ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FROXSP1

20-YEAR COLLABORATION ON SYNCHROTRON RF BETWEEN CERN AND J-PARC

C. Ohmori*, K. Hasegawa, Y. Morita, H. Okita, M. Shirakata, Y. Sugiyama, F. Tamura, M. Yoshii, J-PARC, Tokai, Ibaraki, Japan
M. Paoluzzi, M. Brugger, M. Brucoli, H. Damerau, S. Danzeca, C. Rossi
CERN, Geneva, Switzerland

Abstract

In 2002, KEK/J-PARC and CERN started the collaboration on the RF systems of Low Energy Ion Ring to use magnetic alloy loaded cavities for heavy ion collision program at LHC. It was an exchange of our expertise on the wideband cavities and high-power solid-state amplifiers. This paper summarizes the 20-year collaboration which includes many synchrotrons at both facilities: J-PARC rapid cycling synchrotron (RCS) and main ring (MR), CERN Proton Synchrotron, PS Booster, Antiproton Decelerator, Extra Low Energy Antiproton ring, and MedAustron. With the improvements of cavity core by the magnetic annealing, field gradient and compactness of cavity were improved to fulfill the needs of the LHC Injector Upgrade (LIU) program. Radiation-hard and compact high-power solid-state amplifiers were also developed for LIU and future accelerator improvements.

INTRODUCTION

In a synchrotron, particles circulate on the fixed orbit. Therefore, the magnetic field of bending, quadrupole and other magnets are ramped according to the variation of particle momentum. The variation in particle velocity is significant in hadron and proton synchrotrons, although it remains negligible in electron synchrotron. On the resonant-type cavity technology for hadron beam acceleration, it has been an issue how we change the resonant frequency of the RF cavity. When synchrotrons were invented as a weak-focusing machine in the 1950s, a large amounts of ferrite rods and blocks were used for the cavity [1]. To change the permeability of the ferrite material, a large biasing current was applied on so-called Figure-of-Eight loop which surrounded ferrite materials. In strong focusing machines invented in the late 1950s, the ferrite rings became much smaller than the ferrite bricks of weak focusing machines [2, 3]. The ferrite cavity technology made the energy of these synchrotrons higher. However, the tuning circuit was still inevitable. A large frequency swing was an issue on this scheme to apply for heavy-ion synchrotron because it required a large variation of permeability. In the 1980s, a new approach to extend the frequency bandwidth of RF cavity was tried in Saclay, France. A magnetic alloy, amorphous, material was used as a cavity core instead of ferrite [4]. However, the tuning circuit was still applied to change the resonant frequency because of the large frequency swing.

In the mid-1990s, an iron-based nano-crystalline material, Finemet® [5], was tested as the cavity material in Japan [6]. The material exhibited three significant characteristics: thermal stability, stable shunt impedance on high voltage and a very large permeability [7]. The saturation magnetic flux density B_s of Finemet® (~1.2 T) was higher than that of ferrite (~0.3 T). Therefore, the material has stable shunt impedance to use for ordinary accelerators. Our measurement shows it is stable up to 200 mT as a RF flux density. This was an important feature for a high intensity proton machine. The cavity exhibited wideband characteristics, indicating that cavity tuning circuit was not needed.

In the late 1990s, the first beam test was carried out at HIMAC in National Institutes for Quantum Science and Technology, Japan [8]. It was the first demonstration to show that ion beam acceleration was possible by a compact RF cavity without tuning. This is because magnetic alloys including nano-crystalline and amorphous materials have much higher permeability than ferrites. As a result, $\omega L \sim R$, and $Q \sim 1$, assuming the magnetic alloy cavity system as a paralell LCR circuit. In case of ferrite cavity system, $\omega L < R$, and typically $Q \sim 100$. The ferrite cavity system, therefore, exhibits narrowband characteristics and needs a tuning circuit to sweep the resonant frequency for acceleration. In many proton-ion medical synchrotrons, the cavity system based on the magnetic alloys is adopted because of its simple structure without a tuning circuit and easier beam acceleration [9, 10].

At J-PARC, the cavity bandwidth was controlled. A cut-core technique was used to obtain narrow-band cavity for MR [11]. For RCS, Alexander Schnase used an external inductor to adjust bandwidth for beam acceleration and the 2nd harmonics [12]. Using these technologies, J-PARC succeeded in accelerate the beam at the RCS in 2005 and at the MR in 2006. And, the beam intensity of the RCS reaches 1 MW, which is the design value and the MR delivers 515 kW for T2K long-baseline neutrino experiments.

LOW ENERGY ION RING (LEIR)

Our collaboration between CERN and KEK began in March 2002 to develop the LEIR wideband cavities and high-power solid-state amplifiers of J-PARC. The LEIR is a Pb-ion accelerator converted from the Low Energy Antiproton Ring (LEAR) [13,14]. It is the first ring in the ion-beam injection chain for Pb-ion collision in the LHC. An RF system was required to accelerate Pb-ion beam by a single cavity. Another RF system was installed as a backup. They

* chihiro.ohmori@kek.jp

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FROXSP1

were designed to generate 4 kV with a frequency sweep of 0.72-2.84 MHz for the operation on harmonics $h = 2$. Actual bandwidth was 0.35-5 MHz. Multi-harmonic RF operation was also performed with a single cavity [15].

Figure 1 shows the LEIR cavity designed based on the HIMAC experiences [7, 8]. Direct water cooling scheme is also used in the LEIR cavities similar to the J-PARC RF cavities. The nano-crystalline cores were coated and dipped in cooling water [13]. Since the installation, no significant cavity trouble and variation have been noticed.

The solid-state amplifier has been another key subject for this collaboration. J-PARC required kW-class driver amplifiers to drive tube amplifier as a final stage. Especially, RCS requires 8 kW amplifiers to drive the amplifier as a dual harmonic system. CERN designed a reliable 1 kW solid-state amplifier unit. Now, J-PARC uses 140 units for stable beam operation in both rings.

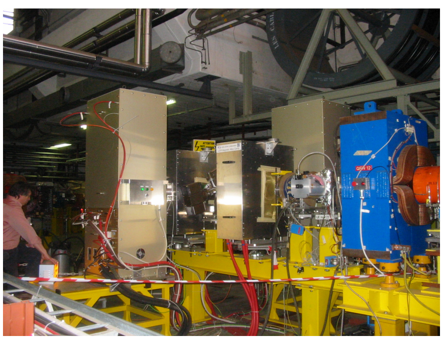

Figure 1: LEIR cavities during installation in 2005.

HIGH IMPEDANCE CORES

Nano-crystals in Finemet® are formed through the high temperature annealing of amorphous Fe-Si-B-Ni-Cu alloy. Magnetic annealing improves the characteristics of the material used for the RF cavity. In the late-2000s, because of the increased demand, the small-size magnetic-annealed materials became available commercially. In 2009, the first mid-size core production was tested at the factory of Hitachi Metal Ltd. in Thailand. The mid-size core yielded a good result. Simultaneously, J-PARC started to build its own magnetic annealing system for large cavity cores in cooperation with the Hitachi Metal Ltd. [16].

CERN and J-PARC have started cooperation to use the magnetic-annealed cores. In 2011, J-PARC succeeded to demonstrate the production of 80 cm diameter core by the magnetic annealing. CERN ordered mid-size cores with a diameter of 33 cm for new projects, PS booster and MedAustron. Magnetic annealing improved cavity impedance without changing the core size. The improved impedance affects the cooling design and even compactness of the cavity space.

After the successful magnetic annealing test production, J-PARC started to build a mass-production system to improve the cavity performance [16]. The system produced magnetic-annealed cores for both J-PARC and CERN. It also supplied the cores for the accelerator R&D in UK.

PS BOOSTER CAVITIES

The PSB is the first synchrotron in the LHC injection chain for proton beam collision. The LHC Injectors Upgrade (LIU) was launched in 2010 in synergy with the High Luminosity LHC (HL-LHC) project [17,18]. It includes the consolidation/upgrade of the PSB RF systems. The consolidation plan was to improve the existing ferrite-loaded RF system. The replacement of all the existing ferrite-loaded RF cavities with wideband RF systems was started as a back-up plan.

In 2011, the magnetic-annealed cores were prepared to install in a test cavity. It was a 5-cell cavity and each cell comprised 2 cores cooled by copper cooling discs. Each cell was driven by a solid-state amplifier installed beside the cavity. The configuration made the system more robust by having a margin for number of cells and amplifiers. The cavity was installed in the PSB. Another test cavity was prepared for the beam test in J-PARC. The beam test using a high intensity beam of 1×10^{14} ppp was carried out [19]. The solid-state amplifier has a direct feedback system and J-PARC prepared a feed forward beam loading compensation system. Both the systems were found to work together.

Radiation damage on the solid-state amplifiers was also investigated. The collimator section of the J-PARC MR was used for an irradiation test of solid-state devices to investigate single-event effects (Fig. 2). After a long shutdown, the irradiation test was also performed at the CERN High Energy Accelerator Mixed-field (CHARM) facility [20]. The tests demonstrated the durability of devices under irradiation and that the total ionization dose effect can be compensated. [21].

Cavity performances and beam test results were reviewed, and the replacement of the ferrite system with the wideband system was approved. While four straight sections were used for the ferrite system, the new system needs only three sections. The J-PARC magnetic annealing system was used for the mass-production of cores because of better characteristics. During the long shutdown (LS2), the replacement works were carried out (Fig.3) [22, 23]. After LS2, PSB was restarted and a more flexible beam operation became available [24]. The maximum RF voltage for acceleration increased to 24 kV from 8 kV.

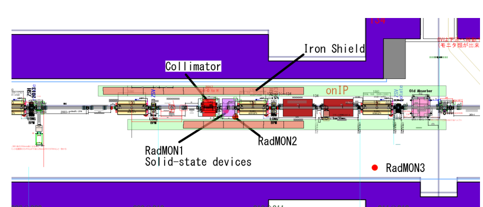

Figure 2: J-PARC MR collimator section. Three radiation monitors (RadMON) were used to estimate the dose on the device.

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FROXSP1

Figure 3: Wideband cavities in PS booster.

PS DAMPER CAVITY

Longitudinal coupled-bunch instabilities limited the intensity of LHC-type beam in PS [25]. A wideband feedback system similar to PSB wideband cavity was installed to damp the dipole mode of the oscillation [26]. The damper cavity worked well up to 2×10^{11} protons per bunch. However, beyond this intensity, quadrupole oscillations were observed. To damp the oscillation, a 40 MHz RF cavity was operated as a higher harmonic RF system, increasing Landau damping. [27]. The design goal intensity (2.6×10^{11} ppb) was achieved by the combination of damper and Landau cavities (Fig. 4) [28].

Because PS is a more radioactive environment than PSB, the solid-state amplifiers to drive the damper cavity were protected in an iron shielding below the cavity. The radiation in the shielding was about 5 Gy/year and acceptable for 5-10 years operation.

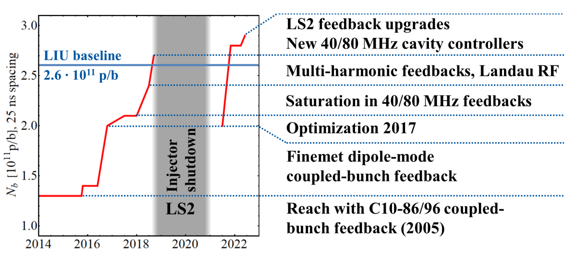

Figure 4: Intensity evolution with LHC-type beam.

ANTIPROTON DECELERATORS

Moreover, the wideband cavity technology is used for Extra Low ENergy Antiproton decelerator (ELENA) and Antiproton Decelerator (AD) [29]. ELENA needs a very wideband system, especially, 100 kHz as the bottom frequency to obtain 100 keV antiprotons. Because ELENA is a very small ring, it requires an extremely compact system. Therefore, a single-gap cavity of approximately 15 cm thickness was used for ELENA. Test-produced cavity cores using J-PARC magnetic annealing system were tested before mass-production for PSB. These cores were used for ELENA. Figure 5 shows the PSB-size and J-PARC-size cores. For AD, a test cavity of PSB was reused after replacing all PSB cavities.

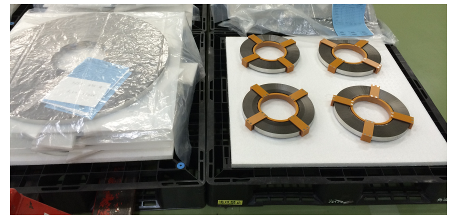

Figure 5: J-PARC-size (left) and PSB-size (right) cores after magnetic annealing. Two PSB-size cores in this photo were installed in ELENA cavity.

IRRADIATION TESTS OF NEW DEVICES

Gallium Nitride (GaN) devices exhibit high power and radiation hardness. In 2019, we tested stability of GaN device under biasing. A small GaN device QPD1013 was set downstream of collimator in the J-PARC MR (Fig. 2). We measured variation in the drain current by the irradiation doses increased up to 30 kGy. The total ionization dose (TID) and neutron flux on the device were measured using RadMON V6 developed by CERN. [30, 31]. In 2020, we prepared an amplifier using high power GaN devices QPD1016 and tested in the same location. We have tested the amplifier under the RF operation of ~300 W with 30% duty. Total dose was 18 kGy and approximately 2×10^{14}neutron/cm^2. No obvious variations in the amplifier gain and single-event effect were observed, as shown in Fig. 6. The variations at 200 Gy and at 15.8 kGy were caused by bias adjustments. The dose corresponds to about 10 years use of feedback amplifier in PS tunnel [32].

Moreover, we also tested small sample of magnetic-annealed cores that are used in CERN and J-PARC. No variations in complex permeability and hysteresis curve were observed under high irradiation.

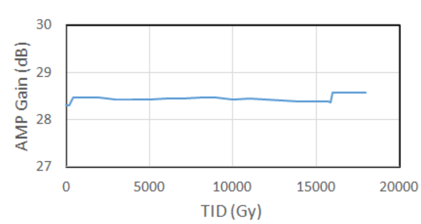

Figure 6: GaN amplifier gain during irradiation test.

SUMMARY

A lasting collaboration between CERN and J-PARC has been successful. The desired beam intensity and quality for LIU have been achieved.

ACKNOWLEDGEMENTS

The authors thank Roland Garoby and Yoshiharu Mori who started the collaboration in 2002. The authors also thank J-PARC Ring RF and SY-RF groups. This work was supported by JSPS KAKENHI Grant Number 19KK0078 and 18K11930.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FROXSP1

REFERENCES

[1] Review of Scientific Instruments vol24 No.9, "Radio-Frequency System Part IV"

[2] I. S. Gardner, in RF Engineering for Particle Accelerators, Proceedings of the CERN Accelerator School, (CERN, Geneva, 1993), pp. 349–374.

[3] H. C. Grassmann, R. Jankovsky and W. Pirkl, New RF System for the 28 GeV Proton Synchrotron at CERN, *Siemens Review* **XLIV** (4), 164-170 (1977).

[4] C. Fougeron, P. Ausset, and J. Peyromaure, "Towards the Construction of an Ultra Short Cavity for Heavy Ions Synchrotron", in *Proc. EPAC'90*, Nice, France, Jun. 1990, pp. 961–964.

[5] Y. Yoshizawa, J. Appl. Phys. 64, 6044 (1988).

[6] Y. Tanabe *et. al.*,"Evaluation of Magnetic Alloys for JHF RF Cavity", in *Proc. APAC'98*, Tsukuba, Japan, Mar. 1998, paper 5D006, pp.390–392.

[7] C. Ohmori *et. al.*,"High Field-Gradient Cavities Loaded with Magnetic Alloys for Synchrotrons", in *Proc. PAC'99*, New York, NY, USA, Mar. 1999, paper THAL1, pp. 413–417.

[8] C. Ohmori *et. al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 547, 249 (2005).

[9] C. Schmitzer *et. al.*, "MedAustron Synchrotron RF Commissioning for Medical Proton Beams", in *Proc.* 7th Int. Particle Accelerator Conf. (IPAC2016), Busan, Korea, pp.844-846. DOI:10.18429/JACoW-IPAC2016-MOPOY001

[10] M. Kanazawa *et. al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 566, 195 (2006). doi.org/10.1016/j.nima.2006.05.276.

[11] C. Ohmori *et al.*, "New Cutting Scheme of Magnetic Alloy Cores for J-PARC Synchrotrons", in *Proc. EPAC'06*, Edinburgh, UK, Jun. 2006, paper TUPCH128, pp. 1313.

[12] A. Schnase *et al.*, "MA Cavities for J-PARC with Controlled Q-value by External Inductor", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper WEPMN040, pp. 2131–2133.

[13] M. M. Paoluzzi, R. Garoby, M. Haase, P. Maesen, C. Ohmori, and C. Rossi, "The LEIR RF System", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper WPAT018, pp. 1619-1621.

[14] A. Beuret *et. al.*, " The LHC Lead Ion Injector Chain",in *Proc.* EPAC2004, Lucerne, Switzerland, pp.1153-1155.

[15] M. E. Angoletta *et al.*, "CERN's LEIR Digital LLRF: System Overview and Operational Experience", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper TUPEA057, pp. 1464–1466.

[16] C. Ohmori *et. al.*, "Development of a high gradient rf system using a nanocrystalline soft magnetic alloy", Phys. Rev. ST Accel. Beams, vol. 16, no. 11, p. 112002, Nov 2013. doi:10.1103/PhysRevSTAB.16.112002

[17] M. Meddahi *et. al.*, LIU Technical Design Report - Volume I: Protons (CERN, Geneva, Switzerland, 2015) Rep. CERN-ACC2014-0337

[18] R. Garoby *et al.*, "Upgrade Plans for the LHC Injector Complex", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper TUXA02, pp. 1010–1014.

[19] F. Tamura *et. al.*, "Beam Test of the CERN PSB Wide-band RF System Prototype in the J-PARC MR ", in *Proc.* 5th Int. Particle Accelerator Conf. (IPAC'14) Dresden, Germany, 2014, p. 3385. doi:10.18429/JACoW-IPAC2014-THPME065

[20] J. Mekki, M. Brugger, R. G. Alia, A. Thornton, N. C. D. Mota and S. Danzeca, IEEE Trans. Nucl. Sci. **63** (2016) no.4, 2106-2114. doi:10.1109/TNS.2016.2528289

[21] C. Ohmori and M. M.Paoluzzi, IEEE Trans. Nucl. Sci. 66, 2188 (2019)

[22] M. M. Paoluzzi *et al.*, "Design of the New Wideband RF System for the CERN PS Booster", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 441–443. doi:10.18429/JACoW-IPAC2016-MOPMW024

[23] M. M. Paoluzzi "The New 1-18 MHz Wideband RF System for the CERN PS Booster", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3063–3065. doi:10.18429/JACoW-IPAC2019-WEPRB107

[24] S. C. P. Albright*et al.*,"New Longitudinal Beam Production Methods in the CERN Proton Synchrotron Booster", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 4130–4133. doi:10.18429/JACoW-IPAC2021-THPAB183

[25] H. Damerau *et. al.*, ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators, 2017, p. 33.

[26] H. Damerau, M. Paoluzzi, "Design of the PS longitudinaldamper", CERN-ACC-NOTE-2013-0019, CERN, Geneva,Switzerland, 2013

[27] H. Damerau, A. Lasheen, and E. N. Shaposhnikova, "Higher-Harmonic RF System for Landau Damping in the CERN PS", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 728–731. doi:10.18429/JACoW-IPAC2018-TUPAF026

[28] H. Damerau *et al.*, "Improved Longitudinal Performance of the LHC Beam in the CERN PS", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOTK046, this conference.

[29] T. Eriksson *et al.*, "ELENA - From Installation to Commissioning", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3327–3330. doi:10.18429/JACoW-IPAC2017-WEPVA034

[30] G. Spiezia *et. al.*, Proceedings of 10th International Congress on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, 2011.

[31] G. Spiezia *et. al.*, "A New RadMon Version for the LHC and its Injection Lines", *IEEE TNS*, vol. 61, no. 6, Dec 2014, p3426. DOI:10.1109/TNS.2014.2365046

[32] G. Favia, "Design report of a 1kW power amplier for the PS RF 10MHz system," CERN-ACC-NOTE-2018-0048, 2018.