WIDEBAND LOW-OUTPUT IMPEDANCE RF SYSTEM FOR THE ISIS SECOND HARMONIC CAVITY

Y. Irie#, S. Fukumoto, K. Muto, H. Nakanishi, T. Oki, A. Takagi (KEK, Ibaraki, Japan), J. Dooling, D. Horan, R. Kustom, M. Middendorf (ANL, Argonne, U.S.A.), D. Bayley, I. Gardner, R. Mathieson, A. Seville, J. Thomason (STFC/RAL/ISIS, Chilton, Didcot, Oxon,U.K.)

Abstract

A low-output-impedance RF system for the second-harmonic ferrite-loaded cavity in the ISIS synchrotron has been developed by collaboration [1] between Argonne National Laboratory (US), KEK (Japan) and Rutherford Appleton Laboratory (UK). The system comprises a driver stage with 250kW tetrode and a final stage with 240kW triode, both of which are operated in class A. The output impedance is less than 30 Ω over wide frequency range of 2.6-6.2MHz. However, distortions of voltage waveform in the driver stage have been a long-standing issue. It was found such distortions could be mitigated by arranging the two anode chokes of the vacuum tubes to have different higher-order-mode characteristics.

INTRODUCTION

Precise phase control of the second harmonic cavity to the fundamental one is essential to stabilize the beam motion and to maximize the stable phase space area. A low output-impedance RF system (LOI), which is free from heavy beam loading, has been investigated for future high-intensity synchrotrons. The low-impedance characteristics are realized by a feedback from plate to grid of the final triode amplifier. The output impedance over the wide frequency range of interest is less than 30 Ω, and the voltage gain of the final triode is more than 20. Fig.1 shows the schematic of the LOI system. In reference [2], comparisons of measurements with calculations are discussed in detail.

Although the cavity voltage showed a sine-wave, the voltage waveform in the driver stage (hereafter, grid voltage) was distorted, especially above 5MHz [3]. Such distortions bring serious phase errors into the ferrite bias tuning loop, and make it difficult to operate the cavity on tune. In the following sections, measures to mitigate the waveform distortion are discussed.

HIGHER-ORDER-MODE OF AN ANODE CHOKE

As is well known, an electric circuit with many elements of inductor, capacitor and resistor is liable to

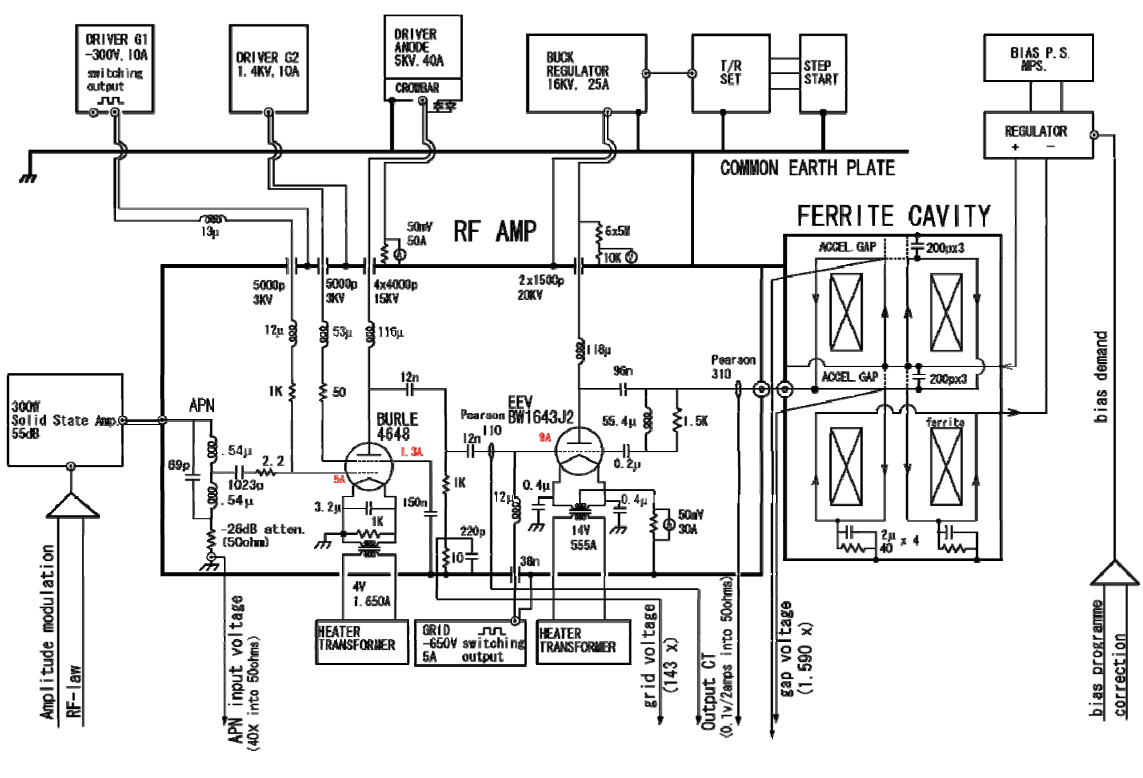

Figure 1: Schematic of the low output-impedance RF system.

#yoshiro.irie@kek.jp

have a complicated impedance structure with many parallel and series resonances. A real inductor, for example, is never of pure inductance, but has stray capacitance between each coil element. Fig. 2 shows an impedance of the LOI anode choke, where the fundamental mode (3.9MHz) and higher-order-modes (HOMs) are seen. As is in the ISIS synchrotron, the LOI is driven in a frequency swept mode at 50Hz from 2.6 to 6.2MHz. The driver input is then written as,

$$\mathrm{v}(t) \propto Sin(\omega_0 t + mSin(\Omega t))$$
$$\propto \sum_{n=-\infty}^{\infty} J_n(m) Sin(\omega_0 - n\Omega)t,$$

where ω_0=2π×4.4MHz, Ω =2π×50Hz and $m=\Delta\omega/\Omega$= 3.6×10^4. Since $J_n(m)$ is non-zero only for 2.6≤ ω_0-$n\Omega$ ≤6.2MHz, any frequency components over the frequency range exist at anytime in the RF cycle. In the actual system, however, higher harmonics of these components should also exist due to non-linear response of the vacuum tube. It can be thought that all these frequency components have a chance to grow by exciting relevant resonances which exist in the system. The original waveform will then be distorted by these spurious modes.

The circuit simulation code, TopSpice [4], is used for the LOI analysis. In the simulation, an inductor was modelled by the circuit in Fig. 3. Each coil element is expressed by an inductance L1, L2, etc which is assumed to couple the adjacent coil by the coupling coefficient K=0.5, and the next adjacent one by 0.3 and the third adjacent one by 0.1. Similarly, capacitive coupling is also assumed for the coil pairs to be inversely proportional to their distance as 20pf, 10pF, 20/3pF and so on. Shunt resistor, 20k, is attached across each coil element. In the simulation, number of terminals is chosen, for simplicity, to be 13 for the anode chokes and 5 for the feedback coil between plate and grid of the final triode. The calculated impedance is also shown in Fig. 2 for comparison. The resonant frequencies of the fundamental mode (~3.8MHz) and the 1st HOM (~11.3MHz) agree well with each other.

CIRCUIT SIMULATION

Grid-to-cathode impedance (Z_{gk}) in the driver stage and plate-to-grid impedance (Z_{pg}) at the triode are important parameters to characterize the LOI [5]. In modeling the LOI, these parameters were confirmed to be consistent with measurements. The inductance of the ferrite-loaded cavity (L_{cav}) was so changed that the cavity stays on tune, i.e. $L_{cav}(t)=1/(\omega^2(t)\ C_{cav})$, where C_{cav} is the cavity gap capacitance, 1,760pF. The cavity shunt impedance was chosen to be 538ohms [3]. Although simulation by TopSpice has not been able to reproduce the waveform distortions in the experiments, it showed interesting features under slightly different conditions from the real experimental ones: (1) system diverges faster when C_{cav} becomes smaller value, i.e. with lower cavity Q-value, and (2) such divergence/ distortions can be mitigated when the 1st HOM peaks locate at different frequencies for driver and final anode chokes. Although the feedback coil was treated as a simple coil in the latter case, experiments were performed aiming for waveform improvement in the following two cases. Case 1: frequency of the1st HOM peak was shifted by shorting a few turns at one end of the anode choke so that peak locations are different with each other. Case 2: HOMs were damped by adding a secondary winding with a termination resistor R~280ohms to the anode choke.

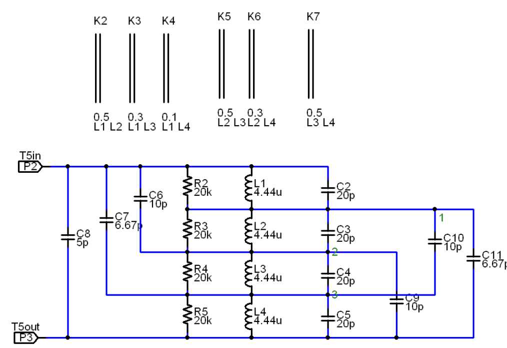

Figure 3: Inductor model with 5 terminals (4 turns).

EXPERIMENTAL RESULTS

The LOI is operated in class A. In order to save plate dissipations, a grid switching scheme is applied for both vacuum tubes: grid bias is set at conduction in the acceleration cycle, and at cutoff in another half-cycle.

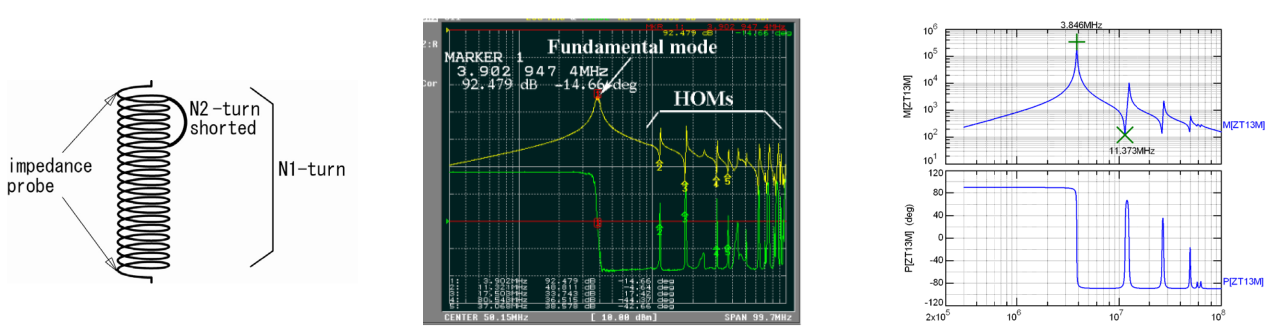

Figure 2: Impedance of the driver anode choke with N1=36 and N2=5 (middle), and its simulation model with N1=12 and N2=0 (right). N1 and N2 stand for total turns and shorted turns at one end, respectively.

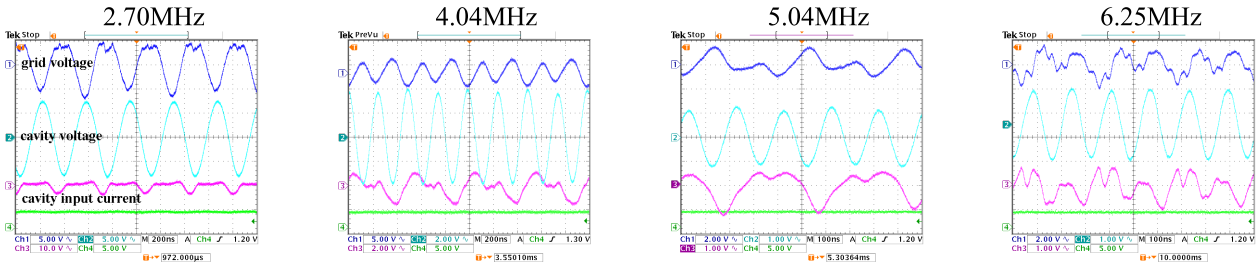

Figure 4: RF waveforms without HOM peak shift (N2=0). From top trace, grid voltage (143×), cavity gap voltage (1,590×) and cavity input current (20A/V) .

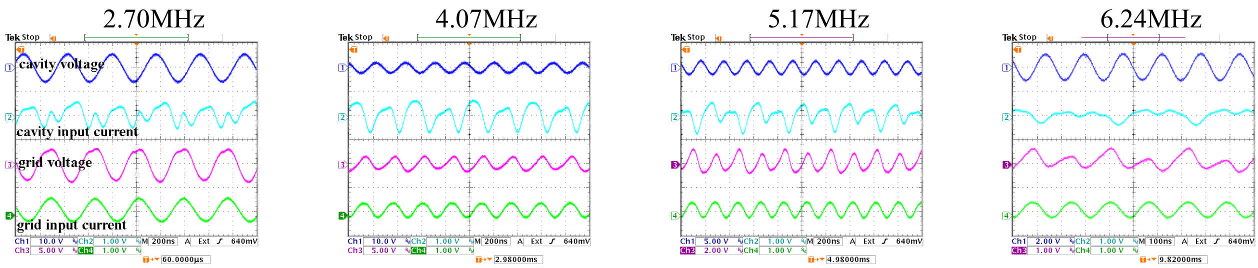

Figure 5: RF waveforms with HOM peak shift (N2≠0). From top trace, cavity gap voltage (1,590×), cavity input current (20A/1V), grid voltage (143×) and grid input current (20A/1V).

Closed loop controls for cavity tuning and RF voltage level were not implemented yet in this experiment. However, the ferrite-bias current was controlled manually so as to minimize the cavity input current. Experimental conditions are summarized in Table 1. In the anode chokes, N2 turns were shorted to shift the 1st HOM peak toward higher frequency as shown in Table 2. The frequency difference between the driver and anode chokes is then 1.695MHz instead of 1.183MHz. Detailed waveforms are compared in Figs. 4 and 5 on the effect of peak shift. Grid voltage waveform is greatly improved above 5MHz.

Experiment was also performed for the anode chokes with a damping resistor. The results were, however, very similar to those in Fig. 5.

Table 2: 1st HOM Location of Anode Choke [MHz]

Driver anode choke (N1=36)		Final anode choke (N1=46)	
N2= 0	N2= 4	N2= 0	N2= 7
9.338	10.803	10.521	12.498

CONCLUSIONS

A wideband low-output impedance RF system has been developed in collaboration with the labs, ANL, RAL and KEK for the future high-intensity proton synchrotron. The system operates in class A, and output impedance is less than 30ohms over the frequency range 2.6-6.2MHz at 50Hz repetition rate. By modifying the anode choke characteristics, a long-standing issue on the waveform distortion at the grid voltage was improved significantly, although there still exists a distortion to some extent above 5MHz. Further investigation for improvement is required for the beam test in the ISIS synchrotron, which is planned in February, 2011.

Table 1: Parameters of LOI Operation

repetition rate	50Hz	
class of operations	class A for triode and tetrode	
duty factor	54% by grid switching	
RF frequency	2.6 MHz (t=0msec) ~ 6.2 MHz (t=10msec)	
	RF OFF	RF ON
Triode Supply: anode voltage average anode current grid voltage at conduction grid voltage at cutoff	 16.6kV 12.1A	 15.2kV 14.2A -340V -500V
Tetrode Supply: anode voltage average anode current G1 voltage at conduction G1 voltage at cutoff G2 screen grid voltage	 6.6 ~ 6.7kV 14 ~ 17A 1.4kV	 6.6 ~ 6.7kV 13 ~ 16.2A -60V -200V 1.4kV
ENI A-300 output		25Vrms

REFERENCES

[1] http://www-accps.kek.jp/Low-Impedance_Cavity/
[2] T. Oki et al, EPAC'04, Lucerne, July 2004, TUPKF034, p.1036 (2004); http://www.JACoW.org.
[3] Y. Irie et al, EPAC'06, Edinburgh, June 2006, MOPCH118, p.321 (2006); http://www.JACoW.org.
[4] Penzar Development, P.O.Box 10358, Canoga Park, CA91309 USA
[5] T. Oki et al, Nucl. Instr. and Meth. A565 (2006) 358.