Simulation Packages in Accelerator Studies for the ν Factory

V. Daniel Elvira

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

Abstract. The muon collider and the neutrino source are very challenging projects. Recently, a feasibility study for a 20 GeV muon storage ring yielding on the order of 10^{19} muon decays per year has been successfully completed by the muon collider/neutrino source collaboration. Simulation tools are crucial to support these conceptual design efforts. In this paper, we will present different software packages used in simulations related to the neutrino factory study.

INTRODUCTION

Theoretical arguments indicate that new physics, beyond the standard model, associated with the electroweak gauge symmetry breaking and fermion mass generation will emerge in parton collisions at or approaching the TeV energy scale.

The LHC (hadron collider under construction at CERN) will provide hard parton-parton collisions with typical center-of-mass (COM) energies of a few TeV. The route toward TeV-scale lepton-antilepton colliders is less clear. In circular e^+e^- colliders the energy loss increases as E^4/ρ, where E is the particle energy and ρ the radius of the orbit. Linear colliders avoid this problem but would be very long (30-40 km) to attain the TeV energy scale. In addition, radiation during beam-beam interaction would limit the precision of the COM energy (1). For a lepton with mass m the radiative energy losses in a circular orbit are inversely proportional to m^4. This means that the energy loss problem could be solved by using muons ($m_\mu \approx 207 m_e$), therefore enabling higher energies to be reached and smaller rings to be used (2, 3).

A muon collider would be a unique facility for neutral Higgs boson studies through the s-channel resonance production, since the cross section is proportional to m_μ^2 (more than 40,000 times larger than in a e^+e^- collider). Measurements can also be made of W boson and Top quark pair production as well as, eventually, supersymmetric particles. The muon storage ring could also be used as an intense source of neutrinos of well-defined flavor to study the ν-mass hierarchy, the mixing matrix driving flavor oscillations, and CP-violation.

Both the muon collider and the neutrino source are very challenging projects. Recently, a feasibility study for a 20 GeV muon storage ring yielding on the order of 10^{19} muon decays per year has been successfully completed by the muon collider/neutrino source (ν/μ) collaboration (4). Simulation tools are crucial to support these conceptual design efforts. In this paper, we will present different software packages used in simulations related to the neutrino factory study (5). In particular, we will discuss the packages used to simulate the accelerator section which would perform ionization cooling, the main challenge in the design of both the neutrino source and the muon collider.

DESIGN AND TECHNICAL CHALLENGES

The neutrino source is based on an intense proton beam driven onto a target. The outgoing pions are captured by a solenoid and then decay into muons which are cooled (beam size in position-momentum space is reduced), accelerated, and transfered to a storage ring. A fraction of the muons will decay in a straight section, which will produce an intense, well collimated neutrino beam.

The design of the target is an important technical issue to address. The cooling section or channel is, however, the main challenge to face. Accelerator physicists define “emittance” to measure the size of a beam in position-momentum space. The simplest expression for a muon beam normalized emittance, assuming there are no correlations between the six coordinates defining the state of a muon, is:

$$E_N = (\sigma_x \sigma_{p_x} \sigma_y \sigma_{p_y} \sigma_{ct} \sigma_E)/m_\mu^3 \,.$$

The cooling factor is defined as the ratio of emittances at the end and the beginning of the channel. The large emittances at the end of the capture solenoid, are a manifestation of the pions coming out of the target at large angles. As a consequence, the beam equations are not linear. In other words, theoretical predictions based on linearized envelope equations or linear transport matrices are not a good approximation to the problem. The use of solenoids as focusing elements is a unique feature of the neutrino source design. Conventional quadrupole based focusing cannot be used due to the large emittances involved.

Ionization cooling is the principle used to reduce the beam size. The muons are directed to low Z absorbers (typically liquid hydrogen or lithium hydride). The muons loose momentum both longitudinally (z-direction) and transversely. An electric field, applied as the beam goes through r.f. cavities, replenish the muon momentum only in the longitudinal direction. A cooling effect should be observed for muons in the plane transverse to the beam direction. Muons are heavy enough so that the cooling effect produced by energy loss is greater than the heating effect due to multiple scattering.

The unprecedented technical challenges in the design of the new generation of accelerators are very demanding on the software packages used for simulations. They should not only support different types of r.f. cavities, magnetic fields, and provide very precise tracking capabilities over long distances. They must also allow the introduction of absorbers with complex geometry and good modeling of dE/dx, straggling, and multiple scattering.

ACCELERATOR SOFTWARE

Many beam physics software packages were used to simulate different elements of the neutrino factory. We will concentrate only on those extensively used for the cooling simulations. For completeness, we cite in this section several other packages utilized in the neutrino source design:

- MARS(6) is a Monte Carlo code for simulation of hadronic and electromagnetic cascades, muon and low-energy neutron transport in shielding and in accelerator and detector components. It was used for pion production and target simulations in the neutrino source design.

- MAD(7) (Methodical Accelerator Design) is a computer program to design and calculate the properties of particle accelerators. COSY INFINITY(8) is an arbitrary order beam dynamics simulation and analysis code. It allows the study of accelerator lattices, spectrographs, beamlines, electron microscopes, and many other devices. MAD and COSY INFINITY were used for lattice design of the neutrino source re-circulator linear accelerator and muon storage ring.

- MAFIA(9) is a multi-purpose ECAD system designed to solve all kinds of electromagnetic problems. It was used to generate electromagnetic field maps of r.f. cavities which were then interfaced to other simulation packages.

SOFTWARE FOR COOLING SIMULATIONS

For conceptual design, fast and simple programs (mostly privately developed by a single author) were used. Once we agreed on the basic design of a cooling channel, it was necessary to perform a detailed simulation, which included a realistic modeling of the geometry, the electromagnetic fields, and the physics processes. Two packages were supported: ICOOL(10) and DPGEANT (based on GEANT3(11)). Here are the basics about both packages:

- **ICOOL** is being developed by Rick Fernow at Brookhaven National Laboratory specifically for muon cooling studies associated with the ν/μ project. It is written in Fortran, and includes a well targeted library maintained by the ν/μ collaboration. It comes as a pre-built executable and is user-driven via a simple ASCII file, where generic accelerator elements like solenoids, dipoles, r.f. cavities, etc can be defined. The ability for modeling these elements is therefore limited. Their geometry is also restricted to 2D (longitudinal and transverse directions). No graphic capabilities are available.

- **DPGEANT** is based on the popular HEP detector simulation kit tool developed at CERN (GEANT3). It has been upgraded by Paul Lebrun at Fermilab to perform double precision tracking and support electric fields. It is written in Fortran, and includes an extensive physics library maintained by CERN. The user has to define the beam line elements, that is both the volume shapes and electromagnetic field maps. This implies more flexibility but also more work. The geometry of the accelerator elements can be defined in 3D but is limited to a set of pre-defined shapes. Primitive graphics capabilities are available.

Both packages simulate the physics processes associated with dE/dx, delta rays and Moliere multiple scattering (ICOOL is based on the GEANT3 implementation). ICOOL was developed on a PC running Windows, but it also runs on SGIs, SUNs and CRAYs. GEANT3 has been ported to virtually all computers used in HEP. Typically, we use DPGEANT on a PC running LINUX. The speed of the two packages is approximately the same.

A COOLING EXAMPLE USING GEANT4

GEANT4(12) is the object oriented C++ version of the CERN GEANT package. It is the result of a collaborative effort of more than 100 physicists around the world. It offers several obvious advantages like an interface with CAD systems, more basic shapes (new shapes and physics processes can be added with no changes in the tracking code), a more complete set of EM processes, better hadronic physics, and modern 3D visualization. In addition, double precision is built-in. Other reasons to migrate to GEANT4 are that C++ is a language better suited than Fortran for large software packages with a large number of contributors, and that the new generation of students and computing professionals are not proficient in Fortran anymore (or willing to use it). In addition, CERN will probably discontinue support for GEANT3 at some point in the future (new accelerator projects are long term). Good visualization and geometry flexibility is not just a luxury but a need when studying complex cooling channels like the helical wiggler which seeks to achieve emittance exchange using wedge absorbers inside a solenoid plus a dipole. The principle behind this channel is the use of a dipole which rotates in the transverse plane along the longitudinal direction to produce an increasing p_z dispersion as a function of the radial distance (r) to the center of the beam (large p_z corresponds to large radius). In this way, the longitudinal emittance is reduced by the effect of the absorber being increasingly thick as a function of r. Figure 1 (side view) shows a muon (trace in red) moving along a helical channel. The yellow and green wedges are the absorbers and the blue disks are an ideal representation of r.f. cavities. Open Inventor (13) allows direct manipulation of the objects on the screen, plus perspective rendering via the use of light.

CONCLUSIONS

The complex problems we are facing in the design of the next generation of accelerator machines call for large and multidisciplinary software packages which take elements from accelerator, particle, and even plasma physics. At Fermilab, we are migrating toward GEANT4 for detailed simulations, and developing classes of beam physics related objects (solenoids, r.f. cavities, etc) to facilitate the application of this tool kit to accelerator physics.

I would like to thank my colleagues from the ν source/μ collider collaboration for their contributions to this work.

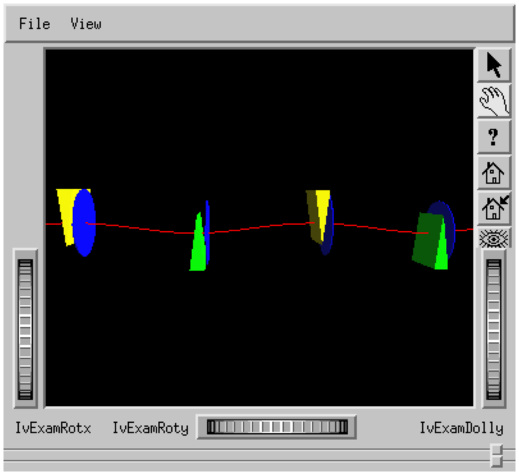

FIGURE 1. Side view of a helical cooling channel (Open Inventor).

REFERENCES

1. Tigner, M., in *Advanced Accelerator Concepts*, edited by J. S. Wurtele, AIP Conf. Proc. # 279 (AIP, New York, 1993), p. 1.
2. Ankenbrandt, C., *Status of muon collider research and development and future plans*, Phys. Rev. Special Topics - Accelerators and Beams, **2**, 081001 (1999).
3. HTTP://WWW.FNAL.GOV/PROJECTS/MUON_COLLIDER/HISTORY.HTML
4. The Muon Collider/Neutrino Source Collaboration, *A Feasibility Study of a Neutrino Source based on a Muon Storage Ring*. Submitted to Phys. Rev. Special Topics - Accelerators and Beams. FERMILAB-PUB-00-108-E, Jun 2000. 158pp.
5. Lebrun, P., *Computational Needs for Muon Colliders and Muon Storage rings*, ICAP2000 conference , Darmstadt, Germany (2000).
6. HTTP://WWW-AP.FNAL.GOV/MARS
7. HTTP://WWWSLAP.CERN.CH/ FCI/MAD/MAD_HOME.HTML
8. HTTP://WWW.BEAMTHEORY.NSCL.MSU.EDU/COSY
9. HTTP://WWW.CST.DE/MAFIA/MAINPAGE.HTM
10. R. C. Fernow, ICOOL: *A Simulation Code for Ionization Cooling of Muon Beams*, Particle Accelerator Conference, 1999, New-York, paper # THP31. HTTP://PUBWEB.BNL.GOV/PEOPLE/FERNOW/ICOOL/README.HTM
11. HTTP://WWWINFO.CERN.CH/ASDOC/GEANT_HTML3/GEANTALL.HTML
12. HTTP://WWWINFO.CERN.CH/ASD/GEANT4/GEANT4.HTML
13. Open Inventor. Registered trademark of Silicon Graphics Inc.