NuFact02 Machine Working Group Summary

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Abstract. This is a summary of discussions that took place in the Machine Working Group at NuFact02.

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1. Introduction

At νFact'02, the muon-based neutrino factory was confronted with existing and planned neutrino facilities. When it was first discussed in 1999 in Lyon [1], it raised great enthusiasm, especially because it was thought to be the only machine capable of measuring CP violation in the leptonic sector. Since that time the pendulum has partially swung back. Two successive detailed studies [2, 3] have shown that a neutrino factory and the needed R&D were both expensive. In terms of present experiments, neutrino oscillations have been confirmed at SuperK and SNO and results are soon expected from KamLAND. K2K, MiniBOONE, MINOS and CNGS are going ahead and new perspectives have been opened by off-axis pion-based neutrino beams and the approval of the high intensity Japanese Hadron Facility. Crests and troughs of a wave are common in long term projects. They are even healthy because they force us to scrutinize the first ideas and sometimes to invent new ones to reach a realistic and affordable design. This analysis has been applied to target systems (section 2), RF capture and cooling of the muons (section 4) and accelerators (section 5). The new concept of pure electron neutrino or anti-neutrino beams produced by β-decay is discussed in section 3.

2. Target systems

2.1. Potential interest of neutrino factory technologies for super-beams

A neutrino factory relies on multi-MW proton beams and as a result programmes of new target and pion collection systems have been launched. On the other hand conventional neutrino beams work at the most in the hundreds of kW range and do not encounter special technological difficulties. However, the situation may change in the medium term due to the commissioning of new more powerful proton drivers such as JHF, which, in its first stage, will operate at 0.75 MW. It was therefore interesting to investigate if the development carried out for a neutrino factory could be profitable to conventional beams and a common session between working groups 1 and 2 was held on that subject. In the first part, the various conventional beam facilities were reviewed and are summarized in working group 2's report [4]. In the second part, the radio-active beams (see next section) and the recent developments achieved for a neutrino factory were discussed.

2.2. High power density targets

There are two extreme regimes in the operation of a target at a given beam power [5]. If the proton beam hits the target at a sufficiently high repetition rate, say higher than 20 Hz, then the instantaneous temperature rise is low enough so that the elongation of the target remains below the elastic limit, the target can resist the shock induced by the proton beam and the only problem consists of evacuating the heat deposited in the target quickly enough. If the repetition frequency is low, the target has ample time to cool down between two shots but the instantaneous temperature rise is exceedingly high and generates shock waves or even cavitation [6] that breaks the target. The SPL beam and the CERN neutrino factory belong to the first category. The target is made of tantalum granules and designed for integration into a magnetic horn [5]. Spherical granules have the ideal volume to cooling area ratio. Helium gas flowing at 100 m/s with a 20 atm input pressure is the cooling medium. The equilibrium temperature reaches very conservative values (200 °C) when the beam is distributed over several targets.

When proton drivers are synchrotrons, the shock regime may prevail. This is the basic reason to study renewable targets, for example fast flowing mercury jets. However, research is also being pursued at BNL [8] on solid targets as well. Graphite is used for most conventional beams and seems to be able to stand pulsed proton beams at a power level near 1 MW. It could serve as an alternative to tantalum beads, but only for high energy proton beams ($\sim$ 20 GeV) because it is a poor source of negative pions for low energy ($\sim$ 2 GeV) protons. A new development in solid targets concerns Invar type materials. The amplitude of the shock waves is proportional to the thermal expansion coefficient for a given temperature rise; it is kept small when this coefficient itself is small as in Super Invar. These materials may be used in both a stationary or a moving target, the latter consisting of a fast rotating band [9, 10].

A liquid target is another potential solution and can be in the form of a free jet or of a closed circuit. A mercury jet has been exposed to AGS and CERN PS Booster beams. In the experiment E951 at BNL, a target of 19 cm length, 2.5 m/s speed and 1.2 cm mean diameter was subjected to a bunch of $4\,10^{12}$ protons at 24 GeV. The target exploded 40 μs after the collision, a long time as compared to the beam target interaction time, and the Hg drops were ejected at a velocity of 10 m/s. At CERN, the explosion mechanism of the target has been studied using a thimble or a trough as a container for the mercury in the ISOLDE beam (1.4 GeV, pulses of up to 4 bunches of $8\,10^{12}$ protons). The maximum temperature reached 250 °C. The Hg droplets had a radius of the order of 0.8 mm and the splash typically rose 4 cm in 4 ms. The velocity of mercury drops scaled linearly with the deposited energy and, at the highest pulse intensity ($3\,10^{13}$ protons), velocities as high as 45 m/s have been measured.

In another approach the mercury flows in a closed circuit when the target is traversed by a pulsed current of 2.5 MA [12, 13]. Then the pions are focused near the end of the target and the pion brightness is greatly increased. Moreover, the target can be separated from the collector. Though the parameters of a conducting target seem to be extreme, it must be noted that 1 MA solid lithium lenses have been succesfully used for the capture of antiprotons. The electrodynamics and thermodynamics of a conducting mercury target will be further studied both theoretically and experimentally for PRISM.

2.3. Pion collectors

Two types of pion collectors are presently under investigation: a magnetic horn and an adiabatic solenoidal system. A horn of 300 kA pulsing at 50 Hz has been designed and manufactured at CERN [14]. Initial tests have been performed at 1 Hz and 30 kA to determine the spectrum of the mechanical vibrations. The beneficial effects of distributing the proton beam over several targets have been mentioned and they apply to the horn as well [7]. By associating a horn with each target, the repetition frequency is divided by the number of channels. There is however a cost in capture efficiency because the pion beams are recombined in an alternating gradient channel whose optical β-values are higher than in a long solenoid and lead to a larger emittance of the muon beam. However the losses can be tolerated when the advantages of a system of long life-time ensuring high integrated neutrino intensity and a reduced maintenance cost are considered. Moreover, splitting the beam allows an evolutionary design of the target system starting with one channel, testing one target system in real conditions and adding more channels with time. It thus opens the way to the highest beam power.

The solenoids designed at BNL [8] mix resistive and superconducting coils. For PRISM [13], the coils are superconducting and shielded by a tungsten cylinder, which increases the magnetic volume substantially and makes the solenoid costly, hence the interest for a conducting target. A prototype of the PRISM solenoid will be tested in the K2K beam this year.

When a metallic target traverses a magnetic field, magneto-hydrodynamical effects manifest themselves [11]. A dedicated experiment [6] to study these effects has been performed at LCMI in Grenoble (France). A mercury jet of 4 mm diameter and 10 m/s speed was injected into a 20 T solenoidal field with an angle of 6 degree with respect to the field. Alteration of the jet shape and a 25% reduction in jet velocity were observed.

2.4. Trends in target and pion collector developments

The first thing that stands out when the present and future target systems are compared is the huge gap between the simple solid targets and horns used today and the nuclear fusion like systems envisaged for some schemes of neutrino factory. To realize that fact was already a very interesting output of that common session. One can then question the real need for such a line of development especially within the context of a global effort of cost reduction of a neutrino factory. As super-beams will be the next generation of neutrino experiments, the solutions based on solid targets should certainly be given priority. Concerning the optics, a neutrino factory collects the pion and eventually the muon beams in accelerators, whereas the present experiments aim at maximizing the number of events in a distant detector using the pion decay only. The boundary conditions are thus different and it would be necessary to evaluate the performance to cost ratio of the collectors for each application in order to choose the best device.

3. β-beams

Discussions about producing pure electron neutrino beams [15] using the decay of radio-active beams were among the highlights of the workshop. The choice of the decays, the collimation of the neutrino beam and a preliminary accelerator beam complex have been discussed.

3.1. Choice of β decays

The choice of the radio-active isotope is determined by its lifetime and the neutrino energy $E_{\nu 0}$ in the center of mass of the nucleon. Too short life times produce unacceptable beam losses in the accelerators and too long ones do not provide the right production rate of neutrinos. The compromise is near 1 s for the half-life at rest. The value of $E_{\nu 0}$ comes in the expression of the emission angle of the neutrinos and must be as low as possible. The electron neutrino or anti-neutrino is produced in a three-body decay. Helium and neon isotopes have been selected for β^- and and β^+ decays:

$$
\begin{aligned}
{}^6_2He &\rightarrow {}^6_3Li\, e^-\, \overline{\nu}_e \\
{}^{18}_{10}Ne &\rightarrow {}^{18}_{9}F\, e^+\, \nu_e
\end{aligned}
$$

The average center of mass energy is 1.937 MeV for $\overline{\nu}_e$ and 1.86 MeV for ν_e while it is $3m_\mu/10$ ($\sim$ 31.7 MeV) for a muon decay.

3.2. Collimation of the neutrino beam

The number of neutrinos which reach the detector is proportional to the ratio of the solid angle of the detector seen from the source to the total solid angle of emission. It scales like $(\gamma/l)^2$ where γ is the Lorentz factor of the parent particle and l, the distance from the source to the detector. To compare two sources, the ratio l/E_ν must be maintained constant to get the same probability of oscillations between two neutrino flavors; here the neutrino energy E_ν is $2\gamma E_{\nu 0}$, where $E_{\nu 0}$ is the neutrino energy in the center of mass of the parent particle. The flux of oscillated neutrinos at the far detector is thus independent of γ and scales like $E_{\nu 0}^{-2}$. The number of interactions is proportional to the neutrino energy and the merit factor of a neutrino beam is simply $\gamma/E_{\nu 0}$. This merit factor is actually altered by the background due to π^0 production in the detector [16] and the neutrino cross-section, which departs from linearity when E_ν is below a few GeV. The combination of the two effects amounts to a reduction of the merit factor of the β beam by a factor 4 about in the 200-600 MeV energy range envisaged for the observation of $\nu_e - \nu_\mu$ oscillations. Taking these effects into account, the ratio of β to muon beams merit factor would be of the order of 2.5. This argument assumes that the intensity is the same for the two types of beam, an hypothesis that needs confirmation. The nice collimation of electron neutrinos produced by β-decays has stimulated the study of a β-beam complex. However, whether the combination of β and super pion beams will produce more or less physics than a muon based neutrino factory is still an open question.

3.3. Accelerator complex

The present design assumes a γ value of the order of 150 so that the neutrino energy is near 600 MeV and $\nu_e - \nu_\mu$ oscillations could be observed in a detector located in the Frejus tunnel at 130 km from CERN. Such a γ value means an equivalent proton energy of 450 GeV for $^{6}_{2}He$ and 281 GeV for $^{18}_{10}Ne$. As the anti-neutrino cross-section is smaller than the neutrino cross-section, the intensity of a helium beam must be higher than that of a neon beam. The CERN accelerator complex which will already be used for heavy ions in LHC has been very naturally re-evaluated for β-beams [17]. The β-beam system comprises

• a proton driver, the SPL [18],
• a target and ion source,
• a first cyclotron for acceleration to 50 MeV per nucleon,
• an accumulator,
• a fast cycling cyclotron which boosts the beam to 300 MeV per nucleon,
• the PS synchrotron for acceleration to 3.5 and 7.8 GeV per nucleon for helium and neon respectively,
• the SPS synchrotron for final acceleration,
• a superconducting decay ring of SPS circumference and racetrack shape.

The study has revealed a number of problems and found solutions to some of them. To produce the ambitious number of events in the neutrino detector, it has to be proven that the beam intensities can be achieved first at production and then all along the accelerator chain by careful control of the space charge effects. Accelerating unstable ions contaminates the machines by hadronic interactions; to what extent beam losses can be tolerated is still a major concern. The accumulation of heavy ions in the decay ring was initially thought to be a basic limitation. In fact, an ingenious scheme of bunch merging blows up the beam emittance respecting Liouville's theorem, but the outer particles belong to an "old" beam that is de-populated by decay. It is thus possible to gain an order of magnitude in the number of stored particles over the storage capacity of a beam of stable particles.

4. Neutrino factory front end

Complete neutrino factory baseline designs have been developed in the U.S., Europe and Japan. Much of the current simulation work is concentrating on finding less expensive methods for providing a neutrino factory with performance equivalent to these baseline designs.

4.1. Phase rotation

Phase rotation systems used in some of the designs made use of a costly 250 m long induction linac or low frequency RF to reduce the energy spread of the beam prior to cooling. A promising alternative [19] involves capturing the muon beam after the decay regions with a string of high frequency RF cavities. Muons of both signs can be captured simultaneously. The cavity frequencies vary from ≈300 MHz to 190 MHz, while their gradients grow adiabatically to ≈5 MV/m. The bunched beam then undergoes a high frequency time-energy phase rotation in a short linac section before cooling. A fixed gradient ≈10 MV/m is used in this section. The system has been simulated thoroughly using Simucool and Geant. They obtain 0.35 μ/p in the useful portion of longitudinal phase space after the bunching. The potential cost savings may be several hundred million dollars over the induction linac design. Optimization of the system is continuing.

In the previous technique, the original proton bunch structure disappears but in a bunch-to-bucket approach, as studied at CERN and RAL, it is conserved. There is a new front end design [20] for CERN that eliminates the 44 MHz cavities. The new system has a total length of ≈115 m and uses 88 MHz RF in the whole front end. The decay region after the target is reduced to 15 m. With 4 T solenoids and 4 MV/m RF gradient, the relative number of muons in the RLA acceptance is increased by a factor of 2.5. The final normalized transverse emittance delivered to the linac is ≈5 mm-rad.

An alternative front end design has been proposed [21, 22] that replaces the low frequency RF phase rotation with a reverse-phase-slip achromatic lattice with bending magnets of alternating polarities. Such a lattice is often referred to as a magnetic chicane. The large energy spread of the pion-muon bunches causes a shearing in longitudinal phase space. The chicane system reduces non-linearities in the subsequent acceleration of the muons in the linac. A new optics design has been done at CERN. The muon bunch is compressed in a strong focusing lattice and the particle density in the RF bucket is increased by a factor of 1.8. Work is continuing on minimizing the distortion to horizontal phase space. At RAL, regular solenoid focusing is used before and after the chicane, which is made up of 12 weak focusing combined function magnets. The design is compatible with the linac-compressor ring option for the proton driver in the CERN scheme. The chicane magnets have been designed [23] using Opera-3d. The basic unit consists of three dipoles that bend the beam successively by 64^o, -27^o, and 64^o. Focusing is provided by edge angles and by shaping the pole pieces. The magnets have a vertical gap of 30 cm and a peak field of 1.46 T.

4.2. Muon cooling studies

The main physical processes involved in ionization cooling, energy loss and multiple scattering, have been reexamined from first principles [24]. Accurate simulations of cooling performance must take into account the existence of correlations and non-gaussian tails in the distributions. The double differential cross section for transverse and longitudinal momentum transfers was derived from photoabsorption cross sections, where there are now good data available for media properties. Preliminary results were given for atomic and molecular hydrogen.

A quadrupole-based linear preecooling channel [25] might be useful for reducing the very large muon emittance coming from the production target. A FODO lattice was selected, since it has large transverse and chromatic acceptance. The average beta function for the channel varies from 1.6 to 1.9 m over the momentum range accepted by the U.S. 2.75 m cooling lattice. The quadrupoles have a length and aperture of 60 cm and a 1 T poletip field. The liquid hydrogen absorbers are located midway between the FODO quads, where the beta functions for both transverse planes are the same. A channel containing 30 cells cooled the transverse normalized emittance down to 4 mm-rad. This beam could be injected directly into an FFAG accelerator in the Japanese scenario or be followed with additional cooling or emittance exchange in the other scenarios.

One of the most significant simulation advances in the past year has been the improvement in the design of ring coolers [26]. Three families of ring coolers have been designed and simulated. Besides the economy of recirculating the beam, rings provide convenient regions containing dispersion that can be used for emittance exchange. As a result these cooling rings also reduce the longitudinal emittance of the muon beam. A convenient cooling figure of merit has been defined as the ratio of initial to final 6D emittance times the transmission.

The first ring that showed considerable promise was designed by V. Balbekov. This is a 37 m circumference ring with solenoidal focusing. Transverse cooling takes place in cylindrical liquid hydrogen absorbers. Bending is done in combined function dipoles. Emittance exchange occurs in a wedge-shaped piece of LiH. The figure of merit for examples of this ring is ≈40-100. Currently the simulations use hard edged approximations, but work is progressing on using more realistic fields [27, 26]. A TOSCA model has been made of the combined function dipoles and steel end plates have been designed to terminate the solenoid fields.

A second solenoidal design [26, 28] started with a working RFOFO transverse cooling lattice and added a gentle bending field to form a ring. The ring has a circumference of 33 m and a minimum beta function of 40 cm. A single wedge-shaped liquid hydrogen absorber is used for both transverse cooling and emittance exchange. The RF cavities are in dispersive regions in this design. The dipole field required is generated by tipping the solenoid coils through a small angle. The maximum figure of merit is ≈160.

The third family of rings uses quadrupole or dipole pole face focusing [29, 26]. Initial lattice layouts were determined using the design code SYNCH. The designs have evolved considerably over the past year. Currently the best results are obtained using a ring with ≈33 m circumference and 250 MeV/c muon momentum. A single wedge-shaped liquid hydrogen absorber is used in each cell. The merit factors for examples of this type of ring were ≈16-100. Ideas for future study include using Li lenses in the ring in order to get the transverse emittance low enough for a Higgs factory.

Although the ring designs have shown great progress, considerable work remains to be done. All the simulations need more detail, including adding windows for the RF cavities and absorbers and using more realistic field models. There may be thermal problems from the additional energy deposition in the absorbers. The design of kickers for these small rings with large emittance beams is a particular problem. The merit factors for all the ring designs drop significantly when the lattice symmetry is broken to include space for injection/extraction. For example, the RFOFO figure of merit falls from 160 to 110.

An alternative idea for cooling the muon beam is to use frictional cooling [30]. This scheme involves slowing the muons down to keV kinetic energies, where higher momentum muons lose more energy in atomic interactions than low energy muons. The magnitude of dE/dx is very large there, so the muons can lose energy in a helium gas cell. The particles are reaccelerated using DC electric fields. A complete scenario is being developed starting with a reoptimization of the pion characteristics at the target. Some of the problems that must be addressed include loss of muons from muonium formation or atomic capture and the design of the extraction windows.

4.3. Work towards a muon cooling demonstration

Most of the neutrino factory scenarios depend on some initial ionization cooling to prepare a muon beam for subsequent acceleration. However, cooling cells involve unique combinations of apparatus that have never been used before. Thus it is prudent to demonstrate experimentally the performance of a section of a cooling channel. This is the goal of the MUCOOL and MICE programs.

805 MHz cavities suitable for cooling applications have been built and tested at high power [31]. These cavities are unique in that they can use Be end windows across the aperture to get the maximum cavity field on the beam axis. The effects of window thickness and coatings were tested. Effects caused by the superimposed solenoid field were checked. The cavity was operated at gradients up to 33 MV/m. Surface damage and RF breakdown issues are being studied. A 201 MHz cavity has been designed and is ready for construction.

A new window for the liquid hydrogen absorbers was designed [32] using finite element analysis. The windows are as thin as possible on the beam axis and grow in thickness towards the edge in order to prevent buckling. Studies also showed that the new design should allow a better fluid flow contour to develop at the windows. Prototype windows have been manufactured and tested [33]. The shape of the machined aluminum windows was measured using photogrammetry. The measurements agreed well with the predictions from finite element analysis. A series of windows have successfully undergone room temperature and cryogenic rupture tests for safety considerations. Experiments have looked for density variations in hydrogen cells with forced flow cooling.

The MICE project is an international collaboration to demonstrate ionization cooling with a muon beam. PATH simulations [20] of 88 MHz and 201 MHz cooling sections for MICE showed similar performance. A cooling figure of merit was designed that monitored the increase in the number of muons inside a 4D acceptance hyperellipsoid. MICE will use spectrometers in front of and after the cooling cell under test in order to measure the change in phase space variables for single particles [34]. The transverse momentum is determined from the diameter of the projected circle, while the longitudinal momentum is found from the distance for a 2π phase advance in the solenoidal field. Beam emittances and all beam correlations can be determined offline in software. Work on the reconstruction codes has shown that the predicted small cooling effect from 2 cells should be measurable.

Two options are being examined for the particle detectors in the spectrometers. The first option is to use crossed planes of scintillating fibers [35]. Similar detectors have been used for D0 and MUSCAT. The detector has three layers of 0.35 or 0.50 mm diameter round fibers crossing at 120^o. The active area has a 30 cm diameter. The position resolution should be $\approx 40\,\mu$m. The fibers are read out with visible light photon counters. The second option is to use a TPG chamber [36]. This novel detector combines a TPC with a GEM (gas electron multiplier). The chamber is highly transparent, but produces a very large number of points per track. The chambers would have an active area 1 m long and 30 cm in diameter. The readout would use a data acquisition system similar to HARP.

One problem faced by any experiment trying to measure the performance of a cooling cell is the background of x-rays from the RF cavities [37]. Measurements have been made of the x-ray background surrounding the 805 MHz cavity at Fermilab. The problems arise from field emission from the surfaces inside the cavity that are subjected to very high electric fields. Studies are underway to examine surface treatments and conditioning schemes to minimize this background. Even if these studies are not successful, a small drop in gradient may make the measurements possible since the emitted current is proportional to approximately the tenth power of the field.

5. Proton driver and muon acceleration

5.1. Proton drivers design and status

High intensity proton synchrotrons for a driver have been designed in Europe [38], the US [39], and Japan and the construction of the Japan Hadron Facility [40] has started in Japan.

One of the European designs is an 8 GeV, 50 Hz machine, which can be built as an upgrade of the ISIS synchrotron. The lattice consists of 60 degree cells and the sextupole harmonic components are automatically canceled in each arc. Gradient magnets are commonly connected with fast trim quadrupoles for tuning. The beam power is expected to be 4 MW at most. Another synchrotron-based design in Europe is a 30 GeV, 8.33 Hz machine studied at CERN. The phase advance of the lattice is 72 degrees. An acceptance of 170 π mm-mrad with 75 mm bore radius is obtained. The total cost is estimated to be about 10% less than the linac-based driver [18].

In the US an upgrade of the AGS is being considered. By increasing the repetition rate by 10 times from 0.5 to 5 Hz and the total number of batches from the booster, the beam power is expected to be 4 MW eventually; it is 0.14 MW at present. Another path to 4 MW in the AGS requires a Superconducting Linac (SCL) and a 2.5 GeV accumulator. A detailed tracking study was presented [41] for a transitionless proton driver lattice. Enhancement of dynamic aperture is observed in a sextupole-corrected lattice, but the tolerance on random errors in the quadrupole magnets seems to be hard to satisfy.

Although JHF is a multi-purpose facility including a spallation neutron source and not a dedicated proton driver, it has adequate machine specifications for a super neutrino beam at present and for a power upgrade to a few MW in the future. The main concern is the beam loss in the synchrotrons. The design allows for 4 kW beam loss at the collimator of the 3 GeV rapid cycling synchrotron (RCS) and for 7.5 kW loss at the electrostatic septum (ESS), which is used for slow extraction. The main components of the 50 GeV Main Ring (MR) have already been ordered and a proton beam is expected within 5 years.

5.2. RLA

Fast acceleration is required to accelerate muons from a few GeV/c to 20 GeV/c. A design based on a Recirculating Linac Accelerator (RLA) was proposed first and intensive studies are going on. Three improvements are proposed to suppress emittance degradation [42]:

- a smooth transition from the cooler to the spreader and recombiner,
- making a short section in the spreader and recombiner,
- optimized linac optics for multi pass beams.

From the hardware point of view, a 201 MHz superconducting cavity is under development at Cornell and CERN [43]. The Cornell test pit construction is completed and a Nb/Cu cavity arrived at Cornell and was tested. The first results show that the Q value exceeds 10^{10} and the acceleration gradient is 3 MV/m.

5.3. FFAG

Another candidate for muon acceleration is the Fixed Field Alternating Gradient (FFAG) accelerator which appears realistic after the construction of the proof of principle (POP) machine at KEK [44]. The Japanese scenario uses four FFAG's cascading from 0.3 GeV/c to 20 GeV/c with a few MHz frequency RF [45]. The lattice is of scaling type and a singlet focusing structure is now being considered. The low frequency RF with scaling focusing structure provides a huge RF bucket. The acceleration is completed within a quarter of a synchrotron oscillation. The design study is applied to the FFAG based phase rotator PRISM [46]. The experimental results of POP show that 3D tracking studies using GEANT3.21 with 3D magnet field maps generated by TOSCA are reliable.

Non-scaling FFAG's are being studied in the US. A couple of lattice designs have been examined [47]. One by C. Johnstone gives good linear optics behavior and the other by D. Trbojevic shows a stable momentum range of $\pm$ 40%, but large geometric aberrations. A tool for synchrotron lattice design such as DIMAD is adequate for the initial phase of design. The non-scaling FFAG designs assume a fixed RF frequency as high as 200 MHz [48]. In order to minimize the phase slip during acceleration, the phase and voltage of each cavity have to be optimized. One example shows that the whole acceleration can be completed in five turns with a 40% over-voltage in the cavities and a dual harmonic RF system. Ten turns are needed for acceleration at 100 MHz.

The FFAG ring can also be used as a ring cooler [49]. The emittance to particle number ratio is improved by 20% using Li cavity windows of 25 mm thickness as absorbers. More detailed simulations with ACCSIM support these results.

5.4. Fast ramping synchrotron

A "conventional" synchrotron may be used if the ramping can be very fast. A fast ramping synchrotron with TESLA RF cavities operating at 1.3 GHz was proposed [50]. In such a machine a beam could be accelerated from 2 to 20 GeV/c in 30 turns. The magnet laminations are 10 μm thick and made of oriented silicon steel. The peak power is 45 MW, but the average power is only 24 kW because of the very low duty factor. Higher energy accelerators, such as 20 to 180 GeV/c and 180 to 1600 GeV/c, are also proposed where superconducting RF makes sense.

5.5. Tracking technique

For muon tracking, Boris-type algorithms have been developed [51]. The Boris scheme integrates vector and matrix terms separately. As a comparison with other algorithms, error analysis using the example of a 10 T uniform solenoid was performed. It was found that Runge-Kutta gives errors proportional to the integration step length, whereas the Boris procedure does not. Typical speed-up factors of four over what is achieved with Runge-Kutta were obtained.

6. Conclusion

The 2002 vintage of NuFact has been very tasty. Whether muon or β beams will ever be used depends on physics achievements in the next ten years. It is however already manifest that there is an overlap of interests between super-beams and neutrino factories for the proton driver and targetry. The preliminary costing of neutrino factories has boosted the study of "hyper" MTon detectors as an alternative, but perhaps not ideal way to get to the physics. These detectors are very expensive and the point of equilibrium for the cost of an ultimate neutrino facility has actually not yet been found. Moreover, the beam quality provided by neutrino factories remains unsurpassed. It is thus justified to aim at improving the performance to cost ratio of a neutrino factory. The developments in multiple target systems, efficient phase rotators, ring coolers, the preparation of a cooling experiment and a detailed comparison of the acceleration schemes contribute to that goal. Lastly, the combination of intense pion and β beams introduces a new challenge that deserves thorough investigation.

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