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INVESTIGATING THE FEASIBILITY OF DELIVERING HIGHER INTENSITY PROTON BEAMS TO ECN3 AT THE CERN SPS NORTH AREA

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Abstract

Initiated through the Physics Beyond Colliders (PBC) Study Group there is a strong interest from the scientific community to exploit the full intensity potential of the Super Proton Synchrotron (SPS) at CERN for Fixed Target physics experiments before the end of this decade. With the ECN3 cavern in the North Area (NA) identified as a suitable candidate location for a future high-intensity experimental facility compatible with a large variety of experiments, the new PBC ECN3 Beam Delivery Task Force was mandated to assess the feasibility of delivering a slow extracted beam of up to 4×10^{19} protons per year at 400 GeV. This contribution summarises the conclusions of the multifaceted beam physics and engineering studies that have been carried out recently to understand the present intensity limitations and to find technical solutions to meet the request for higher intensity in the NA transfer lines towards ECN3. The necessary modifications to the beamlines, the primary target area, beam instrumentation and intercepting devices, as well as the relevant infrastructure and services are outlined, along with a timeline compatible with the NA Consolidation (NA-CONS) project that is already underway.

PBC PHYSICS PROPOSALS

The PBC Study Group [1] has moved its focus to siting a future high-intensity experimental facility in ECN3 of the NA [2], which was originally designed in the 1970s, to satisfy the demands of a compelling set of PBC experimental physics proposals from Run 4 onward (>2028). A diverse physics programme that is complementary to the energy frontier is an essential part of the European Particle Physics Strategy (EPPS) [3]. CERN's SPS NA offers unique opportunities for high-impact particle physics programmes coherent with ESPP Update 2020 recommendations. Three experimental collaborations have developed scientific proposals and submitted Letters Of Intent (LOIs) to the PS and SPS Experiments Committee (SPSC) for experiments exploiting a future upgrade of ECN3 including HIKE [4], SHADOWS [5] and SHiP [6]. HIKE proposes a comprehensive kaon physics programme along with a beam dump mode to search for Feebly Interacting Particles (FIPs). SHADOWS proposes an off-axis search for FIPs running in parallel with HIKE in beam dump mode, whilst SHiP proposes a dedicated facility searching for FIPs that was originally developed for a new underground cavern [7].

The intensity requests range from $2-4\times10^{13}$ protons per spill (>1 s in duration) and up to 4.0×10^{19} Protons On Target (POT) per year for 5 years. SHiP estimates that they could run up to 1.0×10^{21} POT before reaching the background limit.

ECN3 BEAM DELIVERY

The ECN3 Beam Delivery Task Force assessed the technical feasibility of increasing the 400 GeV proton beam intensity by considering solutions compatible with the NA-CONS project for exploitation after Long Shutdown (LS) 3, i.e. starting in 2028. The complete findings of the Task Force can be found in [8]. The Task Force recommends a dedicated beam delivery scenario that neither requires the present beam splitting (sharing) nor impact of the existing targets to avoid increasing dose rates in the primary beam areas (TDC2 and TCC2) upstream of ECN3; see Fig. 1 for a schematic overview of the location and naming of the surface buildings, experiment halls, tunnels and transfer lines discussed. The dose rates in the primary beam areas from beam-induced radioactivation are already critical and cannot be further increased without significant upgrades of equipment from the 1970s, which employ old design techniques that are not ALARA compliant. The dedicated scenario meets the requirements of all PBC LOIs whilst continuing to share adequate protons to the rest of the CERN accelerator complex and other NA experiments and users [9]. It also reduces the scope of the work required during LS3 in TCC2 to prioritised consolidation items.

Activation From Slow-extraction

A factor of ∼ 4 reduction of the beam loss from slow-extraction is needed to facilitate the intensity upgrade without impact on the present day radiological situation in the SPS. The Run 4 implementation timeline is too short for the development of the advanced crystal technology needed to replace the electrostatic septa, which will remain the workhorse of the SPS slow-extraction system for many years to come. Instead, R&D is focused on beam loss reduction techniques that significantly improve the efficiency of the present electrostatic system [10, 11]. The required extraction beam loss reduction factor can be achieved with the crystal shadowing technique developed at CERN [12] along with the phase-space folding technique [13].

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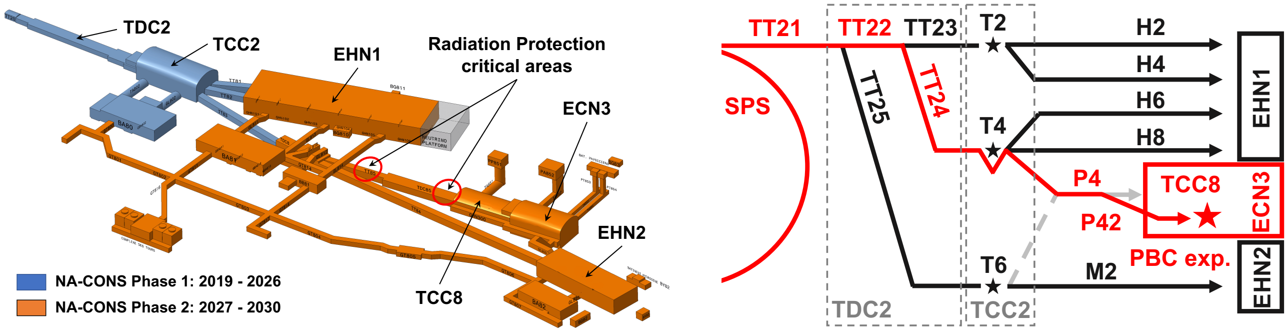

(a) NA-CONS project baseline scope and timeline

(b) NA transfer lines and dedicated beam delivery scenario

Figure 1: Relevant NA locations and naming of surface buildings, experiment halls, transfer tunnels and lines.

Bypassing the TCC2 Primary Targets

It is proposed to bypass the T4 target station with a closed, vertical magnetic bump pulsing on the dedicated ECN3 cycles to avoid a significant upgrade of the TCC2 target systems. The front-end of the T4 production target is composed of multiple 2 mm thick Be plates of different lengths (between 40 - 500 mm) arranged one on top of another with a separation of 40 mm, which provides the possibility to bump the beam vertically between the target plates and towards ECN3. The MTN dipole magnets in the T4 wobbling system (allowing to impinge on the T4 target at different angles and allow to select different secondary particle types and energies for the H6 and H8 beamlines) can be kept powered in DC mode and parallel operation of the H6/H8 beamlines in EHN1 maintained. A prototype bumper magnet has already been installed during the Year End Technical Stop (YETS) 2022/23 to demonstrate the concept.

ECN3 Beam Delivery Improvements

Primary Transfer Line Optics The optics in TT20 was rematched for the dedicated cycle to ECN3 by transmitting it unsplit through two sets of splitters (TT21 to TT22 and TT22 to TT24) and so that two existing bumper magnets can be used in combination with a newly installed magnet for the vertical T4 target bypass. Not all magnets and power converters in the P42 beamline will have Pulse-to-Pulse Modulation (PPM) functionality before LS4 and so these magnet strengths were left unchanged from the NA operational cycle. Measurements showed a discrepancy with the expected focal point location at the T4 target and during a campaign of optics measurements similar discrepancies with the MADX model were also observed. The present working hypothesis for the discrepancy is that the inaccuracy on quadrupole magnet transfer functions (current to optical strength) is the main contributor as indicated by numerical minimisation of the error between beam-based measurements and MADX model [14]. The magnets were designed and manufactured in the 1970s and the quality of the available documentation is lacking. A magnetic measurement campaign has been launched as part of the NA-CONS project to tackle this issue.

Radiation Protection (RP) Two critical areas above the tunnel of the P42 transfer line between TCC2 and TCC8 with insufficient shielding have been identified, see Fig. 1a. First mitigation measures have already been implemented and further improvements to the shielding have been proposed [15]. A measurement campaign supported with FLUKA simulations indicates that the observed radiation fields are caused by beam losses in the tunnel of just $\sim 10^{-4}$ [16–18]. A new Beam Loss Monitoring (BLM) system recently installed will allow the beamline to be tuned to minimise the prompt beam loss. In the worst-case of accidental beam loss, only moderate improvements to the shielding would ensure radiation levels to stay well below the limit [15]; civil engineering studies for such shielding improvements have already been launched. With these improvements implemented, the high-intensity beam transfer from TCC2 to TCC8 is expected to be compliant with CERN's RP code.

Beam Instrumentation In view of urgently understanding the primary beam transmission from SPS to ECN3, new instrumentation was installed during the recent YETS 2022/23. Additional beam profile monitors (BSGs, 4 in total) were installed in P42 to perform optics and dispersion measurements along with a new BLM system, comprising 13 monitors chosen at critical locations to measure and optimise the prompt beam loss, which is not presently possible. It is also proposed to upgrade the instrumentation around the TCC2 targets to include BSGs. An intensive effort was carried out by the Task Force to improve the absolute calibration of intensity monitors. Two successful calibrations with activation foils were carried out in front of the existing production target (T10) upstream of ECN3. Simultaneous irradiation measurements for all targets (T2/T4/T6 and T10) are planned to provide an accurate (~ %) transmission measurement from T4 to T10, i.e. from TCC2 to TCC8.

Aperture A radiation hotspot in the P42 transfer line at an aperture bottleneck in the junction where the P6 beamline merges with P42 was identified, the unused magnets on P6 removed and the P42 vacuum chamber enlarged during the YETS 2022/23 [19].

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Survey and Alignment The realignment and smoothing of the NA primary lines is important in the context of the high-intensity upgrade including the connection of the survey network from TT20 through the T4 target system to P4/P42. The survey of P42 is already underway and started in the recent YETS 2022/23 to smooth the worst misalignments measured.

Machine Protection

The machine protection architecture [20] foreseen as part of the NA-CONS project is compatible with a dedicated ECN3 beam delivery scenario. The Beam Interlock System is modular and can be easily adapted to the needs of future beam transfer and target systems, however the system will need to decode which cycle-type is being played. A detailed study on the required machine protection inputs is needed for the beam delivery of high-intensity beams to ECN3.

Magnets and Power Converters

The dedicated beam delivery scenarios will include either (i) a short, dedicated ECN3 cycle (1.2 s flat top over a 7.2 s cycle) compatible with SHiP or (ii) a long, dedicated ECN3 cycle (4.8 s flat top over a 14.4 s cycle) compatible with HIKE/SHADOWS. Both cycles are compatible with the powering solution foreseen in the NA-CONS project baseline [21].

Beam Intercepting Devices

The majority of the primary Beam Intercepting Devices (BIDs) are already being considered in the NA-CONS project in order to solve a series of operational issues encountered during recent years and to increase reliability. Beam-matter interaction and thermo-mechanical studies of the different devices were carried out to understand their robustness to an increase in the pulse and average beam intensity [22, 23]. The most critical BIDs in TDC2 and TCC2, including the splitter collimators (TCSCs) and target systems, do not need significant upgrade with the choice of the dedicated beam delivery scenario [24]. However, the TCSCs in TDC2 and the mobile dump collimators (Target Attenuator eXperimental, XTAX) located downstream of the primary targets in TCC2 would be damaged if impacted directly by a single pulse of the dedicated beam [25]. To avoid the upgrade of these devices it is therefore of vital importance to ensure their apertures are protected against shaving or full beam impact, requiring the safety and machine protection considerations to be studied in detail.

P42 Transfer Line Dump The fraction of the beam that does not interact with the T4 target on the operational NA cycles will still enter P42 towards ECN3, as it does today, because the MTN dipoles cannot be pulsed. It is proposed to dump this small amount of beam, if needed, on a new dedicated absorber installed in the upstream part of P42. Instead, this small fraction of beam could be transported to the production target in TCC8 and exploited for physics in ECN3, alongside the dedicated cycles. However, during Run 4 not all power converters downstream of TCC2 will be capable of pulsing in PPM mode. The operation of the two different cycles in P42 will be challenging but not impossible before LS4 and before the power converters have been fully consolidated to pulse in PPM mode. If the protons on the NA operational cycle either (i) cause transmission losses in P42 or (ii) pose problems for the experimental user in ECN3, they can be dumped on the P42 transfer line dump. An effort will be made to re-use an available, compatible spare device, potentially already activated as to reduce the amount of radioactive waste.

TCC8/ECN3 INFRASTRUCTURE

The impact on the NA-CONS project was analysed in detail and synergies identified to minimise the cost and demand on resources when including the required upgrade of the primary beamlines and TCC8/ECN3. A new target complex in TCC8 is a requirement to handle the multi-hundred kW average beam power impacting the production target [26]. The future experimental user requirements were collected to allow preliminary cost and resource estimates for future infrastructure and service needs [27] using the studies carried out in [7] to give preliminary cost estimates where more detailed information was not available. Access separation of TCC8 will be needed to allow for work on the target and experiment installation in ECN3 during Run 4 whilst beam operation continues to the rest of the NA. The civil engineering work required in TCC8/ECN3 is limited to minor excavations and reinforcements, a service building for target ancillaries and power converters, as well as an additional shaft for equipment installation (in the case of the SHiP experiment) [28]. The reuse of existing, consolidated and upgraded infrastructure will come at a significantly reduced cost compared to the construction of a new underground experimental complex.

TIMELINE & OUTLOOK

The beam delivery of high-intensity beams to a new experimental facility in ECN3 is technically feasible and can be implemented in synergy with NA-CONS for operation in Run 4. Importantly, the advancement of the consolidation of additional service buildings from NA-CONS Phase 2 into LS3 can be avoided. A timeline has been proposed that prioritises the relevant consolidation work in TDC2 and TCC2, but relaxes the demand for additional resources in LS3 by decoupling and staggering the work planned in TCC8/ECN3 to mostly after LS3, aiming at completion and experiment commissioning before the end of 2030. A timely decision is needed before the end of 2023 in order to remain compatible for physics operation in Run 4 and to guarantee the start of a detailed Technical Design Phase for the chosen experiment's target complex and experiment-specific upgrades needed in TCC8/ECN3.

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