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NEUTRINO FACTORY PLANS AT CERN

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For the Neutrino Factory Working Group

The considerable interest raised by the discovery of neutrino oscillations and recent progress in studies of muon colliders has triggered interest in considering a neutrino factory at CERN. This paper explains the reference scenario, indicates the other possible choices and mentions the R&D that are foreseen.

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1 Introduction

CERN is considering a neutrino factory [1,2,3] as a possible option for the post LHC era. In such a facility, electron-neutrinos and muon-neutrinos are created in equal amounts by high-energy muon decay. The detectors are located close to the source and at long (~ 700 km) or very long (~ 3000 km) distances. The problem is the production of intense muon beams and their rapid acceleration to the final energy. However, a very solid conceptual background exists, since muon colliders were studied in the 90's [4,5,6]. For less demanding neutrino production, the muon beam emittance can be higher than for a collider, and energy lower than 50 GeV is sufficient. The front-end of a muon collider, with a more modest ionization cooling section, thus inspires the design of most scenarios for neutrino factories [7], except the FFAG scenario. In the case of CERN, the availability of LEP cavities, the considerable experience with 40 and 80 MHz cavities, as well as site considerations have favoured a scenario based on low energy (2.2 GeV) protons. The factory consists of a proton driver, a target area, a muon front-end, a sequence of muon accelerators, and a muon decay ring.

2 The Proton Driver

A low-energy, high-power system consisting of a 2.2 GeV linac, a fixed-field accumulator and a compressor produce the 10^{16} protons/s required for having 10^{14} muons/s in the muon decay ring. The time structure and bunch length of the proton beam is appropriate for acceleration and storage of the resulting muon beam.

Since the CERN PS injectors (50 MeV Linac and 1.4 GeV Booster) cannot deliver the beam power required for a Neutrino Factory, a Superconducting H Linac (SPL) has been proposed [8,9] with an average beam power of 4 MW, an energy of 2.2 GeV, and a repetition rate of 75 Hz. It uses 116 of the 352 MHz superconducting LEP cavities for the acceleration from 1 GeV to 2.2 GeV, and similar cavities with lower β for acceleration to 1 GeV. The layout is shown in Fig. 2. Regarding the acceptable radiation level, the large aperture of the LEP RF cavities permits the transmission of the halo to the end of the linac, where scraping and dumping of the halo will be done before injection into the rings.

Figure 2. Layout of the Superconducting Linac

The SPL accelerates H^- (rather than protons, to allow charge exchange injection using a foil stripping into the following circular machine) in bursts of 2.2 ms duration. The muon lifetime at 50 GeV is about 1 ms, and each burst should be separated by at least 2 ms. The repetition frequency of 75 Hz of the SPL fulfills this condition. The beam should be accumulated to obtain further:

- a burst duration compatible with the circumference of the muon storage ring (i.e. <2 km). The burst length will be reduced by a factor of 660 by accumulation in a ring of suitable circumference, but the bunch length will be increased.
- a bunch duration compatible with the RF accelerating the muons. This reduction of bunch duration is done at the expense of an increased energy spread of the proton beam, which is unimportant for muon production.

The functions of accumulation and bunching are separated into two rings (Fig. 3) of 3.3 μs revolution time, corresponding to the length of the old Intersection Storage Rings (ISR) tunnel at CERN [10].

The 44 MHz RF captures the 352 MHz SPL bunches, in groups of 8, and there are 146 of them around the ring. For 2.2 ms SPL burst length, the charge exchange injection is made in 660 turns. At the end of the injection, the central part of the 44 MHz buckets is filled in a quasi-uniform way by the filamentation.

At the end of the accumulation, the 146 bunches are fast ejected and single-turn injected into the bunch compressor. This ring has the same circumference and also 44 MHz RF. The bunch compression is performed in 7 turns by phase rotation; the resulting bunch length on target is 3 ns.

Other scenarios have been studied for different proton energies, in collaboration with Rutherford Appleton Laboratory [11]: at 5 GeV/50 Hz and at 15 GeV/25 Hz, both with 2 boosters and two rings; and a 180 MeV/56 mA H linac, similar to the European Spallation Source design. A 30 GeV/8 Hz machine [12] injecting into the SPS ring above transition energy γ_t would provide naturally short bunches because of the high γ_t . It had been also studied for the case higher energy and lower repetition rate would be preferred.

In addition to its use for the Neutrino Factory, the SPL could provide a higher brilliance beam for the PS and improved beam characteristics for other experiments such as: CERN Neutrinos to Gran Sasso (CNGS) operated by SPS, Antiproton Decelerator (AD), Neutrons Time of Flight (n-TOF), and Isotope Separator On Line (ISOLDE). The 800 m SPL could be installed along the boundary of the CERN Meyrin site, close to the accumulator and compressor rings which could both be housed in the ISR tunnel.

3 Pion Production, Collection and Decay

Most evaluations are based on liquid jet targets inside solenoids, but no satisfactory engineering design has yet emerged. Active research is underway to produce practical systems of targets and collectors. The target could be a liquid mercury jet. Although only a small fraction of the beam power is lost in the 30 cm long target (2 radiation lengths), the temperature of the jet may rise by hundreds of degrees. For pion collection efficiency, the target is inside the magnetic field or very close to it. All the charged particles emitted forward whatever their sign, spiral in the field and reach the end of it if their transverse momentum is not too high.

The results of the HARP experiment [13] will establish data for the pion production. Meanwhile the generation of particles from a proton beam on a mercury target in a magnetic field can be calculated with codes for hadronic cascade simulations, such as FLUKA, with the data presently available.

An example of these calculations is shown in Fig.4, for a 2.2 GeV beam on a 30 cm long, 0.75 cm radius Hg target. The target is inside the 20-T magnetic field of a 15-cm diameter solenoid. The calculated total production per incident proton in forward direction is $\sim 0.1 \pi^+$ (average energy 310 MeV) and $0.075 \pi^-$ (average energy 288 MeV). This simulation [14] predicts that the forward production of π^+ increases by a factor 15 if the energy is increased by a factor 8 from 2 to 16 GeV. With 10^{23} proton per year on the target, the total neutron dose in the solenoid is $\sim 10^{11}$ Gy per year from neutrons and is $\sim 1.4 \cdot 10^{10}$ Gy per year from γ .

The collection of π^+ in an interval of ± 100 MeV around a central kinetic energy of ~ 200 MeV, corresponds to 40% of the forward yield, the momentum acceptance being imposed by the

Figure 4. Example of π^+ production (not normalized), by a 2.2 GeV proton on a 30 cm mercury target

Other options are also being considered for the collection of pions:

- a pulsed magnetic horn [7]. Particles of one sign are bent towards the axis; those of the opposite sign are deflected away (see Fig.5)
- a cylindrical liquid mercury target carrying a high pulsed current along its length, with a radial distribution of circulating mercury at both ends for cooling and shock-wave damping. This arrangement is not yet designed [15].
- a rotating solid target followed by focusing devices [7].

Figure 5. Principle of focusing by the transverse magnetic fields of a horn

4 MUON FRONT END

This is the section from the exit of the muon collector up to the entrance to the recirculator, according to the reference scenario [16,17].

4.1 Phase Rotation

At the end of a 30 m decay channel focused by a 1.8 T solenoid, 99% of the 300 MeV/c (or 191 MeV kinetic energy) π^+ have decayed. The bunching is partially lost, as the high-energy

Figure 6. Energy versus phase of a bunch after the target and after the 30 m. decay channel

4.2 Ionization Cooling

Cooling reduces the normalized emittance in order to fit the acceptance of the recirculators. It results from absorption of the energy in tanks filled with H_2 , so longitudinal and transverse momenta are both reduced. In each cooling unit, RF re-acceleration restores the longitudinal momentum, not the transverse one and the angle of the particle with the axis diminishes. The multiple Coulomb scattering counteracts the reduction of the angle. But within the present parameters, this effect is weak. The optics of the cooling line is setup to maintain a high divergence and thus make the cooling efficient. Fig.7 shows the reduction of the momentum by the energy loss (a), the increase of the transverse momentum by scattering (b), the re-acceleration (c), the rotation of the ellipse of emittance keeping the divergence high (d).

Figure 7. Ionization cooling, RF re-acceleration and rotation of the ellipse of emittance

4.3 Linear Acceleration

Figure 8 shows the linear acceleration of a bunch of particles in a linear accelerator.

- Cooling and associated re-acceleration are repeated again at 88 MHz with cavities of 15 cm bore radius, a field of 4 MV/m and built-in solenoids. A reduction of the emittance by a factor 4 is expected.
- Acceleration at 88 MHz (4 MV/m), then 176 MHz (10 MV/m), up to 2 GeV.

The muon losses expected from production through cooling and acceleration to 2 GeV are shown in Fig. 8:

Figure 8. Muon budget in the RF scheme, up to 2 GeV

A cooling experiment is to be studied at CERN using a PS proton beam at 26 GeV and a target area. An energy absorber associated with energy-compensating RF cavities could reduce the emittance by 5 to 10% [21].

5 ACCELERATION FROM 2 GeV TO 50 GeV

Rapid Cycling Synchrotrons, recirculators and Fixed Field Accelerating Gradient accelerators have been proposed for accelerating the muons to full energy. The CERN scenario uses recirculators, but an alternative solution, with FFAG rings, could avoid bunch rotation and cooling. FFAG accelerators have a very large acceptance, and the magnetic field, being constant with time, allows for fast acceleration. In principle, the radial extension of vacuum chamber and magnets is limited by a magnetic field varying with radius R as:

$$B = B_0 (R / R_0)^n$$

with large B_0 and n values.

Successive sector magnets with fields of alternating sign increasing with radius give a net curvature toward the machine centre. In a genuine FFAG as proposed at KEK [18,19,20], the closed orbits for different energies are similar and the number of betatron oscillations is the same for all energies. For machines with only a few turns, crossing resonance lines is not disastrous and keeping Q constant not a strict condition.

In CERN scenario, two recirculating accelerators RLA1 and RLA2 increase the muon beam energy to 10, then to 50 GeV [22]. Each consists of two linacs, with 352 MHz superconducting

isochronous. The beam acceleration occurs at the crest of the RF wave, and the muon energy spread, initially equal to 12.5%, is adiabatically damped.

Table 1. *Recirculating linear accelerators*

	RLA1	RLA2	
Energy	2 to 10	10 to 50	GeV
Number of turns	4	4	
Length of linacs	2×340	2×1900	m
Circumference	806	4442	m

6 MUON STORAGE RING

About 77% of the muons survive acceleration in the RLAs. They are then injected into the muon storage ring at 50 GeV, with two high-beta long straight sections aligned with the neutrino detectors at distances of 700 and 3000 km [24]. Neutrinos produced in the arcs are lost for physics, so arc length is minimized.

A short straight section in the arc could be used for short base line detector. Both triangular and bow tie shape decay rings have been investigated (see Table 2). The ring is equipped with RF to preserve the bunching of the muon beams, necessary for detection with position monitors and avoiding the depolarization of the muons. The normalized rms emittance is 1.7π mm rad; the aperture limit is at 3σ , the relative rms momentum spread is 0.5%. The muon beam divergence contributes quadratically to the divergence of the neutrinos, which is $\sigma'_v \approx 1/\gamma_\mu \approx 2 \cdot 10^{-3}$.

Choosing the contribution of the divergence of the muon beam to be ten times less, $\sigma'_\mu \approx (1/10) \sigma'_v \approx 0.2$ mrad, the normalized muon beam divergence is $\gamma_\mu \sigma'_\mu \approx 0.1$. The aperture limitation of the long straight section of 3σ limits the muon divergence to 0.6 mrad.

The average power density due to the electrons from the decays is 150 W/m. Due to the contribution of the long straight sections much higher power density is dissipated at the entrances of the arcs.

Table 2. Muon Storage Ring (bow-tie shape)

Energy	50	GeV
Length of straight section	576	m
Vertical extension of ring	150	m
Circumference	2008	m
Bending angle of arcs	2×250	deg.

The layout of the neutrino factory according to the preliminary study at CERN is shown Fig. 9. The machine tunnels will be constructed in the molasse layer in the vicinity of CERN.

Figure 9. Layout out of Neutrino Factory [24]

7 CONCLUSIONS

The CERN scenario of the Neutrino Factory is conditioned by the investigation of limited regions of the parameter space. A Superconducting linac, an accumulator and a compressor deliver a 2.2 GeV, 5 MW primary beam with the convenient temporal structure. Pions are collected close to the maximum of the production avoiding the need of a too large momentum acceptance. Compression and relatively modest energy cooling give the emittance and time structure necessary for the acceleration to 50 GeV and the decay of more than 10^{21} muon per year in the straight sections of a bow-tie decay ring. Other options are being studied in the US and Japan. The final choice of the parameters should emerge from the comparison of the various projects.

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