The ENUBET Beamline

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The ENUBET ERC project (2016-2021) is studying a narrow band neutrino beam where lepton production can be monitored at single particle level in an instrumented decay tunnel. This would allow to measure $\nu_\mu$ and $\nu_e$ cross sections with a precision improved by about one order of magnitude compared to present results.

In this proceeding we describe a first realistic design of the hadron beamline based on a dipole coupled to a pair of quadrupole triplets along with the optimisation guidelines and the results of a simulation based on G4beamline. A static focusing design, though less efficient than a horn-based solution, results several times more efficient than originally expected. It works with slow proton extractions reducing drastically pile-up effects in the decay tunnel and it paves the way towards a time-tagged neutrino beam. On the other hand a horn-based transferline would ensure higher yields at the tunnel entrance. The first studies conducted at CERN to implement the synchronization between a few ms proton extraction and a horn pulse of 2-10 ms are also described.

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1 ENUBET (Enhanced NeUtrino BEams from kaon Tagging)

Neutrino experiments are now limited by the knowledge of the initial fluxes, the current achievable precision in the absolute cross section measurements is $O(5-10\%)$. A dedicated facility based on conventional accelerator techniques and existing infrastructures designed to address this problem would impact the entire field of neutrino oscillation physics. The ENUBET facility [1, 2, 3] addresses simultaneously the two most important challenges of the next generation neutrino experiments: a superior control of the flux and flavour composition at source and a high level of tunability and precision in the selection of the energy of the outgoing neutrinos. At present the flux of $\nu_\mu$ beams is not directly measured but relies on detailed simulations of the neutrino beamline and on extrapolations of target hadro-production data. Moreover, most of the next generation oscillation experiments will measure $\nu_e$ appearance at the far detector. By improving the precision on $\nu_\mu$ and $\nu_e$ cross sections by about one order of magnitude ENUBET results would be of great value for current (NOvA, T2K) and next generation long-baseline experiments (DUNE, Hyper-Kamiokande).

The ENUBET proposal [4] was motivated by the idea of developing “monitored neutrino beams”: a facility where the only source of $\nu_e$ is the three-body semileptonic decay of kaons: $K^+ \to \pi^0 e^+ \nu_e \,(K_{e3})$. The goal is to build a detector capable of identifying the positrons from $K_{e3}$ decays while operating in the harsh environment of a conventional neutrino beam decay tunnel.

The ENUBET beamline will allow performing $\nu_\mu$ cross section studies with a narrow band beam where the neutrino energy is known a priori with 10% uncertainty and $\nu_e$ cross section measurement with 1% precision with a monitored neutrino beam where the positrons from $K_{e3}$ decays are monitored at single particle level by the calorimeters instrumenting the decay tunnel [4].

This can be achieved using conventional magnets by maximising the number of $K^+$ and $\pi^+$ at tunnel entrance, by minimising the total length of the transferline to reduce kaon decay losses and by keeping under control the level of background transported. Momentum and charge-selected hadrons ($K^+, \pi^+$) being injected in the instrumented decay tunnel need to be collimated enough such that any undecayed meson is capable of escaping the region without hitting the tagger inner surface: this allows not to swamp the instrumentation with excessive particle rates and to limit the monitoring to the decay products of $K$ decays. Furthermore it is very important to tune the shielding and the collimators to minimise any beam induced background in the decay region. The beamline presented here is composed by a short ($\sim 20$ m) transferline followed by a 40 m long decay tunnel. The hadron beam considered has a reference momentum of 8.5 GeV/c with a momentum bite of 10%.

The proton interactions in the target are simulated with FLUKA, we have con-
sidered various proton drivers (400 GeV, 120 GeV and 30 GeV protons) and target designs. The results reported in this document refer to 400 GeV protons and a beryllium target 110 cm long with a 3 mm diameter. The optic optimization is performed with TRANSPORT to match the ENUBET specifications for momentum bite and beam envelope. The beam components and lattice are then implemented in G4Beamline that fully simulates particle transport and interactions.

We have considered two possibile beamlines: the first one makes use of a focusing horn placed between the ENUBET target and the following transferline (“horn-based transferline”) while in the second one the transferline quadrupoles are placed directly downstream the target (“static transferline”).

Here we describe more in detail the static design, whose performance turned out to be significantly better than early estimates reported in the ENUBET proposal [1] and it offers several advantages in terms of cost, simplification of technical implementation and performance of particle identification. Moreover a static transferline would pave the way to the so-called tagged-beams. A “tagged neutrino beam” is a facility where the neutrino is uniquely associated with the other particles of the parent kaon. Since in the static focusing system the proton extraction can last up to several seconds, the instantaneous rates of particles hitting the decay tunnel walls is reduced by about two orders of magnitude compared with the horn option. In the ENUBET static option the time between two \(K_{e3}\) decays is 1.3 ns. A neutrino interaction in the detector can thus be time linked with the observation of its associated lepton in the decay tunnel: this has never been perfomred in any neutrino experiment and would represent a major breakthrough in experimental neutrino physics.

Results obtained for the horn-based transfer line are presented as well and related studies are also being pursued due to the remarkable \(\nu\) fluxes that can be achieved.

## 2 Static transferline

The static configuration is very promising since it allows to perform the focusing using DC operated devices (unlike pulsed magnetic horns) compatible with a traditional slow extraction of several seconds. The ENUBET beam (see Figure [1]) is a conventional narrow band beam where, unlike most of the current beams, the decay tunnel is not located in front of the focusing system and the proton extraction length is slow (2 s). The best configuration achieved consists in a quadrupole triplet followed by a dipole that provides a 7.4° bending angle and by another quadrupole triplet.

Particles produced by proton interactions in the target are focused, momentum selected and transported to the tunnel entrance. Non-interacting protons are stopped in a proton beam dump. Off-momentum particles reaching the decay tunnel are mostly low energy particles coming from interactions in the collimators and other beamline components together with muons that cross absorbers and collimators. At
8.5 GeV/c we expect \( \sim 50\% \) of \( K^+ \) to decay in a 40 m long tunnel. The rate of background particles is several order of magnitude smaller than present beams and the instrumentation located in the decay tunnel can monitor lepton production at single particle level. Figure 2 shows the momentum distribution as well as the XY profile of \( K^+ \) entering/exiting the decay tunnel.

![Figure 1: Schematics of the ENUBET beam in the static focusing option.](image1)

![Figure 2: Left: momentum distribution of \( K^+ \) entering/exiting the decay tunnel. Right: XY profile of the \( K^+ \) beam at tunnel entrance and exit.](image2)

The length of the decay tunnel is optimized in order to have \( K_{e3} \) decays as the only \( \nu_e \) source: electron neutrinos from decay in flight of kaons represent \( \sim 97\% \) of the overall \( \nu_e \) flux. The positrons from three body decays are emitted at large angles and hit the instrumented walls of the tunnel before exiting. The identification of particle hitting the tunnel walls is performed by longitudinally segmented calorimeters [4], positrons are separated from photons using a photon veto made of plastic scintillator tiles located just below the innermost layer.

The static beamline transports at the tunnel entrance \( 19 \times 10^{-3} \pi^+/\text{POT} \) and \( 1.4 \times 10^{-3} K^+/\text{POT} \) in [6.5÷10.5 GeV/c] range, improving by 4 times the kaon yield with respect to the first estimate reported in [1] and requiring about \( 4.5 \times 10^{19} \) POT at CERN SPS to carry out both \( \nu_\mu \) and \( \nu_e \) cross section programs. An additional advantage of the static solution is the possibility to directly monitor the rate of muons from \( \pi^+ \) decays after the hadron dump, it cannot be done for the higher rates in the horn-based solution but since it is reduced by two order of magnitude in the static option the \( \nu_\mu \) flux can be monitored with the same level of precision of \( \nu_e \).
3 Horn-based transferline

In the horn-based solution a magnetic horn is placed between the target and the following transferline. This horn needs to be pulsed for 2-10 ms and cycled at several Hz during the accelerator flat-top. The studies concerning the proton extraction scheme ("burst-mode extraction") to combine a few ms proton extraction with 2-10 ms horn pulses are on-going at CERN. As presented in Figure 3 we could already confirm the proof-of-concept of feed-forward burst spill optimization: the "Autospill-Burst" algorithm developed leads to a burst length optimization from 20 to 10.6 ms. From this benchmark the studies will continue to explore the full simulation and to address remaining issues towards the full operability.

Figure 3: Left: Algorithm of feed-forward implemented and capable of optimizing the burst length towards 10 ms. Center: Proof that the algorithm is capable to reduce the burst length from \(\sim 20 \text{ ms}\) to \(\sim 10 \text{ ms}\) (10.6 ms) in 3 interactions. Right: burst-extraction over a whole SPS spill (CERN-BE-OP-SPS, F.Velotti, M.Pari, V.Kain, B.Goddard).

The flux produced at the tunnel entrance is 4-5 times larger than in the static option: at the SPS we expect \(77 \times 10^{-3} \pi^+/\text{POT}\) and \(7.9 \times 10^{-3} K^+/\text{POT}\) in \([6.5\div10.5 \text{ GeV}/c]\) range. This represents an improvement factor of 2 in kaon transport with respect to the first estimate reported in [1].

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