ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB130

DESIGN OF A VERY LOW ENERGY BEAMLINE FOR NA61/SHINE

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Abstract

A new, low-energy beamline branch is currently under consideration for the H2 beamline at the CERN North Area. This new branch would extend the capabilities of the current infrastructure enabling the study of particles in the very low, 1-13 GeV/c, momentum range. The design of this new beamline involves various stages. Firstly, a study of the secondary targets to maximise the yield of secondary hadrons. Secondly, the development of high acceptance transverse optics with high momentum resolution on the order of a few %. Finally, we discuss the first considerations on instrumentation to enable particle identification and background rejection. The first experiment to profit from this new line could be NA61/SHINE, but other possible future fixed target experiments or test-beams installed in the downstream zones could also use the low-energy particles provided. The aim is to arrive at a complete design of this branch by the end of 2021, which, pending the approval of the CERN scientific committees, could be envisaged for construction after 2024. This timescale is compatible with requests for measurements by various large international collaborations, in the next 10-year horizon.

INTRODUCTION

In recent years there has been a growing interest from the neutrino community in more comprehensive hadron production measurements, especially in the low momentum regime, between 1 – 10 GeV/c. This demand has arisen due to the comparatively large uncertainties on the cross sections in these energy ranges which in turn has led to significant uncertainties in neutrino flux predictions [1]. The measurement of both particle yields and cross-sections of protons, pions and kaons in this momentum range, would significantly decrease these uncertainties and therefore are of great relevance to the work being done by many collaborations, such as T2K, DUNE, JSNS2 among many others [1–3].

CERN's North Area Experimental Area with its numerous fixed-target experiments is one of the best facilities to obtain such measurements. Here, in the North Experimental Hall 1 (EHN1), beamlines deliver a broad range of secondary beams with momenta as low as 20 GeV/c up to the Super Proton Synchrotron's (SPS) nominal energy of 400 GeV/c [4] and various intensities, between 10^3 – 10^7 particles per spill. These beams can be primary, secondary or tertiary beams, with variable spot-sizes and intensities for the different experimental zones. While this facility provides an environment rich with physics opportunities, the current beamlines in EHN1 are not suited for the transport of the low energy particles required by neutrino experiments.

There are several reasons for this [4]. Firstly, the North Area beamlines were designed in the 1970s with the purpose of transporting particles with momenta over 300 GeV/c. The magnet power supplies are therefore not suited to operate with the very low currents required to transport lower momentum particles.

Secondly, the primary production target for the high-energy secondary beams that reach the experiments in the North Area is located over 500 m upstream of the experimental halls, meaning that a significant fraction of low energy pions and kaons would have decayed by the time they would reach the experiment.

Finally, the acceptance of the existing beamlines is quite small, approximately 1 mrad angular acceptance in both x and y planes, but low energy particles are typically produced at much larger production angles. To capture these particles and achieve a satisfactory rate a larger angular acceptance is necessary.

In order to satisfy the above requirements, a new, specially designed, low energy tertiary branch placed between the existing beamline elements is investigated in this paper.

The new branch would be designed as an insertion to the H2 line by adding a secondary target to produce low energy particles, that would be subsequently captured, momentum-selected and transported downstream. This new branch would first serve the SPS Heavy Ion and Neutrino Experiment (NA61/SHINE), a multi-purpose facility which performs hadron production measurements in various types of collisions [5]. NA61/SHINE has a broad range of physics goals, which include the search for the critical point of strongly interacting matter, the study of the properties of deconfinement, and precise hadron production measurements for improved calculations of initial neutrino fluxes in long-baseline neutrino experiments. Several publications have arisen out of the last of these physics goals [6, 7] and shown the interest in these measurements, however, for NA61/SHINE to reach even lower energies, a low energy beamline branch will be a necessity.

TARGET CONSIDERATIONS

High statistics are essential to reduce statistical uncertainties in hadronic cross section measurements. Therefore, maximising the number of particles produced and accepted is a driving factor in the design of this beamline. The choice

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of secondary target used for particle production, is therefore a key factor. Hence, numerous G4Beamline [8] simulations have been carried out to study how the the particle yield, momentum spread and composition of the secondary beam were affected by different choices in size and material of the target and by the primary beam's energy.

In the aforementioned Monte-Carlo simulations, cylindrical targets of beryllium, carbon, inconel, copper, tungsten and gold have been studied, with lengths ranging from a few centimetres to over a meter. Different primary and secondary beam momenta have also been investigated, ranging from 40 to 400 GeV/c. To investigate the possible systematic uncertainties of the different physics lists, the simulations have been carried out using GEANT4's FTFP_BERT physics list and then have been compared to simulations run using QSGC_BIC physics lists. The results between the two lists have been found to be generally consistent, within a few %, providing sufficient substantiation for the estimation of particle yields and as expected from previous results [9].

Different targets produced significantly different results, which has led to the choice of three main targets with three different impinging beam configurations, in order to optimise for different situations enabling a broad range of physics possibilities. These targets, designated 'yield' target, the 'hadron' target, and the 'balanced' target, respectively maximise the number of particles produced overall, maximise the proportion of hadrons to leptons in the beam or generate a beam which is a good compromise between the previous two. All these targets are tungsten cylinders with a 20 mm radius for facilitating the construction, however further optimisation of the shape will follow at a later stage. In the high yield scenario, the target will be 20 cm long and the beam impinging on this target will be at 400 GeV/c. The high composition target will be 15 cm long while using a 70 GeV/c secondary beam, and finally, the balanced target will be a 30 cm long target using a 400 GeV/c beam. By using a multi target switching station, it will be easy to remotely switch between targets for different experimental runs. The particle yields for the 'high yield' target, assuming a 10 day run with 3000 spills per day and a conservative 10^6 particles on target per spill are shown in Table 1. In these simulations, a 20 mrad acceptance was assumed and particle decays were considered.

TRANSVERSE OPTICS

A low energy beamline presents many technical challenges, chief among these being the need for the largest possible acceptance. At the same time, the length of the beamline must also be minimised while providing a good momentum resolution. In addition, it is necessary to have a small beam spot size at the end of the beamline, at the position of the experimental target or detector, and to have zero dispersion through the beamline after the momentum selection station.

In the beamline's front-end, just downstream of the secondary target, a doublet of large aperture quadrupoles with opposite polarities is used to maximise the acceptance of the beamline and keep the betatron oscillations under control until the momentum selection point. The momentum selection station is comprised of a four bend achromat of large aperture dipole magnets. In the maximum dispersion point, a collimator cleans the off-momentum particles allowing only a narrow momentum band to continue towards the experiment. The final section of the optics, which focuses the beam on the NA61 target, is comprised of a triplet of large aperture quadrupoles. The preliminary optics are shown in Fig. 1. The figure also shows the momentum resolution for a 2 cm collimator opening, however, a resolution as low as 1% can be achieved at the cost of particle rate by closing the collimator slit further.

Table 1: Predicted Particle Yields and Beam Compositions for the High Yield Target in a 10 Day Run, A Typical Scenario for NA61/SHINE. The composition of the beam does not reach 100% as the leptonic part is not being shown.

Momentum	Particle	Yield	Composition
2 GeV/c	$\pi+$	11×10^6	25%
	p	4×10^6	9%
	$K+$	0.2×10^6	0.50%
6 GeV/c	$\pi+$	41×10^6	70%
	p	6×10^6	11%
	$K+$	2×10^6	3%
13 GeV/c	$\pi+$	75×10^6	81%
	p	8×10^6	8%
	$K+$	5×10^6	6%

Figure 2 shows the area of phase space occupied by particles produced by the target and the area of phase space accepted by the beamline. While a large asymmetry in the accepted phase space can be seen, with the horizontal plane accepting a larger range of positions and the vertical plane accepting a large range of angles, this set-up has been found to maximise the number of particles reaching the end of the beamline.

INSTRUMENTATION

This beamline will be equipped with different particle identification devices to enable the tagging of particles over the entire momentum range of the beamline. The minimum necessary instrumentation to identify particles from the 2 GeV/c to 13 GeV/c involves the use of a scintillator, a time of flight system and three threshold Cerenkov counters filled with CO_2.

The scinitllator detector will be used to provide the total number of charged particles being transported by the beamline, while a time of flight (TOF) system will enable the identification of particles in the lower energy part of the momentum range. A resolution of 200 ps and a beamline length of 40 meters would enable the a resolution of 4 sigma of protons up to 8 GeV/c and kaons up to 4 GeV/c.

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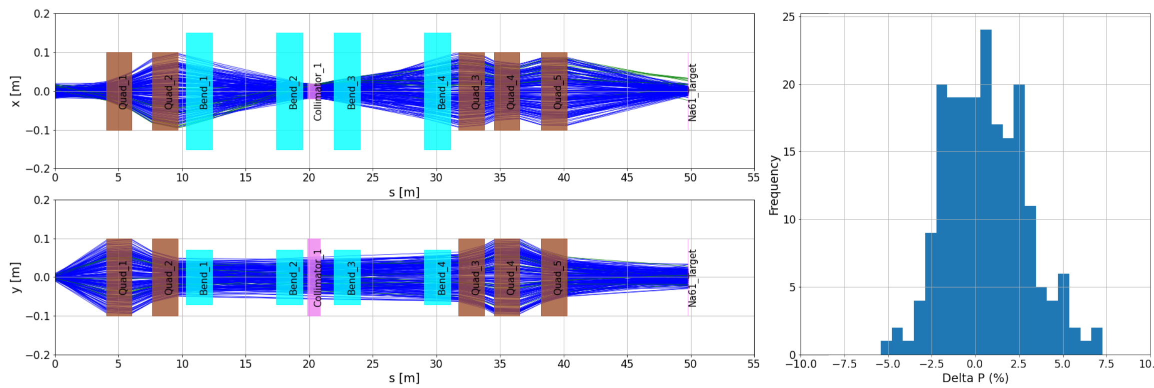

Figure 1: Tentative optics for the new low energy branch of the H2 line in EHN1. The horizontal plane is shown in the top plot on the left and the vertical plane shown lower left plot. The secondary target ends at $s = 0$. The blue lines represent particle tracks and have been obtained using MAD-X's PTC code [10]. On the right is the momentum distribution of the particles which reach the end of the beamline with a 2 cm collimator opening.

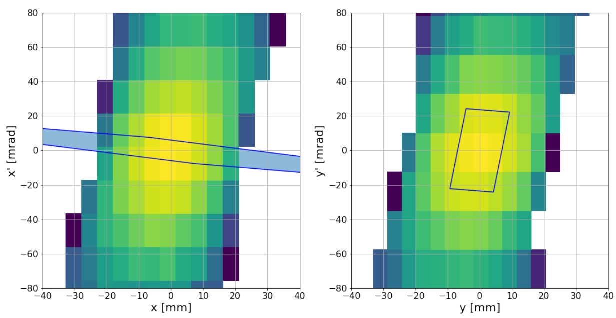

Figure 2: The produced particles' phase-space overlayed with the accepted phase space of the beamline. On the left is the horizontal plane and on the right that of the vertical plane.

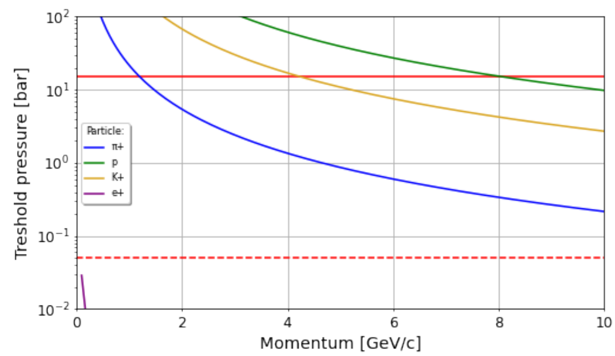

Figure 3: The threshold Cherenkov counter threshold curves for various particles. The solid red line is the maximum pressure of 15 bar, while the dashed red line represents the minimum pressure. Particles can be detected if threshold curve is below the maximum pressure.

Above this momentum the arrival time of different particles will begin to overlap, rendering them indistinguishable with this technique. In this momentum region however, as shown in Fig. 3, it is possible to use the threshold Cerenkov counters to identify the different species with good efficiency (about 5 photoelectrons per particle). One of the detectors will be used to detect exclusively electrons, while the others will enable the identification of pions and kaons. Details of the effect of this instrumentation on the beam quality will be investigated in detail in the future.

SUMMARY

In this work, we discussed the current design status, as well as an outlook on the performance of a novel, low energy beamline branch, currently being developed for the H2 beam at the CERN North Area. The selection of the targets, the expected rates and beam compositions produced by these, along with the optics for the acceptance quadrupoles and momentum selection have been described. A first proposed instrumentation and particle identification scheme has been discussed. The results presented in this paper have been found to well satisfy the current requirements of the low energy programme of NA61/SHINE as a first user.

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