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Impact of filling scheme on beam induced RF heating in CERN LHC and HL-LHC

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Abstract

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Impact of filling scheme on beam induced RF heating in CERN LHC and HL-LHC

by Francesco GIORDANO

At CERN, after the first maintenance cycle (Long Shutdown 1, LS1) of the Large Hadron Collider (LHC), several sectors of the accelerator present a beam-induced heating much larger than expectations. This work compares data measured by cryogenic instrumentation with the expected heat load for various filling schemes and shows that impedance is not reasonably the major cause of the additional heat load. With this aim, the scaling of the power loss is analyzed carefully. In particular the scaling of the computed power loss from beam coupling impedance with the number of bunches is well understood only for a very broad band Impedance and for a very narrow band Impedance in ideal filling schemes that assume that the machine is full of equispaced bunches. This thesis analyzes also this dependence with number of bunches of the impedance of a resonator for a wide range of quality factors and more realistic filling schemes. The commonly assumed scaling with the square of number of bunches for narrow band resonators is shown to be valid only in very specific cases.

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List of Abbreviations

CERN	C onseil E uropéen pour la R echerche N ucléaire
LHC	L arge H adron C ollider
SPS	S uper P roton S ynchrotron
LS1	L ong S hutdown 1

*To my parents, my brother Valerio and my girlfriend
Emilia...*

Introduction

The acronym CERN represents the French words Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research), which was held at the time of its foundation. It was later adopted to refer at the institution itself, that is now commonly described as the European Organization for Nuclear Research.

CERN is famous for its accelerator complex that is a succession of machines that accelerate particles to increasingly higher energies. Each machine boosts the energy of a beam of particles, before injecting the beam into the next machine in the sequence (fig. 1). However, most of these accelerators are also directly involved in experiments at (relatively) low energies. The last element of the accelerators succession is the Large Hadron Collider (LHC), where beams are accelerated up to the record energy of 6.5 TeV per beam.

After the first maintenance cycle (Long Shutdown 1, LS1) of the Large Hadron Collider (LHC), several sectors of the accelerator present a beam-induced heating much larger than expectations. One of the main assumption on this problem states that the heat load is due to an impedance; aim of this thesis is to demonstrate that no reasonable impedance could explain this heat load.

CERN's Accelerator Complex

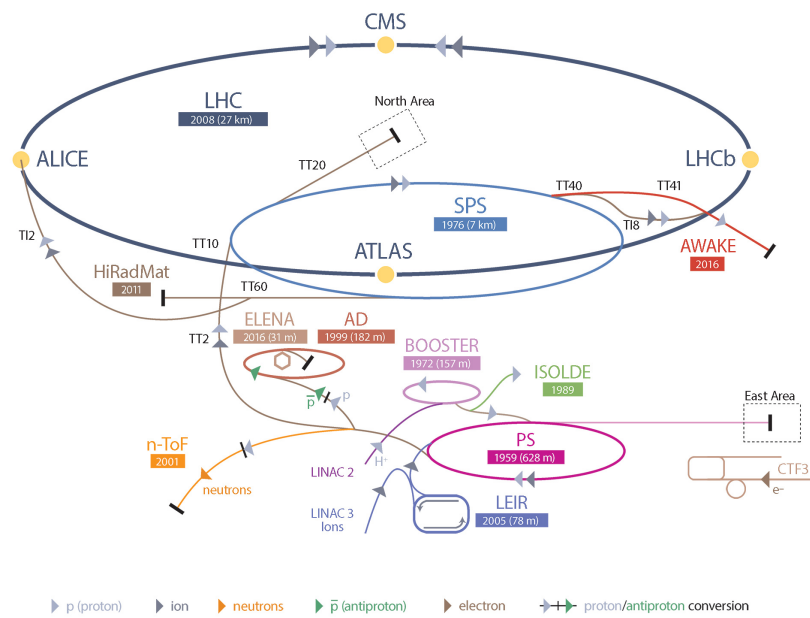


FIGURE 1: CERN accelerator complex.

Part I

Background

Chapter 1

Power Loss and Impedance

1.1 Overview

In this chapter, we first introduce the concept of wake function and beam coupling impedance focusing in particular on the longitudinal case. In the longitudinal plane, we also discuss the relationship between the beam coupling impedance and the energy loss by a bunch of particles. After that, it is defined the Power Loss and also how to numerically compute it because its calculation will be the core of this thesis. In the end, the concept of a filling scheme is introduced for a circular collider and in particular for the LHC. All of these are backgrounds needed for the understanding of what will follow.

1.2 Wakefields

The wake function describe the interaction of the beam with the surrounding environment. Its name came from its shape, because it acts like the wake left from a boat which is travelling into the see. This example indeed particularly fits with the beam wakefields because , due to the speed of the particle in the LHC, the field is all behind the source, like the waves are always behind the boat which generates.

The electromagnetic (EM) problem is posed setting the Maxwell's equations with the beam as source term and boundary conditions given by the structure in which the beam propagates. In order to well understand the wakefields it is very common to consider a simple case of a single space charge that

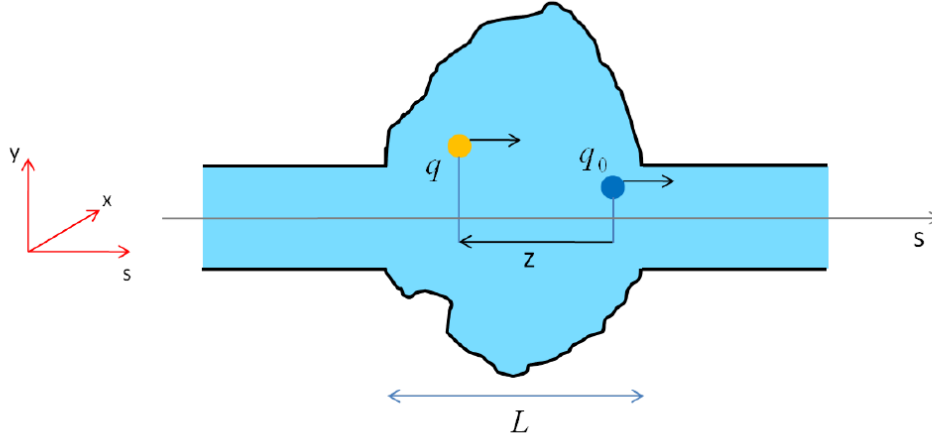


FIGURE 1.1: Source and test charge particles [14]

acts like a source followed by a test charge (Fig: 1.1). Before to proceed, we have to do the following hypothesis :

- Wakefields are considered superimposed to the external fields (dipoles, quadrupoles, RF cavities etc.)
- The particles are moving at the same speed $v = \beta \cdot c$, so they keep the same distance between each other (Rigid motion approximation).

The wakefields are related to the momentum variation :

$$\Delta \mathbf{p} = \int_{-\infty}^{+\infty} \mathbf{F}(x_s, y_s, z_s, x_t, y_t, z_t) dt \quad (1.1)$$

where (x_s, y_s, z_s) are the source's coordinates and (x_t, y_t, z_t) are the test particle coordinates. The force acting on the particle is the Lorentz's one :

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1.2)$$

$\mathbf{E}$ and $\mathbf{B}$ are obtained by solving the Maxwell's problem. Now it's possible to define the wakefields as [12]:

$$W(x_s, y_s, z_s, x_t, y_t, z_t, t)[V/C] = -\frac{1}{q_s q_t} \int_{-\infty}^{+\infty} \mathbf{F} \cdot d\mathbf{z} \quad (1.3)$$

It's easy to see that this definition is strongly related to the momentum if we consider that $d\mathbf{z} = \mathbf{v}dt$ so [8]:

$$W = -\frac{v}{q_s q_t} \int_{-\infty}^{+\infty} \mathbf{F} \cdot \mathbf{t} \quad (1.4)$$

that is clearly related to the momentum :

$$W(x_s, y_s, z_s, x_t, y_t, z_t, t)[V/C] = -\frac{v}{q_s q_t} \Delta p \quad (1.5)$$

1.2.1 Longitudinal Wakefields and Impedance

The wakefields are always decomposed on the longitudinal and on the transverse planes. Let's call W_l the longitudinal and W_t the transverse ones. We use to distinguish those two components because they lead to different effects inside the machine. Let's focus ourself on the longitudinal case because in the power loss computation only the longitudinal impedance plays a role. As for the the wakefield also the electromagnetic field of the electromagnetic problem inside the beam pipe could be decomposed as follows:

$$\mathbf{E} = E_l \hat{\mathbf{z}} + E_t \hat{\mathbf{t}}, \quad \mathbf{B} = B_l \hat{\mathbf{z}} + B_t \hat{\mathbf{t}} \quad (1.6)$$

For the longitudinal case we, have that $\mathbf{v} = v\hat{\mathbf{z}}$ so the magnetic field does not give any contribution to the longitudinal component of the Lorentz force (eq. 1.2), so neither to the momentum , nor to the wakefields. In this case, we have that:

$$W_l(x_s, y_s, z_s, x_t, y_t, z_t, t)[V/C] = -\frac{v}{q_s q_t} \Delta p_l \quad (1.7)$$

where:

$$\Delta p_l = \int_{-\infty}^{+\infty} q_t E_l(x_s, y_s, z_s, x_t, y_t, z_t) dt \quad (1.8)$$

At this point we can define the longitudinal coupling impedance as :

$$Z_l(x_s, y_s, x_t, y_t, w) = \int_{-\infty}^{+\infty} W_l(x_s, y_s, z_s, x_t, y_t, z_t) e^{j\omega t} dt \quad (1.9)$$

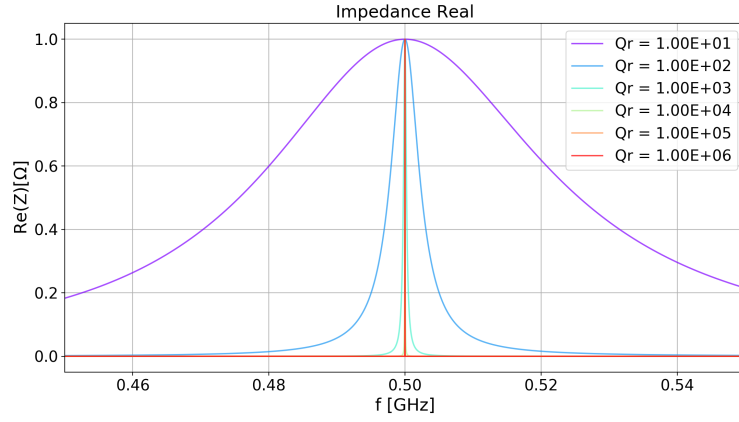
with $t = \frac{s}{v}$ and $s = z_t - z_s$. It's easy to observe, with our assumption of rigid motion approximation, that this impedance only depends on the relative distance between the particles, s , and not on their absolute position z_s, z_t .

1.2.2 Resonator Impedance model

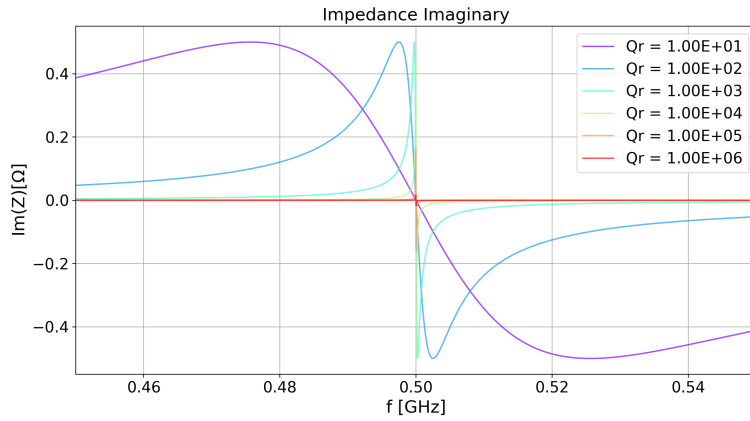
The Resonator Impedance model is an already very well known model of an impedance that is very useful for our purpose because in a first order approximation we can always model any impedance inside the LHC as a resonator impedance. The impedance formula is the following one [11]:

$$Z(f) = \frac{R_s}{1 + jQ_r(\frac{f}{f_r} - \frac{f_r}{f})} \quad (1.10)$$

varying Q_r , the width in frequency of this impedance changes while f_r allows us to select the mode that we are interested into :



(A) Real part of a Resonator Impedance,
 $R_s = 1, f_r = 0.50GHz$



(B) Imaginary part of a Resonator Impedance,
 $R_s = 1, f_r = 0.50GHz$

FIGURE 1.2: Resonator Impedance

Differences between Narrow and Broad Band Impedance

The beam related Impedance is defined in the frequency domain, therefore the *bandwidth* concept is widely used. In particular, we distinguish between the *narrow band* and the *broad band* Impedance:

- narrow band : an impedance that covers just few lines of the power spectrum.

- broad band : an impedance that covers all the lines of the power spectrum.

A narrow band impedance usually has $Q_r > 10^3$ while a broad band has $Q_r = 0$. However, because the bandwidth is influenced also by the f_r , those definitions may change with the position in frequency of the impedance itself so, in each context, it will be specified of which kind is the considered impedance.

1.3 Power Loss

The main relation that will follow us in all this thesis is the one that relates the Power loss with the longitudinal impedance. To obtain that relation, we have to start, always under the rigid motion approximation, from the Energy Loss. We know that for $v \simeq c$ we have $E \simeq mv^2$, so the longitudinal wakefield could be written from the eq. 1.7 as [14]:

$$W_l(z_t - z_s) = -\frac{\Delta E(z_t - z_s)}{q_s q_t} \quad (1.11)$$

so it is clear that the wakefields are strongly related to the Energy Loss :

$$\Delta E(z_t - z_s) = -W_l(z_t - z_s) q_s q_t \quad (1.12)$$

In order to relate our bunch distribution to the charge particle, we can introduce $\lambda(z)$ as the longitudinal particle distribution. It gives us the number of charges per unit length, normalized to the total number of charges in the bunches N_b or, in a more easy way, the integral of $\lambda(z)$ along a single bunch gives us 1. So, the electrical charge in a bunch slice dz' at a coordinates z' will be $\lambda(z')eN_b dz'$. It's now easy to consider the infinitesimal increment of Energy Loss as :

$$dE(z_t - z_s) = -W_l(z_t - z_s) \lambda(z_s) e N_b dz_s \lambda(z_t) e N_b dz_t \quad (1.13)$$

$$dE(z_t - z_s) = -W_l(z_t - z_s) \lambda(z_s) \lambda(z_t) e^2 N_b^2 dz_s dz_t \quad (1.14)$$

$dE(z_t - z_s)$ is the energetic variation given by a source slice of the bunch at z_s acting on a test slice at z_t . The whole bunch energetic variation is given by [7]:

$$\Delta E = - \int_{-\infty}^{+\infty} dz_t \int_{-z_t}^{+\infty} dz_s W_l(z_t - z_s) \lambda(z_s) \lambda(z_t) e^2 N_b^2 \quad (1.15)$$

the source that can affect a test slice, at ultra-relativistic velocities is only the one preceding it. If now we remember that a convolution integral is equal to a Fourier inverse transform of a product of the Fourier transform we have:

$$\Delta E = - \int_{-\infty}^{+\infty} dz_t \int_{-\infty}^{+\infty} \frac{dw}{2\pi} Z_l(w) \Lambda(w) e^{-jw \frac{z_t}{v}} \lambda(z_t) e^2 N_b^2 \quad (1.16)$$

where $\Lambda(w) = F_T[\lambda(z)]$. Now we have to do the same with the integration in dz_t ,

$$\begin{aligned} \Delta E &= - \frac{e^2 N_b^2}{2\pi} \int_{-\infty}^{+\infty} dw Z_l(w) \Lambda(w) \left[\int_{-\infty}^{+\infty} dz_t e^{jw \frac{z_t}{v}} \lambda(z_t) \right]^* \\ &= - \frac{e^2 N_b^2}{2\pi} \int_{-\infty}^{+\infty} dw Z_l(w) \Lambda(w) \Lambda^* \\ &= - \frac{e^2 N_b^2}{2\pi} \int_{-\infty}^{+\infty} dw Z_l(w) |\Lambda(w)|^2 \end{aligned}$$

because the wakefields are real, from the Fourier Transform proprieties we have:

$$Z_l^*(w) = Z_l(-w) \quad (1.17)$$

that tells us that $Im[Z_l(w)]$ is odd. Now, considering that $\lambda(z)$ is real, $|\Lambda(w)|^2$ is even so their product integrated on a symmetric domain is zero. Or we can just observe that the Energy Loss is real, so the imaginary part of the impedance should not contribute to its calculation. Finally we have that the Energy Loss results to be:

$$\Delta E = - \frac{e^2 N_b^2}{2\pi} \int_{-\infty}^{+\infty} dw Re[Z_l(w)] |\Lambda(w)|^2 \quad (1.18)$$

To obtain the Power Loss now we have just to divide ΔE for the time interval in which the Energy has been lost from the beam.

1.3.1 Numeric calculation of the Power Loss

Very interesting for our purpose is understanding how the P_{loss} can be numerically implemented by a calculator. Thanks to the [10], we have for M identical, equally spaced, well-separated gaussian bunches that:

$$P = M Z_{loss} I_b^2 \quad (1.19)$$

where $I_b = N_b e f_0$ is the "bunch current" and Z_{loss} is the "effective loss impedance" defined as [13]:

$$Z_{loss} = M \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_b)] e^{-(p\sigma w_b)^2} \quad (1.20)$$

with $w_b = Mw_0$. From this formula it is very interesting to note that for a broad band impedance, P is linear with M while for a really narrow-band impedance, P is quadratic with M . Indeed, with a broadband impedance, we have that the sum can be approximated with an integral and, with an easy change of variable $x = pw_b$, we can see that M disappears from Z_{loss} . On the other way, if the impedance is very narrow in frequency, we will have just one term in the sum and so P will increase quadratically with M , however the behaviour of the P_{loss} will be described in detail in the following chapters.

It's clear that this formula came from the general case of the eq. 1.18 but there are some important things that should be underlined. First of alls we have that each term of the sum is Mw_0 far from each others because in the eq. 1.20, an ideal filling scheme has been considered (M bunches equally spaced); if the filling scheme wouldn't have been ideal, we would have a line in the spectrum for each f_0 , due to the FFT of the bunch non ideal filling-scheme. The f_0 distance is fixed from the machine length because from the Fourier theory we know that the resolution in frequency is $1/T$ where T is the signal duration in time. Another important point is that this formula doesn't easily let us understand what will happen with a "middle-bandwidth" impedance case and this will be explained with the description of the script that follows.

1.4 Filling Schemes

The *Filling Scheme* is the scheme of the filling of the machine. In particular, it is the detailed time distribution of the bunches of protons. Dividing the LHC in 3564 slots, the filling scheme is the map of the slots that are occupied from the bunches (1 bunch per slot). Because it is not easy to understand all the consequences of the filling scheme on the Power Spectrum and so on the Heat Load, we use to divide it in two category: Ideal Filling Scheme and True (or LHC like) Filling Scheme.

1.4.1 Ideal Filling Scheme

A Filling Scheme is Ideal if it respect the followings assumptions:

- All the slots filled.
- All bunches with the same sigma (parameter that gives us the length of the bunch in time).
- All bunches equispaced.

Because a plot of all the fill would just appear as a blue square, a zoomed image is reported here:

1.4.2 LHC typical filling scheme

Removing all the assumptions done for the Ideal Filling Scheme, we get the typical one. As example, it is reported here the case of the fill 5979 that has the following longitudinal distribution:

- Number of bunches= 2556.
- Distance between two consecutive bunches $\simeq 25ns$

Looking at the figure 1.4, it is possible to see that the there are some empty spaces and in particular there are several group of bunches all together. Each one of this group of bunches is named *batch*. If we zoom in, it is easier to identify the batches: The batches are also trains of bunches that are injected

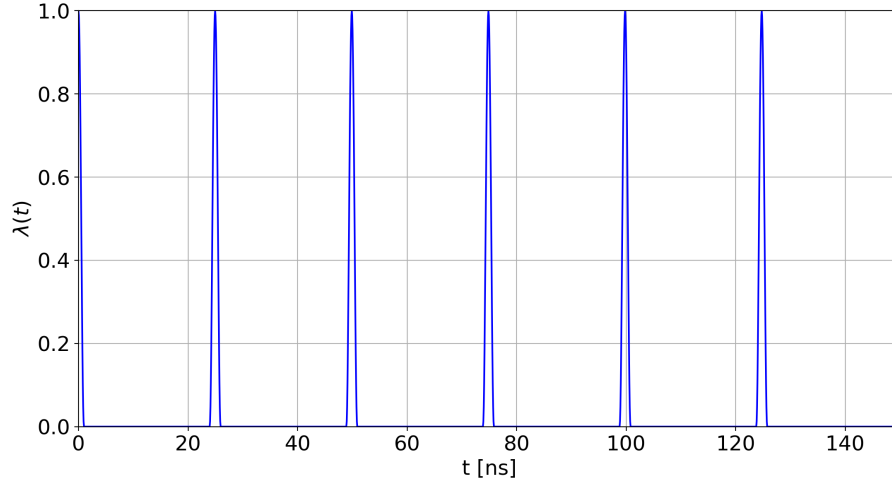


FIGURE 1.3: Ideal Filling Scheme (First 7 bunches)

in one time inside the LHC, so we could say that the LHC is filled one batch per time. The main filling schemes used for the LHC are: $25ns$, $50ns$, $100ns$, $8b4e$. While for the first 3, it is only the bunch spacing that varies, the $8b4e$ is particular and it worth to look to it.

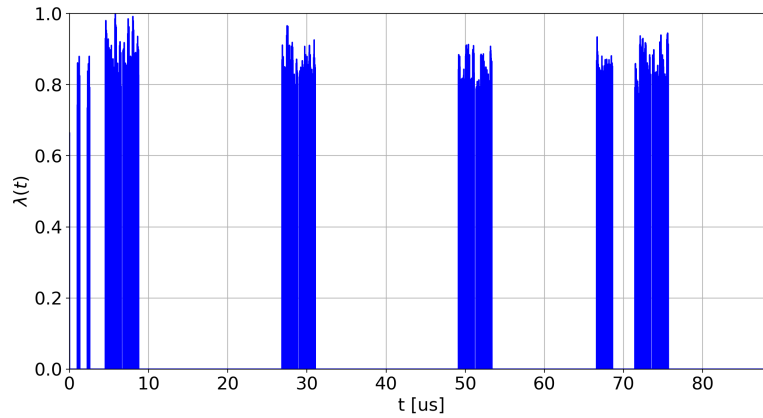


FIGURE 1.6: Fill 4525, Full Machine

$8b4e$ means 8 slots filled and 4 slots empty, as it can be seen zooming around few bunches:

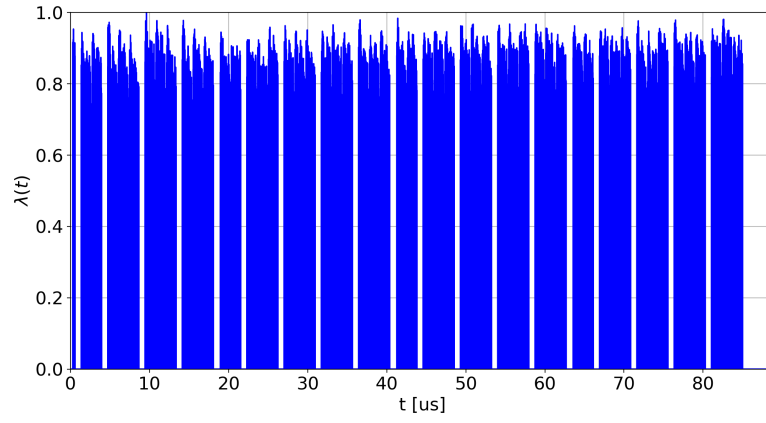


FIGURE 1.4: Fill 5979, Full Machine

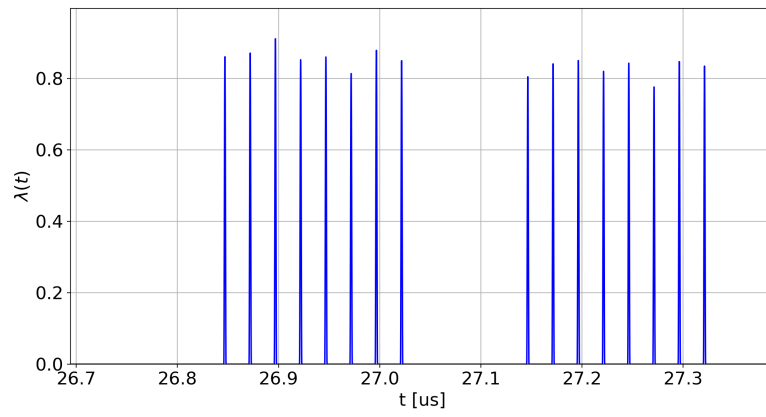


FIGURE 1.7: Fill 4525, Few bunches

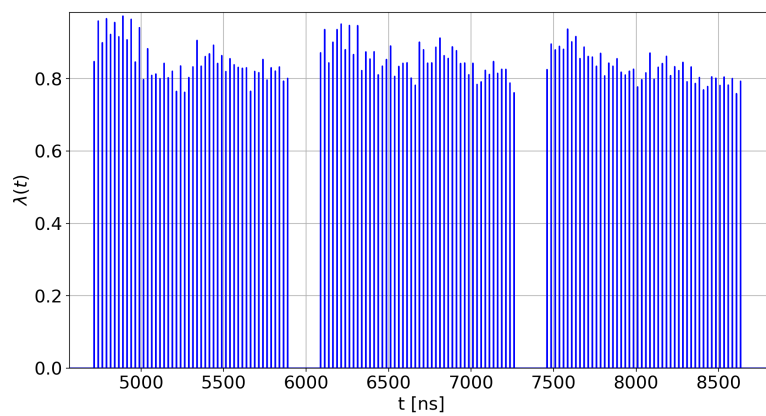


FIGURE 1.5: Fill 5979, 3 Batches Zoom

Chapter 2

Heat load issue inside the LHC sectors

The *Beam Induced Heating* is a well known problem for every particle accelerator often it is the bottleneck when we try to increase the energy of the beam. The LHC is divided in 8 sectors as shown in figure 2.1.

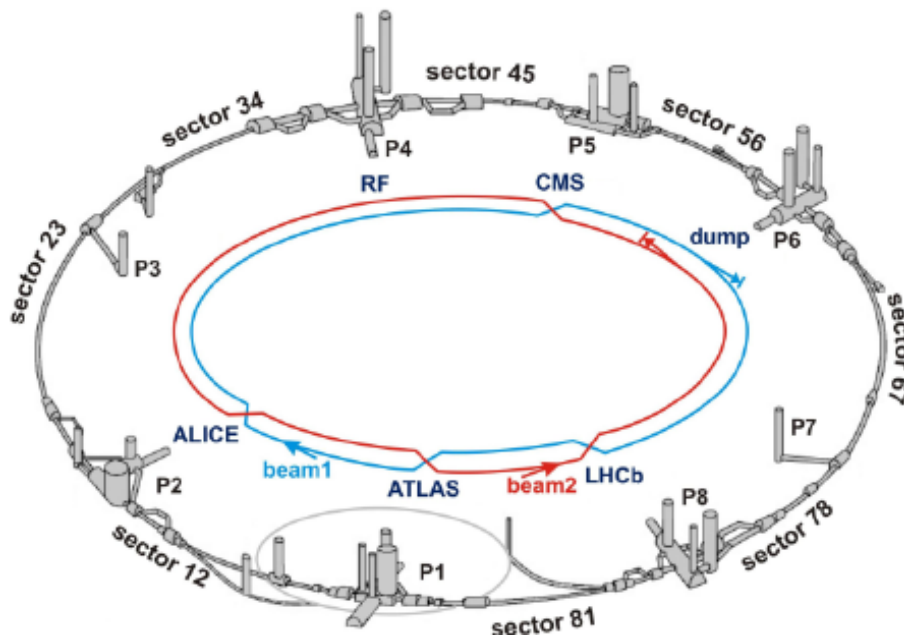


FIGURE 2.1: Layout of the LHC with the experiments and the Sectors

In early 2013, the CERN accelerator complex shut down for two years of planned maintenance and consolidation. The work prepared the accelerators

and experiments for running the LHC at the higher energy of 13 TeV. When the machine has been restarted, huge heat load has been observed for several sectors. From figure 2.2 we can see that after the LS1 the heat load is increased

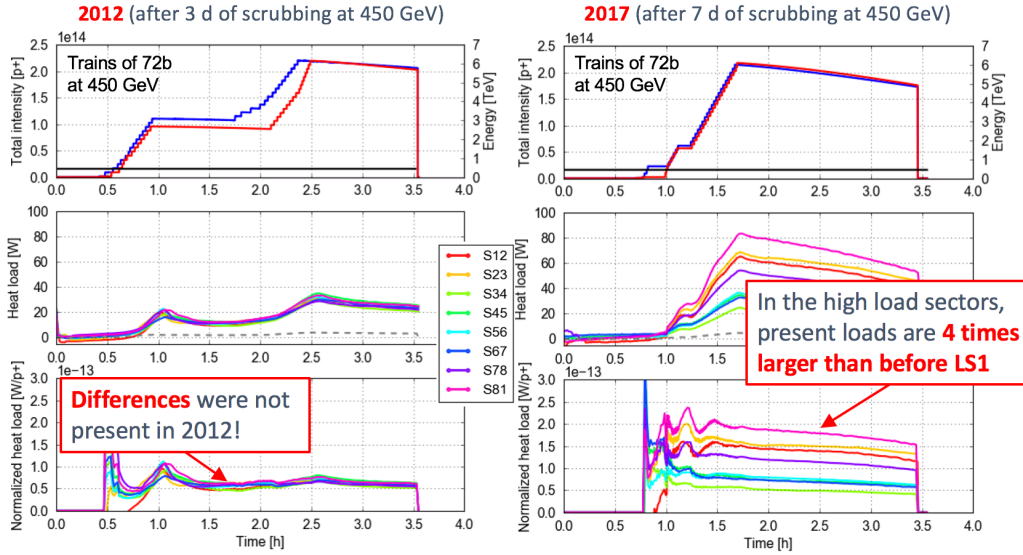


FIGURE 2.2: 2012 vs 2015 measurements [2]

and the sectors have also different losses.

After those measurements, the source of this heat load has been investigated between two most probable phenomena:

- Impedance
- Electron Cloud

Working for the impedance Team, the target of this thesis has been to demonstrate that an impedance can not reasonably explain this heat load. To reach this goal, a good knowledge of the Power Loss formula is needed and for this purpose the thesis is focused on its first part on the analysis of the dependence of the the power loss on number of bunches of the 1.19.

Part II

Proposal

Chapter 3

Methodology

The Heat Load plots 2.2 are not sufficient to identify the source of the problem. This issue requires a very good knowledge of the Power Loss related to impedance. To reach the target, the following steps have been executed:

- Development of a Python Script capable of calculating with high accuracy the Power Loss related to impedance inside any circular accelerator.
- Analysis of the behaviour of the Power Loss varying the number of bunches and the bandwidth of the impedance.
- Method 1: Filling of the LHC with two particularly related fillings schemes.
- Method 2: Analysis of the measured data and comparison with the script with many fills.

The analysis of the behaviour of the Power Loss varying the number of bunches and the bandwidth of the impedance is not an instrument needed in the heat load problem faced in the last part of this thesis. However this study has been done with the aim of understanding when, for a certain power loss, we have a narrow or a broad band impedance. Indeed a good knowledge of the power loss scaling with the number of bunches was missing in literature and was also needed in order to understand, from a power loss measurement, what kind of impedance is generating the heat load.

The removal of the impedance as the source of the heating has been done using 2 different methods in order to be more confident on the results obtained. The method 1 does not require any assumption on the impedance model while for the method 2 a resonator model impedance has been considered because

inside the LHC is very improbable to have an impedance that does not respect that model. The method 2 uses the results obtained in the work [1] made by Benoit Salvant where detailed assumptions on the most probable impedance that could be the source are done.

3.1 Development of a Python Script capable of calculating with high accuracy the Power Loss related to impedance inside any circular accelerator

Since there were no tool capable of simulating what we need with enough accuracy a Python script has been developed. The previous script available in the section was not able to interact directly with the database and it also had not all the free parameters of this new version (phase shift tuning, beam mode, beam number, length of the accelerator etc.). This script has been used for the analysis of the Power Loss formula with the number of bunches but also for the computation of the Power Loss of realistic fillings schemes. The Script has been validated with the measurements before studying any results that it has produced. After that the power loss formula has been studied because its scaling with the number of bunches was needed in order to better understand if the source of heating was an impedance or not.

3.2 Analysis of the behaviour of the Power Loss varying the number of bunches and the bandwidth of the impedance

The target of the thesis requires to be able to understand, for a given power loss, whether the source of the heating is an impedance or not. Since the number of bunches is something easy to vary, we focused on the scaling of the formula varying it. With different impedance, the Power Loss behaves differently

varying the number of bunches. Assuming the Power Loss acting like:

$$P_{loss} \propto c \cdot M^\alpha$$

the plot of $\alpha(Q_r)$ has been computed because a good knowledge of its scaling was missing in literature and often needed in order to understand, from a power loss measurement, the kind of the impedance inside the device (narrow-band or broad-band).

3.3 Method 1: Filling of the LHC with two particularly related fillings schemes

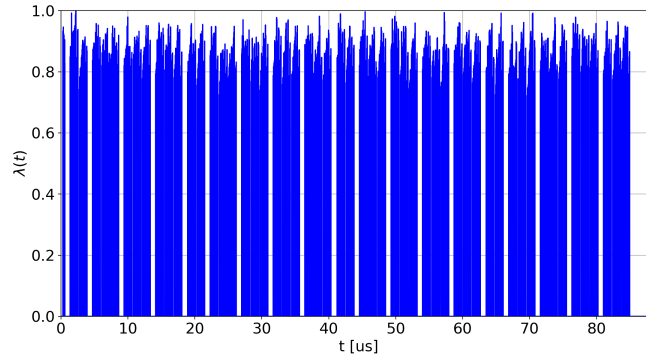
The first method uses 2 fillings schemes with very similar power spectrum. Looking at the Power Loss formula:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{+\infty} \text{Re}[Z(pw_0)] |\Lambda(pw_0)|^2$$

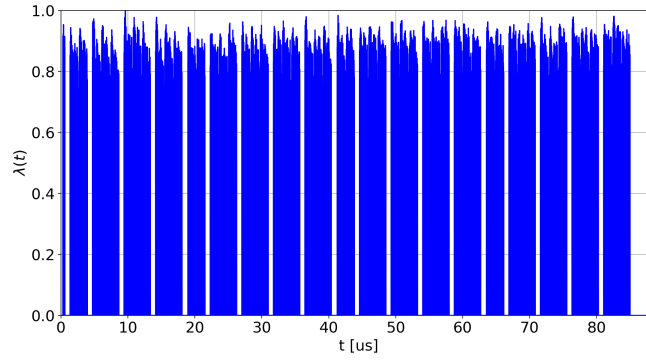
it is possible to observe that given two fillings with the same $|\Lambda(pw_0)|^2$ and knowing the impedance with the previous analysis it is possible to predict which should be the ratio between the power loss in the two cases. To this purpose, the fills 5980 and 5979 have been studied due to their really similar fillings schemes (figures: 3.1b, 3.1a). Calculating the ratio between the heating of these two fill and comparing it with the measurements, it is possible to state if an impedance could be the source of the heat load.

3.4 Method 2: Analysis of the measured data and comparison with the script with many fills

The second methods tries to reproduce the cryogenic measurements with a resonator model impedance. With the Cryogenic measurements of the sector 23 (figure: 3.1), using the Python script we have looked for an impedance that could have reproduced the same plot of the measurements. This Impedance



(A) Fill 5980, 50ns with 1284b



(B) Fill 5979, 25ns with 2556b

has been investigated between a range previously studied in [1] where a non-conformity in an interconnect was supposed to be the source of the heat load.

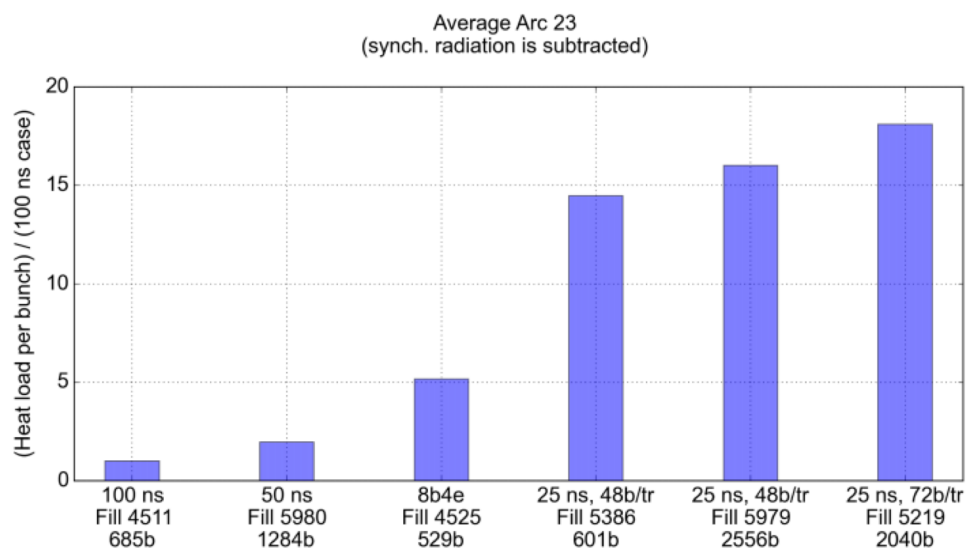


FIGURE 3.1: Cryogenic measurements of the sector 23 [2].

Chapter 4

Script Implementation

The script has been built to calculate the Power Loss and it is the main tool used during the thesis work. It has many functions and the Power Loss is just one of its many outputs. It has been done because it is an instrument that all the HSC section may need and for this reason, efforts have been done trying to make it as much user friendly as possible.

The *for cycles* are reduced to the minimum and wherever it has been possible, they have been replaced with matrix products in order to make it the as faster as possible. On an average PC, it can computes a LHC filling scheme with more than 1 milion of points in less than 30 seconds. The Power Loss is computed without any assumption on the filling scheme, so the formula implemented is:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] |\Lambda(pw_0)|^2 \quad (4.1)$$

where we can see that the bunch power spectrum $|\Lambda(pw_0)|^2$ is sampled each w_0 , instead that Mw_0 (see 1.19) because we are not assuming any ideal filling scheme. Since it is very structured and has a lot of inputs and outputs parameters, some lines worth to be spent on them and also on its mains functionalities.

4.1 Input Parameters

The mains input parameters are:

Variable	Type	Unit	Description
M	int	nd	Slots (if filled one slot contains one bunch)
l	float	s	Time interval where $\lambda(t)$ is non-zero for each bunch.
d	float	s	Distance in time between two slots.
shape	string	nd	The longitudinal shape of a single bunch (Gaussian, Binomial or Parabolic).
J	int	nd	Turns in the machine.
ppbk	int	nd	Points per bucket (Resolution parameter).
realMachinelength	bool	nd	Automatically set the total length equal to the machine length.
AFromFile	bool	nd	Load the amplitude from database.
stdFromFile	bool	nd	Load the bunch length from database.
NbFromFile	bool	nd	Load the average protons per bunch from database.
phiFromFile	bool	nd	Load the phase shift from the database.
fillNumber	int	nd	Fill number.
beamNumber	int	nd	Beam number.
fillMode	string	nd	Mode of the fill (ex: RAMP, FLATTOP, etc.)
startDate	date	nd	Date of the data to load.

There are also others global parameters that could be set that allow to customize in detail the filling of the machine.

4.2 Main functionalities

The script that is presented here is able to implement a certain filling scheme with the following proprieties:

- Tunable bunch shape between : Parabolic, Gaussian and Binomial.
- Tunable distance between bunches , in particular it's the bucket length that will be resized.
- Each bunch could have a different σ , amplitude and phase shift eventually loaded from database.
- For each bunch it is possible to define the domain where the longitudinal shape is non-zero, or, in other terms, it's possible to cut the tails of each bunch in the filling-scheme.
- Even if the distance between 2 consecutive bunches is fixed, it is possible to give a different phase shift in time to each bunch.

When we talk about implementing a filling scheme, we mean that we are going to plot the $\lambda(z)$ function defined in the section 1.3 but in the time domain so $\lambda(t)$ that it's easy to obtain with our "rigid motion approximation", because we just need to set $z = vt$ in the z domain one.

4.3 Main Operation Mode

The script has two mains operation modes:

- Customized filling scheme.
- Timber Loaded filling scheme.

Both of the operation modes are very useful, indeed the Customized one is used to simulates fillings that are not going to run in the machine but could be very interesting to study, while the Timber loaded is used to study real fillings that have been inside the machine.

4.3.1 Customized Filling Scheme

Having a totally customized filling scheme is very important. First of all, it is easier to validate the script with theoretical result and also because sometimes it can be very useful to implement some fillings that are non-real in order to have a worst case evaluation.

```
M=3564#number of buckets

realMachineLength=True
l=12e-9 #seconds [s]
d=2.4950746876791241e-08
J=1
AFromFile=False
stdFromFile=False
NbFromFile=False
phiFromFile=False
intensity_from_file=False
```

FIGURE 4.1: Typical inputs for a customized filling scheme.

In figure 4.1 it is shown that all the parameter related to the load from database are set to *False*. In this case there is a function named *initializeData(M,d)* that has a for cycle where it is possible to define, for each slot, the amplitude, the bunch length and the phase shift of the bunches.

4.3.2 Timber loaded Filling Scheme

To get the data from the database all the variables of the figure 4.1 should be equal to *True*. At this point we have to decide how to select the fill from the database. If we set *fillNumber* equal to zero the first fill after the *startDate* will be loaded. If *fillNumber* is equal to a true fill number then we can choose the *fillMode* between the following list:

- SETUP
- INJECTION
- PRERAMP

- RAMP
- FLATTOP
- SQUEEZE
- ADJUST
- STABLEBEAM
- BEAMDUMP
- CYCLING
- NOBEAM

When the inputs are given in this way, the timestamps of the selected fill can not be chosen, they are automatically calculated.

Part III

Numerical and Experimental Result

Chapter 5

Validation of the Script

Before we can rely on the Script, it is necessary to validate it. Due to its complex structure also the validation its not easy to do. The first step is to compare easy and ideal situations that is possible to calculate analytically, so it will be possible to see if the script is implementing the formulas as we are expecting. After that, a comparison between the outputs and the measurements is needed in order to understand if it will be possible to rely on the script for the futures simulations.

5.1 Ideal Filling Scheme Spectrum

The Ideal situation is the best one to start validating the script. Our filling scheme will be a train of bunches with a Gaussian shape as shown in fig. 5.1.

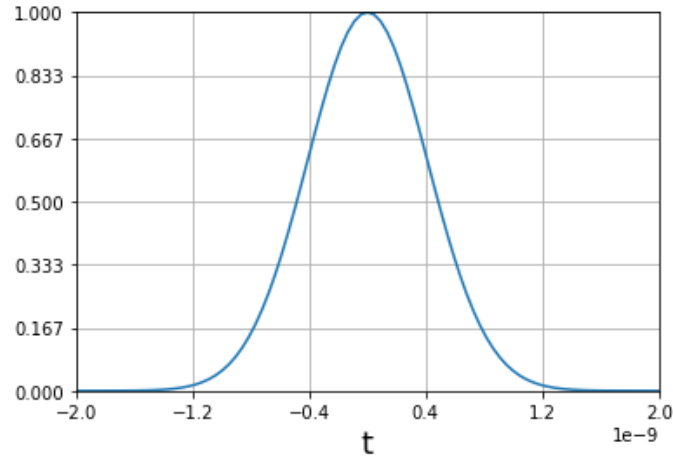


FIGURE 5.1: Single bunch Gaussian shape

The ideal case is made by :

- All buckets filled.
- Same amplitude.
- Same sigma.
- No phase shift (equi-spaced bunches).

With those assumptions our filling scheme with $d = 25ns$ and spectrum are represented in figures: 5.2a, 5.2b, 5.2c.

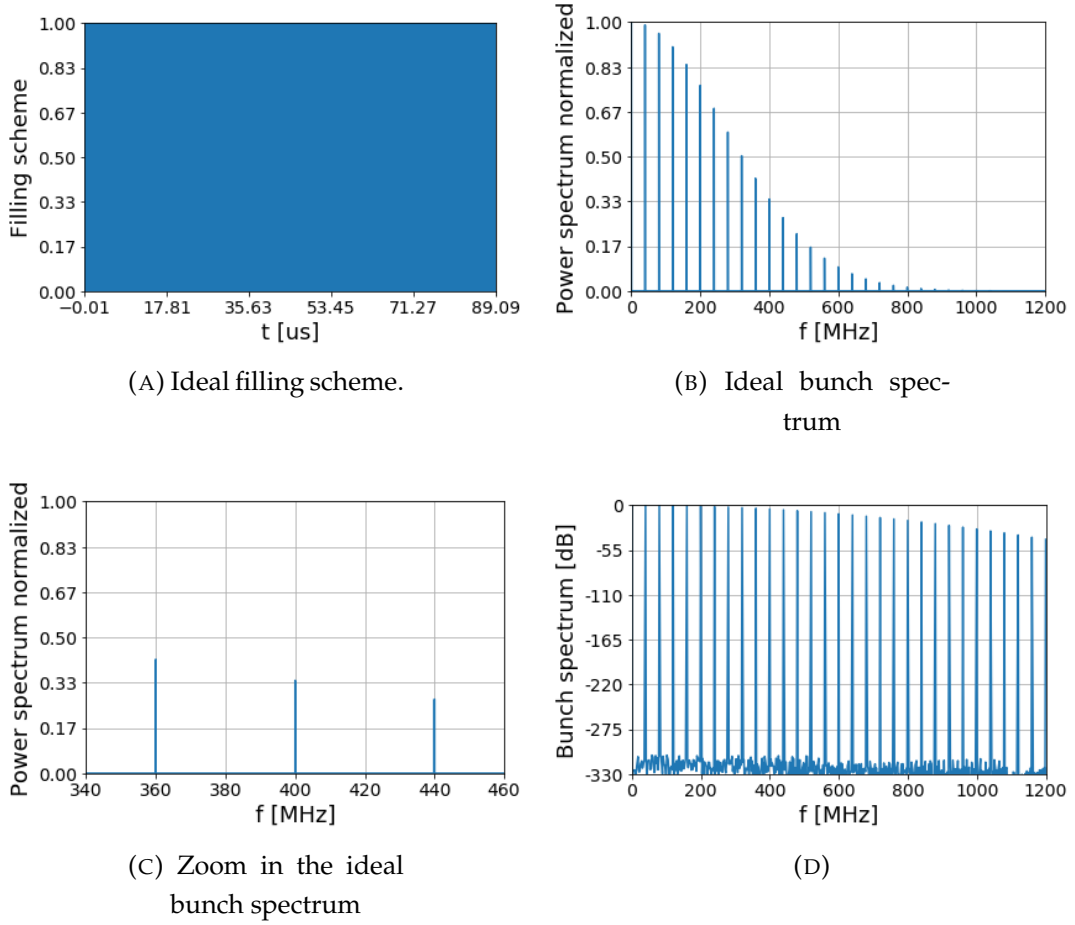


FIGURE 5.2: Ideal Gaussian filling scheme.

The ideal case allows to check if the script respects the following FFT properties that we need for our simulations :

- The FFT of a Gaussian is still a Gaussian with a different σ .
- The FFT of a replicated signal is the FTT of the signal itself sampled each $1/T$ where T is the period, $F[\sum_{n=-\infty}^{+\infty} s(t+nT)] = \sum_{n=-\infty}^{+\infty} S(f)\delta(f-n/T)$

It is important to observe that, with and ideal filling scheme, the spectrum is "clean" because we have only the main lines each 40 MHz (due to the 25 ns spacing in time) and between those line we don't have any noise. This is a first confirmation that the script is working because the ideal case is exactly as

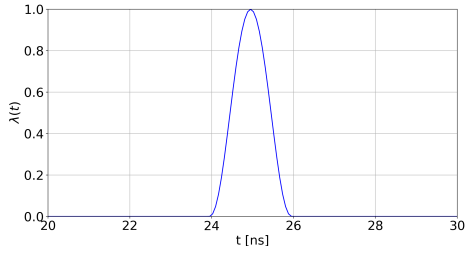
expected. Someone could say that looking at the dB plot there is something around -300 dB but that noise is caused by the accuracy of the numeric representation of the computer (double precision).

5.1.1 Varying Bunch Length

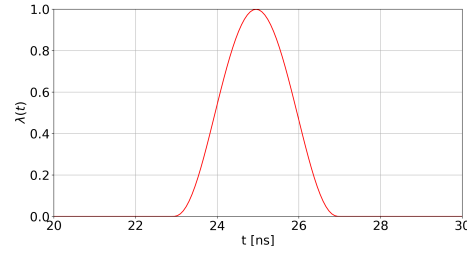
From the Fourier theory we know that:

$$\sigma_t = \frac{1}{\sigma_f}$$

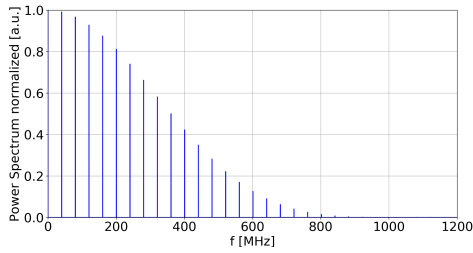
then a very quick test is to vary the sigma in time and check the results in frequency.



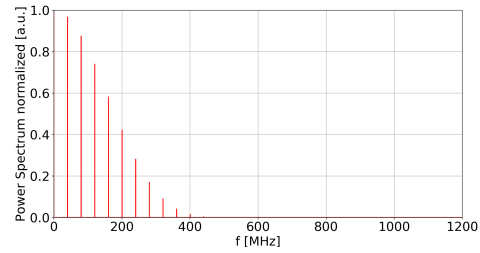
(A) Time Domain,
Bunch Length: 1.2ns



(B) Time Domain,
Bunch Length: 2.4ns



(C) Frequency Domain,
Bunch Length: 1.2ns



(D) Frequency Domain,
Bunch Length: 2.4ns

FIGURE 5.3: Spectrum comparison varying the bunch length.

As it can be seen in figures 5.3a, 5.3a ,5.3c and 5.3d, the script respects this property.

5.1.2 Sinusoidal Amplitude Modulation

Another variation that can be analytically evaluated and then cross-checked with the script is a sinusoidal modulation of the amplitude of the bunches. Because the Power Spectrum is the FFT of the filling scheme we have:

$$\begin{aligned}
 F[\lambda(t) \cdot (1 + A \sin(w_0 t))] &= \\
 F[\lambda(t)] + F[\lambda(t)] \cdot [F(A \sin(w_0 t))] &= \\
 \Lambda(w) + \Lambda(w) * A[\delta(w - w_0) + \delta(w + w_0)] &= \\
 \Lambda(w) + A \cdot \Lambda(w - w_0) + A \cdot \Lambda(w + w_0). &
 \end{aligned}$$

We can see that a sinusoidal oscillation of the amplitude in time is equal to a sampling in frequency each w_0 far from each main line, where w_0 is the frequency of the sinusoidal oscillation itself. It is also very important to observe that the background noise is still very low. Implementing a filling scheme that has an amplitude modulation of $A(t) = (0.5 + 0.5 \sin(2\pi f t))$ with $f = 0.2 \text{ MHz}$ we have:

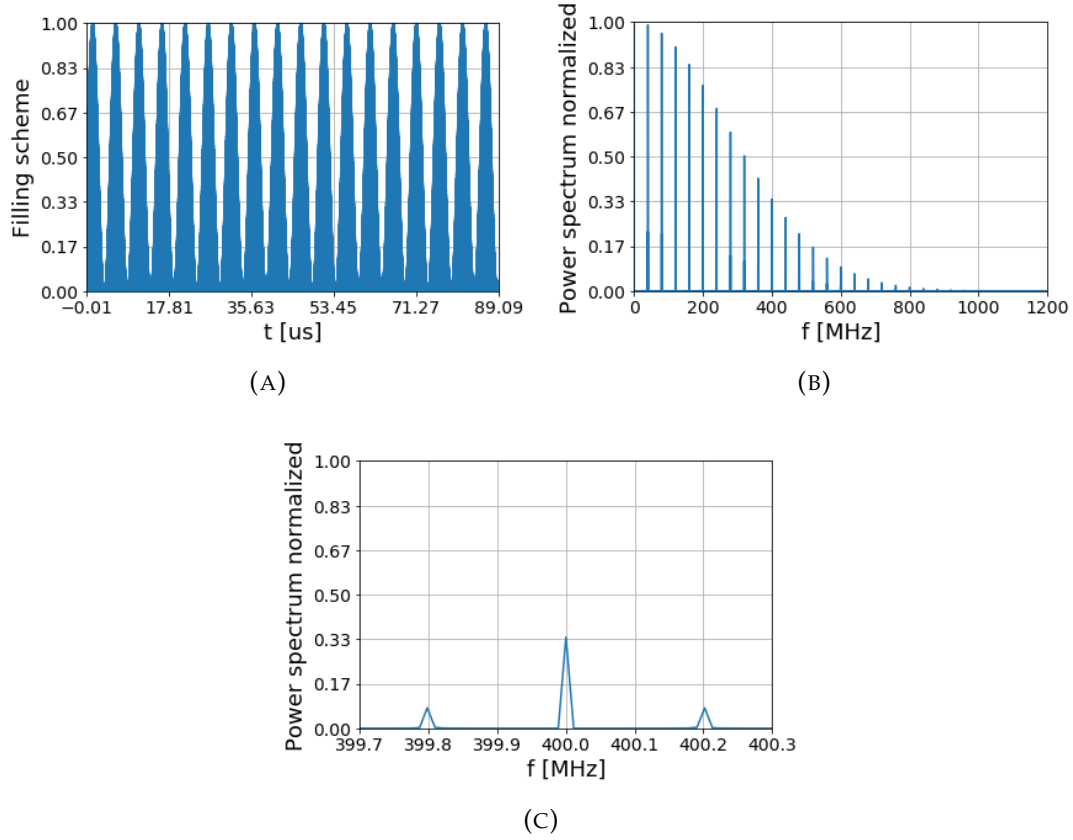


FIGURE 5.4: Sinusoidal amplitude Gaussian filling scheme.

Figures 5.4c shows that we have 2 peaks 0.2MHz far from the main lines and that is true for all the main lines as expected.

5.2 LHC Filling Scheme Spectrum

In the real case usually the variation of the amplitude is not regular so we can't make any easy observations like for this simple case. Furthermore also the sigma varies randomly and not all the buckets are filled. Let's consider the fill 4565 :

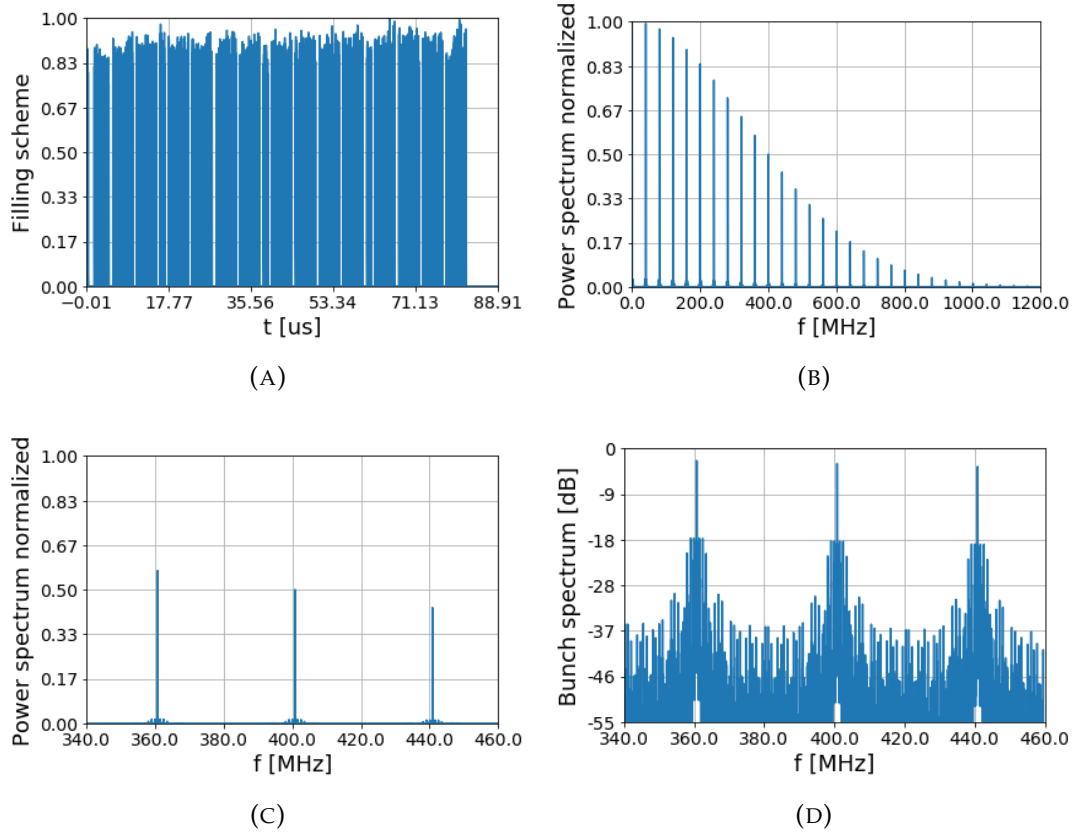


FIGURE 5.5: LHC filling scheme 4565

The first thing that can be observed from this fill is that the background noise is much bigger than the ideal cases, the reason of that is the presence of empty buckets that make the filling scheme no more periodic and irregular. Also the non-ideal amplitude and the non-ideal sigma are of course sources of noise, but the presence of empty buckets is a much stronger noise source.

5.3 Main lines relations between different filling-scheme

The main lines in a Power Spectrum are the biggest part of the Power Loss if there is an impedance that covers these lines, so it is very important to understand how they are related to the main parameters of the beam and in particular how they vary if the filling scheme changes. The relation between the main lines is very interesting from the heat load point of view and it is also a really good test case to validate the script because it can be analytically calculated.

5.3.1 Analytic point of view

In order to simplify the following discussion, we are going to consider the particular case of 25 ns and 100 ns filling schemes but this argument could be expanded to a general case with the appropriate assumption.

From now we will refer to the 25 ns filling scheme with $\lambda_{25}(t)$ and to the 100 ns one with $\lambda_{100}(t)$. If we call T the total length of the machine in time, we can write :

$$\lambda_{25}(t) = \lambda_{100}(t) + \lambda_{100}(t - \frac{T}{4}) + \lambda_{100}(t - \frac{T}{2}) + \lambda_{100}(t - \frac{3}{4}T) \quad (5.1)$$

making the FFT both side we get :

$$\begin{aligned} \Lambda_{25}(f) &= \Lambda_{100}(f) + \Lambda_{100}(f)e^{-j2\pi f \frac{T}{4}} + \Lambda_{100}(f)e^{-j2\pi f \frac{T}{2}} + \Lambda_{100}(f)e^{-j2\pi f \frac{3T}{4}} \\ &= \Lambda_{100}(f)(1 + e^{-j2\pi f \frac{T}{4}} + e^{-j2\pi f \frac{T}{2}} + e^{-j2\pi f \frac{3T}{4}}) \end{aligned}$$

We are interested in the relation between the main lines so we have to evaluate this relation in the frequencies of all the main lines.

Considering :

- $f_{1n} = \frac{4}{T}n$ 0, 40Hz, 80Hz ..
- $f_{2n} = \frac{1}{T} + \frac{4}{T}n$ 10Hz, 50Hz, 90Hz ..
- $f_{3n} = \frac{2}{T} + \frac{4}{T}n$ 20Hz, 60Hz, 100Hz ..

- $f_{4n} = \frac{3}{T} + \frac{4}{T}n$ 30Hz, 70Hz, 110Hz ..

we want to show that $\Lambda_{25}(f) = 4\Lambda_{100}(f)$ for $f = f_{1n}$ and zero for the others.
Let's calculate :

$$\Lambda_{25}(f_{1n}) = \Lambda_{100}(f_{1n})(1 + e^{-j2\pi f_{1n} \frac{T}{4}} + e^{-j2\pi f_{1n} \frac{T}{2}} + e^{-j2\pi f_{1n} \frac{3T}{4}})$$

$$\Lambda_{25}(\frac{4n}{T}) = \Lambda_{100}(f_{1n})(1 + e^{-j2\pi \frac{4nT}{4T}} + e^{-j2\pi \frac{4nT}{2T}} + e^{-j2\pi f \frac{12nT}{4T}})$$

then remembering that $e^{-j2\pi n} = 1, \forall n \in \mathbb{Z}$ we got :

$$\Lambda_{25}(f_{1n}) = 4\Lambda_{100}(f_{1n})$$

for the f_{2n} case, looking just to the exponents, we have :

- $-j2\pi f_{2n} \frac{T}{4} = -j2\pi \frac{4nT}{4T} - j2\pi \frac{T}{4T} = -j2\pi n - j\frac{\pi}{2}$
- $-j2\pi f_{2n} \frac{T}{2} = -j2\pi \frac{4nT}{4T} - j2\pi \frac{2T}{4T} = -j2\pi n - j\pi$
- $-j2\pi f_{2n} \frac{3T}{4} = -j2\pi \frac{4nT}{4T} - j2\pi \frac{3T}{4T} = -j2\pi n - j\frac{3\pi}{2}$

which means :

$$\Lambda_{25}(f_{2n}) = \Lambda_{100}(f_{2n})(1 + j - 1 - j) = 0$$

also for f_{3n} and f_{4n} we get to the same conclusion. Considering that the Power Loss acts like the square of the Spectrum, we can say that for all the main lines we have :

$$P_{25} = \Lambda_{25}^2(\frac{4n}{T}) = 16\Lambda_{100}^2(\frac{4n}{T}) = 16P_{100}$$

5.3.2 Script observation

The idea is to consider several example, that will show the validity of the Script by filling the machine with different filling scheme of 25 ns and 100 ns.

Ideal half machine

The first example that we are going to consider is filling half of the machine one time with a 25 ns filling scheme and then with a 100 ns filling scheme :

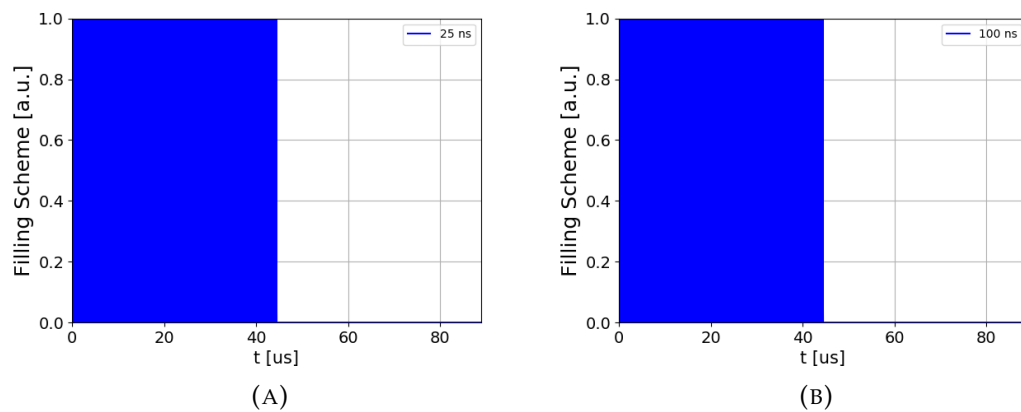


FIGURE 5.6: 25 ns and 100 ns half machine filling scheme

The spectrum obtained computing these fills results to be :

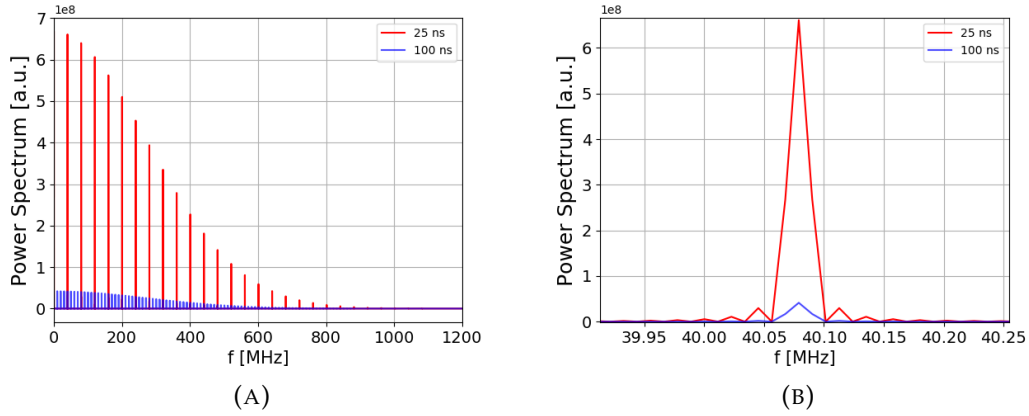


FIGURE 5.7: 25 ns and 100 ns half machine spectrum

From the figure 5.7b it is possible to verify that the ratio between the main lines is 16. Furthermore from 5.7a we see also that all the main lines that are not a f_{1n} multiple (remember $f_{1n} : 0, 40 \text{ MHz}, 80 \text{ MHz}$) are zero. Looking to this plot it is possible to think that the factor 16 from the number of bunches, indeed if we fill half of the machine with bunches one time spaced 25 ns and then spaced 100 ns. In the 100 ns case, just the quarter part of the bunches of the first case will be present in the LHC. To state this, we need other example, of more general cases.

Bunches divided in two batches

The half machine case it's a very ideal one, usually the bunches in the LHC are injected divided in several batches. Let's consider these filling schemes :

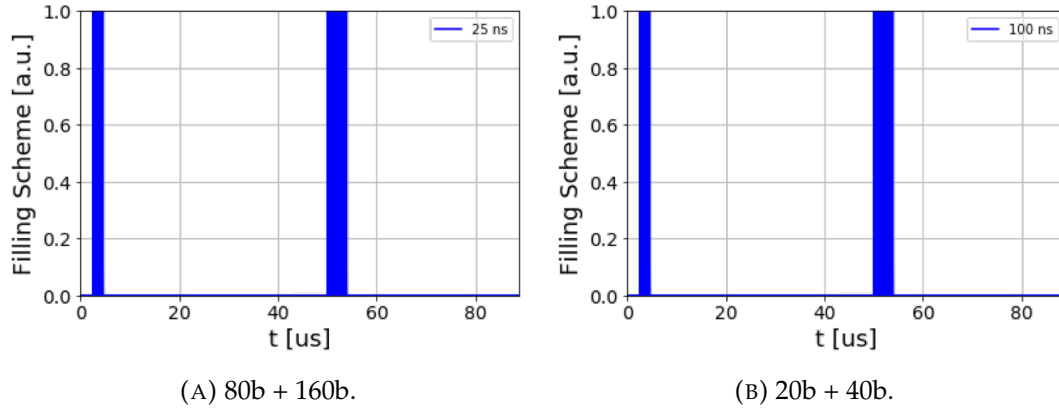


FIGURE 5.8: 25 ns and 100 ns batch.

And the corresponding spectrum results to be :

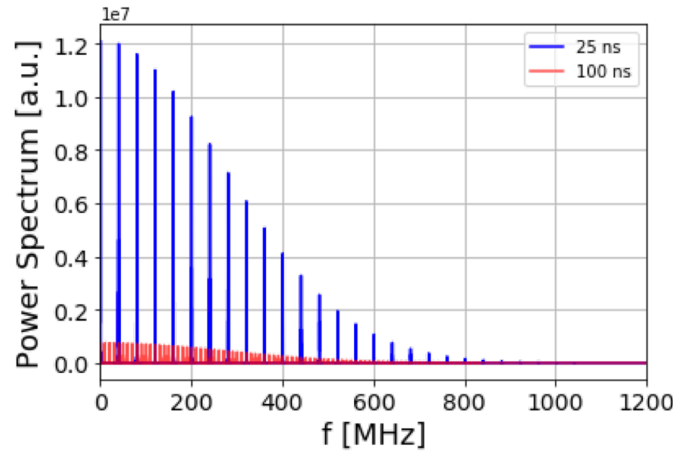


FIGURE 5.9: Power Spectrum of 25 ns and 100 ns batches.

where we can see again a factor 16 between the two fillings. So we are converging on the number of bunches as the reason of this factor 16.

Considering a shifted filling scheme with the same number of bunches :

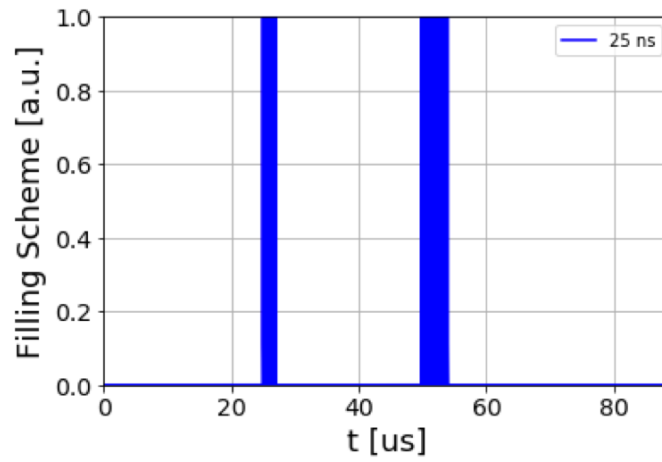


FIGURE 5.10: 80b + 160b shifted.

Comparing its spectrum with the non-shifted filling scheme we get :

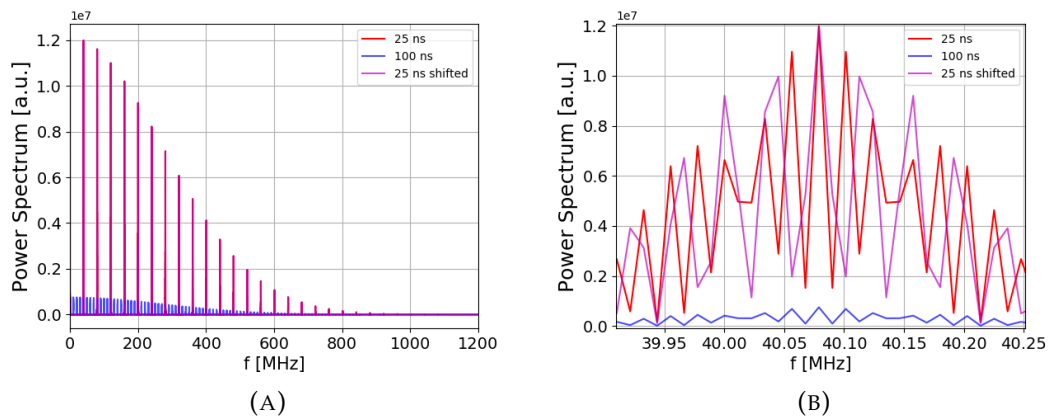


FIGURE 5.11: 25 ns, 25 ns shifted batch and 100 ns batch.

The figure 5.11b shows us that even if the batch are shifted, what really influences the heights of the main lines is the number of bunches in the filling scheme. There is now just one case to analyse to confirm this result.

Full machine vs separated trains

Filling the machine with the same number of bunches but one time filling all the machine and the other splitting the bunches in several trains is the last case that we have to analyse. If the heights of the main lines really depends only on the number of bunches, we should find out that both filling schemes have exactly the same heights of the main lines. The situation in time that we are considering is the following one :

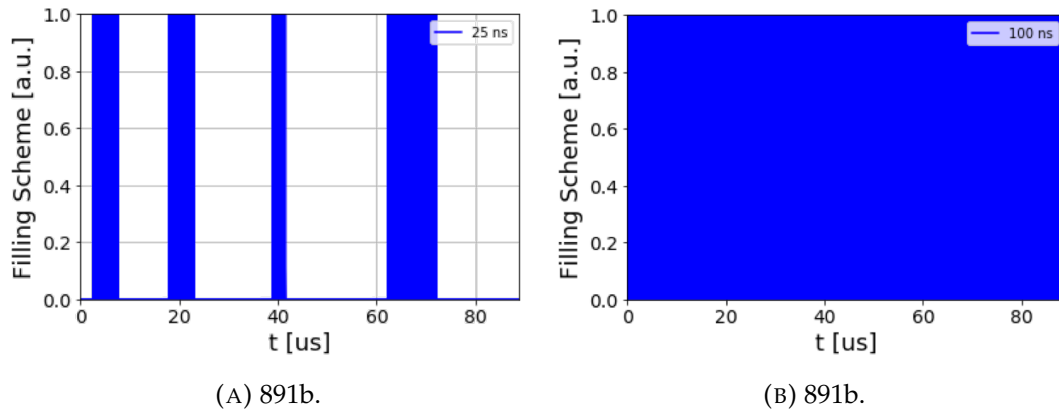


FIGURE 5.12: 25 ns several batches and 100 ns full machine.

Looking just to one main line of these filling schemes we have :

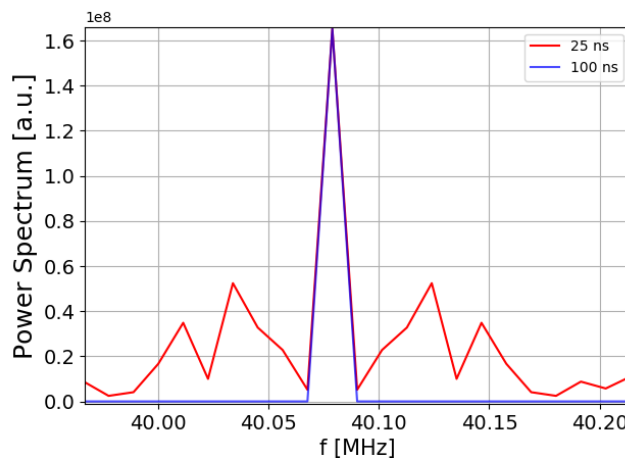


FIGURE 5.13: 25 ns vs 100 ns , 891b Spectrum.

The figure 5.13 confirms that the only thing that matters is the number of bunches in the heights of the main lines because we have totally different filling schemes that have in common just the number of bunches.

5.3.3 Main lines width

The height of a line is not the only factor that matters for the Power Loss computation, indeed, if the impedance is not very narrow in frequency, a wider main line means more Power Loss. We are interested in showing how the length in time of a filling scheme influences the width of its spectrum main lines.

Analytic explanation

The analytic expression of our longitudinal distribution in time for a full machine is the following one:

$$\lambda(t) = \sum_{n=1}^M g_n(t) * \delta(t - nd) \quad (5.2)$$

where M is the number of bunches, d the distance between two bunches and $g_n(t)$ is the Gaussian distribution of the n -th bunch with a certain sigma σ_n . If the machine is not full, we can write the longitudinal distribution as it follows :

$$\lambda(t) = \text{rect}(At) \cdot \sum_{n=1}^M g_n(t) * \delta(t - nd) \quad (5.3)$$

where the $\text{rect}(At)$ models the length in time of our filling scheme. To see how this $\text{rect}(t)$ can affect the main lines, we have to get the spectrum by making an FFT:

$$F[\text{rect}(At) \cdot \sum_{n=1}^M g_n(t) * \delta(t - nd)] = F[\text{rect}(At)] * F[\sum_{n=1}^M g_{\mu=nd}(t)] \quad (5.4)$$

$g_{\mu=nd}(t)$ is the Gaussian that has $\mu = nd$ because the convolution between a Gaussian function and a Dirac's delta train is a train of Gaussian functions that have mean equal to the delta position.

Before to go on, it's important to understand what is the $F[rect(At)]$, in particular what is the role played by the gate length factor A . We already know that:

$$\int_{-\infty}^{+\infty} rect(t)e^{-j2\pi ft} dt = \frac{\sin(\pi f)}{\pi f} = sinc(\pi f) \quad (5.5)$$

so if we set $At = \tau$ in the 5.5 we get:

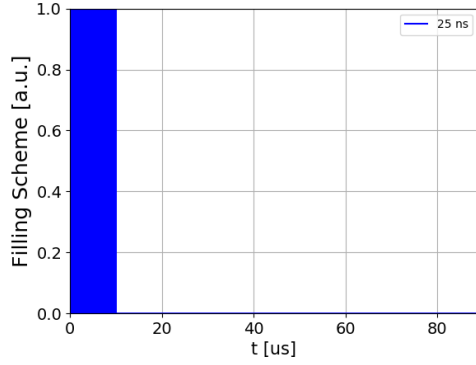
$$\frac{1}{A} \int_{-\infty}^{+\infty} rect(\tau)e^{-j2\pi f \frac{\tau}{A}} d\tau = \frac{1}{A} \frac{\sin(\pi \frac{f}{A})}{\pi \frac{f}{A}} = \frac{1}{A} sinc(\pi \frac{f}{A}). \quad (5.6)$$

Making the limit we have:

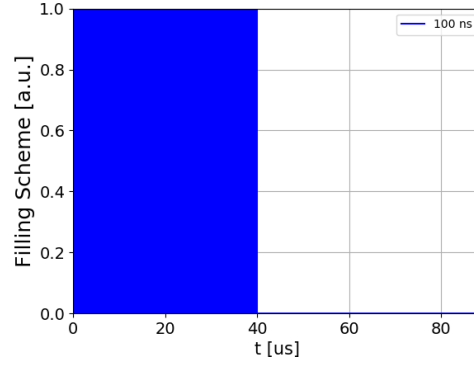
$$\lim_{f \rightarrow 0} \frac{1}{A} sinc(\pi \frac{f}{A}) = \frac{1}{A}$$

that means that the line in $f = 0$ has a factor $\frac{1}{A}$ in amplitude. Looking at the equation 5.4, there is a convolution between the $FFT[rect(At)]$ and the Gaussian FFT of the Gaussian train that means that we have, for every main lines $\frac{1}{A} sinc(\pi \frac{f}{A})$ centred on the main lines (we need to remember that the FFT of a replicated signal is a sampled signal as explained in the subsection 5.1). This sinc factor on every main line changes the width of the main lines, in particular as longer it is the train in time as narrow will be the main lines width.

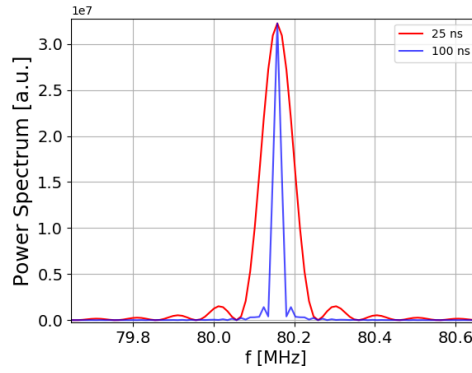
Let's conclude with some pictures from the script that show this property:



(A) 400b 25 ns.



(B) 400b 100 ns.



(C) Main line of the two spectrum

5.4 Spectrum Measurements versus Script's results

The last and also most important step that is needed to validate the script is the comparison between its results and the measurements. Because different models of the bunch can be used in the script, we have focused on the two that better match the measurements:

- Gaussian.
- Binomial.

The measurements are made with the Spectrum Analyser that is installed inside the LHC. This instrument automatically saves each 5 minutes the Power Spectrum in dB of the beam.

5.4.1 Gaussian distribution

The first model that is also the most popular one is the Gaussian. Each bunch is represented as:

$$\lambda_n(t) = \frac{A_n}{\sigma_n \sqrt{2\pi}} e^{-\frac{(t-\phi_n)^2}{2\sigma_n^2}}$$

Where we have that:

$$\int_{-\infty}^{+\infty} \lambda_n(t) dt = A_n$$

With $A_n = 1$ the single bunch distribution is shown in figure 5.14.

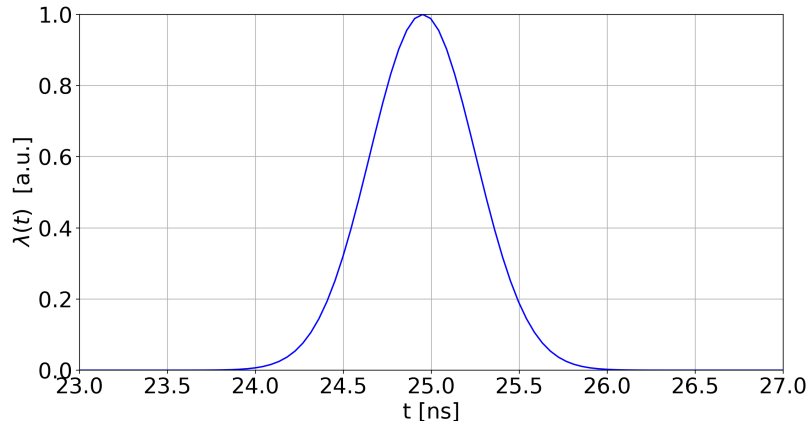


FIGURE 5.14: Gaussian Distribution.

Comparing the measurements and the Script's results for the fill 5979 we have:

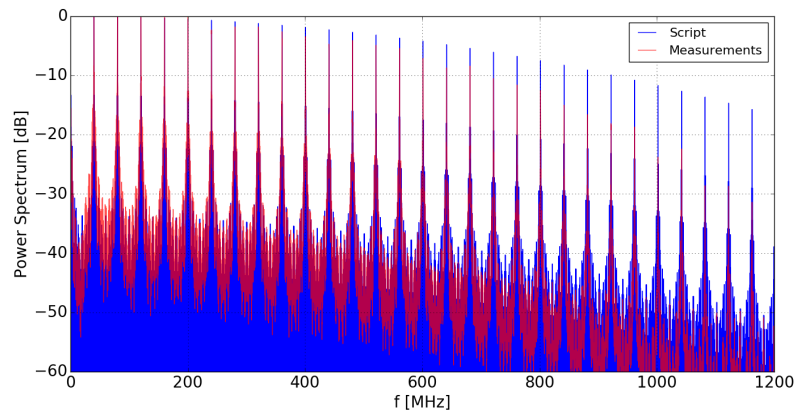


FIGURE 5.15: Measurement vs Script Gaussian model.

Figure 5.15 shows an acceptable but not excellent agreement on the broad range. If we look closer to the side bands we have:

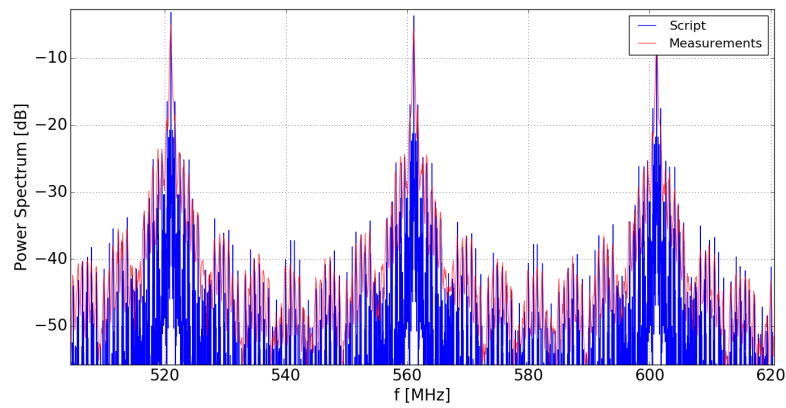


FIGURE 5.16: Measurement vs Script Gaussian model Zoom.

In figure 5.16, is possible to see that the agreement on the detailed scale is very good.

5.4.2 Binomial distribution

The Binomial distribution is given by [3]:

$$\lambda_n(t) = \frac{2A_n}{H} \left(1 - 4 \frac{(t - \phi_n)^2}{H^2}\right)^{2.5}$$

where:

$$H = \sqrt{\frac{2}{\ln(2)}} \sigma_n * 4$$

Also here is interesting to see the distribution represented in figure 5.17.

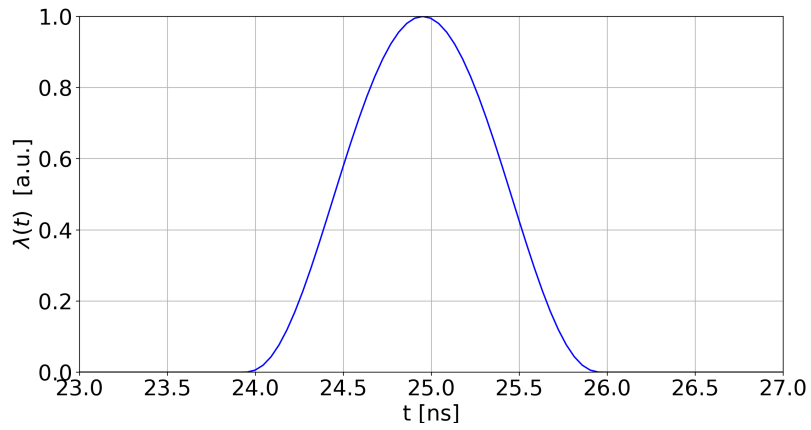


FIGURE 5.17: Binomial Model.

Or even more interesting the comparison with the Gaussian model in figure 5.18.

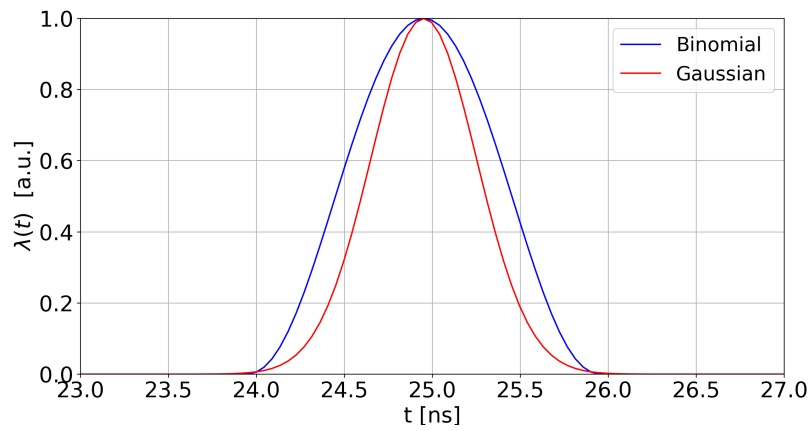


FIGURE 5.18: Gaussian vs Binomial Models.

As it can be seen in figure 5.19, the agreement on the broad range is much better for the Binomial distribution.

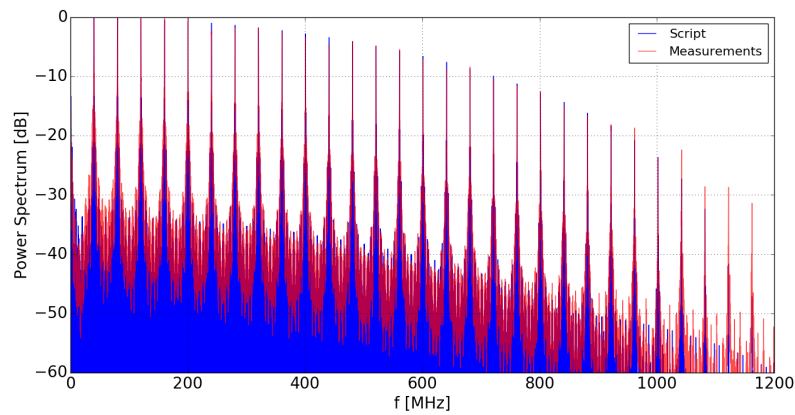


FIGURE 5.19: Measurement vs Script Binomial model

Also the detailed agreement is very good as can be seen from 5.20.

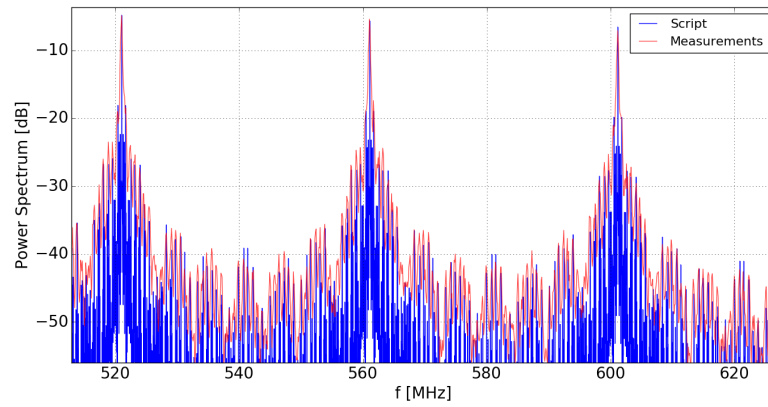


FIGURE 5.20: Measurement vs Script Binomial model

We can conclude that both the models have good agreement but the Binomial one is better for the long scale case.

Chapter 6

Analysis of the dependence on the number of bunches of the Power Loss

6.1 Power Loss Formula

In the Chapter 1, we have already introduced the Power Loss Formula that for simpleness has been copied here :

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] |\Lambda(pw_0)|^2$$

We want to show how the P_{loss} behaves when M is varying. To do this we have to assume that the bunches are :

- Equi populated (same sigma and amplitude)
- Equi spaced
- Gaussian (to write the bunch spectrum in an explicit way)

Under those assumptions the P_{loss} can be written as:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_b)] e^{-(p\sigma w_b)^2} \quad (6.1)$$

where $w_b = Mw_0$. This formula is telling us that, in this particular case, we don't need all the points but we can just sum the lines that we have each Mw_0

and obtain the same result. This is possible because the FFT of a replicated signal is a signal sampled each $1/d$ where d is the distance between the two replications and in an ideal case, like this one, we have just a line each $f_b = 1/d$ and zero everywhere else. If we call T_0 the length of the machine in time we have a bunch, in this ideal case, each T_0/M so because $f_0 = 1/T_0$ (the length in time is equal to the resolution in frequency) we get $w_b = Mw_0$.

It is important to notice that inside the sum we have $Re[Z(pw_b)]$, this term indeed drives the behaviour of the P_{loss} with the number of bunches. We have already briefly said in the subsection 1.3.1 that :

- $P_{loss} \propto M^2$ in case of narrow band impedance
- $P_{loss} \propto M$ in case of broad band impedance.

In the following lines we are going to better explain this behaviour by introducing a resonator impedance model.

6.1.1 Analytic derivation of the two limit cases

In this subsection we are going to show that:

- $P_{loss} \propto M^2$ in case of narrow band impedance
- $P_{loss} \propto M$ in case of broad band impedance

under the assumption of bunches:

- Equi populated (same sigma and amplitude)
- Equi spaced

As already shown before, in this case the P_{loss} formula can be written as:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} Re[Z(pMf_0)] |\Lambda(pMf_0)|^2 \quad (6.2)$$

For the narrow band case it is enough to observe that we have only one term in the sum because all the others go to zero in the product with the impedance. Indeed narrow means that the impedance is not zero only for a small interval

of frequencies and under our assumption at maximum we will have only one line of the spectrum inside that interval.

Regarding the broad band case we can replace the sum with an integral committing an error that is as smaller as higher are the number of points of the Spectrum (Λ) and thus we can write:

$$P_{loss} = M^2 I_b N_b e \int_{-\infty}^{+\infty} \text{Re}[Z(Mf)] |\Lambda(Mf)|^2 df$$

where f_0 inside I_b^2 has become df . Applying the change of variable $f^* = Mf$ we have that:

$$df = \frac{f^*}{M}$$

so the P_{loss} can be written as:

$$P_{loss} = M I_b N_b e \int_{p=-\infty}^{\infty} \text{Re}[Z(f^*)] |\Lambda(f^*)|^2 df^*$$

with the integral that does not have any dependence from M and so we can observe that:

$$P_{loss} \propto M$$

as we wanted to show.

6.2 Power Loss approximation

From the already known behaviour of the Power Loss regarding the narrow band and the broad band case, we can assume that in all the middle cases it acts like :

$$P_{loss}(M, Q_r) \propto c M^{\alpha(Q_r)} \quad (6.3)$$

where c is a constant, M is the number of bunches and α is the only parameter that depends from Q_r . In particular we have $\alpha = 1$ for the broad band case ($Q_r = 0$) and $\alpha = 2$ for the narrow band case ($Q_r = \infty$ but for the computation $Q_r = 10^6$ will be enough). Our aim is to see how α depends on Q_r , to do that we have to elaborate the 6.3 as follow for each fixed Q_r :

- Normalize P_{loss} on his maximum.
- Make the logarithm both side to take α out from the exponent.

After that we will get :

$$\log(P_{loss}) = \alpha \log(cM)$$

Because we have normalized P_{loss} on his maximum and because the dependence of Q_r is only in α , $\log(cM)$ is the same for every Q_r . In particular for the narrow band case we know that $\alpha = 2$ so it is possible to calculate $\log(cM)$ and then cross-check the result with the broad band case where $\alpha = 1$. If no mistakes are done, we should get exactly the same value of $\log(cM)$ in both cases.

6.3 Differences in different way to fill the machine

The first step to plot $\alpha(Q_r)$ is to calculate the $P_{loss}(M)$. In particular we have to set different filling scheme with different values of M , but how we can do it? There are two way to vary M :

- Ideal way: Keep machine full and change bunch spacing
- Real way or LHC like : Keep bunch spacing and fill machine progressively

Filling the machine in different ways led to different results in the Power Spectrum. All computations are made with ideal Binomial bunches and only at the end a realistic situation will be presented that will be better understood after all the studies presented.

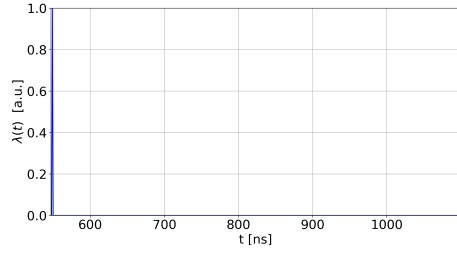
6.3.1 Ideal way: Keep machine full and change bunch spacing

Keep the machine full means that all the bunches are equispaced and that they fit perfectly in the full machine length. This means that we are changing the bunch spacing and so the distance between the main lines in frequency. It is important that the mode that we are studying is not moving in frequency while

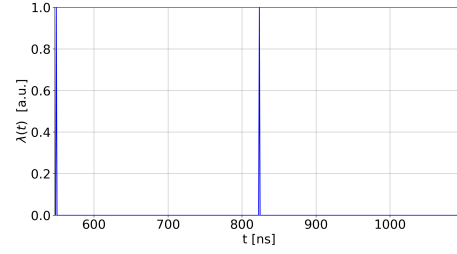
we are filling the machine so the choice of the mode to analyze and also the choice of the various filling needed to fill the machine should be very careful. For all the analysis $f_r = 400.8 MHz$ has been chosen. The number of bunches and so their distance are:

M (Number of bunches)	d [ns]
162	548
297	299
324	274
594	149
891	99.8
1188	74.8
1792	49.9
3564	24.9

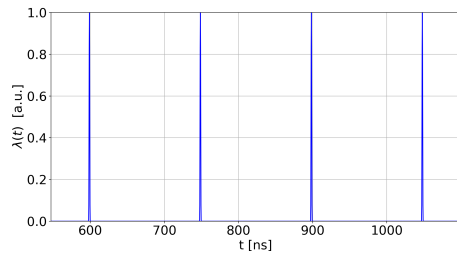
In fig. 6.1 are represented some of the time steps of the machine filling are represented. With the previous fillings we get several plots of the Power Loss with the number of bunches as it can be seen in fig. 6.2. The $\alpha(Q_r)$ plot is represented in fig. 6.3. The α is varying between 1 and 2 as expected because these are the cases of very narrow and broad band impedances. The plot is very steep and the range of Q_r where α is varying is small because we have filled the machine only with ideal fillings where the machine was always full and so we have only ideal Spectrum with no side bands between the main lines.



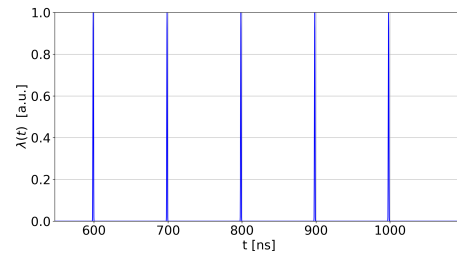
(A) 162b 548ns.



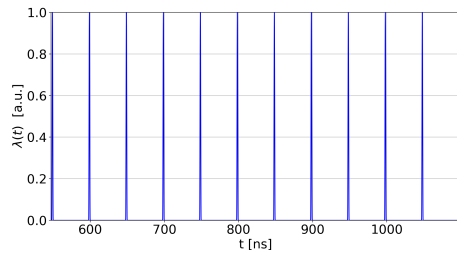
(B) 324b 274ns.



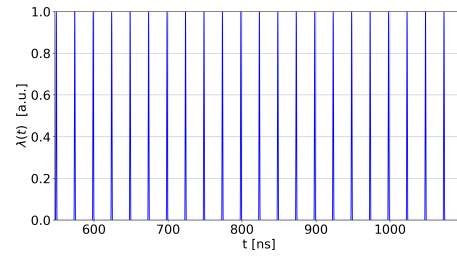
(C) 594b 149ns.



(D) 891b 99.8ns.



(E) 1792b 49.9ns.



(F) 3564 24.9ns.

FIGURE 6.1: Time steps in filling the machine with equispaced bunches.

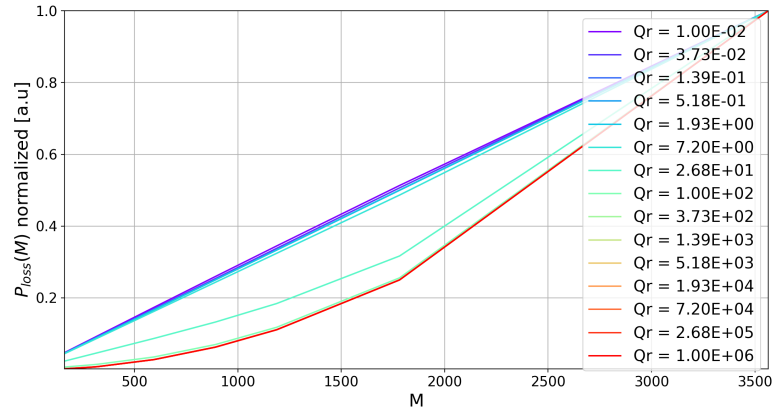
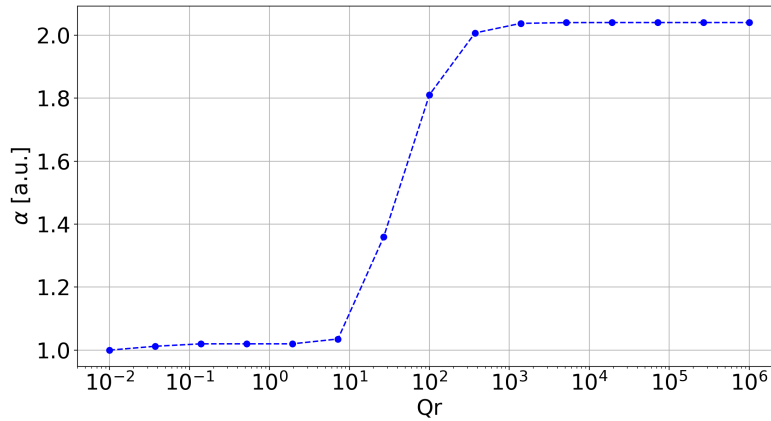
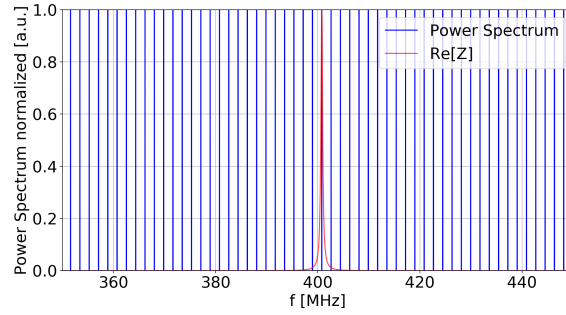


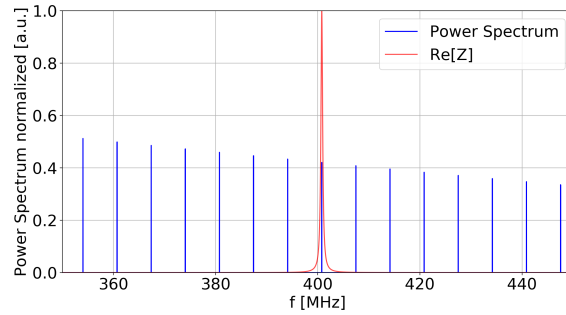
FIGURE 6.2: Power Loss with number of bunches.

FIGURE 6.3: α for different Impedance bandwidth.

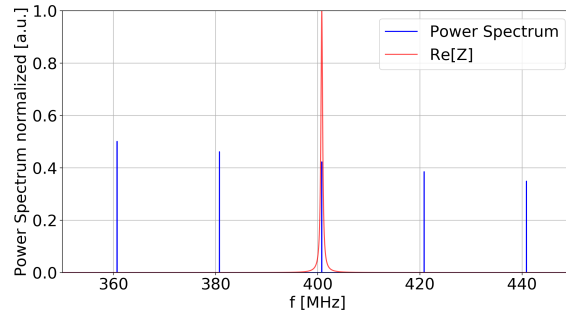
The very steep behaviour of α can be explained with fig. 6.4 indeed because of the very clean Spectrum, with an Impedance of $Q_r = 10^3$ we are already touching almost only the main line. One lines only means that there is only one term in the Power Loss sum of eq. 6.2 that means quadratic behaviour. In particular if the contribute of the main line only is calculated we have that fig. 6.5 is very similar to fig. 6.3.



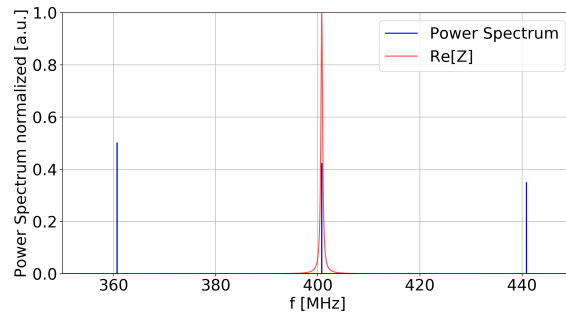
(A)



(B)



(C)



(D)

FIGURE 6.4: Main line spacing filling the machine.

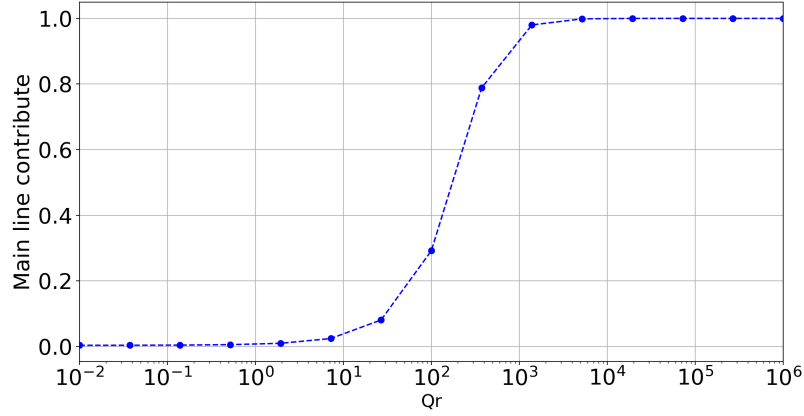


FIGURE 6.5: Main line contribute in range 390-410 MHz.

6.3.2 Real way or LHC like : Keep bunch spacing and fill machine progressively

The plots are much more realistic if we fill the machine progressively as it really happens inside the LHC. Filling progressively means that we keep the bunches equispaced and we add each time more bunches until all the machine is filled as can be seen in fig. 6.6.

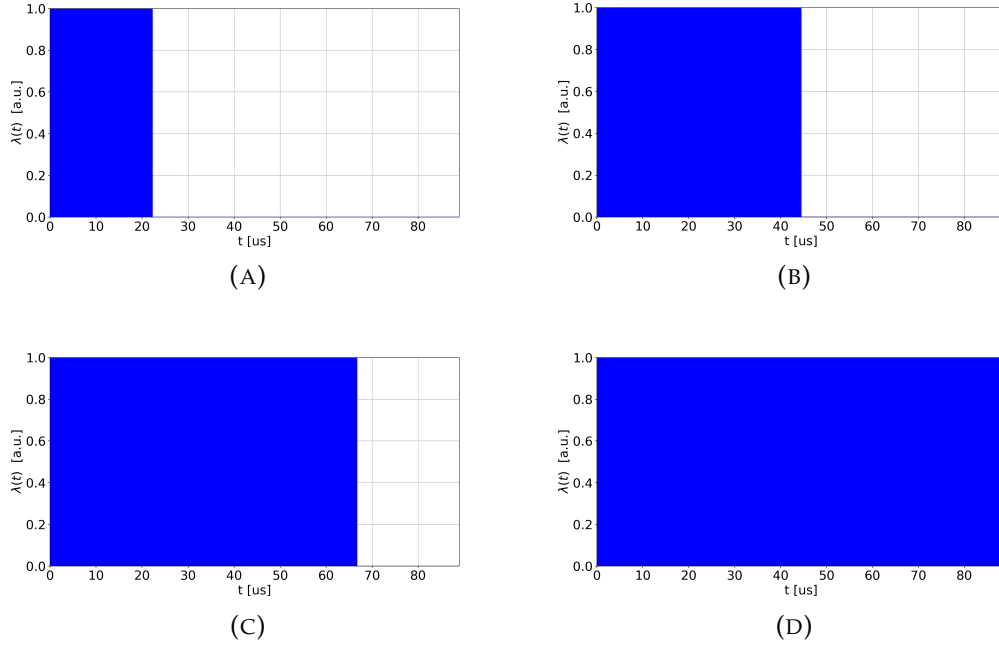


FIGURE 6.6: Progressive filling of the machine.

This kind of filling leads to side bands in frequency according to Fourier's theory. The results are plotted in fig. 6.7 and fig. 6.8. In particular in fig. 6.8 it is possible to observe that at least $Q_r = 10^5$ is needed in order to have $\alpha = 2$. This can be explained looking at the Spectrum in fig. 6.9 where, around the main line, there are side bands that were not present in the other way of filling the machine. Even if these lines seem small they contribute a lot in the Power Loss computing, indeed looking at fig. 6.10 it is clear that for $Q_r > 10^5$ only the main line is playing a role and that is also why only for this Q_r we have the quadratic behaviour.

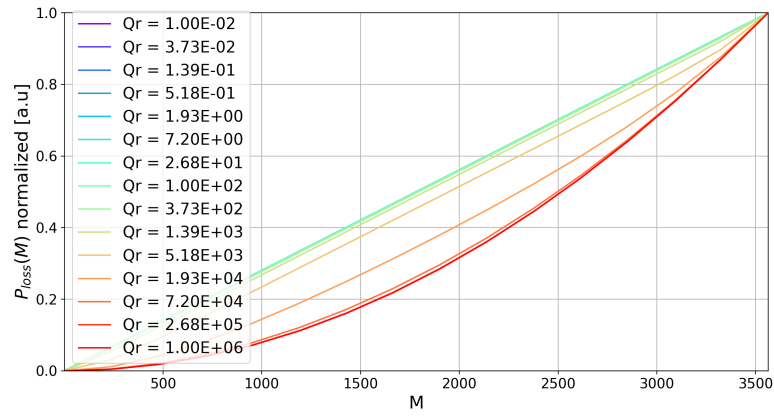
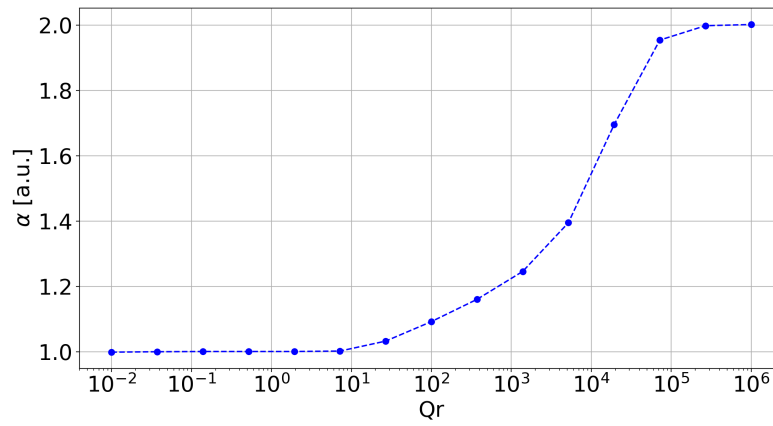


FIGURE 6.7: Power Loss with number of bunches.

FIGURE 6.8: α for different Impedance bandwidth.

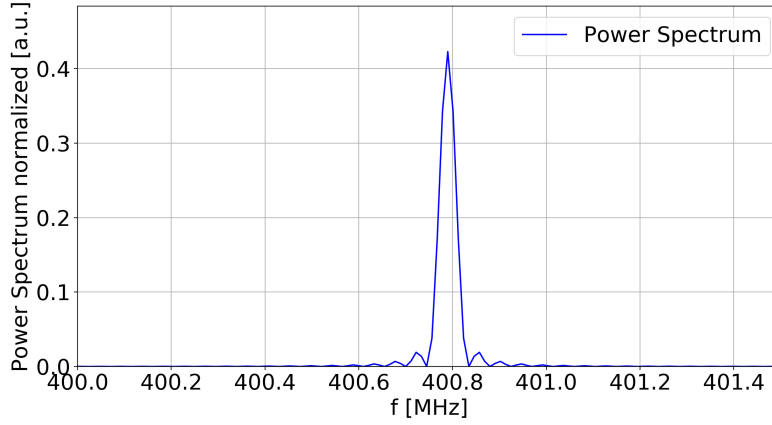


FIGURE 6.9: Spectrum of the progressive filling.

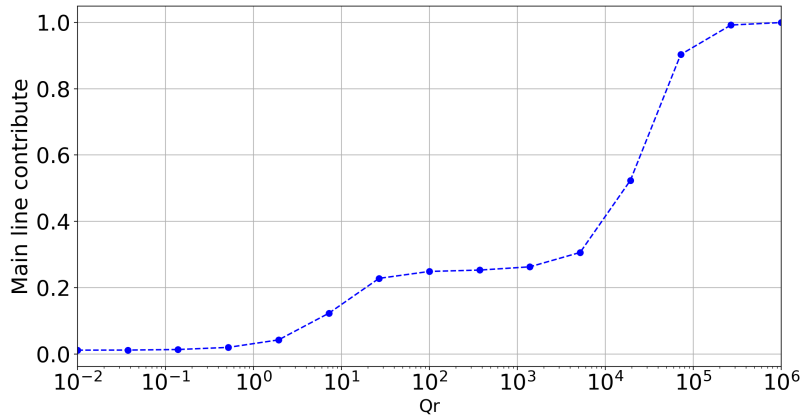


FIGURE 6.10: Main line contribute in range 390-410 MHz.

6.4 Analysis of the differences between the two way of filling the machine

The way of filling the machine influences a lot the Power Loss behaviour ([4], [5]), indeed overlapping the two plot (fig. 6.11) we have two different behaviours.

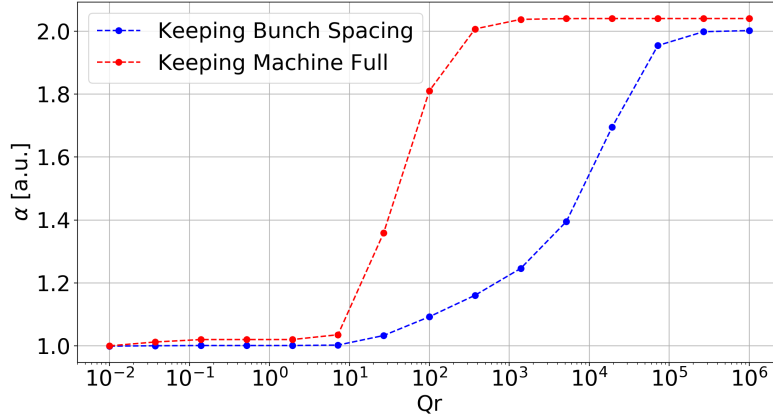


FIGURE 6.11: Comparison on the α plots.

It is important to observe that the only thing that matters is the spacing between the bunch so if we use a realistic filling scheme like fig. 6.12 we will get exactly the plot of 6.8.

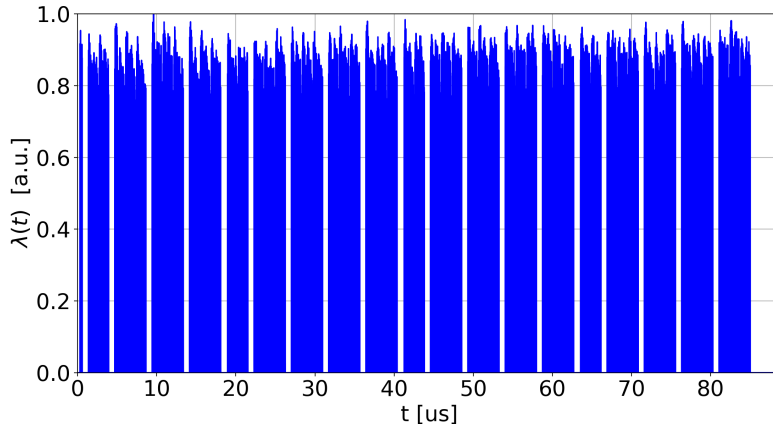


FIGURE 6.12: Fill 5979.

As briefly said in the previous subsections the answer of this difference in the plots is in the spectrum. Discontinuity in time leads to side-bands in frequency and that is why a progressive way of filling has such a large interval where $\alpha(Q_r)$ is varying. In fig. 6.13 it is clear that for $Q_r = 10^3$ the fill obtained

ideally has only the main line covered by the impedance while the other spectrum has also side bands. That explains why we have a quadratic behaviour for the ideal case but not for the realistic one.

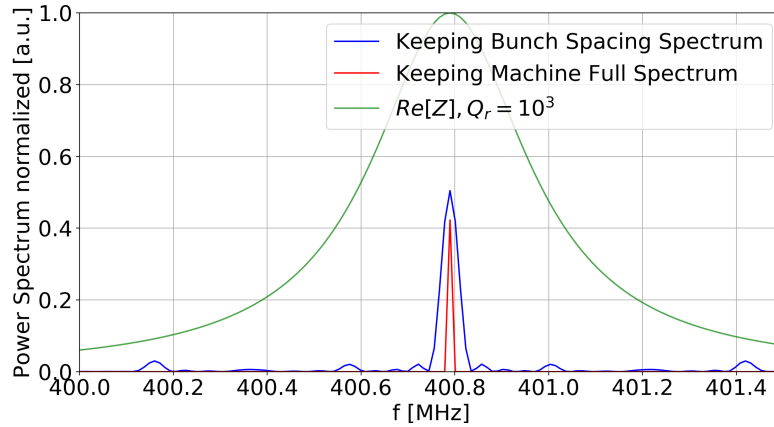


FIGURE 6.13: Comparison between the Spectrum obtained filling differently the machine.

In conclusion, it is nice to observe that also the plot of the comparison between the contribution of the main line in the two cases (fig. 6.14) is similar to fig. 6.11. That also confirms what has been just been discussed, because the quadratic behaviour of the power loss is reached when only the main line is contributing to it.

6.4. Analysis of the differences between the two way of filling the machine 71

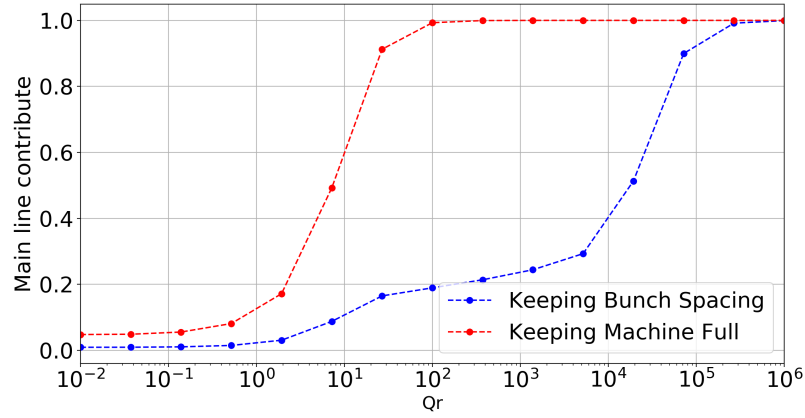


FIGURE 6.14: Comparison between the the contribution of the main line in the two cases.

Chapter 7

Removal of the Impedance as the source of Heat Load Problem in the LHC sectors

The last chapter of this thesis is centred on the problem discussed in the Chapter 2. As a member of the impedance Team at CERN this thesis approaches only the impedance point of view of this really wide argument. The problem has been faced with two different ways and the same results have been reached, this has been done to convince more on the reliability of the conclusions obtained. The first method is more general and does not requires any assumption on the impedance while the second method requires a resonator model impedance.

7.1 Method 1: The 25ns and 50ns fills

The first method use two very similar fills. In the Chapter 6, a detailed analysis on the Power Loss formula has been done. Looking at:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] |\Lambda(pw_0)|^2$$

it is possible to observe that 2 fills with the same Λ and the same I_b have the ratio of their Power Losses that depends only on M . In particular we can say:

- $\frac{P_{loss1}}{P_{loss2}} = \frac{M_1}{M_2}$ for a broad band impedance.

- $\frac{P_{loss1}}{P_{loss2}} \leq \frac{M_1^2}{M_2^2}$ for a narrow band impedance.

The fill 5979 and 5980 have run in the LHC in July 2017 with really similar Power Spectra because they have almost the same filling scheme. The 5979 is a 25ns fill, while the 5980 is a 50ns fill, so we have that:

$$M_{5979} \approx 2M_{5980}$$

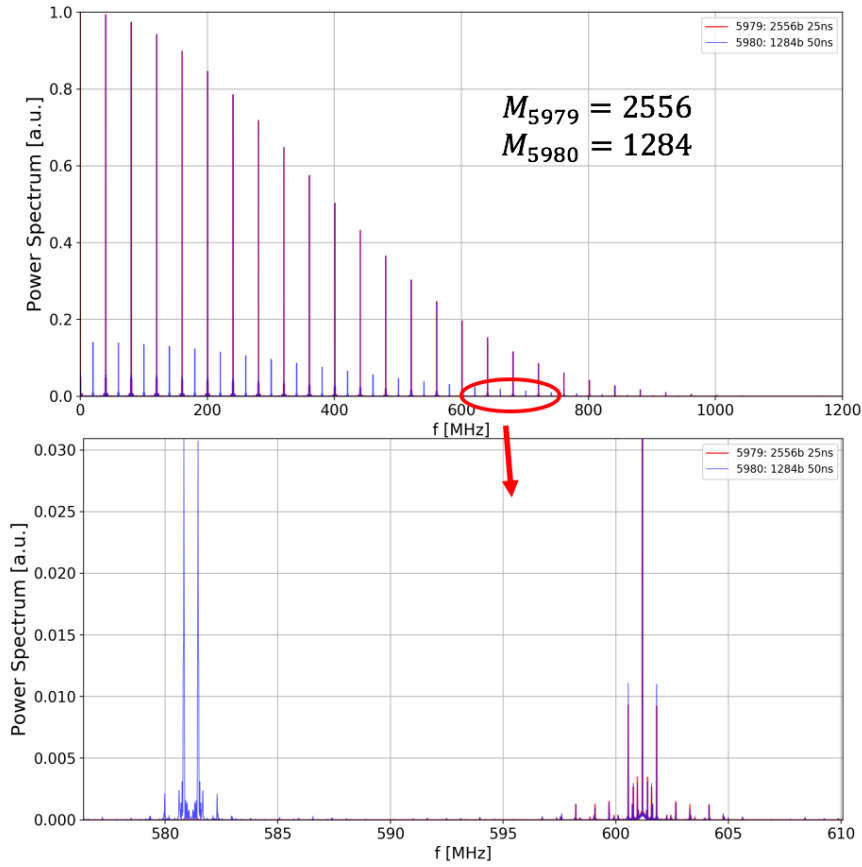


FIGURE 7.1: Comparison of the fill 5979 and 5980 Power Spectrum.

In fig. 7.1 we see a match between the spectrum only around the evens main lines. This is not a problem because the measurements show a huge heat load for the 25ns fill that has less lines than the 50ns (25ns has only the evens

main line) and this means that if exist this impedance should be around an even main line . Knowing the exact number of bunches in the fills we expect that:

- $\frac{P_{loss5979}}{P_{loss5980}} = 1.99$ for a broad band impedance.
- $\frac{P_{loss5979}}{P_{loss5980}} \leq 3.96$ for a narrow band impedance.

These two cases have been studied separately in the followings subsections.

7.1.1 Broad Band case

With the Script the ratio between the Power Loss has been calculated with a resonator model impedance that has:

- $R_s = 1\Omega$ (does not matters in the ratio).
- $Q = 0$ (very broad band case).

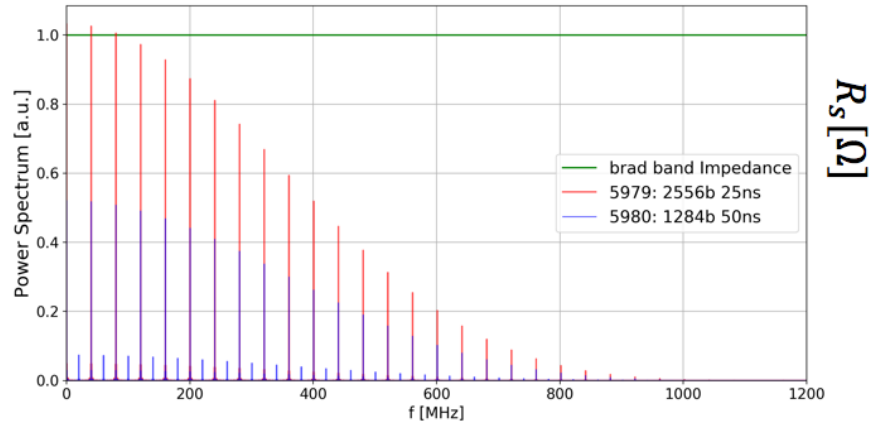


FIGURE 7.2: Broad band impedance situation.

In fig. 7.2 there are both the spectrum and also the impedance used in the computation. The numerical result given by the script has been:

$$\frac{P_{loss5979}}{P_{loss5980}} = 2.04$$

As expected.

7.1.2 Narrow Band case

The narrow band case is easier to analyze if we write the Power Loss formula as follows:

$$P_{loss} = I_b^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] |\Lambda^*(pw_0)|^2$$

where $|\Lambda^*(pw_0)|^2$ is the not normalized power spectrum. From this formula, we can understand that, for each w_0 , the ratio between the power losses is equal to the ratio between the $|\Lambda^*(pw_0)|^2$ that in this case results to be:

$$\frac{P_{loss5979}}{P_{loss5980}} \approx 4$$

as it can be seen in fig. 7.3.

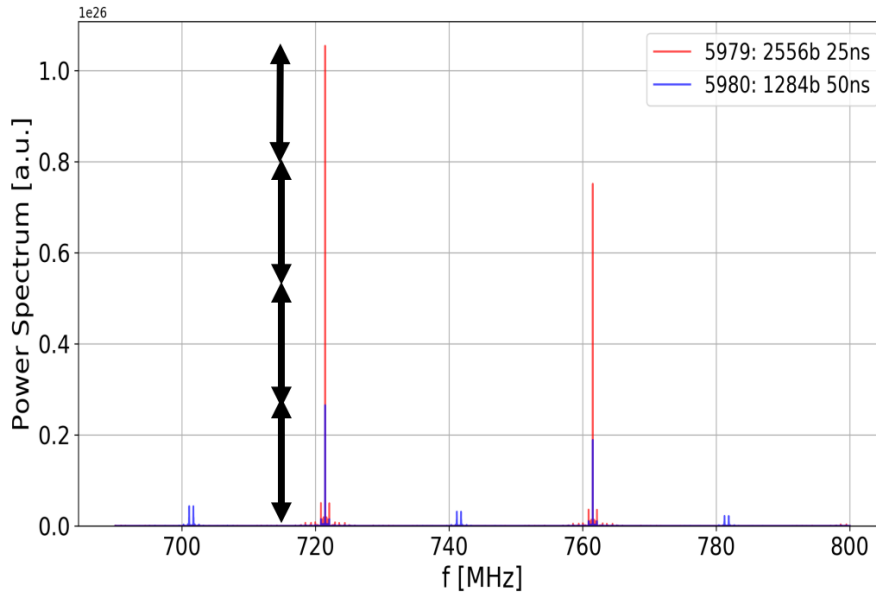


FIGURE 7.3: Fill 5979 and 5980 spectrum not normalized.

7.1.3 Comparison with the Cryogenic Measurements

The cryogenic measurements in the sector 23 are represented in fig. 7.4.

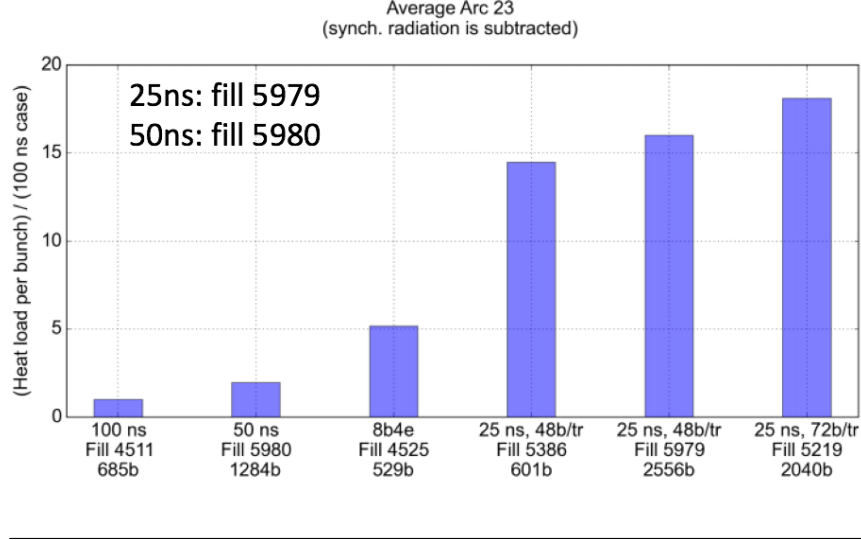


FIGURE 7.4: Cryogenic measurement in sector 23.

It is important to observe that the plot of the measurements are normalized on the number of bunches. This means that :

$$\frac{P_{loss5979}^*}{P_{loss5980}^*} \approx 8 \Leftrightarrow \frac{P_{loss5979}}{P_{loss5980}} \approx 16$$

where P^* is the normalized power loss. This ratio can not be explained with neither with narrow band nor with a broad band impedance. Because in the chapter 6, it has been demonstrated that all the values of α are between 1 and 2, we can also state that no impedance can explain the discussed heat load.

7.2 Method 2: Fitting of the Measurement with a resonator model impedance for various fills

The second method scans the parameters of a resonator model impedance given from a previous study on the most probable source of the impedance that could cause the heat load measured. In the study of [1], it is shown that

one of the most probable source of this heat load could be the impedance related to a non-conformity in interconnects. This study assumes a resonator model impedance introduced in the subsection 1.2.2, and give us the range of the parameters that this impedance should have:

- $10^3 < Q_r < 10^4$
- $700MHz < f_r < 780MHz$

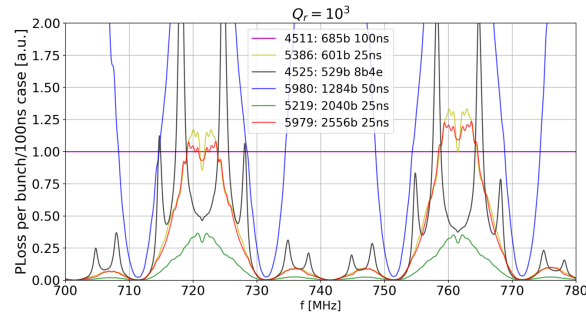
With this information, the power loss has been calculated as a function of the f_r (resonance frequency, it gives us the position of the impedance in frequency) for several values of Q_r considering various fills.

The 25ns and the 50ns fillings are enough to exclude the impedance as a source but to be more convinced, a more accurate analysis has been done. Considering the fills:

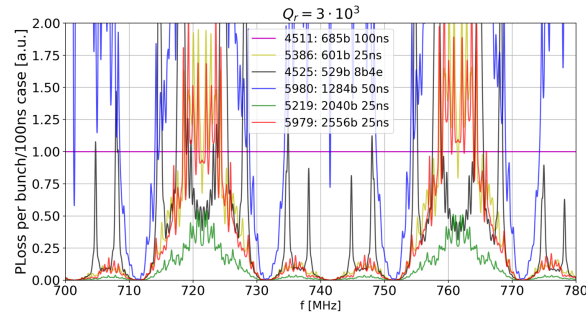
Fill Number	Number of bunches	Bunch Spacing
4511	685	100ns
5980	1284	50ns
4525	529	8b4e
5386	601	25ns
5979	2556	25ns
5219	2040	25ns

it has been looked for an impedance that matches the measurement heat load for all the fills. A single mismatch with the heat load of one fill means that it is not an impedance the source of the heat load because the impedance does not vary if the filling scheme is changed [6]. Under the assumption of the subsection 7.2, considering a resonator model impedance, the Power Loss as function of f_r has been plotted for all the fills considered. f_r is the resonance frequency of a resonator model impedance and it gives us the position in frequency of the impedance itself. In particular the plots have been normalized on the measurement so in each plot (one for each Q_r) we have looked for the f_r where all

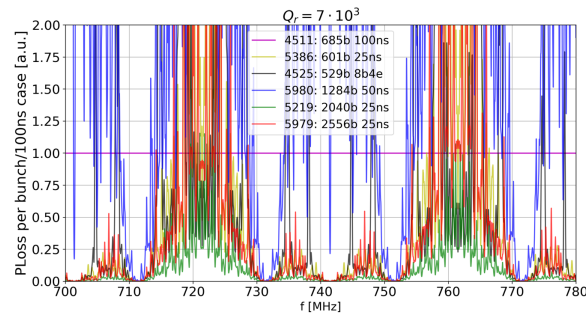
the Power Loss where close to 1. Being close to 1 after the normalization on the measurements means matching the measurements.



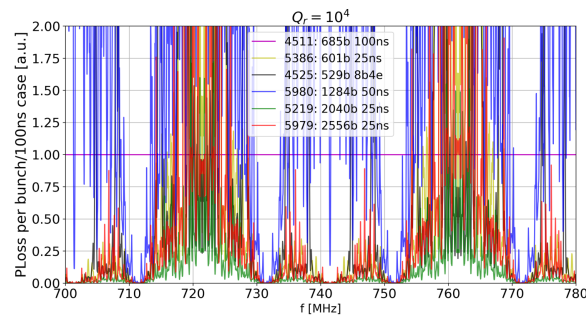
(A)



(B)



(C)



(D)

FIGURE 7.5: Power Loss as function of f_r , normalized on the measurements.

With an algorithm all the plots of fig. 7.5 have been scanned looking for a f_r where all the fills were in a $\pm 50\%$ range from 1. No frequency has been found. Therefore we exaggerate the uncertainty that was already huge to $\pm 65\%$ finding a match for $f_r = 764.03 MHz$ with $Q_r = 10^4$. Using these data, we got an impedance that has been used to reproduce the measurements in fig. 7.6 without a good agreement for all the fills. Furthermore, the R_s needed to match the measurements with that impedance is $9.4 M\Omega$, definitely not a reasonable value.

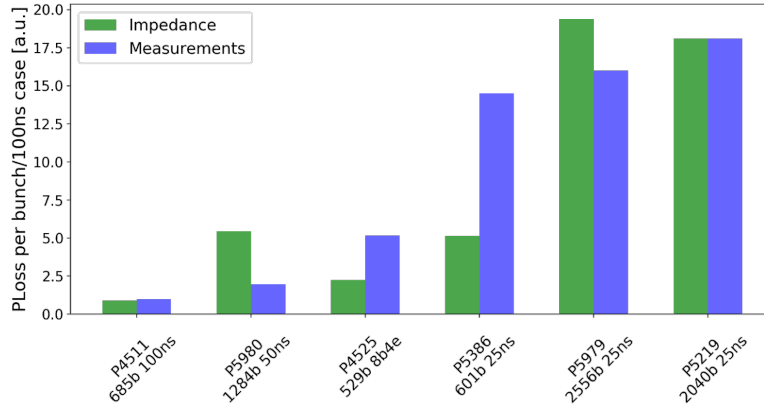


FIGURE 7.6: Compare between the measurements and the heat load produced by the most probable impedance.

Conclusion

The impact of the filling scheme on the LHC has been studied focusing in particular on the heat load issue faced in 2017 inside the machine. The whole problem has been solved building a Python script that computes with high accuracy: the filling scheme, the power spectrum and the power loss. The script has been validated with many theoretical situations and its spectrum has been compared successfully with the measured one from the LHC instrumentation. It has also been shown that the commonly assumed scaling with the square of number of bunches for narrow band resonators is valid only in very specific cases ($Q_r < 10$ and $Q_r > 10^5$) because the side bands in the spectrum play an important role in the power loss computation. We have seen that these side bands mainly come from the empty space in the filling scheme and because all the realistic fillings schemes have empty slots they are definitely not negligible.

Therefore the fills 5979 and 5980 of June-July 2017 have been studied and, due to their really similar power spectrum, the ratio of their power loss has been computed and compared to the measurements showing that an impedance can not reasonably justify the heat load problem.

Furthermore, also a multi-fill analysis has been done trying to fit the cryogenic measurements with the best-fit heat load impedance without any agreement. The only match found is an impedance with an enormous $R_s (\propto M\Omega)$ and moreover the uncertainty interval has been extended to unrealistic value ($\pm 65\%$) in order to find that match. We can conclude that the power loss scales squarely with the number of bunches only for a very high value of $Q_r (> 10^5)$, so even if the ratio between two measures gives an almost linear behaviour with M that usually imply the presence of a broad-band impedance with our study we know that we could be in presence of a narrow-band impedance in that case. In the end we can also state that no reasonable impedance can be the

source of the observed heat load.

Appendix A

Normalisation of the Spectrum and physical consistency

A.1 General case

The Power Loss formula in its most general way can be written as [9] :

$$P_{loss} = \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] |\tilde{I}(pw_0)|^2 \quad (\text{A.1})$$

where $\tilde{I}(w) = F[I(t)]$ and $I(t)$ is the beam current .

Given a longitudinal bunch distribution $\lambda(t)$ the beam current can be written as :

$$I(t) = N_b e \lambda(t) \quad (\text{A.2})$$

where the longitudinal distribution should be normalised in order to have :

$$\int_{-\infty}^{+\infty} \lambda(t) dt = M \quad (\text{A.3})$$

with M as total number of bunches in the beam. For a single bunch case we will have $M = 1$.

It's important to observe, in order to better understand what follow, that the average of the beam current result to be :

$$\langle I(t) \rangle = N_b e \frac{1}{T} \int_{-\infty}^{+\infty} \lambda(t) dt = M N_b e f_0 \quad (\text{A.4})$$

That is the the total number of charge over the time that the beam needs in order to make a single turn in the machine.

A.2 Single Gaussian Bunch

Considering the case of a single Gaussian bunch the beam current results to be:

$$I_g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}} N_b e \quad (\text{A.5})$$

with $\int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}} dt = 1$.

If we want to get the P_{loss} we first need to get the Fourier Transform of $I_g(t)$. We already know that :

$$F[e^{-ax^2}] = \sqrt{\frac{\pi}{a}} e^{-\frac{\pi^2 w^2}{a}}$$

so with $a = \frac{1}{2\sigma^2}$ we get :

$$\tilde{I}_g(w) = F[I_g(t)] = N_b e f_0 e^{-w^2 \sigma^2} \quad (\text{A.6})$$

where f_0 is coming out from the Fourier Transform formula of a periodic signal.

The Power Loss result to be :

$$P_{loss} = N_b^2 e^2 f_0^2 \sum_{p=-\infty}^{\infty} \text{Re}[Z(pw_0)] e^{-w^4 \sigma^4} \quad (\text{A.7})$$

This formula tells us two important things :

- $\max(\tilde{I}(t)) = N_b e f_0$ so without $N_b e f_0$ factor the spectrum has been normalised on his maximum that result to be its DC component.
- The DC component is, from the Fourier theory, the average of the signal in time and in this case the DC component result to be $N_b e f_0$ that perfectly match the average current previously calculated

This study can be extended also to a more general case with M identical Gaussian bunches where it can be demonstrated that in the power loss formula there is also, for that case, a factor M outside the sum.

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