SPS STUDIES IN PREPARATION FOR THE CRAB CAVITY EXPERIMENT

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Abstract

A local Crab Cavity (CC) scheme will recover head-on collisions at the Interaction Points (IPs) of the High Luminosity LHC (HL-LHC), which aims to increase the LHC luminosity to $L \sim 5 \cdot 10^{34}$ cm$^{-2} \cdot$ s^{-1}. The first time that CC will ever be tested with proton beams will be in 2018 in the SPS machine. The available dedicated Machine Development (MD) time after the installation of the cavities will be limited and therefore good preparation is essential in order to ensure that the MDs are as efficient as possible. This paper presents the simulations and experimental studies performed in preparation for the future MDs and discusses the next steps.

INTRODUCTION

The upgrade of the LHC, the High Luminosity LHC (HL-LHC) [1] aims to increase the luminosity to $L \sim 5 \cdot 10^{34}$ cm$^{-2} \cdot$ s^{-1}. One of the new aspects that leads to this luminosity increase is the installation of a local Crab Cavity (CC) [2] scheme that recovers head-on collisions at the Interaction Points (IPs). Since the CC have never been used in proton machines, it is crucial to ensure that there will be no detrimental side effect for the beam in the HL-LHC machine. With this in mind, a set of prototype CC will be first installed in the SPS, to serve as a test-bed in 2018. Due to the limited time available for Machine Development (MD) studies, good preparation and planning of the studies to be performed with CC is essential. The following sections present the simulations and analysis studies performed in preparation of the MDs and discuss their results.

HT MONITOR READING

The crabbed beam in the SPS will be observed with the Head-Tail (HT) monitor. Since this instrument was designed to measure chromaticity and observe transverse instabilities, i.e. relatively large intra-bunch beam oscillations, it is important to ensure that the transverse offset along the bunch due to the crabbing of the beam can be detected with the instrument's resolution.

In the presence of a CC kick the beam will have a crabbed Closed Orbit (CO) around the machine, i.e. particles within the bunch will have different closed orbits depending on their longitudinal position. For a given longitudinal slice, the CO will be deformed in a similar way as with a localised dipole error. The vertical CO,

$$\mathrm{y(s)} = \frac{\theta}{2} \frac{\sqrt{\beta(\mathrm{s})}\sqrt{\beta_\mathrm{k}(\mathrm{s})}}{\sin(\pi \mathrm{Q})} \cos(\Delta_\phi - \pi \mathrm{Q})$$

depends on the dipole kick, θ, the beta-values at the HT monitor and kick-location, $\beta(s)$ and $\beta_\mathrm{k}(\mathrm{s})$ respectively, the phase-advance between the monitor and the kick, Δ_ϕ, and the vertical tune, Q_y.

Therefore, a larger vertical CO distortion at the HT monitor can be obtained by moving the Working Point (WP) closer to the integer tune as this increases the overall CO size. A WP change also results in a change of the phase-advance between the HT monitor and the location of the kick, and can 'shift' the CO such that its maximum is at the HT location.

Figure 1 shows the change of the vertical CO and the normalised vertical CO, $\mathrm{y_{norm}}$, as computed by MAD-X [3], at the HT monitor location with respect to the vertical tune, when a kick corresponding to 6.8 MV is applied at a 55 GeV beam; as the maximum voltage of a CC is 3.4 MV, 6.8 MV is the case where the two CCs have the same phase. The $\mathrm{y_{norm}}$ is normalised to the maximum CO, $\mathrm{y_{COmax}}$, the β at the location where the CO is maximum, β_yCOmax, and β at the HT monitor, β_HT: $\mathrm{y_{norm}} = \frac{\mathrm{y_{HT}}\sqrt{\beta_\mathrm{yCOmax}}}{\mathrm{y_{COmax}}\sqrt{\beta_\mathrm{HT}}}$. The vertical CO reading at the vertical operational tune (26.18, shown with a blue star) is as large as $\sim$ 4.3 mm, which is expected to be within the monitor's resolution. This WP results in a $\mathrm{y_{norm}}$ that is only 30% smaller than the one corresponding to the optimal WP of ~26.86, so a WP change is not justified. The shape of the crabbed beam at the location of the HT monitor can be seen in Figure 2 (1σ, 2σ and 3σ in red, green and blue respectively). Experimental studies are foreseen in order to identify the resolution limitations of the instrument.

The available vertical aperture for the crabbed beam in the SPS was studied for a kick corresponding to 6.8 MV at 55 GeV, 120 GeV and 270 GeV. Figure 3 shows that at 3σ there is no aperture limitation for any of these energies. Depending on the actual CO before crabbing, the WP could be moved a little bit closer to the integer to enhance the effect of the CC in case of limited resolution of the HT monitor.

WIRE SCANNER

An alternative approach for measuring the effect of the crabbing on the beam profile using the Wire Scanners (WS) in the SPS is also under investigation. In this respect, the expected beam shapes were compared for a nominal and a crabbed bunch (kick corresponding to 6.8 MV at 55 GeV) at

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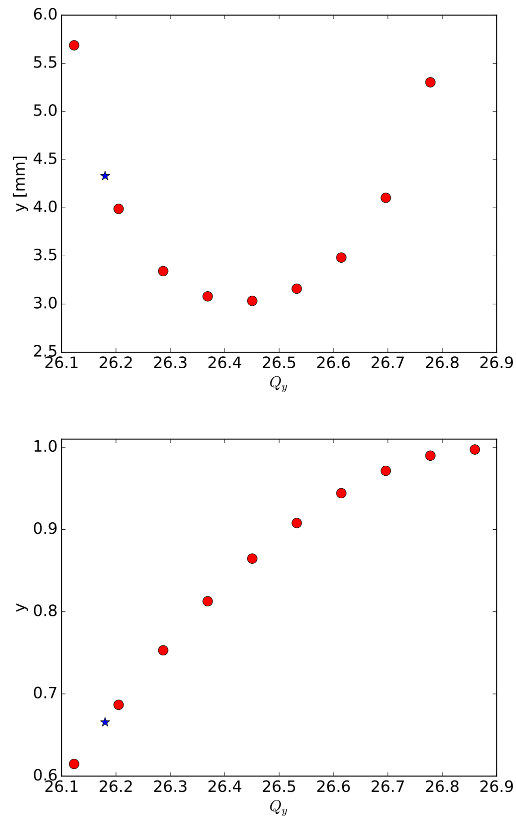

Figure 1: Absolute (top) and normalised (bottom) vertical CO offset at the HT monitor as a function of Q_y; blue star: vertical operational tune (26.18).

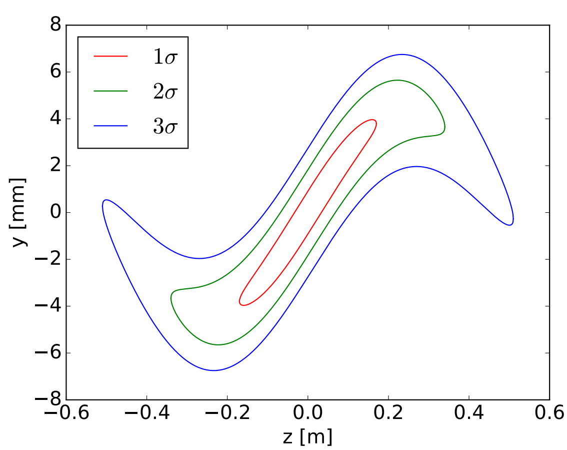

Figure 2: 1σ, 2σ and 3σ (red, green and blue respectively) of the crabbed beam at the HT monitor (55 GeV, V=6.8 MV).

the location of WS416 and the results are shown in Figure 4. The vertical beam profile changes significantly when the CC are switched on (see Figure 5); the change in shape is obvious (the profile is not gaussian anymore) and it should be easily measured in the SPS.

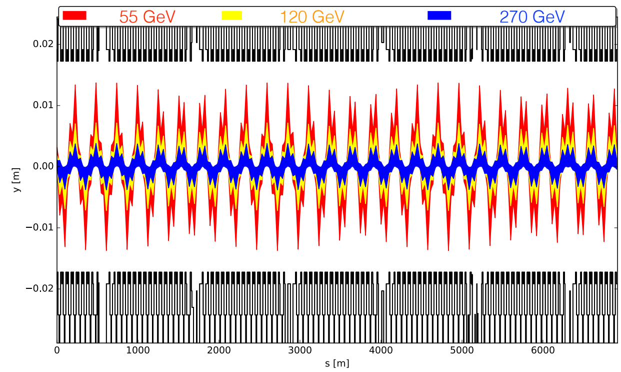

Figure 3: 3σ beam of 55, 120 and 270 GeV. For all three cases the beam is within the aperture limits.

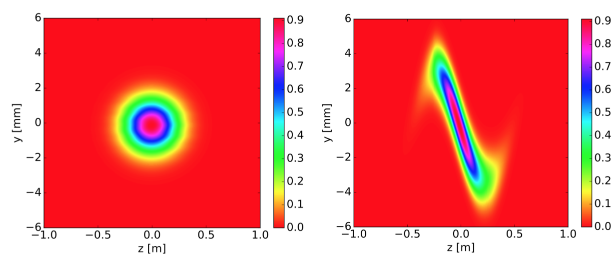

Figure 4: 2D gaussian beam in y and z, without (left) and with a kick corresponding to 6.8 MV (right).

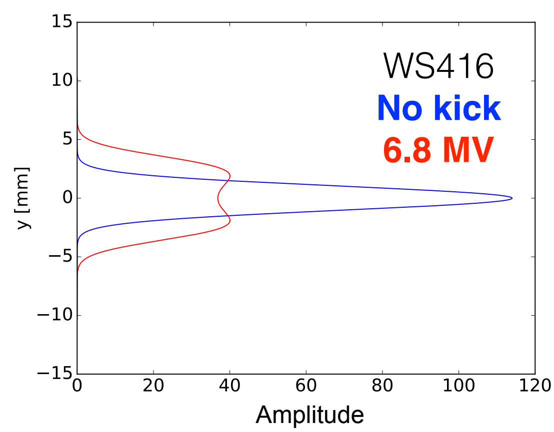

Figure 5: Vertical beam profile without (blue) and with a kick corresponding to 6.8 MV (red).

EXPERIMENTAL STUDIES IN THE SPS

One of the main concerns that needs to be addressed in the SPS experiments, is the induced emittance growth driven by phase jitter in the crab cavities. In order to distinguish from the effect of CC noise, good understanding and characterisation of the natural emittance growth is thus very important. In the past, several experimental sessions were carried out in the SPS, mainly focused on the characterisation of the natural emittance growth in coast beams (bunched beam, constant energy), with the following main conclusions [4]:

- The natural emittance growth in the SPS is substantial at low energies ($d\epsilon_x/dt = 140 - 370\%$, $d\epsilon_y/dt = 57\%$

at 55 GeV) and moderate at higher energies ($d\epsilon_x/dt \sim \epsilon_y/dt = 17 - 18\%$ at 120 GeV) for coasting beams.

- The emittance growth appears to be primarily a single bunch effect.
- The effect of the working point is minimal with very low intensity bunches even in the proximity of 3rd resonance.
- The chromaticity had a strong effect and the growth was approximately proportional to Q'.

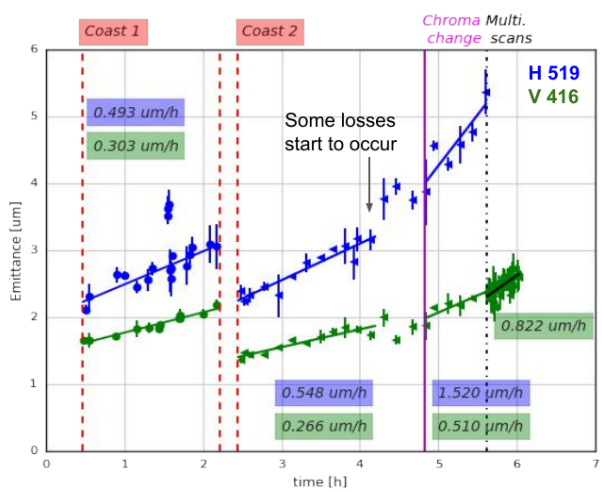

Figure 6: Fit results of the emittance evolution for the 4 different periods of the MD of December 2016.

In 2016, two dedicated experiments took place in the SPS at a coast energy of 270 GeV. In the experiment of December 2016 a first coast (Coast 1) was injected with a single bunch intensity of 4.25×10^{10} p/bunch. The chromaticity of the machine was corrected to 0.5 and 1 in the horizontal and vertical planes respectively. After 1.8 hours in Coast 1, the beam was damped and a fresh beam with a lower bunch intensity of 1.65×10^{10} p/bunch and same chromaticity values was injected (Coast 2). The bunch evolution was recorded for 2.5 h under the same conditions while later the chromaticity was increased by 2 units in both planes. In the last 15 min, the number of the wire-scans was drastically increased in order to study the impact the scattering on the wire has on the natural emittance growth. Figure 6 shows the evolution of the horizontal (blue) and vertical (green) emittances during the MD. A linear fit was applied to the 4 different periods of the experiment. The fit results are also indicated in the plot. The main conclusions coming from this analysis are:

- No slope increase was observed when reducing the intensity by almost a factor of 4.
- A clear slope increase of a factor of 2 and 3 in the horizontal and vertical planes respectively, was observed after the chromaticity increase.
- During the multiple wire-scans, a slight increase in the vertical emittance growth slope was observed. However, the time interval of those measurements was small and the spread of the data is large. In order to extract conclusive results, the experiment has to be repeated in a more systematic way, for a longer time period and for lower chromaticity values.

CONCLUSIONS

The HL-LHC will increase the luminosity to $L \sim 5 \cdot 10^{34}\ \mathrm{cm^{-2} \cdot s^{-1}}$, by incorporating, amongst others, a CC scheme. To ensure the validity of this configuration, the SPS will be used as a test-bed in 2018. Prior to the CC installation, dedicated MDs will take place in order to ensure good understanding of the machine and the limitation of its instruments.

The crabbed beam will be measured with the SPS HT monitor. Simulations showed that for the vertical operational tune of 26.18 the vertical CO for a kick corresponding to 6.8 MV at 55 GeV is ~ 4.3 mm, a value that is expected to be readable by the HT monitor. An MD in the SPS with the HT monitor experts will be focused on understanding the instrument's limitations. In addition, the 3σ of a 55 GeV, 120 GeV and 270 GeV beam is within the SPS aperture, which means we could even approach the integer tune and enhance the cavity's effect. This simulation will be repeated in the future including errors in the SPS.

In addition to the HT monitor, the WS can be used to measure the effective broadening of the vertical beam profile due to the crabbing. The change in the vertical beam profile when a kick corresponding to the maximum voltage in both CC is applied at 55 GeV is obvious and should be easily measured.

The induced emittance growth driven by phase jitter in the CC needs to be studied in the SPS experiments in order to distinguish between the natural emittance growth and the cavity noise. In the MD of December 2016 there was no emittance change when reducing the intensity by a factor of ~4, whereas the emittance slopes were doubled and tripled in the horizontal and vertical planes respectively, when increasing the chromaticity by 2 units. Finally, the small vertical emittance increase observed during the multiple wire-scans needs to be verified by repeating this experiment in a more systematic way, for a longer period of time and lower chromaticity values.

REFERENCES

[1] The HiLumi LHC Collaboration, G. Apollinari et al., "HL-LHC Preliminary Design Report", 2015

[2] R. Calaga, "Crab cavities in the SPS", LHC Performance Workshop, 23-26 January 2017

[3] MAD - Methodical Accelerator Design, `http://mad.web.cern.ch/mad/`

[4] R. Calaga et al., "Proton-beam Emittance Growth in SPS Coasts", Proc. of IPAC'12, paper THPPP007, p. 3737.

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