EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 2000-026 (PP)

STATUS OF STUDIES FOR A NEUTRINO FACTORY AT CERN

H. Haseroth (for the Neutriono Factory Working Group)

Abstract

There is a strong interest from the physics community for high-quality, high-intensity neutrino beams as produced by a neutrino factory. With the help of other European laboratories, CERN has started a study on some of the many technological challenges of such a facility. Present ideas concerning the proton driver, as well as the muon accelerator complex, are presented and plans for the future are described.

7th European Particle Accelerator Conference, 26th-30th June 2000
Vienna, Austria

Geneva, Switzerland
11 July 2000

STATUS OF STUDIES FOR A NEUTRINO FACTORY AT CERN

H. Haseroth (for the Neutrino Factory Working Group)
CERN, Geneva, Switzerland

Abstract

There is a strong interest from the physics community for high-quality, high-intensity neutrino beams as produced by a neutrino factory. With the help of other European laboratories, CERN has started a study on some of the many technological challenges of such a facility. Present ideas concerning the proton driver, as well as the muon accelerator complex, are presented and plans for the future are described.

1 INTRODUCTION

The production of neutrinos with accelerators (neutrino factories) has gained considerable interest among its possible future clients. The original interest started with the study of muon colliders [1,2]. These colliders could open the way to lepton collisions at extremely high energies. Circular electron colliders are limited in energy due to the high synchrotron radiation emitted by the electrons. Although this radiation decreases with larger radius of the accelerator, it increases with the fourth power of the relativistic γ factor. For this reason it seems unrealistic to build circular machines with higher energies than LEP. The only possibility for higher energies seemed to be linear colliders with all their technical challenges. Another, more straightforward solution is the use of heavier leptons, as the synchrotron radiation at the same energy is much reduced because of the smaller γ which is inversely proportional to the rest mass. Muon beams seem to be possible candidates for this purpose. Muons can be readily produced by the decay of pions, which in turn can easily be produced by bombarding a target with high energy protons. The "only" remaining problem is the production of muon beams with the required density in phase space, necessary for collider operation. In spite of some impressive progress towards this goal, no technically feasible solution has yet been found. A substantial R&D effort will be required to make progress.

With the apparent discovery of neutrino oscillations and the increased interest in neutrino physics in general, the situation has changed drastically. What appeared to be almost science fiction in the context of muon colliders is now, due to the reduced requirements for a neutrino factory, much closer to reality. The R&D effort for the muon colliders turned out to be very useful for a neutrino factory, and the increased interest from the physics side has produced a high activity on the accelerator side, so that considerable progress has been made towards a neutrino factory. It is interesting to note that in turn a part of this progress is also beneficial for the design of a muon collider.

2 THE BASIC CONCEPT OF THE NEUTRINO FACTORY

The first part of the basic concept has been outlined above: a proton driver which delivers a high-power proton beam onto a target; a system for collection of the produced pions and their decay products, the muons. The resulting muon beam has to be accelerated and, to achieve an optimum intensity, the energy spread and the transverse emittance have to be reduced. This is done by “phase rotation” and ionisation cooling. After acceleration with a linac and “RLAs” (Recirculating Linear Accelerators) the muons are injected into a storage ring or rather decay ring, where they decay in long straight sections in order to deliver the desired neutrino beams. Different proposals have been made, e.g. [3], the latest being a study initiated by FNAL [4]. This study has the advantage that all subsystems have been (at least almost) properly engineered and it has demonstrated the technical feasibility of such a machine.

Our reference scenario (Fig. 1) does not pretend to be the best solution or to describe necessarily the machine which will finally be built. It is rather intended as a working scenario.

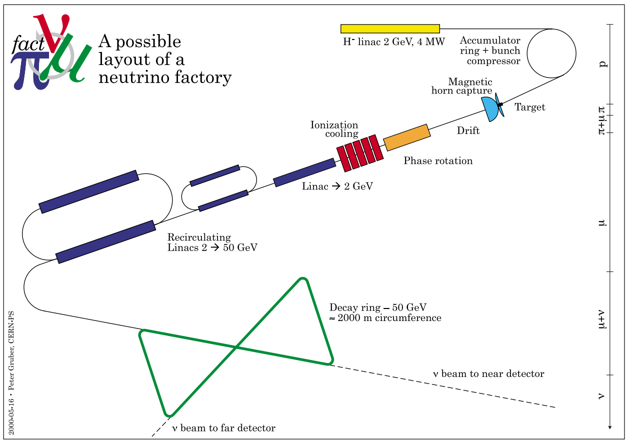

Figure 1- Possible Layout of a neutrino factory

The first part of a neutrino factory is the "proton driver" which, in order to provide an intensity of 10^{21} neutrinos/year, should deliver a beam power of the order of 4 MW. In the CERN scheme we have selected a linear accelerator with a beam energy of 2.2 GeV [5,6]. The reasons for this choice are the availability of LEP cavities and klystrons when this machine is shut down, and the desire to have a higher brilliance for the PS beam intended for the LHC. This linac accelerates H^- ions and operates at 75 Hz and a pulse duration of 2.2 ms with 11 mA. The beam is injected into an accumulator (charge exchange injection) and subsequently into a compressor ring to produce the necessary short bunch lengths of the order of nanoseconds. 140 bunches at a frequency of 40 MHz will be sent onto a target to produce short pion bunches decaying into muons which are captured, and reduced in energy spread and in transverse emittance. The muons are then accelerated to 50 GeV and injected into a storage ring (decay ring) where they are kept for the duration of their lifetime (1.2 ms at this energy). The muons decaying in the long straight sections of this ring produce the required neutrino beams.

3 THE MAIN SUBSYSTEMS

3.1 The Linac

The SPL (superconducting proton linac), actually an H^- linac, as proposed [5,6] is based on the idea of re-using the LEP cavities and ancillary equipment after its decommissioning. It would use the β=1 cavities of LEP in the energy range from around 1 to 2.2 GeV, and β=0.52, 0.7 and 0.8 cavities from 120 MeV to 1 GeV. The development of the β=0.7 and 0.8 cavities, being very much based on the original LEP cavities, a good part of the hardware can be recuperated. The β=0.52 cavities, however, need some more development. Below 120 MeV a drift tube linac will be used, being fed from an RFQ at 7 MeV. The RFQ will be split at 2 MeV for the installation of a chopper, necessary for minimising beam losses at the high energy side. First engineering layouts on the CERN site have been made.

3.2 Accumulator and Compressor Rings

The CERN-specific 2.2 GeV/75 Hz scenario, using the SPL, features an Accumulator and a Compressor ring in the ISR tunnel. Both rings have high-γ_t lattices ensuring fast debunching of the linac microbunches, as well as very fast bunch rotation (~7 turns) in the compressor. The feasibility of H^- injection and of the final bunch rotation has been shown. The accumulator lattice and the lattice of the intersecting compressor have been designed. More refined simulations, including the effect of space charge on momentum compaction and of the microwave instability, have given very satisfactory results [7]. The length of the ejected pulses is given by the circumference of the ring: 3.3 μs. It was possible to increase the number of bunches, originally 12 to 140 because of the use of rf cavities instead of an induction linac as in the FNAL study. This helps with space charge problems.

3.3 Alternative Proton Drivers

As it may turn out that 2.2 GeV is not an ideal energy for a neutrino factory, alternative scenarios to 4 MW proton drivers have been studied.

In close collaboration with RAL, a scenario for a site-independent synchrotron was established. A 5 GeV/ 50 Hz and recently, also a 15 GeV/25 Hz scenario was investigated, lattices were designed and H^- injection and final bunch compression was studied and shown to be feasible [8]. In case that low repetition rates would be needed, we have explored a 30 GeV/8 Hz configuration, using the ISR tunnel for the driver [9]. The high-γ_t-lattice of the latter provides naturally short bunches without compression.

3.4 Target

This device, which has to survive a 4 MW proton beam, is an extremely critical item, although only a small fraction of the beam power is lost in the target. For the moment we have kept only the specification of a 4 MW beam power, as established at the Nufact99 workshop in Lyon. No design has yet been made, but model tests are under way [10] for a pulsed liquid metal (Hg) target. So far the model has only operated with water (similar viscosity), but tests are foreseen in the near future with Hg. The next step will be to inject the Hg jet into a high magnetic field (which maybe necessary for the collection of the pions) and/or by exposing it to the ISOLDE beam at CERN. This beam, which has only 1.4 GeV, can however be adjusted to deliver the same power density as in our favoured scenario. The repetition rate of course will be lower by two orders of magnitude. It might be worthwhile to point out a few characteristics implied by our scenario (2.2 GeV, 75 Hz operation):

- the energy dumped in the target will be higher than in the case of a proton beam with higher energy (typically by a factor 2).
- the energy per unit volume is also likely to be higher.
- however, the energy per pulse is reduced because in our scenario the repetition frequency is higher.

In case a low-Z material can be used (e.g. Li), a substantial gain is expected for the production of positive pions. To profit from this fact, however, it is necessary to switch from high Z to low Z between different runs.

The HARP experiment [11] is intended to measure the production of pions and their characteristics for different target materials. The results of this experiment may be decisive for the future orientation of our study.

3.5 Decay channel, phase rotation, cooling, capture and first acceleration

The pions produced in the target have to be collected so that they are useful for the final production of a high-quality muon beam. The FNAL study and most other proposals use a 20 T solenoidal field for this purpose. Hence we foresee tests of our Hg target with a high magnetic field. Another possibility we explore is the possibility of horn focusing, where CERN has considerable experience. The critical issue is the high operating frequency of 75 Hz. More calculations, and tests, are required to establish the feasibility. The advantage of a horn could be its lower price and perhaps better collection efficiency.

The decay of the pions would take place in any case in a solenoidal channel where debunching occurs, i.e. there is a correlation between position and energy of the resulting muons. This energy spread will be reduced with rf cavities working with modest gradients in the range of 2-4 MV/m at 40-80 MHz. This rf scenario [12,13] is well adapted to our high repetition rate (75 Hz) and the large number of proton bunches impinging on the target (12 originally, now 140). Another advantage is that it works immediately with a bunched beam that is adapted to further acceleration in the subsequent linac. The characteristics of the rf cavities are similar to the American designs (closed with Be foils or grids), but have a more modest power consumption. The cooling follows basically the "standard" scheme of ionisation cooling, i.e. reduction of the total momentum of the muons (by ionisation losses of the beam passing through liquid H_2, LiH or Li) and reconstitution of the longitudinal momentum component with rf cavities. The following muon linac will have solenoid focussing up to around 1 GeV before acceleration to 2 or 3 GeV, operating at a multiple of the frequency used in the cooling channel.

3.6 Further Muon acceleration and Decay Ring

Two RLAs take the muons from the first linac to a final energy of 50 GeV, an energy which seems to be favoured by most of our possible future clients. Acceleration has to be fast, because of the limited lifetime of the muons, and to accelerate with a normal linac would be very costly.

To allow the muons to decay in a "useful" way, i.e. by producing neutrino beams in the desired direction and with a good quality, a muon storage ring operating at 50 GeV with a triangular shape, extending also in the vertical dimension, has been designed [14]. It sends neutrino beams from two long straight sections, in which the muon beam divergence is small, to two distant detectors at 1000 and 3000 km distance. It is calculated for a normalised emittance of about 1.67 mm and an rms momentum spread of 0.5%. The verification of the optical design included the tracking of many thousands of muons during their lifetime. The total height of the ring is less than 250 m and hence smaller than the thickness of the molasse near the CERN site.

4 CONCLUSIONS

A preliminary scheme for a CERN neutrino factory has been proposed. It is intended to continue this study and future work may well show that some elements of this scenario need substantial modification, or even replacement by other components. The results of the HARP [11] experiment expected for next year may also provoke some modifications.

5 ACKNOWLEDGEMENTS

The present work is the result of the effort of the Neutrino Factory Working Group at CERN. The help of other laboratories, in particular RAL, but also GSI, FZJ and CEA, and of members of the American Neutrino Factory and Muon Collider Collaboration is gratefully acknowledged.

REFERENCES

[1] C.M. Ankenbrandt et al., Status of Muon Collider Research and Development and Future Plans, Phys. Rev. ST Accel. Beams 2, 08001 (August 1992).

[2] B. Autin, A. Blondel, J. Ellis (Eds.), Prospective Study of Muon Storage Rings at CERN, CERN 99-02, ECFA 99-197 (April 1999).

[3] R. Palmer, C.D. Johnson, E. Keil, A Cost-Effective Design for a Neutrino Factory, CERN SL-99-070, (1999).

[4] N. Holtkamp, D. Finley (Eds.), A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring, FERMILAB pub-00/08-E, (2000).

[5] M. Vretenar (Editor), Report of the Study Group on a Superconducting Proton Linac as a PS Injector, CERN/PS 98-063 (RF-HP), (1998).

[6] R Garoby, M. Vretenar, Status of the Proposal for a Superconducting Proton Linac at CERN, CERN/PS/ 99-064 (RF), (1999).

[7] R. Cappi et al., Design of a 2 GeV Accumulator-Compressor for a Neutrino Factory, this conference.

[8] C.R. Prior et al, Synchrotron Based Proton Drivers for a Neutrino Factory, this conference.

[9] H. Schonauer et al, A Slow-Cycling Proton Driver for a Neutrino Factory, this conference.

[10] C.D. Johnson, Study of the Behaviour of a Pulsed Liquid Jet Target, CERN NUFACT-Note 27, (2000).

[11] Spokesperson: F. Dydak, Proposal to Study Hadron Production for the Neutrino Factory and for the Atmospheric Neutrino Flux, HARP PS-214, CERN-SPSC/99-35, SPSC/P315, (1999).

[12] A. Lombardi, A 40-80 MHz System for Phase Rotation and Cooling, CERN NUFACT-Note 20, (2000).

[13] A. Lombardi et al., Phase Rotation, Cooling and Acceleration of Muon Beams: a Comparison of Different Approaches. To be published in the proceedings of LINAC2000.

[14] E. Keil, A 50 GeV Muon Storage Ring Design, CERN SL/2000-013 AP, CERN NUFACT-Note 26, (2000).