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Uncut core loaded cavity with parallel inductor to reach Q=2 for J-PARC RCS

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Abstract

The optimum quality factor of the acceleration cavities for the J-PARC Rapid Cycling Synchrotron is Q=2. The first approach [1] used cut-cores, where the distance between the core halves in the cavity tank defines the quality factor while keeping the shunt impedance. Problems in core manufacturing made it unlikely that the RCS cavity tanks can be filled completely with cut-cores before first day operation.

The next step [2] was the so-called hybrid structure. 4 of the 6 cavity tanks are filled with uncut cores at Q=0.6 and only 2 tanks are loaded with cut cores at wider distance (Q=4), which is easier to manage. In total this achieves Q=2. Issues with the cut-core manufacturing remained, so RCS day-1 operation will start with uncut core cavities. However, Q=0.6 limits the maximum beam power. We present an idea, based on the hybrid cavity to add a parallel high quality circuit of inductor and capacitor to change the resonant frequency from 1 to 1.7 MHz and the total Q-value from 0.6 to 2, thus enabling almost full beam power operation of RCS with uncut cores loaded cavities.

アンカットコアと並列インダクタを用いたJ-PARC RCSのためのQ=2空胴

1. Introduction of Hybrid cavity

The idea of the hybrid cavity is to connect resonators with different Q-value and resonant frequency in parallel to achieve the desired total Q and resonant frequency. This requires a tight coupling between the resonators. The original setup of the J-PARC RCS cavity consisted of 3 gaps in parallel, with 2 tanks at each gap, and each gap filled with 3 cut-cores. For a Q-value of 2, according to fig. 1, the distance between the parts each core is cut into has to be less than 1mm.

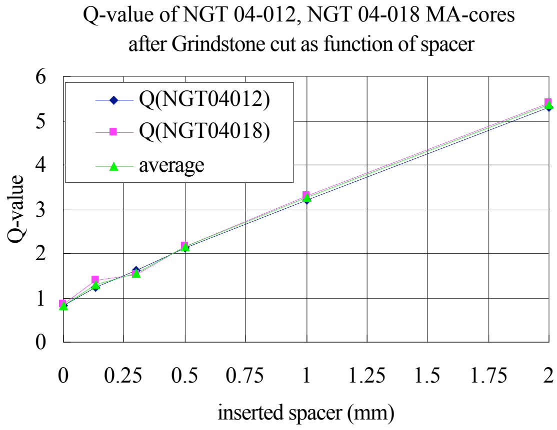

Fig. 1: Q-value as function of inserted spacer

The arrangement of the 3 cut-cores in a tank is shown in fig. 2. Only the upper core located near the groundside is visible. A thin spacer separates the cores after cutting and coating, and a stainless-steel band around fixes the shape.

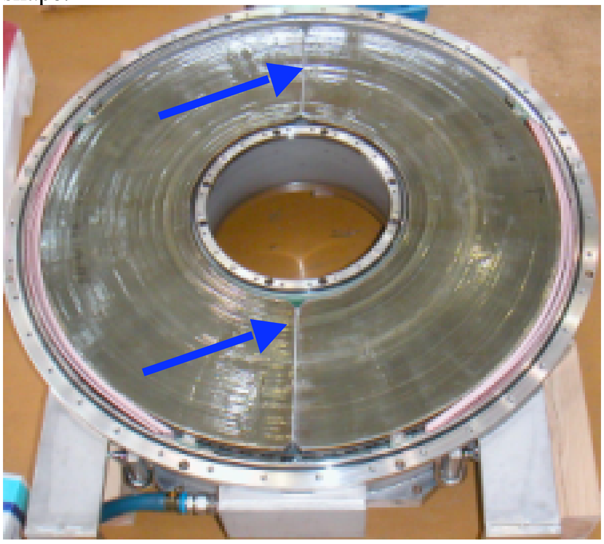

Fig. 2: RCS cut-cores in a cavity tank. Arrows indicate the spacers defining the Q-value.

Because of tolerances in the order of 0.5mm, a setup where all 6 tanks contain cut-cores with Q~2 is difficult. The idea of the hybrid cavity was to combine tanks with uncut-cores (Q~0.6) in parallel to tanks with cut-cores set at Q~4. Then the number of cut-cores is smaller, which reduces production complexity and costs. In case of 4 outer tanks with Q~0.6 and 2 inner tanks with Q~4 only 1/3 of cores needs cutting and the set-up with higher Q is

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more practical, because then the spacer thickness is more than 1mm, which is bigger than the tolerances.

Assuming a parallel equivalent circuit with $R_{p1} = R_{p2} = R_{p3}$, single gap resonant frequencies $f_1=f_3$, and quality factors $Q_1=Q_3$, the resulting resonant frequency f_{hy} and Q-value Q_{hy} are:

$$f_{hy} = \sqrt{\frac{2f_1Q_1 + f_2Q_2}{2Q_1/f_1 + Q_2/f_2}} \quad (1)$$

$$Q_{hy} = \frac{1}{3}\sqrt{(2f_1Q_1 + f_2Q_2)(2Q_1/f_1 + Q_2/f_2)} \quad (2)$$

With actual values: $Q_1=0.6$, $f_1=1$ MHz (uncut cores at gap 1 and 3), $Q_2=4.5$, $f_2=2$ MHz (cut cores at gap 2), the resonant frequency is $f_{hy}=1.72$ MHz at $Q_{hy}=1.98$. This set-up was tested at high power and operated as expected. Unfortunately, still problems related to the cut-core manufacturing were reported, therefore it was decided to prepare for RCS day-1 operation with uncut cores, which should be more reliable, because there is a smaller number of process steps. The schedule for RCS [3] is too tough for further testing of the hybrid cavity idea: each of the 10 cavities is scheduled to be tested for at least 300 hours to ensure the cores can stand long term operation. Therefore the cut-core [4] process study is continued for the Main-Ring (MR), because MR installation will be later than RCS installation. The Q-value of the MR-cavities will be 10~20, which relates to distance between core parts on the order of 10mm which does not give any tolerance problems at all. Using uncut-cores for MR is not preferred, because the larger ratio of outer to inner diameter of the cores will lead to overheating at the inner radius as is shown in [5], when the design voltage is applied. However for relaxed acceleration voltage specifications, and limited beam power, uncut cores might be used for MR, too.

2．Extension of Hybrid cavity

For RCS day-1 operation, uncut cores in the RCS cavities result in approximately $Q_p=0.6$ with a resonance near $f_p=1$MHz. For a beam power higher than in the order 100kW, it is desirable to operate with a resonance near $f_x=1.7$ MHz and $Q_x=2$ [6]. The idea of the hybrid cavity was to combine resonators with different Q and resonant frequency. However, the variation was less than one order of magnitude.

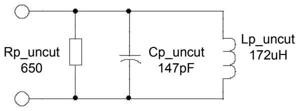

Fig. 3: simplified equivalent circuit of 1 RCS gap with uncut cores: $Q_p=0.6$, $f_p=1$MHz

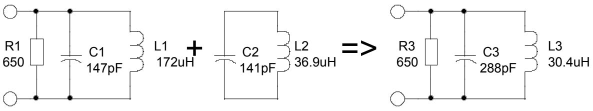

Fig. 4: Adding a parallel resonator (C2, L2) changes resonant frequency and Q-value

Here we extend this idea to combining tanks filled with low Q uncut cores (fig. 3) with a high Q (>100) parallel circuit (fig. 4). The values for a comparably high Q resonant circuit with air core inductor L_x and vacuum capacitor C_x are obtained by eqn. (3) and (4). Fig. 5 compares the impedance of a cavity with 6 uncut core tanks for the 2 cases with/without an inductor $L_x=12\mu$H and a capacitor $C_x=400$pF in parallel.

$$L_x = \frac{R_p}{2\pi(f_xQ_x - f_pQ_p)} \quad (3)$$

$$C_x = (Q_x/f_x - Q_p/f_p)/(2\pi R_p) \quad (4)$$

The water-cooled inductor L_x connected inside the tube amplifier to the cavity bus bars is shown in fig. 6. The high Q vacuum capacitor C_x is located at the center cavity gap.

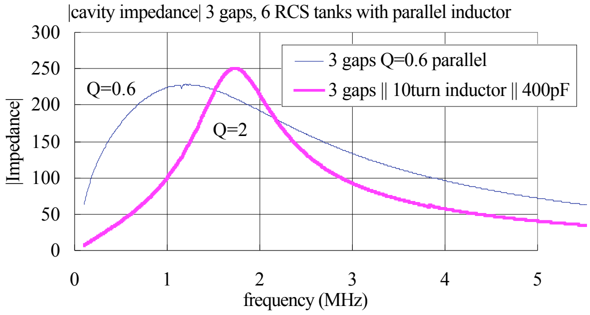

Fig. 5: $Q_x=2$ at 1.7MHz with parallel inductor

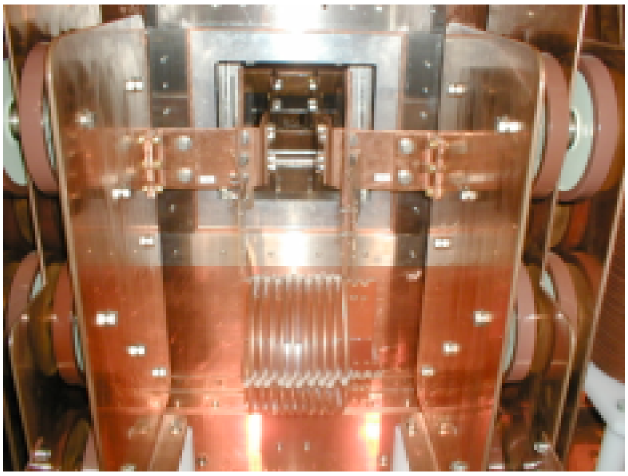

Fig. 6: 10 turn inductor installed for testing inside the push-pull RCS tube amplifier

For estimation of the dissipated power in the inductor and the environment we tried to measure the Q-value with a network-analyzer for both cases, inside and outside the amplifier. However the values (Q~100) were lower than expected, therefore we concluded, that our network analyzer cannot directly measure the Q-value of our inductor. We added the 400 pF vacuum capacitor to the inductor and computed the Q-value from bandwidth and resonant frequency in table 1 for both cases, outside the amplifier (fig. 7) and inside the amplifier (fig. 8), but not connected to the amplifier.

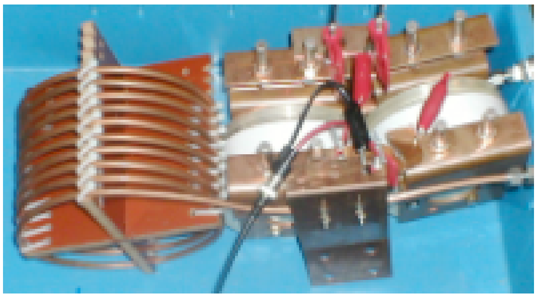

Fig. 7: inductor and 400 pF parallel outside the amplifier

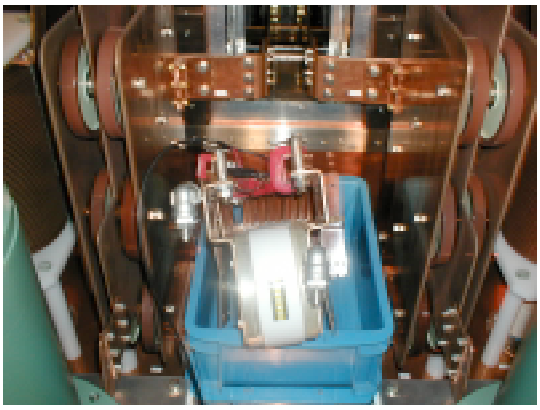

Fig. 8: inductor and 400 pF parallel inside the amplifier

Table 1: component values from data in fig. 9

	Inductor outside	Inductor inside
C_{par}	400 pF	400 pF
L_{par}	14.3 µH	14.0 µH
R_{par}	95000 Ohm	35000 Ohm
f_{center}	2106.58 kHz	2127.56 kHz
Q	500	187
Power: 15kV peak at 30% duty	355 W	964 W

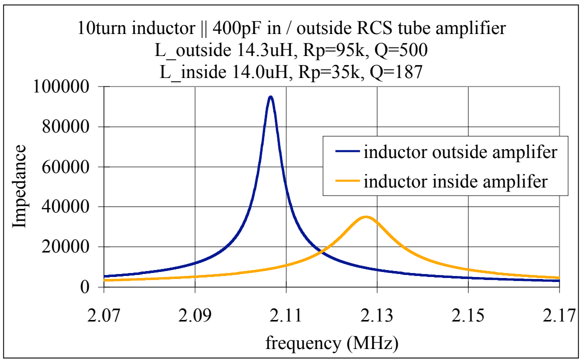

Fig. 9: The impedance of the circuits in fig. 7 and 8

Approximately 350W will be dissipated in the inductor and 610W in the environment near the inductor for 30% duty RCS operation. Water-cooling for the inductor will not help for cooling of the environment, therefore air-cooling is preferable.

3. Conclusion

We demonstrate Q=2 at 1.7MHz for RCS high beam power operation with comparably small changes to the final stage tube amplifiers. This way, almost full beam power operation of RCS with uncut core loaded cavities becomes possible. This restriction is not given by the idea of the extended hybrid cavity, but is related to the achievable tank impedance and the number of cavities, which are installed in RCS. The prototype version allowed first high power test. Long run high power tests with the production version will confirm the feasibility to apply this modification to all RCS setups with uncut cores.

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