THE SECOND HARMONIC RF SYSTEM FOR J-PARC MR UPGRADE

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Abstract

Power upgrade scenario of J-PARC Main Ring includes replacement of RF cavities with higher field gradient using magnetic alloy, Finemet ®-FT3L, cores than the present ones. It also needs to install the second harmonic RF cavity in the other section where dedicated water system for RF cavities is not available. Installation scenario of the second harmonic RF will be presented.

INTRODUCTION

The J-PARC MR supplies 390 kW proton beam to the T2K experiment and 45 kW to the J-PARC Hadron Facility. After the upgrade of anode power supplies of the RCS RF systems, the RCS is ready to provide 1 MW beam to the MLF although the beam power is limited by the MLF target. In 2014 and 2015, 5 set of 3-gap cavities were replaced with new FT3L ones [1–3]. One cavity has 4 accelerating gap and the others have 5 gaps although 5-gap cavities were modified as 4-gap one to save the RF power from tube amplifiers. These five FT3L cavities are used for the beam acceleration and two old cavities are still used as the second harmonic ones to handle 2×10^{14} protons. Another old cavity stands by as a back-up cavity. In this summer, the other 4 old cavities will be replace with FT3L cavities. After the replacement, two FT3L cavities will be available as the second harmonic RF and two sets of the cavity will be reserved as back-up ones.

The upgrade project of the MR is under way and three new power supply buildings for main magnets are funded to improve the repetition of acceleration cycle to about 1 Hz. The replacement of whole 9 RF cavities will provide the RF voltage of 500 kV for 1.28 sec repetition to make the same bucket size as present. The RF voltage will be 600 kV for 1.16 sec repetition after the upgrade of anode power supplies. These accelerating cavities are installed in a straight section, INS-C, where the high quality cooling water is available to use the direct water cooling of the FT3L cores.

When the high-repetition operation of the MR will start, the second harmonic RF system should be placed in another place. The 8 m-long straight section is available in the INS-A where injection and collimation instruments are located. Because the section is upstream of the instruments, the radiation level is relatively low. However, the dedicated water supply for the RF cavities is not available [4, 5]. Therefore, we choose a step-by-step scenario for the second harmonic RF when the high-repetition operation starts. Firstly, the old direct-water-cooling cavities will be installed and operated for some years. Because the power consumption in the cores is low, the cut-core gaps which is the weak parts of the cavity can be covered additional water proof materials if necessary, to stand for some years. Secondly, these cavities will be replace by air-cooled cavities which are already reported [6].

THE PRESENT SECOND HARMONIC RF

To accelerate 390 kW beam, two set of the old 3-gap cavity have been modified for the second harmonic RF. The resonant frequencies of the cavities were tuned by adjusting the resonant capacitors. Each cavity generates 35 kV and the total voltage of 70 kV is used to handle 2×10^{14} protons. Figure 1 shows the bunch shapes after injection. The injection bunches have same shape for both cases. After a few synchrotron oscillations, the injected beam bunches fits to the RF bucket and the quadrupole oscillation is damped in case of the dual harmonic capture. However, the quadrupole oscillation continues in case of the single harmonic capture. The beam loss was observed when the bunch length becomes small by the quadrupole oscillation.

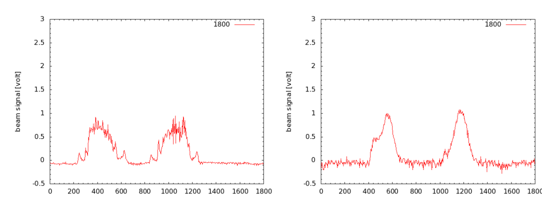

Figure 1: Comparison of bunch shapes 9 ms after injection. Right figure shows bunch shape of 390 kW beam with the second harmonic RF voltage of 70 kV. Left figure shows bunch shape of 330 kW beam without the second harmonic RF.

Figure 2 shows the currents of anode DC power supply in case of 390 kW beam (white) and no beam (yellow). A push-pull tube amplifier is driven by the 1 MW power supply. The RF voltage is applied during the injection and reduces to zero in 20 ms. The peak current of the circulating beam becomes 100-120 A before the extraction and the bunching factor is about 0.05. Because the bunch becomes narrow during the beam acceleration, the second harmonic component of the beam increases and the anode current also becomes large to cancel the beam loading effect on the second harmonic RF. Figure 2 shows 28 A is consumed to compensate the beam loading by 2×10^{14} protons on the three-gap cavity. The feed forward scheme is used for the beam loading compensation [7, 8]. When 3×10^{14} protons are accelerated, the anode current to compensate will be 42 A. Figure 2 also shows the anode current for the fundamental harmonics. During 100 ms before the extraction, the anode current for the fundamental frequency reduces because the synchronous phase

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moves to zero. However, the current for the second harmonic RF stays constant before the extraction because the second harmonic component of the beam does not change. Figure 2 also shows the anode current jumps when the new bunches are injected from the RCS. The anode current reduces quckly because the bunching factor of the injected beam increases in a few synchrotron motions as shown in Fig. 1.

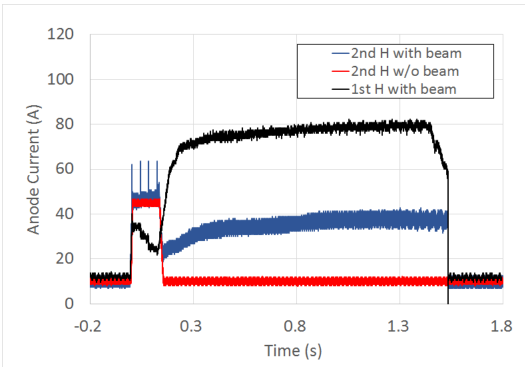

Figure 2: Anode currents of the push-pull tube amplifier for the second harmonic RF with 390 kW beam (blue) and without beam (red), and for fundamental RF with 390 kW beam (black). Idling currents of tube amplifiers are 10 A.

The temperature rise of the cavity cooling water gives a power consumption of 3.3 kW/cell with no beam and 3.9 kW with 390 kW beam, respectively. The temperature difference is much less than 1 °C and the difference might come from the beam-induced noise on the Pt100 sensors. The calculation with the RF voltage and cavity impedance is 2.6 kW/cell and smaller than the water temperature measurement.

THE SECOND HARMONIC RF FOR HIGH REPETITION OPERATION

Short Term Solution

When the high repetition operation starts, the 9 cavities will be used for the acceleration. The old RF cavities taken out will be used for the second harmonic RF to save the budget to make new RF cavity. These cavities will be installed in the injection straight section as shown in Fig. 3. New anode power supplies, driver amplifiers, auxiliary power supplies for tube amplifiers and LLRF for the second harmonic system will be installed in the power supply building near the injection straight section.

Long Term Solution

An air-cooled cavity [6] is considered as a long-term solution for the second harmonic cavity because the cooling water for the cavity is not dedicated system and the power consumption in the cavity is low as described in the previous section. A test cavity has been assembled as shown in Fig. 4 and the power test will start after the summer shutdown. A large air blower is located beside of the cavity. In side of the cavity, 10 FT3L cut cores are installed. As the distance

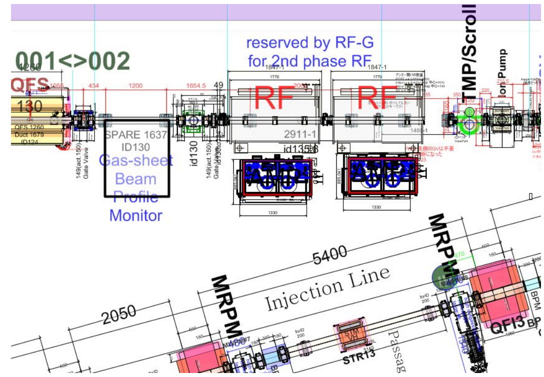

Figure 3: The second harmonic RF will be installed upstream of the injection straight. The upper line is the MR and the lower line is injection one, respectively.

between the core is approximately 5 mm, a special tool was used to install the cores as shown in Fig. 5.

Figure 4: An air-cooled cavity for the second harmonic RF. The air flows from the inside of cores to the outside. The warm air will be cooled by heat exchanger located to the upper and lower of the cavity. The air will circulate between the blower and cavity.

The cavity impedance was measured in assembling process. Figure 6 shows the impedance when 2, 4 and 10 cores are installed. The resonant frequency was adjusted at the second harmonic RF frequency of the J-PARC MR. It shows the cavity impedance is proportional to the number of cores. When ten cores were installed, the impedance is 2.5 times higher than present direct water cooled cavity. When the repetition of the MR becomes two times faster, the power consumption of the new cavity will be 80 % of the present operation. The power loss in a core will be less than the previous estimation [6].

HIGHER FREQUENCY APPLICATIONS

Another advantage of an air-cooled cavity is operation at higher frequency. Because the direct water cooled cavity

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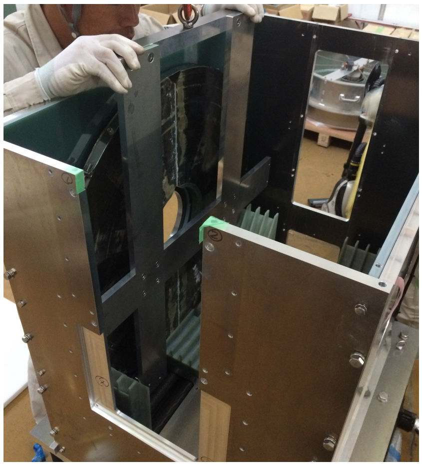

Figure 5: Installation of a FT3L cut core in the cavity shroud. To install the core, a special tool is prepared. Each core is installed in a slot and fixed to keep the distance between the cores.

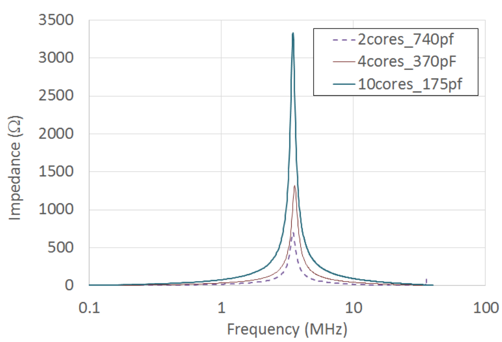

Figure 6: Cavity impedance with 2, 4, and 10 MA cores. The impedance is 2.5 times higher than present second harmonic cavities. The resonant capacitor was chosen to set the resonance around 3.4 MHz.

has larger capacitance by the large dielectric constant of water, the frequency range of a cavity operation is limited. In case of an air-cooled cavity, it has less capacitance effects. Figure 7 shows the cavity impedance of cut core loaded one for different setup.

Wideband Application

Figure 7 suggests the air-cooled cut core cavity can be used for the wideband application beyond 10 MHz. As the material has high impedances at high frequency, the cavity loaded with 4 cut cores has higher than 1.5 kΩ at 17 MHz. The Q-value of the cavity is 3.4.

Narrow Band Application

The air-cooling cavity may be possible to use as a blow-up cavity for a high intensity accelerator to control the longitudinal emittance. In this case, the band width should be optimized to avoid the beam loading effects. The Q-value of the cavity can be controlled by two way. One is the gap height of cut cores [9]. The other is the capacitance as shown

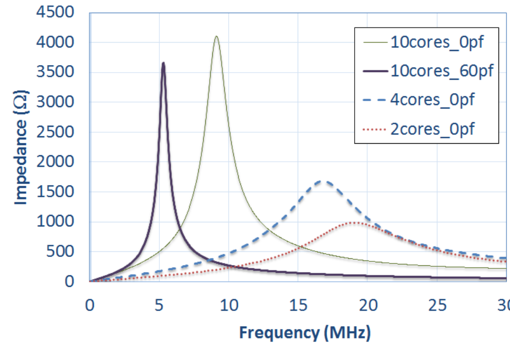

Figure 7: Behavior of the cavity impedance at high frequency. Solid, bold, dashed and dotted lines are the impedance of the cavity loaded with 10 core, with 10 cores and capacitance, with 4 cores and with 2 cores, respectively.

in Fig. 7. Adding more capacitance, the Q-value can increase. The present scenario of the emittance control at the J-PARC MR is based on the fixed frequency [10]. The narrow band cavity may fit the blow-up during the acceleration [11, 12].

CONCLUSION

The replacement work of the J-PARC MR cavities is in progress and whole replacement will finish in this summer. In parallel, the preparation of the second harmonic cavities is also ongoing. As a short term plan, two old direct water cooling cavities will be used. After R&D works, they will be replaced by air-cooled cavities. The cavity test of the air-cooled cavity has started.

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