Libera Single Pass H
Evaluation Measurements at ESS

Manuel Cargnelutti, April 21st 2014, Lund (SE)

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1. Introduction

The aim of the document is to describe the measurements performed at the European Spallation Source (ESS) with Libera Single Pass H, an instrument intended for phase, position and charge monitoring in hadron and heavy ion LINACs. The device measurements are based on the analysis of two frequency components (first and second) of the RF signals induced by the beam on the BPM pickups.
The document is organized as follows: Chapter 2 introduces the BPM system foreseen for the ESS linac, discussing their operating conditions, expected signal levels and the performance requirements from the BPM electronics. Chapter 3 describes Libera SPH configuration according with the ESS parameters. In Chapter 4, a background on measurements theory and the most important parameters is given, as well as a description about how they are evaluated. Chapter 5 and 6 present the achieved results, entering in details on the test setups and conditions. Chapter 7 describes the procedure and the results achieved measuring the Interlock signal response time. Chapter 8 summarizes the results and draws the conclusions of the measurements.

Background:
- Libera SPH background information (more here)
- ESS facility (more here)

1.1 Two different approaches

In order to evaluate the performance of an instrument that elaborates the RF signals coming from the accelerator BPMs, it is necessary to simulate such signal conditions. Without signals coming directly from the accelerator, this is possible in at least two ways, and both have been considered and are described in this document:

1. Splitting the RF signal. Starting from a suitable RF signal, it is possible to generate four instrument inputs just splitting it (i.e. using a 4-way splitter). By controlling the properties of the signal (harmonic components, power level, attenuations on each instrument input, etc..) it is possible to simulate several conditions that are foreseen in the accelerator according with beam current, position displacement, etc..

2. Using a BPM test-bench. A reliable way to simulate the signals coming from the real accelerator is to use a wire that passes through a model of the beam pipe, where a BPM is located. In this way the instrument inputs are coming directly from the BPM pickups.

The first solution is general and characterize the instrument regardless of the BPM and the pickups used to get the RF signals. If one has a model that puts in relation the beam characteristics (current, beta-factor, position, etc..) the BPM characteristics (geometry, pickup size and capacitance, etc..) with the expected output RF signal, then providing such an expected signal to the instrument is a reliable way to simulate the situation and get useful information.
The second approach is optimal for evaluating how the whole system (beam pipe+BPM+Electronics) works together. Furthermore, only in this case is possible to evaluate the beam position accuracy of the instrument, since with a simple slit it is possible to move the wire within the pipe and check the measured position.

2. ESS beam position monitors

This chapter introduces the ESS LINAC, focusing on the expected beam parameters, the BPM characteristics and and the requirements for the electronics readout system. Different types of beam position monitors will be used in the machine, here the focus is on the button BPMs.
The aim of this analysis is to define which are the signal levels that are expected at the instrument input according with all the influent parameters. With this information, as mentioned in point 1 - Section 1.1, it is possible to define the RF signals and their dynamic range for the measurements with Libera SPH.
ESS has also designed and assembled a BPM test bench with 60mm pipe, a BPM and an horizontal moving slit. This will be described in Section 2.3.

2.1. Accelerator parameters

The ESS LINAC BPM system is described in details in [1]. Some of the accelerator parameters that are useful for the understanding of the whole system are presented in Table 1.

Parameter	Value	Unit
Max Energy	2	GeV
Pulse repetition rate	14	Hz
Pulse duration	2.86	ms
Max pulse current (nominal)	62.5	mA
Longitudinal bunch size (1σ)	2-3	mm
RF frequency	352.21 and 704.42	MHz

Table 1: ESS LINAC operating conditions

An important thing to note is that even though the RF frequency is supposed to change from 352.21 MHz in the warm LINAC to 704.42 MHz in the super-conductive LINAC, the bunch repetition rate will remain 352.21 MHz in both sections. This means that the first harmonic component of the BPM RF signals will always be 352.21 MHz, the second at 704.42 MHz and so on...
The beam pattern will be organized in periodic pulse structures with 14 Hz repetition frequency. Within each structure, the pulse will have a duration of 2.86 ms. The pulse duration defines also the number of meaningful samples that the instrument will provide.

The next table presents some other parameters related to the BPM detectors and the requirements for the BPM electronics.

Parameter	Value	Unit
Position measurement accuracy	100	μm
Position measurement resolution	20	μm
Phase measurement accuracy	1	deg
Phase measurement resolution	0.2	deg
Phase measurement range	+/- 180	deg
Beam pipe diameter	60, 100	mm
Meas. radius wrt beam pipe	50	%
BPM cable length	~60	m
Electronics response time	1-2	μs
ADC sample rate	50-100	MSa/s
ADC bit number	16	bits

Table 2: BPM detector and electronics requirements

2.2. Button BPMs operating conditions

From Table 2 it 's evident that two different beam pipe diameters (and so two different button BPMs) will be used: the first one has 60 mm diameter and the second has a 100 mm diameter.
Among the factors which influence the BPM output RF signals, we can list the most important ones:

- geometry (physical dimensions, shape)
- button diameter
- button capacitance
- beam current
- β-factor (related to the speed of the particles)
- beam position

From the models and simulations done by ESS it is possible to know what are the levels foreseen at the instrument input for both BPMs, and evaluate the influence of the parameters listed above. Of course in this analysis there are many degrees of freedom, but from the operative point of view only the maximum and minimum power levels are needed.
When presenting the numbers, two different scenarios will be distinguished depending on the beam position:

1. Centered beam: if the beam is in the center of the pipe, all the four signals coming from the pickups have almost the same amplitude, as you can observe in Figure 1, left picture.

2. Off-centered beam: the beam is expected to move within a radius which is in the worst case half of the pipe radius. In this condition the amplitude of the four signals is not the same, and the signal from the pickup closer to the beam will be stronger than the one from the opposite pickup – see Figure 1, right picture. This situation is simulated with a different setup and a different dynamic range is covered.

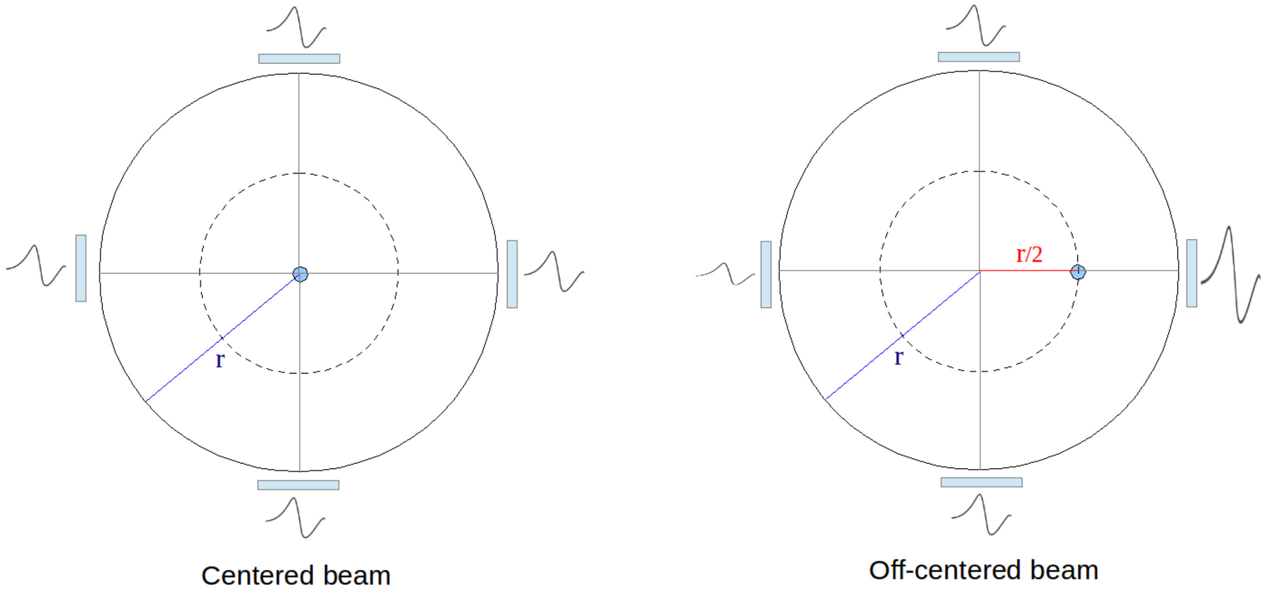


Figure 1: Beam position scenarios for the evaluation of the BPM signals

2.2.1 60 mm BPM

This BPM will be installed in the spokes section of the linac. Its main parameters and operation conditions are reported in Table 3:

Parameter	Value	Unit
BPM diameter	60	mm
Button diameter	24	mm
Button capacity	5.2	pF
β-factor range	0.41 – 0.56	
Beam current range	6.25 - 62.5	mA

Table 3: Parameters and operating conditions of the 60 mm BPM

Considering a centered beam, the condition in which the buttons output is higher is when the current is maximum and the β-factor minimum. In the same way BPM output is minimum when the current is at the minimum and the β-factor maximum. Table 4 presents the numbers gathered from the analytical models.

Parameter	min	max
output level @ 352.21 MHz	-27.83 dBm	- 5.12 dBm
output level @ 704.42 MHz	-25.41 dBm	-2.7 dBm

Table 4: Output levels expected from the 60 mm BPM – centered beam

In the case an off-centered beam with a displacement of half of the radius is considered, the maximum expected level gains 8.72 dB and the minimum level loses 8.72 dB. This is a linear estimation for the BPM output power dependency on the position, and Table 5 presents the expected levels.

Parameter	**min** (lowest input)	**max** (highest input)
output level @ 352.21 MHz	-36.55 dBm	3.6 dBm
output level @ 704.42 MHz	-34.14 dBm	6.02 dBm

Table 5: Output levels expected from the 60 mm BPM – 50% pipe radius displacement

2.2.2 100 mm BPM

This BPM will be installed after the spokes section, in the super-conductive part of the linac. Its main parameters and operation conditions are presented in Table 6:

Parameter	Value	Unit
BPM diameter	100	mm
Button diameter	40	mm
Button capacity	5.2	pF
β-factor range	0.57 – 0.95	
Beam current range	6.25 - 62.5	mA

Table 6: Parameters and operating conditions of the 100 mm BPM

In the same way it is possible to evaluate the foreseen signal levels in case of centered beam:

Parameter	min	max
output level @ 352.21 MHz	-27.98 dBm	- 3.55 dBm
output level @ 704.42 MHz	-25.56 dBm	-1.13 dBm

Table 7: Output levels expected from the 100 mm BPM – centered beam

Similarly, considering the case of half of the radius displacement, the maximum level expected will gain 8.72 dB and the minimum will loose 8.72 dB. This is a linear estimation for the BPM output power dependency on the position, and Table 8 presents the expected levels.

Parameter	**min** (lowest input)	**max** (highest input)
output level @ 352.21 MHz	-36.7 dBm	5.17 dBm
output level @ 704.42 MHz	-34.28 dBm	7.59 dBm

Table 8: Output levels expected from the 100 mm BPM – 50% pipe radius displacement

2.2.3 100 mm BPM with de-bunched beam

During the commissioning there will be a need to measure a low-current debunched beam (check the article for more details). In this case the second harmonic frequency component will disappear, while for the first one a further attenuation up to 70 dB is expected.

This pushes the lower limit of the input power until -100 dBm, a level which is out of the Libera SPH operating range, and it is also below the noise floor measured with the spectrum analyzer. Anyway an evaluation of the position measurements at very low signal input levels will be presented in Section 6.3.

2.2.4 Conclusions

Now that all the possible cases are evaluated, it is possible to estimate the input signal levels that should be provided to the instrument to cover all the operating conditions. With the results that will be presented, one will be able to have the complete picture of the instrument performance.

Centered beam:

- First harmonic ranges from -3.55 dBm to -27.98 dBm
- Second harmonic ranges from -1.13 dBm to -25.56 dBm

50% Off-Centered beam:

- First harmonic ranges from 5.17 dBm to -36.7 dBm
- Second harmonic ranges from 7.59 dBm to -34.28 dBm

NOTE 1: in the case of off-centered beam the minimum power level refers to the instrument input which belongs to the pickup which is more distant from the beam. According with Figure 1, the other inputs will have a higher signal level, in particular the two pickups in the middle will have 8.72 dB more and the one close to the beam will have 17.44 dB more. The same consideration is valid in case of the maximum power level: this is referred to the more powerful signal, and the others have a lower power.

NOTE 2: All these numbers consider also the losses in the cables from the BPM to the place where the instruments are supposed to be installed in the facility.

2.3. ESS BPM test-bench

A first BPM test bench has been designed and manufactured at ESS. It consists of a 60mm beam pipe section with a button BPM in the middle – see Figure 2. The size of the buttons is 16 mm, which is not the size foreseen for the final version (24 mm). The beam is simulated with a 0.5 mm copper wire that passes throughout the pipe, terminating on a BNC connector on both sides: one will be used as an input port, the other is terminated to a 50 Ohm load – see Figure 3. The BNC connectors are fixed to two side-panels which are screwed to the steel ground floor. The pipe and the BPM are mounted on a moving support which is electrically in contact with the side panels and the ground floor.

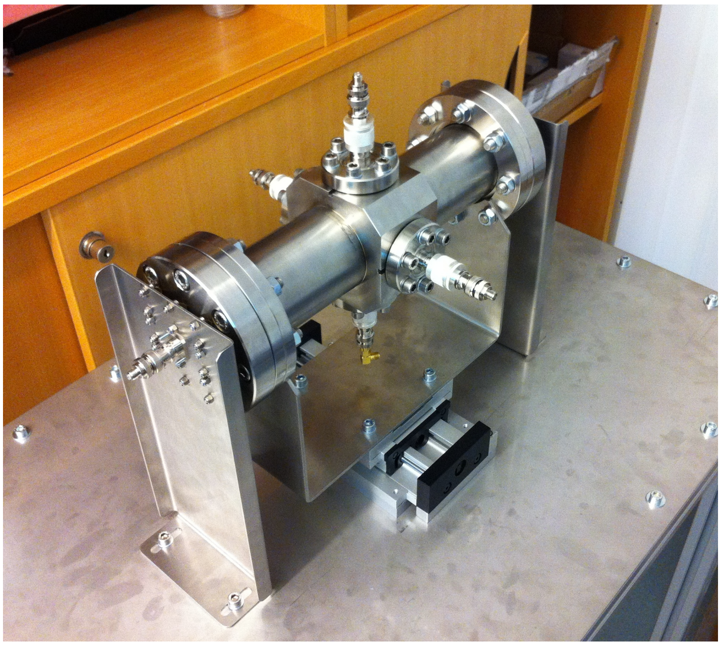


Figure 2: BPM test bench

This support is provided with an horizontal slit – see Figure 2 – which enables the movement of the pipe along the horizontal axis. The slit has a resolution of 50 micrometers and a range which is enough to move the wire within half of the pipe radius (+/- 15 mm).

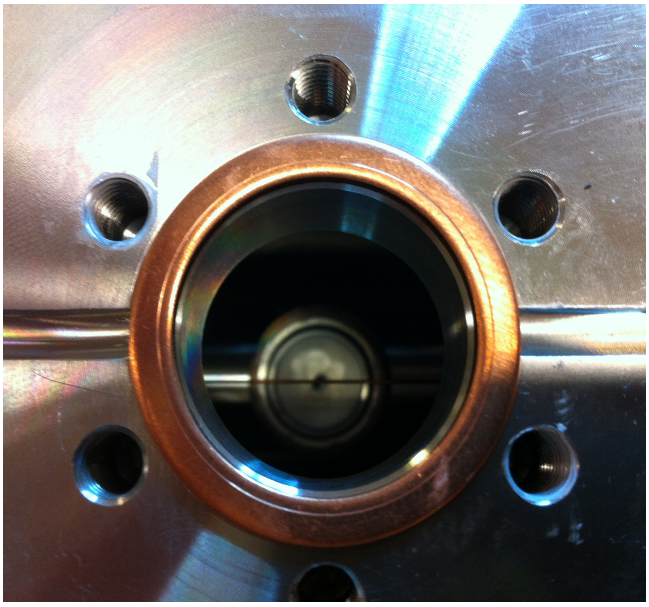


Figure 3: The wire passing through the BPM

Even if this is not the final model, such a test bench can be extremely useful to perform the position measurements with Libera SPH. Upon calibration, it is possible to evaluate the position resolution and accuracy as well as characterizing the BPM linearity.

3. Libera SPH configuration

This chapter describes the configuration of the Libera SPH unit used to perform the measurements at ESS. **It is worth mentioning that the RF front-end of the BPM board was not changed for the purposes of the measurements at the ESS**. The bandwidth of the instrument is limited to 700 MHz by the filters in the RF front-end and by the ADCs, meaning that the second harmonic at 704 MHz is attenuated more (around 10 dB). With a proper customization according with ESS operating conditions, much better results are expected.

3.1. Sampling frequency and data rates

In order to optimally separate the frequency components after the down-conversion, the ADCs sampling frequency is set to 125 MHz. This implies that the raw ADC signal is provided at **125 Msample/s**

Regarding the configuration of the SPH signal, (the one delivering position, phase, amplitude, etc...) the decimation is set to 125. Decimation specifies how many ADC samples are used to calculate every SPH signal sample. According to this, the SPH signal is delivered with the rate of **1 Msample/s**.

3.2. Macro-pulse windowing

From ESS specifications, the beam is characterized by macro-pulses of the duration of 2.86 ms which are repeated with a 14 Hz frequency. Each macro-pulse will then generate 357500 ADC samples – see Figure 4.

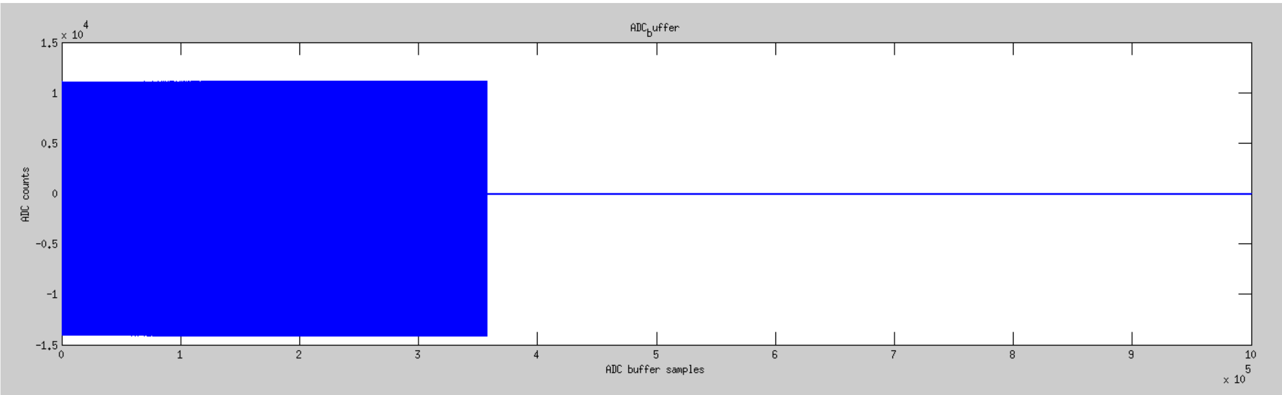


Figure 4: Macro-pulse signal acquired from the instrument ADCs

The instrument is configured to process only the ADC samples which belong to the macro-pulse for phase and position calculations. Considering the signal rates, this means that for each macro-pulse, 2860 SPH signal samples are available. Each SPH sample consists of signals amplitudes, positions and phases for both harmonics and time-stamp information.
In the performed measurements, up to 2000 samples are acquired from each pulse. In this way it is possible to simulate a gated signal even if the RF signal is not physically gated.

3.3. Instrument calibration

The instrument calibration is required for the position measurements: offsets and proportional constants can be set according with the specific BPM properties and reference position. This will be described in more details in Section 6.2.3.

For all the measurements without the test-bench, the calibration parameters were the default ones: offsets set to zero and proportional constants (sensitivity parameters) to 10mm. This is also presented in Table 9.

Parameter	Value	Unit
Sampling frequency	125	MHz
Decimation	125	
ADC signal rate	125	MSa/s
SPH signal rate	1	MSa/s
SPH samples acquired per macro-pulse	2000	Sa
Offset parameters (Ʊx, Ʊy)	0	mm
Proportional constants (kx, ky)	10	mm

Table 9: Libera SPH configuration parameters

4. Measurement definitions

This chapter introduces some measurement concepts that later on will be largely used in this document. In order to evaluate a measurement instrument, there are several parameters which provide specific information. Some of them are *Accuracy*, *Precision, Resolution* and *Stability*.
The purpose here is to describe how this parameters are evaluated, to make the reader understanding exactly what such parameters mean. To define them clearly, a little review was necessary. Particularly useful were articles [2-3] that introduce all three concepts referring to the ISO Guide 99 definitions.

4.1. Resolution

Resolution is defined as:

"*Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.*"

While quantities subject to measurement are inherently continuous, the instruments used to measure them are operating in the digital world, where the number of the values that can be assigned to the physical quantity depend on the number of bits of the ADCs. A limited range of possible values cannot cover the input continuous range, and this is known as "limits to resolution".

For these systems there are two factors that can limit the resolution:

1. The digitization process properties. If we have a reduced number of bits to encode each input value, the resolution will be limited since many different analog values will be mapped with the same digital value - Figure 5 gives a clear 2D example. Other factors as non linearities and missing ADC steps can locally influence it.

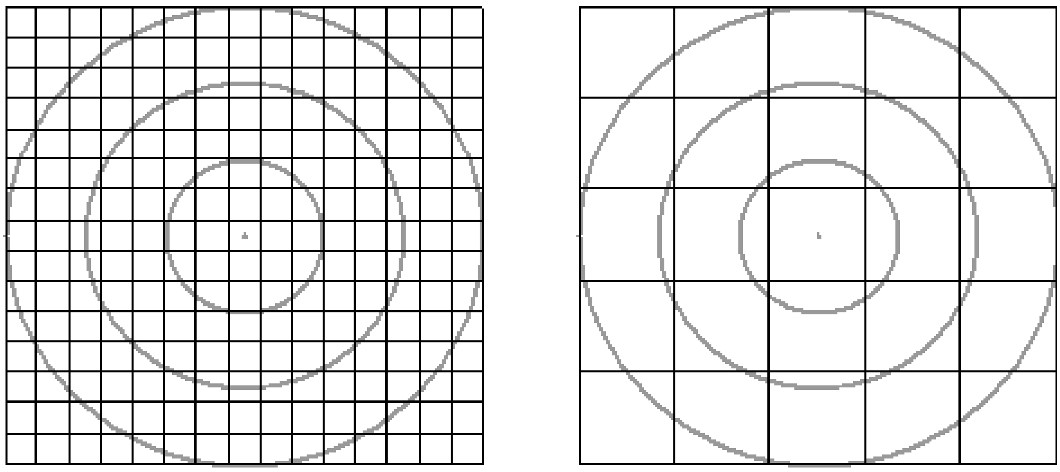


Figure 5: Resolution dependency on levels of digitization

2. Noise. If the physical quantity we want to measure is affected by noise, this will limit the measurement resolution. Noise can cover some low significant bits of the ADC samples, making them meaningless.

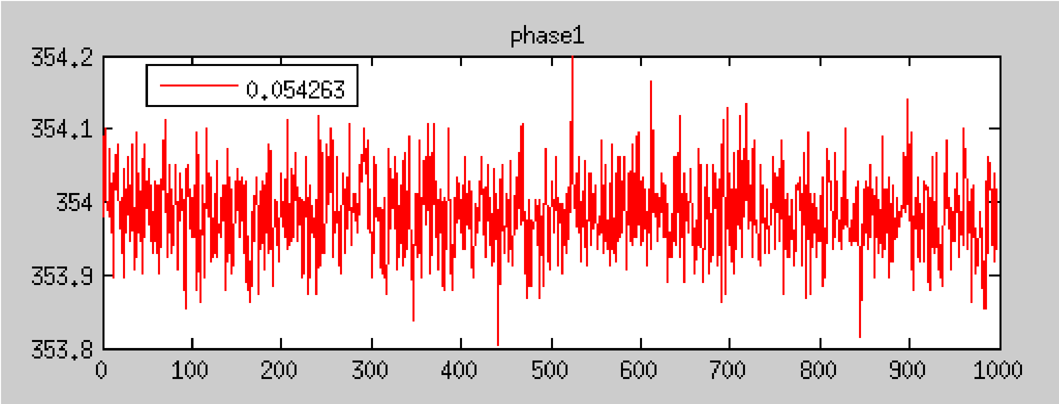


Figure 6: Resolution dependency on signal noise

Libera SPH provides data acquired through 16-bits ADCs. It is then possible to assume that the limiting factor for the resolution is the input signal noise.
The resolution of the measurements (position, phase, etc...) is evaluated considering the standard deviation of the samples acquired within one trigger acquisition. As described in Chapter 3, 2000 samples are acquired for each macro-pulse, and the standard deviation is calculated on this set of samples.

4.1.1 Factors which influence the resolution

The limiting factor for the resolution is the signal to noise ratio at the instrument inputs, so it is expectable that it will depend on the four inputs levels compared to the noise floor. Consequently, the resolution also depends on the beam position, since this will change the signal to noise ratio at the four inputs. On the other side, the phase of the BPM signals in relation with the reference signal will not influence the resolution.
Resolution is in principle not influenced by the number of considered samples, even though its value is less stable considering less samples.

4.2. Precision

Precision is defined as:

"*Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified condition*."

Basically this parameter indicates how repeatable is a measurement, repeated in defined conditions. A precise instrument will always give the same result, while a not precise one will provide measurements widely spread. Often precision is confused with accuracy, and Figure 7 is helpful to disambiguate these two concepts.

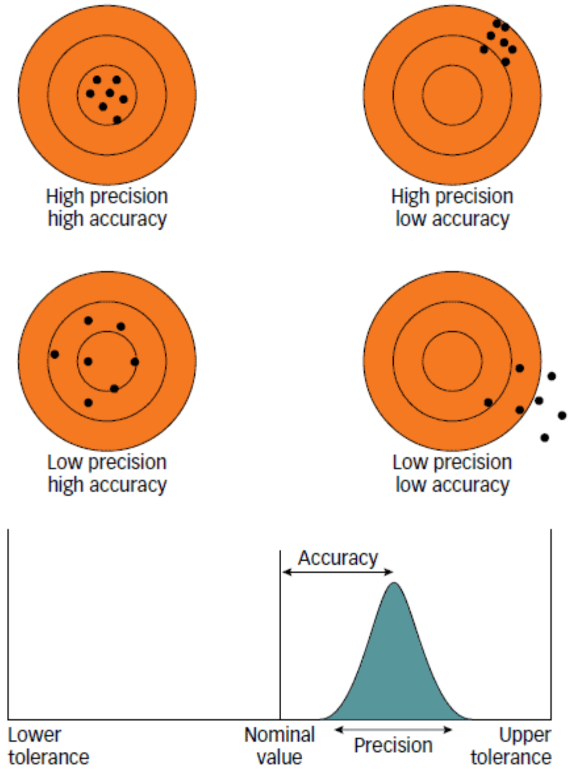


Figure 7: Precision and accuracy

Precision is evaluated acquiring data from different trigger events. 2000 samples are collected from every trigger event, and for each acquisition the mean value is calculated. This removes the noise contribution and provides one measurement per each trigger event.

Measurements are collected from 100 trigger events and can be considered as independent measures achieved in similar conditions. Finally, the precision is evaluated as the standard deviation of the 100 measurements. Consequently, it doesn't matter what is the value of these 100 acquisitions, but only how similar they are. The time needed for the acquisition is around a couple of minutes.

4.2.1. Factors which influence the precision

In principle the precision of the instrument should not be influenced by the signal it is measuring. Anyway, we should consider that when the signal-to-noise ratio degrades, we can expect a worse precision.

Precision can be influenced by the number of samples considered for each measurement: as the number of samples decreases, the noise is more and more influent and will start to affect the results.

Since the acquisition time is around two minutes, this parameter will not consider drifts due to changes in the environment conditions. This will be evaluated in long term tests.

4.3. Accuracy

The definition of accuracy is:

“*Closeness of agreement between a measured quantity value and a true quantity value of a measurand.*”

As Figure 7 shows, the accuracy tells how far are the instrument measurements from the real value of what one wants to measure. To evaluate it, data is acquired from a trigger event and 2000 samples are averaged to remove the noise influence and obtain one value. The accuracy is estimated as the difference between the measurement and the real value.

A big challenge in the accuracy estimation is **how to know the real value of the quantity we want to measure**. This is quite challenging for both phase and position measurements and will be described in Sections 5.1 and 6.2.5.

4.4. Stability and long-term stability

The idea behind stability measurements is to evaluate how a given measurement (in this case phase or position) is influenced by other factors, which can be the phase, position, input signal level but also temperature and time.
As an example, the evaluation of the stability of the position measurement against phase, answers the questions: “How much does the phase influence the position measurement? Does the position change upon a change in phase between reference and input signals?”. This evaluations don't involve long time and environment temperature changes.

Long-term stability on the other side is a measure of the instrument consistency over time. In principle the idea is to leave the instrument in one condition for a time which is relatively long compared to the other measures described so far, and to evaluate if and how much the measurements drift. Another factor to which the instrument is exposed to during long term tests is the temperature variation.
During the tests, the measures of the instrument are regularly evaluated, acquiring 2000 samples and considering the mean value of each acquisition. Temperature changes can be induced either by leaving the window open or changing the rotating speed of the instrument fans. It is evident that this is an extreme situation, in normal conditions the temperature drifts slowly and without influencing so much the electronics temperature.
The long term stability is evaluated as the maximum peak-to-peak deviation of the measures against time and temperature.

4.5. NOTE

All the definitions presented in this chapter apply both for the first and for the second input signal harmonics. This provides the information about the signals read from the instrument. Regarding the phase measurements with the second harmonic, please remember that if the measurements are used to evaluate the phase relation with the first harmonic, then all the measurements are divided by two.
Because of the linearity of the standard deviation, then also resolution and precision should be divided by two, as well as the error in the accuracy evaluation. **This means that considering the phase results on the second harmonic presented in this document, keep in mind that they should be divided by a factor of two.**

5. Measurements with 4-way splitter

This chapter describes all the phase and position measurements performed using a 4-way splitter to get the four instrument inputs. As discussed in Section 1.1, this approach is useful to evaluate the performance of the instrument with no influence from the BPM. Two setups are evaluated: a first one to simulate the signal condition in case of beam at the center of the pipe and a second one for a beam shifted at half of the pipe radius.

5.1. Characterization of the phase shifter

Libera SPH features phase measurements comparing the phase of the input signals with the phase of the reference signal. Measurements are provided for the first and the second harmonic components of the BPM signals.
In order to evaluate the properties of the phase measurements, it is necessary to have a way to change the phase difference between the input signals and the reference signal. In these measurements, the analog phase shifter ATM P1214D [4] is used.

With a rotating knob and a graduated scale that ranges from 0 to 1600, it is possible to define 16 equal phase shift steps which provide:

- relative shift from 0 deg to roughly -56.85 deg @ 352.21 MHz
- relative shift from 0 deg to roughly -113.43 deg @ 704.42 MHz

Although this device is described in the manufacturer's documentation, it's not perfectly linear and it isn't trivial to know exactly what is the exact shift value of each individual step. In other words, it's hard to find an instrument more accurate than the one under test that can be used to characterize the phase shifter.

The best option is to measure the ATM with the Vector Network Analyzer [5] available in the ESS laboratory. The instrument accuracy in the range between 100kHz and 4.5GHz, measuring the phase of the transmission parameter S21 which module is around 1 (0 dB), is around **0.2 deg –** see Figure 8.

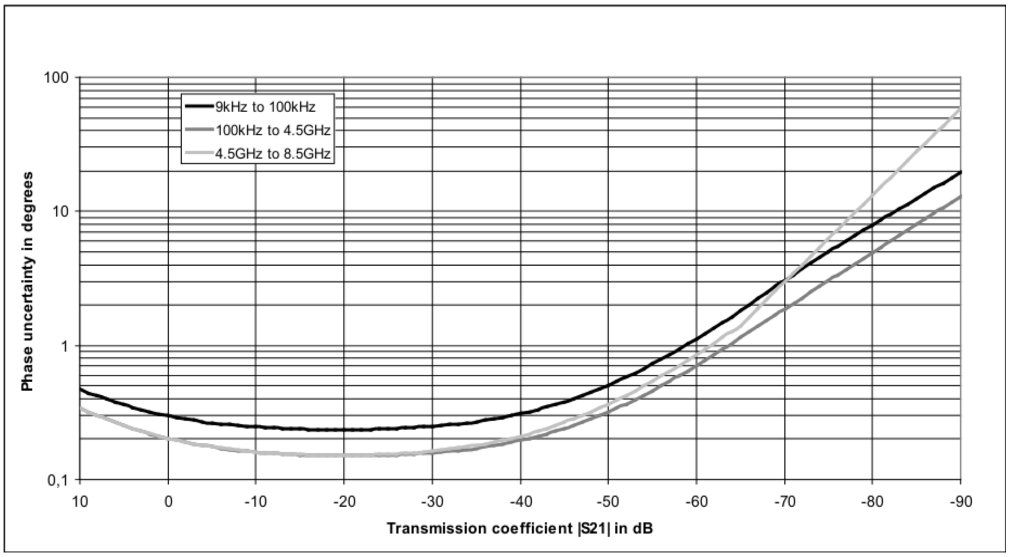


Figure 8: VNA accuracy specified by the manufacturer [5]

To perform the measurements, the VNA is first calibrated with its own calibration kit and then the phase shifter instrument is connected to it.
A possible source of errors, even in this simple setup, is the phase shifter knob. This is a mechanical line stretcher and repeating several time the measure at the same position it is possible to observe little variations in the measurement. In order to avoid this non-deterministic error, the measurements are repeated 10 times for each knob position. The result is the average of the measurements, after excluding the highest and lowest values.

Figure 9 reports the measurements for the harmonic at 352.21 MHz. The first graph shows the phase shift introduced in function of its units. The second graph shows the phase shift introduced by each shifter step (100 units of the phase shifter). The blue lines are the real measurements, while the red lines are the linear interpolation of the results that assume that every phase shifter step is equal to the average step.

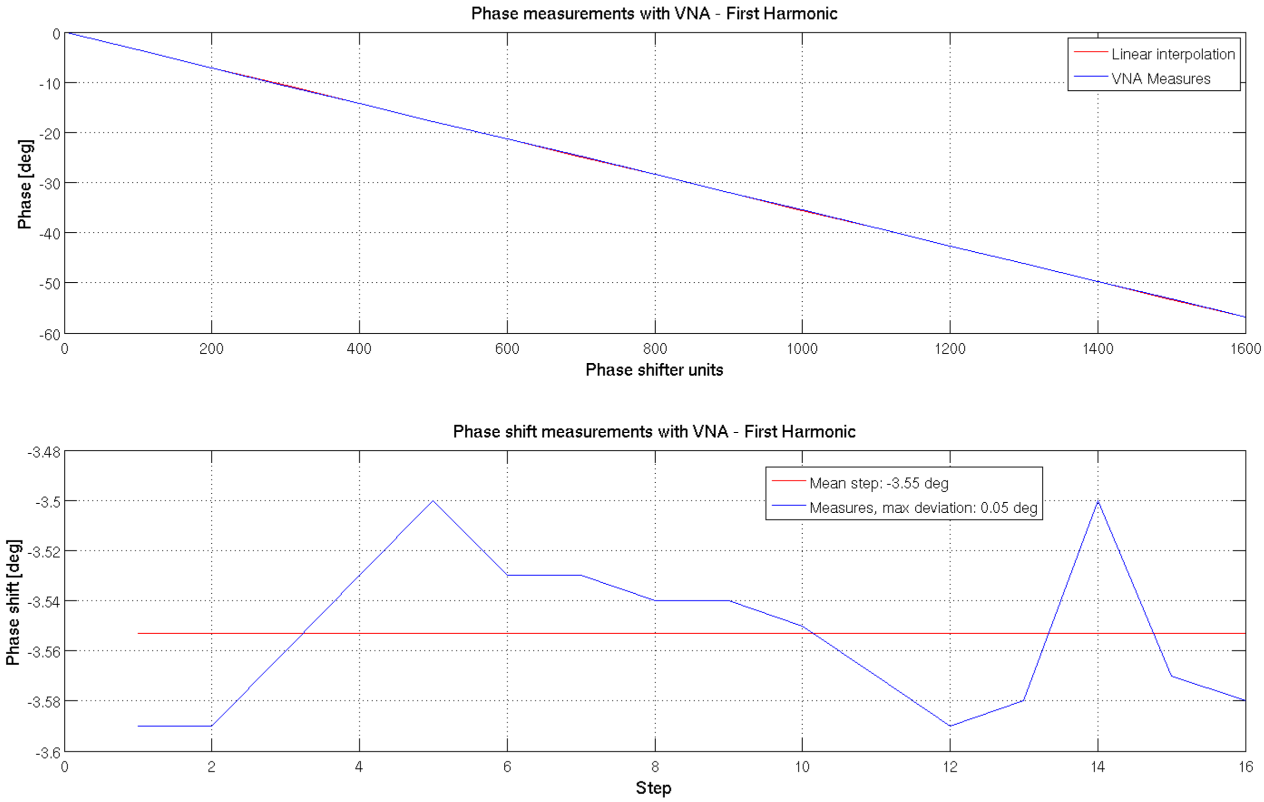


Figure 9: Phase shifter characterization at 352.21 MHz

From the graph it is evident that the phase shifter is not perfectly linear and the measured phase shifts are a little different from the mean value.

Figure 10 shows the same characterization for the second harmonic at 704.42 MHz. As expectable, the phase shifts are roughly doubled in comparison with the first harmonic. Still the non-linearity of the shifter is visible, and with a very similar profile.

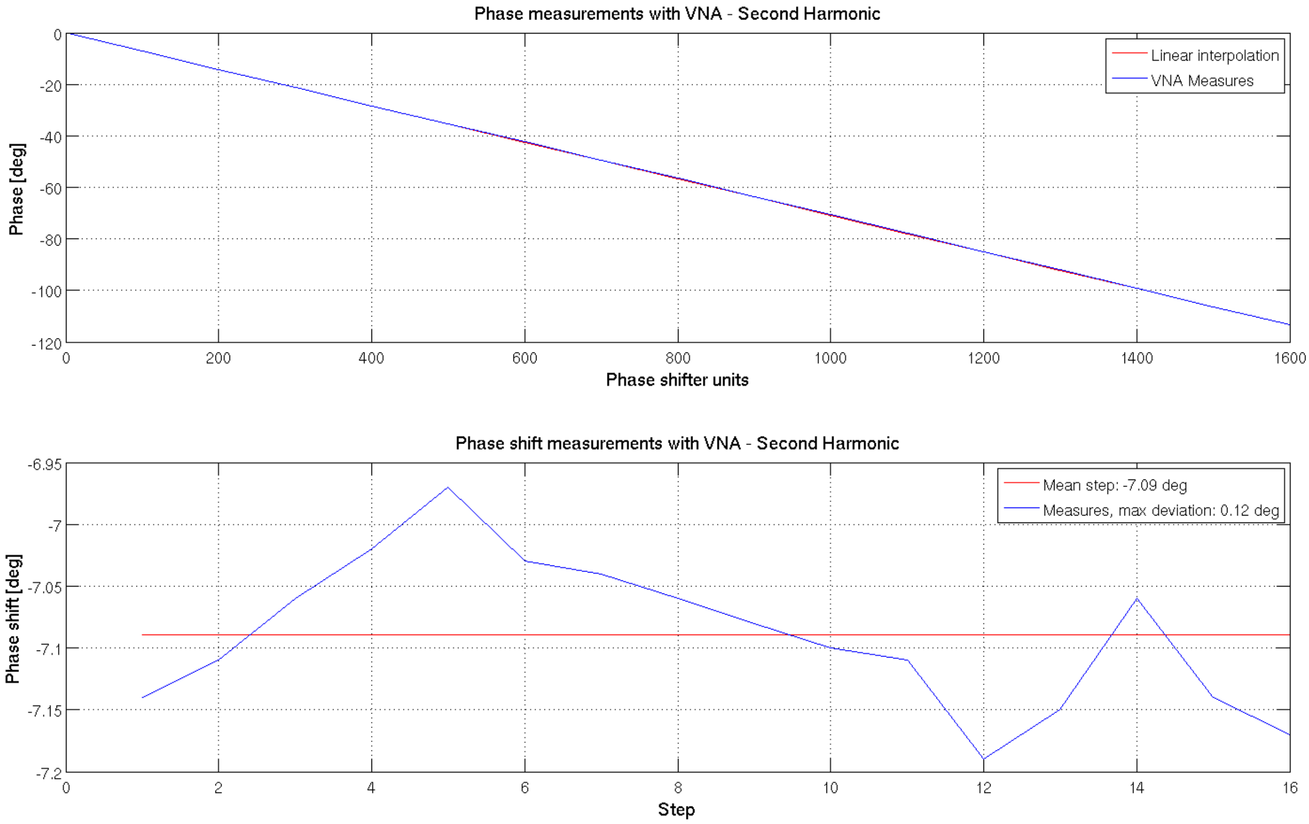


Figure 10: Phase shifter characterization at 704.42 MHz

For the evaluation of the accuracy of Libera SPH, it is **possible to assume that the real value of the phase shifter steps is the value given by the VNA measurements**, which correspond to the blue curves in Figure 9 and 10. This is somehow biasing the results depending on the VNA accuracy, which is not excellent, but remains the only way to compare two independent measurements.

5.2. Measurements with centered beam

This section describes the measurements which are done providing the instrument with four input signals with roughly the same amplitude. This simulates the situation when the signal is at the center of the pipe. The dynamic range that will be covered by these measurements is chosen accordingly with ESS specifications described in section 2.2.4, and will be described in details in sub-section 5.2.2.

5.2.1. Measurements setup

Since this is the first presented measurement setup, the main components will be described. In principle for establishing a good setup there are many ways, although several things should be considered:

- signal level: to perform measurements with a wide signal level range, a powerful RF generator is needed (30 dBm output is ideal). It has to drive all the splitters, attenuators and wires which are necessarily before the instrument inputs.

- signal harmonic components: it is necessary to monitor exactly what are the harmonics present within the instrument input bandwidth (up to 700Mhz). Reference signal should be a pure tone. If signal amplifiers are used in the test-setup, their noise figure and spurious components should be considered.

- impedance matching: the whole setup has 50 Ohm characteristic impedance. However, there are some components that are not perfectly matched with 50 Ohm. Examples are the pulse-generating diode, pre-amplifiers or the BPM test-bench. In this case putting some attenuators in the signal path can help to reduce the amplitude of the reflected waves.

- Stability: phase measurements are extremely sensitive to every movement in the setup. All the wires and moving components should be properly fixed. After everything is put together it is good to wait some time in order that the strengths in the wires are released, otherwise these can be source of drifts in the measurements.

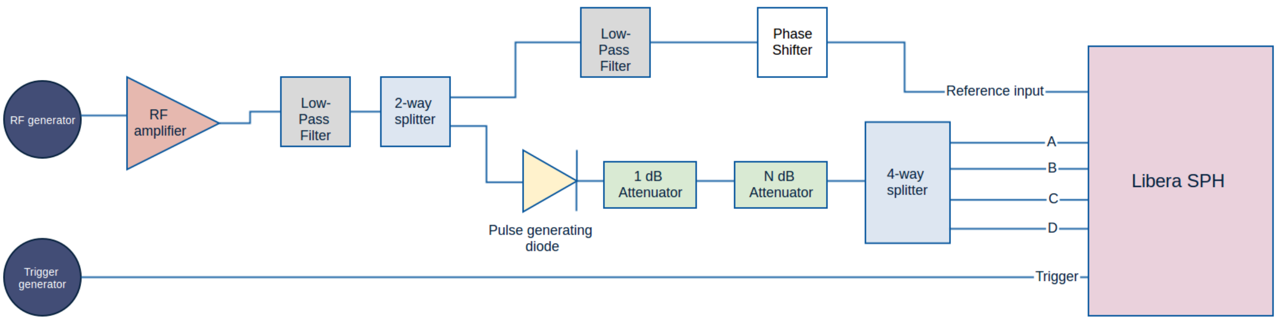


Figure 11: Test setup for measurements with centered beam

Figure 11 presents a schema of the test setup used for the measurements with centered beam conditions. Since the RF generator [6] is particularly weak (maximum output level is limited to 7 dBm), it is directly connected to an RF amplifier [7] that amplifies the signal up to 25 dBm. Then a 300 MHz low-pass filter [8] cleans out spurious harmonics that can eventually be generated by the amplifier.
The signal is then split in two [9]: the first output provides the reference signal for the instrument through another low-pass filter and the phase-shifter [4].
The second output is used to generate the instrument inputs. The role of the pulse generating diode is to generate a signal which contains also the second harmonic – this will be presented in section 5.2.2. Afterwards, a 1 dB attenuator reduces the effect of the impedance mismatching. Afterwards there is place for other attenuators that used to lower the level of all four signals during the measurements. After the four-way splitter [10], the signals are connected to the instrument inputs.
The trigger signal is generated with the waveform generator feature of the Oscilloscope [11]. This is a TTL square signal with 14 Hz frequency – 50% duty-cycle.

5.2.2. Instrument full scale input and dynamic range of the measurements

As soon as the test-setup is defined, the “full-scale” input signal is defined. This is the highest signal provided to the instrument. In order to cover the foreseen dynamic range, some attenuators can be placed in front of the 4-way splitter.
Usually the full-scale is set to reach around 20 thousand counts after the ADCs. Because of the limits in the generator output power, it is not possible to go above 15k counts.
Figure 12 shows 100 samples acquired from the ADC signal: peak is calculated for each channel dividing the peak-to-peak value by two. Reference signal peak was around 18k counts.

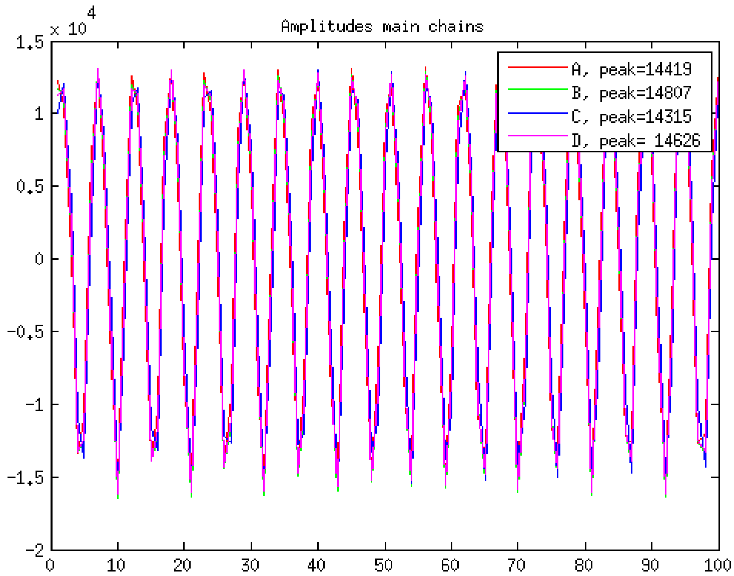


Figure 12: ADC signals acquired from Libera SPH

It's good to evaluate also the spectrum of the input signal: the level of the two signal harmonics and the noise level. Figure 13 presents a measurement taken from the spectrum analyzer [12], while Figure 12 presents an oscilloscope screen-shot with the pulse shape in the time domain.

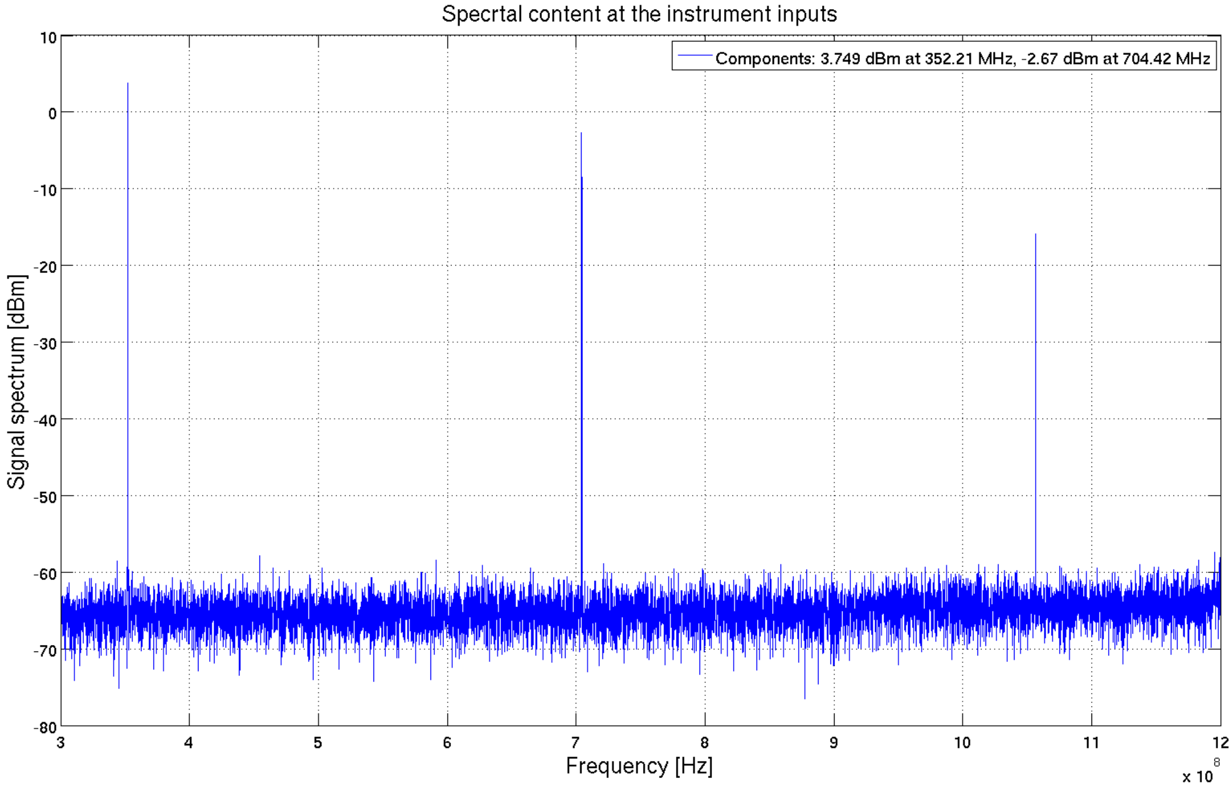


Figure 13: Spectrum of the instrument input signals

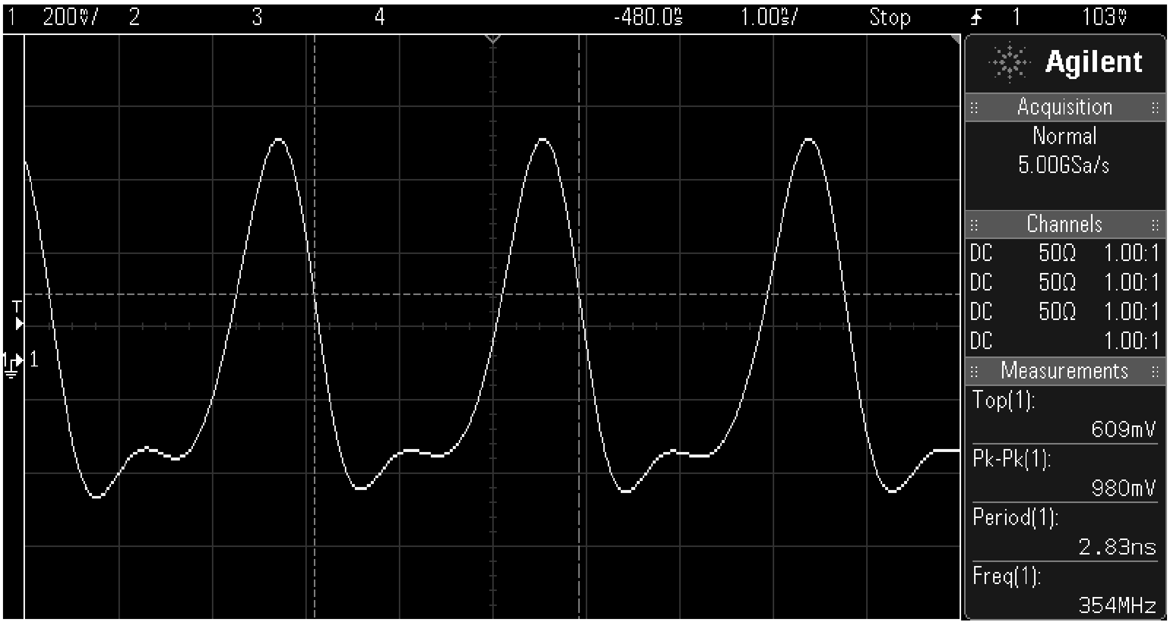


Figure 14: Instrument input signal - time domain

The noise floor is below -60 dBm and the amplitudes of the two harmonics are respectively **3.75 dBm at 352.21 MHz and -2.67 dBm at 704.42 MHz**. These levels are identified for both harmonics as **0 dBFS**, which means 0 dB with reference to the full scale level. With this notation it is easy to identify the other levels with reference to the full scale, so for example -5 dBFS means that the signal level at both harmonics is 5 dB lower than at the full scale.
Finally, according with the signal levels expected at ESS and described in sub-section 2.2.4, Table 10 presents the dynamic range that will be covered in these measurements.

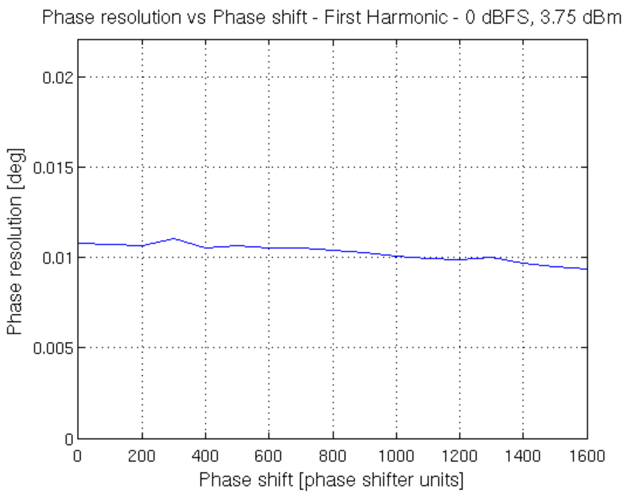
Reference level	Level of First Harmonic	Level of Second Harmonic
0 dBFS	3.75 dBm	-2.67 dBm
-5 dBFS	-1.25 dBm	-7.67 dBm
-10 dBFS	-6.25 dBm	-12.67 dBm
-15 dBFS	-11.25 dBm	-17.67 dBm
-20 dBFS	-16.25 dBm	-22.67 dBm
-25 dBFS	-21.25 dBm	-27.67 dBm
-30 dBFS	-26.25 dBm	-32.67 dBm
-35 dBFS	-31.25 dBm	-37.67 dBm

Table 10: Input signal dynamic range for both harmonics

NOTE: with this setup it is not possible to cover the entire range foreseen for the second harmonic (from -25.56 dBm up to -1.13 dBm). Anyway with higher signal level we expect better performance from the instrument.

5.2.3. Resolution measurements

As previously discussed in Section 4.1.1, the phase and position resolution of the instrument is not expected to depend on the actual phase measurement. Following diagrams prove that this is true. With 0 dBFS signal input, the phase shifter is used to shift the reference signal through 16 equal steps. Figure 15 presents the phase resolution for both harmonics, while position signals resolution is presented in Figure 16.



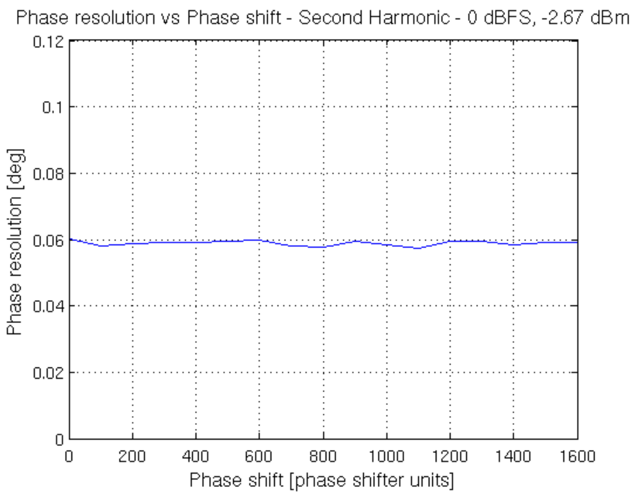


Figure 15: Phase resolution dependence on phase

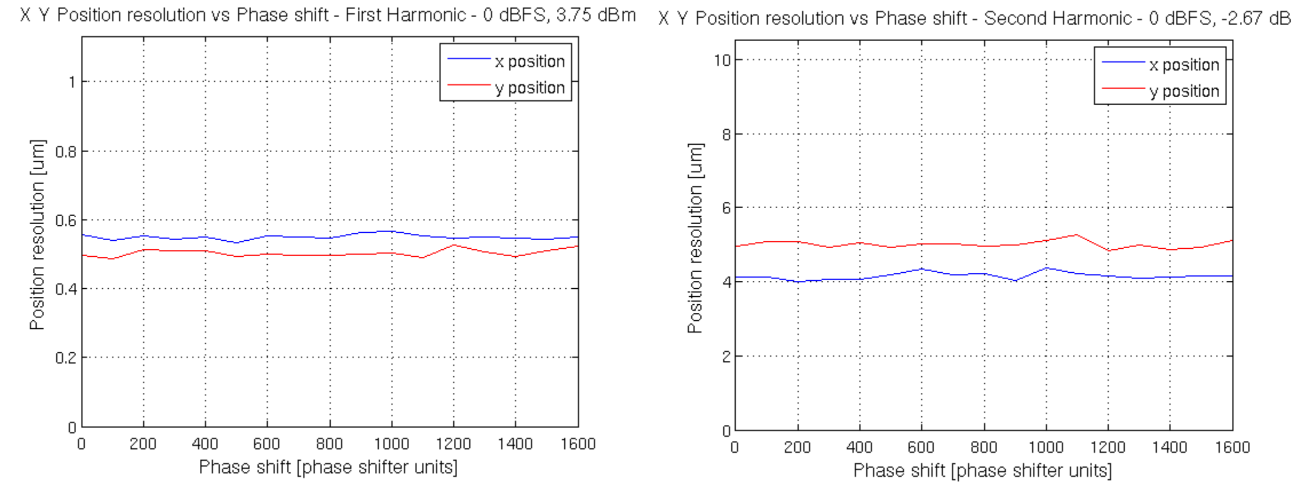


Figure 16: Position resolution dependence on phase

On the other hand, resolution depends on the input signal level. In the next measurements, phase is kept constant, while the input signal level is reduced until -35 dBFS using some attenuators before the 4-way splitter. Figure 17 presents how the phase resolution lowers as the input signal level decreases by 5 dB at each step. The red curve shows the actual ESS requirement on the resolution, which is 0.2 degrees.

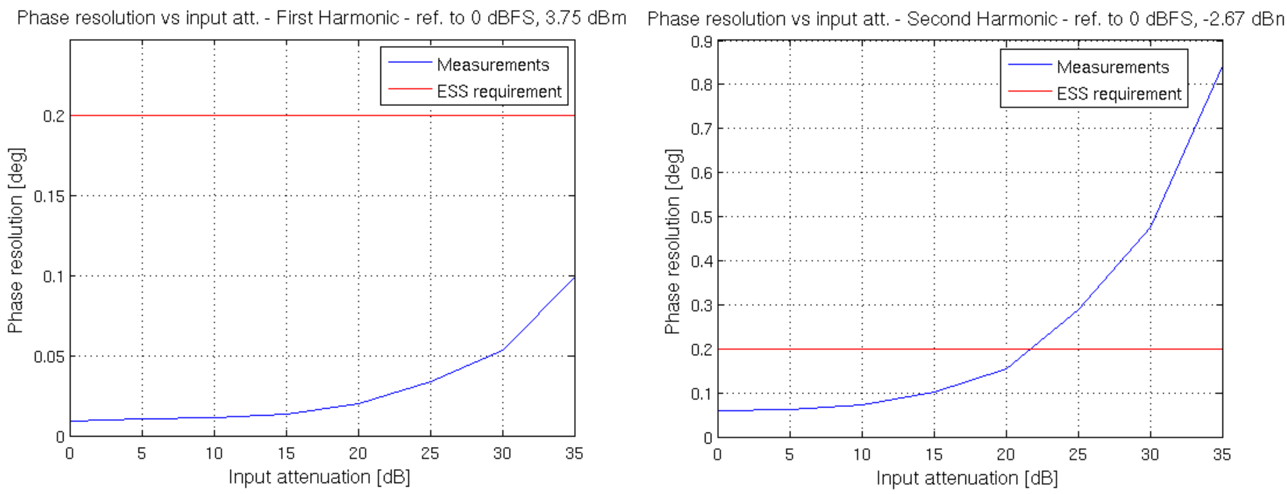


Figure 17: Phase resolution dependence on the input signal level – centered beam

For the first harmonic, resolution is always below 0.1 deg, while for the second harmonic the resolution reaches the limit around -21.5 dBFS. **Considering the resolution of the second harmonic, since it is used to compare the phase with the 352.21 MHz reference, then the measurement should be divided by two**. In this case the limit would be less than -27 dBFS (-29.2 dBm)

Figure 18 presents the same analysis with X and Y position signals. For these signals ESS requires a resolution below 20 µm. As it is possible to see, this is valid down to -32.5 dBFS (-28.75 dBm) for the first harmonic, and down to -15 dBFS (-17.7 dBm) for the second harmonic.

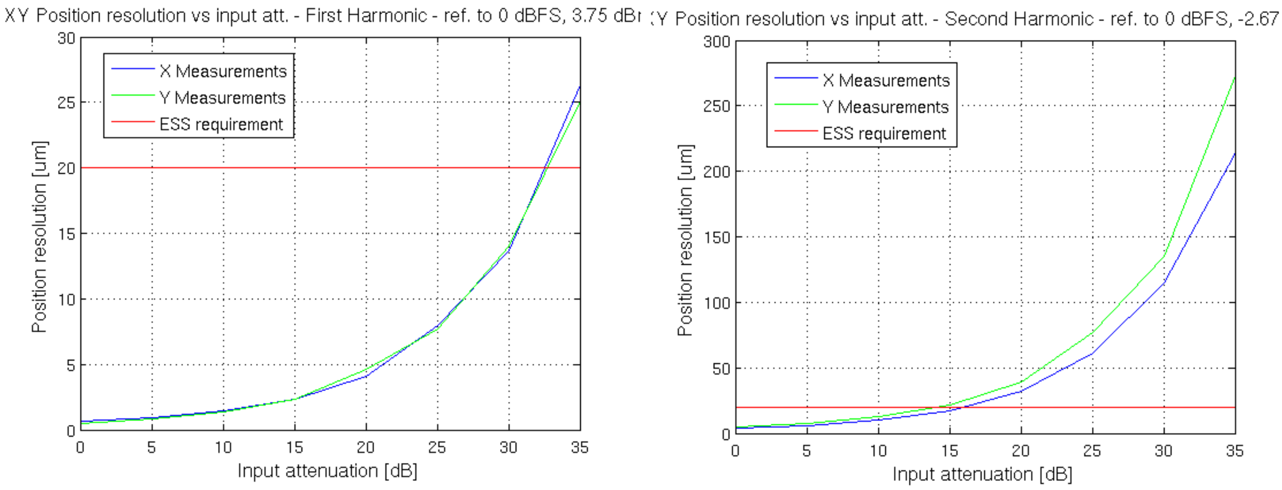


Figure 18: Phase resolution dependence on the input signal level – centered beam

All the measurements presented so far are performed considering 2000 samples of the phase and position signals. It might be interesting to evaluate how the number of considered samples influences the resolution. This is an useful information if the beam pulses are shortened, and at ESS the minimum macro-pulse length is 10 μs, that means only 10 samples of phase and position signals.

With input signals at 0 dBFS, the number of considered samples per macro-pulse was decreased from 2000 samples to 100 by steps of 100 samples, and from 100 to 5 by steps of 5 samples. Figures 19 and 20 present the results.

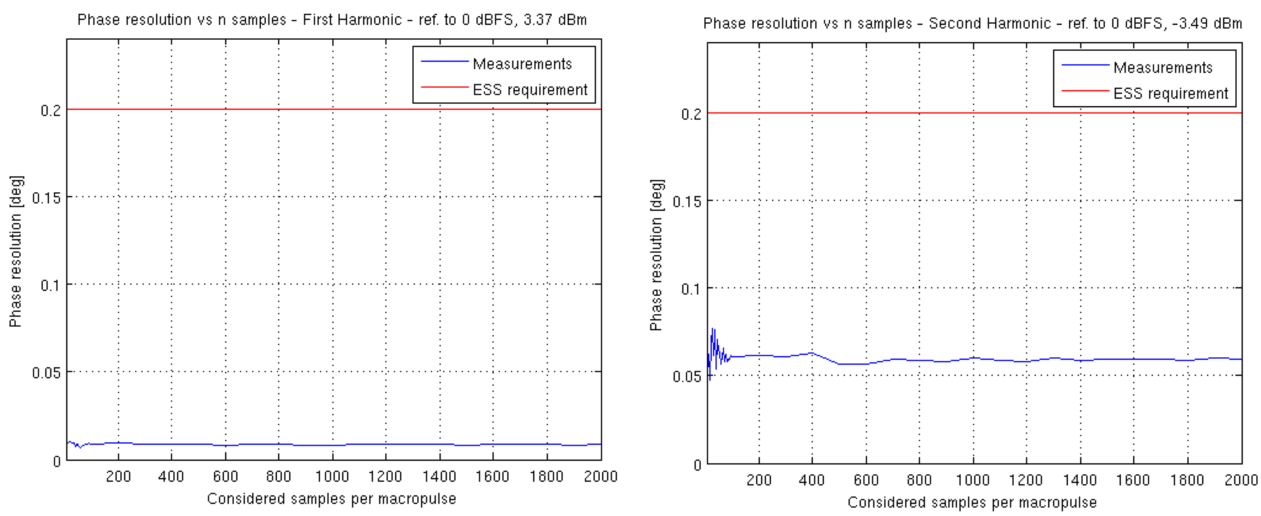


Figure 19: Phase resolution dependence on number of samples per macro-pulse, 0 dBFS

Decreasing the number of considered samples, the resolution doesn't show a specific dependence. Below 100 samples it tents to be more unstable, and this is expectable since its value depends more and more on the acquired samples. The same trend is visible in Figure 21 and 22, where the test is repeated with -10 dBFS input signal level.

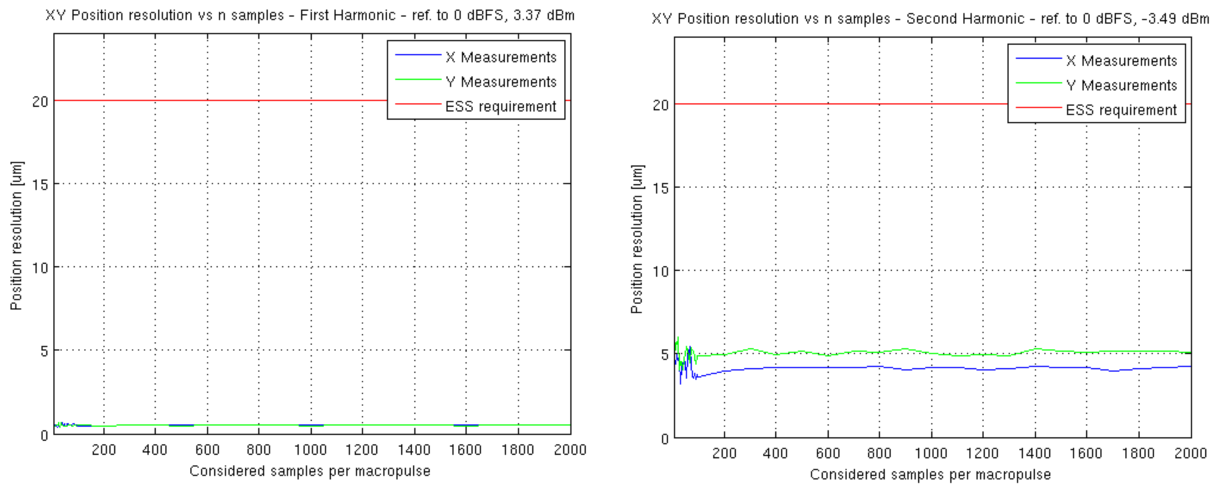


Figure 20: Position resolution dependence on number samples per macro-pulse, 0 dBFS

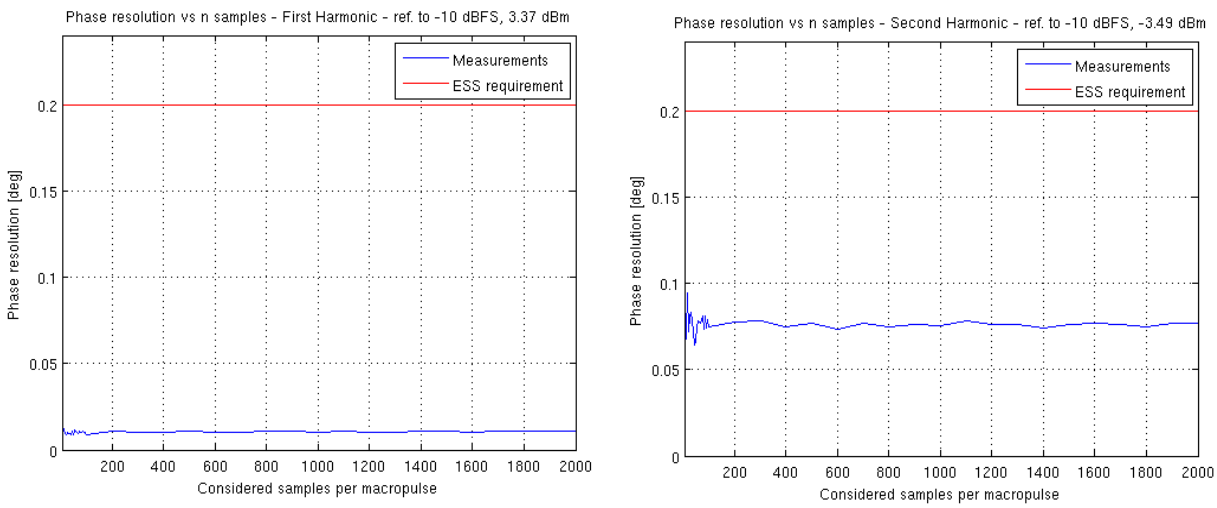


Figure 21: Phase resolution dependence on number of samples per macro-pulse, -10 dBFS

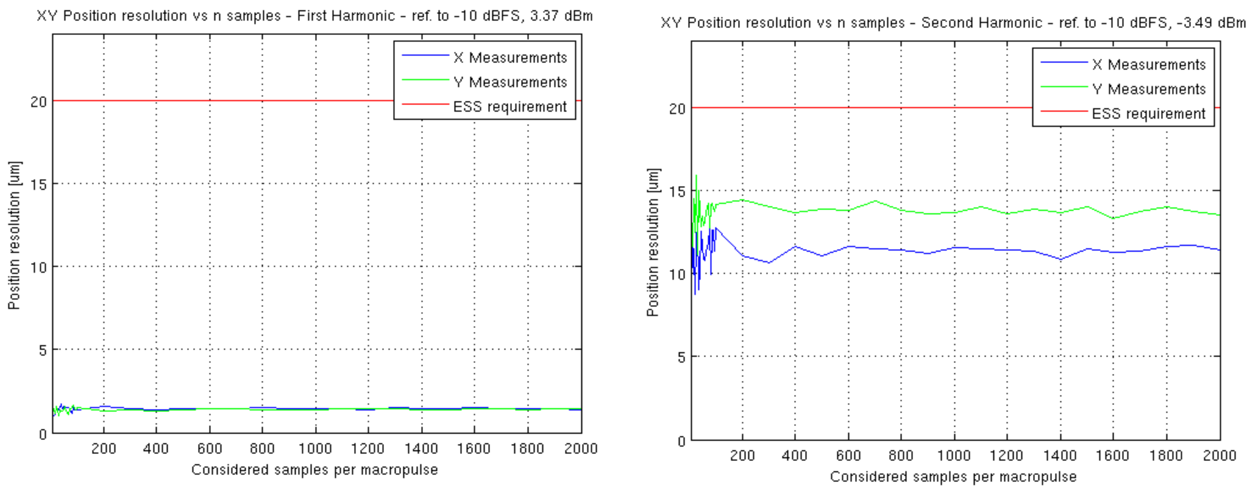


Figure 22: Position resolution dependence on number of samples per macro-pulse, -10 dBFS

5.2.4. Precision measurements

As mentioned in Section 4.2.1, measurement precision should not depend on the phase measured, while might have a dependency on the signal input level. The measurements in Figures 23 and 24 show the precision dependency on the phase shift. With 0 dBFS input, the phase shifter is used to shift the reference signal through 16 equal steps. As it is possible to see the phase and position precision is not influenced at all.

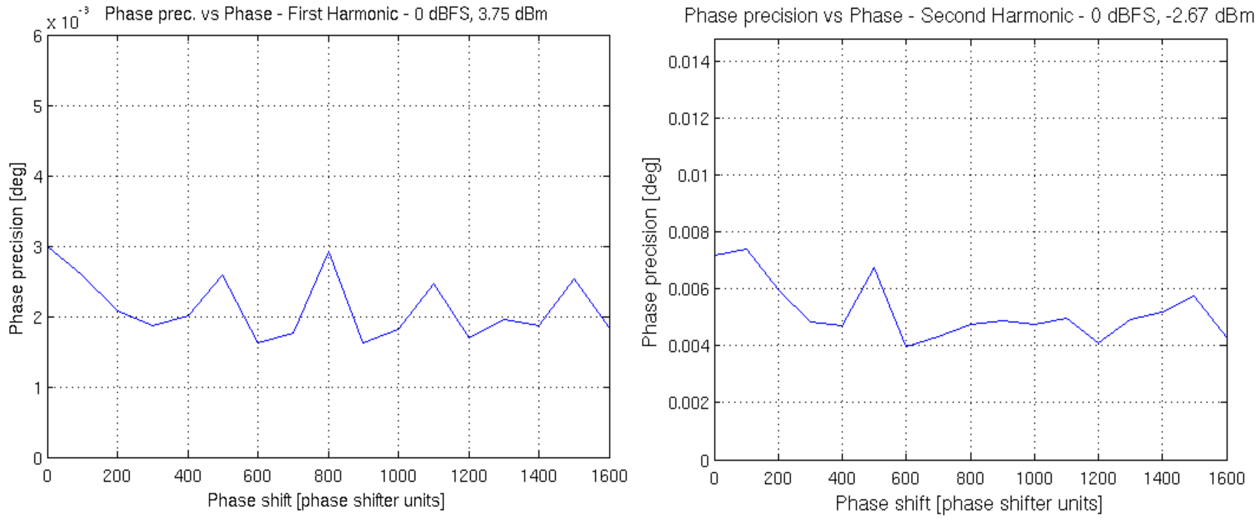


Figure 23: Phase precision dependency on phase

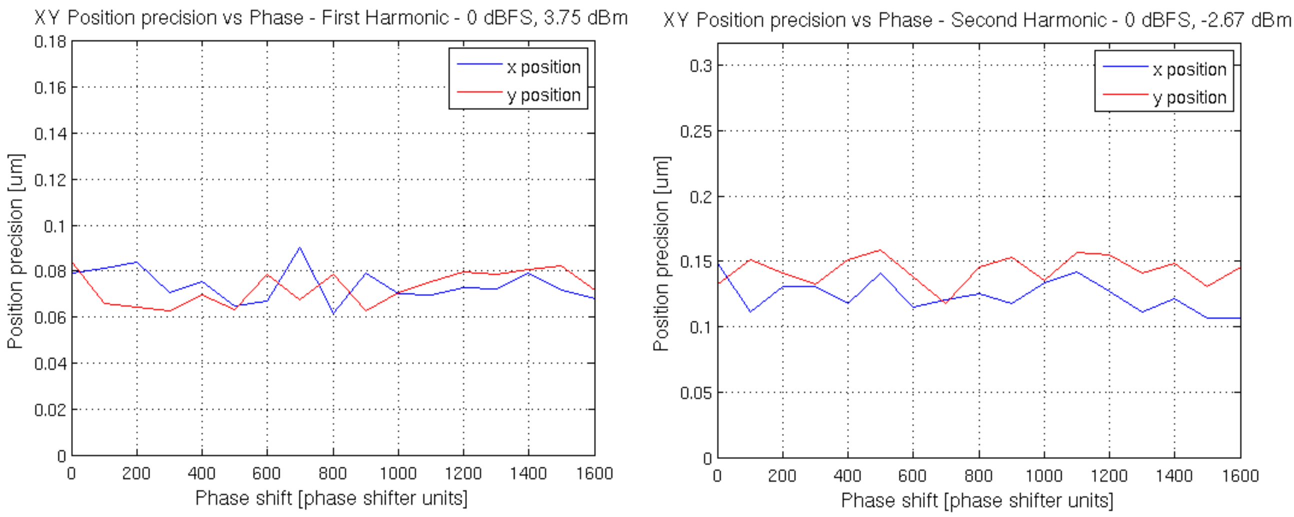


Figure 24: Position precision dependence on phase

In the same way, instrument precision is evaluated lowering the input signal from 0 dBFS to -35 dBFS by steps of 5 dB. Figures 25 and 26 present the results for phase and position. While the influence is barely visible for the phase measurements, it is quite clear how the signal level influences the position precision. Nevertheless, the results are excellent.

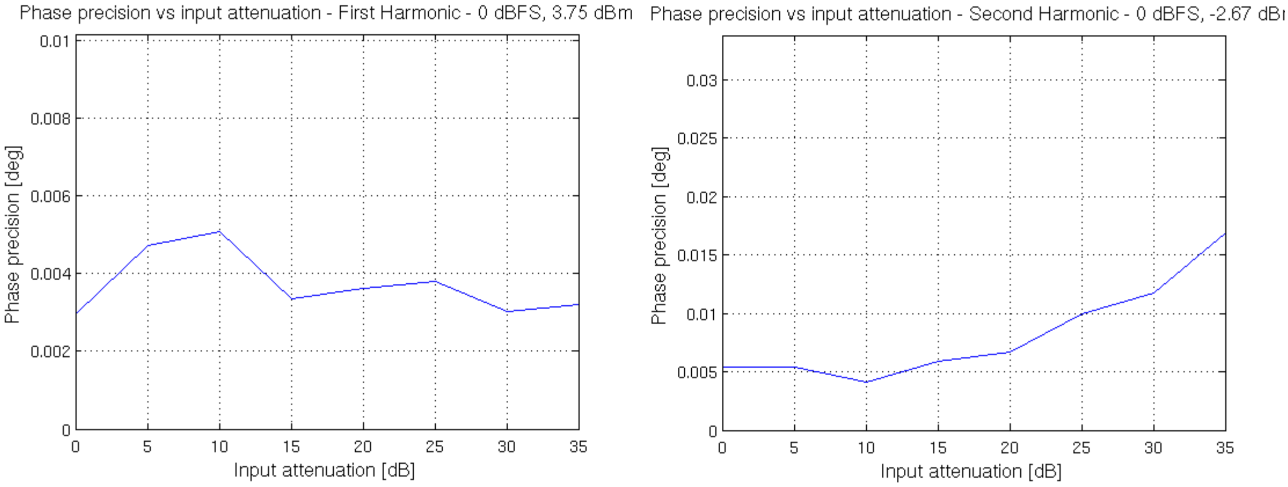


Figure 25: Phase precision dependence on the input signal level

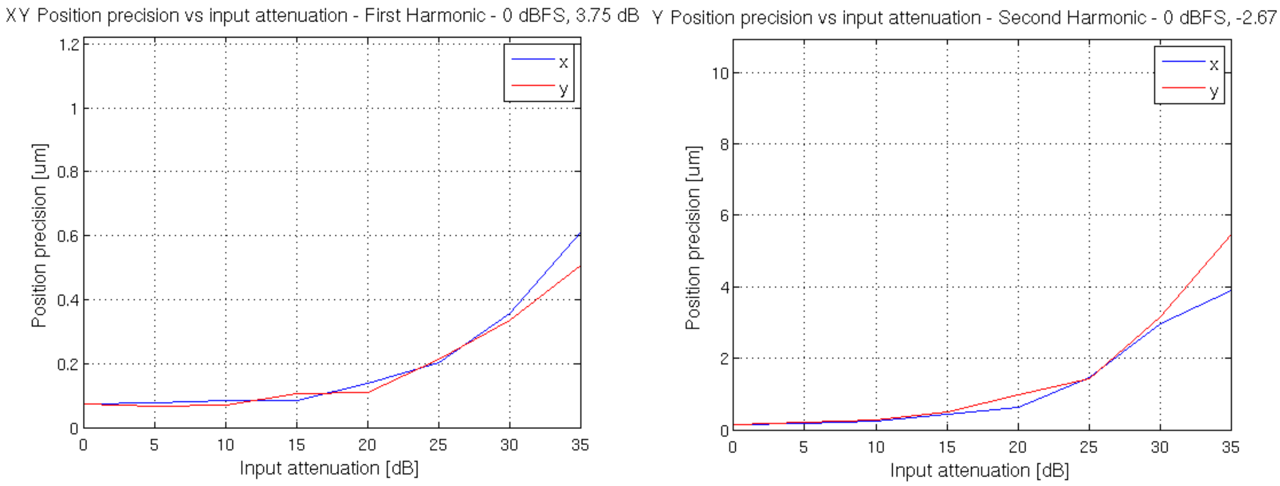


Figure 26: Position precision dependence on the input signal level

As for the resolution, also the precision is evaluated in function of the number of samples considered in each independent measurement.

NOTE: Reducing the number of samples considered for each measurement makes the noise more and more influent on each of them. It is expected to have an exponential dependency in function of the number of samples. This dependency is shown in Figures 27 and 28, for a -10 dBFS input signal level.

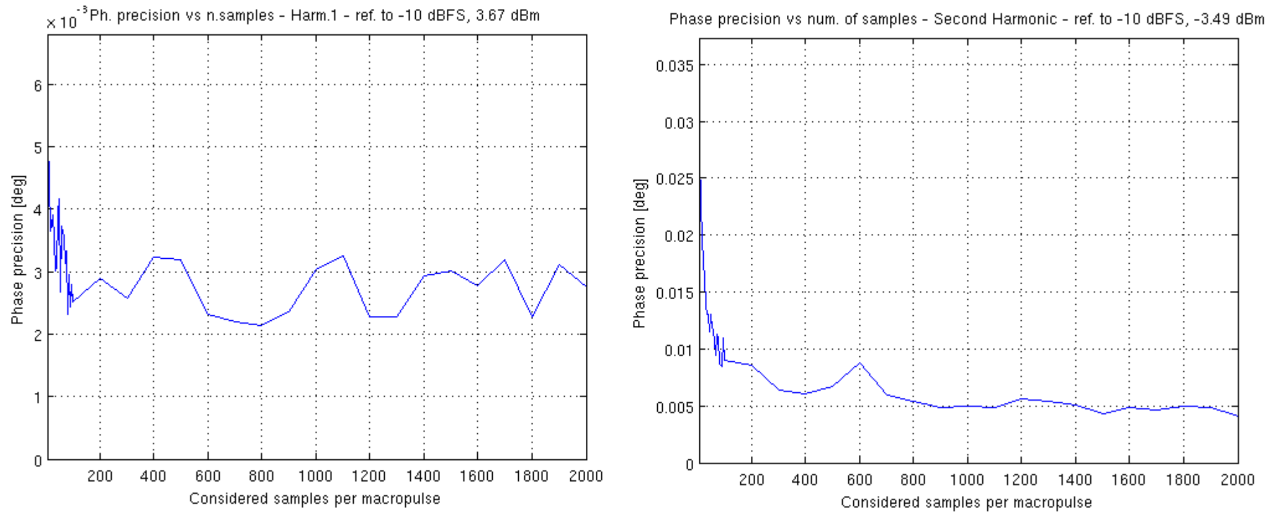


Figure 27: Phase precision dependence on number of samples per macro-pulse, -10 dBFS

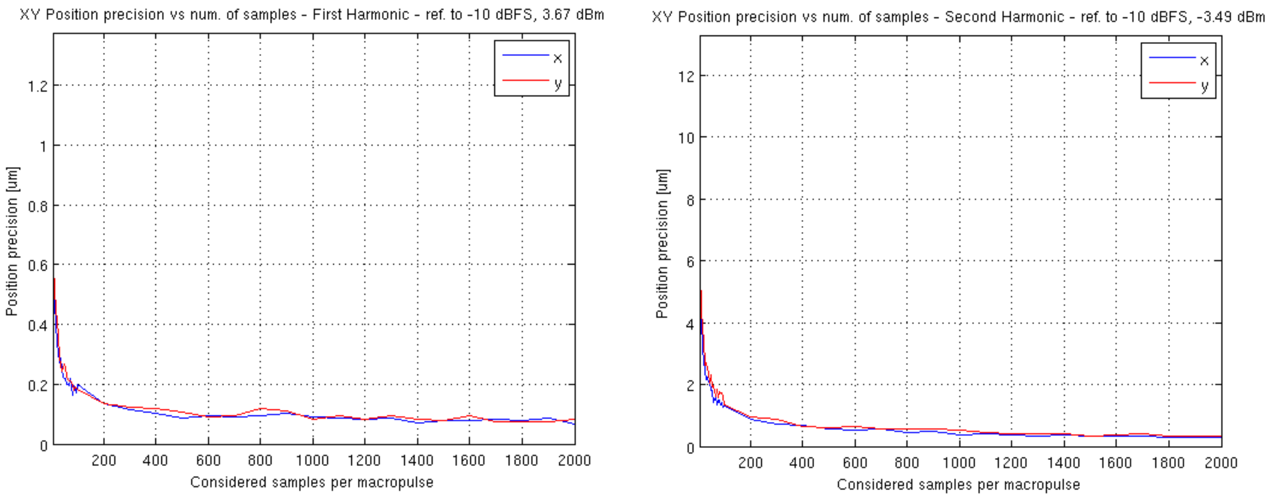


Figure 28: Position precision dependence on number of samples per macro-pulse, -10 dBFS

5.2.5. Accuracy measurements

The phase accuracy of the instrument is evaluated comparing the phase shift measures obtained with the instrument with those achieved with the VNA – see Section 5.1.

The phase shifter is used to shift the reference signal through 16 equal steps, corresponding to 100 units in the shifter device. The measures are repeated 10 times for each phase shifter position. The result is the average of the measurements, after excluding the highest and lowest values. The measurements are performed at four different input amplitudes which are 0, -10, -20 and -30 dBFS respectively.

Figures from 29 to 36 show the results achieved at all the input levels, first for 352.21 MHz harmonic and then for 704.42 MHz harmonic. The first plot shows the total phase shift introduced by the shifter in function of the shifter units, while the second shows the phase shift introduced by each step (100 units).

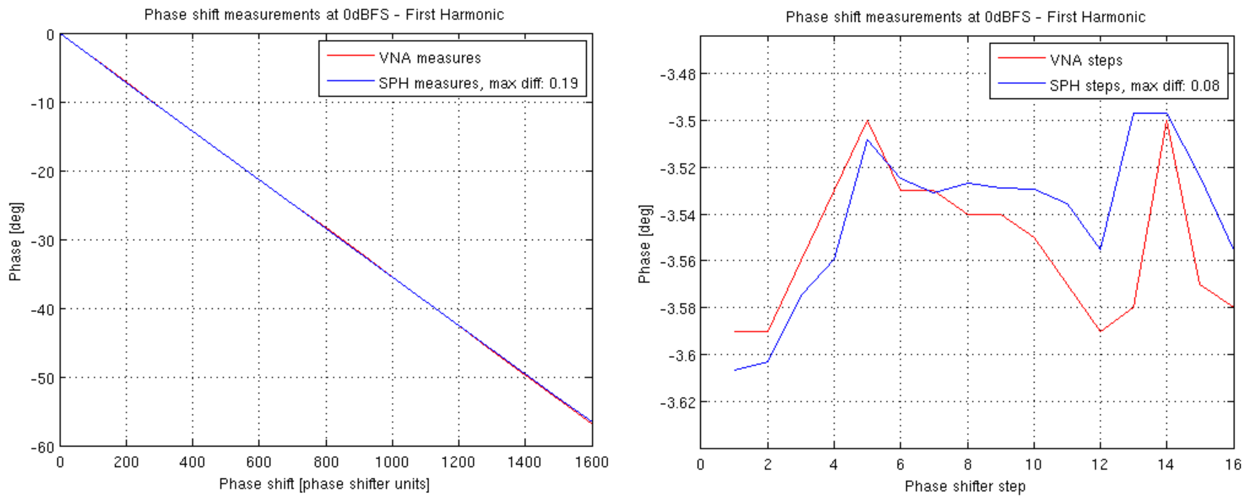


Figure 29: Phase accuracy at 0dBFS - First harmonic

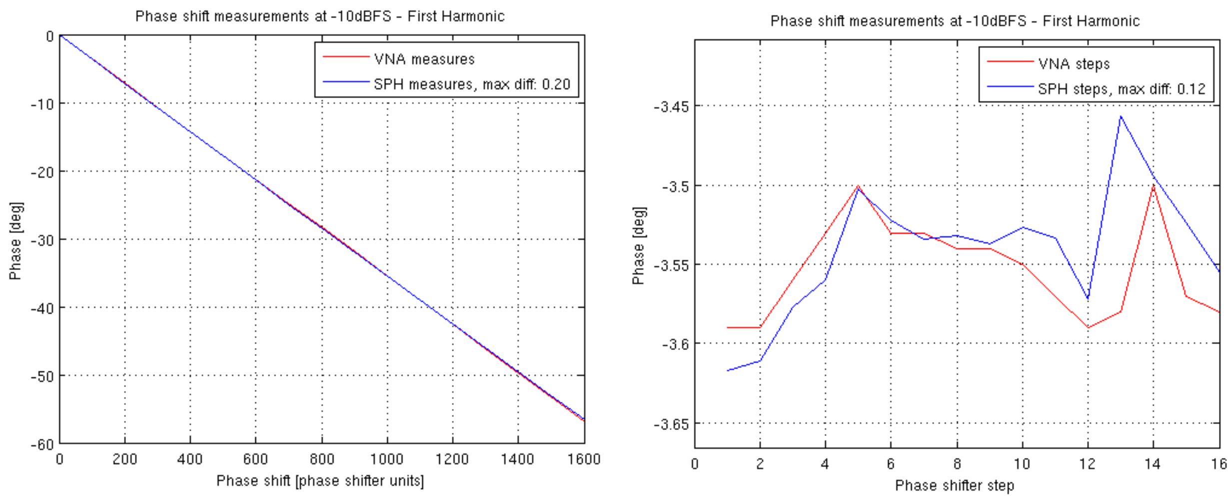


Figure 30: Phase accuracy at -10dBFS - First harmonic

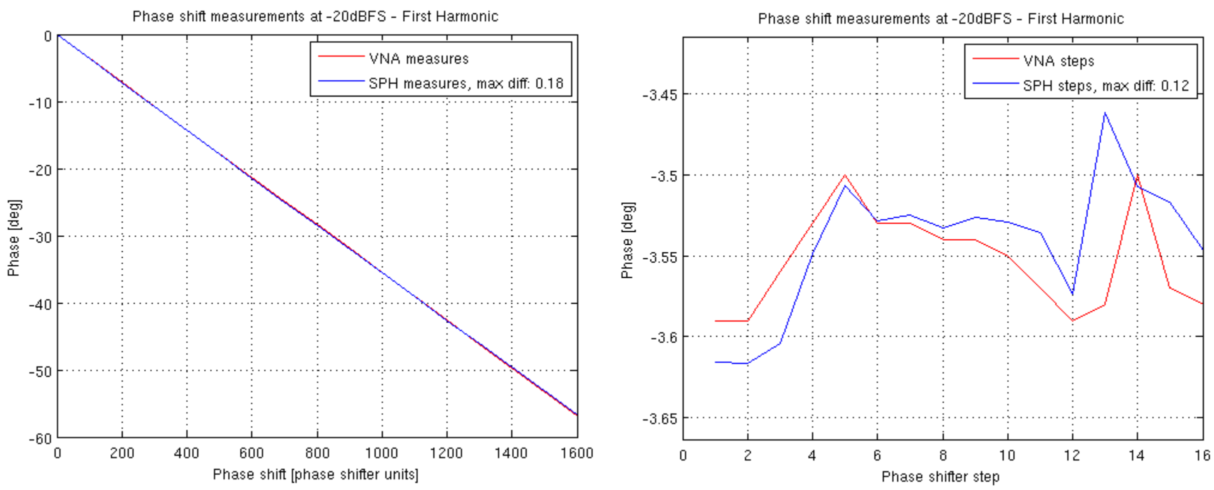


Figure 31: Phase accuracy at -20dBFS - First harmonic

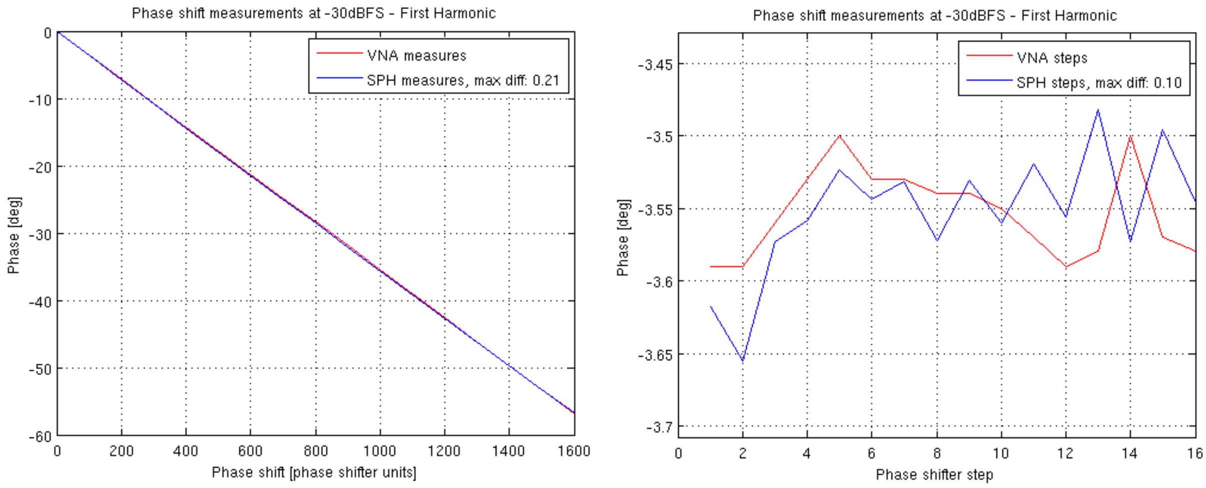


Figure 32: Phase accuracy at -30dBFS - First harmonic

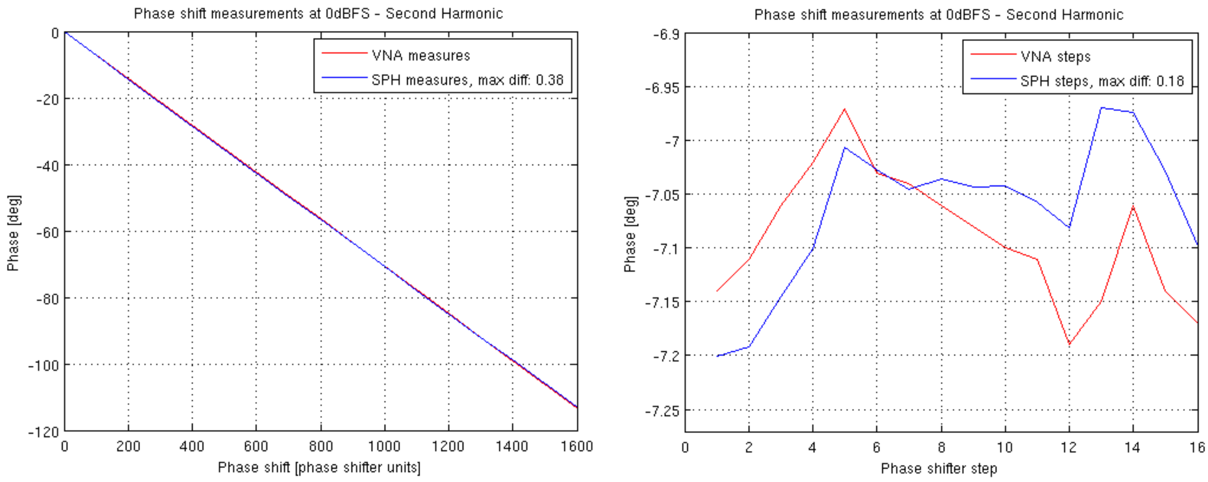


Figure 33: Phase accuracy at 0dBFS - Second harmonic

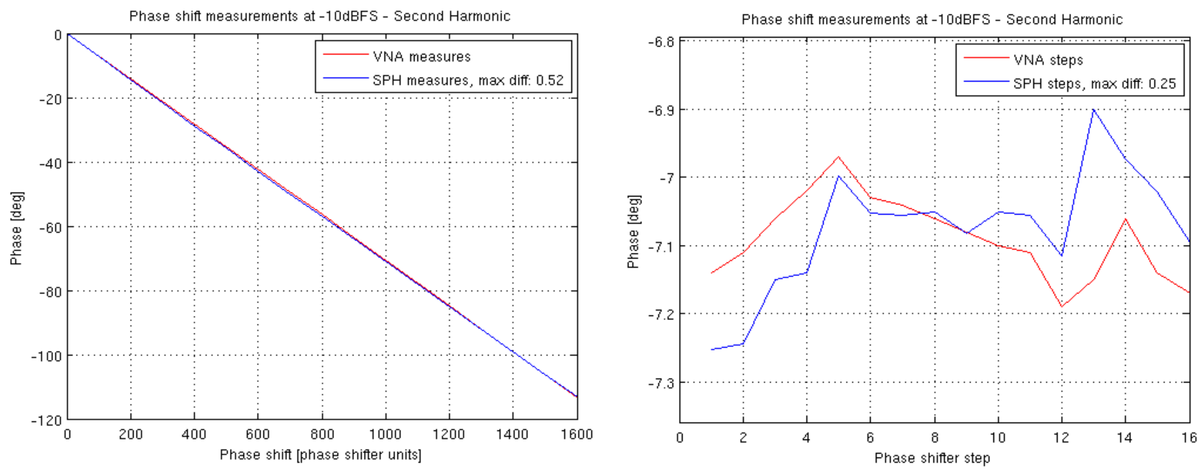


Figure 34: Phase accuracy at -10dBFS - Second harmonic

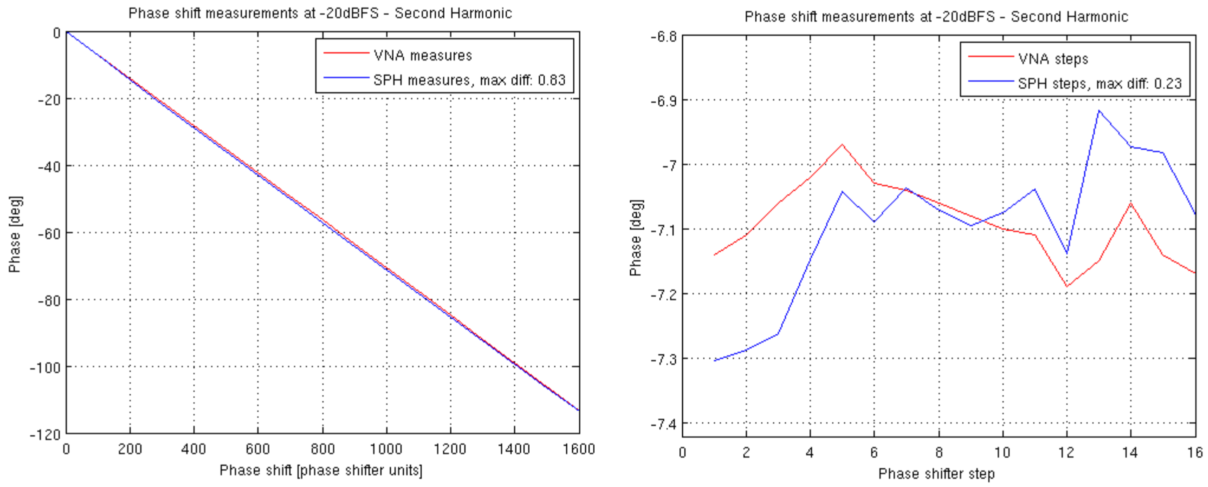


Figure 35: Phase accuracy at -20dBFS - Second harmonic

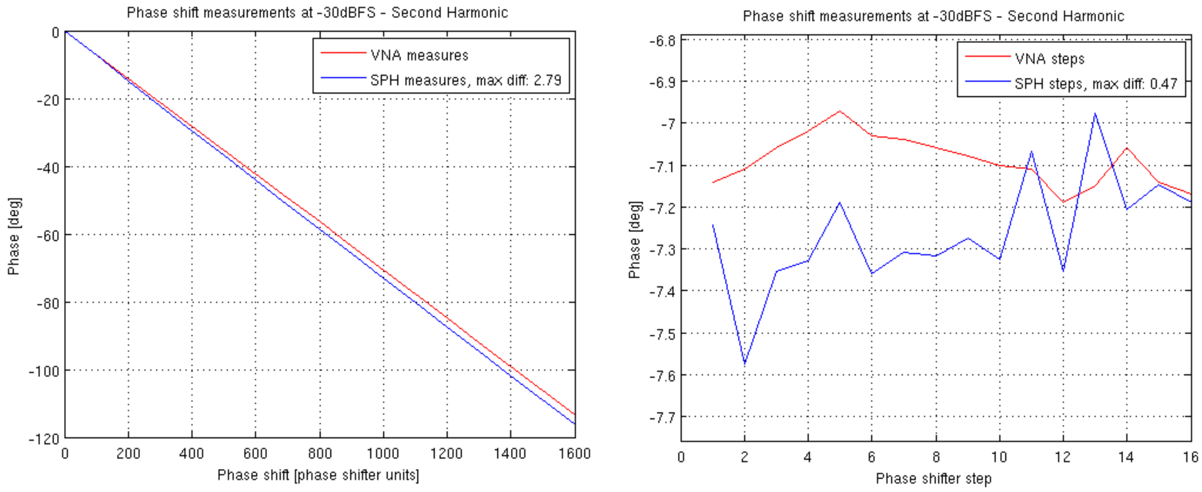


Figure 36: Phase accuracy at -30dBFS - Second harmonic

From the results, several considerations are possible:

1. The step values measured with the VNA and with Libera SPH have the same profile. This means that the non linearity which is measured by both Libera and the VNA is coming from the phase shifter.

2. Observing the total phase measurements, the curves tent to cross each other several times. This means that the accuracy of the instrument is not dependent on the phase shift it is measuring.

3. Measures with the second harmonic tent to deteriorate faster lowering the signal level, if compared with the first harmonic. This is explainable considering that the level of the second harmonic is 6 dB lower at the input. As mentioned in Chapter 3, this component is outside the instrument bandwidth, and it gets even more attenuated (circa 10 dB more). With a proper front-end customization according with ESS parameters, better results are expected.

4. The overall accuracy is within ESS requirements. An exception is the second harmonic measurements at -30 dBFS, but this level is out from the expected signal range of the accelerator. Considering the accuracy of the second harmonic, it is important to keep in mind that if this is used to compare the phase shift with the 352.21 MHz reference, then the measurement and the error should be divided by two – see also the note in Section 4.5.

5.2.6. Stability measurements

The **first** stability measurement answers the question: "*How much does the phase influence the position measurement?".* This evaluation is possible observing the position during the phase accuracy measurements, presented in the previous Section. In the ideal case position is not influenced by the measured phase. Figures 37-40 present the position measurements for first and second harmonics.

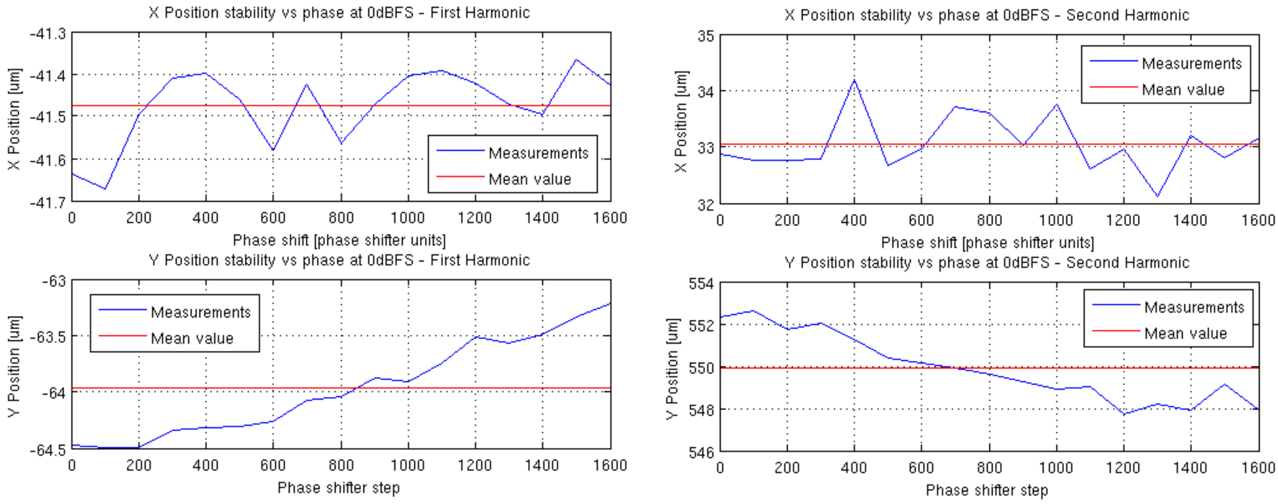


Figure 37: Position stability vs phase at 0dBFS

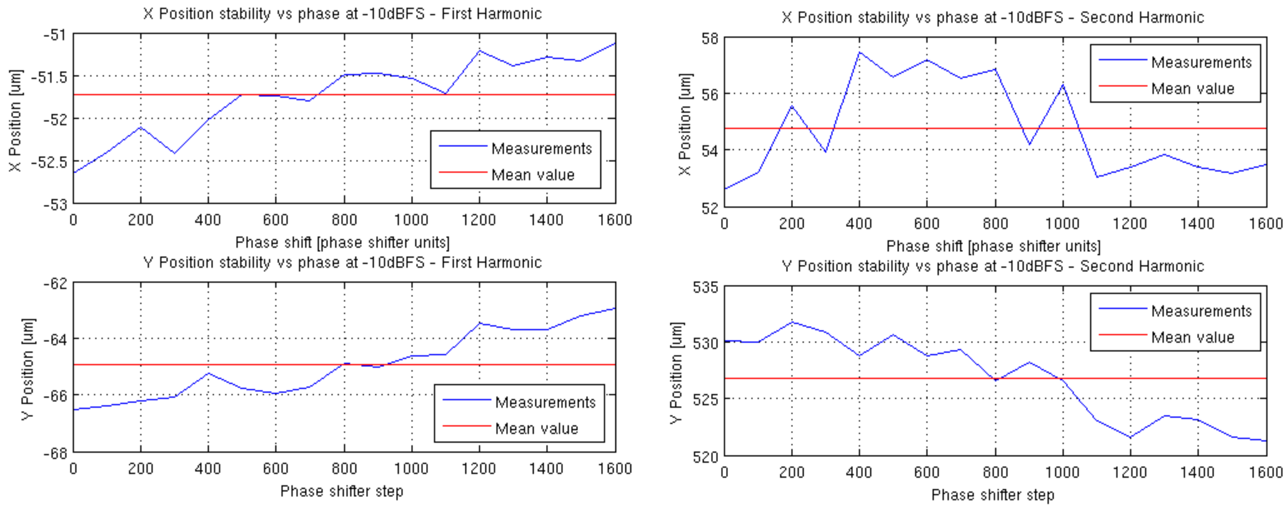


Figure 38: Position stability vs phase at -10dBFS

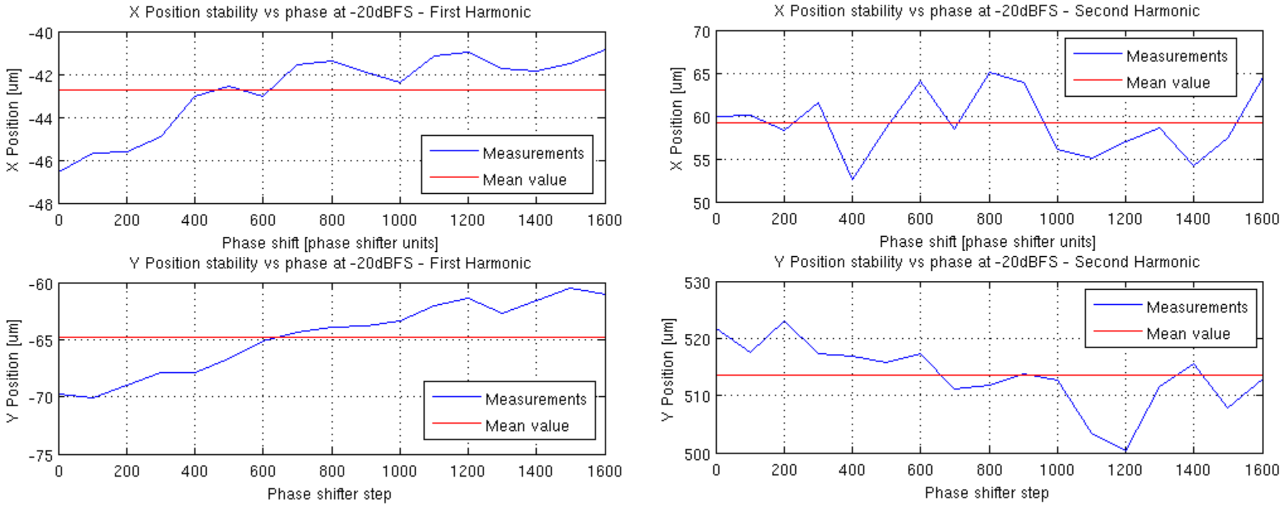


Figure 39: Position stability vs phase at -20dBFS

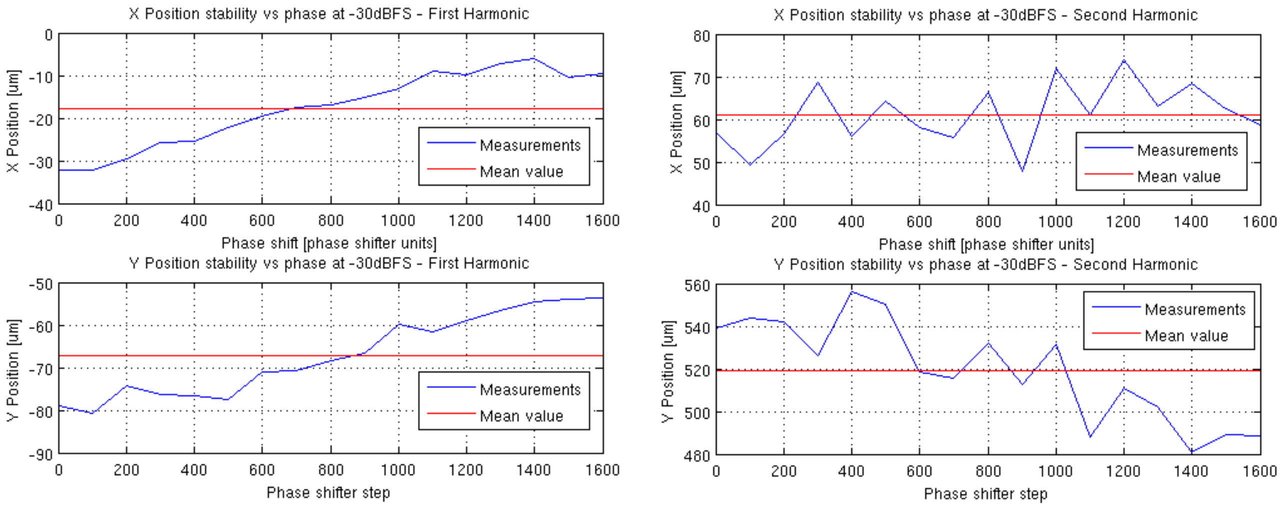


Figure 40: Position stability vs phase at -30dBFS

Since the instrument is not calibrated, the position value is not significant at this moment. Purpose of the test is to evaluate how stable are the measurements around their mean value, depending on the phase shift.

A **second** stability measurement is the evaluation of phase and position stability decreasing the input signal level. In the ideal case, positions and phase measurement should not depend on the input signal levels. In reality the signal to noise ratio decreases with the signal level, consequently some variations are expected.
Of paramount importance in these measurements is the impedance matching within the setup. If this is not perfectly matched, the introduction of one attenuator will influence the reflections between the setup components and eventually also the phase/position readout.

The measurement is performed introducing some attenuators before the 4-way splitter (see Figure 11). The insertion of one attenuator changes the path length and consequently also the phase measurement significantly. With the purpose to correct their influence, the phase shifts of the attenuators are measured with the VNA and are reported in Table 11. Note that 25 and 30 dB attenuators are obtained putting two attenuators in series, so the have roughly a double phase shift.

Attenuator nominal value	Phase shift @ harmonic 1	Phase shift @ harmonic 2
1 dB	-22.66 deg	-45.11 deg
5 dB	-22.01 deg	-43.86 deg
10 dB	-21.43 deg	-42.66 deg
15 dB	-21.70 deg	-43.16 deg
20 dB	-20.19 deg	-40.17 deg
25 dB	-42.21 deg	-84.01 deg
30 dB	-41.50 deg	-82.69 deg

Table 11: Attenuators measurements with the VNA

Figures 41 and 42 present the results of the measurement for phase and position signals. The measurements are carried out exchanging the attenuators in front of the 4-way splitter. Since this approach is invasive on the test-setup, to get a stable readout it is necessary to wait for its stabilization.

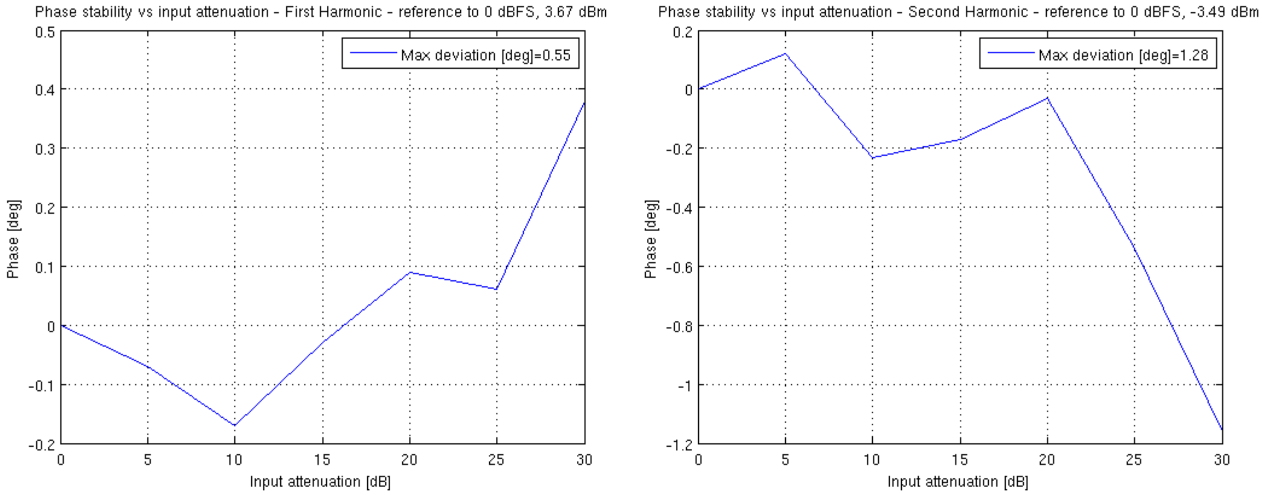


Figure 41: Phase stability vs input signal level

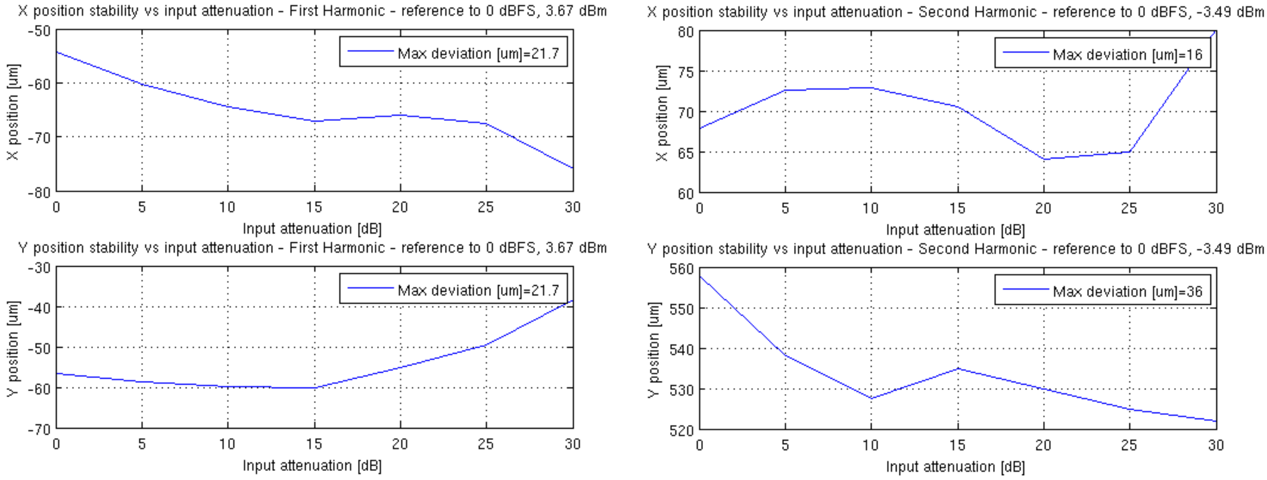


Figure 42: Position stability vs input signal level

As for the phase accuracy evaluation, the phase measurements achieved from the second harmonic should be divided by a factor of two to be compared with the first harmonic. Consequently also the uncertainly reduces by a factor of two. **Please also note that** the input lower level of the second harmonic (-30dBFS is -33.5 dBm) is well below the ESS input signal level expectations.

5.2.7. Long-term stability

The purpose of these tests is to leave the instrument running for a long time and observe if and how the measurements drift depending on the environment conditions, like temperature and humidity. The duration of such measurements is usually in the range of some hours (e.g. 12 h, 24 h).

In the ESS operating conditions, the BPM electronics room will face a temperature variation that might be up to 5 degrees: in these conditions the instrument measurements shouldn't drift too much. Another desirable thing is to observe always the same dependency from temperature: if during the day the temperatures have a cyclic variation, the same trend should be visible in all the measurements.

In the **first** long-term measurement, the phase and position signals were observed for 24 hours, and the office room windows were left open all the time. This induced a change of **6/7ºC in the room temperature** and of **3/4ºC in Libera SPH** sensors – See Figure 43.

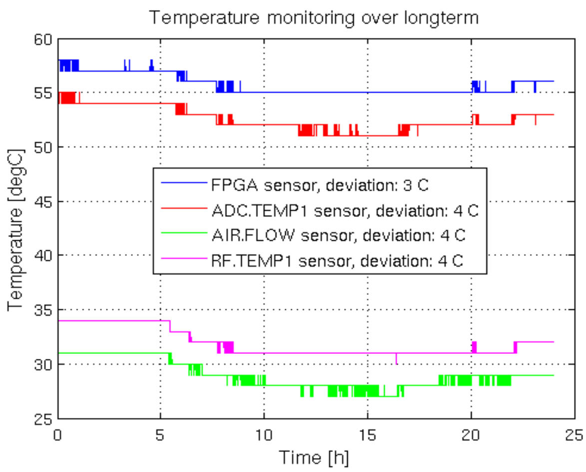


Figure 43: Temperature variation over 24h long-term test

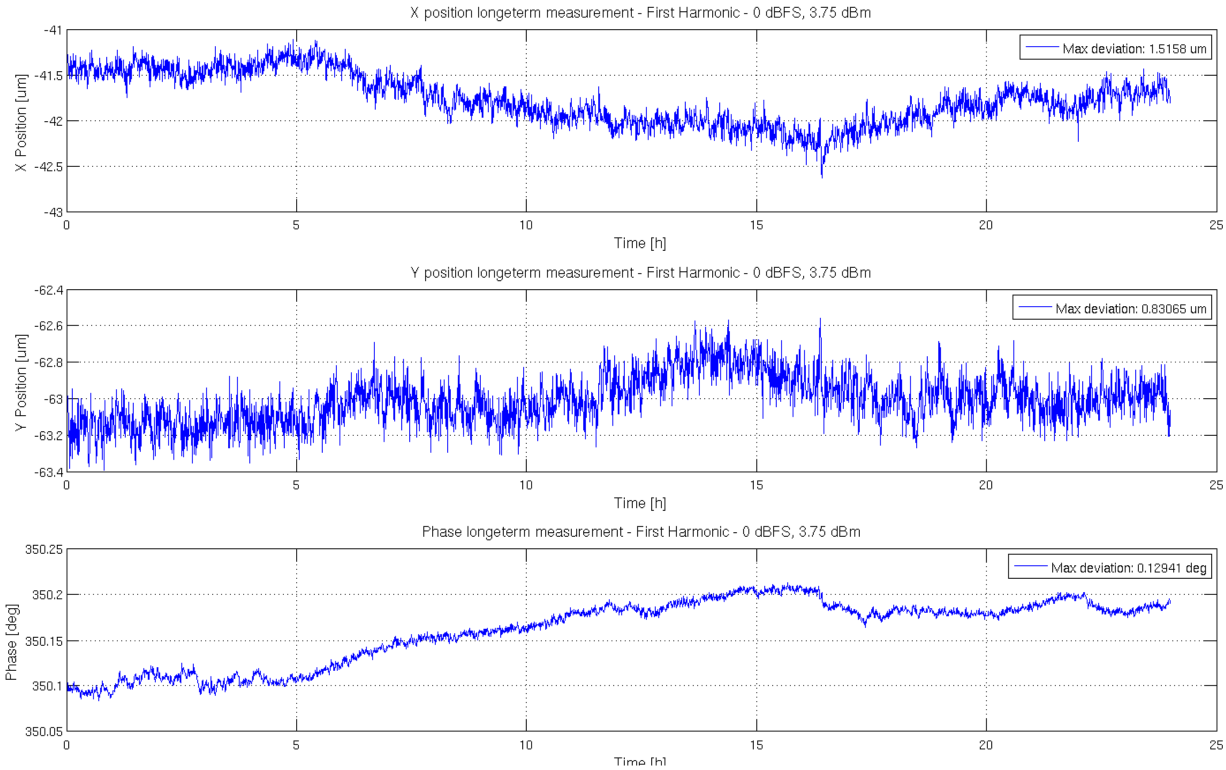


Figure 44: 24h long term measurements - First harmonic

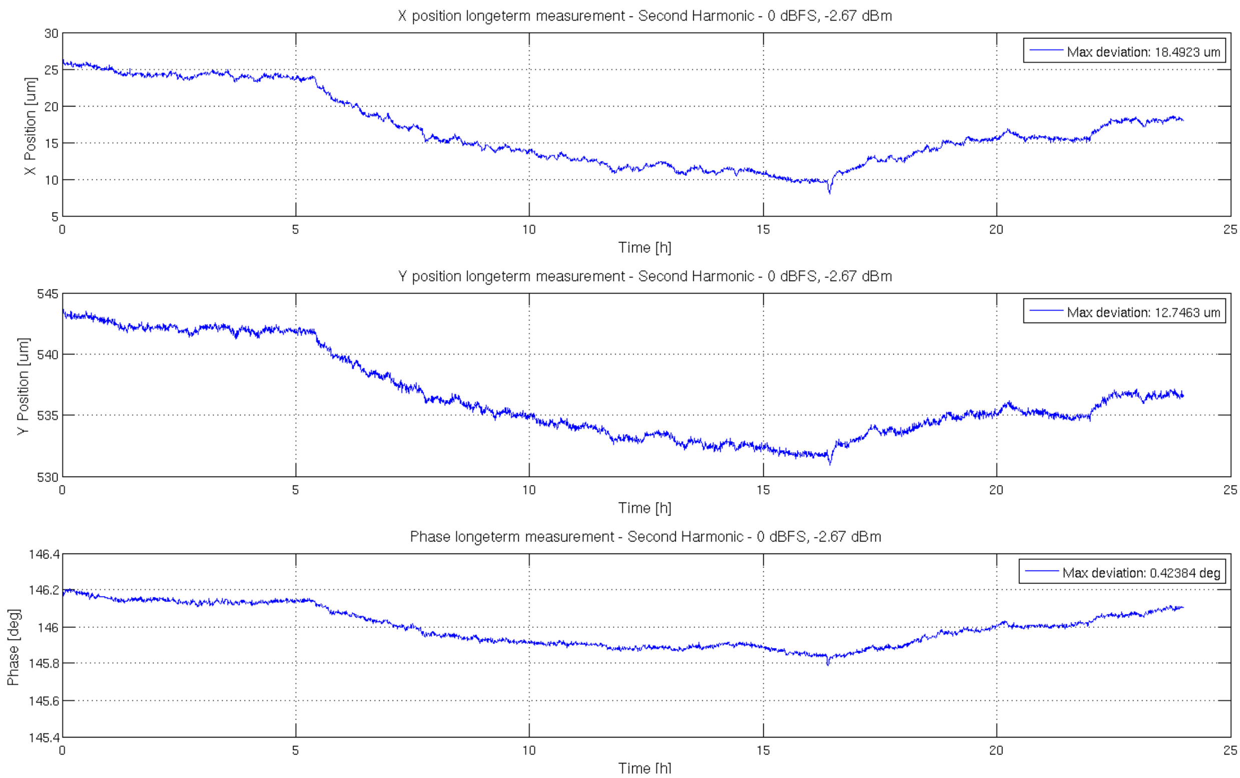


Figure 45: 24h long term measurements - Second harmonic

In the previous pictures, phase and position measurements are presented for the first harmonic (Figure 43) and for the second harmonic (Figure 44). Some things can be noticed from the plots:

1. There is a tight correlation between temperature profile and measurements profile. The temperature had a drift that is not totally symmetric, and the same is observed in positions and phases.

2. Position and phase measurements might have a positive or negative dependency from the temperature.

3. Drifts in the measurements are limited, considering the temperature variation to which the instrument is exposed. Table 12 summarizes the results. Remember that P2P phase variation on second harmonic should be divided by a factor of two if the phased is compared with the first harmonic.

Measurement	P2P variation @ harmonic 1	P2P variation @ harmonic 2
Phase	0.13 deg	0.42 deg
X Position	1.52 µm	18.49 µm
Y Position	0.83 µm	12.75 µm

Table 12: Peak to peak variation of the measurements in a 24h long term test

NOTE: Since the office window was left open, the temperature variation didn't influence only the instrument but also the setup (cables, connectors, etc..) and the devices (RF generator, preamplifier, etc..). So what these numbers report is the result of the influence of the environment conditions on the whole setup, not only Libera SPH stability.

In the **second** long-term measurement, the phase and position signals were observed for 12 hours, this time with closed windows and stable office temperature. The instrument operating conditions were perturbed inducing a couple of sudden fan speed changes. Changing the fans speed from 6000 rpm to 4000 rpm rises the the instrument components temperature (ADC, RF front-end, FPGA, etc..) for about **5ºC**. The correlation between fan speed and sensors temperature is shown in Figure 46.

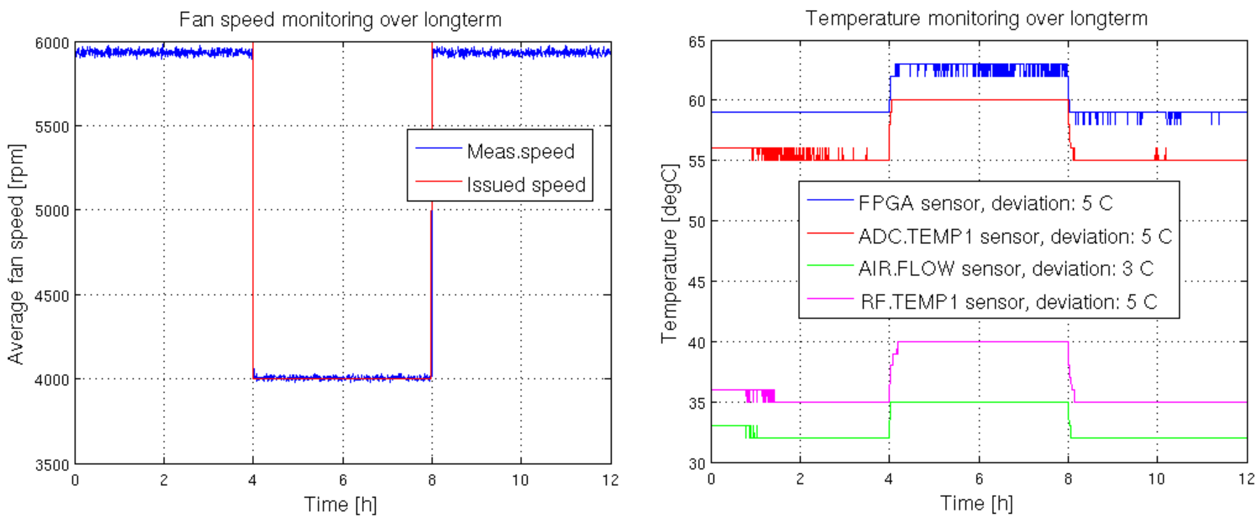


Figure 46: Fans and Temperature change over 12h long-term test

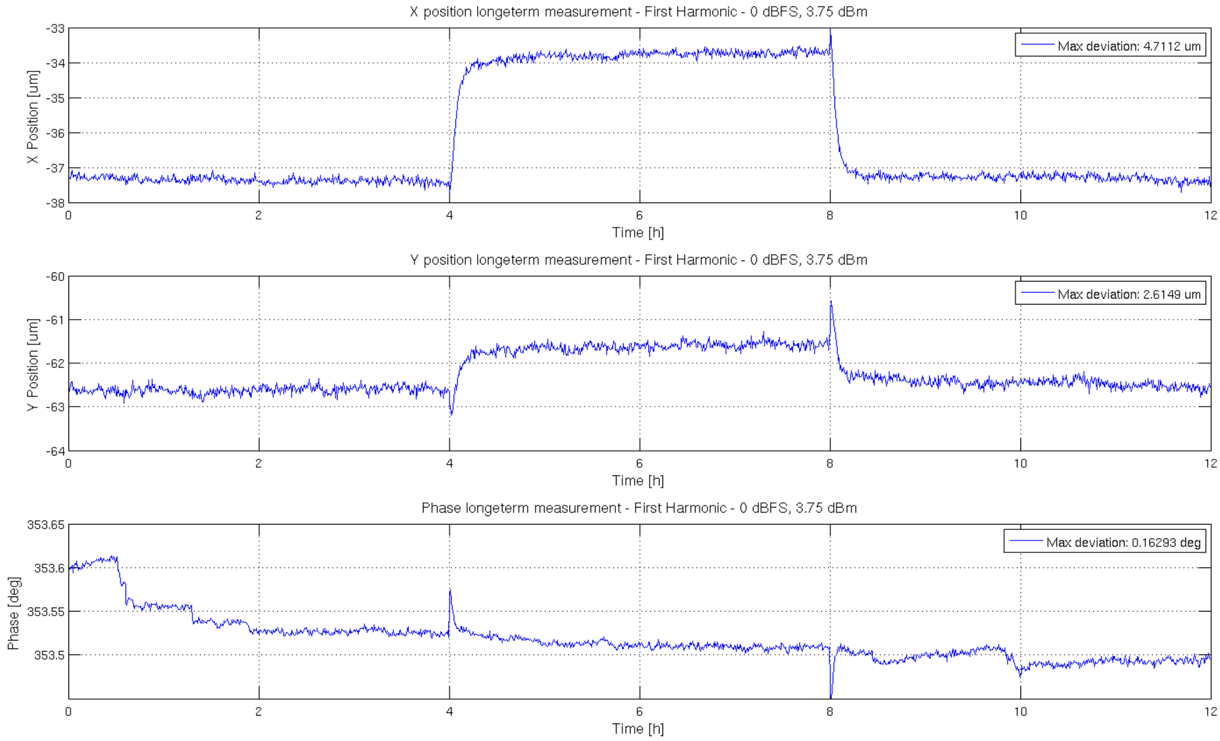


Figure 47: 12h long term measurements - First harmonic

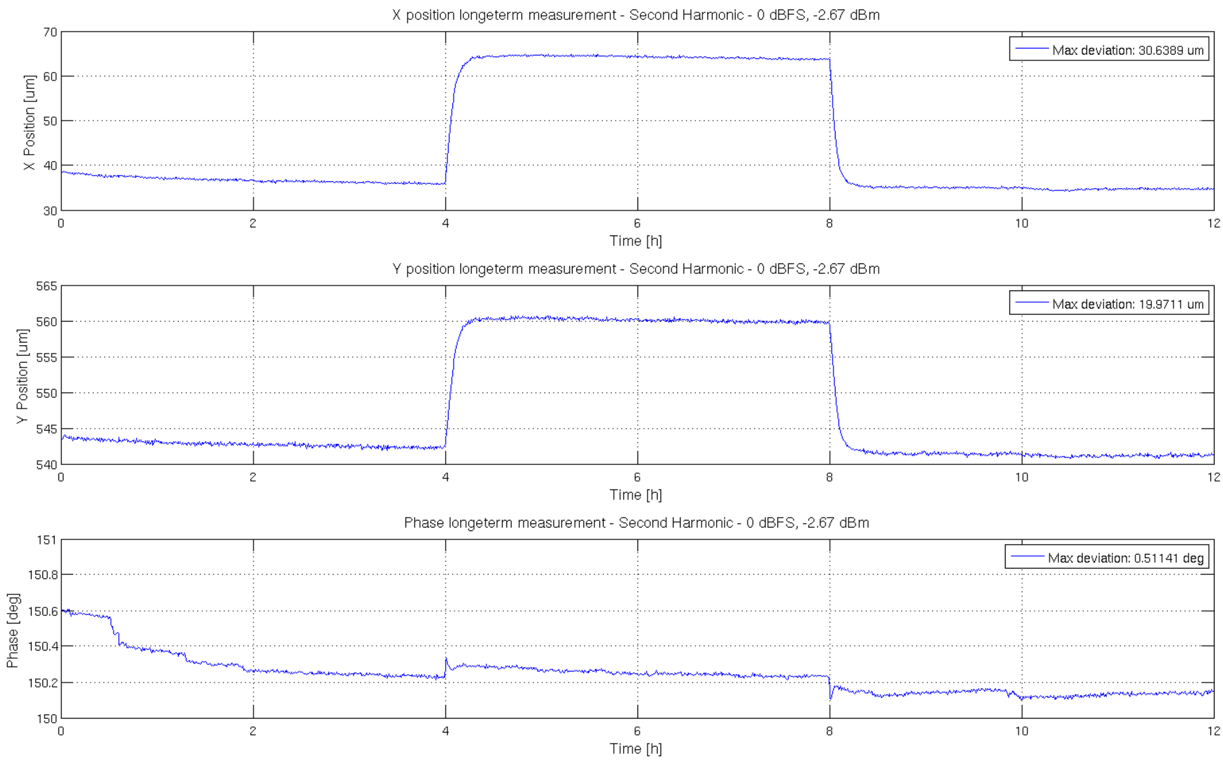


Figure 48: 12h long term measurements - Second harmonic

In the previous pictures, phase and position measurements are presented for the first harmonic (Figure 47) and for the second harmonic (Figure 48). One might notice that:

1. There is a tight correlation between fans, temperature and measurements profile. Measurements show spikes in correspondence of the fan speed changes, and then tent to stabilize following the same temperature time constant.

2. The phase measurements are barely influenced by the temperature changes, apart from the spikes. A possible conclusion is that the phase drifts in the 24h long-term tests were mainly caused by the setup temperature drifts.

3. Overall peak to peak variations are still limited, even if the abrupt fan speed change induces a temperature change which is nearly impossible to observe in the normal working conditions.

Measurement	P2P variation @ harmonic 1	P2P variation @ harmonic 2
Phase	0.16 deg	0.51 deg
X Position	4.71 μm	30.64 μm
Y Position	2.61 μm	19.97 μm

Table 13: Peak to peak variation of the measurements in a 12h long term test

5.3. Measurements with off-centered beam

This section describes the measurements which are done providing the instrument with four different input signals. Their levels are properly tailored to simulate the situation where the beam is half of the radius off-centered. The dynamic range that will be covered by these measurements is chosen accordingly with ESS specifications described in section 2.2.4 (off-centered paragraph), and will be described in details in sub-section 5.3.2.
As mentioned in Section 2.2, the evaluations with off-centered beam are based on a linear estimation of the signal levels in function of the beam position within the pipe. Consequently this is just an approximation that shouldn't be considered for the position measurements. The main purpose of the results is to evaluate how the instrument performs in case the input signals have a big difference in the level.

5.3.1. Measurements setup

At the time these measurements were approached, a new RF generator was available [13]. This offers an output signal up to 26 dBm, so it is possible to move the preamplifier after the two-way splitter, using it only in the signals path and not for the reference signal. This improves different things:

- The reference signal is cleaner since is not on its path anymore;
- It is possible to put an high attenuation (21 dB) after the diode in order to optimize the matching and to make the preamplifier work in the best conditions;
- The quality of the generated RF signal is higher (noise, phase noise, frequency drifts).

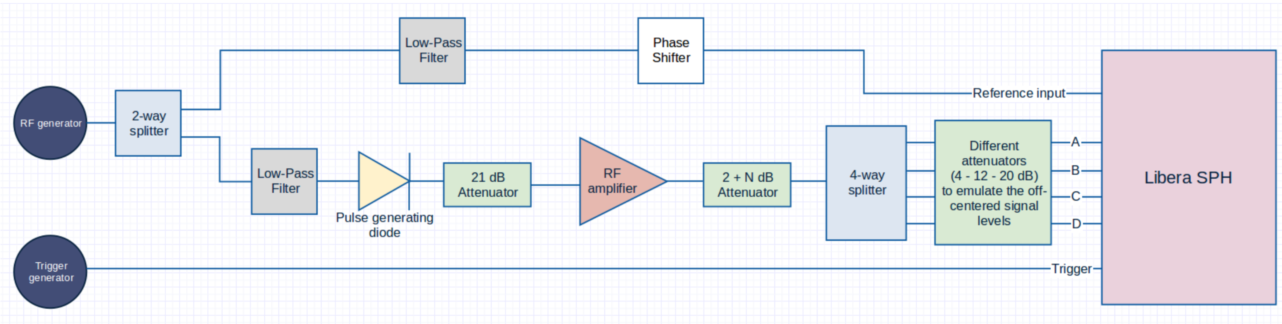


Figure 49: Test setup for measurements with off-centered beam

Figure 49 presents a schema of the test setup used for the measurements with off-centered beam conditions. Apart from the positioning of the RF amplifier, the setup is not changed much. The 21 dB attenuation in after the diode is used for both improving the impedance matching and to optimize the preamplifier output quality (level of the signals for both harmonics and noise floor level).

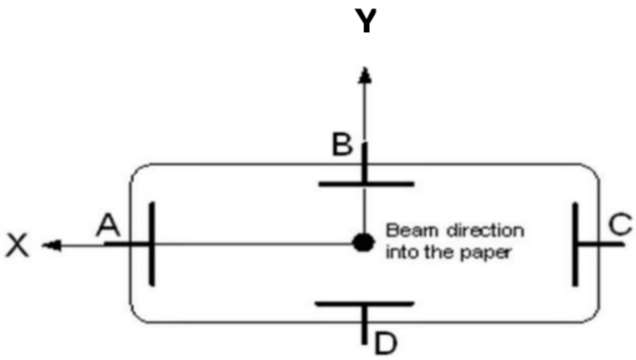


Figure 50: Libera SPH inputs orientation

According with the Libera SPH input channels orientation, it is assumed that the beam position is r/2 displaced in the direction of A. Considering the signal estimations done by ESS, Channel A is then provided with a signal which is 8 dB higher than Channels B and D, and 16 dB higher than Channel C.
To achieve this configuration, attenuators were placed after the 4-way splitter, just before the RF inputs of the instrument. Since every attenuator introduces a phase shift (remember Section 5.2.6), the best choice is to have the same number of attenuators for every input chain, in this case two:

Input A:	2 dB	+	2 dB	→	4 dB
Input B:	6 dB	+	6 dB	→	12 dB
Input C:	10 dB	+	10 dB	→	20 dB
Input D:	6 dB	+	6 dB	→	12 dB

The trigger signal is still generated with the waveform generator feature of the Oscilloscope, TTL square signal with 14 Hz frequency – 50% duty-cycle.

5.3.2. Instrument full scale input and dynamic range of the measurements

Since the test setup is changed, a new full-scale input level is defined for both harmonics. For clarity, it is easy to refer to the highest input level (A), and the other channels follow this level with proper attenuations.

Figure 51 shows 100 samples acquired from the ADC signal: peak is calculated for each channel dividing the peak-to-peak value by two. It is possible to notice the difference between the acquired signals, and that B and D have roughly the same level. Reference signal peak was around 18k counts.

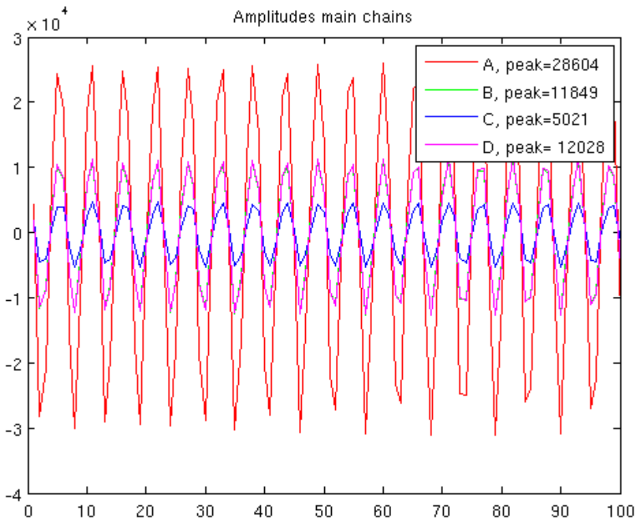


Figure 51: ADC signals acquired from Libera SPH

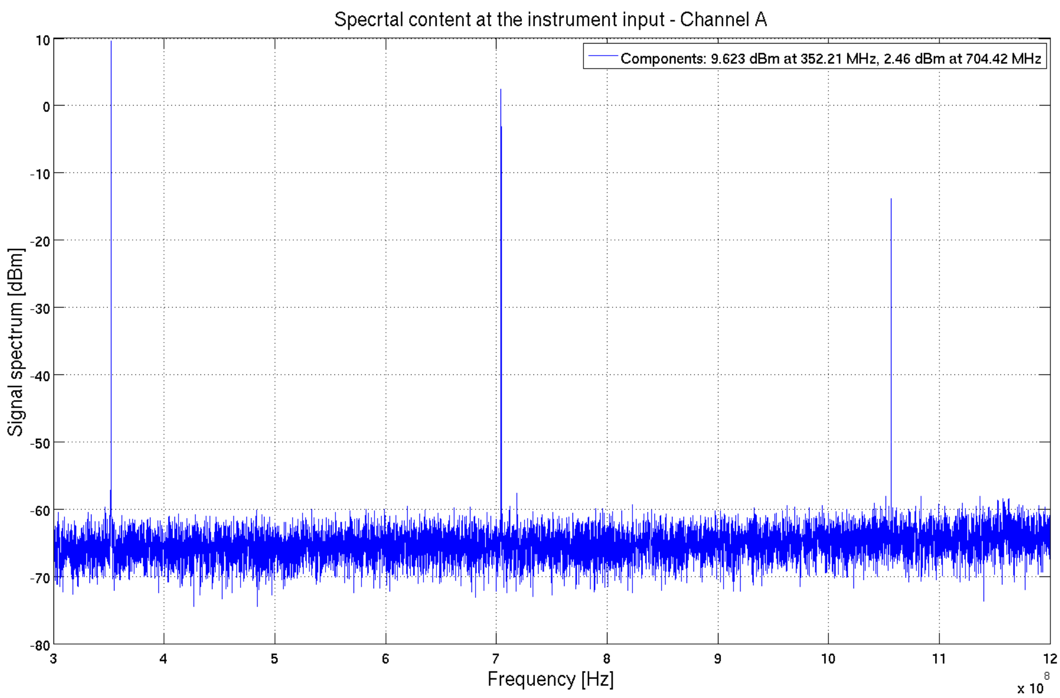


Figure 52: Spectrum of the instrument input signals at 0dBFS

Figure 52 presents a screen shot caught with the spectrum analyzer [12]. The noise floor is below -60 dBm and the amplitudes of the two harmonics are respectively **9.62 dBm at 352.21 MHz and 2.46 dBm at 704.42 MHz**. These levels are identified for both harmonics as **0 dBFS**, as described in Section 5.2.2.

Finally, according with the signal levels expected at ESS described in sub-section 2.2.4, Table 14 presents the dynamic range that will be covered in these measurements. Numbers refer to the highest input, while brackets contain the lowest input level (16 dB lower).

Reference level	Level of First Harmonic	Level of Second Harmonic
0 dBFS	9.62 dBm (-6.38 dBm)	2.46 dBm (-13.54 dBm)
-5 dBFS	4.62 dBm (-11.38 dBm)	-2.54 dBm (-18.54 dBm)
-10 dBFS	-0.38 dBm (-16.38 dBm)	-7.54 dBm (-23.54 dBm)
-15 dBFS	-5.38 dBm (-21.38 dBm)	-12.54 dBm (-28.54 dBm)
-20 dBFS	-10.38 dBm (-26.38 dBm)	-17.54 dBm (-33.54 dBm)
-25 dBFS	-15.38 dBm (-31.38 dBm)	-22.54 dBm (-38.54 dBm)
-30 dBFS	-20.38 dBm (-36.38 dBm)	Out of range

Table 14: Input signal dynamic range for both harmonics

NOTE: with this setup it is not possible to cover the entire range foreseen for the second harmonic (from 7.59 dBm down to -34.28 dBm). Anyway with higher signal level we expect better performance from the instrument, as shown from the first set of measurements.

5.3.3. Resolution measurements

The measurements presented in Section 5.2.3 shown that phase and position resolution of the instrument are not depending on the phase measurement, so this evidence will not be proved again. More interesting is to evaluate the dependency from the input signal level.
In the next measurements, the input signal level is reduced until -30 dBFS putting some attenuators before the 4-way splitter. Figures 53 and 54 present how phase and position resolutions lower as the input signal level lowers. The red curve shows the actual ESS requirement on the resolution, which is 0.2 degrees.

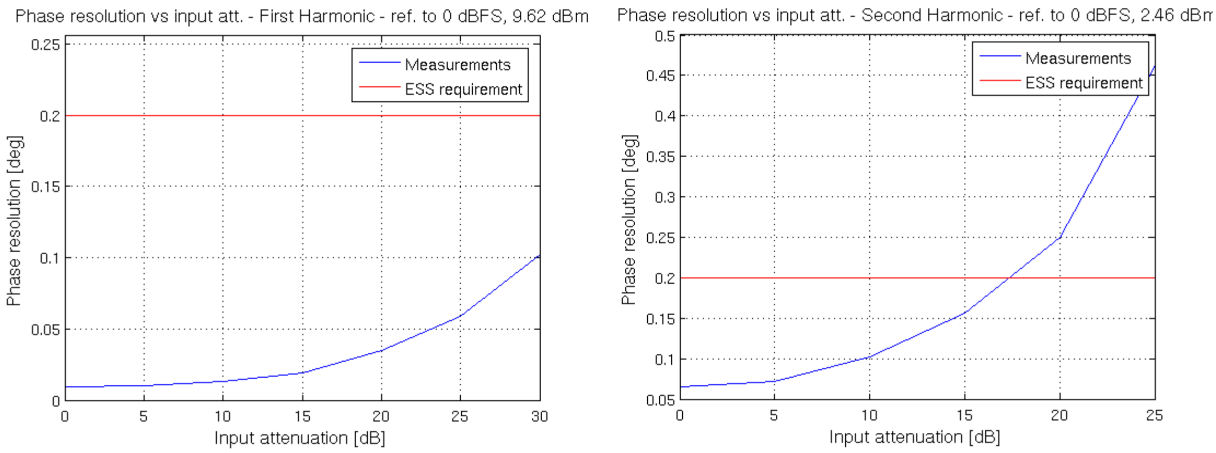


Figure 53: Phase resolution dependence on the input signal level – off-centered beam

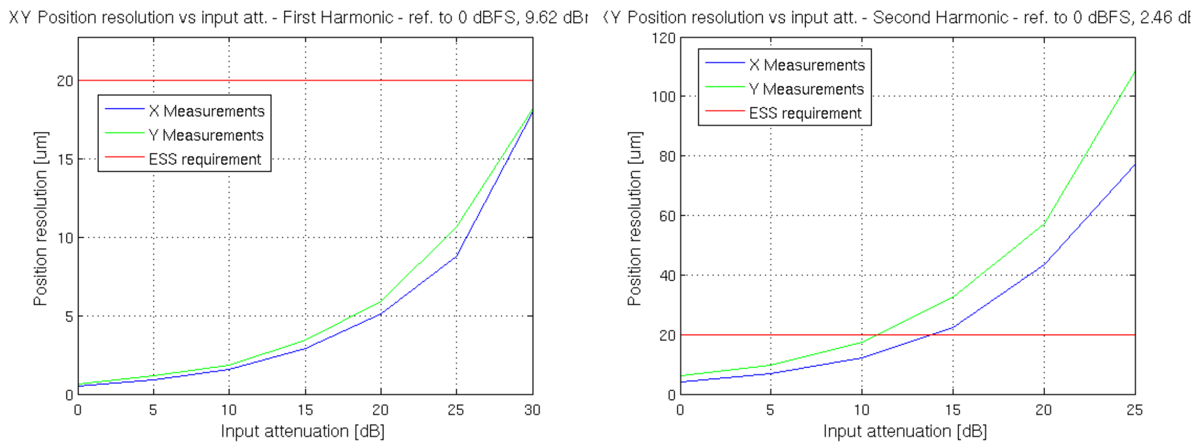


Figure 54: Position resolution dependence on the input signal level – off-centered beam

The phase resolution of the first harmonic is within requirements in the whole covered range, while for the second harmonic it goes out of requirements at -17.5 dBFS (-15 dBm). A similar consideration is valid for the position resolution, too. It is interesting to observe that the resolution on Y position is lower than for the X position: this makes sense since the level of the inputs B and D is 8 dB lower, so the noise is more influent. In general, the resolution with off-centered signal is comparable with that measured with centered beam.

5.3.4. Precision measurements

The measurements presented in Section 5.2.3 shown that phase and position precision of the instrument do not depend on the phase measurement, and this evidence will not be shown again. Anyway, it's interesting to evaluate the relation between precision and input signal level. Figure 55 and 56 present the precision dependency on the input signal level.

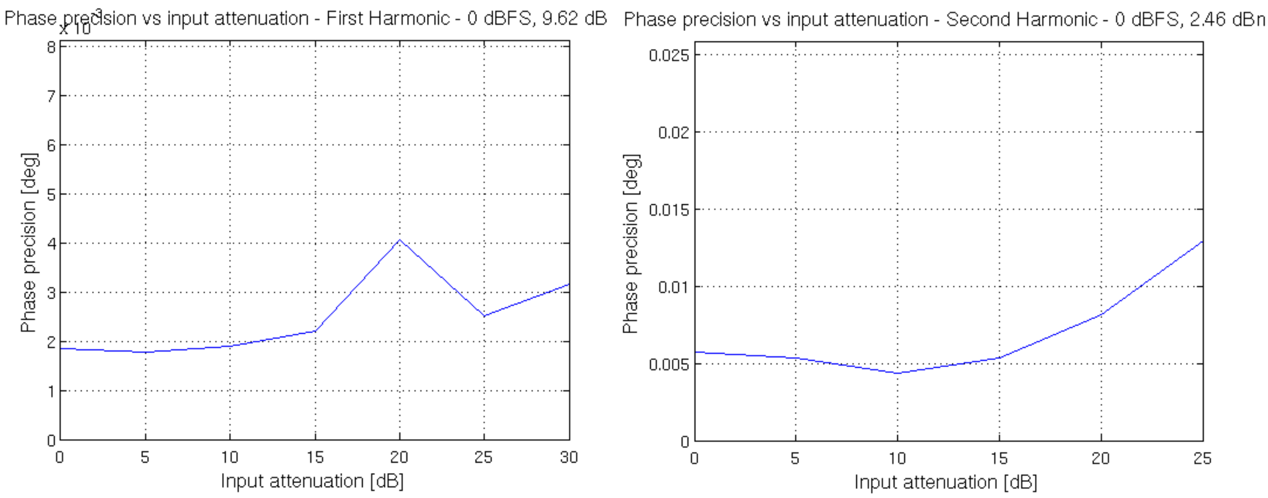
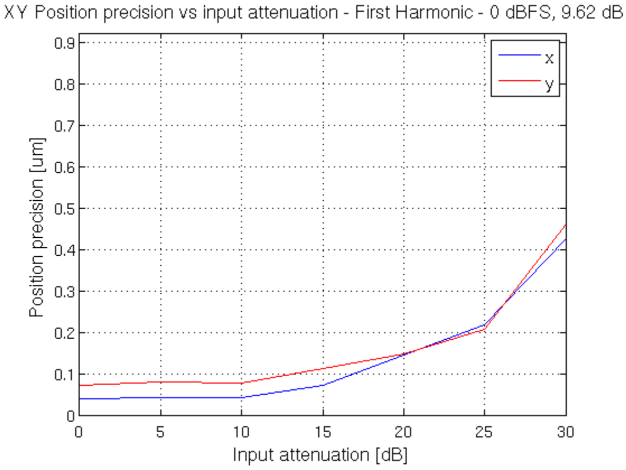


Figure 55: Phase precision dependence on the input signal level – off-centered beam



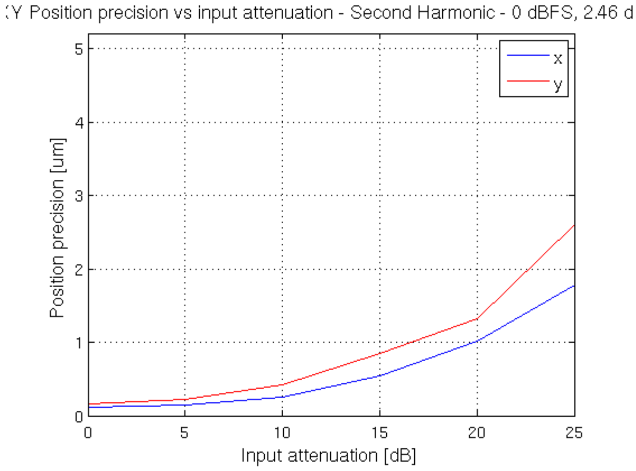


Figure 56: Position precision dependence on the input signal level – off-centered beam

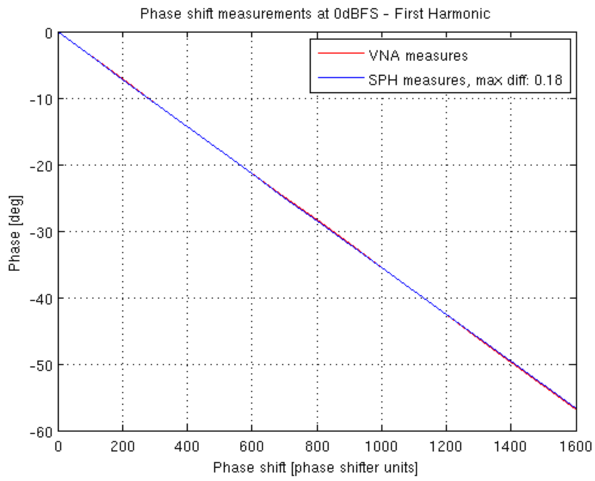
Precision of phase and position signals is the same as in the case of centered beam. As the input signal decreases the same exponential dependency is observable, due to the higher influence of the noise. Furthermore, precision on Y position signal is worse than for X position, as for the resolution.

5.3.5. Accuracy measurements

The phase accuracy of the instrument is evaluated comparing the results with the VNA measurements – as it is done in Section 5.2.5, with the only difference of the signal levels.

The phase shifter is used to shift the reference signal through 16 equal steps, corresponding to 100 units in the shifter device. The measures are repeated 10 times for each phase shifter position. The result is the average of the measurements, after excluding the highest and lowest values. The measurements are performed at four different input amplitudes which are 0, -10, -20 and -30 dBFS respectively.

Figures from 57 to 63 show the results achieved at all the input levels, first for 352.21 MHz harmonic and then for 704.42 MHz harmonic. The first plot shows the total phase shift introduced by the shifter in function of the shifter units, while the second shows the phase shift introduced by each step (100 units).



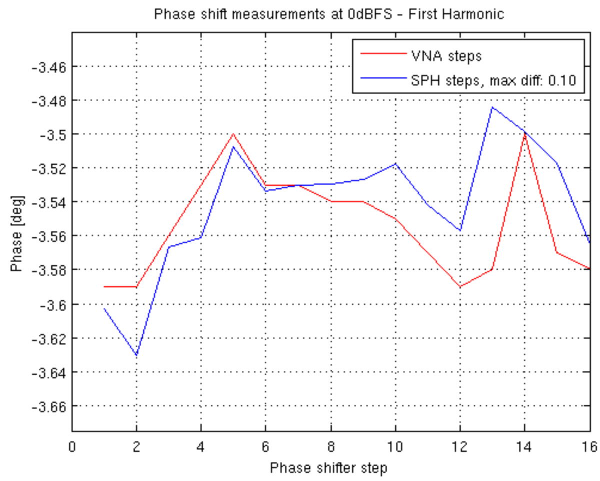


Figure 57: Phase accuracy at 0dBFS - First harmonic

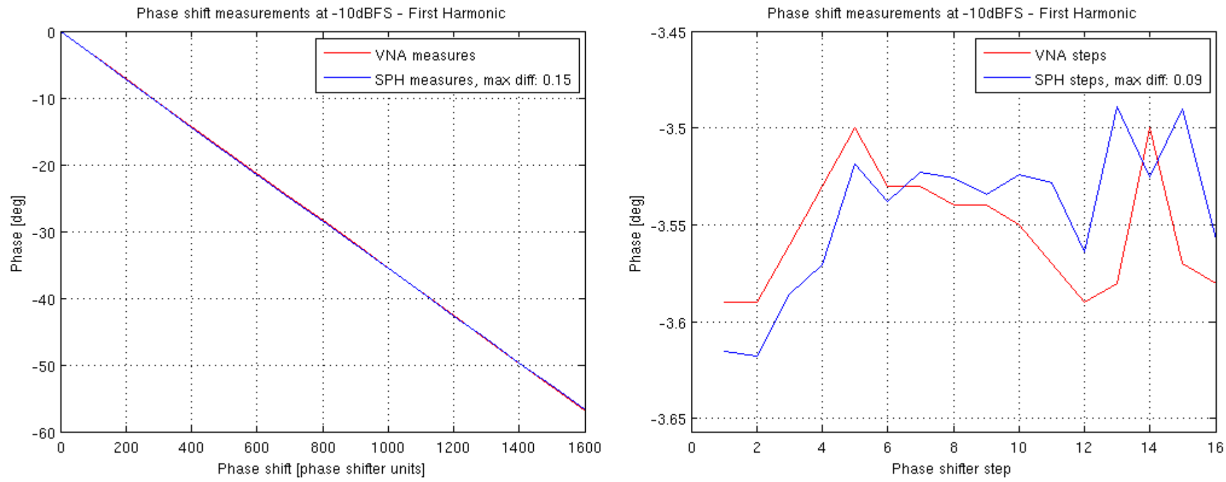


Figure 58: Phase accuracy at -10dBFS - First harmonic

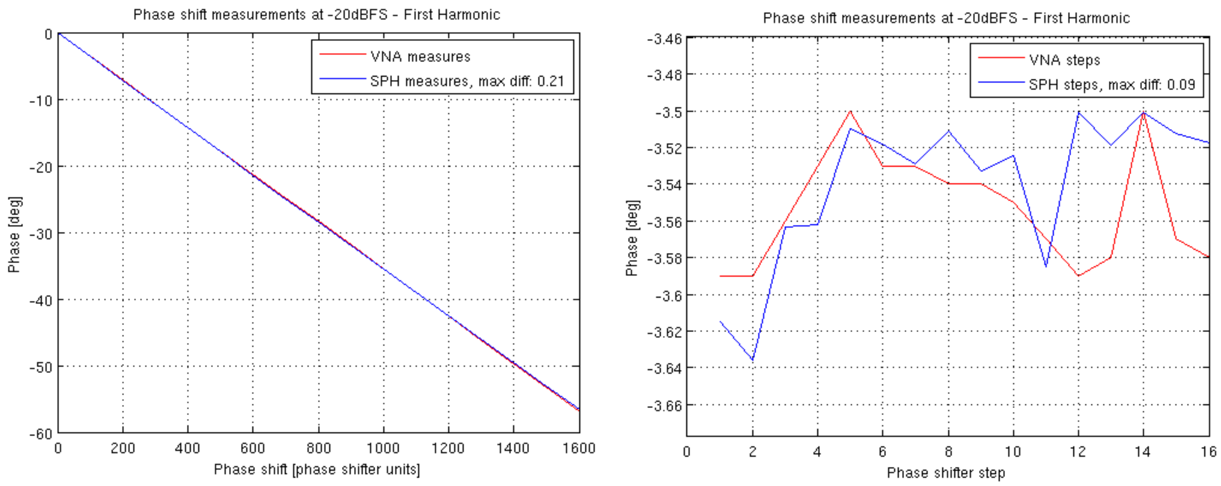


Figure 59: Phase accuracy at -20dBFS - First harmonic

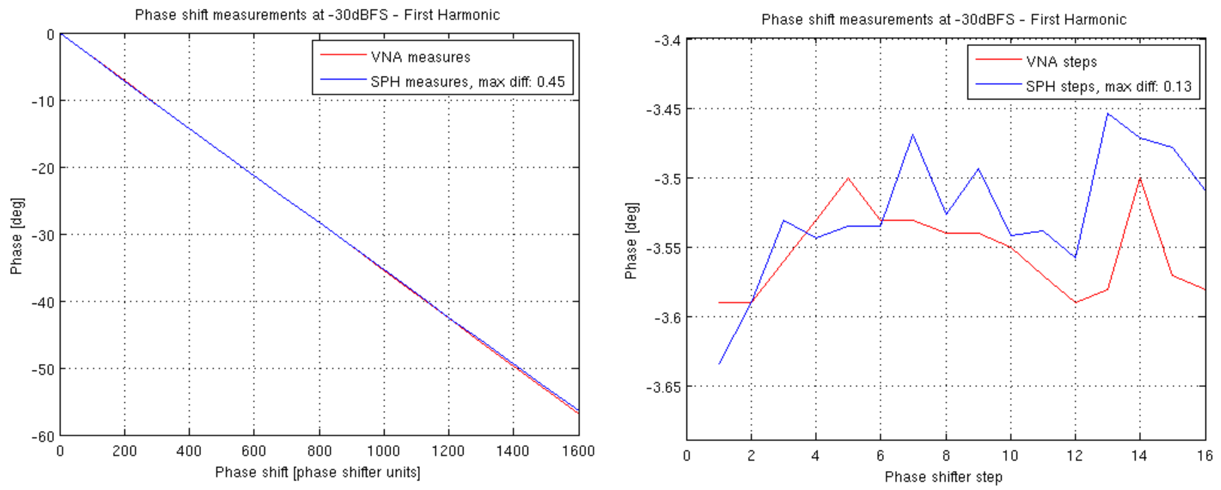


Figure 60: Phase accuracy at -30dBFS - First harmonic

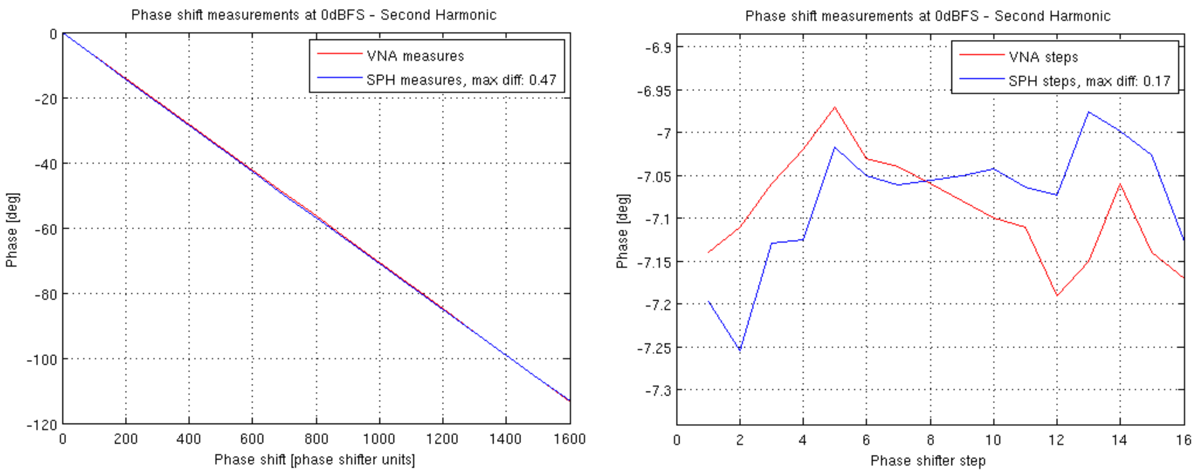


Figure 61: Phase accuracy at 0dBFS - Second harmonic

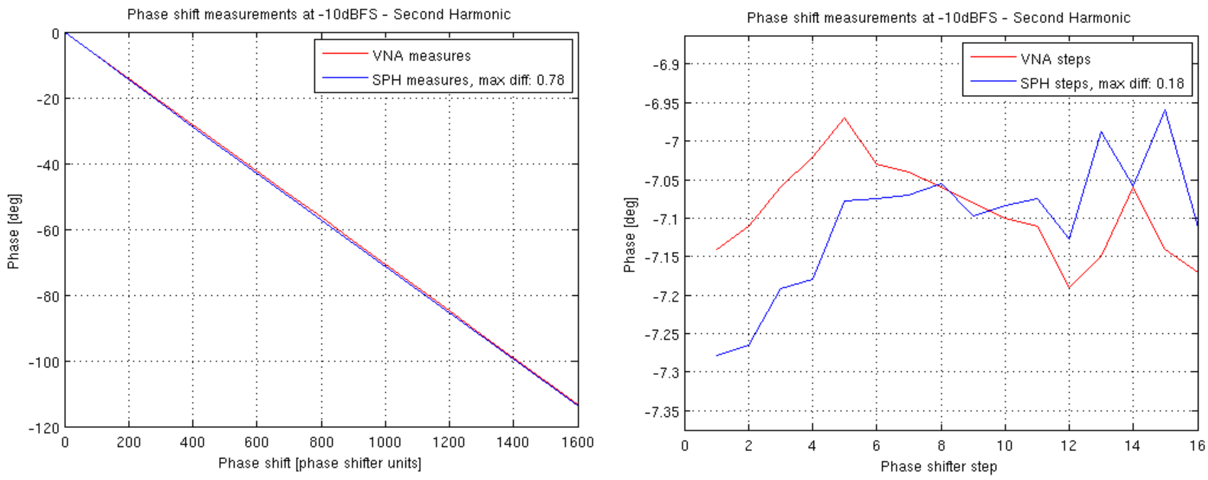


Figure 62: Phase accuracy at -10dBFS - Second harmonic

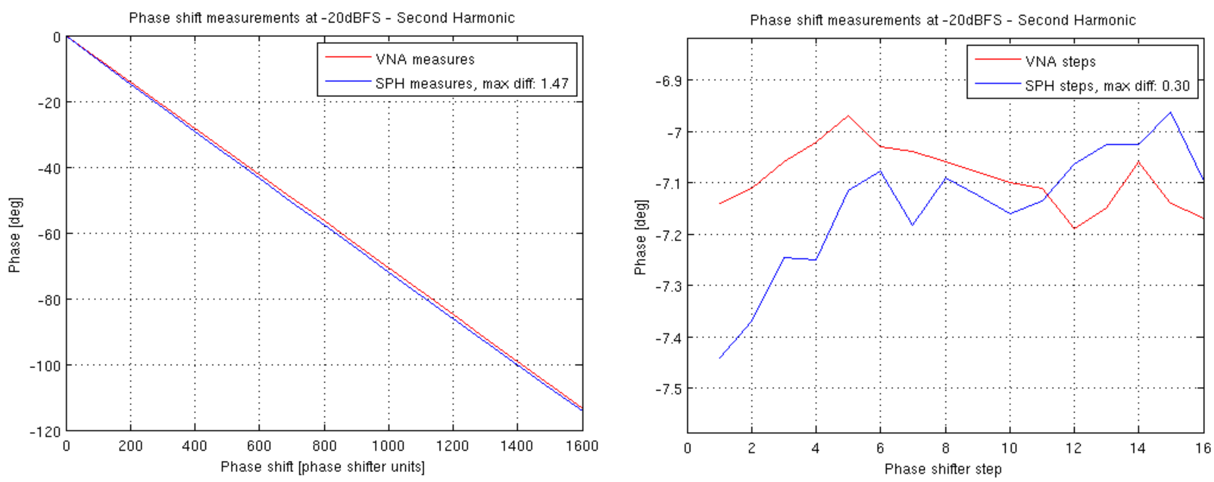


Figure 63: Phase accuracy at -20dBFS - Second harmonic

From the results, the considerations presented in Section 5.2.5 are still valid. The measurements show the same non-linear profile of the phase shifter, as measured with the VNA. Measures with the second harmonic still deteriorate faster lowering the signal level, if compared with the first harmonic. Again, this is explainable considering that first the level of the second harmonic is 7 dB lower than the first one, second it is outside the instrument bandwidth, so it gets even more attenuated.

The overall accuracy is within ESS requirements. An exception is the second harmonic measurements at -20 dBFS. Considering the accuracy of the second harmonic, it is important to keep in mind that if this is used to compare the phase shift with the 352.21 MHz reference, then both measurement and error should be divided by two.

5.3.6. Stability measurements

The stability measurements for the off-centered beam are the same presented in section 5.2.6. The **first** one evaluates the influence of the phase on the position measurement. This evaluation is possible observing theposition measurements during the phase accuracy evaluation, presented in the previous pages. Figures 64-67 present the position measurements on first and second harmonic.

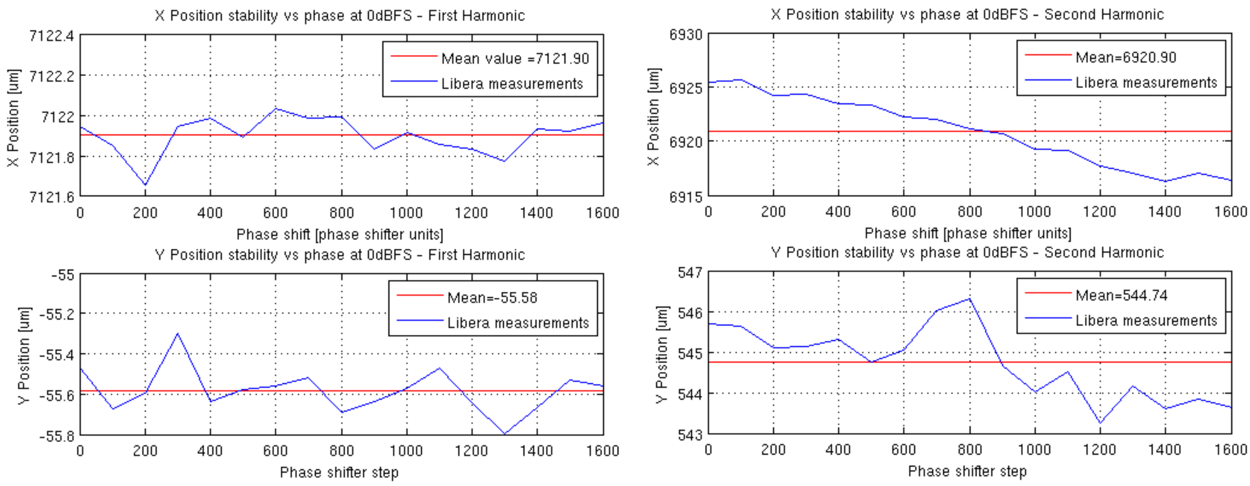


Figure 64: Position stability vs phase at 0dBFS

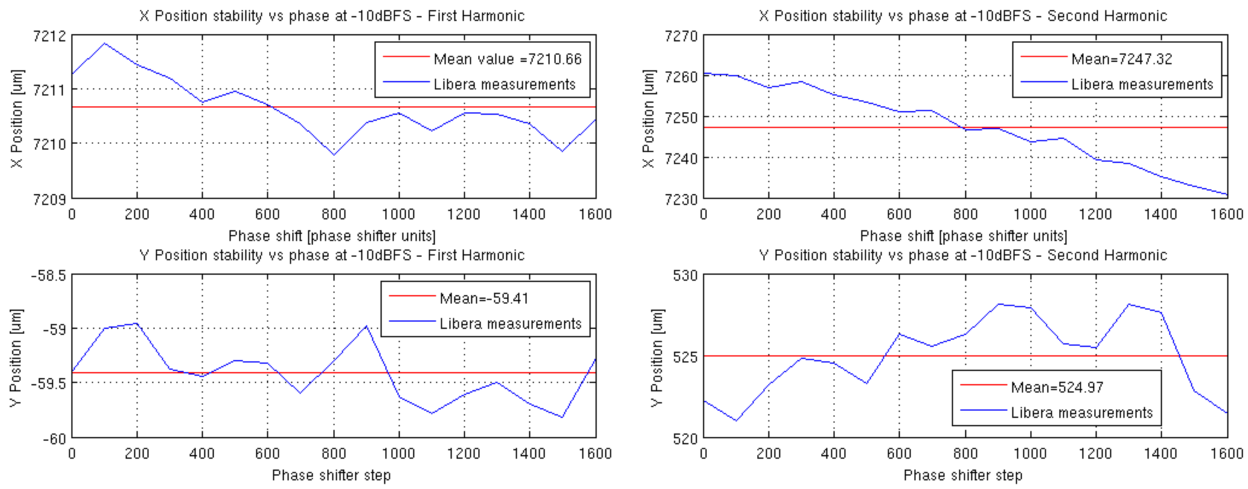


Figure 65: Position stability vs phase at -10dBFS

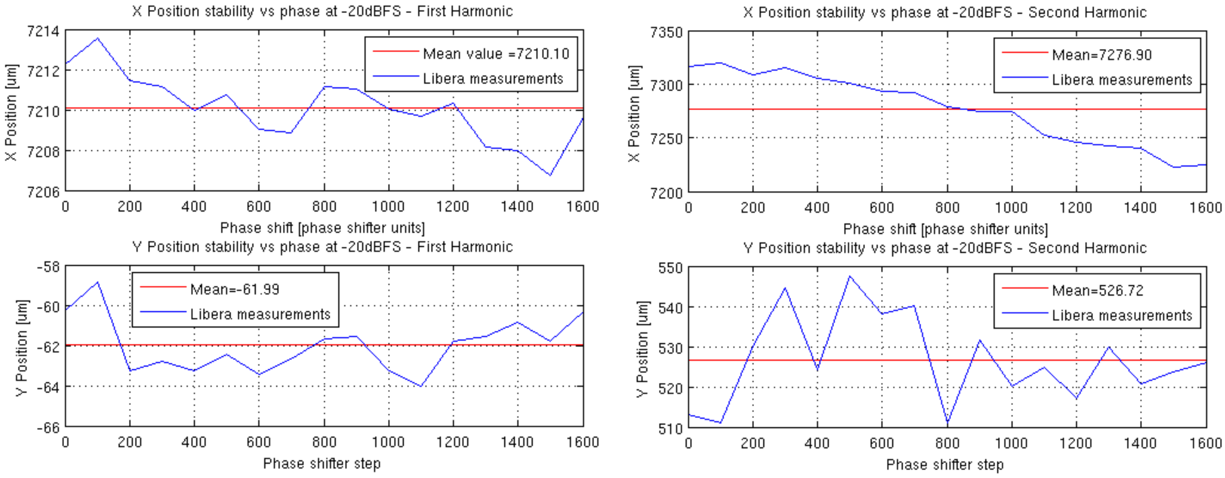


Figure 66: Position stability vs phase at -20dBFS

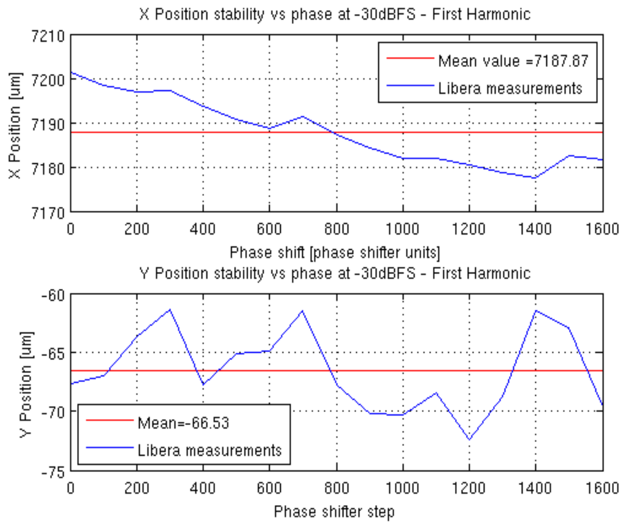


Figure 67: Position stability vs phase at -30dBFS

Since the instrument is not calibrated, the position value is not significant at this moment. Purpose of the test is to evaluate how stable are the measures around their mean value, depending on the phase shift.

The **second** stability measurement is the evaluation of phase and position stability on the input signal level. The same approach and the same attenuators described in Section 5.2.6 are used. Results for phase and position are shown in Figure 69 and 69.

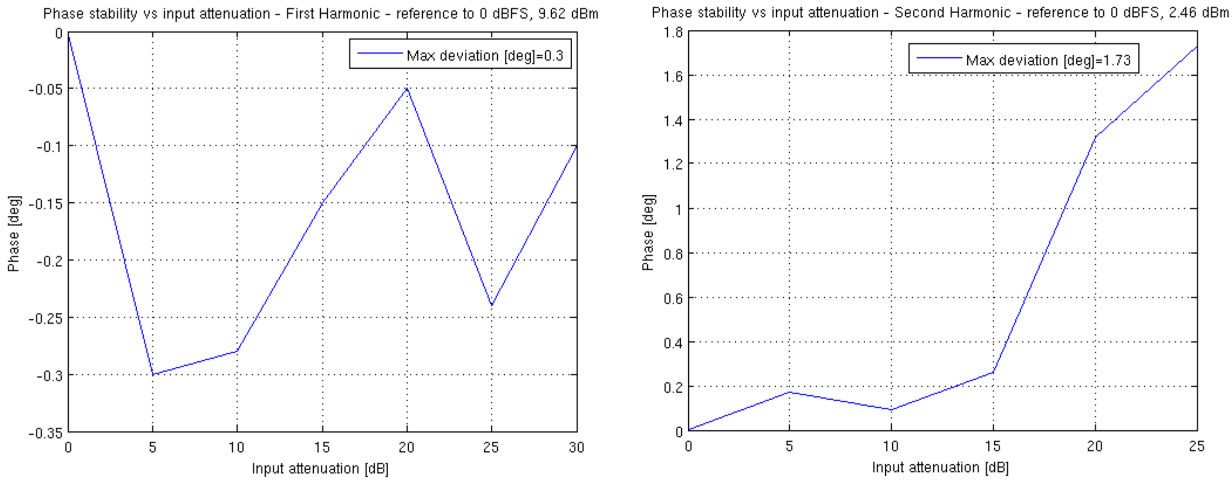


Figure 68: Phase stability vs input signal level

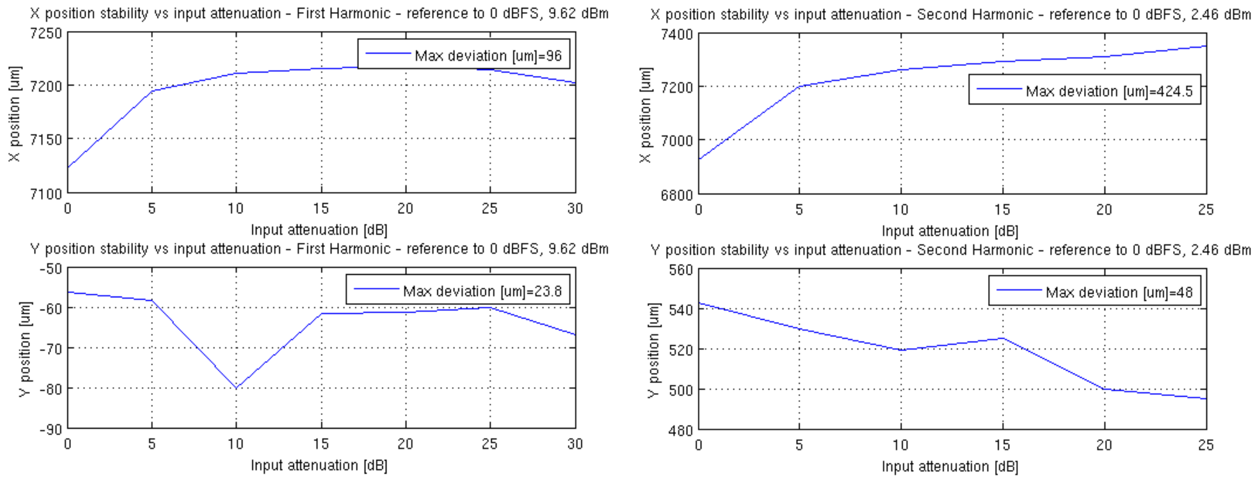


Figure 69: Position stability vs input signal level

As for the phase accuracy evaluation, the phase measurements achieved from the second harmonic should be divided by a factor of two to be compared with the first harmonic. Consequently also the uncertainly reduces by a factor of two.

With reference to the results achieved with centered beam, one can notice that the the phase and Y position stability is comparable. On the other hand, X position is less stable. As the signal level at input C is gets lower and lower, the position is driven only by channel A, and consequently it tents to grow in value and saturate.

6. Measurements with the BPM test-bench

This chapter describes all the position measurements performed using the BPM test-bench designed and manufactured by ESS – described in Section 2.3. With the horizontal moving slit that enables the pipe movement, it is possible to perform position measurements for the evaluation of the position accuracy, at least in the horizontal plane.

6.1. Characterization of the BPM test-bench

From the RF signals point of view, the BPM test-bench can be seen as a six-port device. Two ports (1 and 2) are directly connected to the wire which passes through the pipe, and other forth ports (namely A, B, C and D) are the BPM outputs. Port convention is shown in Figure 70.

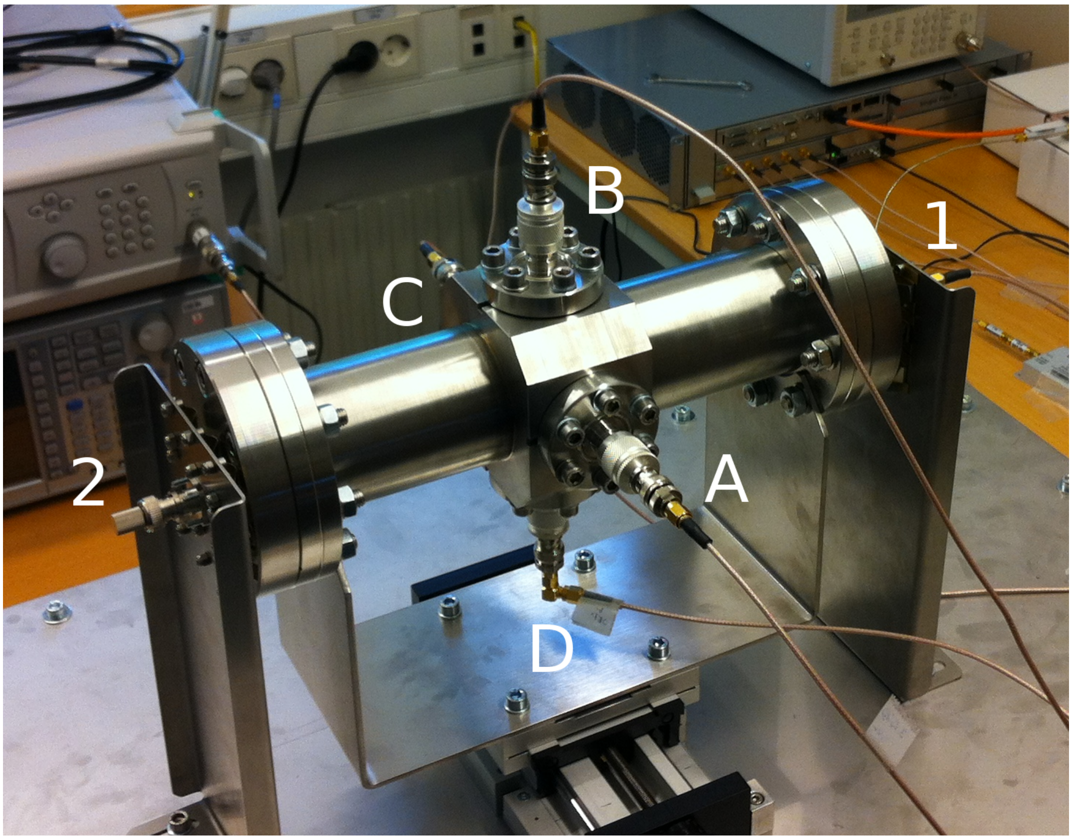
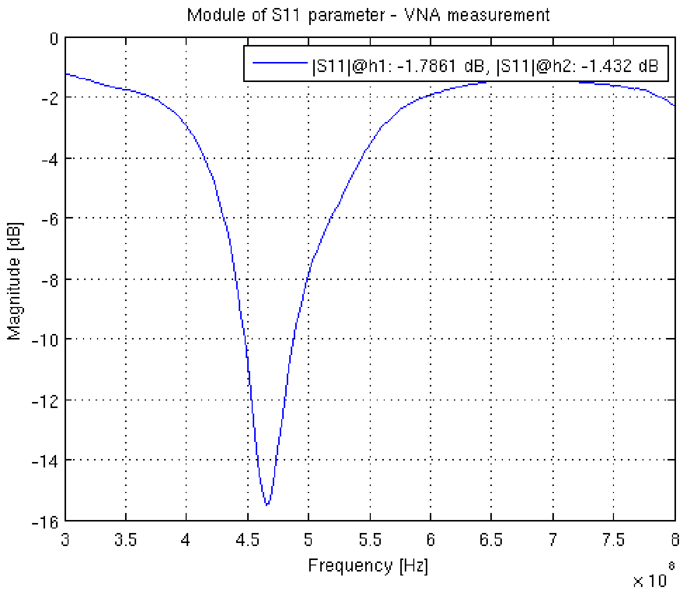


Figure 70: Port convention for the BPM test-bench

Before starting any measurement with the device, it is good to characterize its ports using the VNA. This provides the information about power percentage that is transferred through the pipe, and the portion transferred to the BPM pickups. Due of the impedance miss-matching between RF cables and beam circular pipe and the "homemade" soldering of the wire, it is expected to have an high insertion loss

6.1.1. Module of S11

S11 is the scattering parameter that represents the relation between the reflected wave and incident wave at port 1, the port used for feeding the test-bench. Evaluating the module of this parameter it is possible to measure the **Return loss** at the input of the device.
The VNA was calibrated and configured to measure the parameter, and Figure 71 shows how module of S11 changes from 300 to 800 MHz.



The measurement confirms the bad matching between the RF input (50 Ohm) and the circular waveguide impedance:

- First harmonic |S11| @ h1 = **-1.786 dB** → **66.3 %** of the power is reflected;
- Second harmonic |S11| @ h2 = **-1.432 dB** → **71.9 %** of the power is reflected;

This is the first time the test-benched is assembled and many solutions (e.g. L-C matching networks) can improve the impedance matching.

6.1.2. Module of SA1 and SC1

SA1 and SC1 are the scattering parameters that represent the relation between the waves transmitted to pickups A and C and the incident wave at port 1. Evaluating the modules of these parameters it is possible to measure the **Insertion loss** between input and the BPM RF outputs.
For this measure, the VNA is configured and calibrated as a three-port device, feeding the port one and measuring the power level on ports A and C. The moving slit is set in order to keep the wire at the center of the pipe. Figure 72 shows how the modules of SA1 and SC1 change depending on the frequency.

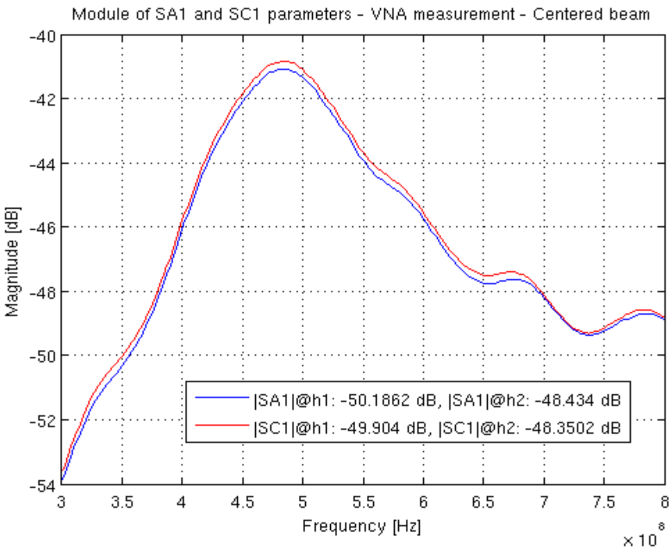


Figure 72: Modules of SA1 and SC1 with centered beam

Because of the beam pipe symmetry, if the wire is centered the two parameters should be very similar, and this is what the measurement shows. Unfortunately the system has a huge insertion loss, which is around 48-50 dB for the first and second harmonic.

If the wire is moved within the pipe, the signal levels from pickups A and C are expected to change accordingly. Figure 73 shows what happens if the the wire is moved off-center by 15 mm, first in the direction of A and then in direction of C.

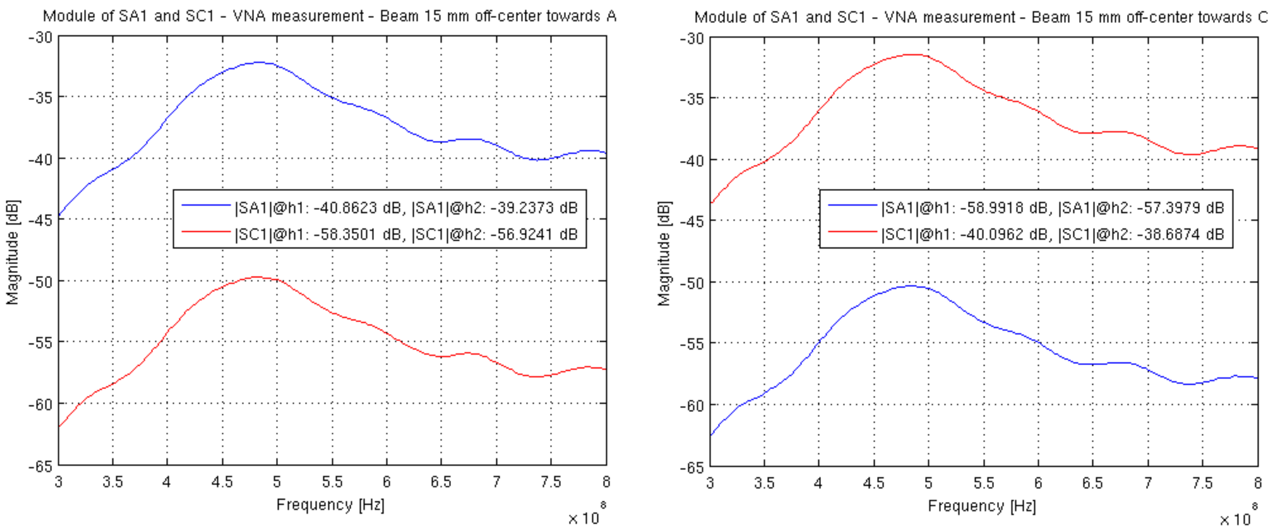


Figure 73: Modules of SA1 and SC1 depending on wire position

In terms of symmetry the system shows quite a good behavior: moving from +15mm to -15 mm the signal traces are just swapped, keeping the same shape and showing almost the same distance. Another interesting fact is that the difference between the power level of the two signals is not far from the one that was estimated in Section 5.3, when the off-centered situation was simulated using attenuators.

<u>Wire 15 mm off-centered towards A:</u>

- First harmonic |SA1| = **-40.86 dB** |SC1| = **-58.35 dB** Δ = **17.49 dB**
- Second harmonic |SA1| = **-39.24 dB** |SC1| = **-56.92 dB** Δ = **17.68 dB**

<u>Wire 15 mm off-centered towards C:</u>

- First harmonic |SA1| = **-58.99 dB** |SC1| = **-40.10 dB** Δ = **18.89 dB**
- Second harmonic |SA1| = **-57.40 dB** |SC1| = **-38.69 dB** Δ = **18.71 dB**

In the measurements presented in Section 5.3, a difference of 16 dB between input A and C was introduced with attenuators. For the purpose of simulating the off-centered beam condition this was a good approximation, at least for resolution, precision and phase accuracy evaluation.
With a more precise positioning of the wire at the geometrical center of the pipe, even more symmetric results are expected.

6.1.3. Module of SB1 and SD1

SB1 and SD1 are the scattering parameters that represent the relation between the waves transmitted to pickups B and D and the incident wave at port 1. With the analysis of these two parameters it is possible to get the information about the pickups in the vertical direction
As before, the VNA is configured and calibrated as a three-port device, feeding the port one and measuring the power level on ports B and D. The moving slit is set in order to keep the wire at the center of the pipe. Figure 74 shows how the modules of SA1 and SC1 change depending on the frequency.

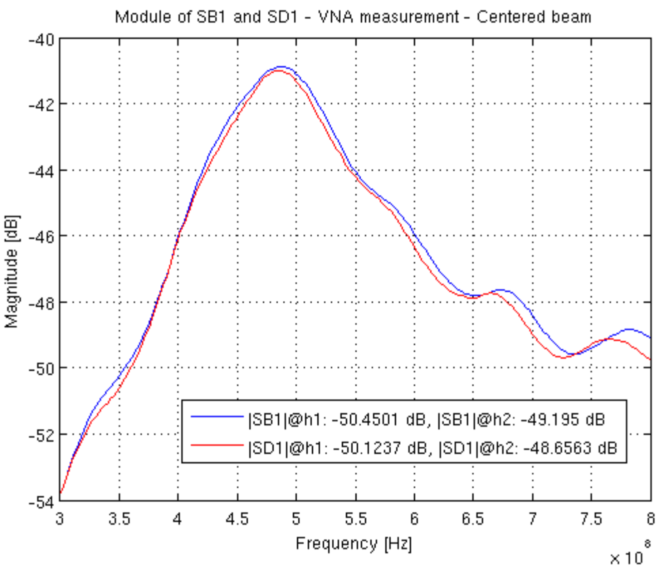


Figure 74: Modules of SB1 and SD1 with centered beam

If the wire is now moved within the pipe, the signal levels from pickups B and D are not expected to change too much. In general their level is expected to decrease because of the increasing distance between wire and pickups, but their values should remain comparable. Figure 75 shows what happens if the the wire is moved off-center by 15 mm, first in the direction of A and then in direction of C.

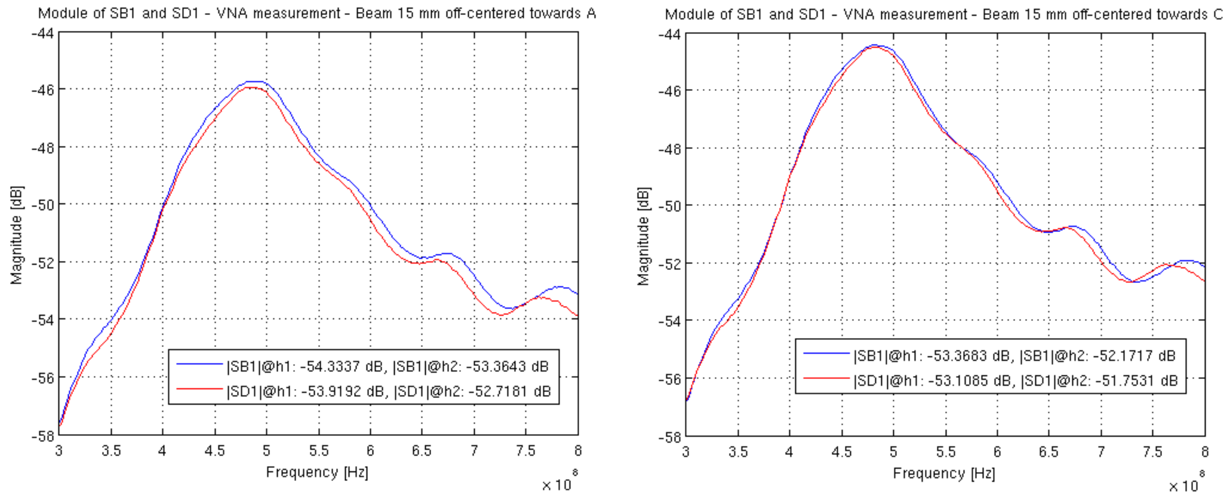


Figure 75: Modules of SB1 and SD1 depending on wire position

From the pictures presented above, the signal levels are 3 dB lower when the wire is at half of the pipe radius. In general the signal levels from pickups B and D are comparable, even though when the wire is closer to pickup A (left-picture) the signal level on pickup B is half a dB higher than level on pickup D. This means that Y position will be slightly positive.
This slight unbalance might be related to different causes, among them a not perfect soldering of the wire in the pipe, or a not precise positioning of the wire at the center of the pipe.

6.2. Measurements in normal signal conditions

After the evaluation of the BPM test-bench with the VNA, it is possible to prepare a new test-setup to connect the test-bench with the instrument. Before performing position measurements it is necessary to calibrate the instrument, at least for X position calculations. This Section describes the test-setup, the instrument calibration process and the results achieved in normal signal conditions. Section 6.3 will explore the performance in case of de-bunched signal conditions.

6.2.1. Measurements setup

For these measurements, the new RF generator was still available. Because of the high insertion loss of the BPM test-bench, the decision was to remove the pulse-generating diode since the second harmonic level would be too low anyway. This means that all the measurements presented in Chapter 6 are related to the first harmonic.
Without the diode, the impedance matching along the test-setup was easier, and the whole setup presented in Figure 76 looks simpler.

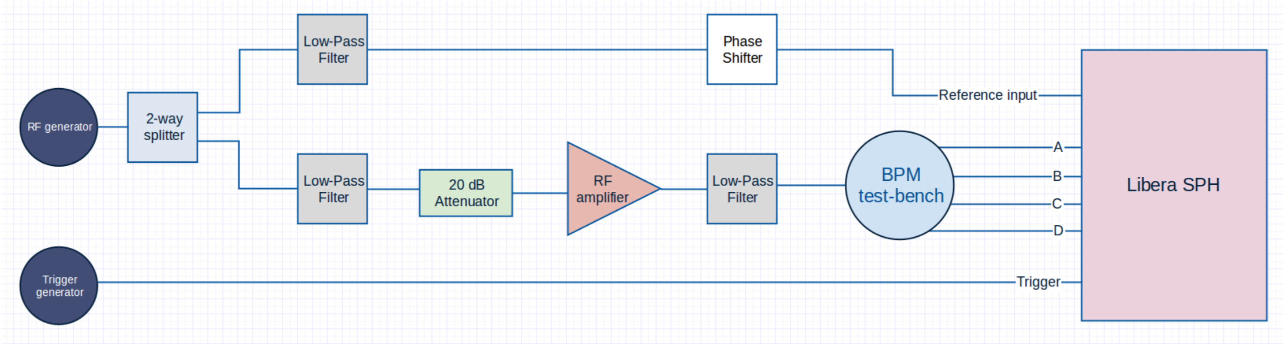


Figure 76: Test setup for measurements with the BPM test-bench

Apart from the pulse-generating diode, the test-setup is again similar to the previous setups. The 20 dB attenuation before the RF amplifier optimizes the signal input level in order to reduce the non-linearity contributions and makes it work far from the saturation condition.

Figure 49 presents a schema of the test setup used for the measurements with off-centered beam conditions. Apart from the positioning of the RF amplifier, the setup is not changed much. The 21 dB attenuation in after the diode is used for both improving the impedance matching and to optimize the preamplifier output quality (level of the signals for both harmonics and noise floor level).

6.2.2. Instrument full scale input and dynamic range of the measurements

As in the previous cases since the test conditions have changed, a new full-scale input level is defined and this time only for the first harmonic. Figure 77 shows 100 samples acquired from the ADC signal: peak is calculated for each channel dividing the peak-to-peak value by two. Please note the low number of counts reachable with the maximum input power level. Reference signal peak was around 18k counts.

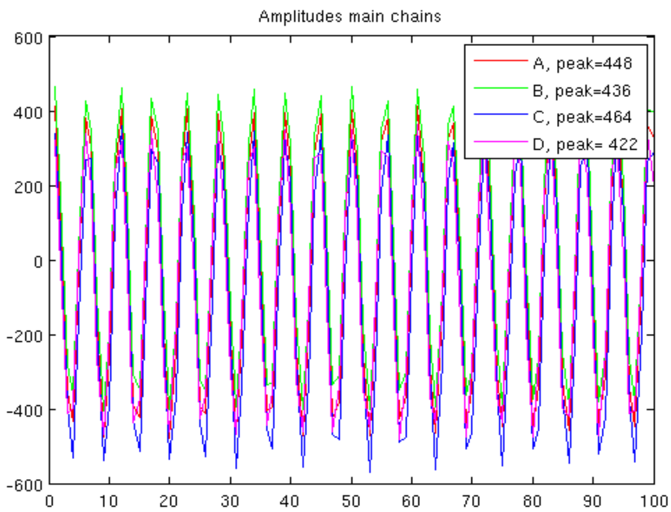


Figure 77: ADC signals from Libera SPH - Centered beam - 0dBFS

If the wire is moved in the range from [-15mm, 15mm], then the levels change accordingly – see Figure 78. In any case the 0dBFS level is defined considering the wire at the center of the pipe. Figure 79 presents a shot from the spectrum analyzer, where the frequency component of the signal at 352.21 MHz is visible.

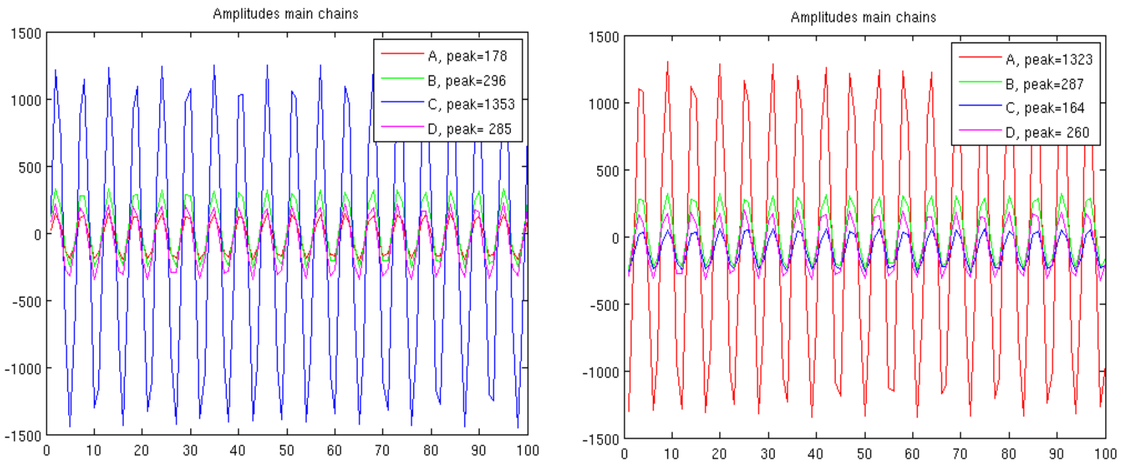


Figure 78: ADC signals at -15mm and +15mm - 0dBFS

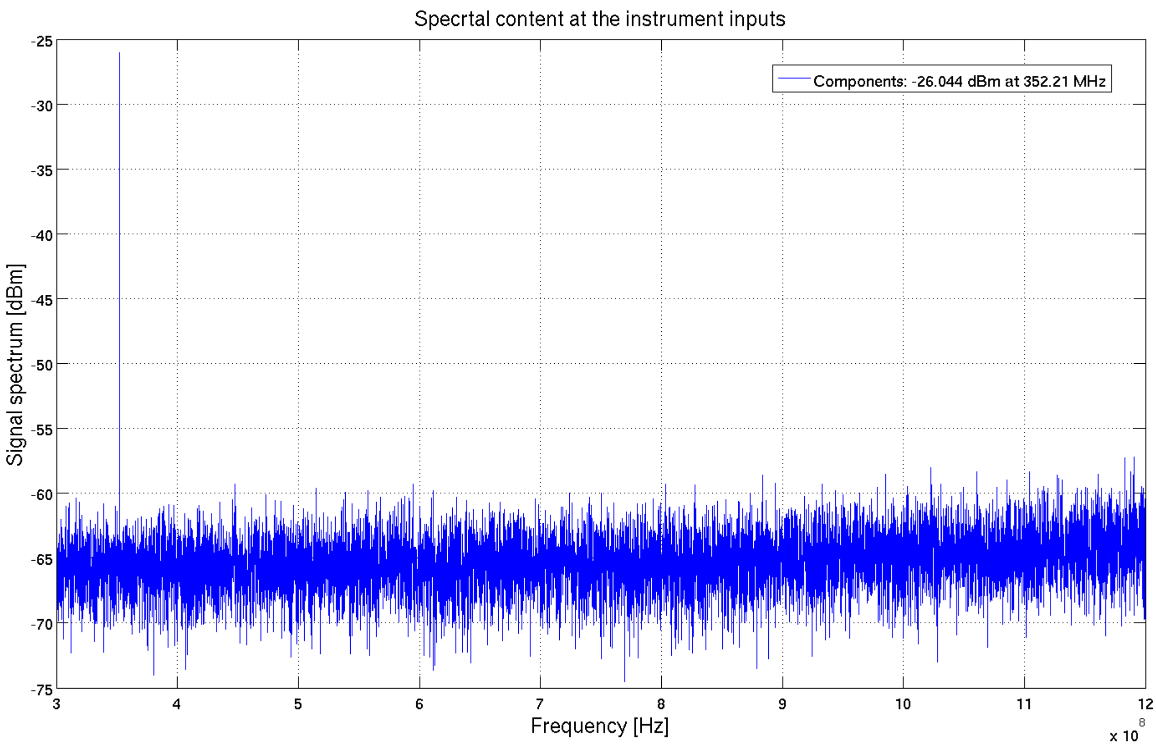


Figure 79: Spectrum of the instrument input signals at 0dBFS

As the spectrum shows, the signal level at the instrument input is -26 dBm, which is already at the lower limit of the dynamic range foreseen for the real machine conditions presented in Section 2.2.4. As a consequence, according with **the normal ESS operating conditions the results will be presented only for the 0dBFS case**.

6.2.3. Instrument calibration

The purpose of the calibration procedure is to match the signal levels observed at the instrument inpits with the wire displacement introduced by the moving slit, in order to establish a coherency between wire movements and position readout. Since the test-bench enables the beam-pipe movement only along X direction, it makes sense to calibrate the instrument only for the X position.

The procedure itself consists in two steps:

1. Geometric calibration: the wire is placed at the geometrical center of the beam pipe, and the amplitudes of the four input signals can be adjusted in the FPGA using four independent gain parameters:

Va'	=	Ka * Va
Vb'	=	Kb * Vb
Vc'	=	Kb * Vc
Vd'	=	Kd * Vd

Purpose of such a calibration is to remove the influence of all the differences in the signal paths, from the button pickups to the RF front-end chains of Libera SPH.
Once this calibration is done, it is expected that with the wire at the center of the pipe, both X and Y position read-outs give values close to zero. Another check that proves the consistence of the calibration is that moving the wire from -15 mm to +15 mm, the X position measurements should be symmetric: negative displacement should be the same as the positive one. Figure 80 show the X position readouts after the geometric calibration. X position is moved from -15mm to 15 mm by steps of 1mm. As it is possible to see, the only point where the measurements are correct is the center of the pipe.

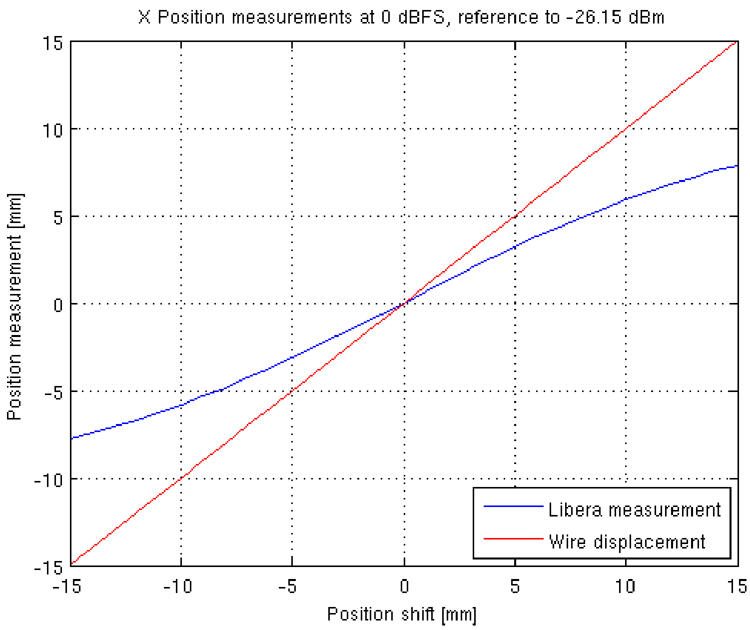


Figure 80: Position measurements after geometric calibration

2. Sensitivity and Offset calibration: the second step of the calibration consists of the tuning of the sensitivity and the offset values. These parameters are present in the "*delta over sum"* formulas used for the position calculations – see Figure 81.

$$X = K_X \frac{(V_A' - V_C')}{(V_A' + V_C')} + X_{OFFSET}$$

$$Y = K_Y \frac{(V_B' - V_D')}{(V_B' + V_D')} + Y_{OFFSET}$$

Figure 81: Position calculation formulas and calibration parameters

The **sensitivity coefficient** adjusts the gain of the formula in order to measure the right beam displacement in a certain region. Since the system composed by pipe and buttons is not linear, it is not possible to set a value which gives accurate readouts at every position but it is necessary to identify a l*inear region* in which the measurements will be fine tuned. According with Figure 80, the linear region is identified from - 5 mm to +5 mm. The Kx coefficient is finally identified with the value that minimizes the position measurement errors in the linear region. Ky is left to the default value.

The **offset parameters** are used to move the "*position reference"* to a point which is not the geometric center of the beam pipe. In the considered case our reference is exactly the geometric center, so the offsets are left to zero, which is the default value.

Parameter	X position	Y position
Sensitivity	15.63	10
Offset	0 µm	0 µm

Table 15: Libera SPH calibration coefficients

NOTE: It might happen that the sensitivity parameter is already known before the calibration, since it is related to the geometry and characteristics of the BPM. The presented approach is general and works also in the case this parameter is not known.
From the ESS simulations for the BPM, the estimated BPM sensitivity was 15.18, which is close to the presented empirical result.

6.2.4. Resolution measurements

In Chapter 5, phase and position resolution have been evaluated against factors like phase, input signal level and number of considered samples per macropulse. Now with the test-bench another evaluation is possible: the dependency of the resolution on the beam position.

In the results presented in Figure 82, the wire is moved from -15mm to +15mm by steps of 1mm, and for each step the resolution is evaluated.

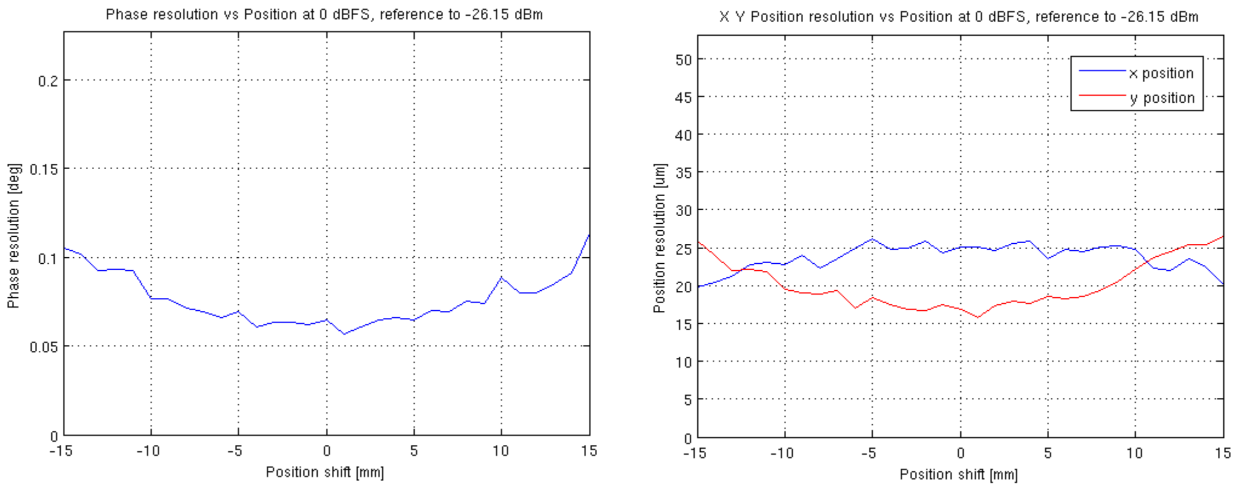


Figure 82: Phase and position resolution vs position at 0dBFS

Three are the main things to observe here:

1. Phase resolution gets worse as the wire gets off the center. This is expected since the phase is calculated as the average of the phases calculated from each input channel.
2. X and Y position resolution are expected to be the same in the center of the pipe. Here the difference is due to the different sensitivity coefficients applied to the two formulas – see Table 15.
3. X resolution gets better when the wire is off-centered. This because either A or C signal get stronger and influence more the resolution, while the other signal is negligible. This is not valid for Y position resolution, since the wire moves on the horizontal plane and both B and D signals get lower.

6.2.5. Accuracy measurements

Before presenting the results of the measurements, it is good to remind how the position accuracy is evaluated and what are the factors that might influence its evaluation. The ideal case would be to have an instrument able to measure the wire position with reference to the geometric center of the beam pipe, and compare its exact position with the Libera SPH readout. Obviously this is not possible with the structure shown in Figure 70.

The only way is to use the rotating knob numeric reference to get the “true” value for the X position, meaning that is not possible to estimate the Y position accuracy. **X position accuracy will be evaluated as the difference between the rotating knob numeric reference and the instrument measured position.**

In this way some non-ideal factors will influence the measurement:

1. The slit is based on a rotating infinite screw moved by a control knob. It is hard to evaluate how accurate and repeatable is this system.

2. The rotating knob has 50 μm resolution, which is half of the accuracy requirement of ESS.
3. The slit moves the beam pipe, bending the BPM RF cables. This might influence the measurements.

Figure 83 presents the X and Y position measurements achieved moving the slit from -15mm to 15 mm by steps of 1mm. The X position plot presents also the ideal value expected from a perfect slit, while the Y position plot reports only the measurements. In comparison with Figure 80, now the instrument is calibrated and shows very nice results, especially in the linear region from -5mm to 5mm, afterwards the saturation effect is more evident. Y position on the other side in not constant but has a slight increase (200 μm). This might be expected since the VNA measurements gave a similar result – see Figure 75.

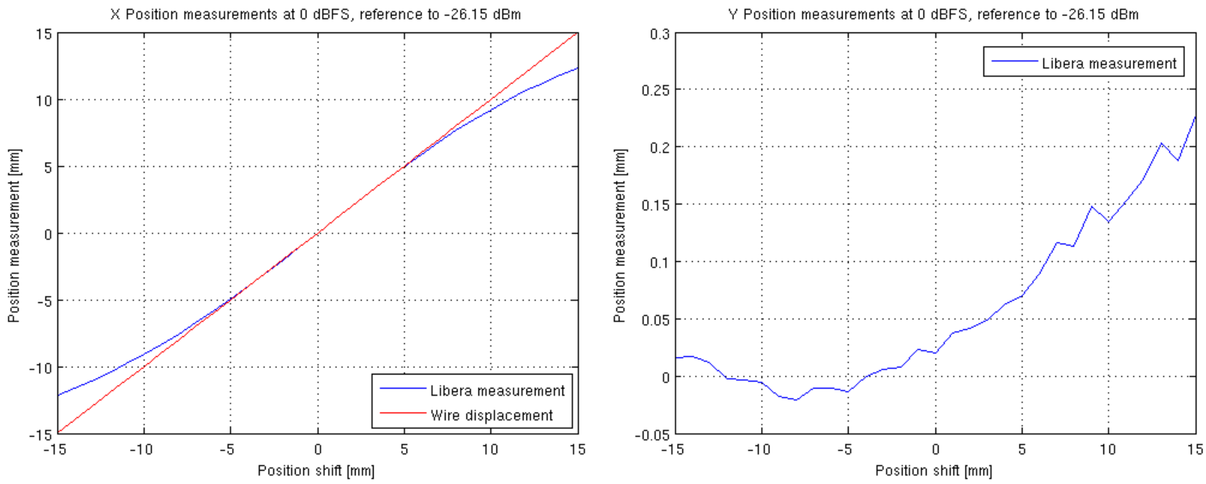


Figure 83: X and Y position measurements at 0dBFS

To evaluate the accuracy of the X position measurement, the difference between the measured values and the ideal value is presented in Figure 84. The first plot shows the accuracy in the whole position range, while the second one focus in the linear region of the BPM, where the instrument was fine-calibrated.
From the second plot, the accuracy is within the ESS requirements in the whole linear range.

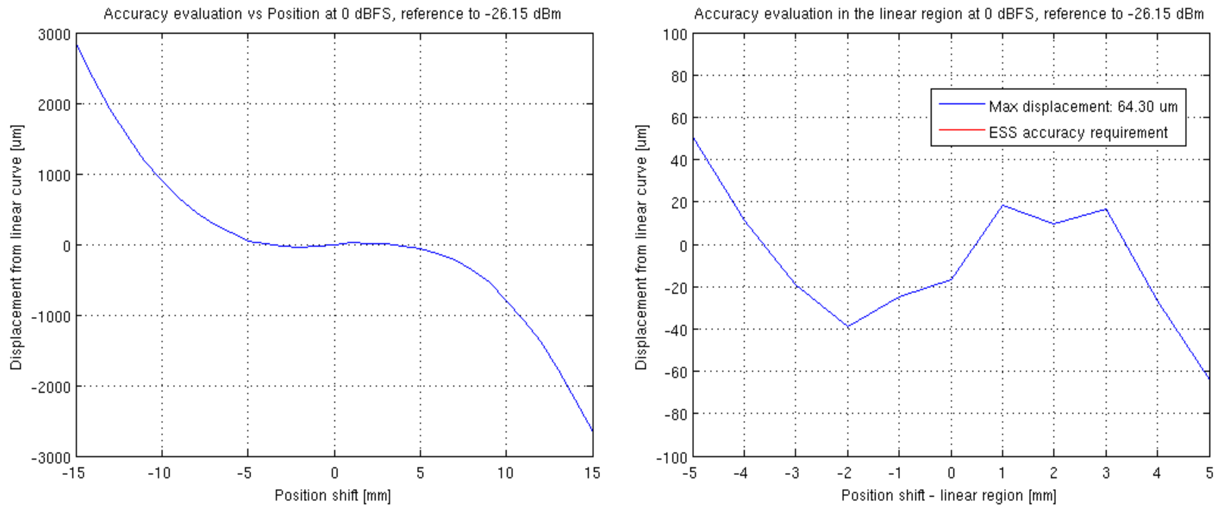


Figure 84: X position accuracy at 0dBFS

6.3. Measurements in debunched signal conditions

An important concern at ESS is the capability to get some useful information from the BPM electronics in case of debunched beam [1]. This condition will be faced during the commissioning of the machine, for example during cavities phase scan. Since all downstream cavities will be unpowered, the beam can become significantly debunched in the longitudinal direction.
In this condition the current pulses will be lower in amplitude but wider in time, and will start to overlap with the others. The consequence on the signal is that the second harmonic will basically disappear and the first one will be much much lower.
ESS requires that even in this case, the instrument should provide at least a rough estimation of the beam position, to complete the tuning process and to dump the beam without facing a risk of damage to the Linac components .

6.3.1. Measurements setup and input dynamic range

The signal conditions described above are simulated lowering the level of the harmonic components of the signal, using the same test setup presented in Section 6.2.1. In debunched beam conditions, the second harmonic just disappears, and the first one is attenuated up to 70 dB.
Considering the proposed setup, this is achieved putting some attenuation before the BPM test-bench. One thing that should be considered is the noise floor at the instrument input – see Figure 79. In any case it will not be possible to go down for 70 dB because the signal will not be distinguished from the noise.
The input reference level (0dBFS) is the same described in the previous measurements, so the results presented here will start from -10 dBFS, which can already be considered as debunched beam condition. Figure 85 shows the input signal spectrum at -30 dBFS, which is the last condition where the RF signal can be separated from the noise.

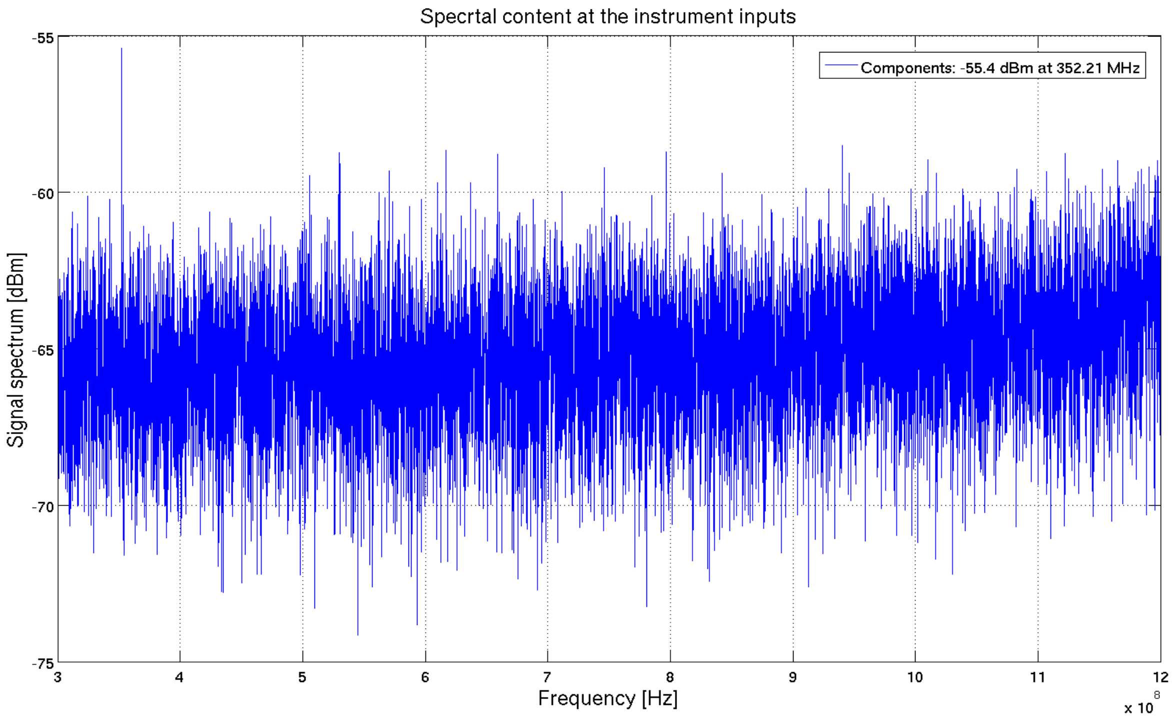


Figure 85: Spectrum of the instrument input signals at -30dBFS

As a further demonstration, Figure 86 presents the ADC signals acquired from the instrument in two conditions: the left plot shows an acquisition done at -40dBFS with wire at the center of the pipe, while the right plot shows an acquisition with no signal applied to the test-setup. As you can notice, there is no noticeable difference.

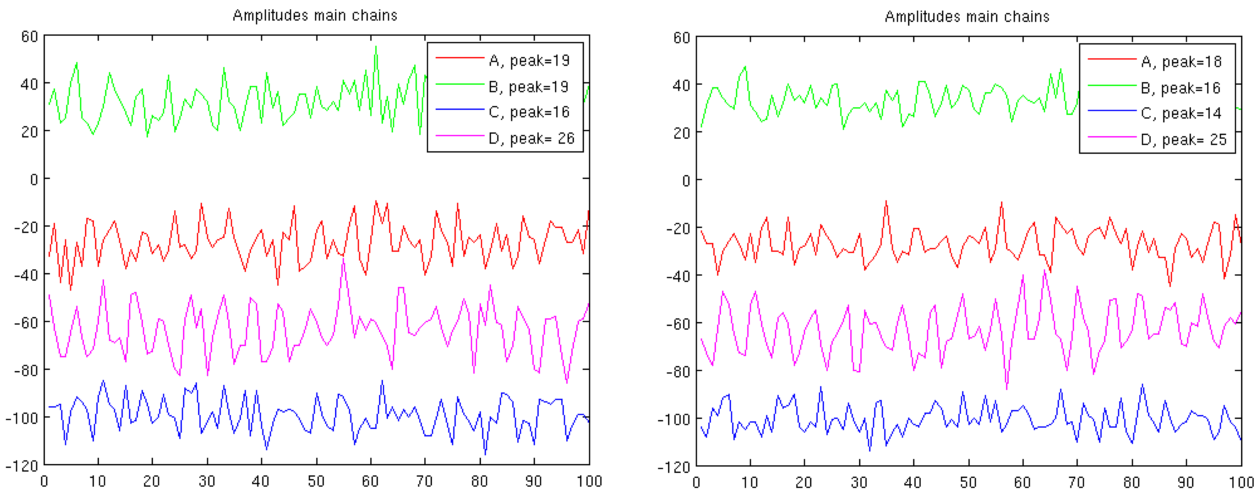


Figure 86: ADC signal acquisitions: a) at -40dBFS b) without RF signal generation

Accordingly with previous comments, Table 16 presents the dynamic range covered in the measurements in debunched conditions.

Reference level	Level of First Harmonic
0 dBFS	-26.15 dBm
-10 dBFS	-36.15 dBm
-20 dBFS	-46.15 dBm
-30 dBFS	-56.15 dBm

Table 16: Input signal dynamic range for the first harmonic

6.3.2. Measurements at -10 dBFS

Figures below present the results of the measurements at -10 dBFS. Figure 87 shows the raw signals acquired from the ADCs, while Figure 88 presents phase and position resolutions. As expected, lowering the signal level lowers the instrument resolution, even though the dependency from the position is the same.
Figure 89 presents X and Y position measurements depending on the wire position: results are still excellent even at this input level.
Figure 90 finally shows the accuracy evaluation, first in the whole X position range, then in the linear region of the BPM. Again, in this region the accuracy is within ESS requirements.

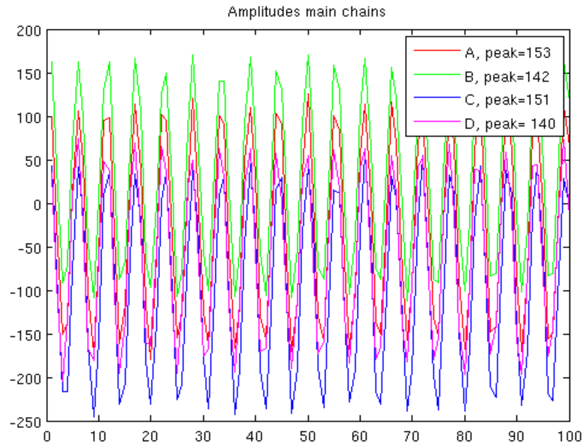
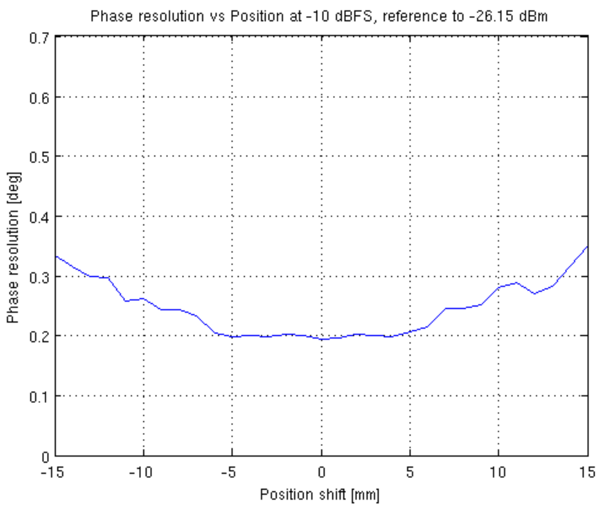


Figure 87: ADC signal levels at -10 dBFS



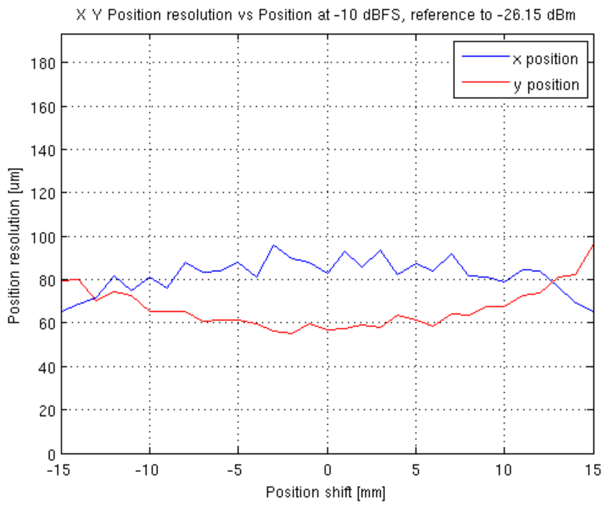
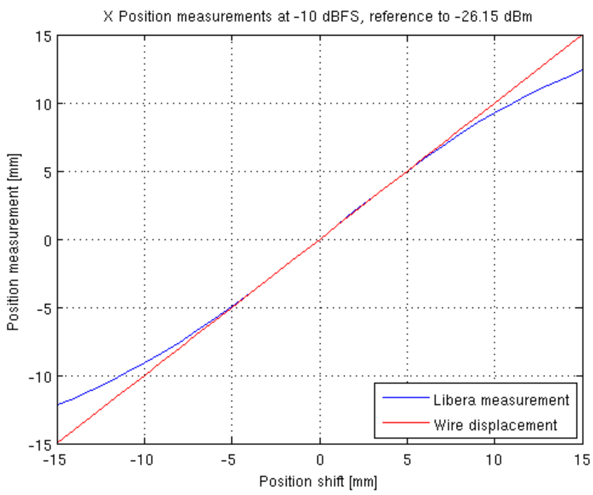


Figure 88: Phase and position resolution vs position at -10dBFS



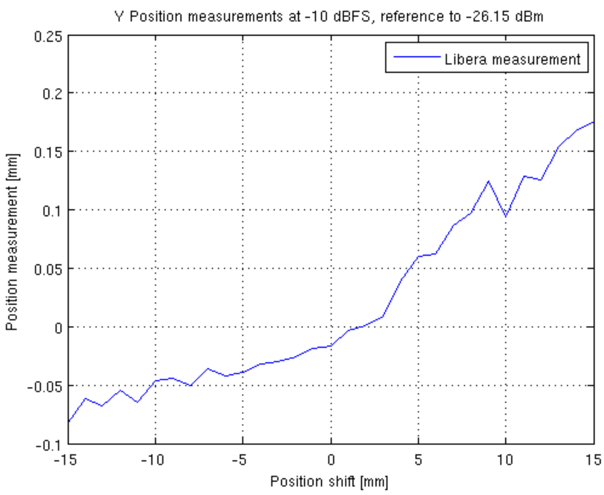


Figure 89: X and Y position measurements at -10dBFS

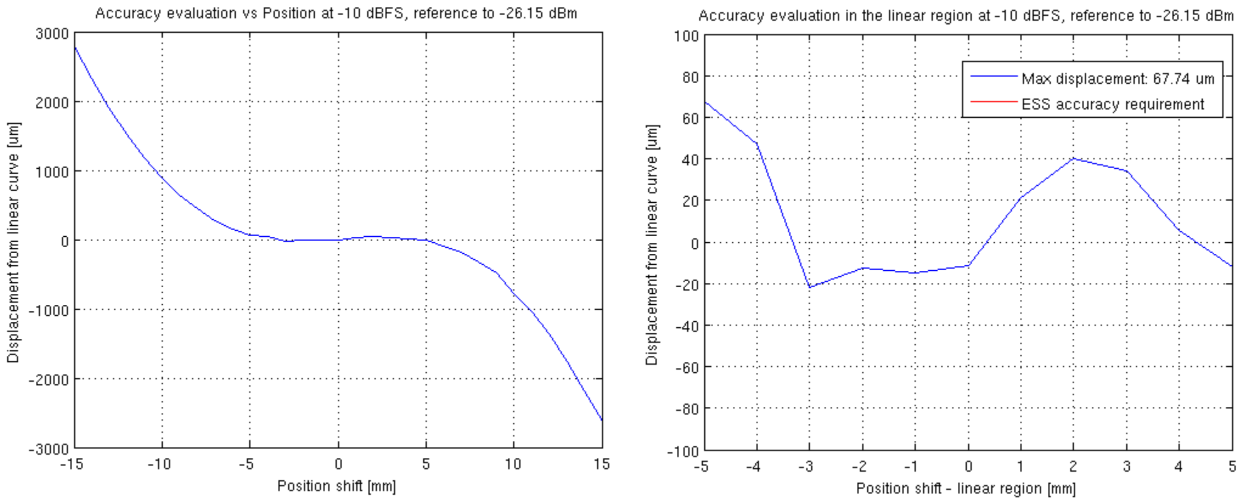


Figure 90: X position accuracy at -10 dBFS

6.3.3. Measurements at -20 dBFS

Figures below introduce the results of the measurements at -20 dBFS. Figure 91 shows the raw signals acquired from the ADCs: peak-to-peak levels are now around 100 counts and the differences between each RF path from the BPM to the instrument start to be more and more visible.
Figure 92 presents phase and position resolutions, while Figure 93 shows X and Y position measurements depending on the wire position: some offsets start to appear, probably because of the differences between the signals which are not compensated anymore by the geometric calibration.
Figure 94 finally shows the accuracy evaluation, first in the whole X position range, then in the linear region of the BPM. The offset on the X position measurements is more visible here.

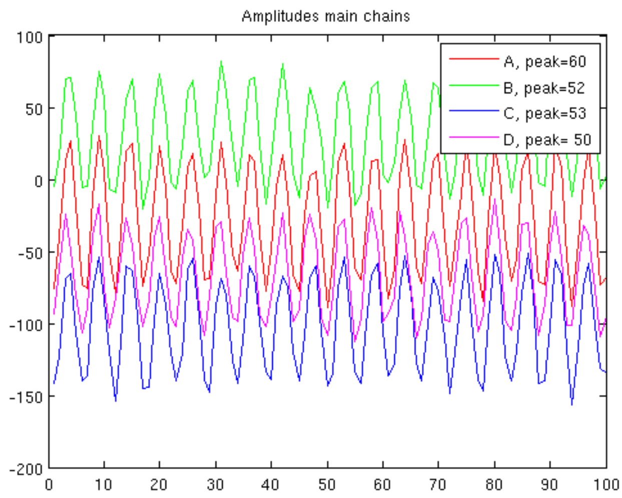


Figure 91: ADC signal levels at -20 dBFS

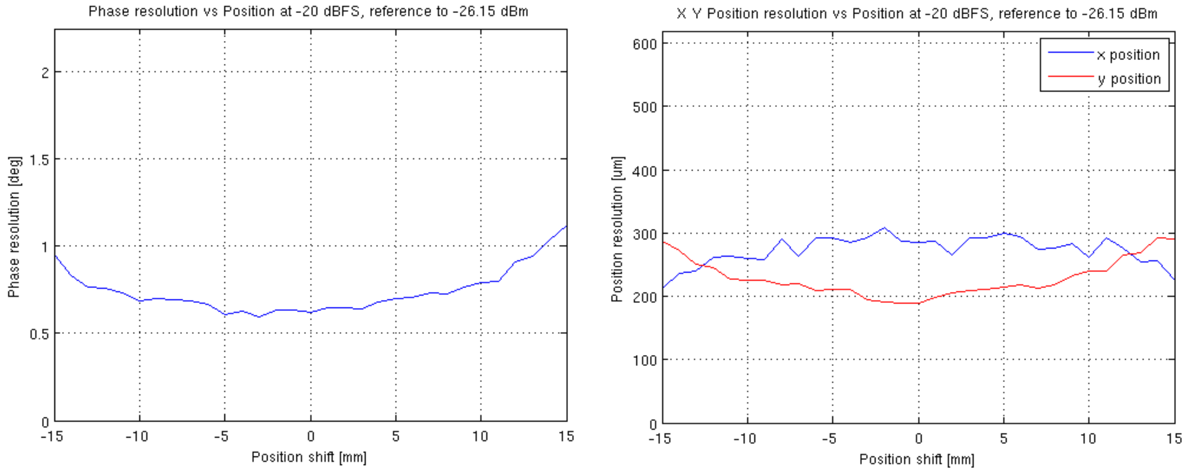


Figure 92: Phase and position resolution vs position at -20dBFS

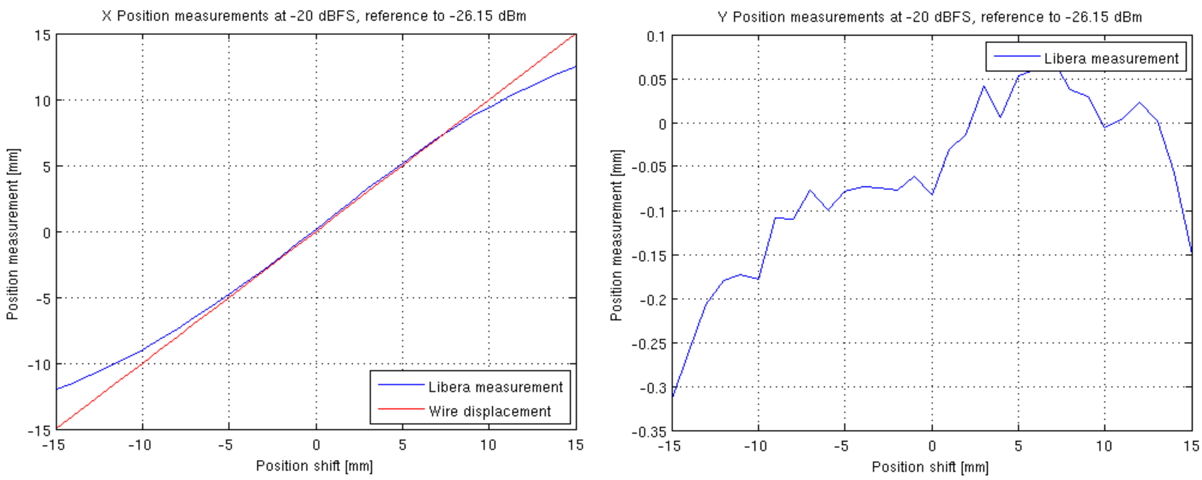


Figure 93: X and Y position measurements at -20dBFS

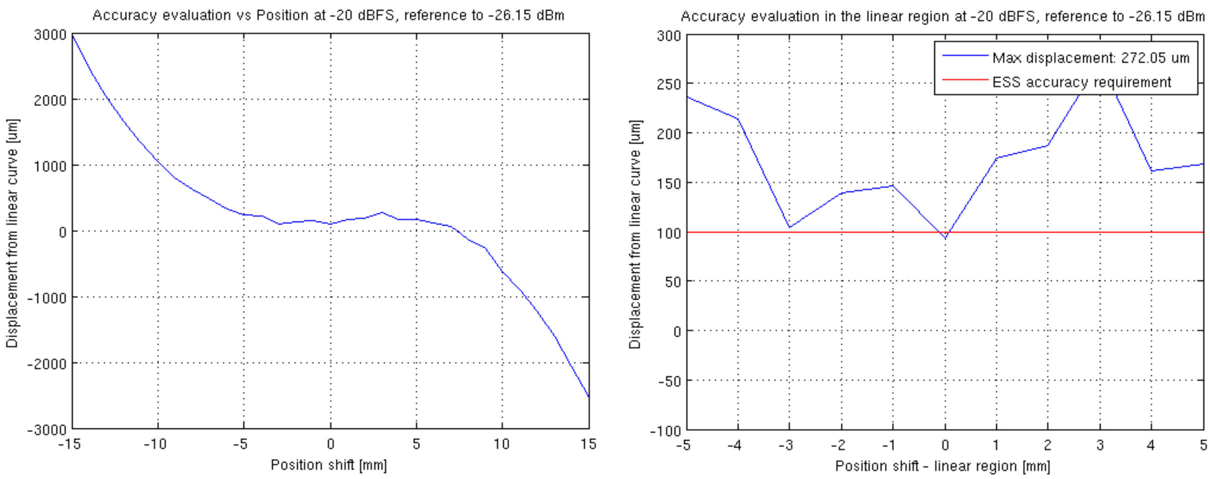


Figure 94: X position accuracy at -20 dBFS

6.3.4. Measurements at -30 dBFS

Figures below introduce the results of the measurements at -30 dBFS. Figure 95 shows the raw signals acquired from the ADCs: peak-to-peak levels are now around 50 counts and the nose influence starts to appear on the signals shape.

Figure 97 shows X and Y position measurements depending on the wire position: even though the curves don't match anymore, the instrument gives a reliable measurement which is enough for a rough position estimation.

From Figure 98 it is possible to see that the accuracy in the linear region is still below 1.5 mm, quite a surprising result from a signal which is just some dBs above the noise floor.

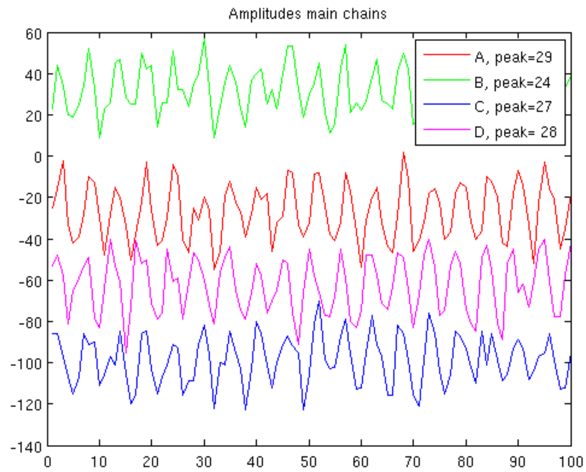


Figure 95: ADC signal levels at -30 dBFS

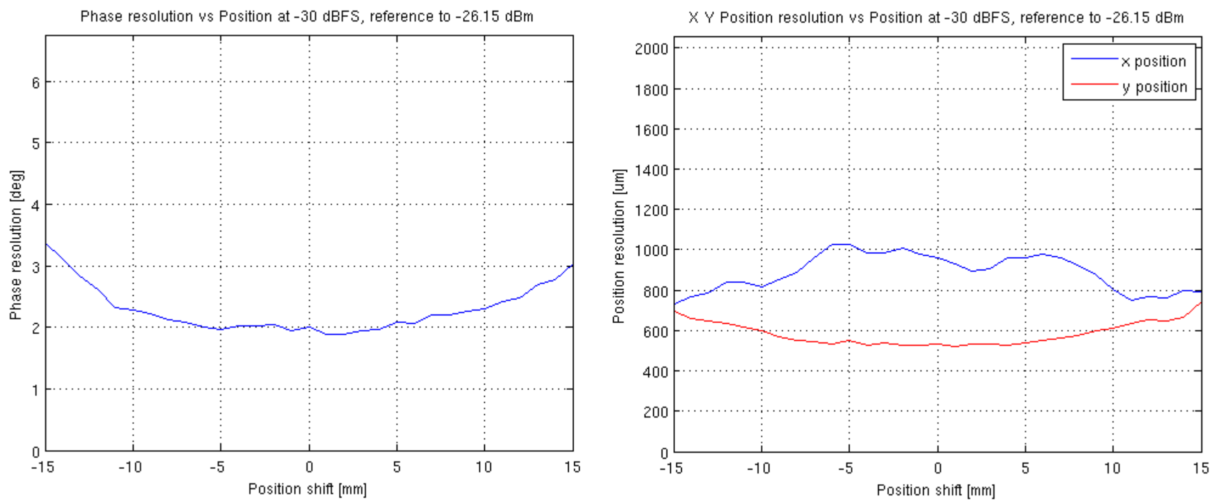


Figure 96: Phase and position resolution vs position at -30dBFS

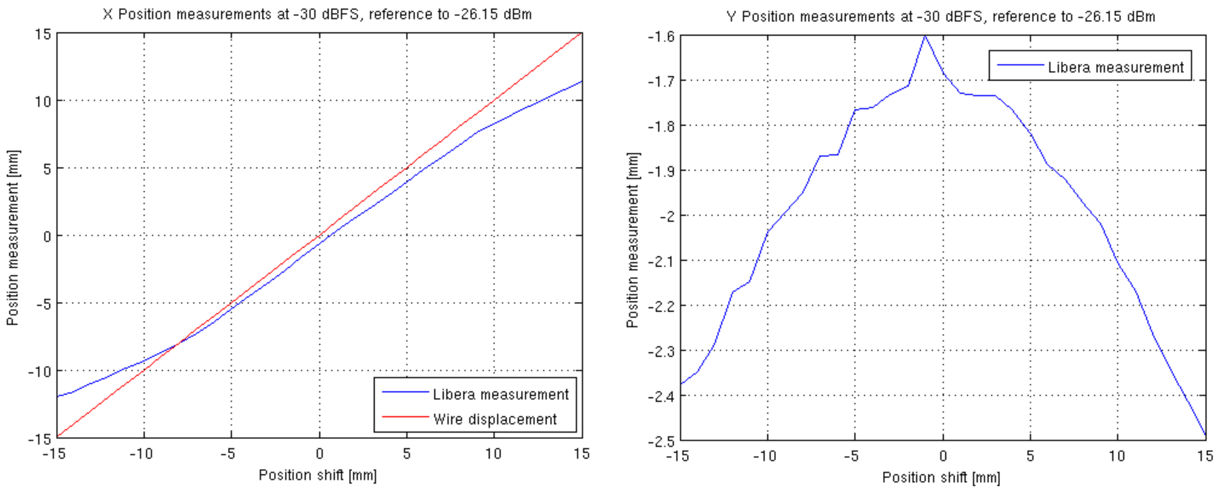


Figure 97: X and Y position measurements at -30dBFS

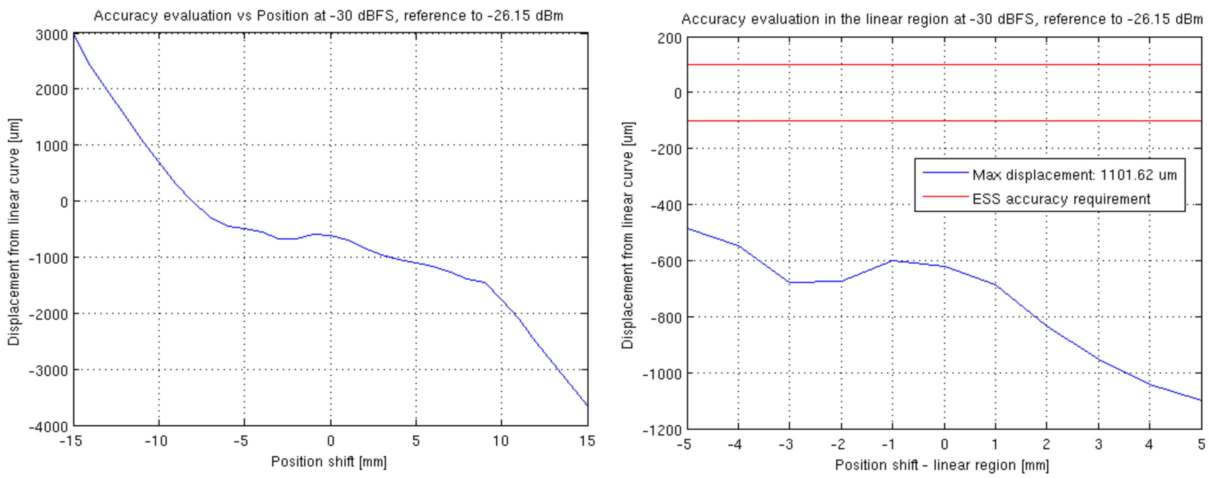


Figure 98: X position accuracy at -30 dBFS

NOTE: The instrument performance with debunched beam conditions can be improved repeating the geometric calibration it at a lower input signal level. This makes sense if “normal” and “debunched” conditions are separate and two different calibrations can be applied.

7. Interlock response time

This chapter presents the results of the measurements of the interlock response time of Libera SPH. Purpose of the measurement is to evaluate the delay between the moment in which an interlock condition becomes true and the moment when the Interlock output (ILK) rises.

Libera SPH can be configured with two interlock conditions:

1. Position. These conditions set the X and Y position ranges in which the beam can lie in normal operating conditions. The four limits are expressed in nanometers and identify a rectangle. If the beam goes off this limits, the interlock is triggered.

2. ADC counts. This condition specifies a condition directly on the ADC signal levels. With 16 bits the saturation is reached at 32767 counts. With this setting it is possible to set an Interlock threshold to a lower count limit to protect the machine.

The reaction time of the instrument in these conditions is related to the rate at which such signals are processed. ADC signal is processed at 125MSa/s, so it is expectable that the reaction time will be faster than in the case for the position, since SPH is processed at 1MSa/s. The settings for both Interlock conditions are visible in the Interlock GUI panel shown in Figure 99.
The Interlock output is provided through a specific TTL output signal through a differential LEMO connector.

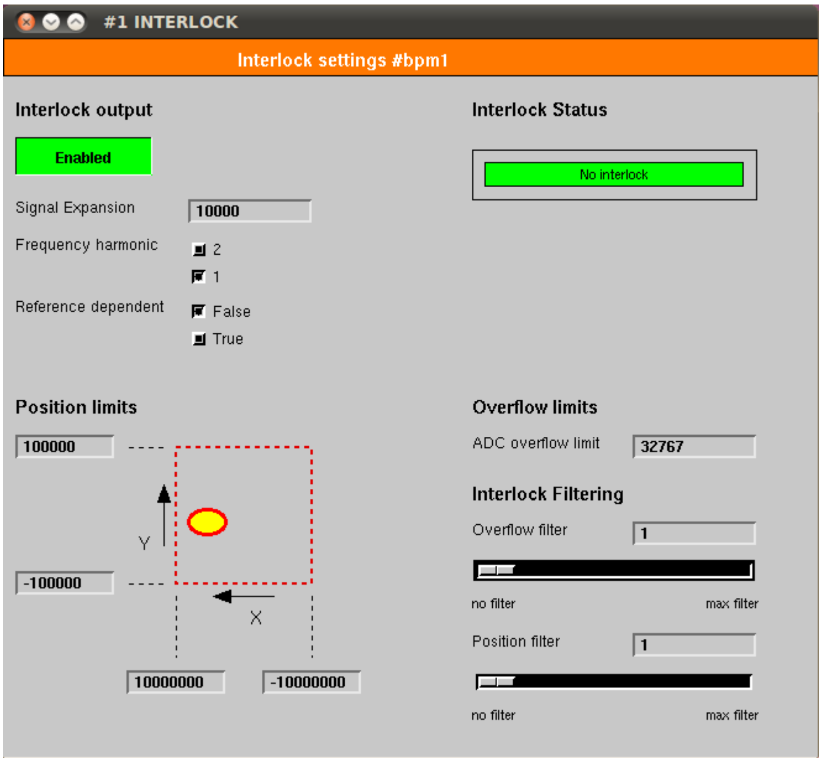


Figure 99: Libera SPH Interlock configuration through GUI

7.1. Measurement setup

In this measurement an Interlock condition is simulated and the reaction time of the ILK output of the instrument is measured. The easier condition to simulate is a position Interlock, induced using an RF gate to change the value of one instrument input at a defined time. Figure 100 shows the measurement setup.

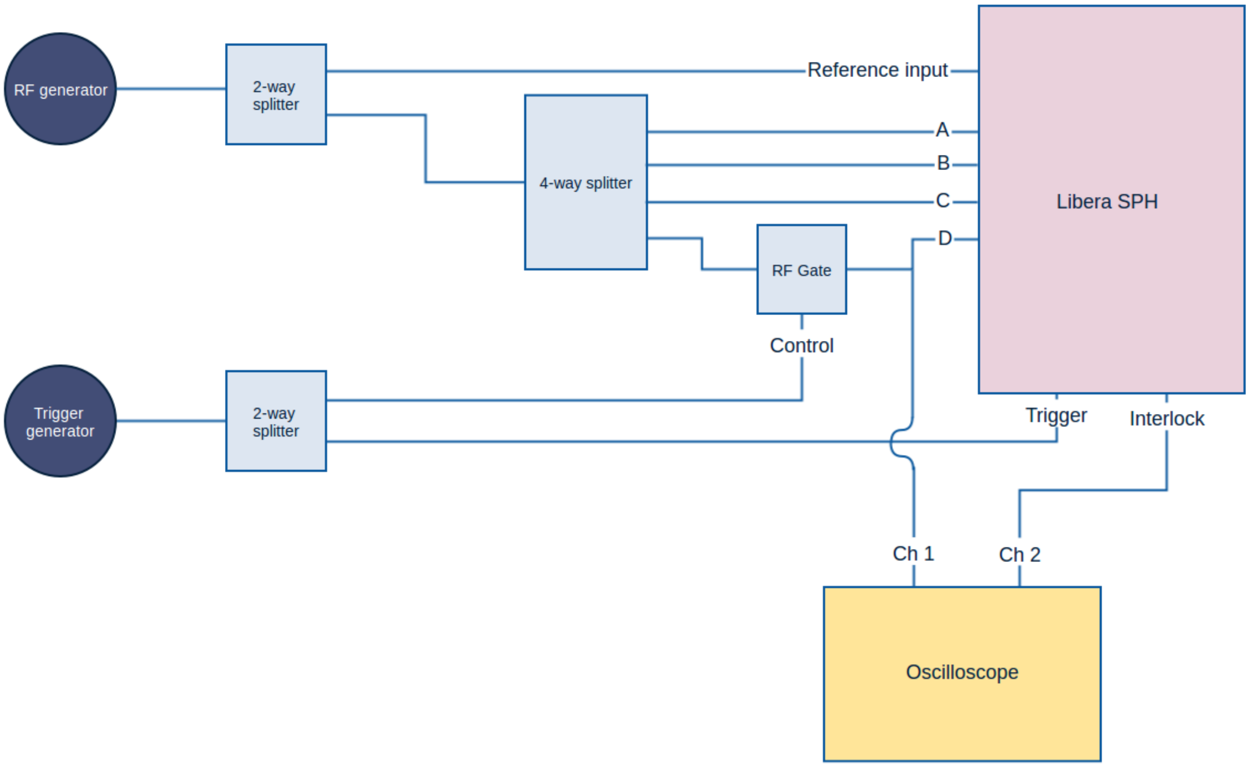


Figure 100: Setup for the Interlock response time measurement

The principle here is that one instrument input (D) is gated by an RF gate [14] controlled by the trigger generator. When the gate is ON, D signal has the same level as the other inputs. When the gate is OFF, then the signal is disabled and the instrument acquired noise.
To measure the Interlock response time, the position limits should be set in order to trigger the Interlock only in one gate condition – for example when the gate is ON. In this way, in every trigger signal period, the interlock output is triggered.
In order to measure the Libera response time, the instrument input D and the Interlock output are connected to two Oscilloscope input channels. The ILK output is provided through a differential LEMO connector, and a converter is used to convert it to a normal TTL signal.

Figure 101 presents the situation in which the Interlock output of the instrument is triggered. This is a screen-shot captured from the oscilloscope.
The vertical markers are placed to measure the time needed to reach 50% of the Interlock final value. This time is around **3.22 microseconds**.

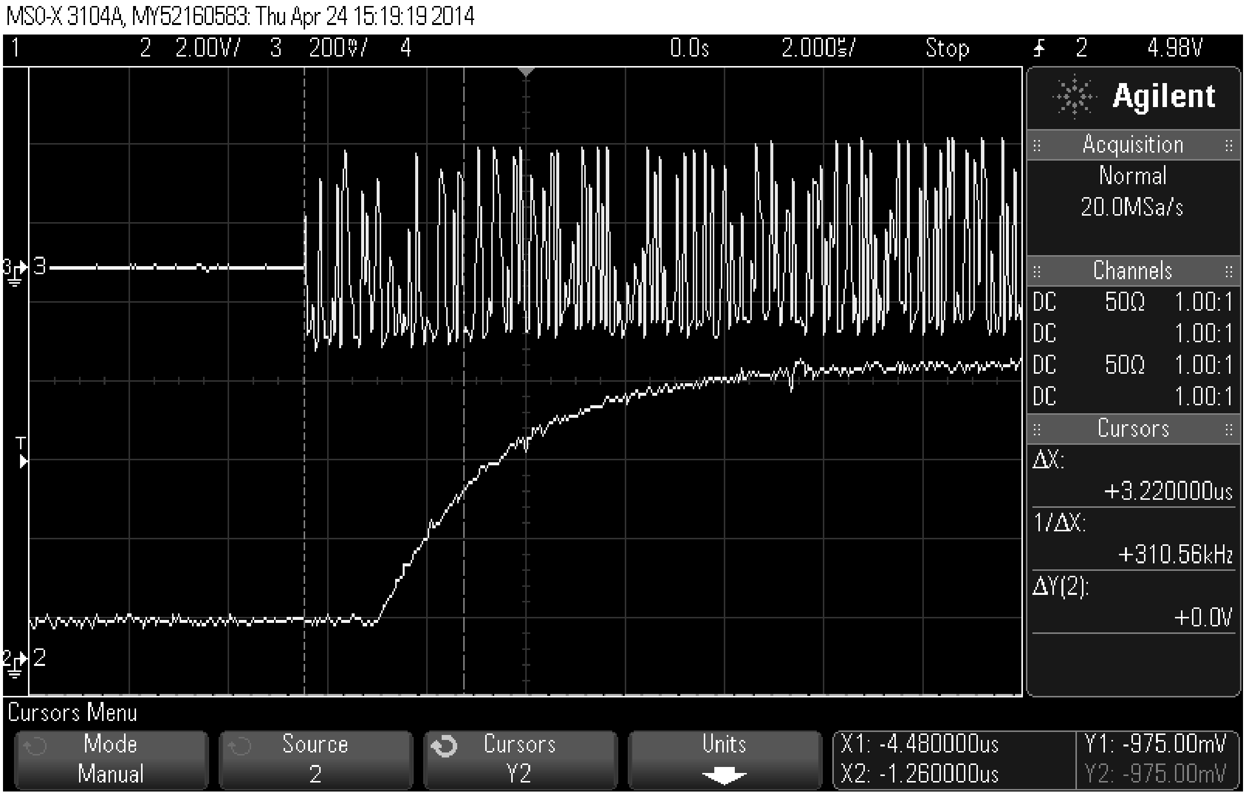


Figure 101: Interlock response time measurement

8. Conclusions

Libera Single Pass H was extensively evaluated in six weeks of measurements at ESS. The generous time budget and the good communication level with people at ESS, in particular H.Hassanzadegan, allowed to deeply understand the conditions and requirements foreseen for the final machine. Based on these guidelines, different measurement setups were evaluated, including a first BPM test-bench designed and manufactured at ESS.

In order to make everybody understand the results, the measurement parameters like *resolution*, *precision*, *accuracy* and *stability* were discussed in details, as well as the methodology that should be used to calculate them. Finally all the measurements were carried out, trying to evaluate the dependence of every significant parameter on the signal and setup conditions.

Most of the achieved results are within the ESS requirements specified in [1], even though the unit carried at ESS was not customized for the ESS working conditions (RF bandwidth in particular). Excellent results were achieved evaluating the long-term stability, phase accuracy and position measurements with debunched beam. Even better results are expected with a BPM board customization tailored on the ESS conditions.

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[14] Instrumentation Technologies RF gate (link)

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