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Tetra Muon Cooling Ring

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Overview of Neutrino Factory Simulations

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Abstract. We give a brief overview of recent simulation activities on the design of neutrino factories. Simulation work is ongoing on many aspects of a potential facility, including proton drivers, pion collection and decay channels, phase rotation, ionization cooling, and muon accelerators.

INTRODUCTION

The neutrino factory is considered by many people [1] to be the ultimate facility for producing large fluxes of well-characterized neutrinos for long baseline oscillation experiments. There are at present three well-developed schemes for neutrino factories based on muon storage rings from the U.S. [2], CERN [3], and Japan [4]. In addition studies have been done on numerous variations for parts of each of the systems. There is in addition a major alternative (beta beam) approach [5], where the neutrinos come from the decay of stored radioactive ions, rather than from muon decays. An overview of machine-related activities in this field in 2002 can be found in the summary of the Machine Working Group at NuFact02 [6].

In this review we will only consider work on the machine designs for neutrino factories. This leaves aside some related ongoing work on "superbeams" and muon colliders. Simulations for targetry and cooling demonstration experiments (MICE) will be omitted since they are covered in other papers in these proceedings. Besides classic Monte Carlo tracking, we generalize the definition of *simulation* to include other computer-aided system designs, such as new lattice designs.

The discussions that follow consider recent simulations on the proton driver, the "front end" systems and the muon accelerators. The front end of a neutrino factory is concerned with all the manipulations required to collect the pions off the target and to prepare a suitable muon bunch for acceleration.

PROTON DRIVER

The baseline CERN proton driver is a 2.2 GeV linac followed by accumulator and bunch compression rings. The baseline U.S. driver is a 16-24 GeV proton synchrotron, while the baseline Japanese driver is the 50 GeV J-PARC synchrotron. Although most recent driver work was done in connection with superbeam facilities, a MW-class proton machine would certainly also be suitable for a neutrino factory if it were built. A new study has been done [7] on upgrading ISIS to 1 MW proton beam power. A lattice has been designed for a new 8 GeV synchrotron operating at 16 Hz. The machine is about 3 times larger than the present ISIS machine, with a mean radius of 78 m.

PION COLLECTION AND DECAY

The baseline designs for pion collection either make use of a horn (CERN) or a tapered solenoid (U.S. and Japan). This is followed by a pion decay region, consisting of a suitable length of empty magnetic channel. New studies of the CERN channel have been made using ZGOUBI [8]. The simulation used realistic magnetic models for the quadrupoles, dipole and solenoids. A theory of π/μ longitudinal beam transport was developed in order to check the results. The simulation of the longitudinal phase space distribution of the muon bunch 40 m from the target agreed well with a MATHMATICA implementation of the theory. Work is under way to check the transverse phase space simulations and to include the effects of the finite size of the parent bunch.

An alternative CERN collection scheme switches the beam among four target and horn systems. A funneling system consisting of large-aperture quadrupoles and pulsed dipoles has been designed for collecting the four beams into a common decay channel [9].

Another decay channel optimization was done using MARS [10]. The initial beam distribution came from an 80 cm long graphite target. The pion collection was studied as a function of the adiabatic solenoid field taper. A 7.2 m long taper was found to work better than a short 2.4 m long one. The decay channel was 47 m long and used a solenoid field strength of 5 T. This was followed by a second tapered region that brought the final field value down to 1.25 T. Final yields were ~0.19 μ/p for each muon charge. This was an increase of 18% over the muon yields in the U.S. Feasibility Study 1.

BUNCHING AND PHASE ROTATION

The baseline neutrino factory designs make use of phase rotation to decrease the large initial energy spread in the muon beam. Phase rotation is done with induction linacs in the U.S. design and a linear 88 MHz RF channel for the CERN design. No separate phase rotation is required in the Japanese design since the FFAG accelerators have a momentum acceptance of ±50%.

An alternative U.S. scheme first bunches the beam using varying-frequency RF with adiabatically increasing cavity gradient [11]. Fig. 1 shows the bunched beam resulting from a 60 m long buncher. Studies have shown that 10 discrete frequencies are sufficient to get almost the maximum possible yield. This is followed by a short section to do a 90° phase rotation. The RF frequency for the rotator may have a slight "vernier" variation to maximize the throughput. Simulations have taken the phase-rotated beam and injected it into the U.S. Feasibility Study 2 cooling channel. Even though the phase rotated beam was not matched for this channel, the muon yield at the end of cooling was 0.22 μ/p, comparable to the yield in Study 2. These results have generated considerable interest because the system appears to be considerably cheaper than the induction linac solution and the system can in principle collect both signs of muon charges simultaneously.

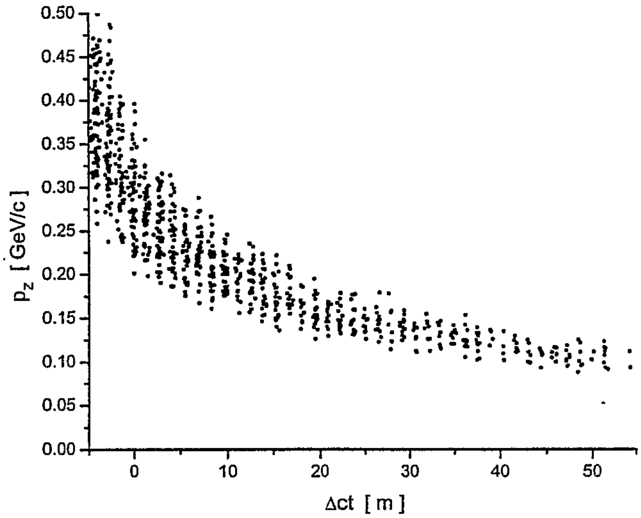

FIGURE 1. Longitudinal phase space following an adiabatic buncher. The initial beam distribution corresponded to 24 GeV protons on mercury. The decay channel length was 76 m and the buncher length was 60 m. The frequencies in the buncher varied from 385 to 216 MHz, while the gradient increased linearly to 6.5 MV/m.

Work is currently looking into producing both shorter and longer bunch trains. A short train would be necessary for injection into a cooling ring, while a longer train would result in a smaller longitudinal emittance in each bunch.

A second study has also considered bunching and phase rotation using high frequency RF [12]. In one configuration a fairly long drift space of 80 m is followed by three 4 m long bunching stations spaced 20 m apart. The frequencies of the cavities in the three stations are ~250, 200, and 165 MHz. This is then followed by another 80 m drift space. When the pulses in the resulting bunch train are overlapped, 73% of the particles lie within a 120° phase interval. Simulations of phase rotation of the bunched beam show that 71% of the particles have an energy spread $\Delta E/E < 10\%$.

IONIZATION COOLING

The baseline U.S. and European schemes use linear cooling channels. The baseline Japanese scheme does not use cooling. There has been a great deal of activity over the past few years examining the performance of cooling rings [13]. Unlike the linear channels in the baseline scenarios, rings also provide emittance exchange with the longitudinal phase space and produce much greater 6-dimensional emittance reduction.

Two common measures of cooling performance are

$$M(s) = \frac{\varepsilon_{6N}(0)}{\varepsilon_{6N}(s)} \frac{N(s)}{N(0)}, D(s) = \frac{N(s)/V}{N(0)/V}$$

where s is the accumulated distance traveled around the ring, ε_{6N} is the normalized 6-dimensional emittance, N is the number of muons and V is a fixed 6-dimensional acceptance volume.

The first successful cooling ring simulation was for the "tetra" ring designed by V. Balbekov [14]. Cooling has been successfully simulated using hard-edge modeling of the magnet fields with ICOOL, GEANT and Balbekov's private design code. Simulations of this ring have produced M-factors as high as 90. Work is in progress on improving the modeling with a more realistic description of the fields. Realistic field maps have been made using TOSCA [15]. As a first step towards more realistic modeling hard-edge simulations have been made leaving gaps in the lattice at the locations where flux returns and field clamps would be located. Extra focusing coils were placed symmetrically at the ends of the solenoid to match into the bending dipoles. The transmission dropped by about 25% when 15 cm gaps were inserted. Other studies are examining the effects of allowing the solenoid fringe field to extend into the dipole region. Recent simulations using COSY have looked at the effects of including fringe fields [16]. Adding fringe fields to the dipoles had a particularly dramatic impact on the performance. Future studies will include the effects of adding damping in the simulations.

A second family of ring coolers uses transverse focusing from quadrupoles or from rotated pole faces on the dipoles [17]. The basic strategy for the design of these rings was to first find a linear optics lattice using SYNCH. The performance was then studied with tracking in hard-edge fields using ICOOL. These rings produce different transverse emittances in the x and y directions since the emittance exchange takes place in the x-s plane. M-factors as high as 1000 have been obtained for some small dipole-only models. One 3.5 m circumference model in particular might be interesting to use for an experimental demonstration of ring cooling. Work has begun on using realistic field models for these rings. Preliminary studies with COSY indicate that the fringe fields could significantly degrade the predicted hard-edge performance. Other work is looking into whether it is possible to include lithium rods in the lattice to greatly reduce the transverse emittance.

The most realistic ring model is currently the RFOFO cooling ring [18]. This ring uses a lattice of alternating polarity solenoids for focusing. The bending field is produced by tipping the solenoid axes by 3°. Modeling of this ring is done with 3-dimensional, Maxwellian fields. The ring has a 33 m circumference divided into 12 identical cells. Energy loss occurs in wedge-shaped liquid hydrogen absorbers. The energy is restored using 201 MHz RF cavities with a field gradient of 12 MV/m. The minimum beta function at the center of the absorbers is 38 cm and the maximum dispersion is 8 cm. Because of the presence of a small radial magnetic field on-axis, the closed orbits follow approximately helical paths. Fig. 2 shows the performance of an "ideal" ring with realistic fields, but before the addition of windows or space for injection. The M-factor of the ideal ring is 112 and the D-factor is 8.9.

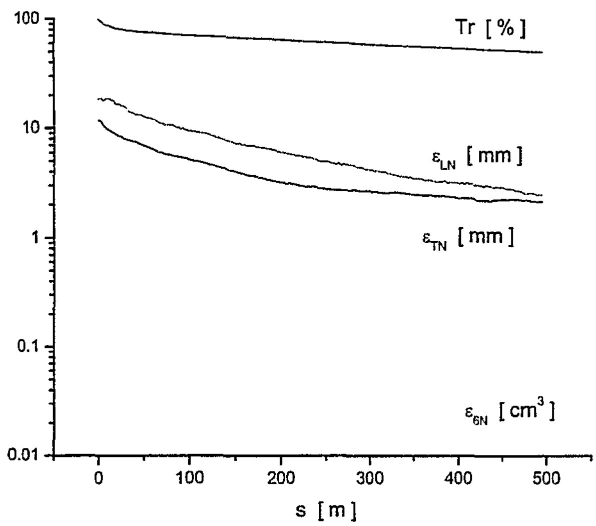

FIGURE 2. Performance of the ideal RFOFO ring cooler; normalized longitudinal, transverse and 6-dimensional emittances and transmission including decay as a function of accumulated distance. One turn is 33 m.

Studies [19] have looked at real world perturbations, such as adding aluminum windows around the absorbers, adding beryllium windows across the aperture of the RF cavities, and leaving two empty cells for the injection/extraction system. This realistic model gives a D-factor of 4.2, still indicating a significant increase in muons suitable for acceleration. Future work will concentrate on including this ring cooler as part of a complete neutrino factory front-end scenario.

The design of a racetrack shaped muon cooling ring has begun at RAL [20]. This design has the virtue of leaving long straight sections for injection and extraction. It uses solenoidal focusing and reaches a minimum beta function of 13 cm at the absorber locations. Tracking of single muons in the ring was done using Opera3D. Future work will include adding absorbers and RF to the ring simulations to study cooling.

Although the cooling performance of these rings looks promising, it is not clear at this time whether they will have a role to play in a neutrino factory[1]. Ring coolers have three serious problems that do not presently have satisfactory solutions. (1) The major uncertainty is whether it is possible to build a kicker with large enough strength and short enough risetime to efficiently inject the muon bunch into the ring. The problem comes from the fact that the muon bunch has a normalized transverse emittance (~12 mm rad) that is very large and that these rings have a small circumference (~35 m). Preliminary designs for a suitable kicker have 3 orders of magnitude more magnetic stored energy than the most powerful kicker built so far [21]. (2) It is uncertain whether the extra power deposited in the liquid hydrogen absorbers by the multiple

[1] There is no question that ring coolers will play a vital role for muon colliders.

passes in the ring can be successfully removed. (3) The 50 ns risetime of the assumed kicker and the small ring circumference limit the maximum length of the injected bunch to ~12 m. A suitable buncher and phase rotation system needs to be designed to collect most of the muons into a bunch train this short.

One possible scenario [22] is to take the beam from a bunch compressor ring designed for a muon collider and injected it into the RFOFO cooling ring. The simulated normalized transverse emittance was reduced from 6.3 to 2.5 mm, the normalized longitudinal emittance was reduced from 25 to 3.2 mm, while the yield fell from 0.11 to 0.054 μ/p in this exercise. Presumably a bunch compression ring specifically designed for a neutrino factory could improve the muon throughput.

MUON ACCELERATION

The baseline acceleration system for the U.S. and European designs is a Recirculating Linear Accelerator (RLA), similar to the electron machine at Jefferson Laboratory. The Japanese scheme uses a sequence of Fixed Field Alternating Gradient (FFAG) accelerators. Recent studies [23] have improved on the RLA design used in the U.S. Study 2. The optics was enhanced to give smooth transitions between the arcs and the linacs and in the spreaders and recombiners. Three families of sextupoles were used to restore longitudinal phase space linearity in the arcs. Multi-particle tracking studies showed only minimal emittance dilution with small particle losses of 0.8% from clipping the large amplitude tails.

There has been considerable activity on simulating the performance of FFAGs [24]. The scaling type FFAG is being studied primarily by the Japanese, while non-scaling designs are being examined by other groups. Scaling FFAGs have a betatron tune that is independent of energy. Non-scaling FFAGs have closed orbit variations and time of flight ranges that are small. Studies [25] of the first 0.3-1 GeV/c Japanese FFAG ring show that the accepted transverse emittance is 30 mm, while the longitudinal acceptance is 4.6 eV-s (13 m). Many of the recent simulations have concentrated on the performance of the 10-20 GeV ring [26]. The baseline triplet lattice has been compared with new singlet (FODO) and doublet lattices. The singlet ring has a radius of curvature of 55 m and uses 6 T bending fields. Tracking studies have been performed using the PTC code. The code can read in field maps from TOSCA, for example, then do symplectic kick-drift-kick tracking. Transverse acceptances and coupling between the horizontal and vertical planes has been studied. Non-scaling FFAGs are being studied with FODO, minimum emittance, triplet and racetrack lattices [24,27].

PROSPECTS

Simulation work on neutrino factories is still an active and productive area of research. Much of the current work is devoted to finding ways to improve the performance/cost ratio of future machines. New schemes continue to be proposed and examined. Fortunately code development has progressed in tandem with these new developments. Besides the topics mentioned above, investigations are also continuing on other alternatives, such as cooling channels containing high pressure hydrogen gas [28], quadrupole-focused linear precooling channels, and using FFAG arcs in an RLA [29]. Given continued support, one can anticipate much more simulation progress in the future.

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