

FIRST BEAM EXPERIMENTS AT ISIS WITH A LOW OUTPUT-IMPEDANCE SECOND HARMONIC CAVITY

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Abstract

First beam test with the low output-impedance second harmonic cavity (LOI), was performed in April, 2011 using the ISIS synchrotron at 2.1×10^{13} protons per pulse, which corresponds to the circulating beam current of 2.3~5.2A. The LOI was proven to be stable under such a high intensity beam. The output impedance of LOI was derived from the beam induced voltage across the cavity gap, resulting in 35ohm at 3.4MHz, which agrees well with the measurement by the network analyzer. Issues on the present LOI system and a plan for further beam experiments are also described.

INTRODUCTION

In order to alleviate the space charge related issues in the high intensity proton synchrotron, collaboration on the LOI started in 1996 with KEK in Japan, ISIS at RAL in the U.K. and ANL in the U.S.A [1].

The LOI comprises high power amplifiers and a ferrite-loaded cavity. The 240kW triode valve (e2V BW1643J2) and 250kW tetrode valve (BURLE 4648) are used as the final and driver amplifiers, respectively. Wideband low output-impedance characteristic is realized by a proper choice of parameters in the grid-to-ground impedance (Z_{gg}) and the plate-to-grid feedback impedance (Z_{pg}) of the final amplifier [2]:

$$Z_{out} \cong \frac{r_p}{1 + \mu\beta}$$

Here, Z_{out} is the output impedance, r_p the plate resistance, μ = amplification factor and β = voltage feedback ratio = $(Z_{gg}/\omega C_{gk})/(Z_{pg} + (Z_{gg}/\omega C_{gk}))$, where C_{gk} is the grid cathode capacitance. A few tens of ohms can be realized by this method over the frequency range of interest. The LOI is then free from beam loading, and the precise control of the cavity phase becomes possible in order to flatten the beam longitudinally.

BEAM INDUCED VOLTAGE

Beam induced voltage was measured at the cavity gap in Fig. 1. The RF was on for all the fundamental RF system (1RF) and the second harmonic RF system 8 (2RF8), and no RF for the other 2RF systems. The dc bias current was set for LOI and 2RF5 cavities to resonate at 3.4MHz at 2.16msec after field minimum. The 2RF4 cavity is kept in an “off-tune” mode, where the cavity resonant frequency is set by the bias current to locate

between the fundamental and the second harmonic frequencies.

The induced voltage shows a sharp peak for 2RF5 cavity where the drive amplifier is switched off. Such resonance does not appear for other systems. The voltages at 2.16msec are 6.24kV, 156V and 600V for 2RF5, LOI and 2RF4, respectively.

The beam bunch shape was also measured at 2.1ms (Fig. 2), which is given by the sum signal of the beam position monitor electrode. The bunch shape can be expanded as

$$BS(t) = a + \sum_{k=1}^n c_k \sin(2\pi k f_0 t + \theta_k), \quad (1)$$

where f_0 is the fundamental frequency, 1.6854MHz, n = 15, and c_k and θ_k the parameters to be fitted. The fitted curve is also shown with a red-line in Fig. 2.

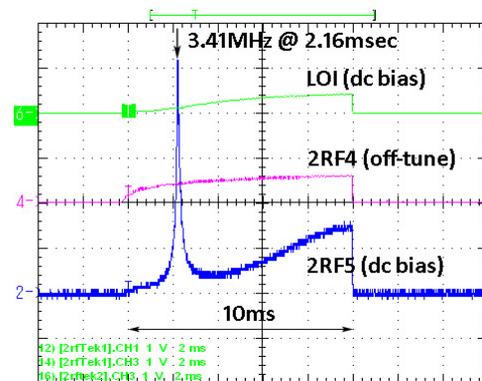


Figure 1: Beam induced voltage at the cavity gap. Acceleration period is 10ms.

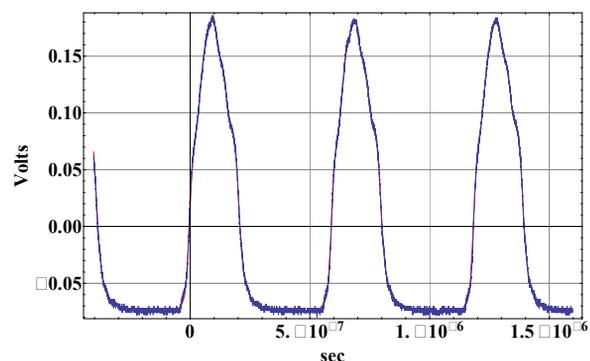


Figure 2: Beam bunch shape at 2.1ms (blue). Red line is a fitted curve by eq. (1).

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OUTPUT IMPEDANCE

The 2RF cavity consists of two half-cavities coupled with a bias winding (Fig. 3). The beam induced voltage at resonance is then given by,

$$V_b = 2I_b \times (R//R//Z_{out}),$$

where I_b is the beam current passing through each half-cavity gap, R the shunt impedance of half-cavity. For the 2RF5 cavity, $Z_{out} \gg R$. The induced voltage is then approximated by,

$$V_b \cong 2I_b \times R / 2 \quad \text{for 2RF5.} \quad (2)$$

For the LOI, Z_{out} is much lower than R . Then,

$$V_b \cong 2I_b \times Z_{out} \quad \text{for LOI.} \quad (3)$$

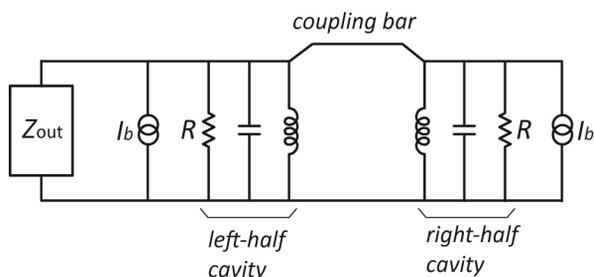


Figure 3: Equivalent circuit of beam-cavity interaction for two-gap system.

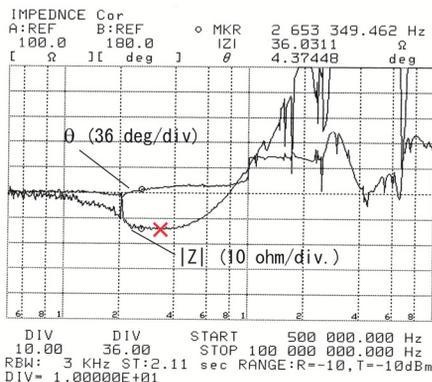


Figure 4: Comparison of LOI output impedance. Impedance curve ($|Z|$) is obtained by the measurement with a network analyzer, where red-cross (35.0Ω) at 3.4MHz is in this experiment.

Using the 2RF current component ($k = 2$) in eq. (1) with eq. (3), the LOI output impedance is derived to be

$$Z_{out} = 35\Omega \quad \text{for LOI.}$$

In Fig. 4, this value is compared with the measurement by the network analyzer. Good agreement is obtained. Similarly, the cavity shunt impedance is obtained with eq. (2) as

$$R/2 = 1.37\text{k}\Omega \quad \text{for 2RF5.}$$

Impedance reduction by using the LOI is 1/40.

OPERATION IN A BIAS SWEPT MODE

Beam acceleration was tested with the LOI and 2RF8 (fig. 5). The 2RF8 cavity is driven by a BURLE 4648 tetrode without a beam feedforward loop, and each cavity gap is shunted by a liquid resistor at $4.8\text{k}\Omega$. Other two 2RF systems were kept in an off-tune mode. The beam intensity was 2.1×10^{13} protons per pulse, which corresponds to the circulating beam current of $2.3\text{--}5.2\text{A}$. The LOI was stable under such a high intensity beam.

The grid and cavity gap voltages were used for phase detection (PD) to tune the cavity. However, as seen in the figure, the PD signal is noisy and the LOI gap voltage should have been reduced significantly in the middle through the end of the cycle. This is due to large waveform distortion of the grid voltage, although the cavity gap voltage showed a smooth sine waveform. Such distortion made it difficult to tune the cavity for higher gap voltage.

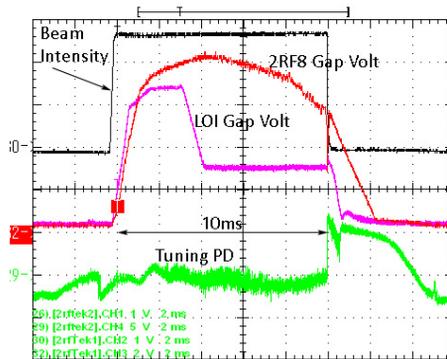


Figure 5: First acceleration test at 2.1×10^{13} protons per pulse. Peak voltages are 4kV for LOI and 10kV for 2RF8. Tuning phase detection (PD) is in $50^\circ/\text{div}$.

Waveform Distortions

Figure 6(a) shows the grid voltage waveform at 4.7MHz of the 2RF frequency. Waveform distortion is quite serious that the zero-cross point, which is essential in the phase detection, cannot be detected correctly due to a large content of the sub-harmonic component. The 2RF harmonic is created by the frequency doubler from the 1RF master oscillator output. Separate measurement shows 2.2% of 1RF component is included in the doubler output, which will be fed into the driver amplifier. Although the content is small, very large distortion in the grid voltage waveform is produced due to the Miller effect upon grid-plate capacitance of the final triode.

The cavity is tuned at resonance for the 2RF frequency, where the voltage gain of the final triode is high. The grid-plate capacitance is then increased by the same amount of gain (Miller effect), and is added across grid and ground. This effect considerably lowers the input impedance, Z_{in} , seen looking into the grid. It is small, on the contrary, to the 1RF and higher frequency components because the cavity is off-resonant and the gain is lower for these frequencies. Then, the input impedance remains

much higher than that for the 2RF frequency. The circuit simulation code, TopSpice [3], was used to calculate the input impedance. The result is shown in Fig. 7, where Z_{in} is $312\ \Omega$, $11.7\ \Omega$ and $40.6\ \Omega$ for 1RF, 2RF and 4RF components, respectively [4]. Since the output impedance of the driver amplifier is very large ($>5\text{k}\Omega$), it acts as a constant current source, of which output is proportional to the input voltage. Consequently, each harmonic component in the input is amplified by their corresponding input impedance, resulting in a significant

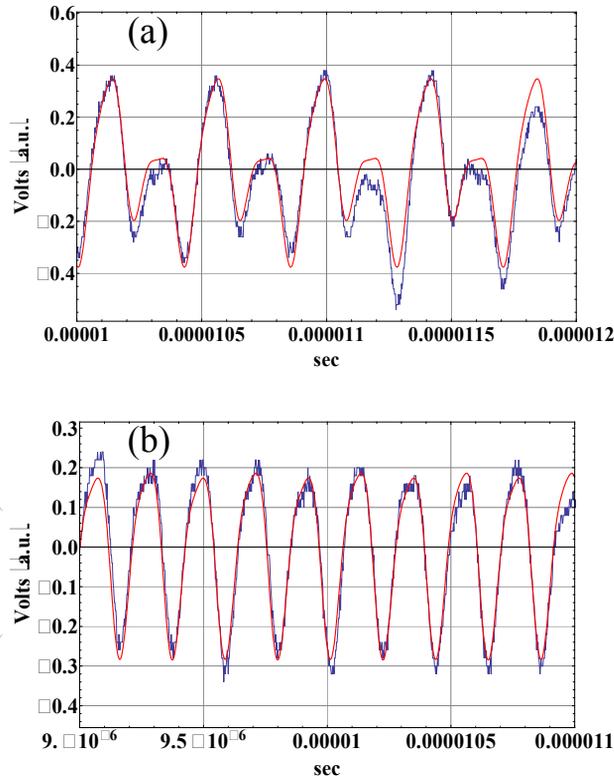


Figure 6: Grid voltage of the final amplifier at 4.7MHz (a) without, and (b) with a variable bandpass filter.

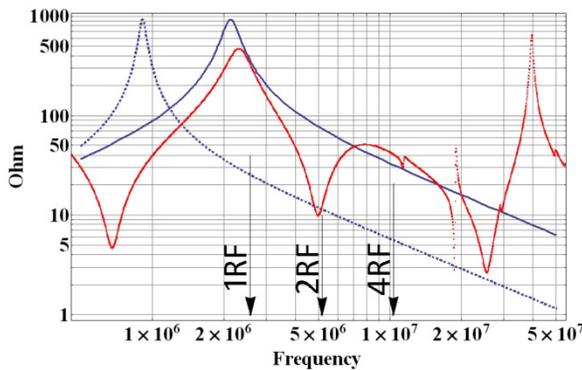


Figure 7: Input impedance by the simulation (red). Cavity resonant frequency is 5.15MHz. Input impedance is simply modelled as a parallel resonant circuit with (blue dot) and without (blue solid) Miller effect, where voltage gain is 20.

increase of the 1RF and 4RF components against the 2RF one. The TopSpice simulation agrees well with the experiments in terms of the grid voltage waveform distortion as shown in Fig. 8. Here, the harmonic contents at the driver input are 2.2% and 0.6% for 1RF and 3RF harmonics, respectively, which are taken from the separate measurements. The 5% content was assumed for 4RF harmonic to fit the experimental data. It is thought that 4RF harmonic comes from the non-linear response of the amplifiers in the following stage.

Variable Bandpass Filter

The variable bandpass filter was created on the National Instruments PXI platform to eliminate the 1RF and those higher than 3RF harmonics in the frequency doubler output [5]. More than 20dB attenuation of the 1RF component was obtained. Fig. 6(b) shows the test result of grid voltage waveform using the filter, where it has almost recovered a smooth sine waveform.

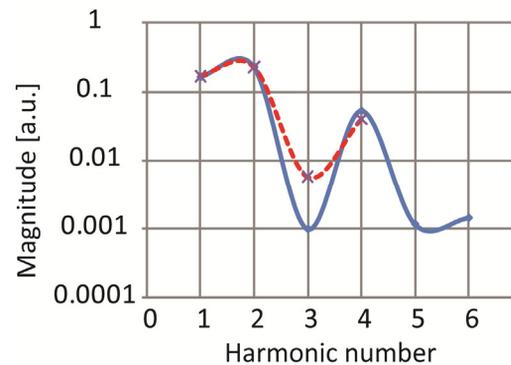


Figure 8: Harmonic distribution of the grid voltage at the final amplifier. Experiments are in blue line, and the simulation in red dashed-line. Simulation result is normalized to the experimental one at harmonic number=2.

CONCLUSIONS

It was proved by the first beam experiment in the ISIS synchrotron that the low output-impedance second harmonic cavity (LOI) has a low enough impedance as designed. However, the grid voltage waveform in the final amplifier was seriously distorted due to a small amount of sub-harmonic content in the driver input stage. Elimination of such content is required for further beam experiments.

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