DEVELOPMENT OF NEW PULSE DRIVER FOR HIGH POWER PULSED MAGNET

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Abstract

The KEK injector linac injects electron and positron beams into four rings: the high-energy ring (HER), low-energy ring (LER), PF ring, and PF-AR. The HER and LER are SuperKEKB main rings. The PF ring and PF-AR are light source rings. These rings require several beams with different charges and energies. The LER beam is a positron. Simultaneous four-ring top-up injections were achieved in 50 pps. We have already installed pulsed magnets downstream of the linac for pulse-to-pulse difference beam injection. Pulsed quadrupole magnets require a pulsed current of 300 A. For these pulse magnets, we use an energy-recovery-type pulse driver. We can change the optics using these pulsed quadrupole magnets and drivers.

However, the quadrupole magnet has a small aperture. It cannot be installed in the upstream section because of its large beam size; in particular, the positron primary electron beam has the largest beam size. Thus, we installed a new larger-aperture quadrupole magnet and high-power pulse driver. The magnet current was 600 A, and the required power was approximately four times higher than that of the old driver. In the summer of 2023, large-aperture quadrupole pulsed magnets were installed upstream of the linac. The power of the new pulse driver was 600 A at 400 V, which is an energy-recovery type. We achieved high efficiency with a simple pulse-width control. We intend to introduce this high-power and high-efficiency pulse driver.

INTRODUCTION

KEK has four storage rings for the electron/positron collider rings and two light source rings. The collider rings are the high-energy ring (HER) and the low-energy ring (LER), which are the SuperKEKB main rings [1]. The PF ring and PF-AR are light source rings. Table 1 lists the injection beam specifications for each ring. As the requirements of the beams were different, we changed the linac acceleration conditions. We achieved simultaneous top-up injection of the four rings using two types of electron guns and several pulse magnets [2]. Figure 1 shows a schematic of the KEK electron/positron injector linac. We used a photocathode RF gun to generate the HER low-emittance electron beam. The required emittances were 40 and 20 mm-mrad in the horizontal and vertical directions, respectively. The other gun is a thermionic DC gun for the positron primary electron beam, which had a high charge of 10 nC per bunch. The DC gun is also used for the light source rings (PF and PF-AR). A positron beam is generated by hitting a tungsten target in a flux concentrator (FC) with primary electrons [3]. A damping ring was used to reduce the emittance of the positron beam. The damping ring was installed between Sectors 2 and 3, as shown in Fig. 1. In Sectors 3-5, all the quadrupole magnets (Q magnets) are pulsed magnets. Downstream of the damping ring, the transverse beam sizes were small in all modes; therefore, a pulsed Q magnet with a 20 mm aperture could be used. This small-aperture-type magnet is called the PM_32_4 type. The Q magnets in Sectors 3–5 were replaced by pulsed Q magnets in 2017 [4]. The inductance of the Q magnet was 1.0 mH, and the maximum pulse current was 330 A. The pulse driver raises a current within 3 msec at a voltage of 220 V. However, these pulsed Q magnets and pulse drivers cannot be used upstream of the injector because of the large positron primary beam size. In the bending sector (J-arc), we could not independently match the beams because the Q magnets were DC magnets.

Table 1: Specifications of Each Beam

Ring	Beam	Energy	Charge
HER	Electron	7.0 GeV	4.0 nC
LER	Positron	4.0 GeV	4.0 nC
PF ring	Electron	2.5 GeV	0.3 nC
PF-AR	Electron	6.5 or 5 GeV	0.3 nC

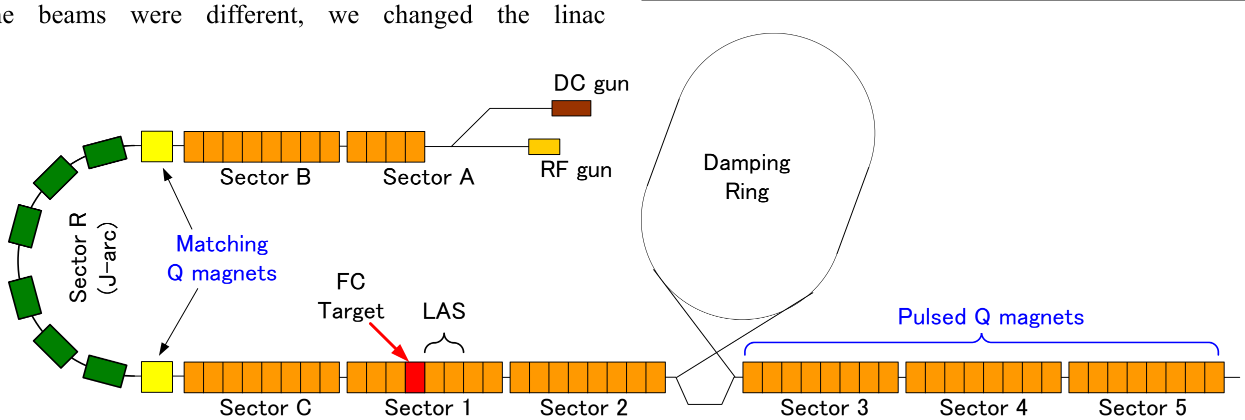

Figure 1: KEK injector linac consisting of eight acceleration sectors and a 180° bending sector. Sectors 3 to 5 have a pulsed Q magnet. The new large-aperture quadrupole magnets were installed in the summer of 2023 for matching.

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Therefore, we replaced the DC Q magnets at the J-arc entrance and exit with pulsed Q magnets. The positron primary beam is prone to charge loss because of its large beam size and wide energy spread in the J-arc. Beam matching at the J-arc is also important for HER electron beams, because an unexpectedly large β (Twiss parameter) creates transverse wake fields that worsen the emittance. The Twiss parameter mismatch also makes it difficult to adjust the electron beam, which must pass through a small hole adjacent to the positron generation target. Installing a pulsed Q magnet in the matching section is useful for beam tuning.

A large-aperture Q magnet was necessary because of the large beam size of the J-arc. However, the existing pulsed Q magnet (PM_32_4 type) has a narrow aperture, whereas a large-aperture Q magnet requires a high current. Therefore, we developed a new high-power pulse driver for large-aperture Q magnets. This large-aperture Q magnet is called the PM_R0_01 type. Table 2 lists the specifications of the pulsed Q magnet. The new PM_R0_01 type has an aperture that is more than twice that of the old type. Figure 2 shows a photograph of the PM_R0_01 type Q magnet. The required current was as high as 600 A, necessitating a new pulse-current driver. A new high-power pulse driver was developed.

Table 2: Specifications of the Q Magnet

	PM_32_4	PM_R0_01
L@ 1 kHz	1.0 mH	1.1 mH
Max. Current	330 A	600 A
Gap	ϕ 20 mm	ϕ 44 mm
Length	200 mm	300 mm
Magnetic field	60 T/m	20 T/m

Figure 2: Photo of the new pulsed Q magnet.

PRINCIPLE OF PULSE DRIVER CIRCUIT

The inductance of the drive magnet was 1.1 mH, and we intended to increase the current to 600 A within 3 ms; therefore, we applied a voltage of 400 V to the magnet. The circuit configuration is straightforward and consists of a capacitor (14 mF), a charger (400 V), and an H-bridge circuit, as shown in Fig. 3. The H-bridge has two diodes and two insulated gate bipolar transistors (IGBTs) as switches. The current amplitude was adjusted by controlling the switching timing of the two IGBTs, and energy recovery was performed. The control phase was further divided into three stages.

- Rising phase
- Flywheel phase
- Energy recovery phase

Figure 4 shows the three phases and current waveform. First, the two IGBTs are ON in the rising phase, and the charging voltage of the capacitor is applied directly to the magnet. Subsequently, in the flywheel phase, the high-voltage-side IGBT is OFF. The low-voltage-side IGBT, diode, and load magnet form a closed loop. During this phase, the current change is very slow. Beam path through in this timing. Finally, both IGBTs are OFF. The stored energy in the magnet returns to the capacitor as a charging current. This driver requires an external trigger pulse. The current amplitude is controlled by varying the pulse width. The flywheel timing pulse is generated by the internal circuit of the driver. In practice, the flywheel time width is approximately 100 μs.

The magnetic energy was 2.0 J at 600 A ($W = L\,I^2/2$). If energy recovery is not used, the power consumption would be 10 kW at 50 pps. Energy recovery is important to achieve power savings and easy cooling.

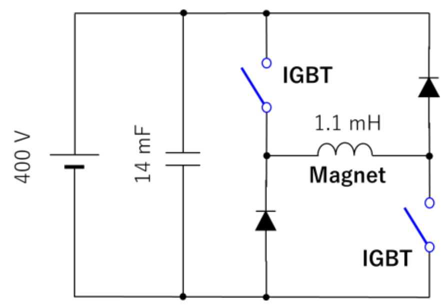

Figure 3: Circuit configuration of the pulse driver.

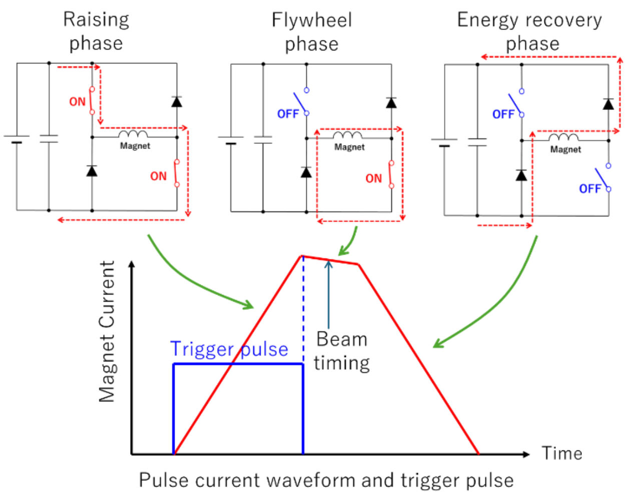

Figure 4: Principle of the pulse driver circuit and current waveform.

ASSEMBLY AND OPERATION

The driver devices were selected with sufficient current and voltage margins. A general-purpose power supply was used as the charger. The driver was divided into a capacitor and an IGBT housing. Each chassis was a 4U 19-inch rack. The driver contained an electronic circuit that received an external trigger and generated an isolated trigger for the IGBTs. Figure 5 shows a photograph of the pulse driver unit. The driver was completed in 2023, and seven units were installed on the beamline. Full operation began in autumn of that year.

Figure 6 shows the current waveform of the driver with a pulsed Q magnet as the load. The graph shows the results for different trigger pulse widths. With a pulse of approximately 2.5 ms, a current of 600 A can be applied, and 50 pps operation has been successfully achieved. An energy recovery efficiency greater than 80% has been achieved. The drivers have been in operation since the autumn of 2023, and are sufficiently stable to be used under actual operating conditions with pulse-to-pulse current-change operation. Individual beam matching is now possible in the J-arc, which has been particularly helpful in reducing the loss of positron primary beams.

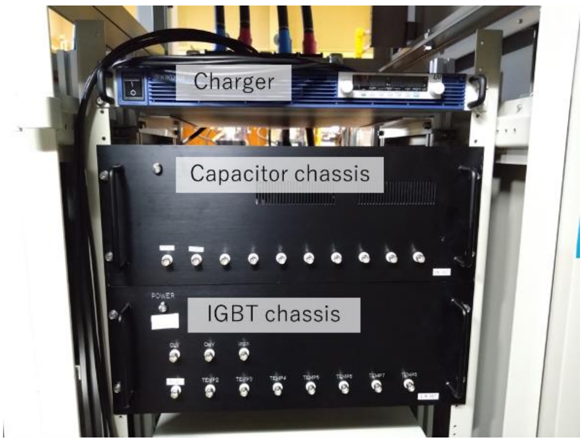

Figure 5: Pulse driver. Charger, capacitor chassis, and IGBT chassis.

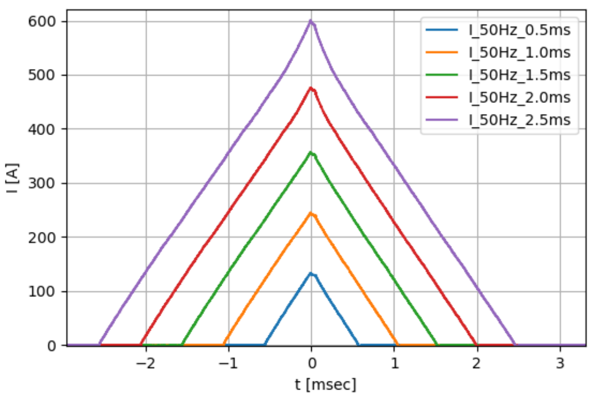

Figure 6: Current waveform.

SUMMARY

A 600 A 400 V class pulse magnet driver was developed for a KEK electron/positron injector. This high-power pulse driver was used for a large-aperture Q magnet. New drivers and Q magnets were installed in the matching section of the J-arc. The J-arc represents the bending section of the injector linac. The KEK injector performs a 50 pps pulsed operation by injecting individual beams into four rings. For this pulse-to-pulse injection, individual matching in the J-arc is crucial. The large-aperture pulsed Q magnet achieved individual-beam matching. Seven pulsed Q magnets and their high-power drivers were installed in the autumn of 2023. We achieved stable pulse-to-pulse operation with a maximum current of 600 A. Operation with these pulsed Q magnets particularly contributed to an increase in positron beam generation. Thus, high-power pulse drivers contribute to the four-ring high-quality beam injection in KEK.

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