# POSSIBILITY OF RESONANT EXCITATION OF THE JHF 3-GEV SYNCHROTRON MAGNETS USING A MULTI-NETWORK

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*Abstract*

Two model networks have been constructed in order to investigate the possibility of resonant excitation of the JHF 3-GeV synchrotron magnets using a multi-network. Each model network comprises a dummy magnet, a resonant capacitor and a pulse power supply. The main subject of the model networks is to synchronise the phase of each resonant current. It was found that the main origin of the phase fluctuation was the ripple of a rectifier of the pulse power supply. As the result, stable operation was obtained within a phase fluctuation of 0.3 mrad.

## 1 INTRODUCTION

The Japan Hadron Facility (JHF) is a project aimed at a kaon factory and a facility to utilize secondary particles for the research of condensed matter[1]. The JHF accelerator complex comprises the 200-MeV Linac, the 3-GeV synchrotron and the 50-GeV synchrotron. The 3-GeV synchrotron supplies a proton beam to the neutron-production target in the facility for the research of condensed matter, as well as to the 50-GeV synchrotron. In order to obtain a high-intensity secondary beam, the beam intensity is required to be as high as possible. In addition, the repetition of acceleration was determined to be 25 Hz at first and 50 Hz in the future.

In such a high-intensity accelerator, the space-charge effect and instabilities are so hard that the tune will be an essential role to cure such effects. Therefore, it is desirable that the tune value can be set according to the beam intensity. This requirement implies that the bending magnets and quadrupole magnets must be excited separately.

In a rapid-cycling synchrotron with a repetition higher than 10 Hz, magnets are excited using a White circuit or a resonant network[2][3]. The BESSY 800-MeV injector is a rapid-cycling synchrotron with a repetition of 10 Hz, and synchrotron magnets are excited using three independent White circuits[4]. On the other hand, the KEK 500-MeV Booster is also a rapid-cycling synchrotron with a repetition of 20 Hz. The Booster magnets are the combined-type and are excited using a single resonant network with 3 meshes. Therefore, in KEK there has been no experience concerning the synchronous operation of the multi-network required for separated excitation of the magnets in the JHF 3-GeV synchrotron. This is why the model network has been constructed.

## 2 TOLERANCES

Using a resonant network, synchrotron magnets are excited by a current with the following waveform:

$$I = I_{DC} - I_{AC}\cos(\omega t + \delta) \quad . \tag{1}$$

Here, $I_{DC}$ is the dc bias current and $I_{AC}$ is the amplitude of the ac current; ω is the repetition frequency and δ is the phase difference with respect to the clock-timing which determines the accelerator cycle. Since there are three types of magnets in the JHF 3-GeV synchrotron, i.e. bending magnets, quadrupole magnets for focussing and quadrupole magnets for defocusing, it is necessary to operate three independent resonant networks within some tolerances for stable beam acceleration.

### *2.1 Tolerance for C.O.D.*

In the 3-GeV synchrotron, the maximum excursion of the horizontal c.o.d. is restricted to within less than 3 mm. The corresponding field error of the bending magnet was estimated to be $8.8 \times 10^{-4}$. Since the dc and ac components of the bending fields are controlled independently, both the dc and ac current are controlled within an error of $2.1 \times 10^{-4}$. This requirement is not very difficult, since the field has already been stabilized within an error of the same order as that in the KEK Booster.

### *2.2 Tolerance for Tracking Error*

The tune stability is required to be less then 0.01. The corresponding focusing error was estimated to be $8.7 \times 10^{-4}$. This implies that the dc and ac components of the current for the quadrupole magnet must be stabilized within $2.0 \times 10^{-4}$.

In multi-network excitation there is another possibility of a tune error. Since the phase of the ac component of the magnet current depends on the resonant frequency and Q-value in each resonant network, there may occur a phase difference among the three resonant networks. Fortunately, such a phase difference is almost constant and can be compensated by adjusting the trigger timing. A small phase drift may occur due to a change in the temperature of the circumference. It is expected to be slow enough to be compensated by a variable delay circuit. The tolerable phase drift was estimated to be $8.0 \times 10^{-4}$ rad, which corresponds to 5 μsec for 25 Hz operation.

Higher harmonics contained in the exciting current deforms the current waveform. Since the extent of the contamination of higher harmonics is dependent on the resonant frequency and Q-value of the resonant network, the difference in the waveform causes a tracking error. Since such an error is unavoidable, the resonant networks must be fabricated so as to have resonant frequencies and Q-values as close as possible.

## 3 MODEL CIRCUITS

The multi-network is simulated by two resonant circuits and pulse power supplies. Each resonant circuit comprises a dummy magnet of 10 mH and a resonant capacitor of 1 mF in order to obtain a resonant frequency of 50 Hz. Table 1 gives measured values of the resonant frequencies and Q-values of model circuits.

Table 1:Resonant frequency and Q-value of the model circuits

| Circuit | Resonant Frequency (Hz) | Q-value |
|---|---|---|
| No.1 | 48.88 | 78 |
| No.2 | 48.76 | 73 |

A pulse power supply comprises an energy-storage capacitor ($C_f$), a charging circuit and a discharging circuit, as shown in Fig. 1. The rectifier ($V_s$) charges $C_f$ through a filter choke ($L_f$). Then, a thyristor (SCR) is triggered to discharge $C_f$ through the pulse choke ($L_p$), so that a half-sine-like current pulse ($i_p$), is generated.

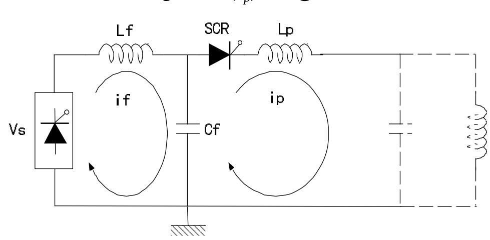


Figure 1: Basic construction of the pulse power supply.

As mentioned above, any higher harmonics contained in the resonating current must be reduced in order to avoid a tracking error. Therefore, a pulse power supply is not suitable for the excitation of a multi-network. In spite of such a disadvantage, a pulse power supply has been adopted, since the future upgrade of the magnet operation, i.e. dual frequency operation or flat bottom operation[5][6], is straightforward without any improvement of the power supply.

A trigger pulse for firing the thyristor is fed to each pulse power supply through a variable delay, which compensates for a proper phase shift due to the resonant frequency and Q-value of each resonant circuit. Such a phase shift is given by

$$\delta = \tan^{-1}\left(\frac{\omega \cdot \omega_0}{Q \cdot (\omega_0^{\,2} - \omega^2)}\right) \qquad . \qquad (2)$$

Here, δ is the phase shift, $\omega_0$ the resonant frequency, $\omega$ the operation frequency of the power supply and Q the Q-value. The amplitude of the magnet current is monitored by a current transformer, and the zero-crossing timing is measured by a back-leg winding.

Synchronous operation of the multi-network is the main subject in this experiment. A fluctuation of the zero-crossing timing with respect to the trigger timing determines the phase tracking error. The fluctuation of the zero-crossing timing was measured to be 2 μs in full width. Since the operation frequency was 48.82 Hz, the corresponding phase fluctuation amounted to +/- 0.31 mrad. As mentioned in 2.2, phase tracking must be performed within a phase error of 0.8 mrad in order to compensate for any phase drift. Therefore, it was found that the timing measurement system could resolve the prescribed tolerance to the phase drift.

The relative phase difference between two resonant circuits was measured to be 1.0 ms. A consistent value of 1.15 ms was obtained in terms of eqs (2). Such a phase difference was compensated by delaying the trigger timing of the pulse power supply for the circuit with the earlier phase. The fluctuation of the relative phase was measured to be less than 1μs, which was smaller than expected if the pulse power supply fluctuates randomly. This implies that an a.c. power line causes the phase fluctuation, since two pulse power supplies were connected to the same breaker.

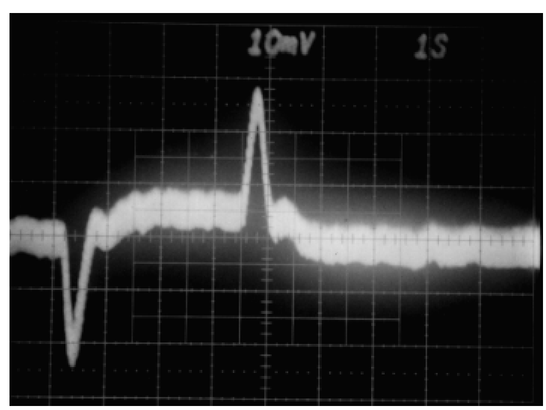


Figure 2: Phase response of the model circuit.

The relative phase changes drastically and relaxes when $V_s$ is suddenly changed, as shown in Figure 2. Here, the trace time is 1 s/div and the vertical scale corresponds to a phase drift of 1 μs/div. In this case, $V_s$ is changed by –0.5% at first, corresponding to the first peak. Then, $V_s$ is changed by +0.5%, corresponding to the second peak. Such a spike-like response was measured, and it was found that the peak value was proportional to the relative change of $V_s$, as shown in Figure 3.

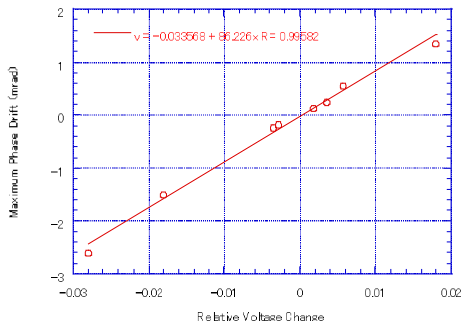


Figure 3: $V_s$ dependence of the maximum phase response.

On the other hand, the amplitude modulation was observed. Figure 4 shows the upper envelope of the back-leg signal. Here, $V_{pp}$ of the back-leg signal is 5.5 V. The envelope is modulated by $1.0\text{x}10^{-4}$ with respect to the amplitude.

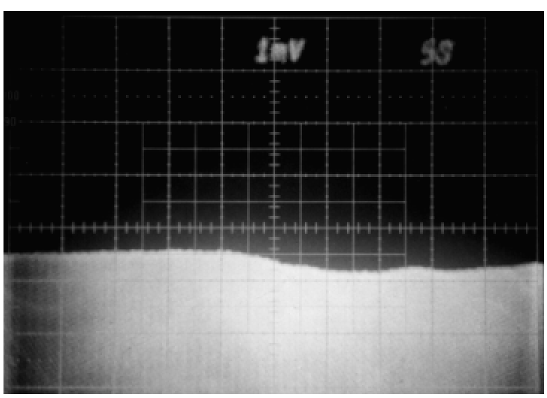


Figure 4: Upper envelope of the back-leg signal.

## 4 DISCUSSION

The phase fluctuation was measured to be +/- 0.31 mrad by detecting the zero-crossing timing of a back-leg signal. This shows that the resolution of timing detection is sufficient for phase control, since the tolerable phase error is +/- 0.8 mrad. A slow-amplitude modulation of $1.3\text{x}10^{-4}$ was observed in the model circuit. This value also satisfies the required tolerance of $2\text{x}10^{-4}$.

Both the phase fluctuation and amplitude modulation can be explained qualitatively, taking account of the ripple of $V_s$. Since the amplitude of the magnet current is proportional to $V_s$ in the stationary state and the resonant circuit sees $V_s$ every switching timing of the SCR, the resonant circuit is excited by a driving force with a slow frequency on the order of the difference between the ripple frequency and operation frequency. Therefore, the amplitude and phase of the magnet current are modulated with such a frequency. As a result, it is expected that the amplitude modulation and phase fluctuation can be reduced by reducing the ripple of $V_s$.

## 5 CONCLUDING REMARKS

In order to investigate the possibility of a resonant excitation of synchrotron magnets using a multi-network, model circuits were constructed. The phase fluctuation and amplitude modulation were found to be within the tolerance required by the JHF 3-GeV synchrotron. Therefore, it is hoped that the multi-network can be used for resonant excitation of the magnets of the JHF 3-GeV synchrotron. In addition, further improvement is expected by reducing the ripple of the power supply.

Since a pulse power supply essentially excites higher harmonics of the resonating current, a tracking error cannot be avoided. Therefore, resonant networks must be fabricated to have resonant frequencies and Q-values as close as possible, so that the tracking error can be made to be tolerable. A measurement of the Q-value dependence of the waveform is now being prepared.

Since a long-term stabilization of the multi-network is the final goal of our experiment, a feedback system for magnets of the JHF 3-GeV synchrotron will be designed.

## ACKNOWLEDGMENTS

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