PROCEEDINGS OF SCIENCE

Start to End Simulation of a Neutrino Factory

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Studies of most of the constituents of the accelerator complex of a Neutrino Factory are now sufficiently advanced to identify a baseline design, and simulation of the muon beam, from the pion target to the decay rings, should be a near-term possibility. This paper, an abbreviated version of note IDS-NF-003 [1], considers the main issues to be addressed in computer modelling and highlights such difficulties as interfacing between different accelerating structures. It summarises the main simulation codes, identifying their strengths and limitations. Finally, it outlines a procedure for a coordinated work programme aimed at ensuring the success of the Neutrino Factory project.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

PoS(Nufact08)083

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1. Introduction

While computer modelling plays a large part in the design of any accelerator facility, the Neutrino Factory is so diverse in the nature of its constituents as to make reliable, accurate simulations harder to perform and yet even more important before engineering work can go ahead. Each section must be individually modelled in detail to give confidence that it performs to expectations. Then a final start-to-end simulation has to be carried out to demonstrate compatibility and ascertain the output neutrino flux to the long-range detectors.

The preferred constituent accelerators of a Neutrino Factory are based on the recommendations of the International Scoping Study [2] and are: a high power proton driver, a pion production target, the muon front-end, a series of muon accelerators and finally a muon storage ring which directs the neutrinos from the decay through the Earth to the detectors. The target itself effectively acts as an interface between the proton driver and the muon accelerators. The pions that it produces have a distribution that is a function of both its geometry and the parameters of the impinging proton beam. The sections that follow the target control and transport the muon beam, and differ widely in their purpose and mode of operation. Thus modelling codes need to treat the large aperture, high field solenoid capture channel; the technically difficult bunching and phase rotation sections; the novel, and as yet untried, ionisation cooling channel, with its overlapping rf gradients and solenoid fields; a sequence of muon linacs, dog-bone RLAs and FFAG accelerators; and finally specially designed muon decay rings with a variety of geometries. Modelling could well require several different codes and raise important issues relating to their compatibility, capabilities and underlying physics. The status of benchmarking needs checking as well as an understanding of each code's strengths and weaknesses. It is unlikely that any one code can achieve a full simulation at the present time, though it may be possible to identify one or more candidates that could be developed to that end at some future stage.

2. Feasibility

Ideally a start-to-end simulation would start with the beam from the ion source in the proton driver and track it through to the Neutrino Factory target. The pions produced would then be followed as they decay to muons through the remainder of the accelerator complex. However the treatment of a proton beam is very different to the approach adopted for muons. Beams in proton drivers have generally quite small transverse dimensions and can be simulated by paraxial equations of motions with third order chromatic corrections. The muon beam in a Neutrino Factory will be very much larger and tracking will have to include terms to a much higher order to achieve the same degree of accuracy. In the proton accelerator, complex mechanisms such as beam chopping and injection phase space painting have to be modelled, and require specially written codes. Most importantly, high intensity proton beams experience severe space charge effects, and taking this into account means that all simulation particles need to be propagated together in time, so that techniques such as ray-tracing, commonly used for muons, are excluded.

A survey of codes suitable for modelling proton accelerators is given in [3] and a spreadsheet comparing capabilities and limitations can be found at [4]. Codes like WARP-3D and GPT can treat the beam coming from the ion source and the initial acceleration. Specialist codes, such as

PARMTEQ, could be used for the RFQ. For the main linac, there are many codes available of which IMPACT is probably the most recent and subject to the most sustained development. Detailed calculation in linear accelerators is perfectly feasible because they are generally single-pass and many millions of simulation particles can be used to explore transmission, emittance growth and halo formation. Rings, however, are harder to model because of the large number of revolutions to be tracked (maybe 20,000 in a synchrotron for example); and during the injection, trapping and acceleration cycles, the beam is constantly evolving, necessitating full 3D-analysis. The codes most able to model self-consistently in realistic CPU-time are ORBIT and SIMBAD. Other codes, such as SIMPSONS, could do the full 3D simulation but would be heavy on computing time.

There is much experience of modelling accelerators from work on projects such as SNS and J-PARC, and development will carry on independently to provide faster, more accurate, modelling codes for the proton driver. But, so far as the treatment of muons is concerned, it should be acceptable to generate a model distribution from the Neutrino Factory target using a proprietary code like MARS, using as input some predetermined ideas about the impinging proton beam. MARS has built-in data from experimental studies of particle production, such as HARP, and is constantly being updated as further information becomes available. The main issue with muon tracking is beam loss and decay. Studies show that for every pion generated by the beam on target roughly 0.2 muons are within the acceptance of the subsequent accelerators. When decays are included, steps have to be taken to ensure that enough particles are being tracked to the end to provide reliable statistical data. Some options are listed in [1].

3. Codes Available for Muon Tracking

The proton codes mentioned above are not suitable for handling muon beams in NF-like channels at the present time, but others have been constructed for this purpose in recent years.

ICOOL [5] is a 3-dimensional tracking program that was originally written to study ionisation cooling of muon beams, but has since developed to cover pion collection, rf phase rotation and acceleration in FFAG rings.

Muon1 [6] started from a need to model the pion capture channel, where particles can have wide ranging energies and directions of travel. With subsequent development, it now has the potential to model most, if not all, of the muon sections of the Neutrino Factory.

G4MICE [7] is based on GEANT4 and was developed specifically to model the MICE ionisation cooling experiment [8]. It is now capable of treating a range of combined accelerator and detector simulation.

G4Beamline [9] was also developed from the GEANT4 toolkit, and is intended to perform accurate and realistic simulations of beam-lines and related systems using single-particle tracking. Its flexibility has been demonstrated by simulating complex beamlines like MICE and the Neutrino Factory Study II SFOFO muon cooling channel.

OptiM was used at Fermilab to model the Tevatron and originated as a linear optics code, similar to MAD but with an integrated GUI. For Neutrino Factory studies it has been used to handle beam optics in the initial muon linac and the downstream dog-bone RLAs.

S-Code [10] is a new code developed to treat FFAG accelerators in a very general way. It has been used successfully to model EMMA, the electron model of a non-scaling muon FFAG under construction in the U.K. [11], and also produced the first attempt at a continuous simulation of a muon beam in a Neutrino Factory[12].

ZGOUBI [13] is a ray-tracing code that computes particle trajectories in arbitrary magnetic and/or electric field maps or analytical models. The code is a compendium of numerical recipes for simulation of most types of optical elements encountered in beam optics. Its versatility is demonstrated in [10], where examples include simulations of a radial FFAG, a spiral FFAG accelerating protons from 17 to 180 MeV (ignoring space charge), a linear FFAG lattice with serpentine acceleration, and an isochronous muon FFAG based on a pumplet lattice. A recent application has seen a study of muon beam polarisation in a bow-tie storage ring.

4. Work programme

Of all the codes described here, Zgoubi is arguably best able to simulate the Neutrino Factory from the exit of the cooling channel through acceleration to the decay rings. S-Code and possibly G4Beamline would be good candidates for cross-checking.

Assuming that a single repository has been set up providing read-access, the following are among the necessary conditions for success of the project.

- Ensure there is one single person (the “Co-ordinator") who has responsibility for co-ordination between all sections of the simulation study. The Co-ordinator can decide who should have write-access to the files in the central repository.
- All codes should be properly documented and user manuals regularly updated.
- The set of MARS files or equivalent for input to the muon front-end should be updated and added to as appropriate. These should allow for changes in target materials and geometry, as well as effects of any alteration in the proton beam.
- Master lattices files should be stored in the central repository and notification sent to the start-to-end simulation group whenever any are revised. Files should be labelled with version numbers and accompanied by a note of changes made, as appropriate. Note that sets of files for tracking may need to comprise more than a single input file to a beam optics code.
- Attention should be paid to interfaces between different codes and, where necessary, conversion modules written so that output from one code can be directly imported to another. The fact that different codes may use different units should also be taken into account. It might be useful to identify a standard format in which data-sets are stored, with modules available to convert files between each one of the codes in use and this standard. Interfaces between codes would then always be via the standard structure.
- All beam distribution files should be stored in the same repository, clearly labelled with time and date and any special characteristics, as appropriate. Uploading to the central repository should be via the Co-ordinator, who has responsibility for assessing the exact status of the data-sets (a master data-set that should be used for all subsequent simulations, or an alternative based on a new idea for study of some special features only, for example).
- It is important to ensure that all files are properly backed up on a regular basis.

- Rigorous attempts should be made at comparison between codes. Given the list above, there are at least two codes capable of modelling different regions of the muon part of Neutrino Factory, and it should be confirmed that they predict similar beam behaviour and output similar quantities to an agreed level of accuracy. Where there are discrepancies, these should be reported to the Co-ordinator and attempts made to track down the source.
- Codes that rely on experimental information (such as the effects of different absorber materials, for example) should be updated as new data becomes available, with users notified via the Co-ordinator.

The aim is a start-to-end simulation that is reliable, gives confidence that all aspects have been investigated in detail, provides enough information for engineering and construction, and gives confidence that there are no hidden surprises in store when operation goes ahead.

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