Developments on Next-Generation Beam Handling of High-Energy Particles by using Non-linear Characteristics

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Abstract: Various developments had been conducted to produce a fast-response magnet by the traditional concepts based on the use of linear-characteristic elements, but the improvement is limited by the transmission theory. The application of non-linear phenomena is important to achieve further improvements. The recent progress and the future plan of the developments to produce a fast-response and strong field for high-energy particle handling are described here.

Keywords: High-energy particle, Pulse, Handling, Non-linear, Transmission, Particle accelerator.

1. INTRODUCTION

High-energy particles travel near the velocity of light *c*, so fast response devices are required for high-energy beam handling [1], especially for selective beam injection/ejection/correction [2]. Many mechanisms, which produce ON and OFF with a long flattop clearly, are necessary to satisfy such a fast requirement, and non-linear phenomena are useful as the most important technique. The power supplies have been developed to apply semiconductor materials earlier than the development of magnets.

The non-linear phenomena used as the conventional techniques, the recent progress of the developments and the future plans are summarized in this paper.

2. PULSE GENERATION FOR EXCITATION OF PULSED DEVICES

A large current pulse is required for excitation of a fast-response and strong-field magnet. Various waveforms of such a current are also required according to each experimental purpose. A high-voltage and large-current switching technique and a pulse forming technique are necessary to produce such a current pulse.

A high-voltage and large-current switching can be achieved by non-linear effects of an electric discharge and plasma phenomena using a vacuum tube. Thyratron [3] works at fastest switching and is often used to a fast-response device such as a kicker magnet system. Such a vacuum tube is, however, thought to be hard for ordinary engineers to maintain it, so the high-voltage and large-current switching by using non-linear band gap of semiconductor materials has been developed since twenty years before. Semiconductor materials have been used for switching on various electronics from of old, but the switching voltage is less than several volts because of the band gap energy. An assembly of many semiconductor materials connected in series and in parallel is necessary to produce a fast-response and large current pulse. Multi-driving technique is important to avoid unbalance of load voltage, which induces overload and breakdown of semiconductor materials. The power supplies using MOSFET [4], SI-thyristor [5], SiC [6] and soon have been developed for high-voltage and fast-response switching recently, although there is no semiconductor switching to surpass vacuum tubes.

There are also devices to form pulse waveforms by using non-linear characteristics, such as the pulse compression technique using magnetic saturation. On the other hand, the pulse forming technique by piezoelectricity is now under development [7]. The characteristic impedance can be changed rapidly by increasing the capacitance in pulse transmission lines (Figure **1**). The pulse current makes mechanical pressure, of which the value is almost proportionate to the square of the current value, to dielectric materials. A small current is hard to flow, and a large current is easy to pass the device, then a similar pulse

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compression effect as magnetic compression can be expected. Almost all dielectric materials are fragile, so some buffer materials (Figure **2**), which can be used for high-voltage, are required. A semiconductor tape, which is used for an electric insulation in a high-voltage coaxial cable, and similar plastic materials are applicable to solve the problem. A simulated LC ladder circuit in the case including mechanical pressure by magnetic force characterized by a material parameter η using non-magnetic materials can be described as follows:

$$V_n = \frac{d[LI_{n+1}]}{dt} + V_{n+1}$$
$$I_n = \frac{d[CV_n]}{dt} + I_{n+1} \tag{1}$$
$$C \equiv C_0(1+\eta I_n^{\ 2})$$

The time deferential of voltage and current are obtained, and those parameters indicate the possibility to produce an impact change of characteristic impedance, as written by eq. (2).

$$\frac{dI_{n+1}}{dt} = \frac{V_n - V_{n+1}}{L}$$
$$\frac{dV_n}{dt} = \frac{I_n\{1 - \frac{2\eta C_0 V_n}{L}(V_{n+1} - V_{n+2})\} - I_{n+1}}{C_0(1+\eta I_n^{\ 2})} \tag{2}$$
$$< \frac{I_n - I_{n+1}}{C_0}$$

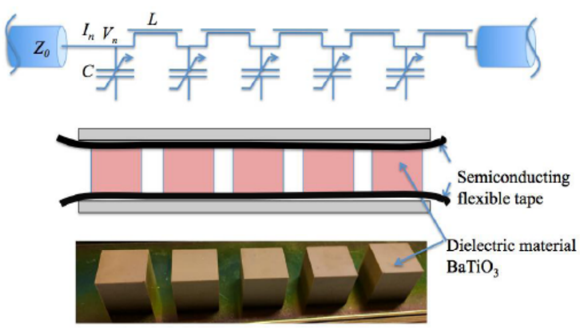

Figure 1: Example of capacitive pulse modulation. The top figure shows the equivalent circuit. The middle one shows the mechanical structure. The bottom figure shows one candidate of the dielectric materials, $BaTiO_3$.

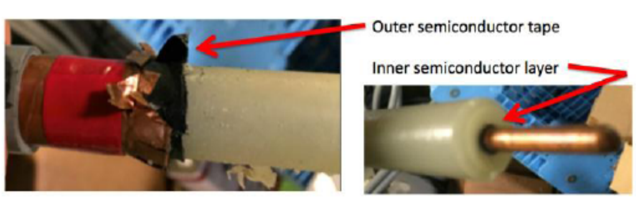

Figure 2: Example of semiconducting materials used for high-voltage coaxial cables.

For small η, the time deferential of voltage is almost same value as that for the normal transmission line.

$$\frac{dV_n}{dt} \sim \frac{I_n - I_{n+1}}{C_0} \tag{3}$$

For large η, the time deferential of voltage is almost independent on current, which flows throughout an inductor.

$$\frac{dV_n}{dt} \sim -2\frac{V_n}{Z_0 I_n}\frac{(V_{n+1} - V_{n+2})}{L/Z_0} \tag{4}$$

3. FAST-RESPONSE MAGNETS

There is a practical limitation to produce high electric field due to an electrical breakdown, 30 kV/cm for instance in air. Pulsed magnets are, therefore, used to control higher-energy particles. An electric field and a magnetic field with magnetic material yoke, shown in Figure **3**, produced by a power supply with voltage V_f and characteristic impedance Z_0, can be estimated in the case as follows:

$$E \sim \frac{V_f}{a}$$
$$B \sim \mu_0 \frac{V_f}{aZ_0}. \tag{5}$$

The characteristic impedance of a power supply is around 10 Ω for fast-response pulses. The effect ratio on high-energy particle motion in a magnetic field is larger that in an electric field.

$$(ratio) \equiv \frac{cB}{E} \sim \frac{c\mu_0}{Z_0} = \frac{Z_c}{Z_0}, \tag{6}$$

where Z_c is the characteristic impedance in vacuum, 377 Ω.

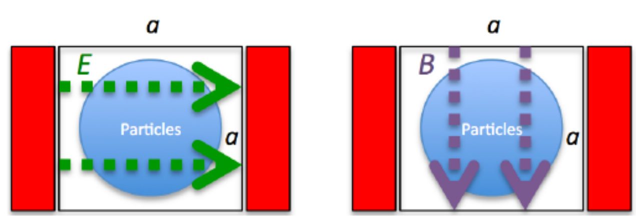

Figure 3: Comparison of effects on high-energy particle motion with electric and magnetic fields.

The field effect by a magnetic field is very strong, but a fast response is hard to be produced due to the inductance of a magnet. The distributed type of magnets had been developed, but the field was very weak. The performance of fast response and field strength lies on the competitive relation, which can be derived by the pulse transmission theory [8].

$$2V_f = V + Z_0 I \sim \frac{d\Phi}{dt} + \frac{Z_0}{L}\Phi \quad (7)$$

The equation shows the performance limitation of fast-response magnets by the traditional concepts based on the devices with linear characteristics.

The improvement of field performance by using non-linear characteristics of magnetic materials has been performed. The key point is excitation over saturation of magnetic materials used for yoke. A strong field can be produced by using magnetic materials as yoke before saturation, and a fast response can be produced by reduction of the actual inductance over saturation. On the other hand, zero-field formation is also important, so a magnetization must be prohibited. The upper limitation of field performance by the method is decided by the magnetization condition. A hard ferrite can produce high field, but a fast response performance cannot be obtained due to the eddy current effect. A soft ferrite is often used for a fast response magnet, although the saturation field is weak. The experiment of large current excitation was performed to confirm the reduction of inductance and fast recovery of saturation by using a simple capacitor bank discharge, as shown in Figure **4** (Tables **1** and **2**). Figure **5** shows the observed magnetic field and current. A simple sinusoidal waveform with a resistive damping should be obtained in the case using elements with linear characteristics. The observed current waveforms are similar to the calculated results (Figure **6**), and are distorted near 12 kA, which is equivalent to the value excited by a short trapezoid pulse, as shown in Ref 1. It indicates that field saturation and fast recovery were achieved. The reduction of the inductance according to charging voltage is induced quickly in comparison with lower-voltage excitation. The effect is also observed in the change of sinusoidal frequency clearly. A remanent flux density was less than 0.5 Gauss, which is 0.1 % of a main field and is enough to be ignored for high-energy particle handling.

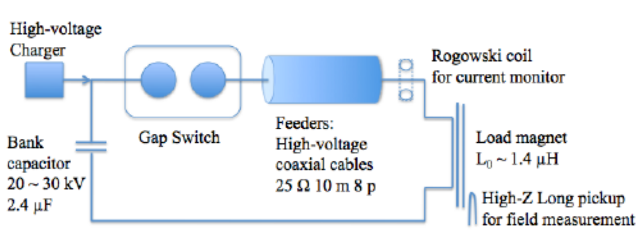

Figure 4: The equivalent circuit for the large current excitation.

Table 1: Representative Parameters of the Power Supply

Parameters	Values
Charging Voltage	40 kV
Capacitance of Bank	3.75 µF
Pulse feeders	8 coaxial cables of Z0 = 25 Ω

Table 2: Representative Parameters of the Load Magnet

Parameters	Values
Type of yoke	Twin C
Air gap *w* x *h*	140/2 [mm] x 55 [mm]
Ferrite yoke w_f x l_f	50 [mm] x 250 [mm]
Magnet length *a*	400 [mm]
Ferrite material	L6H, *Bs* = 0.3 T

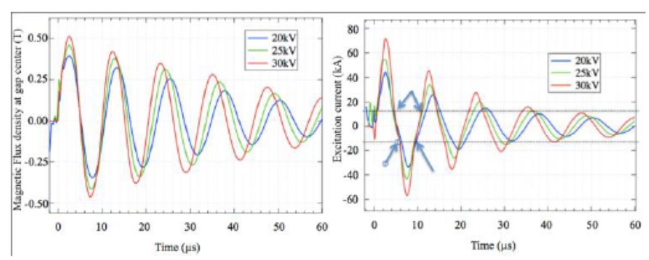

Figure 5: The measured results of magnetic flux density and current for excitations at bank voltages of 20 kV, 25 kV and 30 kV.

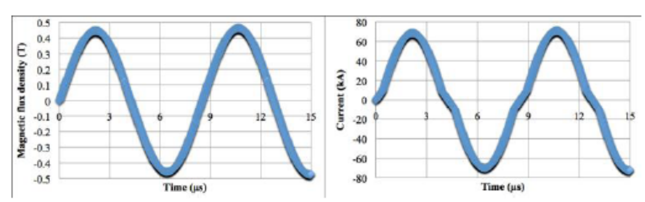

Figure 6: The simulated waveforms of magnetic flux density and current for excitations at bank voltages of 30 kV. The similar effects were observed as the measured results. Note that a damping term was not included in the calculations.

4. NON-LINEAR FIELD PRODUCTION IN MAGNET BY POWER SUPPLIES

The conventional magnet does not change the performance largely for long time after installation into an accelerator complex. This means that a stable performance is produced for high-energy particle handling, but it has no feasibility to adjust the field performance and to obtain higher-quality high-energy beam. The technique to produce various field patterns in time and in space has been developed by only changing the outputs of the power supplies recently [10]. Figure **7** shows the representative patterns to produce a dipole field and a quadrupole field. The yoke was separated and each section was excited by a power supply independently, so various waveforms in space and in time can be produced, as shown in Ref. 11. This technique is useful especially in the highly irradiated environment.

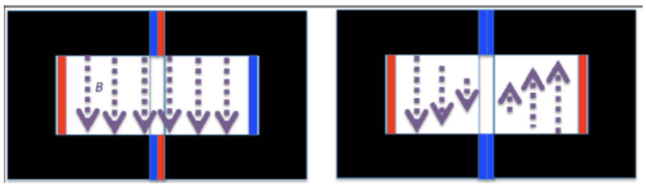

Figure 7: Field patterns produced by changing the outputs from power supplies.

5. FIELD WAVEFORM MODIFICATION BY USING QUENCH

The superconducting effect brings a superior strong field, especially for the devices, as which the Joule loss is treated as the severe problem. The strong electric field of 35 MV/m has been achieved on a resonant cavity study, and the strong magnetic field of DC 10 T has been also achieved. The transient phenomena induce the serious problem, called as quench, so the superconducting method was not applied to pulsed magnet systems. The time variation of magnetic flux induces eddy current everywhere, and heats the surroundings up, which cannot maintain the superconducting condition. It is, however, an attractive phenomenon to produce ON/OFF states clearly. Figure **8** shows one example of the applications. The magnet is excited by multi-turn coils. Some of the coil is superconducting, and the others are normal conductors. The superconducting coils stop the field increment just after quench, and a long flattop can be expected. If the excitation duration is enough short, the heating is subtle, and the cooling is expected to become effective again. The experiments to confirm a fast recovery, similar to that for magnetic saturation described in Sec. 2, will be conducted in the nearest future.

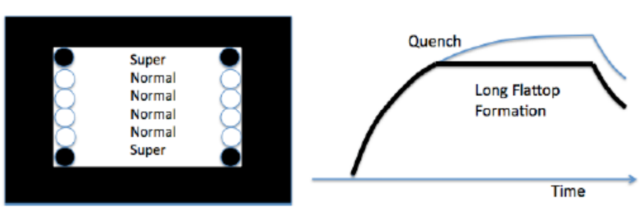

Figure 8: Layout of coils and yoke of a magnet, and the expected field waveforms.

6. FIELD AMPLIFICATION

Frequency resonance brings higher electromagnetic field, such as a 35 MV/m resonant electric field in resonant cavities. The best performance on electric field is obtained by finding the imaginary part of characteristic impedance to be zero, so to write, the output voltage V_o to be determined to the proportionate to the inverse of the pure resistance *r*. The amplification ratio is estimated to be the ratio of characteristic impedance *Z* and the pure resistance.

$$V_o \sim \frac{Z}{r} V_f \tag{8}$$

It would be better in the case of possibility to amplify magnetic field at the same manner, but the amplification ratio is less than 1 because the resonance condition is equal to simple excitation by a power supply with characteristic impedance of *Z*. The method, which is similar to the laser amplification, is now under developed.

7. TRANSIENT AND DIGITAL FIELD BENEFIT

The digital technology has been developed rapidly in this decade, and the proton acceleration by the digital electric field has been accomplished first in the world [12]. But the electric field waveforms were not clear step pulses or sinusoidal, were transient with some droop. The cause of the funny waveforms is simple decay of a cavity inductance and characteristic impedance of power supply system. It was decided as a regrettable conclusion of the characteristic difference between vacuum tubes and semiconductor switching devices because of many physicists, not engineering scientists [13].

The droop was treated as the bad effect phenomenon [14], but it is very useful to accelerate and confine the high-energy particles like as rf devices by the famous combined function theory of synchrotron motion. On the other hand, the roles can be separated by simple compensation of capacitance in electric circuit. The experiment was performed at the system of the 0.5 mH cavity excited by the 125 Ω power supply. The droop, which can be estimated by the time constant of 0.5 mH / 125 Ω = 4 μs, is induced, equivalent to 11% drop for 0.5 μs flattop. Figure **9** shows the experimental result of the case applying the capacitance compensation of 100 pF, including dielectric loss of high-voltage 125 Ω cables. Although there was a slight mismatch, a favorable waveform with a useful flattop was obtained.

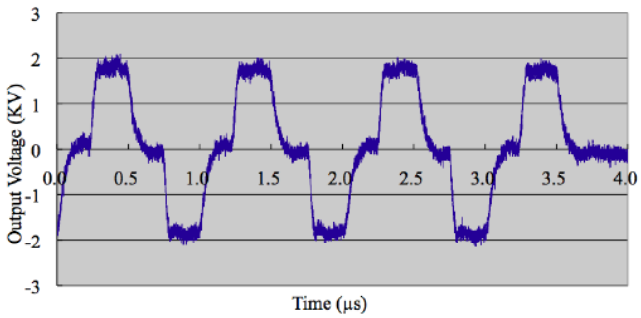

Figure 9: Observed 1.8 kV rectangular pulsed operation at 1 Mpps high-repetition rate measured at the output of the rf cavity by a loop-coil.

8. EXCITATION BY HIGH-CURRENT BEAM: MULTI BEAM EFFECTS

High-energy particles are accelerated, for example, by rf devices driven by low-energy electron beam. Low-energy particles are often used for beam handling and acceleration of high-energy particles. Fast response magnet excited by high-energy particle beam is now under developed. This method is very expensive to produce high-energy particles as a rigid excitation current, but it explores a new frontier of fast -response and high-field pulsed magnet. Metal conductors are required for conventional magnet excitation because a rigid current path is required to form a desirable uniform magnetic field. In the case, there is a limitation of forward voltage to induce an unfavorable electrical breakdown, which might cause instability of performance and serious troubles. High-energy particles run directionally, except for a long path, so metal conductors are not necessary, and an unfavorable electrical breakdown is not induced, although some of electrons are lost in surroundings. Higher energy produces higher directionality and suppresses transverse beam enhancement, loss and voltage drops (Figure **10**). The Lorentz factor shows a non-linear characteristic. The magnetic field waveform can be simulated by combination of the circuit equations and kinetic equation with the relativity theory.

$$Snm_0c^2\gamma + \frac{l}{2}I^2 = (const.) : I = enc\beta S$$
$$\delta\gamma = \gamma - \gamma_0 = -\frac{nSe^2 l}{2m_0}(1 - \frac{1}{\gamma^2}); \gamma \equiv \frac{K + m_0c^2}{m_0c^2} \quad (9)$$

where S, n, m_0, c, γ, l, I, e and K indicate the cross-section of the electron beam, the density of electrons, the invariant mass of electrons, the velocity in vacuum, the Lorentz factor, the inductance of the magnet, the beam current, the elementary charge and the kinetic energy of electrons, respectively. A rectangular waveform is difficult in the case of high-energy particle excitation, but it is possible to form a trapezoid waveform by superimposing of two time-different beams (Figure **11**). A fast-rise time and a long flattop are expected shown as the calculation results in Figure **12**. It would be useful method by using many kinds of particles or elementary particles at the same manner. Excitation current produced by the combination of the charged particles flows brings a new fast current operation due to the annihilation or neutralization (Eq. 10). It is expected very short and localized magnetic field nearby the object of particles (Figure **13**), especially for quantization of magnetic field to reveal the problem of the monopole or time-phase transition study of magnetic field.

$$\nabla \cdot J = (annihilation.or.neutralization) \neq 0 \quad (10)$$

where J indicates current vector.

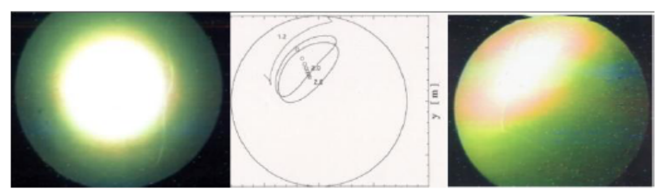

Figure 10: The cross-section of 1.8 MeV 1 kA 250 ns electron beam produced by the Japan Large current Accelerator (JLA) in Japan Atomic Energy Research Institute (JAERI) [15]. The left photograph shows cross-section of the electron beam. The core radius is about 90 mm. The outer bright radius is about 120 mm. The high-current electron beam was well handled by a magnet as shown in the right photograph, which is equivalent to the simulated beam cross-section of 1.8 MeV electrons as shown in the centre graph.

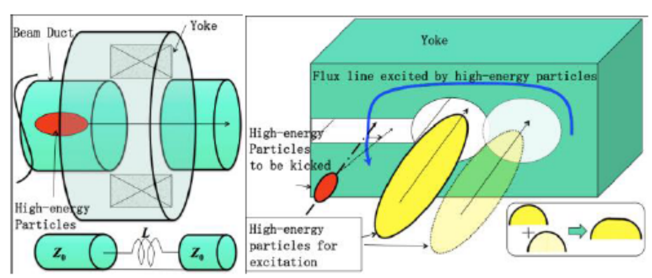

Figure 11: The schematic drawing of the excitation by high-energy particles.

SUMMARY

The possibility to apply the non-linear phenomena to produce a fast-response and strong field, which is required to control high-energy particles, is discussed by various approaches. High-energy particles travel near the velocity of light, so the application of the non-

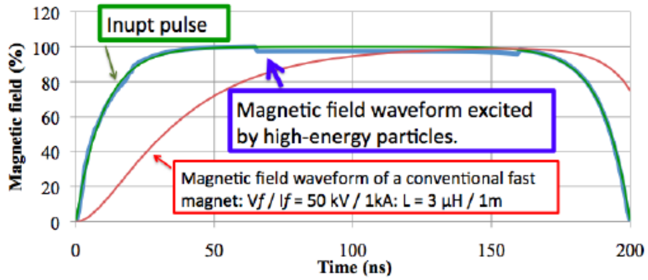

Figure 12: The simulated field waveforms for the case of the high-energy particle excitation in comparison with an example of conventional magnetic field. There is a slight drop at 62 ns, but a fast-rise time and a long flattop are obtained.

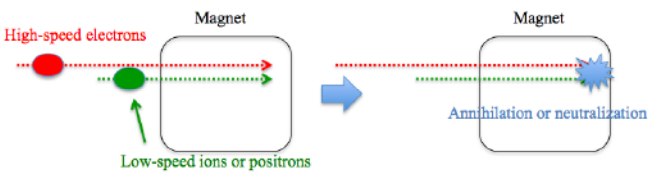

Figure 13: Schematic drawing of the example of current stop by annihilation or neutralization.

linear characteristics is valid because it can produce ON/OFF states clearly and define the identity of materials or phenomena. There are still remained to develop load devices, which are expected to bring further performance.

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