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EMITTANCE GROWTH IN COAST IN THE SPS

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Abstract

The CERN SPS will be used as a test-bed for the LHC prototype crab-cavities, which will be installed and tested in the SPS in 2018. As the time available for experimental beam dynamics studies with the crab cavities installed in the machine will be limited, a very good preparation is required in advance. One of the main concerns is the induced emittance growth, driven by phase jitter in the crab cavities. In this respect, several machine development (MD) studies were performed during the past years to quantify and characterize the emittance evolution of proton beams in coast in the SPS. In these proceedings, the experimental observations from past years are summarized and the MD studies from 2016 are presented. Finally, a proposal for an experimental program for 2017 is discussed.

INTRODUCTION

For the LHC upgrade, the use of a crab-crossing scheme is foreseen aiming to restore an effective head-on collision at the interaction regions. When particles pass through a crab cavity (CC), they receive a z-dependent transverse kick. They can thus be used in order to compensate the crossing angle at the interaction region, minimizing in this way the geometric luminosity loss which otherwise arises from the crossing angle [1, 2].

The crab cavities have been successively operated in KEKB [3] but have never been tested in high energy and high current proton machines. It is therefore of paramount importance to test them in another hadron machine before their full installation into the LHC. For this reason, two LHC prototype CC will be installed in the SPS during the technical stop at the end of 2017 and will be tested in 2018 in special machine development sessions. The SPS test is the only way to get conclusive answers on several aspects, like emittance growth, machine protection, RF non-linearity, instabilities, etc.

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. A good understanding and characterization of the natural emittance growth in the SPS is thus very important in order to distinguish from the effect of crab cavity noise. Several machine development sessions with coast beams in the SPS were devoted in the past years to the natural emittance growth studies [4]. In these proceedings, the results from past studies are summarized and the machine development studies of 2016 are presented. Finally a proposed experimental program for 2017 is discussed.

PREVIOUS STUDIES

Several experimental sessions were carried out in the past, aiming to characterize the long-term natural emittance growth in the SPS. Three different energies have been studied and the results until 2012 are summarized in [4]. The main conclusions from those studies were:

- The natural emittance growth in the SPS is substantial at low energies and moderate at higher energies 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 the 3rd order resonance.
- Chromaticity had strong effect and the growth was approximately proportional to Q'.

While in the experiments up until 2012 both horizontal and vertical emittances had similar growth slopes, a different behavior was observed in 2015. The results from the MD of October 2015 are presented in fig. 1, showing a much larger horizontal growth compared to the vertical one. A similar trend was observed in the MD of May 2015 as well.

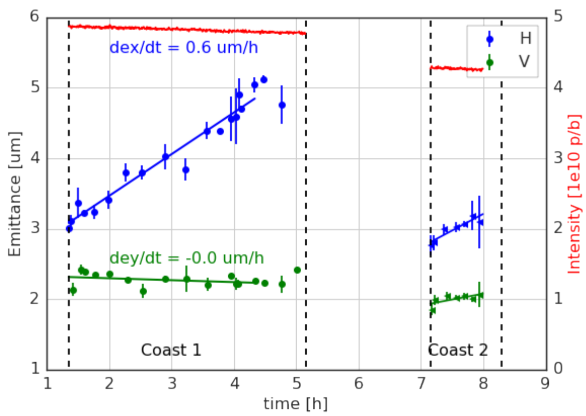

Figure 1: Emittance growth studies in coast beam in the SPS at 270 GeV, in 2015.

MD STUDIES IN 2016

In 2016, two machine development slots were dedicated in the natural emittance growth studies in coast beams at 270 GeV, aiming to reproduce the observations of 2015.

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July 2016

The first MD study took place on the 13^{th} of July 2016. A low intensity bunch of 2.35×10^{10} protons/bunch was injected in the SPS and a closed orbit of 5 mm was measured. The chromaticity was set to 2.5 in both H and V planes, in order to be similar to the values of the October 2015 experiment. The linear wire-scanners (517H, 517V) were used to measure the natural emittance evolution. Figure 2 shows the intensity (gray) and the horizontal (blue) and vertical (green) emittance evolution in time. After around 2 h in coast, a sudden jump was observed in the emittance evolution and the bunch got de-bunched, as shown in fig. 3. On the multiQ, a coherent oscillation was observed, for which the origin was not known. It is also interesting to notice, that even though almost no losses were observed in the BCT-DC data (red line in fig. 3), the Mountain Range Sum data (purple) indicate slow off bucket losses, of the order of 20 % within 1.6 h. At the same time, a bunch length increase of around 10 % is indicated by the Mountain Range Bunch Length data (green).

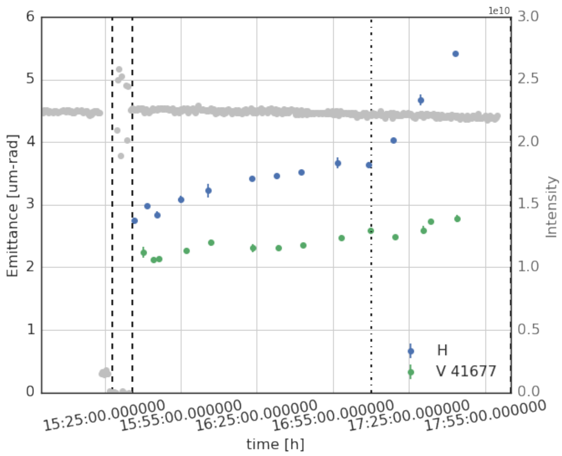

Figure 2: Intensity (gray) and horizontal (blue) and vertical (green) emittance evolution during the MD on coast in the SPS at 270 GeV in July 2016.

For the analysis of the emittance evolution, only the data of the first 1.6 h were used, thus before the sudden jump in bunch length. A linear fit was applied to the emittance data for both horizontal and vertical planes, and the results are shown in fig. 4 and summarized in Table 1.

Even though the experimental conditions were very similar to the ones of October 2015, both horizontal and vertical emittance growth were observed. The vertical emittance growth rate though, is slower that the horizontal one, by a factor of 2.5.

December 2016

The second MD of 2016 took place on the 7^{th} of December and was carried out with a single bunch at 270 GeV. During the MD the evolution of the horizontal emittance was recorded with a rotational wire-scanner (519H) while

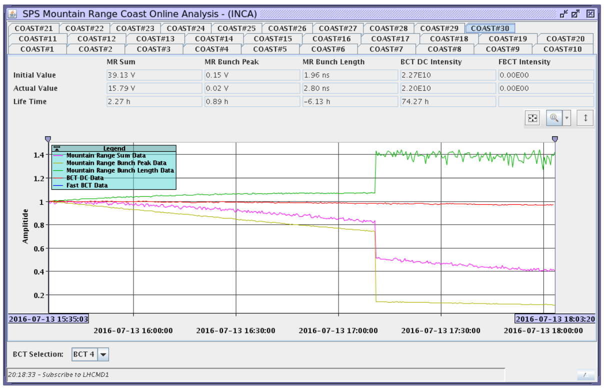

Figure 3: Mountain Range Data, showing the sudden debunching of the bunch after around 2 h in coast and the slow de-bunching during the first 2 h in coast.

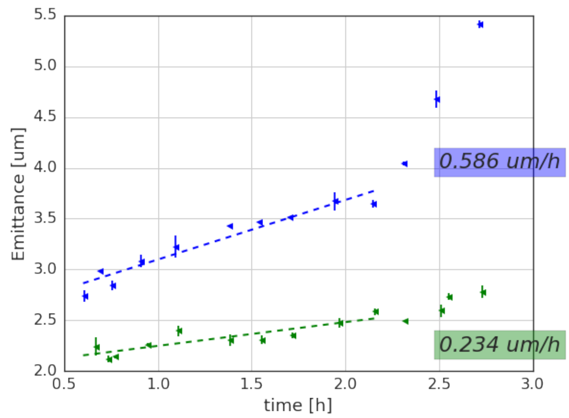

Figure 4: Linear fits and estimation of the emittance growth in the horizontal (blue) and vertical planes (green), before the debunching.

the vertical emittance evolution was recorded with a rotational (416V) and a linear (517V) wire-scanner.

A first coast (Coast 1) was injected with a single bunch intensity of 4.25×10^{10} ppb. 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 dumped and a fresh beam was injected (Coast 2), with a lower bunch intensity of 1.65×10^{10} ppb and same chromaticity values. 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. Figure 5 shows the evolution of the bunch intensity (gray), and the horizontal (green) and vertical (blue and cyan) emittances during the MD.

In [5], the impact of the multiple coulomb scattering effect on the transverse emittance growth during the wire scans is discussed. Emittance measurements from 2004 were corrected to the expected growth due to the wire scans, showing negligible or no growth in the vertical plane after this correction. Aiming to verify those observations, the rate of acquisition of vertical beam size profiles with the

Table 1: Summary results from the MD of July 2016

Parameter	Value
Init. emittance H/V [μm·rad]	2.85/2.16
Intensity [ppb]	2.25×10^{10}
Chromaticity H/V	2.5/2.5
Time [h]	1.6
$d\epsilon_x/dt$ [μm/h]	0.59
$d\epsilon_y/dt$ [μm/h]	0.23

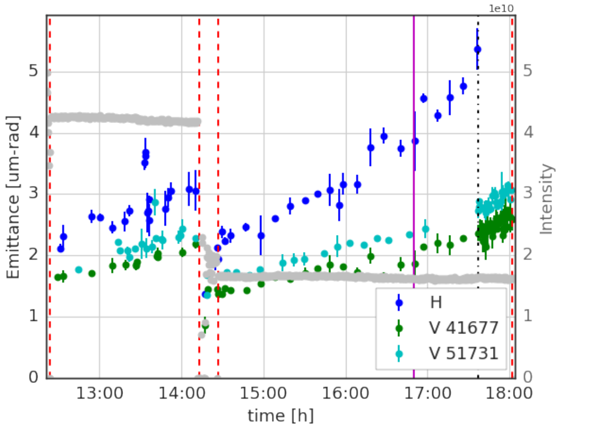

Figure 5: Data from the MD with coast beam in the SPS of December 2016. Horizontal (green) and vertical (blue (WS416) and cyan (WS517)) emittance evolution and intensity (gray) evolution.

linear wire-scanner was drastically increased during the last 15 min in Coast 2; in the first part of Coast 2 10 WS were performed in 1.8 h while in the last 15 min of the MD 24 WS were performed.

Figure 6 shows the snapshots from the Mountain Range application in the control room for both coast 1 and coast 2. Similar to the July MD, even though almost no losses were observed in the BCT-DC data (red), the Mountain Range Sum data (purple) indicate slow off bucket losses and a bunch length increase (green). For coast 1, off-bucket losses of the order of 25% and a 20% bunch length blow up were observed within the 1.8 h. For coast 2, the observations are similar for the first 1.8 h while later, the bunch length decreases and the total machine losses start to increase as well. At the same time, an increase in the horizontal emittance is also observed.

The MD data were divided in 4 groups and a linear fit was applied to the horizontal and vertical emittances versus time for each period:

1. Coast 1
2. Coast 2 before the chroma change
3. Coast 2 after the chrom change, before the multiple WS
4. Coast 2 during the multiple WS

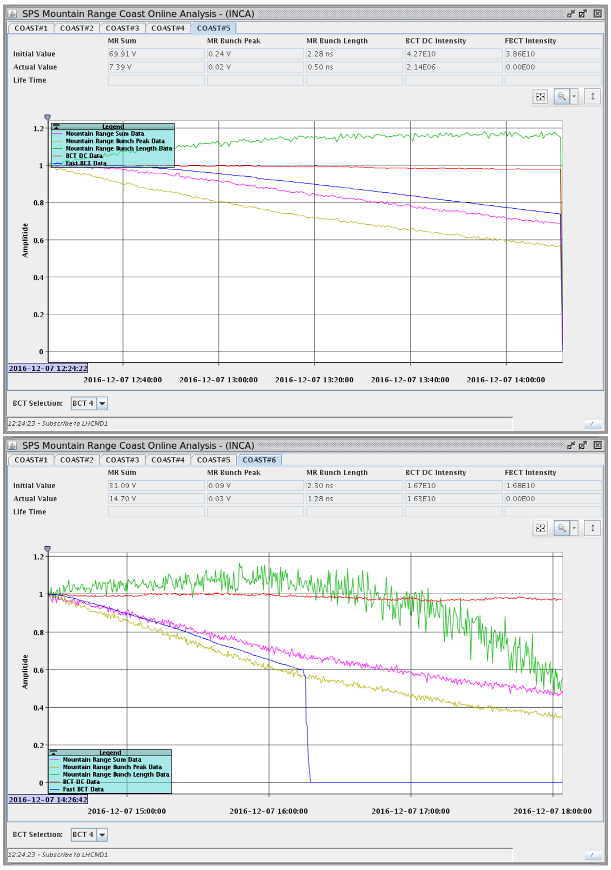

Figure 6: Data from the December 2016 MD with coast beam in the SPS. Mountain Range Data, showing the slow de-bunching of the bunch during coast 1 (top) and coast 2 (bottom).

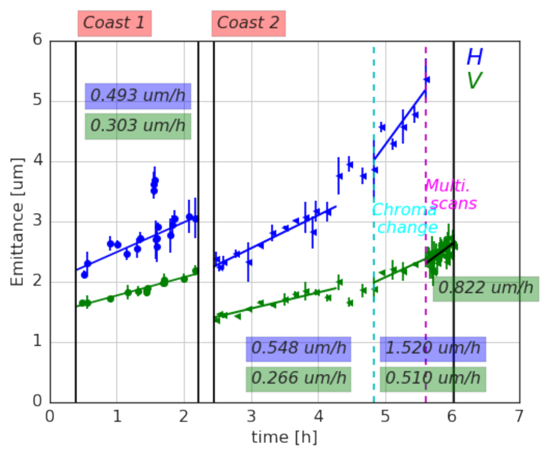

Figure 7: Fit results for the 4 different periods of the MD of December 2016.

The 4 periods and the fit results are presented in fig. 7 and summarized in Table 2. The main conclusions coming from this analysis are:

- Comparing the slopes between coast 1 and the first part of coast 2, no slope increase was observed even though the intensity was reduced by almost a factor of 4. Note that for coast 2, the same time interval of measurements was used as for Coast 1.

- After the chromaticity change, a clear slope increase was observed in both planes; a factor of 2 increase in the vertical plane and a factor of 3 in the horizontal one.
- 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.
- Slow de-bunching was observed in both coasts, similar to the MD of July, which needs to be understood.

Table 2 summarizes all the observations from this MD.

EXPERIMENTAL PROGRAM FOR 2017

As the available time for experimental beam dynamics studies with the crab cavities installed in the SPS will be limited, a very good preparation in advance is essential. In this respect, several studies are proposed for 2017 in dedicated or parallel Machine Development slots and are listed below.

Natural emittance growth in coast

The characterization of the natural emittance growth in the SPS is very important in order to disentangle it from the induced emittance growth from the crab cavities. With this in mind, the following studies are proposed, in dedicated MD sessions:

- Study the impact of the vacuum levels on the natural emittance growth. An MD at the beginning of the year, where the vacuum levels are expected to be worse and one at the end of year, after degrading the vacuum.
- Systematic chromaticity scan to identify the horizontal and vertical chromaticity values that result in the smallest emittance growth.
- Study different intensities.
- Multiple Wire Scan experiment in a more systematic way.
- Commissioning and cross-calibration of the Beam Gas Ionization monitor.
- Identify the effect of the damper on the emittance evolution on coast without the CC.
- Vacuum and power supply monitoring during each MD.

Head Tail monitor

The Head-tail monitor is the most sensitive instrument available in the SPS and is foreseen to be used for the crabbing validation. In this respect, several studies are proposed in preparation for the 2018 measurements:

- Study the accuracy of the instrument at different intensities.
- Identify the minimum kick that can be measured.
- Simulations are currently in progress to be used as a guideline.

Closed orbit correction

In past MDs an rms orbit of 3-5 mm has been measured.

- Verify if we can correct further the orbit.
- Verify if the normal YASP can be used efficiently at 270 GeV or if it is more efficient to use the extraction kickers.
- Identify the optimal kickers and the sensitivity of the BPMs around the crab location.

Collimation studies

- Verify if the collimation system works properly

Studies with shorter bunch length

- Look at the effects of the non-linearities of the RF curvature due to the different frequencies of the SPS main RF system (200 MHz) and the Crab Cavities (400 MHz).

SUMMARY

Two LHC prototype crab cavities will be tested in the SPS in 2018. After the installation of the CC in the SPS, only a limited time will be available for dedicated beam dynamics studies, thus a good preparation in advance is essential for an efficient testing in 2018. With this in mind, during the last years several machine development sessions were dedicated to the characterization of the natural emittance growth in the SPS. In these proceedings, the results from the 2016 studies have been presented. A clear dependence on the chromaticity has been concluded, with the emittance growth rate increasing with the chromaticity increase. On the other hand, for the emittance growth correlation with the number of wire scans was not very conclusive and needs to be repeated in a more systematic way. Based on the observations from the previous years and the tests that need to be performed in 2018, an experimental program for 2017 has been proposed.

Table 2: Summary results from the MD of December 2016

Parameter	Period 1	Period 2	Period 3	Period 4
Init. emittance H/V [μm·rad]	2.23/1.61	2.25/1.41	4.0/1.98	/2.30
Intensity [10^{10} p/b]	4.25	1.65	-	-
Chromaticity H/V	0.5/1	0.5/1	2.5/3	2.5/3
Time [h]	1.8	1.8	0.8	0.4
dϵ_x/dt [μm/h]	0.49	0.55	1.52	-
dϵ_y/dt [μm/h]	0.30	0.27	0.51	0.82
Number of linear WS	17	10	-	24
dϵ_y/scan [nm/scan]	31.2	63.5	-	14.3

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