Cavity voltage calibration for J-PARC Ring RF

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Abstract

The J-PARC RCS (Rapid Cycling Synchrotron) is in the commissioning phase and has reached the milestones of acceleration to 3 GeV and extracting the beam to MLF and MR (Main-Ring). In RCS operation we noticed a discrepancy between expected synchrotron frequency as function of acceleration voltage seen by the beam and the measured value at injection energy. Also we found a difference between expected and measured synchronous phase during acceleration. This indicated that the voltage seen by the beam seems to be lower than the voltage supplied by the acceleration cavities. In the following it is shown that this difference can be explained by an unwanted capacitive coupling to the inside of the probes, which were used at time of cavity calibration. This knowledge is applied to the calibration of the MR cavities.

J-PARC Ring RFの空胴の電圧較正

1. Introduction

J-PARC RCS [1] is in the commissioning phase and routinely accelerates the proton beam to 3 GeV, which is then extracted either to the MLF neutron target or to the MR (Main-Ring). An important part of commissioning is to characterize the performance of accelerator components. The task of the RCS RF system [2, 3] is to provide the acceleration voltage to the beam. We have to make sure that frequency, amplitude and phase are within specifications. Here we focus on the amplitude.

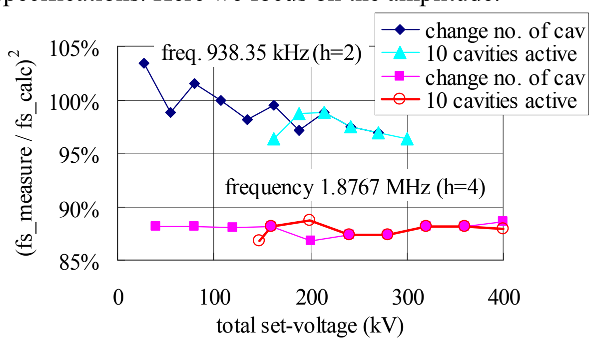

Figure 1: Relation of measured and calculated f_s.

As consistency check for the relation between RF voltages supplied by the cavities and voltage seen by the beam we measured the synchrotron frequency. Data from February 2008 at RCS injection are shown in Figure 1. On the x-axis is the total set-voltage. For a pure sine wave the relation between voltage V_{acc} seen by the beam, and synchronous frequency f_s is given by

$$f_s \propto \sqrt{V_{acc}} \ . \qquad (1)$$

The graph shows the square of the ratio of measured and calculated synchrotron frequency. In case of operation at fundamental *(h=2)* the ratio of f_s^2 is not so far from 100%. Formally, using eq. 1 it looks like the ratio of acceleration voltage seen by the beam and expected voltage is near 100%. However, at twice the frequency, called *(h=4)*, the ratio of f_s^2 is in the order of 88%. By looking at monitor signals, we confirmed that the AVC loop of each cavity (AVC details in [4]) was working properly, so this could not explain the difference. Also we compared the case of all 10 cavities working at same variable voltage level to the case of fixed voltage level and number of active cavities varied. This confirmed that the 10 cavities operate quite similar.

Figure 1 is explained by higher harmonics coming from distortions due to non-linear characteristics of tube amplifiers. At *(h=4)* the operation frequency 1.8767 MHz is near to the RCS cavity resonance, so that the cavity acts like a filter. Then the higher harmonic content and the variation of f_s^2 as function of amplitude are small. In contrast at the fundamental *(h=2)* at 938.35 kHz, the harmonic content is higher, because the harmonics are nearer to the cavity resonance. So the relative f_s^2 in case of *(h=2)* shows the influence of higher harmonics.

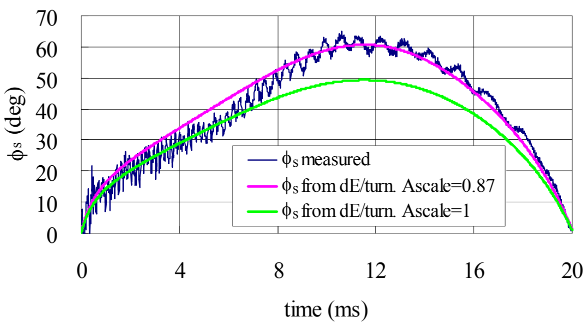

Figure 2: Measured and calculated ϕ_s.

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In J-PARC RCS, voltage and phase are precisely defined by patterns stored to the LLRF system memory. From frequency pattern one can calculate momentum and required energy change *dE* per turn. The expected synchronous phase ϕ_s is computed from amplitude pattern. Figure 2 compares the measured difference of beam-phase and phase of cavity vector-sum at *(h=2)* to the expected ϕ_s. The green curve assumes a correct cavity calibration *(Ascale=1)*. Then the maximum Max(ϕ_s) is approximately 50º. However, the measured Max(ϕ_s)=63º is nearer to the pink curve, which assumes that the voltage seen by the beam is 87% of the voltage in the pattern. The calculation does not include effects of higher harmonics. Still, at Max(ϕ_s) the RF frequency (approx. 1.62 MHz) is near to the cavity resonance, so that the effect of higher harmonics on Max(ϕ_s) can be regarded as small. So, we searched a 10% order effect to explain why the voltage seen by the beam was smaller than expected from cavity calibration with High-voltage (HV) probes.

2. Checking HV probes in MR test cavity

Calculations with Superfish for a single gap of the RCS cavity geometry (figure 3) confirmed that the transit-time effect is less than 1% and can be neglected. Also the induced voltage by the H-field in the cavity to the probes was found to be negligible. Note: the H-field distribution in the cores might not be correct for Finemet.

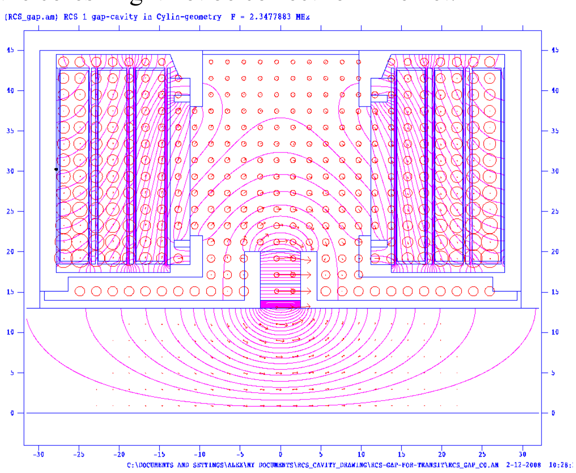

Figure 3: RCS cavity calculation (cylinder coordinates).

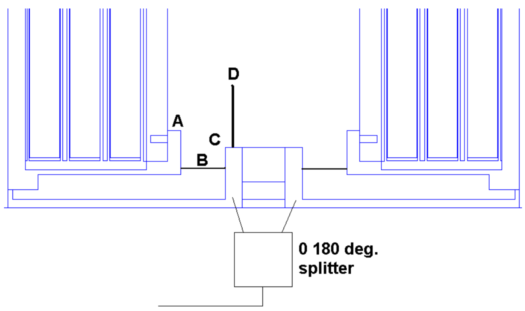

Figure 4: Measurement points in MR cavity setup.

The 10 RCS cavities are installed in the RCS tunnel, which is a radiation-controlled area. To minimize exposure the next tests were performed at an MR cavity in the Hendel test bench. According to figure 4, the points A-D were defined, which are same potential, because they are on connected metal surfaces. The cavity gap was driven in push-pull by a splitter with the RF signal from a signal generator. When measuring the voltage at the points A-D with a small (1:10) probe, there was almost no variation – as expected. But with an (1:1000) HV-probe, the voltage at each point was different as shown in figure 5. Figure 6 shows the HV-probe location at position B. There the ratio of HV-probe to (1:10) probe is 125%. We found the source of the cavity calibration issue.

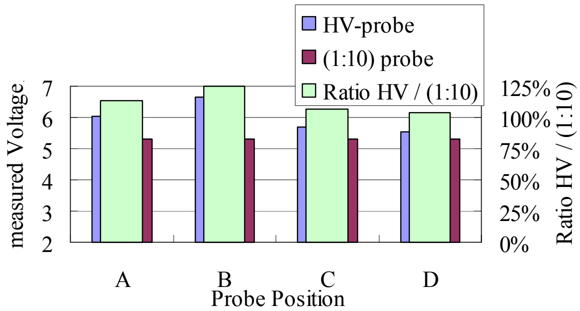

Figure 5: Comparison of HV-probe with (1:10) probe.

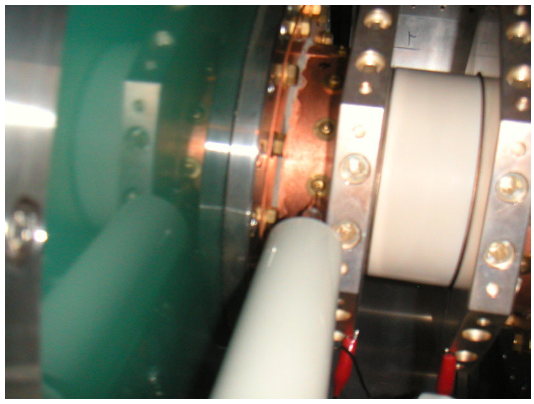

Figure 6: Location of the HV-probe in position B.

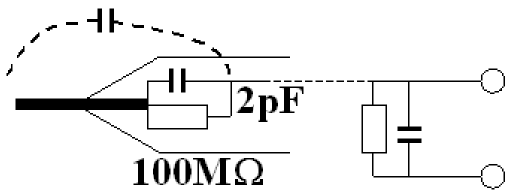

Figure 7: Equivalent circuit of inside of HV-probe.

Figure 7 indicates that the inside of an HV-probe near the tip can be modelled as a 2 pF capacitor in parallel to a 100 MΩ resistor. In case of RF signals, a parasitic coupling of 0.2 pF (dashed line in figure 7) is enough to explain a 10% higher than expected voltage reading.

3. Measuring with HV-probes in RCS cavity

From figs. 5-7 and further tests we knew that increasing the distance from gap to the sensitive area inside the probe could reduce the unwanted capacitive coupling.

With a set of 25mm probe extensions we measured the HV-probe signal as function of total extension length in an RCS cavity. Figure 8 shows a case of using 4 extension pieces to obtain 100mm extension.

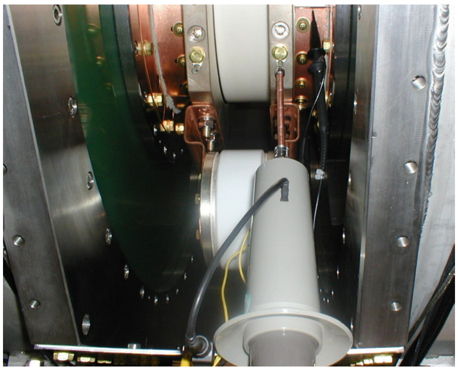

Figure 8: HV-probe with 100mm extension (RCS cavity)

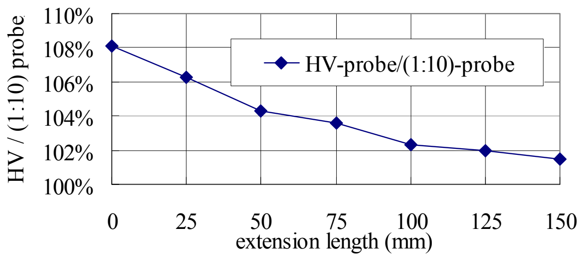

Figure 9: Ratio HV-probe to (1:10) probe vs. extension

Figure 9 shows the expected behaviour that the voltage seen by HV-probe is reduced with longer extension. The shielded cable of the small probe on ground potential can decrease the capacitive coupling of high potential points to the HV-probe if it is too near to the sensitive area of the HV-probe. So the cable position was adjusted. Consequently the metallic support of the HV-probes has an effect when near to the sensitive area. Therefore we made a PTFE-support, shown below the HV-probes in Fig. 11.

With a set-up of figure 10 we compared the 11 available HV-probes and selected a matched pair. We verified that the effect of extensions to an HV-probe outside a cavity is small compared to the position near a cavity gap.

Figure 10: HV probe extension outside cavity

4. Recalibration

After the effects became clear, we re-calibrated the 10 RCS cavities. We reduced the capacitive coupling by putting a 50mm extension to the probe tips and measured at the 200pF gap capacitors under defined placement conditions (figure 11) with a pair of matched probes.

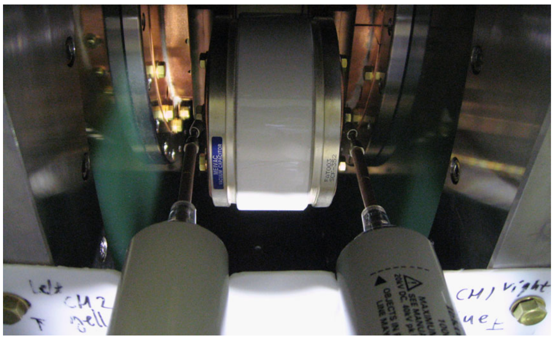

Figure 11: HV-probes with 50mm extension (RCS cavity)

The voltages seen at re-calibration were in the range of 84%-90% of the values at calibration before – in average 87%. In RCS beam study we verified that the new calibration is correct. The 87% scaling factor was confirmed by ϕ_s measurements (like in fig. 2) described in detail in [5, 6]. Calculations including the effects of harmonics show that the beam sees the expected voltage within an uncertainty in the order of 2%.

5. Applying to MR calibration

For MR, this knowledge was used in the calibration procedure. We found a voltage reading reduction in the order of 5% by probe tip extension. Recently in June we confirmed that expected and measured synchrotron frequency at MR injection match well, so that expected voltage and voltage seen by the beam are within +/-2%.

6. Summary and Outlook

The effect of unwanted capacitive coupling to the inside of HV-probes was found. After calibration with probe tip extension, beam tests at both RCS and Main ring confirm that expected and voltage seen by the beam match within approximately 2%. Including higher harmonics in the calculation of expected synchrotron frequency and location of ϕ_s with respect to the phase of the fundamental RF can help to further explain details of the beam study results.

References

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