

Noise studies with Crab Cavities in the SPS for
the HL-LHC project



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by

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Day Month Year

Abstract

Acknowledgments

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List of Symbols

E_b	Energy
CC	Crab Cavity
V_{CC}	CC voltage
f_{CC}	CC frequency
ϕ_{CC}	CC phase
Q_x	Horizontal tune
Q_y	Vertical tune
ψ_y	Vetical phase advance

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1 | Introduction

This is the introduction of my PhD thesis.

1. Introduction

Testing for footers and headers Testing citation [1]. wefeklje

Test list of symbols with E_b .

2 | Basics of accelerator beam dynamics

3 | Theory of Crab Cavity noise induced emittance growth

4 | Experimental studies 2018: Operational setup and beam instrumentation

In 2018, two prototype Crab Cavities (CCs) were installed in the SPS to be tested for the first time with proton beams. A series of dedicated machine development studies was carried out in order to validate their working principle and answer various beam dynamic questions. One of the operational issues that needed to be addressed concerned the expected emittance growth due to noise in their RF system, which is the main subject of this thesis. As mentioned in Chapt... a theoretical model had already been developed and validated by tracking simulations [1]. As a part of the first experimental campaign with CCs in SPS a dedicated experiment was conducted to benchmark these models with experimental data and confirm the analytical predictions. The objective of this chapter is to provide an overview of the general machine setup for the CC experiments and introduce the instruments and methods used for measuring the beam parameters of interest for the emittance growth studies.

The chapter is structured as follows: Section 4.1 describes the installation of the CCs in the SPS and the experimental machine configuration. According to the theoretical model we need to measure the crab cavity voltage, the emittance and the bunch length.

The use of the Head-Tail (HT) monitor as the main diagnostic device for measurement of the crabbing is presented in Section 4.2. Last, the analysis of the HT measurements for the calibration of the CC voltage and the reconstruction of the crabbing are discussed in Sections 4.2.2 and ?? respectively. test

4.1 Crab Cavities in the SPS

For the SPS tests two prototype CCs of the Double Quarter Wave (DQW) type were fabricated by CERN and were assembled into the same cryomodule which is shown in Fig. 4.1 [2]. The cryomodule was installed in the SPS-LSS6 zone, Fig. 4.2, and was placed on a mobile transfer table [3]. The table moved with high precision and without breaking the vacuum the cryomodule in the beam line for the CC tests and out of it for the usual SPS operation. The main parameters for the CC experiments in SPS are shown in Table 4.1

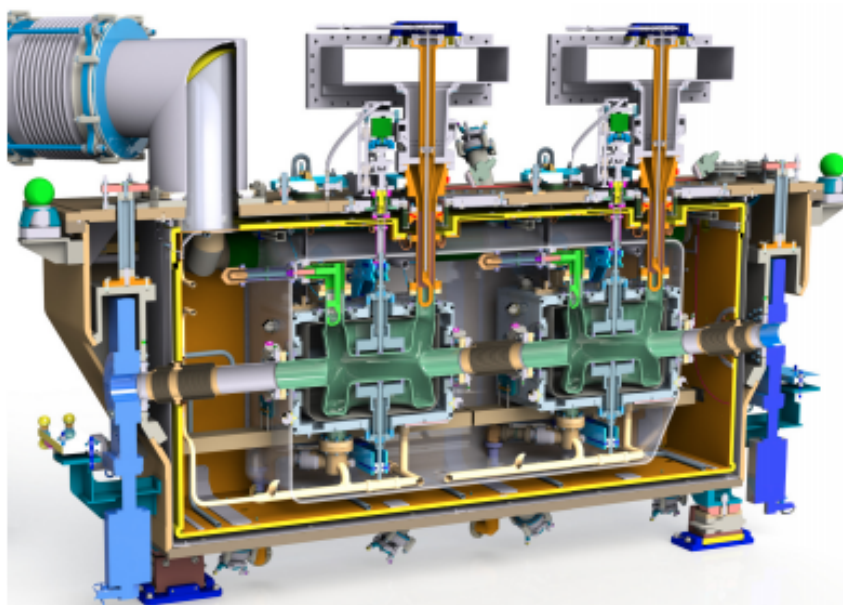


Figure 4.1: Cut of the CC cryomodule [2].

4.1.1 Operational considerations

For the beam tests with the CCs in the SPS the approach regarding the energy ramp and the adjustment of the phasing with the main RF system needed to be evaluated and they are briefly discussed here.

Energy ramp

SPS receives the beam at 26 GeV. It was observed that if the ramp to higher energies was performed with the CC on, the beam was lost while crossing one of the vertical betatron sidebands due to resonant excitation [4]. Therefore, it was established that

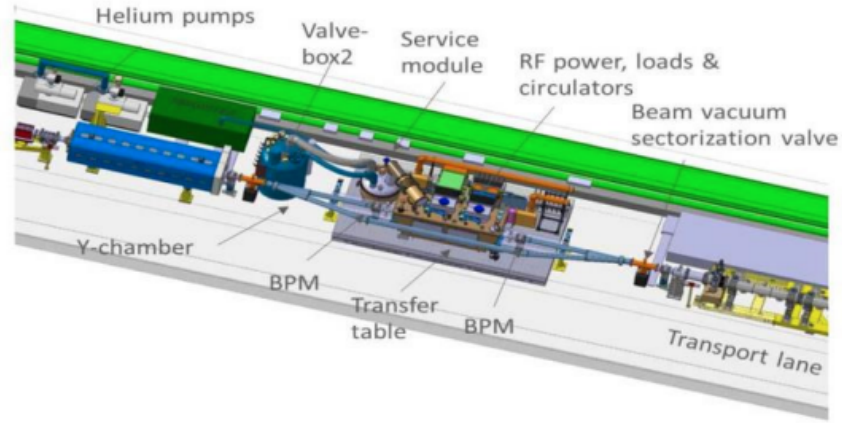


Figure 4.2: Installation of the cryomodule in the SPS-LSS6 zone [3].

Table 4.1: Parametes for the SPS CC tests

Parameters	Units	Values	
E_b	[GeV]	26, 270	
Main RF frequency	[MHz]	200	
Q_x / Q_y	[-]	26.13 / 26.18	
		CC1	CC2
crabbing plane	[-]	vertical	vertical
s-location	[m]	6312.72	6313.32
$V_{CC, MAX}$	[MV]	4.3	4.3
f_{CC}	[MHz]	400	400
$\beta_{x,CC} / \beta_{y,CC}$	[m]	29.24 / 76.07	30.31 / 73.82
$\alpha_{x,CC} / \alpha_{y,CC}$	[m]	-0.88 / 1.9	-0.91 / 1.86
$D_{x,CC} / D_{y,CC}$	[m]	-0.48 / 0	-0.5 / 0

the acceleration has to be performed with the CC off and its voltage must be set up only after the energy of interest has been achieved. It should be noted here that this will be the approach also for the HL-LHC.

Crab Cavity - main RF synchronisation

Another issue of concern was the fact that the CC operate at the fixed frequency of 400 MHz while the SPS main RF system operates at 200 MHz. In order to make sure

that the beam will experience the same effect from the CC each turn the SPS main RF has to be re-phased such as it becomes synchronous with the crabbing signal. For studies at the injection energy of 26 GeV this synchronisation took place shortly after the injection. For studies at 270 GeV, like the emittance growth measurements, the synchronisation took place at the end of the ramp shortly after the cavity was switched on [5].

4.2 The Head-Tail monitor

The HT monitor was the main diagnostic device deployed for the calibration of the CC voltage. Additionally, it was used for the measurement and the physical illustration of the crabbing. This made it a very useful tool in the time of the experiments as it provided a direct validation of the effect of the CC kick on the beam. The HT monitor was originally designed for measuring chromaticity and transverse instabilities. Therefore its use as a crabbing diagnostic should be explained here. The methods and procedures described in this section were developed at CERN and they are described here for the completeness of the thesis.

In the first part of this section some general information on the instrument along with example signals will be presented. Subsequently, the post processing of the HT signal in the presence of the CCs. Last, the calibration of the CC voltage from the HT data is described. The experimental data presented in this section were acquired at the SPS injection energy of 26 GeV with only one CC, CC1, at $\phi_{CC} = 0$ for simplicity. That energy option was chosen as the effect of CC kick on the beam is stronger and thus more visible than in higher energies.

General information

The HT monitor is a high bandwidth version of a standard beam position monitor but it can measure the transverse offset within the bunch. This makes it ideal for the measurement of the intra-bunch offset caused from the CC kick. Its reading consists of the sum Σ and the difference Δ of the electrode signals of a straight stripline coupler (Fig. 4.3) [7, 6] over a defined acquisition period. The Σ signal is the longitudinal line density while the Δ signal corresponds to the intra-bunch offset.

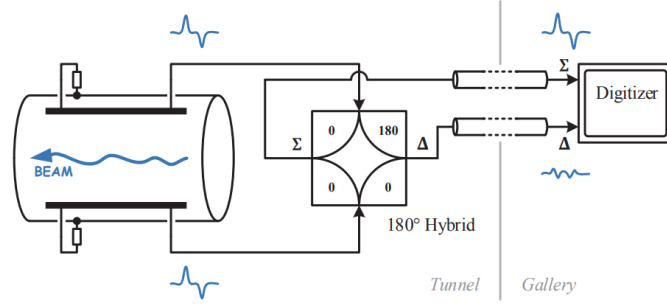


Figure 4.3: Diagram of the SPS HT monitor [6].

The raw signals from the HT monitor require a specific post processing procedure, which is described in Ref. [6], in order to give useful information. Figure 4.4 shows some example signals obtained from the HT monitor after the basic post processing is applied. Moreover, Fig. 4.5 shows a 2D representation of the HT monitor reading. It is worth noting here that in the specific example a clear periodic oscillation of the vertical intra-bunch offset (vertical Δ) signal is observed. This is a result of the main RF system not being synchronous with the CC frequency.

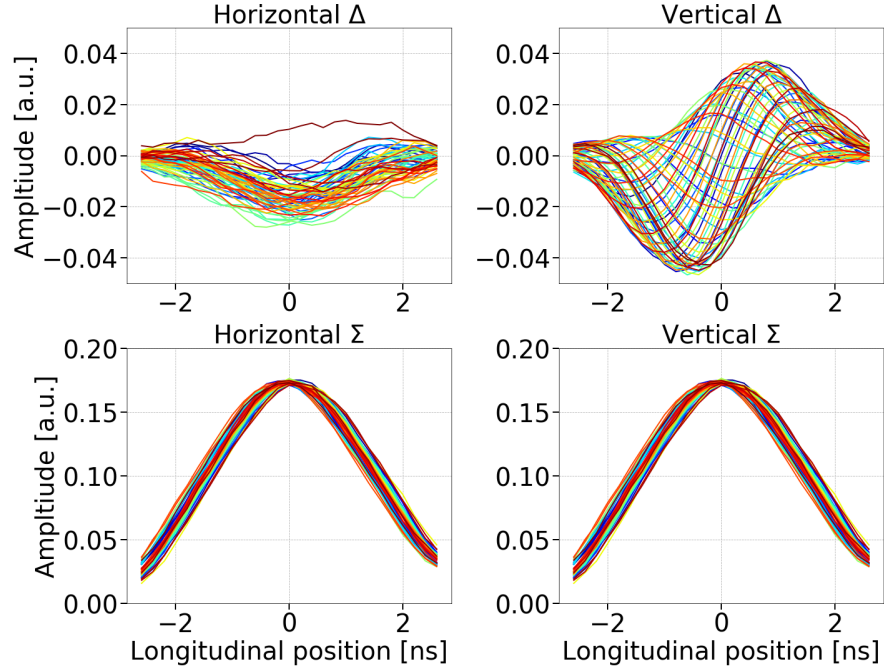


Figure 4.4: Example Δ and Σ signals from the HT monitor with respect to the longitudinal position within the bunch over several SPS revolutions, after the basic post processing (Ref. [6]) but before the baseline correction. The different colors indicate the signals from different turns.

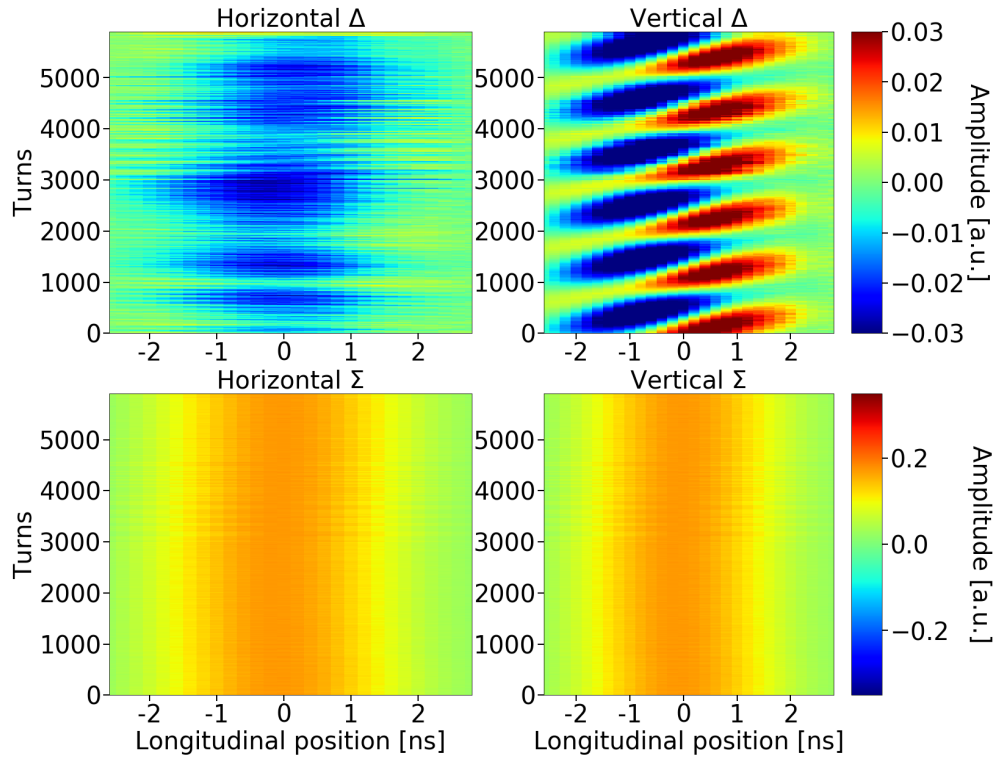


Figure 4.5: 2D representation of example Δ and Σ signals with respect to the longitudinal position within the bunch obtained from the HT monitor over several SPS revolutions.

4.2.1 Post processing in the presence of Crab Cavities

To obtain useful information from the HT monitor signal in the presence of the CCs there are a few steps that differ from the standard post processing procedure and they are described below.

Heat-Tail monitor baseline correction

One issue of concern is the correction of the Δ signal baseline due to orbit offsets and non-linearities of the instrument [6]. During the normal post processing, the correction is achieved by computing the mean of the Δ signals over all turns and then subtracting this static offset from the signal of each turn. However, in the SPS tests, where the CCs are well synchronised with the main RF system (Section 4.1), the crabbing signal is also a static intra-bunch position offset and thus would also be removed with the usual method.

Therefore, for the CC experiments a reference measurement had first to be made

with the CC unsynchronised. The mean of the Δ signal over this reference period was the baseline which then was subtracted from the Δ signals acquired after the synchronisation (Fig 4.6). The datasets before and after synchronisation are easily distinguishable in the 2D HT monitor reading as displayed in Fig. 4.7

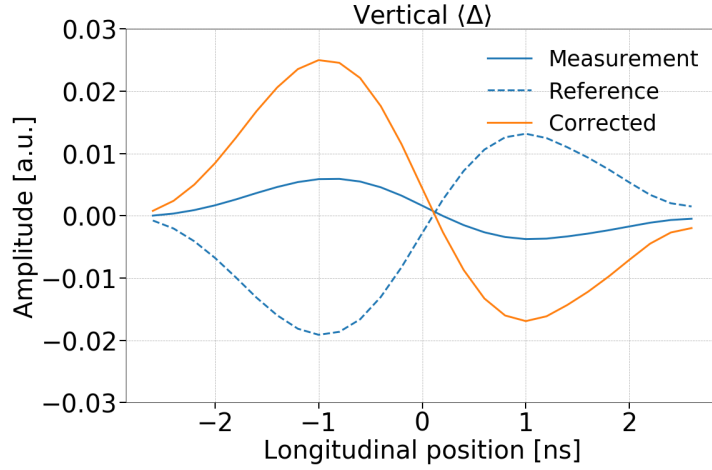


Figure 4.6: HT monitor baseline correction for the SPS CC tests.

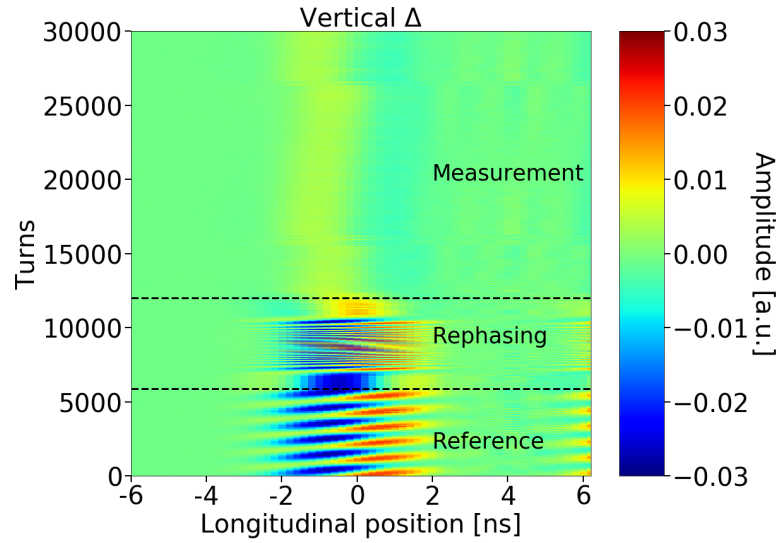


Figure 4.7: HT acquisitions before and after the synchronisation of the SPS main RF with the CC.

Headtail monitor calibration

The last step, to make the HT acquisitions meaningful is to convert the measured intra bunch offset, $\langle\Delta\rangle$, from arbitrary units to mm. The scaling is achieved by division with the $\langle\Sigma\rangle$ signal and with a normalisation factor which is provided by the calibration of the HT monitor [8]. The normalisation factor for the SPS was mea-

sured at 0.1052 in 2018 [9]. Figure 4.8 shows the intra bunch offset from the CC kick in mm and after the baseline correction.

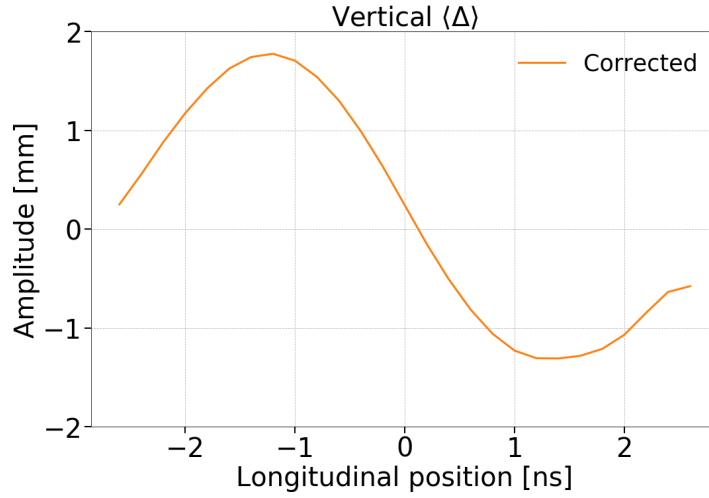


Figure 4.8: Intra-bunch offset from the CC kick expressed in mm after the removal of the baseline.

4.2.2 Crab Cavity voltage calibration

This section discusses the beam based measurement of the CC voltage from the HT monitor signal. The calibration was performed by calculating the kick required to reconstruct the measured intra-bunch offset using Eq. (4.1). Equation (4.1), which is obtained from Chaos' Eq. (1) from chapter 4.7.1 in Ref. [10], gives the vertical orbit shift (in meters) from the CC kick, θ , at the HT monitor location as follows:

$$\Delta y_{HT} = \frac{\sqrt{\beta_{y,HT}}}{2 \sin(\pi Q_y)} \theta \sqrt{\beta_{y,CC} \cos(\pi Q_y - |\psi_{y,HT} - \psi_{y,CC}|)}, \quad (4.1)$$

where β_y is the beta function, Q_y is the tune, and ψ_y is the phase advance in tune units. The same applies for the horizontal plane. The indices HT and CC indicate the optic parameters at the location of the HT monitor and CC respectively.

The deflection from the CC is written as $\theta = -\frac{qV(t)}{E_b}$, where q is the charge of the particle, E_b the beam energy and $V_{CC}(t) = V_{CC} \sin(2\pi f_{CC}t + \phi_{CC})$ is the voltage that a particle experiences while passing through the CC. Computing the maximum of $V_{CC}(t)$ gives the cavity voltage, V_{CC} .

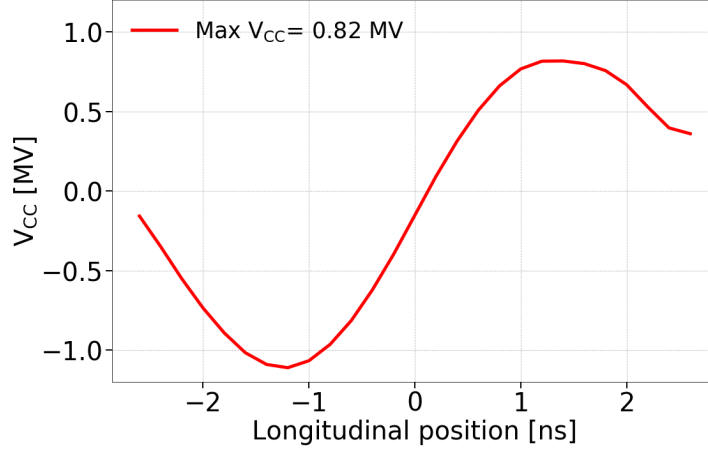


Figure 4.9: CC voltage calibration from the HT monitor.

It should be noted here, that the measured intra-bunch offset, Δy_{HT} , is inserted in Eq. (4.1) after removing the baseline and converting it in mm as discussed in Section 4.2.1. Figure 4.9 illustrates the cavity voltage computed from the HT signals shown already in this section. The corresponding beam and optic parameters are listed in Table 4.2

Table 4.2: Parameters for computing the CC voltage from the example HT monitor measurements discussed in this chapter

Parameters	Units	Values
$\beta_{y,HT} / \beta_{y,CC1}$	[m]	49.19 / 76.07
$\psi_{y,HT} / \psi_{y,CC1}$	[-]	15.68 / 23.9
Q_y	[-]	26.13
E_b	[GeV]	26

Reconstruction of crabbing

The reconstruction of the crabbing from the HT monitor measurements and the physical illustration of it are presented here. This technique was developed at CERN in 2018 and it was extensively used throughout the experimental campaign with CCs as alongside the calibrated voltage it gives a straightforward estimation of the applied CC kick, as illustrated in Fig. 4.10.

To obtain this physical illustration of the effect of the CC kick on the beam one needs

to modulate the measured longitudinal profile, $\langle \Sigma \rangle$, with the measured intra-bunch offset (e.g. Fig. 4.8). For the transverse plane a gaussian distribution is considered with σ obtained from the wire scanner (addressed in more details in the following section). The color code is normalised to the maximum intensity within the bunch.

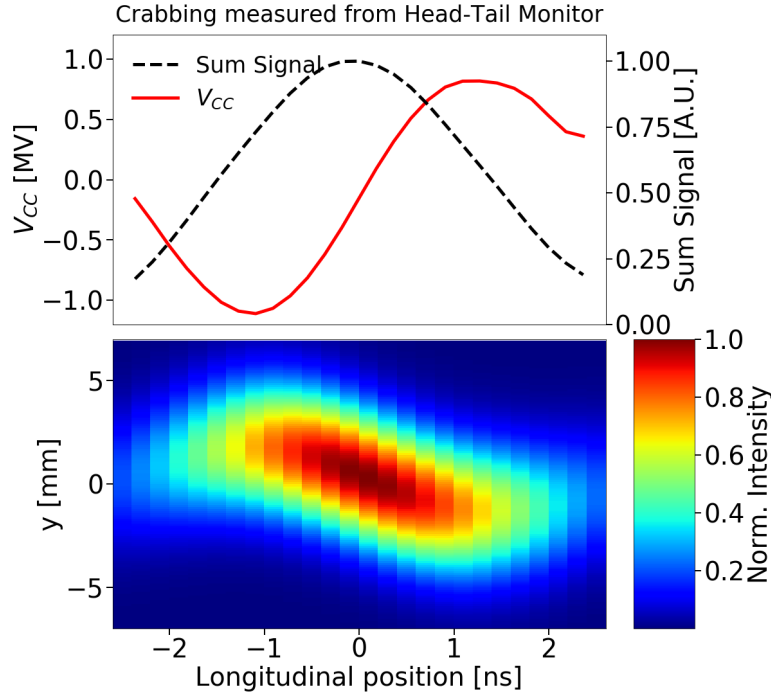


Figure 4.10: Illustration of the crabbing from the HT monitor signal.

4.3 The Wire Scanners

The SPS is equipped with rotating beam wire scanners (WS) [11, 12] to measure the transverse beam emittance. The working principle is the following: a thin wire rapidly moves across the beam and a shower of secondary particles is generated, which is then detected by a system of scintillator and photomultiplier, as sketched in Fig. 4.11.

Hence, the WS signal consists of the measured light intensity with respect to the wire position. As the wire crosses the beam over multiple turns the transverse beam profile is obtained. It is worth noting that in every passage of the beam from the WS two scans are performed with the wire moving in the forward direction (IN scan) and then backwards (OUT scan) [13]. An example of the WS profiles is shown in

Fig. 4.12

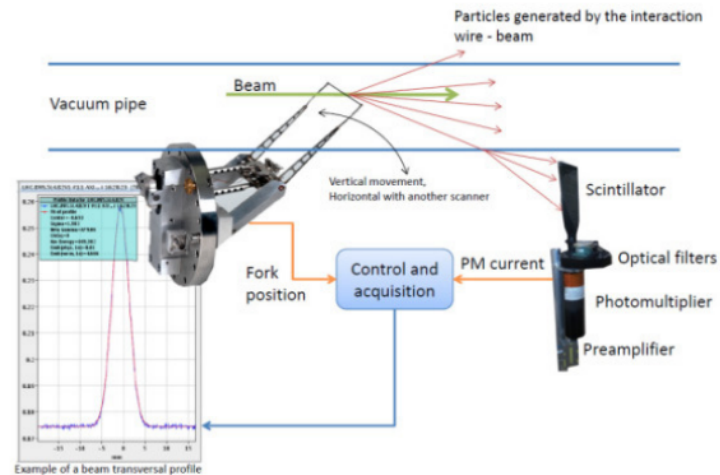


Figure 4.11: Sketch of the SPS rotational wire scanners [12]

Measuring transverse beam emittance

tes tets tes

- which one will be used in the experiment and why? (past studies showed they are not destructive) - How to Obtain emittance from porifile: Gaussian 4p fit - Dispersion for H plane. (for the 2018 was very small not taken into account)

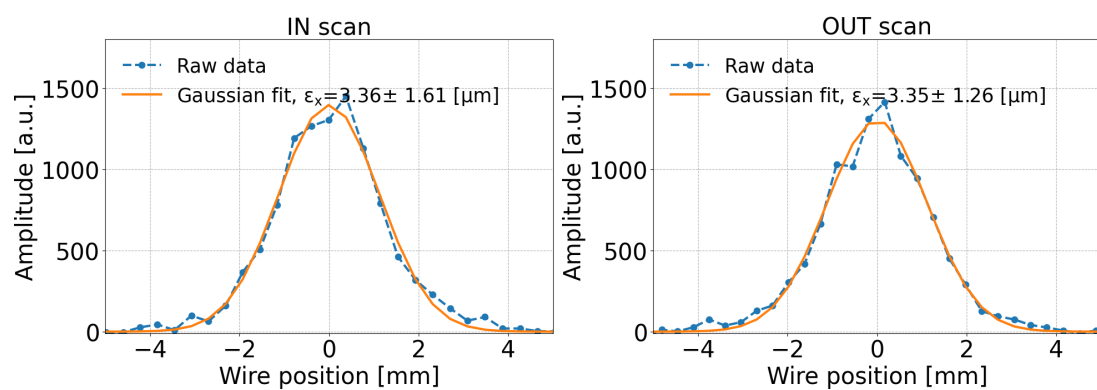


Figure 4.12: A figure with two subfigures

4.4 The mountain range or whatever was used for the bunch length measurement

4.5 ABWLM

4.6 BCT? with what was the intensity measured

4.7 Conclusions

Post processing steps for the ones I have performed the analysis. The others just menitoned.

5 | Emittance growth measurements with Crab Cavity noise in 2018

In 2018, two prototype Crab Cavities (CCs) were installed in the SPS to be tested for the first time with proton beams. One of the operational issues that needed to be addressed concerned the expected emittance growth due to noise in their RF control system. A theoretical model that describes this emittance growth had already been developed and validated by tracking simulations [1]. Based on those studies a dedicated experiment was performed to benchmark the models with experimental data and to confirm the analytical predictions. In particular, the idea was to inject various noise levels in the CC RF system and record the emittance evolution. In this chapter, the experimental procedure, the measurement methods and results are presented and discussed.

The chapter is structured as follows: Section 4.1 describes the operational setup for the SPS CC tests and discusses the main diagnostic deployed for the derivation of the CC voltage.

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5.1 Crab Cavities in the SPS

For the SPS tests two prototype CCs of the Double Quarter Wave (DQW) type were fabricated by CERN and were assembled into the same cryomodule [2]. The cryomodule was installed in the SPS-LSS6 zone and was placed on a mobile transfer ta-

ble [Garlasch:2648553]. The table moved with high precision and without breaking the vacuum the cryomodule in the beam line for the CC tests and out of it for the usual SPS operation. For the emittance growth measurements only one of these CCs was used and its main optics and design parameters are listed in Table ??.

5.2 Experimental procedure

5.2.1 Machine and beam configuration

5.2.2 Measurement methods

What do we measure and how? emittance (show plots) bunch length ABWLM → we take the measurement directly from the responsible team → show also from the instrument that we saw the unstable bunches.

5.3 Experimental results

5.3.1 Overview

- bunches 2, 3 and 4 unstable

5.3.2 Comparison with the theory

This chapter is adapted from the the studies published in Ref. [14]

5.4 Experimental Setup

Several experimental studies have been performed (2010-2017) to identify the optimal conditions for the emittance growth studies with CCs in the SPS [15, 16]. Based on these preparatory studies, the measurements in the SPS were performed with four low intensity ($\sim 3 \cdot 10^{10}$ ppb) bunches at 270 GeV. To minimise the emittance growth from other sources [16] the first order chromaticity, Q' , of the machine was corrected to small positive values ($\sim 1-2$) in both the horizontal and the vertical planes. During the measurements the Landau octupoles were switched off. It should be note, though, that a residual non-linearity was present in the machine mainly due to multipole components in the dipole magnets [17, 18]. Only one CC was used, providing a vertical kick to the beam. The transverse feedback system was switched off. Even though the emittance growth is a single bunch effect four bunches were used to reduce the statistical uncertainty of the measurements. The distance between the bunhces was 524 ns. An overview of the relevant SPS parameters during the experiment is given in Table

5.4.1 Injected RF noise

In order to characterize the CC noise induced emittance growth, controlled noise was injected into their LLRF system and the evolution of the bunch was recorded for about 20-40 minutes. The injected noise was a mixture of amplitude and phase noise up to 10 KHz, overlapping and primarily exciting the first betatron sideband at ~ 8 kHz. The phase noise was always dominant.

6 | Investigation of the discrepancy

7 | Simple model of describing the decoherence suppression from impedance

8 | Application and impact for HL-LHC

9 | Conclusion

A | Appendix Title

Bibliography

- [1] P. Baudrenghien and T. Mastoridis. “Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities”. In: *Phys. Rev. ST Accel. Beams* 18 (10 Oct. 2015), p. 101001. DOI: 10.1103/PhysRevSTAB.18.101001. URL: <https://link.aps.org/doi/10.1103/PhysRevSTAB.18.101001>.
- [2] C. Zanoni et al. “The crab cavities cryomodule for SPS test”. In: 874 (July 2017), p. 012092. DOI: 10.1088/1742-6596/874/1/012092. URL: <https://doi.org/10.1088/1742-6596/874/1/012092>.
- [3] Rama Calaga, Ofelia Capatina, and Giovanna Vandoni. “The SPS Tests of the HL-LHC Crab Cavities”. In: (2018), TUPAF057. 4 p. DOI: 10.18429/JACoW-IPAC2018-TUPAF057. URL: <https://cds.cern.ch/record/2649807>.
- [4] Rama Calaga. *SPS Crab Cavity test RF Test Program*. Accessed: 11-11-2021. URL: <https://indico.cern.ch/event/718127/contributions/2951305/attachments/1645650/2629988/SPSCCtestv3.pdf>.
- [5] Carver Lee. *First proton beam dynamics results with crab cavities*. Accessed: 10-11-2021. URL: https://indico.cern.ch/event/800428/attachments/1804664/2945632/CrabCavity_BE_Seminar.pdf.
- [6] Thomas Levens, Kacper Łasocha, and Thibaut Lefèvre. “Recent Developments for Instability Monitoring at the LHC”. In: (2017), THAL02. 4 p. DOI: 10.18429/JACoW-IBIC2016-THAL02. URL: <https://cds.cern.ch/record/2313358>.
- [7] R. Jones and H. Schmickler. “The measurement of Q' and Q" in the CERN-SPS by head-tail phase shift analysis”. In: *PACS2001. Proceedings of the 2001 Particle Accelerator Conference (Cat. No.01CH37268)*. Vol. 1. 2001, 531–533 vol.1. DOI: 10.1109/PAC.2001.987561.

- [8] T. E. Levens et al. “Automatic detection of transverse beam instabilities in the Large Hadron Collider”. In: *Phys. Rev. Accel. Beams* 22 (11 Nov. 2019), p. 112803. DOI: 10.1103/PhysRevAccelBeams.22.112803. URL: <https://link.aps.org/doi/10.1103/PhysRevAccelBeams.22.112803>.
- [9] Tom Levens. *Beam instrumentation with SPS Crabs*. Accessed: 11-11-2021. URL: https://indico.cern.ch/event/718127/contributions/2951309/attachments/1646050/2630808/BI_SPS_Crabs.pdf.
- [10] Alexander Wu Chao et al. *Handbook of accelerator physics and engineering; 2nd ed.* Singapore: World Scientific, 2013. DOI: 10.1142/8543. URL: <https://cds.cern.ch/record/1490001>.
- [11] J. Bosser et al. “Transverse emittance measurement with a rapid wire scanner at the CERN SPS”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 235.3 (1985), pp. 475–480. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/0168-9002\(85\)90096-8](https://doi.org/10.1016/0168-9002(85)90096-8). URL: <https://www.sciencedirect.com/science/article/pii/0168900285900968>.
- [12] OE Berrig et al. *CERN-SPS Wire Scanner Impedance and Wire Heating Studies*. Tech. rep. Geneva: CERN, Sept. 2014. URL: <https://cds.cern.ch/record/1972478>.
- [13] B Dehning et al. “Accuracy of the SPS transverse emittance monitors”. In: (Apr. 2005), 3 p. URL: <https://cds.cern.ch/record/895164>.
- [14] Natalia Triantafyllou. “INVESTIGATION OF DAMPING EFFECTS OF THE CRAB CAVITY NOISE INDUCED EMITTANCE GROWTH”. In: (2021), TBA. DOI: TBA. URL: TBA.
- [15] R Calaga et al. “Proton-beam emittance growth in SPS coasts”. In: *Conf. Proc.* C1205201 (May 2012), THPPP007. 3 p. URL: <https://cds.cern.ch/record/1451286>.
- [16] Fanouria Antoniou et al. “Emittance Growth in Coast in the SPS at CERN”. In: *J. Phys.: Conf. Ser.* 1067 (2018), MOPMF061. 7 p. DOI: 10.18429/JACoW-IPAC2018-MOPMF061. URL: <https://cds.cern.ch/record/2649815>.

- [17] Michele Carlà et al. “Studies of a New Optics With Intermediate Transition Energy as Alternative for High Intensity LHC Beams in the CERN SPS”. In: (2018), TUPAF022. 4 p. DOI: 10.18429/JACoW-IPAC2018-TUPAF022. URL: <https://cds.cern.ch/record/2664976>.
- [18] Androula Alekou et al. “SPS Long Term Stability Studies in the Presence of Crab Cavities and High Order Multipoles”. In: (2018), WEP2PO008. 3 p. DOI: 10.18429/JACoW-HB2018-WEP2PO008. URL: <https://cds.cern.ch/record/2640326>.