

# nuSTORM at CERN: Executive Summary

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## Abstract

The Neutrinos from Stored Muons, nuSTORM, facility has been designed to deliver a definitive neutrino-nucleus scattering programme using beams of  $\bar{\nu}_e$  and  $\bar{\nu}_\mu$  from the decay of muons confined within a storage ring. The facility is unique, it will be capable of storing  $\mu^\pm$  beams with a central momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of 16%. This specification will allow neutrino-scattering measurements to be made over the kinematic range of interest to the DUNE and Hyper-K collaborations. At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known. The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better. By exploiting sophisticated neutrino-detector techniques such as those being developed for the near detectors of DUNE and Hyper-K, the nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of  $\bar{\nu}_e A$  and  $\bar{\nu}_\mu A$  scattering cross-sections with percent-level precision;
- Provide a probe that is 100% polarised and sensitive to isospin to allow incisive studies of nuclear dynamics and collective effects in nuclei;
- Deliver the capability to extend the search for light sterile neutrinos beyond the sensitivities that will be provided by the FNAL Short Baseline Neutrino (SBN) programme; and
- Create an essential test facility for the development of muon accelerators to serve as the basis of a multi-TeV lepton-antilepton collider.

To maximise its impact, nuSTORM should be implemented such that data-taking begins by  $\approx 2027/28$  when the DUNE and Hyper-K collaborations will each be accumulating data sets capable of determining oscillation probabilities with percent-level precision.

With its existing proton-beam infrastructure, CERN is uniquely well-placed to implement nuSTORM. The feasibility of implementing nuSTORM at CERN has been studied by a CERN Physics Beyond Colliders study group. The muon storage ring has been optimised for the neutrino-scattering programme to store muon beams with momenta in the range 1 GeV to 6 GeV. The implementation of nuSTORM exploits the existing fast-extraction from the SPS that delivers beam to the LHC and to HiRadMat. A summary of the proposed implementation of nuSTORM at CERN is presented below. An indicative cost estimate and a preliminary discussion of a possible time-line for the implementation of nuSTORM are presented the addendum.

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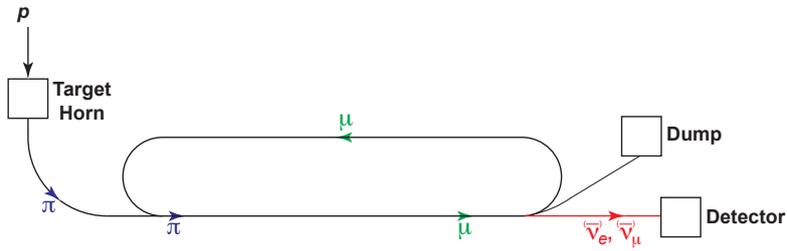
\* Author list presented in the addendum.

## 1 Introduction

In 1961 the first true neutrino beam was created at CERN using the Van der Meer horn to focus pions produced in the bombardment of a solid target by protons extracted from the PS. Such horn-focused beams have been used at CERN, ANL, BNL, FNAL, IHEP, KEK, and J-PARC first to establish the quark-parton model and the Standard Model and then to study neutrino oscillations and to search for new phenomena such as the existence of sterile neutrinos.

The Deep Underground Neutrino Experiment (DUNE) [1, 2, 3, 4, 5] in the US and the Tokai-to-Hyper-Kamiokande (Hyper-K) [6, 7, 8, 9] experiment in Japan will use horn-focused pion beams produced using proton-beam powers in excess of 1 MW to search for the violation of CP invariance. The high-flux beams illuminating the large DUNE and Hyper-K detectors will allow very large data sets to be accumulated. Projections of the rate at which data will be collected indicate that the statistical error will be reduced to the percent level by 2028–30. To optimise the discovery potential requires that the systematic uncertainties be reduced to the percent level on a comparable timescale. The systematic uncertainties are dominated by the lack of a micro-physical understanding of neutrino–nucleus interactions and, in particular, the  $\bar{\nu}_e A$  cross-sections.

The Neutrinos from Stored Muons, nuSTORM, facility is based on a low-energy muon decay ring (see figure 1). Pions, produced in the bombardment of a target, are captured in a magnetic channel. The magnetic channel is designed to deliver a pion beam with central momentum  $p_\pi$  and momentum spread  $\sim \pm 10\% p_\pi$  to the muon decay ring. The pion beam is injected into the production straight of the decay ring. Roughly half of the pions decay as the beam passes through the production straight. At the end of the straight, the return arc selects a muon beam of central momentum  $p_\mu < p_\pi$  and momentum spread  $\sim \pm 16\% p_\mu$  that then circulates. Undecayed pions and muons outside the momentum acceptance of the ring are directed to a beam dump. The intense flux of muons incident on the dump may serve as a test-bed for the development of the technologies required to deliver high-brightness muon beams [10, 11].



**Fig. 1:** Schematic of the nuSTORM neutrino-beam facility.

At low neutrino energy ( $\lesssim 2$  GeV),  $\bar{\nu}_{e,\nu} A$  scattering is dominated by the quasi-elastic (QE) and  $1-\pi(\Delta)$  processes. At higher energies,  $E_\nu \gtrsim 2$  GeV, poorly-known multi-pion resonance-production as well as shallow-and deep-inelastic scattering processes play an increasingly important role. The nuSTORM facility must be capable of delivering neutrino beams that cover this poorly known region with energies that span from the QE-dominated regime to the kinematic regime where deep-inelastic-scattering dominates ( $E_\nu \gtrsim 3$  GeV). To span this range requires that nuSTORM be capable of storing muon beams with a central momentum,  $p_\mu$ , in the range  $1 \lesssim p_\mu \lesssim 6$  GeV/c [12].

A detector placed on the axis of the production straight will receive a bright flash of muon neutrinos from pion decay followed by a series of pulses of muon and electron neutrinos from subsequent turns of the muon beam. Appropriate instrumentation in the decay ring and production straight will be capable of determining the integrated neutrino flux with a precision of  $\lesssim 1\%$ . The flavour composition of the neutrino beam from muon decay is known and the neutrino-energy spectrum can be calculated precisely using the Michel parameters and the optics of the muon decay ring. The pion and muon momenta ( $p_\pi$  and  $p_\mu$ ) can be optimised to:

- Measure  $\bar{\nu}_e A$  and  $\bar{\nu}_\mu A$  interactions with per-cent-level precision over the neutrino-energy range  $0.2 \lesssim E_\nu \lesssim 6$  GeV; and
- Search for sterile neutrinos with exquisite sensitivity.

nuSTORM will be the first neutrino-beam facility to be based on a stored muon beam and will provide a test-bed for the development of the technologies required for a multi-TeV muon collider and/or a neutrino factory. It will also serve the nuclear physics community by providing a unique probe of flavour-dependent collective effects in nuclei and a new tool to study the origin of nucleon spin. CERN is uniquely well-placed to implement nuSTORM; its proton infrastructure is well matched to the nuSTORM requirements and the scientific and technology-development outcomes of nuSTORM are an excellent match to CERN’s mission. It is conceivable that the implementation of nuSTORM at CERN will drive a step-change in capability comparable to that produced by Van der Meer’s focusing horn and create a new technique for the study of the nature of matter and the forces that bind it.

## 2 Motivation

### 2.1 Neutrino-nucleus scattering

#### 2.1.1 Impact on searches for leptonic CP-invariance violation

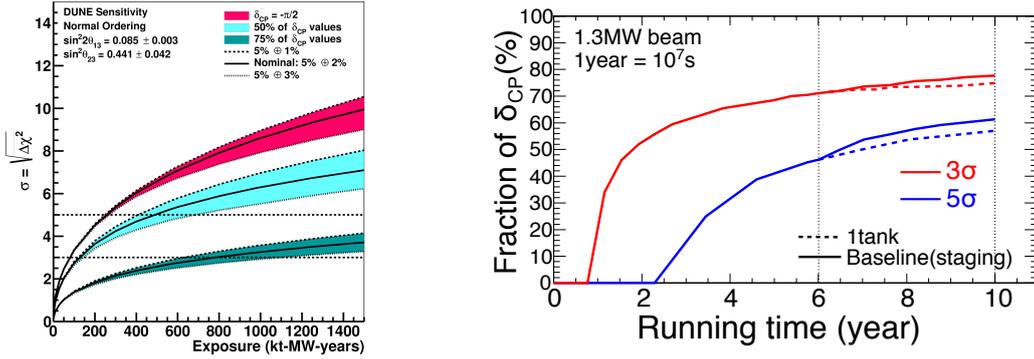
The search for CP-invariance violation (CPiV) in present and planned long-baseline neutrino-oscillation experiments relies on the measurement of the rate of  $\bar{\nu}_e$  appearance in  $\bar{\nu}_\mu$  beams. The phenomenological description of the effect relies on the assumption of three neutrino-mass eigenstates that mix to produce the three neutrino flavours [13, 14, 15, 16]. CPiV arises in this framework if the value of a phase parameter,  $\delta$ , is such that  $\sin \delta \neq 0$ .

The oscillation probability is a function of the source-detector distance (the baseline) and the neutrino energy. Neutrino interactions that occur as the neutrino beam passes through the earth introduce a “matter effect” that causes the oscillation probability of neutrinos to differ from that of anti-neutrinos. This introduces an “apparent” CPiV effect that depends on the neutrino mass hierarchy. The discovery of CPiV in neutrino oscillations requires that the “true” CPiV that depends on  $\delta$  be distinguished from the apparent CPiV that arises from neutrino interactions with the earth.

The projected sensitivity to CPiV of the DUNE experiment is plotted as a function of exposure in figure 2 [1, 3]. An exposure of  $\sim 288$  kt MW years will be achieved after seven years of running, with the planned staging to reach a total detector mass of 40 kt and a proton beam-power of 1.2 MW [17]. Equal exposures in neutrino and anti-neutrino mode have been assumed. The DUNE collaboration presents the sensitivity as a function of the assumed normalisation uncertainties on the  $\bar{\nu}_e$  appearance signals. Reducing the  $\bar{\nu}_e$  normalisation uncertainty from 3% to 1% brings the exposure required to exclude CP invariance at the  $3\sigma$  confidence level over 75% of all possible values of  $\delta$  down from  $\sim 1100$  kt MW years to  $\sim 600$  kt MW years.

The projected sensitivity of the Hyper-K experiment is also shown in figure 2 [7]. An exposure of  $13 \text{ MW} \times 10^7 \text{ s}$  will be achieved after ten years assuming a 1:3 ratio between neutrino and anti-neutrino running. The planned staged implementation of two 187 kt detectors is indicated, a proton beam-power of 1.3 MW at 30 GeV has been assumed. The systematic uncertainties assumed by the Hyper-K collaboration in their estimation of the CPiV sensitivity of their experiment are dominated by the combined “flux and near-detector” and the “cross-section model” uncertainties [7].

The present lack of precise knowledge of  $\bar{\nu}_{e,\mu} A$  cross-sections and relevant nuclear effects introduces systematic uncertainties in the extraction of oscillation parameters and can introduce systematic biases. Such biases may arise from mis-classification of events [19] or, more often, mis-reconstruction of the energy of the incident neutrino [20, 21, 22, 23, 24, 25]. A discussion of possible sources of bias is presented in [26]. Any effect that differs in  $\bar{\nu}_{e,\mu} A$  scattering from  $\nu_{e,\mu} A$  scattering, and is not quantitatively understood, is particularly pernicious since such a difference may be misinterpreted as a signal for CPiV.



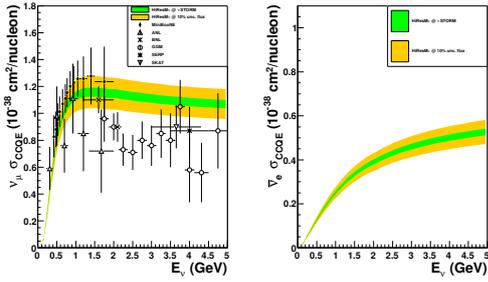
**Fig. 2:** Left panel: Expected sensitivity of the DUNE experiment to CP-invariance violation plotted as a function of exposure in kt-MW-years assuming equal running in neutrino and anti-neutrino mode, for a range of values for the  $\nu_e$  and  $\bar{\nu}_e$  signal-normalisation uncertainties (from 3% to 1%) added in quadrature to an uncertainty of 5% on the normalisation of the background. The sensitivities shown are for the exclusion of CP-invariance conservation over 75% of the available range of values of  $\delta$  assuming the normal hierarchy. The three bands show the significance when  $\delta_{CP} = -\pi/2$ , and the minimum significance for 50% and 75% of true  $\delta_{CP}$  values. The figure is taken from [1, 18]. Right panel: Expected sensitivity of the Hyper-K experiment to CPiV. The fraction of all values of the CPiV phase,  $\delta$  ( $= \delta_{CP}$ ), for which  $\delta = \delta_{CP} = 0, \pi$  can be excluded at  $3\sigma$  (red) or  $5\sigma$  (blue) is plotted as a function of running time. An exposure of  $13 \text{ MW} \times 10^7 \text{ s}$  is expected to be achieved after 10 years of operation. Figure updated from [7].

The next generation of long-baseline neutrino-oscillation experiments, DUNE and Hyper-K have the potential to observe CPiV violation. To maximise the scientific impact of the large, statistically significant data sets that they will collect requires that the  $\langle \bar{\nu}_e \rangle$  and  $\langle \bar{\nu}_\mu \rangle$  cross-sections be known with percent-level precision and that uncertainties associated with cross-section models are also under control at the percent level.

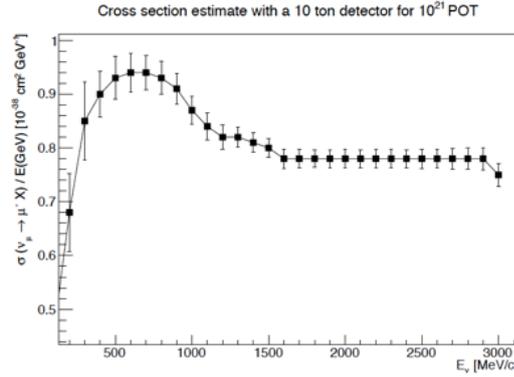
### 2.1.2 Potential for impact on understanding of the structure of the nucleus

Theoretical understanding of the structure of the nucleon is detailed and precise and can be used to predict cross-sections for a wide variety of processes over a wide kinematic range. However, the theoretical description of the structure of the nucleus is considerably less accurate and requires development to describe, for example, the distribution of bound-nucleon momentum within the nucleus and correlations among the nucleons that make up the nucleus [27]. Phenomenological models of lepton-nucleus scattering are based on the present understanding of nuclear physics and exploit a wealth of electro-production data to determine a number of phenomenological parameters. Such models have been shown to give a reasonable description of some of the present electron-nucleus scattering data but, with the need to incorporate axial-vector nucleus scattering, are inadequate to explain even the current measurements of neutrino-nucleus scattering. Consequently, large systematic uncertainties are required when today's models are used to extrapolate beyond the range of energies, nuclei, or types of process on which they have been approximately "tuned" [28]. A review of the challenges that must be overcome to deliver a good description of the hadronic final states in neutrino-nucleus interactions is presented in [29].

It is in this regard that neutrino-nucleus scattering measurements at nuSTORM can strongly benefit the community. Certainly neutrino-nucleus scattering has the potential to make both seminal and historic contributions to the development of more precise descriptions of nuclear structure since the neutrino offers a probe that is polarised and is sensitive to quark flavour and isospin. However, much more accurate, precise neutrino-scattering data are required to constrain the models of neutrino-nucleus interactions. Presently, the best efforts to control the neutrino-flux uncertainty in neutrino-scattering measurements are able to reduce the uncertainties to the 5–6% level. A nuSTORM facility that is able to deliver a



**Fig. 3:** The CCQE cross-section plotted as a function of incident neutrino energy ( $E_\nu$ ). The total uncertainty from nuSTORM is shown by the width of the coloured bands: the green (yellow) band shows 1% (10%) neutrino-flux uncertainty combined with the detector uncertainty [10, 11]. A compilation of measurements for  $\nu_\mu$  beams is also shown; there is limited or no data available for  $\bar{\nu}_e$  beams.



**Fig. 4:**  $\nu_\mu$  CCQE cross-sections obtained using a 10 tonne totally active scintillator detector for  $10^{21}$  POT at a distance of 50 m from the end of the nuSTORM storage ring [33].

precisely calibrated flux of both  $\bar{\nu}_e^{(-)}$  and  $\bar{\nu}_\mu^{(-)}$  with uncertainties  $\sim 1\%$  is required if neutrino-nucleus-scattering measurements are to contribute to the understanding of nuclear structure.

## 2.2 Sterile neutrino search

A detailed sterile neutrino analysis was presented in [30]. The analysis considered the sensitivity of a  $\nu_\mu$  appearance experiment at nuSTORM to the presence of sterile neutrinos in a model in which a fourth, sterile, neutrino is allowed to mix with the three Standard Model neutrinos. By evaluating the sensitivity in the parameter space of the mass-squared splitting and the sine of the mixing angle, the sensitivity of nuSTORM was shown to be such that the region of parameter space presently allowed at the 99% confidence could be excluded with a significance of  $10\sigma$ .

## 3 Experimental programme

The experimental programme of nuSTORM was described in detail in the Letter of Intent and Proposal to FNAL [10, 11] and in the Expression of Interest to CERN [31].

The precise knowledge of the neutrino flux at nuSTORM must be matched by a high-precision detector capable of delivering neutrino measurements with 1–2% precision. A number of near detector concepts have been studied in the context of Neutrino Factory and DUNE studies. For example, the HiResM $\nu$  detector [32], gaseous argon or liquid argon detectors inside a magnetic field would meet the requirements.

Figure 3 shows the expected charged-current quasi-elastic (CCQE) cross-section performance, plotted as a function of neutrino energy  $E_\nu$ , in a detector, such as HiResM $\nu$ , exposed to the nuSTORM beam. The figure shows the precision with which the cross-section would be measured if the systematic uncertainties estimated for the HiResM $\nu$  detector are combined with the 1% flux uncertainty from nuSTORM (green); the detector systematics dominate over the 1% flux uncertainty. A compilation of measurements of the CCQE cross-sections for muon-neutrino beams (there is limited or no data available for electron-neutrino and electron-anti-neutrino beams) is also shown. nuSTORM has the potential to improve the systematic uncertainty on muon-neutrino (muon-anti-neutrino) CCQE cross-section measurements by a factor of  $\sim 5$ – $6$  and would provide unique contributions for electron-neutrino and electron-anti-neutrino CCQE measurements.

Recently, an analysis was performed to extract  $\nu_\mu$  charged-current quasi-elastic scattering events simulated with the GENIE neutrino interaction generator [34] in a totally-active scintillator detector, with muon reconstruction in a magnetised-iron detector [33]. Events were generated for incident neutrino energies uniformly distributed between 0.5 GeV and 3 GeV, reweighted to the nuSTORM flux and scaled to the number of interactions expected for an exposure of  $10^{21}$  POT on a 10 ton fiducial mass at a distance of 50 m from the end of the production straight. The study included a multi-variate-analysis event selection and particle identification to separate muons from pions. An expected quasi-elastic  $\nu_\mu$  CC cross-section measurement, based on the  $\mu^+$  decay rates, is shown in figure 4. The uncertainties include statistical, detector systematic (2–3%) uncertainties and the 1% nuSTORM flux uncertainty, which makes a relatively small contribution to the overall uncertainty, leaving the detector systematic as the dominant source of uncertainty.

## 4 Overview of accelerator facility and possible implementation at CERN

A detailed design for nuSTORM and its implementation at FNAL is presented in [11, 35]. This design was optimised to maximise sensitivity for the light-sterile-neutrino search outlined above. The PBC nuSTORM study group re-optimised the FNAL design for the neutrino-scattering programme and for its implementation at CERN.

After considering the various options at the SPS for possible fast extraction to a nuSTORM facility it was decided to concentrate on the existing fast extraction channel in LSS6 of the SPS. This channel serves both HiRadMat and the LHC via the TT60/TI2 transfer line (see figure 5).

### 4.1 SPS beam delivery

The SPS accelerator has demonstrated its ability to produce beams in the sub-MW range for neutrino experiments. For CNGS the fast extracted 400 GeV/c proton beam from the SPS operated with a 6 s cycle with two batches of  $10.5 \mu\text{s}$  per cycle with up to  $2.25 \times 10^{13}$  protons each, corresponding to a maximum beam power of 510 kW. The beam required by nuSTORM is similar, albeit at the lower momentum of 100 GeV/c. The beam power of 156 kW considered for nuSTORM corresponds to a total intensity of  $4 \times 10^{13}$  per cycle, clearly demonstrated during the CNGS era to be within the reach of the PS and SPS. The ‘standard’ Fixed Target beam from the SPS, with a bunch spacing of 5 ns, will be used for nuSTORM. Beam will be extracted from the SPS in two separate batches, each of length  $10.5 \mu\text{s}$ , separated by 50 ms. The key SPS beam requirements are shown in table 1.

An operational model that can incorporate the nuSTORM cycle requirements into regular SPS operations has been developed. nuSTORM operation is compatible with standard North Area SPS operations which, at present, includes provision of beam to the LHC, HiRadMat, AWAKE, and a vigorous machine development programme.

### 4.2 Fast extraction from the SPS

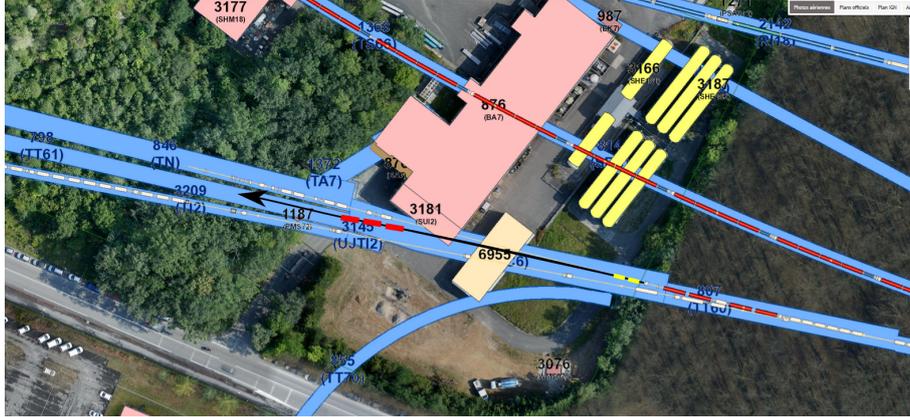
Extraction of the CNGS-like fixed target beam at 100 GeV is limited in the horizontal plane by the septum protection TPSG to around  $5\sigma$  and in the vertical plane by the extraction septum MSE to about  $4\sigma$ . These apertures are considered reasonable. The pulse structure, two  $10.5 \mu\text{s}$ -long pulses, however, poses an issue for the extraction-kicker system. The present system in LSS6 cannot reach the required rise time of around  $1 \mu\text{s}$ . Without an upgrade of the system, only one pulse per cycle can be extracted which will significantly reduce the number of protons on target (POT). An upgrade of the kicker system is technically feasible at moderate cost.

### 4.3 Beam transport to target

Around 230 m downstream of the SPS extraction point, the TT60 line is split into the lines TI2 (LHC beam to P2) and HiRadMat (material test facility in the TN tunnel), see figure 5. It is proposed to provide

**Table 1:** Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	$4 \times 10^{13}$
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	$4 \times 10^{19}$
Total PoT in 5 year's data taking	$2 \times 10^{20}$
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance ( $1 \sigma$ )	8 mm.mrad
Max. normalised vertical emittance ( $1 \sigma$ )	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	$10.5 \mu\text{s}$
Number of bunches per extraction	2100
Bunch length ( $4 \sigma$ )	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	$2 \times 10^{-4}$

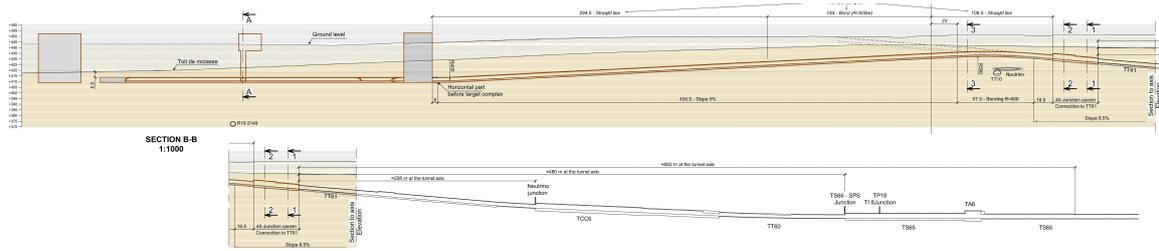


**Fig. 5:** Beam lines from the SPS LSS6 extraction point, the nuSTORM line (black arrow) is shown branching off the HiRadMat line and bending horizontally and vertically into TT61.

beam to nuSTORM by constructing a new branch off the HiRadMat beam-line downstream of a main bend (MBB.660213) using C-shaped switching dipoles of the MBS type. Branching off the HiRadMat line makes use of large aperture QTL-type quadrupoles (80 mm diameter). After the switching section, the beam needs to be bent vertically to match the slope of the TT61 transfer tunnel using two MBB type dipoles; an additional MBB dipole is used to compensate for the switching angle in the horizontal plane.

After switching from the HiRadMat line, a 290 m section of beam-line is housed in existing tunnels. At the end of this section, a junction cavern must be constructed to allow the branch into the new tunnel. A beam line of length  $\sim 585$  m is required in the new cavern and new tunnel (see figure 6). Along this line there are two horizontal bending sections that require 5 and 10 MBB-type dipole magnets respectively and two vertical bending sections which require 6 and 3 MBB-type dipoles respectively. Since all bending sections bend in one plane only, a careful choice of magnet locations in the optics might allow for an achromatic design.

A FODO lattice with 30 m half-cell length is assumed. Large aperture QTL-type quadrupoles, which



**Fig. 6:** Elevation drawing of the nuStorm beam line from SPS extraction on the right of the top figure to the target complex to the far left.

are usually used for SPS fixed target beam lines, have been considered. For a total length of 875 m beam line, 30 quadrupoles are required. Three additional quadrupoles are needed for the final focus, the same magnet type has sufficient aperture. Each quadrupole shall be equipped with a corrector magnet and, between the final focus and the target, a set of two correctors per plane is considered for orthogonal steering.

Beam instrumentation will consist of dual-plane beam-position monitors at each quadrupole, 4 screens in the switching and final-focus areas, 2 beam-current transformers, and 10 loss monitors along the line.

Two power supplies will be required for the FODO quadrupoles. An additional 8 supplies will be required for the initial matching and final-focus sections. The main dipoles will require several different power supplies, optimisation with strong correction magnets or trim supplies could be envisaged.

#### 4.4 Pion-production target and pion capture

The basic structure of the pion-production and capture scheme developed at FNAL has been adopted. Protons extracted from the SPS at 100 GeV are focused on a solid (low- $Z$ ) target placed inside a focusing horn. A pair of quadrupoles collect the particles focused by the horn. The beam is then passed through a short transfer line composed of dipoles, collimators and quadrupoles to reduce the radiation load on the downstream transfer line. It is proposed that the target and initial focusing section is contained in an inert helium atmosphere to reduce activation and corrosion of beam-line equipment by limiting the presence of ozone and nitrogen oxides. The target-and-collection system will be installed underground in a cavern with a shaft giving access to a surface building. The shaft and surface building will be offset with respect to the incoming proton beam direction, the target, and the out-going pion beam.

The FNAL proposal used a water-cooled graphite target, based on that successfully used on the NuMI beam. In a CERN implementation, the vast experience accumulated with the operation of the CNGS neutrino beam line would be exploited. In this case, a radiation-cooled graphite target heats the vessel in which it is embedded. The vessel is cooled using a forced flow of inert gas. Alternative schemes studied for the CENF Project in 2014 would use a graphite target cooled by the forced convection of helium or other inert gas; such a solution is similar to that used in the T2K neutrino beam-line. The key issues to be addressed in a future detailed design of the target and capture system are radiation safety and the containment for transport of a beam with a momentum spread of  $\sim 10\%$ . These requirements have led to the consideration of the scheme successfully used in the PS complex to produce anti-protons for physics in the Anti-proton Decelerator (AD). In the AD, pulses of the 26 GeV/c PS proton beam are delivered at an intensity of  $1.5 \times 10^{13}$  protons-per-pulse (ppp) in 4 bunches over a period of 450 ns. The beam is focused to a spot of size  $0.5 \times 1 \text{ mm}^2$  at the iridium target. Focusing is provided by a water-cooled magnetic horn, pulsed at 400 kA. The beam is captured using a quadrupole beam line that includes a pair of dipoles to provide a ‘dog leg’ that reduces the proton contamination in the beam downstream of the target. The uncollided proton beam that has not interacted in the target is transported to a dump. The nuSTORM Target Complex (TC) design could be based on the extensive work done for the CENF Project. In this design, the target, horn and various target-related systems would be moved vertically in the target hall on specially designed supporting structures, which would also provide the

fine alignment for the beam equipment. Shielding blocks would fit in the vertical space in an optimised manner to minimise radiation streaming to the surface. Annexed underground areas would house all related services required for the operation of the infrastructure, including cooling and ventilation units and powering systems for the horns.

As in the FNAL design, pion-capture is provided by a magnetic horn. CERN has built horns for the CNGS beam line and had developed a genetic algorithm to optimise the horn design for the LAGUNA-LBNO proposal; this design is still employed in the LBNF Project. In addition, horns for the anti-proton machine have operated for many years and are still operated today. Recently, a newly optimised horn was redesigned and rebuilt to serve experiments on the AD. A horn test bench has been built. Experience gained from the construction, test and operation of the AD horn has been used to inform the estimation of the cost of the pion-capture system.

#### **4.4.1 Injection line and proton absorber**

The design of the injection line from the target enclosure to the storage ring employs a C-shaped bending magnet. To reduce the radiation load on the downstream beam lines, a double spectrometer in the target hall should be considered. The design of the proton absorber could be based on the current SPS internal dump that was installed in 2017. Alternatively, the new LIU-SPS dump could be adapted to cope with the power requirements imposed by nuSTORM. The concept of stochastic injection of pions into the storage ring will be adapted for use in the revised storage ring design.

### **4.5 Storage ring design**

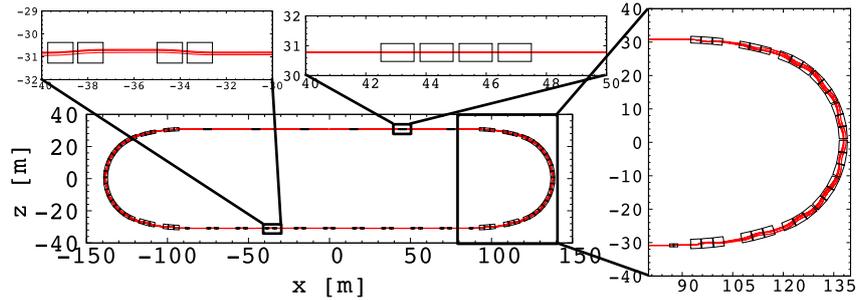
The baseline design for the storage ring presented in [11] exploited large-aperture quadrupole magnets to produce a FODO lattice optimised to store 3.8 GeV/c muons with a momentum acceptance of  $\pm 10\%$ . The acceptance of this design was limited by the natural chromaticity of the FODO ring. To serve the neutrino-scattering programme, the ring was redesigned to store muon beams with a central momentum of between 1 GeV/c and 6 GeV/c and momentum acceptance of up to  $\pm 16\%$ , thereby increasing the neutrino flux. To keep both the momentum and transverse dynamic acceptance large simultaneously, a hybrid concept was developed, see figure 7. Conventional FODO optics, used in the production straight, are combined with ‘fixed-field accelerator’ (FFA) cells, for which the chromaticity is zero, in the arcs and in the return straight. This allows the revised lattice to achieve:

- Zero dispersion in the quadrupole injection/production straight; and
- Zero chromaticity in the arcs and in the return straight, thereby limiting the overall chromaticity of the ring.

The arcs exploit superconducting combined-function magnets with magnetic fields of up to  $\sim 2.6$  T. The return straight is based on combined-function room-temperature magnets. The production straight uses large-aperture room temperature quadrupoles. The mean betatron functions in both the production and return straights are kept large enough to minimise the contribution of betatron oscillations to the angular spread of the neutrino beam, such that both can be used to serve a neutrino-physics programme.

### **4.6 Infrastructure**

The nuSTORM TC houses the target and beam-line components, and accommodates the services required to ensure the safe operation. The TC will be an isolated concrete enclosure that provides a shielded environment for the target components. The shielding requirements were established in the FNAL design and would need to be reviewed carefully for implementation at CERN. Based on the FNAL proposal a size of  $50 \times 16$  m<sup>2</sup> in plan is assumed. The TC is followed by a tunnel to house the beam-line that transports the secondary beam from to the Muon Decay Ring (MDR) and a small cavern to house the steel and concrete Primary Beam Absorber.



**Fig. 7:** Schematic drawing of the revision of the muon storage ring. The beam circulates in an anti-clockwise direction. The production straight (at  $z \sim 30$  m) is composed of large aperture quadrupoles that produce the large values of the betatron function required to minimise the divergence of the neutrino beam produced in muon decay. The lattices of the arcs and return straight are based on the fixed-field accelerator (FFA) concept and allow a large dynamic aperture to be maintained.



**Fig. 8:** General arrangement of infrastructure required for nuSTORM shown in brown (right) and the future far detector site (left).

The MDR will be below ground in a tunnel that will house the beam-line components. A small cavern to house the pion absorber will also be incorporated. A surface building for services and cryogenics is also required.

#### 4.7 Civil engineering

A study of the civil engineering (CE) required for the implementation of nuSTORM has been carried out by CERN's SMB-SE Future Accelerator Studies section to identify design constraints and considerations in order to produce an outline CE design. The proposed location for nuSTORM is just north of CERN's Meyrin site, entirely within France. The major CE elements required to implement nuSTORM are:

- A 40 m long junction cavern to allow connection to the existing tunnel TT61;
- A 545 m long extraction tunnel;
- A target complex;
- A 625 m circumference muon decay ring;
- A near detector facility; and
- Support buildings and infrastructure.

The proposed design allows for the implementation of a far detector on CERN land at Point 2 of the Large Hadron Collider in Saint-Genis-Pouilly. The general arrangement is shown in figure 8.

The ground conditions of the Geneva Basin are well understood and a large amount of information is available from previous ground investigations. The CE works will involve a significant length of tunnelling within the molasse Rock that consists of alternating strata of marls and sandstone. This rock is generally considered good for tunnelling. Underground structures would be mined in the molasse with

overground structures founded within the Moraines above. The preliminary design has optimised the location and orientation of the tunnel to enable the tunnelling to remain in the molasse while avoiding clashes with existing infrastructure. Although the muon decay ring crosses the line of the LHC, there is nearly 35 m vertical clearance. Therefore, no effect on the LHC during works or operation is expected.

The development of the geometry has been governed primarily by beam delivery and experimental requirements. However, radiation protection and safety factors have also been taken into account. The CE works required are relatively straight forward and should not present any feasibility issues. The works could all be carried out using methods which are common in the tunnelling and construction industries.

#### **4.8 Radiation protection**

nuSTORM requires a primary proton beam power of the order of 200 kW. Therefore radiation protection considerations place strong constraints on the design of the facility. The radiation-protection guidelines for the design of such a high-power facility will be clearly specified in the full nuSTORM report.

The radiological and environmental assessments carried out for the design of the CENF target facility [36] were used for a preliminary radiological evaluation of nuSTORM. The radiological assessment of the CENF target facility includes detailed studies of the expected prompt- and residual-dose rates on the various accessible areas of CENF as well as the levels of the stray radiation in the surrounding experimental and public areas. Furthermore, the study included the evaluation of the risk due to activated air and helium and the consequence of its release into the environment. Also studies on soil activation and radioactive waste zoning were conducted. All studies were based on simulations using the FLUKA Monte Carlo particle transport code [37, 38]. Due consideration has been given to: prompt and residual radiation; air and helium activation; soil activation; and environmental considerations. The findings are presented in [36].

The preliminary RP evaluation of the proposed nuSTORM facility showed the general feasibility of the project in terms of exposure of persons to radiation and the radiological impact on the environment. At a later stage, detailed studies to optimise the facility according to the ALARA principle should be performed. However, at the present state of technological development, engineering solutions by which the radiological impact can be minimised are available.

### **5 Readiness and expected challenges**

The nuSTORM essentials of production, transport, and ring are conceptually well developed. The recent studies summarised here represent a preliminary look at the possibilities of siting nuSTORM at CERN. It appears that the SPS can provide the beam and offers a credible fast extraction location allowing the beam to be directed towards a green field site at a suitable distance from existing infrastructure. Initial civil engineering sketches have established a potential footprint and the geology is amenable to an installation at an appropriate depth. Although no dedicated study has yet been performed, given the proposed depth, radiation protection issues should be manageable. There is considerable target expertise at CERN and initial thoughts on target, horn and absorbers deem these to be reasonable challenges.

Up to the target and pion capture, the deliverables fall within established CERN expertise. The current muon decay ring is based on the FFA concept which, though feasible, will require the development of magnet designs that allow production at a reasonable cost. Other challenges include: detailed evaluation of proton-beam extraction and associated hardware upgrades; detailed civil engineering studies; target and target complex design studies; and detailed consideration of radiological implications.

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