# FERRITE PROPERTY EFFECTS ON A FAST KICKER MAGNET

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*Abstract*

The present J-PARC main ring (MR) injection system employs four lumped kicker magnets. Their task is to injection two bunches per cycle from the Rapid Cycling Synchrotron to the defined bucket in the MR. The operation must be loss-free to avoid any damage to the accelerator. However, the present injection kicker's field have relatively long rise time and large reflection field that do not satisfy the requirements of high beam power operation. Besides the upgrade of the main kickers, two small fast compensation kickers are being studied in parallel to correct the main kicker performance. Since high magnetization rates in magnetic materials are associated with considerable magnetic losses, high quality Nickel Zinc ferrite magnetic materials are required to ensure the performance of the compensation kickers. Therefore, the studies of ferrite materials effects on the parameters of both compensation kickers have carried out to optimize the design.

## INTRODUCTION

The J-PARC is a high intensity proton beam accelerator facility that consists of a LINAC, a Rapid Cycle Synchrotron and a Main Ring (MR). The harmonic number of the MR is nine. Four successive batches from the RCS are injected into the MR to fill 8 RF buckets spaced at 300 ns interval. Fig. 1 shows the injection scheme.

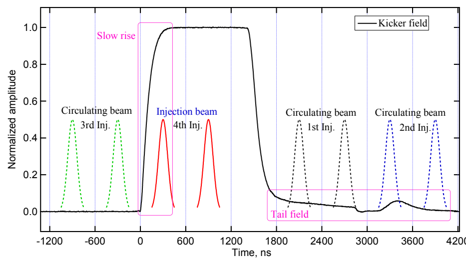


Figure 1: Injection scheme of MR.

The injection system must minimize the injection beam loss and place the newly injected beam onto the correct trajectory, which is extremely important in high beam power operation. To this end the critical demands are posed on the kicker field, which must rise from zero to full in the time interval between the circulating beam and the start of the injected beam, and fall to zero within the time interval and keep zero in order not interfering the subsequent circulating beam.

The present injection kicker is lumped inductance type and the field rise time depends on the total inductance in the pulsed circuit. The total inductance of the present kicker is nearly 1100 nH, and a miss-matching circuit has to be use to speed up the rise time to 350 ns. However, the miss-matching circuit, together with other parameters, lead to nearly 5% reflection tail field (Fig. 1). The long rise time of kicker field restricts the maximum beam length in the ring, which prevents the implementation of second harmonic cavities that is very important to reduce the space charge effects in high power operation. The remaining tail field will give excessive kick angle to the circulating beam and causing beam losses.

To improve the kicker performance, methods of using compensation kickers are being studied in parallel with the main kicker upgrade [2]. Since the compensation pulse is in the order of 100 ns, the magnetization rate is very high, and the magnetization behaviour is entirely different from DC conditions. Therefore, the magnetic materials effects on performance is of a great concern, and the dynamic studies of magnetic materials have been taken to know how the ferrite affects the kicker performance. The main magnetic parameters of ferrite are frequency dependent, which are characterized by the frequency dependant complex permeability of ferrite,

$$\mu_s = \mu_s' - j\mu_s''$$

Where, $\mu_s'$ is the real permeability, and $\mu_s''$ is the imaginary permeability. Fig. 2 compares the complex permeability dispersion of three different ferrite materials CMD5005, CMD10 and C2050 (Ceramic Magnetics, Inc.). The effects of the 3 different ferrite materials are studied for optimization.

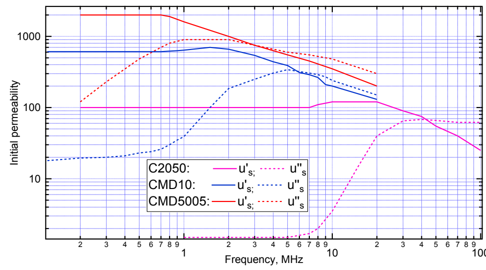


Figure 2: Basic parameters of ferrite.

## RISE COMPENSATION KICKER

### *Rise time improvement*

The kicker excitation current shown in Fig. 1 starts at zero and exponentially grows to maximum in 350 ns. The increasing current is governed by,

$$I = I_0(1 - e^{-\alpha t})$$

Where, $I_0$ is the maximum current, and $\alpha$ is the time constant determined by the parameter of $R$, $L$ and $C$ in the circuit. The $\alpha$ can be obtained by fitting the current the waveform. The slow exponential growth current can be speeded up by superimposing a small compensation current as illustrated in Fig. 3. Practically, a small

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correction kicker can be installed near the main kickers to realize this purpose.

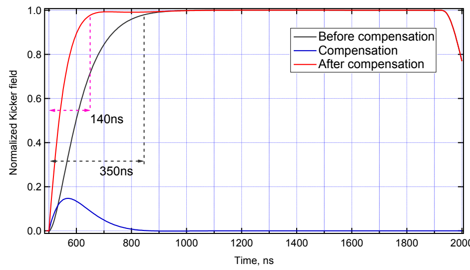


Figure 3: Compensation kicker to fasten rise time.

### *Basic circuit*

The basic circuit of the rise compensation kicker can be realized by a simple LRC series circuit as shown in Fig. 4. The kicker excitation current is the capacitor discharge current. In order to compensate the rise edge only without introducing ripple to the flattop, a slightly over-damped compensation current is needed, which is given by,

$$i(t) = A_1 e^{-\omega_0(\varsigma+\sqrt{\varsigma^2-1})t} + A_2 e^{-\omega_0(\varsigma-\sqrt{\varsigma^2-1})t}$$

Where, $\omega_0 = 1/\sqrt{LC}$ is the radian frequency, and $\varsigma = \frac{R}{2}\sqrt{C/L}$ is the damping factor.

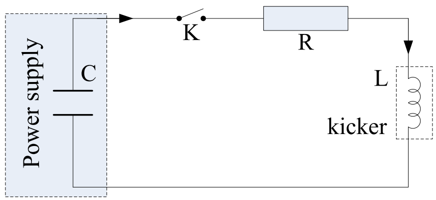


Figure 4: Basic circuit of rise compensation kicker.

### *Ferrite effects on circuit parameter L*

The compensation current pulse shape is required to be very delicate to correct the rise time exactly. However, the inductance of the compensation kicker is determined by the ferrite material which is frequency dependent. Thus, the material property may have considerable effects on the performance of the compensation kicker particularly at high frequency range. In view of magnetic field generation high permeability materials are preferable. But high permeability materials normally have narrow bandwidth, which will degrade the signal response at high frequency. Fig. 5 compares the frequency dependent coil inductance using different ferrite materials.

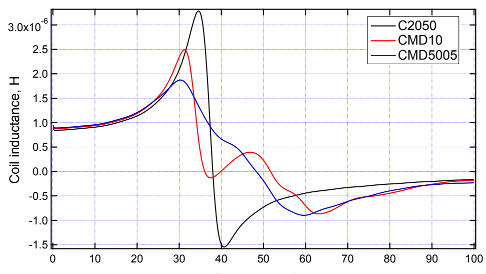


Figure 5: Coil inductance vs. frequency.

### *Ferrite effects on coupling impedance*

The beam passing through kicker aperture can become a high power current source, which will induce magnetic field inside the ferrite core that not only affects the beam motion but also consumes considerable EM energy causing temperature increase in the ferrite core. The effect is defined by the longitudinal coupling impedance, which is dependent on the property of magnetic materials. Fig. 6 compares the longitudinal impedance with 3 different ferrite materials.

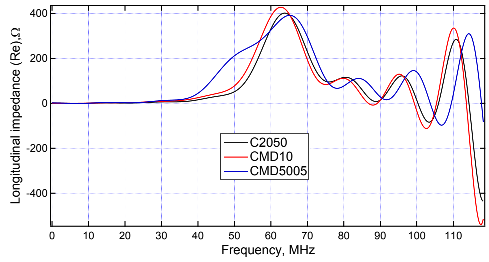


Figure 6: Longitudinal impedance comparison.

## TAIL COMPENSATION KICKER

The irregular tail field (Fig. 1) provides different error kick angle to different subsequent circulating beams. Thus, to correct these errors exactly a fast transmission line kicker that can provide arbitrary waveform has been studied. Conventional transmission line kicker design uses parallel plates as cell decoupling capacitors, which makes the design and construction more complicated. In order to ensure the kicker field without any degradation when travelling through the kicker, high cut-off frequency of the kicker is a key parameters that is given by [2],

$$f_c = \frac{1}{\pi\sqrt{(L_n + 4L_{cs})C_n}} \qquad (2)$$

Where, $L_{cs}$ the stray inductance of cell capacitor. Fig. 7 shows the basic circuit of the tail compensation kicker system.

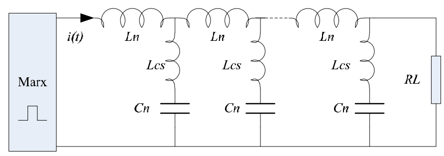


Figure 7: Tail compensation kicker circuit.

### *Transmission line kicker with lumped capacitor*

Conventional design of transmission line kicker has high frequency property because of the interleaved high voltage plates as cell capacitance can provide very small stray inductance [3]. However, it is difficult to reduce the character impedance of the kicker due to the vacuum dielectric materials, which limits the excitation current. To further reduce the impedance, lumped capacitor with high permittivity dielectric materials is implemented. The structure is shown in Fig. 8.

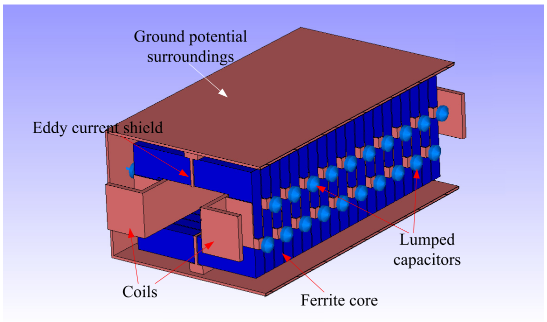


Figure 8: Tail compensation kicker.

### *Ferrite effects on circuit parameters*

The character impedance of each cell of the transmission line kicker must be uniformly distributed to eliminate the reflection field and to suppress field ripple. The cell character impedance is defined by the cell inductance and the cell lumped capacitance. However, the cell inductance is determined by the ferrite property and the location of the individual ferrite blocks. The compensation kicker consists of 20 ferrite blocks with thickness of 20.5 mm separated by 2 mm copper plates as shown in Fig. 8. The cell inductance can be determined by the magnetic flux of each ferrite block, which is shown in Fig. 9.

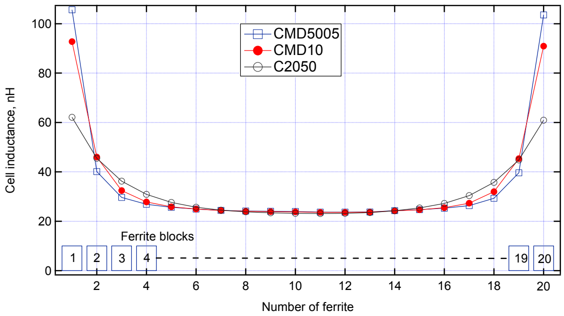


Figure 9: Cell inductance distribution (DC).

It shows clearly that the cell inductance is location dependent due to the different leakage magnetic flux. The cell inductance is frequency dependent also. Fig. 10 compares the total coil inductance versus three different ferrite materials. The AC inductance is larger than that calculated in DC case.

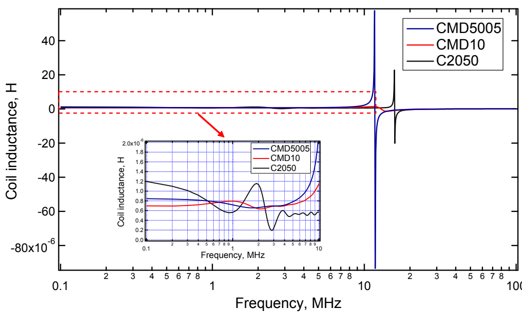


Figure 10: Frequency dependent coil inductance.

### *Ferrite effects on coupling impedance*

Comparing to the lumped inductance rise compensation kicker, the transmission line kicker has relatively small longitudinal coupling impedance, which is because of the cell capacitors. Fig. 11 compares the coupling impedance calculated in three different ferrite materials.

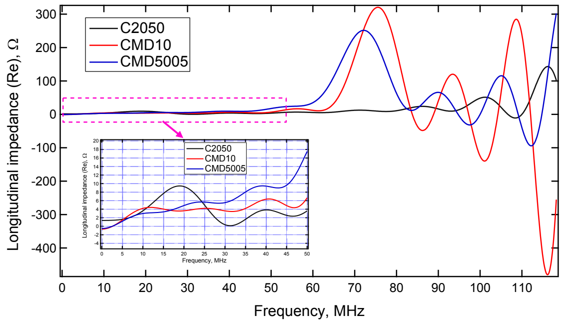


Figure 11: Longitudinal coupling impedance comparison.

The coil inductance and the kicker impedance made of ferrite C2050 has considerable oscillations even if at low frequency, which makes the performance unstable.

### *Ferrite effects on magnet impedance*

In ideal case the characteristic impedance is constant within the working frequency. However, the frequency dependent property of magnetic materials and the complicated structure enlarge the parasitic effects, which has considerable impact on the compensation kicker performance. For instance, the transmitted parameter Z21 is seriously deformed as shown in Fig. 12, which will deform the kicker filed shape.

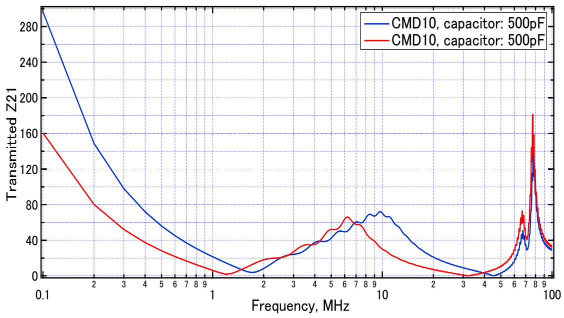


Figure 12: Frequency dependent Z21.

## CLUSION

Compensation kickers together with upgrade of the main kickers will improve the performance greatly, and can satisfy the requirements of high beam power operation. A simple prototype transmission line kicker has been developed [3] for proof of principle and parameters test.

## REFERENCES

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[3] S. Fukuoka, K. fan et al, "Development of a fast compensation kicker system for J-PARC maing ring injection", IPAC'2013.