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The design of the beamline for the ENUBET experiment

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Summary. — The ENUBET project aims at reducing the flux related systematics on a narrow band neutrino beam by monitoring the associated charged leptons in an instrumented decay tunnel. A key element of the project is the design of a transferline with conventional magnets that maximizes the yield of K^+ and π^+, while minimizing the total length to reduce meson decays in the non-instrumented region. In order to limit particle rates on the tunnel instrumentation, a high level of collimation is needed. At the same time, a fine-tuning of the shielding and the collimators is required to minimize any beam-induced background in the decay region.

1. – The ENUBET beamline

The aim of the ENUBET (Enhanced NeUtrino BEams from kaon Tagging) ERC project is to develop the concept of monitored neutrino beams [1], where the neutrino flux could potentially be determined with a precision of the order of 1%. In a monitored neutrino beam, the production of neutrinos is evaluated by measuring the rate of leptons produced in the decay tunnel that, in the case of ENUBET, will be instrumented with a modular cylindrical calorimeter (4.3 radiation lengths, 0.45 interaction lengths per module). The measurement of large-angle positrons from the $K^+ \to e^+\pi^0\nu_e$ decay, that hit the tunnel walls, is directly linked to the flux of ν_e. ENUBET also considers the possibility of measuring the ν_μ flux, by monitoring the muons from the large angle decays of kaons ($K^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\pi^0\nu_\mu$) in the decay tunnel, and the muons from pion decays ($\pi^+ \to \mu^+\nu_\mu$) instrumenting the hadron dump.

An essential part of the project is proper focusing of the secondary particles. The design needs to ensure that the overall rate in the instrumented region is mainly determined by kaon decays products. The transferline is optimized for $8.5\,\text{GeV}/c$ mesons with a 10% momentum bite. This design is given by requirements of having kaons as the main source of ν_e, ensuring a good e^+/π^+ separation, maximizing the total number of produced kaons, and relevance for future oscillation experiments (leading to a ν_e beam peaked at an energy of $4\,\text{GeV}$).

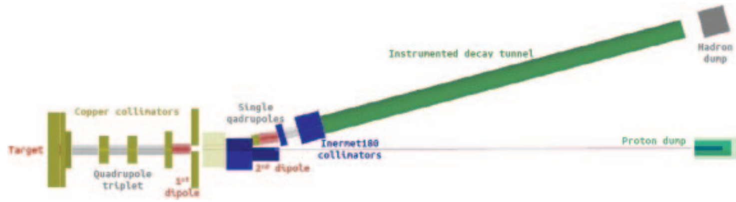


Fig. 1. – G4beamline design of the ENUBET facility.

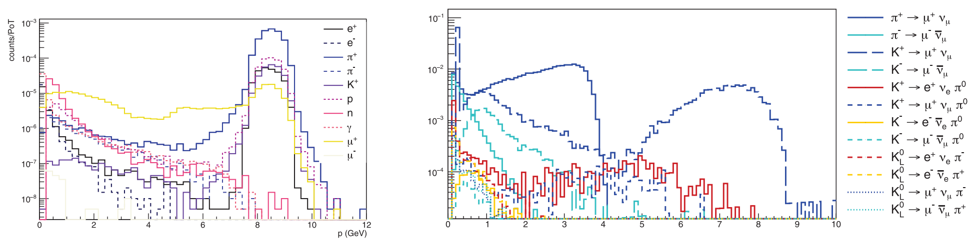
2. – Proton target design

The largest yields of mesons in their region of interest per incoming proton are obtained for 400 GeV/c incoming protons. This is the configuration that has been mostly studied but also 30 and 120 GeV/c have been considered. The target optimization in terms of material and dimensions has been performed in order to maximize the kaon production in the region of interest, for a beamline with 20 mrad angular acceptance. Different materials have been tested with FLUKA [2,3] and G4beamline [4] simulations, the most promising ones are graphite, beryllium and Inconel [5]. The last version of the beamline employs a graphite target with a length of 70 cm and a radius of 3 cm.

3. – Transferline design

The development of the ENUBET beamline is performed by taking into account the following guidelines [6,7]: 1) use of conventional magnet fields and apertures (normal-conducting devices, with apertures below 15 cm); 2) keep under control the level of background (pions, muons and positrons produced by interactions in the transferline elements) transported to the tunnel; 3) maximize the number of K^+ in the momentum range of interest at tunnel entrance; 4) minimize the total length of the transferline ($\sim$ 20 m) to reduce kaon decay losses before the entrance of the decay tunnel; 5) contain the beam within the tunnel, so that non decaying particles can reach the beam dump without hitting the instrumented inner surface of the tunnel. The beamline (shown in fig. 1) consists of a short (20 m) transferline followed by a 40 m long decay tunnel. The secondary hadrons produced in the interaction of the proton beam on the target are momentum and charge selected by two normal conducting dipoles, bending the beam by 14.8° towards the instrumented decay tunnel (lepton tagger). Non-interacting protons are stopped in a beam dump. Off-momentum particles reaching the decay tunnel are mostly low energy pions, electrons, positrons and photons coming from interactions in other beamline components, and muons from pion decay that cross absorbers and collimators. The beamline has been studied and designed with different simulation packages. The optics has been designed and optimized with TRANSPORT [8]. G4beamline has been used to choose and implement the geometry of the beamline elements. FLUKA is used for doses assessment (sect. **3**˙1). GEANT4 [9] allows for a fine tuning of the collimators and for a detailed description of the backgrounds in the instrumented decay tunnel (sect. **3**˙2).

GEANT4 reproduces the geometry of the G4beamline simulation and has been validated against it by comparing the spectra of particles at the tagger entrance (shown in fig. 2(a)). The strength of the implemented GEANT4 simulation is its significant flexibility: it is possible to easily control all the parameters, from the collimator dimensions and positions to the magnet apertures and fields. It also allows one to precisely map



(a) (b)

Fig. 2. – Particle spectra from GEANT4, at tagger entrance (a) and neutrino interaction rates at far detector, with the breakdown by decay mode (b).

different kinds of background entering the instrumented decay region, thus facilitating the optimization of the beamline design (see sect. **3**˙2). Moreover, the output contains the information on all the particle decays along the beamline: in this way it is possible to reconstruct the neutrino signal at the far detector and to estimate the rate of neutrinos from different sources (fig. 2(b)).

3˙1. *Doses estimation with FLUKA*. – The estimates of the ionizing doses and neutron fluences for all the elements of the beamline have been performed with a FLUKA simulation [5]. We are particularly interested in the decay tunnel region, where the instrumentation will be placed, and in the focusing quadrupole closer to the target. At this location the dose is acceptable, of the order of 100–300 kGy for 10^{20} PoT (Protons on Target). Most importantly neutron doses have been assessed. They are compatible with the operation of the detector that the collaboration has designed, *i.e.*, a sampling calorimeter with SiPM readout. More details are available in ref. [10].

3˙2. *Beamline optimization with GEANT4*. – The collaboration has developed a new version of the ENUBET beamline that could ensure a larger neutrino flux at the detector, while preserving a reasonable background from the beam halo at the instrumented decay tunnel. Further reduction of background at the tagger level can be given by the insertion of additional shielding at the end of the transferline, before the tunnel entrance. In order to find the best geometry for the new collimators to be placed in the latest design, we employ an automatic approach based on a genetic algorithm [11] that scans the parameter space and that makes sure, by defining an appropriate Figure of Merit, that a good signal-to-noise ratio is preserved.

In particular, in the current version of the beamline, an Inermet180 block with a conical aperture dumps low energy particles hitting the tagger. A similar collimator is needed in the new design, together with some additional shielding elements. A study for the optimization of dimensions and apertures of these collimators is in progress. The Figure of Merit chosen is the ratio between the number of K^+ arriving at the tunnel entrance (signal) and the number of positrons, electrons and charged pions hitting the tunnel walls and coming from the transferline (background). Figure 3 shows the implementation of the beamline in GEANT4, with a detail of the Inermet180 collimators to be optimized.

3˙3. *Multi-momentum beamline*. – Electron neutrinos from the reference beamline described in the previous sections are peaked at about 4 GeV, *i.e.*, at the typical energy

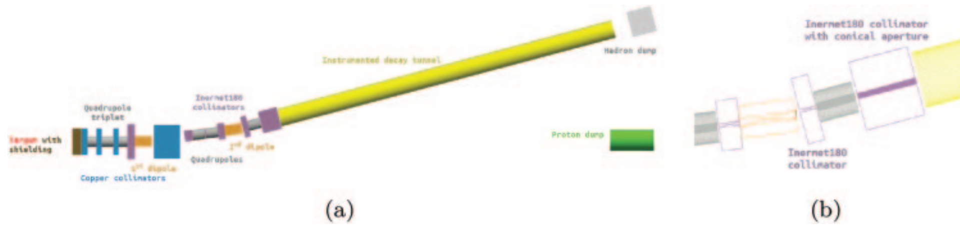


Fig. 3. – Beamline design implemented in GEANT4 (a) with an improved collimation system (b).

of the neutrino beam that will be employed by DUNE. This new beamline design is able to focus secondaries with different central values of the momentum (4, 6, 8.5 GeV/c) in order to cover also lower neutrino energies like those that will be exploited by HyperK. The optics optimization for the ENUBET multi-momentum beamline is performed using TRANSPORT and G4beamline: starting from the optimized graphite target (see sect. **2**), this beamline features a quadrupole triplet followed by an achromatic bending section (13.35° deflection) and another quadrupole triplet. Background studies with FLUKA and first estimations of kaon fluxes are ongoing.

4. – Conclusions

In this contribution, a short summary of the work that is being carried out to design a suitable beam for a monitored neutrino beam has been presented. The current design already allows having an event by event reconstruction of leptons associated to neutrinos with a usable signal-to-noise ratio to get a significant reduction of flux systematics. Further improvements from a systematic optimization campaign, based on a genetic algorithm run on a powerful computing cluster, are expected soon.

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