NuFact'03 Machine Working Group Summary

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Abstract. The machine working group sessions at NuFact workshops have always been characterized by the presentation and discussion of both new ideas and the developments in existing concepts and by lively debate. The machine sessions at NuFact'03 were no exception to this. In this article, we will try and summarize the work presented and the discussion that took place.

1. INTRODUCTION

The machine working group session at NuFact'03 demonstrated the continuing development in the ideas for the accelerator components of future high intensity neutrino facilities. In comparison to NuFact'02, there was more emphasis this year on the Neutrino Factory, with focus on the most challenging or expensive items of the accelerator complex, as determined by recent studies in the US [1] and Japan [2]. In particular, there were many presentations related to a Neutrino Factory in Japan based on FFAGs and centered around the J-PARC accelerator complex [3]. A staged approach to building the complete machine is envisaged, with physics at each stage. In the US, design work has been focused on cheaper alternatives for the muon frontend of a Neutrino Factory and on the muon acceleration. Cooling rings have received a lot of attention and the parallel program of R&D on cooling has made considerable progress through the MICE experiment and the MUCOOL collaboration. In addition, the development of a target and collector able to withstand the 4MW proton beam has continued both experimentally and theoretically, particularly in Europe and the US. Finally, the first ideas for a World Neutrino Factory Design Study, that would tie together much of this work, were considered at this workshop.

In this article, we will attempt to summarize this work and discussion that took place both during and between the working group sessions.

2. PROTON DRIVER

The aim of the proton driver is to deliver a 1 MW beam in the first phase and 4 or 5 MW with a future upgrade. The output energy should be several GeV to 50 GeV depending on the acceleration schemes. One way to realize the facility is to upgrade existing machines. Two examples were shown during the working group session. One is an ISIS upgrade with a new synchrotron [4] and the other is an AGS upgrade with a

1.2 GeV superconducting linac [5]. Of course, to make a new facility from scratch is another option. Although it is not solely for neutrino production, J-PARC in Japan will be a brand new proton driver aiming at 1 MW beam from the beginning [6]. Also as a brand new proton driver, a fixed field alternating gradient (FFAG) based scheme is considered although no detailed parameters are determined [7]. The energy and beam power of these candidates are listed in table 1.

Table 1: Proton drivers – energy and beam power

	Design goal	Future upgrade
ISIS with new synchrotron	1 MW with 8 GeV	5 MW
AGS with 1.2 GeV SCL	1 MW with 28 GeV	unknown
J-PARC	1 MW with 50 GeV	4 MW
FFAG	?	?

The ISIS upgrade plan has three phases. First, they will make a 3 GeV synchrotron with 50 Hz repetition rate as a spallation neutron source, which will also be able to accelerate a beam to 8 GeV at 16.7 Hz to give a test facility for a Neutrino Factory. Secondly, the present ISIS synchrotron will be decommissioned and two new booster synchrotrons and linac will be constructed. Finally, two main synchrotrons operated at 25 Hz each will give 5 MW beam power. In parallel with the machine design, beam studies such as bunch compression and simulation will be carried out in ISIS.

The AGS upgrade plan relies on an increase of the repetition rate. This can be done both by shortening the injection time and by higher ramping rate of the bending field. The former is only possible with direct injection, instead of stacking a few batches from the booster. Therefore, an idea of a 1.2 GeV linac as an injector comes up. There are several reasons why they have picked a superconducting linac instead of warm one. One is simply because of the on-going SNS project, which uses a cold linac structure. Therefore, the same technology can be applied. The other may be more critical, that is the limited real estate that can accommodate the new injector. In any event, the average current is low with a 0.179% duty factor and the choice of superconducting RF sounds reasonable.

Construction of J-PARC started in 2001 and it will deliver a first beam around 2008. J-PARC is multi-purpose facility, not only for particle physics, and consists of a 3 GeV rapid cycling synchrotron and a 50 GeV slow cycling one. The 3 GeV machine will have spallation neutron users and the 50 GeV will deliver a beam either to Kaon factory users by slow extraction or to neutrino users by fast extraction. The upgrade path to a few MW beam power is similar to the AGS upgrade, that is to increase the repetition rate.

Every one agrees that we know how to construct a 1 MW facility even though it is a big challenge. However, the future upgrade to a few MW seems to be still a big jump and, at the moment, no one has the confidence to make it. FFAGs, on the other hand, can be a breakthrough to solve all the problems of conventional high intensity synchrotrons. Table 2 illustrates the uniqueness of an FFAG.

As planned for the AGS and J-PARC, one way, and probably the only way, to increase beam power is to increase repetition rate. Because of space charge effects and beam instabilities, the number of particles per cycle will be limited. Unfortunately, the

repetition rate will be also saturated because of the ramping speed of lattice magnets. An FFAG, on the other hand, uses a static magnetic field and the repetition rate can be very high such as 1000 Hz. Although it is still premature to say that an FFAG is able to deliver high power protons as a proton driver, we should keep eyes on the development because of its high potential.

Table 2: Proton drivers – energy and repetition rate

	Design goal	Future upgrade
ISIS with new synchrotron	16.7 Hz (8 GeV)	25 Hz (6 GeV)
AGS with 1.2 GeV SCL	2.5 Hz (28 GeV)	unknown
J-PARC	0.3 Hz (50 GeV)	1 Hz (50 GeV)
FFAG	1,000 Hz	10,000 Hz

3. TARGETRY

There was a lively discussion as always on the subject of targetry. The issues are centered on the extremely high peak and average power dissipation in any target suitable for a neutrino factory. These include shock from peak power heating, cooling of average power, radiation damage, material lifetime and shielding. There was no shortage of ideas and a wide range of schemes and experimental tests were presented and discussed. Scarcity of funding and limited availability of suitable test beams were common themes.

Bennett and Kirk gave summaries of the European and US targetry programs respectively [8,9], and there were also presentations on the PRISM target in Japan [11] and the MECO target at BNL [10]. A wide range of target options have been proposed including free and confined flowing mercury, figures 1-3, liquid or gas cooled granular targets, figure 4, solid targets of low expansion or shock resistant materials, figure 5, and various rotating band, levitated or projectile targets, figures 6-7. These schemes attempt to address the thermal shock and heat dissipation problems in various ways. The liquid jets are disrupted by the beam pulse but on a timescale much slower than the particle production time, and they are regenerated before the next beam pulse arrives. The constrained mercury attempts to solve the problem of material degradation by constantly circulating the target material, although the entrance window or containment may still be problematic. The solid targets use materials with low thermal expansion rates such as carbon composites or Invar to minimize the thermal shock. These are radiatively or water cooled but target lifetime is still a concern, however they look feasible at ~ 1 MW power levels. Rotating band or other moving solid targets attempt to address the heating and radiation damage problem by spreading successive beam pulses over a larger surface area by continuously moving the solid material. This may work as long as the single-shot damage threshold is not reached. Cooling and servicing the target material and mechanism would be challenging.

Figure 1: Schematic of a free mercury jet

Figure 2: A contained mercury target.

Good progress has been made experimentally to test several of these concepts. Thermal shock measurements have been made on metal and carbon solid targets at BNL, and material properties after high dosage exposure have also been measured, figure 8 [9]. Mercury jets have been tested at BNL with beam from the AGS (without solenoid field) [9], figures 9-10, and in a 20T solenoid at CERN/Grenoble (without beam), figure 11. The E951 experiment at BNL showed disruption of the mercury jet by the beam pulse but it was rapidly reformed and no damage was sustained by the nozzle. The CERN/Grenoble result shows that the strong magnetic field is helpful in damping surface instabilities in the jet. Both of these results are very encouraging. The logical next step is to perform a test with beam in a strong magnetic field. This will require a new magnet, figure 12, and beam time at a suitable facility such as AGS, PS or JHF.

Figure 3: Proposed spallation neutron source target.

The MECO project, BNL E940, plans to use a water-cooled solid target [10]. They have already performed cooling tests on a sample using induction heating rather than a beam. The PRISM project in Japan has just started testing components of a current-carrying mercury loop target [11]. They have also directly measured the radiation heat load into a superconducting magnet with a beam test at KEK.

Figure 4: Granular target cooled by liquid

Figure 5: Solid carbon target.

Figure 6: Rotating band target concept.

4. COOLING

4.1 Simulations

Raja et. al [12] presented results of simulations showing that Geant 3 is now ready and being used for cooling channel simulations. They showed examples of cooling rings with realistic field models, see figure 13, and that it is possible to model complex geometries with this package. ICOOL has been a stalwart of cooling channel development and is now being used for ring coolers. Kahn et. al. showed results for rings with realistic fields [13]. There is no longer any reason to be struggling with

simulations with non-physical field approximations. Makino showed results from a first attempt to model a cooling ring using COSY [14]. The results showed a high sensitivity to magnet end effects. This work is continuing.

Figure 7: Magnetically levitated rotating toroid, radiatively cooled.

Figure 8: BLIP irradiation test target holder after 24 Rads.

Figure 9: E951 Hg jet chamber (no magnetic field).

Figure 10: E951 Hg jet tests, 1 CM diameter jet, 16 GeV, 4 TP protons

Figure 11: CERN/Grenoble test, 4mm jet, 12 m/s, 0, 10, 20 T, no beam.

4.2 Ring coolers

There was a lot of progress on ring coolers presented at this meeting. The Balbekov ring cooler, figure 14, has now been simulated with ICOOL and Geant with realistic fields [13] and there is good agreement between the codes. Significant cooling in 6D is being achieved in the simulations. Work is in progress to replicate this using COSY [14]. Work has continued apace on the RFOFO ring, figure 15. Fernow et. al. presented results from ICOOL showing at least a four fold increase in muon density [15]. The ring has also been simulated by Balbekov using his own code, and work is underway to model it in Geant. Palmer et. al. have looked at perturbations of the ideal ring including missing cells to allow for injection and extraction, various absorber

Rees summarized the Muon frontend studies at RAL [17]. They have been looking at a racetrack cooling ring, figure 18, using solenoids and dipoles. It uses low-frequency RF, like the other ring coolers, and has room for injection and extraction in the straight sections of the racetrack. Simulations are under way using OPERA, Parmela and another new code at RAL.

Figure 14: Balbekov cooling ring

Figure 15: RFOFO ring.

Figure 16: Dipole ring

Figure 17: Lithium Rod ring.

4.3 Alternative Cooling methods

Galea presented a method for frictional cooling in helium gas [18]. He showed simulation results that indicated that the method should work and attempted to verify this with an experiment to cool low energy protons. The experiment did not have a solenoid field and was not able to see the effect but provided some useful data to compare with simulations and some practical experience. Galea is planning a follow up experiment that will include the magnetic field.

Johnson et. al of Muons Inc. presented the latest results in the experimental demonstration of the feasibility of gaseous ionization cooling [21]. Perhaps their greatest success was in developing a new funding source (Muons Inc. has been awarded four small business grants to develop technology for gaseous ionization cooling). This scheme uses high-density gaseous hydrogen as the cooling medium. The hydrogen cools the muon beam but also allows for potentially higher gradient in the RF cavities because it suppresses breakdown and cools the cavity windows. Because the cooling medium is distributed within the RF cavities the packing factor is also greatly improved. Muons Inc. has built an 805 MHz test cell, figure 19, to measure the Paschen curve for gasses, particularly hydrogen, up to high gradients. The data agrees well with DC breakdown data in the literature and extends the range of measurements up to 50 MV/m, see figure 20. At this point the surface finish of the test cell electrodes appears to become significant. Future tests will attempt to improve this or condition the surface to allow higher gradients. Muons Inc. has also been awarded grants to study high-power pulse compression and 6D cooling schemes based on similar technology.

S = solenoid, A = absorber, 36 cavities in blocks of 3

Figure 18: RAL racetrack cooling ring.

Figure 19: 805 MHz test cell.

Figure 20: Paschen curve for hydrogen.

4.4 RF bunching and phase rotation

Some of the most expensive components of the study II Neutrino Factory were the induction linacs for phase rotation. Study II established feasibility but since then work has been ongoing to establish a more cost optimal solution. One approach to this is to use RF phase rotation and bunching, as proposed by Neuffer et. al. [19], see figure 21. Simulations show good performance for a system that would be substantially less expensive than that in study II. To get the best performance from this scheme the downstream cooling channel should be re-optimized. This method also captures both signs of muons. Work is continuing to look for the best combination of RF frequencies and to compare simulations with different codes. Iwashita showed an alternative RF bunching scheme using modulated RF [22]. This could be achieved using a few frequency components. Initial studies are promising and this work is also continuing.

Longitudinal Motion (1-D simulations)

System would capture both signs (μ^+ , μ^-)

Figure 21: RF bunching and phase rotation [19].

4.5 Bunch compressor for a muon collider

Balbekov showed a complete end to end layout for a possible muon collider [23]. This consisted of a target station, phase rotation, bunch compressor ring, matching section, RFOFO cooling ring and lithium lens channel. The scheme is still missing kickers but the other components can now be simulated. This kind of end-to-end simulation will be vital for overall system optimization in the next design study.

4.6 MICE and MuCool

A cooling channel forms one of the technically most changing aspects of a Neutrino Factory accelerator complex. It has long been released that an R&D program is essential to demonstrate that such a channel can be built and will cool and to learn more about the cooling process. The MUCOOL collaboration [24] has existed since 1998 and is focusing on the construction of the elements of a cooling channel, the demonstration that they can work together as expected and the operation of a cooling cell in an intense proton beam. The MICE collaboration [25] will take the cooling cells developed in collaboration with MUCOOL and use a muon beam to show that they will cool and to learn more about the cooling process.

4.6.1 MuCool

The MUCOOL collaboration has already begun the development and construction of all elements of a cooling channel, in close collaboration with MICE. In particular, a 805MHz RF-cavity has been constructed and tested in Lab G in Fermilab partially inside a super-conducting coil very similar to a focus coil. This has produced results of great importance to MICE. It is well-known that RF-cavities produce electrons by field emission and the tests in Lab G have shown that very large numbers of particles can result, see figure 22. This is a problem for MICE because although these electrons will be stopped in the cooling cell absorber, they will produce x-rays which could form a significant background in the detectors used to track the muons (see section 4.6.2). In addition, the electrons are focused by the field from the super-conducting magnet and became intense enough to make a small hole in the window used to seal the vacuum in the cavity in the initial tests in Lab G. A program of measurements has been undertaken to better understand the electron production mechanism and to find ways of reducing it [26].

As well as tests with a 805MHz cavity, the design and construction of a 200MHz cavity, the correct frequency for a cooling cell, has also started [27].

Another area of particular interest has been the construction of liquid hydrogen absorbers [28]. These have two special problems as far as a Neutrino Factory is concerned: safety and removing the heat deposited by the muon beam. The most important safety problem is the windows of the absorber [29]. These need to be as thin as possible to minimize their heating effect on the beam, but they must also satisfy the hydrogen safety requirements. A number of window designs have been considered, all of which make the window thinner in the center than at the edges. Five torispherical windows, with a thickness of less than 400 μm at the center, have been built and tested to destruction at Fermilab to satisfy the local safety requirements. Finite element calculations suggest that an alternative design with a thickness of less than 140 μm will also satisfy these requirements. As far as the heat removal is concerned, FEA calculations of heat deposition are also being made and the proposed schemes for its removal tested [29].

To aid in the MUCOOL aims, a new, dedicated test area is being built in Fermilab at the end of linac [30]. This will allow testing of all elements of a cooling cell together and, in particular, the use of liquid hydrogen, which is not possible in Lab G.

At a later date, it will also be possible to address the final aim of MUCOOL, passing a high intensity proton beam through the cooling cell to test its operation under these conditions.

FIGURE 22. Electron current measurements made with the 805MHz cavity in Lab G at Fermilab under a variety of conditions (see [26] for more details).

4.6.2 MICE

As already mentioned, the aim of mice is to demonstrate that ionization cooling works and to learn more about the cooling process. It will use two cooling cells based on the SFOFO cells from US Study II [1] and place instrumentation around them to identify muons and measure their parameters entering and leaving these cells, see figure 23.

The two cooling cells will bring a reduction of about 10% in the 6D normalized muon emittance, which is not measurable by collective techniques. Therefore, MICE will use a single muon beam, with individual muons passing through the detector in a given time period [31]. The “beam” emittance will then be reconstructed offline from the measured parameters of the muons.

The collaboration submitted a proposal to run the experiment at the Rutherford Appleton Laboratory to an international review panel in January 2003 and defended it in February. The review panel recommended approval of the experiment in May and the collaboration is currently seeking funding to build it. Design and prototyping work continue in parallel.

FIGURE 23. Schematic layout of the MICE experiment.

5. MUON ACCELERATION

As in the previous workshops, three schemes were presented to accelerate muons. One is a re-circulating linear accelerator (RLA), another is a very rapid cycling synchrotron (VRCS) and the last is a fixed field alternating gradient (FFAG) synchrotron.

5.1 Re-circulating linear accelerator (RLA)

There were three talks related to re-circulating linear accelerators (RLA). One was an overview talk on a European Neutrino Factory based on two RLAs by Meot [32]. Another was an optics update presented by Bogacz [33]. The third was on 200 MHz superconducting cavity development by Geng [34].

The so-called CERN design assumes three stages of acceleration of the muons. It starts with pre-acceleration by a linac from 0.3 to 3.0 GeV. The second stage utilizes an RLA that accelerates muons from 3 to 11 GeV in the same RF cavity four times. The final stage is again an RLA from 11 to 50 GeV followed by a 50 GeV triangular muon storage ring.

The initial beam emittance after the cooling channel and therefore before the RLA was updated assuming a ring cooler instead of a cooling channel which was proposed in the Study II. Now, both transverse and longitudinal emittance are reduced and optimization of a RLA based on those new parameters was done. In particular, the reduction of the longitudinal emittance, which is about a factor of 10, impacts on the RLA design a lot. Further optimization is in progress.

Superconducting RF cavity development is good news from a hardware aspect. The field gradient of 11 MV/m is achieved although some problems such as so-called Q-slope still remain.

5.2 Very rapid cycling synchrotron (VRCS)

A more detailed study of very rapid cycling synchrotron (VRCS) was presented by Summers [35]. Here “very rapid” means 4600 Hz, which is similar or even higher than the repetition rate of the FFAG proton driver discussed. One concern of such a high cycling operation is power consumption and voltage induced in a magnet. In fact, the energy stored in each magnet is around 100 kJ and the voltage is 120 kV. The power consumption is, however, still low due to low duty factor and a center tap of SCR stacks eases the voltage problem, namely ± 60 kV. The other issue is an effect of eddy current on a beam. That needs more study.

5.3 Fixed field alternating gradient (FFAG)

This year, more than a half of the machine working group talks discussed a fixed field alternating gradient (FFAG) acceleration scheme. Palmer presented an overview of FFAG schemes in comparison to others [36]. Another talk was the issue of longitudinal dynamics of a non-scaling machine presented by Johnstone [37]. Four talks were on a scaling machine from several view points, such as updated lattice design and particle tracking study [38], superconducting and normal conducting magnet design [39], and one application as a phase rotator of muons which is called PRISM [40].

The first question was whether a scaling or a non-scaling FFAG is suitable for a muon acceleration ring. Besides the beam dynamics issues, Palmer claims that the superconducting magnets become cheaper in a non-scaling machine because of smaller aperture and simpler structure. The design of superconducting magnets for a scaling machine was presented and that shows there are not many technical differences. In any case, this needs further study for both scaling and non-scaling magnets when more detailed optics design is made.

The second question was whether a low or high frequency is adopted. At the moment, a low frequency RF system such as a few MHz is assumed in the scaling design and its gradient is around 1 MV/m. The non-scaling design takes high frequency such as 100 MHz or more and expects a higher gradient than the low frequency RF system. Higher gradient is preferable because of less beam loading and cost. Obviously, other combinations, for example a high frequency system with scaling machine, should be possible and needs to be examined. It is probably true that there is not much difference in cost.

An interesting observation was made by Palmer with respect to the third question, that is whether cooling is necessary or not. The question can be phrased in other words, namely which is smaller: the cost of a cooling system or the cost reduction due to smaller acceptance with a cooling system. Palmer’s answer was that large acceptance magnets for non-cooled beams are cheaper. Furthermore, the cooling system can be a future option to obtain more muons if necessary. The audience seemed to agree.

The fourth issue is if a kicker is feasible for an FFAG design. The kicker is also an issue for a ring cooler. The general consensus was that the kicker for an FFAG is easier than one for a ring cooler for three reasons. The first is the smaller aperture in

an FFAG. The second is the larger circumference and therefore longer rise time. The last is that in an FFAG the orbit kick is made not only by kickers but also by the main lattice magnets.

Finally, a staging scheme for an FFAG based design was discussed taking as an example a path starting from the PRISM project to a Neutrino Factory. It should be emphasized that physics outputs will be made in each stage of the path, see table 3.

6. DESIGN STUDY

So far, three Neutrino Factory feasibility studies have been undertaken, two in the US, in 2000 [41] and 2001 [1], and one in Japan in 2002 [2]. All had limited participation from outside the respective regions. It was recognized in the build up to NuFact'03 that the time is ripe to embark on a "third" study, but that this should be a World Study with participation from all three regions. As a result, a session of the machine working group was devoted to presentations of the form such a study should take as seen from each region and a discussion of how to proceed. In this section, we will give a brief summary of the presentations and outline the conclusions of the discussion.

6.1 View from Europe

The view of the World Design Study (WDS) from Europe is largely determined by a planned bid for funding from the European Union Framework 6 (FP6) Design Study program [42]. The Framework Programs are a method by which the European Commission (EC) provides funding for science in Europe. A number of activities are specified against which bids can be made and in FP6 this includes Design Studies. These will provide funding for both theoretical studies of new infrastructure, including detailed engineering, and R&D on new technologies involved in this infrastructure. About 10 MEUR per study is expected to be available over a time period of up to 4 years. Collaboration with partners outside Europe is strongly encouraged.

In Europe, it is planned to submit a proposal to this program. This is very important for two reasons: (1) to re-invigorate Neutrino Factory activities in Europe, which have suffered considerably following budget cuts at CERN, and (2) to provide funding for a number of planned R&D projects. As a result, Europe would envisage the WDS lasting 4 years, producing a feasibility study for a Neutrino Factory after 2 years and a report including more detailed engineering after a further 2. R&D would be an integral part of the study.

6.2 View from Japan

A first design study for a Neutrino Factory in Japan was completed in 2002. This is centered around the J-PARC facility already under construction at the Tokai campus of the JAERI and is based on FFAGs. A staged approach to building the Neutrino Factory is envisaged, with physics at each stage, as shown in table 3.

TABLE 3. Staged approach to the construction of a Neutrino Factory in Japan.

Stage	Facility	Main physics outcome
1	High power proton driver	Muon g-2
2	PRISM FFAG ring	Muon LFV decays
3	PRISM II ring	Muon EDM
4	1MW Neutrino Factory	Oscillation parameters
5	4.4MW Neutrino Factory	CP-violation
6	Muon collider	Higgs mass & width, etc.....

The plan in Japan for their contribution to the WDS, in the early stages at least, is to continue to investigate FFAGs, both theoretically and experimentally, to assess whether they are a realistic option for a Neutrino Factory. They would seek active participation from the other regions in this work.

6.3 View from the US

Two feasibility studies have taken place in the US, the first based at Fermilab [41] and the second at Brookhaven [1]. The aim of the first was simply to demonstrate the feasibility of the machine and cost was of secondary importance. This it achieved, though the performance was poor. The aim of the second study was to improve on the performance of the first, with the cost being an output of the study. This was again achieved, though the output cost was rather high. For the US, the aim of a third study would be to take the output of the second and reduce the cost, while maintaining the performance. This is seen as a theoretical design and engineering effort, with R&D being done in parallel, but not part of the study.

6.4 Conclusions from the Discussion

Although the discussion which followed the presentations was wide-ranging, considerable time was spent on reconciling the differences in the views summarized above. As a result, a number of important conclusions were drawn:

- There should be a world-wide design study
- A steering group should be created to start the study off
- The study should aim to produce a cost-optimized Neutrino Factory design
- It should include detectors as well as the accelerator

Following the discussion, a six person steering group was created with the membership shown in table 4 and tasked with starting the WDS.

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TABLE 4. WDS steering group

Region	
Europe	Alain Blondel Rob Edgecock (chair) Helmut Haseroth
Japan	Yoshi Kuno Yoshi Mori Kenzo Nakamura
US	Steve Geer Bob Palmer Mike Zisman

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