BEAM TESTS AND PLANS FOR THE CERN PS BOOSTER WIDEBAND RF SYSTEM PROTOTYPE

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Abstract

In the framework of the LHC Injectors Upgrade project (LIU) and in view of a complete replacement of the existing CERN PS Booster (PSB) RF systems, a prototype cavity has been installed beginning of 2012 in the machine. This modular, wideband (0.5 ÷ 4 MHz), Finemet® loaded system uses solid-state power stages and includes fast RF feedback for beam loading compensation. In depth studies have been performed during 2012 to evaluate the system interaction with the new low-level digital electronics, its ability to accelerate the beam and cope with high beam intensity. The encouraging results suggest that this innovative approach can indeed be used to replace all the existing PSB RF systems but additional testing with a full scale prototype is required. This paper reports about the project status, the achieved results, the encountered difficulties and the foreseen prototype completion in preparation during 2013.

INTRODUCTION

The consolidation and upgrade programs foreseen for the PS Booster (PSB) RF systems aim at increasing the extraction energy (2 GeV), the beam intensity (2E13*)* protons) and allow reliable operation during next 25 years. To achieve these goals it is now being considered replacing the existing accelerating equipment covering the *h=1* and *h=2* ranges with a new, modular, wideband (0.5 ÷ 4 MHz) RF system [1]. The new system is based on a standard cell composed of two Finemet® cores placed on either side of a ceramic gap. Each cell, providing ~700 V_{Peak}, is driven by a solid-state power stage and includes fast RF feedback for beam loading compensation. To evaluate this approach and prove its ability to deal with the PSB beams, a 5-cell wideband prototype cavity has been installed in the machine beginning of 2012. Particular interest is placed on the beam interaction with the wideband cavity impedance, the wake field effects on the beam and reliability aspects of the solid-state amplifier.

During spring 2012 dedicated digital beam control electronics have been prepared as shown in the block diagram of Fig. 1. As the bucket height requested during most of the accelerating cycle cannot be achieved with the voltage available from the prototype cavity alone, the beam control system permits driving it in parallel with the existing C02 RF system (*h=1*). Nevertheless, towards the end of the cycle the voltage required to handle the beam can be reduced below 3 kV so that the acceleration process can ideally be completed by the new system alone. The test digital beam control system was based upon the LEIR LLRF. A description of each building block, its hardware implementation and hints on some beam control capabilities can be found elsewhere [2], [3]. Data acquisition and control were done in {I,Q} coordinates. Extensive digital signal processing was carried out by the FPGA hosted on each daughter card as well as by the DSP where all control loops were implemented. The phase loop was enabled to reduce fast beam oscillations and the cavity input for the phase loop could be switched between C02 and the wideband prototype cavity signals, the latter being the one typically used in the tests. The extraction synchronisation loop was also enabled, so that the beam could be sent to the dump and properly disposed of, thus allowing beam intensities of 10E10 protons or higher without activating the PSB machine. An {I,Q} servo loop implementing amplitude and phase control was used to generate the prototype system driving signal. The user-selectable harmonic of this signal was kept equal to 1 during the tests.

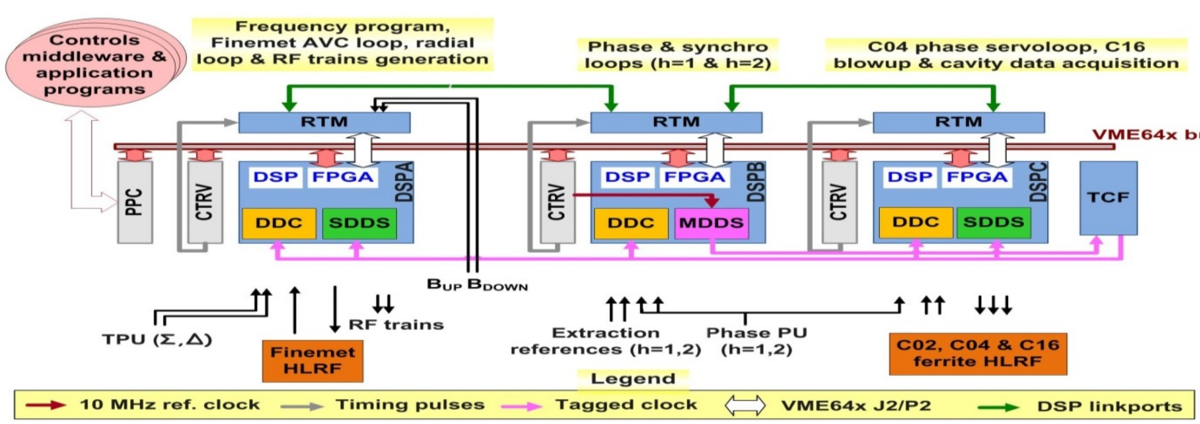

Figure 1: PSB test LLRF - schematic view.

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The {I,Q} servo loop took into account frequency-dependent factors such as voltage attenuation due to the cables and the phase rotation given by the Finemet® system transfer function. To accelerate with the prototype cavity and the C02 systems working in parallel, a frequency-dependent rotation was applied to the voltage program, thus allowing compensating for the different location and cable lengths between the two systems.

BEAM TESTS

RF feedback effectiveness

The first tests where meant to check the RF feedback loop effectiveness on the gap impedance (Fig. 2) reduction as seen by the beam.

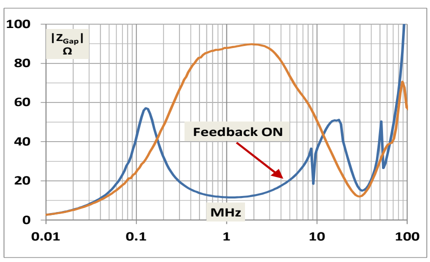

Figure 2: Measured single cell gap impedance.

For this a single turn (40E10 protons) was injected and accelerated using the C02 RF system alone. The corresponding beam induced voltage across a test cavity gap was then measured with and without fast RF feedback (Fig. 3). Measurements show a relative induced voltage amplitude change by a factor ~3 (10 dB) which is lower than expected as the impedance reduction in the beam revolution frequency range is ~7.5 (17.5 dB).

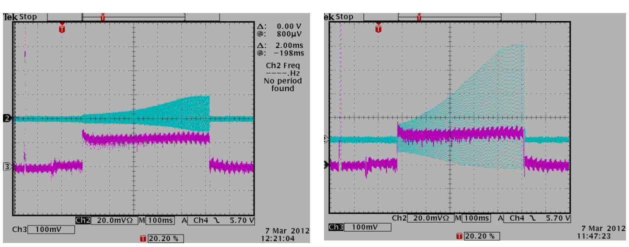

Figure 3: Red: Beam current ~ 0.4A/div - Blue: Gap voltage 20V/div. Left: with RF feedback, right: without RF feedback.

Simulations have shown that this apparent discrepancy is due to the gap impedance shape vs. frequency and corresponds to its interaction with the beam current high frequency harmonic components.

Acceleration tests

The second series of tests aimed at accelerating the beam with the prototype cavity. As mentioned above, the bucket height achievable with the tests cavity alone cannot contain and accelerate a substantial beam from injection to extraction with the available magnetic cycle. For this reason the C02 system is also used at this stage. When carrying out the tests, the maximum voltage achievable with the prototype system was 2 kV_P owing to the limitation coming from the saturation of the gap voltage input in the LLRF electronics.

A first test was done with a single turn injection beam. The C02 RF system provided 8 kV_P and the test system 2 kV. After capture 6.6E11 protons were contained in the bucket and accelerated to 1.4 GeV. Figure 4 shows the main parameters during the cycle while in Fig. 5 the beam distribution at capture and prior extraction are reconstructed using the Tomoscope. From the last it can be seen that the whole beam can be contained in a substantially smaller bucket that would correspond to an accelerating voltage of ~2.5 kV_P.

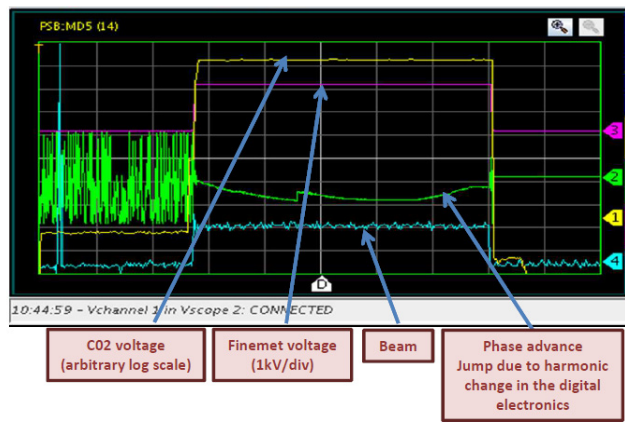

Figure 4: Main parameters during accelerating cycle.

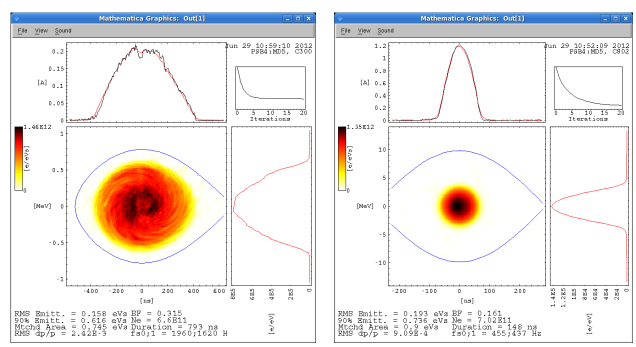

Figure 5: Single turn beam at capture (left) and extraction (right).

The voltage program has then been re-adjusted and the C02 contribution reduced to 500 V_P during last 50 ms of the cycle. In these conditions the beam could be correctly accelerated and extracted. Nevertheless, increasing the beam intensity drove the C02 tuning system into instability due to excessive beam loading. The voltage had thus to be increased to 1 kV_P for 4 turns injection and 1.5 kV_P for 8 turns injection. Figure 6 shows the latter condition where 4.6E12 protons were accelerated. The corresponding peak beam current at extraction was ~6 A which corresponds to 60% of present maximum current in the PSB. As shown in Fig. 7, the effects on the test system gap voltage where clearly visible but did not substantially alter the beam characteristics. This topic deserves more detailed studies when acceleration will be possible with the test system alone.

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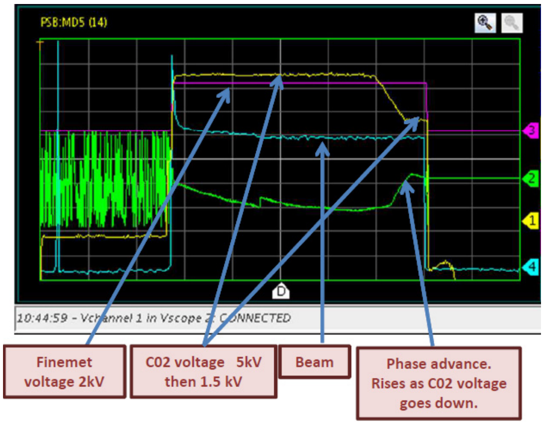

Figure 6: Main parameters with 4.6E12 protons.

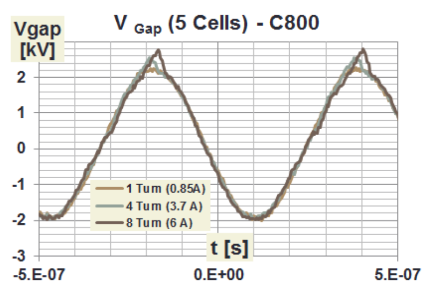

Figure 7: Gap voltage at the end of acceleration cycle for different beam intensities.

RADIATION ISSUES

By the time the saturation problems in the LLRF were solved and testing with higher beam intensity and increased test system voltage could be resumed, the amplifiers exhibited instabilities that did not allow operation. The problem was mainly due to unforeseen radiation effects on the solid-state devices. Typically MOSFETs submitted to radiations exhibit a threshold voltage (V_{TH}) shifting due to charges getting trapped in the gate isolating layer. For N-channel MOSFETs the shift is such that the device goes into conduction with lower V_{TH} values. This effect can be partly recoverable. A measurement campaign was organized at J-PARC where a test set-up could be installed in the vicinity of the Main Ring (MR) collimator. The set-up included a RadMon system to measure the received dose and electronics to measure the I_D vs. V_{GS} transfer function. Different MOSFET types where tested to doses above 10 kGy. MRF151 is a standard device already in use in the PSB and employed in the test system. SD2942 and VRF151 are equivalent devices but the latter has enhanced V_{DS} characteristics. Differently from the previous models having V geometry, the MRFE6VP6300 is a modern L type device with superior performance but lower maximum V_{GS}. Figure 8 plots the relative evolution of V_{GS} required for I_D=1 A vs. received dose until device failure. It can be noticed that all devices survived 2 kGy, react in a similar way but the L-MOS type seems less affected and stabilizes at one point.

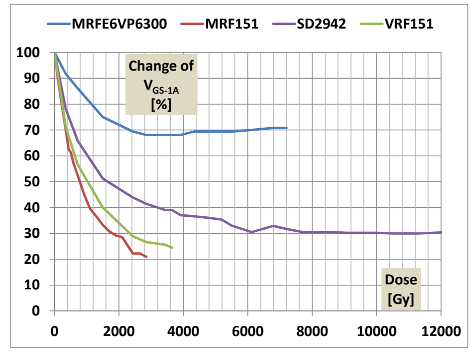

Figure 8: Relative change of V_{GS} vs. received dose.

UPGRADES AND PLANS

2012 results, though encouraging, need to be completed before confirming the Finemet® based choice for the PSB RF system consolidation/upgrade. The test system will be upgraded during 2013 adding a second 5-cells cavity so that beam acceleration will be possible without the C02 contribution. Based on the radiation tests done in J-PARC new amplifiers will be produced and will include compensation methods to mitigate the radiation effects. A completely new monitoring system will be deployed to allow better analysis of the amplifier characteristics and the fast RF feedback loop gain will be reduced for better system stability. A new and more powerful LLRF system will be deployed in the PSB. It will have a higher number of drive channels, operate on multiple harmonics, compensate for the reduced RF feedback loop gain and improve the overall wake field cancelation. At restart in 2014, after the validation of the improvements, the test system will possibly be used for beam production to build up experience on reliability and provide information for the final design. Testing the system on the second harmonic and for multi-harmonic drive is also foreseen.

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REFERENCES

[1] M.M. Paoluzzi et al. "Studies on a wideband, solid-state driven RF system for the CERN PS Booster", IPAC'12, New Orleans, May 2012, THPPP011; http://www.JACoW.org.

[2] M.E. Angoletta et al., "CERN's LEIR Digital LLRF: System Overview and Operational Experience", IPAC '10, Kyoto, Japan, May 2010, p. 1464.

[3] M. E. Angoletta et al. "CERN's PS Booster LLRF Renovation: Plans and Initial Beam Tests", IPAC '10, Kyoto, Japan, May 2010, p. 1461.

[4] A. Krusche et al., "The New Low-Frequency Accelerating Systems for the CERN PS Booster", EPAC '98, Stockholm, Sweden, June 1998, p. 1782.