The ideal neutrino beams

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Abstract. The advance in neutrino oscillation physics is driven by the availability of well characterized and high flux neutrino beams. The three present options for the next generation neutrino oscillation facility are super beams, neutrino factories and beta-beams. A super-beam is a very high intensity classical neutrino beam generated by protons impinging on a target where the neutrinos are generated by the secondary particles decaying in a tunnel down streams of the target. In a neutrino factory the neutrinos are generated from muons decaying in a storage ring with long straight sections pointing towards the detectors. In a beta-beam the neutrinos are also originating from decay in a storage ring but the decaying particles are radioactive ions rather than muons.

I will in this presentation review the three options and discuss the pros and cons of each. The present joint design effort for a future high intensity neutrino oscillation in Europe within a common EU supported design study, EURONU, will also be presented. The design study will explore the physics reach, the detectors, the feasibility, the safety issues and the cost for each of the options so that the community can take a decision on what to build when the facilities presently under exploitation and construction have to be replaced.

1. Introduction
The detailed study of neutrino properties requires a well defined and intense neutrino source. Historically, man made neutrino sources have either been nuclear power plants or neutrinos from pion and kaon decay collected and directed towards the detectors systems from targets irradiated with a charged particle beams. In the last 10 years considerable progress has been made on the study of alternative concepts such as neutrinos from stored high energy muons [1] or stored high energy radioactive ions [2]. The first is generally referred to as neutrino factories and the latter as beta-beams. In parallel the development of new high power target and collector systems for conventional neutrino beams has made major progress thanks to projects such a T2K [3], MINOS [4] and CNGS [5]. As new intense proton accelerator are becoming available in Japan, Europe and USA an important increase of neutrino flux from such facilities can be expected. The common goal of all new plans for accelerator based neutrino sources are higher flux and better knowledge of the initial characteristics including detailed knowledge of the flavor composition of the neutrino beams. In this paper, the three concepts will be reviewed with some focus on beta-beams.

2. Superbeams or high power conventional neutrino beams
Conventional neutrino beams are generated from kaon and pion decay. The mesons are usually created in a target through proton irradiation. Magnetic elements downstream of the target selects the sign of the mesons and focuses the kaons and pions into a decay tunnel. Positive
Meson decay will generate muon neutrinos while negative meson decay will generate anti-muon neutrinos. The tunnel must be adapted in length to the meson energy to assure that a maximum of them have time to decay before all remaining particles are stopped at the end of the tunnel. In the ideal case, only one flavor of neutrinos from the selected sign of mesons will continue towards the detector but some contamination of other flavors are unavoidable. The decay of residual “wrong” charged mesons and neutral kaons will generate a a few percent background of the opposite flavor of muon neutrinos while three body decay of kaons and muons will generate a background of roughly a percent of electron and anti-electron neutrinos. The detectors can be positioned off-axes to assure a narrower energy spread of neutrinos of a certain energy or on-axis in a so-called wide-band neutrino facility to optimize the flux and assure the broadest possible energy spectrum.

2.1. Challenges and development work for conventional neutrino beams
The development of conventional neutrino beams towards so called super beams is driven by the availability of new high intensity proton drivers. The JPARC [6] in Japan will feed the T2K [7] experiment which is scheduled to start operation in 2009. The JPARC facility uses coupled rapid cycling synchrotrons and could eventually deliver over 1 MW on target for the neutrino facility. The Superconducting Proton Linac (SPL) [8] at CERN is still a project in planning but could possible deliver first low power beams around 2017. The linac could eventually deliver more than 4 MW on target for a neutrino facility, see figure 1 as an example of a superbeam from CERN to Frejus using SPL [9]. The Project X at Fermi lab in USA is also under planning and could eventually deliver high intensity protons for a Wide Band facility. It is possible that Project X will be combination of a linac and a rapid cycling synchrotron.

The target required for multi MW facilities must still be developed. The MERIT [10] experiment at CERN which took data in 2008 has as objective to test the liquid mercury jet concept using a high filed solenoid to magnetically contain the jet and collect the produced mesons. This type of target can be used for both conventional neutrino beams and neutrino factories. A target using metal powder has been proposed at RAL [11], simulations and first tests are under way to establish the feasibility of such a design.
3. Neutrino factories

In a neutrino factory the neutrinos originate from the decay of muons which are created via pions by protons impinging on a target. The muons have to be captured, cooled, accelerated and put into a decay ring with straight sections pointing towards the detectors. The muon decay is well understood. Consequently, the composition and spectral characteristics of the resulting neutrino beam can be calculated with high precision. Furthermore, the use of a decay ring will result in a well collimated neutrino beam. The intensity will scale with the power of the driver beam but it will also depend heavily on the efficiency of the capture and cooling schemes and the swiftness of the acceleration as muons are very short lived. The IDS study [12] aims at $5 \times 10^{20}$ neutrinos along the straight sections of two independent storage rings of 25 GeV, see figure 2. This would require a driver beam intensity of some 4 MW at 5-10 GeV depending on the driver type. The target can either be a fast rotating solid target or a liquid metal target. Even metal powder targets have been considered. Approximately a third of the driver beam power will be absorbed in the target with the remaining beam power being lost in a beam dump downstream of the target. The pions emerging from the target are captured with a magnetic horn or a superconducting solenoid. The muons from the pion decay are cooled in an cooling channel in which ionization cooling is applied to reduce the beam emittance. The resulting muon beam is accelerated with recirculating linacs and a Fixed Field Alternating Gradient accelerator and finally stored in two independent race track storage rings with straight sections of some 600 meter.

3.1. Challenges and development work for neutrino factories

The driver, target and collector issues are shared with superbeams and are presently being addressed by both communities together. The collected muons from the decaying mesons will collectively occupy a large longitudinal and transverse emittance and to assure reasonable

Figure 2. The siet independent neutrinofactory which has been taken as starting point for the International Design Study for a neutrinofactory [12].
efficiency for the acceleration they have to be cooled (the emittance has to be reduced). Known cooling methods such as stochastic cooling or electron cooling are neither fast enough nor very suitable for the short lived muons so new methods have to be developed. The most promising concept is a combination of ionization cooling coupled with bunch rotation. The ionization cooling of muons will be tested at RAL at the MICE experiment [13]. The fast acceleration required to assure that a maximum of these short lived particles survive to the decay ring can be done using Recirculating Linacs or Fixed Field Alternating Gradient (FFAG) accelerators. A electron model of a non-scaling FFAG is presently being built at Daresbury in the UK. The objective of this experiment called EMMA [14] is to demonstrate feasibility.

4. Beta beams

The beta-beam concept was first proposed by P. Zucchelli [2] and a first scenario for beta beams was proposed at CERN already in 2002 [15], see figure 3. In this scenario the ions are produced in a thick target using a proton beam of 1 GeV, extracted as neutral atoms and re-ionized and bunched in a high frequency ECR source. The first step of acceleration is a linear accelerator which brings the ions to a kinetic energy of 150 mega-electron volts (MeV) per nucleon. Subsequently, this beam is injected into a Rapid Cycling Synchrotron (RCS) in which the energy is increased to 500 MeV per nucleon. After this first step the beam enters the existing CERN accelerator complex and is accelerated in the Proton Synchrotron (PS) to its maximum energy, transferred to the Super Proton Synchrotron (SPS) and finally ejected to a decay ring. The last step is done using a scheme which permits the new ions to be merged with the ions already circulating in the decay ring so that ions which still can decay (and create neutrinos) are not wasted and ejected from the decay ring too early. The important steps to retain is:
i) that a sequence of accelerators are used to accelerate bunches of ions ii) that the ions are produced continuously in a target and bunched and iii) that the ions are accumulated in a few short bunches in a decay ring with long straight sections to generate a pulsed neutrino beam. The essence of the CERN proposal in 2002 was the re-use of existing heavy ion accelerators to reduce cost and gain time for the construction of a beta-beam facility. With a similar intention a study was undertaken in the US in 2004 investigating the possible use of existing accelerators at Brookhaven National Laboratories and Fermi National Laboratories [16].

5. Challenges and development work for beta-beams

The acceleration of heavy ions is used at both CERN for the heavy ion programme at LHC and at BNL for the RHIC programme. The only difference for beta-beams is that ions are radioactive and that they decay during acceleration. The decay will cause beam losses and possible some contamination in the low energy parts of the facility. Though, it is important to remember that even stable ions are lost during acceleration and storage due to the interaction with the rest gas in the accelerator. In the higher energy machines the losses from a beta beam are similar to the losses for any stable ion beam. However, in the decay ring the situation is different as all ions have to decay to generate neutrinos and as the accumulation process will cause important losses during injection. A major challenge for beta beams has been to design a magnet protection system and collimation system.

The ions used should live long enough to generate useful neutrinos in the decay ring but not so long that huge amounts are accumulated causing space charge related problems in the decay ring. Isotopes such as $^{18}$Ne for electron neutrinos and $^{6}$He for anti-electron neutrinos are proposed to be used. They both have a half-life of approximately a second and neither have any long-lived daughter isotopes which could cause problems in the low energy part. The production could be done through spallation or via neutron capture from a neutron converter using a facility such as the proposed EURISOL facility [17]. Another approach is to create compound nuclei at low energy with very intense light ions beams impinging on a thick target [18]. It has also been
proposed to use a small storage ring with an internal target for production [19, 20]. The stable projectile ions circulating in the ring will undergo ionization cooling due to the repeated losses in the thin internal target and the subsequent re-acceleration on each turn. This will keep the ions in the ring while the reaction products can be collected off-axes in a foil or a gas cell.

5.1. Other types of beta-beams
Monochromatic electron neutrino beams could be produced using isotopes decaying through electron capture [21]. The half life of most isotopes decaying through electron capture is long as they often are close to stability due to an energy threshold for the competing beta+ decay. In a recent study [22] it has been shown that some rare earth isotopes with short half lives (in the order of 10s of seconds) decay by pre-dominantly electron capture due to a hindered transition to the ground state. These isotopes could possible be used for such a facility. The beta-beam studied at CERN in 2002 and later within the EURISOL design study [17] proposed to make use of existing accelerators at CERN and was thus limited to a Lorentz gamma of 100. A frequently requested upgrade is to increase the energy of the neutrinos for a longer baseline experiment [23]. Such an upgrade would require the construction of a new SPS, possibly in the same tunnel as the existing SPS but with higher field super conducting dipoles to boost the gamma to at least 300. At these higher energies it is also possible to relax on the duty factor as the resulting neutrino energy will be well out of the atmospheric background. Alternative accumulation scenarios, such as barrier bucket accumulation [24] could be used and as they suffer less severe losses so an additional gain in intensity could also be made. another way to higher energies is to use high-Q value isotopes such as $^6$Li and $^8$B [25].On the other end of the energy scale a low energy beta-beam facility has been proposed [26] for nuclear and astrophysics measurements. At the lowest energy scale, beta beams could maybe be used for precision measurements of the neutrino mass [27], especially if it is combined with extreme beam cooling to reduce the energy spread of the ions in the ring.

Figure 3. The beta-beam facility at CERN as described in [15].
6. Conclusions

Several new concepts for generating neutrino beams have been studied in the last 10 years. A decision on a future high intensity neutrino oscillation facility will be taken based on physics; the physics which remains to be addressed after first results from running experiments have been analyzed and the physics reach of the different options for a future facility. Other significant factors which will influence the choice is cost, feasibility and safety. The machine physics community must work closely together to establish these factors for each option with as high precision and detail as possible. World wide collaborations is a necessity to make this possible. The prize is likely to be well worth the effort!

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