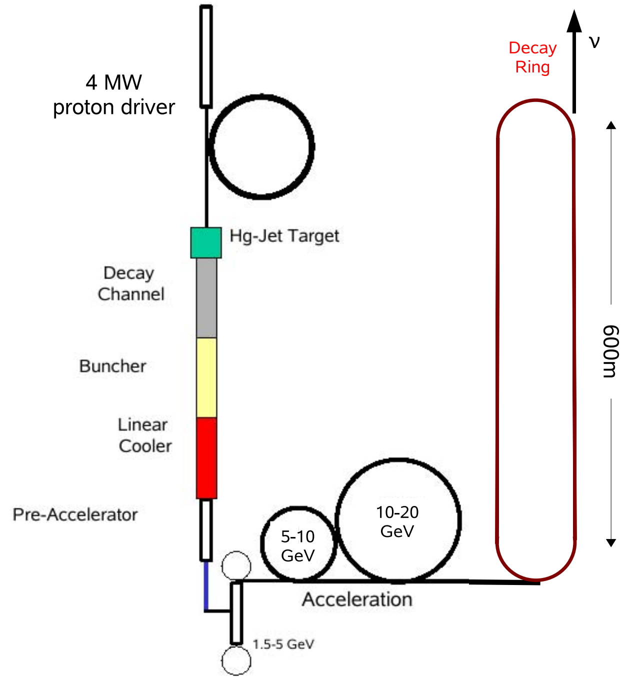

Figure 1: Schematic layout of a neutrino factory

Plans are now in place for a fully International Design Study (IDS) in which all members of the community will take part. As a prelude, a call was made in August 2005 for the physics case for a facility to be re-evaluated, and options for the accelerator complex and neutrino detection systems to be re-assessed. The principal objective of this so-called International Scoping Study was to lay the foundations for a full conceptual design study of the facility. ISS was hosted by the U.K's Rutherford Appleton Labora-

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tory, and the work plan was prepared in collaboration with the ECFA/BENE network in Europe, the Japanese NuFact-J team, the US Muon Collider and NF Collaboration, and the UK Neutrino Factory consortium.

GOALS OF THE ISS ACCELERATOR STUDY

The ISS structure comprised a steering group overseeing main work packages covering accelerators, detectors and neutrino physics. This paper covers only the work of the Accelerator Council, headed by M. Zisman (LBL) with R. Fernow (BNL), R. Garoby (CERN), Y. Mori (KURRI), R. Palmer (BNL) and C. Prior (RAL) as members. The main goal was to identify a linked complex of accelerators that could deliver the kind of neutrino beams at the detectors required by the physics working group. Muon energies of 20 GeV upgradable to 50 GeV are needed, and pulses of both neutrinos and anti-neutrinos were requested, separated by about 100 ns at detectors roughly 3000 km and 7500 km away. Not all scenarios prove compatible and some areas - for example, the target - pose greater problems, and therefore limitations, than others.

PROTON DRIVER

At the start of the accelerator chain, the proton driver sets the muon bunch structure that subsequently generates the neutrinos at the far detector systems. In addition to cost, the following factors influence its design specifications:

- The required production of 10^{21} neutrinos per year;
- Muon yields as a function of the proton energy and of the target material;
- Heating and stress levels for the target material;
- Muon capture as a function of proton bunch extent;
- Proton pulse structure and time duration on the target;
- Peak beam loading levels in the $\mu^{\pm}$ accelerators;
- Bunch train stacking in the μ^+ and μ^- decay rings.

After considering these, the proton driver specifications have been set at:

- An average beam power of 4 MW, a pulse repetition frequency of 50 Hz and a kinetic energy of 10 ± 5 GeV.
- An rms proton bunch duration of 2 ± 1 ns and a proton bunch number of either three or five in each pulse.
- A sequential extraction delay of $\geq 17\ \mu$s per bunch
- A pulse duration of $\leq 40\ \mu$s for a liquid mercury target or $\leq 70\ \mu$s for a solid metallic target.

The beam power needed from the proton driver was set at about 4 MW at the first NF conference in 1999 and the ISS saw no reason to change this recommendation. US Study I based its design around the Fermilab main injector with a booster upgraded to the megawatt level, and Study II assumed an upgraded AGS would form the driver for the facility. Theoretical studies at RAL have led to designs for 4 MW drivers based on synchrotrons at 5, 8, 15 and 30 GeV, and a 10 GeV FFAG accelerator fed from a synchrotron booster. CERN's NF study was based on a 2.2 GeV superconducting linac (later increased to 3.5 and then 5 GeV) and a system of accumulator and compressor rings, and Fermilab has subsequently undertaken design of an 8 GeV linac, which is now favoured over an upgraded synchrotron booster. These drivers have different architectures and together produce proton beams with large range of energies, repetition rates, and pulse structures. A comparative table was published in [8] and one of the tasks of the ISS team was to consider the suitability of each machine for a revised Neutrino Factory, assessing which might be adapted to meet the requirements.

In order to generate bunches of pions and muons from the target with a sufficiently small longitudinal emittance for acceleration, the proton driver is required to deliver its beam power in bunches of 1-3 ns (rms) duration. Typical design features are illustrated by the RAL 10 GeV FFAG-based driver, shown in Figure 2.

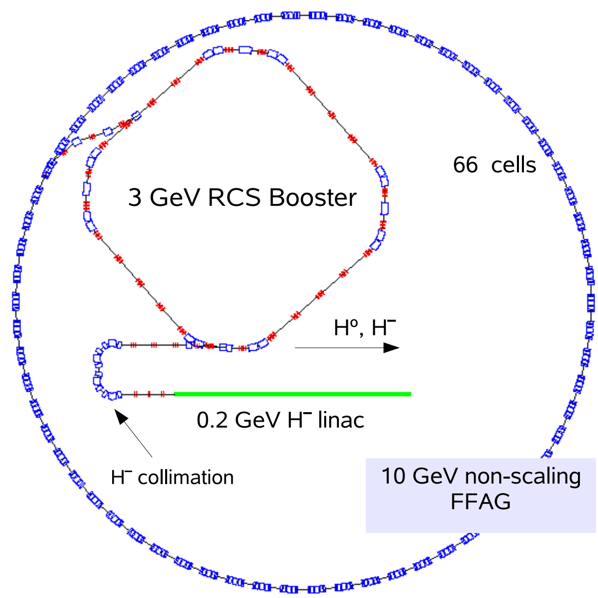

Figure 2: 10 GeV proton driver based on a synchrotron booster and an FFAG accelerator

High beam intensity is required, with small longitudinal emittance, which is considered to be achieved most easily by charge-exchange injection at about 200 MeV. In this model, an H^- linac, featuring a fast beam chopper to facilitate low loss injection, injects (after collimation in a 180° achromatic arc) into a 0.2-3 GeV rapid cycling synchrotron. An RCS seems most appropriate for this type of beam accumulation, and the injection scheme, which dictates the lattice design, is based on ideas developed for the European Spallation Source (ESS) [9]. The linac current is 30 mA (after chopping) and three bunches [1] each of 1.67×10^{13} protons are accumulated in the ring. The beam is then transferred to a 3-10 GeV non-scaling FFAG accelerator. An FFAG is chosen because it allows a high duty cy-

[1] Operation with five bunches is also possible.

cle and thus lower RF accelerating fields; adiabatic bunch compression is eased; and (compared with options based solely on synchrotrons) single booster and driver rings and transfer lines can be used, saving cost. The FFAG has the additional advantage that the bunches can be held in their compressed state and transferred to the target as needed in order to reduce stress in the target and to create the required muon bunch separations ($\gtrsim$ 100 ns) in the final decay rings.

Scenarios based on full-energy linacs, such as that developed at CERN using the superconducting proton linac (SPL), require higher beam power and dedicated rings for the bunch compression. First designs also had around 140 bunches in each pulse, which is now recognised as an unsuitable bunch pattern for target and detector requirements. However a new scheme at CERN using a series of holding rings may have partially resolved the problem.

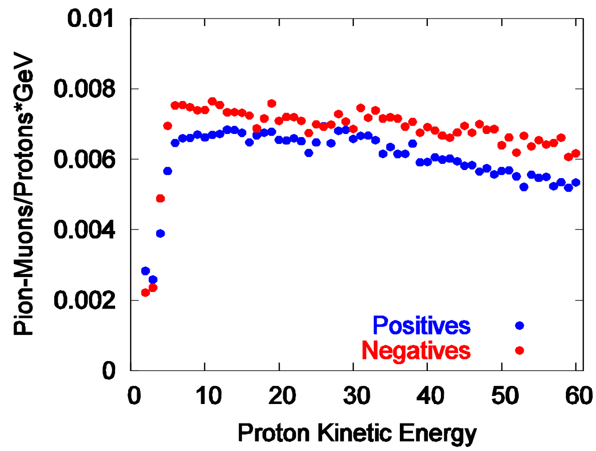

Figure 3: Muon production efficiency for a mercury-jet target as a function of proton driver beam energy.

TARGET

During the ISS, an investigation was carried out of the different distributions of pions/muons coming from different target materials for different proton driver beam energies, repetition rate and bunch length. Liquid mercury, carbon, copper and tungsten targets were considered, under beams from 1-120 GeV and bunch lengths up to 10 ns. The MARS code (versions 14 and 15) was used and the resulting distributions tracked through a model capture and cooling channel using ICOOL. The figure of merit assumed for comparison was the number of muons per proton GeV that were captured within transverse and longitudinal acceptances of 30π mm.rad and 150π mm.rad respectively. It was found that a mercury target at 10 GeV performs about 10% better than at 24 GeV (the AGS energy), that carbon is best at 5 GeV but that mercury at 10 GeV is about 20% better than carbon at 5 GeV both for μ^+ and μ^-. A sample comparison for mercury at different energies is shown in Figure 3; note that, although the curves are fairly flat, there is a peak at about 10 GeV and the benefit of going to higher energies (such as the ability to achieve shorter bunches and thus better performance) is outweighed by the additional cost.

Increasing the driver repetition rate lowers the stress on the target because of the reduced intensity per pulse. It also reduces the beam loading in the RF accelerating cavities. However, at the same time, the average power consumption in the RF systems is increased. The ISS team chose 50 Hz as a benchmark, which is regarded as an acceptable and achievable compromise. The proton pulse length also relates to the dynamic stresses in the target, so that a liquid mercury jet target would perform best at very short pulse lengths whereas a solid target would prefer a longer pulse. Such considerations suggest that some models of proton driver are much better suited to certain types of target. Liquid mercury was chosen for the ISS baseline target; however a moving solid target is not ruled out and development work continues.

MUON FRONT-END

Pions emanating from the target need to be captured and controlled as they decay into muons. For a Neutrino Factory a system of solenoids with tapering fields is used. The muons are then passed through an RF phase rotation system that reduces the energy spread of the beam and increases its bunch length. The transverse emittance is then reduced in an ionisation cooling channel to optimise the overall beam intensity in the accelerating stages of the facility.

A comparative study was undertaken in the ISS in an attempt to identify the front-end channel likely to produce the greatest number of neutrino events, assuming the same pion production estimate from a 10 GeV proton beam. The channels, which differ mainly in their choice of RF frequency, were:

- the Japanese design Nufact-J, with a frequency of 5 MHz; this has no cooling and uses large aperture FFAGs for muon acceleration;
- the CERN linear channel with cooling and a frequency of 88 MHz; and
- the US Study IIa linear cooling channel and a frequency of 201 MHz.

The only scheme that meets the design goal of 10^{21} muon decays per year is the US Study IIa channel. This is able to transmit muons of both signs. The channel has a total length of just under 300 m and starts with 12 m of capture solenoids varying from 20 T down to 1.75 T, followed by a 100 m section where the pions decay to muons. In the next 50 m, the muons undergo adiabatic bunching scheme in RF cavities of modest gradient, followed by RF phase rotation with higher gradients and frequencies that decrease as the beam progresses down the channel [10]. The energy spread is reduced to about 10% and the emerging beam consists of trains of about 80 interleaved $\mu^{\pm}$ bunches. Cooling then takes place in an 80 m solenoid channel with high gradient 201 MHz cavities and LiH absorbers. This reduces the transverse emittance from 17 to about 7.4π mm.rad, and

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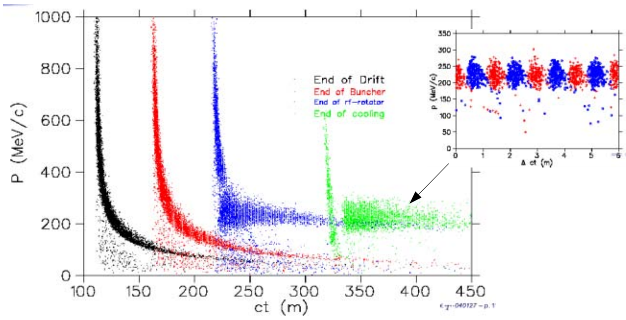

Figure 4: Simulation of muon front-end with adiabatic bunching scheme

increases the number of muons that can be accepted by the following accelerating structures by a factor of 1.6.

MUON ACCELERATION

Early schemes for muon acceleration relied on recirculating racetrack linacs to reduce costs by using multiple passes through the RF cavities. However they were limited by the number of passes and the maximum energy gain. In recent years a major step forward has been the development of FFAG accelerators for muon acceleration, instigated by work in Japan. Because the fields are fixed and magnets do not have to be ramped as in a synchrotron, rapid acceleration is possible, maximising the number of muons that can be accelerated and stored before they decay. Muon FFAGs are also likely to be cheaper, and one of the aims of the ISS study was to assess the various options to find an acceptable balance between performance and cost.

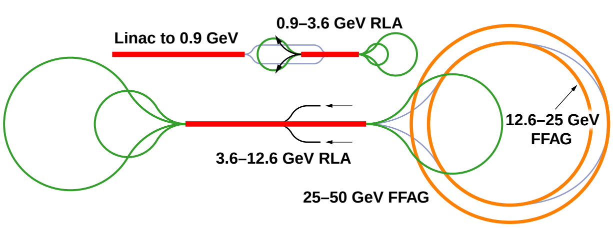

Figure 5: Neutrino Factory muon acceleration scheme

The muon beam emerges from the front-end with a mean energy of 138 MeV and has to be accelerated to an energy in the range 20–50 GeV; 25 GeV is used here for illustration. The chosen system, shown in Figure 5, starts with a pre-accelerator linac to avoid problems that the large muon beam size might create in a recirculator (RLA). The linac accelerates the beam to 0.9 GeV, at which energy an RLA is possible, and the phase slip, caused by the variation in time-of-flight with energy, is tolerable. The beam is then accelerated in two dogbone RLAs, making 3.5 passes in each, gaining energy to 3.6 GeV in the first, and to 12.6 GeV in the second (see Figure 5). Dogbone RLAs give improved cost efficiency over normal linacs and racetrack RLAs, but features such as the non-zero energy spread in the beam, the transverse beam size and the space required for magnet coils restrict the number of separate return arcs into which the beam can be directed and so limit the number of passes through the accelerating structures.

The use of FFAG accelerators effectively allows for a single arc for all beam energies and avoids the switchyard difficulties. But FFAGs work more efficiently at higher energies and study has revealed some difficulties in matching from one to the next. Cost optimisation also suggests that a factor of roughly two in energy gain should be the goal in designing such a system. The ISS chosen scenario therefore uses RLAs for the initial acceleration to 12.6 GeV and then an FFAG for acceleration to 25 GeV. A second FFAG can be added if an energy of 50 GeV is required.

The Nufact-J design was based on scaling FFAGs, which require wide aperture magnets and have large time-of-flight variations with energy. Superconducting magnets are needed and the cost is very high. It is also difficult to achieve high accelerating gradients at the low Nufact-J frequency (5 MHz), which is also incompatible with the optimal ISS front-end system described above. Recent developments have focused on linear non-scaling FFAGs, in which most of the bending is placed in the defocussing magnets, resulting in less orbit excursion and a relatively small time-of-flight variation. This in turn allows the use of the higher, 201 MHz, RF frequency and permits higher accelerating gradients. The main difficulty, revealed in the ISS study, is that the variation in time-of-flight for particles with large transverse amplitude causes phase slip at the RF cavities, and this can be particularly problematic for multiple stages of FFAGs. Nevertheless, pending the outcome of further studies, an RLA+FFAG accelerating system seems the best option at the present time.

MUON STORAGE RINGS

The final stage is to store the muons in dedicated rings where they decay in long straight sections directed at distant detector sites. The geometries evaluated in the ISS study were for racetrack, triangular and bow-tie shaped μ^+ and μ^- rings, and in each case designs were identified for 20 GeV rings upgradable to 50 GeV. The racetrack ring is generally the most flexible and is suggested as the ISS preferred model, though depending on the siting of the NF facility and the detectors, the triangular designs could conceivably be preferred. The racetrack ring shown in Figure 6 is configured for muons of one sign only; it has a single 600 m production straight and an overall circumference of 1608 m, giving an efficiency (=straight/circumference) of 37%. The ring can be pointed in a downward sloping tunnel towards any detector, so separate rings and separate tunnels would be used for detectors at 3000 km and 7500 km. An adaptation of the lattice, with shorter production straights and reduced efficiency, could be used for counter-rotating $\mu^\pm$ beams. The maximum tunnel depth is 435 m. Figure 6 also shows the optical parameters needed for such a design, with 15 cell superconducting FODO arcs and long dispersion-free straights. The racetrack design uses quadrupoles in the production section with $\beta \sim 153$ m and a transverse acceptance of 67.5π mm.rad. The ratio of muon to neutrino rms divergent angles is 0.11, within the specification of 0.14.

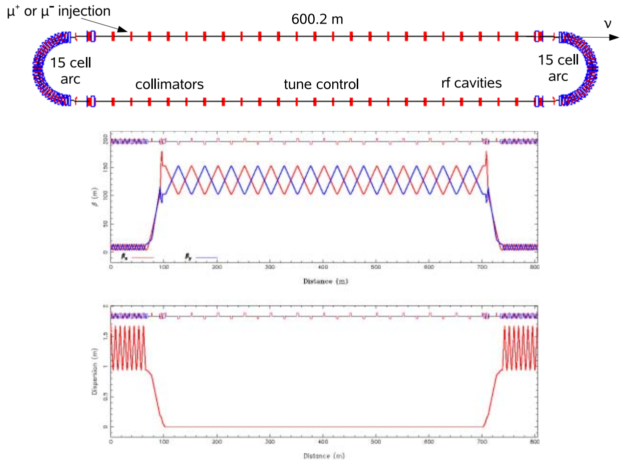

Figure 6: Racetrack decay ring; betatron and dispersion functions

Figure 7 shows a sample isosceles triangular ring with an apex angle of $52.8°$. The circumference is the same as for the racetrack design, but there are two production straights each of $\sim$ 400 m, giving an efficiency of $2 \times 24.8\%$. In contrast to the racetrack model, the triangular rings have been designed with eight 4 T solenoids in the straights. The ring dynamic aperture is improved through a lower β value (94.3 m) whileø the ratio of muon to neutrino rms divergence angles remains within specifications. Two such rings could be constructed in the same tunnel, with μ^+ in one and μ^- in the other, the bunches interleaved in time so as to give the required 100 ns separation between ν and $\bar{\nu}$ at the detectors. The choice of detector sites is however restricted. The

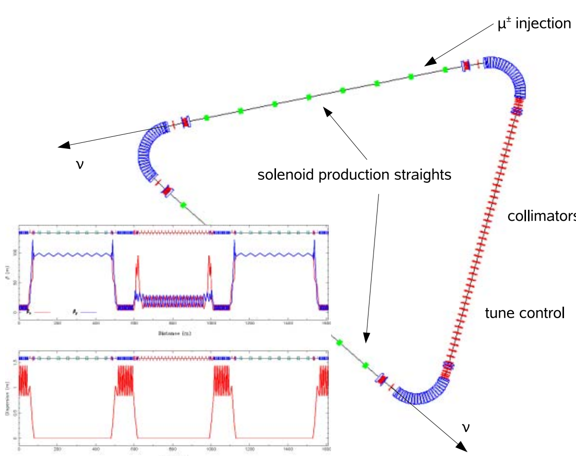

Figure 7: Isosceles decay ring, apex angle $52.8°$

upper straight would point at a detector at 3000 km, leaving freedom of rotation about this direction to determine a site at 7500 km. The apex angle could also be adjusted if necessary, An example for a Neutrino Factory based at BNL could be the Homestake mine in South Dakota (2525 km) and the Arlit gold mine in Niger (7369 km). The rings in this case would have an angle of $53°$, be oriented at $28°$ to the vertical with a maximum depth of 384 m.

The third model of a decay ring - a bowtie design - is similar to the triangular ring but with slightly longer production straights and greater efficiency. It would require a tunnel only 300 m into the ground. The muon polarisation is preserved and interferes with the accuracy of the related beam instrumentation. However this drawback may be overcome by suitably tuning the lattice.

NEUTRINO FACTORY R&D

Apart from theoretical studies, there are four main areas of NF R&D activity in progress at present, aimed to provide insight into the feasibility of many of the design ideas.

- The proton driver front-end test stand at RAL, designed to develop a high current H^- ion source and test fast beam chopping. This is essential to meet the requirements of very low loss ring injection and beam accumulation.
- The MERIT experiment at CERN to study liquid mercury jet targets. A parallel experiment at RAL explores thermal shock and lifetime in solid targets.
- The MICE experiment at RAL will demonstrate ionisation cooling, develop high gradient RF cavities in magnetic fields and study LiH absorbers.
- The EMMA project at the Daresbury Laboratory, constructing an electron model to test beam dynamics in a non-scaling FFAG. First results are expected in 2010.

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