Effect of phase relation between ripples of ring dipole and quadrupole magnets on time structure of the slow extracted beam

Akira NODA, Akio MORITA, Koji NODA*, Masayuki KUMADA*, Kazuo HIRAMOTO** and Hiroshi KUBO**
Institute for Chemical Research, Kyoto University (ICR)
Gokanosho, Uji-city, Kyoto 611-0011, Japan
*National Institute of Radiological Sciences (NIRS)
4-9-1 Inage-ku, Anagawa, Chiba-city, Chiba 263-0024, Japan
**Hitachi Co. Ltd.

Abstract

Effect of the ripple in the excitation currents of dipole and quadrupole magnets on the time structure of the slow extracted beam has been investigated. With suitable chromaticity correction, the effect of the current ripple can be completely cancelled out between dipole and quadrupole magnets if these ripples have the same phase.

1 Introduction

Recently the scanning of a pencil beam has been applied for clinical use both in GSI and PSI as the method to form a desired dose distribution in an enlarged 3-dimensional volume. In such a case, the beam ripple is required to be reduced as small as possible. In the case of synchrotron, where the beam energy can be varied pulse by pulse as GSI, it is very convenient to change the range of the ion beam in a human body, but the extracted beam from the synchrotron has, in general, large ripples and is considered to be difficult to apply for the scanning method.

We have been developing the beam monitor system to detect the beam ripple in the extracted beam in order to control the scanning speed according to the beam intensity at each instant[1]. The reduction of the beam ripple, however, is more straight forward and at HIMAC in NIRS the current ripples in the lattice magnets have been reduced to be less than ~10^{-6}[2]. At HIMAC, it is also pointed out that the current ripple in the bending magnet also has an important effect on the extracted beam ripple as the horizontal focusing quadrupole, Q_F[3].

At ICR, Kyoto University, a compact synchrotron with combined-function lattice has been developed as a reference design of a dedicated machine for proton therapy[4]. The combined function synchrotron is considered to be insensitive to the current ripple if the ring chromaticity is appropriately controlled, because for this case the same magnet plays both roles of bending and focusing and ripple in the bending and focusing magnet has the same phase[5].

Utilizing the very low ripple synchrotron, HIMAC and applying external artificial ripple currents, which can be controlled in amplitude and phase, we have experimentally

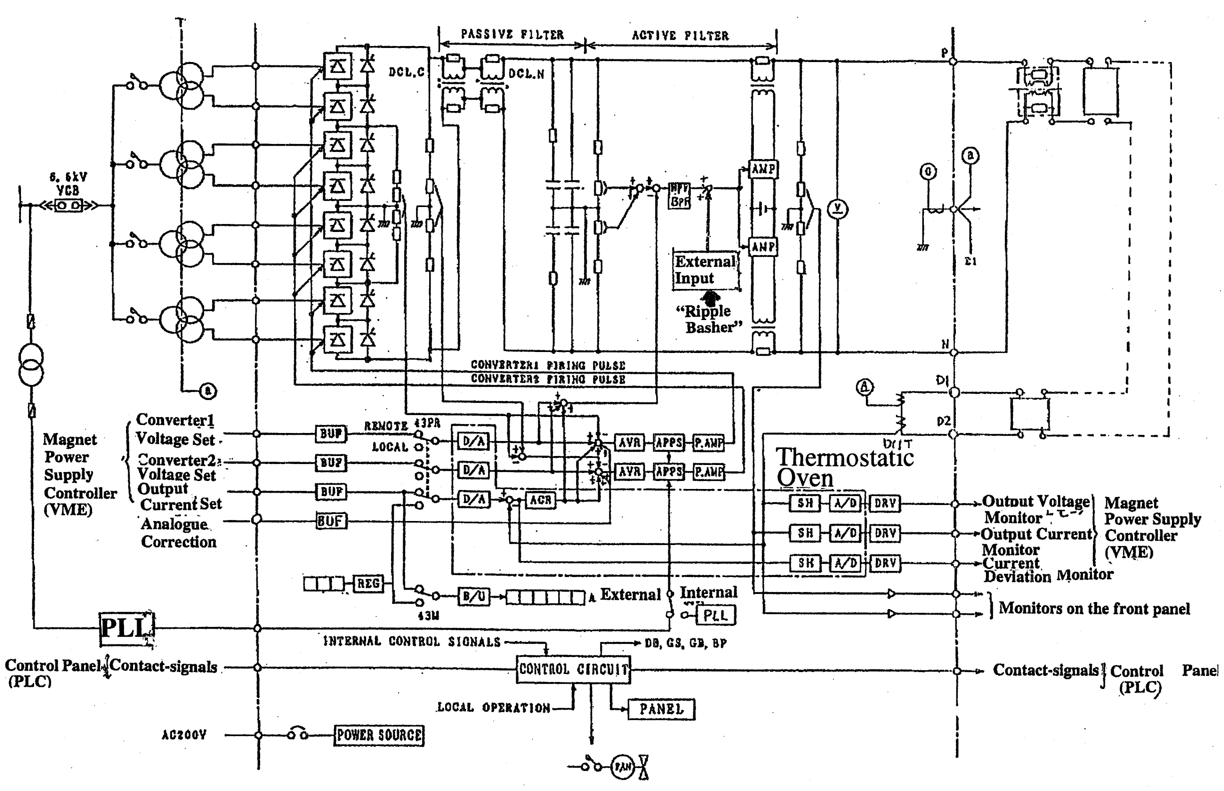


Fig.1 Block Diagram of the power supply for bending magnets of HIMAC.

investigated the effect of the ripples to the extracted beam controlling the amplitude and phase relation between ripples in bending and horizontally focusing quadrupole magnets.

2 Basic Idea of Ripple Compensation

The tune change($\Delta\nu$) due to current ripples in bending(δ_d) and quadrupole magnets(δ_q) is given by Hiramoto as

$$\Delta\nu = -\frac{\delta_d}{4\pi}\int\left(\frac{2}{\rho^2}-\frac{2\eta}{\rho^3}+\frac{4B_{40}\eta}{\rho}\right)\beta ds$$
$$-\frac{\delta_d}{4\pi}\int B_{60}\eta\beta ds+\frac{\delta_q}{4\pi}\int B_{40}\beta ds,$$

where B_{40} and B_{60} are quadrupole and sextupole magnetic fields, respectively normalised with magnetic rigidity of the beam with central momentum. β, η and ρ are beta-function, dispersion function and radius of curvature, respectively[5]. If the amplitudes and phases are the same between ripples of bending and quadrupole magnets, then δ_q can be replaced with δ_d, which leads to the relation,

$$\Delta\nu = -\frac{\delta_d}{4\pi}\int\left(\frac{2}{\rho^2}-\frac{2\eta}{\rho^3}+\frac{4B_{40}\eta}{\rho}+B_{60}\eta-B_{40}\right)\beta ds.$$

This relation is exactly the same as the tune difference due to momentum difference when δ_d is replaced with $\Delta p/p$. This means that in the condition where the chromaticity is completely compensated the ripples of the bending and quadrupole magnets can be also compensated if they are the same both in amplitude and phase.

3 Experimental Procedure

Utilizing HIMAC with very low ripple less than 10^{-6}, it is possible to make investigation about the effect of the ripple on the time structure of the extracted beam. In Fig.1, the block diagram of the power supply for bending magnets is shown. The one for the quadrupole magnets has a similar structure.

It is not so easy to control the intrinsic ripple of the power supply freely, so we have applied an external signal for each power supply(B and Q_F). The applied signal has a sinusoidal shape, which is provided by "ripple basher"[3].

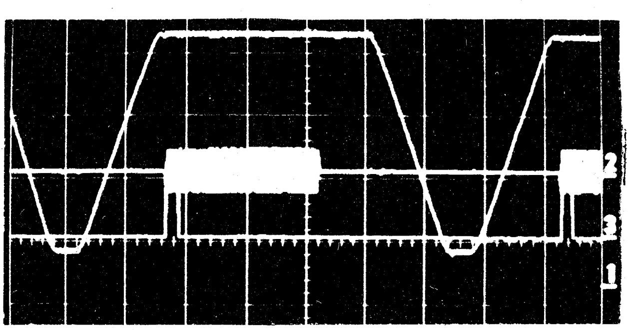
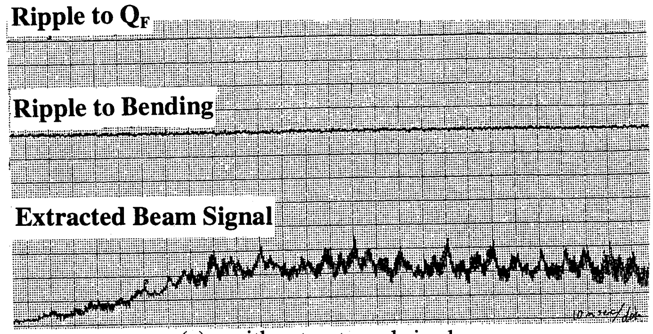
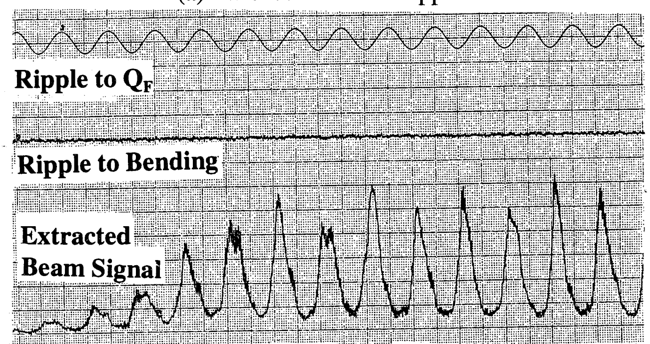


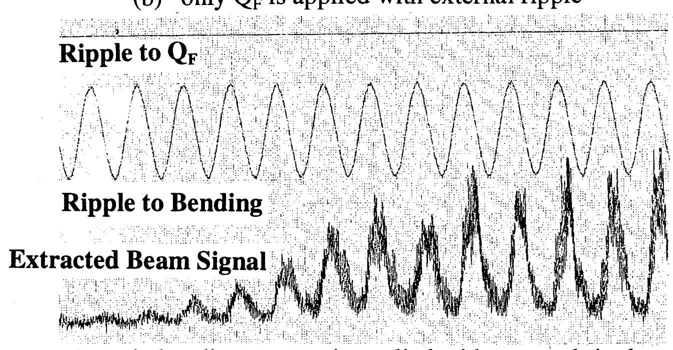
Fig. 2 The ramping pattern of the bending magnets(upper), and the applied "ripple basher" signal(center). Horizontal time scale is 0.5 s/div.



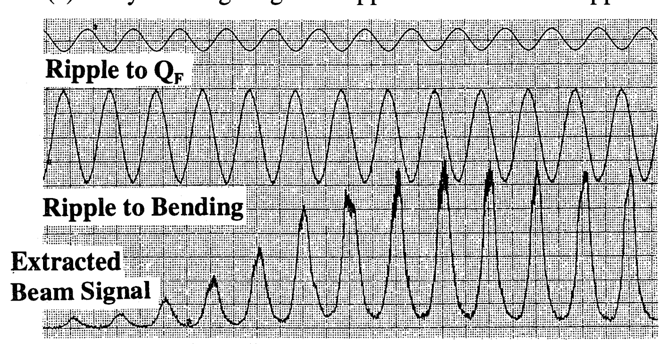
(a) without external ripple



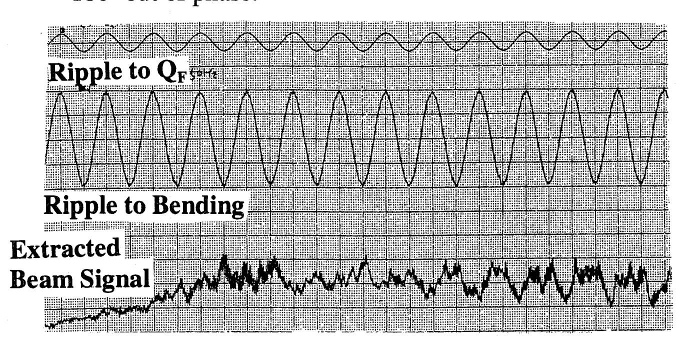
(b) only Q_F is applied with external ripple



(c) only bending magnet is applied with external ripple



(d) both Q_F and bending magnets are applied with ripples 180° out of phase.



(e) both Q_F and bending magnets are applied with ripples in phase

Fig. 3 Externally applied ripples to QF (upper), bending (center) and slowly extracted beam signal (lower). Horizontal scale is 10 ms/div.

Each "ripple basher" has five channels. The sinusoidal harmonics of 50 Hz from the fundamental to the 24th can be generated. Each channel of the "ripple basher" can be set at one of these harmonics.

We have applied sinusoidal external signals from 50 Hz to 600 Hz to the power supplies of the bending and quadrupole magnets at the External Input shown in the center of Fig. 1. In Fig. 2, the ramping pattern of the bending magnets is shown(upper trace) together with the externally applied "ripple basher" signal with gate width of 1.25 s(center trace). The lower trace is the timing signal for the "ripple basher".

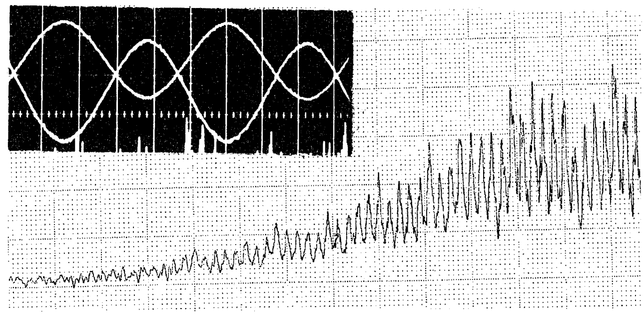
In the present experiment, the ordinary slow extraction which drives the horizontal tune to the third order resonance ν_H=3.6666···· in order to study ripple effect. The excitation currents of bending, Q_F and Q_D are 1047.0 A, 616.5 A and 621.8 A, respectively at the beginning of the flat top. The betatron tunes at the beginning of the flat top are measured to be 3.68~3.69 and 3.14 in horizontal and vertical directions, respectively. The excitation currents of sextupole magnets are 33.14 A, 24.11 A and 6.00 A for SXDR, SXFR and SXF, respectively, which leads to rather small horizontal chromaticity within the condition beam loss is not so large.

4 Experimental Results

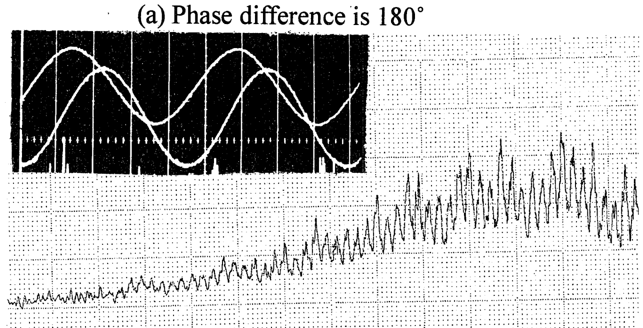
The amplitudes of sinusoidal ripples externally applied to the power supplies of bending and Q_F magnets are adjusted to have almost the same effect on the slowly extracted beam. At the present experiment, the really applied ripples are 1.47 x 10^{-4} and 1.6 x 10^{-5} for bending and Q_F magnets, respectively.

In Fig. 3, the externally applied ripples of 50 Hz to Q_F (upper trace) and bending magnet (center trace) and the time structure of the slowly extracted beam (lower trace) are shown. Fig. 3(a) shows the case without any external ripple. Fig. 3 (b) and (c) correspond to the cases where only Q_F and bending magnets are applied with external ripple, respectively. In the case of Fig. 3(c), the beam signal of the extracted beam is not filtered, while in the other cases filter is used for the beam signal, which is the reason the beam signal in Fig. 3 (c) has some fluctuation. In the case of Fig. 3 (d), the externally applied ripples to Q_F and the bending magnets are 180° out of phase, while these are in phase in the case of Fig. 3(e). It is seen that the effect of the ripples applied to Q_F and bending magnets are enhanced when they are out of phase while this effect is compensated when the ripples are in phase. It should be noted that the error of such cancellation will be amplified when the extraction process proceeds and the horizontal tune comes very close to the resonance, which, we think, is the reason why some time structure of 50 Hz begins to appear at the later part of the beam spill even in Fig. 3(e) with ripples in phase.

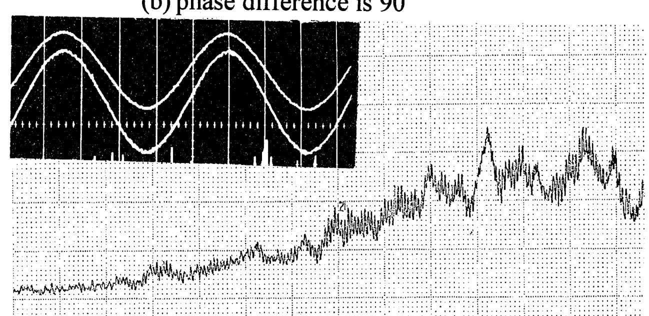
The same measurement has been performed to higher harmonics up to 600 Hz and similar cancellation phenomena have been observed. In Fig. 4 (a), (b) and (c), the extracted beam signals are shown for the cases where phase difference between ripples externally applied to Q_F and bending magnets are 180°, 90° and 0°, respectively together with the pictures which show the phase relation.



(a) Phase difference is 180°



(b) phase difference is 90°



(c) Phase difference is 0°

Fig. 4 Effect of ripple with 450 Hz to the extracted beam. Horizontal scale is 10 ms/div.

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