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SPS LONG TERM STABILITY STUDIES IN THE PRESENCE OF CRAB CAVITIES AND HIGH ORDER MULTIPOLES*

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Abstract

A local Crab Cavity (CC) scheme will recover the head-on collisions at the IP of the High Luminosity LHC (HL-LHC), which aims to increase the LHC luminosity by a factor of 3-10. The tight space constraints at the CC location result in axially non-symmetric cavity designs that introduce high order multipole CC components. The impact of these high order components on the long term stability of the beam in the SPS machine, where two prototype crab cavities are presently installed in the CERN SPS to perform tests with beam, is presented. Furthermore, the Dynamic Aperture is studied in the presence of the SPS errors. Future plans are discussed.

INTRODUCTION

The High Luminosity LHC (HL-LHC) aims to increase the LHC luminosity to L $\sim 5 \cdot 10^{34}$ cm$^{-2} \cdot$ s^{-1}. Among others upgrades, a Crab Cavity (CC) scheme will be implemented that will recover the head on collisions at the Interaction Point (IP). Since the CCs have never been used in proton machines, it is of paramount importance to test the validity of the scheme before its installation in the LHC. With this in mind, the SPS machine will serve as a test-bed of two vertical HL-LHC prototype CCs, installed one right next to each other, from April to November 2018.

The tight space constraints in the HL-LHC call for asymmetric cavity designs that include high order multipole components which could affect the long term Dynamic Aperture (DA). The DA in a perfect (no errors) SPS machine are presented in this paper for different CC configurations. Simulations in the presence of SPS multipoles are also presented.

CRAB CAVITY MULTIPOLES IN A PERFECT SPS LATTICE

The DA of a perfect (no errors, chromatic sextupoles for chromaticity correction are ON) SPS machine was simulated for different CC configurations:

- SPS, no CCs
- SPS, with CCs
- SPS, with CCs + Q
- SPS, with CCs + S
- SPS, with CCs + O
- SPS, with CCs + QSO,

where SPS is the bare SPS lattice without aperture. In the cases where multipoles were used only one crab cavity RF multipole error was applied (Q: Quadrupolar, S: Sextupolar, O: Octupolar) at the location of the first CC; QSO stands for the case where all multipole errors were applied at the same time. Since the SPS experiments will be performed with different CC phase configurations, at a first stage the CCs were simulated in a phase-cancelling mode, where the first and second CC were set to 0° and 180° respectively, whereas at a second stage the two CCs were simulated having their phase set to 0°. In the first case, the effect of the kick of the first CC is cancelled by the effect of the kick of the second; in the latter case the effect of the second kick is added to that of the first one.

The SPS parameters at the location of the CCs are given in Table 1 and the values of crab cavity RF multipoles, taken from [1], in Table 2. Note that the SPS CC experiments

Table 1: Parameter Table

Parameter	Value
nCavities	2
s Location [m]	6312.7213, 6313.3213
Transverse tilt [deg]	90
V_{kick} per cavity [MV]	3.4
f [MHz]	400
β_{x1}, β_{y1} [m]	29.24, 76.07
β_{x2}, β_{y2} [m]	30.31, 73.82
μ_{x1}, μ_{y1}	23.88, 23.90
μ_{x2}, μ_{y2}	23.89, 23.90
D_{x1}, D_{y1} [m]	-0.48, 0.0
D_{x2}, D_{y2} [m]	-0.50, 0.0
D'_{x1}, D'_{y1} [m]	-0.02, 0.0
D'_{x2}, D'_{y2} [m]	-0.02, 0.0
Q_x, Q_y	26 .13, 26.28
α_c	0.0019
E_{inj} [GeV]	26.00
γ_{rel}	27.71
$\epsilon_{n,x}, \epsilon_{n,y}$ [µm · rad]	2.50, 2.50
V_{RF} [MV]	2
$\Delta p/p$	1.00E-3
Bunch length [m]	0.23
ϵ_s [eV · s]	0.5

will be performed at four different energies: 26, 55, 120 and 270 GeV, for various CC voltage values. The simulations were performed for the injection energy, E = 26 GeV, as this exhibits the largest CC kick, with V_{CC} = 2 MV, $\Delta p/p = 10^{-3}$ and $Q'_{x,y} = 0.0$. The indices 1, 2 indicate the first and second CC respectively.

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Table 2: Values of CC Multipoles in Units of mTm/m^{n-1}

Multipole	Value
b_2 (Q)	-0.06
α_3 (S)	1159
b_4 (O)	-4

The simulations were performed using MAD-X [2] and SixDesk [3], for 1E6 turns. Since the CCs are vertical, quadrupolar and octupolar errors are normal multipoles (b_2, b_4), whereas the sextupolar errors are skewed (α_3).

The DA with respect to angle for the studies described in the previous section are shown in Fig. 1 for the cases where the CCs are in a phase-cancelling (top) or same-phase (bottom) mode respectively.

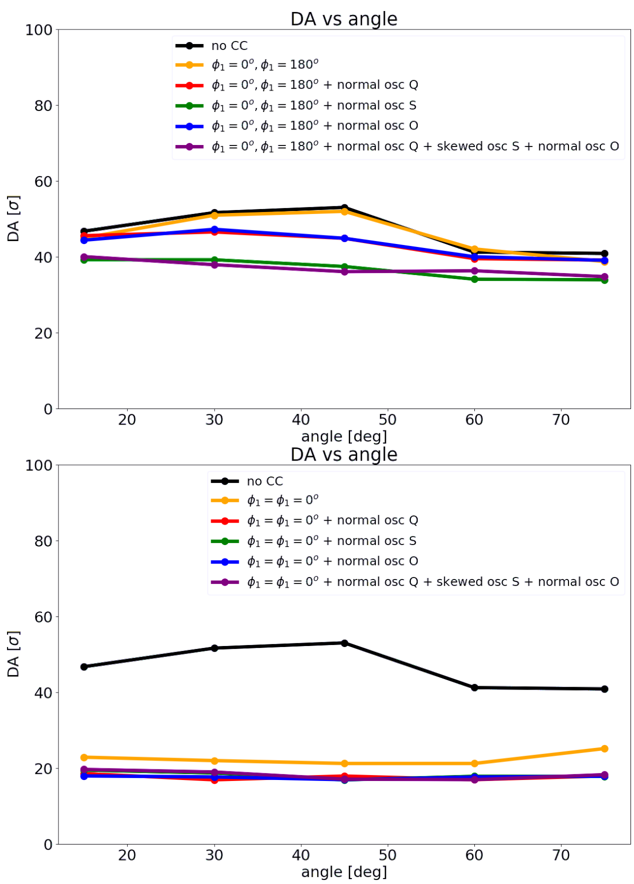

Figure 1: DA in σ with respect to angle in transverse phase space for the cases where the CCs are in a phase-cancelling mode (top), i.e. $\phi_1 = 0^o$ and $\phi_2 = 180^o$, and a same phase mode (bottom), i.e. $\phi_{1,2} = 0^o$.

From Fig. 1 (top) it can be seen that, as expected, the DA when the CCs are in the phase-cancelling mode (orange line) is very similar to the case where no CCs are present (black line). Note that all multipoles have an insignificant impact on the DA. The skewed sextupole (green line) has a slightly larger effect which can be expected as it is the strongest. The DA when all multipoles are used simultaneously (purple line) is very similar to that of the skewed sextupole case and is as high as 40-45σ.

On the other hand, when the CCs have the same phase the DA is reduced by a factor of almost 3, as shown in Fig. 1 (bottom). Note that in this case the sextupolar multipole (green line), and the case where all multipoles are used simultaneously (purple line) have a very similar effect to that of the other multipoles.

NON-LINEAR OPTICS FROM CHROMATICITY MEASUREMENTS

The results above use the nominal SPS optics model, which accounts only for non-linear fields produced by the chromatic sextupoles. On the other hand other sources of non-linearities are known to be present in the SPS, among which the most important ones are the odd multipoles produced by the error harmonics of the main dipole magnets and remanent fields in sextupoles and octupoles due to magnetic hysteresis, the latter relevant only at low energies. Some effort has been made in order to establish the SPS non-linear optics model with beam-based measurements at injection energy (26 GeV), the latest results being summarized in Ref. [4].

By repeating chromaticity measurements (see Figure 2) with 3 different optics (Q20, Q22, Q26, where the integer part of tune is 20, 22 and 26 and the non-integer part is 0.13 and 0.18 in the H and V plane respectively), exhibiting different betatron and dispersion functions, it was possible to disentangle the contribution of the different non-linear errors. Thus an effective optics model has been built by fitting the

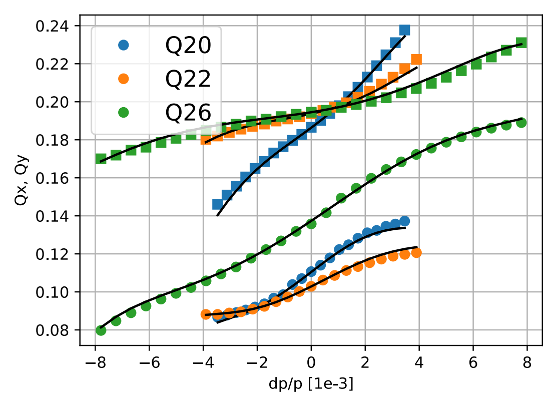

Figure 2: Horizontal (dots) and vertical (square) fractional tune measured during a typical momentum scan for Q20, Q22 and Q26. Because of the different dispersion values in the 3 optics, the dp/p range has been adjusted in order to cover the same radial excursion. The chromaticity computed from the effective model obtained from the fit of the 3 measurements is also shown (black curves).

strength of the multipolar errors in order to reproduce the experimental observations with the 3 different optics. The procedure has been repeated 5 times for different machine configurations, allowing to establish an average model and to evaluate the statistical uncertainties.

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To confirm the validity of the effective non-linear model at higher energy, a single chromaticity measurement of the Q26 optics at 270 GeV was acquired and used to fit a model containing the odd multipoles produced by dipoles only. Independent parameters for each multipolar error have been allowed for each of the two different kinds of SPS dipoles, MBA and MBB.

Table 3 shows a comparison of the simplified model measured at 270 GeV against what was measured at injection energy [4]. The two models are found to be compatible, except for the sextupolar component of the MBA dipoles (b_{3a}). However such a discrepancy is likely to be attributed to a calibration error of the sextupoles used to correct chromaticity. The overall good agreement extends the validity of the effective model measured at injection energy to the conditions used for the CC simulations.

Table 3: Multipole Errors from SPS Nonlinear Model

Multipole	26 GeV	270 GeV
$b_{3a}[\mathrm{m}^{-2}]$	$(-2.8 \pm 0.6) \cdot 10^{-3}$	$8.1 \cdot 10^{-4}$
$b_{3b}[\mathrm{m}^{-2}]$	$(1.6 \pm 0.3) \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
$b_{5a}[\mathrm{m}^{-4}]$	-7.9 ± 0.5	9.2
$b_{5b}[\mathrm{m}^{-4}]$	-6.8 ± 1.5	-10
$b_{7a}[\mathrm{m}^{-6}]$	$(8.8 \pm 2.6) \cdot 10^{4}$	$1.3 \cdot 10^{5}$
$b_{7b}[\mathrm{m}^{-6}]$	$(1.7 \pm 0.8) \cdot 10^{5}$	$1.4 \cdot 10^{5}$

The effect the CCs have on the DA depends strongly on the CC voltage and the initial $\Delta p/p$ or longitudinal action, z; particles with large initial $\Delta p/p$ or z will perform large synchrotron oscillations and will therefore experience a larger CC kick variation. Figure 3 illustrates the minimum DA for 1E6 turns in the SPS, in the presence of errors up to b_5 when both CCs are operated with their phase set to 0^o; the CC multipoles were not included since it was demonstrated they have only minor effect on DA (Fig. 1, bottom).

The results depict the effect of a varying voltage per CC, from 0.0 MV to 2.5 MV, and for different longitudinal actions, z_{init}, and $(\Delta p/p)_{init} = 0$. The lines represent the physical aperture. Note that at $z_{init} = 200$ mm, i.e. 1 σ_z at E_{inj}, the physical aperture reduces from 7.63 σ in the absence of CC kicks to 3.16 σ for 2.5 MV per CC. For $V_{CC} = 2$ MV the DA is reduced to half for particles with $z_{init} = 200$ mm. Note that for large z_{init} and CC voltage values the limitation comes from the DA rather than the physical aperture. It should be highlighted that this study is optimistic as the b_7 multipoles were not included.

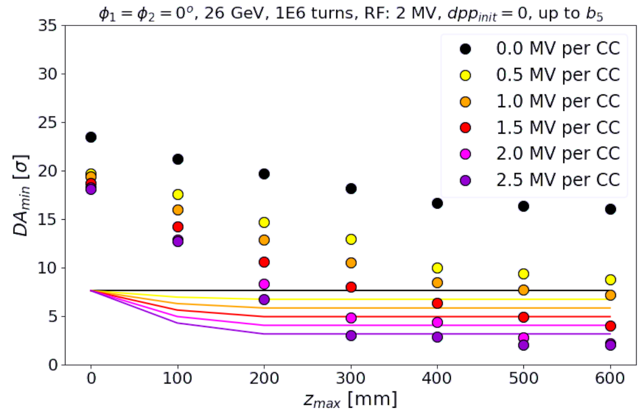

Figure 3: Minimum DA for values of voltage per CC from 0.0 MV to 2.5 MV, for different longitudinal actions, z_{init} and $(\Delta p/p)_{init} = 0$.

CONCLUSIONS AND FUTURE PLANS

The HL-LHC aims to increase the LHC luminosity by incorporating, amongst others, a CC scheme. The first time that CCs will be used with a proton beam will be in 2018 during the CC SPS experiments, for which two vertical prototype HL-LHC CCs have been installed in the SPS one right next to the other. Simulations were performed to study the DA in the SPS for different beam, CC and machine configurations. In the ideal SPS lattice with chromatic sextupoles, but without including any machine errors, the DA is reduced by a factor of two when the CCs are operated with $\phi_1 = \phi_2 = 0^o$ and their maximum voltage of 3.4 MV, whereas it is practically not affected by the CC multipoles.

When including the SPS errors up to b_5, the DA is reduced significantly to values as low as 5 σ. For $V_{CC} = 2$ MV the DA is reduced to half for particles with an initial longitudinal position of $z_{init} = 200$ mm (1 σ at E_{inj}). The reason for the strong reduction of the DA is under investigation.

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