A NEW CONCEPT OF A FAST MAGNETIC KICKER SYSTEM: BRIDGED-T NETWORK LUMPED KICKER

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Abstract

This study proposes a novel fast magnetic kicker system: the bridged-T network lumped kicker. The rise time is comparable with that of a transmission line kicker, while the input impedance can be matched with the characteristic impedance of the pulse power supply. A lumped magnet core and matching elements form the bridged-T network, so that the complex structure associated with a transmission line magnet is no longer required. A demonstration of the proposed scheme is also performed and the results are as anticipated.

INTRODUCTION

In order to make a synchrotron compact, a high-field bending magnet that reduces the synchrotron's ring radius and a high-field gradient accelerating cavity with a wideband RF amplifier are required. These components have been studied with successful results. However, a limited straight-section length and rapid cycling mean that the injection/extraction of beams into/from the synchrotron ring are important issues that need to be addressed in order to make a ring compact.

A fast kicker is a high-power pulse magnet system for injection/extraction. It should be compact so that it can be easily installed in a straight section having a limited length, and it should be operated with extremely short rise/fall times. It is difficult to apply a conventional kicker magnet, such as a transmission line magnet [1, 2], to a compact ring.

As an alternative to conventional kickers, this study proposes a novel fast magnetic kicker system: the bridged-T network lumped kicker. The bridged-T network is sometimes called an all-pass filter, a constant resistance network or a Zobel network [3]. With this type of network, the input impedance can be purely resistive, while the load impedance depends on the frequency. The bridged-T network transforms a lumped inductive magnet into a complete impedance matched kicker without the need for a complex structure, and the rise time is comparable with that of a transmission line kicker.

PROPOSED REFLECTION-FREE KICKER SYSTEM

Bridged-T network lumped kicker

The proposed kicker system shown in Fig. 1 is a bridged-T network composed of a lumped kicker and elements that follow a matching condition. Thus, the input impedance, $z_{\rm in} = v_{\rm in}/i_{\rm in}$, is exactly equal to R.

This network behaves as a low-pass filter. The current transfer function ($G_{\rm im} \equiv |\, i_{\rm m}/(v_{\rm in}/R)|$) gives the cut-off (–3 dB) angular frequency ($\omega_{\rm c}^{\rm BTN}$) as a solution of $G_{\rm im}{}^2 = 1/2$, which is expressed by

$$\omega_{\rm c}^{\rm BTN} = \sqrt{2\left(\sqrt{5}+1\right)}\,\frac{R}{L} \cong 2.54\times\frac{R}{L}.$$

The step response of this system gives the rise time as

$$t_{\rm rise}^{\rm BTN} = \frac{2\pi}{3\sqrt{3}}\frac{L}{R} \cong 1.21\times\frac{L}{R}.$$

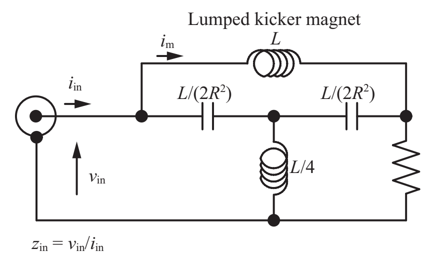

Figure 1: Proposed kicker system: Bridged-T network lumped kicker.

Advantages

The proposed bridged-T network kicker offers several advantages. Even if a lumped inductance magnet is applied to a fast kicker, complete impedance matching is realized, in principle. A complex structure, such as the one for the transmission line magnet, is no longer required, while the rise time is comparable with that of a transmission line kicker. The impedance matching characteristic with a simple structure provides a reflection-free kicker system. Distortion in the pulse waveforms and an unexpected magnetic field caused by reflections can be avoided. Thus, it is possible to design an inexpensive but reliable system with a reduced risk of machine failure.

The transmission line magnet is usually installed in a vacuum chamber in order to withstand the high voltage between the capacitor plates. Such capacitor plates are not necessary for the proposed kicker, and external vacuum installation becomes possible. In this case, a large vacuum enclosure with an expensive feedthrough is unnecessary. Although the aperture's dimension increases due to the requirement for a ceramic beam chamber [2], the beam loss caused by outgassing from the ferrite magnet core is reduced.

Based on these advantages, the proposed kicker is an optimal system for a compact synchrotron. Applying this

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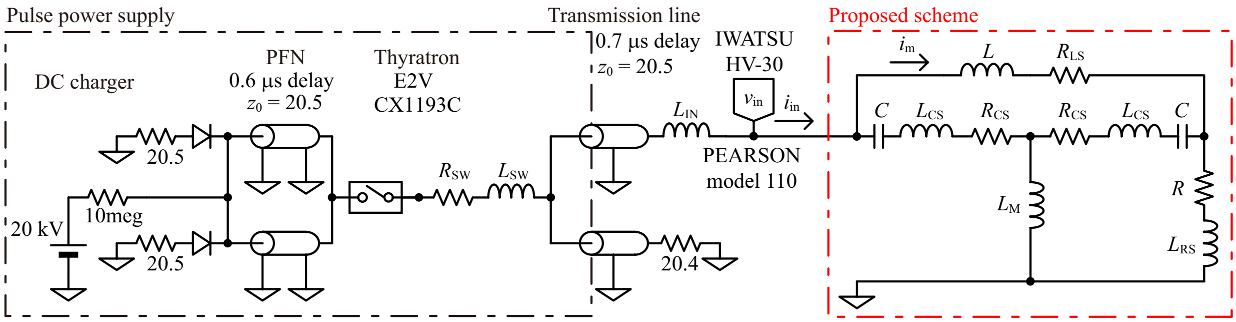

Figure 2: System setup.

Table 1: Design parameters of the model kicker system. Measured and assumed values are shown in round and square brackets, respectively.

Magnet core	
Gap height (mm)	55
Gap width (mm)	140
Core length (mm)	400
Inductance L (μH)	1.40 (1.40)
Matching elements	
Terminator resistance R (Ω)	20.5 (19.4)
Matching capacitance C (nF)	1.67 (1.67)
Matching inductance L_M (μH)	0.35 (0.36)
Parasitic components	
R_{LS} (Ω)	(0.2)
L_{RS} (μH)	(0.1)
L_{CS} (μH)	(0.05)
R_{CS} (Ω)	(0.6)
L_{IN} (μH)	(0.5)
R_{SW} (Ω)	[1.4]
L_{SW} (μH)	[0.8]
Input pulse	
Input voltage (kV)	10 (9.3)
Input current (kA)	0.5 (0.48)
Ramping time (ns)	50 (52)
Magnetic field	
Field rise time (ns)	132 (133)
Field flat top (μs)	1.2
Field strength (mT)	14.4
Kick strength (mTm)	5

system to a large synchrotron is also favourable because of its reliability and simplicity. As an example, a beam extraction system from a rapid-cycle synchrotron is given. A resonant slow extraction method cannot be applied to such a synchrotron, and only fast extraction is available where a relatively fast rise time is required. Because the extraction system comprises many kickers to achieve such a fast rise time, lower construction costs are also required. The proposed kicker is also useful for a painting injection method where a zero post-pulse field is required.

DEMONSTRATION

System setup

As shown in Fig. 2, the model system consists of a typical pulse power supply and the proposed kicker magnet forming a bridged-T network. The design parameters are listed in Table 1, where the measured and assumed values are also shown in round and square brackets, respectively.

The aperture of the ferrite magnet core is 140 mm in width and 55 mm in height, and the length of the magnet is 400 mm. The measured inductance of the magnet (L) is 1.40 μH. A terminator resistor (R) is prepared to be matched with the characteristic impedance (20.5 Ω) of the pulse power supply. Two ceramic capacitors (C) and an inductor (L_M) are attached to the magnet core in accordance with the matching condition, as shown in Fig. 1. The impedances of these matching elements, listed in Table 1, are measured with an ADVANTEST R3765CG network analyzer. Although the measured values differ from the calculated values determined by the matching condition, further optimization is not performed. As shown in Fig. 2 and Table 1, several parasitic components exist. The matching condition is also disturbed by the parasitic components, such as the resistance (R_{LS}) of the magnet, the lead inductance (L_{RS}) of the terminator, the lead inductance (L_{CS}) and the resistance (R_{CS}) of the matching capacitor.

The pulse power supply is designed for the J-parc Main Ring kicker system and was applied in this demonstration. Although the designed charging voltage is 60 kV, it was operated at only 20 kV. Because the on-resistance (R_{SW}) of a thyratron depends on its working point and R_{SW} decreases with the charging voltage, a lower charging voltage increases the ramping time. The lead inductance (L_{SW}) across the thyratron also contributes to the longer ramping time. The ramping time of this power supply was tested for 20-kV operation with a pure resistance used as a load, and the measured ramping time was 52 ns. Relative to the SPICE simulation, R_{SW} and L_{SW} were assumed to be 1.4 Ω and 0.8 μH, respectively.

The kicker magnet is connected with the pulse power supply through a transmission line. Because the pulse inlet connector at the end of the transmission line is not designed for the proposed kicker system but for the J-parc kicker system, the connector is directly wired with the magnet. The measured lead inductance of the wire was 0.5 μH. The input voltage (v_{in}) and current (i_{in}) were measured by an IWATSU HV-30 1000:1 high voltage probe and a PEARSON model 110, respectively. To measure the pulsed-kicker magnetic field, a long search coil (600 mm in length and 10 mm in width) was used. The induced voltage across the coil (v_s) was integrated to obtain an integrated magnetic field, BL.

Test Results

The pulse response test result is shown in Fig. 3. Including the parasitic components shown in Fig. 2, SPICE simulations are also performed. The test results agree well with the calculations. The field rise time is 133 ns, which agrees with the calculation for a 52-ns ramping time for the pulse power supply. However, a bump at around 1.8 μs and a small post-pulse at 2.4 μs after turn-on are observed in Fig. 3. SPICE simulations suggest that the bump is caused by the high on-resistance (R_{SW}) and the post-pulse by the lead inductances, L_{IN}, L_{CS} and L_{RS}.

Input impedance was measured by an ADVANTEST R3765CG network analyzer. The result is shown in Fig. 4. The frequency dependence is quite small. The contribution of the lead inductance (L_{CS}) across capacitors appears in the frequency range 1–15 MHz, and the lead inductance (L_{RS}) of a terminator contributes above 15 MHz.

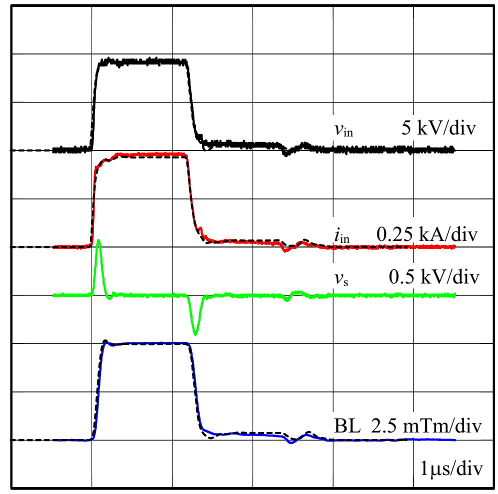

Figure 3: Pulse response. The dashed lines show calculations from a SPICE simulation.

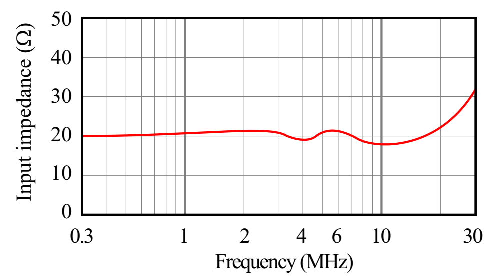

Figure 4: Input impedance.

CONCLUSIONS

A novel fast magnetic kicker system, is proposed. This system consists of a lumped magnet core and matching elements that form a bridged-T network. If a proper terminator is prepared, then, in principle, the input impedance can be set as purely resistive. The low-pass current transfer function gives the cut-off frequency, and it provides a fast rise time performance that is comparable with that of a transmission line kicker. Even if a lumped magnet is used, these characteristics can be maintained without the need for a complex magnet structure, such as the one found in a transmission line system.

The proposed scheme was tested, and the results were consistent with expectations. Several issues arose during testing: the lead inductance of the terminator caused an impedance mismatch in the higher frequency range that produced reflections and an unexpected post-pulse; a higher on-resistance led to not only a slower ramping time but also a post-pulse; a lead inductance across capacitors caused a weak impedance mismatch in the middle-frequency range. However, if a tapered coaxial terminator [4] and a high charging operation are applied the pulse waveform will be improved.

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