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FEASIBILITY STUDIES FOR THE EXTRACTION OF BOTH LHC BEAMS FROM CERN SPS USING A COMMON KICKER

F. M. Velotti, W. Bartmann, C. Bracco, E. Carlier, K. Cornelis, B. Goddard, V. Kain, M. Meddahi, CERN, Geneva, Switzerland

Abstract

The CERN Super Proton Synchrotron has to fulfil the demanding intensity specifications for the High Luminosity LHC (HL-LHC) era, with a doubling of the presently achieved operational beam intensity. One of the main problems to be addressed is given by impedance-driven beam instabilities. About 40 % of the total measured SPS impedance is due to the kickers, of which the extraction kickers in two of the SPS straight sections are the largest systems. A potential upgrade is explored which would strongly reduce the number of extraction kickers required in the SPS, by performing non-local extraction. In this scenario LHC Beam 1 would be kicked by the extraction kicker in SPS Long Straight Section 4 (LSS4), normally only used for Beam 2, to be extracted in LSS6. The concept and the expected performance of such a scheme are presented along with detailed simulation results.

INTRODUCTION

The CERN SPS is equipped with two extraction kickers (MKE.4 and MKE.6), one injection kicker (MKP), two tune measurements kickers (MKQH and MKQV) and two dump kickers (MKDV and MKDH). Those systems are the source of about 40 % of the total SPS measured impedance; calculations and machine studies proved that this could be a limiting factor in reaching the aimed HL-LHC beam intensity [1] [2].

In the contest of the feasibility study performed for the CENR Neutrino Facility (CENF), a new type of extraction from the SPS was proposed and tested in 2012 [3]: *the non-local extraction*. The nominal fast extraction from the SPS (LSS4 and LSS6) is realised combining extraction bump, kicker and septum deflections; all these elements belong to the same LSS. Instead, the non-local extraction concept permits a fast beam ejection from an extraction channel devoid of kickers.

In this paper, the possibility of extracting both beam 1 (B1) and beam 2 (B2) towards the LHC using the same fast pulsed magnet MKE.4 is explored. Nominally, B1 is extracted from LSS6, using MKE.6, and B2 from LSS4, using MKE.4. In the proposed concept the extraction channels will stay the same, but only the MKE.4 will be used (Fig. 1).

First, in order to optimise the kicker strength needed to extract the beam (i.e. the phase-advance between kicker and septum), a different horizontal working point (WP) was explored. Then, to quantify the expected performance of this extraction method and identify possible degradations or limitations, machine aperture and extraction stability analysis were carried out.

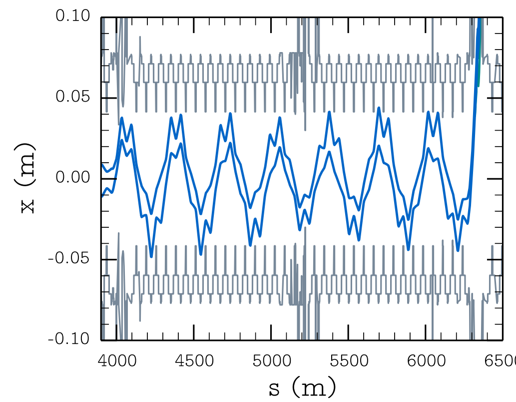

Figure 1: Horizontal extraction trajectory for non-locally extracted LHC beam from LSS6 using the MKE in LSS4. The MKE.4 is installed at s=3975 m and the first extraction septum in LSS6 is at s=6327 m.

KICKER PHASE ADVANCE

To optimise the needed MKE.4 kick θ, i.e. minimise the orbit oscillations and maximise the orbit excursion at the extraction point ($x(s_2)$), the MKE.4 (at s_1) and the extraction septum in LSS6 (at s_2) need to be at relative phase-advance as close as possible to $\Delta\psi_x = \pi/2$ since:

$$x(s_2) = \theta\sqrt{\beta_x(s_1)\beta_x(s_2)}\sin(\Delta\psi_x), \qquad (1)$$

where $\beta_x(s)$ is the horizontal beta function at s location.

The current nominal SPS optics is the so-called *Q20* (Low γ-transition); the fractional part of the horizontal and vertical tunes are listed in Table 1. For this optics, the relative phase-advance between the kicker in LSS4 and the septum in LSS6 is about $3/2\pi$, which makes not feasible the non-local extraction for B1. A different fractional part of the horizontal tune was thus explored. A natural choice is to move the WP to an island in the specular part of the tune diagram, i.e. $Q_x = 20.87$. In this way, the relative phase-advance between s_1 and s_2 is about $\pi/4$, which translates into an orbit excursion of 70% the one obtainable with $\Delta\psi_x = \pi/2$.

ERROR STUDIES

The non-local extraction technique has two intrinsic sources of possible aperture limitation: large betatron os-

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Table 1: Beam parameters of nominal LHC beam type at top energy into the SPS used for sumulations.

Parameter	Unit	Value (Nominal/Non-local)
Momentum	GeV/c	450
$\varepsilon^N_{x,y}$	π.mm.mrad	3.5
Δp/p	10^{-3}	0.2
Q_x	-	20.13 / .87
Q_y	-	20.18

cillations and not exactly $\pi/2$ phase-advance between the kicker and the septum. A trade-off between the kicker strength and the extraction bump amplitude has to be found to maximise the available aperture for both circulating and extracted beam.

To evaluate the expected performance of this new concept, orbit and optics functions at the extraction point have to be compared with the nominal values.

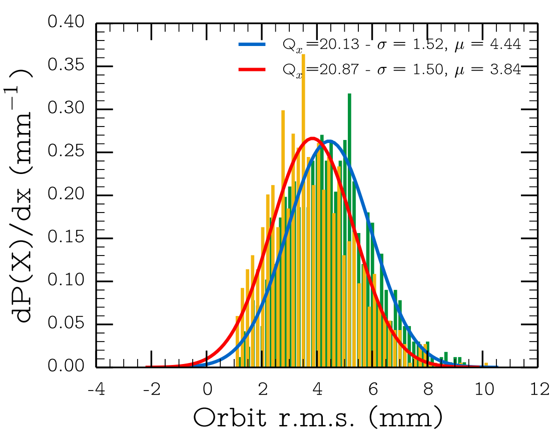

Figure 2: Horizontal r.m.s. orbit distributions obtained misaligning all the quadrupoles in the SPS with MAD-X. Green: Q_x = 20.13. Yellow: Q_x = 20.87.

Aperture Analysis

The SPS orbit is dominated by the quadruple misalignments: no correction can be applied at top energy due to lack of strength in the correctors [4]. To obtain a realistic simulation scenario, MAD-X calculations were done applying random quadrupole misalignments ($\sigma_{dx,dy}$ = 100 μm) which could reproduce the measured orbit at 450 GeV with Q20 [5]. The horizontal r.m.s. orbit distributions among the 1000 different simulated machines, for both working points, are shown in Fig. 2.

Due to the big oscillation amplitudes (about 20 mm) the available aperture for the non-locally extracted beam is indeed smaller than for the simple local extraction. The figure of merit used to compare the apertures, in the two different cases analysed, is the minimum acceptance in the machine, defined as $A_{min} = \min \frac{aper_H - |x|}{\sigma_x}$, where $\sigma_x = \sqrt{\beta_x \varepsilon_x + (D_x \Delta p/p)^2}$, D_x is the dispersion function, ε_x the geometrical emittance, Δp/p is the fractional momentum difference and $aper_H$ is the horizontal mechanical aperture. In Fig. 3 the distribution of the minimum acceptances is shown. The aperture bottleneck, for the extracted beam, is at the entrance of the first extraction septum (MST) in LSS6, as expected. In some cases instead, the minimum acceptance was at the extraction septum in LSS4 or at the collimator (TCSM) in LSS5. The 5 per mil of the simulated extraction trajectories had minimum acceptance lower than 6 σ_x in LSS4 or LSS5. To increase the acceptance at the TCSM a two-sextant long counter-phase bump was matched. It is a closed orbit bump with maximum amplitude of 10 mm at the QF.52, obtained using 30 horizontal correctors between LSS4 and LSS6. Also, the MSE, which is installed on a movable gird, was moved 4 mm away from the circulating beam centre.

The distribution of the minimum acceptances when the beam is normally extracted from LSS6 is shown in Fig. 4.

To increase the acceptance for the non-locally extracted and circulating beam, the kicker strength was kept as low as possible, i.e. 33 kV, and the bump amplitude was increased (10 mm higher than the nominal). From the plots in Fig. 3 and 4 is clear that the non-local extraction concept has an intrinsic lower global acceptance.

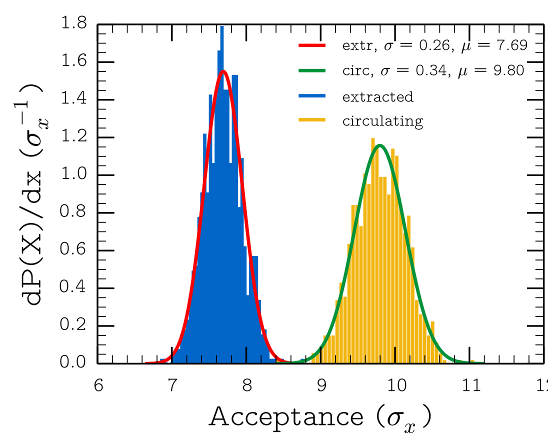

Figure 3: Acceptance analysis, in the horizontal plane, for circulating and non-locally extracted beam.

Extraction Stability

The orbit reproducibility at extraction is one of the key parameter for a good and safe beam transport from the SPS to the LHC. In these Transfer Lines (TLs) there is a complete collimation system. Large beam oscillations in the TLs produce high losses at the collimators and can lead to important injection oscillations in the LHC where the available aperture is very tight [6].

The extraction stability is one of the main concerns for this kind of extraction due to the high brightness of the beam

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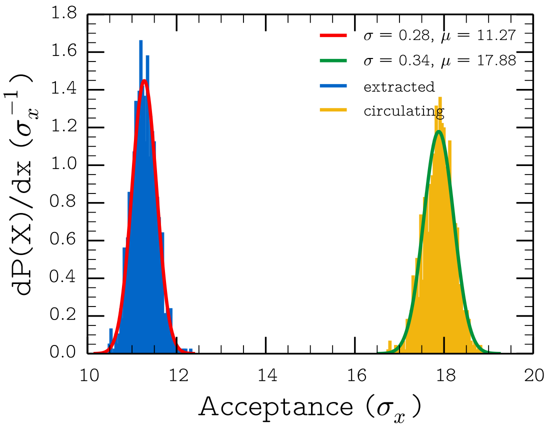

Figure 4: Aperture analysis, in the horizontal plane, for circulating and normally extracted beam (present situation).

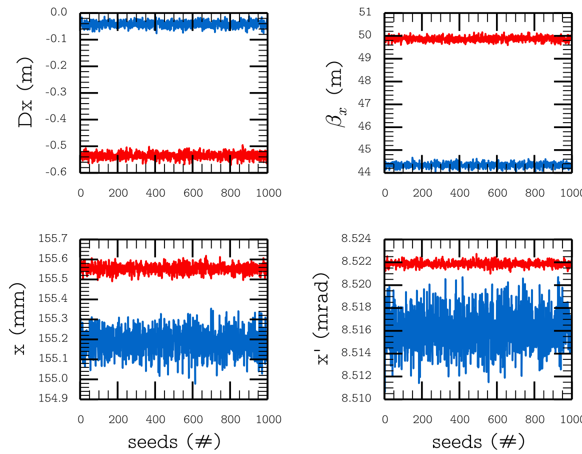

Figure 5: Orbit and optic functions at the BTVE.6 calculated for 1000 different scenarios. Red: Normal extraction. Blue: Non-local extraction.

transported. Both in TI8 and TI2, stability issues were already recorded [7] with the current extraction systems.

The expected quality of the extraction and its sensitivity to the machine dynamic errors were evaluated calculating the beam position, transverse momentum, beta and dispersion functions just downstream of the MSE.6 (at the monitor BTVE.6) for 1000 different cases (Table 2). Non-local and local extraction simulations started with a non-zero orbit (x_{rms} = 5.5 mm) obtained with the same quadrupole misalignments.

The results of the extraction stability analysis for the horizontal plane are shown in Fig. 5. Simulations show that the shot-to-shot orbit variation is three times larger for non-locally extracted beam, although, if compared with measurements,[1] the expected extraction stability is only about 6% worse than the present situation.

Table 2: Errors assigned to the SPS active elements. A seed from the above error analysis was used to compare both non-local and normal extraction. The horizontal orbit r.m.s. was 5.6 mm in both cases.

Errors	Distribution	Value
Quads $\Delta k/k_0$	Norm	σ = 1e-4
Dipoles $\Delta B/B_0$	Norm	σ = 1e-4
MKE $\Delta B/B_0$	Uniform	±1e-2
MSE $\Delta B/B_0$	Norm	σ = 0.11e-3
MST $\Delta B/B_0$	Norm	σ = 0.11e-3

CONCLUSION

Simulations show the feasibility of the non-local extraction of beam 1 when the fractional part of the horizontal tune is changed.

The Monte Carlo simulations show an aperture reduction, for both extracted and circulating beam, in case of non-local extraction. Also, the expected extraction stability seems to be slightly worse (about 6%) than the one guaranteed by the current system. However, the potential big gain in terms of impedance reduction has to be carefully evaluated with the possible operational performance reduction.

Further studies are still required to fully optimise this concept, as well as measurements with beam are needed to validate these results.

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[1] The measured standard deviations of x and x' for normally extracted B1 are about one order of magnitude bigger than the simulation model.