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THE ENUBET MULTI MOMENTUM SECONDARY BEAMLINE DESIGN

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Abstract

The aim of neutrino physics for the next decades is to detect effects due to CP violation, mass hierarchy, and search for effects beyond the Standard Model predictions. Future experiments need precise measurements of the neutrino interaction cross-sections in the GeV/c regime, currently limited by the exact knowledge of the initial neutrino flux on a $\sim 10-20\%$ uncertainty level. The ENUBET project is proposing a novel facility, capable of constraining the electron neutrino flux normalization through the precise monitoring of the K_{e3} ($K^+ \to e^+\pi^0\nu_e$) decay products in an instrumented decay tunnel. ENUBET can also monitor muons from the two-body kaon and pion decays (ν_μ flux) and measure the neutrino momentum with about 10% precision without relying on the event reconstruction at the detector level. We present here a novel design based on a multi (4–8.5 GeV/c) momentum range secondary beamline that widens the cross-section energy range that can be explored by ENUBET and, therefore, the physics capabilities of the facility. In this contribution, we discuss target optimization studies and we show preliminary results on the new line's optics and the layout design. We finally provide an outlook on the expected performance of the line.

INTRODUCTION: THE ENUBET PROJECT

Uncertainty on the knowledge of neutrino fluxes currently limits the precision of cross-section measurements to O(5–10%) [1]. Most of the present and proposed future neutrino experiments rely on the appearance of the electron neutrino (ν_e), like T2K [2], NOνA [3], DUNE [4] and HyperK [5], hence the direct measurement of the ν_e cross-section is attracting great worldwide interest [6], and the problem has not yet been solved despite the efforts on accelerator neutrino beams since the 1970s [7, 8]. The ENUBET project aims to develop an experimental facility that will provide a beam of ν_e originating from the decays of positively charged kaon mesons(K^+) [9]. Such a facility requires the semi-leptonic decay of kaons $K^+ \to \pi^0\, e^+\, \nu_e$ (K_{e3}) to be the only source of electron neutrinos. The K_{e3} decay is tagged and monitored in a fully instrumented decay tunnel to improve the precision of the existing cross-section measurements [10] by an order of magnitude. For this purpose, a challenging optimization of the secondary particles (kaon) beamline, the momentum selection, the collimators, and finally the decay tunnel's length is necessary [11]. More specifically, the future ENUBET neutrino beam will be based on a two-stage approach. At first, the charged kaons will be produced via the interaction of high-energy protons on a target material. After the target, the kaons will be captured, focused, momentum selected, and transported through a short ($\sim 20-30$ m length) beamline up to the entrance of a ~40 m long, instrumented decay tunnel. At the second stage, inside the decay tunnel, kaons selected in a narrow momentum bite will decay producing a narrow-band ν_e beam. The electron neutrino flux will be therefore monitored by observing the positrons produced from decays and emitted at a large-angle with a longitudinally segmented calorimeter instrumenting the decay tunnel. ENUBET is also suitable for monitoring of large angle muons from kaon decays and low angle muons from pion decays, which provide a high-precision monitoring of the ν_μ flux.

PROTON EXTRACTION

In order to monitor the kaon decay products on a particle-by-particle basis and at the same time maintain a local rate at the level of ~1 MHz/cm^2 at the tagger, the ideal operation of ENUBET will be based on a slow-extraction scheme. Hence the full proton intensity is continuously extracted during several seconds. This will also allow for reconstruction on an event-by-event basis at the detector level. Focusing using quadrupoles (as an alternative option to a pulsed horn) would allow a proton extraction up to several seconds, which decreases the instantaneous rate of particles in the decay tunnel by nearly two orders of magnitude with respect to a burst mode extraction (pile-up mitigation) and shorten the beamline, thus reducing kaon decay losses, while keeping a sustainable acceptance. Both options of static and horn focusing are being pursued by ENUBET, and the corresponding proton extraction modes have been developed and tested at the CERN Super Proton Synchrotron - SPS [12].

PRIMARY BEAM & TARGET

The ENUBET secondary beam will be produced using a high-energy proton beam impinging on a solid target. While the engineering details of the target station are underway, we have evaluated the performance of different target materials (in terms of production yields) and the effects of primary proton momenta on these yields. The NP06/ENUBET team

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has conducted extensive optimization studies based on the FLUKA [13, 14] and G4beamline [15] simulation codes, using various materials, such as : graphite (density 2.2 g/cm^3), beryllium (density 1.81 g/cm^3), Inconel (density 8.2 g/cm^3) and various high-Z materials such as gold and tungsten. Each target prototype is modeled geometrically as a cylinder with variable radii between 10 and 30 mm and lengths extending from 5 to 140 cm. We initially analyzed different primary momenta to confirm the growth behavior for particle production as expected by Ref. [16]. FLUKA simulations have shown that the nominal energy of the SPS (400 GeV/c) is so far the optimal choice for kaons compared to lower primary energies, we then proceeded to compare the geometry and material of the target. The best materials for the charged kaon production in the momenta of interest proved to be graphite (2.23 g/cm^3 density), beryllium, and Inconel-718. The kaon yields for both graphite and beryllium are shown in Fig. 1 and Fig. 2. Higher-Z materials would be better candidates for kaons production but are not considered here due to their poor thermo-mechanical properties. Graphite is a known and well-tested material employed in several neutrino beams thanks to its heat endurance and production yields [17]. However, graphitic materials in various grades like POCO graphite [18] or even in the enhanced form of CFC [19] (used in other beam intercepting devices, like collimators) seem to pose severe limitations on radiation damage that need to be carefully assessed before a complete target design can be envisaged. Inconel is quite a novel choice that is under consideration for nuSTORM [20] and ENUBET, but already at use at CERN in other applications (like the new CERN-PS East Area Beam Stoppers), with promising properties. This is under investigation. A conservative option for ENUBET remains a graphite-based target ~70 cm long with a ~30 mm radius.

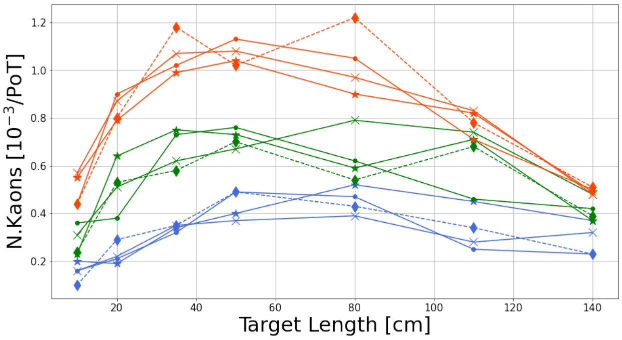

Figure 1: Kaon yields as a function of the graphite target length. The targets have been tested with a primary beam with 400 GeV/c momentum. The figure of merit for this study is the number of kaons of given energy within 10% momentum bite that enters and is transported along an ideal beamline with ±20 mrad angular acceptance in both planes, starting 30 cm after the target. The error bars are not plotted to ease the reading; the simulation statistical errors are negligible (1%), while the Monte-Carlo systematics amounts to ~ 20%. Colors refer to different kaon momenta (blue is 4 GeV/c, green is 6 GeV/c, and red is 8.5 GeV/c) while the marker style identifies the target radius.

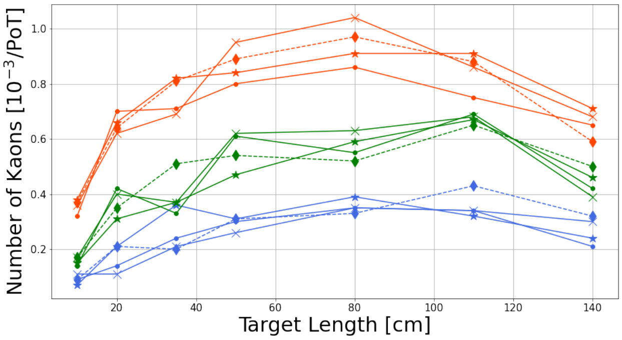

Figure 2: Same as Fig. 1, but for Beryllium targets.

MULTI-MOMENTUM SECONDARY BEAMLINE

The multi-momentum beam-line design for ENUBET will concern secondary particles of 4, 6 and 8.5 GeV/c K^+ momenta, allowing the exploration of a larger phase-space of neutrino cross-section measurements, including the region of interest of T2K/HyperK.

Kaon Production Angle With Respect to the Target

The beamline design is based on the same principles as other low-energy secondary beamlines at CERN [21], thus with stringent requirements on the overall acceptance and the collimation. Specifically, strict momentum selection and background suppression are necessary for ENUBET. Given the fact that the electrons are dominating the production especially in the lower energies (<6 GeV/c), we are considering the placement of the beamline at a non-zero angle (having the effect that transported kaons are produced at an angle to the target). An analysis of the yield as a function of the production angle is shown in Fig. 3. We first considered a beamline placed at a horizontal angle of 40 mrad (2.3°) to the target. This expedient would be beneficial in electron suppression.

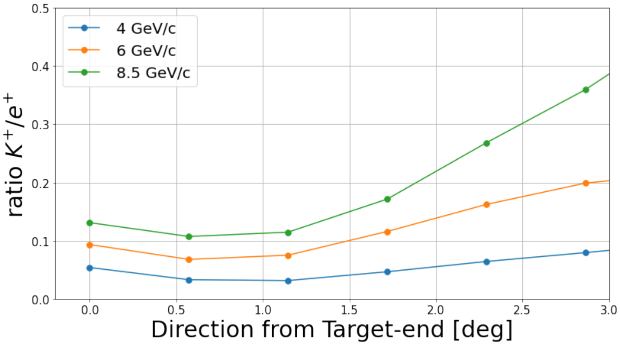

Figure 3: Particles ratio production with respect to the beamline direction.

Due to geometrical constraints given by the magnets apertures, we are then bound to reconsider a lower maximum angle of production.

Optics

The optics optimization for the multi-momentum ENUBET beamline is performed in first-order using TRANSPORT [22]. The optics will be validated with high-order tracking simulations and full Monte-Carlo studies with G4Beamline and MAD-X/PTC-TRACK ([23]) to evaluate higher-order effects. The background and radiation environment optimization studies will be performed using FLUKA. The conceptual layout can be summarized as follows: downstream the optimized Graphite target, a large-aperture quadrupole triplet defines the initial phase-space of the charged kaons (see Fig. 4). Large aperture dipoles and iron collimators select the particles, including the sought-for kaons, in a narrow momentum range. A focusing lens in the middle allows for proper dispersion recombination. This way the majority of background particles outside the nominal momentum band are not transported by the beamline. The 18.18° dipole deflection allows for a sufficient separation between the kaon beam and at the same time for a proper dump of the 400 GeV/c primary beam without contaminating the decay tunnel. The proton dump configurations are still under evaluation. The remaining positron background will be filtered by a 5 mm tungsten or lead absorber. At the end of the line, a final quadrupole triplet performs the final shaping of the beam, that passes through the decay tunnel with a small divergence. The overall maximum angular acceptance of this preliminary design is ±20 mrad in both planes. The magnets adopted for this design are existing models currently installed in the East Area at CERN [24].

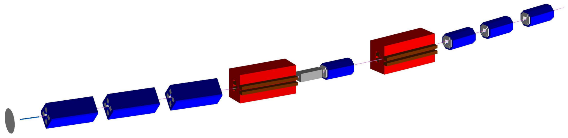

Figure 4: “Multi-Momentum” Beamline layout in G4Beamline. Starting with an 80 cm long graphite target, we placed a Q200 quadrupole triplet. The bending section is composed of two large deflection bends, a collimator of $9 \times 9\,\mathrm{cm}^2$ aperture followed by a 5 mm thin tungsten absorber and a QFL focusing magnet [24]. Before the decay tunnel, a final large-aperture (QFL type) quadrupole triplet has been installed.

Instrumentation

Extensive studies on proper instrumentation for other low energy beamlines have been performed in the past [25]. These detectors are crucial for beam tuning in the commissioning phase and for beam monitoring during the run. As an example of the latter, they can be used to provide direct momentum measurement via a magnetic spectrometer, or time-of-flight measurements for identifying heavy particles on an event-by-event basis. For ENUBET, the material budget should be kept at a minimum. Beamline detectors should be also able to sustain the expected rate of $\sim 10^{11}$ kaons per few s spill. The transverse size of the detectors must also be significant, given the fact that the kaon beam (especially close to the momentum selection section) may have large transverse dimensions, of the order of $10 \times 10\,\mathrm{cm}^2$. Various detectors based on scintillating fibers [26] or silicon strips are being considered for this project and will be evaluated in detail.

CONCLUSIONS

The ENUBET project aims to design a neutrino facility that produces a beam of tagged electron neutrinos originating from the K_{e3} decay ($K^+ \rightarrow \pi^0\, e^+\, \nu_e$) process. The neutrinos will be tagged and monitored in the decay tunnel through the associated positrons, aiming to reach an overall precision of 1% on the flux, thus leading to a substantial improvement in the precision of cross-section measurements. The collaboration has greatly progressed in designing a multi-momentum secondary beamline that will allow for a more efficient study of the neutrinos energy spectrum of interest for future long-baseline experiments (0.5–8.5 GeV/c). Here, we present an extensive target optimization study, as well as the first outlook on this multi-momentum beamline performance.

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