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J-PARC Contributions to the LHC InjectorUpgrade (LIU) Project

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J-PARC accelerator is a pioneer in the development of wideband RF systems using a nanocrystalline material, FINEMET®. In 2014, magnetic-annealed nanocrystalline [1] cores were installed in the J-PARC Main Ring RF systems and they showed excellent performance. The cores were produced using a large magnetic-annealing system developed in J-PARC [1] and transferred to the core manufacturing company for mass production.
The LHC Injector Upgrade (LIU) was launched in 2010 in synergy with the High Luminosity LHC project (HL-LHC) [2]. It includes the consolidation/upgrade of the PS Booster RF systems [3, 4]: all the existing ferrite-loaded RF cavities are being replaced with wideband RF systems during the 2019-2020 long shut down. The magnetic-annealed cores improve the cavity performance and reduce the number of the straight sections for RF systems. In 2013, during the first long shut down of the LHC, LS1, we performed a beam loading test in J-PARC using a one-cell type Booster cavity. The beam test using a high intensity beam proved that direct-feedback can work in conjunction with the other beam loading compensation system [5]. J-PARC also cooperates on the R&D of a Rad-Hard solid-state amplifier. A recent irradiation test shows that the amplifier can withstand up to 2 kGy under mixed field irradiation [6]. J-PARC contributions for the LIU project will be reported.

KEYWORDS: J-PARC, CERN, Wideband Cavity, LHC Injector Upgrade (LIU)

1. Introduction

Magnetic Alloy, FINEMET®, loaded cavities [7] are employed for the beam acceleration at the J-PARC Rapid Cycling Synchrotron (RCS) and Main Ring (MR). Both cavity systems aim to accelerate the high intensity beam and are designed to optimize the cavity bandwidth and RF voltage to satisfy the requirements. The RCS cavities has a wideband of Q $\sim$ 2 around 1.7 MHz to cover the acceleration frequency and second harmonics. The bandwidth of the RCS RF system is also controlled by an external inductor, which is located in the tube amplifier beside the cavity to reduce the beam loading effects by higher harmonic components of the concerned beam. The MR cavity adopts a cut-core scheme to reduce the inductance of the core and the bandwidth of the cavity. As the MR has harmonic number of 9 and an empty RF bucket in the ring and the peak beam current exceeds 100 A, the bandwidth is optimized to sweep the RF frequency by 3 % from 1.67 MHz to 1.72 MHz. The RCS RF system accelerates 1 MW beam, which is the design value. The MR system accelerates 2.6×10^{14}proton per pulse, which corresponds to a 500 kW beam power.

The magnetic alloy cores in the MR cavity were magnetic annealed in an oven setup that was developed in J-PARC [1], that consists of a large oven and a modified dipole magnet which was used for a spectrometer in the KEK east counter hall. The cores have two times less power loss than the material that was annealed without the magnetic field because the magnetic domain of material is controlled [1, 8]. The cavities achieved a field gradient of 32 kV/m before the installation. By the installations of these cavities in MR, the second harmonic RF becomes available to reduce transverse space charge effects at the injection and the beam power increases. The magnetic annealed cores will be used in the RCS cavities in future to accelerate 1.2 MW or higher.

CERN and J-PARC have been cooperating for many years for ring RF systems. In 2002, a collaboration on the RF system of the Low Energy Ion Ring (LEIR) was started [9]. LEIR was built by transforming Lowe Energy Antiproton Ring to accumulate and accelerate Lead ions for Lead-Lead collision at the LHC. The cavity shroud was produced in KEK and the magnetic alloy cores with waterproof coating were installed in it at CERN. After the installation, no hardware failure or missing performance was reported. In 2012, the collaboration restarted for the LHC injector upgrade project (LIU). The collaboration includes the R&D for wideband RF cavities for the CERN PS Booster [4] and damper cavity for the longitudinally coupled bunch instability in the PS [10]. The reference [11] shows that the damper cavity stabilized the beam up to 2×10^{11} ppb. Finally, the LIU baseline intensity of 2.6×10^{11} ppb was achieved by adding Landau cavity [12].

The R&D started as a backup of the consolidation of existing ferrite-loaded RF systems. After the R&D and technical reviews, FINEMET® cavity systems were approved to replace the ferrite system in the CERN PS Booster. The replacement was performed during a long shutdown, LS2, and completed in 2019. The same wideband system is also used for anti-proton deceleration at ELENA because very wideband response is necessary to decelerate to very low energy [13].

2. Magnetic Annealing

Figure 1 shows the magnetic annealing oven in the core production company. The inner dimensions of the oven are 1.2 m(W) × 1.6 m(L) × 0.4 m(H) to produce large size cores for accelerators. Thanks to the use of the oven, more than 300 cores for the MR which have 0.8 m diameter and 324 cores for the CERN PS Booster which have 0.33 m diameter were produced. Magnetic annealing enabled to improve the core impedance by a factor of two, increasing the available cavity voltage. By adopting the magnetic annealing cores for the J-PARC MR, the available RF voltage increased. The necessary RF voltage is obtained by the six RF stations instead of nine old systems. The second harmonic RF voltage of 110 kV is applied to achieve the bunching factor larger than the designed value of 0.3 and it improved the beam intensity significantly. In addition, one cavity system stands by as a spare, which also improves beam availability during the 500 kW beam operation. Magnetic annealed cores are well-suited for PS Booster because the number of cavity cells could reduce and one free space was produced by the RF system replacement.

The results of the production for the PS Booster are shown in Fig. 2. Because the required RF frequency range is 0.5 to 17 MHz, the shunt impedance at 0.5, 1, 5, 10, and 20 MHz was measured for all the cores. Earlier, these frequency ranges were covered by three different ferrite loaded cavity systems. They were C02 for acceleration, C04 for the second harmonic RF, and C16 for the higher harmonic RF to blow up the longitudinal emittance. These ranges are now covered by a single type of wideband cavities. Figure 2 showsthe results of the core production. The core characteristics are stable during the entire production.

3. CERN PS Booster RF

Beam loading on the wideband cavity was an issue that needed investigation. In 2013, a cavity system driven by a solid-state amplifier was installed in the J-PARC MR. The high intensity beam of 1×10^{13} protons per bunch was used to evaluate it. In this test, a fast feedback in the solid-state amplifier and the existing feed forward compensation sytem of J-PARC were tested. It is reported

Fig. 1. Magnetic Annealing Oven.

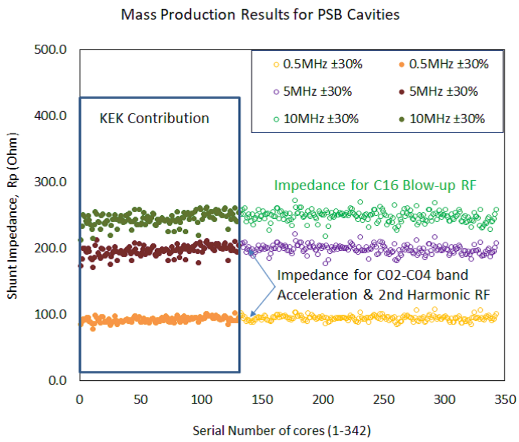

Fig. 2. Results of core production for the PSB. Vertical axis is the core impedance at 0.5 MHz, 5 MHz, and 10 MHz.

that both compensations worked together and beam loading effects were cancelled out [5]. After the LS1, two sets of 5-cell cavity system were installed in one of four Booster rings. Beam tests, including reliability runs, were carried out by the system. The system worked stably under typical beam operations. It is also found that the production cost of the wideband system is much less than the consolidation of ferrite systems. Finally, CERN approved the replacement of ferrite systems with the new wideband ones.

Figure 3 shows a new RF system that is installed in the PSB. The PSB is a four-storey accelerator and the RF systems also pile up. Inside of the RF cavity, two magnetic alloy cores were installed and cooled by copper cooling discs as shown in Fig. 4. Each acceleration cell generates 700 V, and 8.4 kV is available by two sets of 6-cell system in a straight section that corresponds to the acceleration voltage of the Booster. The acceleration cell is driven by a solid state amplifier beside the cavity. Three straight sections are used for the RF system in the rings.

4. Solid-state amplifiers

The other key issue regarding the cavity system is related to a solid-state amplifier that drives the wide band cavity. The amplifier is located beside the cavity in the Booster tunnel. In the Booster,

Fig. 3. New Booster RF systems.

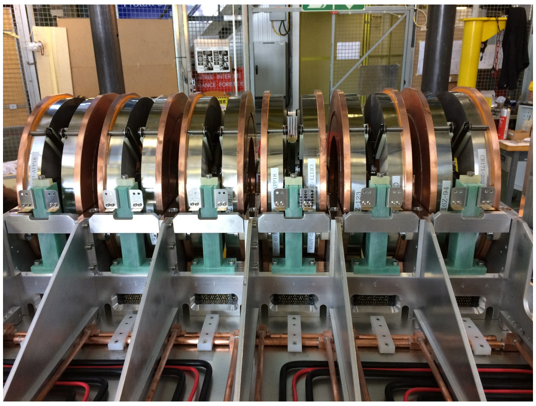

Fig. 4. FINEMET® cores and cooling discs in a 6-cell cavity.

solid-state amplifiers have been used for feedback in the tube amplifiers for many years. Experience suggests that the radiation effect in the Booster ring is not fatal; however, it is necessary to evaluate it as solid-state devices are expected to be used widely for new RF systems. To drive one cell, a solid state amplifier uses 17 MOSFETs. In a straight section, 816 MOSFETs are used for four Booster rings. In the Booster, 2448 MOSFETs are used in 3 RF sections.

In 2013, the first evaluation test was performed in J-PARC collimator section during a long shut down of the CERN accelerators, LS1 [14]. The setup is shown in Fig. 5. The dose in the section was approximately 500 Gy/day during high power operation. The dose and neutron flux were measured using RadMON, which was developed at CERN [15]. In the section, the halo of the circulating proton beam is collimated and secondary particles were produced, including charged particles and neutrons. All MOSFETs show good results. A MOSFET which has a high break down voltage was chosen to drive the cavity directly because the amplifier may be affected by the large beam-induced voltage. To improve the gain stability and lifetime of amplifiers, a mitigation scheme was developed and improved. After the first irradiation test in 2013, a cobalt gamma-ray source, a proton beam at PSI and mixed filed irradiation at CHARM and J-PARC were used. The recent irradiation test at CHARM [16] shows a gain stability up to 2 kGy by the mitigation technique. In case of the present Booster, 2 kGy means 100 years for the present radiation level at new RF sections [5].

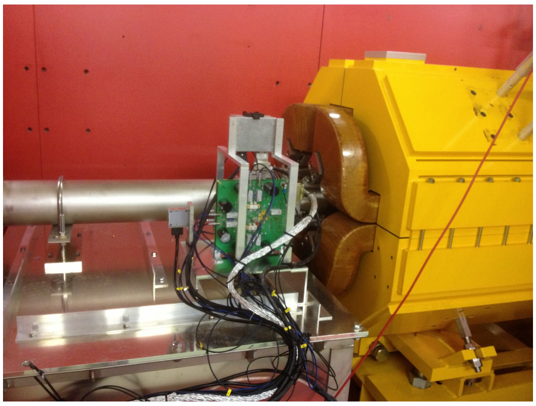

Fig. 5. Irradiation test at J-PARC MR collimator section.

5. Conclusions

CERN and J-PARC have been cooperating on hadron ring RFs for many years. J-PARC collaborated on the RF system upgrade of LIU. The replacement of the Booster RF system are underway during the long shut down, LS2. The beam instability at CERN PS has also been successfully damped in cooperating with the wideband system and existing Landau cavities. The collaboration was fruitful for both institutes and will be continued.

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