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DEVELOPMENT OF A SOLID-STATE PULSE GENERATOR DRIVING KICKER MAGNETS FOR A NOVEL INJECTION SYSTEM OF A LOW EMITTANCE STORAGE RING*

T. Inagaki†, H. Tanaka, RIKEN SPring-8 center, 679-5148 Sayo, Japan
C. Kondo, K. Fukami, S. Takano, JASRI / RIKEN Spring-8 center, 679-5148 Sayo, Japan
K. Sato, H. Akikawa, Nihon Koshuha Co. Ltd., 224-0054 Yokohama, Japan

Abstract

A novel off-axis beam injection system, based on a closed linear bump orbit launched by identical kicker magnets is proposed for a low emittance electron storage ring. In order to close the bump orbit within a few μrad, the pulsed magnetic field of the kickers should be synchronized within a timing jitter of 1 ns and an amplitude difference of 0.1%. A prototype solid-state pulse generator has been developed to drive the two kicker magnets connected in parallel. In the operation test of the prototype pulse generator, a half-sinusoidal pulse current with the peak value of 2.2 kA and the pulse width of 3.3 μs was obtained by two load inductors substituting for kicker magnets. The current waveforms of both inductors were matched well within ±0.2%, promising to achieve the identity of the two kicker magnets by using a common pulse generator as a parallel driver. The time width of the pulse current was wider than the design value. We plan to reduce the inductance of the circuit and to shorten the pulse width.

INTRODUCTION

A next generation electron storage ring such as a diffraction-limited light source pursues an extremely low emittance. It leads a small dynamic aperture and short beam lifetime [1-5]. The top-up injection is hence indispensable to keep the stored beam current. The beam orbit fluctuation caused by beam injections disturbs utilization of an electron beam with a sharp transverse profile.

In order to solve these problems, a novel off-axis in-vacuum beam injection system was proposed. In the system, kicker magnets driven by high-precision solid-state pulse generators to launch a closed linear bump orbit is the key to suppress the horizontal orbit fluctuation down to a level of several μrad. Here, a big challenge is to achieve the magnetic field identity of the kickers within an accuracy of 0.1%. This paper overviews the proposed injection system and reports the development status focusing on the solid-state pulse generator.

DESIGN

Off-axis In-vacuum Beam Injection Scheme

Figure 1 schematically shows the beam injection section at the ring. Four identical kicker magnets are placed in a straight section dedicated for beam injection. No nonlinear magnets such as sextupoles are in the injection section, and closed injection bump orbit can be obtained by the kickers irrespective of its amplitude. Two pulse generators, each connecting the two kicker magnets as illustrated in Fig. 1, generate half-sinusoidal pulse magnetic field to launch the bump orbit for the beam injection. Since the single pulse generator provides the pulsed currents to the two kicker magnets, their temporal profiles are synchronized, free from a timing jitter, and the amplitude fluctuation is common to the two kickers. Therefore, the mismatch of kicker magnetic field in this injection system occurs not one by one but rather between matched pairs of kickers on both sides of the bump orbit, resulting in smaller amplitude of transient oscillation of stored beam.

A low emittance beam from a high-performance linear accelerator is delivered through a windowless transport line to the storage ring. A differential pumping system is installed in the end of the transport so as to maintain an ultra-high vacuum in the ring. A permanent-magnet based DC septum and an in-vacuum type pulse septum deflects the injection beam to the storage ring. The permanent magnet provides operational reliability and stability as well as energy saving. The in-vacuum pulse septum enables a small amplitude of an injection beam by reducing a septum thickness.

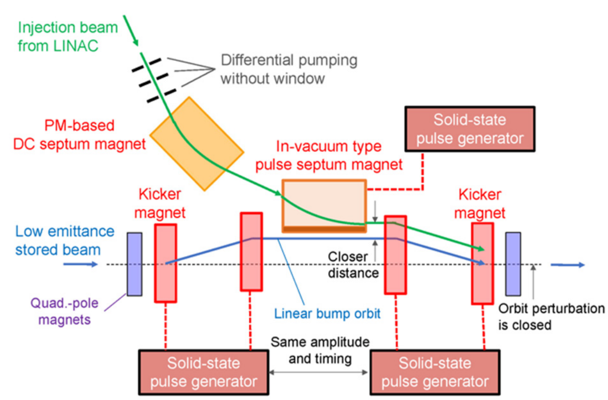

Figure 1: Schematic of the off-axis in-vacuum beam injection system.

Beam Injection Section and Kicker Magnet

Table 1 summarizes design parameters related to kicker magnets for beam injection. The amplitude of bump orbit and the deflection angle of kicker magnets are determined based on the preliminary design of the beam injection section for a new 3 GeV light source ring planned in Japan. According to these parameters, we are designing prototype of the kicker magnet. The kicker magnet consists of C-

* Work supported by Ministry of education, culture, sports, science and technology JAPAN (MEXT).
† inagaki@spring8.or.jp

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shaped yoke of silicon-steel laminated core and a 2-turn coil. To obtain magnetic field strength of 0.25 T and a frequency response up to 1 MHz, thin silicon steel sheets will be used. The driving pulse width for kickers is determined as twice the revolution period of the ring. The requirements of current stability and timing jitter for the pulse generator are determined so that the amplitude of transient stored beam oscillation not exceed 10 µm, which is caused by the discrepancies between matched pairs of kickers on both sides of the bump orbit.

Table 1: Design Parameters of Injection Bump Orbit, Kicker Magnets, and the Pulse Generator

Injection bump orbit	
Amplitude	8 mm
Kicker magnet	
Deflection angle	5.5 mrad
Pole length	216 mm
Gap width	23 mm
Magnetic field at center	0.25 T
Coil turn number	2
Inductance	4 µH
Pulse generator	
Peak current	2.2 kA+2.2 kA
Pulse width	2.2 µs
Current stability	< 0.1%
Timing jitter	< 1 ns

Prototype Pulse Generator

Two out of the four kicker magnets are simultaneously driven by a common high current pulse generator as illustrated in Fig. 1. The two magnets are connected in parallel to the common pulse generator with an adequate cable

The diode array blocks the return current from the kicker magnet. We chose an ultrafast recovery diode with a reverse voltage of 1.2 kV and a recovery time of 135 ns (for If=100 A, room temperature) and stack 80 diodes serially to obtain enough blocking voltage. After passing the diode array, the current path is divided into halves, each passing through the variable inductor and connected to high voltage coaxial cables. The variable inductor consists of an air-core 5 turn coil with a movable inner cylinder of aluminium. The inductance can be manually adjustable in the length offset corresponding to the time of flight of the beam. The current ratio of the two magnets is inverse of the impedance ratio of the two current paths. Variable inductors are equipped for each current path to compensate the current imbalance of kickers.

As a high voltage switching device, we do not use a thyratron. We use a stack of high power semiconductors, which has better repeatability, smaller timing jitters, and longer lifetime than thyratrons. An LC resonant circuit consisting of a main capacitor, a solid-state switch, and a diode array serially connected provides a half-sinusoidal current pulse to each magnet.

Figure 2 shows the designed circuit diagram of the prototype pulse generator driving two injection kicker magnets in parallel. The capacitance and the charging voltage of the main film capacitor is determined to be 93 nF and 50 kV, respectively, to obtain the pulse current of 2.2 kA and the pulse width of 2.2 µs.

The solid-state switch is required to have a high withstand voltage of 50 kV, a fast turn-on time of several 100 ns, and a high pulse current conductivity of 4.4 kA. We use 14 high voltage type insulated-gate bipolar-transistor (HV-IGBT) modules serially connected as the switch. Each HV-IGBT module has a maximum applied voltage of 6.5 kV and a maximum DC current of 750 A. For each IGBT module, snubber RC circuit is attached to absorb the turn-on surge and mitigate the overvoltage when the turn-on timing of one of the modules is delayed. A monitor of collector-emitter voltage is used to detect the overvoltage for the interlock. A gate driver is the commercial product newly developed for this HV-IGBT. To insulate the HV-IGBT modules and attached circuits up to 50 kV, the trigger pulse for the HV-IGBT and the interlock status are transmitted by optical fibers. Electrical power of a 30 kHz switching current is supplied to the gate driver via an isolation transformer.

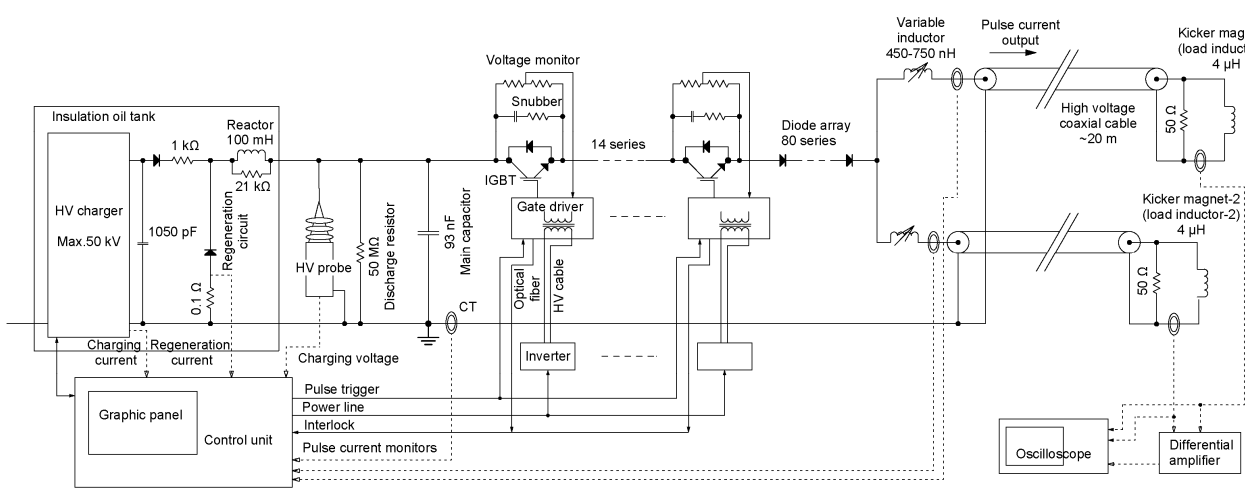

Figure 2: Circuit diagram of the prototype pulse generator driving two injection kicker magnets in parallel.

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range of 450 to 750 nH. The pulse timing for the two kickers can be finely adjusted by changing the effective length of the bus bar. A stray capacitance and an inductance of the coaxial high voltage cable distorts the sinusoidal waveform of the current pulse. In order to dump the voltage ringing, 50 Ω resistor is attached in parallel to the kicker magnet.

Once the half-sinusoidal current pulse is terminated, the main capacitor is charged reversely. The capacitor is positively charged again by the regeneration circuit, which consists of a diode array and a 100 mH reactor. After the regeneration, a high voltage charger raises the voltage of the main capacitor to the target value within a period of 100 ms. The output pulse current is proportional to the charging voltage. We use an inverter-type high precision charger with a voltage regulation accuracy of less than 0.1%, which is originally developed for the klystron modulator at SACLA [6].

PERFORMANCE

We assembled the prototype pulse generator as shown in Figure 2 and examined the performance by using a pair of dummy air-core inductors with 4 μH inductance each, instead of actual kicker magnets. Figure 3 shows the waveforms of the main capacitor voltage, pulse currents of the two dummy inductors measured with current transformers (CTs), and the search coil signal (cross section S=450 mm^2) detecting the derivative of magnetic field of one of the inductors. The pulse current of 2.2 kA was successfully obtained for both the inductors. The observed pulse width of 3.3 μs was longer than the design value of 2.2 μs. We consider a certain inductance of the HV-IGBTs, the diodes and the high voltage cables distorted the pulse. To obtain the shorter pulse width as designed and to increase the margin for pulse current, we are considering improvements, for example, by replacing the HV-IGBTs with fast thyristor modules and by modifying the configuration of the diode array.

Figure 4 shows a preliminary data comparing the pulse currents of the two dummy inductors, observed for the charging voltage of 20 kV. We used a differential amplifier to measure the difference in detail with sufficient resolution. The observed difference of the currents in the two inductors is less than ±0.2% of the peak current including the measurement error. We plan to improve the accuracy of the measurements and also the equality of the current pulses for the two inductors. The present results are promising to achieve the identity of the two kicker magnets by using a common pulse generator as a parallel driver.

We measured the stability of the charging voltage of the main capacitor by using a high voltage probe. The maximum fluctuation of the voltage was about 0.01%, much better than the required stability of 0.1%. Measurement of the timing jitter of the output pulse is in preparation.

Another remaining issue is the detailed design of kicker magnets which assures the identity of inductance of individual magnets. This year we plan to design and fabricate the prototype kicker magnets. Then we will investigate the performance for actual operation conditions with the prototype kicker magnets.

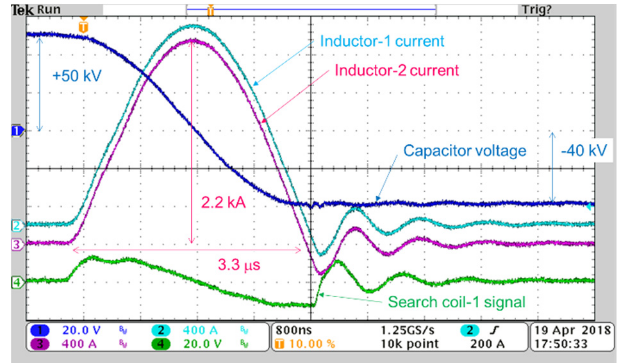

Figure 3: Waveforms of the capacitor voltage, current of load inductors, and the search coil-1 signal.

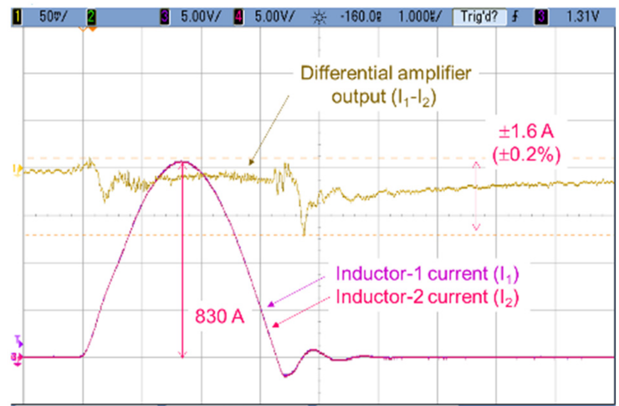

Figure 4: Waveforms of the pulse currents of the load inductors, and their difference amplified by the differential amplifier, operating with the charging voltage of 20 kV.

CONCLUSION

An all solid-state type high current pulse generator for kicker magnets is being developed. For good synchronism and equality of the pulse magnetic field, two kicker magnets are connected in parallel to a common pulse generator. A prototype of the pulse generator was designed and assembled. In the performance test of the prototype pulse generator, a half-sinusoidal pulse current with the peak value of 2.2 kA and the pulse width of 3.3 μs was obtained by two load inductors substituting for kicker magnets. The measured difference of the two current waveforms for the inductors was less than ±0.2%. Promising results have been obtained to achieve the identity of the two kicker magnets by using a common pulse generator as a parallel driver. The obtained pulse width of 3.3 μs is larger than the design value. Reduction of the inductance are considered and will be tested to obtain the shorter pulse width as designed.

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