

Studies of the emittance growth due to noise in the Crab Cavity RF systems



Thesis submitted in accordance with the requirements of the
University of Liverpool for the degree of Doctor in Philosophy

by

Natalia Triantafyllou

Day Month Year

Abstract

Acknowledgments

List of Figures

1.1	Schematic view of the CERN accelerator complex. The different colors correspond to the different machines. The year of commissioning and the type of particles used in each one of them are also indicated along with the circumference for the circular machines. The image is courtesy of CERN.	2
1.2	Visualisation of the CC kick (green line) on the bunch particles (blue dots). The bunch here appears much smaller than the CC wavelength which means that only the linear part of the kick affects the bunch. This will be the case for the HL-LHC scenario.	5
1.3	Layout of the LHC and the SPS. The CC location for the HL-LHC configuration is marked. Two CCs (one per ring) will be installed on each side of ATLAS (red) and CMS (orange). Two prototype CCs were also installed in the SPS (magenta) in 2018, to be tested before their installation in LHC. The layout can be found in Ref. [9] and was modified inspired by Ref. [10].	6
1.4	Collision with and without the use of CCs [11]. CCs restore the overlap between the bunches recovering the luminosity reduction caused by the crossing angle, θ_c . The blue and red colors indicate two bunches in the different rings.	6
2.1	Co-ordinate system used to describe particles motion in a synchrotron. This is a rotating co-ordinate system, with $(\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z)$ being the unit vectors, which follows the reference trajectory along the accelerator. . .	13

2.2 Longitudinal bunch slicing for the implementation of wakefields kicks in PyHEADTAIL. Without the slicing technique (left) the wake kicks on the red macroparticle are generated from all the green macroparticles resulting to computationally heavy simulations. Instead, when the bunch is sliced longitudinally (right) the wake kicks on the macroparticles in the red slice i are generated by the macroparticles in the green slices j , decreasing significantly the computation time. The figures are a courtesy of M. Schenk [34]	25
2.3 Graphic representation of the accelerator model and tracking procedure in PyHEADTAIL (inspired by the graphs in Refs. [34, 36]). In this example the ring is splitted in four segments separated by the interaction points (IPs). Wakefield and multiple kicks are applied on the macroparticles in IP2 and IP4. The macroparticles are transported between the IPs by a linear map (which can include detuning effects) in the transverse plane. The longitudinal coordinates are updated once per turn without being visualised in this plot.	26
4.1 Cross section view of the CC cryomodule [21]. It has a total length of 3 m [39] and at its core there are the two DQW cavities, which are illustrated with light green color.	30
4.2 Diagram of the SPS HT monitor [43]. The beam is passing through a straight stripline coupler which is followed by a 180° hybrid. This configuration provides the sum (Σ) and the difference (Δ) signal of the two electrodes.	33
4.3 Example difference and sum signals (top and bottom plots, respectively) from the HT monitor, in time scale, with respect to the longitudinal position within the bunch over several SPS revolutions, after the basic post processing [43] but before the baseline correction. The different colors indicate the signals from different turns (every 100 turns).	33
4.4 2D representation of example difference and sum signals with respect to the longitudinal position within the bunch obtained from the HT monitor over several SPS revolutions.	34

0. List of Figures

4.5 HT monitor baseline correction for the SPS CC tests. The baseline signal (blue dashed line) refers to the mean of the difference signals acquired before the CC - main RF synchronisation. The measured signal (blue solid line) corresponds to the mean of the difference signal acquired after the synchronisation. Last, the corrected signal (orange solid line) is obtained after subtracting the baseline from the measured signal.	35
4.6 HT acquisitions before and after the synchronisation of the SPS main RF with the CC.	35
4.7 Intra-bunch offset from the CC kick expressed in millimeters after the removal of the baseline.	36
4.8 CC voltage reconstruction from the HT monitor.	37
4.9 Demonstration of the crabbing from the HT monitor signal. CC voltage and sum signal (longitudinal line density) measured from the HT monitor (top) together with the density plot (bottom) which visualises the effect of the CC kick on the beam.	39
4.10 Demonstration of the sinusoidal fit on the HT monitor reading in order to obtain the CC parameters. A four-parameter sinusoidal fit is performed using Eq. (4.2) in order to obtain the amplitude, V_{CC} , the frequency, f_{CC} , the phase, ϕ_{CC} , and the voltage offset, k . The fit results are given in the yellow box.	40
4.11 Phase scan with CC1 at 26 GeV. The sensitivity of the measured CC voltage (left) and its uncertainty (right) on the phase is studied. The error bars of the voltage, V_{CC} , indicate the uncertainty, ΔV_{CC} . The error bars of the uncertainty, ΔV_{CC} , and the phase, ϕ_{CC} , correspond to the error of the respective fit result (see Appendix A.2) The error bars are not visible here as they are smaller than the markers.	41

5.1 Demonstration of the sinusoidal fit on the HT monitor reading in order to obtain the CC parameters as described in Section 4.4. The fit results, are given in the yellow box. The measured voltage amplitude, V_{CC} , was found to be 0.99 MV while its uncertainty, ΔV_{CC} , was measured at 0.04 MV. The measured voltage value agrees well with the requested value of 1 MV.	45
5.2 Example amplitude (left) and phase (right) noise spectra measured with a spectrum analyzer E5052B [52] during the emittance growth studies with CCs in SPS. The noise extends up to 10 kHz (grey dashed line) overlapping the first betatron sideband at \sim 8 kHz (green dashed line). The spikes at high frequencies correspond to the harmonics of the revolution frequency and are a result of the bunch crossing.	47
5.3 Sketch of the SPS rotational wire scanners [54]. The wire moves across the proton beam generating secondary particles which are then detecting by a scintillator and a photomultiplier. From the measured photomultiplier current the beam profile is reconstructed.	50
5.4 Vertical beam profile obtained from the BWS.41677.V instrument. The measured data points (light blue) are fitted with a four parameter gaussian (orange) to obtain the beam size. The calculated emittance and its uncertainty are also shown.	50
5.5 Bunch by bunch horizontal (top) and vertical (bottom) emittance evolution during the experiment on September, 15, 2018. The four different colors indicate the different bunches. The different applied noise levels are also shown while the moments when the noise level changed are indicated with the grey vertical dashed lines. The emittance growth rates along with their uncertainties for the seven different noise settings are displayed at the legend at the bottom of the plots.	54
5.6 Summary plot of the emittance growth study with CC noise in 2018. The transverse emittance growth rate, for the four bunches, is shown as a function of the different levels of applied noise.	55

0. List of Figures

5.7 Evolution of the beam in transverse and longitudinal planes during the CC noise induced emittance growth experiment. Top: Horizontal emittance growth measured with the SPS WS. Middle: Vertical emittance growth measured with the SPS WS. Bottom: Bunch length evolution measured with the ABWLM (small markers) and the Wall Current Monitor (bigger markers).	57
5.8 Longitudinal profiles (top) and relative bunch position with respect to the center of the RF bucket (bottom) acquired with the Wall Current Monitor. The acquisitions correspond to the times when the sudden jumps in the bunch length evolution are observed (see Fig. 5.7).	58
5.9 Intensity evolution as measured with ABLWM (smaller markers) and with the Wall Current Monitor (bigger markers) during the experiment with CC noise in 2018.	60
5.10 Summary plot of the emittance growth study with CC noise in 2018 focused on bunch 1 only. The measured emittance growth rate (blue) and the expected growths from the theoretical model (black) are shown as a function of the different levels of applied noise.	62
7.1 Horizontal (left) and vertical (right) impedance model of the SPS. The model is available in the public gitlab repository of Ref. [63].	67
7.2 Horizontal (left) and vertical (right) wakefunctions of the SPS. The wake functions are available in the public gitlab repository of Ref. [63]. For comparison the bunch length in the SPS CC experiments is ~ 1.85 ns ($4\sigma_t$).	68
B.1 Sampling of the continuous signal $y(t)$ at a finite number of points N . The sampled signal is the discrete-time signal $y(n\Delta t)$ with Δt the sampling interval and n an integer such that $n \in [0, N - 1]$	80
B.2 Example of a signal sampled at discrete time intervals, and the corresponding discrete Fourier transform.	81
B.3 Power spectrum of $y = \sin(2\pi f t)$, $f = 50$ Hz.	83
B.4 Single-sided power spectrum of the signal shown in Fig. B.2(a).	84

B.5 Instantaneous voltage of an oscillator in the presence of (a) amplitude noise, (b) phase noise, and (c) both amplitude and phase noise.	86
B.6 Steps required to generate the sequence of noise kicks to be applied in the simulations from the measured noise spectrum.	90
B.7 Power spectral density computed from the time series ϕ_n produced from a measured power spectrum (black), compared with the original measured power spectrum (green).	91
B.8 Comparison between emittance growth found from simulations in PyHEADTAIL and emittance growth expected from an analytical model [62]. The emittance growth is driven by amplitude and phase noise, with kicks in the simulations generated from a measured power spectrum. .	93

List of Tables

2.1	Multipole errors from SPS non-linear model, at 270 GeV	20
4.1	Crab Cavities design parameters for the SPS tests in 2018.	31
4.2	Parameters for computing the CC voltage from the example HT monitor measurements discussed in this chapter.	38
5.1	Main machine and beam parameters for the emittance growth studies with CCs in SPS in 2018.	46
5.2	Phase and amplitude noise levels injected in the CC RF system for the emittance growth studies of 2018. The listed values correspond to the average PSD values over a frequency range of ± 500 Hz around the first betatron sideband, f_b . The calculated effective phase noise for the parameters of the first bunch are also listed.	49
5.3	Comparison between the measured and the calculated transverse emittance growth rates for bunch 1 for the different noise levels, and average bunch length for each case.	62
7.1	Relevant machine and beam parameters used to study the impact of the beam transverse impedance on the emittance evolution due to CC RF noise with the PyHEADTAIL code.	69

List of Symbols

E_b	Energy
J_x	Horizontal particle action
J_y	Vertical particle action
f_{rev}	Revolution frequency
V_{RF}	Main RF voltage
f_{RF}	Main RF frequency
CC	Crab Cavity
V_{CC}	CC voltage
f_{CC}	CC frequency
ϕ_{CC}	CC phase
β_{CC}	Beta function at the CC
Q_x	Horizontal tune
Q_y	Vertical tune
Q_s	Synchrotron tune
D_x	Horizontal dispersion function
D_y	Vertical dispersion function
β_0	Relativistic beta
γ_0	Relativistic gamma (Lorenz factor)
N_b	Bunch intensity i.e. number of particles (here protons)
Q'_x	Horizontal first order chromaticity
Q'_y	Vertical first order chromaticity
σ_t	Rms bunch length
ϵ_x^n	Horizontal normalised emittance of the beam
ϵ_y^n	Vertical normalised emittance of the beam
ϵ_x^{geom}	Horizontal geometric emittance of the beam
ϵ_y^{geom}	Vertical geometric emittance of the beam
ΔQ_x^{rms}	Betatron horizontal rms tune spread
ΔQ_y^{rms}	Betatron vertical rms tune spread
α_{xx}	Horizontal detuning coefficient

0. List of Tables

α_{yy}	Vertical detuning coefficient
$\alpha_{xy} = \alpha_{yx}$	Cross-detuning coefficients
k_{LOF}	LHC Software Architecture (LSA) trim editor knobs for SPS Landau octupoles, LOF family
k_{LOD}	LHC Software Architecture (LSA) trim editor knobs for SPS Landau octupoles, LOD family

Contents

Abstract	iii
Acknowledgments	v
List of figures	xi
List of tables	xii
List of symbols	xiv
1 Introduction	1
1.1 The CERN accelerator complex	1
1.1.1 The CERN Super Proton Synchrotron	3
1.2 High-Luminosity LHC project and Crab Cavities	3
1.2.1 Crab cavities	4
1.3 Motivation, objectives and thesis outline	7
2 Basics of accelerator beam dynamics	11
2.1 Motion of charged particles in electromagentic fields	11
2.2 Single-particle beam dynamics	14
2.2.1 Transvserse motion	15
2.2.2 Longitudinal motion	18
2.3 Collective effects	18
2.3.1 Beam transverse impedance	18
2.4 Optics models of accelerators	18
2.5 General parameters of the studies	19
2.5.1 SPS optics	19

0. Contents

2.6 Luminosity	20
2.7 Emittance	20
2.8 Transfer maps	21
2.9 Action angle variables	21
2.10 Wakefields and impedances	22
2.11 Tracking simulation codes	22
2.11.1 PyHEADTAIL	22
2.11.2 Sixtracklib	25
3 Theory of Crab Cavity noise induced emittance growth	27
3.1 Modelling of phase and amplitude noise in simulations	28
4 Calibration of the Crab Cavities for the SPS tests in 2018	29
4.1 Crab Cavities' installation in the SPS	29
4.2 Operational considerations	30
4.3 SPS Head-Tail monitor as the main diagnostic	31
4.3.1 General information	32
4.3.2 Post processing in the presence of Crab Cavities	34
4.3.3 Crab Cavity voltage reconstruction	36
4.3.4 Demonstration of crabbing with proton beams	37
4.4 Characterisation of measured Crab Cavity voltage	38
4.4.1 Definitions of the amplitude and the uncertainty of the measurement	38
4.4.2 Dependence of the crab cavity voltage and offset on the phase .	41
5 Experimental studies 2018: emittance growth from Crab Cavity noise	43
5.1 Experimental configuration and procedure	43
5.1.1 Preparatory experimental studies	44
5.1.2 Machine and beam configuration	44
5.1.3 Experimental procedure	46
5.2 Injected RF noise	46
5.3 Emittance growth measurements	48
5.3.1 SPS Wire Scanners	49
5.3.2 Experimental results	52

5.4	Bunch length and intensity measurements	55
5.4.1	ABWLM and Wall Current Monitor	56
5.4.2	Bunch length measurements	56
5.4.3	Longitudinal profile measurements	58
5.4.4	Intensity measurements	59
5.5	Comparison of measured transverse emittance growth with the theoretical predictions	59
5.6	Conclusions and outlook	62
6	Investigation of the discrepancy	64
6.1	Benchmarking with different simulation software	64
6.1.1	PyHEADTAIL	64
6.1.2	Sixtracklib	64
6.2	Sensitivity to the non-linearities of the main SPS dipoles	64
6.3	Simulations using the measured noise spectrum	64
6.4	Sensitivity studies	65
6.5	b3b5b7 multiple errors	65
7	Simulation studies: Suppression mechanism from the beam transverse impedance	66
7.1	SPS transverse impedance model	66
7.1.1	Coherent tune shift with intensity and growth rate	67
7.2	Simulations setup	68
7.3	First observations of emittance growth suppression by the impedance	70
7.4	Characterisation of the emittance growth suppression by the impedance	70
8	Experimental studies 2021	71
9	Simple model of describing the decoherence suppression from impedance	72
10	Conclusion	73
A	Definitions and methods of statistical analysis	74
A.1	Basic terminology	74
A.1.1	Averages	74
A.1.2	Measuring the spread	75

0. Contents

A.1.3 Data sets with more than one variables - Covariance	76
A.2 Least squares fitting	76
A.3 Propagation of uncertainty	77
B Fundamentals of signal analysis and measurement	78
B.1 Continuous-time analysis	78
B.2 Discrete-time analysis	80
B.3 Measuring amplitude and phase noise	85
B.4 Applying a measured noise spectrum in numerical simulations	87
B.4.1 Crab cavity noise in numerical simulations	87
B.4.2 Measured noise spectrum	88
B.4.3 Generating time series	88
B.4.4 Validation of the time series reconstruction	91
C Appendix c	94
C.1 Detuning with amplitude	94
D Glossary and defintions	97
Bibliography	105

1 | Introduction

Particle accelerators were first developed in the early 20th century as a tool for high-energy physics research. By increasing particles' energy they allow us to investigate the subatomic structure of the world and to study the properties of the elementary particles and the fundamental forces. On a basic level, accelerators increase the energy of charged particles using electric fields. Through the years significant technological progress has been achieved resulting in higher energies and greatly enhanced performance of the machines. Additionally, various types of accelerators have been developed (cyclotrons, linacs, synchrotrons etc) using different types of particles (hadrons or leptons) and their use was also expanded in other fields such as medicine and industrial research.

1.1 The CERN accelerator complex

CERN (European Organisation of Nuclear Research), located on the Franco-Swiss border near Geneva, is at the forefront of the accelerator physics research as it operates an extensive network of accelerators, illustrated in Fig. 1.1, including the well-known Large Hadron Collider (LHC) [1].

LHC is a circular machine, 27 km long, built about 100 m underground and is currently the largest and most powerful accelerator. It accelerates and collides two counter-rotating beams of protons or ions (circulating in two different rings) at the four main experiments which are located around the LHC ring, namely ATLAS, CMS, ALICE and LHCb. The highlight of CERN and of the LHC operation up to now was the discovery of the Higgs boson in 2012 from ATLAS [2] and CMS [3], from proton collisions at 3.5 TeV (center-of-mass energy of 7 TeV), which was a milestone for the standard model.

1. Introduction

The beams used by the LHC are produced and gradually accelerated by the injector chain which is a sequence of smaller machines boosting the energy of the beam. In particular, Linac4 (which replaced Linac2 in 2020) accelerates the protons up to 160 MeV, the Proton Synchrotron Booster (PSB) up to 2 GeV, the Proton Synchrotron (PS) up to 26 GeV and the Super Proton Synchrotron (SPS) up to 450 GeV. Finally, the protons are injected in the LHC where they are accelerated up to the collision energy of 6.5 TeV (center-of-mass energy of 13 TeV). It should be noted, that LHC delivered collisions with center-of-mass energy of 7 TeV during Run 1 (2010-2013) which was increased to 13 TeV for the Run 2 (2015-2018) and for Run 3 (2020-present).

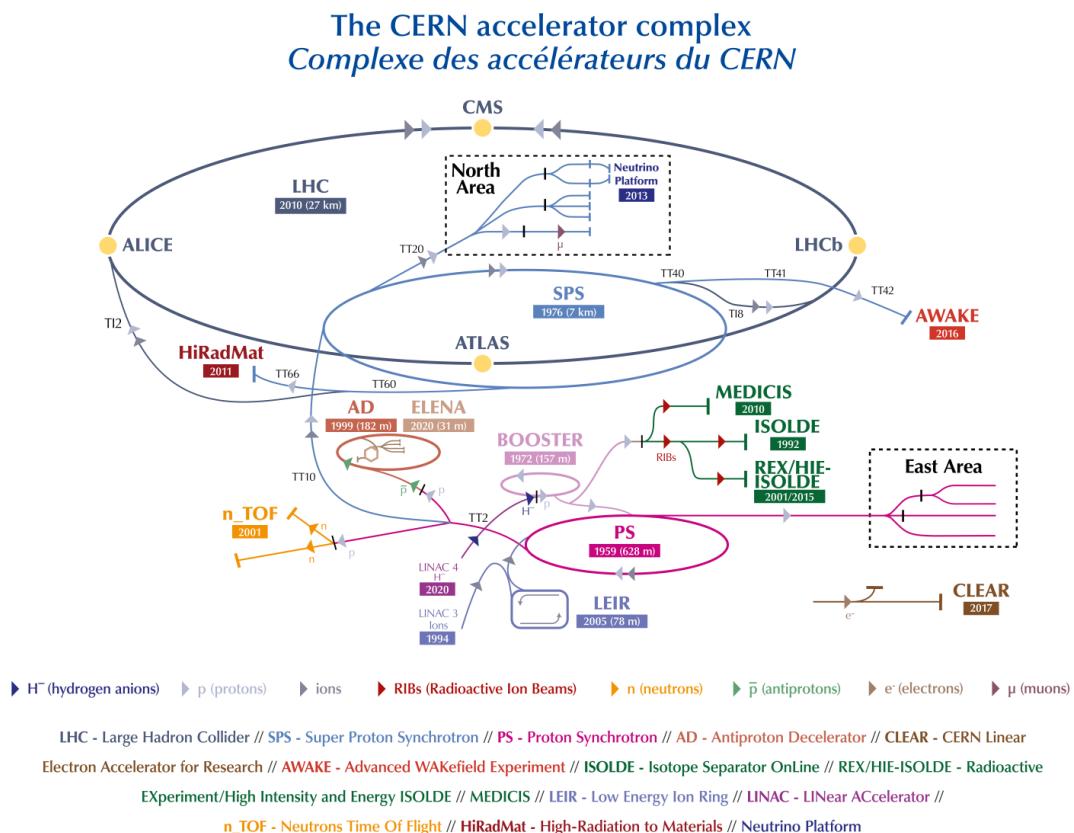


Figure 1.1: Schematic view of the CERN accelerator complex. The different colors correspond to the different machines. The year of commissioning and the type of particles used in each one of them are also indicated along with the circumference for the circular machines. The image is courtesy of CERN.

It is worth mentioning that not only protons but also lead ions are accelerated in the LHC, starting their journey from Linac3 and LEIR and then following the same route as proton beams.

Finally, the accelerators in the injector chain not only prepare the beam for the LHC but also provide beams to various other facilities and experiments at lower energies. Examples are the Anti-proton Decelerator (AD) which studies antimatter, the Online Isotope Mass Separator (ISOLDE) which studies the properties of the atomic nuclei using radioactive beams, and the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) which investigates particle acceleration by proton-driven plasma wakefields.

1.1.1 The CERN Super Proton Synchrotron

The majority of the research described in this thesis was conducted for the Super Proton Synchrotron (SPS). Thus, some additional information about this machine is provided here. The SPS (shown with light blue color in Fig. 1.1) was first commissioned in 1967 and has a circumference of 6.9 km. It used to operate as a proton-antiproton collider ($\text{Sp}\bar{\text{p}}\text{S}$) and later on as an injector for the Large Electron Positron collider (LEP) while it also provided beams for fixed-target experiments (e.g. in the North Area). Even though the SPS can accelerate various particle types (protons, antiprotons, electrons, and heavy ions) the following information will concern its operation with proton beams which is the topic of the research presented in this thesis.

Currently, the SPS is the second biggest accelerator at CERN and it can accelerate protons from 26 GeV up to 450 GeV. Due to its past use as a collider, it can also operate as a storage ring. This operational mode is called "coast" and was used for the majority of the experimental studies presented in this thesis. During coast, the bunches circulate in the machine for long periods at constant energy. The highest energy at which SPS can operate in coast is 270 GeV due to limited cooling of the magnets to transfer away the heating when operating at high energy and consequently at large currents for long periods.

1.2 High-Luminosity LHC project and Crab Cavities

High-Luminosity LHC (HL-LHC) [4, 5] is the upgrade of the LHC machine which will extend its potential for discoveries. In particular, it aims to increase the instan-

1. Introduction

taneous luminosity by a factor of 5 beyond the current operational values and the integrated luminosity by a factor of 10.

The luminosity, along with the energy, is a key parameter defining the performance of a collider as is a measure of the collision rate. The instantaneous luminosity is expressed as [6]:

$$\mathcal{L} = \frac{n_b f_{rev} N_1 N_2}{4\pi \sigma_x \sigma_y} \frac{1}{\sqrt{1 + (\frac{\sigma_z}{\sigma_{x\text{ing}}} \frac{\theta_c}{2})^2}}, \quad (1.1)$$

where f_{rev} is the revolution frequency of the machine, n_b is the number of colliding bunch pairs, $N_{1,2}$ is the number of particles per bunch, $\sigma_{x,y}$ is the transverse beam size at the interaction point, σ_z the rms bunch length, $\sigma_{x\text{ing}}$ the transverse beam size in the crossing plane and θ_c is the full crossing angle between the colliding beams. The crossing angle, is often introduced between the bunches in a collider to reduce parasitic collisions and get rid of the remnants after the collision. For reference, in the LHC, the crossing angle has order of magnitude 10^{-4} radians.

The integrated luminosity is the one that ultimately defines the performance of the machine as it provides the total number of recorded events. It depends both on the instantaneous luminosity and on the machine availability. The integrated luminosity, is expressed as [4]:

$$\mathcal{L}_I \equiv \int_{\Delta t} \mathcal{L} dt, \quad (1.2)$$

where \mathcal{L} is the instantaneous luminosity as defined in Eq. (1.1).

HL-LHC aims to achieve instantaneous luminosity of $\mathcal{L} \sim 5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and an increase on the integrated luminosity from 300 fb^{-1} to 3000 fb^{-1} over its lifetime of 10-12 years and considering 160 days of operation per year [7].

1.2.1 Crab cavities

To achieve its luminosity goals, HL-LHC will employ numerous innovative technologies. Crab cavity technology (will be denoted as CC in this thesis) [8] is one of the key components of the project as it will be employed to restore the luminosity

reduction caused by the crossing angle, θ_c (see Eq. (1.1)).

A crab cavity is an RF cavity which provides a transverse, sinusoidal like, kick to the particles depending on their longitudinal position within the bunch. A graphical visualisation of the kick is shown in Fig. 1.2. It can be seen that the head (leading part) and the tail (trailing part) of the bunch receive opposite deflection while the particles at the center remain unaffected.

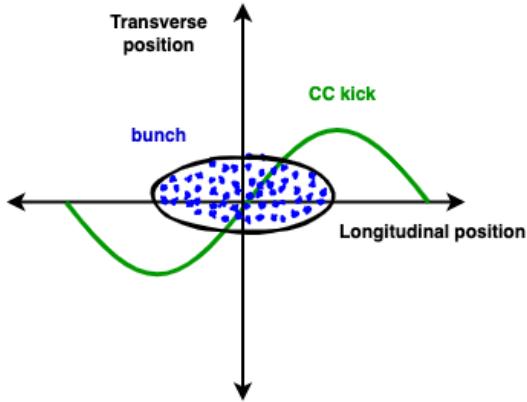


Figure 1.2: Visualisation of the CC kick (green line) on the bunch particles (blue dots). The bunch here appears much smaller than the CC wavelength which means that only the linear part of the kick affects the bunch. This will be the case for the HL-LHC scenario.

The CCs will be installed in the two main interaction points of LHC, ATLAS and CMS. According to the plan, two CCs will be installed on each ring and on each side of the interaction points (eight in total). This is displayed in Fig. 1.3 with the red (ATLAS) and orange (CMS) markers. The reason why two CCs are needed in each ring on each side of the IP is discussed in the following paragraphs (local vs global scheme).

In this configuration, the bunches receive the transverse deflection from the first pair of CCs just before reaching the interaction point. This results in a rotation of the bunch, which mitigates the crossing angle and restores the head-on collisions. The deflection is cancelled once the bunches reach the second pair of CCs which are symmetrically placed at the opposite side of the interaction point. The collision of the bunches in the presence of the CCs is illustrated in Fig. 1.4 [11].

The above scheme, with CCs before and after the interaction point, is called the local crabbing scheme. An alternative scheme, named the global crabbing scheme, was

1. Introduction

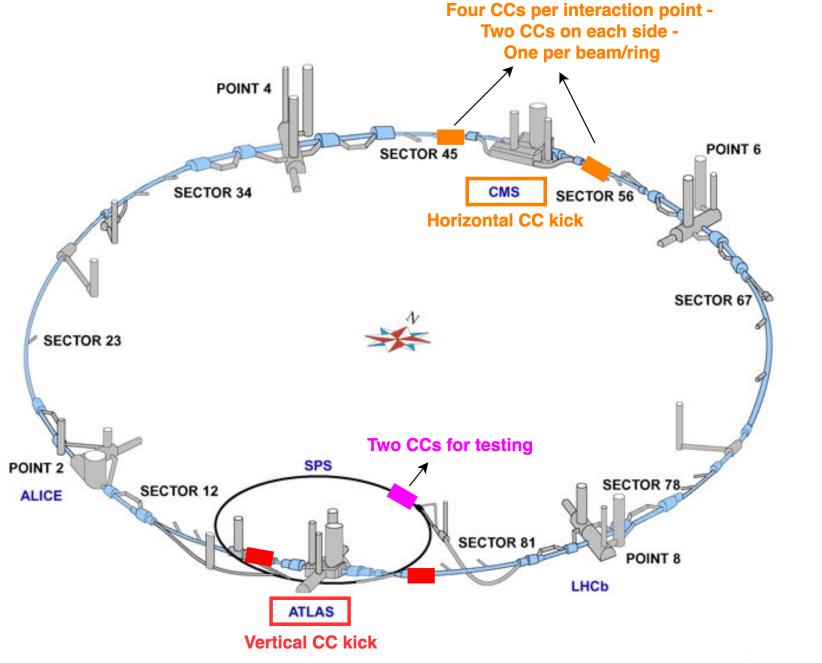


Figure 1.3: Layout of the LHC and the SPS. The CC location for the HL-LHC configuration is marked. Two CCs (one per ring) will be installed on each side of ATLAS (red) and CMS (orange). Two prototype CCs were also installed in the SPS (magenta) in 2018, to be tested before their installation in LHC. The layout can be found in Ref. [9] and was modified inspired by Ref. [10].

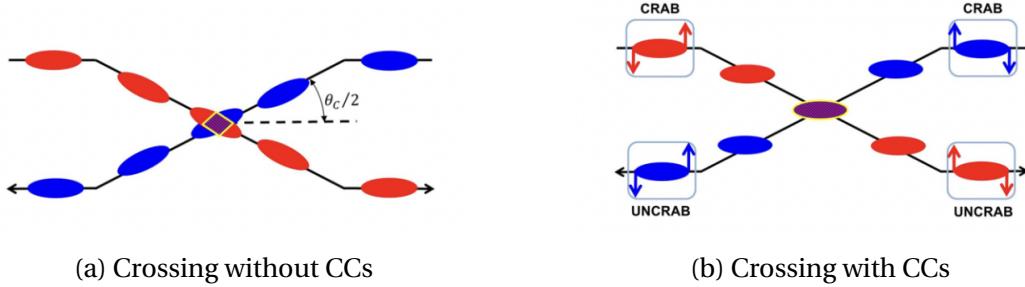


Figure 1.4: Collision with and without the use of CCs [11]. CCs restore the overlap between the bunches recovering the luminosity reduction caused by the crossing angle, θ_c . The blue and red colors indicate two bunches in the different rings.

also under discussion in the first stages of the project. In such a scheme, the closed orbit distortion that is caused by the fact that the head and the tail of the bunch are kicked in opposite directions propagates in the ring, resulting in transverse bunch oscillations [5]. This scheme is cost-efficient compared to the local scheme as it only requires two CCs. However, it introduces significant constraints on the betatron phase advance between the interaction points and the CCs. The constraints are enhanced by the fact that the bunch crossing in ATLAS takes place in the vertical

plane while in CMS in the horizontal. To this end, the local CC scheme was chosen for the HL-LHC configuration.

In order to accommodate the crossing in both transverse planes two CC designs have been developed: the Double-Quarter Wave (DQW) and the RF dipole (RFD), which provide vertical and horizontal deflection respectively. Information on their design can be found in Refs. [12, 13, 14, 15]

The CCs have already been successfully used in the KEKB collider in Japan, during 2007-2010, with lepton beams ($e^+ - e^-$) [16, 17, 18]. However, there are significant differences in the beam dynamics in the presence of CCs in leptons and hadrons (HL-LHC case). One of the most crucial points is the impact of errors (e.g. RF noise) which leads to beam degradation [19, 20]. This is not an issue of concern for lepton beams as they nevertheless experience emittance damping due to synchrotron radiation. For proton beams, the synchrotron radiation damping is much weaker meaning that the beam degradation can lead to emittance growth which eventually can result in loss of luminosity.

As the CCs have never been used with protons before, two prototype superconducting CCs were installed in the SPS (Fig. 1.3, magenta markers) to test the technical systems, to validate their operation with proton beams and to identify and address potential issues before their installation in LHC. The SPS provides an ideal test bed for these studies as it allows testing under conditions that are closer to those in HL-LHC than any other machine. In particular, the SPS operates with proton beams, can run in storage-ring mode, and in terms of the energy reach is second only to LHC. The two CCs that were installed in SPS [21] were identical, fabricated at CERN and of the DQW type (like the ones that will be used in ATLAS interaction point in HL-LHC).

1.3 Motivation, objectives and thesis outline

As mentioned above, one of the main concerns regarding the CC operation with protons is the emittance growth due to noise in their RF system as it leads to luminosity loss. For the HL-LHC, the target values regarding the luminosity loss and

1. Introduction

emittance growth are very tight. In particular the maximum allowed luminosity loss due to CC RF noise induced emittance growth is targeted at just 1%, during a physics fill, which corresponds to an CC RF noise induced emittance growth of 2 %/h [22, 23, 24]. To this end, a good understanding and characterization of the emittance growth mechanism is crucial for the HL-LHC project.

It should be added here that a physics fill is the time period during which the beams are successfully injected in the LHC at the desired conditions, they are accelerated at the desired energy and they are kept in the machine for consecutive collisions. After some hours, due to beam degradation the beams are dumped and a new fill is prepared. A fill in the HL-LHC will last a couple of hours.

This thesis focuses on understanding, characterising and evaluating the mechanism of CC RF noise-induced emittance growth including numerical and experimental studies. The studies presented in this thesis were conducted for the SPS machine since it has proton crabbing operational experience and allows direct comparison of predictions from models and experimental data. It should be emphasised that the CC tests in SPS constitute the first experimental beam dynamics studies with CCs and proton beams. The results and the understanding obtained from this research are essential for the HL-LHC, in order to predict the long-term emittance and to define limits on the acceptable noise levels for the CCs.

This thesis reports research that was carried out between 2018 and 2022, based at CERN and it structured as follows:

Chapter 2 presents the basics of accelerator beam dynamics focusing on the concepts that are relevant for understanding the studies presented in this thesis. **This paragraph needs to be re-written after you finish chapter 2.** In particular, definitions are given for linear optics, non-linear optics, of emittance, transfer maps, wake-fields, detuning with amplitude. Finally, the two simulation codes used in this thesis for macroparticle tracking, PYHEADTAIL and Sixtracklib, are described.

The mechanism of noise induced emittance growth and in particular of the CC RF noise induced emittance growth is explained in Chapter 3. The modelling of the noise effects in the simulations is also discussed. **Finalise after writing chapter 3.**

Chapter 4 is devoted to the methodology used for the calibration of the CCs. The first sections provide some general details on the CC installation and operation in the SPS. The instrument that is used as the main diagnostic is described. Finally, the post-processing of the measurements to characterise the CC voltage and phase is explained.

The results from the first experimental studies of the emittance growth from CC RF noise in the SPS are presented in Chapter 5. First, the experimental configuration and procedure is reported. Second the artificial noise injected in the CC RF system for the measurements is discussed in detail. Subsequently, the emittance growth measurements are presented along with the measured bunch length and intensity evolution for completeness. Last the measured emittance growth rates are compared with the predictions from the theoretical model (described in Chapter 3). It was found the the measured growth rates were systematically a factor of 4 on average lower than the predictions.

Various possible factors were investigated as a possible explanation for this discrepancy. These extensive studies, which took place over two years are described in Chapter 6. Initially, the theory was benchmarked with different simulation software: PyHEADTAIL and Sixtracklib. The sensitivity of the emittance evolution on the non-linearities of the SPS machine (which was not included in the theory of Chapter 3) was also tested. Last, thorough studies were performed to exclude the possibility that the discrepancy is not a result of possible errors in the analysis of the experimental data or the actual noise levels applied on the CCs. However, none of these factors could explain the discrepancy.

Finally, simulations including the SPS transverse impedance model (not included in the theory (of Chapter 3) showed a significant impact on the emittance growth. Chapter 7 discusses the investigation and characterisation the phenomenon of the emittance growth suppression from the beam coupling impedance as observed in simulations with PyHEADTAIL. It was shown that the suppression is related to the dipole motion which is excited by the CC RF phase noise.

Chapter 8, presents the results from the second round of emittance growth measurements with CCs in SPS that took place in 2022. The objective of these exper-

1. Introduction

imental studies was to validate the mechanism of the suppression of the CC RF noise-induced emittance growth from the beam coupling impedance as observed in simulations (described in Chapter 7). This would also confirm that this impedance-induced effect is the reason for the discrepancy observed in the 2018 experiment between the measurements and the theoretical predictions. The experiments of 2022 successfully confirmed the suppression mechanism, despite the very challenging conditions of the studies.

In Chapter 9, further experimental results with the use of the SPS transverse damper as a source of noise are shown. The measurements took place in 2022, after the CC experiment for the same machine and beam conditions. The objective was to obtain further measurements which would validate the mechanism of the suppression of the noise-induced emittance growth by the impedance. The use of the damper is an appropriate configuration as it provides dipolar noise kicks in the beam and as shown in Chapter 7 the suppression mechanism is related to the dipole motion. The experimental results from use of the damper are also compared with the predictions from a recently developed theoretical model from X. Buffat which describes the emittance growth suppression from a collective force.

Last, Chapter 10 summarizes the conclusions of the thesis. The project is viewed from a broad perspective highlighting its importance. Potential follow up studies are proposed. [Comment on Appendix?](#).

2 | Basics of accelerator beam dynamics

The definitions and notations used throughout this thesis are based on the book of A. Wolksi in Ref. [25] unless it is stated otherwise. In this chapter, the basic concepts of accelerator beam physics that are essential for understanding the studies presented here are introduced. The focus is put on the concepts for synchrotrons with proton beams. Additionally, in the last section, the tracking simulation codes used in this work are described.

Synchrotrons are circular accelerators where the particles follow a fixed closed-loop path. In a synchrotron, electric fields accelerate the particles while magnetic fields steer and focus them. The magnetic fields are not constant but they vary according to the particles' energy, allowing acceleration and operation in very high (relativistic) energies. The LHC and SPS machines at CERN are synchrotrons like the most of the machines used for High Energy Physics experiments. Usually, in synchrotrons, the beams consist of multiple bunches, longitudinally spaced around the machine, which of course interact with each other. However, these multi-bunch interactions are not relevant to the studies presented in this thesis. Therefore, they are not addressed in the following paragraphs.

2.1 Motion of charged particles in electromagnetic fields

The motion of a particle with charge q and velocity $\mathbf{v} = (v_x, v_y, v_z)$ moving in an electric field \mathbf{E} and a magnetic field \mathbf{B} is defined by the influence of the Lorentz force:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}). \quad (2.1)$$

At this point, it is appropriate to mention that in this thesis the vectors are denoted

2. Basics of accelerator beam dynamics

in bold font (e.g. **E**).

In synchrotrons, the electric fields, which are generated by Radiofrequency (RF) cavities, are used for accelerating the beams. The magnetic fields, are used to steer (dipoles) and focus (quadrupoles) and apply corrections (sextupoles, octupoles and higher order multipoles) at the motion of the beam.

Reference trajectory and reference particle

The sequence of the various electromagnetic elements around the accelerator ring is called the machine lattice. The ideal path that passes through the center of all the magnets is called the design orbit or the reference trajectory. This reference trajectory (red line Fig. 2.1) has circumference $C = 2\pi R$ (where R is the radius of the ring) and is predetermined by the construction of the accelerator.

The particle that follows this trajectory is called the reference particle and has a momentum p_0 , an energy E_0 , and a velocity v_0 . This particle is often called the synchronous particle as it always passes from the center of the RF cavities (assuming constant speed and no losses). For a proton, the reference momentum is given by:

$p_0 = \gamma_0 m_p v_0$, where m_p is the proton rest mass.

Magnetic rigidity

At this point, it is appropriate to introduce the concept of magnetic rigidity, $B_0\rho$, which is often used in accelerators as a normalisation factor and is a measure of how the charged particles resist bending by a dipolar magnetic field. Assuming that a proton moves only under the influence of a uniform vertical dipole field $\mathbf{B}_0 = (0, B_0, 0)$, it would follow a circular path of radius ρ which is defined by the Lorentz force (Eq. (2.1)) being equal to the centripetal force, as follows:

$$ev_0 B_0 = \frac{\gamma_0 m_p v_0^2}{\rho} \Rightarrow B_0 \rho = \frac{\gamma_0 m_p v_0}{e} \Rightarrow B_0 \rho = \frac{p_0}{e}, \quad (2.2)$$

where e and m_p are the charge and rest mass of a proton respectively, p_0 is the reference momentum, and $\gamma_0 = \frac{1}{\sqrt{1-\beta^2}}$ is the relativistic gamma or Lorentz factor, where $\beta = v_0/c$ is the relativistic β . In the ultra-relativistic regime which is the case in the studies presented in this thesis, $\beta = 1$.

If the particle momentum is given in GeV/c (usual units in high energy accelerators)

then the unit of magnetic rigidity is T · m.

Co-ordinate system

However, the individual particles do not follow the reference trajectory: an example trajectory is shown in Fig. 2.1 with the blue line. The co-ordinate system used to describe the individual trajectories of the beam particles around the accelerator is illustrated in Fig. 2.1 and it is known as Frenet-Serret system. It consists of the orthogonal co-ordinate system $\Sigma(s) = (\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z)$ whose origin moves along the reference trajectory (red line) together with the beam.

The variable s denotes the distance along the reference trajectory. In accelerator physics, s is usually chosen as the independent variable instead of time, t . Therefore, at any given location s around the ring, the coordinates $(x(s), y(s), z(s))$ give the horizontal, vertical, and longitudinal position of the particle with respect to the origin of the orthogonal moving system Σ . In the following paragraphs, the dependence of the co-ordinates on the position s along the ring is omitted when possible to facilitate the notation (e.g. $x(s)$ will be denoted as x).

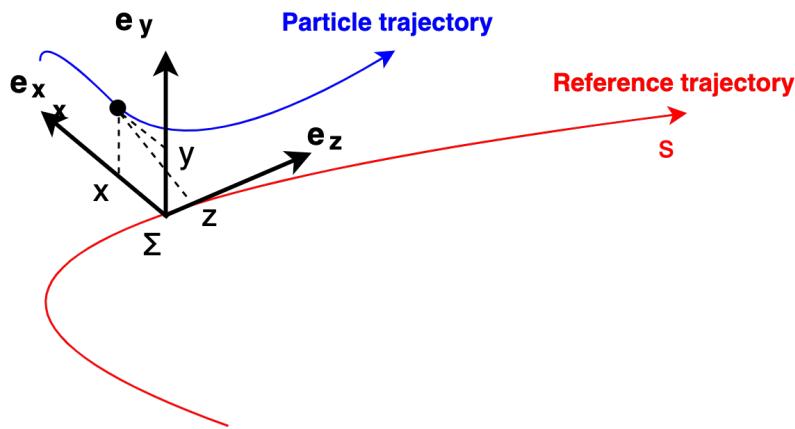


Figure 2.1: Co-ordinate system used to describe particles motion in a synchrotron. This is a rotating co-ordinate system, with $(\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z)$ being the unit vectors, which follows the reference trajectory along the accelerator.

At any point s along the reference trajectory each particle is represented by the following 6-dimensional vector $(x, x', y, y', z, \delta)$ where:

$$x' = \frac{dx}{ds} = \frac{dx}{dt} \frac{dt}{ds} = \frac{v_x}{v_z} = \frac{p_x}{p_z} \approx \frac{p_x}{p_0}, \quad (2.3a)$$

$$y' = \frac{dy}{ds} = \frac{dy}{dt} \frac{dt}{ds} = \frac{v_y}{v_z} = \frac{p_y}{p_z} \approx \frac{p_y}{p_0}, \quad (2.3b)$$

$$\delta = \frac{\Delta p}{p_0} = \frac{p - p_0}{p_0}, \quad (2.3c)$$

where p_0 is the momentum of the reference particle as defined in the previous paragraph.

It can be seen that x' and y' are basically the normalised momenta with the reference momentum p_0 and δ is the relative momentum offset from the reference particle. The co-ordinates and the momentum of the reference particle are ($x = y = z = 0$) and ($p_x = p_y = 0, p_z = p_0$) respectively.

Furthermore, if the direction of motion of the particle has a small angle with the reference trajectory, the paraxial approximation is valid: $p_x, p_y \ll p_z = p_0$ which means that $x' \approx p_x$ and $y' \approx p_y$. This approximation is valid for the studies presented in this thesis. ***p₀ = 1? not clear to me***

To summarize, the motion of the particles is separated in the transverse and longitudinal planes where it is described with the (x, x', y, y') and (z, δ) co-ordinates respectively. In order to avoid a possible misconception it seems appropriate to clarify here, that the longitudinal parameter z indicates the longitudinal offset from the reference particle at the center of the bunch. If $z > 0$ ($z < 0$) the corresponding particle reaches earlier (later) than the center of the bunch at an arbitrary reference point.

2.2 Single-particle beam dynamics

In this first section, the interactions between the particles within a bunch are neglected, hence the term single-particle beam dynamics.

Two-dimensional complex fields

As already discussed, the motion of the charged particles inside a circular accelerator is controlled by magnetic fields. In this thesis, the magnets are considered purely transverse elements. Their effect is therefore described with two-dimensional mul-

tipole fields, acting in the horizontal and vertical planes¹.

The description of two-dimensional magnetic fields in accelerator physics is discussed using the concept of multipole expansion and is expressed as a complex quantity. The complex quantity it allows to describe a two-dimensional field in (x, y) space (to be compatible with the co-ordinates used for describing the particle's trajectory as discussed in the previous section). Therefore, the magnetic field around the beam is expressed as follows [25]:

$$B_y(x, y) + iB_x(x, y) = \sum_{n=1}^{\infty} C_n(x + iy)^{n-1}, \quad (2.4)$$

where n indicates the order of the field component: $n=1$ for a dipole (steering), $n=2$ for quadrupole (focusing (chromticity correction), $n=4$ for octupole (error or field correction) etc. $C_n = (b_n + i\alpha_n)$ is a complex constant which denotes the strength and orientation of the multipole field. The coefficients $b_n = \frac{1}{(n-1)!} \frac{\partial^{n-1} B_y}{\partial x^{n-1}}$ and $\alpha_n = \frac{1}{(n-1)!} \frac{\partial^{n-1} B_x}{\partial x^{n-1}}$ denote the strength of a normal and skew (normal multipole rotated by $\pi/2(n - 1)$) multipole respectively in units of T/m^{n-1} .

Usually, in accelerator physics the values of the multipole strengths are quoted normalised to the magnetic rigidity as defined in Eq. (2.2) and are denoted by:

$$k_n = \frac{b_n}{B_0 \rho}, \quad (2.5)$$

and is expressed in units of T/m^n . This is the convention that will be used in this thesis.

2.2.1 Transverse motion

In the transverse plane the motion is orthogonal to the reference trajectory (see Fig. 2.1) and its co-ordinates are (x, x', y, y') . For the discussion on the transverse beam dynamics, the (x, x') and (y, y') co-ordinates will be both described by (u, u') when possible to facilitate the notation.

Linear dynamics

¹Examples of three-dimensional treatment can be found in [25, 26]. However, the two-dimensional treatment is most often used in accelerator physics as it provides a good description for the majority of the magnetic elements.

2. Basics of accelerator beam dynamics

Here the transverse motion of a particle moving the two-dimensional fields described in Eq. (2.4) is discussed. For now the discussion is limited only in dipolar and quadrupolar components ($n = 1$ and $n = 2$) hence the name linear dynamics.

As mentioned above, the particles (but the reference one) transversely oscillate around the reference trajectory. This motion, through an arbitrary periodic sequence of dipoles and quadrupoles is called betatron motion and can be described with the following equations of motion [27]:

$$x'' - \frac{\rho + x}{\rho^2} = -\frac{B_y}{B_0\rho} \frac{p_0}{p} \left(1 + \frac{x}{\rho}\right)^2, \quad (2.6)$$

$$y'' = \frac{B_y}{B_0\rho} \frac{p_0}{p} \left(1 + \frac{x}{\rho}\right)^2, \quad (2.7)$$

where s is the distance along the reference trajectory, $B_0\rho$ and ρ the magnetic rigidity and radius as defined in Eq. (2.2), B_y, B_x the transverse magnetic fields of Eq. (2.4), and p_0 the reference momentum.

For on-momentum particles ($\delta = 0$) the above betatron equations of motion are simplified to the equation of harmonic oscillator, named the Hill's equation [27]:

$$u''(s) + K_u(s)u(s) = 0, \quad (2.8)$$

where $u = (x, y)$ and:

$$K_u(s) = \begin{cases} \frac{1}{\rho(s)} + k(s), & u = x \\ -k(s), & u = y \end{cases} \quad (2.9)$$

It should be noted that for Eq. (2.8) it is assumed that the motion in horizontal and vertical plane are independent (uncoupled).

As $K_u(s)$ is a periodic function, the two independent solutions of the second order differential Eq. (2.8) can be expressed using the Floquet theorem [28] as follows (see Appendix A, Sec. I.5 in Ref. [27]):

$$u(s) = a_u w(s) e^{i\psi_u(s)}, \quad u^*(s) = a_u w(s) e^{-i\psi_u(s)}, \quad (2.10)$$

where α_u is a constant, and $u(s)$ and $w(s)$ are the amplitude and phase functions and $u^*(s)$ is the complex conjugate of $u(s)$. $K_u(s)$ is real-valued, therefore the amplitude and phase functions fulfill the following equations:

$$w''_u + K_u(s) w(s) - \frac{1}{w_u(s)^3} = 0, \quad (2.11)$$

where:

$$\psi'_u(s) = \frac{1}{w_u(s)^2} \Rightarrow \psi_u(s) = \int_{s_0}^s \frac{ds}{w_u(s)^2} \quad (2.12)$$

The above equations are called the betatron envelope and phase equations. At this point it is appropriate to introduce the betatron or twiss or Courant-Snyder parameters:

$$\beta_u(s) = w_u(s)^2, \quad (2.13a)$$

$$\alpha_u(s) = -\frac{1}{2} \beta'_u(s), \quad (2.13b)$$

$$\gamma_u(s) = \frac{1 + \alpha_u(s)^2}{\beta_u(s)}, \quad (2.13c)$$

with $\beta'_u(s) = d\beta_u(s)/ds$.

Matrix formalism and Courant-Snyder parameters

The solutions of the Hill's equation can be also described using a matrix formalism as:

$$\begin{pmatrix} u \\ u' \end{pmatrix}_{s_1} = M_u(s_1|s_0) \begin{pmatrix} u \\ u' \end{pmatrix}_{s_0}, \quad (2.14)$$

where $u = (x, y)$. The transfer matrix from the position s_0 to the s_1 , $M_u(s_1|s_0)$, equals to [27]:

2. Basics of accelerator beam dynamics

$$\begin{aligned}
M_u(s_1|s_0) &= \begin{pmatrix} \sqrt{\frac{\beta_u(s_1)}{\beta_u(s_0)}}(\cos \Delta\psi_u + \alpha_u(s_0) \sin \Delta\psi_u) & \sqrt{\beta_u(s_0)\beta_u(s_1)} \sin \Delta\psi_u \\ -\frac{1+\alpha_u(s_0)\alpha_u(s_1)}{\sqrt{\beta_u(s_0)\beta_u(s_1)}} \sin \Delta\psi_u + \frac{\alpha_u(s_0)-\alpha_u(s_1)}{\sqrt{\beta_u(s_0)\beta_u(s_1)}} \cos \Delta\psi_u & \sqrt{\frac{\beta_u(s_0)}{\beta_u(s_1)}}(\cos \Delta\psi_u + \alpha_u(s_1) \sin \Delta\psi_u) \end{pmatrix} \\
&= \begin{pmatrix} \sqrt{\beta_u(s_1)} & 0 \\ -\frac{\alpha_u(s_1)}{\sqrt{\beta_u(s_1)}} & \frac{1}{\beta_u(s_1)} \end{pmatrix} \begin{pmatrix} \cos \Delta\psi_u & \sin \Delta\psi_u \\ -\sin \Delta\psi_u & \cos \Delta\psi_u \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{\beta_u(s_0)}} & 0 \\ \frac{\alpha_u(s_0)}{\sqrt{\beta_u(s_0)}} & \sqrt{\beta_u(s_0)} \end{pmatrix},
\end{aligned} \tag{2.15}$$

where $\Delta\psi_u = \psi_u(s_1) - \psi_u(s_0)$ is the betatron phase advance between the two locations while $\alpha_u(s_i)$ and $\beta_u(s_i)$ are two of the three Courant-Snyder parameters at the location s_i , where $i = (0, 1)$.

The Courant-Snyder parameters are also known as Twiss parameters.

Lee p.49: beta is the betatron amplitude function, while alpha is related to the slope of the betatron amplitude function.

Non-linear dynamics

2.2.2 Longitudinal motion

In the longitudinal plane the motion is tangential to the reference trajectory and is described by the co-ordinates (z, δ) .

2.3 Collective effects

2.3.1 Beam transverse impedance

2.4 Optics models of accelerators

MADX

Table with parameters for sps lattice, eg average beta function, tune etc. circumference, Q20 and Q26.

presentation AUTH?

See sondre's thesis for inspiration on the structure.

2.5 General parameters of the studies

2.5.1 SPS optics

The studies presented in this thesis were performed for the nominal SPS optics for the LHC filling which are called Q26 optics as the higher integer part of the tune in both planes is 26.

SPS nominal model

The model for the Q26 optics can be found in the official CERN repository [29] and will be referred to as the nominal SPS model in this thesis. The values of the optics parameters in what follows correspond to the model values unless stated otherwise.

SPS non-linear model

Move this section to chapter 6. The nominal SPS model includes only the non-linear fields produced by the chromatic sextupoles. However, one of the most important sources of non-linearities in SPS are the odd multipole components of its main dipole magnets. For some of the studies presented in this thesis their impact on the beam dynamics must be studied and therefore they should be included in the nominal model.

The multipole error of the SPS main dipoles are unfortunately not available from magnetic measurements. On this ground a non-linear optics model of the SPS has been established with beam-based measurements of the chromatic detuning over a range of momentum deviation [30, 31]. The optics model was obtained by assigning systematic multipole components to the main lattice magnets, in the nominal model of SPS, in order to reproduce the tune variation with the momentum deviation as it was measured in the real machine. The calculations were performed with MAD-X [].

The values of the multipole components up to seventh order obtained from this

2. Basics of accelerator beam dynamics

method are given in Table 2.1 where, (b_3^A, b_3^B) , (b_5^A, b_5^B) and (b_7^A, b_7^B) stand for the sextupolar, decapolar and decatetrapolar mutipoles respectively. Note that different values have been obtained foreach of the two different kinds of SPS main dipoles (MBA and MBB) which are marked withthe indices A and B respectively.

Table 2.1: Multipole errors from SPS non-linear model, at 270 GeV.

Multipole	Value
b_3^A, b_3^B	$8.1 \times 10^{-4} \text{ m}^{-2}, 1.1 \times 10^{-3} \text{ m}^{-2}$
b_5^A, b_5^B	$9.2 \text{ m}^{-4}, -10 \text{ m}^{-4}$
b_7^A, b_7^B	$1.3 \times 10^5 \text{ m}^{-6}, 1.4 \times 10^5 \text{ m}^{-6}$

random multiple errros? Like in APR.Ch.3.2.2.

2.6 Luminosity

$$\mathcal{L} = \frac{n_b f_{\text{rev}} N_1 N_2}{4\pi\sigma_x\sigma_y} \frac{1}{\sqrt{1+(\frac{\sigma_z}{\sigma_{\text{xing}}})^2}}$$

2.7 Emittance

Defintion 1: The statistical emittance is expressed in terms of the beam distribution:

$$\epsilon_x^{\text{geom}} = \sqrt{\langle x^2 \rangle - \langle px^2 \rangle - \langle xpx \rangle^2}. \quad (2.16)$$

This is the geometric emittance.

$$\epsilon_x = \epsilon_x^{\text{geom}} \beta_0 \gamma_0. \quad (2.17)$$

Defintion 2: For a gaussian beam distribution the normalised beam emittance it applies:

$$\epsilon_x = \frac{\sigma_x(s)^2 - \delta^2 D_x^2(s)}{\beta_x(s)} \beta_0 \gamma_0 \quad (2.18)$$

where $\sigma_x(s)$ is the beam size, $\beta_x(s)$ is the beta function, $D_x(s)$ is the dispersion fat a specific location s along the accelerator, $\delta = \Delta p / p_0$ is the momentum spread and

β_0, γ_0 the relativistic parameters. Similar expression is valid for the vertical plane, with the difference that there is no dispersion.

2.8 Transfer maps

Need to mention them briefly as you refer to them at the PyHEADTAIL section.

2.9 Action angle variables

The action for the x-plane is:

$$J_x = \frac{1}{2}(x_n^2 + x p_n^2) \quad (2.19)$$

where

$$x_n = \frac{x}{\sqrt{\beta_x}}, \quad x p_n = \frac{\alpha_x x}{\sqrt{\beta_x}} + \sqrt{\beta_x} x p \quad (2.20)$$

the normalised coordinates and α_y, β_y the twiss parameters. The same applies for the y-plane.

s The statistical geometric emittance equals the average of the actions distribution:

$$\epsilon_x^{geom} = \langle J_x \rangle \quad (2.21)$$

The distribution of actions is an exponential distribution (further explanation needed?). Therefore, its mean equals its standard deviation. (this property is used in the appendix for the computation of the rms tune spread.)

From Eq. (2.19) we write:

$$e^{-J/\epsilon} = e^{(-x^2/2\epsilon - px^2/2\epsilon)} \quad (2.22)$$

From this equation it can be seen that the actions follow an exponential distribution.

2.10 Wakefields and impedances

he terms dipolar and quadrupolar have been chosen as the dipolar wake function acts on the test proton like a dipole magnet (the kick is the same whatever its transverse location), whereas the quadrupolar term acts like a quadrupole magnet (the kick increases linearly with the transverse offset of the test particle). Benoits thesis p.44

2.11 Tracking simulation codes

In this section the two tracking simulation codes used in this thesis to study the noise-induced emittance growth are presented. Both codes are macroparticle tracking libraries that simulate the particle motion in the six-dimensional (6D) phase space $(x, x', y, y', z, \delta)$. The first code performs tracking between interaction points around a circular accelerator with the use of transfer matrices while the second one uses the detailed optics model of the machine.

2.11.1 PyHEADTAIL

PyHEADTAIL [32] is an open-source 6D macroparticle tracking code, developed at CERN, which was originally designed to study collective effects in circular machines and to be easily extensible with custom elements. Details on its implementation and its features can be find in Refs. [33, 34]. Below the main steps of a simulation are listed:

- 1. Machine initialisation:** The accelerator ring is splitted into a number of segments of equal length, after each of which there is an interaction point (IP). At the interaction points the macroparticles experience kicks from various accelerator components (feedback system, multipoles etc) or from collective effects such as the wakefields. The machine parameters, such as the circumference, the betatron and synchrotron tunes and the optics at the interaction points are defined. It should be noted that PyHEADTAIL uses smooth approximation which means that only a few segments are defined per turn.

2. **Bunch initialisation:** A particle bunch is represented by a collection of macroparticles, each of which represents a clustered collection of physical particles. Each macroparticle is described by four transverse (x, x', y, y') and two longitudinal coordinates (z, δ), a mass and an electric charge. For the studies presented in this thesis 10^5 macroparticles are sufficient for an accurate representation of the bunch, unless it is stated otherwise. There are various distributions available. In this thesis the simulations are performed using a Gaussian distribution in transverse and longitudinal planes.
3. **Transverse tracking:** In the transverse plane, the macroparticles are transported from one interaction point to another by linear transfer matrices which take into account the optics parameters at the beginning and the end of the corresponding segment. For example, in the horizontal plane the transport of each macroparticle from IP1 to IP2 along the ring is given by:

$$\begin{pmatrix} x_i \\ x'_i \end{pmatrix}_{\text{IP0}} = M \begin{pmatrix} x_i \\ x'_i \end{pmatrix}_{\text{IP1}}, \quad (2.23)$$

where $i = 1, \dots, N$ with N being the number of macroparticles and the matrix M is given by:

$$M = \begin{pmatrix} \sqrt{\beta_{x,\text{IP0}}} & 0 \\ -\frac{\alpha_{x,\text{IP0}}}{\sqrt{\beta_{x,\text{IP0}}}} & \frac{1}{\sqrt{\beta_{x,\text{IP0}}}} \end{pmatrix} \begin{pmatrix} \cos(\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}) & \sin(\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}) \\ -\sin(\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}) & \cos(\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}) \end{pmatrix} \begin{pmatrix} \sqrt{\beta_{x,\text{IP1}}} & 0 \\ -\frac{\alpha_{x,\text{IP1}}}{\sqrt{\beta_{x,\text{IP1}}}} & \frac{1}{\sqrt{\beta_{x,\text{IP1}}}} \end{pmatrix} \quad (2.24)$$

where $\alpha_{x,\text{IP0/IP1}}$ and $\beta_{x,\text{IP0/IP1}}$ are the optics parameters at the interaction points IP0 and IP1 respectively and $\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}$ the phase advance from IP0 to IP1. As smooth approximation is used, the phase advance equals:

$$\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}} = Q_x \frac{L}{C}, \quad (2.25)$$

where Q_x is the horizontal betatron tune, C the machine circumference and L the length of the corresponding segment. It should be noted that if no detuning source is added (see next step) the matrix M is the same for all particles.

4. **Chromaticity and detuning with transverse amplitude:** The chromaticity (up to higher orders) and amplitude detuning are implemented as a change

2. Basics of accelerator beam dynamics

of the phase advance of each individual particle as follows (example for the horizontal plane):

$$\Delta\mu_{x,i\text{IP0}\rightarrow\text{IP1}} = \Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}} + (\xi_x^1\delta_i + \alpha_{xx}J_{x,i} + \alpha_{xy}J_{y,i})\frac{\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}}{2\pi Q_x}, \quad (2.26)$$

where $i = 1, \dots, N$ with N being the number of macroparticles, $\Delta\mu_{x,\text{IP0}\rightarrow\text{IP1}}$ is the phase advance for all macroparticles defined in the previous step, ξ_x^1 the horizontal chromaticity of first order normalised to the tune α_{xx} and α_{xy} are the detuning coefficients, while J_x and J_y are the horizontal and vertical actions of the macroparticle. Therefore, in the presence of detuning the elements of the M matrix are different for every particle.

5. **Longitudinal tracking:** In PyHEADTAIL the longitudinal particle dynamics are described with the longitudinal equations of motion (ref to eq earlier.) The longitudinal coordinates are advanced once per turn after solving numerically the equations of motion [34]. The motion can be linear or not (non-linear RF system). The studies presented in this thesis use the linear longitudinal tracking.
6. **Transverse impedance effects:** In PyHEADTAIL, wakefield kicks are used to implement the effect of the transverse impedance in time domain. To improve the computational efficiency, the total impedance of the full machine is lumped in one of the interaction points along the ring and the kicks are applied on the macroparticles once per turn. Additionally, instead of computing the wakefield kicks from each particle to the rest individually, the bunch is divided in a number of longitudinal slices and the macroparticles in each slice receive a wakefield kick generated by the preceding slices² [35]. This is illustrated schematically in Fig. 2.2. A large number of slices is required such as the wakes can be assumed constant within the slice. A high number of macroparticles is also needed in order to avoid statistical noise effects caused by undersampling [33]. For the studies presented in 500 slices are used over a range of three rms bunch lengths in both directions from the bunch cen-

²This is valid in the ultrarelativistic scenario when no wakefield is generated in front of the bunch. The condition applies for the SPS experiments described in this thesis, performed at 270 GeV.

ter with the bunch being represented by 10^6 macroparticles (instead of 10^5 required for simulations without impedance effects).



Figure 2.2: Longitudinal bunch slicing for the implementation of wakefields kicks in PyHEADTAIL. Without the slicing technique (left) the wake kicks on the red macroparticle are generated from all the green macroparticles resulting to computationally heavy simulations. Instead, when the bunch is sliced longitudinally (right) the wake kicks on the macroparticles in the red slice i are generated by the macroparticles in the green slices j , decreasing significantly the computation time. The figures are a courtesy of M. Schenk [34]

The wakefield kicks are computed using a convolution of the wake function with the moments of each particle. The wake functions are available from detailed impedance model of the machine which are obtained from a combination of theoretical computations, electromagnetic simulations and can be imported in PyHEADTAIL in form of tables. More details on the SPS impedance model are provided in Section 7.1.

7. **Data acquisition:** The updated bunch coordinates after each turn are available at IP0 for post processing. Typically, 10^5 turns are required for the noise-induced emittance growth simulation presented in this thesis.

Figure 2.3 shows a graphic representation of the accelerator model and the tracking procedure supporting the steps described above.

2.11.2 Sixtracklib

2. Basics of accelerator beam dynamics

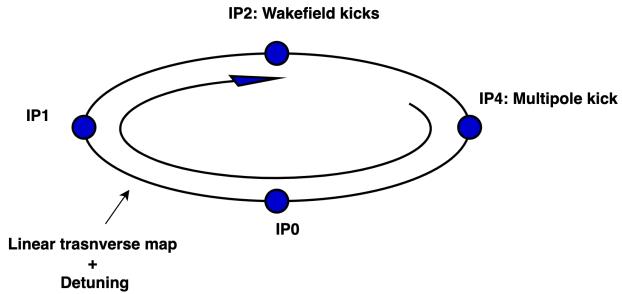


Figure 2.3: Graphic representation of the accelerator model and tracking procedure in PyHEADTAIL (inspired by the graphs in Refs. [34, 36]). In this example the ring is splitted in four segments separated by the interaction points (IPs). Wakefield and multiple kicks are applied on the macroparticles in IP2 and IP4. The macroparticles are transported between the IPs by a linear map (which can include detuning effects) in the transverse plane. The longitudinal coordinates are updated once per turn without being visualised in this plot.

3 | Theory of Crab Cavity noise induced emittance growth

2. Noise, reference to noise studies ... to kek. mention why they are different.

For a uniform noise spectrum across the betatron tune distribution, the emittance growth resulting from amplitude noise can be estimated from:

$$\frac{d\epsilon}{dt} = \beta_{CC} \left(\frac{eV_{CC}f_{rev}}{2E_b} \right)^2 C_{\Delta A}(\sigma_\phi) \sum_{k=-\infty}^{+\infty} S_{\Delta A}[(k \pm \bar{\nu}_b \pm \bar{\nu}_s)f_{rev}]. \quad (3.1)$$

For phase noise, the emittance growth can be estimated from:

$$\frac{d\epsilon}{dt} = \beta_{CC} \left(\frac{eV_{CC}f_{rev}}{2E_b} \right)^2 C_{\Delta\phi}(\sigma_\phi) \sum_{k=-\infty}^{+\infty} S_{\Delta\phi}[(k \pm \bar{\nu}_b)f_{rev}]. \quad (3.2)$$

In these formulae, β_{CC} is the beta function at the location of the CC, V_{CC} the CC voltage, f_{rev} the revolution frequency of the beam, E_b the beam energy, and $\bar{\nu}_b$ and $\bar{\nu}_s$ the mean of the betatron and synchrotron tune distribution. $S_{\Delta A}$ and $S_{\Delta\phi}$ are the power spectral densities (PSD) [37] of the noise at all the betatron and synchrobetatron (for the amplitude noise case) sidebands. $C_{\Delta A}$ and $C_{\Delta\phi}$ are correction terms to account for the bunch length:

$$C_{\Delta A}(\sigma_\phi) = e^{-\sigma_\phi^2} \sum_{l=0}^{+\infty} I_{2l+1}(\sigma_\phi^2), \quad (3.3)$$

$$C_{\Delta\phi}(\sigma_\phi) = e^{-\sigma_\phi^2} \left[I_0(\sigma_\phi^2) + 2 \sum_{l=1}^{+\infty} I_{2l}(\sigma_\phi^2) \right], \quad (3.4)$$

with σ_ϕ the rms bunch length (in radians) with respect to the CC frequency f_{CC} , and $I_n(x)$ the modified Bessel function of the first kind.

3. Theory of Crab Cavity noise induced emittance growth

You need to described how they are modeled in pyheadtail.

3.1 Modelling of phase and amplitude noise in simulations

4 | Calibration of the Crab Cavities for the SPS tests in 2018

This chapter focuses on the setup and the calibration of the CCs in the SPS for the 2018 tests. The objective is to provide a full understanding of the operational aspects of the CCs in the SPS and clarify the measurement of the CC voltage.

The presented studies were performed by the author in addition to the first round of analysis in 2018. They were motivated by the results of the experimental campaign (Chapter 5), which appeared to differ significantly from the theoretical predictions without apparent reason. As the reason for that discrepancy was not understood, having a closer look and reviewing the procedure of the CC voltage calibration was essential, given that it is one of the most crucial parameters for the emittance growth studies (see Chapter 3, Eq. (3.1) and Eq. (3.2)).

The chapter is structured as follows: Section 4.1 describes the installation of the CC system in the SPS. Thereafter, Section 4.2 elaborates on details for their operation in the SPS machine. In Section 4.3, the use of the Head-Tail (HT) monitor as the main diagnostic in the CC tests is discussed, focusing on the reconstruction of the CC voltage from its reading. Last, Section 4.4 provides a characterisation of the beam based CC voltage measurement and defines the voltage amplitude and its uncertainty.

4.1 Crab Cavities' installation in the SPS

For the SPS tests two prototype CCs of the Double Quarter Wave (DQW) type, which will be referred to as CC1 and CC2 throughout this thesis, were fabricated by CERN and

4. Calibration of the Crab Cavities for the SPS tests in 2018

were assembled in the same cryomodule, shown in Fig. 4.1 [21]. For its installation an available space was found at the SPS Long Straight Section 6 (SPS-LSS6) zone. As this section is also used for the extraction of the beam to the LHC, the cryomodule was placed on a mobile transfer table [38] which moved the cryomodule in the beamline for the CC tests and out of it for the usual SPS operation without breaking the vacuum.

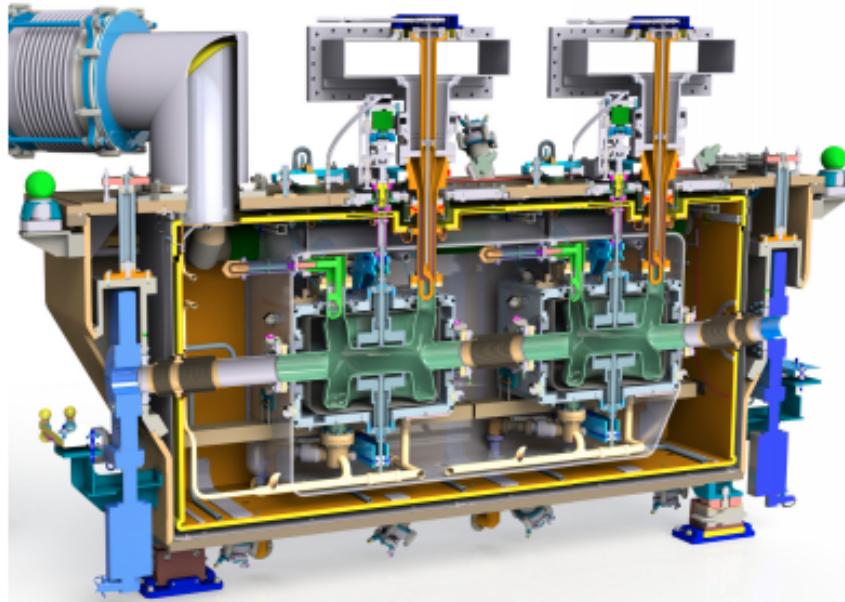


Figure 4.1: Cross section view of the CC cryomodule [21]. It has a total length of 3 m [39] and at its core there are the two DQW cavities, which are illustrated with light green color.

The main CCs parameters are listed in Table 4.1. Their location along the SPS ring is also indicated, in case someone would like to repeat the analysis described in this thesis.

4.2 Operational considerations

For the beam tests with 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 proton beam at 26 GeV from the PS. It was found that the ramp to

Table 4.1: Crab Cavities design parameters for the SPS tests in 2018.

Parameter	Value	
	CC1	CC2
crabbing plane	vertical	vertical
s-location*	6312.72 m	6313.32 m
CC voltage, V_{CC}	≤ 3.4 MV	≤ 3.4 MV
CC frequency, f_{CC}	400.78 MHz	400.78 MHz
Horizontal / Vertical beta function, $\beta_{x,CC} / \beta_{y,CC}$	29.24 m / 76.07 m	30.31 m / 73.82 m
Horizontal / Vertical alpha function, $\alpha_{x,CC} / \alpha_{y,CC}$	-0.88 m / 1.9 m	-0.91 m / 1.86 m
Horizontal / Vertical dispersion, $D_{x,CC} / D_{y,CC}$	-0.48 m / 0 m	-0.5 m / 0 m

* The s-location is referred to the location of the elements along the SPS ring with respect to the start of the lattice i.e. element QF10010 which is a focusing quadrupole. The s-location is given to allow the studies to be reproduced.

higher energies could not be performed with the CC on, as the beam was getting lost while crossing one of the vertical betatron sidebands due to resonant excitation [40]. Therefore, it was established that 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 is worth noting that this approach will also be used in the HL-LHC.

Crab Cavity - main SPS RF synchronisation

It was important to ensure that during the "coast" the beam will experience the same kick from the CC each turn. In other words the SPS main RF system operating at 200 MHz needed to be synchronous with the CC operating at 400 MHz. Due to the larger bandwidth of the SPS main RF system the CC was used as a master. Therefore the CC was operating at a fixed frequency and phase, while the main accelerating cavities were adjusted to the exact half of the CC frequency and were re-phased so that they become synchronous with the crabbing signal. For the studies at higher energies the synchronisation took place at the end of the ramp shortly after the cavity was switched on [41].

4.3 SPS Head-Tail monitor as the main diagnostic

The SPS is equipped with a high bandwidth pick-up of approximately 2 GHz allowing to resolve the intra-bunch motion. This instrument is called Head-Tail (HT) monitor and was originally designed for measuring chromaticity and transverse instabilities. However, in the SPS CC tests, the HT monitor was the main diagnostic

4. Calibration of the Crab Cavities for the SPS tests in 2018

device deployed for the demonstration of the crabbing and the measurement of the CC voltage (explained in details in Section 4.4). 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 CC will be discussed. Last, the calibration of the CC voltage from the HT data is described and the visualisation of the crabbing is displayed. The experimental data presented in this section were acquired, on May 30, 2018 (time-stamp: 13:51:05), at the SPS injection energy of 26 GeV with only one CC, CC1, at phase $\phi_{CC} = 0$ (this means that the particle at the center of the bunch doesn't receive any transverse deflection) for simplicity. That energy of 26 GeV was chosen to provide a better understanding of the methods used as the orbit shift from the CC kick is stronger and thus more visible than at higher energies.

4.3.1 General information

As already mentioned, the HT monitor is a high bandwidth version of a standard beam position monitor, which means that it can measure the transverse displacement 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. 4.2) [42, 43] over a defined acquisition period. The sum signal is the longitudinal line density while the difference signal corresponds to the intra-bunch offset. The system operates on timescales such that the signals are given as a function of the position within the bunch.

The raw signals from the HT monitor require a specific post-processing procedure [43], in order to provide useful information. Figure 4.3 shows some example signals obtained from the HT monitor after the basic post-processing is applied. Moreover, Fig. 4.4 shows a 2D representation of the HT monitor reading. It is worth noting here that in the specific example a clear modulating pattern in time of the vertical

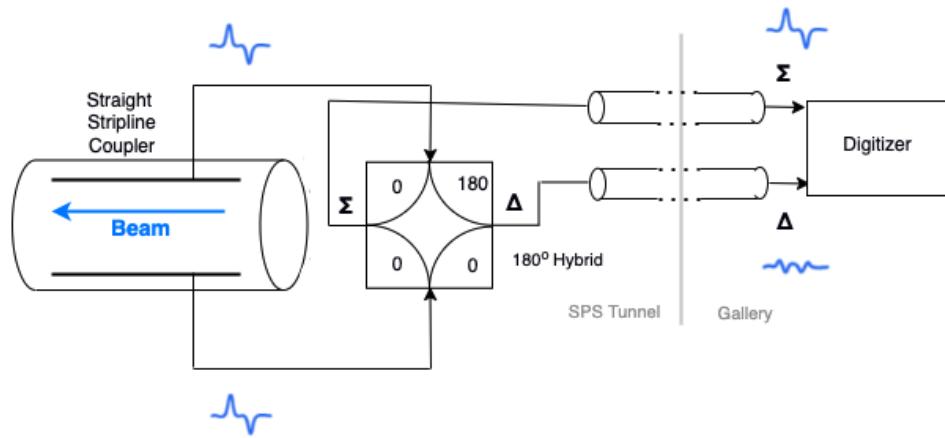


Figure 4.2: Diagram of the SPS HT monitor [43]. The beam is passing through a straight stripline coupler which is followed by a 180° hybrid. This configuration provides the sum (Σ) and the difference (Δ) signal of the two electrodes.

intra-bunch offset (vertical Δ) signal is observed. This is a result of the phase slip between the CC and the main RF system because they are not yet synchronised.

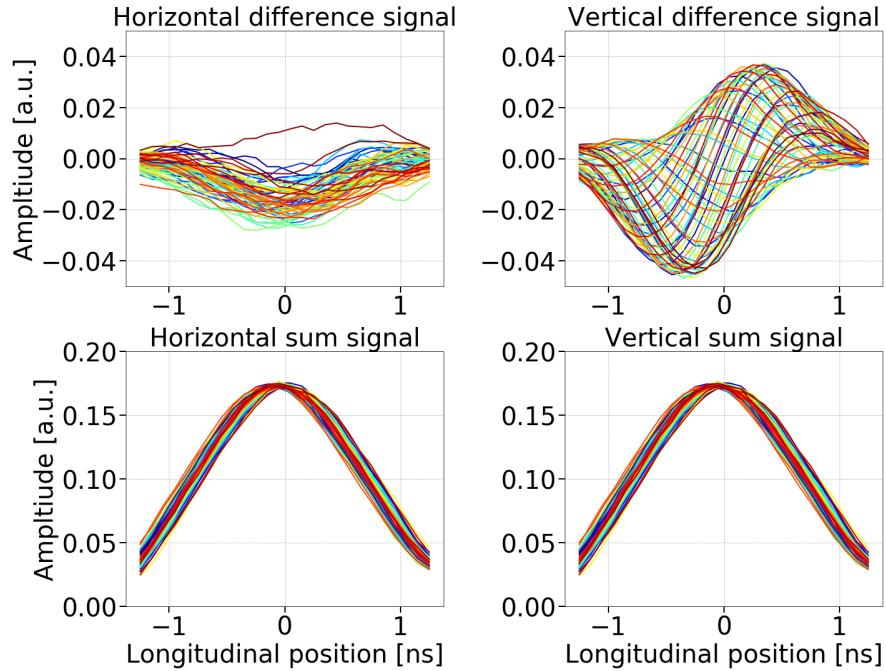


Figure 4.3: Example difference and sum signals (top and bottom plots, respectively) from the HT monitor, in time scale, with respect to the longitudinal position within the bunch over several SPS revolutions, after the basic post processing [43] but before the baseline correction. The different colors indicate the signals from different turns (every 100 turns).

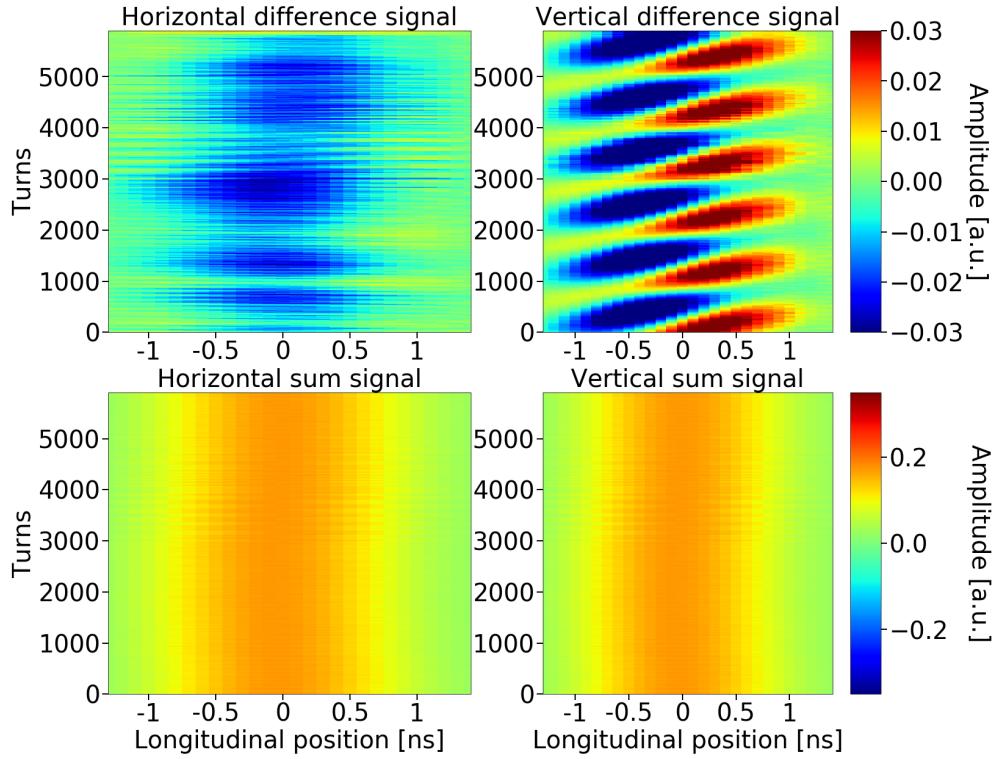


Figure 4.4: 2D representation of example difference and sum signals with respect to the longitudinal position within the bunch obtained from the HT monitor over several SPS revolutions.

4.3.2 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.

Head-Tail monitor baseline correction

The HT monitor measurement has a baseline on the difference signal which needs to be removed. The baseline is a result of orbit offsets and non-linearities of the instrument and is constant from turn to turn [43]. Therefore, during the normal post processing procedure (without CCs), the baseline is computed as the mean of the difference signals over all turns and then the correction is achieved by 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 4.2), the crabbing signal is also a static intra-bunch position offset and thus would also be removed with the usual method. Because of technical limitations it was not feasible to switch off the CC for those kind of measurements. Thus, the following technique

was used.

For the CC experiments a reference measurement had first to be made with the CC not being synchronous with the main RF system. The baseline was computed as the mean of the difference signals over this reference period and subsequently it was subtracted from the average of the difference signals acquired after the synchronisation (Fig 4.5). The datasets before and after synchronisation are easily distinguishable in the 2D HT monitor reading as displayed in Fig. 4.6

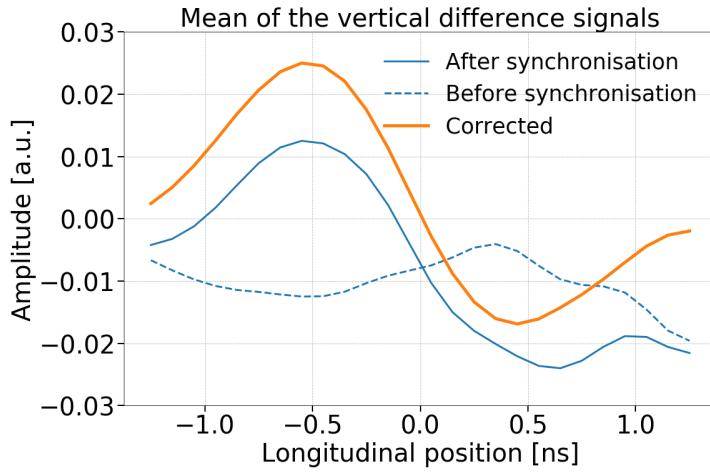


Figure 4.5: HT monitor baseline correction for the SPS CC tests. The baseline signal (blue dashed line) refers to the mean of the difference signals acquired before the CC - main RF synchronisation. The measured signal (blue solid line) corresponds to the mean of the difference signal acquired after the synchronisation. Last, the corrected signal (orange solid line) is obtained after subtracting the baseline from the measured signal.

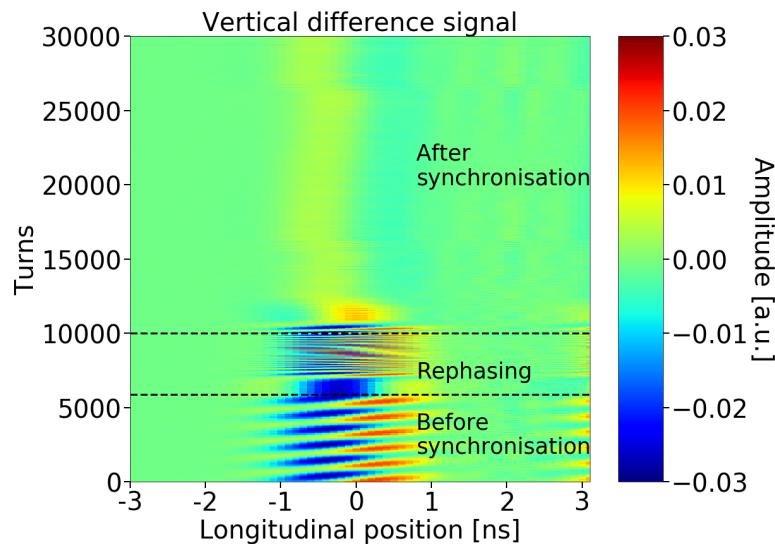


Figure 4.6: HT acquisitions before and after the synchronisation of the SPS main RF with the CC.

Head-Tail monitor scaling

The last step to make the HT acquisitions meaningful is to convert the measured intra bunch offset (the mean of the difference signals following phase synchronisation and baseline correction) from arbitrary units to millimeters. The scaling is achieved by dividing by the mean of the sum signals (which is a function of the position along the bunch and is calculated for each point individually over many turns) after the synchronisation and with a normalisation factor which is provided by the calibration of the HT monitor [44]. The normalisation factor for the SPS was measured at 0.1052 in 2018 [45]. Figure 4.7 shows the intra-bunch offset from the CC kick in millimeters and after the baseline correction.

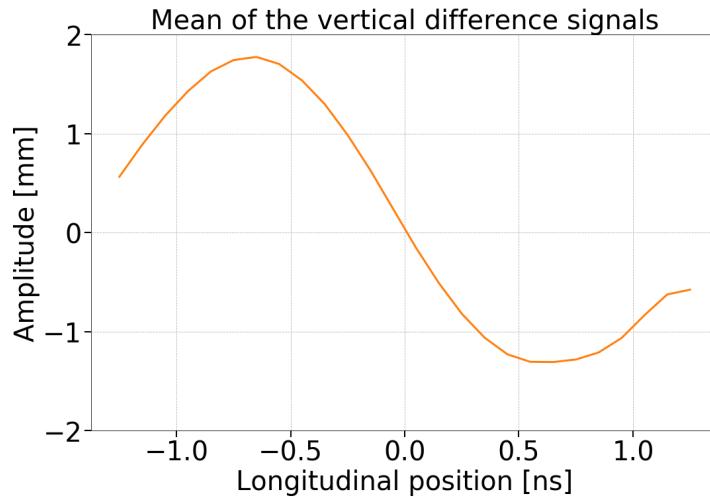


Figure 4.7: Intra-bunch offset from the CC kick expressed in millimeters after the removal of the baseline.

4.3.3 Crab Cavity voltage reconstruction

This section discusses the reconstruction of the CC voltage from the HT monitor signal. First, Eq. (4.1) was used to calculate the CC kick, θ , required to reconstruct the measured intra-bunch offset. Equation (4.1), which is obtained from Eq. (1) from chapter 4.7.1 in Ref. [46], 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 $|\psi_{y,HT} - \psi_{y,CC}|$ is the vertical

phase advance (in tune units) between the CC and the HT monitor. The same applies for the horizontal plane. The subscripts HT and CC indicate quantities at the location of the HT monitor and CC respectively.

The CC voltage is then reconstructed from the CC kick which is written as $\theta = -\frac{qV_{CC}(t)}{E_b}$, 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. In the context where the HT monitor measures the signal as a function of time, t , the voltage in the above formula is expressed accordingly as $V_{CC}(t)$, where $t = 0$ the center of the bunch.

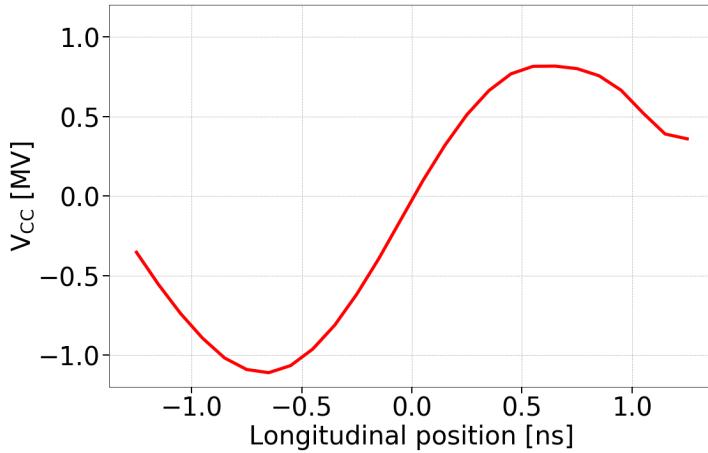


Figure 4.8: CC voltage reconstruction from the HT monitor.

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 to millimeters as discussed in Section 4.3.2. Figure 4.8 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.

4.3.4 Demonstration of crabbing with proton beams

Additionally, the measurements from the HT monitor were used for reconstructing the crabbing and representing schematically the beam projection in the transverse plane. The technique for reconstructing the crabbing was developed at CERN in 2018 and was extensively used throughout the experimental campaign with CCs since (together with the calibrated voltage) it gives a straightforward estimate of the applied CC kick, as illustrated in Fig. 4.9.

4. Calibration of the Crab Cavities for the SPS tests in 2018

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

Parameter	Value
Beta function at the HT monitor, $\beta_{y,HT}$	49.19 m
Phase advance to the HT monitor*, $\psi_{y,HT}$	$15.68 \times 2\pi$
Beta function at the CC1, $\beta_{y,CC1}$	76.07 m
Phase advance to the CC1*, $\psi_{y,CC1}$	$23.9 \times 2\pi$
Vertical betatron tune, Q_y	26.18
Beam energy, E_b	26 GeV

* The phase advances are measured from the start of the lattice which is considered the element QE10010 that is a focusing quadrupole.

To obtain this schematic representation, which in practice is a density plot showing the effect of the CC kick on the beam, one needs to multiply the measured longitudinal profile (the mean of the sum signals acquired after phase synchronisation) with the measured intra-bunch offset, mean of the difference signals acquired after the synchronisation. An example of this is shown in Fig. 4.7. For the transverse plane a gaussian distribution is considered with σ obtained from the wire scanner (addressed in more detail in the following section). The color code of Fig. 4.9 is normalised to the maximum intensity within the bunch.

4.4 Characterisation of measured Crab Cavity voltage

This section gives the definitions of the amplitude of the beam-based measurement of the CC voltage and its uncertainty that will be used in this thesis. Additionally, their dependence on the CC phase is discussed for completeness.

4.4.1 Definitions of the amplitude and the uncertainty of the measurement

The voltage amplitude, V_{CC} , is obtained from a sinusoidal fit on the reconstructed voltage, $V_{CC}(t)$, from the HT monitor reading. The standard procedure of least squares fitting (see Appendix section A.2) is followed. In particular, $V_{CC}(t)$ is fitted with the following three-parameter (V_{CC} , ϕ_{CC} , k) model function which also

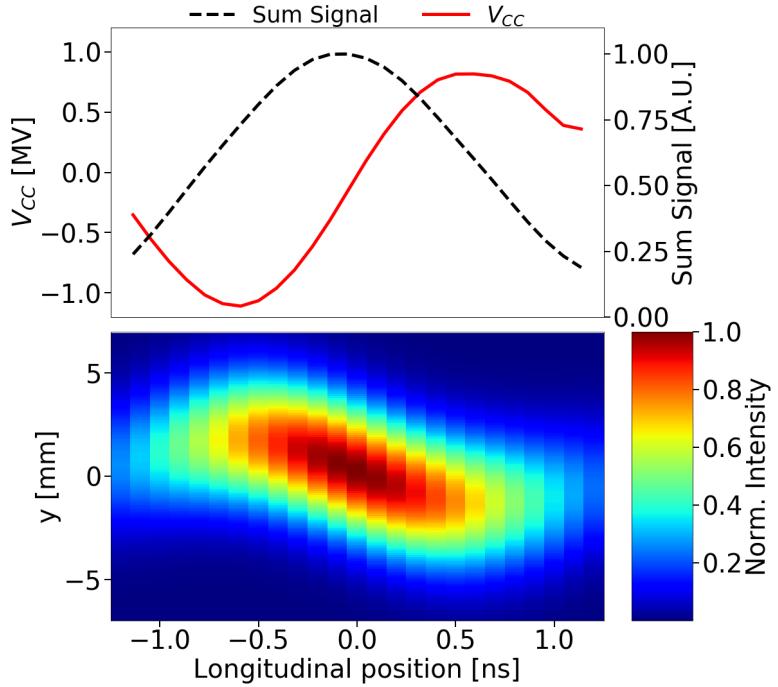


Figure 4.9: Demonstration of the crabbing from the HT monitor signal. CC voltage and sum signal (longitudinal line density) measured from the HT monitor (top) together with the density plot (bottom) which visualises the effect of the CC kick on the beam.

provides the CC phase and voltage offset:

$$f(x) = V_{CC} \sin(2\pi f_{CC}x + \phi_{CC}) + k, \quad (4.2)$$

where V_{CC} is the amplitude of the CC voltage, ϕ_{CC} the CC phase and k the voltage offset. The fit is performed for a fixed CC frequency, as the operational value is well known and in particular it equals, $f_{CC}=400.78$ MHz. The offset parameter is added to the model function as it is clear from Fig. 4.8 and 4.9 that the reconstructed CC voltage, $V_{CC}(t)$, is not centered around zero. The asymmetry seems to be a result of the HT monitor pick up and cable response [47]. However its origin is not yet fully understood and will have to be addressed in the future.

In order to obtain results that correspond to the experimental conditions the following constraints are imposed to the fit. First the voltage amplitude, V_{CC} , is requested to always be positive and higher than 0.7 MV. Furthermore, the part of the signal that corresponds to the tails of the bunch is excluded from the fit in order not to degrade its quality. Consequently, only the part of the signal for which the corresponding

4. Calibration of the Crab Cavities for the SPS tests in 2018

normalised sum signal is above 0.4 is used for the fit.

Fig. 4.10 shows the result of the fit for the same signal that was analysed in the previous section. As indicated on the top of the plot, the red solid line corresponds to the reconstructed CC voltage, while the blue solid line corresponds to the result of the sinusoidal fit. It can be seen that only the part of the signal for which the normalised sum signal (black dashed line) is above 0.4 is used. Finally the blue dashed line shows the result of the fit after the voltage offset is subtracted, so that is centered around zero. The parameter values obtained from the fit are given in the legend. Last, the density plot is also shown at the bottom of the figure for a complete visualisation of the crabbing.

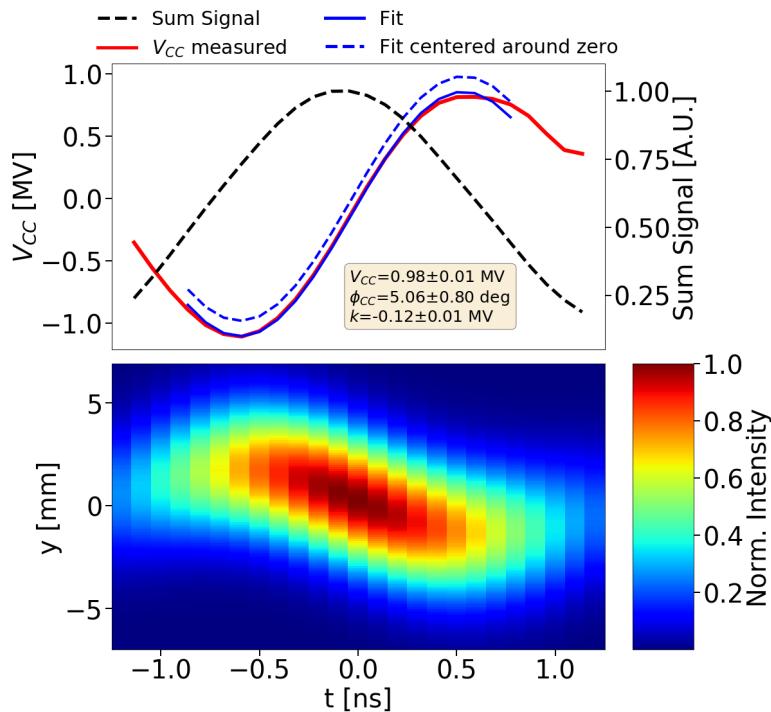


Figure 4.10: Demonstration of the sinusoidal fit on the HT monitor reading in order to obtain the CC parameters. A four-parameter sinusoidal fit is performed using Eq. (4.2) in order to obtain the amplitude, V_{CC} , the frequency, f_{CC} , the phase, ϕ_{CC} , and the voltage offset, k . The fit results are given in the yellow box.

In this thesis, the uncertainty on the measured voltage amplitude, ΔV_{CC} is defined as the absolute value of the voltage offset, k , instead of the error of the fit on the voltage amplitude. This is because the voltage offset depicts better the uncertainty of the voltage seen by the beam, V_{CC} . Therefore, for the analyzed example here the CC voltage was measured to be $V_{CC} = 0.98$ MV and its uncertainty $\Delta V_{CC} = 0.12$ MV.

4.4.2 Dependence of the crab cavity voltage and offset on the phase

The impact of the CC phase on the voltage experienced by the beam and on the uncertainty of its measurement was also studied experimentally. Data for the study were collected on 30 May. 2018, at the SPS injection energy of 26 GeV for a range of different settings of the phase of CC1. The results are summarised in Fig. 4.11.

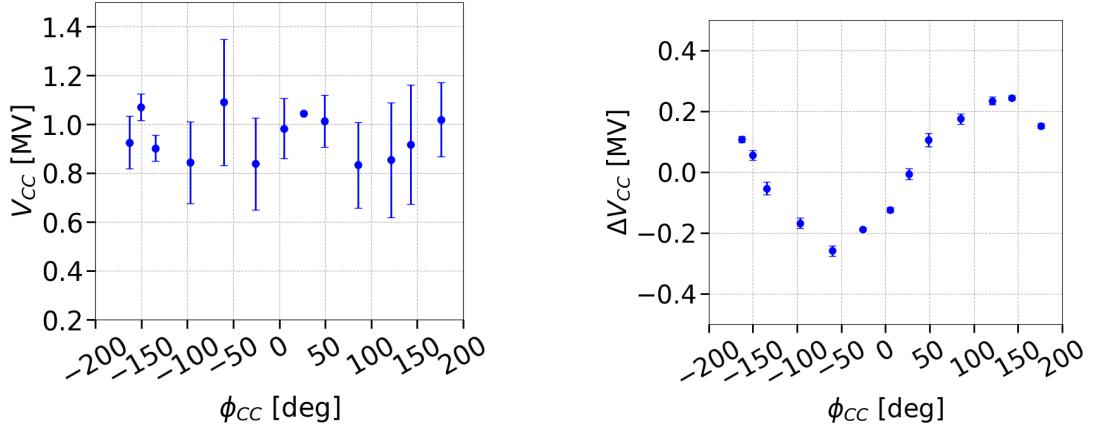


Figure 4.11: Phase scan with CC1 at 26 GeV. The sensitivity of the measured CC voltage (left) and its uncertainty (right) on the phase is studied. The error bars of the voltage, V_{CC} , indicate the uncertainty, ΔV_{CC} . The error bars of the uncertainty, ΔV_{CC} , and the phase, ϕ_{CC} , correspond to the error of the respective fit result (see Appendix A.2). The error bars are not visible here as they are smaller than the markers.

In the left plot the error bars of the voltage, V_{CC} , indicate the uncertainty, ΔV_{CC} . In the right plot, the error bars of the uncertainty, ΔV_{CC} , correspond to the error of the fit result for the V_{CC} parameter (see Appendix A.2). The horizontal error bars in both left and right plots, of the phase, ϕ_{CC} , correspond to the error of the fit result for the phase parameter (see Appendix A.2). It should be noted that the error bars of the phase values are smaller than the markers and are hence not visible in the plots.

The phase scan does not reveal any systematic dependence of the measured voltage, V_{CC} , on the phase, as expected. However, there is a variation of the voltage offset, ΔV_{CC} , with the phase. The origin of this, which seems to be a systematic effect, is not yet understood and will be addressed in the future to fully characterise the behavior of the beam in the presence of a phase offset in the CC. It should be pointed out that the impact of this effect on the interpreting the CC noise induced emittance

4. Calibration of the Crab Cavities for the SPS tests in 2018

growth measurements is limited and thus it will not be a matter of concern for this thesis.

5 | Experimental studies 2018: emittance growth from Crab Cavity noise

In Chapter 3 the theoretical model for the transverse emittance growth caused by amplitude and phase noise in a CC was discussed. On September 5, 2018, a dedicated experiment was conducted in the SPS to benchmark this model against experimental data and confirm the analytical predictions. In particular, the aim was to inject artificial noise in the CC RF system and compare the measured emittance growth rates with the the theoretically computed ones. In this chapter the measurement results from the SPS are presented and discussed. The work published in Ref. [48] is the basis of this chapter.

Section 5.1 describes the machine setup and the beam configuration for the emittance growth measurements. This includes a summary of the preparatory studies conducted in the previous years. In Section 5.2 information on the noise injected in the CC RF system is provided. The measurements of transverse emittance growth are presented in Section 5.3 while the complementary measurements of bunch length and intensity in Section 5.4. The conclusions of the first experimental campaign with CC noise in SPS are drawn in Section 5.6.

5.1 Experimental configuration and procedure

This section gives an overview of the experimental setup and the procedure that was followed. First, it briefly discusses the preparatory studies that were performed during 2012-2017 [49, 50, 51], explaining the choice of the intensity and energy values for which the emittance growth measurements were conducted. Furthermore, it presents in detail the rest of the beam and machine conditions during the experi-

ment. Last, the experimental procedure is explained.

5.1.1 Preparatory experimental studies

For studying the long-term emittance evolution a special mode of operation was set up in the SPS which is called "coast" (in other machines, it is referred to as storage ring mode) with bunched beams. In this mode, the bunches circulate in the machine at constant energy for long periods, from a few minutes up to several hours, similar to the HL-LHC case.

To make sure that the SPS can be used as a testbed for the emittance growth studies with CCs an extensive preparatory campaign was carried out through 2012-2017 [49, 50, 51]. The primary concern was the emittance growth that was observed in the machine from other sources than injected noise and will be referred to as the natural emittance growth in this thesis. The natural emittance growth needs to be well characterised and be kept sufficiently small in order to distinguish and understand the contribution from the CC noise.

From these studies, it was concluded that the optimal coast setup is at high energies, with low chromaticity and bunches of low intensity as it minimises the natural emittance growth [51]. The highest energy for which the SPS could operate in "coast" was 270 GeV and thus the experiments were performed at this energy. That limitation was introduced due to limited cooling of the magnets to transfer away the heating when operating at high energy and thus at large currents for long periods. Moreover, as the natural emittance growth was found to be a single bunch effect four bunches were used. That choice was made to reduce the statistical uncertainty of the measurements but not to increase the beam intensity.

5.1.2 Machine and beam configuration

During the experiment the Landau octupoles were switched off. Nevertheless, a residual non-linearity was present in the machine mainly due to multipole components in the dipole magnets [30, 31]. The transverse feedback system was also switched off. Unfortunately, no measurements of chromaticity are available from the day of the experiment. However it was ensured that the chromaticity was cor-

rected to small positive values.

Last, only one CC, CC2, was used for simplicity and it operated at 1 MV. This value was validated with the HT monitor (post-processing procedure described in Chapter 4). Unfortunately, only one beam based measurement of the CC voltage is available which is displayed in Fig. 5.1. It is clear that the measured value of voltage amplitude, $V_{CC} = 0.99 \pm 0.04$ MV, is in good agreement with the requested one. It should be noted, that due to the beam energy of 270 GeV the crabbing is less visible than the example discussed in Chapter 4 (see Fig. 4.10) for 26 GeV. Therefore, here the part of the signal that is used for the fit is the one for which the normalised sum signal (black dashed line) is above 0.2 (instead of 0.4 that was the condition for the case of 26 GeV)

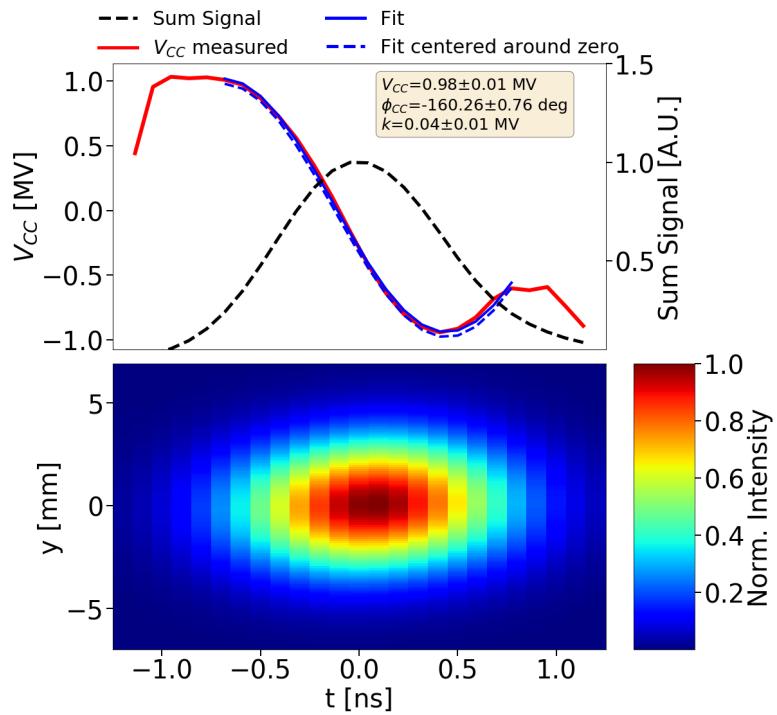


Figure 5.1: Demonstration of the sinusoidal fit on the HT monitor reading in order to obtain the CC parameters as described in Section 4.4. The fit results, are given in the yellow box. The measured voltage amplitude, V_{CC} , was found to be 0.99 MV while its uncertainty, ΔV_{CC} , was measured at 0.04 MV. The measured voltage value agrees well with the requested value of 1 MV.

The main machine and beam parameters used for the emittance growth measurements in 2018 are listed in Table 5.1.

5. Experimental studies 2018: emittance growth from Crab Cavity noise

Table 5.1: Main machine and beam parameters for the emittance growth studies with CCs in SPS in 2018.

Parameter	Value
Beam energy, E_b	270 GeV
Revolution frequency, f_{rev}	43.375 kHz
Main RF voltage / frequency, V_{RF} / f_{RF}	3.8 MV / 200.39 MHz
Horizontal / Vertical betatron tune, Q_x / Q_y	26.13 / 26.18
Horizontal / Vertical first order chromaticity, Q'_x / Q'_y	$\sim 1.0 / \sim 1.0$
Synchrotron tune, Q_s	0.0051
CC2 voltage / frequency, V_{CC} / f_{CC}	1 MV / 400.78 MHz
Number of protons per bunch, N_b	3×10^{10} p/b*
Number of bunches	4
Bunch spacing	524 ns
Rms bunch length, $4\sigma_t$	1.8 ns*
Horizontal / Vertical normalised emittance, $\epsilon_x^n / \epsilon_y^n$	$2 \mu\text{m} / 2 \mu\text{m}^*$
Horizontal / Vertical rms tune spread, $\Delta Q_x^{rms} / \Delta Q_y^{rms}$	$2.02 \times 10^{-5} / 2.17 \times 10^{-5}$ †

* The value corresponds to the requested initial value at the start of each coast. The measured evolution of the parameter through the experiment is presented in the Sections 5.3 and 5.4.

† Here the rms betatron tune spread includes only the contribution from the detuning with amplitude present in the SPS machine. More details along with the calculations for the listed values can be found in Appendix C.1.

5.1.3 Experimental procedure

The experiment took place on September 5, 2018, and was given a total time window of about 6 hours (start:~10:30, end:~17:00). In order to characterize the CC noise induced emittance growth, different levels of controlled noise were injected into the low-level RF system and the bunch evolution was recorded for about 20-40 minutes (for each noise setting). The experiment was conducted over three coasts, since a new beam was injected every time the quality of the beam was seen to be degraded e.g. very large beam size. In the following, the different noise settings will be denoted as "Coast N -Setting M ", where N stands for the coast number and M for the different noise levels applied in each coast in chronological order. After the experiment, the measured growth rates would be compared with the theoretically expected values from the model described in Chapter 3.

5.2 Injected RF noise

The noise injected in the CC RF system 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. The noise levels were measured with a spectrum analyzer E5052B [52] and are expressed as $10\log_{10}\mathcal{L}(f)$ [dBc/Hz]. The relation between the measured noise levels and the power spectral densities (PSDs) in Eq. (3.1) and Eq. (3.2) is given by $S_\Delta = 2\mathcal{L}(f)$, with $S_{\Delta A}$ in 1/Hz and $S_{\Delta\phi}$ in rad²/Hz. This relation is extensively discussed in Appendix C and specifically in B.3. Figure 5.2 displays an example measurement of amplitude (left) and phase (right) noise acquired during the experiment.

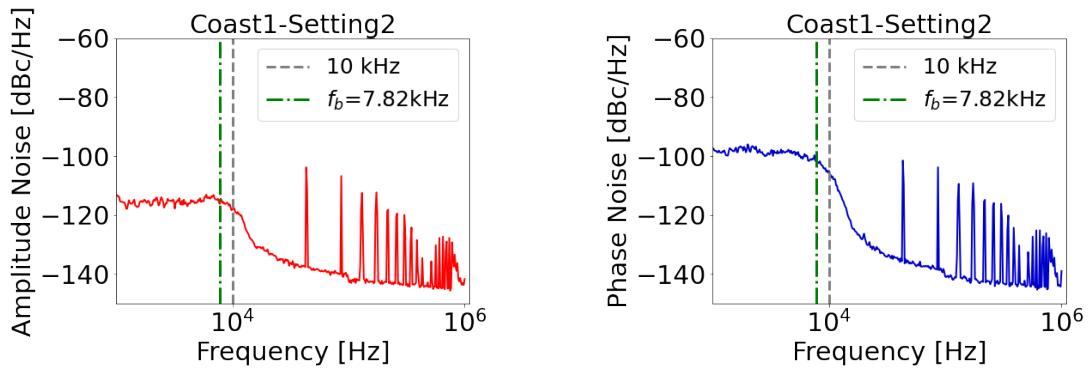


Figure 5.2: Example amplitude (left) and phase (right) noise spectra measured with a spectrum analyzer E5052B [52] during the emittance growth studies with CCs in SPS. The noise extends up to 10 kHz (grey dashed line) overlapping the first betatron sideband at ~ 8 kHz (green dashed line). The spikes at high frequencies correspond to the harmonics of the revolution frequency and are a result of the bunch crossing.

PSD values of interest

As already discussed in Chapter 3 the noise induced emittance growth depends on the noise power at the betatron and synchrobetatron sidebands for the phase and amplitude noise respectively (see Eq. (3.2) and Eq. (3.1)). Therefore, the noise power values of interest for this thesis are the ones at the first betatron $f_b = 0.18 \times f_{rev} = 7.82$ kHz and at the synchrobetatron sidebands at $f_b \pm Q_s \times f_{rev} = f_b \pm \sim 220$ kHz.

However, it can be clearly seen from Fig. 5.2 that the measured noise spectra are noisy: random changes in amplitude are observed from point to point within the signal. To this end, the PSD value at the first betatron sideband, f_b , is determined as the average of the PSD values over a frequency range of ± 500 Hz around it, while its uncertainty is considered to be the standard deviation over that range. In the following, it is assumed for simplicity that the PSD at the synchrobetatron sidebands

5. Experimental studies 2018: emittance growth from Crab Cavity noise

equals the PSD at the first betatron sideband as they lie very close to each other. At this point, it should be mentioned that the validity of these assumptions was tested with numerical simulations which used the measured spectra (Chapter 6).

The emittance growth measurements were performed with seven different noise levels. The values of the phase and amplitude noise for each setting are listed in Table 5.2.

Effective phase noise

In order to make a meaningful comparison between the different levels of noise, the concept of effective phase noise is introduced: this is the phase noise level that would lead to the same emittance growth as that from both phase and amplitude noise according to the theoretical model (Chapter 3).

For the calculation of the effective phase noise the averaged bunch length for each case is used (bunch length measurements at Section 5.4). The uncertainty on the effective phase noise is computed following the standard procedure of the propagation of the uncertainty (Appendix A.3). [Do I need to show all the calculations?](#). The calculated effective phase noise values for the experimental conditions are also listed in Table 5.2. The values shown correspond to the results using the parameters of the first bunch. However, the difference between the values for the other bunches is very small and is also within the displayed uncertainties. The noise levels mentioned in the following analysis of the experimental data correspond to the calculated effective phase noise.

5.3 Emittance growth measurements

This section presents the transverse emittance growth measurements with CC RF noise. It discusses first the measurement of the beam emittance with the SPS wire scanners (WS) and then it provides an overview of the emittance growth measurements for the four bunches over all the different noise settings.

Table 5.2: Phase and amplitude noise levels injected in the CC RF system for the emittance growth studies of 2018. The listed values correspond to the average PSD values over a frequency range of ± 500 Hz around the first betatron sideband, f_b . The calculated effective phase noise for the parameters of the first bunch are also listed.

	$10 \log_{10} \mathcal{L}(f)$ [dBc/Hz]		
	Phase noise	Amplitude noise	Effective phase noise
Coast1-Setting1	-122.6 ± 0.6	-128.1 ± 0.6	-121.8 ± 0.5
Coast1-Setting2	-101.4 ± 0.8	-115.2 ± 0.6	-101.3 ± 0.8
Coast2-Setting1	-115.0 ± 0.8	-124.1 ± 0.5	-114.6 ± 0.7
Coast2-Setting2	-111.4 ± 0.6	-115.7 ± 0.4	-110.2 ± 0.5
Coast3-Setting1	-110.9 ± 0.9	-116.9 ± 0.4	-110.1 ± 0.8
Coast3-Setting2	-106.4 ± 0.3	-112.9 ± 0.6	-105.8 ± 0.3
Coast3-Setting3	-101.4 ± 0.7	-106.9 ± 0.5	-100.6 ± 0.6

5.3.1 SPS Wire Scanners

The SPS is equipped with wire scanners (WS) to measure the transverse beam emittance. The SPS WS system is described in detail in Ref. [53, 54]. For the SPS tests, the emittance was measured with WS both for the horizontal and vertical plane (BWS.51995.H and BWS.41677.V respectively).

The working principle is shown in Fig. 5.3. A thin wire rapidly moves across the proton beam and a shower of secondary particles is generated. The signal from the secondary particles is then detected by a system of scintillator and photomultiplier (PM) detectors outside of the beam pipe. By measuring the PM current as a function of wire position over multiple turns the transverse beam profile is reconstructed. An example of a vertical profile is shown in Fig. 5.4.

Fitting of transverse profiles

Assuming gaussian beams and for $u = x, y$ being the index that respectively corresponds to the horizontal and vertical plane, the rms beam size, σ_u , is obtained following the standard procedure of least squares fitting (see Appendix A.2). In particular, the measured beam profiles from each scan are fitted with the following four-parameter (A, k, μ, σ_u) gaussian function:

$$f(x) = k + Ae^{-\frac{(x-\mu)^2}{2\sigma_u^2}}, \quad (5.1)$$

5. Experimental studies 2018: emittance growth from Crab Cavity noise

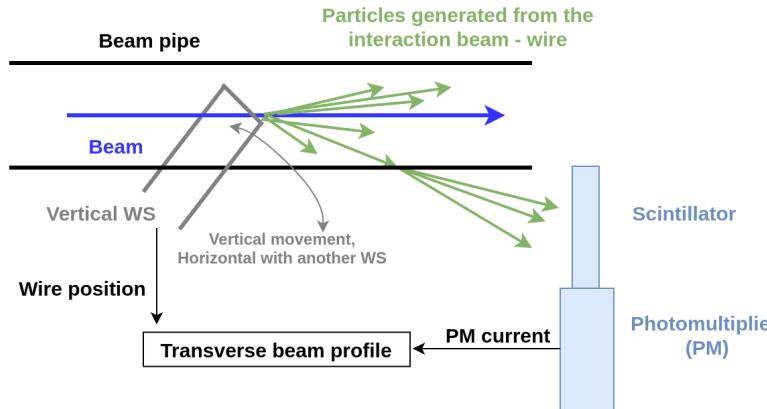


Figure 5.3: Sketch of the SPS rotational wire scanners [54]. The wire moves across the proton beam generating secondary particles which are then detected by a scintillator and a photomultiplier. From the measured photomultiplier current the beam profile is reconstructed.

where k is the signal offset of the PM, A is the signal amplitude, μ is the mean of the gaussian distribution and σ_u its standard deviation. The uncertainty of the measured rms beam size, $\Delta\sigma_u$, is defined as the error of the fit of the σ_u parameter (see Appendix A.2).

An example of the beam profile measured from the SPS WS at a specific time is shown in Fig. 5.4 (light blue dots) along with the gaussian fit (orange line).

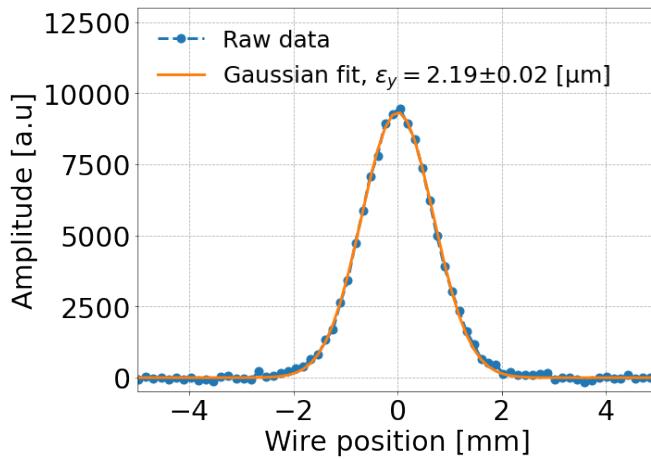


Figure 5.4: Vertical beam profile obtained from the BWS.41677.V instrument. The measured data points (light blue) are fitted with a four parameter gaussian (orange) to obtain the beam size. The calculated emittance and its uncertainty are also shown.

Computing the normalised beam emittance

The formula for computing the normalised beam emittance from the beam size, σ_u is given by:

$$\epsilon_u = \frac{\sigma_u^2}{\beta_{u,WS}} \beta_0 \gamma_0, \quad (5.2)$$

where σ_u is the rms beam size, $\beta_{u,WS}$ the beta function at the WS location and β_0, γ_0 the relativistic parameters. Note that $u = x, y$ is the index that respectively corresponds to the horizontal and vertical plane.

Assuming that the relativistic parameters are free of error, the uncertainty of the computed emittance, $\Delta\epsilon_u$, depends on the uncertainty of the measured beam size, $\Delta\sigma_u$ and of the beta function at the location of the WS, $\Delta\beta_{u,WS}$, as follows:

$$\Delta\epsilon_u = \sqrt{\left(\frac{\partial\epsilon_u}{\partial\sigma_u}\right)^2 \Delta\sigma_u^2 + \left(\frac{\partial\epsilon_u}{\partial\beta_{u,WS}}\right)^2 \Delta\beta_{u,WS}^2} = \epsilon_u \sqrt{\left(\frac{2\Delta\sigma_u}{\sigma_u}\right)^2 + \left(\frac{\Delta\beta_{u,WS}}{\beta_{u,WS}}\right)^2}. \quad (5.3)$$

For the computation of the emittance values from the CC experiment of 2018, the following points were considered. First, in the 2018 SPS operational configuration, the dispersion was small at the WS location and thus its contribution to the beam size was considered to be negligible¹. Moreover, for the studies at 270 GeV beam energy, $\beta_0 \gamma_0$ equals 287.8 and the beta functions were 81.5 m and 62.96 m at the locations of the horizontal and vertical WS respectively. Last, the uncertainty on the beta functions at the location of the WS, $\Delta\beta_{u,WS}$, is 5% in both planes, which represents the rms beta-beating in the SPS [55].

Further considerations

It is worth noting here that during each measurement with the WS the beam profile is actually acquired twice as the wire crosses the beam in the forward direction (IN scan) and then in the reverse direction (OUT scan). For the 2018 measurements the emittance values obtained from IN and OUT scans, $\epsilon_{\text{IN}} \pm \Delta\epsilon_{\text{IN}}$ and $\epsilon_{\text{OUT}} \pm \Delta\epsilon_{\text{OUT}}$,

¹The dispersion at BWS.51995.H location in 2018 was $D_x = -15$ mm. At 270 GeV, the energy spread, δ , is of the order of 10^{-4} . Thus, from Eq. (2.18) the horizontal normalised emittance from the dispersion is expected at the order of 10^{-6} μm . Comparing to the observed beam size during the CC tests of a few microns the dispersion is negligible. The measured D_x, D_y were found to be very small and thus their contribution is also considered negligible. The plan is to perform some measurements in 2022 to get a feeling of their values at the location of the wire scanners

5. Experimental studies 2018: emittance growth from Crab Cavity noise

were found to be very similar. In the analysis of the 2018 measurements, the average emittance from the two scans, $\epsilon_{\text{avg}} = \langle \epsilon_{\text{IN}}, \epsilon_{\text{OUT}} \rangle$, is used. The uncertainty in the average, $\Delta\epsilon_{\text{avg},1}$, is given by [56]:

$$\Delta\epsilon_{\text{avg},1} = \frac{|\epsilon_{\text{IN}} - \epsilon_{\text{OUT}}|}{2\sqrt{2}}. \quad (5.4)$$

The propagated uncertainty from the measurement errors, $\Delta\epsilon_{\text{IN}}$ and $\Delta\epsilon_{\text{OUT}}$, is given by:

$$\Delta\epsilon_{\text{avg},2} = \frac{1}{2} \sqrt{\Delta\epsilon_{\text{IN}}^2 + \Delta\epsilon_{\text{OUT}}^2}. \quad (5.5)$$

Assuming that $\Delta\epsilon_{\text{avg},1}$ and $\Delta\epsilon_{\text{avg},2}$ are independent, the combined uncertainty in the average, $\Delta\epsilon_{\text{avg}}$, is given by:

$$\Delta\epsilon_{\text{avg}} = \sqrt{\Delta\epsilon_{\text{avg},1}^2 + \Delta\epsilon_{\text{avg},2}^2}. \quad (5.6)$$

Finally, some emittance increase is expected during each wire scan, due to multiple Coulomb scattering. This effect has been extensively studied in Ref. [57]. For the rotational SPS WS and the energy of 270 GeV, at which the CC experiments were performed the expected emittance growth from the WS is expected to be between 0.0-0.2% per scan in both transverse planes. However, a conservative number of scans were carried out, ~ 20 scans per bunch and per plane during ~ 1 hour, in order to minimise the contribution from this effect.

5.3.2 Experimental results

In this section, an overview of the emittance growth measurements is presented. Figure 5.5 displays the bunch by bunch transverse emittance evolution through the total duration of the experiment. The three different coast segments are distinguished in this plot with the blue dashed vertical lines. The values of the effective phase noise are also displayed (see Table 5.2), while the moments when the noise level changed are shown with the grey vertical lines. The four different colors (blue, orange, red, green) correspond to the four different bunches. For the bunches the notation "bunch N " will be used, where $N = \{1, 2, 3, 4\}$ according to their position in the bunch train. The errorbars of the emittance values correspond to the uncertainty computed using

Eq. 5.6. However, as they are very small compared to the scale of the plots they are barely visible. Last, the emittance growth rates, $d\epsilon_u/dt$, for each setting and for each bunch are displayed at the bottom of each plot along with their uncertainties. The growth rates are obtained following the standard procedure of weighted least squares fitting (see Appendix A.2). In particular, the measured beam profiles from each scan are fitted with the following polynomial:

$$p(x) = c_0 + d\epsilon_u/dt \times t \quad (5.7)$$

where t is the time in seconds, $d\epsilon_u/dt$ the growth rate in meters per second and c_0 the constant offset in meters. The uncertainties of the growth rates correspond to the error of the fit (see Appendix A.2).

First observations and comments

Figure 5.5 demonstrates a clear emittance growth in the vertical plane which is expected due to the vertical CC. However, the CC noise is observed to induce growth also in the horizontal emittance as a result of residual coupling in the machine. Thus, the total emittance growth given by $d\epsilon_x/dt + d\epsilon_y/dt$ should be considered in the following. That was confirmed by PyHEADTAIL simulations [58] in the presence of CC RF noise and transverse coupling.

Furthermore, both the phase and amplitude noise levels for Coast1-Setting1 were found to be below the noise floor of the instrument. Therefore, the transverse emittance growth observed during that case is a result of other sources (natural emittance growth, see Section 5.1.1) and will be considered as the background growth rate in the analysis below. [Is this approach ok? instead of using 0.45 and 0.55 um/h for the y and x planes respectively.](#)

Summary plot

Figure 5.6 provides a clearer view of the measurements presented in Fig. 5.5. It displays the measured emittance growth rates for each one of the four bunches for the different levels of injected noise. The horizontal error bars correspond to the uncertainty of the effective phase noise (see Section 5.2) while the vertical error bars cor-

5. Experimental studies 2018: emittance growth from Crab Cavity noise

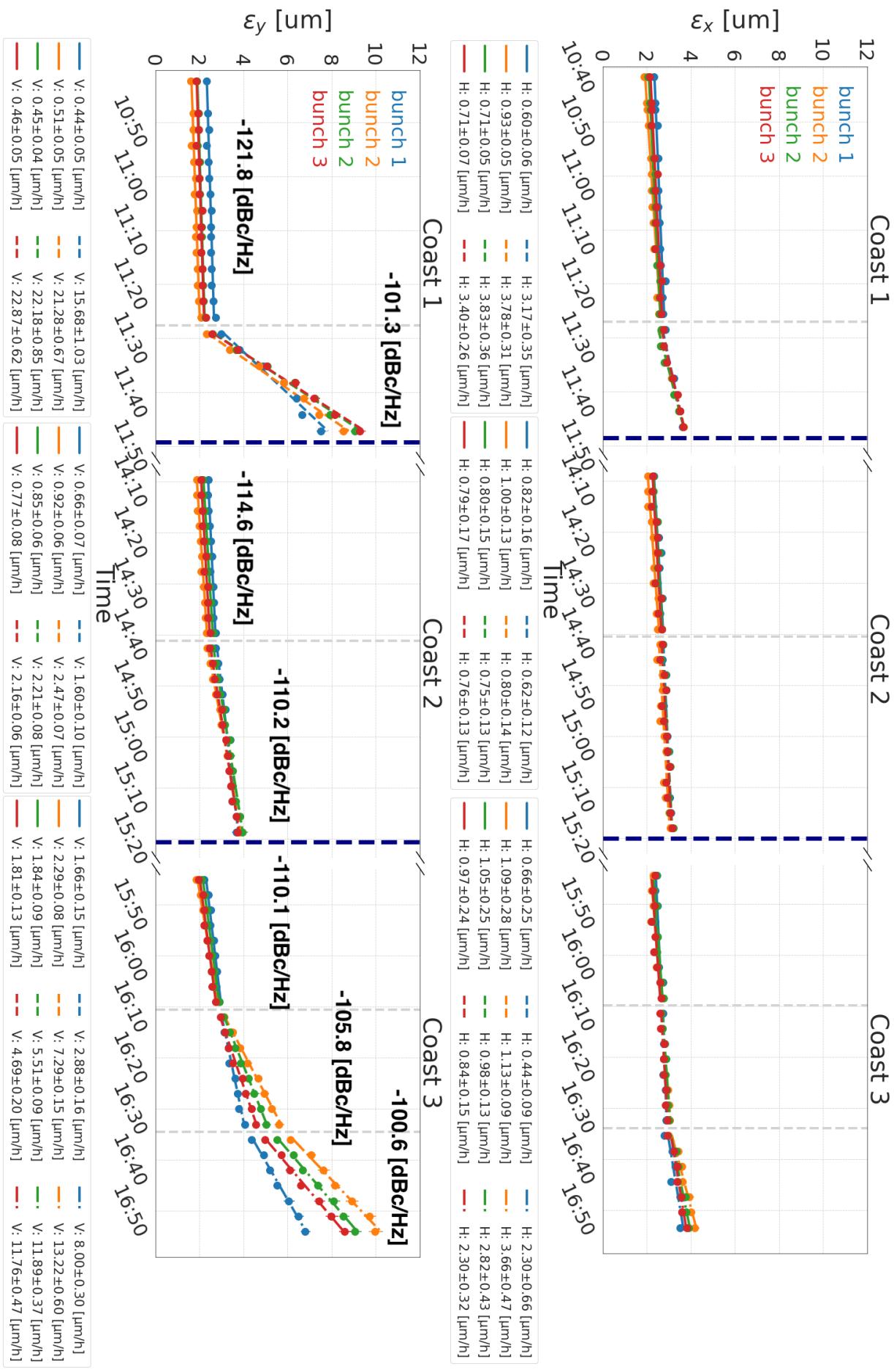


Figure 5.5: Bunch by bunch horizontal (top) and vertical (bottom) emittance evolution during the experiment on September, 15, 2018. The four different colors indicate the different bunches. The different applied noise levels are also shown while the moments when the noise level changed are indicated with the grey vertical dashed lines. The emittance growth rates along with their uncertainties for the seven different noise settings are displayed at the legend at the bottom of the plots.

respond to the uncertainty of the total transverse emittance growth calculated from the uncertainties of the horizontal and vertical growth rates following the standard procedure of the propagation of the uncertainty (Appendix A.3).

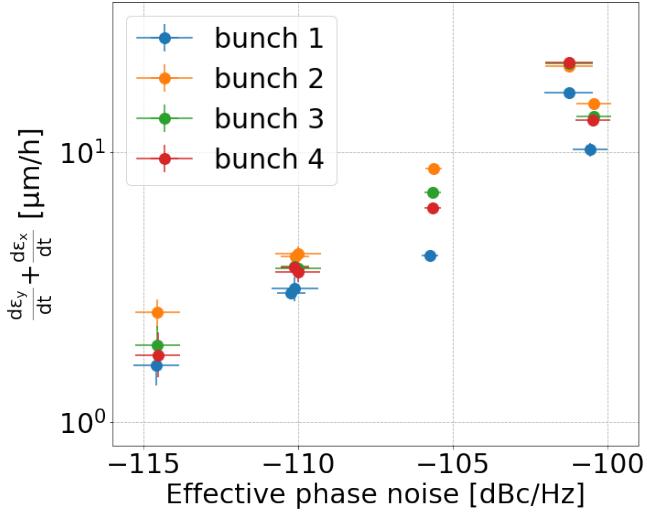


Figure 5.6: Summary plot of the emittance growth study with CC noise in 2018. The transverse emittance growth rate, for the four bunches, is shown as a function of the different levels of applied noise.

From the plot it becomes clear that the measured emittance growth was different for the four different bunches. Furthermore, the first bunch (blue) had systematically the smallest growth rate.

An attempt to understand these observations will be presented in the following section, based on a possible correlation between the transverse emittance growth and the beam evolution in the longitudinal plane.

5.4 Bunch length and intensity measurements

The measurements of the bunch length and intensity that took place in parallel with the emittance growth measurements are presented in this section. The goal is to get a more complete insight of the experimental conditions and possibly explain the different emittance growth rates observed for the four bunches which was discussed in the previous section. Initially, a short introduction on the instruments used for the measurements is provided. After that, the evolution of the longitudinal plane and of the intensity is analysed and discussed.

5.4.1 ABWLM and Wall Current Monitor

The bunch length was measured with two different instruments the ABWLM² [59] and the Wall Current Monitor [60]. Both ABWLM and Wall Current Monitor acquire the longitudinal bunch profiles, while ABWLM is much faster than the Wall Current Monitor. In the ABWLM case the bunch length is obtained by performing a gaussian fit on the acquired profiles. Only the calculated bunch length values are available but not the profiles themselves. For the case of the Wall Current Monitor the bunch length is estimated by computing the full width half maximum of the profiles and then using it to estimate the standard deviation of a gaussian distribution. The longitudinal profiles and the calculated bunch lengths are available for each acquisition. Furthermore, the Wall Current Monitor provides additional information on the relative bunch position with respect to the center of the RF bucket, which will also be used in the following analysis. No further details on the operation of these instruments are discussed here as the offline analysis was not performed by the author.

[How is the intensity calculated?](#)

5.4.2 Bunch length measurements

The bunch length measurements that took place during the CC noise induced emittance growth studies are shown in the bottom plot in Fig. 5.7. The small markers correspond to the data acquired with the ABWLM while the bigger markers correspond to the data acquired with the Wall Current Monitor. The two upper plots contain the transverse emittance growth as discussed in Section 5.3.2. This is for easier comparison of the beam evolution in the transverse and in the longitudinal plane. The color code corresponds to the four different bunches.

Four main observations can be made. First, the plot demonstrates a very good agreement between the ABWLM and the Wall Current monitor. Second, an approximately bunch length increase of $\sim 9\%/\text{h}$ is observed for bunch 1 (blue) in all the three coasts. This rate, which is computed from the ABWLM data, is similar to the blow-up observed in the SPS for similar machine conditions [50]. Third, the bunch

²(A for RF, B for Beam, W for Wideband, L for Longitudinal, M for Measurement)

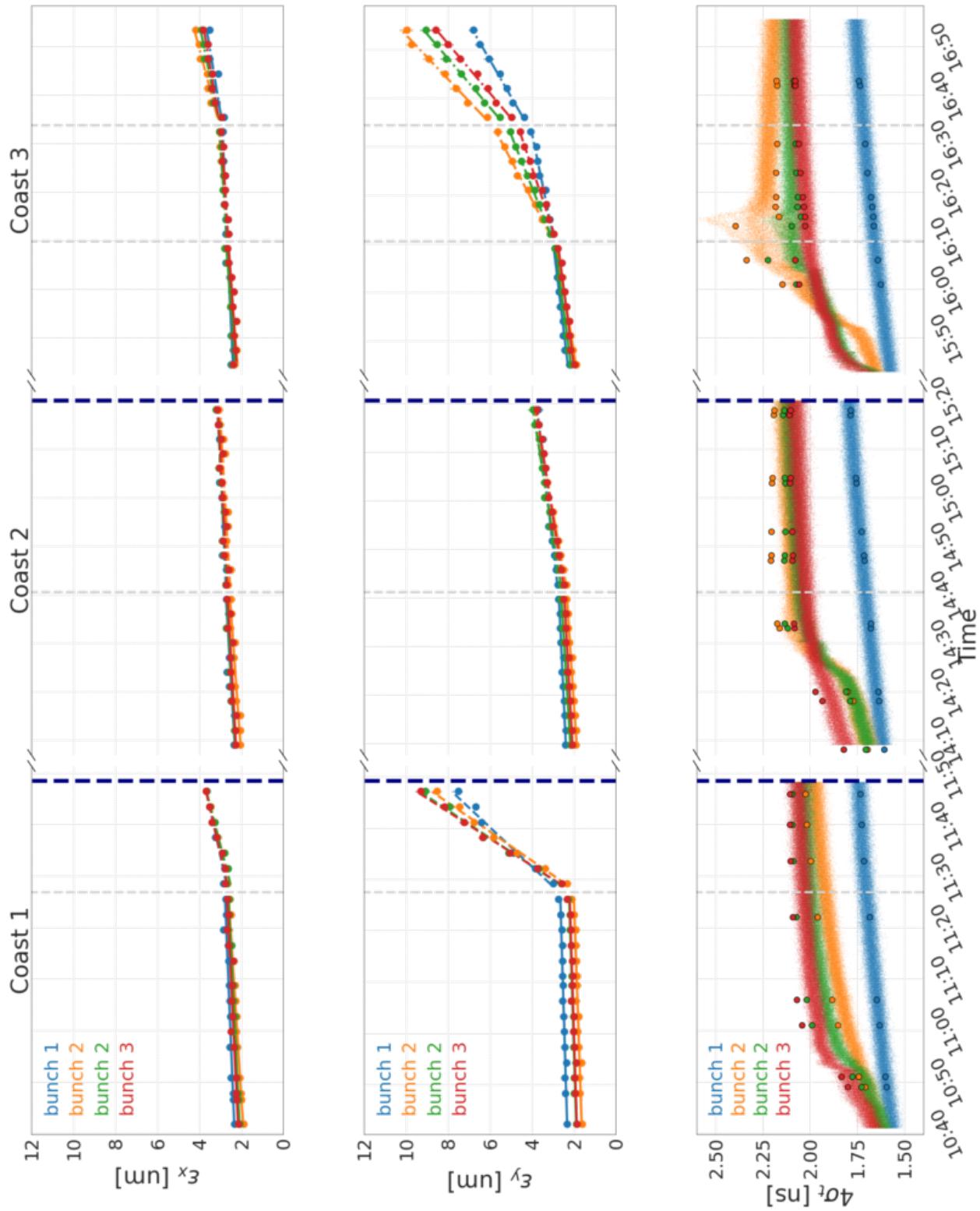


Figure 5.7: Evolution of the beam in transverse and longitudinal planes during the CC noise induced emittance growth experiment. Top: Horizontal emittance growth measured with the SPS WS. Middle: Vertical emittance growth measured with the SPS WS. Bottom: Bunch length evolution measured with the ABWLM (small markers) and the Wall Current Monitor (bigger markers).

5. Experimental studies 2018: emittance growth from Crab Cavity noise

length increase for the last three bunches (2, 3, and 4) is larger than the increase for bunch 1. However, bunches 2, 3, and 4 seem to be longitudinally unstable as sudden jumps appear in their bunch length evolution and this could explain the faster bunch length increase. Last, no correlation is observed between the bunch length evolution and the change of noise level. In order to validate that bunches 2, 3, and 4 are unstable, the longitudinal profiles acquired with the Wall Current Monitor are studied in the next paragraph.

5.4.3 Longitudinal profile measurements

Two example longitudinal profile acquisitions from the Wall Current Monitor are discussed here as they can provide further insight on the sudden jumps observed in the bunch length values for bunches 2, 3, and 4. The selected acquisitions correspond to the moments where the sudden jumps are performed in the second and third coast and are shown in Fig 5.8. The relative bunch position with respect to the center of the RF bucket of each bunch for an acquisition period of 7 ms is also illustrated in the bottom plots of Fig. 5.8 for completeness.

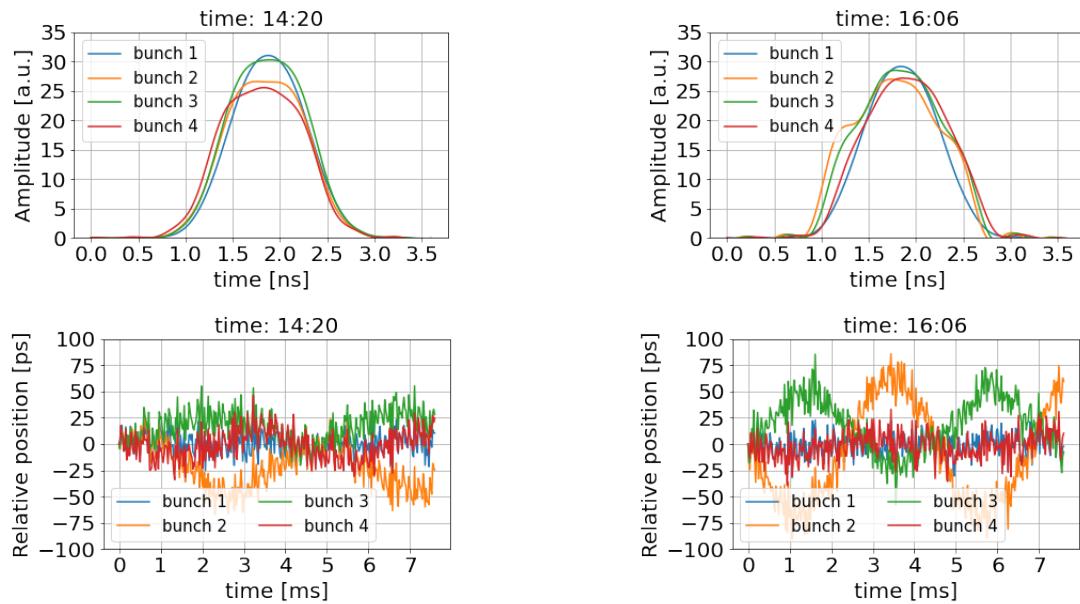


Figure 5.8: Longitudinal profiles (top) and relative bunch position with respect to the center of the RF bucket (bottom) acquired with the Wall Current Monitor. The acquisitions correspond to the times when the sudden jumps in the bunch length evolution are observed (see Fig. 5.7).

From Fig. 5.8, it becomes clear that bunches 2, 3, and 4 (orange, green, and red) are

5.5. Comparison of measured transverse emittance growth with the theoretical predictions

longitudinally unstable. This is believed to be due to the fact that the phase loop was sampling only the first bunch because of the large bunch spacing of 525 ns [61]. For this reason, the following analysis is focused only on bunch 1, which was not affected by the instability. However, in the next paragraph the intensity measurements for all the four bunches are exceptionally illustrated.

5.4.4 Intensity measurements

The bunch by bunch intensity measurements that were performed along the experiment with artificial CC noise are displayed in Fig. 5.9. In particular the intensity values normalised with the intial value are shown for each bunch. The four different bunches are indicated with the four different colors. The acquisitions from both the ABWLM and the Wall Current Monitor are illustrated with the small and bigger markers respectively.

The following observations can be made. First, there is very good agreement between the measruments from the ABLWM and the Wall Current Monitor. Second, losses of $\sim 2\text{-}4\%/\text{h}$, computed from the ABLWM acquisitions, are observed for bunch 1 (blue) in all the three coasts. This rate is even smaller than observed in the SPS in coast studies without external noise ($\sim 10\%/\text{h}$) [50]. Last, more significant losses are observed for the longitudinally unstable bunches (bunch 2,3, and 4). However, this is not of concern as the last three bunches will not be included in the following analysis as discussed in the previous paragraph (5.4.3).

5.5 Comparison of measured transverse emittance growth with the theoretical predictions

This section focuses on the main objective of the experiment which was the comparison of the measured transverse emittance growth with the expected values as computed from the theoretical model discussed in Chapter 3. As already discussed (Section 5.4.3), the comparison considers only bunch 1 as the other three bunches were found to be longitudinally unstable.

Figure 5.10 compares the the measured (blue) and the theoretically calculated (black)

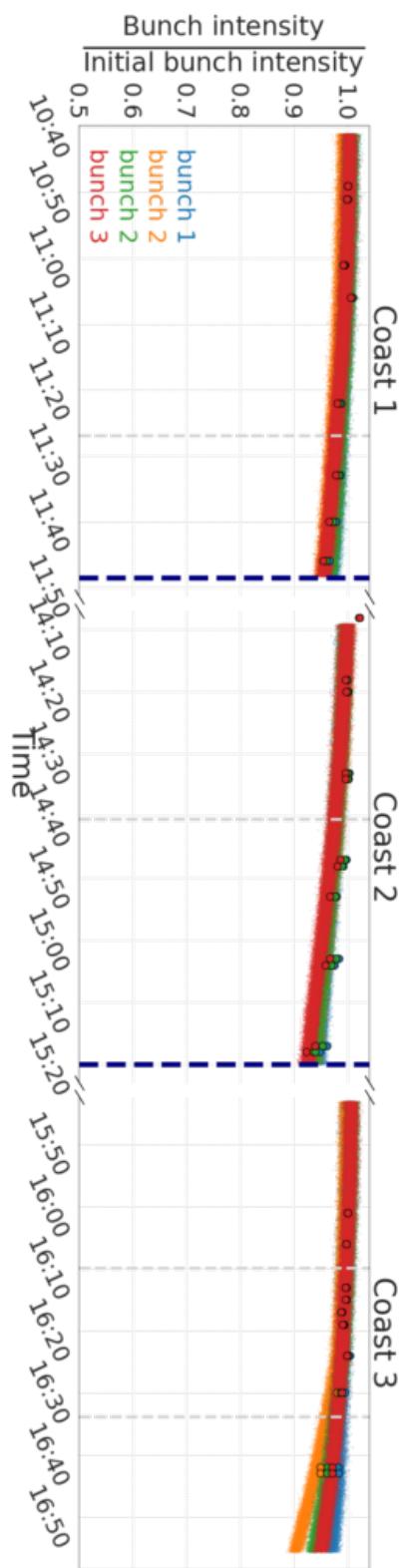


Figure 5.9: Intensity evolution as measured with ABIWM (smaller markers) and with the Wall Current Monitor (bigger markers) during the experiment with CC noise in 2018.

5.5. Comparison of measured transverse emittance growth with the theoretical predictions

emittance growth rates of bunch 1 for the different noise levels. For the comparison, the background growth rate from other sources (measured during Coast1-Setting1, as discussed in Section 5.3) is subtracted from the measured values. In particular the background growth was measured $0.6 \mu\text{m}/\text{h}$ and $0.44 \mu\text{m}/\text{h}$ for the horizontal and vertical plane respectively. One should keep in mind that background subtraction has practically no impact for high noise levels. Instead, it is significant for small noise levels.

The expected emittance growth due to CC noise was estimated for all noise settings using Eq. (3.2). The growth was computed for the beam energy of 270 GeV, considering the vertical beta function at the location of the CC2 of 73.82 m and the revolution frequency of SPS which is 43.37 kHz. For each setting, the measured noise PSDs (i.e. effective phase noise) and the average bunch length over each observation window were used in the calculation. These values are listed in the first two columns of Table 5.3.

The horizontal error bars, for both measured and calculated growths, correspond to the uncertainty of the effective phase noise values (see Table 5.2). The vertical error bars for the measured growth are defined as the error of the linear fit on the emittance values (see Section 5.3). The vertical error bars on the theoretically calculated rates are computed following the standard procedure of propagation of the uncertainty. It should be mentioned here that only the uncertainties on the effective phase noise ($\sim 13\%$ on average for bunch 1) are included in the error propagation. The beam energy and the revolution frequency are assumed to be free of error, while the uncertainties of the rest of the parameters: bunch length, CC voltage and beta function ($\sim 2\%$, 0.01% , and 5% respectively) are not included as they are much smaller than those of the noise.

From Fig. 5.10 it becomes evident that the theory systematically overestimates the measured growth rates. The averaged discrepancy over all noise levels is a factor of 4: numerical values are given in Table 5.3. The measurements seem to go in the good direction but actually they show that there is a significant uncertainty on the predictions of the theoretical model. The accuracy of the model is essential for defining the specifications for the design of the HL-LHC CC LLRF. Therefore, understanding

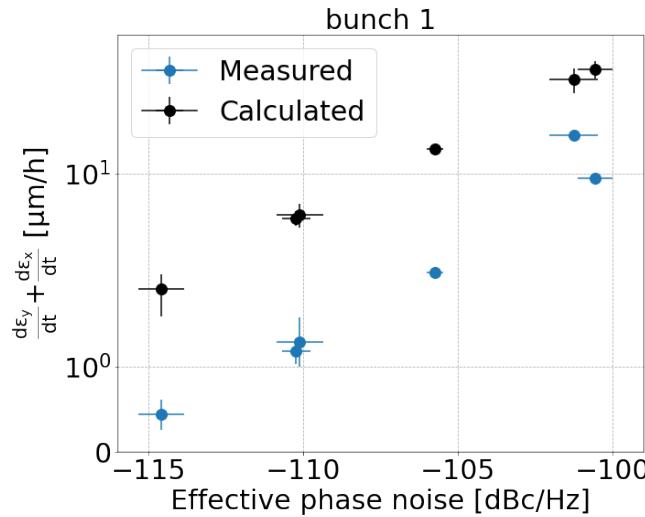


Figure 5.10: Summary plot of the emittance growth study with CC noise in 2018 focused on bunch 1 only. The measured emittance growth rate (blue) and the expected growths from the theoretical model (black) are shown as a function of the different levels of applied noise.

the reason behind the observed discrepancy with the measurements which would also allow to decide if the reduction of the factor 4 can be propagated for the HL-LHC predictions is fundamental. The studies performed to explain the discrepancy will be described in the following chapters.

Table 5.3: Comparison between the measured and the calculated transverse emittance growth rates for bunch 1 for the different noise levels, and average bunch length for each case.

$10 \log_{10} \mathcal{L}(f)$ [dBc/Hz]	$\langle \sigma_\phi \rangle$ [rad]	Growth rate [μm/h]	
		Measured	Calculated
-114.6	1.05	0.44	1.9
-110.2	1.10	1.18	5.10
-110.1	1.03	1.28	5.38
-105.8	1.06	2.28	14.50
-101.3	1.08	17.81	40.55
-100.6	1.09	47.42	9.26

5.6 Conclusions and outlook

The objective of the first experimental campaign with CC noise in the SPS was to benchmark the available theoretical model which predicts the noise induced transverse emittance growth against measurements. For this reason, a dedicated exper-

iment took place in the SPS in September of 2018, with different leves of artificial noise injected in the CC RF system. Four bunches circulated in the machine for long periods of time and their emittance evolution was recorded to be compared with the theoretical predictions.

The experiment demonstrated that the transverse emittance of all the four bunches increased for stronger noise. However, during the analysis it was found that only the first bunch of the train was stable in the longitudinal plane. For this reason, only the data from the first bunch were used for the comparison with the theoretically calculated emittance growth rates. The comparison showed that the theoretically overestimates the measurements by a significant factor of 4. The reason behind this discrepancy needs to be understood as the predictions of the theoretical model will be used to define limits and acceptable noise levels for the HL-LHC CCs. Therefore, the next chapters focus on explaining the observed discrepancy.

6 | Investigation of the discrepancy

6.1 Benchmarking with different simulation software

Benchmarking of theory with pyheadtail (one turn map) and Sixtracklib (element by element tracking).

6.1.1 PyHEADTAIL

- real CC element - local vs global cc scheme - How emittance is computed. No dispersive contribution. studies vertical plane.

6.1.2 Sixtracklib

Remember that in chapter 6 it was demonstrated that there is no visible difference on the cc rf noise induced emittance growth if the noise kicks are modeled as kicks on the momentum or the real rf multiple + used in a global or local scheme.

pyheadtail vs sixtracklib:

6.2 Sensitivity to the non-linearities of the main SPS dipoles

Simulation studies with sixtracklib

6.3 Simulations using the measured noise spectrum

Sixtracklib PyHEADTAIL and the exact machine parameters

6.4 Sensitivity studies

1. Sensitivity to how noisy is the noise spectrum
2. On the CC voltage
3. On the different bunch lengths.

6.5 b3b5b7 multiple errors

Contribution of the non-linearities with sixtracklib.

All these factors were excluded as possible sources of the discrepancy.

7 | Simulation studies: Suppression mechanism from the beam transverse impedance

During the dedicated experiment that took place in the SPS in 2018 with the CCs, the measured emittance growth was found to be a factor four (on average) lower than expected from the theory (see Section 5.5). The reason for this discrepancy remained unresolved for some time, as detailed follow-up studies (see Chapter 6) investigated and excluded a number of possible explanations for the discrepancy. It was recently found, that the beam transverse impedance, which is not included in the theory [62] used for the comparison with the measurements may impact the noise-induced emittance growth and explain the experimental observations. Here, the damping mechanism from the beam transverse impedance is investigated as observed in detailed PyHEADTAIL simulations.

The structure of this chapter is as follows:

7.1 SPS transverse impedance model

The PyHEADTAIL studies presented in this chapter are performed including the detailed transverse impedance model of the SPS machine [63]. This model has been developed through a combination of theoretical computations, electromagnetic simulations and was benchmarked with beam-based measurements [35, 64, 65, 66]. It includes the contributions from all the individual elements in the SPS lattice i.e. the resistive wall, the indirect space charge, the kickers, the RF cavities (200 MHz and 800 MHz), the step transitions and the horizontal and vertical beam position monitors [66]. As discussed in Section 2.11.1, the model needs to represent the global impedance of the full machine. Thus, the total impedance is obtained

by summing up the impedance of each element weighted with the beta function at its location and by dividing the sum by the average beta function of the SPS. For the Q26 optics the average horizontal and vertical beta functions are 42.09 m and 42.01 m respectively. Figure 7.1 shows the complete transverse impedance model of the SPS machine with the disentangled dipolar (blue) and quadrupolar (orange) terms to be plotted separately.

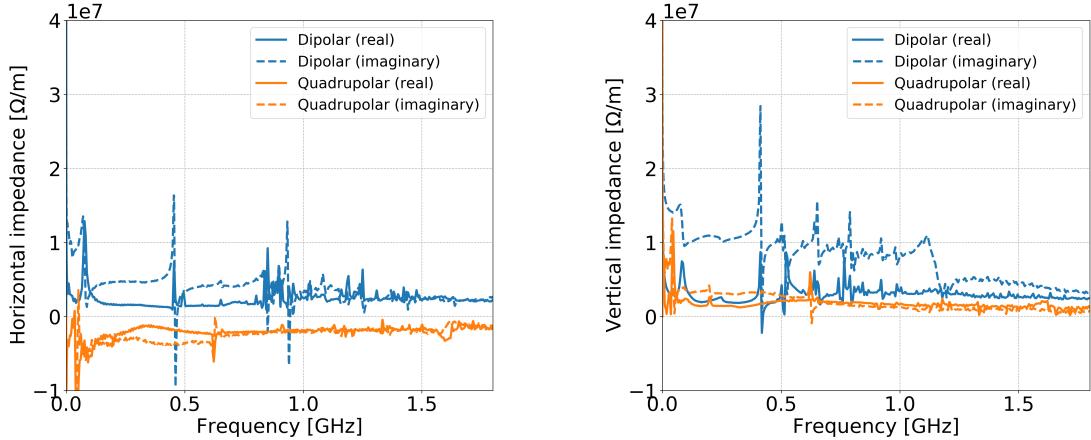


Figure 7.1: Horizontal (left) and vertical (right) impedance model of the SPS. The model is available in the public gitlab repository of Ref. [63].

The contributions from the wall, the kickers and the step transitions are visible at the low frequencies (up to ~ 0.4 GHz). The impedance of the RF cavities and the beam position monitors (BPMs) corresponds results to the peaks observed between ~ 0.4 -1 GHz.

Wake functions

As already discussed in Section 2.11.1, in order to include the impedance effects in PyHEADTAIL simulations the real-value wakefields in time domain are used. The wakefield kicks are computed as a convolution of the wake function with the moments of each particle. The total transverse dipolar (blue) and quadrupolar (orange) wake functions for both planes of the SPS can be found in the gitlab repository of Ref. [63] and they are plotted in Fig 7.2.

7.1.1 Coherent tune shift with intensity and growth rate

- growth rate of mode 0 - shift of mode 0 One of the properties which is also used for checking the correct implementation of the model. which as we will say later on

7. Simulation studies: Suppression mechanism from the beam transverse impedance

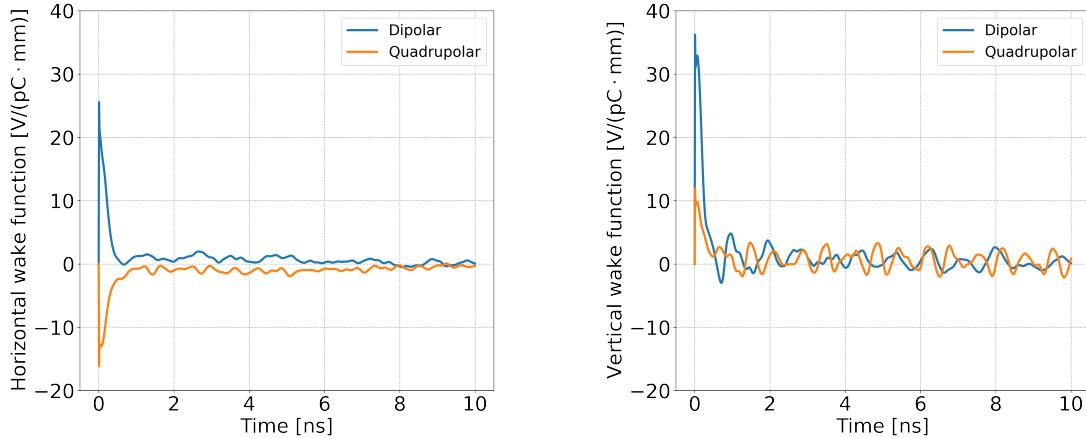


Figure 7.2: Horizontal (left) and vertical (right) wakefunctions of the SPS. The wake functions are available in the public gitlab repository of Ref. [63]. For comparison the bunch length in the SPS CC experiments is ~ 1.85 ns ($4\sigma_t$).

is relevant to the suppression mechanism is the coherent tune shift with

- model benchmarked but not as thorough for ... not for single bunches at that low intensity?
- we figured out

7.2 Simulations setup

This section describes the setup of the PyHEADTAIL simulations that were performed to study the impact of the beam coupling impedance on the emittance growth due to CC RF noise. The relevant machine and beam parameters are summarised in Table 7.1. The optics parameters were extracted from the SPS design parameters (nominal model for Q26 optics: Section 2.5.1), except for the vertical alpha function at the location of the CC2, $\alpha_{y,CC2}$ which is set to zero for simplicity as its value doesn't affect the emittance evolution. **Maybe elaborate a bit more on why it doesn't affect it?** The rest of the listed parameters were chosen to be very close to the experimental conditions during the emittance growth measurements of 2018 (discussed in Chapter 5).

Crab Cavity RF noise levels

For the simulation studies presented in this chapter, the phase and amplitude noise are modeled as random kicks on the particles' momentum according to the work of

Table 7.1: Relevant machine and beam parameters used to study the impact of the beam transverse impedance on the emittance evolution due to CC RF noise with the PyHEADTAIL code.

Parameter	Value
Beam energy, E_b	270 GeV
Number of protons per bunch, N_b	3×10^{10} p/b
Horizontal / Vertical betatron tune, Q_x / Q_y	26.13 / 26.18
Horizontal / Vertical first order chromaticity, Q'_x / Q'_y	1 / 1
Main RF voltage / frequency, V_{RF} / f_{RF}	5.088 MV / 200.39 MHz
Synchrotron tune, Q_s	0.0051
CC2 voltage / frequency, V_{CC} / f_{CC}	1 MV / 400.78 MHz
Vertical beta function at CC2, $\beta_{y,CC2}$	73.82 m
Vertical alpha function at CC2, $\alpha_{y,CC2}$	0 m
Vertical dispersion at CC2, $D_{y,CC2}$	0 m
Number of bunches	1
Rms bunch length, $4\sigma_t$	1.8 ns*
Horizontal / Vertical normalised emittance, $\epsilon_x^n / \epsilon_y^n$	$2 \mu\text{m} / 2 \mu\text{m}^*$
Horizontal / Vertical rms tune spread, $\Delta Q_x^{rms} / \Delta Q_y^{rms}$	$2.02 \times 10^{-5} / 2.17 \times 10^{-5}$ †

* Initial values at the beginning of the tracking.

† Here the rms betatron tune spread includes only the contribution from the detuning with amplitude present in the SPS machine. More details along with the calulcations for the listed values can be found in Appendix C.1.

T. Mastoridis and P. Baudrenghien in Ref [62], as follows:

$$\textbf{Phase noise: } y'_{i,1} = y'_{i,0} + A \cos \left(\frac{2\pi f_{CC}}{c\beta_0} z_i \right), \quad (7.1)$$

$$\textbf{Amplitude noise: } y'_{i,1} = y'_{i,0} + A \sin \left(\frac{2\pi f_{CC}}{c\beta_0} z_i \right), \quad (7.2)$$

where $i = 1 \dots N$ with being N the number of macroparticles used in the simulation, f_{CC} is the CC frequency in Hz, c is the speed of light in m/s, β_0 the relativistic beta and z_i the longitudinal position of each particle in m. The factor $A = V_{CC}$

Amplitude detuning

Parameters particularly for simulations without impeadance effects

Parameters particularly for simulations with impeadance effects

The parameters used for the simulations were

7. Simulation studies: Suppression mechanism from the beam transverse impedance

imulations used the SPS design parameters and the beam conditions as in the experiment of 2018.

Table with parameters, including macroparticles number + slices + average beta funtion for convinience.

7.3 First observations of emittance growth suppression by the impedance

7.4 Characterisation of the emittance growth suppression by the impedance

8 | Experimental studies 2021

9 | Simple model of describing the decoherence suppression from impedance

- The use of damper is an appropriate configuration as it provides dipolar noise kicks in the beam and as shown in Chapter 7 the suppression mechanism is related to the dipole motion.
- More machine time. no cryo module and team needed. only two people..
- Less uncertainties from CC setup.

10 | Conclusion

A | Definitions and methods of statistical analysis

A.1 Basic terminology

This appendix, introduces the basic terminology of statistical analysis and gives the definitions that are used in this thesis. The definitions follow the book by R. J. Barlow [67] where one can find a more detailed insight.

A.1.1 Averages

Arithmetic mean

For a data set of N data $\{x_1, x_2, x_3, \dots, x_N\}$ the arithmetic mean or just mean of the value of x is:

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^N x_i. \quad (\text{A.1})$$

Below, two properties of the arithmetic mean are discussed as they are used in this thesis.

- The mean of the sum of two variables x and y is equal to the sum of their means, ie:

$$\langle x + y \rangle = \langle x \rangle + \langle y \rangle \quad (\text{A.2})$$

- If x and y are independent the mean of their product equals:

$$\langle x \cdot y \rangle = \langle x \rangle \cdot \langle y \rangle \quad (\text{A.3})$$

Root mean square

In the classical definition in mathematics, the root mean square (rms) is an alternative to the arithmetic mean and is defined as:

$$x^{rms} = \sqrt{\frac{x_1^2 + x_2^2 + x_3^2 + \dots + x_N^2}{N}} = \langle x^2 \rangle. \quad (\text{A.4})$$

- **Disclaimer:** It is common in physics and in sciences in general for the term rms to correspond to what is actually defined as standard deviation (see definition in Appendix A.1.2). This convention, is also followed in this thesis.

A.1.2 Measuring the spread

Variance

For a data set of N data $\{x_1, x_2, x_3, \dots, x_N\}$ the variance of x expresses how much it can vary from the mean value, $\langle x \rangle$. The variance, $\text{Var}(x)$, is defined as:

$$\text{Var}(x) = \frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)^2. \quad (\text{A.5})$$

Alternatively, the variance can be expressed in a simpler way as follows (see Ref. [67] p.24-25):

$$\text{Var}(x) = \langle x^2 \rangle - \langle x \rangle^2. \quad (\text{A.6})$$

Standard deviation

The square root of the variance is the standard deviation (std):

$$\sigma_x = \sqrt{\text{Var}(x)} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)^2}, \quad (\text{A.7})$$

or as follows from Eq. (A.6):

$$\sigma_x = \sqrt{\langle x^2 \rangle - \langle x \rangle^2}. \quad (\text{A.8})$$

The spread in a data set is usually expressed with the standard deviation instead of the variance, as the standard deviation has the same units with the variable x .

Full width half maximum

An alternative measure of the spread is the full width half maximum (FWHM).

A.1.3 Data sets with more than one variables - Covariance

In the case that each element of the data set consists of a pair of variables, $\{(x_1, y_1), (x_2, y_2), (x_3, y_3), \dots, (x_N, y_N)\}$ the covariance expresses the extend to which x and y tend to vary together. The covariance between x and y is defined as:

$$\text{Cov}(x, y) = \frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)(y_i - \langle y \rangle). \quad (\text{A.9})$$

It can be seen that the covariance of variable x with itslef equals the variance. In particular, it is written:

$$\text{Cov}(x, x) = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)^2} = \text{Var}(x) = \sigma_x^2. \quad (\text{A.10})$$

A.2 Least squares fitting

In sciences, many quantities can not be measured directly but can be inferred from measured data by fitting a model function to them. Common model functions are the Gaussian, polynomial, or sinusoidal. The fitting procedure followed in this thesis is called "least squares" and is described below based on Ref. [68].

Suppose that we have N data points (x_i, y_i) and that $y = f(x, \alpha, \beta)$ is the model function that describes the relationship between the points. The objective of the fit is to determine the optimal parameters α, β such as the model function describes best the data points. This is done by minimising the χ^2 statistics with respect to α and β :

$$\chi^2 = \sum_{i=1}^N [y_i - f(x_i, \alpha, \beta)]^2, \quad (\text{A.11})$$

where y_i is the observed value and $f(x_i, \alpha, \beta)$ the expected value from the model. In other words, χ^2 is a measure of deviation between the measurement and the expected result, and thus its minimisation results in the best fit i.e. to the optimal parameters α, β .

Weighted least squares fitting

Suppose that we have N data points $(x_i, y_i \pm \Delta y_i)$, where Δy_i is the uncertainty of y_i y,

and that $y = f(x, \alpha, \beta)$ is the model function that describes the relationship between the points. To define the optimal parameters α, β taking into account the impact of the uncertainty Δy_i , Eq. (A.11) is written as:

$$\chi^2 = \sum_{i=1}^N \frac{[y_i - f(x_i, \alpha, \beta)]^2}{\Delta y_i^2} \quad (\text{A.12})$$

Error of the fit

The standard deviation of the fit results, $\sigma_\alpha, \sigma_\beta$, is estimated by the square root of the diagonal of their covariant matrix:

$$\begin{pmatrix} \sigma_\alpha^2 & \text{Cov}(\alpha, \beta) \\ \text{Cov}(\beta, \alpha) & \sigma_\beta^2 \end{pmatrix} \quad (\text{A.13})$$

In this thesis, the uncertainties of the fit results, $\Delta\alpha, \Delta\beta$, are defined as the standard deviation, σ_α and σ_β , of the corresponding optimal parameters.

The values of the optimal parameters and their covariance matrix are computed in this thesis using the `scipy.curve_fit` [69] function of the Python programming language.

A.3 Propagation of uncertainty

Suppose that y is related to N independent variables $\{x_1, x_2, \dots, x_N\}$ with the following function:

$$y = f(x_1, x_2, \dots, x_N). \quad (\text{A.14})$$

If $\{\Delta x_1, \Delta x_2, \dots, \Delta x_N\}$ the uncertainties of $\{x_1, x_2, \dots, x_N\}$ respectively, the uncertainty of y , is given by [67]:

$$\Delta y = \sqrt{\left(\frac{\partial f}{\partial x_1} \Delta x_1\right)^2 + \left(\frac{\partial f}{\partial x_2} \Delta x_2\right)^2 + \dots + \left(\frac{\partial f}{\partial x_N} \Delta x_N\right)^2} \quad (\text{A.15})$$

B | Fundamentals of signal analysis and measurement

This appendix discusses the basic terminology of signal processing and gives the definitions which are used in this thesis. The focus is on Fourier transform and the power spectral density. First the most general mathematical definitions which concern signals continuous in time and with infinite time duration are discussed. Secondly, the definitions are given for signals sampled at a finite number of points, which are considered for the measurements and for the computational analysis. Furthermore, the quantities that are used most often for noise power spectrum measurements and their relationship to the mathematical definitions of the power spectral density are discussed. Finally, the way of applying a measured noise spectrum in numerical simulations is described.

B.1 Continuous-time analysis

Fourier transform

A physical process (or signal or time series) can be described in the time domain by a continuous function of time, e.g. $y(t)$, or else in the frequency domain, where the process is specified by giving its amplitude \hat{y} as a function of frequency, e.g. $\hat{y}(f)$ with $f \in (-\infty, +\infty)$. In other words, $y(t)$ and $\hat{y}(f)$ are essentially different representations of the same function. In general, $\hat{y}(f)$ can be a complex quantity, with the complex argument giving the phase of the component at the frequency f .

One can switch between these two representations using the Fourier transform method. In this thesis the Fourier transform of a time series $y(t)$, which will be denoted in this

document by \hat{y} , is defined as [70]:

$$\hat{y}(f) = \int_{-\infty}^{\infty} y(t) e^{-2\pi i t f} dt, \quad (\text{B.1})$$

where f stands for any real number. If the time is measured in seconds the frequency, f , is measured in hertz.

The inverse Fourier transform, which is used to re-create the signal from its spectrum, is defined as:

$$y(t) = \int_{-\infty}^{\infty} \hat{y}(f) e^{2\pi i t f} df. \quad (\text{B.2})$$

Power spectral density and total power

The power spectral density, $S_{yy}(f)$, of a signal (or a time series), $y(t)$, will be used extensively in this thesis: it describes the distribution of the power in a signal between its frequency components, and is defined as the Fourier transform of the autocorrelation function, $R_{yy}(t)$ [37]:

$$S_{yy}(f) = \hat{R}_{yy}(f) = \int_{-\infty}^{\infty} R_{yy}(\tau) e^{-2\pi i \tau f} d\tau. \quad (\text{B.3})$$

The continuous autocorrelation $R_{yy}(\tau)$ is defined as the continuous cross-correlation integral of $y(t)$ with itself, at lag τ [71]:

$$R_{yy}(\tau) = (y * y)(\tau) = \int_{-\infty}^{\infty} \bar{y}(t) y(t + \tau) dt, \quad (\text{B.4})$$

where $*$ denotes the convolution operation and $\bar{y}(t)$ represents the complex conjugate of $y(t)$.

According to the cross-correlation theorem [71]:

$$\hat{R}_{yy}(f) = \bar{\hat{y}}(f) \hat{y}(f) = |\hat{y}(f)|^2, \quad (\text{B.5})$$

where $\hat{y}(f)$ is the Fourier transform of the signal as defined in Eq. (B.1).

From Eq. (B.3) and Eq. (B.5) the power spectral density of a signal $y(t)$ can be simply

written as the square of its Fourier transform:

$$S_{yy}(f) = |\hat{y}(f)|^2, \quad (\text{B.6})$$

with $f \in (-\infty, +\infty)$.

B.2 Discrete-time analysis

Discrete-time signals

Figure B.1 shows a part of a continuous signal $y(t)$. As already mentioned, for the measurements and the computational analysis, signals (or time series) sampled at a finite number of points are considered. Such signals are called discrete-time signals and in most cases they are sampled at equal points in time. For example, in Figure B.1, it is assumed that the continuous signal, $y(t)$, is sampled at intervals Δt creating a set of N points. The length in time between the first and final sample is $T_{\text{sample}} = \frac{N-1}{N} T$, where $T = N\Delta t$.

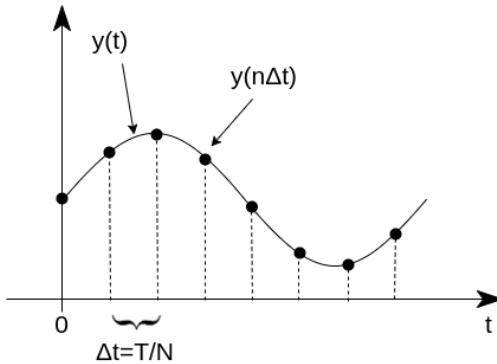


Figure B.1: Sampling of the continuous signal $y(t)$ at a finite number of points N . The sampled signal is the discrete-time signal $y(n\Delta t)$ with Δt the sampling interval and n an integer such that $n \in [0, N - 1]$.

Discrete Fourier transform

Let us consider a discrete-time signal, y_n which is sampled at N consecutive samples, $y_n = y(n\Delta t)$, with $n \in [0, N - 1]$ such that Δt is the sampling interval. For later convenience, we assume that N is an odd integer. As a first step, we note that the in-

tegral of Eq. (B.1) can be represented by a discrete sum in the limit that $\Delta t \rightarrow 0$:

$$\hat{y}(f) = \int_{-\infty}^{\infty} y(t) e^{-2\pi i f t} dt = \lim_{\Delta t \rightarrow 0} \sum_{n=-\infty}^{\infty} y(n\Delta t) e^{-2\pi i f n\Delta t} \Delta t. \quad (\text{B.7})$$

Based on the expression for the summation in Eq. (B.7), we define the discrete Fourier transform as follows:

$$\hat{y}_k = \sum_{n=0}^{N-1} y(n\Delta t) e^{-2\pi i \frac{kn}{N}}. \quad (\text{B.8})$$

Here, the index k is an integer in the range $-\frac{N-1}{2}$ to $\frac{N-1}{2}$. Each component \hat{y}_k of the discrete Fourier transform is related to the component $\hat{y}(f)$ of the continuous Fourier transform of $y(t)$, for $f = k/T$, in the limit $\Delta t \rightarrow 0$ and $N \rightarrow \infty$ (and where it is assumed that $y(t) = 0$ for $t < 0$ and for $t > T$).

It should be noted that the discrete Fourier transform is calculated only at integer values of k , and therefore for N samples the discrete Fourier transform will consist of N numbers. The components of the discrete Fourier transform are calculated at frequencies f_k that are integer multiples of $\Delta f = 1/T = f_s/N$, with $f_s = 1/\Delta t$ the sampling frequency. In that case, $f_k \in [-\frac{N-1}{2T}, \frac{N-1}{2T}]$. An example of a discrete Fourier transform is shown in Fig. B.2.

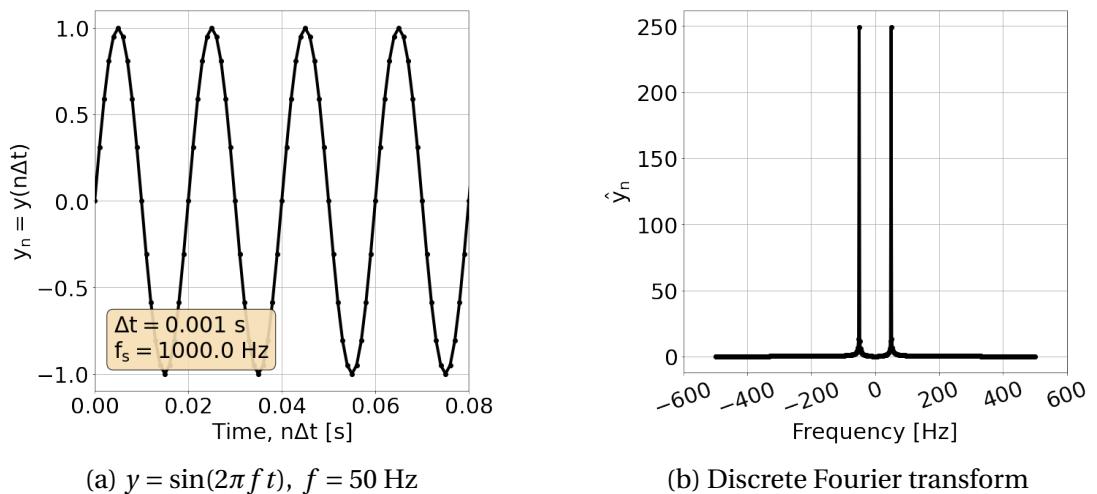


Figure B.2: Example of a signal sampled at discrete time intervals, and the corresponding discrete Fourier transform.

B. Fundamentals of signal analysis and measurement

The inverse discrete Fourier transform is defined as:

$$y_n = y(n\Delta t) = \frac{1}{N} \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} \hat{y}_k e^{2\pi i \frac{kn}{N}}, \quad (\text{B.9})$$

where $n \in [0, N - 1]$ and where n and k are both integers.

The definitions given in Eq. (B.8) and Eq. (B.9) are consistent with those used in numpy, in the numpy.fft function [72] package of the Python programming language.

Power spectral density

Following Eq. (B.6) the power spectral density of a discrete-time signal should be estimated as follows:

$$S_{yy}(f_k) = A |\hat{y}_k(f_k)|^2, \quad (\text{B.10})$$

where $f_k \in [-\frac{N-1}{2T}, \frac{N-1}{2T}]$. A is a normalisation constant which is introduced in order to obtain the correct amplitudes at each frequency and thus the correct noise power. There are several different conventions for the choice of this normalization. In this thesis, the following normalization is considered (see more details in the dedicated paragraph at the end of this section):

$$S_{yy}(f_k) = \frac{1}{N^2 \Delta f} |\hat{y}_k(f_k)|^2, \quad (\text{B.11})$$

where $\Delta f = 1/T$ the frequency resolution and N the number of samples.

Figure B.3 shows an example power spectrum of the time-domain signal shown in Fig. B.2a. It can be seen that the spectrum that results from the analysis above is two-sided, which means that it has both positive and negative frequencies. It is also symmetric around the DC component ($f = 0$ Hz), which is actually a property of a real signal.

The power spectral density is expressed in terms of the square of the amplitude of the signal per unit frequency. For example, for a signal defined in units of voltage, V, (e.g. from an oscillator) the units are V^2/Hz .

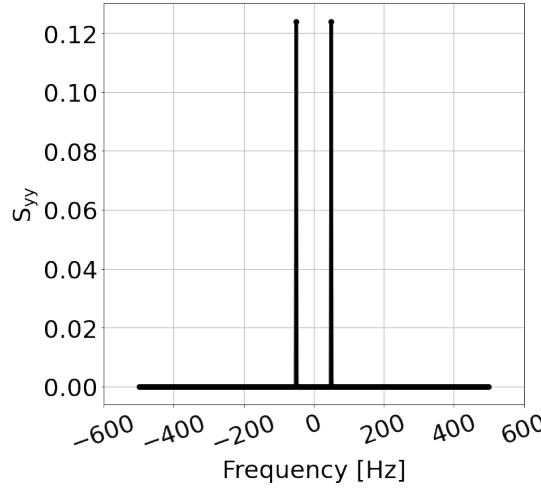


Figure B.3: Power spectrum of $y = \sin(2\pi f t)$, $f = 50$ Hz.

Conversion of a two-sided power spectrum to a single-sided power spectrum

As already mentioned, the frequency spectrum of a real signal is symmetric around the DC component and therefore the information contained in the negative frequency is redundant. For this reason, most of the instruments used in experiments to display a frequency analysis show just the positive part of the spectrum (single-sided spectrum).

In order to convert from a two-sided spectrum to a single-sided spectrum, the negative part of the spectrum is discarded, and the amplitudes of the positive frequency components (excluding the DC component, so for $f > 0$) are multiplied by a factor 2:

$$G_{yy}(f_k) = \begin{cases} 0, & f_k < 0 \\ S_{yy}(f_k), & f_k = 0 \\ 2S_{yy}(f_k), & f_k > 0 \end{cases} \quad (\text{B.12})$$

where $S_{yy}(f_k)$ is the two-sided spectrum and $G_{yy}(f_k)$ the single-sided spectrum. Figure B.4 illustrates the single-sided spectrum of the signal shown in Fig. B.2a.

Normalisation factor for the power spectral density of a discrete-time signal

This paragraph, discusses the choice of the normalisation factor $A = 1/(N^2 \Delta f)$ for the power spectral density of a discrete-time signal defined in Eq. (B.10):

$$S_{yy}(f_k) = A |\hat{y}_k(f_k)|^2. \quad (\text{B.13})$$

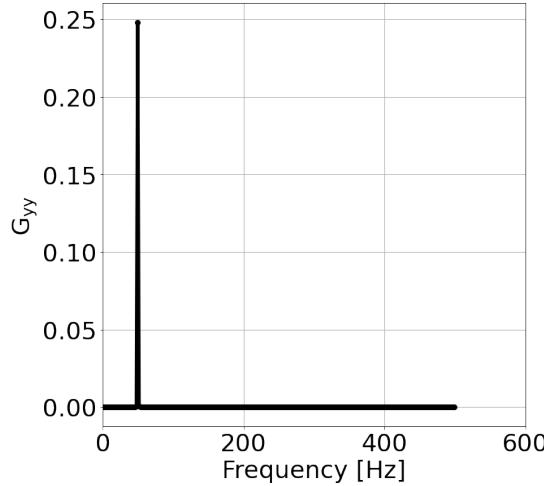


Figure B.4: Single-sided power spectrum of the signal shown in Fig. B.2(a).

Consider the example of a discrete-time series $y_n = y(n\Delta t)$ where n is an integer such that $n \in [0, N-1]$. y_n represents a sequence of successive points equally spaced in time, drawn from a normal distribution with known standard deviation σ and zero mean, $\mu = 0$. The variance of this collection of N equally spaced values is given by:

$$\sigma^2 = \frac{1}{N} \sum_{n=0}^{N-1} |y_n|^2. \quad (\text{B.14})$$

According to Parseval's theorem [71], the variance can be written as:

$$\sigma^2 = \frac{1}{N^2} \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} |\hat{y}_k|^2, \quad (\text{B.15})$$

where \hat{y}_k is the discrete Fourier transform of y_n .

Using Eq. (B.3), the autocorrelation function $R_{yy}(\tau)$ for a continuous-time signal can be found from the inverse Fourier transform of $S_{yy}(f)$:

$$R_{yy}(\tau) = \int_{-\infty}^{\infty} \bar{y}(t)y(t+\tau) dt = \int_{-\infty}^{\infty} S_{yy}(f) e^{2\pi i t f} df. \quad (\text{B.16})$$

For zero lag, this becomes:

$$R_{yy}(0) = \int_{-\infty}^{\infty} S_{yy}(f) df = \sigma^2. \quad (\text{B.17})$$

This expresses the fact that the autocorrelation of a zero-mean stochastic process

(such as y_n) is equal to the variance. It should be noted here that this integration over the spectral components yields the total power of the process.

For a discrete-time signal, we require that the power spectral density $S_{yy}(f_k)$ corresponds to the power spectral density for the continuous-time signal. In that case, Eq. (B.17) becomes:

$$\sigma^2 = \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} S_{yy}(f_k) \Delta f. \quad (\text{B.18})$$

From Eq. (B.15) and Eq. (B.18) this leads to:

$$\frac{1}{N^2} \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} |\hat{y}_k|^2 = \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} S_{yy}(f_k) \Delta f, \quad (\text{B.19})$$

and hence:

$$\sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} \frac{|\hat{y}_k|^2}{N^2 \Delta f} = \sum_{k=-\frac{N-1}{2}}^{\frac{N-1}{2}} S_{yy}(f_k). \quad (\text{B.20})$$

Therefore, to satisfy the requirement that the power spectral density for the discrete-time signal corresponds to that for the continuous-time signal, we define the power spectral density for a discrete-time signal:

$$S_{yy}(f_k) = \frac{|\hat{y}_k|^2}{N^2 \Delta f}. \quad (\text{B.21})$$

Hence, the normalisation factor in Eq. (B.10) is chosen to be:

$$A = \frac{1}{N^2 \Delta f}. \quad (\text{B.22})$$

B.3 Measuring amplitude and phase noise

Amplitude and phase modulation are two of the main types of noise in the output signal of an oscillator. The instantaneous output voltage of an ideal oscillator can be expressed as:

$$V(t) = V_0 \sin(2\pi f_0 t), \quad (\text{B.23})$$

where V_0 is the nominal peak voltage amplitude and f_0 the nominal frequency.

B. Fundamentals of signal analysis and measurement

However, in practice, small inaccuracies will introduce amplitude and phase modulations. These modulations are included in the above signal by adding stochastic processes, represented by $\phi(t)$ and $\epsilon(t)$, as follows:

$$\begin{aligned} V(t) &= (V_0 + \epsilon(t)) \sin(2\pi f_0 t + \phi(t)), \\ &= \left(1 + \frac{\epsilon(t)}{V_0}\right) V_0 \sin(2\pi f_0 t + \phi(t)), \\ &= (1 + \alpha(t)) V_0 \sin(2\pi f_0 t + \phi(t)), \end{aligned} \quad (\text{B.24})$$

where $\phi(t)$ is the deviation from the nominal phase $2\pi f_0 t$, $\epsilon(t)$ is the deviation from the nominal amplitude and $\alpha(t) = \epsilon(t)/V_0$ is the normalised amplitude deviation. An example of a signal with phase and amplitude noise is shown in Fig. B.5.

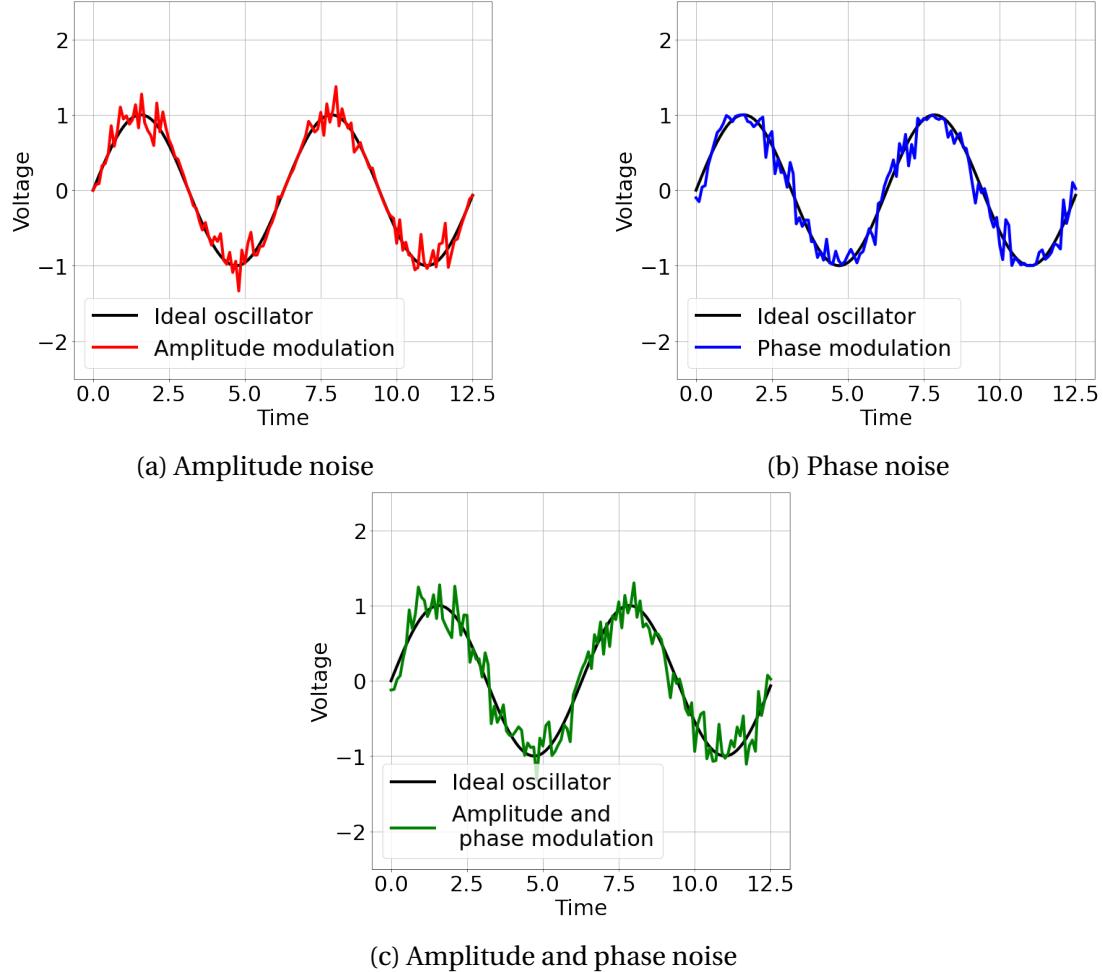


Figure B.5: Instantaneous voltage of an oscillator in the presence of (a) amplitude noise, (b) phase noise, and (c) both amplitude and phase noise.

Following the IEEE [73] conventions, the amplitude and phase modulation are measured by one-sided spectral densities, $G_{yy}(f)$. From Eq. (B.11) and Eq. (B.12), the

amount of amplitude noise can be expressed as:

$$G_\alpha(f_k) = 2S_A(f_k) = \frac{2}{N^2\Delta f} \left(\frac{|\hat{\epsilon}(f_k)|}{V_0} \right)^2 = \frac{2}{N^2\Delta f} |\hat{\alpha}(f_k)|^2, \quad (\text{B.25})$$

and the amount of phase noise can be expressed:

$$G_\phi(f_k) = 2S_\phi(f_k) = \frac{2}{N^2\Delta f} |\hat{\phi}(f_k)|^2, \quad (\text{B.26})$$

where f_k lies in a range of positive frequencies and $\hat{\alpha}(f_k)$ and $\hat{\phi}(f_k)$ are the discrete Fourier transforms of the modulation signals $\alpha(t)$ and $\phi(t)$ respectively. The units of the $G_\alpha(f_k)$ are V^2/Hz and the units of $G_\phi(f_k)$ are rad^2/Hz .

However, instruments used in experiments do not usually display directly the single-sided spectral density G_{yy} . Instead, the quantity $10\log_{10}\mathcal{L}(f_k)$ [dBc/Hz] is shown, with [73]:

$$\mathcal{L}(f_k) = G_{yy}(f_k)/2, \quad (\text{B.27})$$

where f_k ranges from 0 over the positive part of the spectrum. It should be emphasised that here \mathcal{L} is two-sided, as defined in [73], though it is considered that the instrument displays only the positive frequencies.

B.4 Applying a measured noise spectrum in numerical simulations

The goal of this section is to describe how one can convert the measured noise spectrum from a spectrum analyzer to a discrete time series that can be used for numerical simulations.

B.4.1 Crab cavity noise in numerical simulations

As follows from the discussion in section ??, phase and amplitude noise can be represented by discrete time series $\phi_n = \phi(n\Delta t)$ and $\alpha = \alpha(n\Delta t)$ respectively, so that the crab cavity (CC) instantaneous voltage is given by:

$$V_{CC}(n\Delta t) = V_0(1 + \alpha(n\Delta t)) \sin(2\pi f_0 n\Delta t + \phi(n\Delta t)), \quad (\text{B.28})$$

where V_0 and f_0 are the nominal crab cavity voltage and frequency respectively, $n \in [1, N - 1]$ and N is the number of samples.

In numerical simulations, N is taken to be equal to the number of turns in the simulation. The total time simulated is $T = N\Delta t$, where Δt is the sampling interval. Since the phase and amplitude noise are sequences of noise kicks which are applied to the CC voltage every turn, Δt is equal to the time needed for one turn around the machine. For the SPS, with a revolution frequency $f_{rev} = 43.38$ kHz, $\Delta t = 1/f_s = 1/f_{rev} \approx 23 \mu\text{s}$.

B.4.2 Measured noise spectrum

In the experiment performed in 2018, the amplitude and phase noise levels were measured with a spectrum analyser E5052B [52] and are expressed in terms of the quantity $10\log_{10}\mathcal{L}(f_k)$ [dBc/Hz] (see section ??). Figure B.6a shows an example of a phase noise spectrum acquired during the experiment, and which extends from 1 kHz to 10 MHz. The spectral lines observed at high frequencies correspond to harmonics of the revolution frequency.

B.4.3 Generating time series

In the following, the steps required to generate the discrete time series α_n and ϕ_n from the measured noise spectrum are discussed. The procedure involves converting the measured noise power to the two-sided power spectral density $S_\phi(f_k)$ and then using the inverse Fourier transform to produce the discrete-time series of noise kicks. In detail, the steps are as follows:

1. Convert the measured noise power $10\log_{10}\mathcal{L}(f_k)$ [dBc/Hz] to $G_\phi(f_k)$ [rad^2/Hz] using Eq. (B.27) (Fig. B.6b).
2. Re-sample the noise spectrum. The measured noise power values are equally spaced in frequency on a logarithmic scale. A linear interpolation is needed such that they are equally spaced on a linear scale, every $\Delta f = f_s/N$. As already mentioned, since the beam encounters the crab cavities once each turn, $f_s = f_{rev}$ (= 43.38 kHz for the SPS). To this end, the linear interpolation extends up to $f_s/2$ as illustrated in Fig. B.6c. In our simulations, $N = 10^5$ turns are used.

3. Create the positive spectral components of the two-sided power spectrum, S_ϕ , using Eq. (B.12) for $f_k > 0$. The result is shown in Fig. B.6d.
4. Compute the amplitude of the spectral components of the Fourier transform, $|\hat{\phi}_n(f_k)|$ according to Eq. (B.11). It should be noted, however, that this computation is done only for the positive part of the spectrum. Fig. B.6e depicts the result of this computation.
5. Generate the phase information for each positive spectral component. By definition the power spectral density does not contain any information about the phase of the frequency components. Therefore, one should generate this information by giving a random phase $\theta(f_k)$ obtained from uniform distribution between 0 and 2π .
6. Construct a one-sided frequency domain signal, $\hat{\phi}_n^{\text{os}}(f_k) = |\hat{\phi}_n(f_k)| e^{i\theta(f_k)}$. Once again this computation is done only for the positive spectral components, with $f_k \in [\Delta f, +\frac{f_s}{2}]$.
7. Construct the two-sided Fourier transform spectrum. First, create the negative components of the Fourier transform by taking the complex conjugate of the positive components. Furthermore, the information for the zero frequency component (DC) is missing from the measured spectrum, since this extends from 1 kHz to 10 MHz. In order to do the conversion correctly, the zero frequency term is set to 0, so that $\hat{y}_n(0) = 0$. The two-sided Fourier transform is then given by:

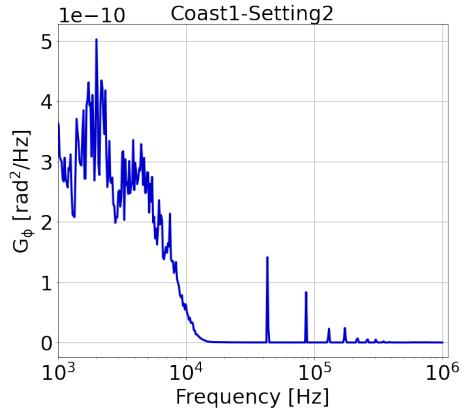
$$\hat{\phi}_n(f_k) == \begin{cases} |\hat{\phi}_n^{\text{os}}(f_k)| \overline{e^{i\theta(|f_k|)}}, & f_k \in \left[-\frac{f_s}{2}, -\Delta f_s\right] \\ |\hat{\phi}_n^{\text{os}}(f_k)| = 0, & f_k = 0 \\ |\hat{\phi}_n^{\text{os}}(f_k)| e^{i\theta(|f_k|)}, & f_k \in \left[\Delta f_s, +\frac{f_s}{2}\right] \end{cases} \quad (\text{B.29})$$

It is clear that $\hat{\phi}_n(f_k)$ has both positive and negative frequencies and the magnitude is symmetric in f_k .

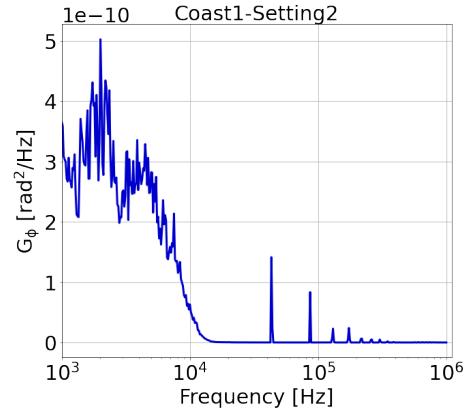
8. Finally, apply the inverse Fourier transform, Eq. (B.9), to $\hat{\phi}_n(f_k)$. The output is a random discrete time series of N values sampled every $\Delta t = 1/f_s = 1/f_{rev}$. In other words, ϕ_n forms the sequence of noise kicks that will act on the particles

B. Fundamentals of signal analysis and measurement

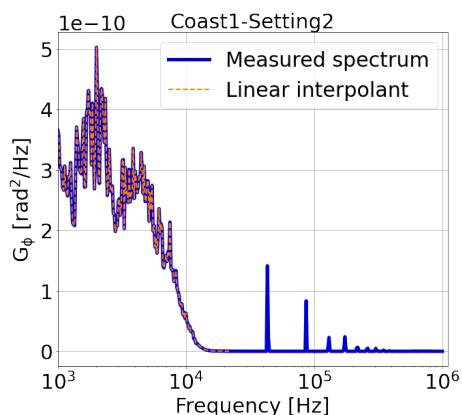
in the beam on each turn in the simulations.



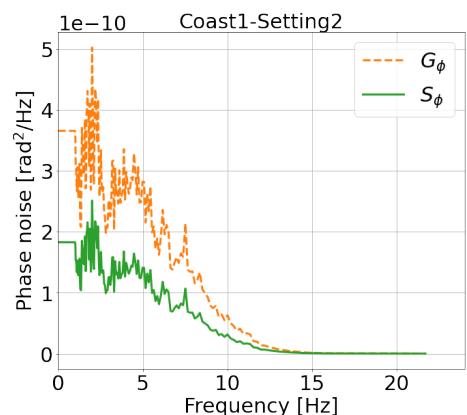
(a) Phase noise spectrum measured with a spectrum analyzer E5052B, in units dBc/Hz.



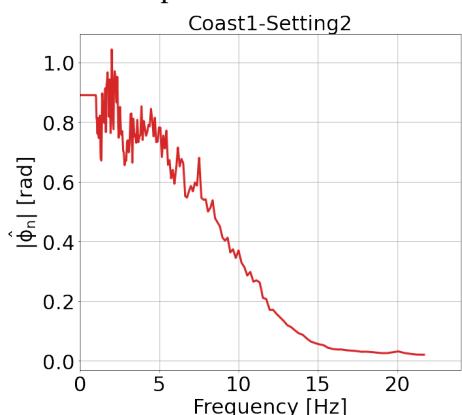
(b) Measured phase noise spectrum in units rad²/Hz.



(c) Linear interpolation of the measured noise spectrum.



(d) Positive spectral components of the two-sided power spectrum S_ϕ .



(e) Amplitudes of the spectral components of the Fourier transform.

Figure B.6: Steps required to generate the sequence of noise kicks to be applied in the simulations from the measured noise spectrum.

B.4.4 Validation of the time series reconstruction

This section describes the benchmarks that were carried out to ensure that the method described in section B.4.3 produces a valid time series for a set of noise kicks, for a given power spectrum.

Comparison of measured and reconstructed power spectrum

Figure B.7 shows the results of the first benchmark, comparing the measured power spectral density with the power spectral density computed from the generated time series ϕ_n . The two power spectra appear to be consistent with each other, which supports the validity of the method described above for generating the sequence of noise kicks from a given power spectrum.

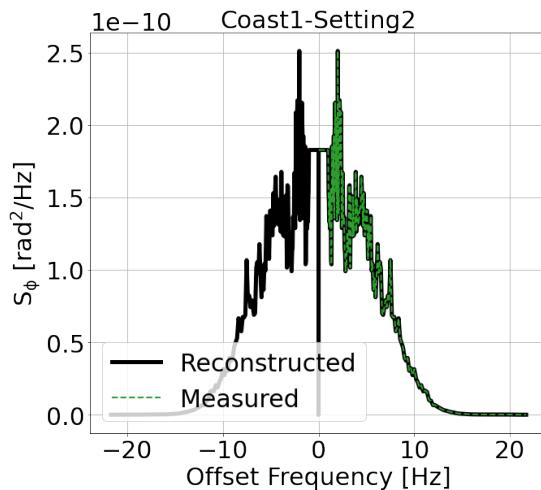


Figure B.7: Power spectral density computed from the time series ϕ_n produced from a measured power spectrum (black), compared with the original measured power spectrum (green).

PyHEADTAIL simulations

Another way to validate the method for producing a sequence of noise kicks from a measured power spectrum is to perform numerical simulations using the generated noise kicks, and compare the resulting emittance growth with the predictions from an analytical model [62].

In the simulations, which were performed with PyHEADTAIL, the beam was tracked for 10^5 turns which corresponds to about 2.5 s in the SPS. A kick representing the effect of the crab cavities was applied on each turn. The noise kicks that the beam

B. Fundamentals of signal analysis and measurement

encounters every turn at the CC location were generated from the phase and amplitude noise spectra of from Coast1-Setting2 of 2018 (Fig. 5.2).

It should be noted, however, that the sequence of noise kicks includes a random factor through the set of random phases $\theta(f_k)$. To reduce the uncertainty in the results, multiple simulation runs were conducted. The set of random phases was regenerated randomly for each of 10 runs with a different seed each time. For each run, the initial bunch distribution was also regenerated randomly 3 times. The mean and the standard deviation of the emittance values obtained from the tracking were computed over all trials. The emittance growth rate was computed by performing a linear fit to the mean of the emittance values.

Figures B.8a and B.8b show the emittance growth for the case of amplitude noise and phase noise respectively. The emittance evolution in the presence of both types of noise is also illustrated in Fig. B.8c. The simulated emittance growth rates show very good agreement with the predictions from the analytical model. The results again support the validity of the method for generating a sequence of noise kicks from a measured noise power spectrum, described in section B.4.3.

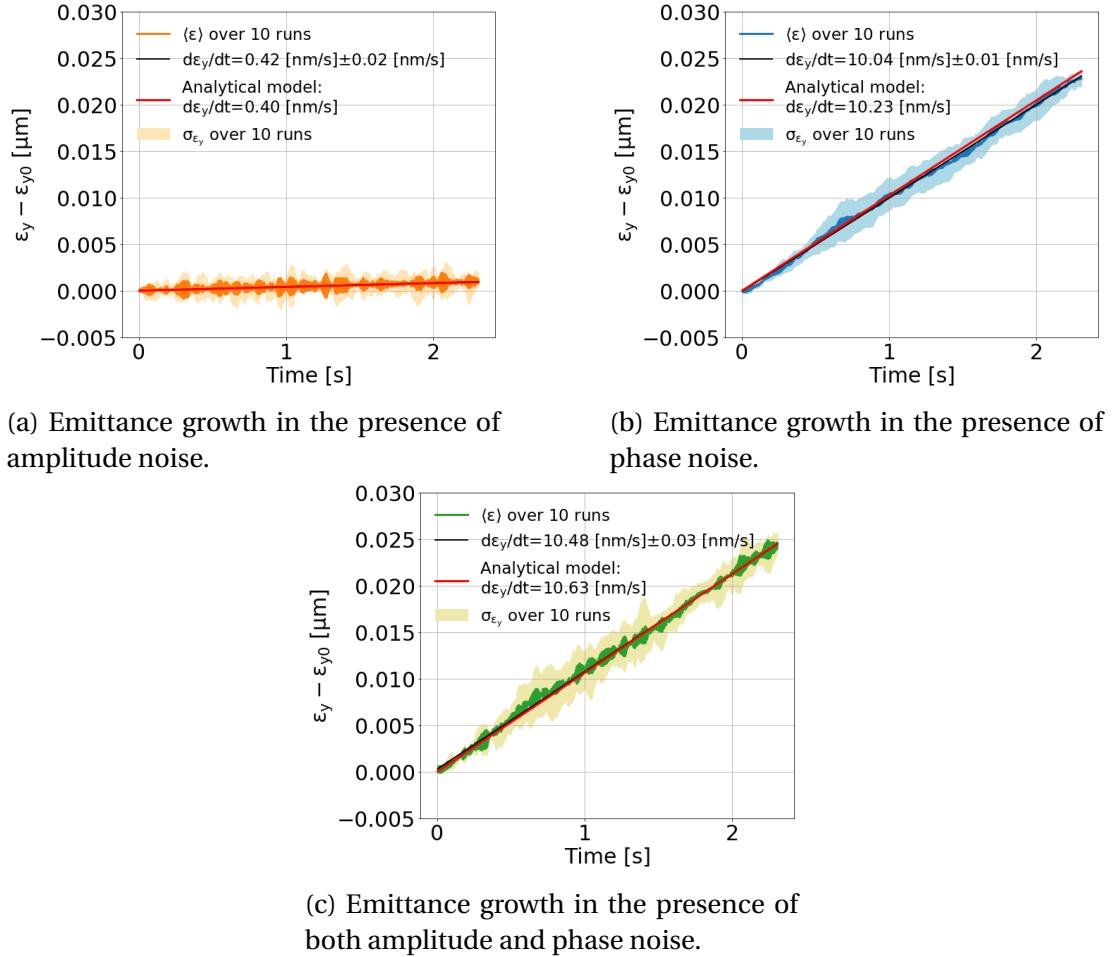


Figure B.8: Comparison between emittance growth found from simulations in PyHEADTAIL and emittance growth expected from an analytical model [62]. The emittance growth is driven by amplitude and phase noise, with kicks in the simulations generated from a measured power spectrum.

C | Appendix c

C.1 Detuning with amplitude

- The linear detuning is given by the following formula, for octupole components

The detuning with amplitude is computed by:

$$\Delta Q_x = 2(\alpha_{xx}J_x + \alpha_{xy}J_y) \quad (\text{C.1})$$

$$\Delta Q_y = 2(\alpha_{yy}J_y + \alpha_{yx}J_x) \quad (\text{C.2})$$

where α_{yy} , α_{xx} and $\alpha_{xy} = \alpha_{yx}$ are the detuning coefficients with units [1/m] and J_x , J_y the action variables.

Rms detuning with amplitude

From the definition of variance, the variance of the vertical amplitude detuning is given by:

$$\begin{aligned} \text{Var}(\Delta Q_y) &= \langle \Delta Q_y^2 \rangle - \langle \Delta Q_y \rangle^2 \\ &= \langle 2^2(\alpha_{yy}J_y + \alpha_{yx}J_x)^2 \rangle - \langle 2(\alpha_{yy}J_y + \alpha_{yx}J_x) \rangle^2 \\ &= 2^2 [\langle (\alpha_{yy}J_y + \alpha_{yx}J_x)^2 \rangle - \langle \alpha_{yy}J_y + \alpha_{yx}J_x \rangle^2] \\ &= 2^2 [\langle (\alpha_{yy}J_y)^2 + 2\alpha_{yy}\alpha_{yx}J_yJ_x + (\alpha_{yx}J_x)^2 \rangle - (\langle \alpha_{yy}J_y \rangle + \langle \alpha_{yx}J_x \rangle)^2] \\ &= 2^2 [\alpha_{yy}^2 \langle J_y^2 \rangle + 2\alpha_{yy}\alpha_{yx} \langle J_yJ_x \rangle + \alpha_{yx}^2 \langle J_x^2 \rangle - \alpha_{yy}^2 \langle J_y \rangle^2 - 2\alpha_{yy}\alpha_{yx} \langle J_y \rangle \langle J_x \rangle - \alpha_{yx}^2 \langle J_x \rangle^2] \\ &= 2^2 [\alpha_{yy}^2 \langle J_y^2 \rangle + \cancel{2\alpha_{yy}\alpha_{yx} \langle J_yJ_x \rangle} + \alpha_{yx}^2 \langle J_x^2 \rangle - \alpha_{yy}^2 \langle J_y \rangle^2 - \cancel{2\alpha_{yy}\alpha_{yx} \langle J_yJ_x \rangle} - \alpha_{yx}^2 \langle J_x \rangle^2] \\ &= 2^2 [\alpha_{yy}^2 (\langle J_y^2 \rangle - \langle J_y \rangle^2) + \alpha_{yx}^2 (\langle J_x^2 \rangle - \langle J_x \rangle^2)] \\ &= 2^2 [\alpha_{yy}^2 \text{Var}(J_y) + \alpha_{yx}^2 \text{Var}(J_x)] \end{aligned} \quad (\text{C.3})$$

In the development of Eq. C.3 the properties of the mean discussed in Eq. (A.2) and (A.3) are used.

Now, according to the definitions introduced in Appendix A.1, the root mean square (rms) for the vertical amplitude detuning is written:

$$\begin{aligned}
 \Delta Q_y^{rms} &= \sigma_{\Delta Q_y} = \sqrt{\text{Var}(\Delta Q_y)} \\
 &= \sqrt{2^2 [\alpha_{yy}^2 \text{Var}(J_y) + \alpha_{yx}^2 \text{Var}(J_x)]} \\
 &= 2\sqrt{\alpha_{yy}^2 (\sigma_{J_y})^2 + \alpha_{yx}^2 (\sigma_{J_x})^2} \\
 &= 2\sqrt{[\alpha_{yy}(\sigma_{J_y})]^2 + [\alpha_{yx}(\sigma_{J_x})]^2}
 \end{aligned} \tag{C.4}$$

where σ_{J_y} and σ_{J_x} stand for the standard deviation of the action variables J_y and J_x respectively

The actions, J_x and J_y follow an exponential distribution (see Eq. (2.22)). It is known that for an exponential distribution the mean equals the standard deviation. Therefore, Eq. C.4 can be written as follows:

$$\Delta Q_y^{rms} = 2\sqrt{[\alpha_{yy}\langle J_y \rangle]^2 + [\alpha_{yx}\langle J_x \rangle]^2}. \tag{C.5}$$

Following Eq. (2.21), the rms tune spread from amplitude detuning can be also written as:

$$\Delta Q_y^{rms} = 2\sqrt{(\alpha_{yy}\epsilon_y^{geom})^2 + (\alpha_{yx}\epsilon_x^{geom})^2}. \tag{C.6}$$

Equivalently, the horizontal rms tune spread from amplitude detuning is given by:

$$\Delta Q_x^{rms} = 2\sqrt{(\alpha_{xx}\epsilon_x^{geom})^2 + (\alpha_{yx}\epsilon_y^{geom})^2}. \tag{C.7}$$

Disclaimer: In the analysis presented above, the actions J_x and J_y refer to the initial distribution, for which they are actually independent. The actions later in time, are coupled due to the non-linear of the lattice.

Rms betatron tune spread in the SPS at 270 GeV

In this thesis, the rms betatron tune spread includes only the contribution from the

C. Appendix c

detuning with amplitude present in the SPS machine. This is a result of the SPS multiple components in the main dipole magnets (see Section 2.5.1). However, experimental studies [74] indicated stronger amplitude detuning than predicted from these multiple components. The measured amplitude detuning can be reproduced in simulations by switching on the Landau octupole families with strengths $k_{LOF} = k_{LOD} = 1 \text{ l/m}^4$.

Using the values of the multipoles listed in Table 2.1 and setting the strength of both octupole families at 1 l/m^4 the corresponding detuning coefficients are obtained with MAD-X. In particular, $\alpha_{xx} = 923.45 \text{ l/m}$, $\alpha_{xy} = \alpha_{yx} = -1122.451 \text{ l/m}$, $\alpha_{yy} = 705.15 \text{ l/m}$. It should be noted that these values are obtained for zero linear chromaticity in both transverse planes.

The tune spread is computed for the requested initial emittances for the emittance growth measurements of 2018 and 2021, $\epsilon_x^n = \epsilon_y^n = 2 \mu\text{m}$. Using Eq. (2.17) it can be seen that these values corresponds to geometric emittances of $\epsilon_x^{geom} = \epsilon_y^{geom} = 6.95 \text{ nm}$. By inserting these values of detuning coefficients and geometric emittances in Eq. (C.7) and Eq. (C.6) the rms tune spread is found to be, $\Delta Q_x^{rms} = 2.02 \times 10^{-5}$ and $\Delta Q_y^{rms} = 2.17 \times 10^{-5}$, in the horizontal and vertical planes respectively.

D | Glossary and definitions

Peak to peak: Peak-to-peak (pk-pk) is the difference between the maximum positive and the maximum negative amplitudes of the wave.

<https://electronics.stackexchange.com/questions/313269/peak-to-peak-vs-amplitude>

Landau octupoles

Check the HL-LHC report to take ideas.

Bibliography

- [1] Oliver Sim Brüning et al. *LHC Design Report*. CERN Yellow Reports: Monographs. Geneva: CERN, 2004. doi: 10.5170/CERN-2004-003-V-1. URL: <https://cds.cern.ch/record/782076>.
- [2] ATLAS collaboration. “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”. In: *Physics Letters B* 716 (1) (2012), pp. 1–29. URL: <https://www.sciencedirect.com/science/article/pii/S037026931200857X>.
- [3] CMS collaboration. “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”. In: *Physics Letters B* 716 (1) (2012), pp. 30–61. URL: <https://www.sciencedirect.com/science/article/pii/S0370269312008581>.
- [4] CERN Yellow Reports: Monographs. *CERN Yellow Reports: Monographs, Vol. 10 (2020): High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. en. 2020. doi: 10.23731/CYRM-2020-0010. URL: <https://e-publishing.cern.ch/index.php/CYRM/issue/view/127>.
- [5] Oliver Brüning and Lucio Rossi. *The High Luminosity Large Hadron Collider*. WORLD SCIENTIFIC, Feb. 2015. doi: 10.1142/9581. URL: <https://doi.org/10.1142/9581>.
- [6] W. Herr. “*Particle Colliders and Concept of Luminosity*”. at CERN Accelerator School. 2012. URL: <https://cas.web.cern.ch/sites/default/files/lectures/constanta-2018/l1.pdf>.
- [7] O. Brüning and L. Rossi. *The High Luminosity Large Hadron Collider: the New Machine for Illuminating the Mysteries of Universe*. Vol. 24. World Scientific Publishing Company, 2015.

- [8] Rama Calaga. “Crab Cavities for the High-luminosity LHC”. In: (2018), THXA03. 5 p. DOI: 10.18429 / JACoW- SRF2017 - THXA03. URL: <https://cds.cern.ch/record/2673544>.
- [9] Hans Peter Beck. *First Results from the Large Hadron Collider*. Accessed: 24-06-2022. URL: <https://www.sps.ch/artikel/progresses/first-results-from-the-large-hadron-collider-24>.
- [10] Silvia Verdú-Andrés. *Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities*. Talk presented at th International Particle Accelerator Conference in 2015, Richmond VA (USA). Accessed: 24-06-2022. URL: https://accelconf.web.cern.ch/IPAC2015/talks/mobd2_talk.pdf.
- [11] Silvia Verdú-Andrés et al. “Crab cavities for colliders: past, present and future”. In: *Nucl. Part. Phys. Proc.* 273-275 (2016), 193–197. 5 p. DOI: 10.1016/j.nuclphysbps.2015.09.025. URL: <https://cds.cern.ch/record/2263119>.
- [12] C. et al Zanoni. “Design of Dressed Crab Cavities for the HL-LHC Upgrade”. In: (2015), THPB070. 5 p. DOI: 10.18429 / JACoW- SRF2015 - THPB070. URL: <https://cds.cern.ch/record/2288282>.
- [13] Subashini De Silva et al. “Electromagnetic Design of 400 MHz RF-Dipole Crabbing Cavity for LHC High Luminosity Upgrade”. In: (2015), THPB053. 5 p. DOI: 10.18429 / JACoW- SRF2015 - THPB053. URL: <https://cds.cern.ch/record/2288607>.
- [14] Binping Xiao et al. “Design, prototyping and testing of a compact superconducting double quarter wave crab cavity”. In: *Phys. Rev. Spec. Top. Accel. Beams* 18 (Feb. 2015), 041004. 10 p. DOI: 10.1103 / PhysRevSTAB.18.041004. arXiv: 1502.04088. URL: <https://cds.cern.ch/record/1992565>.
- [15] S Verdú-Andrés et al. “Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities for SPS Test”. In: (May 2015), 3 p. URL: <https://cds.cern.ch/record/2113440>.
- [16] T. et al. Abe. “Beam operation with crab cavities at KEKB”. In: *2007 IEEE Particle Accelerator Conference (PAC), Albuquerque, New Mexico, USA*. Vol. TU-PAN045. 2007, pp. 1487–1489. DOI: 10.1109/PAC.2007.4440798.

D. Bibliography

- [17] Y. Funakoshi. “Operational experience with crab cavities at KEKB”. In: (Oct. 2014). Comments: 10 pages, contribution to the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, CERN, Geneva, Switzerland, 18-22 Mar 2013, 27–36. 10 p. DOI: 10.5170/CERN-2014-004.27. arXiv: 1410.4036. URL: <https://cds.cern.ch/record/1955812>.
- [18] K. Oide et al. “Compensation of the Crossing Angle with Crab Cavities at KEKB”. In: *Proc. PAC'07* (Albuquerque, NM, USA, Jun. 2007). JACoW Publishing, Geneva, Switzerland, pp. 27–31. URL: <https://jacow.org/p07/papers/MOZAKI01.pdf>.
- [19] R. et al. Calaga. “First demonstration of the use of crab cavities on hadron beams”. In: *Phys. Rev. Accel. Beams* 24 (2021), 062001. 6 p. DOI: 10.1103 / PhysRevAccelBeams.24.062001. URL: <https://cds.cern.ch/record/2773279>.
- [20] Androula Alekou et al. “Beam dynamics simulations with Crab Cavities in the SPS machine”. In: (2019), MOPGW095. 4 p. DOI: 10.18429/JACoW-IPAC2019-MOPGW095. URL: <https://cds.cern.ch/record/2696109>.
- [21] 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>.
- [22] Luis Eduardo Medina Medrano et al. *Effective pile-up density as a measure of the experimental data quality for High-Luminosity LHC operational scenarios*. Tech. rep. Geneva: CERN, Jan. 2018. URL: <https://cds.cern.ch/record/2301928>.
- [23] T. Mastoridis P. Baudrenghien. *Crab Cavity RF noise: Update 2*. Accessed: 27-06-2022. URL: https://indico.cern.ch/event/1044711/contributions/4389271/attachments/2264292/3861025/CC_Noise_Feedback_PB.pdf.
- [24] I. Ilias Efthymiopoulos. *Luminosity estimates including noise from crab cavities (without feedback)*. Accessed: 27-06-2022. URL: https://indico.cern.ch/event/1044711/contributions/4389268/attachments/2264203/3844208/ie_WP2CCemitBU_14.06.2021.pdf.
- [25] Andrzej Wolski. *Beam Dynamics in High Energy Particle Accelerators*. Imperial College Press, 2014.

- [26] R A Beth. “Complex Methods for Three-Dimensional Magnetic Fields”. In: (1971). URL: <https://cds.cern.ch/record/889480>.
- [27] S Y Lee. *Accelerator physics; 3rd ed.* Singapore: World Scientific, 2012. URL: <https://cds.cern.ch/record/1425444>.
- [28] G. Floquet. “Sur les équations différentielles linéaires à coefficients périodiques”. fre. In: *Annales scientifiques de l'École Normale Supérieure* 12 (1883), pp. 47–88. URL: <http://eudml.org/doc/80895>.
- [29] *Official optics repository of the CERN Super Proton Synchrotron (official name SPS)*. Accessed: 16-2-2022. URL: <https://gitlab.cern.ch/acc-models/acc-models-sps/-/tree/2021/>.
- [30] 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>.
- [31] 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>.
- [32] *PyHEADTAIL code repository*. Accessed: 19-6-2022. URL: <https://github.com/PyCOMPLETE/>.
- [33] Adrian Oeftiger. *An overview of PyHEADTAIL*. Accessed: 05-06-2022. URL: <https://cds.cern.ch/record/2672381/files/CERN-ACC-NOTE-2019-0013.pdf>.
- [34] Michael Schenk. *Beam dynamics simulations with the PyHEADTAIL and PyE-CLOUD macroparticle codes*. Accessed: 05-06-2022. URL: https://www2.kek.jp/accl/legacy/seminar/file/PyHEADTAIL_PyECloud_2.pdf.
- [35] Benoit Salvant. “Impedance model of the CERN SPS and aspects of LHC single-bunch stability”. Presented on 04 Mar 2010. 2010. DOI: 10.5075/epfl-thesis-4585. URL: <https://cds.cern.ch/record/1274254>.

D. Bibliography

- [36] Volodymyr Rodin, A. Oeftiger, and Carsten Welsch. “Simulation of intra-beam scattering in PyHEADTAIL”. In: Nov. 2021. DOI: 10.18429/JACoW-IPAC2021-WEPAB215.
- [37] A. Papoulis. *Probability, Random Variables, and Stochastic Processes*. Communications and Signal Processing. McGraw-Hill, 1991. ISBN: 9780070484771. URL: <https://books.google.ch/books?id=4IwQAQAAIAAJ>.
- [38] 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>.
- [39] P Baudrenghien et al. “Functional Specifications of the LHC Prototype Crab Cavity System”. In: (Feb. 2013). URL: <https://cds.cern.ch/record/1520896>.
- [40] 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>.
- [41] 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.
- [42] 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.
- [43] 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>.
- [44] 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>.
- [45] 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.

- [46] 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>.
- [47] Tom Levens. *Head-Tail Monitor for CCDiagnostics*. Accessed: 11-04-2022. URL: https://indico.cern.ch/event/826475/contributions/3457525/attachments/1872464/3081710/2019-07-02_HL_WP2_tlevens.pdf.
- [48] Natalia Triantafyllou et al. “Investigation of Damping Effects of the Crab Cavity Noise Induced Emittance Growth”. In: *12th International Particle Accelerator Conference*. Aug. 2021. DOI: 10.18429/JACoW-IPAC2021-TUPAB256.
- [49] 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>.
- [50] A Alekou et al. *Emittance growth in coast in the SPS*. Accessed: 26-11-2021. URL: https://indico.cern.ch/event/609486/contributions/2457542/attachments/1433340/2318716/EmittanceEvolutionCoastSPS_2017_April.pdf.
- [51] 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>.
- [52] K. Gheen. *Phase Noise Measurement Methods and Techniques*. Accessed November 5, 2020. Agilent Technologies. URL: <https://studylib.net/doc/18034081/phase-noise-measurements>.
- [53] 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>.
- [54] 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>.

D. Bibliography

- [55] Rogelio Tomas et al. “Improved algorithms to determine the non-linear optics model of the SPS from non-linear chromaticity”. In: July 2007, pp. 4231–4233. ISBN: 978-1-4244-0916-7. DOI: 10.1109/PAC.2007.4439986.
- [56] Department of Physics University of Pennsylvania and Lab manual astronomy. *Managin errors and uncertainties*. Accessed: 18-03-2022. URL: <https://www.physics.upenn.edu/sites/default/files/Managing%20Errors%20and%20Uncertainty.pdf>.
- [57] Federico Roncarolo. “Accuracy of the Transverse Emittance Measurements of the CERN Large Hadron Collider”. Presented 2005. 2005. URL: <https://cds.cern.ch/record/1481835>.
- [58] Philippe Baudrenghien. *LLRF experience for SPS & HL-LHC Outlook*. Accessed: 11-11-2021. URL: <https://indico.cern.ch/event/787363/contributions/3367294/attachments/1865644/3067685/HL-LHC19v6.pdf>.
- [59] F. Follin G. Papotti. *Online bunch length measurement for SPS OP*. Accessed: 26-11-2021. URL: https://indico.cern.ch/event/774525/contributions/3218683/attachments/1756129/2847423/20181120_LIUSPSBD.pdf.
- [60] G. Papotti. “A Beam Quality Monitor for LHC Beams in the SPS”. In: (Sept. 2008), 4 p. URL: <https://cds.cern.ch/record/1124099>.
- [61] T. Argyropoulos. *Private communication, Nov 2020*.
- [62] 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>.
- [63] *Repository of SPS impedance model*. Accessed: 3-6-2022. URL: https://gitlab.cern.ch/IRIS/SPS_IW_model.
- [64] Carlo Zannini. “Electromagnetic Simulation of CERN accelerator Components and Experimental Applications”. Presented 15 Apr 2013. Mar. 2013. URL: <https://cds.cern.ch/record/1561199>.
- [65] B Salvant et al. “Update of the SPS Impedance Model”. In: (June 2010), 3 p. URL: <https://cds.cern.ch/record/1271349>.

- [66] Carlo Zannini et al. “Benchmarking the CERN-SPS Transverse Impedance Model with Measured Headtail Growth Rates”. In: (2015), MOPJE049. 4 p. URL: <https://cds.cern.ch/record/2141779>.
- [67] R. J. Barlow. *Statistics. A Guide to the Use of Statistical Methods in the Physical Sciences*. Manchester Physics Series. Wiley, 2013. ISBN: 9781118723234. URL: <https://liverpool.idm.oclc.org/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat00003a&AN=lvp.b3130057&site=eds-live&scope=site>.
- [68] K. K. Gan. *Chi Square Distribution (χ^2) and Least Squares fitting*. Accessed: 03-03-2022. URL: <https://www.asc.ohio-state.edu/gan.1/teaching/spring04/Chapter6.pdf>.
- [69] *SciPy API Documentation*. Accessed: 16-2-2022. URL: https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html.
- [70] William H. Press et al. *Numerical Recipes: The Art of Scientific Computing*. 3rd ed. USA: Cambridge University Press, 2007. ISBN: 0521880688. URL: http://www.e-maxx-ru.1gb.ru/bookz/files/numerical_recipes.pdf.
- [71] R. Bracewell. *The Fourier Transform and its Applications*. 2nd ed. McGraw-Hill, 1986.
- [72] NumPy Project and Community. *NumPy API Documentation*. Accessed November 5, 2020. URL: <https://numpy.org/doc/stable/reference/routines.fft.html>.
- [73] “IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology—Random Instabilities”. In: *IEEE Std Std 1139-2008* (2009), pp. c1–35. DOI: 10.1109/IEEESTD.2008.4797525.
- [74] Hannes Bartosik et al. “Improved Methods for the Measurement and Simulation of the CERN SPS Non-linear Optics”. In: (2016), THPMR036. 4 p. DOI: 10.18429/JACoW-IPAC2016-THPMR036. URL: <https://cds.cern.ch/record/2207443>.