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The Design of the ENUBET Beamline †

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Abstract: The ENUBET project aims to reduce the flux-related systematics to 1% on a narrow band neutrino beam through monitoring the associated charged leptons in an instrumented decay tunnel. A key element of the project is the design of a meson transfer line with conventional magnets that maximize the yield of K^+ and π^+ while minimizing the total length to reduce meson decay outside the instrumented region. In order to limit particle rates in the tunnel instrumentation, a high level of beam collimation is needed, thus allowing non-decayed mesons to reach the end of the tunnel. At the same time, fine-tuning of the shielding and the collimators is required to minimize any beam-induced background in the decay region. The magnetic lattice is optimized with TRANSPORT. The focusing of mesons from the target is performed with a static (quadrupole-based) system that, coupled with a slow proton extraction scheme, allows for a significant pile-up reduction at the tunnel instrumentation while retaining a particle yield large enough for high-precision neutrino cross-section measurements on a 3 year time scale. Charge and momentum selection in an 8.5 GeV ± 10% momentum bite is performed by a double dipole system. Shielding elements are optimized with full simulation of the facility in Geant4. In particular, a powerful genetic algorithm is used to scan the parameter space of the collimators automatically in order to find a configuration that minimizes the halo background in the decay tunnel while preserving a large meson yield. This contribution will report the results of the optimization studies and the final design of the ENUBET beamline, together with dose estimation through a FLUKA simulation. The design of an alternative secondary beamline with a broad momentum range (4, 6, and 8.5 GeV/c) that could enhance the physics reach of the facility is additionally discussed.

Keywords: accelerator physics; neutrino physics; beam physics

1. The ENUBET Project

The CERN-NP06 project [1] and the ERC-funded ENUBET aim to design and build a novel facility that will provide the first monitored neutrino beam of ν_e and ν_μ. ν_e originate from the decay of positively charged kaons, more specifically from semi-leptonic decay $K^+ \rightarrow \pi^0 e^+ \nu_e$ (K_{e3}), while ν_μ are produced by both kaons ($K_{\mu\nu}$ and $K_{\mu3}$ channels) and pions ($\pi_{\mu\nu}$ channel). The products of kaon decay have been monitored using a fully instrumented decay tunnel about 40 m long, while a range meter placed downstream of the tunnel monitors the pion decay. An extensive overview dedicated to the diagnostics of accelerator-driven neutrino beams can be found in [2]. ENUBET aims to increase the precision of neutrino cross-section measurements to the order of the 1% level in the GeV scale [3]. The source of the secondary mesons is obtained through a primary proton beam impinging on a fixed target. We present in this R&D work the key parameters and challenges of designing ENUBET's secondary beam. The following sections will describe the optimization of the production stage and both optics designs pursued to maximize the number of neutrinos reaching the neutrino detector. Given the physics scope, the beamline has very stringent requirements in terms of maximum length and acceptance. Currently, ENUBET has two main beamline configurations in parallel: the baseline beamline configuration and the "multi-momentum" beamline layout. Both designs are presented in this work.

2. Proton Extraction

The optimal operation of ENUBET is based on a slow extraction scheme, which allows the facility to monitor the decay products of kaons while preserving the local rate at the level of $\sim$1 MHz/cm^2 inside the instrumented decay tunnel. In order to enable event-by-event reconstruction at the detector level, the entire intensity of the extracted proton beam should be slowly and uniformly extracted from the target over a duration of several seconds. In contrast to horn focusing magnets that require burst mode extraction of protons, front-end focusing employing quadrupoles would allow the extraction of protons (and subsequently the production of kaons) for up to several seconds, while reducing the instantaneous rate of particles reaching the decay tunnel by nearly two orders of magnitude. Corresponding proton extraction methods have been devised and tested at the CERN Super Proton Synchrotron (SPS), and ENUBET is exploring both static (with quadrupoles) and horn focusing solutions [4].

3. Target Studies

The production of a secondary hadron beam is achieved with a high-energy proton beam impinging on a solid target. We have assessed the effects of several target materials (in terms of production yields) and the fluence of various "primary" proton momenta on these yields. The optimization procedure allowed us to investigate a variety of materials, including graphite (density: 2.2 g/cm^3), beryllium (1.81 g/cm^3), Inconel (8.2 g/cm^3), and several high-Z materials including gold and tungsten. This study was performed using FLUKA [5,6] and G4Beamline [7] simulation codes. Each target prototype was modeled geometrically as a cylinder with lengths ranging from 5 to 140 cm and radii between 10 and

30 mm. A phenomenological model extrapolated by pre-existing measurements predicted the production yields in a non-perturbative regime [8]; we then verified the model by testing each target with different primary momenta with FLUKA simulations. Compared to lower primary energies, the nominal energy of the CERN SPS (400 GeV/c) is confirmed to be the optimal choice for the maximum kaon yield production on the GeV/c scale, specifically a nominal momentum of 8.5 GeV/c. Next, graphite, beryllium, and Inconel-718 proved to be the optimal materials for both pion and kaon production. The particle yields for the graphite target are shown in Figure 1. This plot encompasses the production yield at all possible lengths and radii, from which an optimal length of around 70 cm is clear.

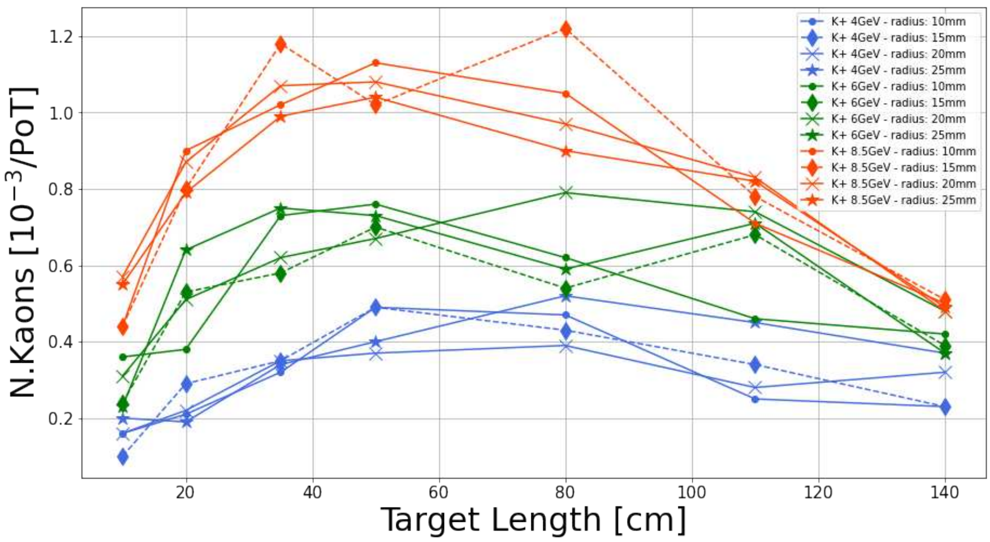

Figure 1. Kaon yields as a function of the graphite target length. A primary beam with 400 GeV/c momentum was used to evaluate the targets. The number of kaons of a given energy that enter and are transported along the beamline with ±20 mrad angular acceptance in both planes is the figure of merit for this study. Monte Carlo systematics are generally in the order of ∼10% and the simulated statistical errors are small (1%); thus, the error bars are not plotted to ease interpretation of the plot. Blue is 4 GeV/c, green is 6 GeV/c, and red is 8.5 GeV/c in terms of kaon momenta, whilst the marker style indicates the target radius: a dot is 10 mm, a square is 15 mm, a cross is 20 mm, and a star is 25 mm.

When discussing high-power targets, graphite is a well-known and well-tested material [9]. However, the exact and final implementation in the case of ENUBET (in terms of mechanical properties and cooling) needs to be carefully studied. Graphitic materials in general, such as POCO graphite or even the enhanced form of CFC [10], have long been an appealing option for beam-intercepting devices. Inconel is a material with promising qualities now in use at CERN in various applications (such as the brand new CERN-PS East Area Beam Stoppers). ENUBET's current baseline choice is a graphite-based target with dimensions of ∼70 cm and ∼30 mm. The design specifications of the target station will be the subject of future studies.

4. Baseline Studies

Shown in Figure 2, the baseline design is a fully static beamline as required by the slow extraction scheme. The line is optimized for 8.5 GeV/c secondaries using normal conducting quadrupoles and dipoles for a total bending angle of 14.8°. The optics were designed through several TRANSPORT [11] iterations, following implementation on G4Beamline and Geant4 for an extensive validation of the first-order calculations, allowing us to investigate the effect of the presence of material between the magnetic elements. Final pre-tunnel collimation and the employment of a 50 mm thick tungsten plate serving as a positron filter accomplish additional background reduction. Assuming a 500 ton neutrino detector placed at around 50 m from the tagger exit and using the CERN-SPS accelerator as a driver, delivering 4.5×10^{19} PoT per year to the ENUBET target, we should be able to collect about $10^4 \nu_e$CC in 3 years of data collection. Out of this number, 80% of the total neutrino flux is produced by taggable neutrinos and hence produced by K_{e3} decay.

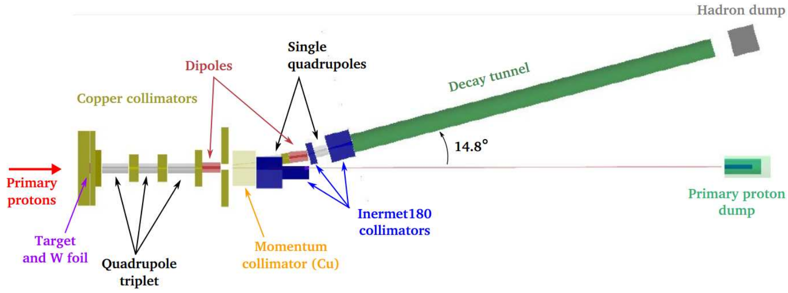

Figure 2. Baseline layout of the G4Beamline showing the main stages of the line.

Optimization Algorithms

This line has been the subject of further optimization to improve the signal-to-noise ratio in the instrumented decay tunnel. These studies require full tracking and interaction of the particles through all elements and materials present in the beamline. The whole framework is based on a genetic algorithm (GA) running on a computing cluster and based on the employment of the Geant4 [12] Monte Carlo code. The figure of merit optimized regards the last two collimators placed before the decay tunnel, as seen in Figure 3. The optimization study iterated over five parameters, i.e. the collimators' apertures and the number of hits inside the tunnel, to maximize the ratio of the number of K^+ reaching the tunnel entrance and background particles hitting the tunnel walls. In this Figure of Merit (FOM), the background is defined as the positrons and pions coming from the beamline and not from the tunnel events (kaon decay). This process converges in about 2 weeks and hence uses 100 beamlines per iteration. The preliminary results of this optimization study improved the positron and pion background suppression by a factor of $\sim$2, with an improvement of 28% in the kaon yield, allowing an estimation of 2.4 years of data collection to collect 10^4 ν_{eCC} at the neutrino detector.

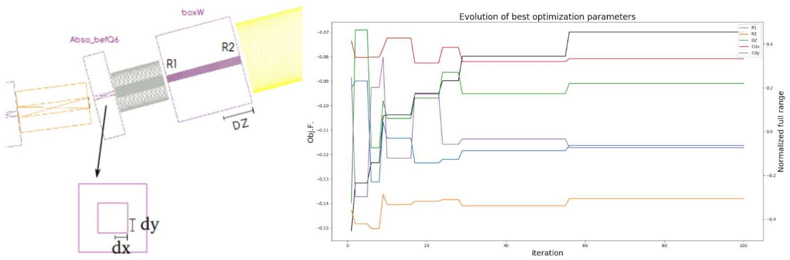

Figure 3. Schematics of the last two collimators placed upstream of the tagger (**on the left**) and convergence plot of the beamline iterations to maximize the FOM (**on the right**).

5. Multi-Momentum Line Studies

Similar to CERN's other low-energy secondary beamlines [13], the multi-momentum beamline is designed with tight requirements for global acceptance, collimation, and background reduction. Previous particle production studies proved the positron dominance in the production spectrum of the target, particularly at lower momenta (<6 GeV/c) [14]. A beamline configuration that is positioned at a certain angle to the target would be one mitigation strategy for this specific background. For the case of the ENUBET "multi-momentum" beamline, we optimized and placed the line at 0.5° with respect to the target.

The line is optimized so that 4, 6, and 8.5 GeV/c K^+ momenta can be transported from the target toward the decay tunnel. The optics diagram is displayed in Figure 4, and first-order calculations were performed using TRANSPORT. To assess the impact of different materials on the beam properties, comprehensive Monte Carlo simulations using G4Beamline [7] were used to validate the results.

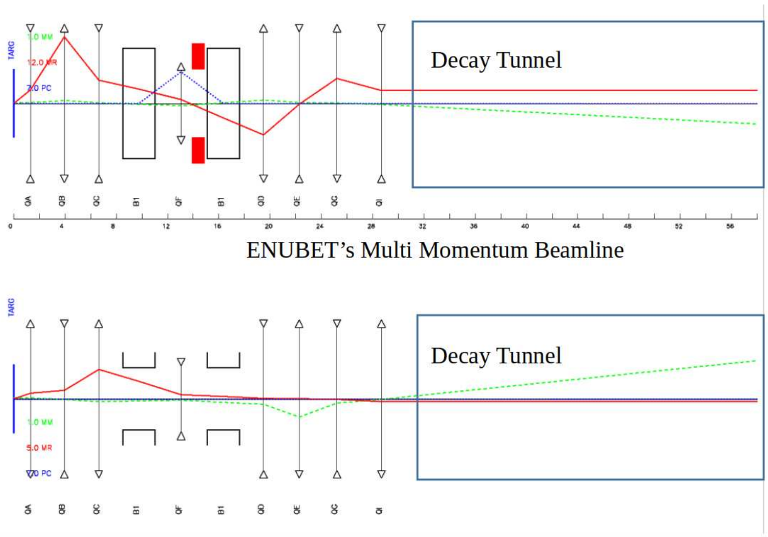

Figure 4. Horizontal (**top**) and vertical (**bottom**) planes of the beamline optics. The R-matrix parameters are represented graphically by each line; the blue line corresponds to dispersive rays, the red line to angular rays, and the green line to cosine-like rays. The beam is set to have a smooth focus in both planes toward the decay tunnel.

The conceptual design of this line proposal is displayed in Figure 5. A large-aperture quadrupole triplet defines the accepted phase space of the charged particles downstream of the target. Large aperture dipoles and an iron-based collimator with a slit of 90 mm select (in the first order) the particle momenta that finally have a momentum bite (dp/p) of ±10%. The 400 GeV/c non-interacting primary beam that exits from the side aperture of the C-shaped dipole is properly dumped without contaminating the decay tunnel thanks to the overall 18.18° line deflection. This angle helps to clearly separate the kaon beam from the primaries. A final quadrupole quadruplet at the end of the line shapes the beam in the direction of the decay tunnel, creating a parallel beam that traverses the tunnel longitudinally without touching the instrument walls. The magnets used in this design are existing ones, have known properties, and are now placed and in use at CERN's East and North Areas [15].

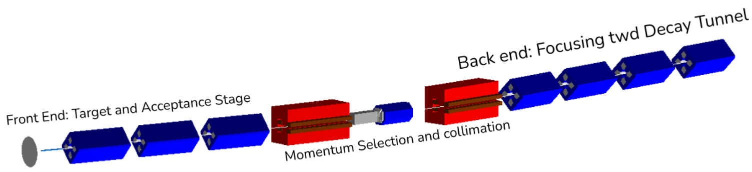

Figure 5. "Multi-momentum" beamline layout in the G4Beamline with the magnetic elements and the appearing collimating structures.

6. Conclusions

We present here a summary of the performance of both beamline designs, listed in Table 1. In conclusion, we have two stable designs both fully implemented in the G4Beamline. The baseline configuration has achieved the goal of a 1% precision level for the flux. Future studies will evaluate the performance of the multi-momentum alternative design and validate the flux precision. Ongoing studies are evaluating possible beamline equipment to monitor the secondary beam profile and intensity. Current possible candidates are the "Giga-Trackers" [16] already in use within the NA62 collaboration [17]. Finally, the genetic optimization performed in the baseline configuration will test the multi-momentum beamline for further optimization.

Table 1. Both beamline proposals' particle rates at the tagger entrance for all momenta configurations.

Particles (10^{-3}/PoT)	8.5 GeV/c	6 GeV/c	4 GeV/c
Baseline Beamline			
K^+	0.34	/	/
π^+	4.13	/	/
Optimized Baseline Beamline			
K^+	0.43	/	/
π^+	5.1	/	/
Multi-Momentum Beamline			
K^+	0.68	0.28	0.08
π^+	7.9	4.1	1.7

Author Contributions: The study presented in this paper is based on the end-to-end simulation and prototypes developed by the ENUBET collaboration listed above. The manuscript was prepared by E.G.P. and revised by the co-authors. All authors have read and agreed to the published version of the manuscript.

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