Summary of the accelerator sessions

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1 Overview

The development of beams for neutrino physics is, worldwide, the subject of several projects and of intense R&D programs towards future facilities. In the accelerator sessions, without undervaluing the presently running facilities (CNGS at CERN, NuMI at FermiLab and T2K in Japan), we focused on future installations. After a brief introduction to each project, their R&D issues and plans were discussed, with emphasis on ongoing or possible participation of European laboratories, CERN in particular.

The first session covered the development of beta-beams, followed by the plans for the next generation of the more conventional but high intensity pion/kaon-decay beams (superbeams) in Asia, USA and Europe. The second session was devoted to the R&D effort towards the Neutrino Factory and the possible connection to a muon collider. In addition, the sessions included a presentation of the EC funded design study EUROnu, one on future neutrino facilities, and a proposal to revive a neutrino beam from the CERN PS. We will discuss the most salient points raised in the presentations and in the summary discussion at the end.

2 Neutrino beam possibilities

Accelerator generated neutrinos have so far been produced from the decay of pions/kaons produced by intense proton beams on a light material target. The beam power on target is the determining performance factor. Fermilab (NUMI) and CERN (CNGS) have reached a beam power of 300-400 kW. Further plans **(superbeams)** involve reaching a range of 1-4 MW; such plans exist in Japan (T2K beam and upgrade), US (NUMI upgrade and LBNE) and a study is ongoing for the low energy beam from the CERN SPL. Reaching higher purity or intensities, or producing a different neutrino flavor, requires a new technology, where the decaying particle is accelerated and stored in a decay ring. In the **neutrino factory,** a beam of muons is prepared and accelerated to an energy of ~25 GeV, and beams of up to ~25 GeV (ν_e & $\bar{\nu}_\mu$) (resp. $\bar{\nu}_e$ & ν_μ) are produced in the decay of μ^+ (resp. μ^-). An alternative is the **beta-beam** in which weakly decaying ions are accelerated and decay to produce perfectly pure electron neutrino beams with an energy of a few per mil of the ion energy. Production of high intensities of muons or β-emitter ions requires intense proton beams on special target materials; in addition new methods such as ionization cooling must be used to increase the available intensity. In all cases, the generated neutrinos (ν_μ's or ν_e's) are directed towards a large detector located at a distance carefully chosen to provide sensitivity to the neutrino oscillation phenomena.

All three options present considerable technical difficulties; in addition, the community is presented with a challenge: a decisive next step in intensity and beam technology is likely to require coordination at international level, and choices to be made. These choices will depend on the physics capabilities, but also on cost, safety and feasibility considerations, both on the accelerator and detector sides. Progress in collecting this crucial information is object of the ongoing R&D.

The EUROnu EC FP7-funded program (Edgecock) is the presently available framework where R&D on future neutrino facilities is conducted and coordinated in Europe. It covers all three options: superbeams, beta-beams and neutrino factory and has established synergies and collaboration with international bodies. EUROnu has 15 collaborative institutes throughout Europe including CERN. The goal of EUROnu is to present a performance and cost comparison between the three options to the CERN Council Strategy Group. As coordinating body EUROnu tries to bring people working on neutrino physics in Europe together, promoting collaboration and not competition. A critical issue for EUROnu to complete its goals is the costing and safety evaluation of the facilities.

3 Superbeams

3.1 Super beam plans in Japan were summarized by Hasegawa. The T2K neutrino beam is under commissioning (first protons on target in April 2009, first neutrino events in December 2009). The experiment requested a total integrated beam power larger than 0.75MW × 15000h at any proton energy between 30 and 50 GeV. The 2.5 degrees off-axis beam provides a muon neutrino beam with 0.5% electron neutrino contamination at a peak of energies situated around 650 MeV. The international collaboration comprises 500 physicists of whom 50% are from European institutions, with several important contributions from CERN: the NA61 Experiment for measurement of hadron production; CERN test beam for detectors; donation of UA1/NOMAD magnet and support for related issues; Micromegas production by CERN TS/DEM group and tests at CERN; infrastructure for detector preparation; CERN-KEK cooperation on super-conducting magnets for neutrino beams.

The not replaceable parts of the beam line (the decay volume and the hadron beam stop) are designed to withstand 4 MW beam power. The KEK roadmap includes upgrades of the T2K facility to 1.7 MW, with a date of around 2015, as well as the detector R&D towards a large mass detector (Water Cherenkov or Liquid Argon) that could be sited at Kamioka or at distances between 650 (Okinoshima Islands) and/or 1100 km (in Korea), thus allowing sensitivity to the mass hierarchy and CP violation for large enough values of $\sin^2 2\theta_{13}$. The synergy with proton decay searches in the huge non-magnetic detectors was emphasized.

3.2 Neutrino plans in US were discussed by Yung-Kee Kim. Fermilab, as the main US particle physics accelerator laboratory, has visions for the future which encompass the high energy frontier, the intensity frontier (and neutrinos) and the cosmic frontier. Neutrino physics is a very high priority on the Fermilab plans. An upgrade of the proton accelerator complex using superconducting technology developed for the ILC is considered with possible power of the order of 2MW. This has applications for high intensity, low energy measurements, such as the search for lepton number violation in muon interactions, but is also fundamental for high performance neutrino beams. The first step (2012) will be the delivery of high intensity beams to the NOvA (810km) off-axis experiment. On a time scale of 2018 a wide-band superbeam from 2MW proton power will be aimed at the DUSEL lab in South Dakota (1300 km), where large detectors (100kton Water Cherenkov and/or 20kton LArgon) have been proposed. Among the high energy frontier projects, Fermilab seems to focus on the muon collider – naturally synergetic with the neutrino factory. The first feasibility and design studies of the Neutrino Factory were performed in the US and a Muon Accelerator Program has now been launched to evaluate the muon collider.

3.3 Superbeam plans in Europe have been associated with the opportunities offered by the development of the Superconducting Proton Linac at CERN (Roland Garoby). High reliability, flexibility in the time structure as well as the relative ease of power upgrade make such an accelerator suitable for a variety of applications: accelerator driven waste transmutation, a proton driver for EURISOL and thus the beta-beam, and an injector of low emittance beams for the LHC. Associated with an accumulator, the SPL provides the adequate time structure for a superbeam. The HARP results for particle production have shown that energies as low as 3-4 GeV are suitable for neutrino applications. Progress in the design of a superbeam facility from the SPL has taken place within EUROnu (Marcos Dracos). A new horn design provides higher flux, higher energy (maximum flux at 400 MeV for 3.5GeV protons) and better purity. This neutrino energy is similar to that of the beta-beam. At that energy the optimal baseline will be typically 200-300 km, although 125km (CERN-Fréjus) already provides interesting results. The integration of the target inside the horn and the rapid pulsing of the horn (30-50 Hz) constitute the main challenges in the design. There is a clear synergy with the LAGUNA design study. The possibilities offered by a higher energy neutrino beam from a would-be high power version of the proposed PS2 were not explicitly presented at the session, but in the discussion – by allowing a longer baseline, such as CERN to Pyhasälmi, the experiment acquires sensitivity to the matter effects and thus the determination of the mass hierarchy.

3.4 PS Neutrino beam proposal (Carlo Rubbia); it was proposed to resurrect the old neutrino beam line from the PS (used for oscillation studies in BEBC/CDHS/CHARM and suggested for the proposal P311). With two detectors (Liquid Argon modules of the same type as those of ICARUS in C. Rubbia's proposal) this provides a chance to perform a definitive measurement of oscillations in the energy regime of LSND and MiniBooNE. It can also be seen as a way to provide measurement of some neutrino cross sections needed for the design of future beams, and a useful test bed for neutrino detectors and beam R&D such as target and collection systems. The beam would require pulsing of the horns at 2Hz, which could lead to the development of a power supply for super beam horns.

4 Neutrino Factory

4.1 The Neutrino Factory (talks of Kirk, Zisman and Pozimsky) produces intense beams of electron neutrinos with energy above the tau production threshold. It is the device with the greatest ultimate sensitivity for the study of neutrino oscillations. The performance comes as a result of using several new concepts pushed to their limits. The efforts that are ongoing consist of three main experimental activities (MERIT, MICE, and EMMA) carried out by international collaborations, and an International Design Study for the Neutrino Factory (IDS-NF).

Producing a large number of muons requires the highest possible beam power (4MW is, somewhat arbitrarily, considered) on a production target embedded in magnetic field. The MERIT experiment was carried out at CERN by a collaboration led by US colleagues. The experiment tested the concept of a liquid mercury jet target embedded in a 15T magnetic field using an intense beam from the CERN PS. It can be said that MERIT has successfully demonstrated the Neutrino Factory/Muon Collider target concept. However the infrastructure for a 4MW target system needs to be designed and engineered; this has generic value beyond a Neutrino Factory specific target station. CERN participation in MERIT was crucial to its success; CERN participation in the development of a 4MW target system would be both welcome and beneficial to the entire accelerator physics community.

Ionization cooling is the only practical way of reducing the muon beam phase space and is an essential feature of muon accelerators, Neutrino Factory and Muon Colliders. The MICE experiment aims at establishing its practical feasibility, by building a cooling cell and testing it precisely in a variety of configurations. The experiment is in the beam commissioning step at RAL, and the first complete muon ionization cooling cell ever built is under construction around the world; first measurements of cooling are expected in 2012. A major unknown in the performance of cooling cells is the accelerating gradient that can be achieved when RF cavities are embedded in the guiding magnetic field. This is studied in the MUCOOL program at Fermilab where a variety of RF cavities at various frequencies is being tested. There is experimental evidence that the maximal gradient can be reduced by a factor more than two, but this reduction is dependent on the field configuration and on the surface of the cavities. Testing the large 200MHz cavity requires a dedicated large size coil which is under construction. CERN has contributed to MICE in its early conception phase and by providing RF amplifiers. It would be of great interest if the contribution of CERN would continue.

Muon acceleration must be fast. For the neutrino factory with $E_\mu \leq$ 25GeV, there is no time to ramp the magnetic field in a synchrotron. Linacs, recirculating linacs or FFAGs are possible solutions. FFAGs offer potentially the best use of expensive RF hardware, and are actively studied. An electron model non-scaling FFAG, EMMA, is under construction at Daresbury Lab (UK), the injection line is now under commissioning. The FFAG has rather complex and non-linear beam dynamics properties that EMMA intends to measure and compare with the available models and tracking codes.

The concept of neutrino factory is 12 years old and has been the object of several studies already. The design is altogether rather stable now. The European contribution of IDS-NF proceeds largely through EUROnu, work packages are now in place. The main aim of the study is to arrive at a credible cost estimate and safety assessment by 2012. In both domains the IDS-NF is somewhat short of resources, so additional contribution of CERN expertise would have an extremely valuable and visible impact.

4.2 Muon Collider (Steve Geer). One of the interests in the Neutrino Factory is that it may be a step towards a Muon Collider. What is impressive here is that the footprint of the muon collider is relatively compact, making it an attractive possibility for several sites; the physics potential is that of a high energy lepton collider, with the added bonuses of a very well defined energy and energy spread compared to the high energy electron machines and of the specific muon couplings. The technological gap needed to evolve from a Neutrino Factory to a Muon Collider is however not small! Fermilab is actively planning to start R&D on Muon Collider in parallel to that of the Neutrino Factory, promoting synergies as much as possible.

5 Beta-beam

The Beta-beam (talks of Wildner, Stora, Mitrofanov) is studied in the framework of EUROnu. It presents a number of challenges, but benefits from the experience of the nuclear physics community – at CERN related to ISOLDE. The facility has evolved from a baseline design, developed in the EURISOL design study, that uses a lot of CERN infrastructure. If the chain Booster-PS-SPS remains (as seems to be the case now), the scheme will remain valid. If not, the compatibility with PS2 needs to be ascertained. There are intensity limitations due to irradiation in the PS, SPS and in the storage ring, but for the baseline ^{6}He and ^{18}Ne scenario these seem manageable (but at the limit). The storage ring is expensive but feasible.

The main challenge of the beta-beam is to achieve sufficient ion production. The baseline beta-beam uses ^{6}He (for anti-electron-neutrinos), which can be produced in sufficient amounts by spallation from ~200kW of GeV-protons. Electron neutrinos require ^{18}Ne at a rate of $2x10^{13}$/s, which is at least an order of magnitude more than what can be achieved directly with the above intensity of GeV-protons. More promising solutions involve e.g. a 700kW 10 MeV proton beam on a molten sodium salt (^{23}Na(p,α2n)^{18}Ne reaction), which in principle could produce the required rate of 2 10^{13} ^{18}Ne/s. Much R&D is needed before this (or others possibilities given in T. Stora's paper) become real possibilities.

An alternative set of ions are ^{8}Li (for antineutrinos) and ^{8}B (for neutrinos), which could be produced by inverse kinematics (^{7}Li(d,p)^{8}Li and ^{6}Li(^{3}He,n) ^{8}B) in a ring using ionization cooling. So far the study is promising for ^{8}Li but ^{8}B seems difficult. There is another issue with these isotopes which have a higher Q value: the neutrino flux is reduced as $1/Q^2$ while the higher neutrino energy only buys a factor Q due to the increased cross-section. Consequently, for the same physics reach they require higher intensities, which challenges the intensity limits in the PS,SPS, and storage ring.

The beta-beam thus appears as a very attractive solution also in view of its synergy with the superbeam and the large detectors for nucleon decay searches. The aim of the present study within EUROnu is to assess feasibility of the intensity and design issues for the Li/B option and come up with a cost estimate and a safety assessment. Similar cost and safety assessment for the He/Ne option studied within EURISOL if not included in the final report should be done including updated scenarios for the ^{18}Ne production. As the beta-beam design is deeply embedded in the CERN accelerator complex, additional support from local resources at CERN, that not presently available, would be necessary – and welcome.

Conclusion

Neutrino physics is a very lively field with lot of challenges and room for innovative ideas in accelerator physics. European teams are very active in the field within international collaborations. In addition to the construction and operation of the CNGS neutrino beam, CERN has made important contributions to the neutrino studies: MERIT experiment, support to MICE, EURISOL study of beta-beams, SPL concept as proton driver among others. However CERN's involvement is presently quite limited in this area of great potential.

An increased role of CERN with well targeted contribution in support of existing studies in EUROnu and IDS-NF, for example in the cost and safety assessment of the proposed installations, could have considerable scientific and technological impact. CERN's support to proposals like the resurrection of the PS neutrino beam or others, where neutrino physics and R&D can be combined would be important scientifically but also to keep the momentum of the European teams involved in neutrino physics, and prepare the ground for future projects either in European based superbeams, beta-beams or neutrino factory or as important partners in international collaborations.

Neutrino physics differs from some other areas of particle physics in that its future physics goals are relatively well defined and known in advance to be interesting. The main challenges are technical. CERN involvement would benefit the field in helping to push towards the ambitious future facilities which we know now we will need to fully explore the physics of neutrino mixing (in addition, of course, to any surprises that come along the way). In return CERN could benefit from the stability associated with technology development that is "safe", in the sense that we know that future measurements are extremely unlikely to weaken the physics case for these facilities.