MA CAVITIES FOR J-PARC WITH CONTROLLED Q-VALUE BY EXTERNAL INDUCTOR

A. Schnase*, K. Hasegawa, M. Nomura, F. Tamura, M. Yamamoto
JAEA/J-PARC-Center, Tokai, 319-1195, Japan
S. Anami, E. Ezura, K. Hara, C. Ohmori, A. Takagi, M. Toda, M. Yoshii
KEK, Tsukuba, 305-0801, Japan

Abstract

The original J-PARC RCS cavity design [1] used cut-cores to control the Q-value. Adjusting the distance between the C-shaped core parts the optimum Q=2 is reached. Because of problems related to the cut-core surfaces, the "hybrid cavity" [2] was introduced, using tanks with uncut cores (Q=0.6) in parallel to tanks with cut cores with a wider gap (Q=4), resulting in total Q=2.

Although this was successfully tested, the manufacturing procedure for cut-cores involves more steps than for uncut cores. To reduce risks for long-term operation, the RCS cavities are loaded with uncut cores for day-1 operation. In the following, we describe how we establish Q=2 with parallel inductors.

INTRODUCTION

RCS is designed to achieve 1-MW beam power by rapid acceleration with 25 Hz. Given the constraints of the available space for the RF-section, this is only accomplishable by using high-field gradient magnetic alloy (MA) cavities. The optimum quality factor of the MA-loaded cavities for J-PARC RCS is approximately Q=2. With uncut cores (Q=0.6) the maximum beam power is limited due to beam loading effects. Therefore we introduce a parallel inductor, placed in the push-pull tube amplifier driving the cavity, to adjust the Q-value to 2. Figure 1 shows on the left a simplified equivalent circuit $R_1C_1L_1$ of the cavity with uncut cores with resonant frequency $f_1 = \frac{1}{2\pi\sqrt{L_1C_1}}$ and $Q_1 = R_1\sqrt{C_1/L_1}$.

The parallel inductor L_2 adjusts Q_3 of the equivalent circuit $R_3L_3C_3$ to a value near 2 according to eq.1, and the inductor C_2 computed by eq.2 sets the desired resonant frequency f_3 to 1.7 MHz. The losses in the inductor L_2 are more than 2 orders of magnitude lower than the losses in the cavity, modeled by R_1. For a typical air-core inductor Q-value of 500, the losses at 1 MHz are equivalent to a parallel resistor R_{L2}=40 kΩ, thus $R_3=R_1||R_{L2} \approx R_1$ within 0.5% and R_{L2} is neglected in figure 1.

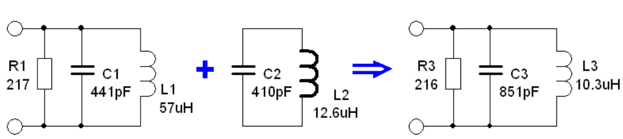

Figure 1: Adjusting the Q-value of J-PARC RCS cavities.

*E-mail: Alexander.Schnase@j-parc.jp

$$L_2 = \frac{R_1}{2\pi(f_3Q_3 - f_1Q_1)} \quad (1)$$

$$C_2 = (Q_3/f_3 - Q_1/f_1)/(2\pi R_1) \quad (2)$$

PROTOTYPES

The idea in figure 1 was verified with a 10-turn prototype inductor installed inside the push-pull tube amplifier, which was connected to an RCS cavity loaded with uncut cores. A parallel vacuum capacitor installed at the central acceleration gap shifts the resonance frequency near to 1.7 MHz. Figure 2 shows the absolute value of the impedance, measured at the central gap before (Q_1=0.6) and after (Q_3=2) modification.

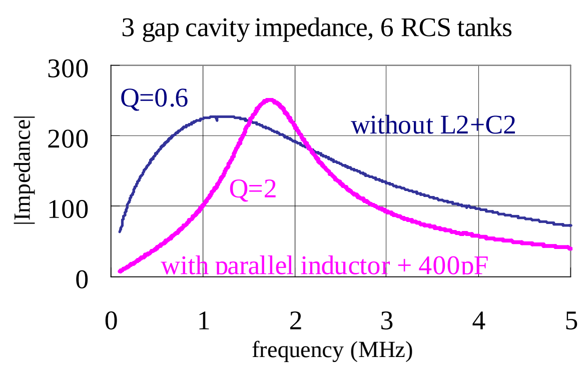

Figure 2: Cavity impedance with and without L_2+C_2.

The setup was successfully tested at the design voltage of 15 kV peak and 1 MHz fixed frequency. The vacuum capacitor C_2 showed no significant temperature rise, therefore we can neglect it for power loss calculation. The Q-value of the 12μH inductor itself is in the order of 500. A parallel 40 kΩ resistor models the loss in the inductor. For 15 kV peak voltage a dissipation in the order of 3 kW peak was expected, and the initial design included water-cooling.

According to eq.2, the necessary inductance depends on the cavity shunt impedance. We prepared several inductors, so that we can match the shunt impedance when we change the MA-cores in the cavity tanks. Direct measurements of the Q-value of an air-core inductor with a network-analyzer gave a factor of 2-4 lower results, when compared to an impedance analyzer. We connected these inductors to a 417 pF vacuum capacitor and confirmed that the Q-value by resonant frequency and bandwidth (table 1) is consistent with impedance analyzer values.

Table 1: Q-value of air-core inductors

# of turns	Pipe dia.	L (μH)	Q	Comment
10	6 mm	13.84	518	Prototype
10	6 mm	14.48	643	
10	8 mm	13.82	549	Power test
9	6 mm	12.57	576	
9	8 mm	12.17	665	

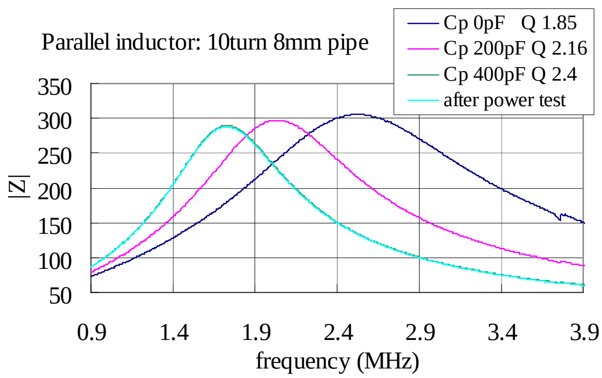

Figure 3: Cavity impedance with 10-turn inductor.

Figure 3 shows that the cavity impedance had increased compared to figure 2, because we were able to use improved [3] MA-cores. Then Q=2.4 was obtained with C_p=400pF. For the high power test with 15kV design voltage we used forced air-cooling, and confirmed that the temperature of the inductor stays below 80°C. With blower off, the temperature increased to 100°C at the first and last turn of the inductor. We confirmed, that the cavity impedance with this inductor and 400pF did not change after the power test. To approach Q=2 with the improved cores, we prepared a 12-turn inductor.

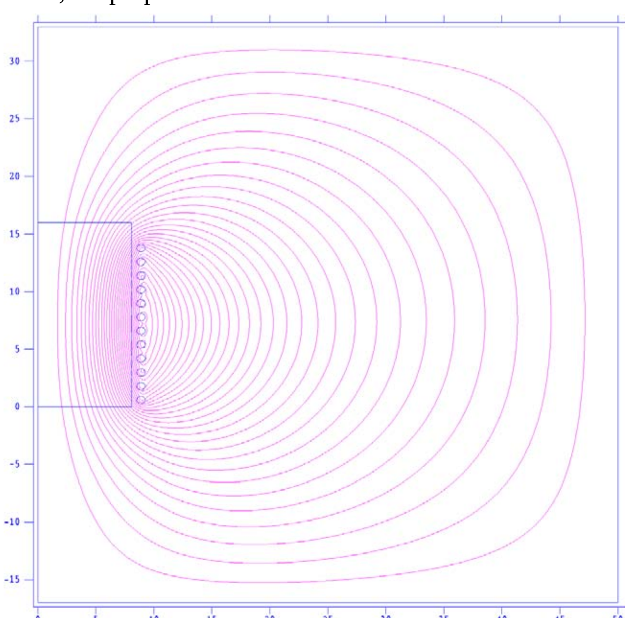

Figure 4: Superfish simulation of the 12-turn inductor.

The inductor was simulated with Superfish to understand the field distribution. We noticed only a small change in Q-value measured at the inductor when put unconnected into the amplifier. This indicates, that the outer field of the inductor does not interact much with the amplifier. Also we confirmed, that the Q-value does not depend on horizontal or vertical mounting position of the inductor. Then we verified the feasibility of convection cooling with a long run test.

LONG RUN TEST

Each of the 10 RCS cavity systems, necessary for day-1 operation, is tested for at least 300 hours to detect initial problems before installation into the RCS tunnel [3]. Figure 5 shows the 12-turn inductor installed into the tube amplifier after a power test. For natural convection cooling, the inductor is in upright position.

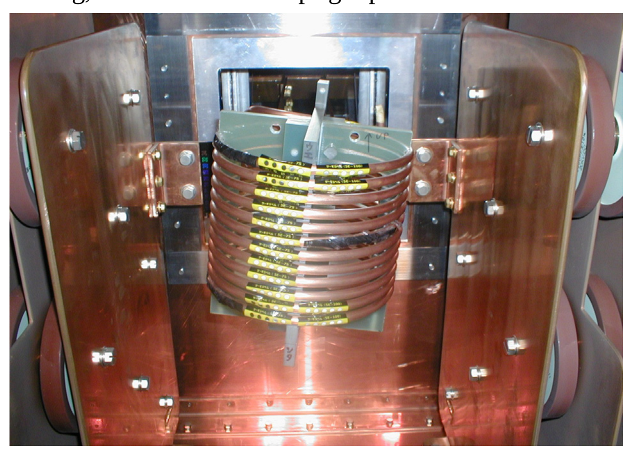

Figure 5: Air-cooled parallel inductor with thermo-labels.

The thermo-labels show that the highest temperature occurred on the first and last turn of the 12-turn inductor. The temperature distribution after an initial 1-hour test along the inductor is compared to the static B-field calculated on the surface of the inductor pipe in figure 6. Assuming that the B-field, which passes through the inductor pipe produces eddy-current loss, we find that a function const*$|B|^2$ + T_0 with T_0=70°C approximates the temperature distribution with an RMS error of 3°C.

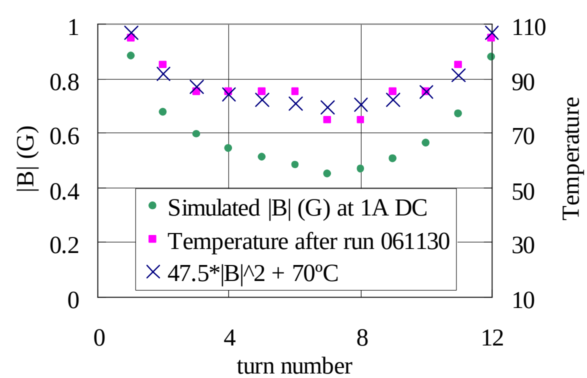

Figure 6: Inductor temperature distribution related to $|B|^2$.

For simulation of 25 Hz RCS operation, a custom DDS provides the low-level RF signal. Frequency and amplitude pattern (Figure 7) for the 40 ms period are defined with 40000 points at 1 MHz sample rate and send from a DSP to the digital synthesizer. The signal generation is comparable to open-loop operation of the RCS LLRF system [4], which is prepared for installation. The amplitude pattern in figure 7 can be used directly when the load impedance is frequency independent. In case of Q=2, the amplitude pattern was iteratively modified in a way, that the amplitude measured at the acceleration gap approached the goal function given in figure 7. This simulates the standard RCS cycle. In simple approximation, the average dissipated power during a standard RCS acceleration cycle is 30% of the peak value.

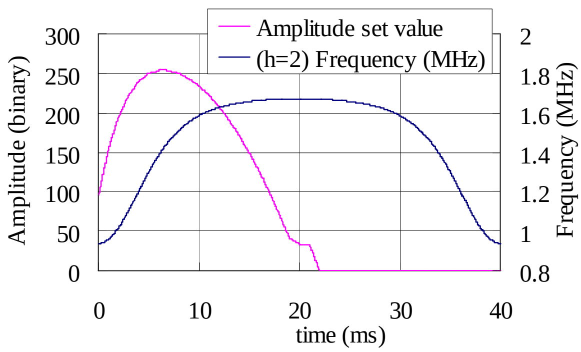

Figure 7: Amplitude and frequency for 25Hz operation

With the experience from the 12-turn inductor, we relaxed the Q=2 requirement and designed an inductor with 14-turns shown in figure 8. This inductor has an inductance of 21.7 µH and a Q-value higher than 600. The design of the support structure was modified to allow better convection cooling without the need for a blower. The dissipated losses in the 14-turn inductor are half compared to the prototype used in figure 2. This inductor became the production version. Power tests confirmed, the temperature with natural convection and either fixed frequency at 30% duty or simulated RCS cycle stays well below 100°C, which gives enough margin.

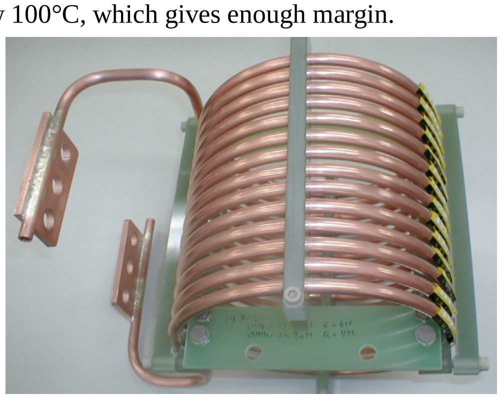

Figure 8: 14-turn inductor production version

The cavity impedance with this 14-turn inductor and several choices of the parallel vacuum capacitor is shown in figure 9. The reduced parallel capacitance of 200 pF is an advantage, and the measured Q=1.76 in combination with the cavity is near enough to the original goal Q=2. In all 10 J-PARC RCS cavity systems [5] these inductors are installed.

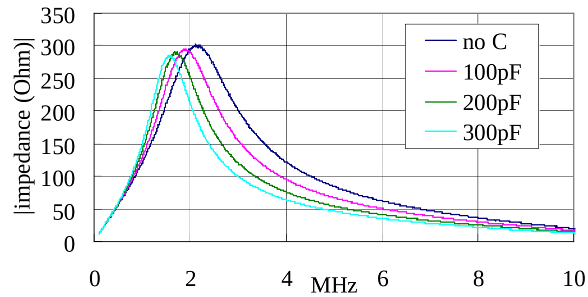

Figure 9: Cavity impedance with 14-turn inductor as function of parallel vacuum capacitor.

The RCS operating range from 0.938 MHz (h=2 at 181 MeV injection) to 5.1 MHz (h=6 at 3 GeV) is free from unwanted resonances – independent of with or without parallel inductor. Also the parallel inductor does not introduce additional parasitic resonances.

SUMMARY

With a parallel high quality air-core inductor and vacuum capacitor the Q-value and resonance of the RCS cavities are adjusted, enabling full beam power RCS operation with uncut cores. This was successfully tested under realistic 25Hz operation conditions. We confirmed that this setup does not introduce additional resonances in the RCS (h=2…6) frequency range, which is important to avoid instabilities at high beam intensities. Compared to cut cores, the possibility to use uncut cores reduced the number of process steps (no molding, cutting or polishing) for core production. This helped to save cost and to keep the schedule.

OUTLOOK

All 10 RCS cavities necessary for day-1 have been installed in the RCS tunnel and are equipped with the production version of the inductor. Before beam operation, we will test how the cavities are working together.

REFERENCES

[1] C. Ohmori et. al, “High Field-Gradient Cavity for J-PARC 3 GeV RCS”, EPAC ‘04, Lucerne, July 2004.

[2] A. Schnase et. al, “Hybrid cavity for J-PARC Rapid Cycling Synchrotron”, Proc. 2nd annual meeting of particle accelerator society of Japan, 2005, Tosu.

[3] M. Yamamoto et. al, “High Power Test of MA Cavity for J-PARC RCS”, this conference TUPAN063.

[4] F. Tamura et. al, “Low Level RF Control System of J-PARC Synchrotrons”, PAC 2005, p3624, Knoxville

[5] M. Yoshii et. al, “J-PARC Ring RF Accelerating Systems”, this conference TUPAN055.