HIGH FREQUENCY MEASUREMENTS OF THE BEAM POSITION MONITORS FOR THE TBL LINE OF THE CTF3 AT CERN*

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Abstract

A series of Inductive Pick-Ups (IPU) for Beam Position Monitoring (BPM) with its associated electronics were designed, constructed and tested at IFIC. A full set of 16 BPMs, so called BPS units, were successfully installed in the Test Beam Line (TBL) of the 3rd CLIC Test Facility (CTF3) at CERN. Two different characterization tests, at low and high frequencies, were carried out on the BPS units: The low frequency test, in the beam pulse time scale (until 10ns/100MHz), determined the BPSs parameters directly related to the beam position monitoring and the high frequency test, reaching the microwave X-Ku bands around the beam bunching time scale (83ps/12GHz). In this paper we describe the results and methods used to obtain the longitudinal impedance in the frequency range of interest. This test is based on the S-parameters measurements of the propagating TEM mode in a matched coaxial waveguide, specifically designed for the BPS, which is able to emulate an ultra-relativistic electron beam.

INTRODUCTION

The CTF3 will demonstrate the essential parts of the CLIC drive beam generation scheme consisting of a fully loaded linac, a delay loop and a combiner ring. The final CTF3 drive beam is delivered to the CLIC Experimental Area (CLEX) comprising the TBL and the Two Beam Test Stand (TBTS). The TBL is designed to study and validate the drive beam stability during deceleration in the power extraction process. The TBL consists of a series of FODO lattice cells and a diagnostic section at the beginning and at the end of the line to determine the relevant beam parameters. Each of the 16 cells in TBL is comprised of a quadrupole, our BPS and a Power Extraction and Transfer Structure (PETS) with a 1.4m length per cell [1].

The BPS monitor is an Inductive Pick-Up (IPU) and the expected performances for a TBL beam type (current range 1-30 A, energy 150 MeV, emittance 150 μm, bunch train duration 20-140 ns, microbunch spacing 83ps (12GHz), microbunch duration 4-20 ps, microbunch charge 0.6-2.7 nC) are a resolution (at maximum current) below 5 μm and an overall precision (accuracy) less than 50 μm. The main benefits argued for using IPUs in the TBL are: position and current intensity measurements in the same device, less perturbed from the high losses in linacs, high output dynamic range for beam currents in the range of interest, broad bandwidth for pulsed beams and short total length. The performance details can be found in [3].

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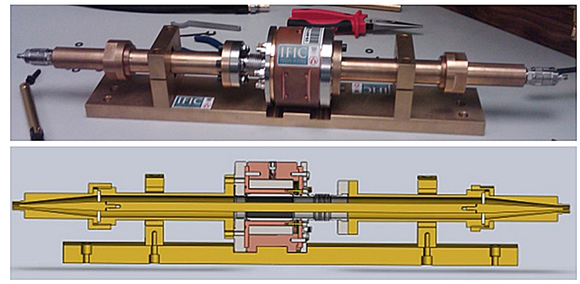

Figure 1: The high frequency coaxial testbench with the BPS inserted for measuring its longitudinal impedance

Apart from the main operation parameters for beam position monitoring, it is also needed to determine the longitudinal impedance of the BPS monitor for the high frequency components generated by the beam bunching frequency in the GHz range. This is important since every BPS monitor produces a longitudinal impedance, $Z_{\|}$, in the line, and higher values of $Z_{\|}$ will produce stronger wake-fields leading to beam instabilities. For that purpose it was built a special high frequency testbench (Fig. 1).

THE BPS MONITOR AND ITS LONGITUDINAL IMPEDANCE $Z_{\|}$

Basic Operation Mechanism

The BPS inner vacuum pipe has a ceramic gap surrounded by gold plated cylinder which is divived along into four orthogonal strip electrodes. The wall current intensity induced by the beam flows through these electrodes at bigger wall diameter, and the beam position is measured by means of the image current distribution among these electrodes that will change according to the beam proximity to them. Thus the current level in each electrode is sensed inductively by their respective transformers, which are mounted on two internal PCB halves as part of the electrode outputs conditioning circuit. In Fig. 2 the BPS cross section view shows the vertical plane electrodes, the wall image current flowing through them and the toroidal transformers mounted on the PCBs (same for the horizontal plane). From the PCB circuits, the output SMA connectors give four voltage signals (V_+, H_+, V_-, H_-) that will drive an external amplifier to yield the three signals for determining the beam position and intensity: the sum signal $\Sigma = V_+ + H_+ + V_- + H_+$), to get the beam current intensity; and two difference signals ($\Delta V = V_+ - V_-$ and $\Delta H = H_+ - H_-$) which are proportional to the horizontal and vertical coordinates of the beam position. Finally, at the digitizer end the coordinates data are obtained from several amplitude samples within the normalized pulse signals as, $x_{H,V} \sim \Delta H, V/\Sigma$. A detailed description of the BPS-IPU monitor can be found in [2].

Image Current Paths

The beam time structure in TBL is made of pulses between 20-140ns composed of micro-bunches of 83ps giving a bunching frequency of 12GHz. The monitor is designed to work in a bandwidth at the beam pulse time scale, from 10kHz (100 µs) to more than 100MHz (10ns), to have a good pulse shape transmission at the electrodes outputs for measuring the beam position. In principle, the image current, regardless of its frequency components, follows the path through the electrodes for normal operation of the monitor. Nevertheless, the longitudinal impedance, $Z_{\|}$, of the device becomes too large for high frequencies of the image current until the bunching frequency, and higher harmonics extending beyond the microwave X band. This is due to the inductive behavior, which increases linearly with frequency, introduced by the larger diameter step seen by the image current when passing over the electrodes. To avoid this, the inner wall of the ceramics (see Fig. 2) was coated with a thin Titanium layer deposited by sputtering, giving an alternative path of minimum inductance to the high frequency components of the image current, and limiting so $Z_{\|}$. In consecuence, the image current frequency components will follow the electrodes path of minimum resistance for the lower and the Ti coating path of minimum inductance for the higher, having a transition frequency determined by the particular impedances of both paths.

Longitudinal Impedance $Z_{\|}$

The resistance value of the coating must be the lowest possible but not too low in order to have a transition frequency above enough the operation bandwidth and to do not reduce it significantly. The work done for a previous IPU obtaining the coating optimal resistance value can be found in [4], the BPS has the same coating with a resistance around 11Ω which does not affect the BPS operation bandwidth. The measurement of $Z_{\|}$ is usually performed with the so called wire method where the device under test (DUT), the BPS monitor, is inserted in a testbench of a coaxial transmission line as shown in Fig. 1. This method assumes that an ultra-relativistic beam has a closely transverse electromagnetic (TEM) field distribution, what is the case of the 150MeV TBL electron beam with $\beta \cong 1$, and it can be emulated with a coaxial structure having pure transverse TEM propagation modes to determine $Z_{\|}$. The Scattering matrix parameters (S-parameters) between the two testbench coaxial ports are directly measured from a Vector Network Analyzer (VNA) in the frequency range of interest. Thus $Z_{\|}$ can be obtained from the transmission coefficient, S_{21}, which is the signal drop along the line. But the typical calculation method for lumped impedances is not valid here because the DUT insertion length is already much larger than the main wavelength of the bunching frequency. Instead, the calculation method for distributed

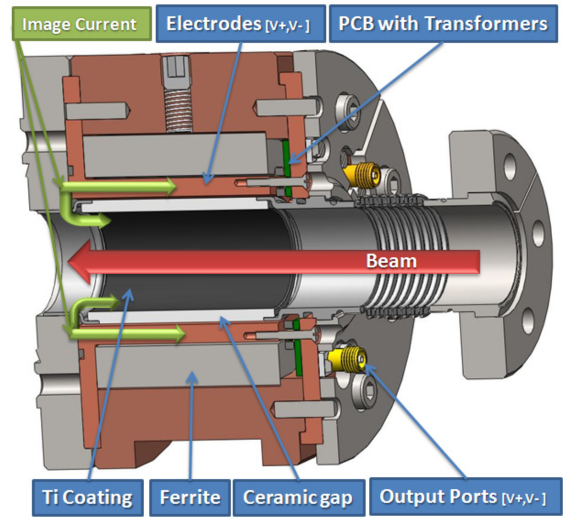

Figure 2: Cross section view of the BPS monitor.

impedance proposed in [5] is used as good approximation for the complex longitudinal impedance

$$Z_{\|} = -2Z_L ln\left(\frac{S_{21}}{S_{21R}}\right) \quad (1)$$

where Z_L is the impedance of coaxial line testbench, S_{21} is the transmission coefficient of the testbench with DUT, and S_{21R} is the transmission coefficient of the reference measurement, with the DUT replaced by a drift tube to remove the testbench dependency.

THE COAXIAL WAVEGUIDE TESTBENCH

The testbench in Fig. 1 was made of 70/30 brass alloy and built as a coaxial airline of 50Ω transverse impedance along the structure, matching with the 50Ω output ports of the VNA. The transverse impedance of a coaxial line is written as

$$Z_{coax} = \frac{c\mu_0}{2\pi\sqrt{\epsilon_r}} ln\left(\frac{r_o}{r_c}\right) \quad (2)$$

where c and μ_0 are, respectively, the speed of light and the magnetic permeability in vacuum, it depends on the dielectric permitivity of the medium between conductors and, geometrically, on the radius of the coaxial center conductor, r_c, and the outer conductor, r_o. Since the outer conductor in the testbench straight section must have the same 24mm aperture diameter of the BPS vacuum pipe, the central conductor is then fixed at 10.422mm diameter by Eq. (2). The testbench input ports are two APC-7mm connectors with screw central conductors what made easier the assembly with the testbench central rod and also with low reflection specifications up to 18GHz. Thereby a cone geometry was chosen in order to have a 50Ω smooth transition between the outer diameters of the connector and the testbench straight section, keeping the conductors diameters ratio at constant value. The end connection to the VNA was done via more popular SMA (or 3.5mm) adaptors with same specifications as the APC-7mm.

The main elements of the coaxial testbench, with the drift tube for reference measurements, was simulated using specialized microwave software FEST3D [6]. The key element in the structure simulation was the transition cones, essentially the cone geometry was loaded into the simulator by linking together short length coaxial waveguides of increasing diameters in a staircase pattern. Cones with several step lengths, l_{step}, were simulated, finally choosing l_{step}=200 µm ensuring small enough steps $l_{step} << \lambda_{max}$ to have no influence due to the staircase discontinuities at maximum simulation frequency, f_{max}=30GHz. Also the selected cone length was l_{cone}=80mm in a compromise between shortest l_{cone} and lowest S_{11} reflection coefficient to get a smooth enough transition. In Fig. 3 are plotted the simulated S-parameters of the full coaxial waveguide with an intermediate section with room to place the BPS and the two symmetric transition cones. This result show a reflection level less than -45dB in the maximum available bandwidth for the only-TEM modes propagation until 22GHz where undesired TM modes starts propagating. The theoretical cut-off frequency was calculated being exactly 21.9GHz. Initially, in the testbench design, it was introduced two PTFE washers at the end of the transition cones, keeping the 50Ω transverse impedance with a diameter step in the outer conductor, to help in the central rod support, but finally they were removed because introduced a resonance aroung 10GHz deteriorating too much the testbench bandwidth.

HF TEST AND MEASUREMENTS

The S-parameters test was carried out using the available VNA equipment at the ESA's *European High Power RF Laboratory* in the *Val Space Consortium* (VSC). It was performed on BPS5s unit randomly selected from the series production and according to the method proposed before to determine its $Z_{||}$ in the 18MHz to 30GHz range. First, the S-parameters between the two ports of the testbench with a drift tube as reference measurement and after, with the drift replaced by the monitor, getting their respective transmission coefficients, S_{21R} and S_{21}. Thus, the plot in Fig. 4 shows the real part of the $Z_{||}$ frequency response calculated from Eq. (1). It can be seen here that the $Z_{||}$ real part exhibit the expected saturation tendency. At low frequencies it increases linearly until the transition frequency, around 800MHz, when the Ti layer image current path becomes dominant for these frequency components limiting $Z_{||}$ below 13Ω. The limitation is continuously effective up to nearly 6GHz, then a first resonance occurs at 6.8GHz with 148Ω resistive peak to come down again below the 13Ω. More peaks starting around 15GHz appears before reaching up to 22GHz, which was taken as our useful testbench bandwidth due to the theoretical limit imposed by the beginning of TM modes propagation, as stated in previous section. Explanation of these resonances needs further study to look for their nature and eventually to check whether the BPS $Z_{||}$ will show the expected saturation tendency at higher frequencies or these resonances really belong to the BPS design.

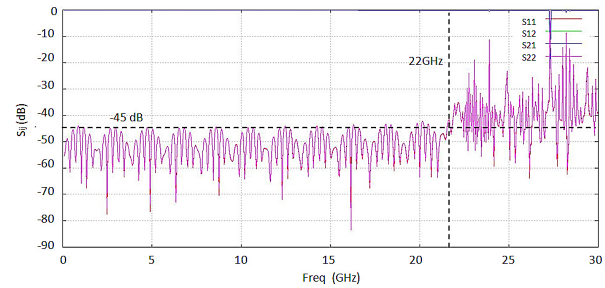

Figure 3: S-parameters simulation of the coaxial testbench.

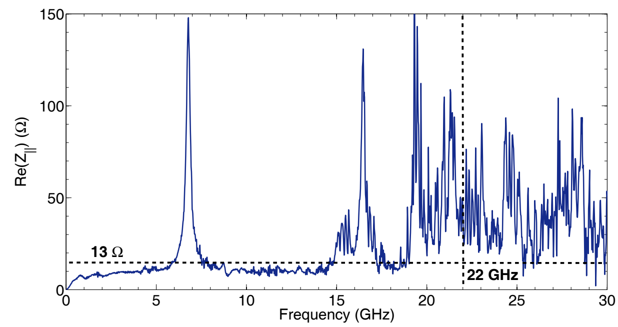

Figure 4: Test result of BPS longitudinal impedance, $Z_{||}$.

CONCLUSIONS AND FUTURE WORK

A coaxial waveguide testbench was particularly designed and built at IFIC, which is suitable to emulate the TBL beam high frequency components in the microwave region above the bunching frequency until 18GHz, in order to determine the BPS longitudinal impedance, $Z_{||}$. The method, testbench simulations and design considerations as well as $Z_{||}$ test results were discussed. Also an alternative method based on ABCD matrix formulation is under study as future work.

ACKNOWLEDGMENTS

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