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THE NEW 1-18 MHz WIDEBAND RF SYSTEM FOR THE CERN PS BOOSTER

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Abstract

The LHC Injectors Upgrade (LIU) project at CERN prepares the injectors to meet the requirements of the High Luminosity LHC. For protons, it includes the new Linac4, PS Booster (PSB), PS and SPS. Among the major changes concerning the PSB, the extraction energy increase from 1.4 GeV to 2 GeV and the higher beam intensity, made possible by the Linac4 together with the new charge exchange injection system into the PSB (2E13 protons), strongly affect the RF system requirements. To deal with this more demanding beam operation, a new RF system was designed. It is based on modern magnetic alloy loaded cavities driven by solid-state amplifiers. Its wideband frequency response (1 MHz to 18 MHz) covers all the required frequency schemes. This new RF system has been produced in 2017 and 2018; installation is planned during 2019, the first year of Long Shutdown 2 (LS2) and commissioning is foreseen in 2020. Most of the production and testing was outsourced to industry; parts acceptance, cavities assembly and pre-testing was done in-house. A quality assurance plan was established to achieve the required high reliability. This paper describes the procurement, production and testing strategies and methodologies. It also reports the achieved results, system performances and relevant statistics.

SYSTEM DESCRIPTION

In the framework of the LHC Injectors Upgrade (LIU) project at CERN, preparing the injectors to meet the requirements of the High Luminosity LHC (HL-LHC) [1], a completely new RF system has been designed [2] for the PSB machine. The new RF system relies on a basic acceleration cell capable of providing up to 700 V_{PK} with an instantaneous bandwidth extending from few hundreds kHz to above 20 MHz. This characteristic allows multi-harmonic operation and the simultaneous coverage of the whole frequency range required in the PSB (1 MHz to 18 MHz).

Figure 1: 6-Cell Cavity.

The cell is composed of a central part housing a vacuum chamber with a ceramic gap at its centre and one Magnetic Alloy (MA) core on either side. A solid-state power RF amplifier (PA), placed on one cavity side, drives the cell with power exceeding 3 kW. The PA includes a gap voltage monitor and allows remote sensing of relevant parameters such as DC currents and temperatures. Six such basic cells make up a cavity and share a common housing, the vacuum chamber with six ceramic gaps, the control and DC supply cabling as well as cooling water distribution (see Fig. 1). Three pairs of cavities placed in three PSB straight sections provide up to 25 kV_{PK} RF voltage. As the machine consists of four superimposed rings, in each PSB straight section a group of eight cavities (48 cells) share a common support (see Fig. 2) that includes forced air and cooling-water distribution. Each cell has independent DC supply, control electronics and gap shorting device.

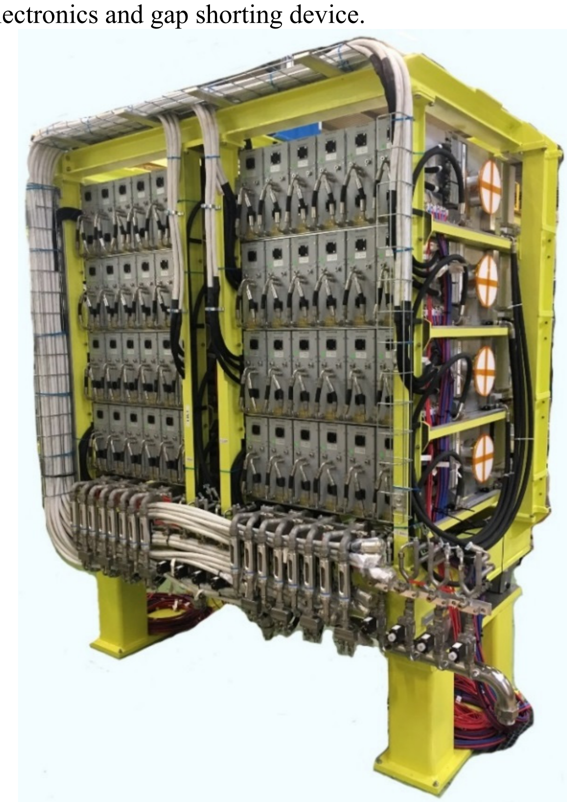

Figure 2: Cavities grouping for one PSB Straight Section.

As the maximum achievable accelerating voltage includes a substantial reserve above the nominal requirements, operation is possible with a reduced number of cells (-15 %). A PLC based interlock system controls the equipment of each straight section. It also interfaces with the low-level RF (LLRF) electronics to make full use of the operational cells and isolate the faulty ones if necessary.

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PRODUCTION AND TESTING

As the system design stretched over few years with various generations of prototypes, and it was modified and upgraded following real conditions testing in the PSB machine, components such as cavity mechanics, PA and dedicated ancillary electronics were entirely developed at CERN. For other items, i.e. DC power converters, the project relied on industrial designs or off-the-shelf parts. The required quantities spanned from few hundreds to few thousand pieces. All production took place in industry based on CERN design or specifications with two exceptions: the vacuum chambers production and the final machining of the cavities mechanics.

Vacuum Chambers

The production of the vacuum chambers (see Fig. 3), each equipped with 6 ceramic gaps, involved three different companies, it required two titanium-coating processes, at the beginning and at the end of the manufacturing, and the exchange of pre-machined materials among the companies with intermediate quality checks done at CERN. This complex process was coordinated by CERN that also took care of the final Ti deposition on the ceramics.

Figure 3: Vacuum Chamber with 6 Ceramic Gaps.

Cavity and Cores Characterization

Electrical MA cores one-turn impedance vs frequency was measured to verify the frequency response conformity and loss resistance (R_P); on all units, the parameters were found exceeding the minimum design values (see Fig. 4). MA cores pairing for use in one cell was based on the measured R_P averaged over the frequency range. Core's pair selection for use in each cavity was done equalizing the average R_P, and thus thermal losses, among the cavities.

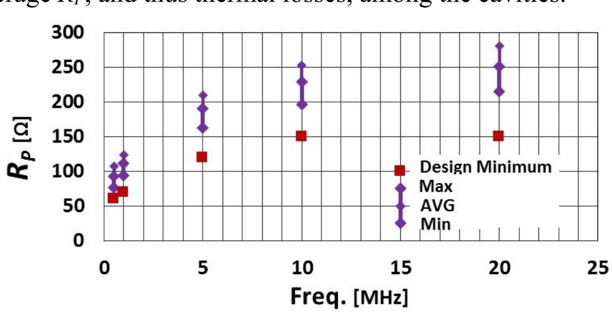

Figure 4: MA Cores Loss Resistance R_P.

Thermal The thermal characteristics of the core/cooling-ring assemblies were measured to evaluate the quality of the mounting process. Table 1 shows the results achieved after correction of non-conformities. The listed values are for a constant 400 W dissipation, which corresponds to the nominal average power. As the maximum core working temperature is 100 °C, a wide margin exists also for the worst core-to-water temperature difference (34.4 °C).

Table 1: Thermal Characteristics of Core/Cooling Ring Assemblies

	ΔT Ring-Water [°C]	ΔT Core-Ring [°C]	ΔT Core-Water [°C]
Avg.	4.0	17.8	21.8
σ	1.0	3.5	3.7
Min	2.1	10.1	14.5
Max	8.8	28.8	34.4

Six couples of MA core/cooling-ring assemblies share a common cavity shroud (Fig.5) and are connected in parallel to the cooling water distribution system.

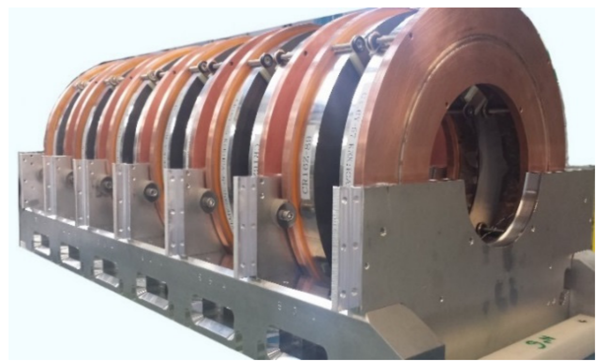

Figure 5: Cavity Shroud with MA Cores and Cooling Rings.

The water sharing among the cells was evaluated by measuring the cell's cooling rate after heating to 50 ± 5 °C (see Fig. 6). The measurement results show a water flow difference lower than 15 % among cells in one cavity.

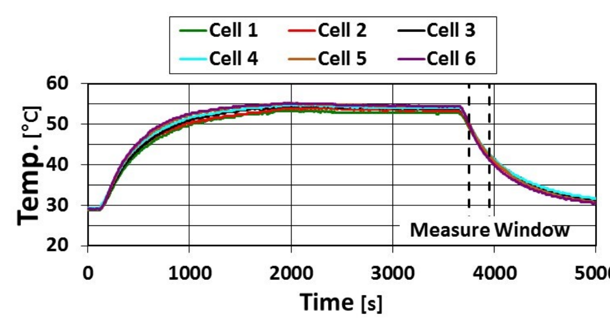

Figure 6: Thermal Transient for the Evaluation of the Water Sharing among Cells in one Cavity.

RF Power Amplifiers

The RF power amplifiers were procured in industry according to CERN design, production and test specifications. The procedures included active devices pairing, full low-level characterization, power testing and thermal cycling. The PA went then through acceptance tests at CERN. When loaded on 50 Ω, all 164 amplifiers showed gain within specifications. The average gain at 1 MHz was 62.3 dB as compared to 62 dB nominal (see Fig. 7) and the low-pass response conformity was excellent to above 30 MHz. This parameter is very important for the implementation of the fast RF feedback.

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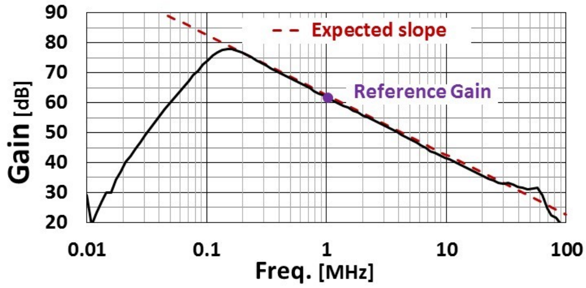

Figure 7: Power Amplifier Frequency Response.

Power Converters and Other Electronics

Each RF power amplifier is supplied by a commercial 50 V, 200 A power source. The manufacturing of all other electronics such as RF driver amplifiers, RF splitters, RF summing amplifiers and all ancillary electronics took place in industry based on CERN design.

Full Cavity

The cavity test includes the measurement of individual cell gap impedance (see Fig. 8) and of the transfer function (see Fig. 9). The gap impedance reduction due to RF feedback is a fundamental key for the acceleration of intense beams in the PSB. Comparing Fig. 7 to Fig. 9, noticeable differences can be seen above 5 MHz. They are mostly due to the non-constant amplifier's load impedance represented by the cavity. Below 10 MHz, the RF feedback loop limits the variations but the loop delay reduces its effectiveness above this frequency.

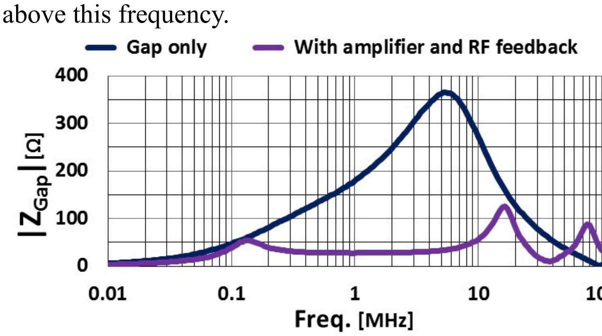

Figure 8: Cell Gap Impedance.

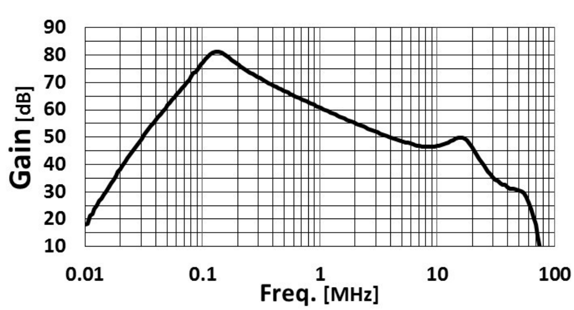

Figure 9: Cell Transfer Function.

The 6-cell cavity was then tested with the whole amplification chain. The input signal is applied to a 4 W driver amplifier through a ≈ 5 MHz high-pass filter used to linearize the PA low pass response. The driver output signal, conveniently split, then drives each PA input. The gap monitors are fed to a RF summing amplifier at which output the total cavity voltage can be measured (see Fig. 10).

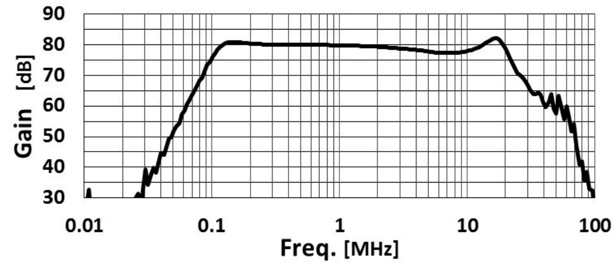

Figure 10: Linearized 6-Cell Cavity Tranfer Funtion.

Two power tests complete the validation procedure. Initially, the system continuously operates during 60 hours at nominal 4.2 kV_{PK} gap voltage. The frequency is swept from 1 MHz to 5 MHz in 500 ms every second. During a second 60 hours test, the system is operated in multi-harmonic mode. The fundamental frequency is swept from 1.0 MHz to 1.8 MHz with additional second and 10th harmonics. The relative amplitudes are set to 40 % for fundamental and second harmonic leaving the remaining 20 % to the 10th harmonic. MA cores and relevant PA internal temperatures are monitored during both tests.

INSTALLATION AND COMMISSIONING

The whole system was manufactured and tested during 2017 and 2018. At the beginning of LS2 the dismantling of the old PSB RF system started in the surface buildings and then continued in the ring during 2019. Some 2000 cables were removed and 1600 new ones are being installed. New water piping for connection to the demineralized water cooling station is being laid down. The state of advancement of the installation work presently matches the schedule that foresees its completion by October 2019 and the end of commissioning by May 2020.

CONCLUSIONS

After some years of intense studies, prototyping and testing with beam, a completely new RF acceleration system has been designed, produced and is now in its installation phase in the CERN PSB. It is the result of a fruitful collaboration among CERN, KEK/J-PARC and industry. The replacement of the previous highly reliable system was an unavoidable and tough challenge imposed by the very demanding beam requirements for the HL-LHC beam. However, it also represented an opportunity to move to modern solid-state PA and MA that has resulted in a system with unique characteristics in terms of instantaneous bandwidth and flexibility.

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