Neutrino Factories: Accelerator Facilities

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Abstract

This paper describes the accelerator facilities needed for a neutrino factory. Such facilities consist of several modules: A proton source, a proton target, followed by muon capture, muon cooling, muon acceleration and muon storage. The status of these modules is presented. The conclusions contain a discussion of the status of neutrino factory studies, and a programme for future research and development.

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1 INTRODUCTION

Fig. 1 shows a schematic layout of the Fermilab neutrino factory [1] which I use as example. The *proton driver* consists of a linear accelerator and a 16 GeV rapid-cycling synchrotron, and puts a MW proton beam onto the *target*. The *phase rotations* and the drift space between them use the correlation between longitudinal μ momentum and velocity to reduce the energy spread in the μ beam. *Cooling* reduces the normalized emittance by about an order of magnitude in each transverse plane. *Linac* and two *recirculating linacs* accelerate the μ beam that is stored in the *storage ring*.

Figure 1: Fermilab neutrino factory layout showing the most important *modules*.

2 NEUTRINO FACTORY MODULES

This chapter contains a discussion of five NF modules, namely proton sources, targetting and capture, cooling, acceleration and storage.

2.1 Proton Sources

The proton source should deliver a few short high-intensity bunches with a few MW of beam power W . This requirement is different from that in spallation neutron sources that also deliver a few MW of beam power, but in many long low-intensity bunches. The proton losses should be small in order to permit hands-on maintenance, and to avoid remote handling over most of the length of the proton source. According to Monte Carlo codes, simulating particle production, the number of π/μ from a target is proportional to W , but relatively insensitive to the proton energy $2 \leq E \leq 30$ GeV. The proton flux is $\dot{N} \propto 1/E$.

The proposed proton sources are inspired by existing synchrotrons and spallation neutron sources, and rely heavily on equipment that is or will be available at various sites for reasons unrelated to NF. A super-conducting linear accelerator [2, 3, 4] with circular pulse accumulator and compressor [5] is being studied at CERN. Rapid-cycling synchrotron(s) are favoured elsewhere. Lower energy synchrotrons can cycle faster. If the product $f_{\text{rep}}E$ of repetition frequency f_{rep} and proton energy E and the proton beam power W are constant, one can show that all synchrotrons have equal numbers of protons N in a cycle.

All synchrotrons must accelerate large numbers of protons N in a cycle, with injection at relatively low energy. This implies their performance is limited by ordinary space charge and other collective effects.

2.2 Targetting and Capture

Figure 2 shows the schematic layout of targetting and capture [6] with involves the following issues:

- Target material: Solid graphite – liquid Hg jet
- Magneto-hydrodynamics of Hg jets, moving conductors in a magnetic field
- Field level – lifetime – radiation – heating – stresses – shielding of the resistive solenoid surrounded by a super-conducting solenoid
- Choice between solenoid channel and magnetic horns
- Choice between induction linac in Fermilab study [1] and RF systems in CERN study for “phase rotation” [7]

The targetry experiment E951 [8] is an approved experiment at BNL, coordinated by K.McDonald of Princeton U. Its goals are to demonstrate performance and lifetime of solid and liquid 1 MW targets in a high-field solenoid, to measure particle yields, and to compare them to Monte Carlo codes. The E951 experiment will include the following steps over the next few years:

Figure 2: Targetting and capture. The protons enter from the left and strike a liquid Hg jet that has an angle with the beam axis. The target is inside a 20 T magnetic field, generated by a resistive solenoid surrounded by a super-conducting solenoid. Tapered matching solenoids match the π and μ beam into the 1.25 T decay solenoids. The energy spread in the beam is reduced by “phase rotation” in an RF system which uses the correlation between μ energy E and their velocity β to accelerate the muons with lower energy, and to decelerate those with higher energy.

- Complete beam line A3 at BNL
- Assess mechanical behaviour of target
- Develop 20 T solenoid and 70 MHz high-gradient RF cavity
- Test solid target in beam
- Test liquid Hg jet in high magnetic field at NHMFL in Florida
- Complete tests with beam at 10^{14} p/pulse

Similar, but hopefully complementary target tests may be carried out in Europe. The approved experiment HARP (PS214) at CERN [9] will obtain particle production data for proton energies between 2 and 15 GeV in 2001.

Figure 3: Engineering drawing [1] of two sections or one lattice period of the FOFO cooling lattice, showing two pillbox type RF cavities with a Be window, three liquid H₂ absorbers, four solenoid coils, and many connections.

2.3 Muon Cooling

The equation for ionization cooling of the normalised transverse emittance ε_n [10]

$$\frac{d\varepsilon_n}{ds} = -\frac{\varepsilon_n}{\beta^2 E} \frac{dE}{ds} + \frac{\beta_{\perp} E_s^2}{2\beta^3 m_{\mu} c^2 L_r E} \quad (1)$$

contains the negative cooling term and the positive heating term with the characteristic scattering energy $E_s \approx 13.6$ MeV. The heating term is kept small if the optics of the cooling channel is arranged such that the transverse betatron amplitude function $\beta_{\perp}$ is small, and the radiation length L_r is large. Cooling and heating rates are both inversely proportional to the muon energy E . Figure 3 shows a typical cooling cell [1]. The ionization loss in the liquid H₂ absorber with Al or Al-Be alloy windows is about 4 MeV. A typical μ beam deposits about 100 W in the absorber. The fluid dynamics and thermal modelling of the absorber are a challenge. A high-gradient RF system compensates the ionization loss. The RF cavities have Be windows or grids of Al tubes across the beam aperture, in order to achieve a high enough shunt impedance. Solenoid focusing surrounds absorber and RF cavities to achieve a small $\beta_{\perp}$ at the absorber.

Fig. 4 shows result of a cooling simulation [1]. Particles with large $\varepsilon_{\parallel}$ are lost at the entrance of the cooling channel. Beyond that point $\varepsilon_{\parallel}$ is constant. The cooling of $\varepsilon_{\perp}$ by a factor ≈ 5 is less than was hoped for. Hence, cooling should be improved.

The μ scattering experiment MUSCAT [11] at TRIUMF by a Birmingham, IC, RAL, Riken, UCLA collaboration aims at measuring scattering angles accurately, and thus distinguishing between various alternative theories of multiple scattering.

An ambitious μ cooling experiment MUCOOL [12] at Fermilab was originally proposed to demonstrate cooling for a $\mu^+\mu^-$ collider. Its adaptation to a NF is under way. Any cooling experiment will be difficult. The tracking devices must measure accurately the expected emittance reduction by a few percent, RMS scattering angles of the order of a mrad, and straggling of the order of an MeV. In order to achieve these goals, the mass in the tracking devices must be very small.

Everybody I know and myself believe that ionization cooling will eventually work. However, since MUCOOL was once proposed, presumably because it was considered necessary and/or useful at the time, some cooling experiment or demonstration is essential. Its failure would be a severe blow to a NF. Apart from serving as a basis for the design of the cooling section in the real NF, such an experiment will demonstrate the beam diagnostics needed for setting up the real NF, not only the cooling experiment proper, and provide a focus for the design of its components.

2.4 μ Acceleration

A linear accelerator and typically two recirculation linear accelerators (RLA) similar to CEBAF [13] accelerate the muons. The muon energies at the output end of the linear accelerator and the first recirculating linear accelerator can be found by a cost optimization, varying RF frequencies, normalized transverse emittance, energy spread and the lattice of the RLA. Fig. 5 shows the optical parameters in the first RLA at CERN. It has the shape of a racetrack with linear accelerators in both long straight sections. The number of muon passes is four. The lattice of the linear accelerators is a simple FODO lattice with one RF module in every half cell. The focusing is adjusted such that the betatron wavelength, and hence the β -functions, are constant on the first pass. In the subsequent passes, the focusing is weaker because of the higher energy, and the β -functions are larger and vary along the linear accelerators. The arcs consist of isochronous pairs of double-bend achromats. The spreaders and combiners that feed the beams from the linear accelerators into the separate arcs, and vice versa, are not yet designed, and replaced by dummy matching sections for the α and β functions.

The total accelerating RF voltage in the two recirculating linear accelerators RLA is more than 12 GV at CERN, and about 11 GV in the Fermilab study in which acceleration was identified as one of the cost drivers [1]. Super-conducting RF is the only way of avoiding a peak RF power that is far too large. R&D towards higher gradients is desirable, because they make the RLA circumference smaller, reduce decay losses and beam loading, but also need shorter bunch trains. Efficient single-turn injection requires that the bunch trains are shorter than the circumference of the smaller RLA. The beam loading at the muon fluences shown in Table 1 and repetition rates of few tens of Hz is severe. At CERN, isochronous RLA accelerate the μ on the crest of the RF waveform, while at Fermilab an-isochronous RLA accelerate the μ off the crest

Figure 4: Cooling simulation results for total transmission and transmission within 6D phase space cut (top), longitudinal emittance $\epsilon_{\parallel}$ (middle), and transverse emittance $\epsilon_{\perp}$ (bottom)

Figure 5: Optical Functions in the four passes through μ RLA1 at CERN. The black and red (dark grey in the printed version) curves show horizontal and vertical amplitude functions $\sqrt{\beta_x}$ and $\sqrt{\beta_y}$. The green (light grey) curve is the horizontal dispersion D_x .

of the RF waveform. The energies at which the μ are transferred from the linear accelerator into μ RLA1 and from μ RLA1 into μ RLA2 remain to be optimized, taking into account two facts. A larger normalised emittance and/or a lower injection energy imply a lower RF frequency, because of the scaling of the beam apertures of the RF cavities with frequency. A larger initial relative energy spread implies fewer passes in RLA, since the energy spread must be much smaller than the ratio of the energies between passes.

2.5 μ Storage Rings

Tab. 1 shows a comparison of the muon storage ring parameters at Fermilab [1] and CERN [14]. The CERN design aims for 2.8 times the ν flux/s of the Fermilab design. Hence, it is more demanding than the Fermilab design on proton source, targetting, collection, cooling, and shielding. However, the CERN design is less demanding on emittance ϵ_{xn} , momentum spread σ_e , physical and dynamic aperture for acceleration

Table 1: Comparison of the Storage Ring Design Parameters at Fermilab and CERN

	Fermilab	CERN	
Energy	50	50	GeV
Shape	Racetrack	Triangle or Bow-Tie	
Distance to detector(s)	≈ 3000	1000 & 3000	km
Year	$2 \cdot 10^7$	10^7	s
Design ν fluence/detector	$2 \cdot 10^{20}$	$2.8 \cdot 10^{20}$	1/y
Normalized emittance ϵ_{xn}	3.2	1.67	mm
Relative RMS energy spread σ_e	1.0	0.5	%
Circumference	1753	2075 or 2008	m

and storage.

In the triangular CERN design, three 500 m long straight sections are connected by three arcs, as schematically shown in Fig. 6, and also in the mimic diagram at the top of Fig. 8. The first two long straight sections point at remote detectors at 1000 and 3000 km. The third long straight section is used for fine adjustments of the tunes. The arcs are composed of rather compact FODO cells. Between the arcs and the long straight sections are dispersion suppressors with modified bending, and matching insertions for the α and β functions. Fig. 7 shows the vertical elevation along the circumference. The first two long straight sections point towards the detectors. The difference between the highest and lowest points is less than 250 m, and fits inside the molasse layer in the neighbourhood of CERN. Fig. 8 shows the optical functions. The Fermilab design has the shape of a racetrack with two long straight sections joined by two arcs. One straight section points at a remote detector at about 3000 km. The weak focusing and the associated large β -functions in the first long straight section(s) of both designs achieve the required value of the normalized divergence $\sigma'\gamma \approx 0.1$.

All muons arriving in a μSR decay there. In the CERN μSR , the power in the $\mu^\pm$ beam is approximately 0.8 MW. Hence, the power in the $e^\pm$ is about 0.28 MW, about 140 W/m on average, and about 70 kW from 500 m of straight section. A warm W liner inside the super-conducting arc magnets absorbs most of this power. Shower simulations by Mokhov [1] show that about 7 W/m end up in the cold mass at Fermilab. A local enhancement of the power deposition is possible, because the $e^\pm$ can travel through the long straight section, but get lost in the dipoles at the entrance of the arcs by energy loss due to synchrotron radiation [15]. Detailed simulations for the CERN μSR [16] show that 45 kW are deposited in the long straight section at room temperature. They can be absorbed by the water cooled vacuum chamber with thick walls or by regularly spaced absorbers. A further 21 kW are deposited in the matching section, consisting of a mixture of room temperature and super-conducting magnets with space for absorbers. Finally, 3.5 kW are deposited in the three or four first dipoles of the dispersion suppressors. These dipoles should have thicker W liners. Negligible extra power beyond 140 W/m is deposited in the remainder of the arcs.

Figure 6: Projection of the triangular CERN μ SR on the (x, z) -plane tangent to the Earth

Figure 7: Vertical elevation of the triangular CERN μ SR along its circumference

In both designs, the first cycle of optical work is essentially done with few outstanding items. Obtaining the dynamic aperture by tracking realistic distributions of more than 10^4 muons through acceleration and storage ring for the full muon life time is easy. The Fermilab study includes a fair amount of engineering, the CERN study practically none. Future R&D on μ SR should include engineering studies of the packaging, installation and operation of the components in tunnels with the slopes required for the long baselines pointing at the ν detectors. The engineers should propose changes to engineering parameters, e.g. magnetic fields, etc., that make a NF easier to build and that reduce its cost. The accelerator physicists should reconsider values for the μ beam parameters normalised emittance, relative momentum spread, muon fluence, their relation to the module parameters, and decisions on ν -factory and detector sites. Another round of optical studies, using results of engineering and optimization, is facilitated by the automated generation of data with *Mathematica* procedures [17] that guarantee the correct geometry, get the thin-element strengths for most optical modules, and feed these data into an optical program such as MAD [18] for thick-element matching, tracking, etc.

3 CONCLUSIONS

Tab. 2 shows the status of neutrino factory studies. The parameters and results of the recent Fermilab and CERN studies are compared to those of the pjv scenario [6], the first attempt at deriving a reasonably complete scenario for a neutrino factory. The CERN results are preliminary. The recent conversion factors are smaller than those predicted by pjv, and the muon fluences observed in simulations are smaller than the design figures. This is a disappointing result. A study of a high-performance neutrino

Figure 8: Optical Functions of the triangular μ SR at CERN. The mimic diagram at the top shows the layout. The three open structures with horizontally focusing (up) and horizontally defocusing quadrupoles (down) are the straight sections. The black rectangles are the three arcs. On either side of the arcs are matching sections. The graph shows amplitude functions $\sqrt{\beta_x}$ in black, $\sqrt{\beta_y}$ in red or dark grey, and the horizontal dispersion D_x in green or light grey.

factory was recently launched at BNL.

I believe that a proof of the feasibility will be achieved soon, mostly by theory and simulation, but also by some prototyping and experimentation. This will allow us to put less emphasis on the internal optimization of the modules, and more emphasis on optimization across modules, by varying the muon energy, and including the cost of the detector(s). After NuFact'00, I understand that two separate figures of merit, energy E , and the product IM of fluence I and fiducial detector mass M should be considered. In order to have an operating NF sooner and/or at a lower price, one might consider staging its construction, making steps in muon fluence I , e.g. by steps in proton beam power and in muon cooling, and in muon energy E . Because of the large number and variety of topics, R&D for an NF offers a wide scope for collaboration on a global scale.

Table 2: Status of Neutrino Factory Studies, showing the proton beam power and energy, the conversion factor, and the expected and observed muon fluences into the μ SR, for the Fermilab and CERN studies, and the pjk scenario

Parameter	pjk	Fermilab	CERN	Units
Proton beam power	4	1	4	MW
Proton beam energy	24	16	2.2	GeV
Conversion factor	0.004	0.0011	0.0023	$\mu/(p \cdot \text{GeV})$
Year	10^7	$2 \cdot 10^7$	10^7	s
Observed muon fluence into μ SR	10^{21}	$1.6 \cdot 10^{20}$	$5.8 \cdot 10^{20}$	1/a
Expected muon fluence into μ SR	10^{21}	$5.3 \cdot 10^{20}$	10^{21}	1/a

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