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DESIGN OF A BUNCH PHASE MONITOR FOR THE CTF3 PRELIMINARY PHASE

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Abstract

The main purpose of the CTF3 preliminary phase is to demonstrate the bunch frequency multiplication. In order to observe the bunch interleaving at each stage of this process and to detect possible phase errors during the injection, a non-intercepting device based on frequency spectrum analysis has been designed. Its purpose is to monitor the beam harmonics at 9, 12, 15, 18 and 21 GHz at each stage of the pulse compression. In this note, we report on the design of such a bunch phase monitor, based on MAFIA simulations, and we give a description of its instrumentation.

1 Introduction

The main purpose of the CTF3 preliminary phase is to demonstrate the feasibility of the new scheme of bunch frequency multiplication, using injection by RF deflectors into the EPA isochronous ring. By creating a time-dependent closed bump of the reference orbit, the RF deflectors allow the interleaving of three to five bunch trains (in the following of this study, the combination factor is always five). Up to now, the only way to monitor the longitudinal structure of the bunch trains in the CTF3 preliminary phase is to use the streak camera. This device measures the synchrotron radiation produced by the electrons in the EPA ring. The structure of the light pulse can be related to that of the bunch trains. Therefore, the streak camera can be used to observe the beam over several turns in the ring, and thus provide a demonstration that the electron pulse compression occurs. In this paper, we present an alternative method to monitor the pulse compression scheme, based on frequency spectrum analysis. When the first pulse is injected into the EPA ring, the distance between two consecutive bunches is 333 ps. Therefore, all the harmonics of 3 GHz can be found in the beam power spectrum. At the end of the pulse compression, the distance between two consecutives bunches is reduced by five and, as a result, only the harmonics of 15 GHz can be found in the beam power spectrum. More details can be found on this issue in Section 2, as well as a study of the effect of a possible phase error at the injection. In Section 3, the response of a coaxial RF pick-up is simulated for the five frequencies of interest, i.e. 9, 12, 15, 18 and 21 GHz. In Section 4, we describe the instrumentation which can be used in order to analyse the signals coming out from the pick-up. Finally, conclusions and outlooks are presented in Section 5.

2 Calculation of the frequency spectrum induced by a train of electron bunches

2.1 Electromagnetic field induced by an electron bunch

Let us consider a bunch of N ultra-relativistic electrons following a straight trajectory in free space. We assume that it has a gaussian longitudinal charge distribution $\Lambda(z)$:

$$\Lambda(z) = \frac{1}{\sqrt{2\pi}\sigma_z} exp\left(-\frac{z^2}{2\sigma_z^2}\right).$$

In cylindrical coordinates, the transverse fields excited by the beam have the following form:

- $H_\theta(r,t) = \dfrac{Ne}{2\pi r} \times \dfrac{1}{\sqrt{2\pi}\sigma_t} exp\left(-\dfrac{t^2}{2\sigma_t^2}\right),$

- $E_r(r,z) = Z_0 \times H_\theta(r,z)$ with $Z_0 = \sqrt{\mu_0/\epsilon_0}.$

Here, σ_t is the rms length of the bunch (it is $\sqrt{8ln2}$ times smaller than its fwhm length). During the preliminary phase of CTF3, one expects σ_t to be of the order of 10 ps fwhm, i.e. 4.25 ps rms. Furthermore, the nominal charge per bunch is 0.1 nC.

2.2 Calculation of the beam power spectrum

The electron bunch moving on a straight trajectory can excite a signal in a RF pick-up coupled to the beam pipe. The Fourier transform of a single gaussian bunch with a rms bunch length σ_t is given by:

$$F(\omega) \propto exp\left(-\frac{\sigma_t^2 \omega^2}{2}\right) \implies F(f) \propto exp(-2\pi^2 f^2 \sigma_t^2).$$

The electromagnetic power induced by a single bunch on the beam pipe is proportional to the squared module of the Fourier transform $|F(f)|^2$:

$$P_{bunch}(f) \propto exp(-4\pi^2 f^2 \sigma_t^2).$$

Let us now consider a train of N_b electron bunches which all have the same gaussian longitudinal charge distribution $\Lambda(z)$. The time distribution of this train can be written as the convolution of the field for one single bunch with a train of Dirac pulses. Its Fourier transform is a sum of pulses:

$$(\vec{E}; \vec{H})_{train} = (\vec{E}; \vec{H})_{bunch} \otimes \sum_{i=1}^{N_b} \delta(t - \tau_i),$$

$$F_{train}(f) = F_{bunch}(f) \times \sum_{i=1}^{N_b} exp(-j2\pi f \tau_i).$$

Therefore, the power spectrum of a train of electron bunches can be derived from the following equation:

$$P_{train}(f) \propto exp(-4\pi^2 f^2 \sigma_t^2) \times \left[\left(\sum_{i=1}^{N_b} cos(2\pi f \tau_i)\right)^2 + \left(\sum_{i=1}^{N_b} sin(2\pi f \tau_i)\right)^2\right].$$

In the CTF3 preliminary phase, each pulse consists of 20 electron bunches spaced by 10 cm. The distance between two consecutive pulses corresponds to the EPA ring circumference. Indeed, the bunch combination process requires $C = n\lambda_0 \pm \lambda_0/N$, where n is an integer, C is the ring circumference, N is the combination factor and λ_0 is the RF wavelength [1]. A bunch frequency multiplication factor of five will be considered in the following. The first plot of Figure 1 shows the power spectrum which corresponds to a train of 20 identical bunches which have a fwhm length of 10 ps and which are spaced by 10 cm. The distance between two consecutive lines is thus 3 GHz. The envelope shown in dashed corresponds to the spectrum of a single bunch with the same rms length as the individual bunches of the train. The last plot of Figure 1 shows the power spectrum at the end of the recombination process, when a pulse consists of 100 electron bunches spaced by 2 cm. The distance between two consecutive lines is now 15 GHz and the envelope remains the same. The three intermediate plots display the power spectrum obtained after the injection of the second, of the third and of the fourth bunch train in the EPA ring.
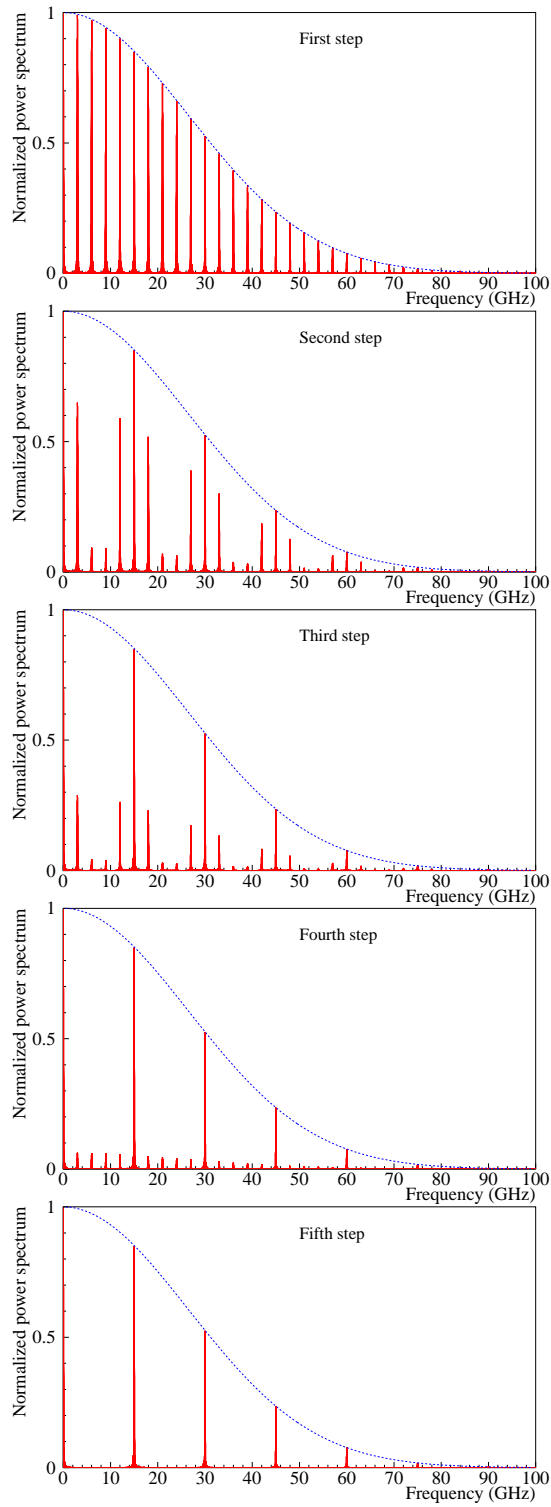
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Figure 1: Normalized power spectra for a train of electron bunches with a fwhm length of 10 ps at various stages of the bunch frequency multiplication process in the EPA ring.

Let us now assume that the charge varies from one bunch another. In this case, the frequency spectrum of one pulse is given by:

$$F_{train}(f) = F_{bunch}(f) \times \sum_{i=1}^{N_b} \frac{q_i}{q_0} exp(-j2\pi f \tau_i),$$

where q_i and $q_0 = Ne$ are respectively the charge for the bunch i and the nominal bunch charge. In order to estimate the effect of the bunch to bunch charge variations, 20 values of q_i were randomly chosen between $0.8q_0$ and $1.2q_0$. The power spectra which are then obtained at the beginning and at the end of the bunch frequency multiplication process are shown in Figure 2. The envelope of the spectrum is no longer a perfect gaussian distribution. However, this effect is quite small.
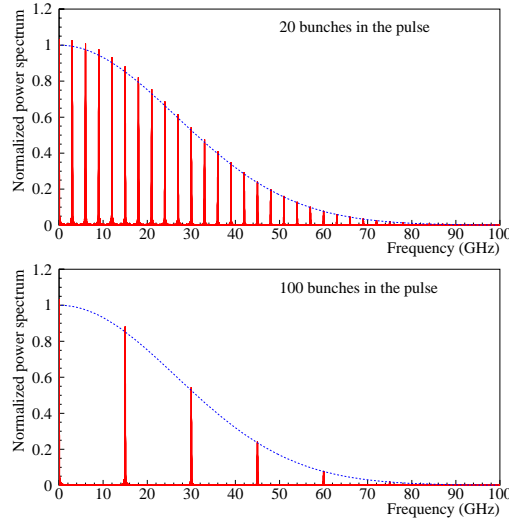

Figure 2: Normalized power spectra for a train of electron bunches with a fwhm length of 10 ps at the beginning and at the end of the bunch frequency multiplication process in the EPA ring. The charge of each bunch is randomly distributed between $0.8q_0$ and $1.2q_0$.

If the recombination process works well, then the distance between the bunches injected at the stage j and the bunches injected at the stage $j + 1$ is $\tau/5$ where $\tau = 333$ ps. However, if a phase error occurs at the injection, one should replace $\tau/5$ by $\tau/5 + \phi$. Let us consider a phase shift ϕ of ± 5 ps. It has a significant effect on the amplitude of the harmonics in the power spectrum, see Figures 3 and 4. If there was no phase error during the pulse injection, only the harmonics of 15 GHz would be present in the frequency spectrum at the end of the bunch combination. But, because of the phase error, some harmonics of 3 GHz, which are not harmonics of 15 GHz, are still found in the spectrum. Since the 3 GHz intrinsic structure of each pulse is not affected by this phase shift, the positions of the lines in the power spectrum remain unchanged, and new harmonics at frequencies other than the multiples of 3 GHz are not observed.
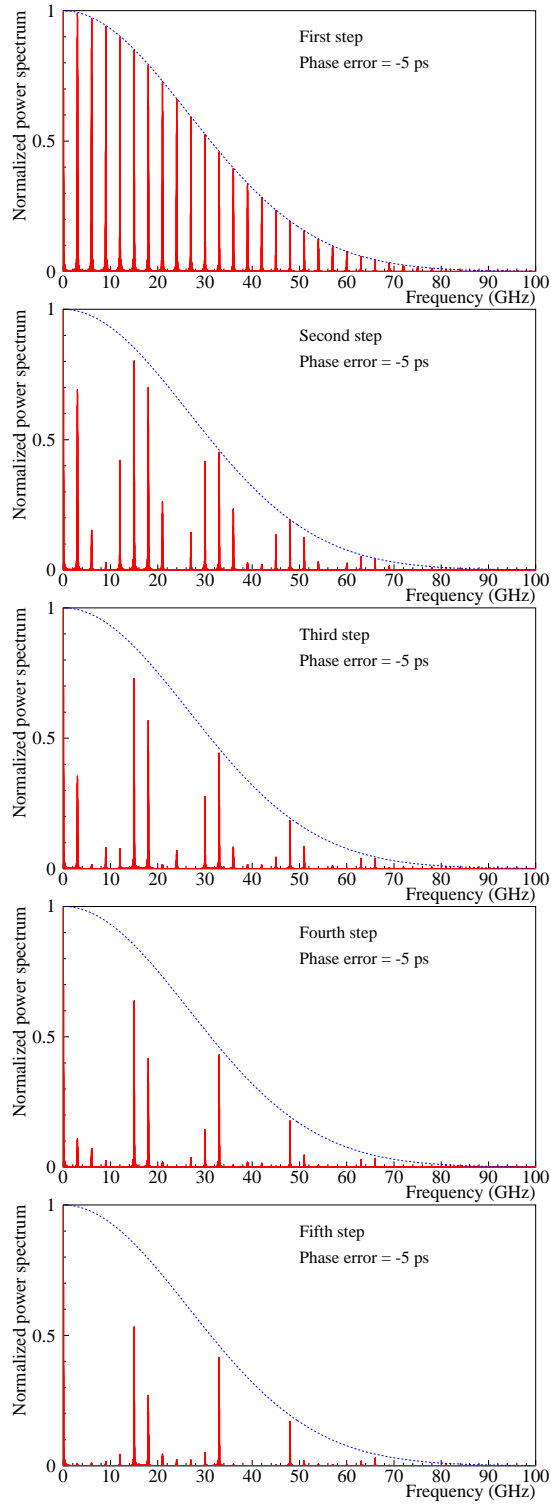
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Figure 3: Normalized power spectra for a train of electron bunches with a fwhm length of 10 ps at various stages of the bunch frequency multiplication in the EPA ring, when a phase error of -5 ps is introduced (see text for details).
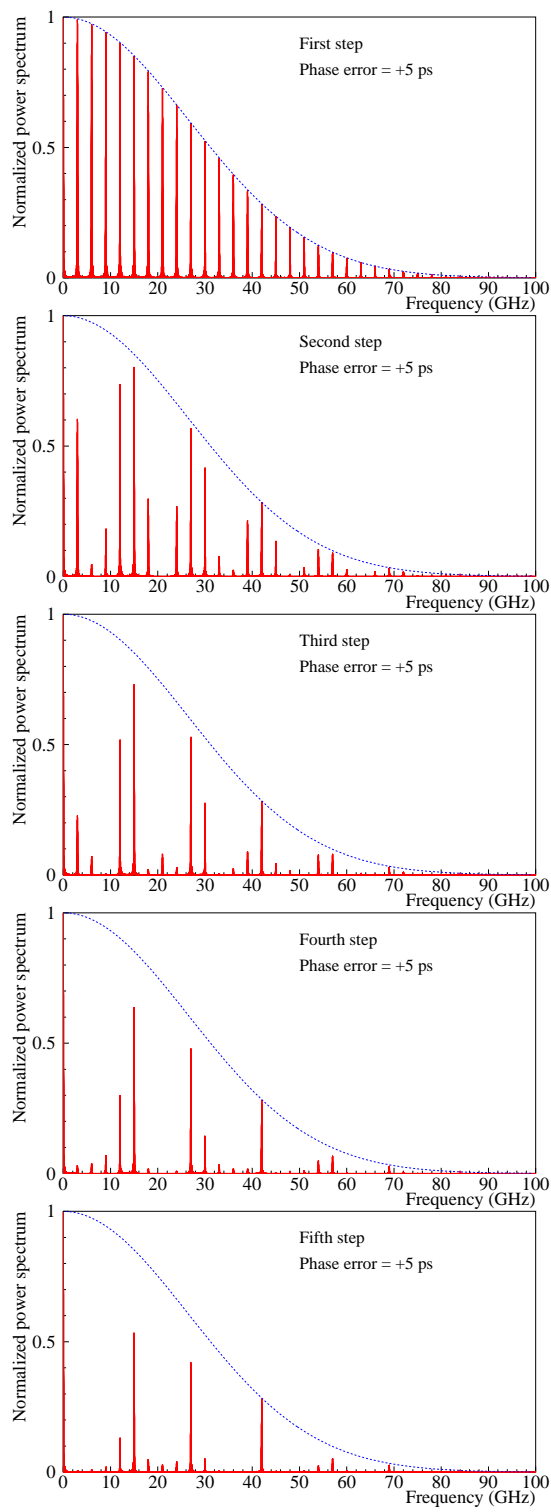
Figure 4: Same as in Figure 3, but with a phase error of +5 ps.

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The amplitude of the lines at 9, 12, 18 and 21 GHz has been compared to the amplitude of the line at 15 GHz, for various values of the phase error. The larger the phase error, the larger the relative amplitudes of some harmonics of 3 GHz which are not harmonics of 15 GHz (see Figure 5).
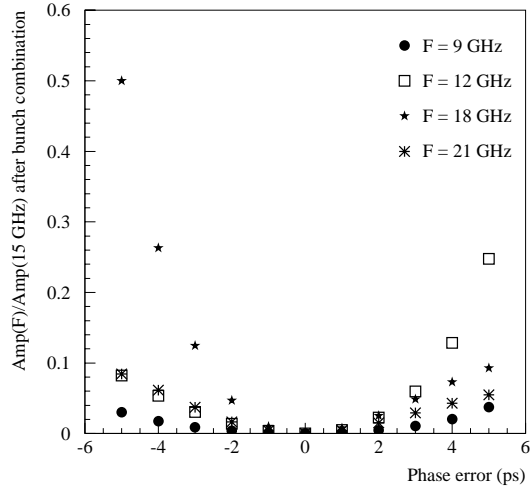

Figure 5: Relative amplitudes of the harmonics at 9, 12, 18 and 21 GHz with respect to the harmonic at 15 GHz at the end of the bunch frequency multiplication process, as a function of the phase error.

We observed that the distorsion of the power spectrum due to a phase error at the injection becomes even more significant at frequencies higher than those considered here. However, the detection of signals at such frequencies does not seem trivial so, in the following of this study, we will focus on the frequency range between 9 and 21 GHz only.

3   Design of the RF pick-up

In this section, we discuss the performance of a coaxial RF pick-up. Since the current on the beam pipe wall have a large peak value, the amplitude of the detected signals is not a limitation in the design of the pick-up. Its transfer impedance can thus remain rather small, which insures that one detects the electromagnetic field produced by the electron bunches without significantly disturbing the beam.

3.1   Estimation of the pick-up transfer impedance

The geometry of the pick-up that we consider in the following is shown in Figure 6. The ratio between the inner conductor radius and the outer conductor radius must remain equal to 2.3 all along the pick-up in order to have an impedance of 50 Ω. One also needs to make sure that only the TEM mode propagates in the coaxial pick-up, and that

high-order TE and TM waveguide modes are evanescent in the frequency range of interest (between 9 and 21 GHz). In order to avoid the propagation of the lowest-order waveguide modes up to 24 GHz, the radius of the inner conductor must be kept smaller than 1.2 mm.
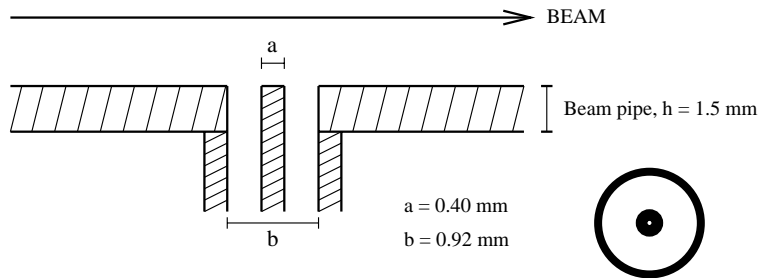

Figure 6: Coaxial RF pick-up designed to detect the electromagnetic field of electron bunches in the CTF3 preliminary phase.

The electromagnetic fields excited in the coaxial line by the passage of an electron bunch through the beam pipe can be calculated by solving Maxwell's equations numerically with MAFIA [2]. This program computes the amplitude of the various modes in the coaxial line. In MAFIA, the amplitude of a mode is defined as the square root of the associated electromagnetic power. Figure 7 shows the time variation of the TEM mode amplitude in the coaxial line when one gaussian electron bunch with a charge of 0.1 nC and with a fwhm length of 10 ps travels on a straight trajectory at the center of a rectangular beam tube which has the following dimensions: $\Delta x = 10$ cm and $\Delta y = 4$ cm.
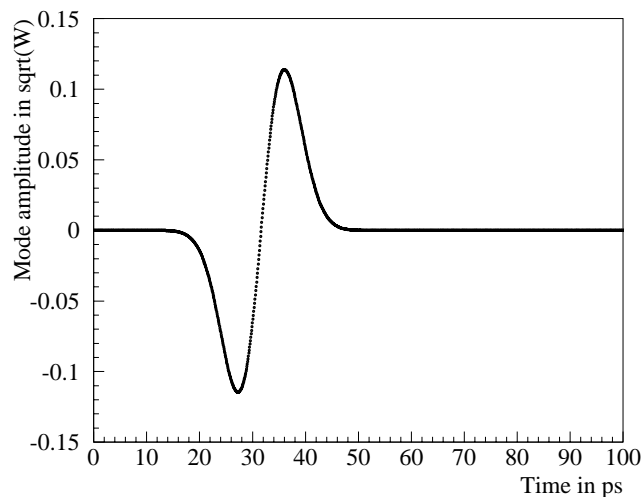

Figure 7: Time variation of the TEM mode amplitude in the coaxial pick-up, when excited by a bunch with a charge of 0.1 nC and with a fwhm length of 10 ps.

The voltage between the inner and outer conductors of the coaxial pick-up is:

$$V = \sqrt{R} \times \text{Mode amplitude,}$$

where $R = 50 \ \Omega$ is the impedance of the coaxial line.

The transfer impedance Z_{tr} is then computed by calculating the ratio between the Fourier transform of V and the Fourier transform of the beam current. Figure 8 shows how Z_{tr} varies with the frequency.
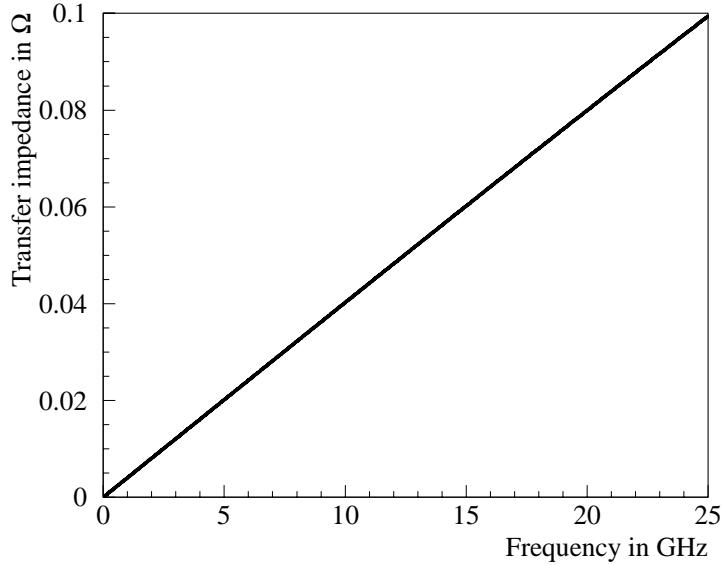

Figure 8: Transfer impedance of the coaxial pick-up.

In the CTF3 preliminary phase, one pulse consists of either 20 bunches spaced by 333 ps when injected into the EPA isochronous ring, or 100 bunches spaced by 67 ps at the end of the frequency multiplication process. The time response of the pick-up is thus the convolution of the time response for one single bunch with a train of Dirac pulses. As a result, the power spectrum in the coaxial pick-up can be calculated as follows:

$$P(f) = \left(\frac{|Z_{tr}(f)| \times I_b(f)}{\sqrt{R}} \right)^2 \times \left[\left(\sum_{i=1}^{N_b} cos(2\pi f \tau_i) \right)^2 + \left(\sum_{i=1}^{N_b} sin(2\pi f \tau_i) \right)^2 \right],$$

where N_b is the number of bunches in the train and τ_i is the position of the bunch i in the train.

The left-hand side plot of Figure 9 shows the power spectrum excited by one bunch train in the coaxial pick-up, for the 8 - 22 GHz frequency range, before the pulse compression (20 bunches spaced by 333 ps). If there is no phase shift at the injection, only the

harmonics of 15 GHz remain in the power spectrum excited by a train of 100 bunches spaced by 67 ps. The right-hand side plot of Figure 9 displays the shape of the peak at 15 GHz after the pulse compression.
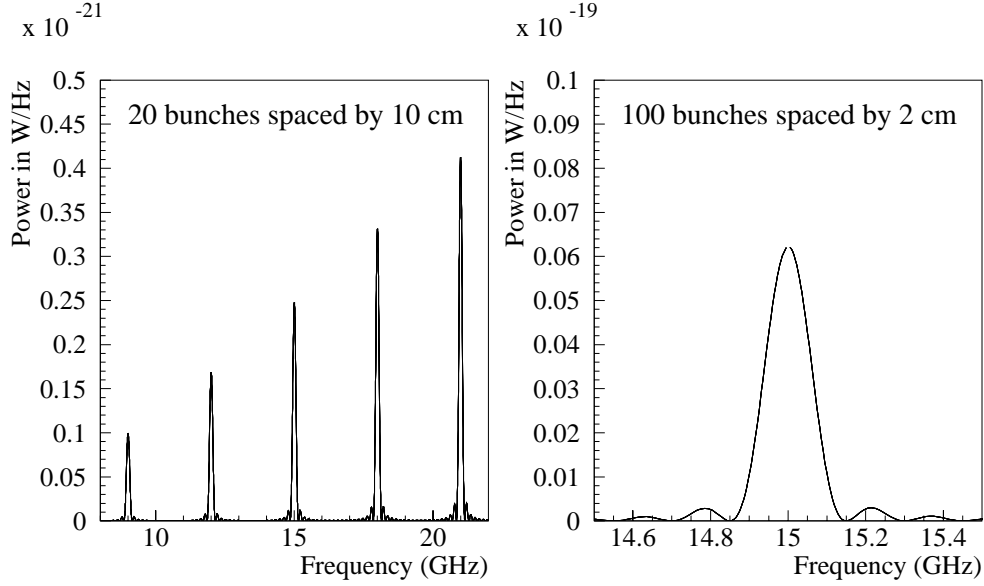

Figure 9: Power spectrum in the pick-up for the 8 - 22 GHz frequency range, before the pulse compression (left-hand side plot) and power spectrum around 15 GHz after the pulse compression when no phase shift is introduced (right-hand side plot).

Each of the peaks in the power spectrum can be expressed as follows:

$$P_i(f) = A_i^2 \times \left(\frac{sin\pi\delta t[f - f_i]}{\pi\delta t[f - f_i]} \right)^2,$$

where $\delta t = 6.6$ ns is the length of the electron bunch train.

When taking the inverse Fourier transform of $\sqrt{P_i(f)}$, one obtains:

$$\sqrt{P_i(t)} = \begin{cases} \dfrac{A_i}{\delta t} \times exp(j2\pi f_i t) \text{ if } |t| < \dfrac{\delta t}{2}, \\ \\ 0 \text{ otherwise.} \end{cases}$$

The mode amplitude in the pick-up is thus the superposition of pulses with a length $\delta t = 6.6$ ns and with an amplitude $A_i/\delta t$, oscillating at a frequency f_i. For each harmonic of interest, the amplitude of the current pulse is given in Table 1, at each stage of the bunch frequency multiplication process.

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Stage of the	Current (in mA) for each harmonic f_i				
pulse compression	9 GHz	12 GHz	15 GHz	18 GHz	21 GHz
1	0.21	0.28	0.34	0.39	0.44
2	0.13	0.45	0.68	0.63	0.27
3	0.13	0.45	1.02	0.63	0.27
4	0.21	0.28	1.36	0.39	0.44
5	0	0	1.70	0	0

Table 1: Amplitude of the current pulse coming out from the coaxial pick-up, for each harmonic of interest, at various steps of the pulse compression.

3.2 Pick-up response vs geometrical parameters

Other possible designs have been considered for the coaxial pick-up, with an inner radius a varying between 0.2 mm and 1.2 mm, the outer radius b being always 2.3 times larger than a in order to keep a characteristic impedance of 50 Ω. In order to estimate the power spectrum as a function of the pick-up size, one first needs to compute the variations of the transfer impedance $Z_{tr}(f)$ with a, see Figure 10.
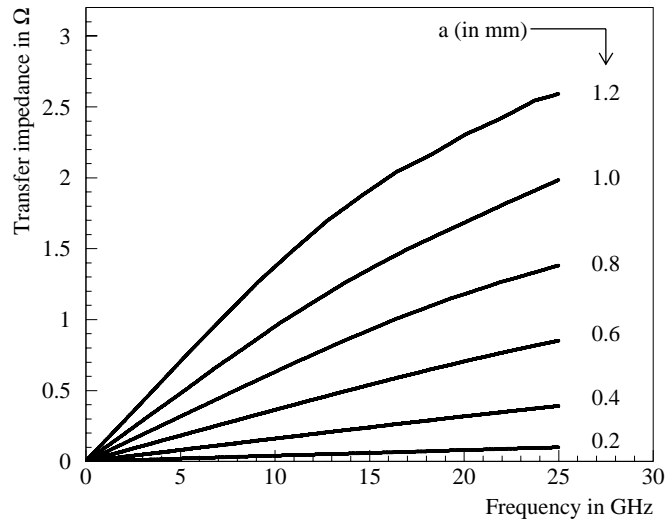

Figure 10: Transfer impedance as a function of the pick-up size.

Table 2 (respectively Table 3) gives the amplitudes of the current pulses flowing in a coaxial pick-up with an inner radius of 0.6 mm (respectively 1.0 mm), for each harmonic of interest, at each stage of the pulse compression.

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Stage of the	Current (in mA) for each harmonic f_i				
pulse compression	9 GHz	12 GHz	15 GHz	18 GHz	21 GHz
1	1.87	2.48	2.99	3.40	3.79
2	1.16	3.98	5.98	5.49	2.33
3	1.16	3.98	8.97	5.49	2.33
4	1.87	2.48	11.96	3.40	3.79
5	0	0	14.95	0	0

Table 2: Same as Table 1, but the inner radius of the coaxial pick-up is 0.6 mm.

Stage of the	Current (in mA) for each harmonic f_i				
pulse compression	9 GHz	12 GHz	15 GHz	18 GHz	21 GHz
1	5.08	6.61	7.80	8.65	9.42
2	3.14	10.62	15.60	13.98	5.78
3	3.14	10.62	23.40	13.98	5.78
4	5.08	6.61	31.20	8.65	9.42
5	0	0	39.00	0	0

Table 3: Same as Table 1, but the inner radius of the coaxial pick-up is 1.0 mm.

3.3 Pick-up response vs beam parameters

In the following, we study the influence of the beam characteristics on the signal coming from the pick-up. For this purpose, we consider the geometry shown in Figure 6, i.e. an inner diameter of 0.4 mm and an outer diameter of 0.92 mm for the coaxial line.

3.3.1 Pick-up response vs bunch length

So far, we have only considered electron bunches with a fwhm length of 10 ps. Here, other bunch lengths have been considered as well. The left-hand side plot of Figure 11 shows that the mode amplitude flowing in the coaxial pick-up strongly depends on the length of the bunch producing the excitation. However, we do not measure time signals with our monitor. As a result, one has to estimate the influence of the bunch length in the frequency domain. The right-hand side plot of Figure 11 shows that the influence of the bunch length on the amplitudes of the harmonics coming out from the pick-up increases with frequency.

Therefore, by measuring the amplitudes of the currents at 9, 12, 15, 18 and 21 GHz before the pulse compression, one may be able to derive the electron bunch length. However, a more efficient and precise method would consist in measuring the amplitudes of all the harmonics of 15 GHz at the end of the pulse compression (after making sure that there is no phase shift during the injection). However, such a method would require the use of an instrument which is sensitive to much higher frequencies than those measured by the monitor described in this paper.
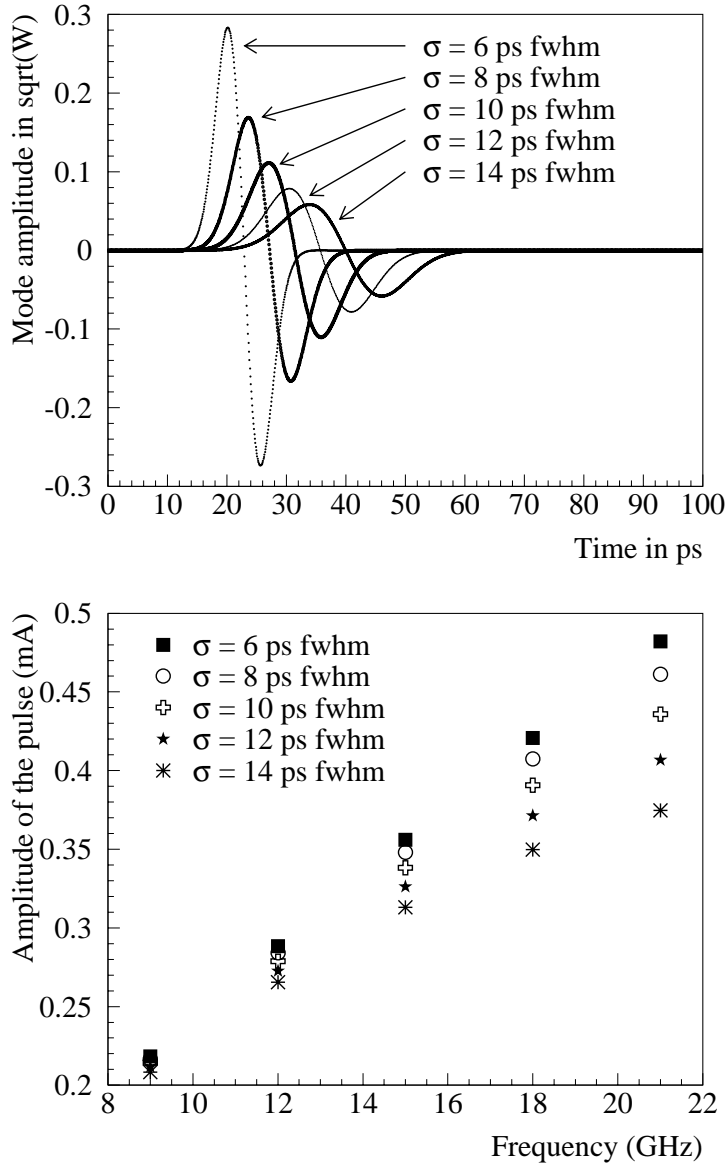
Figure 11: Time variation of the TEM mode amplitude in the coaxial pick-up, when excited by a bunch with a charge of 0.1 nC, for various fwhm lengths (upper plot). Amplitude of the current coming out from the coaxial pick-up as a function of the bunch length, for each harmonic of interest in the 8 - 22 GHz frequency range, before the pulse compression (lower plot).

3.3.2 Pick-up response vs beam position

The signal coming out from the pick-up depends on the transverse position of the bunches in the beam pipe (see Figure 12). Several simulations were thus performed in order to determine how the amplitudes of the detected harmonics change when the beam does not travel at the center of the tube, see Figure 13.
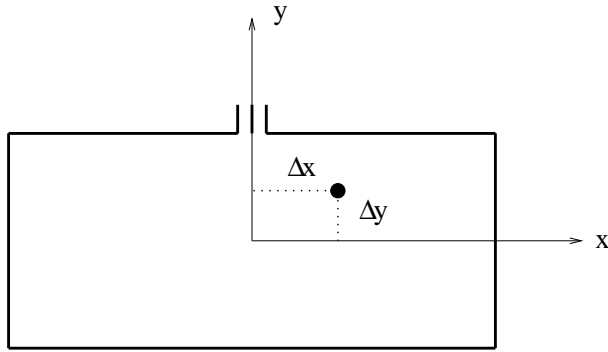
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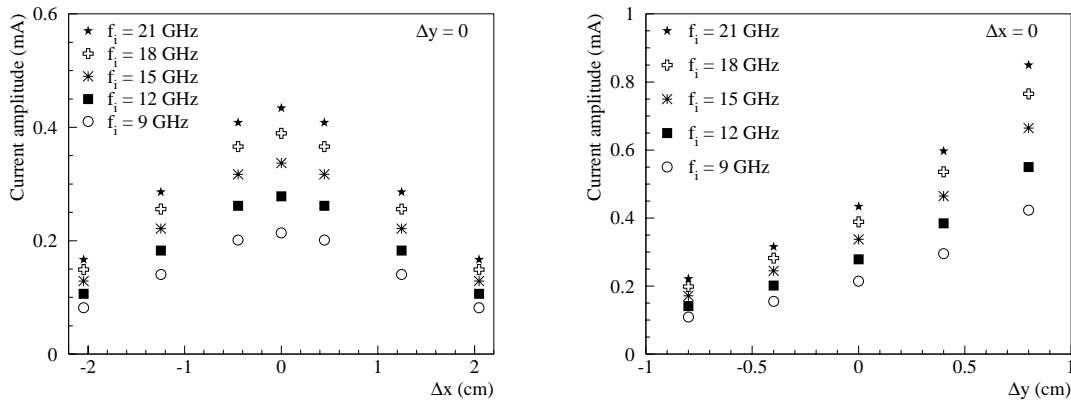Figure 12: Off-center electron bunch in the CTF3 beam pipe.

Figure 13: Variation of the amplitudes of the harmonics coming out from the pick-up with the transverse position of the beam. These simulations were performed before the pulse compression (20 bunches spaced by 10 cm).

The ratios between the amplitudes of the various harmonics do not depend on the transverse position of the beam, in contrary to what occurs when one varies the bunch length. As a result, even if the beam is not at the center of the pipe, one can still monitor the bunch frequency multiplication process by comparing the relative amplitudes of the harmonics at 9, 12, 15, 18 and 21 GHz.

3.3.3 Pick-up response vs phase shift at the injection

A detailed study of the effect of a phase shift during the injection of the electron bunches in the EPA ring was performed in the previous section and will not be reproduced here. The distorsion of the beam power spectrum by a phase shift can be observed by comparing the amplitudes of the various harmonics of interest at the pick-up output, during or at the end of the pulse compression, as shown in Figure 14.
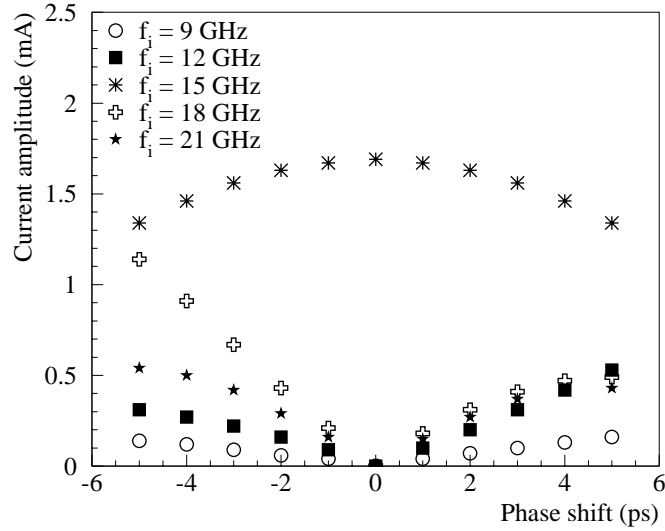
Figure 14: Amplitudes of the harmonics at 9, 12, 15, 18 and 21 GHz in the coaxial pick-up at the end of the bunch frequency multiplication process, as a function of the phase error.

3.4 Study of the feedthrough

In order to transport the RF signals from the coaxial pick-up to the detection system, a miniature ultrahigh vacuum feedthrough [3] is used, see Figure 15. The feedthrough can be considered as a two dielectric coaxial line (for Al_2O_3, one has $\epsilon_r = 9.5$), for which an adaptation to 50 Ω can be achieved over more than half the length of the feedthrough. The distance over which the characteristic impedance differs from 50 Ω is of the order of 1 mm, thus much smaller than the wavelengths of the signals that we want to monitor.
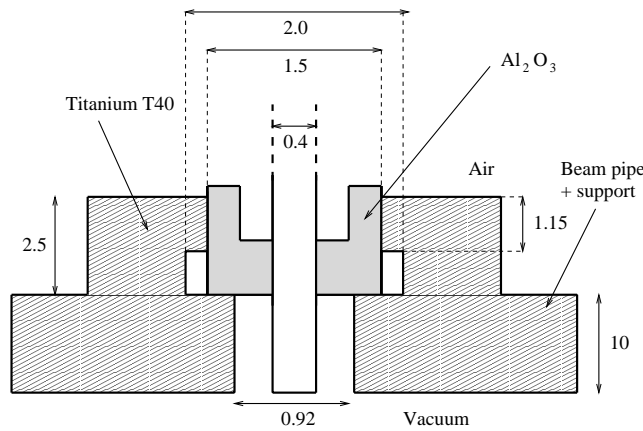

Figure 15: General layout of the miniature ultrahigh vacuum feedthrough used to extract the RF signals (all distances are given in mm).

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In order to connect the feedthrough to the detection system, it is terminated by a Radiall K 46 GHz connector. The diameter of the innermost and outermost conductors are respectively 0.9 mm and 2.5 mm. This coaxial line is filled with a dielectric made of air and kapton, for which the dielectric constant is $\epsilon_r = 1.5$.

The transfer function of the two port system consisting of the feedthrough and the K connector has been estimated with MAFIA for the five frequencies of interest, see Table 4. More than 95% of the current flowing in the pick-up should be transmitted to the detection system, via the feedthrough and the K connector.

Frequency (GHz)	Power loss (dB)
9	0.4
12	0.5
15	0.5
18	0.4
21	0.3

Table 4: Power loss in the miniature ultrahigh vacuum feedthrough terminated by a Radiall K 46 GHz connector, as a function of frequency.

4   Design of the detection system

The signal coming out from the coaxial RF pick-up is a superposition of pulses, at various frequencies f_i and with various amplitudes A_i. Only the harmonics which are multiples of either 3 GHz or 15 GHz are present in the beam frequency spectrum. In this study, we are only interested in detecting the harmonics at 9, 12, 15, 18 and 21 GHz. The instrumentation that we propose to use for this purpose is shown in Figure 16.
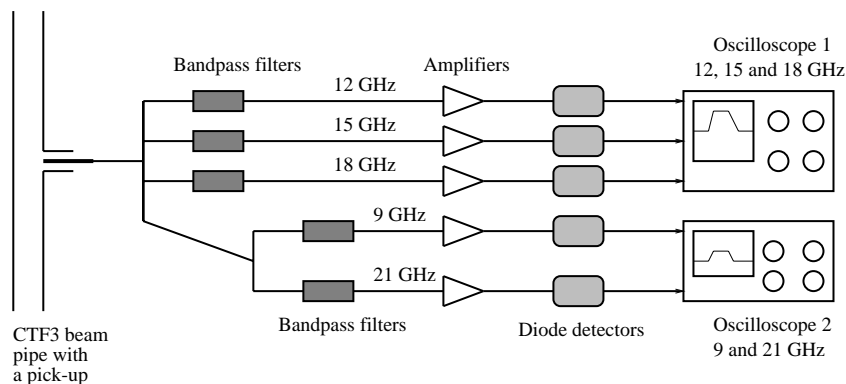

Figure 16: General layout of the instrumentation used to analyse the signals downstream of the coaxial RF pick-up.

The signal coming from the pick-up is divided into five channels, by using two power splitters. Each of these channels is terminated by a bandpass filter, in order to select the harmonic of interest while suppressing the signals coming from the other harmonics. For the filter at 21 GHz, the bandwidth at 3 dB is 2.1 GHz. For the four other channels, two types of filters will be considered. In the first case, the bandwidth Δf is 2% of the nominal frequency f_0, which allows a good selection of the harmonic of interest: if $f = f_0 \pm 3$ GHz, the attenuation is about 70 dB. However, the rise time of a bandpass filter is $1/\Delta f$, i.e. 5.6 ns for the filter at 9 GHz and 2.8 ns for the filter at 18 GHz. Since we want to measure a pulse length of 6.6 ns, another set of filters with a shorter rise time was also considered, with a bandwidth of 1 GHz, i.e. a rise time of 1 ns only. After the bandpass filter, each signal is sent through a low noise amplifier, in order to increase the signal to noise ratio as much as possible upstream of the wideband diode detectors. Two types of amplifiers will be used. For the channels corresponding to 9, 12, 15 and 18 GHz, the bandwidth at 3 dB is 6 - 18 GHz. For the harmonic at 21 GHz, it is 18 - 26 GHz. Each detection line is terminated by a diode detector with a sensitivity of about 200 mV/mW. The signals coming from the detector diodes are measured with two fast multi-channel digital oscilloscopes.

The output signals read on the oscilloscopes can be directly related to the amplitude of the pulses coming from the pick-up, when the transfer function of the detection system is known. For this purpose, calibration measurements will be performed at Uppsala University before the installation of the pick-up and its instrumentation in CTF3.

5   Conclusion and outlooks

In this note, we presented the design of a bunch phase monitor for the CTF3 preliminary phase. It consists of a small coaxial pick-up, with an inner radius of 0.2 mm, placed in the EPA beam pipe and connected to a miniature ultrahigh vacuum feedthrough. The frequency response of this pick-up has been estimated with MAFIA simulations, for five harmonics of interest: 9, 12, 15, 18 and 21 GHz. By measuring their relative amplitude at each stage of the bunch frequency multiplication process, one can accurately monitor the pulse compression and even detect phase errors during the injection.

We have used a combination factor of five for these simulations, but the bunch phase monitor can also be used with other combination factors. If $N = 3$ (respectively 4), only the harmonics at 9 and 18 GHz (respectively at 12 GHz) should remain at the end of the bunch frequency multiplication. The presence of other harmonics would indicate a phase error during the injection.

Before the commissioning of the bunch phase monitor with beam in CTF3, it is necessary to measure the transfer function of the detection system for all the harmonics of interest. The MAFIA simulations for the pick-up and the feedthrough should also be checked with an appropriate testbench set-up. These tasks will be performed at Uppsala University and will be documented in a future note.

Acknowledgements

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