

# EMITTANCE GROWTH IN COAST IN THE SPS AT CERN\*

A. Alekou<sup>1</sup>, F. Antoniou<sup>2</sup>, H. Bartosik, T. Bohl, R. Calaga, L. R. Carver<sup>1</sup>, J. Repond, G. Vandoni  
CERN, Geneva, Switzerland

<sup>1</sup> also at University of Manchester, UK, <sup>2</sup> also at University of Liverpool, UK

## Abstract

The HL-LHC prototype crab-cavities are installed in the CERN SPS, which, for the first time, will allow for a comprehensive beam test with high energy protons. 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. One of the main concerns is the induced emittance growth, driven by phase amplitude jitter in the crab cavities. In this respect, several machine development (MD) studies were performed during the past years to quantify and characterize the long term emittance evolution of proton beams in the SPS. In these proceedings, the experimental observations from past years are summarized and the MD studies from 2016 and 2017 are presented.

## 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 [1, 2]. The crab cavities (CC) have been successively operated in KEKB [3] but have never been used in high energy and high current proton colliders. It is therefore of paramount importance to test them in a hadron ring before their full installation into the LHC. For this reason, two LHC prototype crab cavities were installed in the SPS during the technical stop at the end of 2017 and will be tested in 2018 in special machine development (MD) 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 important 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 present SPS emittance growth is required to distinguish it from the effect of crab cavity noise. As for the SPS test the CC will induce a vertical kick, the most important observable is the vertical emittance growth. Several MD sessions were devoted in the past years to the long-term emittance growth studies in the SPS [4]. For these experiments special cycles with constant energy at a long plateau were set-up in the SPS, called "coast" beam cycles (with bunched beams). In these paper, the results from past studies (2010-2015) are summarized and the MD studies of 2016-2017 are presented.

## PAST STUDIES

Several experimental sessions were carried out in the past, aiming to characterize the long-term emittance growth in the SPS. Three different energies were studied and the results

\*Research supported by the HL-LHC project.

until 2012 are summarized in ref. [4]. From those studies, it was concluded that: the transverse emittance growth in the SPS is primarily a single bunch effect, substantial at low energies and moderate at higher energies. The effect of the transverse tune working point is minimal with very low intensity bunches, even in the proximity of the 3rd order resonance and the chromaticity had a strong effect with the growth being nearly proportional to  $Q'$ .

## MD STUDIES IN 2016-2017

Various machine development sessions were dedicated in 2016 and 2017 to the detailed study of the long-term emittance growth in coast in the SPS. All the experiments were performed with single bunches at 270 GeV, mainly with low intensity ( $1-4 \times 10^{10}$  ppb). Additional observables both in the transverse and longitudinal planes were used.

### Off-bucket Losses

Slow off-bucket losses were observed for all single bunch, low intensity MDs up to 2016. In order to identify the source of those losses, the effects of the RF voltage as well as the low level RF loops were investigated. The RF voltage was seen to have no impact but a clear correlation of the act of the RF feedback with the losses was observed. Figure 1 shows

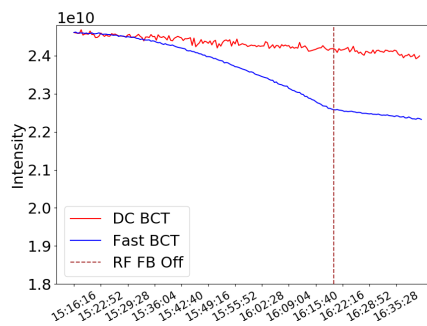


Figure 1: Time evolution of the total intensity from DC-BCT (red) and bunch intensity from the fast BCT (blue). The RF feedback is switched off after 1 h in coast (brown-dashed).

the time evolution of the total beam intensity in the machine as measured by the DC Beam current transformer, DC-BCT (red) and of the bunch intensity as measured by the fast BCT (blue). The experiment was initially performed with the RF feedback on, which was switched off 1 h later (brown vertical line). For the first hour there is a clear deviation between the evolution of the DC-BCT and the Fast BCT curves, indicating slow off-bucket losses. The slopes become similar after the RF feedback is switched off. After this observation all the coast experiments with single bunches



Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

and low intensity were performed without the RF feedback, eliminating the off-bucket losses. However, the RF feedback is necessary for the stability of the nominal higher intensity beams ( $\sim 10^{11}$  ppb).

### Impact of Chromaticity

The last MD of 2016 was dedicated to the study of the chromaticity impact on the transverse emittance growth. A first coast (Coast 1) was injected with a single bunch intensity of  $4.25 \times 10^{10}$  ppb. The  $Q'$  of the machine was corrected to 0.5 and 1 in the horizontal and vertical planes respectively. For lower chromaticity values the beam motion becomes unstable. 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  $1.65 \times 10^{10}$  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 2 shows the time evolution of the horizontal (blue) and vertical (green) emittances during the MD. A linear fit was applied for the three different tests: (1) Coast 1, (2) Coast 2 with reduced intensity and (3) Coast 2 after the chromaticity change. Comparing the fit results it becomes clear that reducing the intensity resulted in a small increase of the horizontal emittance growth and had no impact in the vertical emittance growth. After the chromaticity increase, a clear slope increase was observed, especially in the horizontal plane.

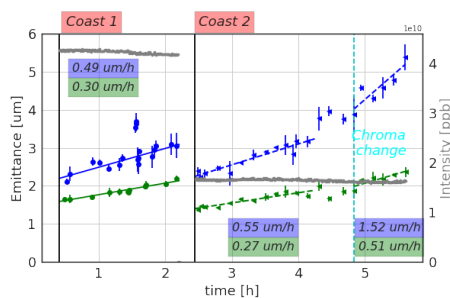


Figure 2: Horizontal (blue) and vertical (green) emittance evolution. A clear slope increase is observed after the chromaticity increase by 2 units (cyan dashed line).

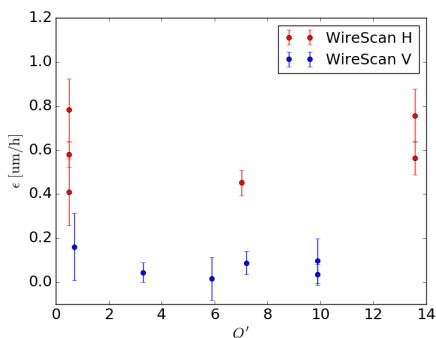


Figure 3: Horizontal (red) and vertical (blue) emittance growth as a function of chromaticity.

A further MD measured the emittance growth as a function of chromaticity, and unlike previous studies [4] no correlation with the chromaticity was observed, as shown in Fig. 3. Furthermore, the vertical emittance growth was a factor of 2-3 smaller than in all previous MDs. In order to understand this discrepancy, a detailed analysis of the data and the MD conditions is currently ongoing. Two main differences were identified and are being investigated: (a) the transverse beam profiles during this MD were more Gaussian and (b) the MD took place after the LHC shutdown and the current to all the extraction elements (kickers and septa) was set to zero.

### Impact of Intra-Beam Scattering

Intra-beam scattering (IBS) is a multiple Coulomb scattering effect, which can lead to the transverse and longitudinal emittance growth. In the case of zero vertical dispersion, like in the SPS, no effect is expected in the vertical plane [5]. The expected emittance growth due to IBS was estimated for all coasts using the IBS module of MADX [6]. The initial bunch characteristics (transverse and longitudinal emittances and bunch intensity) from the measurements were used as input for each case. Even though IBS can explain part of the observed growth, a residual component on top of it is observed and is very similar between the horizontal and vertical planes. A typical example is shown in Fig. 4. The measured horizontal and vertical emittance evolution is shown in blue and green respectively. The IBS prediction is shown in red. Adding the residual vertical emittance growth to the calculated IBS horizontal emittance growth (blue dashed line), the horizontal emittance measurements can be reproduced very well. The same observation is valid for most of the coasts.

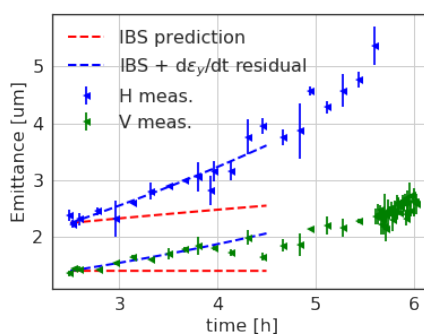


Figure 4: Intra-beam scattering predictions can explain only part of the emittance growth. The residual component is similar in both horizontal and vertical planes.

The impact of the SPS optics on the transverse emittance growth was also investigated. While all the experiments were performed with the so called "Q26" optics (corresponding to an integer tune of 26), one of the machine development sessions was performed using the "Q20" optics (integer tune of 20) [7]. While in the latter case the horizontal dispersion is larger and the IBS effect should be reduced, the observations were very similar: a residual emittance growth of the order of 0.3-0.5  $\mu\text{m/h}$  for both planes.

Table 1: Summary Results from the MDs of 2016-2017 at 270 GeV

MD	$\epsilon_x/\epsilon_y$ [ $\mu\text{m rad}$ ]	$N_b[10^{10}]$	$Q'_x/Q'_y$	$V_{RF}[MV]$	$4\sigma_L[ns]$	$d\epsilon_x/dt$ [ $\mu\text{m/h}$ ]	$d\epsilon_y/dt$ [ $\mu\text{m/h}$ ]
<b>July 2016</b>	2.85/2.16	2.25	2.5/2.5	5.1	1.96	0.59	0.23
<b>Dec. 2016</b>							
1	2.23/1.61	4.25	0.5/1.0	2	2.28	0.49	0.30
2	2.25/1.41	1.65	0.5/1.0	2	2.3	0.55	0.27
3	4.0/1.98	1.65	2.5/3.0	2	-	1.52	0.51
<b>May 2017</b>	Studies of off bucket losses						
<b>June 2017</b>	2.1/1.7	2.5	1.0/1.6	5	1.9	0.67	0.37
<b>July 2017</b>							
1	7.3/4.8	2.2	0.7/1.4	5	1.7	0.33	0.4
2	2.5/2.0	2.2	0.7/1.4	5	2.0	0.45	0.5
<b>August 2017</b>							
1	1.7/1.4	12	-	-	-	2.71	0.31
2	1.6/1.3	11	-	-	-	1.84	0.48

Parasitic transverse emittance measurements were also acquired with nominal intensity ( $1.1 \times 10^{11}$  ppb) with increased IBS effect. The residual growth was also similar in both horizontal and vertical planes and of the order of 0.3-0.5  $\mu\text{m/h}$ .

### Other Sources of Emittance Growth

A summary of all the MDs performed in 2016-2017 is shown in Table 1. The vertical emittance growth shows no strong dependence on the chromaticity, the machine optics or the bunch intensity. Part of the horizontal emittance growth can be explained by IBS while the residual growth appears to be similar in the two planes, varying from 0.3-0.5  $\mu\text{m/h}$ . This gives an indication that the vertical emittance growth is dominated by some other noise mechanisms. The effects of power supply ripple and residual gas scattering are currently under investigation.

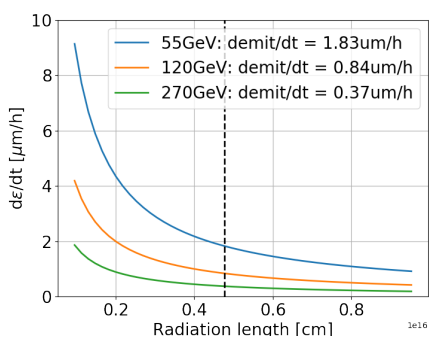


Figure 5: Emittance growth due to residual gas scattering versus the radiation length, for three different energies.

The multiple Coulomb scattering of the proton beam with the residual gas (RGS) in the beam pipe, can lead to emittance growth or beam losses [8]. An analytical parameterization of the RGS emittance growth with the radiation length, is shown in Fig. 5. The different curves correspond to the three coast energies of the SPS, for which emittance growth data are available: 55, 120, 270 GeV [4].

Vacuum decomposition measurements using a residual gas analyzer were performed in the SPS in 2011 [9]. Based on those measurements, corresponding to a radiation length of  $9.53 \times 10^{14}$  cm, the estimated emittance growth is 1.86, 4.19 and 9.14  $\mu\text{m/h}$  at 270, 120, and 55 GeV respectively. Those values are much larger than the observed emittance growth in the machine for all 3 energies. Assuming a 5 times larger radiation length (i.e. better vacuum quality), the estimated emittance growth is 0.37, 0.83 and 1.83  $\mu\text{m/h}$  respectively, which matches very well the observed emittance growth for all three energies. Detailed studies are ongoing in collaboration with the vacuum group, aiming to verify the impact of vacuum quality on the emittance growth.

## SUMMARY

Two LHC prototype crab cavities will be tested in the SPS in 2018. During the test, only a limited time will be available for dedicated long-term emittance growth studies, thus a good preparation in advance is essential for efficient testing. Several machine development sessions were dedicated during the last years to the characterization of the transverse emittance growth in the SPS. A clear dependence of the horizontal emittance growth on the chromaticity has been observed, with the exception of the last MD of 2017 for which a more detailed analysis is ongoing. Part of the transverse emittance growth can be explained by intra-beam scattering, however, a residual growth between 0.3-0.5  $\mu\text{m/h}$  is always present in both planes. The impact of the power supply ripple and the residual gas scattering on the residual growth is currently under investigation. The first RF noise measurements on the crab cavity module in SM18 indicate larger LLRF noise than expected leading to potential emittance growth from phase noise to be between 2-8  $\mu\text{m/h}$  scaled to SPS parameters between bunch lengths of 1-2 ns [10]. This is well above the measured growth with the optimized setup during the SPS 270 GeV coasts. The detailed quantification of the crab induced growth will help deter-

mine the exact specification for the LLRF for HL-LHC to remain well below the 0.05  $\mu\text{m}/\text{h}$ .

## REFERENCES

- [1] R. Calaga, "Crab Cavities for the LHC upgrade", Chamonix 2012, CERN-2012-006 and CERN-ATS-2012-069, <https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2012/html/Welcome.htm>
- [2] Y. Sun et al., "Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider", Phys. Rev. ST Accel. Beams 12, 101002 (2009), <https://link.aps.org/doi/10.1103/PhysRevSTAB.12.101002>
- [3] Y. Funakoshi, "Operational experience with Crab Cavities at KEKB", arXiv:1410.4036v1, <https://arxiv.org/abs/1410.4036>
- [4] R. Calaga et al, "Proton-beam emittance growth in SPS coasts", IPAC2012, New Orleans, Louisiana, USA, THPPP007, <https://accelconf.web.cern.ch/accelconf/IPAC2012/papers/thppp007.pdf>
- [5] A. Piwinski, "Intra-beam scattering", Proceed. of the 9th International Conference on High Energy Accelerators, Stanford, CA, 1974.
- [6] F. Antoniou and F. Zimmermann, "Revision of Intrabeam Scattering with Non-Ultrarelativistic Corrections and Vertical Dispersion for MAD-X", CERN-ATS-2012-066 (2012).
- [7] Y. Papaphilippou et al, "Operational performance of the LHC proton beams with the SPS low transition energy optics", IPAC2013, Shanghai, China, THPWO080, <http://accelconf.web.cern.ch/AccelConf/ipac2013/papers/thpwo080.pdf>
- [8] G. Dugan, "USPAS lectures on Beam loss and beam emittance growth", (2002), <https://www.classe.cornell.edu/~dugan/USPAS/Lect18.pdf>
- [9] H. J. Kim and T. Sen, "Beam simulation of the SPS", (2011), <https://indico.cern.ch/event/149614/contributions/191529/attachments/150842/213584/lhc-cc11-11-14-2011.pdf>
- [10] P. Baudrenghien, T. Mastoridis, private communication.