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MAGNETIC ALLOY LOADED CAVITIES IN J-PARC AND CERN

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Abstract

Magnetic alloy loaded cavities have been used in seven synchrotrons at J-PARC and CERN. In this paper, we review various cavity technologies to satisfy the requirements for the beam acceleration, deceleration, manipulation, and instability damping. This paper also contains improvements of cavity cores by magnetic annealing scheme, quality control of cores during production, the cooling methods of magnetic alloy cores: direct water cooling and indirect one using copper discs, control of cavity bandwidths from broad to narrow bands, and the methods to drive RF cavities by tube and rad-hard solid-state amplifiers.

INTRODUCTION

The research and development of the wideband cavity without tuning circuit, began in 1995 [1]. Finemet, which is a nano-crystalline material that consists of $Fe_{bal.}Cu_1Nb_3Si_{15.5}B_7$, was used in the cavities [2, 3]. Thin amorphous ribbons coated with silica were wound to form a ring-core and annealed to form nano-crystal [4, 5]. One of the cavities was installed in the AGS tunnel in 1998 for a barrier bucket experiment [6]. The other was installed in HIMAC to demonstrate beam acceleration [7]. The cavity also exhibited a dual harmonic acceleration [8].

In 2002, KEK and CERN started collaborating on a wideband cavity for the heavy ion acceleration for lead-lead collisions in LHC [9–12]. J-PARC, which is a joint project of KEK and JAEA, used it as a high-gradient cavity for a high intensity beam acceleration [13–15].

After the beam operation of J-PARC began, a cavity core improvement program started [16]. Magnetic annealing was adopted to control the micro-structure of the magnetic domain of the material and to reduce the RF power loss caused by domain-wall displacement. J-PARC developed a large magnetic annealing oven to produce 80-cm diameter cores for the main ring cavities. The RF power loss in the cores was reduced to half by this technology. Two hundred and eighty cores were produced using the oven which was rent to the production company. Replacement of the cavities was completed in 2016 [17]. The available RF voltage of the cavities increases, which contributes to an increase in the beam intensity [18]. Magnetic-annealed cores were also adopted for a test cavity in the PS booster in CERN and MedAustron which was contributed by CERN [19, 20].

The LIU, LHC Injector Upgrade project, was launched at CERN [21, 22]. The project included a consolidation/upgrade of the PS booster RF system [23] as well as cure of longitudinal coupled bunch instability in PS [24]. In the PS, another wideband cavity was used to suppress several harmonic components of the instability simultaneously [25]. The beam-loading effects on the PS booster cavities were studied using test cavities in the PS booster and J-PARC [26]. Beam loadings on the wide-band cavity, including several harmonics, were also damped using a digital LLRF system [27–31]. The requirements for High Luminosity LHC project were satisfied by the combination of the cavity and another Landau one [32, 33]. Wideband technology was adopted to upgrade the PS booster RF system [34–36]. J-PARC-made magnetic annealing oven was also used to produce 324 cores for the booster. Two test-production cores before the mass production were used for a single-gap cavity of ELENA, Extra Low Energy Antiproton ring [37]. During the long shut down, LS2, all ferrite cavity systems were removed from the booster, and wideband systems were installed. The systems operated properly and have contributed to all the proton beam operations [38]. The test cavities in the booster were also removed in LS2, and one system was installed in the AD, Antiproton Decelerator. The wideband RF system also provided flexibilities for beam tunings and operations [39, 40].

J-PARC RCS demonstrated the beam acceleration beyond 1 MW [41]. RCS started replacing the present wideband systems with single-ended systems that use magnetic-annealed cores [42]. In this paper, we present key technologies for wideband RF systems, including the quality control and evaluation of core materials. The differences of the RF systems between CERN and J-PARC and between rings are also described.

CAVITY COOLING SCHEMES

CERN LEIR and J-PARC adopted a direct water-cooling scheme to cool their cores [9, 16]. The cores were waterproofed to protect the metal from corrosion. An advantage of this scheme is the large cooling power required for higher power loss. The three cores were placed in a water tank. Figure 1 shows the cores in the water tank of LEIR cavity. Two water tanks form a single cavity. In J-PARC, three or four cavity cells were combined to form a multi-gap cavity, and each gap was connected by bus bars as listed in Table 1. Indirect cooling was adopted in the other CERN cavities. Figure 2 shows the PS booster cavity which has 6 cells. The cell consists of two cores, two cooling disc, and an acceleration gap. Silicon paste was used on the side of core for a good heat transfer. A thin polyimide film was placed on the surface of a copper cooling disc. The film was used for insulation between the core and cooling disc. Each cell was driven by a solid-state amplifier [43]. A PT100 thermometer was placed on the core surface. The status of the cores was monitored externally. The indirect cooling

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Table 1: Magnetic Alloy Cavities

Facilities	Rings	Number of Cavities	Cell per Cavity	Total Voltage	Q-value	Cooling	Core	O.D. of core	Purposes
CERN	LEIR	2	1	8 kV	<1	Direct	FT3M	67 cm	Acc., 2nd
	PSB	3 × 4	2 ×6	24 kV	<1	Indirect	FT3L	33 cm	Acc.,2nd, 3rd,blow-up
	PS	1	5	5 kV	<1	Indirect	FT3L	33 cm	damper, barrier RF
	ELENA	1	1	500 V	<1	Indirect	FT3L	33 cm	Decel.
	AD	1	5	4 kV	<1	Indirect	FT3L	33 cm	Decel.
J-PARC	RCS*	11	3	396 kV	~2.3	Direct	FT3M	85 cm	Acc.,2nd
		1	4	36 kV	~2.5	Direct	FT3L	85 cm	Acc.,2nd
	MR*	8	4	448 kV	~20	Direct	FT3L	80 cm	Acc.
		1	4	55 kV	~10	Direct	FT3L	80 cm	2nd
		1	4	55 kV	~10	Direct	FT3M	80 cm	2nd

FT3M and FT3L are the name of cores which were annealed without and with magnetic field.
* Sep. 2023,- RF system upgrades are ongoing at J-PARC.

scheme was applied to the PS damper, ELENA, and AD cavities. Although these cavities consist of cells which have the same structure, the number of cells is different as listed in Table 1. It should be noted that the multi-cell cavity design was adopted in many applications.

Figure 1: Water-proofed magnetic alloy cores in the watar tank of LEIR cavity.

CONTROL OF BANDWIDTH

In the early stage of cavity development, F. Pedersen of CERN pointed out a disadvantage of wideband cavity system to accelerate high intensity beam of 3×10^{14} protons. Specifically, to handle transient and periodic beam loadings, it is required to compensate many harmonic components. To solve these problems, the Main Ring (MR) RF system adopts a cut-core scheme [1, 45]. The Q-value of the present cavity was chosen to be ~20 which is higher than harmonic number of the ring and wider than the required bandwidth for beam acceleration from 3 GeV to 30 GeV. For the RCS, a Q-value of 2 was selected to cover the second harmonic frequency and acceleration from 180 MeV. Instead of using a cut-core scheme, RCS adopts an external inductor scheme using a coil in an amplifier [46]. The new single-ended cavity also has a similar bandwidth [42]. The typical cavity impedance of the Main Ring and RCS are shown in Fig. 3. It also shows a natural impedance of a wideband cavity. The ELENA cavity system requires 100 kHz operation to decelerate the beam to 100 keV. The bandwidth of the solid-state amplifier was improved using a wideband transformer.

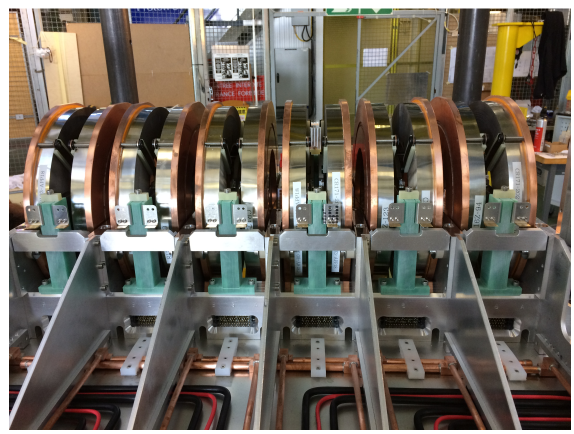

Figure 2: Indirect cooling cavity of PS booster. Cores are mounted on the copper cooling discs.

CERN PS accelerates $2 \sim 3 \times 10^{13}$ protons. Multi-harmonic beam loading was an issue for using a wideband cavity as a damper system. The problem was solved by adopting a digital LLRF to compensate many harmonics and using two solid-state amplifiers to drive each acceleration gap.

CAVITY DEGRADATION

The conditions of the cavities were monitored by regular cavity impedance measurements. Many wideband cavities have a push-pull structure. In this case, a power splitter or balun was used to measure the cavity impedance. At J-PARC,

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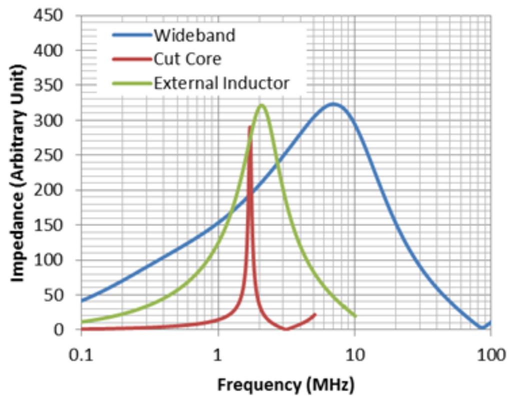

Figure 3: Bandwidths of the wideband cavities controlled by the cut-core scheme and external inductor.

a power splitter was used for monitoring. In early stage of J-PARC beam operation, degradation of cavity impedance was observed, which was caused by the damages on the cores. In Main Ring system, it was caused by corrosion on the cut surface, which was resolved by separating water circuit from the magnets and putting more protection of cut surface [47]. In the RCS, buckling occurred by the heat expansion of the core, which was solved by softening the cores [48]. Thus far, there has been no sign of degradation at J-PARC after replacing to the cavity using improved cores as shown in Fig. 4. The oldest wideband cavity in CERN is at LEIR, which has been in operation for approximately 20 years. The impedance was also monitored, and no degradation was observed.

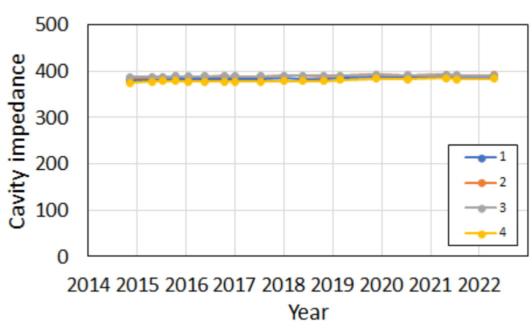

Figure 4: Impedance of MR cavities during 9 years. Four cavities using magnetic-annealed cores were installed in 2014. No significant variation was observed.

EVALUATION OF MAGNETIC ALLOY CORES

Evaluation of Magnetic Characteristics

The core impedance was measured using an LCR meter for all the cores. The measurements were consistent with single-core cavity measurement when a copper tape that was approximately 20 mm in width was used instead of a thin wire. Figure 5 presents the impedance of the cores for PS booster cavities. A total of 324 cores were measured. The resistive impedance of the cores was within ~±10%.

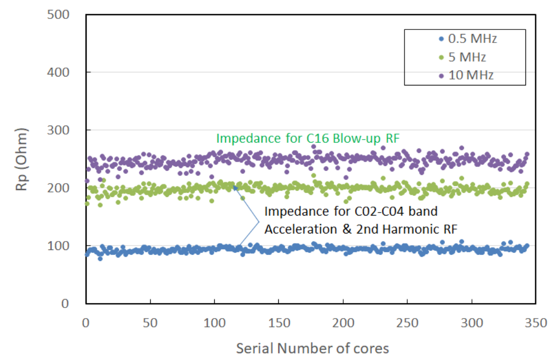

Figure 5: Impedance of all cores for PS booster.

Evaluation of Insulation between Ribbons

Another important aspect of the core production is the insulation between the core ribbon. A silica coating was formed on amorphous ribbon of 13 μm ~ thickness for the insulation between ribbons. The quality of insulation was assessed by using two different methods, one of which was to measure the resistance between one layer and the other layer using a multimeter [5]. The other method was an RF measurement using an inductor withs larger inductance than that of the core.

Radiation Damage

In the CERN PS, a damper cavity has been used to suppress the instability. The dose at this location is a few kGy per year. We initiated a irradiation test of the core in the J-PARC Main Ring. Thus far, 18 kGy and 2×10^{14} n/cm^2 were irradiated, however, no variations have been observed in the permeabilities and hysteresis curves [12]. This test will be continued.

AMPLIFIERS

Tube amplifiers are used in J-PARC RF systems owing to the heavy beam loadings. Radiation damage to solid-state devices was also considered before J-PARC started. No solid-state devices, including diodes, were used in the J-PARC RF systems in the tunnels. Solid-state devices have been used for many years in PS booster tunnel for fast-feedback amplifier to compensate the beam loading. High-power MOSFETs were tested at J-PARC under high radiation condition near a beam collimator. Certain MOSFETs do not suffer from single-event effects, however TID (Total Ionization Dose) effect was observed [44]. Based on the tests in CERN, J-PARC, and other facilities, solid-state amplifiers were chosen to drive the wideband cavities in the PS booster and PS [49].

Each cell of the cavities was driven by one or two amplifiers. This is an advantage for high availability of the RF systems because failures of certain systems do not affect the beam operation when there are margins on the RF systems.

The radiation test at J-PARC also opens the possibility to test devices under high radiation condition. PS ferrite cavity systems use small-tube amplifiers for a fast-feedback. It was reported that a higher feedback gain may improve the beam quality [50]. To improve the gain of the feedback amplifiers, irradiation tests of Gallium Nitride devices have been continued in J-PARC [12]. These measurements are supported by CERN RADMON group [51, 52].

CONCLUSION

Magnetic alloy cavities are used in several accelerators worldwide. J-PARC and CERN have been collaborating on the cavities for more than 20 years. CERN employed the cavity design using a small cell structure driven by a solid-state amplifier. This became a universal design applied to many interesting applications including beam deceleration, instability damping, barrier bucket, and emittance control. J-PARC chose the direct water cooling to achieve high-field gradient for high intensity beam acceleration.

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