EVALUATION OF LIBERA SINGLE PASS H FOR ESS LINAC*

M. Cargnelutti, M. Žnidarčič, Instrumentation Technologies, Solkan, Slovenia
H. Hassanzadegan, ESS AB, Lund, Sweden

Abstract

The Beam Position Monitor system of the ESS linac will include in total more than 140 BPM detectors of different sizes and types. The resolution and accuracy of the position measurement with the nominal 62.5 mA beam current and 2.86 ms pulse width need to be 20 μm and 100 μm respectively, and those of the phase measurement are 0.2 deg and 1 deg respectively. The BPM system also needs to work successfully under off-optimal conditions, ex. with a de-bunched beam, or with the current and pulse width being as low as 6 mA and 10 μs respectively. Options for the implementation of the ESS BPM electronics include: 1) a custom or commercial front-end card combined with a commercial digitizer with in-house developed firmware and 2) a fully commercial off the shelf system.

Libera Single Pass H is an instrument intended for phase, position and charge monitoring in hadron and heavy ion LINACs. The instrument was tested at the ESS laboratory, to prove the feasibility of operation with ESS beam conditions. To give a realistic picture of the device performance, different testing setups were evaluated, including all the signal and environment conditions foreseen for the final ESS linac operation. The results present resolution, precision and accuracy evaluations, as well as stressful long-term and stability tests. This paper presents the achieved results of the Libera Single Pass H for the ESS beam parameters.

INTRODUCTION

During the evaluation of Libera Single Pass H, every parameter that was supposed to influence the instrument performance was treated as a degree of freedom. The measurements were carried out at the ESS laboratories within a 6 weeks time-frame, and the complete report on which this article is based, can be found in [1].

To determine the operating conditions in which the instrument is required to work (input signal levels and dynamic range, temperature variations), the analysis of the ESS beam and BPM characteristics was particularly useful, and it is presented in the next section. The third session explains how parameters like *resolution*, *precision*, *accuracy* are calculated, and for each one a definition is provided. Later on, a basic test setup for the measurements is presented, introducing the role of the most significant components.

Finally the phase and position measurements results are discussed and compared with the ESS requirements.

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ESS BUTTON BPMS

The ESS linac will include BPM detectors of different sizes and types, and a detailed overview is given in [2]. However, most of the detectors will be of electrostatic button type and according with the beam pipe size they will be of two different diameters: 60 and 100 mm. Table 1 introduces some ESS significant parameters which are useful to understand the signal characteristics.

Table 1: ESS Beam and BPM Parameters

Parameter	Value	Unit
RF frequency	352.21 and 704.42	MHz
Bunch repetition rate	352.21	MHz
Pulse repetition rate	14	Hz
Pulse duration	0.01 - 2.86	ms
Pulse current	6.25 – 62.5	mA
BPM diameter	60 and 100	mm
Button diameter	24 and 40	mm
Button capacitance	5.2	pF
Beam max displacement (with ref. to beam pipe)	50	%

It is possible to notice that even if the RF frequency changes from 352.21 to 704.42 MHz passing from the spokes section to the super-conductive linac, the bunch repetition rate remains the same. In terms of the BPM signals, this means that the fundamental harmonic is always at 352.21 MHz, and the other components are multiples of it.

Considering the Libera SPH capabilities, the instrument processes the first and the second harmonic, providing phase and position measurements for both of them.

BPMs Signal Levels

To estimate the signal levels coming from the BPMs, an analytical model of the beam and detectors is used. The expected signal levels for both harmonics are calculated according with the value of the influential parameters. Most are listed in Table 1: geometrical properties, beam current and b-factor all influence the amplitude of the BPM outputs. Considering the extreme cases, with a beam in the centre of the pipe:

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

On the base of the same model, if the beam is 50% off-centred the signal coming from the closest button gains 8.72 dB while the opposite one loses 8.72 dB.

Environment Conditions

The instrument analog part (filters, amplifiers, ADCs) is particularly sensitive to the environment conditions changes, especially temperature and humidity. The maximum drift in temperature foreseen at ESS for the instrumentation is 5 degrees. The same temperature variation was reproduced during the long-term measurements.

MEASUREMENT DEFINITIONS

This chapter introduces some parameters which are important to benchmark a measurement device. Examples are *resolution*, *precision* and *accuracy*. These concepts are widely used in this article, and for clarity reasons they are presented below, according with ISO Guide 99 [3].

Libera Single Pass H is intended for phase, position and charge measurements [4]. Starting from the four BPM signals, position is calculated using *delta-over-sum* formulas. The phase is measured against a fifth input, a pure sine tone used as a reference. The four phases measured using each input are then averaged. Charge measurements are not considered in this scope.

In its normal working conditions, Libera SPH samples the input signals at 125 MHz, with 16 bit ADCs. After the raw ADC data is processed by the *digital-down-conversion* (DDC) algorithm, phase and position samples are provided with 1 MHz rate. This means that at each trigger, for a 2.86 ms macropulse it is possible to acquire up to 2860 phase and position samples from the buffer. If not differently specified, all the presented results are based on the analysis of 2000 samples per trigger.

Resolution

It's defined as the "*Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication*". For a digital instrument, resolution can be limited either by the digitization process (e.g. number of ADC bits) or the signal noise. With 16 bit ADCs, noise can be considered as the limiting factor.

Position and phase resolution is evaluated with the standard deviation, calculated from the samples acquired within a single trigger acquisition.

Precision

It's defined as "*Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified condition*". Each trigger acquisition can be seen as an independent measurement under similar conditions. From each acquisition, the mean value is calculated from 2000 acquired samples. The precision is evaluated as the standard deviation of the mean values obtained from 100 independent measurements.

Accuracy

It's defined as "*Closeness of agreement between a measured quantity value and a true quantity value of a measurand* ". Assuming the real value of the measurand is known, the accuracy is evaluated as the difference between the mean value of an acquisition and the real value.

Stability

The idea behind stability measurements is to evaluate how a given measured quantity is influenced by other factors which can be the phase, position, input signal level, temperature, etc... When the instrument stability is evaluated over time, then the term "*long-term stability*" is used. In all cases, stability is quantified considering the maximum peak-to-peak variation of the measurement.

SETUP WITH 4-WAY SPLITTER

In order to evaluate the performance of an instrument that elaborates the signals coming from the accelerator BPMs, such signal conditions need to be simulated. One possibility is to start from a suitable RF source and split the signal with a 4-way splitter. By controlling the properties of the inputs and outputs (e.g. harmonic components, power levels, etc...) it is possible to simulate several situations which are foreseen in the accelerator according with beam current, position displacement and so on. The only drawback in this configuration is the fact that it is not possible to evaluate the position accuracy.

Figure 1 introduces the setup described above, used for measurements in centred beam conditions (all the four inputs have roughly the same amplitude). Apart from the trigger signal, all the Libera inputs are obtained from the same RF source, a sine tone at 352.21 MHz. On the reference signal path, the analog phase shifter is used to control the phase difference between inputs and reference. On the BPM signal path, the pulse-generating diode provides a signal which contains also the second harmonic, a good approximation of the BPM signals. Attenuators are used both to control the signal level and

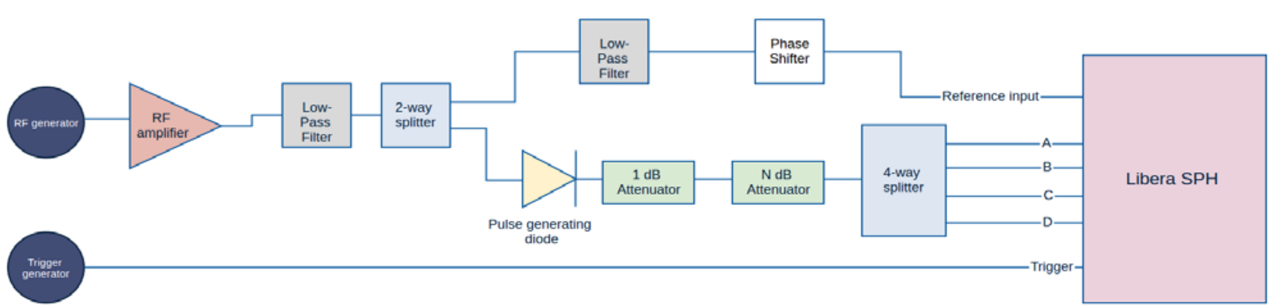

Figure 1: Block diagram of the measurement setup used for measurements with centred beam conditions.

to reduce the signal reflections caused by the diode, since its impedance is not perfectly matched to 50 Ohm. Low-pass filters are used to clean out the unwanted harmonic components from the reference input signal.

MEASUREMENT RESULTS

This section presents part of the results achieved with the setup described above: for the whole set of measurements refer to [1]. Figure 2 shows the resolution of phase and position measurements as the four Libera inputs are lowered, starting from the reference level – 0 dB on the X axis. Both the first harmonic component (left) and the second (right) are considered.

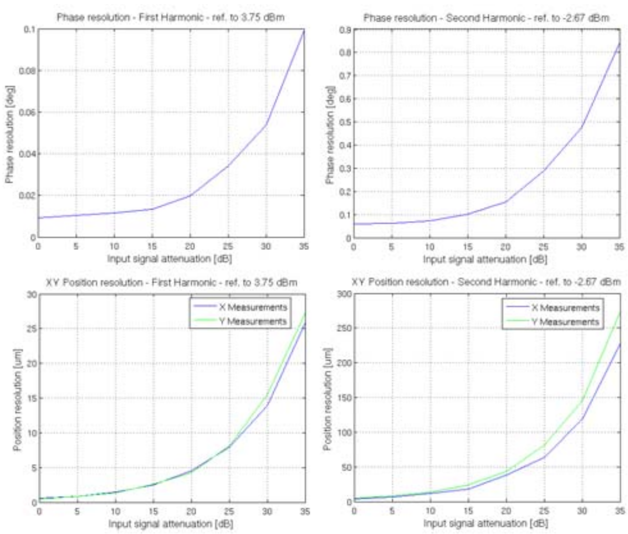

Figure 2: Phase and position resolution measurements.

Considering the measurement results, it is important to keep in mind that the phase shift measured at the second harmonic is two times the shift which affects the first harmonic. Consequently all the results should be divided by a factor of two.

Furthermore, the unit which was used for the measurements has a standard RF front-end with a bandwidth limited by the analog filters to 575 MHz. This attenuates the level of the input signal at the second harmonic. Substantial improvements are expected using an RF front-end tailored on the signal frequencies foreseen at ESS.

Another interesting measurement with this setup is the phase accuracy. Using the line stretcher in the reference signal path, it is possible to shift the phase up to 56.85 deg for the first harmonic, and up to 113.43 deg for the second. This range is divided in 17 equal steps and measurements are performed for each step. In order to evaluate the accuracy of the instrument, the phase shifter was first characterized with a Vector Network Analyser having an accuracy of 0.2 deg in these signal conditions.

Figure 3 presents the results for both harmonics: plots on the left show the total phase shift, while those on the right present the shift introduced by each shifter step. Again, the 2nd harmonic measures should be divided by 2. Single step plots show a non-linearity of the shifter, having the same profile for both VNA and Libera SPH.

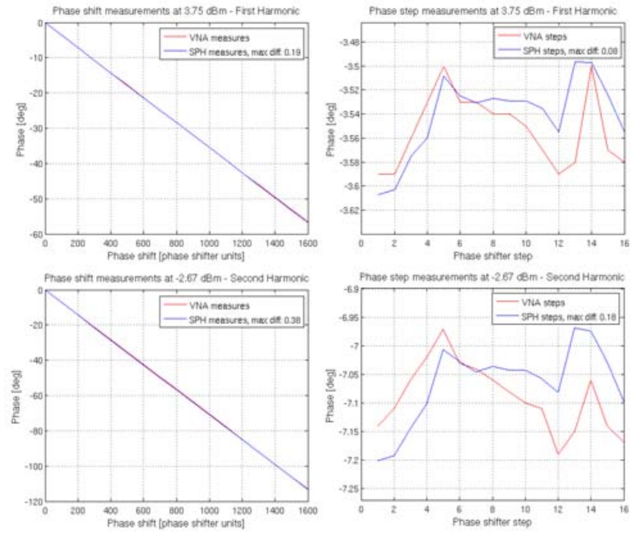

Figure 3: Phase accuracy measurements.

The measurements are then repeated lowering the input signal level and the results proved to be within the requirements in all the BPM expected signal range.

Another important evaluation is the long-term temperature stability. In order to evaluate it, the instrument was left running with the same input signal conditions for 24h.

A room temperature variation of 6-7 °C was induced by leaving the window open. Figure 4 presents the temperature profile measured with the sensors located in the RF front-end. The acquired phase and position signals show a similar profile, with peak-to-peak variations reported in Table 2.

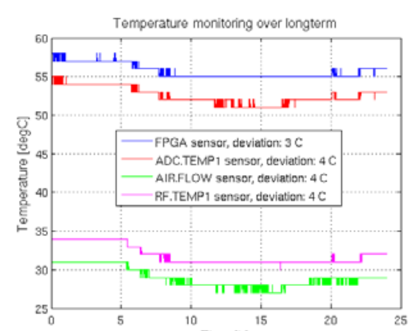

Figure 4: Long-term measurement temperature profiles.

Table 2: Long-term Phase and Position Variations

Parameter	Peak-to-peak	Unit
Phase - 1st harmonic	0.13	deg
Phase - 2nd harmonic	0.42	deg
X pos. - 1st harmonic	1.52	mm
X pos. - 2nd harmonic	18.49	mm
Y pos. - 1st harmonic	0.83	mm
Y pos. - 2nd harmonic	12.75	mm

SETUP WITH BPM TEST-BENCH

In order to evaluate the position measurement accuracy, a possibility is to use a BPM test-bench: a device which consists of a section of the beam pipe with a BPM in the middle of it. Inside of the pipe, the beam is simulated with current impulses which pass through a wire, exciting electromagnetic signals which are captured by the BPM pickups. Mechanical slides can be used to control the wire position, offering the possibility to calibrate the instruments and perform the position measurements. Figure 5 shows the BPM test-bench designed and assembled at ESS.

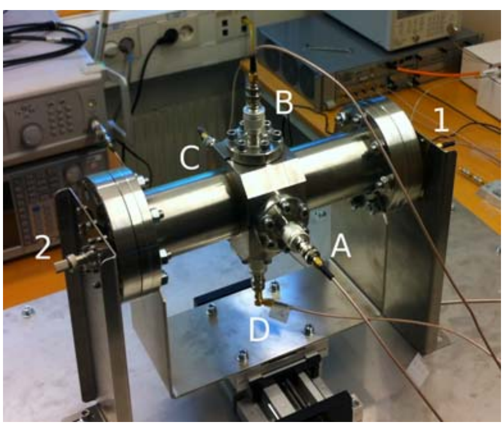

Figure 5: BPM test-bench used at ESS.

Ports 1 and 2 are the wire connectors, while ports A,B,C and D are the BPM outputs which are connected to the instrument. The pipe and BPM diameters are 60 mm and the slide enables to move the wire only in the horizontal plane, with a range of [-15 mm, +15mm] with reference to the centre, and 50 mm resolution.

The system was first characterized with the VNA, which measured an insertion loss (i.e. modules of S_{A1} and S_{C1}) around 48 dB, mainly due to the impedance mismatch between the wire input and the pipe. Because of this limitation, only the first harmonic was usable for the measurements, with a maximum level of -26 dBm (with the wire in the centre of the pipe). The Libera SPH calibration consisted in two steps:

- Using the slide, the wire was centred in the pipe, according with the instrument readout from the ADCs.
- The sensitivity parameter (K_X) was set in order to have a linear region between -5 and +5 mm.

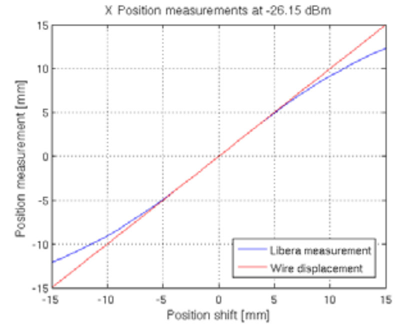

Figure 6: Position measurements with BPM test-bench.

Finally, the whole range between -15 and +15 mm was divided in 1 mm steps where to perform the measurement. Figure 6 presents the X position acquired in the whole horizontal range, while Figure 7 presents the accuracy in the linear region, estimated considering the slide position as the real value. These measurements have shown that the accuracy will be better than 100 mm in the linear region and beyond that, it will degrade due to the BPM non-linearities.

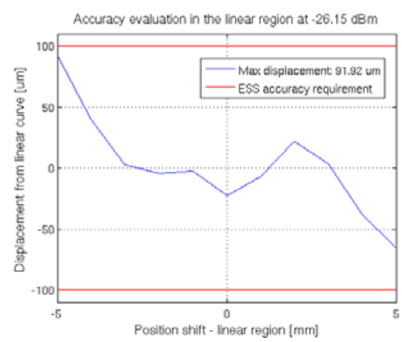

Figure 7: Position accuracy within the BPM linear region.

CONCLUSIONS

This article presents the measurements performed at the European Spallation Source with the Libera Single Pass H instrument. The purpose of the tests was to prove the feasibility of operation according with the ESS beam conditions.

The BPMs analytical models and the foreseen accelerator beam parameters provided enough information to identify the characteristics of the BPM signals which are expected at the instrument input. In order to evaluate the instrument performance, these signal conditions were reproduced in the ESS lab by using different tools and test-setups.

Resolution, precision, accuracy and stability of phase and position measurements were first defined and then evaluated in different conditions, playing with all the influential parameters in a multidimensional field.

The achieved results show that Libera SPH with a standard RF front-end meets the ESS requirements in almost all the conditions, providing accurate results with a good temperature stability. Even better performance is expected with an RF front-end tailored to the ESS machine parameters.

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