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Fast-rise high-field kicker magnet operating in saturation

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ABSTRACT

A new fast-rise and high-field kicker magnet system, based on the excitation over the saturation point of magnetic materials, is proposed. Several experiments have been carried out, and three times larger magnetic field density in a half rise time than a conventional kicker system has been achieved using a highly compact conventional magnet, with a low remanent field, less than 1 G. The new system is useful for particle ejection, especially in compact accelerators used in medical and industrial applications. The outline of this new system and experimental results are described here.

1. Introduction

A kicker magnet system [1–3] is used for a beam handling, especially in high-energy particle accelerators [4–19]. Kicker systems should have very fast response because they are required to change the orbit of beams traveling with the velocity of light. Other requirements of kicker systems include a long flattop and a step pulse, which is the most ideal pulse for such systems. An electric kicker system [19–21] can satisfy these requirements, but it can be used only for low-energy beams due to its weak field or for cases where good field uniformity is not required. A magnet can produce a sufficiently high field, but it does not have sufficiently fast response due to its inductance, L. The relationship between the magnetic field of a magnet and its response can be understood by treating a transmission equation like Eq. (1) as a conservation law:

$$2V_f = \mathrm{d}\Phi/\mathrm{d}t + Z_0 I \tag{1}$$

Using a conventional expression of magnetic flux, this equation can be rewritten as follows:

$$(1/2V_f)\mathrm{d}\Phi/\mathrm{d}t + (Z_0/2LV_f)\Phi = 1 \tag{1'}$$

The first term on the left-hand side can be treated as the response term, and the second term can be treated as the field magnitude term. This equation shows a competition between a fast response and a high field. Fig. 1 shows the relationship with representative magnets used for particle accelerators: a kicker magnet, bump magnets, and a septum magnet. The remanent field should be zero in order that the kicker magnet has zero field at almost all times. It is, therefore, common to design such a magnet to operate at low fields without the saturation of the return core. However, since magnetization requires a sufficient amount of stored energy [22,23], there is a possibility of existence of a non-magnetized region, even around the saturation point. In the case of a short pulse excitation, the averaged stored energy in a magnetic material is very low. Effective inductance is proportional to the slope of the B–H line in Fig. 2. Hence, it reduces largely over the saturation point, to be near the inductance without magnetic materials, and it is possible to achieve a fast response in a high-field region, shown by the hatched area in Fig. 1. In this scheme, a magnet can be smaller than a conventional magnet, because the operation at the saturation point is equivalent to the reduction of the volume of magnetic materials. A distributed type of a kicker magnet has the fastest response among conventional magnets. The structure of this type is very complex and large. The above-mentioned new kicker magnet system is very simple and considerably smaller than conventional kickers with the same performance. Moreover, the characteristic impedance of this system can be reduced. This indicates the suppression of instability by beam coupling impedance [24–26]. This kicker system is called "a hyper kicker system" here, tentatively.

A simple theoretical model of the new compact hyper kicker magnet system is described, and its magnetic performance, obtained from preliminary experiments [27,28], is presented in this paper. The stored energy, related to repetition rate and pulse duration, is one of the important parameters. It will be necessary to have another discussion in the case of the operation at much larger stored energy in future. The experiments have been carried out using 1 μs-wide pulses at a repetition rate up to 10 Hz, which is useful for almost all accelerators.

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2. Estimation using saturation scheme

2.1. Description of magnet

An integral or averaging method with several approximations is useful for obtaining an overview of a system and its easy application to an electrical circuit. A one-dimensional time-dependent approach is described here. A lumped magnet is characterized by dimensions and magnetic field parameters of its gap aperture, $w \times h$, H, and B, its return core, $w_f \times l_f$, H_f, and B_f, (Fig. 3) with a magnetic length of a, excited by current I. Here, H and B indicate the magnetic field and its density, respectively. By using Faraday's law and flux law, the following typical equations are derived:

$$\Phi = Bwa = B_f w_f a \tag{2}$$

$$hH + l_f H_f = I \tag{3}$$

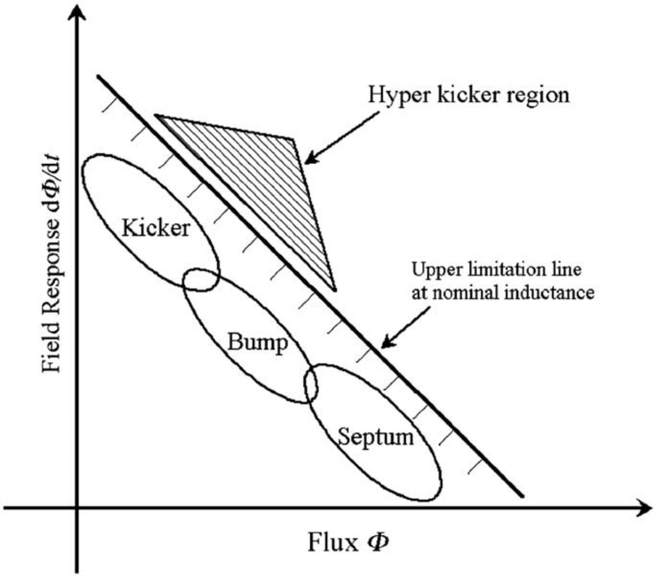

Fig. 1. Conceptual figure for representation of pulsed magnets. The field-magnitude term is plotted on the horizontal axis and the field response term is plotted on the vertical axis.

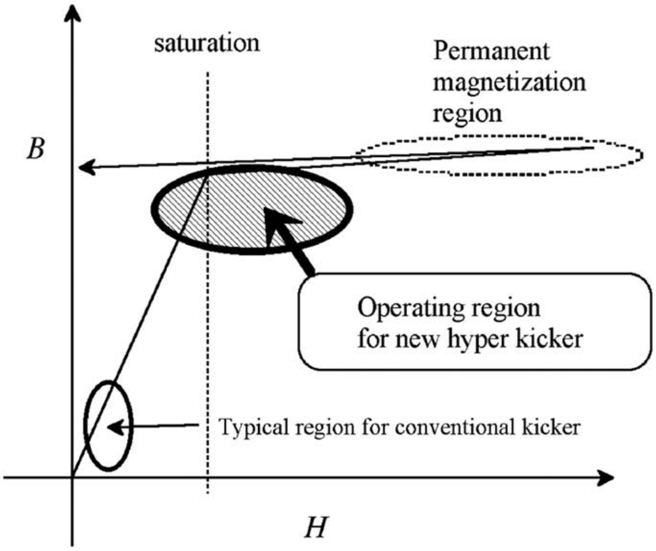

Fig. 2. Schematic figure of the operation point of pulsed magnets.

The B–H characteristic curve of a magnetic material for this system can be approximated as follows:

$$B_f \sim B_s\{1 - \alpha \exp[-\lambda_1 H_f] + (1-\alpha)\exp[-\lambda_2 H_f]\} + \mu_0 H_f \tag{4}$$

Here, the permeability of vacuum is denoted by μ_0, saturation field density, B_s. The parameters α, λ_1, λ_2 are used to describe the characteristic of a magnetic material. The values of those parameters are 0.3 T; 0.65, 0.7, 15 Oe^{-1}, respectively, for the magnetic material L6H made by TDK, used for the experiments.

The following conventional relationship for an air gap is used here:

$$B = \mu_0 H \tag{5}$$

2.2. Equivalent circuit of transmission line

An excitation current is fed from the power supply through transmission lines to the magnet. A power supply of a current source produces trapezoidal pulses of potential V_f and current I_f (Fig. 4). Using the transmission theory, the characteristic impedance of this system Z_0, the reflection potential V_r, the reflection current I_r, a load potential V, and a load current I can be given as follows:

$$V_f + V_r = V \tag{6}$$

$$I_f + I_r = I \tag{7}$$

$$V_f = Z_0 I_f, \quad V_r = Z_0 I_r \tag{8,9}$$

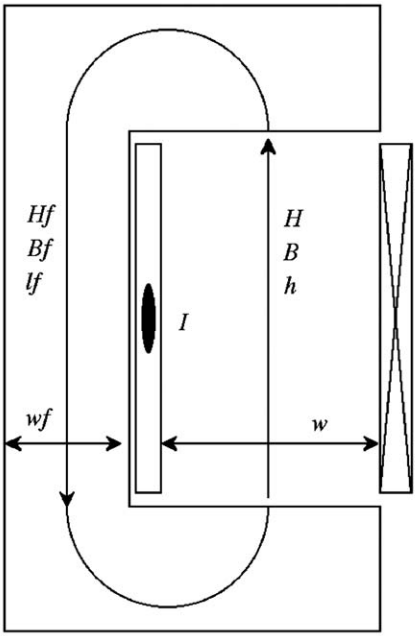

Fig. 3. Magnet model for estimation.

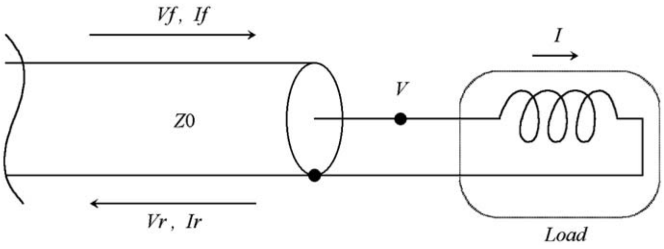

Fig. 4. Electrical model of transmission of pulse.