CERN PS BOOSTER TRANSVERSE DAMPER: 10 kHZ - 200 MHZ RADIATION TOLERANT AMPLIFIER FOR CAPACITIVE PU SIGNAL CONDITIONING

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Abstract

After connection to the LINAC4, the beam intensity in the PS Booster is expected to double and thus, an upgrade of the head electronics of the transverse feedback BPM is necessary. In order to cover the beam spectrum for an effective transverse damping, the pickup (PU) signal should have a large bandwidth on both the low and high frequency sides. Furthermore, in order to extend the natural low frequency cut-off from 6 MHz (50 Ω load) down to the required 10 kHz, with no modification of the existing PUs, a high impedance signal treatment is required. The electronic parts should withstand the radiation dose received during at least a year of service. This constraint implies the installation of the amplifier at a remote location. A solution was found inspired by the technique of oscilloscopes' high impedance probes that mitigates the effect of transmission line mismatch using a lossy coaxial cable with an appropriate passive circuitry. A new large bandwidth, radiation tolerant amplifier has been designed. The system requirements, the analysis, the measurements with the present PUs, the design of the amplifier and the experimental results are described in this contribution.

INTRODUCTION

New pick-up (PU) head amplifiers are needed in the CERN PSB (Proton Synchrotron Booster) for the specific needs of the transverse feedback (TFB) system. This latter feedback was installed in order to damp transverse instability of the beam and it is fully operational with the present beam as injected from the LINAC2 (linear accelerator).

As shown in the Table 1, in 2018 a higher beam intensity (factor 2.5 increase) is expected from the new LINAC4. This will mean a higher voltage on the beam position pick-up installed in the ring and a potential saturation or destruction of the head amplifiers presently installed.

The beam spectrum, as sensed by the beam PUs, is populated at the harmonics of the revolution frequency and at so-called betatron side bands (amplitude modulation) around the revolution lines. The transverse betatron motion is inherently due to the architecture of a synchrotron where the beam experiences a certain number of transverse oscillations at each turn (revolution). This number of oscillations is called the tune and it is a non-integer value (Q.q) with a fractional part q. The side-bands observed in the transverse error signal, calculated as the difference of signals from two opposite pick-up up electrodes of a given H or V plane, are located $q{\cdot}f_{\mathrm{rev}}$ apart from each of the revolution harmonics. f_{rev} is the beam revolution frequency. With minimum values of $q = 0.1$ and $f_{\mathrm{rev}} = 1$ MHz, the lowest frequency betatron band is located at 100 kHz.

In order to have a good damping rate at 100 kHz, the phase error at this frequency should be minimal; this is why a low-frequency −3 dB cut-off pole is requested at 10 kHz. On the higher end of the spectrum, the limit is mainly technological. The head amplifier is required to have the widest possible bandwidth considering the potential high frequency instabilities. Nevertheless, our present limited knowledge of the machine impedance does not allow for precise specifications in that direction, so we are aiming at amplifiers having a bandwidth equivalent to what the PU itself can supply.

Table 1: CERN PSB Machine Parameters with LINAC4

Proton kinetic energy, E_k	160 MeV → 2 GeV
Velocity factor, β	0.533 → 0.948
Revolution frequency, f_{rev}	1 MHz → 1.8 MHz
Maximum protons per bunch, N_p	$2.5 \cdot 10^{13}$ ppb
Minimum bunch length, 4σ	≈150 ns

PICK-UP

The pick-up is using 4 conductive plates engraved on the inner surface of a ceramic tube inside which the beam will flow. This ceramic tube is enshrined inside a cylindrical stainless steel tube. The capacitance between each plate of the PU and its grounded support is measured to be around 630 pF. Under the presence of beam, the PU plate can be represented as a current generator [1] feeding the electrode capacitance in parallel with the monitoring circuit load.

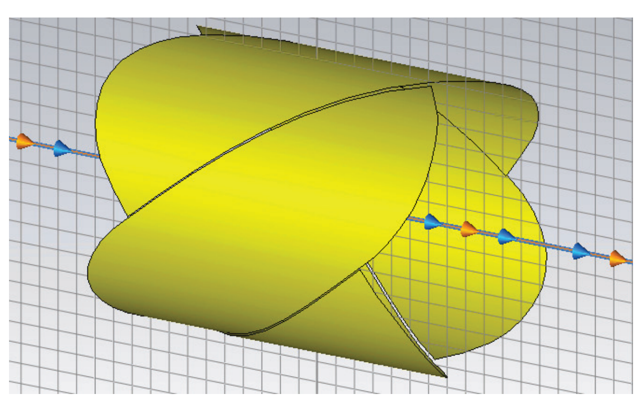

Figure 1: CST PU Model.

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PU Bandwidth Estimation

The lowest cut-off (high-pass) frequency of the pickup, depends on its load impedance. On the high frequency side, the bandwidth is more difficult to predict. The bandwidth depends on the detailed dimensions and impedances of the setup together with the beam velocity (β).

A practical way to measure the PU response is to use the so-called stretched wire technique that reproduces a TEM field [2] representing, with enough precision, an ultra-relativistic beam ($\beta \approx 1$). A conductive wire is placed inside the pick-up along the supposed beam trajectory, and is fed by a swept sine-wave from a Vector Network Analyzer (VNA) as shown in Figure 2. The induced signal is taken from the PU electrode to the 50 Ω measurement port of the VNA.

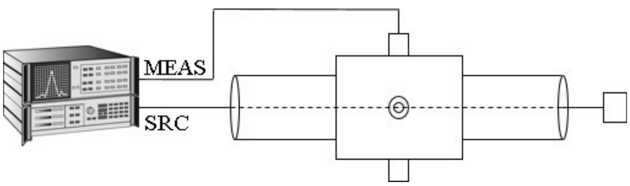

Figure 2: Test bench set-up.

In this measurement one gets the amplitude and phase response of the PU. Both parameters are important, but the phase is most critical as the PU is embedded in a feedback loop where a total 90° phase shift corresponds to a lack of damping and 180° to an unstable behaviour. From the phase response with respect to frequency, the pure delay contribution can be cancelled in order to focus on the non-linear phase error that should be within ±45°.

The PU has also been simulated with a numeric solver (CST studio [3]) using a simplified model. As shown in Figure 3, the PU gain is flat and identical on both the measurement and simulation up to 220 MHz and the measured non-linear phase is within the ±45° boundaries up to 320 MHz when $\beta = 1$.

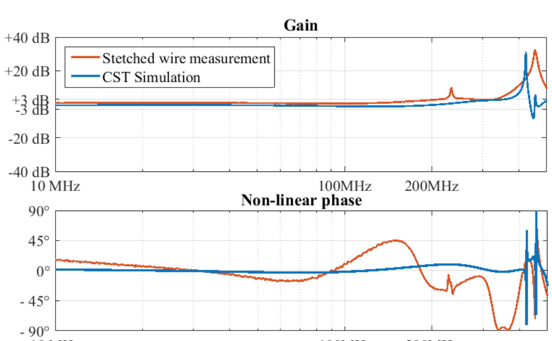

Figure 3: PU frequency response.

PU Signal Amplitude Estimation

Taking into account a high impedance loading in order to limit the natural differentiating behaviour of the PU, one can assume within the obtained bandwidth that a centred beam will induce a voltage [4]:

$$V_{PU}(t) = \frac{1}{\beta c C} \cdot \frac{A}{2\pi r} \cdot I_{beam}(t) \qquad (1)$$

Where V_{PU} is the voltage on the PU electrode, β is the velocity beam factor, c is the speed of light, C is the electrode capacitance, r is the beam pipe radius, A is the PU electrode surface and I_{beam} is the beam current.

Table 2: Signal Amplitude Estimations

Beam parameters	Radial offset	V_{PU}
4σ=150 ns,	0 mm	≈25 V_{pp}
$N_p = 2.5 \cdot 10^{13}$ ppb	10 mm	≈30 V_{pp}
	80 mm	≈80 V_{pp}

The PU sensitivity (defined as the variation of the difference signal of two opposite electrodes, due to a beam transverse displacement) has been measured using the stretched wire technique and has been found to be ≈0.2 dB/mm. This value has been used in Figure 4 to estimate the voltage on one PU electrode depending on the beam position expressed in polar coordinates. The radius is the distance from the centre trajectory and the angle is expressed with respect to the considered electrode azimuth.

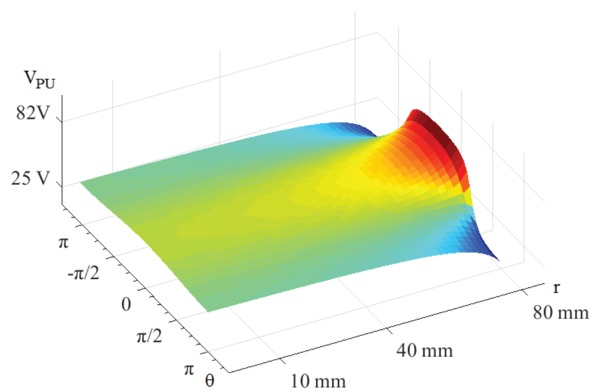

Figure 4: PU's electrode signal amplitude estimation.

As shown in the Figure 5, up to a 20 mm beam position offset the PU response was measured to be linear.

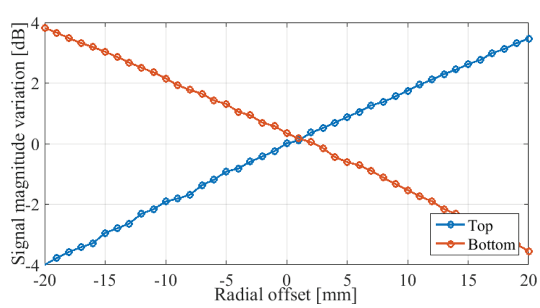

Figure 5: PU Sensitivity.

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RADIATION CONSTRAINTS

The signal from the head amplifier is essential for the TFB system. As such it is an essential part as no high intensity beams (above $4 \cdot 10^{12}$ charges per bunch) can be accelerated without it. In order to extend the electronics lifetime, it was chosen to place it at a reasonable distance from the beam pipe as it is the main source of harmful radiation. The dose decreases exponentially with the distance. At the selected amplifier's location, the radiation dose has been measured with the present accelerated beam. The measured values, together with those estimated for a doubling of the intensity, are reported in table 3.

Table 3: Average Dose Measured and Estimated

Beam intensity	Average dose
$1 \cdot 10^{13}$ ppb	≈3.5 Gy/year
$2.5 \cdot 10^{13}$ ppb	≈ 8 Gy/year

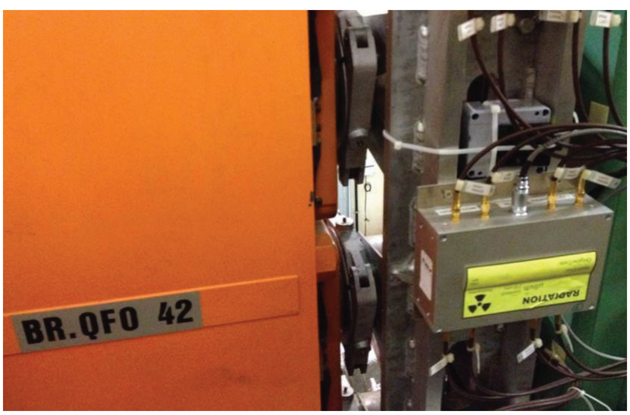

Figure 6: Dosimeter and electronics location.

HEAD ELECTRONICS

As the Head amplifier ends up being distant from the PU connector, a transmission line needs to connect both parts. A one-meter line was found to be sufficient in terms of length. To match the load impedance requirements from the PU perspective, the line must present a high impedance at low frequencies. A lossless coaxial cable terminated with a high unmatched impedance would cause standing waves. To keep a good signal integrity it was chosen to benefit from the design used in oscilloscope probes. This approach is also used in the CERN SPS [5]. This technique is using a lossy coaxial line and a passive network on both ends [6] that allow covering a very large bandwidth with a high perceived impedance.

The high impedance is beneficial in terms of bandwidth, however it may cause a problem when electrons from secondary emissions hit the electrodes, causing an offset signal. As this offset value will depend on the impedance value, a shunt resistive potentiometer will be added to possibly lower the input impedance of the probe as empirically needed.

Table 4: Lossy Cable Characteristics

Resistance, R	210 Ω/m
Inductance, L	0.6 μH/m
Capacitance, C	33 pF/m

Figure 7 depicts the details of the passive networks on both ends of the lossy transmission line.

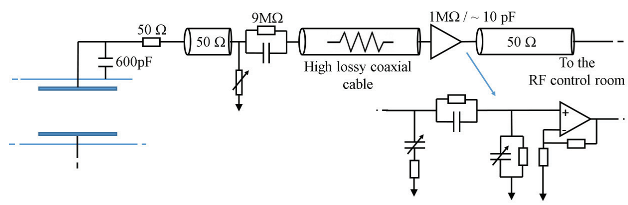

Figure 7: Head amplifier topology.

The designed amplifier setup reaches all the project requirements as can be observed in Figure 8. The frequency response is flat (±3 dB) up to 200 MHz and the non-linear phase error is smaller than ±6°.

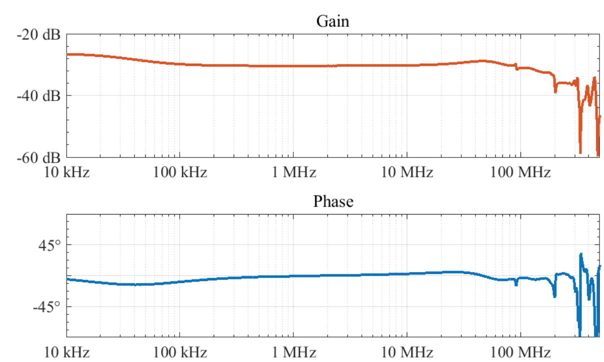

Figure 8: Head amplifier setup frequency response.

In order to increase the tolerance to radiation, the number of active components has been reduced and passive components without PTFE or PVC have been selected. Active components widely known and tested have been used and for the unknown ones a validation test has been planned. In a radioactive environment, single event upsets can be encountered that result in a higher current demand from active components and may cause a thermal damage. In order to avoid such a destruction, current limiting components (polymeric positive temperature coefficient devices) have been installed in different critical paths. These components act as auto-resettable fuses.

To avoid premature replacing and to change the boards at the correct timing, a dosimeter on board is under implementation.

The final validation at the component level is planned for the end of September 2016 and the installation in the machine for the long shut-down 2 (LS2) in 2018.

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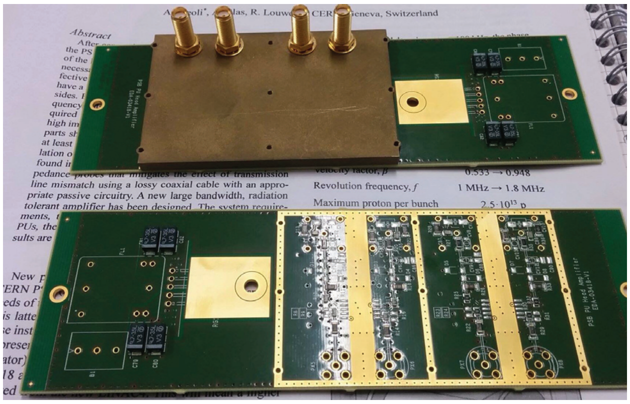

Figure 9: Prototypes boards.

CONCLUSION

A head amplifier setup has been designed to measure the beam position in the CERN PSB even when loaded with the maximum beam intensity expected after the PSB connection to LINAC 4. Its bandwidth extends from 10 kHz to 200 MHz thanks, at the low frequency end, to a passive probe setup as used in commercial oscilloscopes, and on the high frequency side, to high frequency commercial operational amplifiers.

The distance from PU to amplifier allowed by the high impedance probe allows for the reduction of radiation doses. Selected radiation hardening components should further extend the circuit lifetime.

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