The IDS-NF Accelerator Study

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Abstract. The paper outlines the plans of the accelerator group under the International Design Study for a Neutrino Factory. The International Scoping Study, completed in 2006, identified a self-consistent accelerator scenario, which will be used as a baseline design for future work. Essential R&D was also listed, suggesting a programme of development leading into the Conceptual Design Report, to be completed by 2012.

NEUTRINO FACTORY ACCELERATOR COMPLEX

The accelerator complex for a Neutrino Factory comprises five stages:

1. The Proton Driver, which is required to deliver 4 MW of primary beam power.
2. The Production Target, followed by a channel where pions are captured and controlled as they decay to muons.
3. The Muon Front-End, where the muons undergo phase rotation, bunching, and cooling to produce a beam suitable for acceleration.
4. The Muon Accelerators, where particles are accelerated very rapidly and use is made of relativistic Lorentz time dilation.
5. The Decay Rings, where the muon bunch trains are stored for $\sim$ 500 turns. The rings contain long production straights where intense pulses of ν and $\bar{\nu}$ are directed to long-range detectors.

THE LEGACY OF ISS

The recommendations of the 2006 International Scoping Study (ISS) are summarised in [1, 2] and shown schematically in Figure 1. Separate elements are drawn to relative scale, but the actual layout on the site has yet to be considered. Although there are other options that could be used, this represents a self-consistent scenario and is based on the status of current research and technological possibilities. Other ideas await further development before their viability can be fully assessed.

Requirements from the Accelerators

The ISS study took as its starting premise the following set of requirements:

- Muon energies of 20 GeV[1], with a system upgradable to 50 GeV;
- 10^{21} muon decays per year;
- Pulses of ν and $\bar{\nu}$ separated by $\sim$100 ns at detectors roughly 3000 km and 7500 km away.

The Accelerator Group looked at several alternative configurations, before arriving at specifications for a baseline recommendation; and then focused its study on the selected options as a prelude to the subsequent International Design Study (IDS). During the course of the work, a list of essential R&D tasks was created for IDS. However, the single year of the ISS study was insufficient to develop and validate tools for end-to-end simulations of alternative facility concepts; nor was ISS able to carry out an evaluation of cost.

ISS Accelerator Structure

If IDS is to build on present foundations, it is worth reviewing the structure of the ISS Accelerator Study. The programme was managed by the Machine Council, made up of

R. Fernow (BNL)
R. Garoby (CERN)
Y. Mori (KURRI)

[1] A revised figure of 25 GeV was used for the muon acceleration system in the later stages of the study.

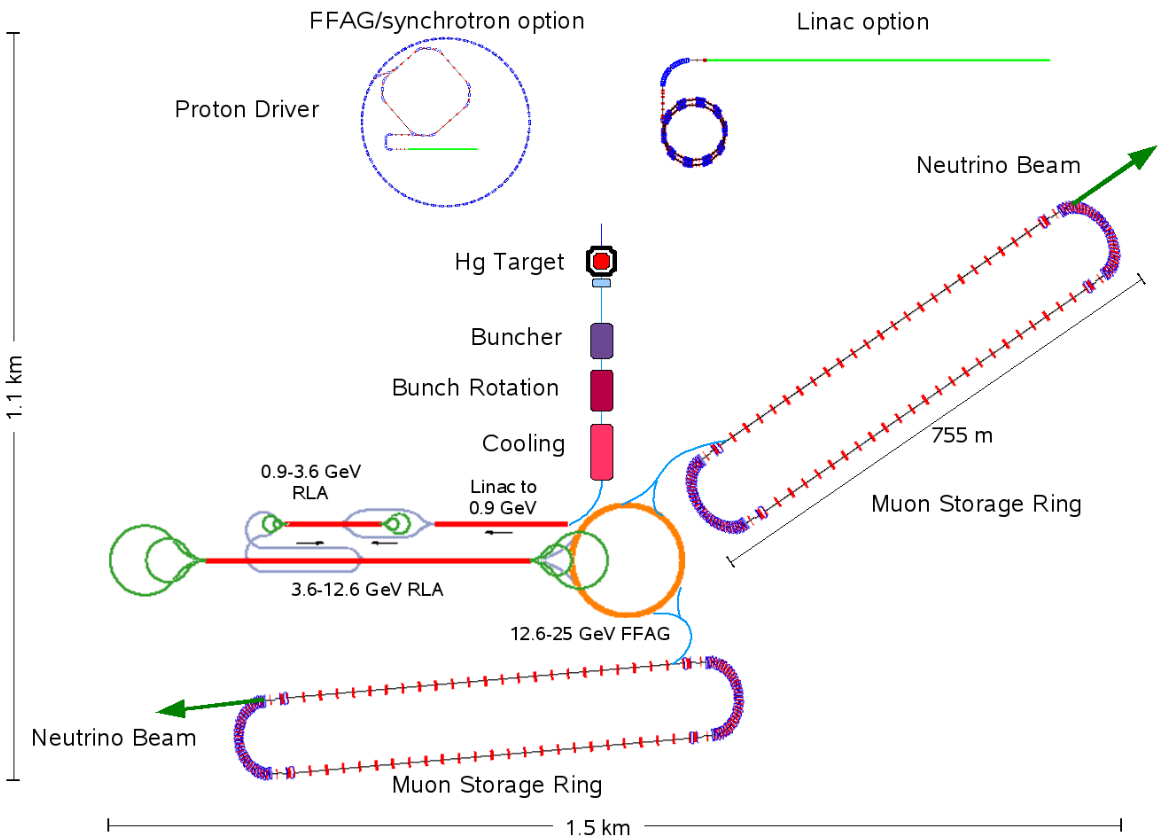

FIGURE 1. Schematic layout of a Neutrino Factory based on ISS recommendations

R. Palmer (BNL)
C. Prior (RAL)
M. Zisman (LBNL, Chairman).

The representation included those most actively involved in recent NF accelerator development in Europe, Asia and the United States. The Council appointed Task Coordinators, who had specific responsibility for guiding the study in their appropriate areas. These were:

- Proton Driver
  - R. Garoby, H. Kirk (BNL), Y. Mori, C. Prior
- Target
  - J. Lettry (CERN), K. McDonald (Princeton)
- Muon Front-end and Cooling
  - R. Fernow, K. Yoshimura (KEK)
- Muon Acceleration
  - J.S. Berg (BNL), S. Machida, Y. Mori, C. Prior
- Decay Ring
  - C. Johnstone (FNAL), G. Rees (RAL).

The Machine Council held monthly telephone conferences, and the group as a whole, including task leaders and others, held quarterly workshops, some of which were tied into full ISS meetings. A summary of the recommendations, pending publication of the final ISS Report, may be found at [2].

ISS Decisions

After reviewing earlier NF design studies, the Machine Council accepted that important advances had been made in many areas and there were many imaginative ideas, but that a fully self-consistent scheme had not properly been developed. The main change in the approach was that requirements in the storage rings and at the detectors were traced back through the whole accelerating structure to impact right through to the proton driver. Taking into account target capabilities, new requirements were identified in terms of intensity and time structure of the proton and muon pulses. Trade-offs were also considered between proton bunch duration, the amount of cooling and its affect on accelerator cost, and the need to transport both μ^+ and μ^- bunches in order to reach the required number of annual muon decays. For the proton driver, in particular, it was accepted that the choice would be site dependent - that it might be more likely that an existing accelerator might be developed rather than construction of a new NF-optimised machine - so a range of possible parameters has been given. Figure 1 shows two possible drivers, one based on a full energy linac plus accumulator and compressor rings (the SPL model at CERN, for example), and the other using synchrotrons (as at J-PARC) or a synchrotron plus FFAG (as proposed by RAL). Outside the specifications, however, it is not easy to see how a viable scenario can be devised.

The ISS parameters may be summarised as:

- Proton energy: 5–15 GeV
- Proton driver bunch structure: 3–5 bunches spaced by $\sim$17 μs
- Proton bunch length: 1–3 ns rms
- Repetition rate: $\sim$ 50 Hz
- Target: the baseline is liquid mercury
- Pion collection: 20 T solenoid capture system
- RF frequency: 201 MHz
- Phase rotation: baseline is the Neuffer bunched beam rotation scheme [3]
- Cooling: 50 m of ionisation cooling
- Acceleration: linac + two dogbone RLAs + one or two FFAGs
- Muon decay ring: nominally racetrack, but the choice is site dependent and options such as triangular or bow-tie rings could also be suitable.

The choice of proton driver energy is based on MARS simulations of the pion and muon distributions from different target materials and their transmission through the chosen muon front-end. Little is gained by spending more money to go to higher energy, while transmission falls below 5 GeV[2]. The scheme has a small number of proton bunches, which can be held in a compressed state in the driver and transported to the target at intervals of about 17 μs so that only one muon bunch train goes through the accelerators at any moment, thereby reducing beam loading.

Simulations using a new code [4] revealed difficulties in accelerating the large muon beam through FFAGs, where particles with large transverse amplitudes can suffer excessive phase slip at the cavities. This restricts the energy range. While a limited number of FFAG turns is fine, ISS decided that, for the baseline scheme, a linac and two dogbone RLAs would be used for the initial acceleration, with just a single FFAG for the final acceleration stage (12.6–25 GeV). Should the physics study indicate a higher energy is needed, a second FFAG might be added later.

The choice of muon storage rings will also depend on the site. For racetracks, two separate tunnels would be needed as the rings would point in different directions and reach different depths (see Figure 1). Geographical location and the local geological structure would therefore be important. Triangular rings would be housed in the same tunnel, but would be less flexible in choice of detector sites, and construction would be challenging. Similar remarks concern bow-tie designs, though their depth into the ground would be much less.

ESSENTIAL R&D

Various R&D tasks were identified by ISS and need to be progressed if the CDR is to be realised within the timescale envisaged.

Proton driver

Test facilities for the front-end of the proton driver are currently under construction at CERN and RAL to develop high current H^- ion sources, 4-vane RFQs and, in particular, demonstrate fast beam chopping. Clean chopping is essential for low-loss ring injection, which is a prime concern for a high intensity driver. The highest level of (pulsed) proton beam power ever reached is currently still only $\sim$180 kW (ISIS and SNS) and a factor of 25 increase is needed to reach the megawatt levels needed for NF. This is an enormous challenge and one that is unlikely to be readily met.

During the course of ISS, a driver was designed specifically to meet ISS requirements [2]. This includes a 3-10 GeV non-scaling FFAG with a new type of lattice referred to as a “pumplet" [5]. Since a non-scaling proton FFAG has never been constructed, an electron test model, scaled so as to replicate the main features (such as orbit excursion, resonance crossing and space charge tune depression) would need to be built and operated before the full machine could ever be contemplated. It should be designed to test both acceleration and nanosecond bunch compression. Note that such a machine would be completely different to the EMMA FFAG (*q.v.*) approved at the Daresbury Laboratory, which is aimed at testing features of the muon accelerating ring.

It will certainly be important to develop FFAG tracking codes with space charge to explore halo formation, beam loss and collimation issues in the proton ring. New fast codes for any type of proton machine are also important, as it is currently only feasible to model the many effects (injection, phase space painting, collimation, ramp-

[2] though the HARP results were still awaited at the time of writing.

ing, beam trapping, acceleration cycles) over a high number of machine revolutions in relatively simple ways because of the high level of CPU required.

R&D is needed to develop high gradient, low frequency RF cavities for synchrotrons and FFAGs, and to study beam loading issues.

Detailed analysis is needed of accumulator and compressor ring designs for linac-based options. A new SPL scenario has been proposed at CERN, and work is needed to develop the rings and verify the overall suitability as a driver for NF. Vacuum studies, analysis of instabilities (such as the electron cloud) and halo formation all need to be addressed.

Target

Both solid and liquid targets are under study, and a new development examines the possibility of a powder jet. The ISS suggested a liquid target as a baseline, partly because studies of solid targets - for example, for spallation sources - give confidence for a proton beam up to 1 MW but doubts remain beyond that. It is therefore important to progress the MERIT experiment at CERN, where a 24 GeV beam from the PS is being directed onto a liquid mercury jet. First results are expected in early November 2007. It is also important to explore high Z-targets and look at, for instance, a Pb-Bi eutectic, which would be solid at room temperature and easier to handle, but is easily liquefied for NF use.

Work will continue to explore the feasibility of solid targets capable of handling more than 1 MW of beam power. Shock tests and irradiation studies are being carried out; and the hot wire experiment at RAL is producing promising results. Since only a fraction of the proton beam power is absorbed by the target, beam dumps need to be looked at, and the general design of a solid target system undertaken, in particular exploring how a moving target can be fitted within the fixed high-field capture solenoid.

It remains also to determine whether the ISS proposals for the bunch structure are acceptable, and to examine, from the standpoint of the target, single bunch and bunch train spacings.

Muon Front-End

The muon front-end is arguably the most settled part of the NF complex, and work now relates mainly to a practical demonstration of cooling and preparing technical details of the bunching and phase rotation sections. The cooling demonstration will be achieved with completion of the MICE experiment at RAL, but there are several associated aspects of R&D, such as the development of high gradient cavities that operate in strong solenoid magnetic fields. Studies are also being undertaken of the recent idea of filling cavities with hydrogen gas, which acts as an insulator and helps prevent RF breakdown. Thermal tests of absorbers with LiH sandwiched in beryllium will be carried out. Other cooling channels will also be studied - encompassing Guggenheim, helical, and dogbone ideas, some of which include options for 6D cooling. The system also needs to be optimised by balancing cooling channel performance against the acceptance of the accelerating systems.

Acceleration

With non-scaling FFAGs identified as possible cost-effective accelerators for large emittance muon beams, there has been a need for a practical demonstration via a small electron model. That goal will be met with the construction of EMMA at the Daresbury Laboratory. The intention is to explore non-linear beam dynamics, examine resonance crossing, study acceleration (time of flight etc), test theory and benchmark FFAG codes. First beam is planned for September 2009.

Other items of R&D include the use of high frequency cavities in scaling FFAGs. Operation of superconducting RF cavities in close proximity to high-field magnets needs to be demonstrated, and the requisite gradients achieved. It will be important, too, to examine further the harmonic number jump proposals (BNL), which could be used both for proton and muon acceleration; a hardware test is a possibility. New non-linear modelling codes would be useful, not only to answers questions that are beyond the scope of existing software, but also to add to the repertoire for bench-marking.

With the ISS decision to rely on two dogbone RLAs for acceleration (see Figure 1), the limitations to the number of passes caused by transverse beam size, energy spread and the space for magnet coils need to be addressed. Similarly, the phase slip problems discovered in passing from one FFAG to another should be re-visited and solutions found.

Decay Rings

In contrast to the Front-End, the decay rings represent the least well developed area of the Neutrino Factory. Lattices for racetrack, triangular and bow-tie options now need to be examined in detail, with full non-linear tracking in models that include collimation and decay. There is tremendous power in the muon beam and consequently substantial heat load in the magnets. Novel designs of combined-function superconducting magnets are needed to deal with this.

Detailed tracking studies of the decay rings should be undertaken. The ZGOUBI code could, for example, be modified, while other code development would be beneficial. The overlap with the Beta-beams ring and the tools used for that study should be monitored closely.

The bow-tie model preserves polarisation and further studies need to be undertaken to assess the effect on the sensitivity of beam instrumentation. Since the ring optics show a nearby polarisation resonance, this might be used to alleviate the problem.

Finally, the possible sites for a Neutrino Factory and the associated detectors should be looked at further, including geological surveys of the suitability of the underlying substructure to depths down to 450 m.

NF AND RELATED WORK WORLDWIDE

In assessing the level of IDS manpower and what work might be carried out on the time-scale available, it may be worth reviewing research currently being carried out world-wide. This is by no means an exhaustive survey and is intended only for guidance.

In the UK, there is a conceptual design study programme, research into solid targets, the proton driver front-end test stand, the non-scaling FFAG ring EMMA, MICE and RF Cavity development. Much of this list - especially MICE - represents international collaborations, with the UK serving as host nation.

At CERN, Linac4, a 160 MeV high intensity pulsed proton injector for the PS complex, has been approved for construction; studies are being carried out on the SPL and accumulator and compressor rings. CERN staff also take part in an EU-funded FP7 programme to explore most NF aspects, but with emphasis on the muon front-end. The international MERIT experiment is currently testing the behaviour of liquid mercury jet targets in an intense proton beam.

Other work in Europe includes FFAG study at LPSC-Grenoble (including medical applications) and FFAG modelling at the University of Rostock. There is also proton accelerator work at laboratories in France and Italy.

In North America, several national laboratories are involved in NF-related development: BNL (muon and proton accelerators, targets), FNAL (neutrino superbeams and muon collider), J-Lab (RLA/dogbone), LBNL/Cornell (High gradient RF), TRIUMF (FFAGs); while organisations such as Muons Inc. are making advances in novel ideas for cooling.

Research in Japan covers FFAG development at KURRI, the PRISM project at Osaka and the J-PARC accelerator complex, with a wide range of applications and areas for study.

The NF community should also note recent developments in the Muon Collider field. Overlap in the projects includes the proton driver and the muon front-end up to and including cooling, and there is an obvious benefit in forging close links and collaboration.

IDS ACCELERATOR PROPOSALS

There had been insufficient time by NUFACT'07 for the IDS Accelerator Group to be identified and a structure put in place. The following have provisionally agreed to serve as the Management Team:

Scott Berg (BNL)
Malika Meddahi (CERN)
Yoshiharu Mori (KURRI)
Chris Prior (RAL).

It is hoped that Mike Zisman (LBNL) might also agree to be involved. No specific programme has yet been identified, though the team expect to meet informally in the normal course of events in the period September to December 2007. It is realised that there is no target expert included in the list and that none of the team has the background needed if the IDS is to contain a large element of engineering-related study. These issues will be addressed as the study progresses.

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