THE INTERNATIONAL DESIGN STUDY FOR A NEUTRINO FACTORY

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Abstract

The International Design Study (IDS) is the successor to the International Scoping Study (ISS), which identified a baseline scenario for a Neutrino Factory [1]. IDS was launched in August 2007, with the aim of developing the baseline to the point where a full, technical design report can be written by 2012. The work is being carried out by several laboratories worldwide, in association with the EU/FP7/EuroNu consortium, which has a similar but complementary programme.

THE IDS BASELINE

The ISS report [2] identifies a preferred scenario giving a self-consistent model for a possible future Neutrino Factory (NF). For the IDS work, some parameters have been slightly refined to provide focus but the general scheme is shown to relative scale in Figure 1. Directed at particle physics research into the Standard Model, the aim of such a facility is to generate intense beams of neutrinos in order to investigate small values of the mixing angle θ_{13}, determine the mass hierarchy and search for CP violation in the lepton sector. This is achieved using a series of particle accelerators to accelerate muon beams to high energies where they decay in dedicated storage rings to give neutrino beams aligned on suitably chosen long-range detectors. The goal is 10^{22} muon decays averaged over a ten year period, or an average of 10^{21} per year of operation.

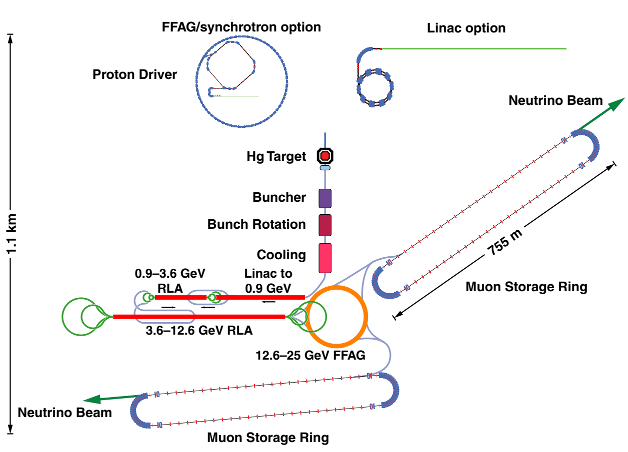

Figure 1: The IDS Baseline Neutrino Factory Design.

Proton Driver

In the NF process, a proton beam impinges on a pion target; the pions decay to muons, which are controlled and accelerated before they in turn decay to give neutrinos. The neutrinos therefore represent a tertiary beam and, since at each decay stage, the fraction of usable particles is small, the proton driver is required to generate high beam power on target. 4 MW was chosen as far back as 1999 and this figure remains the preferred option. Optimisation of the pion production from the target suggests a proton kinetic energy in the range 5-15 GeV. Other requirements are an operating frequency of around 50 Hz with pulses comprising one to three bunches, compressed to 1-3 ns rms at the target. The driver could be a high-current H^- linac feeding accumulator and compressor rings, a series of rapid cycling synchrotrons, or a booster synchrotron injecting into a Fixed-Field Alternating Gradient (FFAG) accelerator. Many designs have been developed in recent years and experience has been acquired through construction of the SNS at Oak Ridge and J-PARC in Tokai-mura, Japan. Only one proposal (the RAL synchrotron plus FFAG model) fits the ISS profile but development of this would require a great deal of study and R&D work on, as yet untried, non-scaling proton FFAGs. Work is underway for high power linacs at CERN (SPL and Linac4) and Fermilab (Project-X) and for upgrades to the ISIS accelerators at RAL. An issue that is being addressed is how these developments of existing infra-structure can be used or adapted to the needs of a future Neutrino Factory along the lines of IDS.

Target

The target on which the proton beam impinges has often been cited as the most challenging aspect of the Neutrino Factory. Both solid and liquid mercury jet targets were studied under ISS, with consideration given to effective pion production and the negative aspects of heating and thermal shock. It is generally accepted that fixed solid targets would work up to about 1 MW; but at higher beam powers, the target would need to be moving and ISS identified the liquid mercury jet as its baseline choice. The promise of such an option has been reinforced in recent months by the success of the MERIT experiment at CERN, where the 24 GeV proton beam from the PS was focused onto a mercury jet contained by a solenoid field up to 15 T [3]. Because of shock and cavitation issues, a liquid target operates best with short pulses of $\lesssim$40 μs (though MERIT suggests this could be longer), whereas solid targets, with the ability to relax during deposition, operate best with longer pulses $\gtrsim$70 μs. These requirements affect both the design of the driver and the downstream muon accelerators. Engineering the NF target is a major task to be addressed during IDS.

Front-End

The pions emanate from the target with a mean energy of about 130 MeV travelling in all directions. The front-end section that follows is designed to capture as many as possible as they decay to muons, and optimise the number that can be successfully transmitted through the subsequent accelerator complex. The baseline IDS front-end design has a 12 m solenoid capture channel with fields tapering from 20 T down to 1.75 T, a decay section of about 100 m, after which the muons undergo adiabatic bunching in a system of RF cavities of quite modest gradient. This is followed by RF phase rotation with higher gradients and frequencies that decrease with progress down the channel. The energy spread is reduced and the beam is formed into trains of about 50 interleaved $\mu^{\pm}$ bunches [4]. An 80 m section of ionisation cooling channel then reduces the transverse emittance and increases the number of muons that can be accepted by the accelerators by about 60%. Transmission was found to be about 0.2 muons per proton on target in a recent study at 24 GeV.

Ionisation cooling is a novel concept and a proof-of-principle experiment, known as MICE (Figure 2), is under construction in the UK to demonstrate feasibility. Single particle trajectories will be traced through LiH absorbers and high gradient RF cavities inside solenoid fields to determine emittance reduction. The strong magnetic fields have a seriously detrimental effect on the effective gradients, and quantifying the effect and finding solutions form a major R&D project.

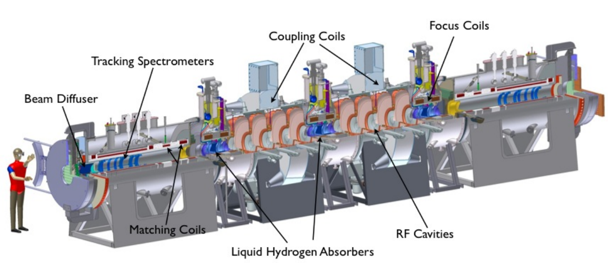

Figure 2: The Muon Ionisation Cooling Experiment, MICE.

Muon Acceleration

The acceleration scheme identified by ISS, and forming the baseline for the IDS study, is shown at the centre of Figure 1. The initial linac takes the beam to 0.9 GeV, at which problems over phase slip, caused by the variation of time of flight with energy, are diminished and the beam can be accepted by a series of two dog-bone re-circulating linear accelerators (RLA). Recirculators help reduce cost but the number of passes that can be made through the accelerating structures are limited. Once the beam reaches an energy of 12.6 GeV it is transferred to a non-scaling FFAG and accelerated to 25 GeV, the nominal top energy for the IDS study. A second FFAG would be needed for higher energy. FFAGs have the advantage of being much cheaper than RLAs but work more efficiently at higher energies. They also avoid the switchyard difficulties that RLAs present. On the other hand, their optics are complex, and there are issues still to be resolved over their performance with large emittance beams.

To explore beam dynamics in non-scaling muon FFAGs, an electron test model is about to be constructed at the Daresbury Laboratory in the U.K. Fed by the injector for the energy recovery linac prototype ALICE, EMMA [5] will accelerate electrons from 10 to 20 MeV in a ring 16.7 m in circumference. Experiments will test theories of non-linear beam dynamics, examine resonance crossing, study acceleration and benchmark simulation codes. First beam is due in September 2009.

Storage Rings

From the accelerators, the muons are transferred to purpose-built storage rings, with long production straights, where they decay to neutrinos which are directed to detectors at distances of about 3000 km and 7500 km. The most flexible designs are based on racetrack lattices (see Figure 1), which can be built to point towards any pair of fixed detectors, and can store both sign muons. The alternative triangular lattices, while more efficient, can send neutrinos to certain combinations of detectors only (dictated by the apex angle) [1]. Two triangular rings could be built side by side in the same tunnel, one serving μ^+ and the other μ^-. However, should one detector fail, the efficiency of the triangular rings would be halved, whereas all the muons could be diverted to the second of two racetracks, preserving performance. For these reasons the racetrack option has been chosen as the baseline for IDS.

IDS WORK PROGRAMME

Developing these ideas is the main task of the International Design Study for a Neutrino Factory. Engineering aspects of critical components need to be included, though at a later stage of the study, and a reasonably accurate cost estimate should be attempted. The work should also bear costs in mind throughout the study, with careful balance of trade-offs between expensive elements, such as ionisation cooling, and ease of operation of other areas, such as the muon accelerators, while preserving the goal of 10^{21} muons per year.

Proton Driver

The primary task of the proton driver group is to design at least one proton driver to demonstrate the NF specifications can be met. Several models are on the table and experience with, for example, J-PARC suggests the main areas of concern (chopping, injection, accumulation, acceleration) are in principle close to being solved. Bunch compression needs to be investigated further and, if possible, experiments carried out to follow on from those on the AGS at BNL in 1999. A cost and performance comparison with other options will be undertaken. Additional work will explore the possibility of a driver with only one proton bunch per pulse; this would benefit target performance and alleviate beam loading issues in the muon acceleration system, as well as opening a path beyond the Neutrino Factory towards a possible future muon collider.

Target

Development of both solid and liquid targets will continue, and the new idea of a powder jet will also be explored. The most important tasks, however, are to analyse the MERIT results to ascertain feasibility of a liquid mercury jet and - because of its impact on other areas of the NF complex - to identify the maximum length of proton bunch train on the target. Engineering work also needs to be carried out on the target infrastructure. This study has implications beyond NF into the whole realm of target-based accelerator physics; in particular it has high importance for upgrading spallation sources such as the SNS at Oak Ridge.

Front-End

The recently funded European neutrino study, EuroNu, focuses in its accelerator work packages on the muon front-end and, as such, the work is closely allied to IDS-NF. One of the main tasks is to re-design and re-optimise the whole front-end scheme, and carry out a full simulation. At least three different codes are available for this, providing opportunities for comparison, bench-marking and development. The aim is to track the pion/muon distribution generated by a target code such as MARS15 through the system so as to provide a particle data-set as input to the acceptance of the acceleration section. In addition, MuCOOL experiments [6] to explore the effects of magnetic fields on normal conducting 201 MHz RF cavities will continue. Success here is crucial, since if the peak RF gradient falls off to the extent that earlier studies found at 805 MHz and solutions cannot be found, current designs will not be viable.

Acceleration

In the acceleration work programme, a detailed analysis needs to be performed of all elements of the acceleration scheme, covering the pre-acceleration linac, dog-bone RLAs and FFAGs. The muon distribution from the front-end (fitting the full normalised acceptances of 30 πmm.rad transversely and 150 πmm.rad longitudinally) should be modelled through the entire system and used to optimise transmission. The tracking should be as detailed as possible and include decays as well as all the non-linear effects associated with such a large emittance beam with high momentum spread. The main ring lattice designs need to be developed for linear non-scaling FFAG accelerators, with particular attention being paid to the injection and extraction systems with kickers. Results from EMMA are expected to throw considerable light on non-scaling FFAG beam dynamics and allow issues such as the effects of resonance crossing on the beam to be addressed.

Storage Rings

Following earlier work (most of which was at 20 and 50 GeV), the storage ring lattices need modification and detailed analysis at 25 GeV, the nominal muon beam final energy chosen for the IDS study. Computational modelling using output from the acceleration section will be carried out to determine acceptance, emittance growth, losses and the flux distribution in the neutrino production straights. The three geometrical options of racetrack, triangular and bow-tie lattices need to be compared for performance, flexibility and cost. In the case of the bow-tie lattice, the muon beam polarisation is preserved and work is underway to ascertain the degree to which this may interfere with the accuracy of related beam instrumentation [7].

Overall

With successful completion of practicable designs for all sections of the NF complex, transfer lines will need to be designed to match the beam between them. While relatively straightforward for the proton driver, this could be a quite complicated task for the muon transport system and may entail modifications to pre-determined input and output parameters. The final stage will be to carry out a full end-to-end simulation from the target to muon decay. This may require code development, and the study should aim to identify transmission and quantify emittance growth at all stages of the NF complex.

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