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Non-local Fast Extraction from the CERN SPS at 100 and 440 GeV

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The Long Straight Section 2 (LSS2) of the CERN SPS is connected with the North Area (NA), to which the beam to date has always been extracted using a resonant extraction technique. For new proposed short- and long-baseline neutrino experiments, a fast single turn extraction to this experimental area is required. As there are no kickers in LSS2, and the integration of any new kickers with the existing electrostatic septum would be problematic, a solution has been developed to fast extract the beam using non-local extraction with other SPS kickers. Two different kicker systems have been used, the injection kicker in LSS1 and the stronger extraction kicker in LSS6 to extract 100 and 440 GeV beam, respectively. For both solutions a large emittance beam was extracted after 5 or 9 full betatron periods. The concept and simulation details are presented with the analysis of the aperture and beam loss considerations and experimental results collected during a series of beam tests.

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Abstract

The Long Straight Section 2 (LSS2) of the CERN SPS is connected with the North Area (NA), to which the beam to date has always been extracted using a resonant extraction technique. For new proposed short- and long-baseline neutrino experiments, a fast single turn extraction to this experimental area is required. As there are no kickers in LSS2, and the integration of any new kickers with the existing electrostatic septum would be problematic, a solution has been developed to fast extract the beam using non-local extraction with other SPS kickers. Two different kicker systems have been used, the injection kicker in LSS1 and the stronger extraction kicker in LSS6 to extract 100 and 440 GeV beam, respectively. For both solutions a large emittance beam was extracted after 5 or 9 full betatron periods. The concept and simulation details are presented with the analysis of the aperture and beam loss considerations and experimental results collected during a series of beam tests.

INTRODUCTION

The Super Proton Synchrotron (SPS) hosts three extraction channels in straight sections: LSS2, LSS4 and LSS6. To date, the first has been always used to slow extract the beam: in fact no kicker systems are installed in this straight section.

Two new neutrino experiments, the CERN Neutrino Facility (CENF) and the LAGUNA/LBNO [1], have been proposed for future SPS operation. Both will require a high-intensity and high-energy beam, of 100 and 400 GeV respectively, to be extracted in one machine revolution from LSS2. Installation of new kickers is not suggested for several reasons, mainly because of the difficult integration with the electrostatic septum and to avoid increasing the overall machine impedance. This led to the new concept of *non-local fast extraction*. The idea is essentially to use one of the already installed kickers in another SPS straight section to perform a single-turn extraction from LSS2.

In order to maximise the opening at the beginning of the extraction channel (TPST, i.e. the protection device of the MST in LSS2), the injection kicker (MKP [2]) and an extraction kicker (MKE in LSS6 [3]) have been chosen for the 100 and 400 GeV case, respectively. From Tab. 1 it is clear that the best choice is the MKP, also because the SPS kickers can only work at the design polarity. For a 400 GeV beam, the MKP is too weak for the required deflection angle. From Tab. 1 none of the MKEs (the only kickers that have enough strength at 400 GeV) have a good relative phase advance with respect to the TPST, hence a new horizontal machine tune, $Q_x = 26.87$, has been used for the tests.

Table 1: Phase advance between kickers and TPST obtained with MAD-X.

Kicker	$\Delta\mu$	$\Delta\psi$ [deg]	Q_x
MKQH.11653	4.63	226.51	26.62
MKQH.11653	4.54	195.52	26.13
MKP.11955	4.19	68.22	26.62
MKP.11955	4.11	40.45	26.13
MKE.41637	17.95	340.18	26.62
MKE.41637	17.61	220.95	26.13
MKE.61634	9.07	24.29	26.62
MKE.61634	8.90	323.94	26.13

100 GeV NON-LOCAL FAST EXTRACTION

The energy of 100 GeV, chosen for CENF, is a compromise between neutrino production efficiency, muon shielding length, aperture in the extraction channel and beamline, and the operational limit of the SPS beam dump [4]. During initial conceptual investigations, an energy of 110 GeV was selected for the proof-of-principle tests in the SPS, where most simulations and measurements were carried out. Tests at 100 GeV were also made to compare apertures in the extraction channel.

Simulations

MAD-X has been used to carry out all the following simulations.

From the values in Tab. 1, the MKP has been chosen, considering the CNGS ($Q_x = 26.62$) orbit. All simulation parameters are summarised in Tab. 2. Five horizontal bumper magnets have been used to match the extraction bump. They are located at the quadrupoles 212, 214, 217, 219 and 221 and guarantee 27 mm bump at the entrance of the TPST.

Table 2: Simulation parameters.

Parameters	**Units**	**Values**
Q_x		26.62
Q_y		26.58
ε_{Nx}	π.mm.mrad	8.0
$\Delta p/p$	10^{-3}	0.4
MKP voltage	kV	52
MKP def. angle at 100 GeV	mrad	0.674
MKP generators		3

In order to gain aperture for the circulating beam, new

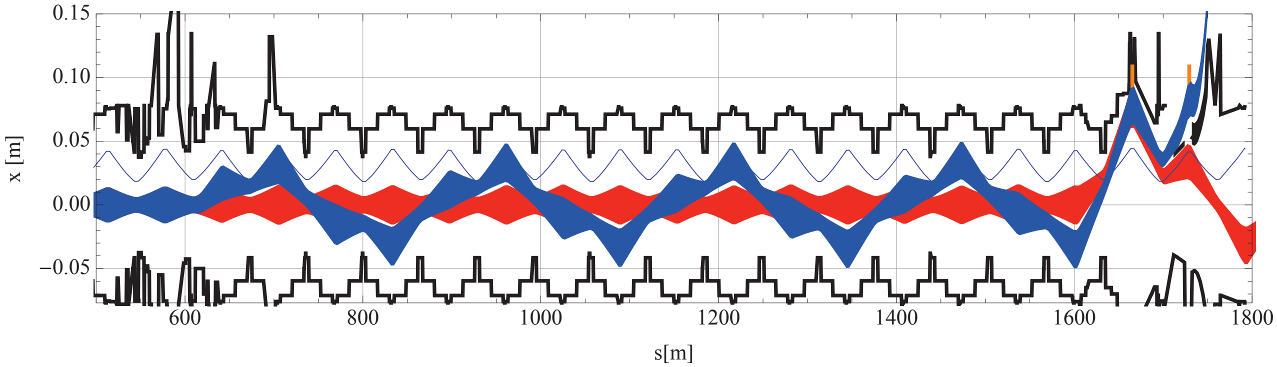

Figure 1: Extracted (blue) and circulating (red) beam envelopes. The $\pm 5\,\sigma_x$ beam envelope is plotted at 100 GeV.

transverse septa positions have been chosen for both MST and MSE. The electrostatic septum (ZS) has been completely retracted, as otherwise the wires intercept the extracted beam.

Using the MKP with the parameters expressed in Tab. 2, the extracted and bumped trajectories are shown in Fig. 1.

An aperture analysis has been performed. The expected r.m.s. value of the measured orbit was about 3 mm, hence a random misalignment has been added to all quadrupoles in the ring, obtained from a Gaussian distribution with standard deviation of 200 μm truncated at $6\,\sigma$. This led to a mean orbit r.m.s. of 2.8 mm. Then, 720 different orbit files with 720 different random number seeds have been recorded applying each time also a correction bump to flatten the orbit just before the TPST upstream aperture. In order to quantify the expected acceptance value, an offline analysis was performed with Matlab. The results obtained, simulating both 110 and 100 GeV extraction energy, are given in Tab. 3, for circulating and extracted beam. The circulating beam at 100 GeV gave a slightly smaller mean acceptance, although the extracted beam has about 1 σ bigger acceptance.

Table 3: Minimum acceptances, averaged over the 720 orbits, with respect to the whole SPS at 100 and 110 GeV.

	100 *GeV* [σ_x]	**110 *GeV* [σ_x]**
Circulating	5.17 ± 0.17	5.42 ± 0.17
Extracted	4.55 ± 0.25	3.52 ± 0.22

Measurements

To check the reliability of the values in Tab. 1, and to check the dependence of the phase advance on intensity and orbit oscillations, a dedicated MD has been carried out. The phase advance was found to be not significantly dependent on beam intensity and horizontal oscillations, with 17.9° ±9.3° measured value.

The whole concept has been tested during another MD. The measured bump was well closed (residual r.m.s. 0.3 mm) and the simulated amplitude optimum value has been confirmed. Simulated septa positions and strengths have been optimised with measurements.

The low intensity (4.5×10^{11} p$^+$) beam has been extracted at the first attempt. Losses at extraction were very small. An emittance of $\varepsilon_{Nx} = 7.1\,\pi$.mm.mrad, i.e. 6% smaller than nominal has been used for these preliminary tests. Also, smaller extraction losses at 100 GeV than at 110 GeV were recorded, as forecasted by simulations.

440 GeV NON-LOCAL FAST EXTRACTION

The LAGUNA experiment requires a 400 GeV beam extracted in a single-turn from LSS2. For operational reasons, simulations and measurements have been carried out at 440 GeV in this first stage.

Simulations

The parameters used for the simulation of this concept are listed in Tab. 4. The horizontal machine tune has been modified to gain opening at the entrance of the TPST. The extraction bump has been re-matched with respect to the new energy and horizontal tune.

Table 4: Simulation parameters.

Parameters	**Units**	**Values**
Q_x		26.87
Q_y		26.58
ε_{Nx}	π.mm.mrad	8.0
$\Delta p/p$	10^{-3}	0.4
MKE voltage	kV	32.28
MKE def. angle at 440 GeV	mrad	0.428

In the almost 2.5 km between MKE and TPST, 9 large betatron oscillations are excited which have to cross LSS1, a machine aperture bottleneck. Hence, a counter-phase bump has been matched to reduce the oscillation amplitude (Fig. 2). It has been realised using 28 horizontal correctors between LSS6 and LSS2. The biggest gain occurs, in terms

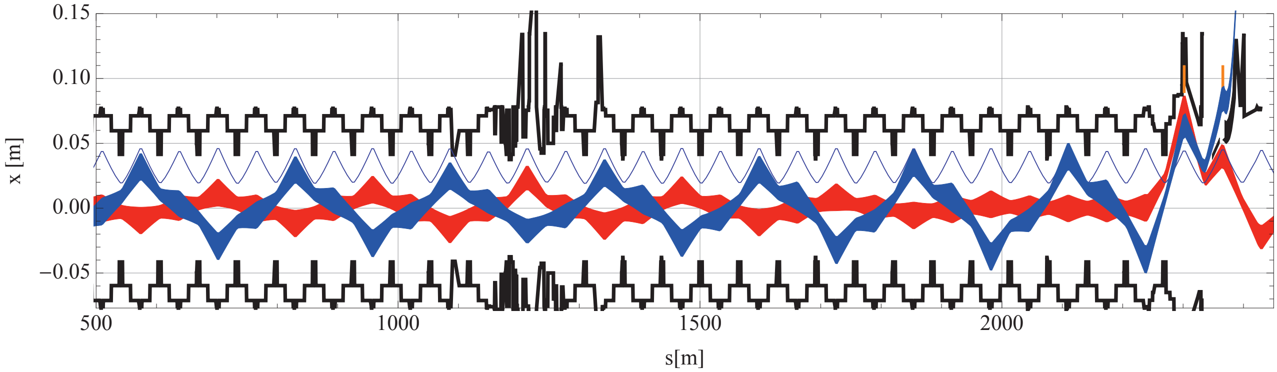

Figure 2: Extracted (blue) and circulating (red) beam envelopes. The $\pm 5\,\sigma_x$ beam envelope is plotted at 440 GeV.

of aperture, at the TIDP (dump block for off-momentum particles).

The aperture analysis has been performed with parameters different from the previous case due to the different horizontal tune. To simulate the measured average orbit r.m.s. of about 3 mm, a random misalignment of all machine quadrupoles of 100 μm r.m.s., truncated at $6\,\sigma$, is needed. The observations of 720 different orbits, obtained with 720 different seeds, have been recorded and analysed. The averages over the 720 seeds of the acceptance minimum with respect to the SPS elements are summarised in Tab. 5. The minimum acceptances spread was wide due to the small beam size at this energy and also to the big betatron oscillation at the TIDP. Although the counter-phase bump is placed to reduce the oscillation amplitude at the TIDP, for a few seeds the horizontal orbit at that longitudinal position was too big to be efficiently reduced due to the limit of the corrector strengths.

Table 5: Minimum acceptances, averaged over the 720 orbits, with respect to the whole SPS at 440 GeV.

	Acceptance average $[\sigma_x]$
Circulating beam	8.85 ± 1.35
Extracted beam	10.36 ± 5.0

Table 6: Measurements configuration.

Parameters	**Units**	**Values**
Q_x		26.87
Q_y		26.58
ε_{Nx}	π.mm.mrad	6.5
Intensity	p^+	2×10^{11}
MKE voltage	kV	32.28

Measurements

The MD carried out to prove the feasibility of this concept has been done using the parameters given in Tab. 6.

The extraction bump was not completely closed. A residual r.m.s. of about 2.5 mm has been measured. The bump optimum has been found between 25 and 30 mm, in agreement with the simulations. The counter-phase bump could not be tested due to lack of time.

When the MKE was switched on, the beam was extracted at the first attempt, using the parameters obtained from the simulations. As expected from simulations, no extraction losses were recorded with this energy.

CONCLUSIONS

Simulations and measurements have shown that the non-local fast extraction from the SPS is feasible for both 100 and 440 GeV beams, up to emittances which approach those of the high-intensity beams, although it has been tested just for low intensity.

The electrostatic septum needs to be completely retracted, making alternating slow and fast extraction, in the same supercycle, from LSS2 impossible.

Further studies are still required, for instance to investigate the beam quality at extraction and the stability of the extracted beam. Optimisation of the working point for the 400 GeV case is also needed together with the improvement of the machine protection systems for this new kind of extraction.

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