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DEVELOPMENT OF HIGH GRADIENT RF SYSTEM FOR J-PARC UPGRADE

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Abstract

A new 5-cell cavity has been developed for the upgrade of the J-PARC Main Ring. In the cavity, high impedance magnetic alloy, Finemet ®-FT3L, cores are loaded. The cavity was installed and has been used for the 320 kW beam operation. The cavity is operated with the RF voltage of 70 kV which is two times higher voltage than the present cavities. Eight more cavities will be assembled and installed in the next two years to increase the repetition rate of the Main Ring. This paper describes the status of cavity operation under the beam loading and status of the mass production of the cavities.

INTRODUCTION

We have been working for the development of magnetic alloy loaded RF system for high intensity proton ring for twenty years. In the first ten years, we have finished basic R&Ds on high field gradient [1], on the technique to control bandwidth [2], and on cut core configuration [3]. The water-proof coating [4] was developed to use magnetic alloys in water tanks. The high gradient RF systems were installed in the J-PARC RCS and MR [5, 6]. At the same time, the technology is also used for medical applications [7] and heavy ion acceleration [8].

In the last ten year, we have improved water-proof coating [4] and protection of cut surfaces of cut cores [9] to afford a stable operation. Now, J-PARC has delivered 500 kW beam to the Material and Life Science Facility and 320 kW for the T2K long base line neutrino experiment. We also worked for R&D of higher gradient RF systems to increase the repetition rate of the MR for the J-PARC upgrade. The key technology of high gradient RF is the development of magnetic alloy core with higher impedance to reduce the power consumption in the cavity. A magnetic annealing oven was constructed leasing a large spectrometer magnet from a high energy experiment during a short rental period of one year [10]. Based on the success of the proof-of-principle production of high impedance magnetic alloy cores, a dedicated magnetic annealing system was developed. The production by the dedicated system shows about 10 % improving on the core impedance because of an optimum magnetic field value and improvements of ribbon winding and insulation [11]. Although the magnetic oven which J-PARC made is designed for the production of large size cores, it is also reported that characteristics of the FT3L cores made by the oven is better than that of commercially available cores for medium size (330 mm) [12].

The dedicated magnetic annealing system was moved to a company according to the contract to produce FT3L in 2013. In these two years, 280 FT3L cores with the outer diameter of 800 mm were produced using the KEK-made production system. These 280 FT3L cores are manufactured for water-proof coating and cut core configuration. For the J-PARC upgrade to deliver 750 kW beam to the T2K experiment, all cavities in the MR will be replaced with new FT3L cavities to accelerate 2×10^{14} protons with 1.3 second cycle. Although the cavities are replaced, the final stage amplifiers and power supplies can be used. According to the power upgrade beyond 750 kW, the power supplies will be modified to increase the capability to drive the power.

5-CELL CAVITY

The first five-cell cavity was constructed and installed in 2014. Each cell consists of two sets of water tanks. Three cut cores are installed in a water tank. The cut core is covered by epoxy water-proof coating for the direct water cooling in the water tank. Between two water tanks, a ceramic gap for acceleration is located. The impedance of each cavity cell is 1450 Ω and it is higher than 1300 Ω of the proof-of-principle FT3L cell installed in 2012 because of the improvements of core impedance since the production of the FT3L cores in 2011 [11]. Before the installation, two sets of high power tests were performed with a total voltage of 80 kV for 1000 hours. It is a standard procedure to test a cavity with higher voltage and higher power dissipation for several hundreds hours before an installation to the tunnel. After the power test, the cavity was disassembled and status of the FT3L cores was investigated. The detail is described in the reference [13]. After re-assembling, the cavity was taken down to the MR tunnel by a crane as shown in Fig. 1 [13]. After the installation, the gap voltage of 14 kV has been generated. A total voltage of 70 kV which corresponds to two times higher voltage than the present cavity is generated.

Figure 2 shows the upgrade plan of the RF system. The upper figure shows the status before installation of the FT3L cavities. The lower figure shows the layout after replacement. Three sets of the 5-cell cavity will be installed in a long straight section where 4 sets of the present 3-cell cavity are installed. Two sets of FT3L cavity will be 4-cell type instead of 5-cell one to fit to short straight sections. Adopting the FT3L material for the cavity, the cavity impedance becomes about 40% higher and the length of the cavity cell is about 500 mm which is 90 mm shorter than the present cavity. The total length of the 5-cell cavity is about 700 mm longer than the present 3-cell cavity and 3 sets of the 5-cell cavity fit to

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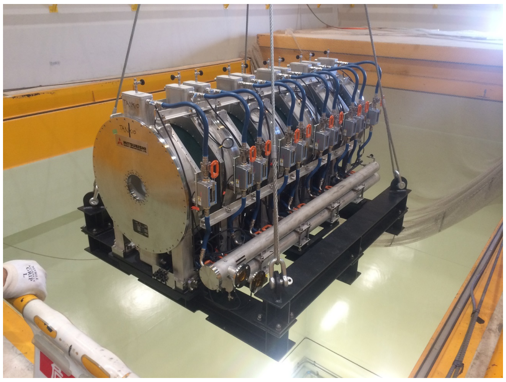

Figure 1: Installation of 5 cell cavities to the J-PARC MR tunnel.

a long straight section. Although the total voltage of 602 kV becomes available after the replacement, it is assumed that the 750 kW beam is accelerated in 0.6 sec by the RF voltage of 550 kV with the synchronous angle of 29.6°. Because this voltage ratio is similar to the present operation, an analysis using the phasor diagram can be done based on the present operation.

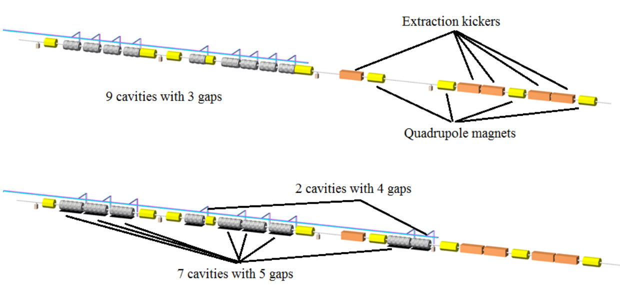

Figure 2: Installation plan of FT3L cavities. Upper and lower figures show before and after the replacement of cavity.

OPERATION OF 5-CELL CAVITY

After the installation of the first 5-cell cavity, one of the present cavities can be reserved for the backup to avoid long interruptions in case of failure of the RF system. Table 1 shows the parameters of the 5-cell cavity and present ones. The 5-cell cavity aims to generate two times higher voltage than the present one. The 5-cell cavity system was designed to accelerate 2×10^{14} protons with a synchronous angle of 30° using the present power supplies. The Q-value of the cavities is chosen to cover the variation of the RF frequency during the beam acceleration (1.67 MHz to 1.72 MHz). Because the cavity does not have a tuning circuit, the resonant frequencies are chosen to be almost inductive. The advantage of the inductive tuning is not only for Robinson instability but also for saving the anode power. The variation of the anode current depends on the resonant frequency of the cavity [13]. The Q-value of the first cavity becomes higher than that of the present ones as shown in Table 1 and the cavity becomes not inductive at the end of acceleration. When, we have accelerated the proton beam up to 2×10^{14} protons, the maximum current of the anode power supply was 106 A and it is close to the limit value of 110 A. Figures 3 show the phasor diagrams for one cell of the present cavities, the first 5-cell cavity and next 5-cell cavities under the heavy beam loading. The bottom figures of Fig 3 also show the phasor diagrams when the MR will be operated with 1.3 sec cycle. Choosing the optimum Q-value and resonant frequency, the beam loading will be as heavy as the present situation of the first 5-cell cavity. The optimum Q-value is between 20 and 22 to cover the bandwidth for the beam acceleration and to avoid severe periodic transient beam loading effects. The feed-forward beam loading compensation system [14] compensates the neighbor harmonics. In case of the Q-value of 20, the RF current, I_G becomes 5 % less than the case of top left figure of Fig. 3. After upgrading the anode power supplies for the final stage amplifiers, it will be also possible to handle 2.7×10^{14} protons for 1 MW delivery as shown in bottom left figure of Fig. 3.

Table 1: Cavity Parameters

Cavity	5-cell	Present cavities
Core Material	FT3L	FT3M
Diameter of Core	800 mm	800 mm
Thickness of Core	25 mm	35 mm
No. of Cells	5	3
Length of Cavity	2591 mm	1846 mm
Impedance/cell	1450 Ω	1050 Ω to 1150 Ω
Cavity Impedance	290 Ω	350 Ω to 380 Ω
Q-value	23.3	21.4 to 22.4
Resonant Frequency	1.718 MHz	1.72 MHz
Max. RF Voltage	70 kV	35 kV
RF Voltage at FT*	64 kV	32 kV

* RF voltage is reduced near the flat top (FT) according to the margin of the bucket height.

MASS PRODUCTION OF FT3L CUT CORE

Mass production of the FT3L cores has been carried out using the KEK-made magnetic annealing system as shown in Fig. 4. The oven has a wide aperture of 1.1 m(H) × 0.37 m(V) × 1.4 m(L) to anneal the FT3L cores with the outer diameter up to 850 mm for the J-PARC. In total, 292 FT3L cores were produced. The impedance of the FT3L cut cores was stable during the production.

The FT3L cores are manufactured for immersion, coating and cutting. The cut-surfaces are polished using a diamond powder to avoid making short circuits between thin ribbon layers of FT3L. Each cut core was observed by an infrared camera with putting the RF power of 500 W to confirm flawless cut surfaces [3]. The polished surfaces are protected by a SiO_2 coating and silicon rubber as shown in Fig. 5 [9]. Fiber reinforced plastics plates are inserted between the cut

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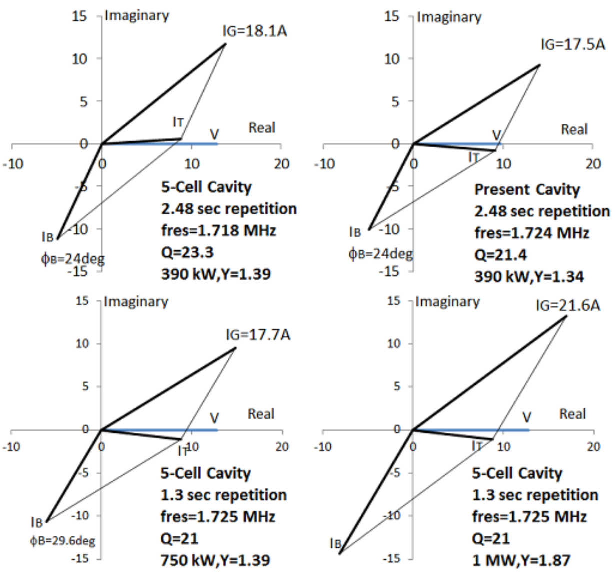

Figure 3: Phasor diagrams for one cell of the first 5-cell cavity (Top Left), the present cavities (Top Right), next 5-cell cavities with 750 kW (Bottom Left) and with 1 MW (Bottom Right) operations. I_G of the next 5-cell cavities with 750 kW operation (Bottom Left) is as large as that of the first 5-cell one with 2×10^{14} protons (Top Left).

surfaces of two halves and the thickness of the plates was adjusted to control the Q-value. The coated two halves of cut core are assembled and installed in a water tank of the cavity. Although these manufacturing procedures are same as the production of the cut cores for the present cavities, a more careful handling was needed to avoid the deformation of the core because the thickness of the ribbon becomes thinner and thickness of the core also becomes thinner than the present ones.

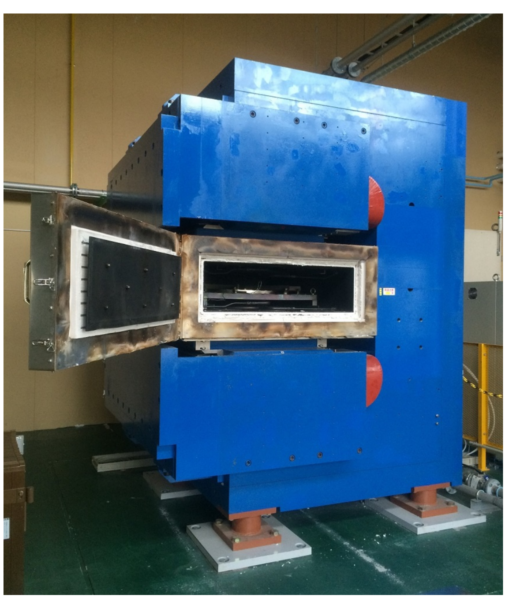

Figure 4: J-PARC-made magnetic annealing oven has been used for production of 292 FT3L cores at Hitachi Metal Ltd.

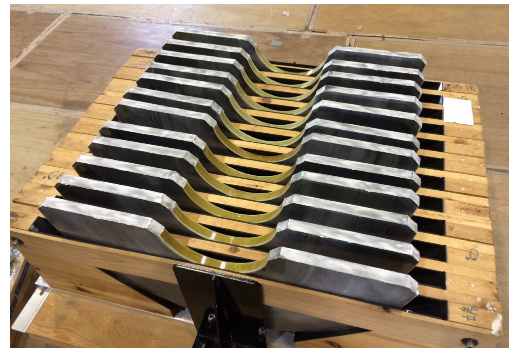

Figure 5: Cut core surfaces are protected with very thin SiO_2 coating and silicon rubber to avoid the corrosion after installing to the water tanks.

CONCLUSION

The first 5-cell FT3L cavity has been developed and installed in the J-PARC MR. It has been operated with 70 kV which is two times higher voltage than present cavities. The beam acceleration test of 2×10^{14} protons suggests that it is necessary to adjust the cavity Q-value and resonant frequency for 750 kW delivery based on the high repetition scenario. For the delivery of higher intensity, it is considered to prepare the upgrade of the anode power supplies.

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