HIGH GRADIENT RF SYSTEM FOR UPGRADE OF J-PARC

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Abstract

Magnetic alloy cavities are successfully used for J-PARC synchrotrons. These cavities generate much higher RF voltage than ordinary ferrite-loaded cavities. The MR (Main Ring) upgrade project aims to deliver the beam power of 750 kW to the neutrino experiment. It includes replacements of all RF cavities for high repetition rate of about 1 Hz. By the replacements, the total acceleration voltage will be doubled, while power supplies and amplifiers remain the same. The key issue is the development of a high gradient RF system using high impedance magnetic alloy, FT3L. A dedicated production system for the Finemet® FT3L cores with 80 cm diameter was assembled in the J-PARC and demonstrated that we can produce material with two times higher μQf product compared to the cores used for present cavities. The first 5-cell FT3L cavity was assembled and the high power test was performed. The cavity was installed in the long shut down from summer to fall. The cavity is used for the beam acceleration with two times high RF voltage.

UPGRADE SCENARIO OF THE J-PARC

The J-PARC aims to deliver 750 kW beam to the neutrino experiment, T2K. To avoid a significant beam loss by the space charge effects and instability, the original plan was modified and a double repetition rate scenario was chosen. The scenario includes about 1 Hz operation of the MR instead of the present 2.48 sec. cycle. It requires replacements of main magnet power supplies, upgrade of injection and extraction systems and increase of the total RF voltage for the acceleration. To store new magnet power supplies, new power supply buildings will be constructed. Because the acceleration time will be 0.5 sec. instead of the present 1.4 sec, required RF voltage is 560 kV which is two times higher than the present 280 kV. To avoid the renewal of RF power supplies which is very expensive, all 9 RF cavities will be replaced by new high gradient ones which can generate two times higher voltage than the present cavities as shown in Figs. 1. The cavity becomes longer than the present one. The spaces where the present 9 cavities are sitting in will be used to install new 7 cavities. An empty drift space between the extraction kickers is used to install two cavities. To fit to these spaces, two cavities with 4 cell structure and seven cavities with 5 cell structure are prepared. In 2015, 4 FT3L cavities will be installed. And, the replacements of all cavities will be finished in 2016. To guarantee the stable operation, we plan to manage the acceleration voltage of 560 kV with 8 RF systems to reserve one system as a spare.

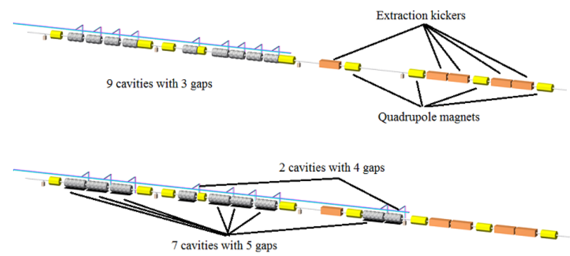

Figure 1: Upgrade scenario of the J-PARC MR cavities. The present cavities (upper) will be replaced by the FT3L cavities (lower) in 2014-2016. The total RF voltage will become more than 630 kV providing enough margin for 1 Hz operation.

DEVELOPMENTS OF FT3L CAVITY

Magnetic alloy, FT3L, has higher shunt impedance than the FT3M, which is used in the J-PARC RCS and MR. However, there did not exist the production system which can anneal them in a magnetic field. To prove the performance of FT3L cores for the accelerator usage, we developed an annealing oven and proof-of-principle tests were carried out [1]. After the success of test production of large size FT3L, a mass production system was constructed and shipped to a company for the production of 280 FT3L cores for the MR upgrade [2].

In 2014, the first FT3L 5-cell cavity was assembled and tested at the RF test bench in summer and fall as shown in Fig. 2 [3]. After the high power test, the cavity was installed as shown in Fig. 3. The cavity was tested with 80 kV RF voltage and is used with 70 kV for beam acceleration (Fig. 4). By the replacement, the beam acceleration can be managed by 7 cavities and 2 present cavities will be used for the second harmonic RF to increase the beam power.

DESIGN OF FT3L CAVITY

Figure 5 shows the characteristics of magnetic materials for the accelerator usage. Ferrites materials show the degradation according to increasing RF magnetic flux in the material. Magnetic alloys, FT3M and FT3L, show stable characteristics in the examined measurement ranges. The FT3L shows two times higher characteristic than the FT3M. Adopting the FT3L material, higher voltage becomes available and the length of cavity cells was reduced.

The present J-PARC MR cavity using the FT3M consists of 3 cavity cells and each cell generate 12.7 kV. To double the RF voltage of the cavity, the gap voltage increases to 15 kV and the number of cells becomes 5 instead of 3.

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Figure 2: The FT3L cavity during high power test. The cavity consists of 5 cells. Each cell connected to two common bus bars driven by a tube amplifier behind the cavity. The total RF voltage of 80 kV was generated during the high power test in the summer and fall. In total, the cavity system was tested for more than 1000 hours.

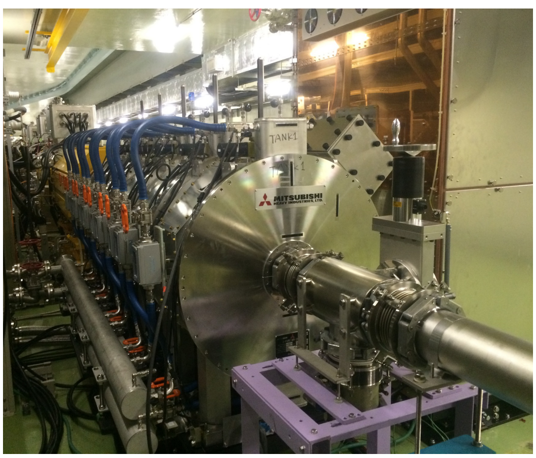

Figure 3: The FT3L cavity installed in the MR tunnel. As the length of the cavity including the beam pipe becomes 2.6 m from 1.87 m, a special instrument was prepared to move the cavity into place. The cavity is installed between two kicker magnets as shown in Fig. 1.

The thickness of the FT3L cores becomes 25 mm instead of 35 mm of the present FT3M cores. The cell length reduces from 592 mm to 502 mm to install 3 FT3L cavities in a long straight section of about 8 m. Although the thickness of the core becomes thinner, the impedance is 1450 Ω and is still higher than the present cavity cell of 1000-1100Ω. Therefore number of cavity cells can be increased from 3 to 5.

As the anode power supply is the most expensive part in the cavity system, we plan to achieve to double the RF voltage without replacements and large modifications. Adopting the FT3L material, the cell impedance was increased by about 40 %. The cavity impedance from the final stage amplifier is 290 Ω and it is as high as the RCS RF cavity.

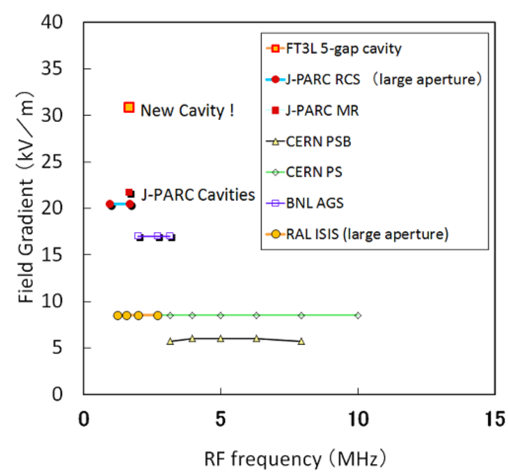

Figure 4: The field gradient of the RF cavities for proton beam acceleration. The field gradients of ferrite cavities (CERN PSB, CERN PS, BNL AGS, RAL ISIS cavities) were limited because of the saturation of the RF magnetic field. The field gradient of the MA cavity was improved by using the FT3L material.

POWER SUPPLIES

The FT3L cavity is used for the 240 kW beam operation and the beam test with 260 kW equivalent. The system is designed to be managed by the present power supplies. Figures 6 show the anode current of the final stage amplifier during the operation with and without the beam. The current limit of the power supply is 110 A. The anode current will be reduced by optimizing the resonant frequency of the cavity to be more inductive. It is expected 2.0×10^{14} protons which corresponds to 750 kW will be handled by the anode power supply.

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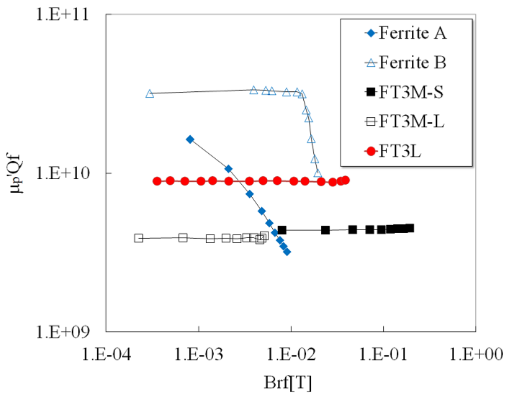

Figure 5: Characteristics of magnetic materials. Horizontal axis is the RF magnetic field in a ring core which is proportional to the RF voltage. Vertical axis is the product of parallel parmeability, Q-value and frequency which is proportional to the shunt impedance. Ferrite A shows typical behavior by the saturation. Ferrite B is high-Q material and shows the "High Loss" effect. A magnetic alloy, FT3L, shows high μQf product and stable characteristics at the high field.

DISCUSSIONS

To improve the field gradient of a loaded RF cavity, the improvements of the cavity shunt impedance is the key issue. Adopting the FT3L material instead of the FT3M, the cavity voltage can be doubled. For the further improvements, we should note that improvements of the materials and developments of thinner amorphous ribbon to reduce the eddy current loss by RF magnetic flux are important issues.

For other applications which need higher field gradient, it should be noted that the materials also fits the usages at higher frequency according to data sheet. Although the RF voltage is low, the material is used to chop the cyclotron beam [4]. And, it should be noted that hybrid cavity of ferrite and magnetic alloy might be a solution for higher frequency [5]. A hybrid cavity system with a magnetic alloy cavity and an external inductor has been adopted for the J-PARC RCS [6] to increase the effective Q-value of the system. The optimum band width of the RCS was obtained by the hybrid cavity system for the beam acceleration and dual harmonic RF. In this ten years, the cut core configuration was established and this cavity can be used for the hybrid systems for the high frequency usages.

CONCLUSION

A 5-cell FT3L cavity has been tested and installed in the J-PARC MR tunnel. It is already used for the beam operation of 240 kW for neutrino experiment. In next summer shut down, 4 more FT3L cavities will be installed. In 2016, all cavities will be replaced with 4-cell and 5-cell FT3L cavities for the high repetition rate operation of the MR. The FT3L cavity will be used for the RCS for the multi-MW operation in future.

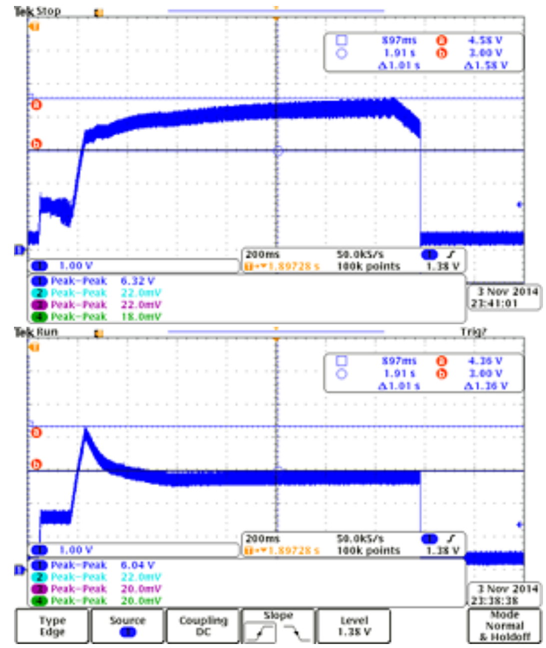

Figure 6: The anode current during operation with the 200 kW beam (top) and without beam (bottom). As the resonant frequency of the cavity does not change during the beam acceleration, the anode current becomes maximum at the beginning of the acceleration when detuning is large. In case of the high power beam acceleration, the maximum anode current is needed at the end of acceleration when the AC component of the beam is high.

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