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STATUS OF EUROPEAN STUDIES FOR A NEUTRINO FACTORY AT CERN

R. Garoby (for the Neutrino Factory Working Group)

Abstract

Studies for a Neutrino Factory at CERN have made remarkable progress during the last year, supported by specialists from numerous laboratories in Europe and in close connection with teams looking at similar projects in the USA and in Japan. Although many options are still open, a reference scheme is pursued and work has advanced on many on its components. The status of these studies is described, as well as the future plans. Potential evolutions of the reference scheme and the possibility of a staged realisation are also commented upon.

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Status of European Studies for a Neutrino Factory at CERN

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Abstract

Studies for a Neutrino Factory at CERN [1, 2, 3] have made remarkable progress during the last year, supported by specialists from numerous laboratories in Europe and in close connection with teams looking at similar projects in the USA and in Japan. Although many options are still open, a reference scheme is pursued and work has advanced on many on its components. The status of these studies is described, as well as the future plans. Potential evolutions of the reference scheme and the possibility of a staged realisation are also commented upon.

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1 CERN Reference Scheme

The neutrinos delivered by a Neutrino Factory result from the decay of high energy muons circulating in a storage ring. These muons are themselves decay products of the pions produced by the interaction of a proton beam with the atoms of a target.

In the CERN scheme (see Fig. 1), the H^- beam supplied, at 75 Hz, by a 2.2 GeV Superconducting Linac (SPL), is injected during 2.2 ms in an accumulator ring whose proton bunches are afterwards shortened in a compressor ring. A mean flux of 1.1 10^{16} protons/s (or $\sim 10^{23}$ protons/year, taking 10^7 s/year) is delivered to the target, with the characteristics listed in Table 1.

A liquid metal jet is being used for the target, inserted inside a magnetic horn for collecting pions over a broad range of kinetic energy (100 to 300 MeV) and a large solid angle. These pions as well as the muons resulting from their decays are transported in a 30 m long decay channel with transverse focusing by a 1.8 T solenoidal field. After passing through this channel, the muon bunches traverse a series of 44 MHz cavities which by "rotation" in the longitudinal phase plane, reduce their energy spread by a factor of 2. The beam

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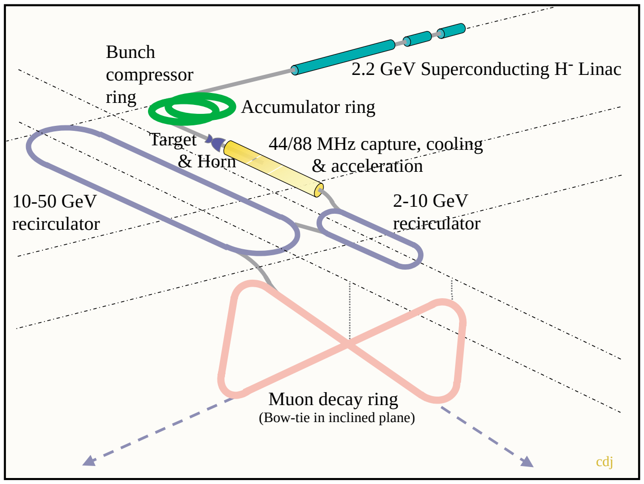

Fig. 1. Layout of the CERN reference scheme for a Neutrino Factory

Parameter	*Value*	*Unit*
Mean Beam Power	4	MW
Kinetic energy	2.2	GeV
Repetition rate	75	Hz
Pulse duration	3.3	μ s
Number of bunches	140	
Pulse intensity	1.51 10^{14}	p/pulse
Bunch spacing (Bunch frequency)	22.7 (44)	ns (MHz)
Bunch length (σ)	1	ns
Relative momentum spread (σ)	5 10^{-3}	
Norm. horizontal emittance (σ)	50	μ m.rad

Table 1
Proton beam on target

then passes through liquid hydrogen cells for ionisation cooling, and 44 and 88 MHz RF structures for recovery of longitudinal energy. After this treatment, 250 m behind the target, each transverse emittance has been divided by four (conversely, the density in each transverse phase plane is multiplied by 4). Solenoidal focusing is still used in the following linear accelerator which operates at harmonics of 44 MHz to increase the energy up to 2 GeV.

A cascade of 2 Recirculating Linear Accelerators (RLA), equipped with LEP-type 352 MHz superconducting RF cavities providing a total of 12 GeV of single-pass energy gain, accelerate this beam in 4 turns up to 50 GeV.

The 3.3 μs burst of 50 GeV muons is injected into the 2 km circumference muon storage ring, where it is left to decay until the next burst is available, 13.3 ms later. More than 10^{14} μ/s enter this ring, and approximately 3 10^{20} neutrinos are then generated every year in each of the long straight sections oriented towards remote experiments, thousands of kilometres away.

2 Proton Driver

2.1 Reference Design

The present design makes extensive use of the large inventory of RF equipment dismantled from LEP. The 800 m long superconducting Linac [4] that accelerates the H^- ions to 2.2 GeV re-uses all klystrons and 60 % of the LEP modules in its high-energy part (see Fig. 2). New $\beta = 0.52$ and $\beta = 0.7$ acceleration modules are assumed between 120 and 390 MeV. Between 390 MeV and 1 GeV, LEP cryostats are re-used, equipped with new 5 cells, $\beta = 0.8$ cavities. Above 1 GeV, LEP modules are used without modification. Below 120 MeV, room temperature accelerating structures are employed. Leaving the ion source at 45 keV, the H^- beam is bunched at 352 MHz and accelerated to 3 MeV in an RFQ. It then passes through a transfer line equipped with fast deflecting electrostatic kickers (”choppers”) which eliminate the unwanted bunches onto a collector and provide the proper time structure for an optimum longitudinal capture in the accumulator. Further acceleration to 120 MeV is made cascading an RFQ, a Drit Tube Linac (DTL) and a Cavity Coupled Drift Tube Linac (CCDTL).

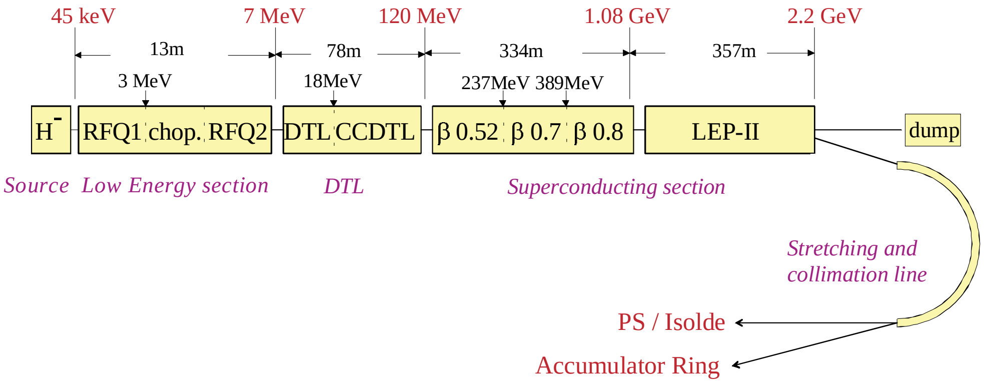

Fig. 2. Layout of the CERN reference scheme for a Neutrino Factory

2.2 GeV protons are accumulated over 660 turns in the accumulator ring, using charge exchange injection [5]. 140 of the 146 buckets generated by the 44 MHz RF system are progressively populated by up to 1.08 10^{12} p/b. At the end of accumulation, the bunches are fast ejected and transferred into the compressor ring, where bunch compression takes place in 7 turns, with 2 MV at 44 MHz and 350 kV at 88 MHz. The 1 ns rms long bunches are then ejected onto the target.

On the CERN site (see Fig. 3), the accumulator and the compressor rings are situated at the location of the ex-ISR, and existing tunnels are re-used for the transfer of the SPL beam to the PS and to the ISOLDE experimental facility.

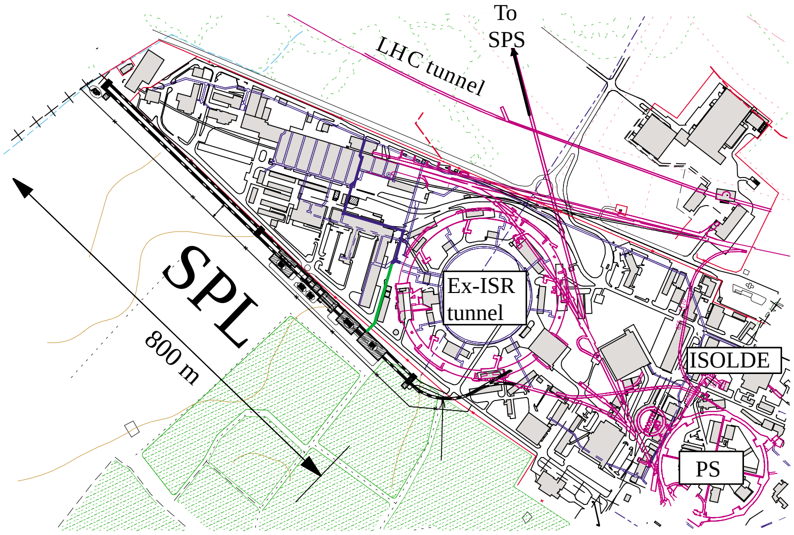

Fig. 3. Proton driver complex on the CERN site

2.2 Ongoing Activities and Design Trends

Theoretical work is concentrated on the refinement of the SPL design and the solution of the remaining problems, in close relation with the development of critical hardware (Table 2). In particular, a recent study has underlined that more work is required for a proper control of the field in the cavities when multiple superconducting resonators are driven by a single klystron [6].

Improvements to the reference design [4] are being studied, based on reducing the repetition rate to 50 Hz, generalising the use of $\beta = 0.8$ cavities up to 2.2 GeV and increasing the beam current during the pulse. Preliminary investigations of the consequences for the accumulator and compressor rings have not revealed any dramatic problem, apart from more stringent impedance requirements because of the microwave instability and the need for more efficient countermeasures against electron clouds and their effect.

Alternatively, if the production of pions from a 2.2 GeV proton beam proves to be unfavourable, or if difficulties arise in the neutrino complex, due to the

Item	*Main Issue*
H^- Source	Design
Chopper	System design
RT Linac	Structures development
SC cavities	Pulsed test of cavities Dev. of low β structures
Klystrons & supplies	pulsed operation
Servo-systems	Field stab. in pulsed mode
Beam dynamics	Optimisation

Table 2
Studies for the proton driver

choice of 23 ns spaced bunches, the design of the proton driver could change and make use of Rapid Cycling Synchrotron(s) (RCS) [7].

2.3 Other Applications and Staged Approach

Apart from its main use as a driver for a future Neutrino Factory, the 2.2 GeV proton source could benefit the rest of the accelerator complex at CERN, replacing the present Linac 2 / PSB set-up and providing improved beam characteristics at the entrance of the PS. The present ISOLDE facility could easily be supplied with 5 times more beam current than at present, while removing constraints from the busy PS supercycle. Moreover, a second generation ISOLDE facility could be accommodated which would fully profit from the SPL beam [8]. Potential benefits for the approved high energy physics experiments are also under study [9].

Recent investigations have underlined the interest for physics of a staged approach where only the proton driver would be needed to generate a conventional neutrino beam aimed at a medium distance experiment (∼100 km) [10].

3 Target and Capture

3.1 Reference Design

The target and pion capture systems fit tightly together and represent one of the most difficult engineering challenges in the design of a Neutrino Factory, for which no solution has yet been tested enough to be considered as viable. In the case of the CERN reference scheme, preference is given to a liquid metal target [11, 12] and horn focusing [13, 14], although solenoid focusing is not discarded.

For convenience, mercury (Hg) is being used for the preliminary tests. Experiments with beam have begun at BNL, sending 24 GeV protons onto Hg in a trough, to be followed by similar tests with 1.4 GeV protons in the ISOLDE target area [12]. Some results have also been obtained by the American collaboration concerning the effect of the proton beam onto an Hg jet [15]. Until now, these tests at 1/100 of the ultimate power density and 1/10 of the foreseen jet speed have shown the expected radial "explosion" during the impact, but no upstream propagation along the jet.

The horn design is demanding because of the ≥50 Hz cycling rate which accelerates mechanical fatigue and causes high thermal dissipation, especially in the waist region of the central conductor where the target will be located. A 300 kA, 1 m long prototype has been designed [16] (Figure 4) as well as its power supply [17]. They are under construction and will be tested within a year. In the full implementation, a 600 kA outer horn is foreseen, surrounding the 300 kA one, for focusing higher energy larger angle pions. For studying the penetration of the Hg jet on axis inside a high field solenoid, a safety accepted experimental set-up is now available. First tests with a 13 T magnet at Grenoble have not revealed any problem. 20 T tests are planned in the near future.

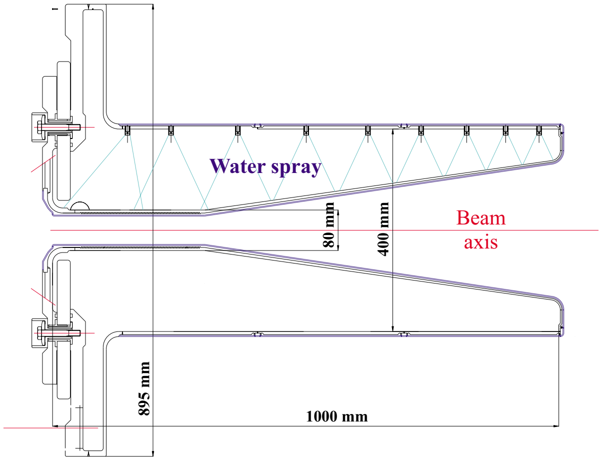

Fig. 4. Prototype horn

3.2 Potential Design Evolutions

The HARP experiment [18] will take data in 2001 and measure precisely the production of pions with 2 to 16 GeV protons on different types of targets.

Results will strongly influence the target design and possibly also the characteristics of the proton driver.

The problems associated with a liquid metal target are still largely unresolved and alternative solutions are being pursued in different laboratories [19]. A new proposal was recently made at CERN of a stationary target with metal spheres [20]. A spent beam absorber is also needed to dump the 3 MW of beam power that remain after the target. No satisfactory solution has yet been proposed for its design.

4 Bunch Rotation and Cooling

4.1 Reference Design

The preferred solution is adapted to the small bunch spacing (namely 23 ns) that can be obtained from a low-energy proton driver [21], [22]. Moreover, the time structure of the primary proton beam is preserved in this solution and no rebunching of the muons is required before acceleration. The essential parameters of the bunch rotation and cooling channel are summarised in Table 3. After a decay path of 30 m, the muon bunches are rotated to reduce their energy spread by a factor of two. Two steps of ionisation cooling are then applied, the first one at the mean energy of 200 MeV, with 24 cm long liquid hydrogen absorber cells and 44 MHz RF, and the second one at 300 MeV with 40 cm absorber cells and 88 MHz RF. The low RF frequency, the need for a high solenoid field on axis and the huge bore aperture resulting from the large beam emittance contribute to make the equipment voluminous. The design is modular, as illustrated in the sketch of the 44 MHz part shown in Figure 5. Acceleration to 2 GeV is obtained in a 450 m long linac using 88 and 176 MHz RF accelerating structures.

	Decay	*Rotation*	*Cooling 1*	*Accel. 1*	*Cooling 2*	*Accel. 2*
Length (m)	30	30	46	32	112	∼ 450
Diameter (cm)	60	60	60	60	30	20
B-field (T)	1.8	1.8	2.0	2.0	2.6	2.6
Frequency (MHz)		44	44	44	88	88 & 176
Cavities gradient (MV/m)		2	2	2	4	4 - 10
Kinetic energy (Mev)		200	200	280	300	2000

Table 3
Parameters of the bunch rotation, cooling and pre-acceleration sections

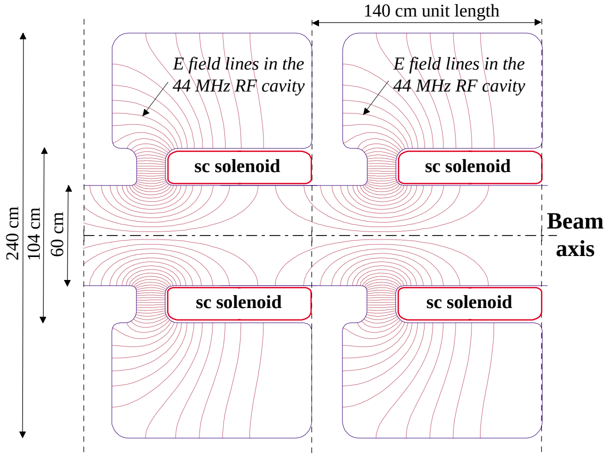

Fig. 5. Cooling channel modules, with 44 MHz cavities and superconducting solenoid

Figure 6 illustrates the computed evolution of transverse emittance along this channel, and its final reduction by a factor of four. The percentage of muons surviving per incident pion is shown in Figure 7. According to the particle production predicted by FLUKA (0.2 π^+/proton at 2.2 GeV), the overall yield of the system is 0.42 % π^+/proton.GeV in the acceptance of the first RLA, corresponding to 10 ^{21} π^+/year.

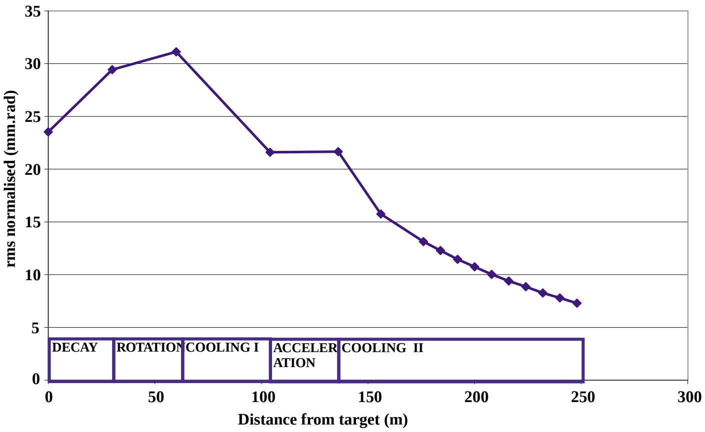

Fig. 6. Evolution of transverse emittance

4.2 Ongoing activities and design trends

Beam dynamics is concentrated on the optimisation of the channel architecture to try to increase the flux of muons delivered inside the acceptance of the first RLA. A test system at 88 MHz to investigate high gradient operation is being prepared with equipment recuperated from the PS after the end of LEP. First results are expected at the end of 2001. Tests in the presence of a high field solenoid will follow in 2002, when the superconducting solenoids presently under design will be available.

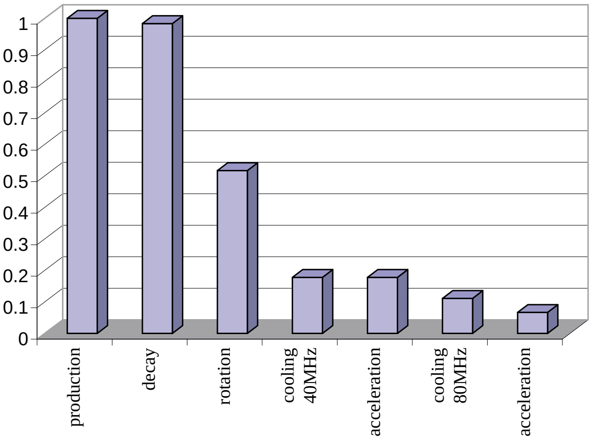

Fig. 7. Percentage of muon/incident pion

Moreover, a muon cooling test facility is considered as a necessity in order to demonstrate full-scale engineering solutions and single-particle cooling without ambiguity [23]. In the present context of limited resources, such a facility will be proposed as a joint international effort, built and exploited by all study teams world-wide.

5 Muon acceleration

5.1 Reference design

Two racetrack-shaped recirculating linear accelerators accelerate the muon beams from 2 to 10 GeV (RLA1) and from 10 to 50 GeV (RLA2) respectively. Both RLAs are isochronous, and the muon bunches are accelerated on the crest of the RF wave. The main parameters are summarised in Table 4 [24]. This part of a Neutrino Factory complex has been identified as one of the most costly [25] and will consequently require detailed engineering optimisation in due time. The 352 MHz LEP-type RF cavities are installed in all straight sections. Spreaders at the end of each linac section, separate the beam into 4 different, vertically-stacked arcs. After the 180° bend, combiners merge the four beam energies into the input of the next linac section.

5.2 Ongoing activities and design trends

A satisfactory optical arrangement is still being sought for the spreaders and combiners. For the RF, a single cell 200 MHz superconducting cavity is being built at CERN for Cornell University, using the "Niobium sputtered on

Parameter	*RLA1*	*RLA2*
Injection energy (GeV)	2	10
Extraction energy (GeV)	10	50
Number of turns	4	4
Linac length (m)	680	3813
RF frequency (MHz)	352	352
Mean arc radius (m)	20	100
Circumference (m)	806	4442
Gradient cavities (MV/m)	7.4	7.4
Normalized admittance (mm rad)	16.5	18.8

Table 4
Parameters of the RLAs

Copper" technology developed for LEP [26] (Figure 8). By using such low-frequency cavities in RLA1 and possibly also in the high-energy part of the preceding linac, acceptance in all planes would be increased. Furthermore, the length of the accelerators will be reduced if the gradient can be made substantially higher than in the existing LEP cavities (7.4 MV/m).

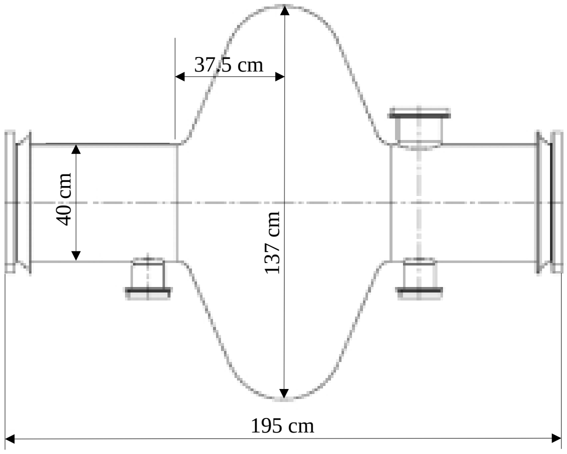

Fig. 8. Single-cell 200 MHz superconducting cavity prototype

6 Muon Storage

6.1 Reference design

A muon storage ring with a symmetrical bow-tie shape and long straight sections aiming at remote neutrino experiments is proposed [27]. Such a shape is interesting for its advantages in terms of site layout and flexibility of orientation. The machine parameters are listed in Table 5, and its geometry is sketched in Figure 9.

Parameter	*Value*
Beam energy (GeV)	50
Muon fluence (s^{-1})	10^{14}
Distance to far experiments (km)	1000 & 3000
Normalised divergence ($\gamma\times$physical rms divergence)	0.1
Vertical slopes (mrad)	-78.6 & -237.9
Circumference (m)	2007.9
% of useful muon decays per circulating muon per detector (%)	28.7
RF frequency (MHz)	352
Peak RF voltage (MV)	120
Mormalised emittance (mm rad)	1.67

Table 5
Parameters of muon storage ring

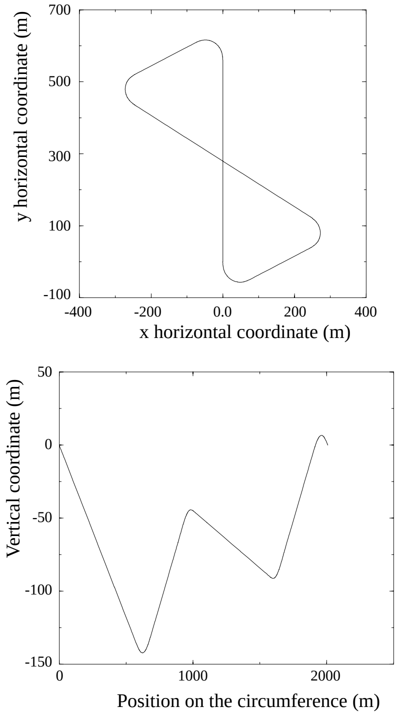

Fig. 9. Percentage of muon/incident pion

One third of the stored muons will decay in the straight sections, so that a total of ~3 10^{20} neutrinos will be sent every year to each remote experiment. The

Gran Sasso laboratory will be one of them, and the location of the other one, ∼3000 km away, is the subject of an ongoing debate. Although challenging, the alignment accuracy of 10^{-5} rad required for the straight sections is considered feasible.

6.2 Ongoing activities and design trends

Engineering developments are needed to help optimise the performance and cost of the storage ring, but no activity has started yet. Beam dynamics studies continue.

7 Conclusion

In the CERN context, where resources are diminishing and the LHC project has top priority, it is quite encouraging to report how much has been done since the study for a Neutrino Factory began, some 3 years ago. In that respect, the recent interest of physicists for a staged approach, where first generation experiments would only use the proton driver part of the Neutrino Factory complex, is highly welcome. Test set-ups are already, or will soon be, available whose results will help improve the quality of the present design and give confidence in the feasibility of the hardware components. An important goal in the near future is to elaborate an international proposal for a muon cooling test facility to be built and exploited by a world-wide collaboration of study teams.

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