AN IMPROVEMENT OF MATCHING CIRCUIT OF RF KICKER ELECTRODES

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Abstract

An RF knockout technology [1, 2] is employed as a beam extraction method at the accelerator of The Wakasa Wan Energy Research Center (WERC) An RF noise of which band width is several tens kHz is applied to the transverse kicker electrodes to increase betatron amplitude of the beam.

We have improved the beam extraction system in the control of the time-structure of the beam spill by feeding the signal from the spill monitor back to noise amplitude. The feedback control system works as an attenuator, therefore it is necessary to increase the noise amplitude of the kicker electrodes for sufficient effect on the spill shape. In order to enhance the voltage, we improved the matching circuit at the input of the electrodes. By introducing the resonating characteristic at the matching circuit, we obtained 3 times larger amplitude at the electrodes. Shape of the spill became well-controllable by this work, and extraction efficiency is also improved.

In the case of a narrowband drive of a capacitive load, the technique presented in this report reduces the drive power drastically. The applications of this technique are, for example, for grid drive of a high power tetrode, that of triode, and drivers of electrostatic devices.

INTRODUCTION

The accelerator complex at the WERC consists of a 5MV Schenckel type tandem accelerator and a 200MeV proton synchrotron. The beams from the synchrotron are used for the proton cancer therapy and material and biological irradiations [3]. For these applications, a slow extraction using the third order resonance excited by sextupole magnets is employed.

Figure 1 shows the beam extraction system of the synchrotron at WERC. Betatron oscillations are excited by the transverse perturbation of the RF field applied to a couple of electrodes (RF-kicker). The bandwidth of RF field is several tens kHz. We must repeat the adjustment of the amplitude pattern of the noise to obtain a permissible time structure of spill for the irradiations. The procedure of the pattern adjustment was not simple; therefore we introduced feedback control of the noise amplitude to simplify the adjustment and to improve the time-structure of the spill. A signal from a spill monitor is fed to a feed back module. A difference between the beam spill signal and reference spill amplitude is integrated and is fed to an amplitude modulator.

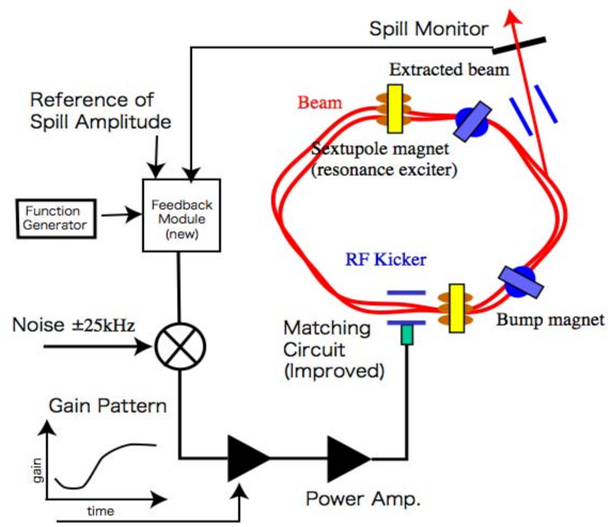

Figure 1: Beam extraction scheme at WERC

While the feedback control made it possible to control time structure of the beam spill easily, the reduction of the average noise amplitude due to the feedback control prevented 100% extraction. We had to study the way to increase the drive voltage of the RF kicker for the perfect extraction. In the course of the study, we noticed that the matching circuit of all-pass filter, which connects the power amplifier and the capacitive load of the kicker electrodes, is not designed properly. We also noticed that an introduction of resonating characteristics for the all-pass filter can realize an effective drive circuit. In this case, the voltage at the kicker is drastically increased.

PRINCIPLE

The circuit diagram of the all-pass filter is shown in Fig. 2, where C_L is the capacitance of the load. If we put C and L at $\boldsymbol{C_L/4}$ and $\boldsymbol{C_L R^2/2}$, respectively, the input impedance of the all-pass filter keeps constant value of R over all frequencies, and its transfer function is

$$F_{ALP}(\omega) = \frac{{\omega_H}^2}{(j\omega)^2 + \omega_H (j\omega) + {\omega_H}^2} \qquad (1)$$

where $\omega_H = 2/(C_L R)$.

Equation (1) indicates that the quality factor of the system is 1.

For an application where the frequency is less than ω_H, and its bandwidth is not so wide, we can increase Q-value. Keeping the relation $C = C_L/4$ and using F-matrix, the transfer function of the circuit in the Fig. 2 is obtained as follows.

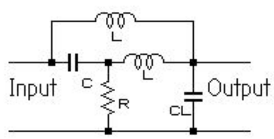

Figure 2: All-pass Filter.

$$F(\omega)=\left[1+j\omega L\frac{1+j\omega C_L R/2+(j\omega)^2 LC_L/2}{R+j\omega L+(j\omega)^2 LC_L R/2}+(j\omega)^2 LC_L/2\right]^{-1}. \tag{2}$$

In order to make the resonance at a lower frequency ω_0, we must increase *L*-value. Response at the resonating frequency of $\omega_0=\sqrt{2/(C_L L)}$ gives the Q-factor of the system;

$$F(\omega_0)\cong\left[j\omega_0 C_L R/2\right]^{-1}=Q$$
$$\text{or}\quad Q\cong\frac{1}{R}\sqrt{2L/(C_L)}. \tag{3}$$

According to the second of Eqs.(3), the Q-factor can be increased with increasing *L*.

In this case, however, the input impedance of the filter is a very large value at low frequency. The impedance is reduced to R at the resonant frequency, and again increases at high frequency.

In order to keep the input impedance to *R* at all frequencies, we must introduce a second resonator, indicated by C_2 and L_2 in Fig. 3. For the above purpose, the quality factor of the second resonator must have nearly the same value as that of the resonating filter (*Q*). The resonating frequency must also be ω_0. These requirements give the order of values of L_2 and C_2;

$$L_2\approx\frac{R}{\omega_0 Q},\quad \text{and}\quad C_2\approx\frac{Q}{\omega_0 R}. \tag{4}$$

The equations only give the orders of values; therefore numeric analysis is necessary to fix the proper values. In our case, L_2 is nearly 2-times larger than that given by

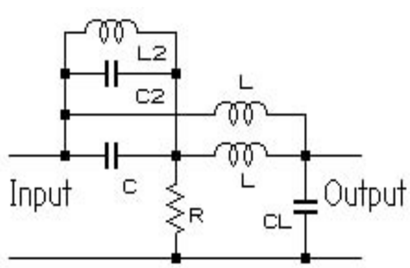

Figure 3: The drive circuit of capacitive load with constant input impedance.

Eqs. (4). After this calculation, *C* and C_2 can be made to single capacitor.

INSTRUMENTATION

At the fast step, we measured the input capacitance of the electrode, and designed basic type of all-pass filter. While the input capacitance is 25pF, we used 35pF for the value of C_L for safety. We get C = 8.75pF. Since manufacturer installed a transformer with step-up voltage ratio of 1:3 at the input of the matching circuit, the termination resistance is 450Ω at 50Ω-drive impedance. This gives the cut-off frequency ω_L to 2π×(20MHz), and L = 3.5μH.

On the other hand, the center frequencies of RF noise onto the kicker are 3.5MHz for the extraction of protons, and 3.9MHz for carbon ions. The bandwidth is far less than 50kHz for both cases. If we introduce a resonance at 3.5MHz, large amplitude amplification can be obtained at the matching circuit. In this case, even at 3.9MHz, we can obtain amplitude gain larger than 1. In order to make ω_0 = 3.5MHz, we must put L = 120μH and C = 8.75pF, and we obtain Q ~ 5.8 from Eq. (3). The Q-value indicates that the voltage at the electrode corresponds to the case where the drive amplifier is increased to 30-times (15dB) larger power in principle.

Numeric calculation using SPICE was performed; the circuit is shown in upper half of Fig. 4. Simulated amplitude-frequency characteristic is shown in lower half of Fig. 4.

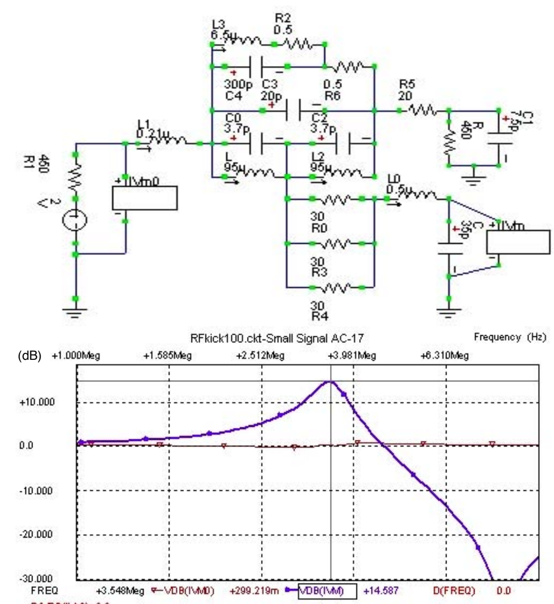

Figure 4: Simulation circuit and its result.

In the circuit in Fig. 4, very small resistances (R2, R6) are inserted due to the problem of convergence. Series resistance (R0, R3, R4) to the load is introduced for safety. Amplification of 14.5dB is obtained at 3.5MHz. Line at the middle indicates the voltage at the drive point. The variation of this voltage is far less than 1dB; this indicates that the input impedance of the matching circuit is very close to 450Ω at all frequencies.

Inductors are prepared at KEK, using ferrite cores with outer and inner diameter of 44 mm and 33 mm, respectively, and thickness of 13 mm.. Permeability of the ferrite (K5, TDK) is nearly 300, which reduces number of turns of the coil and does not affect on the Q-factor.

EXPERIMENTS

The oscilloscope traces of spills of 200MeV proton beam are shown in Fig. 5, where you can find that the use

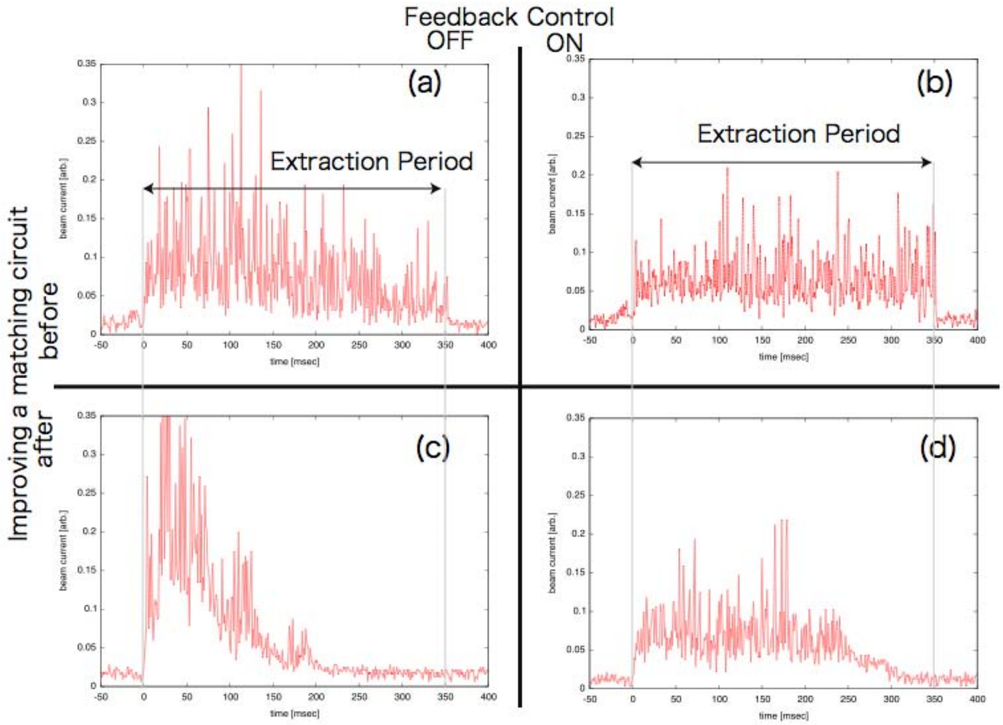

Figure 5: The oscilloscope traces of beam spills of 200MeV proton beam before/after improving the matching circuit, and the feedback control is turned ON/OFF.

of the feedback control realize the constant intensity of the beam during the extraction period. Also the comparison of spills between before and after improvement of the matching circuits is indicated. The bandwidth of RF noise is set at ±25KHz.

By the comparison of the spill signal with the feedback control (Fig. 5-(b)) to that without feedback (a), the spill structure is clearly improved. But in both cases, a fraction of particles in the ring are not extracted during the extraction period of 350msec.

After improving the matching circuit, no remaining protons are observed at the end of extraction in cases of both (c) and (d). The spill shape under the feedback control (d) is, of course, far better than without feedback (c).

The output level of the noise generator is reduced nearly 10dB under the normal operating condition. This indicates that the gain of 10dB is obtained at the matching circuit. The difference from the expected value (15dB) is due to the error in the resonance frequency. We used a function generator and an oscilloscope for the adjustment of the resonating frequency. More precise adjustment may be possible, if we use a network analyzer.

SUMMARY

We installed the feedback control system of the beam spill and improved the matching circuit between the kicker electrode and RF power amplifier. The new matching circuit is a variation of all-pass filter. The amplitude of the RF noise at the kicker was increased drastically due to the resonating characteristics of the filter. This technique can widely be used for the system which drives the capacitive load. The time structure of the spill is improved by the feedback control system, and the extraction efficiency is increased by the filter technique.

ACKNOWLEDGEMENTS

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