A new Wire Position Monitor readout system for ILC cryomodules

F. Bedeschi, G. Bellettini, A. Bosotti, R. Carosi, S. Galeotti, A. Gennai, C. Pagani, F. Paoletti, R. Paparella, D. Passuello, F. Spinella

Abstract— **Wire Position Monitors (WPM) are used to measure the absolute position of superconductive RF cavities in prototype cryomodules developed for electron linacs such as FLASH and XFEL at DESY or the future ILC. The WPM consists of four metallic strips equally spaced in azimuth on a 12 mm diameter cylinder approximately coaxial with a reference wire excited with a 140 MHz RF signal. The position of the cylinder axis with respect to the wire can be deduced from the analysis of the signals induced on the strips.**

In this paper we present a new approach to the readout, digitization and processing of the WPM signals which is shown to produce position resolutions at the 1 micrometer level with a bandwidth of a few kHz. The latter is important to measure typical mechanical vibrations of the cold masses.

I. Introduction

The superconducting cavities and their associated cryomodules are the key elements or the new generation of linear electron accelerators such as FLASH and XFEL at DESY or the future International Linear Collider (ILC).

The ILC for example will consist of thousands of cryomodules, each 12 m long, with eight 9-cell superconducting cavities operating at 1.3 GHz. In one out of three cryomodules one of the cavities is replaced by a quadrupole package. The test program for the first cryomodule prototypes includes measurements of cavity alignment stability and reproducibility during cooldown/warmup operations. The required alignment tolerance for the elements inside a cryomodule is in the order of 100 μm for the cavities and an order of magnitude lower for the quadrupole. It is therefore desirable to install a position monitoring system with a resolution of a few μm.

The system currently installed in most prototypes currently operating in the world is called Wire Position Monitor (WPM) [1]. Each WPM consists of four metallic strips equally spaced in azimuth on a 12 mm diameter cylinder approximately coaxial with a reference wire excited with a 140 MHz signal (figure 1). The relative position of the wire with respect to the cylinder in the transverse plane $x-y$ [2] can be calculated from the analysis of the signals induced on the strips. In particular, in each transverse direction, x or y, the wire displacement from the center $\delta_{x(y)}$ produces

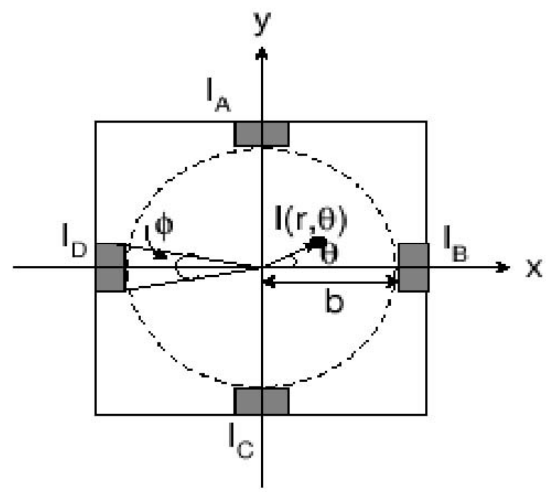

Fig. 1. Bi-dimensional schematic of the WPM

a non-zero asymmetry between the signals collected on the associated pair of strips (normalized difference)

$$D_{x(y)} = \frac{V_{B(A)} - V_{D(C)}}{V_{B(A)} + V_{D(C)}}$$

where $V_{B(A)}$, $V_{D(C)}$ are the two signals (voltages) from the strips on the measurement axis. Neglecting higher order terms it can be shown [3] that

$$D_x = \frac{4\sin(\varphi/2)}{\varphi/2}\cdot\frac{\delta_x}{2b}+\frac{2\sin(3\varphi/2)}{3\varphi/2}\cdot\left[\left(\frac{\delta_x}{b}\right)^3+\frac{3\delta_x\delta_y^2}{b^3}\right] \quad (1)$$

where φ is the azimuthal width of the strips and b the distance between the strips and the center (i.e. the circle radius). A similar expression holds for the vertical position y. Such equations are not very handful to solve in order to calculate the wire position as a function of the normalized differences. A practical method is to put the wire in a well known position, to measure the related strip signals and find the functions $\delta_x = f_x(D_x, D_y)$ and $\delta_y = f_y(D_x, D_y)$ using a fitting program.

For small δ the function $\delta = f(D_x, D_y)$ is approximately linear. For bigger δ, f is well represented by a 2-dimensional 3^{rd} order polynomial, including cross terms:

$$\delta_x = a_{10}D_x + a_{30}D_x^3 + a_{12}D_xD_y^2$$

$$\delta_y = a_{01}D_y + a_{03}D_y^3 + a_{21}D_x^2D_y \quad (2)$$

Typical values of the asymmetry are of the order of 0.1, but in our tests we have used values up to 0.5.

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Corresponding author S. Galeotti is with INFN Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

F. Bedeschi, G. Bellettini, R. Carosi, A. Gennai, D. Passuello, F. Spinella, INFN Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

F. Paoletti, EGO, Via E. Amaldi, 56021 S. Stefano a Macerata - Cascina, Pisa, Italy

A. Bosotti, C. Pagani, R. Paparella, INFN Milano and LASA, Via F.lli Cervi 201, 20090 Segrate (MI), Italy

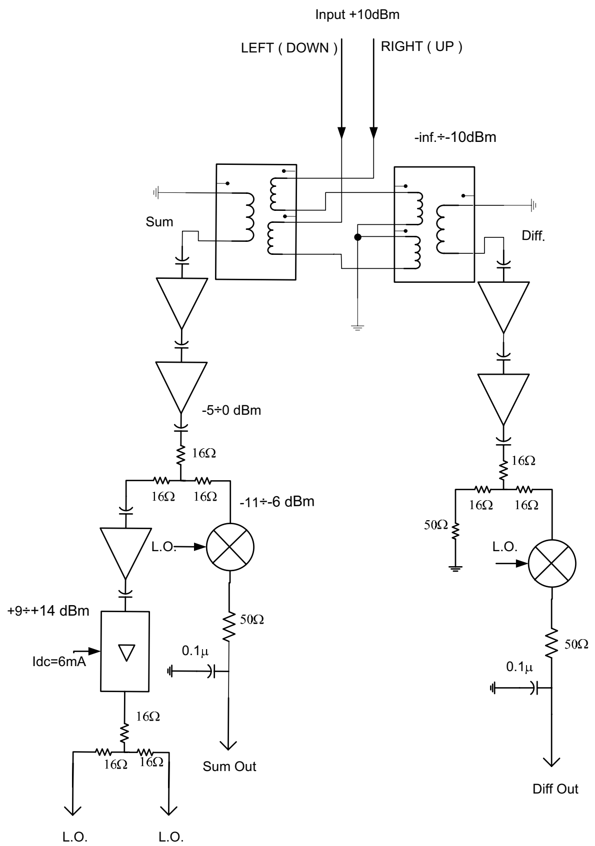

Fig. 2. Conceptual block diagram of the Wire Position Monitor

II. The new WPM readout and digitization system

In this paper we present a new approach to the readout, digitization and processing of the WPM signals. A conceptual block diagram of the analog part is shown in figure 2.

Our device is logically divided in two stages:

In the first stage we process the analog signals coming from each pair of electrodes on the same axis and we determine their sum and the difference analogically using transformers.

We have used transformers with two primary coils and one secondary coil with Ω ratios of 1:1:2. With reference to figure 2, due to the symmetry of the circuit, a common mode signal present at the inputs will produce a signal only on the sum output port, because the magnetic flux produced by the two input currents will sum up on the first transformer and will cancel out on the second one. Exactly the opposite happens in the presence of differential input signals. Due to the linearity of the circuit, it is clear that, in the presence of arbitrary input signals, the sum output port is sensitive only to the common mode; on the other hand the differential output port is sensitive only to the differential mode. A detailed analysis shows that, with the chosen Ω ratios, the input impedance seen by the two input generators does not depend from the input signals and is equal to the input impedance of the amplifiers that follow the two transformers.

The signals sum and difference are then demodulated using two mixers and a Local Oscillator signal. The latter is derived from the sum by applying a large amplification followed by a limiter. The outputs from the mixers are essentially DC levels proportional to the amplitudes of the sum and difference signals.

In the second stage the sum and difference signals are digitized. Then they are processed using standard DSP techniques to produce pairs of time stamped coordinate values. These values are sent to a central system through an ethernet interface.

One obvious advantage of using an analog sum and difference, instead of directly digitizing the electrode signals, is that we are able to use the full ADC range even when the signal are large and the difference is small.

Furthermore, since the Local Oscillator (LO) signal is derived directly from the sum signal, the system is quite self-contained, and can be located anywhere with no need to distribute the Radio Frequency (RF) signal for the LO.

III. Prototype performance

A prototype of this device has been built and tested at the INFN, Pisa, Italy. The test setup consists of a two meter long copper-beryllium wire stretched between two bulkheads.

A drive signal of 140 MHz is applied at one end of the wire, while the other end is terminated to avoid reflections. The wire is shielded with a copper tube of the same diameter of the WPM sensor. Since no counterweight was used to stabilize the wire tension the setup has some sensitivity to temperature fluctuations, for instance those induced by the current flowing through the wire. The WPM signals were picked up from one end of the sensor strip, while the other end was terminated on 50 Ω

This prototype can distribute pairs of coordinates to the network at a maximum frequency of about 5 kHz. This rate is limited currently by the choice of onboard CPU.

The actual device requires a 12V power supply and 0.5 A, but we plan to change the type of amplifiers to reduce the power consumption. The level of the Radio Frequency (RF) at 140 MHz ranges from +7 dBm through -13 dBm at the wire input. Linearity is very good between +7 dBm -8 dBm. The system works at Radio Frequencies between 100 MHz and 150 Mhz, and is optimized for 140 MHz.

In order to study the position resolution of the complete system we have mounted the sensor with the pick up strips on a micrometer stage and applied a target on top of the sensor housing. The target position is measured with a camera connected to a Mitutoyo measuring machine BHN506 [4], which has an intrinsic position resolution of about 1 μm. The output signals for different wire positions are digitized with a 14 bit ADC. We have taken data in the range ±4 mm. In our tests, we have considered only one

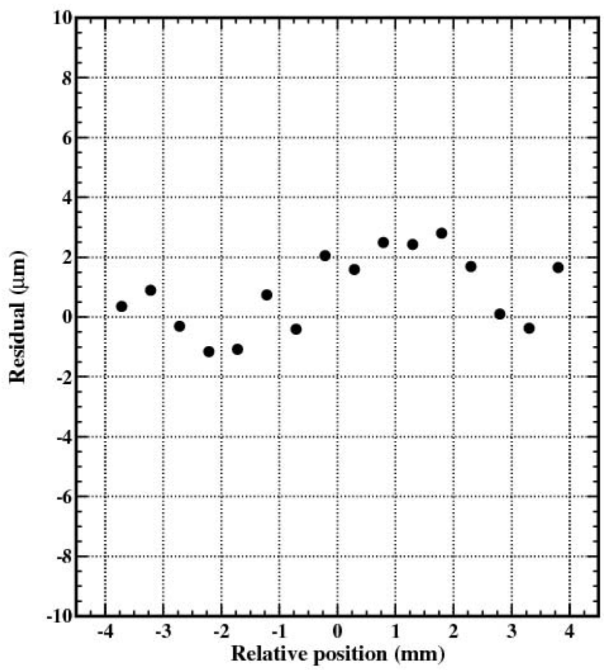

Fig. 3. Residuals versus x Wire Position (mm)

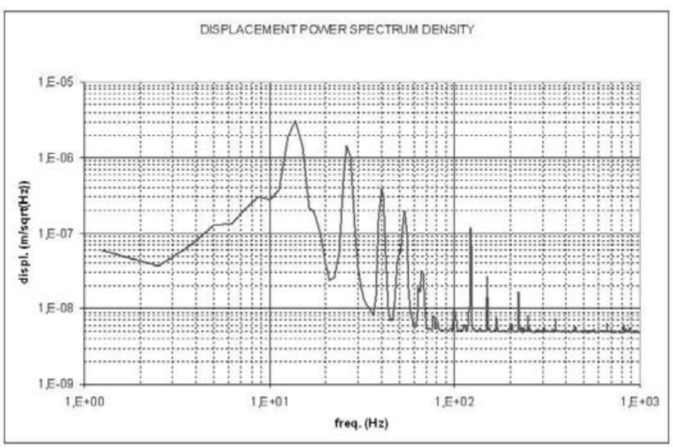

Fig. 4. Displacement noise versus frequency

direction, x, i.e. without the possibility of using y measurements to improve the resolution.

We then fit the wire position as a function of the normalized difference D_x with a 3^{rd} order polynomial. The residuals can be used to estimate the position resolution. They are shown in figure 3 and indicate a resolution close to 1 μm; this is better than results obtained with older electronics [1].

We use the previous fit to calibrate the response of the WPM at a fixed position. In this case the wire is centered between the sensor strips. With an input RF level of +5 dBm the difference signal variation with position is 12 V/m.

In figure 4 we show the noise power spectrum of the difference signal normalized with above calibration. The resonance peaks (14 Hz and harmonics) corresponding to wire resonance modes excited by seismic noise are clearly visible. Above about 100 Hz the noise level is about $6 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$.

In conclusion we have built a compact WPM readout system with excellent position resolution and noise characteristics. This design approach may be applied to other similar applications, for instance beam position monitors.

References

[1] D. Giove, A. Bosotti, C. Pagani and G. Varisco, "A Microstrip Based Position System for the Alignment of the TTF Cryostat," Proceedings of the 1995 Particle Accelerator Conference, May 1-5, 1995, Dallas, TX, USA, Volume 4, p. 2093-2095.

[2] We use a reference frame where x is along the horizontal direction transverse to the wire, y is along the vertical direction and z is in direction of the wire

[3] R. E. Shafer, "Characteristics of directional coupler beam position monitors," *IEEE Trans. on Nucl. Sci., 32 (1985)* p.1933-1937.

[4] http://www.mitutoyo.com