A WIRE-BASED METHODOLOGY TO ANALYSE THE NANOMETRIC RESOLUTION OF AN RF CAVITY BPM

S. Zorzetti[1]*, K. Artoos, F. N. Morel, P. Novotny, D. Tshilumba, M. Wendt
CERN, Geneva, Switzerland
L. Fanucci, University of Pisa, Pisa, Italy
[1]also at University of Pisa, Pisa, Italy

Abstract

Resonant Cavity Beam Position Monitors (RF-BPMs) are diagnostic instruments capable of achieving beam position resolutions down to the nanometre scale. To date, their nanometric resolution capabilities have been predicted by simulation and verified through beam-based measurements with particle beams. In the frame of the PACMAN project at CERN, an innovative methodology has been developed to directly observe signal variations corresponding to nanometric displacements of the BPM cavity with respect to a conductive stretched wire. The cavity BPM of this R&D study operates at the TM110 dipole mode frequency of 15GHz. The concepts and details of the RF stretched wire BPM test-bench to achieve the best resolution results are presented, along with the required control hardware and software.

INTRODUCTION

The CLIC experiment at CERN is an international study of a future Compact LInear Collider. The main purpose is to achieve both high efficiency and luminosity at the Interaction Point (IP) at a beam energy up to 1.5 TeV. Therefore, the required beam size at the IP is in the range of a few nanometres. To achieve this, the beam emittance needs to be maintained over the whole 30 km length of the main linac, implying Beam Position Monitor (BPM) technologies capable of measuring nanometric displacements and a precise alignment between the main accelerator components in the micrometric range. In this scenario, the PACMAN project [1], funded by the European Union's Seventh Framework Programme, aims to prove the feasibility of innovative, high precision alignment methods for BPMs, quadrupoles and accelerating structures, based on stretched and vibrating wire technologies.

CLIC CAVITY BPM AND TESTS

The CLIC cavity BPM design is based on the combination of a monopole TM010 mode reference cavity and a dipole TM110 position cavity, resonating at ~ 15 GHz (a 3D model of the position cavity and pickups is shown in Fig. 1). The initial design in stainless steel was studied through beam measurements in the CLIC Test Facility (CTF3) at CERN and it was later improved to achieve an higher Q value through a copper construction. Five cavity BPM prototypes of the new design are now being studied at CERN. Three BPMs are installed in CTF3 [2] and two others are used by the PACMAN project in a laboratory environment to test stretched-wire methods.

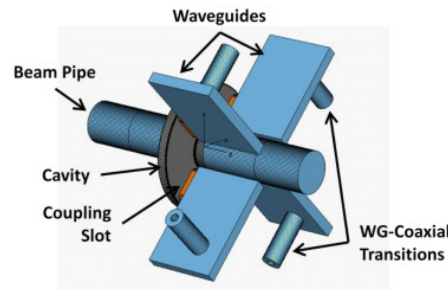


Figure 1: BPM moodel.

The BPM resolution depends on many factors. A relevant signal deterioration is caused by manufacturing imperfections, leading to monopole mode leakage to the position cavity, asymmetries between the lateral pickup ports, or cross coupling between adjacent ports. To avoid a significant degradation of the performances and accuracy, the fabrication tolerances were set very tight. Taking into account the weakest manufacturing aspects, RF simulations of the BPM design anticipated a 50 nm spatial resolution, for 50 ns measurement time with beam [3].

So far, cavity BPM resolution results have mainly been achieved through beam-based techniques. The traditional approach is to pre-align three BPMs in a straight line on a common support, and to predict the position of the central BPM out of the position of the other two. The resolution is extrapolated by the residuals' standard distribution, returned by the difference between the measured position and the calculated one [4].

BPM experiments using particle beams are essential tests for calibrations purposes, e.g. analysing the sensitivity of the cavity as a function of the beam position or the number of charges. However, RF tests, without requiring beam, present a simple way for characterizing first prototypes and pre-align the BPM and its associated quadrupole. The proposed stretched-wire analysis is particularly valuable for finding the electrical center of the position cavity or analysing its high spacial resolution capability.

STRETCHED-WIRE SETUP

To study the BPM resolution, a standalone test bench has been assembled. The main bench components, and measurement procedure are shown in Fig.2, 3. A Vector Network Analyser (VNA) is added for signal read-out. The scattering parameters acquired through this setup allow the measure

* silvia.zorzetti@cern.ch

ISBN 978-3-95450-177-9

of the relative displacement between the wire and the electrical center of the cavity. We found that the most sensitive information is returned by the phase between adjacent ports (e.g. $\angle S14$[1]), which demonstrates a linear behaviour around the electrical center of the cavity [5].

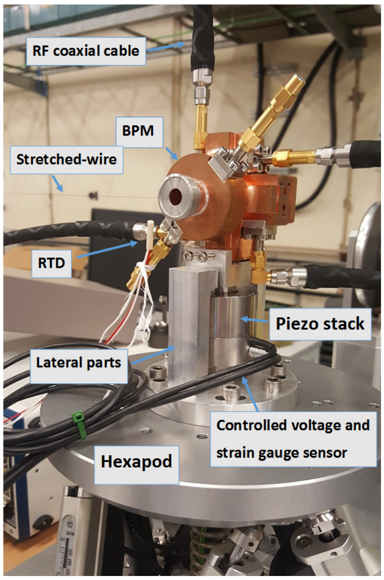


Figure 2: BPM test bench with hexapod and piezo stages.

Laboratory Environment

Environmental tests have been carried out to verify the stability of the laboratory in terms of temperatures and vibrations.

Temperature The resonant frequency of the position cavity versus temperature has a gradient of $-359 kHz/°$ C [6]. As a drift in resonant frequency or Q-factor also affects the stability of the measurements, it is important that the temperature of the laboratory is stable. In this laboratory, the recorded temperature drift is less than 0.3° C over ~ 12 hours (Fig.4). The signal phase, as measured by the VNA, shows a linear dependence from the temperature Fig.5. It is necessary to underline that the temperature was monitored on the complete coaxial assembly, composed of both the BPM and the stretched wire, therefore a change of temperature was impacting not only on the BPM position cavity but on the entire installation.

Vibrations The test bench is mounted on an active optical table to damp vibrations. The chosen model is a Vision IsoStation from Newport, ensuring a reduction of vibration transmission to the vertical and horizontal axis of 85% above 5 Hz and 95% above 10 Hz. Vibration measurements of the ground, the table and the hexapod were performed in order to estimate their possible effect on the wire position measurements. The results are presented in Fig.6 and depend on the period of the day measured: lower vibrations are registered during the night than during the day. However the parameter of interest is the relative motion between the table and the hexapod, as the wire is attached to the table via holders and the hexapod moves relatively to this wire. This always remains below 4 nm [2]. It is necessary to remark that these measurements characterize only the dynamic behaviour of the BPM measuring system and do not provide any information about possible drift or very low frequency vibrations.

Actuators and Sensors

Actuators Two types of actuators are used, a Hexapod for pre-positioning the BPM with respect to the wire (with sub-micrometer minimum incremental motion on 6-DOF [3]), and a piezo to move the BPM with respect to the wire with a finer step size.
The piezoelectric actuator is a high voltage pre-loaded piezo stack P-225 from Physik Instrumente (PI). The actuator has an embedded strain gauge sensor to measure its elongation during operation, with 0.3 nm resolution. The actuator is powered by an E-508 amplifier module and it is driven by an E-509 servo module from the same company. The piezo is operated in closed loop to cancel hysteresis and improve linearity. The input signal to drive the actuator is fed to the control port of the piezo amplifier by a voltage generator, providing DC voltage levels. An input voltage of 10V corresponds to $15 \mu m$ displacement.
The actuator is mounted on the hexapod and drives the BPM in a single direction (vertical axis). The BPM center of gravity was positioned on the axis of the actuator. Due to the small mass (0.7 kg) of the BPM with respect to the high load actuator (12.5 kN), no external linear guidance was used for this simple setup. This was considered sufficient as of the measurement campaign consists of a rather static process. Two lateral parts were used to align around the vertical axis.

Sensor A Copper beryllium wire of 0.1 mm diameter is stretched through the BPM cavity to simulate the particle beam. The choice of the wire is mainly driven by the compatibility with magnetic measurements for the Final PACMAN Bench [7]. In this case it acts as a passive probe, sensing the dipole electric field excited into the cavity. The wire is fixed and mounted to two lateral stretching devices, installed on the table.

Software Automation and VNA Setup

The measurements procedure is completely automated through a controller software developed in LabVIEW (interface in Fig.7), with a state machine to synchronize the different steps.

1 The *hexapod* is moved to prepositioned coordinates. This predetermined point is close to the electrical center and has high sensitivity;

[1] Signal phase acquired exciting from $Port4$ and reading from $Port1$ - Reference to cavity depicted in Fig.3

[2] $x_{\Delta_{RMS}} = \sqrt{x_1^2 - x_2^2}$

[3] three linear axis and three angular ones

ISBN 978-3-95450-177-9

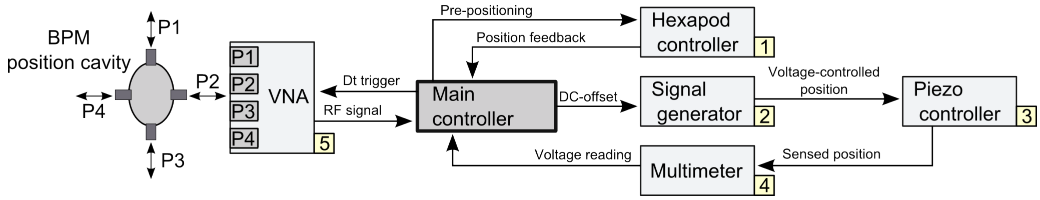


Figure 3: Schematic view of the test bench for resolution nanometric measurements.

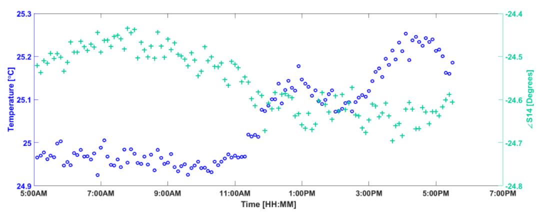


Figure 4: Temperature and cross-section's phase trends.

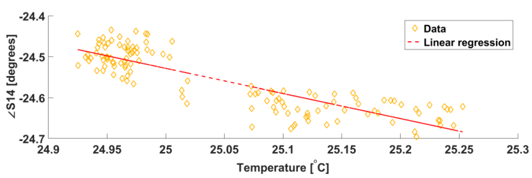


Figure 5: Temperature vs cross-section's phase.

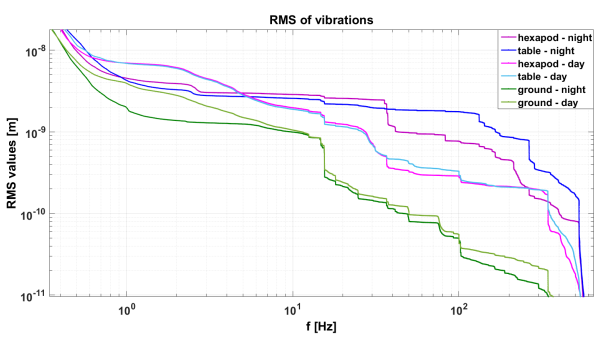


Figure 6: RMS vibrations of the bench.

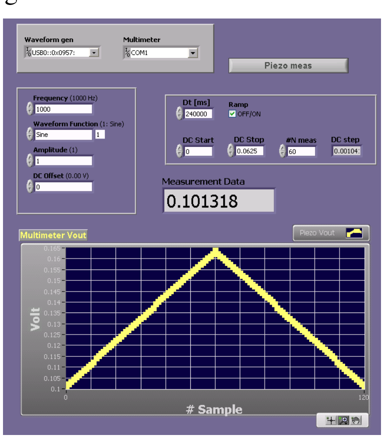


Figure 7: LabVIEW interface, piezo controller.

2 The main controller provides the voltage value to the *signal generator*;

3 The *piezo actuator* is controlled in voltage by the signal generator's output;

4 After the movement of the piezo, a sensed position is sent in closed loop for voltage reading to the *multimeter*;

5 A trigger to a VNA is generated every *Dt* (a user-defined time constant);

6 The *VNA*, connected to the four BPM ports, performs RF magnitude and phase measurements in frequency sweep. The lower the frequency of the sweep (IFBW), the higher the time constant *Dt* needs to be. In the present experiment $IFBW$=70 Hz, with a sweep centered around the position cavity's resonant frequency (~ 15 GHz). Moreover, before taking data, the VNA was calibrated and a phase offset has been applied to center the BPM signal phase in a 0° to ±180° range.

NANOMETRE RESOLUTION RESULTS THROUGH STRETCHED-WIRE MEASUREMENTS

The signal generator is programmed by the LabVIEW interface to sweep in a DC voltage range for a number of steps. After every movement of the piezo, the VNA acquires magnitude and phase data. With this experiment we intend to demonstrate that a few nanometres resolution could be resolved in a static conditions process.

Fig.8a shows the linear dependence between piezo elongation (resulting in wire displacement with reference to the center of the position cavity) and the adjacent ports phase ($\angle S14$). The position displacement is $\Delta l = 25nm$, from a DC voltage offset driving the piezo of $\Delta V \simeq 33.33mV$. A finer DC offset voltage sweep ($\Delta V \simeq 2mV$) shows, with less accuracy, the outstanding BPM sensitivity and ability to detect position displacements of ~ $3nm$ (Fig.8b).

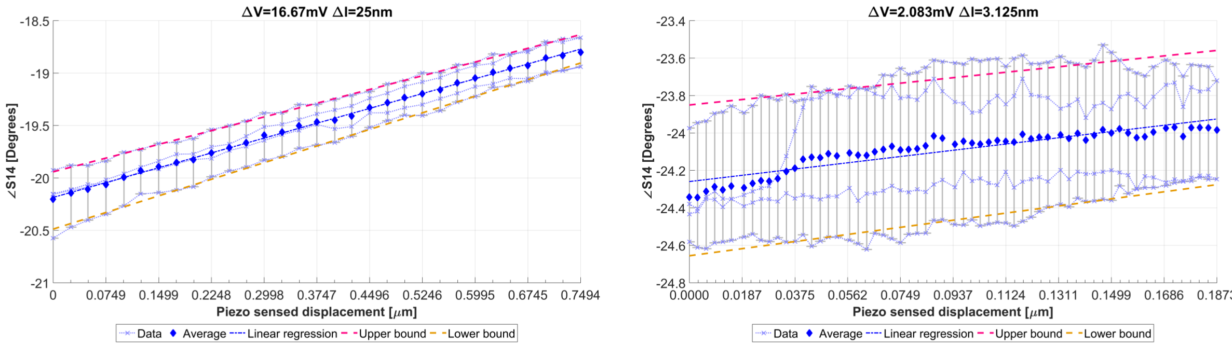
Impact of Environmental Characteristics

The rather high acquisition time (Dt = 240000 ms) results in a very low sampling frequency f_s = 4 mHz. Possible sources of noise at frequencies above f_s, such as air flows or vibrations (4 nm at 1 Hz in Fig. 6) could be considered removed. Although, practical experiences may still be affected by environmental changes over a long time scale (e.g. wire tension or ambient temperature) as they were performed during different time slots and days. To reduce their impact, tests were repeated several times and averaged.

Gradient Distribution

Plots in Fig. 8 show the result of the experience. We observe a dependence between the phase and the piezo elongation expressed in a linear form: $y = ax + b$, where a is the

ISBN 978-3-95450-177-9



(a) $\angle S14$ resolution results at 25 nm piezo step size. (b) $\angle S14$ resolution results at 3.125 nm piezo step size.

Figure 8: BPM nanometre resolution results.

gradient (angular coefficient) and b the line offset. The table below summarizes those parameters for the mean, upper and lower lines, calculated with the mean squared fit method.

Table 1: Gradients and Offsets

Parameter	**Upper error**	**Mean**	**Lower error**
Gradient - 25 nm [Degrees/μm]	1.7472	1.8881	2.1145
Gradient - 3 nm [Degrees/μm]	1.5556	1.7842	2.0283
Offset - 25 nm [Degrees]	-19.9416	-20.1856	-20.4879
Offset - 3 nm [Degrees]	-23.8501	-24.2595	-24.6557

The gradient distribution between every couple of samples ($\frac{\Delta \angle S41}{\Delta l}$) is shown in Fig. 9. The mean (μ) gradient value, presenting a higher probability of occurrence, is close to the computed average value in Table 1. The high variance depends mainly on the impact of environmental characteristics drifts at very low frequencies ($\ll f_s$), as well as from the limited number of observations recorded.

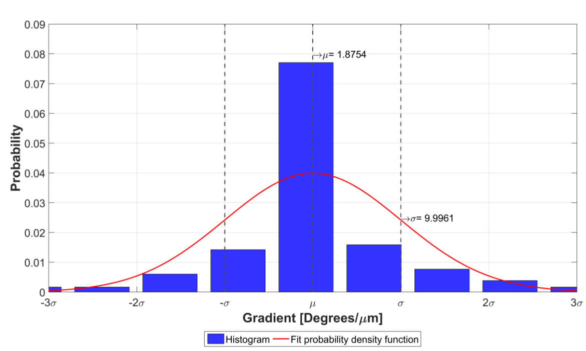


Figure 9: Histogram of gradient values.

CONCLUSION

A test bench to perform static nanometric stretched-wire measurements was developed and first results achieved. The presented experiences demonstrated the mechanical capability of the BPM position cavity of acquiring with nanometric sensitivity the position of a floating conductive stretched-wire, out of its coupling with the electrical field excited by the attached waveguides in the position resonant cavity. This result can be seen as an upper resolution limit for beam-based tests.

REFERENCES

[1] H. Mainaud Durand et al., "Status of the PACMAN project", in *Proc. IBIC'15*, Melbourne, Asutralia, September 2015, pp. 483–486.

[2] J. R. Towler et al., "Development and Test of High Resolution Cavity BPMs for the CLIC Main Beam", in *Proc. IBIC'15*, Melbourne, Asutralia, September 2015, pp. 474–478.

[3] A. Lunin et al., "Design of a submicron resolution cavity BPM for the CLIC main linac", Rep. TD-09-028, December 2009.

[4] S. Walston et al., "Performace of a nanometer resolution BPM system", in *Proc. EPAC'06*, Edinburgh, United Kingdom, June 2006, pp. 1256–1258.

[5] S. Zorzetti et al., "Stretched-Wire Techniques and Measurements for the Alignment of a 15GHz RF-BPM for CLIC", in *Proc. IBIC'15*, Melbourne, Asutralia, September 2015, pp. 487–491.

[6] F. Cullinan et al., "A prototype cavity BPM position monitor for the CLIC main beam", in *Proc. IBIC'12*, Tsukuba, Japan, October 2012, pp. 1–3.

[7] C. Sanz et al., "Characterization and measurement to the sub-micron scale of a reference wire position", in *Proc. CIM'15*, Paris, France, September 2015, Article Number 13005.

ISBN 978-3-95450-177-9