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The origin of magnetic alloy core buckling in J-PARC 3 GeV RCS

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ABSTRACT

We have been operating ten RF cavities loaded with magnetic alloy (MA) cores with a high field gradient of more than 20 kV/m in Japan Proton Accelerator Research Complex (J-PARC) 3 GeV Rapid Cycling Synchrotron (RCS) since September 2007. During 3 years operation, we detected three times the impedance reductions of RF cavities resulting from the buckling of MA cores. To find out the origin of the MA core buckling, we evaluated the thermal stress inside the MA cores in operation and studied the relationship between the MA core buckling and core structure. We figured out that the MA core buckling was caused by the thermal stress that was enhanced due to the impregnation with low viscosity epoxy resin. We improved the MA cores without the low viscosity epoxy resin impregnation and replaced all the cores in one RF cavity with them in March 2010. Up to now we operated the RF cavity loaded with the improved MA cores for 1500 h, it showed no impedance reduction and no buckling.

1. Introduction

J-PARC 3 GeV RCS and 50 GeV Synchrotron (MR) employ RF cavities loaded with MA cores to generate a high field gradient [1]. The RF cavities in RCS employ un-cut cores and the RF cavities in MR employ cut cores to increase the *Q*-value from 0.6 to 26 [2]. This is the first time to accelerate a high intensity proton beam using MA core loaded RF cavities with a high field gradient. Compared with a conventional ferrite loaded RF cavity, the MA core loaded RF cavity can generate a higher field gradient. We achieved successfully the high field gradient of 23 kV/m, and the MA core loaded RF cavity has the potential for even higher gradients [3,4].

During 3 years operation of RCS, we detected three times the impedance reductions of the RF cavities in RCS [5,6]. We opened the two RF cavities that showed the impedance reductions to find out the cause of the impedance reductions and we also opened three other RF cavities to check the MA core condition. 26 MA cores showed buckling at the inner radius and three among them were damaged due to the large buckling. The impedance reductions of the RF cavities in RCS were caused by these three damaged MA cores. On the other hand, MR RF cavities loaded with MA cut cores showed no buckling after 5000 h operation.

To find out the origin of the MA core buckling in RCS, we evaluated the thermal stress inside the cores in operation and studied the relationship between the MA core buckling and the core structure.

In this paper, first we introduce the RF cavity loaded with MA cores in J-PARC RCS, next we describe the impedance reductions of the RF cavities in RCS and buckling of MA cores, third we discuss the origin of the buckling of MA cores, and finally we describe the improvement of MA cores without the low viscosity epoxy resin impregnation.

2. RF cavity loaded with MA core in J-PARC RCS

J-PARC is a multi-purpose proton accelerator facility aiming at MW-class beam power. It consists of a 181 MeV linac, a 3 GeV RCS and a 50 GeV MR, and several experimental facilities; those are a materials and life science experimental facility (MLF) [7], a Hadron experimental hall, and a neutrino beam line to Kamioka.

In the RCS, a proton beam with energy of 181 MeV is accelerated up to 3 GeV with high repetition rate of 25 Hz. One of the difficult challenges was how to achieve a high field gradient of more than 20 kV/m. It is impossible to achieve such a high field gradient with conventional ferrite cores because the saturation limit of magnetic flux density is about 0.28 Tesla [8]. Thanks to higher saturation flux density of 1.35 Tesla for MA cores [8], the RF cavity loaded with MA cores can generate the required field gradient. We improved the core qualities on the basis of the

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results of over 300-hour high power tests [9]. Finally, we achieved successfully the high field gradient of 23 kV/m.

We installed 10 RF cavities in May 2007. Beam commissioning started in September 2007, and we accelerated up to 3 GeV successfully in October 2007 [10]. In November 2008, we installed one more RF cavity for preparation of high power beam acceleration. Up to now we have been operating the RF cavities for 3 years under the condition of the high field gradient of more than 20 kV/m [11,12].

A photograph of an MA core for the J-PARC RCS is shown in Fig. 1. The material we chose for the MA core is a ribbon of amorphous type of soft magnetic alloy. The MA cores are produced by a winding process using ribbons with about 18 μm thickness and 35 mm width. The filling factor, which is defined as the volume ratio of MA ribbons and geometrical dimensions, is about 74–80%. The electrical insulation between the layers of the spiral ribbons is important because all cores see a fraction of the acceleration voltage and the cores at the accelerating gap side are particularly exposed to a high voltage that is half of the accelerating gap voltage. In order to create enough electrical insulation, a coating of SiO_2 with average 2 μm thickness was put on one side of the ribbon.

One RF cavity loaded with MA cores is shown in Fig. 2. The main specifications are given in Table 1. The RF cavity consists of a beam pipe and six water tanks in which three MA cores are stacked. The photograph of MA cores in a water tank is shown in Fig. 3 and a schematic diagram of cross-section of the water tank including 3 MA cores is shown in Fig. 4. The RF cavity has three accelerating gaps that are connected in parallel with bus-bars. The RF cavity is driven in push–pull mode by a final stage amplifier with two high power tetrodes. We attached a low-loss air-core inductor between the bus-bars in the final stage amplifier and a vacuum capacitor of 200 pF to the center of the accelerating gap for adjusting the Q-value to the design value of 2 [13] and the cavity resonant frequency to the design value of 1.7 MHz. A circuit diagram is shown in Fig. 5. The RF cavity length is 1.95 m and the maximum accelerating voltage of one RF cavity is 45 kV.

Concerning the cooling system, we had considered three cooling schemes; those are forced air cooling, indirect water cooling, and direct water cooling. The average power dissipation of one tank is about 20 kW. From the point of view of cooling efficiency, we employed the direct water cooling system [2], and

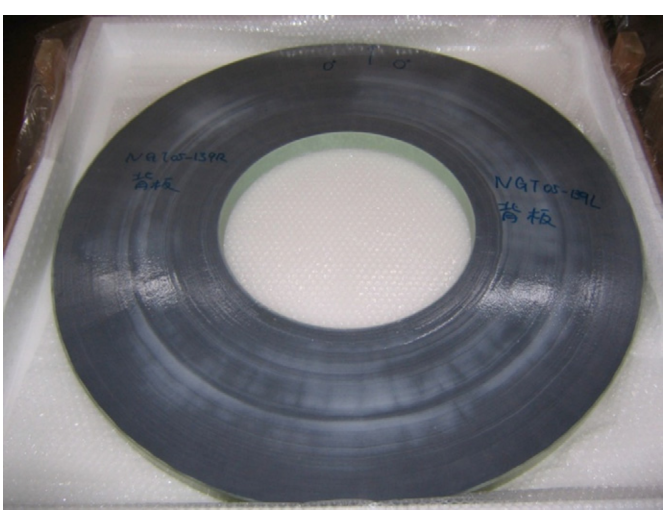

Fig. 1. Photograph of MA core in a padded transport box. The inner and outer MA core diameters are 375 and 850 mm, respectively. The weight is about 100 kg. FRP cylindrical rings are fitted at the inner and outer circumference of the core. The core surfaces are covered with thin glass-fiber sheets for adhesion and high viscosity epoxy resin to prevent rusting in cooling water.

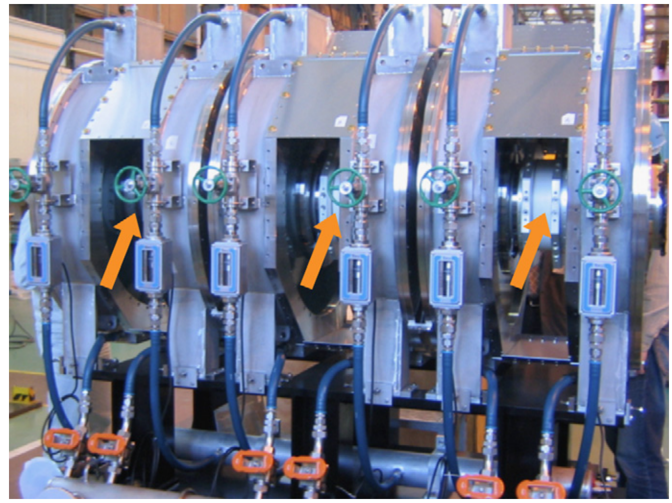

Fig. 2. Photograph of one RF cavity. The RF cavity consists of a beam pipe with large outer diameter of 255 mm and six water tanks. We employed the direct water-cooling system. Cooling water flows into each water tank from the bottom, and the cooling water flow rate of each water tank is about 45 l/min. The RF cavity has three accelerating gaps that are indicated by arrows.

Table 1
Main specifications of RF cavity loaded with MA cores in J-PARC RCS.

Core	Magnetic alloy core
Number of cores/cavity	18
Cavity resonant frequency	1.7 MHz
Fundamental frequency	0.938–1.67 MHz: (h=2)
RF harmonics	2 and 4
Q-value	≈ 2
Cooling system	Direct water cooling
Average power dissipation/cavity	120 kW
Number of accelerating gaps/cavity	3
Cavity length	1.95 m
Maximum field gradient	23 kV/m

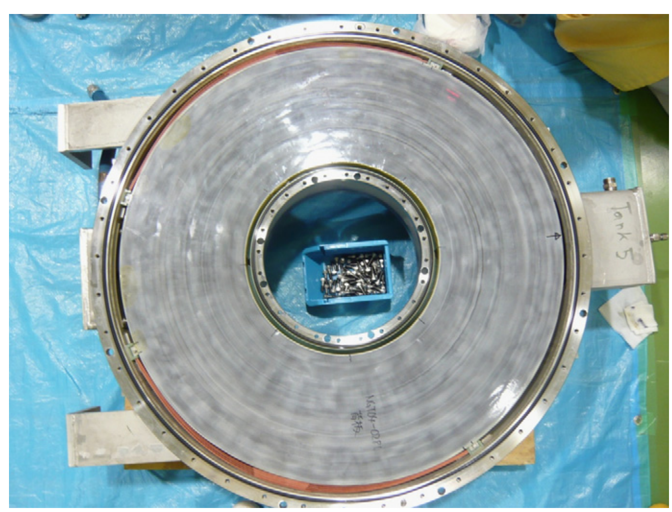

Fig. 3. Photograph of MA cores in a water tank. The lid at the ground side is removed to access the cores. Three MA cores are stacked in the water tank. Those three core positions are called "ground side", "middle position", and "accelerating gap side". The photograph shows the core at the ground side. We put a FRP inner cylinder between the inner of the core and the water tank to improve the electrical isolation because the outside of the inner pipe is on high RF potential. The dark red regions outside of the cores are stacked FRP plates that guide the cooling water flow between the cores, and prevent water-flow bypassing the cores at the outer diameter.