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BEAM TESTS USING A WIDE BAND RF SYSTEM PROTOTYPE IN THE CERN PS BOOSTER

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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 small scale, wide band prototype cavity was installed in 2012 in the machine. Following the encouraging tests done using this limited set up, an almost full scale, RF system prototype has been built and installed in the PSB during the Long Shutdown 1 (LS1). This modular, Finemet® loaded system covers the band 0.5 ÷ 4 MHz corresponding to the *h=1* and *h=2* frequency ranges. It uses solid-state power stages and includes fast RF feedback for beam loading compensation. New dedicated digital low level electronics have been implemented for all loops required for beam acceleration and interfaces with the general PSB control system. It allows using the new equipment at the fundamental and/or second harmonic of the beam revolution frequency as well as operating it in parallel with the existing RF systems. This paper describes the low level and power sections of the project and reports about the achieved results and experience built up so far.

INTRODUCTION AND SYSTEM DESCRIPTION

With the program under implementation in the frame of the LIU project [1, 2] and the coming into operation of the Linac4, the PSB extraction energy will rise to 2 GeV and the beam intensity to 2E13 ppb (nominal) or even 2.5E13 ppb (absolute maximum). This brings the beam peak current to ~32 A (half sine approximation) and the fundamental, second harmonic and DC components to 13 A, 8.5 A and 7.2 A respectively. Among other parameters, the ability of the machine to digest the highest intensities depends on the current and power available from the RF systems. To cope with this more demanding situation the performance of the PSB RF systems must be substantially improved. This can be achieved replacing the existing narrowband, tuned RF systems covering the *h=1* (C02 RF system) and *h=2* (C04 RF system) frequency ranges with cavities based on the wideband frequency characteristics of Finemet® magnetic alloy (MA) [3]. Full exploitation of the wideband characteristics suggests using a cellular configuration in which an accelerating gap is surrounded by a MA core on each side [4, 5], is driven by a solid-state amplifier and produces a fraction of the total accelerating voltage. 12 cells can be fitted in the space presently used by each C02 and C04 cavity for a total 8 kV per section. As three straight sections are presently occupied by these systems, the total maximum voltage can either be kept to 16 kV using two straight sections only or increased to 24 kV. The wide band response allowing multi harmonic operation, flexible adjustment of the *h=1* and *h=2* voltage components is possible and only limited by the total maximum voltage. However, installing wideband cavities in the PSB rings introduces longitudinal impedance covering many revolution frequency harmonics and special care must be taken for compensating the beam-loading. A fast RF feedback loop takes partial care of this and additional measures are implemented in the low level electronics.

Figure 1: 10-cell prototype MA cavity in PSB Ring 4.

To validate the choice of these deep and complex changes the prototype system installed in 2012 was upgraded during LS1 to 10 cells for a total of 7 kV. The experience gained with the 2012 amplifier prototypes allowed designing and producing a new generation of power stages. All weaknesses shown by the previous version were corrected. In particular mitigation of the of radiation effects on the solid-state devices is obtained by

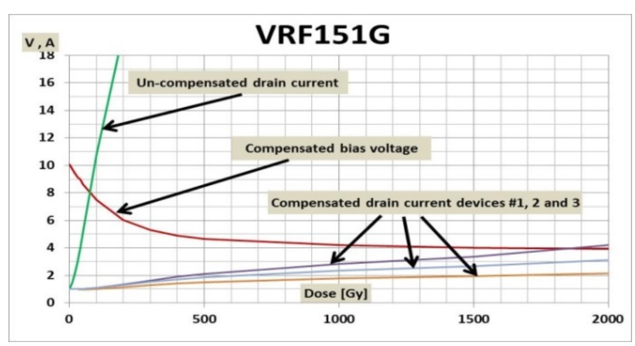

Figure 2: Mitigation of radiation effects on VRF151G RF Mosfet. The compensated device drain current variation vs. integrated dose is greatly reduced.

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way of a special gate bias circuit which includes a Mosfet device sensing the integrated radiation dose and collectively correcting the bias voltage of all the power devices in the amplifier. The parallel design of new digital low level electronics implementing multi-harmonic servo-ing and flexibly interfacing with the other RF systems was completed and profitably used for the beam tests. The new digital low-level electronics [6] is an extension of that successfully deployed in 2014 on the four PS Booster rings. Figure 3 gives an overview of the system deployed on the PSB rings, which controls the C02 (acceleration), C04 (shaping) and C16 (blowup) ferrite HLRF systems, and of the additional part which controls the MA HLRF.

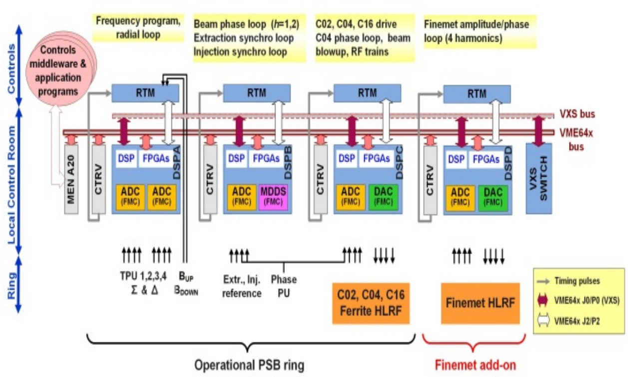

Figure 3: LLRF system overview.

Beam phase and radial loops were fully operational. The cavity input for the phase loop could be switched between ferrite and MA HLRF systems, the former being the one typically used. The extraction synchronisation loop was also operational, so that the beam could be sent to the dump and properly disposed of without activating the PSB machine. Four harmonics of the MA HLRF were servo-ed independently and at the same time with voltage phase and amplitude loops. The MA HLRF was used at harmonic 1 for acceleration and at harmonic 2 for bunch shaping; separate voltage programs for these two harmonics were implemented. An additional phase program controlling the phase of the second MA HLRF harmonic with respect to the first one allowed to create flat-topped bunches with a favourable bunching factor. Two additional user-selectable harmonics could be servo-ed to zero voltage, thus minimising the voltage induced across the MA cavity. For most of the tests carried out the additional harmonics 3 and 5 were used as the most influential. Finally, a frequency-dependent rotation was applied to the voltage program for harmonics 1 and 2, so as to compensate for the different location and cable lengths between the MA and the C02 (for harmonic 1) and between the MA and the C04 (for harmonic 2) HLRF systems. This allowed accelerating the beam with the ferrite and MA systems working in parallel.

WAKE VOLTAGE CANCELLATION

If with the narrowband impedance of ferrite loaded cavities the beam-cavity interaction is mainly limited to the harmonic component at cavity resonance, the wideband response of the MA loaded cells require acting on more harmonics. Assuming the gap impedance to be purely resistive (R_{gap}), frequency independent and driven by the generator and beam currents (fig.4), to obtain the gap current:

$$I_{Gap}=V_{Gap}/R_{gap}$$

the generator must supply:

$$I_{Gen} = \sqrt{(I_{Beam}^2 + I_{Gap}^2 - 2 \cdot I_{Beam} \cdot I_{Gap} \cdot \cos(\alpha))}$$

This simple relation can be applied to compute the generator current required for acceleration but also be used for computing the current needed for cancelling the higher harmonic components by simply zeroing the corresponding $V_{Gap.}$ A linear addition of the different components will then provide the total generator current. All this process is exactly what the digital low level electronics are required to do.

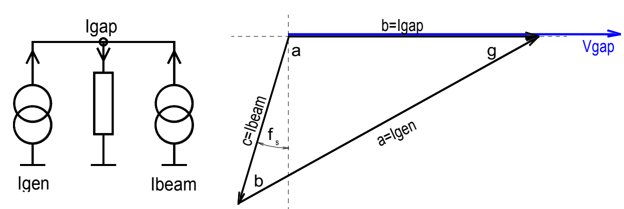

Figure 4: Gap driving currents and vector diagram.

To evaluate the effectiveness of the wake fields cancelling process the beam was accelerated using the C02, C04 and C16 RF systems and the voltage induced across the MA cavity was measured with and without activating the AVC correction. Action was done on harmonics 1, 2, 3 and 5. Figure 5 shows the corresponding voltages in the two cases for the fundamental frequency component. The attenuation is in the order of 30 dB for $h=1$, 20 dB for $h=2$ and $h=3$, 10 dB for $h=5$.These valus are susceptible to improvement as no optimization was done.

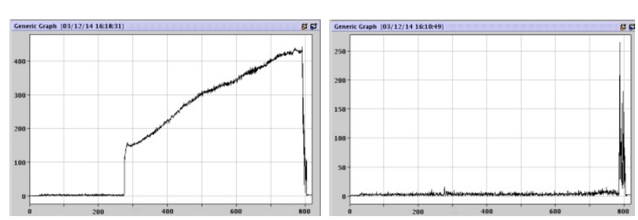

Figure 5: Beam induced voltage at fundamental with and without cancellation (. Beam intensity 475E10 protons.

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BEAM ACCELERATION

Beam has then been accelerated using the available systems in different configurations.

Acceleration Using the MA Cavity Only

When providing 7 kV at *h=1* and without any other RF contribution the system was able to capture 695E10 protons and accelerate 650E10 to extraction.

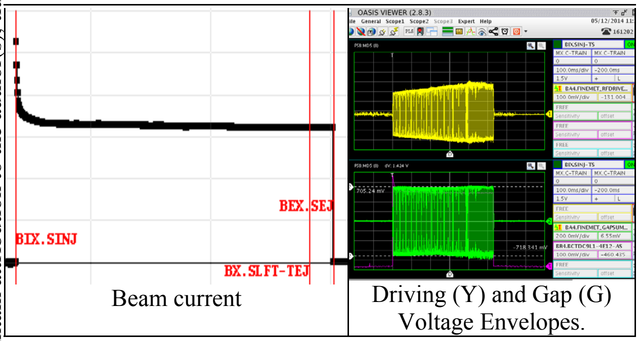

Figure 6: Acceleration with MA cavity only (475E10 ppb).

In this condition some instability appeared on the RF signal towards the end of the accelerating cycle (fig. 7).

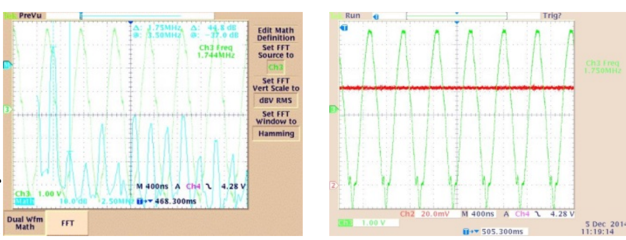

Figure 7: Distortion at the end of the accelerating cycle.

Acceleration Using the MA Cavity as h=1and C04 providing h=2

As the MA cavity and the C04 are all phase aligned with the C02 system it was possible to accelerate using the MA cavity for *h=1* and the C04 for *h=2*. To maintain the phase synchronism the C02 system had to be kept at a minimum voltage which is dictated by the tuning loop stability. With MA cavity providing 7 kV, C02 cavity 2.4 kV and C04 cavity 8 kV 780E10 protons were captured and 730E10 accelerated and extracted. The tomoscope view of fig. 8 shows clear evidence of the two harmonics.

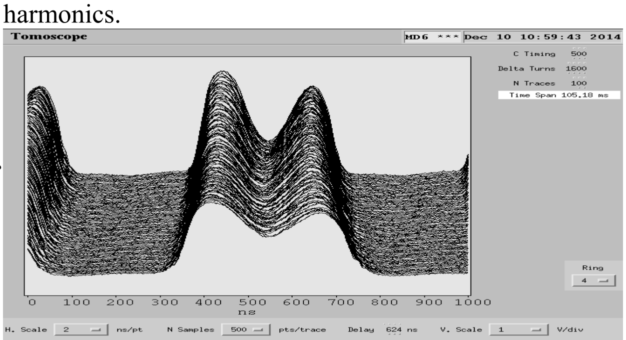

Figure 8: Tomoscope view of accelerated beam. MA cavity providing *h=1* component (780E10ppb).

Acceleration Using the MA Cavity as h=2

Inverting the roles and using the MA cavity to provide the *h=2* acceleration voltage component and leaving the C02 RF system for the fundamental gave again good results. 790E10 protons could be accelerated and their bunch shape and distribution are shown below.

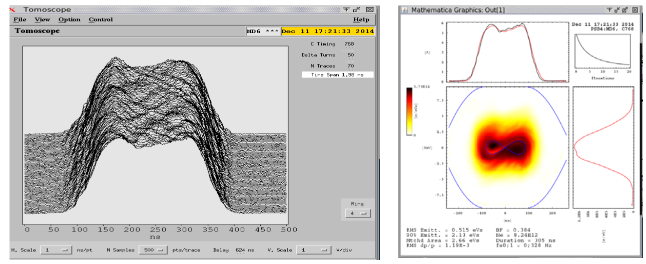

Figure 9: Beam accelerated using MA cavity as *h=2* (790E10ppb).

Acceleration Using the MA Cavity as h=1+2

Finally the MA cavity was used to provide a double-harmonic voltage of 3.5 kV at each component; the C02 and C04 systems providing the missing 4.5 kV.

As expected the beam was correctly accelerated reaching the maximum achieved intensity of 800E10 ppb.

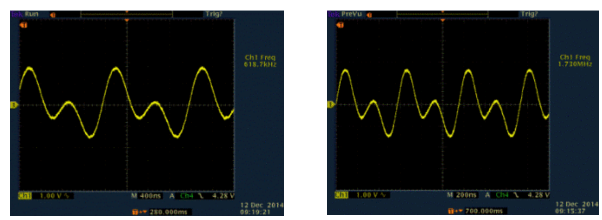

Figure 10: MA cavity double harmonic voltage short after injection and prior extraction.

In these conditions the system could be used with duty-cycle varying from 8% to 68%. The power amplifiers relevant temperatures could be measured and are listed in table 1(bold). The table is completed by some extrapolated values (italics). The limiting parameter is the VRF151 case temperature which must stay below 90 ˚C and is apparently safely inside the limits.

Table 1 – VRF151 Case Temperature vs. Duty-cycle

Number of users per supercycle	Duty Cycle [%]	T_{Case} No RF [˚C]	T_{Case} VRF151 [˚C]
3/38	**8**	**26**	**27**
9/38	**24**	*26.5*	**29**
18/38	**47**	*31*	**36**
26/38	**68**	**34**	**41**
38/38	**100**	**40**	*50*

CONCLUSION

The completion of the PSB prototype RF system and subsequent beam tests provided encouraging results and suggest that this approach can indeed represent a sound solution for the PSB RF systems renovation and upgrade. Thanks to the ability of the digital low level electronics to simultaneously act on many harmonics, a good control of

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the gap voltage, including wake fields cancellation, and multi harmonic operation is possible. Additional testing by summer 2015 will provide a full picture for the project evaluation (review in September) and final decision about its implementation (end 2015).

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