PROCEEDINGS OF SCIENCE

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Development and optimization of the ENUBET beamline

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The ENUBET experiment (NP06/ENUBET at CERN) has the goal of proving the concept of a "monitored neutrino beam", for a superior knowledge of the produced neutrino flux and high-precision cross-section measurement. To achieve this, an instrumented decay tunnel will be used in order to directly monitor the products of the neutrino production vertices. The ENUBET collaboration is studying and designing this facility in all its different aspects: from the data acquisition and detector hardware, to the assessment of systematics and analysis. The present contribution will focus on the topic of the beamline design, highlighting the main results and the most recent developments.

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1. The ENUBET monitored neutrino beam

The concept of a monitored neutrino beam is based on the instrumentation of the decay tunnel [1]. ENUBET has converged on the final detector technology that will be employed [2–5] to discriminate a signal event (a positron from a K_{e3} decay, $K^+ \rightarrow e^+ \nu_e \pi^0$), from the background particles (mostly pions, muons, and other positrons coming from the beamline). The monitoring of signal positrons can be exploited to measure the output ν_e flux with a high-precision up to $O(1\%)$ [1]. By keeping the length of the beamline as short as possible, the amount of produced ν_e not originating from a K_{e3} event (mainly from muon decays) will be only of $O(1\%)$. Recent studies also proved that ENUBET can add further precision on the neutrino flux estimation by also monitoring muons at the tunnel walls, which are mainly generated from the $K_{\mu 2}$ ($K^+ \rightarrow \mu^+ \nu_\mu$) and $K_{\mu 3}$ ($K^+ \rightarrow \mu^+ \nu_\mu \pi^0$) channels. To keep the beam well contained in the instrumented decay region some momentum selection and focusing becomes necessary. To this purpose ENUBET employs a narrow-band neutrino beam, with secondary particles focused at 8.5 GeV/c and with a ±5-10% momentum bite. A narrow band beam can be exploited for using the Narrow-Band Off-Axis (NBOA) technique [6, 7], to directly correlate the neutrino energy to its impact radius at the near detector with a $O(10\%)$ precision, and to achieve a full energy-radius separation between kaon and pion neutrinos. Another critical constraint for the ENUBET beam is to keep the rate of events at the instrumented tunnel walls below a critical pile-up threshold: to ensure this, ENUBET relies on the slow resonant extraction of the primary protons.

2. The baseline design of the ENUBET beamline

The constraints and requirements of the ENUBET experiment described in Sec. 1 have been used to develop a so called "baseline" version of the beamline.

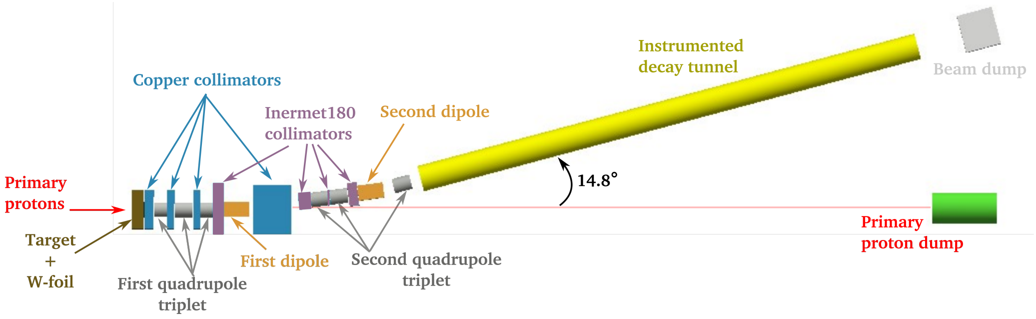

Figure 1: Baseline version of the ENUBET beamline.

Figure 1 shows a view of the beamline. It is based on normal conducting magnets, and a 2 s slow extraction of the primary protons is assumed. The CERN Super Proton Synchrotron (SPS) accelerator has been assumed as the proton driver, thanks to the 400 GeV/c momentum and $\sim 4 \times 10^{13}$ protons per spill. The total length of the beamline, from the target to the beginning of the decay region, is ∼ 20 meters. The design process has been based on a combination of accelerator optics design programs (TRANSPORT [8]) and particle tracking and interaction simulations (FLUKA [9], G4beamline [10], GEANT4 [11]). The main goal has been to maximize the signals (positrons and muons from kaon decays) over the background (particles coming directly from the beamline).

A crucial aspect for the correct operation of ENUBET is the dose received by all of its components. A simulation of both the ionizing dose (Gy) and the neutron dose (neutrons/cm^2) for 10^{20} protons on target (POT) has been performed using FLUKA. Concerning the neutrons, the solution of placing a layer of borated polyethylene between the external layer of the tunnel and the readout SiPM and electronics successfully reduced the neutron dose to the latter devices by about a factor 20. Concerning the ionizing dose, the hottest points of the beamline are the first collimator and first quadrupole, with doses of 100-300 kGy. The dose at the second dipole (~kGy) is significantly lower than at the first, opening for the potential use of a super-conducting second dipole. This has the advantage of reducing the fraction of neutrinos produced outside of the decay region reaching the detector: further studies are currently being performed as a parallel development.

A recent optimization of the proton target main parameters (length, diameter, material) has led to the choice of an improved target design for the baseline version of the ENUBET beamline: a 70 cm-long by 6 cm diameter Graphite rod. Other than increasing the kaon flux (×2) and reducing the positron one (×1.5), this target is also more feasible in terms of its implementation and installation with respect to previously considered longer and thinner candidates.

Overall, the performance of this beamline reached a factor 4 increase in kaon flux with respect to the estimated one in the original ENUBET proposal [1], pointing to the possibility of gathering 10^4 $\nu_{e\mathrm{CC}}$ in about 2 years of data taking (assuming 4.5×10^{19} POT/year), using a 500 t neutrino detector at 50 m distance from the beam dump, and with the CERN-SPS as a proton driver.

3. Horn-based beamline study

The idea of using a strong focusing device, such as a magnetic horn, so to increase the produced neutrino flux and speed up the ENUBET data taking, is tempting and has not been ignored by the collaboration. The main difficulty in using a magnetic horn in ENUBET is to still be able to maintain a sustainable pile-up rate at the instrumented tunnel. To this end, ENUBET has proposed a new compatible extraction scheme. It consists of a pulsed slow extraction with 2-10 ms-long pulses repeated at 10 Hz, along a slow extraction flat-top of a few seconds. As this technique has never been developed before, a dedicated study at the CERN-SPS accelerator has been undertaken. The results of this study were successful [12]: Fig. 2 shows an example of the newly developed extraction scheme, called burst-mode slow extraction. Another parallel study of the standard slow extraction at CERN-SPS has found potential improvements of the proton spill quality in terms of the suppression of some of its noise components, as the power supply ripples [12, 13].

After the results of the burst-mode slow extraction study, a parametrized simulation model of a magnetic horn has been developed based on GEANT4, together with a dedicated optimization framework based on a Genetic Algorithm. This approach was successful, reaching some candidate designs with a potential standalone flux increase up to about a factor 3 (i.e. at the first quadrupole). In order not to lose the gain when tracking this beam along the full beamline, we are currently developing a dedicated beamline version for the magnetic horn, following the same procedure described in Sec. 2.

The genetic optimization framework developed for the magnetic horn has been upgraded to be fully generic, opening for many applications and potential improvements of the ENUBET design.

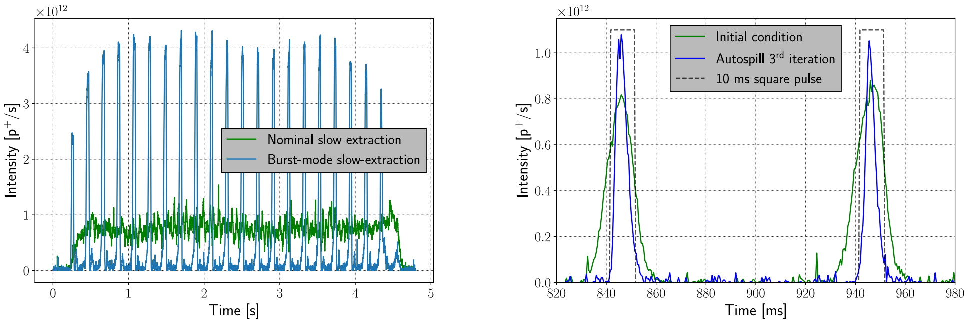

Figure 2: Example of the concept of burst-mode slow extraction compared to a standard slow extraction (left), and proof of in-operation optimization of the extracted pulse length (right). This data has been taken during dedicated tests at CERN-SPS.

The first application has been dedicated to optimize the collimation of the baseline beamline design: the work is ongoing and the first results look promising.

4. The multi-momentum beamline

The neutrino energy spectrum produced by the baseline ENUBET design is peaked at about 4 GeV, within the DUNE region of interest. In order to fully exploit the potential of ENUBET for the future of neutrino physics, it would be convenient to be able to vary its neutrino energy range. To do so, a dedicated study of a so called “multi-momentum beamline” has been started, in collaboration with CERN. A first candidate of the beamline has been developed, relying on existing CERN magnets (geometry and field), driven by standard slow extraction, and $\sim$ 28 m long. The performance in terms of the kaon flux obtained up to now is promising, but further studies on the background at the instrumented decay tunnel are ongoing.

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