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ONE YEAR OF OPERATION OF THE NEW WIDEBAND RF SYSTEM OF THE PROTON SYNCHROTRON BOOSTER

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Abstract

Within the LHC Injectors Upgrade project, the PS Booster (PSB) has been upgraded. Both the injection (160 MeV) and extraction (2 GeV) energies have been increased, bringing also changes in the injection beam revolution frequency, the maximum revolution frequency, and the beam intensity. To meet the requirements of the High Luminosity LHC a new RF system has been designed, based on the wideband frequency characteristics of Finemet®Magnetic Alloy and solid-state amplifiers. The wideband frequency response (1 MHz to 18 MHz) covers all the required frequency schemes in the PSB, allowing multi-harmonics operation. The system is based on a cellular configuration in which each cell provides a fraction of the total RF voltage. The new RF system has been installed in 3 locations replacing the old systems. The installation has been performed during 2019/2020, while the commissioning started later in 2020 and relevant results for the physics have been already observed. This paper describes the new RF chain, the results achieved and the issues that occurred during this year of operation, together with the changes made to the system to improve performance and reliability.

INTRODUCTION

The new RF system is based on a cellular configuration in which each cell provides a fraction of the total RF voltage, up to a peak voltage of approximately 700 V per cell across a frequency range from a few hundred kHz up to 20 MHz. Each cell is built around a vacuum chamber with a ceramic gap at its center and two Finemet disks, one on each side. A solid state amplifier is driving the two sides of the gap with opposite phase signals. To prevent overheating, the cells are water-cooled. Three new RF systems have been installed in the PSB tunnel in sections 5L1, 7L1 and 13L1. Each RF system is composed of 4 cavities, corresponding to the 4 vertically stacked rings of the PSB. Each cavity is equipped with 12 cells arranged in two groups of 6. The voltage requirements in each ring are: 8 kV for acceleration at the beam revolution frequency at *h1* (from 1 to 1.8 MHz), 8 kV for bunch shaping at *h2* and 4 kV for blow-up at *h10* [1]. The cavities installed in the 3 sections provide the required voltage.

SYSTEM DESCRIPTION

The new amplification chain, shown schematically in Fig. 1, is located partly outside the ring and partly in the tunnel.

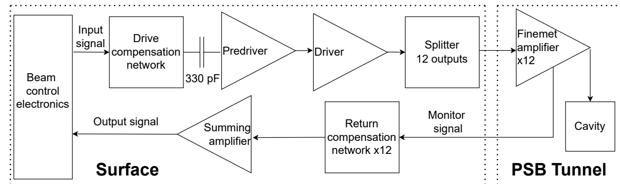

Figure 1: Block diagram of the new RF system for one ring.

The amplification chain begins on the surface where the RF input signal, provided externally by the beam control electronics, is fed through a passive compensation circuit to offset the frequency-dependent attenuation caused by the long cables from the surface to the ring. Subsequently, the signal passes through a 330 pF series capacitor which, together with the pre-driver input impedance, forms a high-pass filter compensating the low-pass response of the Finemet amplifier. Then the signal is fed into two amplifiers in sequence, gaining up to this node ~23 dB at the reference frequency of 1 MHz. Subsequently, the signal is driven through a splitter that partitions it onto 16 outputs; 12 of them are used to feed the 12 Finemet amplifiers composing a cavity. Due to the splitting, each of the outputs provides a signal attenuated of ~12 dB in the entire frequency spectrum of interest.

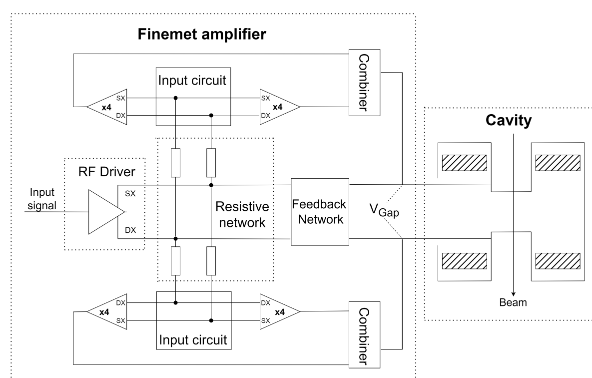

Figure 2: Block diagram of main components of a Finemet amplifier.

The signals from the splitter are fed into the Finemet amplifiers. Figure 2 shows a schematic of the push-pull amplifier, outlining its main components: the RF driver, the dampening resistive network, the two differential halves, each with an input circuit and 8 power MOSFETs and the combiner. The RF driver acts as a high impedance push-pull stage composed of a VRF151G dual power MOSFETs, driving in parallel the gates of all the 16 power MOSFETs in the final stages; eight of these modules are combined together, the same for the other eight and driven in anti-phase to obtain a differential output. Additionally, a radiation compensation

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network for MOSFETs' bias has been implemented in the amplifier, in order to mitigate the threshold gate voltage drift due to the received radiation dose. The wideband response of the Finemet alloy allows multi-harmonic operation but introduces as well longitudinal impedance extending over many revolution frequency harmonics, requiring special attention in compensating the beam loading. Therefore in the amplifier a fast RF feedback network is implemented, which is necessary to control the gap impedance and partially compensate the beam loading; additional compensation is provided by the new digital system of the low-level RF (or *LLRF*). Details can be found in [2, 3]. Finally, through an additional compensation circuit, the monitor signal of each cell is brought back to the surface. At last, the signals pass through a new amplifier that allows to measure each of the output signals, as well as the summed output signal. The power level of the monitoring signals has a general scaling of 2 kV/V as referred to the gap voltage. Figure 3 shows the transfer function of an entire cavity.

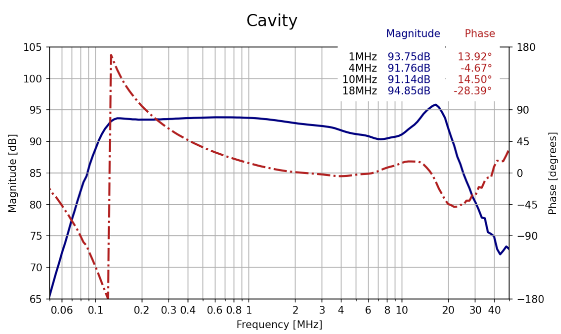

Figure 3: S21 magnitude and phase measurement of an entire cavity (12 cells) of the new RF system.

In terms of achievable accelerating voltage, the system has been built with a reserve above the nominal requirements, so that the cavity can operate normally with up to 2 out of 12 cells unavailable. To increase system reliability, each cell has an independent DC supply and control electronics.

Several parameters can be monitored from the control room on the surface. The system is also protected by a PLC continuously reading critical signals, detecting unexpected conditions and shutting the equipment down in case of errors.

CHALLENGES ENCOUNTERED DURING THE COMMISSIONING

Assembly Faults

During the beam commissioning, some Finemet amplifiers needed to be replaced and repaired due to mechanical and quality issues. The subsequent investigation identified two causes of failure:

- Some low quality components mounted on the Finemet RF driver led to the failure of some amplifiers in the first months of operation of the new RF systems. The RF driver acts as a push-pull stage driving the gates of the 16 power MOSFETs in parallel; the failure of some components leads to the failure of the whole amplifier. After identifying the faulty components, more robust substitutes were selected. As a preventive measure, it was decided to gradually replace these components in all amplifiers.
- Some screws fastening the connection between the 16 output modules and the +40 V DC power supply were found not to be properly tightened. This led to increased contact resistance, eventually causing overheating and damage to the amplifier, necessitating its replacement. Once the problem was identified, it was decided to proceed with a check of all the screws.

Both replacement campaigns are now underway and will continue over the next years. In the amplifiers where the substitution already took place, no further issues have been observed during one year of operation.

RF Output Distortion in the Finemet Amplifier

During the start-up of the new RF systems, differences in the RF output signals have been noticed among the different Finemet amplifiers. The amplifiers had mainly two problems: some of them showed distortion of the output RF signal in the frequency range used for acceleration and bunch shaping (*h1* and *h2*, or approximately 1 to 4 MHz). In addition, all the amplifiers showed distortion of the signal in the range from 7 to 10 MHz. Figure 4 shows these two types of issues; as visible, the RF signal is distorted, and so is the summing current of the 16 output circuits.

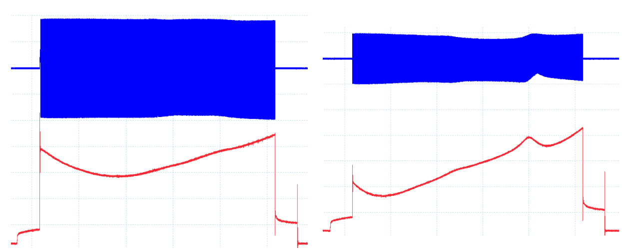

Figure 4: Example of the RF output distortion for Finemet amplifiers: in blue, the RF output signal of a single cell; in red, the summing current of the 16 output circuits. On the left side, the test was performed with a frequency sweep from 1 to 4 MHz; on the right, with a sweep from 1 to 10 MHz.

Due to the frequency patterns used during the operation, the distortion in the 1-4 MHz range is suspected to be the cause of an additional problem experienced during the first year of operation: the failure of several 100 Ω/100 W resistors in the feedback network. On the other hand, the distortion between 7-10 MHz was considered a possible cause of a problem with the digital electronics of the LLRF. At the start of commissioning, it was noted that the new digital feedback system was not able to reach the specifications for harmonics from *h8* to *h16*, thus implying lower efficiency in reducing the beam loading in this frequency range [4].

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A number of tests and measurements were carried out, aiming to understand the source of the problem and to provide a valid solution for increasing the reliability of the amplifiers. Particular attention was given to the resistive network connecting the RF driver circuit and the two input circuits. This connection is realized by a network of 12 resistors (4 branches, 3 parallel resistors in each). These resistors should dampen resonances to prevent instability. Initially, resistors of 3.3 Ω each were installed, yielding a resistance of 1.1 Ω for each branch. After several experiments, it was found that 8 Ω resistance for each branch (3x24 Ω) leads to improved stability. Figure 5 shows that after the modification of the resistive branch a clear improvement of the RF output signal is obtained.

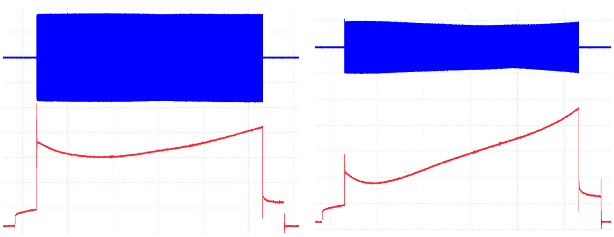

Figure 5: Example of the RF output after resistors modification for Finemet amplifiers. The RF output signal of a single cell in blue and the summing current of the 16 output circuits in red. On the left side the test was performed with a frequency sweep from 1 to 4 MHz while on the right with a sweep from 1 to 10 MHz.

Tests were carried out to evaluate the proposed solution quantitatively; the most relevant results follow. First, harmonic distortion was measured for the 2nd and 3rd harmonics, sweeping the fundamental frequency across the range of interest (1-18 MHz). Results are shown in Figs. 6 and 7, highlighting a reduction in the power of the 2nd harmonic throughout most of the frequency range. For the 3rd harmonic, an improvement is seen mainly in the range from 4 to 16 MHz, however, the power outside this range is sufficiently low to be easily controllable by the digital electronics of the LLRF.

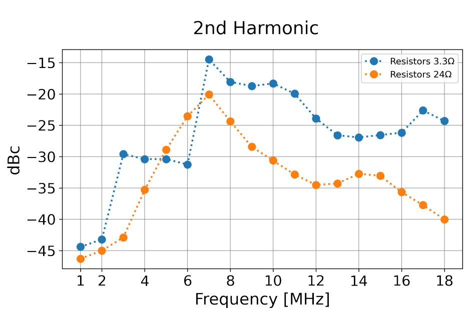

Figure 6: Power level of the 2nd harmonic relative to the fundamental frequency.

Also the gap impedance has been measured and compared with values obtained before the modification. Figure 8 shows that the change in the circuit causes a frequency shift of the peak, as well as an increase of the peak impedance, necessitating an adjustment of the operational parameters of the digital systems in the LLRF. However, this change is made easily via software configuration.

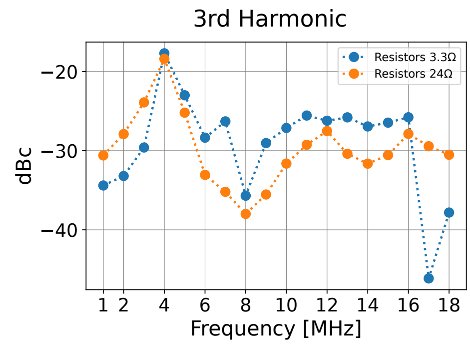

Figure 7: Power level of the 3rd harmonic relative to the fundamental frequency.

Following the promising results, the resistive network replacement campaign for all the Finemet amplifiers is now underway and will continue over the next years. In the amplifiers where the substitution already took place, no further issues have been observed during a year of operation.

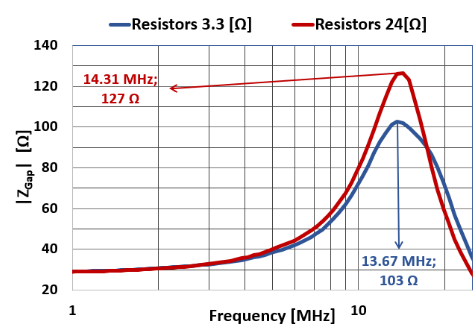

Figure 8: Cell Gap impedance with amplifier and RF feedback before and after the resistors modification.

CONCLUSION

After years of prototyping and tests, a completely new RF system has started to operate in the PSB. The availability achieved during the first year of operation has been over 99%, thanks also to the redundancy of the cells. The changes described earlier have contributed to the increase in the reliability of the Finemet amplifiers. During the beam commissioning it was possible to reach a beam intensity of 10^{13} protons per bunch and all the beams for users were produced within the required specifications. Thanks to the flexibility of the new RF systems, it was possible to use the 3rd harmonic to further lengthen the bunch and also take advantage of bandwidth-limited phase noise for controlled longitudinal emittance blow-up [5]. Over the coming years the consolidation of the system will continue.

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