DESIGN OF THE NEW WIDEBAND RF SYSTEM FOR THE CERN PS BOOSTER

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Abstract

For the renovation and upgrade of the CERN PS Booster (PSB) RF systems a development project was launched in 2012. The design, based on a new approach, aimed at replacing the existing tuned, narrowband RF systems with wideband, modular, solid-state driven units. A wide range of issues had to be addressed spanning from RF power production, radiation hardness of solid-state devices, active cancellation of beam-induced voltages, dedicated low-level electronics allowing multi-harmonic operation and beam stability. Following a three-year prototyping and testing campaign and two international reviews, the project endorsement came at the end of year 2015. It foresees the complete removal of present *h1*, *h2* and *h10* systems and the deployment of a new one covering all the frequency ranges from 1 MHz to 18 MHz. The four PSB rings will be equipped with 144 identical acceleration cells providing 24 kV total RF voltage per ring. This paper describes the design concepts, the retained solutions, the expected performances and includes the procurement and implementation strategies. This activity is part of the LHC Injectors Upgrade project (LIU) [1].

GENERALITIES

System Requirements and Arrangement

The voltage requirements of each of the four rings composing the PSB machine are 8 kV for acceleration at the beam revolution frequency (1÷1.8 MHz), 8 kV for bunch shaping at *h2* (2÷3.6 MHz) and 4 kV at *h10* (10÷18 MHz) for controlled blow-up. Cavities installed in three straight sections (5L1, 7L1 and 13L1 - Fig. 1) will provide the required voltage.

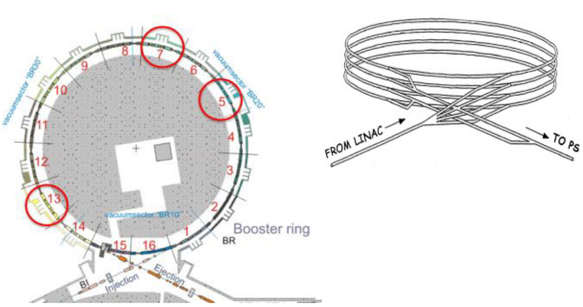

Figure 1: Cavities position in the PSB ring.

Each section will house four superimposed couples of cavities (Fig. 2) as well as the solid-state RF power amplifiers, cooling water distribution and all required wiring. All parts in the three sections will be identical. Below 5 MHz, 24 kV will be available in each ring; above 5 MHz the voltage linearly de-rates to 4 kV at 18 MHz.

As the system allows multi-harmonic operation, the voltage can be freely allocated at the most appropriate frequency giving high operational flexibility.

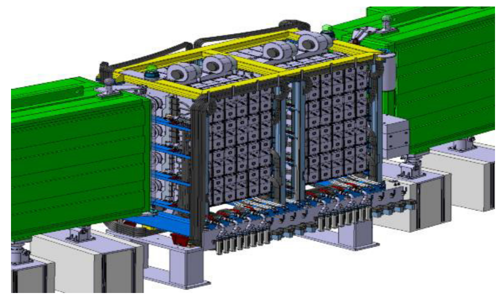

Figure 2: Group of four superimposed couples of cavities in one PSB Section.

All DC power supplies, ancillary electronics, interlock and Low Level Digital Electronics (LL) will be installed in the surface equipment rooms. Ample reserves are foreseen in all elements and full acceleration performance are granted with:

- 12.5 % not operational power Mosfets per amplifier;
- Six unavailable cells per ring.

SYSTEM DESCRIPTION

Basic Acceleration Cell and Cavity

The new RF system relies on a basic acceleration cell capable of providing up to 700 V_{PK} from few hundreds kHz to above 20 MHz (Fig. 3) and allows multi-harmonic operation. 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 (Fig. 4). The MA cores provide a wideband, mostly resistive impedance to isolate the gap from ground and allow building up the required acceleration voltage. A solid-state power RF amplifier (PA), placed on one cavity side, drives the two sides of the gap with opposite phase signals. Place for a second PA cabinet is foreseen for future upgrades. The voltage and associated RF power are available for beam acceleration. The MA cores dissipate a substantial fraction of the power; water-cooled copper rings mounted on the MA cores remove the corresponding heat.

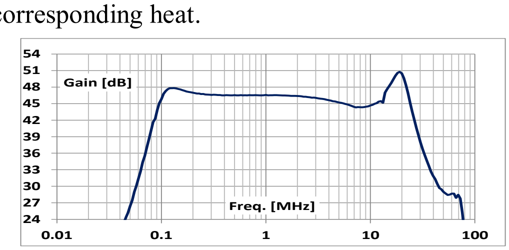

Figure 3: Cell frequency response.

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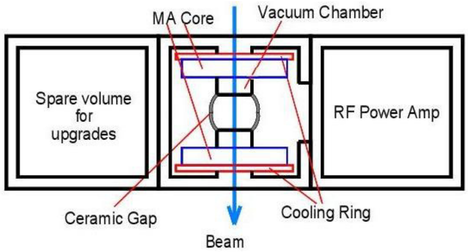

Figure 4: Basic acceleration cell.

A cavity is composed of six cells that share a common housing, the vacuum chamber with six ceramic gaps, all interfaces with the PA, distribution of DC power, control signals and cooling water (Fig. 5).

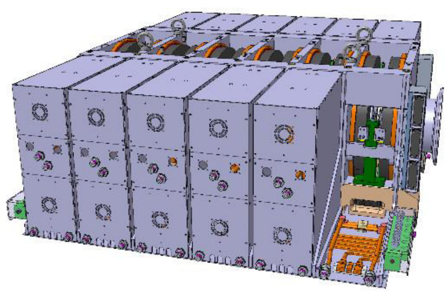
Figure 5: 6-cell cavity with amplifiers assembly.

RF Power Amplifier

The PA is a plug-in unit composed of 16 power stages with the outputs combined into two independent push-pull ports for a total output power exceeding 3 kW. An integrated common input stage provides adequate drive. Although the nominal load impedance of each PA output port is 50 Ω, the amplifier behaves as a current source with good performance over a wide impedance range. This makes it well suited for acceleration of high intensity beams that can heavily change the amplifier load. Details can be found in [2].

Beam Induced Voltage Cancellation

The harmonic content of the beam current can cover many multiples of the beam revolution frequency. Its interaction with the wideband impedance of the MA cores results in induced voltage at each component and can affect the beam stability. Minimizing the gap impedance at relevant frequencies becomes thus mandatory for acceleration of high intensity beams. A fast RF feedback loop implemented in the PA gives a first contribution to reducing the gap impedance by ~10 dB. A substantially higher gap impedance reduction of ~36 dB comes from the action of the LL electronics [3]. The combined effects of the two impedance reduction actions are such that the overall impedance of the 36 cell as seen by the beam (Fig. 6) is about one order of magnitude lower than that of the *h1*, *h2* and *h10* being replaced. Studies of longitudinal beam stability issues have been carried out with simulations, measurements and tests [4]. They suggest that stable beams can be achieved even for the highest foreseen intensities.

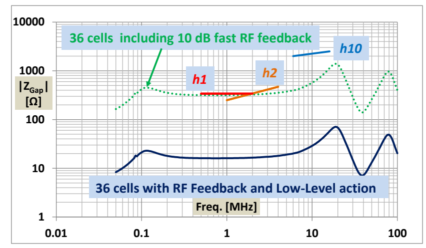

Figure 6: Overall impedance as seen by the beam. *h1, h2* and *h10* are the impedances of the system being replaced.

Low Level Electronics

The Low Level Digital Electronics (LL) are a major component of the RF system that allow full use of the wideband characteristics of the power sections but also effective cancellation of the beam induced voltage. The main benefits of using a digital system are its full, remote and cycle-to-cycle controllability; built-in diagnostics and extensive signal observation capabilities are also important characteristics. The hardware family provides a very high processing power, is compact, flexible and modular. Details can be found in [5]. Two LL sections (Fig. 7) cover the beam control requirements by taking care, in real time (10 μs cycling), of the following functionalities:

- Generation of the frequency program using either the synthetic or measured B-Train;
- Implementation of the beam phase loop;
- Implementation of the beam radial loop;
- Synchronization of the extracted beam with the downstream machine.

Each couple of cavities relating to one PSB ring and installed in one section are treated as a single element.

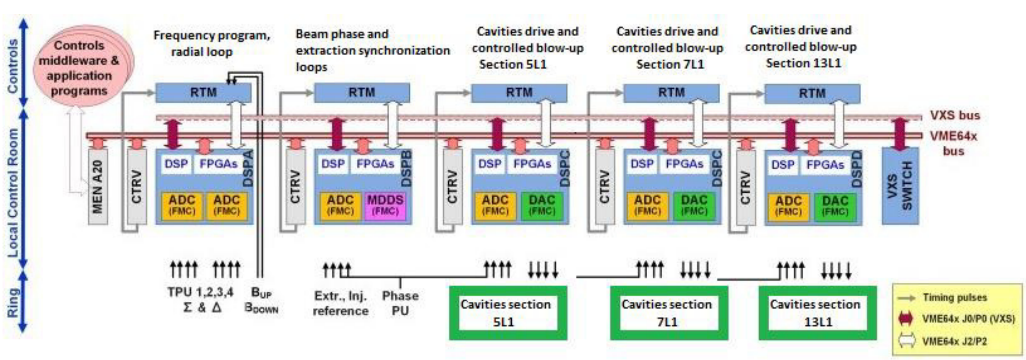

Figure 7: Low level system overview.

Driving signal splitting and gap returns combining is done on the high power side. Three additional LL sections generate the signals for the cavity drive. Using reference voltage programs and cavities gap-voltage return signals, the LL control amplitude and phase of the acceleration voltage at the beam revolution frequency and nine additional harmonics. The action of this servo loop compensates the beam-induced voltage and the beam sees it as a reduction of the cavities impedance. The LL also linearize the power stages frequency response using pre-programmed tables and automatically compensate for the cavities different radial position. These sections also generate the signals for the controlled beam blow-up. High level applications in the control system set the required voltage programs. The application takes into account hardware limitations and information from the RF power system interlocks such as the number of operational cells.

Mitigation of Radiation Effects

Apart from the power RF Mosfets, the PA placed in proximity of the circulating beam use only elements with low sensitivity to radiations. The expected radiation effects on the RF Mosfets are substantially limited to the trapping of charges in the gate isolation layer and the resulting displacement of the threshold voltage. To mitigate this effect the gate bias circuit includes a measurement of the received dose and automatic compensation [3].

Interlocks, Power Supplies, Ancillaries

Each PA is independently supplied by standard industrial power converters (50 V - 200 A) and dedicated electronics allow remote monitoring of Mosfets currents, radiation effects, relevant temperatures. A PLC based interlock system oversees the PA operation, monitors cooling fluids and temperatures, logs data for fault tracing and preventive maintenance programs and interfaces with the control system and the LL electronics. To limit the DC supply losses the cable lengths are minimized by installing the DC converters at the shortest possible distance from the PA.

QUALITY PLAN AND RELIABILITY

The complete RF system for the four PSB rings will be composed of 144 identical cells, the same number of DC power supplies and PA amplifiers, twice as many MA cores, cooling rings and PA interface cards and over 5000 RF Mosfets. To achieve the high reliability required for the PSB operation a quality plan is being defined for the production of the system components, their assembly and installation. The plan will foresee detailed intermediate checks, precise assembly and testing procedures and reporting. To spot weak system elements, optimize maintenance, define the spares parts policy and predict system availability, a reliability analysis of the whole system was carried out [6]. The analysis take in account over-dimensioned system capabilities as well as planned and corrective maintenance. Simulation results suggest a mean availability above 99% with downtime mostly due to DC converters and ancillary electronics. Table 1 summarizes some results.

Table 1: System Availability Predictions

Mean Availability	99.89 %
Mean Time Between Outage	6225 h
Mean Time to Repair	6.23 h
DC Converters contribution to downtime	45 %
Ancillary electronics contribution to downtime	42 %

PROCUREMENTS AND SCHEDULE

Considering the number of required identical components used in the system, most of production and testing is outsourced to industry and components come as “ready-to-install” elements. Parts acceptance, cavities assembly and pre-testing will be done in a dedicated test place also foreseen for later system maintenance. The overall schedule (Fig. 8) foresees having the full system parts available, tested and ready for installation well before beginning of LS when the installation will take place.

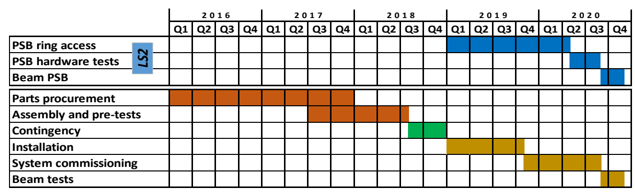

Figure 8: Procurement and installation schedule.

CONCLUSIONS

A new RF system based on modern technology, solid-state RF power stages, modular layout and profiting from high performance LL electronics will replace the existing RF systems of the CERN PS Booster. The adoption of MA technology has been validated and opens the possibility of a new and flexible use of RF systems in the PSB, based on multi-harmonic control. This upgrade will contribute to enhance the characteristics of the LHC beam after LS2. All system components are now defined and the procurement process has started to be ready for installation in January 2019.

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