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A TECHNIQUE FOR BEAM-LOADING CANCELLATION

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Abstract; Problems on beam loading at a second-harmonic cavity and a non-resonant accelerating system can be solved by the technique presented in this report.

INTRODUCTION

A technique for direct beam-loading cancellation is presented. It has its root in a report made in 1989.¹⁾ This technique can be applied to any type of accelerating system having a ferrite-loaded cavity, such as the accelerating system at the KEK-PS, that of the ISIS synchrotron,²⁾ and a non-resonating accelerating system.³⁾ In addition to these applications, the technique can also be applied to loading cancellation at a second-harmonic cavity used for extending the bunch width during the early period of the accelerating cycle in a high-intensity accelerator. The principle of operation is also similar to that of the feedforeward technique used at the ISIS synchrotron.

The system uses an electrically controlled variable delay. The experimental results of a feasibility study of the delay is also presented.

DESCRIPTION OF THE SYSTEM

Since the principle of operation is very simple, a simplified circuit diagram is shown in Fig. 1 to explain the mechanism. As shown in this figure, the anode of the tetrode (V3) is connected to the accelerating gap. The anode current of the tube cancels the loading current which flows from the accelerating gap to the cavity. The tetrode (V3) is driven by a separate cancelling loop. The beam current-signal is picked up at a point near to the accelerating system. The signal is transferred to the driver amplifier via a variable delay. The signal is amplified and transferred back to V3. The total delay time is adjusted to the revolution period of a proton by using the variable delay.

Since the loading cancel loop is separated from that of the accelerating voltage, the automatic cavity tuning system does not be affected by the loading cancel current. Therefore, this system can be applied to any accelerating system having a ferrite-loaded cavity, and also to a second-harmonic cavity.

This system can easily be attached to an existing accelerating system by putting the circuit of V3 in a new cabinet.

Since the output capacitance of V3 is connected in parallel to the cavity resonating circuit, the ferrite bias current increases slightly. The increment in the bias current is easily estimated by the effective gap capacitance and the output capacitance of the tube (V3).

THE POWER OF THE TETRODE

The anode voltage of V3 varies according to the rf voltage at V1 plus the anode DC-voltage. This means that the power at the anode of V3 is not small. In order to estimate the power, we used the accelerating system presented in reference 4 (see Table 1) as an example. Since the system must cancel the loading current from the two accelerating gaps, the cancelling anode current is twice the beam current. Therefore, the power is given by

$$P_A = (V_{DC} - V \cdot \sin \phi_s) \cdot 2I_0,$$

where V_{DC} is the anode DC voltage, V the anode rf voltage at V1, ϕ_s the synchronous phase, and I_o the circulating beam current given by eNf_{rev}. Let $V_{DC} = 10kV$, $V = 7.5kV$ (as in ref. 4), $\phi_s = 0°$, and $I_o = 10A$; the power is 200 kW at the end of accelerating period. Whereas, the average power dissipated at the anode is less than half of this value, one must select the tetrode by its maximum rating on the anode current. This value must be determined by the peak beam current. In our example, the peak anode current must be larger than $2 \cdot I_B$(peak value) $\simeq 2 \cdot 3I_o$.

In order to eliminate the effect due to a voltage swing at the anode to the drive circuit of V3, we used a grounded grid circuit.

The transconductance of a 200kW-class tetrode is on the order of 0.1S. Since the input impedance of the cathode is on order of $10\Omega(=1/g_m)$, a matching transformer is necessary to drive from a power amplifier having an output impedance of 50Ω. Since the peak loading current is on the order of $2 \cdot (3I_o)$, the peak drive voltage is $2 \cdot (3I_o) \cdot 10\Omega = 600V_{pp}$, which corresponds to a drive power of 4.5kW.

Since the grounded grid circuit has a high output impedance, it eliminates the effect due to the cancellation current onto the drive power of V1 and V2.

VARIABLE DELAY

In order to change the delay time of the loop according to the variation in the speed of a proton, we must use an electrically controlled variable delay. Such a device is easily made by using a fast AD converter, a shift resister, and a DA converter while changing their clock frequency according to the variation in the accelerating frequency. As shown in the appendix, the variable delay can also be made by using ferrite-loaded coils and varactor diodes. Since the latter delay element is easily made and also easy to operate, we selected the latter delay element.

Since both the permeability of the ferrite and the capacitance of the varactor diode vary with the temperature, we must use a phase-lock system to maintain the correct phase relation between the cancelling current and that of loading. Since we now assume that a pickup transformer will be installed near to the accelerating system, we can neglect the transit time of a proton from the pickup to the accelerating system. We also assume that the control system for the cancellation system is installed at a point, which can be connected by 100m-cables to the both pickup and the accelerating system. The delay time of the two 100m cables, having a signal propagation speed of 0.9c[m/s], is 740ns. By also assuming a propagation time of 100ns for both the drive amplifier and the low level electronics, a total propagation time of 0.84μs plus a variable delay time is necessary for the signal from the pickup to the terode(V3). On the other hand, the period of revolution of a proton changes from 1.85μs (at 200MeV) to 1.075μs (3GeV). The delay must be varied from 1.01μs to 0.235μs. My experimental work in the appendix shows that the variable delay, which has a delay-time variation from 0.2μs to 1.2μs can be obtained by increasing the number of the unit delay.

If the length of the two cables is longer than 100m, the delay time of one proton revolution at the end of the acceleration cycle would not be obtained. This means that this system is not easy to apply to the 3-GeV Ring in the JHP project. The Ring, according to the present plan, is to be installed in the tunnel of the 12GeV-PS. Two or three installation rooms for rf system must be constructed near to the accelerator tunnel.

Since the variation in the delay time of ΔT_d at the output of the variable delay corresponds to a phase variation of $\omega_{rf}\cdot\Delta T_d$ radians at a frequency of f_{rf}, the loop gain of this phase-lock loop is given by $G_D\cdot A\cdot M\cdot\omega_{rf}\cdot(dT_d/dV)$. Here, G_D is the gain of the phase detector, A is that of the loop filter, and M represents the multiplier. Since the delay time is given by $8.5 \cdot 10^3 [\mathrm{ns}]/V^{1.37}$, the conversion factor of the delay (dT_d/dV) reduces its value from ~310ns/V (at a large delay time area) to ~4ns/V (at a small delay time area). Therefore, as shown in Fig. 1, we must increase the gain by using a multiplier (M) at higher frequencies to maintain a constant loop gain for the total accelerating frequency range. The multiplier (N) controls the magnitude of the cancellation. The control input of N can also be used for a gate input of the loop. The effects of the two multipliers (M and N) are shown by the phaser diagram in Fig. 2.

APPLICATION TO A NON-RESONATING ACCELERATING SYSTEM

Since the application to a second-harmonic cavity is not different from that to the normal accelerating system, only some remarks concerning the application to a non-resonating accelerating system are given.

A non-resonating accelerating system can not be applied to the acceleration of a high-intensity beam. We therefore restrict our discussion to the acceleration of a beam having a circulating beam current of less than 1A. Above this current, the non-resonating accelerating structure reduces its value of the real impedance at a frequency range above 1MHz due to saturation produced by the circulating beam current. Since in this case the loading current deforms the rf wave directly, and reduces the accelerating voltage at the center of the bunch, the radial beam control increases the synchronous phase so as to maintain the beam orbit at the center of the vacuum chamber. The cancellation signal corrects for any distortion of the accelerating voltage at the bunch center, and thus contributes to beam acceleration.

If the power of the rf source is sufficiently large, we can superpose the cancelling signal upon the input signal of the rf amplifier. If the power is not large enough, we must use a tetrode. The anode voltage of the tube must be greater than the rf voltage plus the screen grid voltage. For example, if the accelerating voltage is 1kV, the order of the power at the anode would be ~1kW. Therefore, a tetrode with an anode power of 2 ~ 5kW can be used for the cancellation system. The tetrode of this class has a screen grid voltage of ~400V. We must therefore increase the anode voltage to ~1.6kV. The output capacitance of the tetrode of this class would be nearly 20pF, which is less than half of the gap capacitance of the non-resonating accelerating structure. Since the output capacitance of the tetrode reduces the higher cutoff frequency, in order to minimize the effect of the tube on the system bandwidth, a tube having a smaller output capacitance must be selected.

CONCLUSION

The distinctive feature of direct beam-loading cancellation is that the loop used for cancellation is separated from that of the rf drive. The automatic cavity-tuning loop is not affected by the current of the cancellation. Thus, this loading-cancel technique can be applied not only to the accelerating system of the fundamental frequency with a ferrite-loaded cavity, but also to a second-harmonic rf cavity. It can also be applied to a non-resonating accelerating system. The adjustment of the system must be far easier than the feedforeward technique. By installing the cancelling tube in a separate cabinet, the system can be installed onto an existing accelerating system.

During the study of this technique, a new delay device has been developed. This delay makes the system very simple.

ACKNOWLEDGMENTS

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2) P. Barratt et al, "•••Beam Loading Compensation on the ISIS Synchrotron", Proc. EPAC-90, p949-951, Nice, 1990.

3) S. Ninomiya, "•••Design of a Non-Resonant Accelerating System•••", KEK Report 92-2.

4) S. Ninomiya, "Design Study of a Low Output-Impedance RF Power Source", KEK Report 95-14.

TABLE 1

List of parameters of the Accelerating System in Ref. 4)

Injection/Extraction Energy	200MeV/3GeV
Frequency Range	2.16 ~ 3.72MHz.
Harmonic Number	4
Revolution frequency	0.54 ~ 0.93MHz.
Circulating Beam Current	5.8 ~ 10A.
Average Machine Radius	50m.

APPENDIX. VARIABLE ANALOGUE DELAY

In this case we use a low-pass-filter type delay for simplicity.

The delay circuit is shown in Fig. 3. The circuit is equivalent to that of a transmission cable. Let the equivalent circuit of the cable constitute an n-unit circuit which forms a low-pass filter made by an inductance (L) and a capacitance (C).

The delay time (T_d), characteristic impedance (Z_0), and the cutoff frequency (ω_H) of the circuit are given by

$$T_d = n\cdot\sqrt{LC}, \quad Z_0 = \sqrt{L/C}, \quad \text{and} \quad \omega_H = \frac{1}{\sqrt{LC}}.$$

The capacitance of the varactor diode is given by

$$C_d \simeq \frac{C_0}{(V_0 + V)^\gamma},$$

where C_0 and V_0 are constants of the diode, and γ is a constant having a value of between 0.33 to 2; and V is the reverse voltage at the junction.

The saturating inductor is described by

$$L_S \simeq \frac{L_0}{(1 + k\cdot I_B)^\lambda},$$

where L_0, k, and λ are constants which depend upon the material and the size of the ferrite. In our case the value of λ is 1.3. As shown in Fig. 3, I_B is given by V/R. Therefore, the delay time is given by

$$T_d \simeq \frac{n\cdot(C_0L_0)^{1/2}}{(V_0 + V)^{\gamma/2}\cdot(1 + kV/R)^{\lambda/2}} \simeq \frac{n\cdot(C_0L_0)^{1/2}(R/k)^{\lambda/2}}{V^{(\gamma+\lambda)/2}},$$

where we used approximations of $V \gg V_0$ and $kV/R \gg 1$. Similarly, the characteristic impedance and the higher cutoff frequency are given by

$$Z_o \simeq \left(\frac{L_o}{C_o}\right)^{1/2} \cdot \frac{(V_o + V)^{\gamma/2}}{(1 + kV/R)^{\lambda/2}} \simeq \left(\frac{L_o}{C_o}\right)^{1/2} \cdot \frac{V^{(\gamma-\lambda)/2}}{(R/k)^{\lambda/2}}$$

and

$$\omega_H \simeq \frac{(V_o + V)^{\gamma/2} \cdot (1 + kV/R)^{\lambda/2}}{(C_o L_o)^{1/2}} \simeq \frac{V^{(\gamma+\lambda)/2}}{(C_o L_o)^{1/2}(R/k)^{\lambda/2}},$$

respectively. T_d and $1/\omega_H$ have a control-voltage dependence of $V^{(\gamma+\lambda)/2}$, Since the values of both γ and λ are on the order of 1, $(\gamma-\lambda)/2 \sim 0$; thus, the characteristic impedance (Z_o) does not strongly depend on the control voltage.

For our test experiment of the variable delay, I used the toroid core of a ferrite with $\mu_r = 2000$. The sizes of the core were as follows: outer and inner diameters of 6.3mm and 3mm, respectively, and a thickness of 2.2mm. The larger permeability was selected because of its bias-field dependence: the permeability (μ_r) reduces to 100 at a field of 200A/m; it reduces to only 5 at 2000A/m. A 10-turn coil was wound on the core. A bias current (I_B) of 3A on the coil produces a bias magnetic field of nearly 2000A/m.

The varactor diode has a junction capacitance of 450pF at a reverse voltage of 2V, which reduces to 20pF at 27V.

The estimated values of the unit delay element are:

$L \sim 2\mu H$ at $I_B \simeq 0.4A$, $C \sim 350pF$ at $V \simeq 3.6V$,

we obtain $Z_o \sim 76\Omega$, $T_d \sim 26ns$, $\omega_H \sim 2\pi \cdot 6.0 \cdot 10^6$ rad/s.

$L \sim 0.2\mu H$ at $I_B \simeq 3A$, $C \sim 20pF$ at $V \simeq 27V$,

and $Z_o \sim 100\Omega$, $T_d \sim 2ns$, $\omega_H \sim 2\pi \cdot 80 \cdot 10^6$ rad/s.

However, $n = 40$ is necessary to obtain $T_d = 1.5\mu s$, the test is performed with only $n = 12$. We obtained $T_d = 0.33\mu s$ with a $f_H = 4$ MHz bandwidth at $I_B = 0.4A$, and $T_d = 22ns$ with 40MHz at $I_B = 3A$. The characteristic impedance of the delay was 70Ω. These results are shown in Figs. 4 and 5. In this case the delay time is given by $2120[ns]\cdot V^{-1.37}$. Therefore, for the delay with $n = 48$ unit elements, $T_d \simeq 8500[ns]\cdot V^{-1.37}$, and we can obtain $T_d \simeq 1.32\mu s$ at $I_B = 0.4A$.

For a real application, the sizes of the ferrite core have to be reduced to 1/2 ~ 1/3 in order to reduce the bias current, and, thus, to reduce the necessary power to control the delay. The varactor diode must also be exchanged to a small reverse-voltage type. One can obtain a diode which varies its junction capacitor from 500pF at 1V to 20pF at 8V.

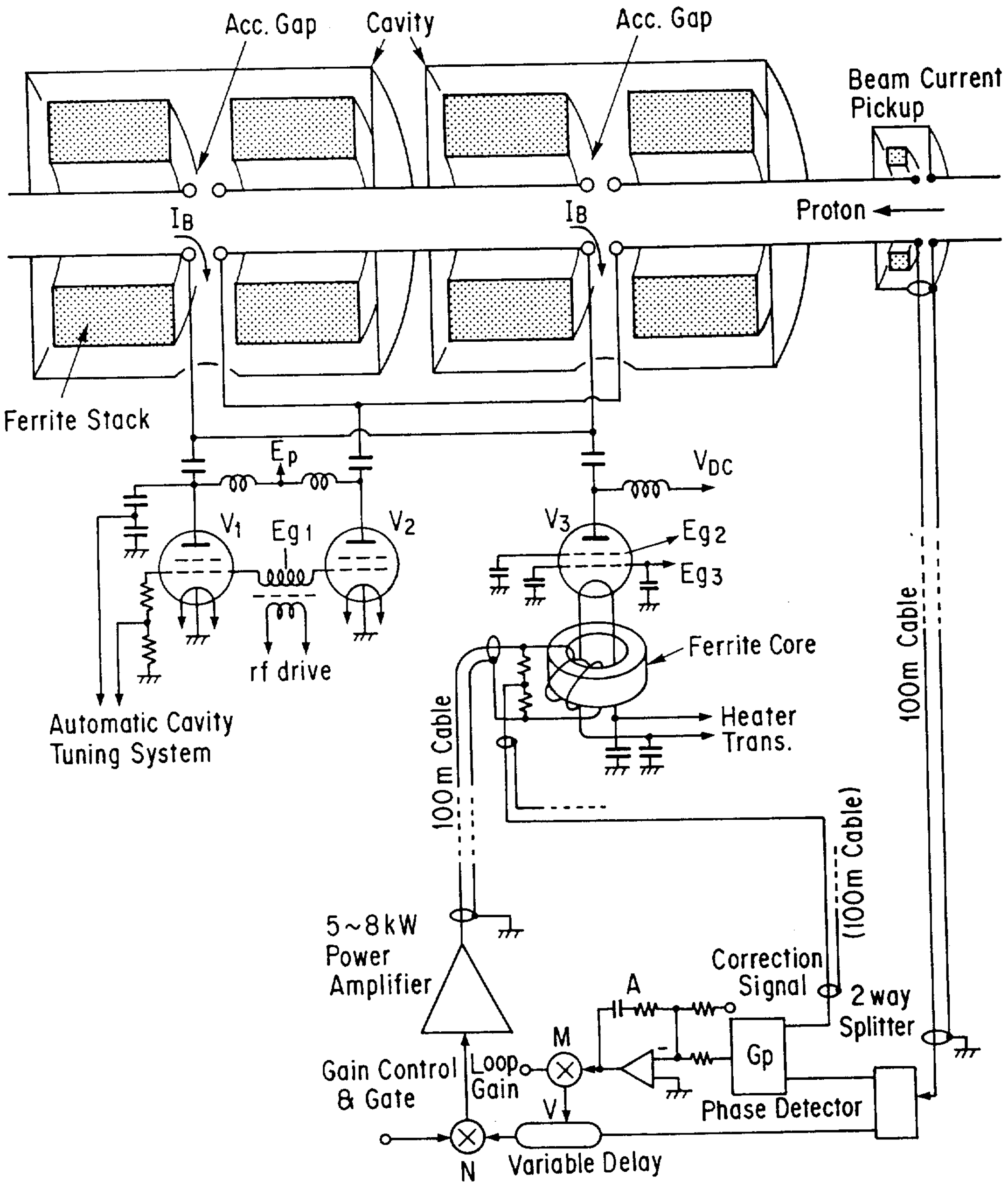

Fig. 1 Schematic diagram of the system.

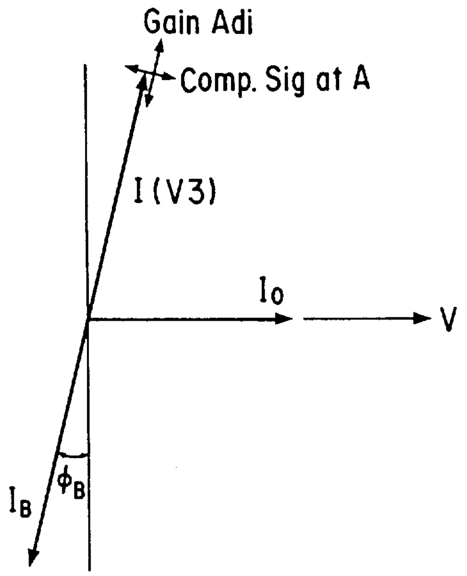

Fig. 2 Phaser diagram.

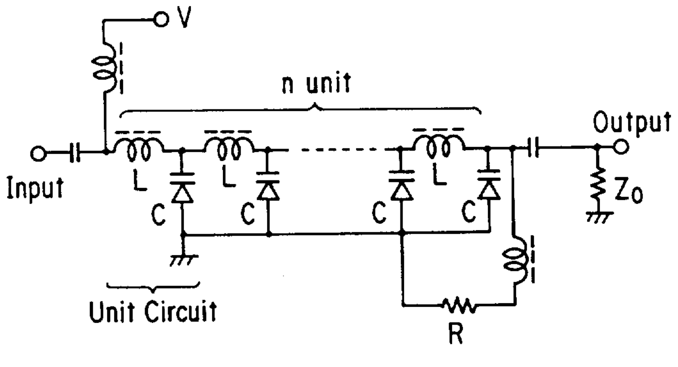

Fig. 3 Delay circuit.

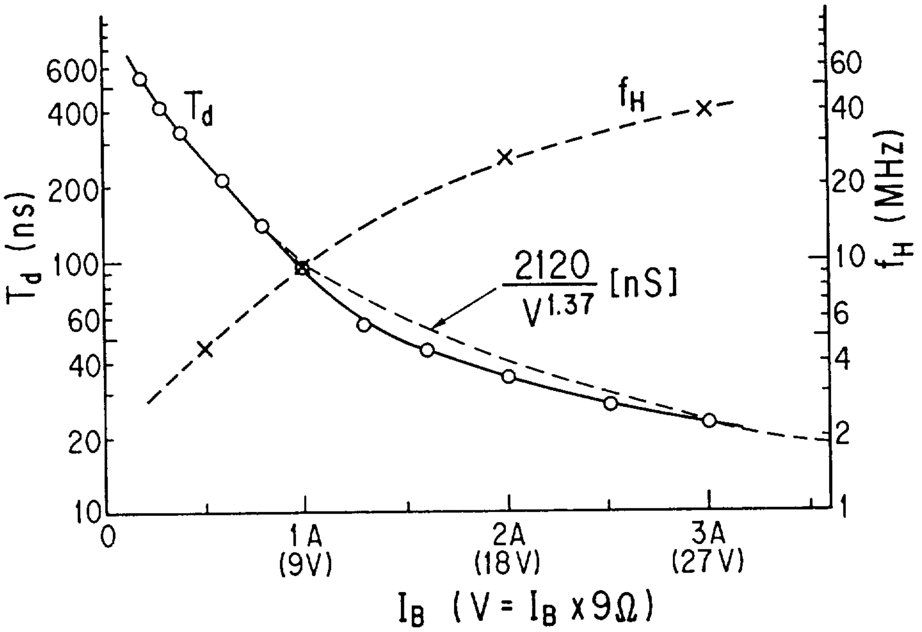

Fig. 4 Variation of delay time vs control current (voltage).

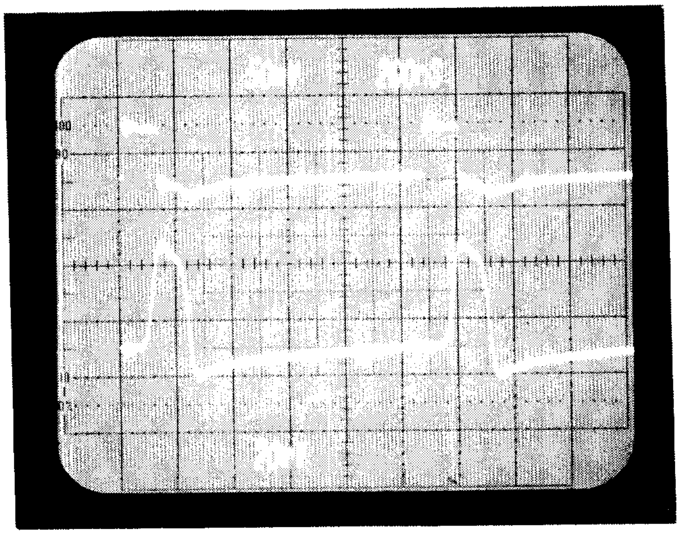

Fig. 5 Example of input pulse(upper) and delayed out(lower) at I_B = 1A.