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DESIGN OF A VERY LOW ENERGY BEAMLINE FOR NA61/SHINE

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Abstract

A new, low-energy branch is being designed for the H2 beamline at the CERN North Experimental Area. This new low-energy branch would extend the capabilities of the current infrastructure enabling the study of particles in the low, 1–13 GeV/c, momentum range. The first experiment to profit from this new line will be NA61/SHINE (SPS Heavy Ion and Neutrino Experiment), a multi-purpose experiment studying hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the SPS. However, other future fixed target experiments or test-beam experiments installed in the downstream zones could also benefit from the low-energy particles provided. The proposed layout and expected performance of this line, along with estimates of particle rates, and considerations on the technical implementation of the beamline are presented in this contribution. A description on the instrumentation, which will enable particle-by-particle tagging, crucial for the experiments scope, is also discussed.

INTRODUCTION

Various neutrino experiments across the globe have shown significant interest in comprehensive hadron production measurements, especially in the low momentum regime, between 1–13 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]. To meet these requests, studies for the development on a new, custom made low-energy beamline has been underway for the past two years. This beamline would be housed in North Experimental Area [2] at CERN and would be serving the NA61/SHINE experiment [3] as a first user. NA61/SHINE is a fixed target experiment with the aims of: a) advancing the understanding of onset of deconfinement and the search for the critical point of strongly interacting matter [4] and b) obtaining precise hadron production measurements for improving calculations of neutrino beam flux in long-baseline neutrino oscillation experiments [5]. Additionally, the new line will enable a new range of measurements that today are not achievable with the current infrastructure. The new branch would be designed as an insertion to the H2 line by including a target to produce low-energy particles, which would be subsequently captured, momentum selected and transported downstream.

The development of this beamline will also expand the experimental capabilities of the CERN's North Area (NA), currently allowing the delivery of beams a with minimum momentum of ~30 GeV/c to all experiments, including NA61/SHINE. This is due to two reasons. Firstly, the H2 beamline, originally designed in the 1970s, was optimised for very high energy (300 GeV/c) beams. The power supplies used are therefore incapable of stably providing the currents required to operate at low energies. Additionally, secondary beams in the H2 line are produced at a primary target, T2 [6], which is located 600 meters upstream of the NA61/SHINE experiment. It is obvious that a large majority of the low energy (1–13 GeV/c particles) produced at T2 would decay before reaching the experimental detectors. Therefore the only way to tackle these issues is via the construction of a wholly new tertiary branch of the H2 line, where the tertiary, low-energy particles are produced closer to the experiment, inside the surface hall.

TRANSVERSE OPTICS

The beamline, shown in Fig. 1, consists of a target where the secondary, low-energy particles are produced [7]. Downstream, a high-acceptance quadrupole doublet, consisting of two large-aperture quadrupoles with opposite polarities, captures and maximises the number of accepted particles. The beam is then focused in the middle of a four-bend achromat, to momentum select the particles. Just before the experiment, a quadruplet focuses the beam onto the NA61/SHINE target, located just before the experiment's Time Projection Chamber (TPC). In the current layout envisaged, only components currently available at CERN, with well know properties, dimensions and performances, have been employed. The quadrupoles are large aperture 'QPL' magnets, while the dipoles are 'MBPL' type magnets [8].

The newly developed optics have an intrinsic momentum resolution better than 2%, however, momentum bites as low as 1% can be reached at the cost of particle rate. Figure 2, obtained using MAD-X PTC [9], shows the betatron oscillations of particles transported by the beamline for a beam with nominal momentum of 13 GeV/c. It is important to note the focusing of the beam in both the horizontal and vertical planes at the NA61/SHINE target, a critical parameter for the experiment.

These optics have been developed using a novel multi-parameter optimisation technique which requires scanning

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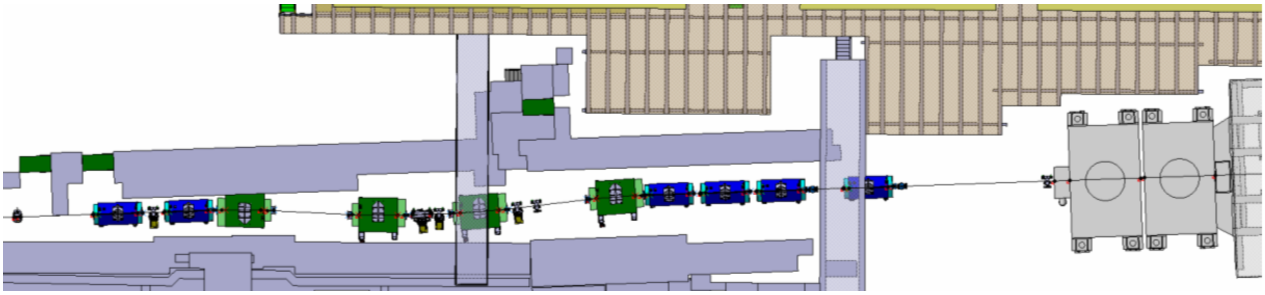

Figure 1: Top view of the low-energy beamline in the NA, with the path of the beam shown in black and travelling from left to right. In the image, the quadrupoles can be seen in blue, the dipoles in green, and the NA61/SHINE TPC is located on the far right of the image. The shielding currently present in the NA can also be seen in the image.

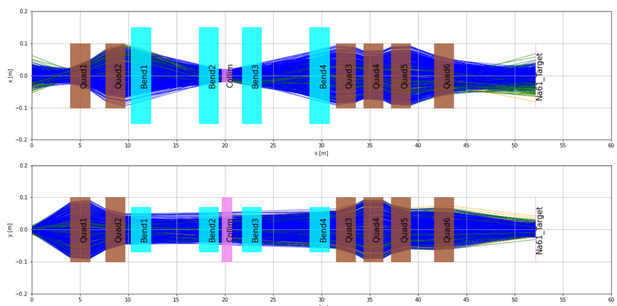

Figure 2: Particle tracks transported through the beamline at 13 GeV/c. A track's colour represents the percentage difference, δp, between that particle's momentum and the nominal momentum. Blue tracks represent δp < 5%, green tracks δp < 10%, and orange tracks δp < 20%.

Table 1: Simulations predicting the particle yields reaching the NA61/SHINE target when using the high-yield target. The table shows yields per spill and per day. A typical datataking scenario for NA61/SHINE consists of approximately 10 days per run.

Momentum	Particle	Yield/spill	Yield/day
2 GeV/c	$\pi+$	220	6.6×10^5
	p	100	3.0×10^5
	$K+$	0	0
	e^+	960	3.9×10^6
13 GeV/c	$\pi+$	5200	1.5×10^7
	p	650	2.0×10^6
	$K+$	320	9.7×10^5
	e^+	380	1.1×10^6

the parameter space available to the beam designer within the physical constraints of the beamline, such as maximum length or maximum magnet strength. From these scans, one can receive the various figures of merit for the beamline such as the acceptance, position of the focal point and so on. In this technique [7], the beam-line has been optimised to meet the requirements of the NA61/SHINE experiment, its first user.

By simulating these optics and tungsten targets, which have been optimised for a high hadronic yield [7], in G4Beamline [10] we have obtained the particle rates per day shown in Table 1. The table summarises the number of expected particles at both the low and high end of the momentum range of the beamline. The results of the simulations are given per SPS spill, assuming a rather conservative 10^6 primary particles impinging on the new secondary target per spill and assuming 3000 daily spills from the SPS towards the NA.

INSTRUMENTATION AND PARTICLE IDENTIFICATION

A key requirement for NA61/SHINE has been to have accurate and reliable particle-by-particle tagging for the secondary particles which reach the end of the beamline. As the beamline's nominal momentum range is from 1–13 GeV/c, a combination of time of flight (ToF) detectors and threshold Cherenkov counters (XCET) will be used. The time of flight will enable the tagging of particles in the lower end of the momentum range, while the XCETs will be used when operating at higher energies. The full scheme for particle identification consists of two scintillating detectors, acting as the start and end point of the ToF, a scintillating fiber to provide the total count of particles, and three XCETs.

Below 4 GeV/c, a time of flight spanning a 40 m distance, with a time resolution of 500 ps is able to successfully resolve the protons and the pions, while any positrons present can be vetoed by an XCET counter. At higher momenta, the beamline will rely on the XCET detectors to identify particles. The momenta at which these detectors will be used, their pressures and which particles will produce a scintillation signal can be seen in Table 2. In addition to the total number of charged particles present, given by the scintillating fibers, it will be possible to obtain the number of particles for each relevant secondary species.

LAYOUT AND RADIATION PROTECTION

Change Between Configurations

As this beamline is to be implemented in CERN's EHN1 surface hall, it must be designed in a way to enable the rapid switch between H2 in standard mode and H2-LE and in a way that the insertion of the low energy branch does not come at the expense of the current capabilities of the H2

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Table 2: Pressures in each XCET and the particles which will be causing a signal in each of the detectors at different momenta. The change from CO_2 to He in XCET1 has been done to ensure that no pions will trigger the detector.

Momentum	XCET1	XCET2	XCET3
4-7 GeV/c	1 bar CO_2 [e^+]	1.75 bar CO_2 [e^+, π]	8 bar CO_2 [e^+, π, k]
7-10 GeV/c	7.5 bar He [e^+]	1.5 bar CO_2 [e^+, π]	3.5 bar CO_2 [e^+, π, k]
>9 GeV/c	7.5 bar He [e^+]	1 bar CO_2 [e^+, π]	2 bar CO_2 [e^+, π, k]

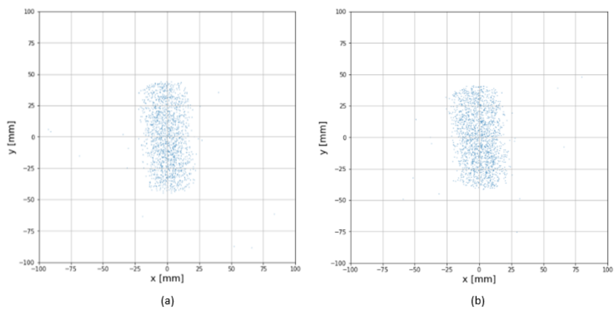

Figure 3: Spotsize of the beam reaching the NA61/SHINE detector for the (a) old and (b) new optics of H2 at 400 GeV/c, assuming all collimators are fully open.

beamline. For a rapid switch between H2 and H2-LE, it will not be possible to completely remove the magnets and replace them with the other beamline's component, as this requires an intervention time of the order of tens of days. To get around this, we envision a system with magnets placed on rails, such that the magnets can be moved in and out of the beam as necessary. This requires the magnets for the low-energy beamline and the H2 beamline to be adjacent to share these rails, which requires significant modification of the H2 line. These changes are currently being investigated.

It is important to ensure that the H2 line will be able to continue providing the same beams to the experiments downstream after undergoing these modifications. Thus, optics equivalent to those currently being used by NA61/SHINE for the 400 GeV/c runs and for the ion runs have been calculated. These new optics have been found to provide a beam with extremely similar properties to the ones currently available, with the additional benefit of slight increase in acceptance. Figure 3 presents the spotsize generated by the new optics compared to the current optics; nearly the same spotsize is being delivered to NA61/SHINE.

Radiation Protection Considerations

CERN's Radiation Protection rules pose limitations on the prompt ambient dose equivalent in areas in the surface halls, like EHN1 [11]. Since a high intensity beam will be impinging on the secondary target of the new branch, the

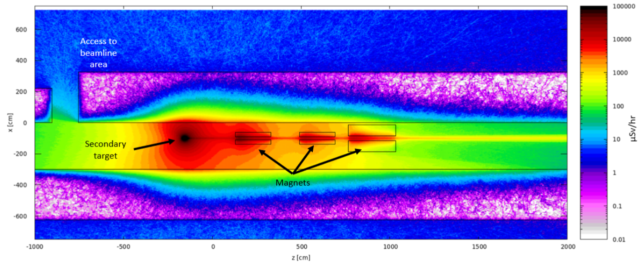

Figure 4: The prompt ambient dose equivalent produced by proton beam impinging on the secondary target of the new low energy line. The preliminary results suggest that the dose can be contained well by the concrete shielding. The critical area is the corridor, above the beamline and shielding and connected via the "access to beamline area".

prompt and activation field needs to be studied in detail. A first study of the prompt radiation can be seen in Fig. 4.

The results, calculated with the FLUKA code, have been normalised to 10^7 400 GeV/c protons as a pessimistic scenario.The results of this preliminary study, show that the prompt dose is of the order of a few µSv/hr in the corridor outside the H2 beamline area. The radiation seems to be contained inside the simulated concrete shielding. This first estimate suggests that the radiation footprint of the beamline is not dramatically different from other similar places at CERN, such as the target station of H2-VLE [12, 13]. The exact shielding modifications necessary will be studied in the next months.

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 beamline at the CERN North Area. The beamline is proposed to be constructed and commissioned in the next years.

This work focused on presenting the final optics of the low energy beamline, along a brief discussion on the particle rates that are expected to reach the experiments. In addition to this, significant work has gone into the study of the implementation of this line in the EHN1 hall, as well as on the challenging optimisation necessary for switching between the proposed low-energy branch and standard operation.

These studies have lead to a proposal of a system of rails alongside the replacement of existing magnetic elements with new ones. The changes this system implies for the H2 beamline have been found to improve the quality of beams that can be delivered to the users of the beamline. Additionally, preliminary studies have shown that issues concerning RP are unlikely to arise. All 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 of the new line.

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