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CLIC BPM-Quadrupole pre-alignment in the frame of the PACMAN Marie Curie Action*

Zorzetti S.[1], Fanucci L.[2], Wendt M.[3]

[1] *CERN (BE-BI-QP) and University of Pisa, Genéve - Switzerland, silvia.zorzetti@cern.ch*
[2] *University of Pisa, Pisa - Italy, luca.fanucci@unipi.it*
[3] *CERN (BE-BI-QP), Genéve - Switzerland, manfred.wendt@cern.ch*

Abstract – **The Compact Linear Collider (CLIC) requires a low emittance beam transport and preservation, thus a precise control of the beam orbit along up to 50 km of the accelerator components in the sub-μm regime is required. Within the PACMAN (Particle Accelerator Components Metrology and Alignment to the Nanometer Scale) Ph.D. training action a study with the objective to pre-align the electrical center of a 15 GHz cavity BPM to the magnetic center of the main beam quadrupole is initiated. Goals, first ideas, some technical details, as well as the challenges of this stretched wire based method will be presented, including calculations, simulations, and first preliminary measurements [1].**

I. INTRODUCTION

The beam position monitor (BPM) is a diagnostic instrument used to measure the position of the beam. From a beam dynamics point of view, the optimal beam trajectory with minimum emittance blow-up will be in the magnetic center of each quadrupole, where non-linear field components are minimum. A series of BPMs distributed along the accelerator are needed to measure and control the beam orbit precisely along all the quadrupoles. The challenge is the pre-alignment of the BPM electrical center to the quadrupole magnetic center in the sub-μm regime, which is mandatory for a successful commissioning of a 50 km long accelerator with low emittance beams.
The strategy chosen for our alignment studies is based on two steps:

- First, to separately characterize the BPM and the quadrupole with stretched-wire measurement methods;
- Second and final, to integrate both components into a dedicated standalone test bench using the same stretched wire.

Among the other components, the test bench includes precision translation stages to mechanically scan the component position with respect to the wire, seismic sensors and metrology equipment. The wire calibration of the BPM will define the electrical center position associated to the electrical signal induced by the particle beam. Referencing the measurement of the magnetic center of the quadrupole magnet to the BPM electrical center, the quad-BPM system will be independent from external references. In this context particular attention has to be paid to the wire chosen, and to the impact that it may have on the BPM cavity.

At DESY for the TESLA Test Facility phase II (TTF2), similar measurements have been performed, achieving a resolution of $10\mu m$[2]. A schematic view of that stretched wire test bench for the alignment is shown in *Fig.*1, and can be used as reference for the future test bench performed in the frame of the PACMAN activities. However the DESY BPM was a stripline BPM, operating at 375MHz, while the PACMAN BPM is an RF cavity operating at 15GHz, this challenging microwave frequency requires a higher resolution potential in the nm regime.

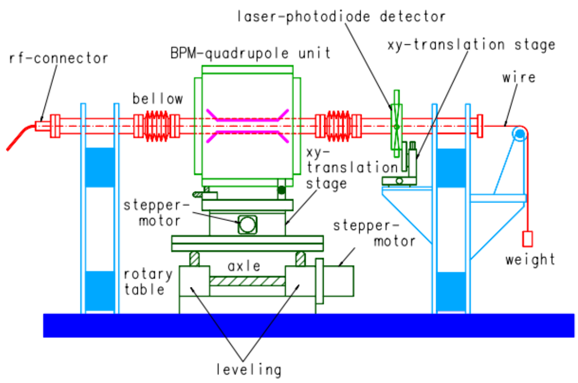

Fig. 1. Schematic view of stretched wire alignment setup at DESY for TTF2

II. THE BEAM POSITION MONITOR IN CLIC

The BPM used for CLIC is a passive resonant cavity, operating at 14GHz (*Fig.* 2), optimized for both a good spatial resolution (<*50nm*), and a good temporal resolution (<*50ns*)[3]. For beam test at the CLIC test facility (CTF) the resonant frequency of this design was modified to

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15GHz, to comply with the beam structure.

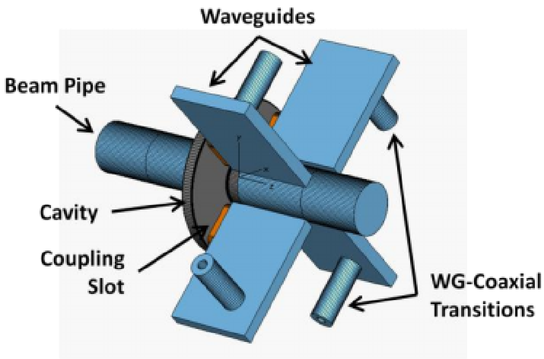


Fig. 2. 15GHz BPM cavity resonator used for CLIC experiment

The cavity BPM can be assimilated to a simple resonant pillbox, in which the following relation holds: *d<2a* (*d=2mm* is the length and *a=11.24mm* is the radius of the cavity *Fig.*3). The fundamental modes excited are transverse modes (TM), two of them are of particular interest: the monopole mode at TM_{010} at 11GHz and the dipole mode at TM_{110} at 15GHz, which has two polarizations.

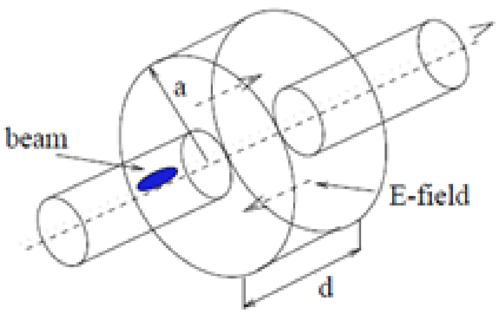
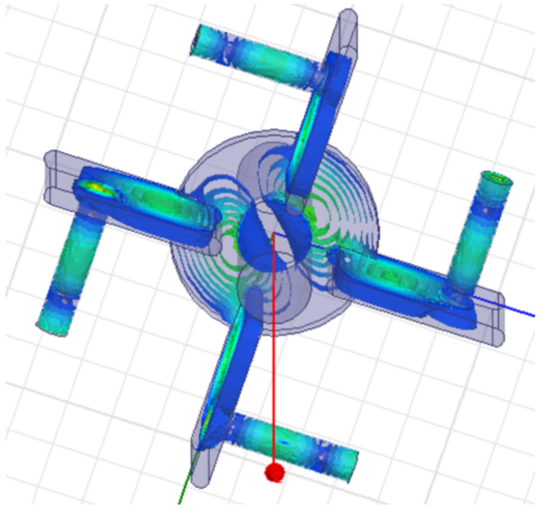


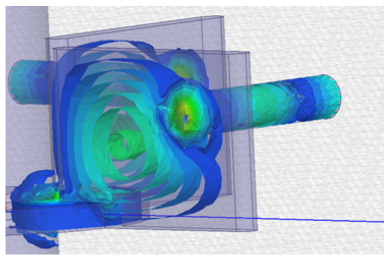
Fig. 3. Pillbox schematic view and parameters

The dipole mode signal of the cavity BPM is proportional to the beam displacement, and coupled out via waveguides with a cut-off frequency between the TM_{010} and the TM_{110} resonant frequencies, to suppress any monopole mode signal contribution. In *Fig.*4a the plot of the electric field, when the TM_{110} mode is excited, is depicted, the coupling through the waveguides is underlined in *Fig.*4b; the simulations have been performed with HFSS.

Because of manufacturing and material imperfections the electrical center may not match with the mechanical center, for this reason the cavity pickup needs to be calibrated. Moreover, the resolution in the nm range needs to be verified. For a cylindrical cavity, resonant frequen-



(a) BPM TM_{110} E-Field



(b) Waveguide coupling

Fig. 4. E-Field HFSS Simulation on a BPM cavity model

cies and Q-Factor, for the TM and TE modes, are given by equations from (1) to (4) [4].

$$f^{TE}_{mnq} = \frac{1}{2\pi\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{p'_{mn}}{a}\right)^2 + \left(\frac{q\pi}{d}\right)^2} \quad (1)$$

$$f^{TM}_{mnq} = \frac{1}{2\pi\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{p_{mn}}{a}\right)^2 + \left(\frac{q\pi}{d}\right)^2} \quad (2)$$

$$Q^{TE}_{mnq}\frac{\delta}{\lambda} = \frac{[1-(\frac{m}{p'_{mn}})^2]\sqrt{[(p'_{mn})^2+(\frac{q\pi a}{\lambda})^2]^3}}{2\pi[(p'_{mn})^2+\frac{2a}{d}(\frac{q\pi a}{d})^2+(1-\frac{2a}{d})(\frac{mq\pi a}{p'_{mn}d})^2]} \quad (3)$$

$$Q^{TM}_{mnq}\frac{\delta}{\lambda} = \frac{\sqrt{(p_{mn})^2+(\frac{q\pi a}{d})^2}}{2\pi(1+\frac{2a}{d})} \quad (4)$$

Where p_{mn} are the zeros of the Bessel functions. $\delta = \frac{1}{\sqrt{\pi f \mu_r \sigma}}$ is the skin depth, that considers the losses in the material, μ_r is the permeability of the metallic cavity.

III. ANALYSIS ON A GENERIC RF TEST CAVITY

To better understand the underlying theory, numerical simulations and measurements have been performed on an available simple cavity, with a deepen study of the effects of the wire on resonant frequencies and Q-Factor. In the frame of these simulations, two different simulations software have been used, HFSS, using a frequency domain solver (FD), and CST Studio, using a time domain (TD) solver.

The cavity under test is made by aluminium (*Fig.*5) and it has different geometrical properties than the BPM cavity; since $d > 2a$ ($a = 21.27cm$ and $d = 60cm$) both TE and TM modes are excited. Nevertheless this exercise is very useful in order to understand the impact of the stretched wire on the eigenmodes, as well as to compare theory, different numerical simulations and measurements.

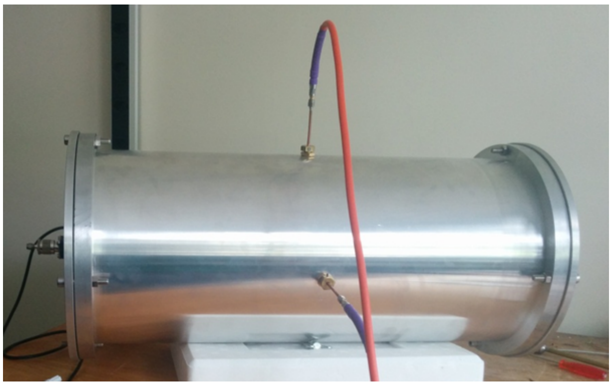


Fig. 5. Generic RF Cavity under Test

A. STRETCHED WIRE SETUP

When a single wire is stretched through a cavity, a TEM field is excited, and lower frequencies are simply passed through. The setup is based on a coaxial transmission line, and it is necessary to terminate it with the characteristic impedances to minimize reflections, see block schematic in *Fig.*6. At the resonant frequencies, the resonator will absorb energy from the signal passing through the wire, the effect can be analyzed performing S21 measurements with a vector network analyzer (VNA).

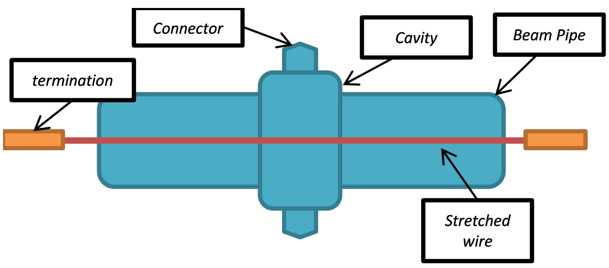


Fig. 6. Cavity stretched wire block diagram

B. EIGENMODES

Considering the geometrical properties of the cavity under test, the dominant mode is the TE_{111}. In tables below, the results achieved by calculations, measures, CST, and HFSS eigenmodes simulations are displayed for this mode.

	Expected	Measured	
		no wire	wire
TE_{111}	*862.9MHz*	*863.0MHz*	*862.9MHz*
QTE_{111}	*47496*	*21469*	-

Table 1. TE_{111} mode resonant frequency and Q-factor Expected vs. Measured

	CST	
	no wire	wire
TE_{111}	*863.0MHz*	*863.0MHz*
Q TE_{111}	*26300*	*26350*

Table 2. TE_{111} mode resonant frequency and Q-factor simulation results using CST Studio

	HFSS	
	no wire	wire
TE_{111}	*854.9MHz*	*854.9MHz*
Q TE_{111}	*45259*	*45242*

Table 3. TE_{111} mode resonant frequency and Q-factor simulations results using HFSS

Comparing the analytical calculations (using equations (1) and (3)), and the CST and HFSS eigenmodes simulations, we noticed that CST is more precise regarding the value of the resonant frequencies, while HFSS performs a more accurate estimation of the Q-Factor.

*Fig.*7 shows the TM_{010} monopole mode with and without the stretched wire. This measurements is of big interest for our cavity BPM studies, as it demonstrates that also in presence of the stretched wire the TM modes can still be evaluated. We observe that the value of the resonant frequencies matches the theoretical one, while the Q-Factor drops down.

C. SCATTERING PARAMETERS

The scattering parameters have been measured and simulated. Here the two software behave differently: the TD solver in CST performs the Fourier transformation of a time domain pulse, the more compressed is the pulse, the more precise will be the transformation; the FD solver in HFSS solves point by point the Maxwell equations in frequency domain. CST gives a good qualitative response,

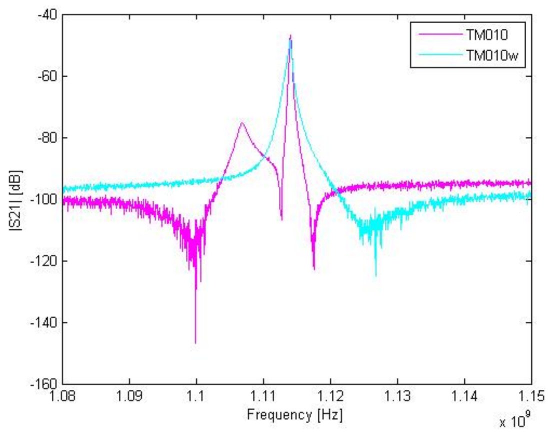


Fig. 7. Q-Factor evaluation on a simple RF Test Cavity, with and without the stretched wire

while HFSS is more precise on single points in the frequency domain. In *Fig.*8 the comparison between real measurements and CST numerical simulation is available.

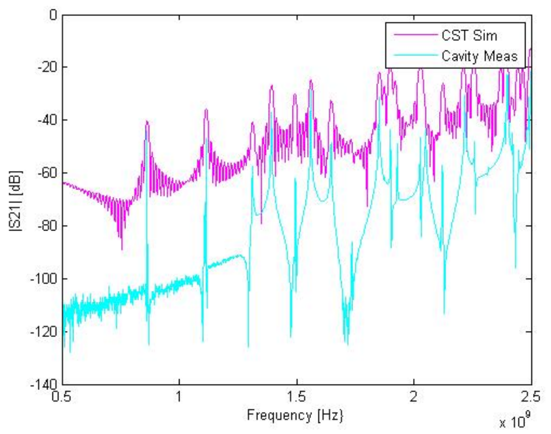


Fig. 8. CST Simulation and S21 Measurements

IV. BPM TEST BENCH AND PRELIMINARY MEASUREMENTS

A. TEST BENCH

In the frame of the PACMAN project and the BPM study, a first goal is a stand alone RF test bench stretched wire to evaluate the cavity BPM (*Fig.*9). This test bench will help to demonstrate the resolution, which is estimated as $< 50nm$ for bunched beams, and the issues related to the stretched wire signal excitation. With the help of the metrology, we will try to reference the electrical center found to mechanical fiducials, and to prove the reproducibility of the measurement method.

The test bench, mounted on an active optical table (to damp vibrations), is at the moment under design. It will

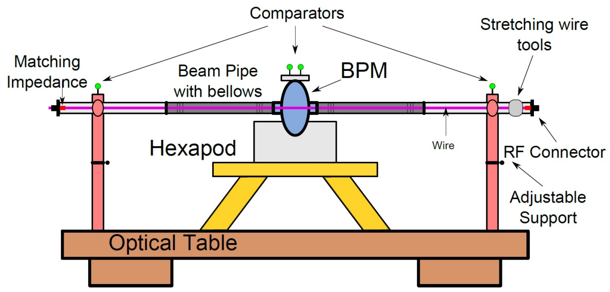


Fig. 9. CLIC BPM Test Bench

include:

- Hexapod: to precisely move the BPM with respect to the wire at a $sub-um$ resolution in 6 degrees of freedom (DOF). We will use only 4 DOF: the two axis perpendicular to the beam directions and the respective angles;
- Beam Pipes: there will be two types of beam pipes, those without bellows as support for the flanges, and those with the bellows, to allow the movement;
- Adjustable Supports: to support the BPM and the beam pipes on the optical tables;
- Comparators and metrology instrumentation: to measure the physical position of the BPM and to make a pre-alignment of the system;
- Stretching wire tools: mechanics and RF matching networks to control the stretching wire, as well as to minimize reflection.

B. BPM MEASUREMENTS

A very preliminary stretched-wire measurement of the dipole mode of the cavity BPM has been performed, also measurements with the wire to verify the simulated eigenmode frequency. The stretched wire test was realized in a simplistic, not optimized setup (*Fig.*10).

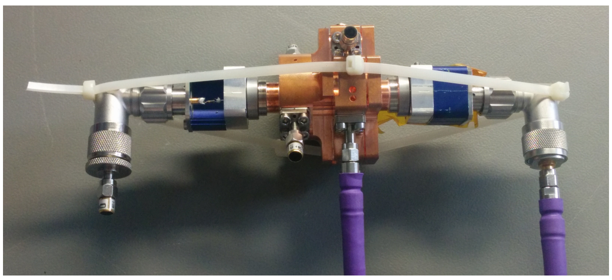


Fig. 10. First BPM test setup

*Fig.*11 displays two traces, showing the TM_{110} dipole mode from one of the cavity BPM excited through the wire and through port coupling. It is valuable to observe that the wire does not alter the frequency of the dipole mode substantially.

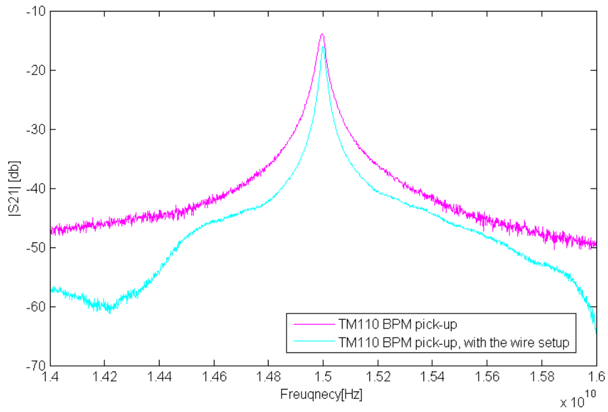


Fig. 11. TM_{110} on BPM pickup

V. CONCLUSIONS

Simulations, measurements and analytic calculations have been performed on a simple RF cavity, in order to establish a first contact with the RF measurements and simulations, and the stretched wire setup, as well as to lay the foundations for the future work to be done on the CLIC BPM.

Regarding the BPM first measurements demonstrate the proof-of-principle of the instrument and the achieved results give confidence that the method has a very good potential for the aimed goal.

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