ENUBET'S MULTI MOMENTUM SECONDARY BEAM LINE

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Abstract

In order to study the remaining open questions concerning CP violation and neutrino mass hierarchy, as well as to search for physics beyond the Standard Model, future experiments require precise measurements of the neutrino interaction cross-sections in the GeV regime. The absence of a precise knowledge of the neutrino flux (mainly due to uncertainties on the parent hadrons production cross sections) currently limits this measurement to a 5-10% uncertainty level. The ENUBET project is proposing a novel facility, capable of constraining the neutrino flux normalization through the precise monitoring of kaon decay products in an instrumented decay tunnel. The collaboration has conducted numerous studies using a beamline with a central kaon momentum of 8.5 GeV/c and a ±10% momentum spread. We present here an alternative beam-line design, broadening the range of kaons to include momenta of 4, 6, and 8.5 GeV/c, thus allowing ENUBET to explore cross sections over a much larger momentum range. Specifically, we discuss the status of this design, the optimization studies performed, the early results, and the expected performance in terms of kaon mesons and neutrino rates.

THE ENUBET PROJECT OVERVIEW

The ENUBET project [1] aims to develop an experimental facility that will provide a beam of ν_e originating essentially only from the decays of positively charged kaon mesons (K^+), more specifically from the semi-leptonic decay $K^+ \rightarrow \pi^0 e^+ \nu_e$ (K_{e3}), and that will be monitored by measuring the associated positrons in the decay tunnel. More recently the monitoring technique has been extended to ν_μ from $K_{\mu 3}$ and $K_{\mu 2}$. The project's physics goal is to improve the precision of the existing cross section measurements [2] by one order of magnitude. In this work, we present the design of a novel secondary beamline that will provide a secondary beam of charged kaons and therefore a narrow-band neutrino beam. The ENUBET beamline design has various stringent requirements, among them being the production and acceptance of kaons from a high intensity (O(10^{13}) protons/spill), 400 GeV/c proton beam impinging on a target. An extensive overview of the challenges that accelerator-driven neutrino beams present can be found in [3]. The momentum selection, transport, collimation, and focusing of the produced kaon beam (with an intensity $O(10^{11}$ kaons/spill) are the key parameters of the work showcased in this R&D project. The instrumentation details of the decay tunnel are not discussed in this paper but can be found in other dedicated works [4, 5].

MULTI MOMENTUM BEAMLINE

As discussed in the introduction, the "multi-momentum" line will transport secondary particles of 4, 6, and 8.5 GeV/c momenta, allowing the exploration of a larger phase-space of neutrino cross-section measurements, including the region of interest of T2K/HyperK [6, 7]. The multiple momenta will be transported through the electromagnet's field scaling in dedicated runs for each momentum bin. It must be made clear that for each momentum, the "momentum-bite" (dp/p) acceptance of the line is ±10% around the central value. Also, all other momenta between ≈1 and 8.5 GeV/c can be transported theoretically towards the decay tunnel; however the beamline parameters have been optimized further for these three momenta, and results for those momenta are presented in this paper.

Proton Extraction

To monitor the decay products of kaons on a particle by a particle basis, while maintaining a local rate at the level of ~1 MHz/cm^2 inside the instrumented decay tunnel, ENUBET's ideal operation is based on a slow-extraction scheme. Therefore, the total intensity of the extracted proton beam should be slowly and homogenously extracted on the target over several seconds, enabling event-by-event reconstruction at the detector level. The front-end focusing using quadrupoles (as an alternative to a pulsed horn) would allow extraction of protons (and therefore the production of kaons) for up to several seconds, reducing the instantaneous rate of particles reaching the decay tunnel by almost two orders of magnitude compared to extraction in burst mode. Both static (with quadrupoles) and horn focusing options are being studied by ENUBET, and the corresponding proton extraction methods have been developed and tested at the CERN Super Proton Synchrotron - SPS [8].

Target Studies

The secondary mixed-hadron beam of ENUBET will be generated by a high-energy proton beam impinging on a solid

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target. Whilst the design details of the target station constitute a future study, we have evaluated the performance of different target materials (in terms of production yields) and the effects of different 'primary' proton momenta on these yields. Extensive optimization studies based on the FLUKA [9, 10] and G4beamline [11] simulation codes, using various materials, such as : graphite (density 2.2 g/cm^3), beryllium (1.81 g/cm^3), Inconel (8.2 g/cm^3) and various high-Z materials such as gold and tungsten. Each target prototype was modeled geometrically as a cylinder with variable radius between 10 and 30 mm and lengths extending from 5 to 140 cm. We initially analyzed different primary momenta to confirm the theoretical particle production yields as expected by phenomenological measurements for this non-perturbative regime [12]. FLUKA simulations have shown that the nominal energy of the CERN SPS (400 GeV/c) constitutes the optimal choice for the maximum kaon yield production compared to lower primary energies. Taking this momentum as the baseline, we then proceeded to optimize the geometry and material of the target. Our studies have shown that the optimal materials for the charged kaon production in the momenta of interest proved to be graphite, beryllium, and Inconel-718. The kaon yields for graphite are shown in Fig. 1, where the optimal length seems to be around 70 cm. Higher-Z materials (like e.g W) would be better candidates for kaons production but they are not taken into account here because of their poor thermo-mechanical properties for the assumed proton intensities of the order of 4×10^{13} protons/spill.

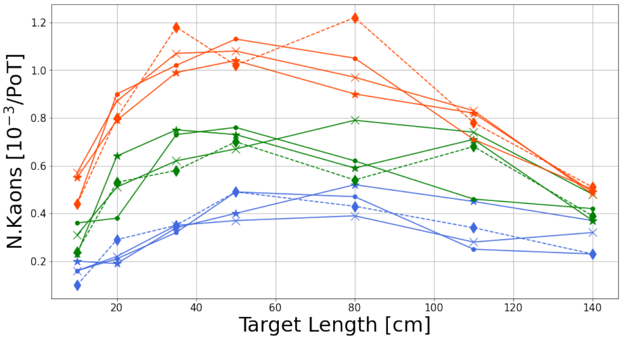

Figure 1: Kaon yields as a function of the graphite target length. The targets have been tested with a primary beam with 400 GeV/c momentum. The figure of merit for this study is the number of kaons of given energy within 10% momentum bite that enters and is transported along the beamline with ±20 mrad 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 amount 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.

Graphite is a well-known and well-tested material in high power targetry [13]. In general, graphitic materials in varying degrees such as POCO graphite [14] or even in the enhanced form of CFC [15] constitute since long an attractive choice for beam intercepting devices, however, the exact implementation for the case of ENUBET (in terms of mechanical properties and cooling) needs to be carefully studied. An alternative option would be Inconel, a material being considered for the nuSTORM target [16] and already used at CERN in other applications (such as the new CERN-PS East Area Beam Stoppers) with promising properties. Up to date, and pending more detailed studies, ENUBET's baseline option remains a graphite-based target with a length of ~70 cm and a radius of ~30 mm.

Secondary Beamline Layout and Optics

The multi-momentum beamline design is based on the same principles as CERN's other low-energy secondary beamlines [17], with strict requirements for global acceptance, collimation, and background reduction. From the particle production studies [18], it was confirmed that positrons dominate the production of secondary particles, especially in the lower momenta (<6 GeV/c). Ways to understand the effect of and possibly mitigate this background are being studied. One mitigation measure for this specific background would be a beamline layout that is placed at a certain angle with respect to the target. This has been envisaged and optimized for the case of the ENUBET "Multi-Momentum" beamline, that lies at an 1 degree angle from the primary target. This beamline design is being optimized for transporting secondary particles of 4, 6, and 8.5 GeV/c K^+ momenta. The optics diagram is shown in Fig. 2 and the calculations have been performed in first-order using the well established software TRANSPORT [19]. The results have been validated with full Monte Carlo simulations using G4Beamline [11] in order to evaluate the effect of the various materials in the beam properties. Up to now, a satisfying agreement between the programs has been found. The conceptual layout of the

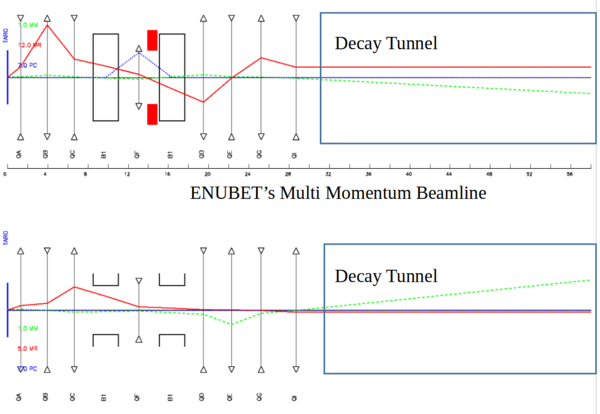

Figure 2: Beamline optics showing horizontal (top) and vertical (bottom) planes. Each line is a graphic representation of the R- matrix parameters: the green lines represent the cosine-like rays, the red line the angular rays while the blue line corresponds to the dispersive rays. The beam is tuned to have a smooth focus towards the decay tunnel in both planes.

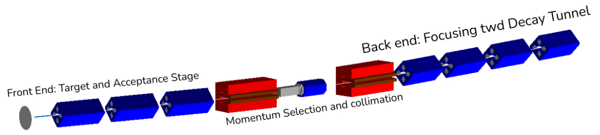

Figure 3: "Multi-Momentum" beamline layout in G4Beamline with the magnetic elements and the collimating structures appearing.

new line is shown in Fig. 3: downstream of the optimized graphite target, a large-aperture quadrupole triplet defines the accepted phase-space of the charged particles. Large aperture dipoles and iron-based collimators select the particles' momentum, within a narrow (± 10%) momentum range. The 18.18° dipole deflection provides a sufficient separation between the kaon beam and at the same time allows for a proper dump of the 400 GeV/c primary beam that escapes from the C-shaped magnet's aperture without contaminating the decay tunnel. At the end of the line, a final quadrupole quadruplet performs the shaping of the beam towards the decay tunnel providing a parallel beam that transverses longitudinally the tunnel without interacting with the instrumented walls. 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 and North Area of CERN [20], with known properties and production costs. Once established the basic layout, optimization studies involving computational algorithms to maximize the performance of the line and the overall particle acceptance were performed. The first results of this study is shown in Table 1.

Table 1: Comparison of the first triplet parameters calculated first with TRANSPORT and then through an optimization algorithm.

	Version 1	Optimized
Strengths [T/GeV]		
k1	-0.358753	-0.255934
k2	0.346788	0.34746
k3	-0.234153	-0.233052
Drifts [m]		
d1	0.300	0.300
d2	0.650	0.640
d3	0.685	0.640
d4	0.870	0.870
Phase Space Acceptance [mm*mrad]	1612	1625

From the above table, it can be seen that the two different set of parameters (optimized and not) show a comparable phase space acceptance (in terms of phase space area, i.e mm*mrad). However, the optimized version does not take into account the minimum distance necessary for the primary beam to escape.

Magnets Studies

A critical part of this work was the implementation of detailed field maps that describe in detail the magnetic field behavior inside the beam pipe and in the yoke of each magnet. A comparison between the energy spectrum of kaons reaching the decay tunnel using the default "generic" bends/quadrupoles of G4BeamLine and the realistic field maps is shown in Fig. 4. This figure shows a comparable rate between the version of the line with generic magnets and the version with finite-elements calculated field maps.

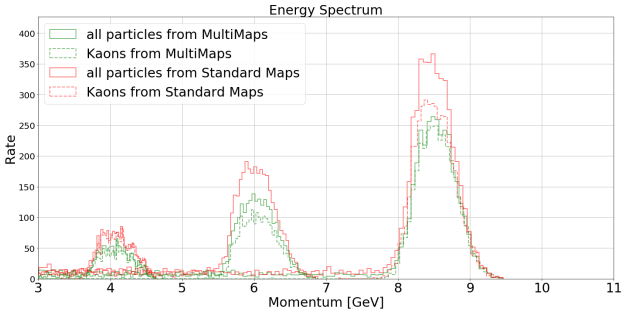

Figure 4: Comparison between kaons selection at decay tunnel entrance with performed with standard G4BeamLine magnets (green) and realistic magnets (red).

CONCLUSION

In this contribution, we presented ENUBET's studies to design a neutrino facility producing 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 initial hadronic production flux, thus leading to a substantial improvement in the precision of cross section measurements. The collaboration has advanced in designing a multi-momentum secondary beamline that will allow for a more efficient study of the neutrino energy spectrum of interest for future long-baseline experiments (0.5–8.5 GeV/c). Here, we have shown the extensive target optimization study needed to design the multi-momentum beamline outlook and its expected performance, which looks satisfactory for the experiment's physics goals. The current beamline design produces an 8.5 GeV/c ±10% kaon rate of 0.5×10^{-3} particles per proton on target at the entrance of the decay tunnel.

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