

# PLUSE-TO-PULSE BEAM MODULATION FOR 4 STORAGE RINGS WITH 64 PULSED MAGNETS

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## Abstract

In 2017, sixty-four pulsed magnets (28 quadrupoles and 36 steerings) were installed in the KEK electron positron linac for simultaneous injection to four different rings. Since each ring requires different injection energy, magnetic field in the injector linac has to be changed shot by shot (every 20 ms) according to the destination of the beam. To realize such operation, novel pulsed power supplies and an EVENT timing system compatible PXI based control system were developed. Installation and commissioning of the system were successful and it has been working for one year without severe trouble.

## INTRODUCTION

The KEK injector linac [1] has delivered electrons and positrons for particle physics and photon science experiments for more than 30 years. Figure 1 shows electron and positron accelerator complex in the KEK Tsukuba site. There are four storage rings, i.e. two rings for light source, PF and PF-AR, and two rings for electron positron collider, SuperKEKB [2] HER and LER. In addition to them, positron damping ring have been in operation since February 2018. All of the rings require full energy injection, 2.5 GeV for PF, 6.5 GeV for PF-AR, 4 GeV for SuperKEKB LER and 7 GeV for SuperKEKB HER as shown in the Fig. 1. To satisfy the requirement, 64 pulsed magnets were installed in 2017 and 32 more are planned to be installed in 2018. Using these magnets, magnetic field can be changed shot by shot in 20 ms and was optimized for each destination.

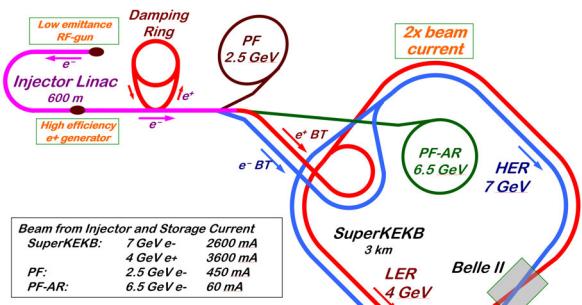


Figure 1: A schematic view of the electron and positron accelerator complex in the KEK.

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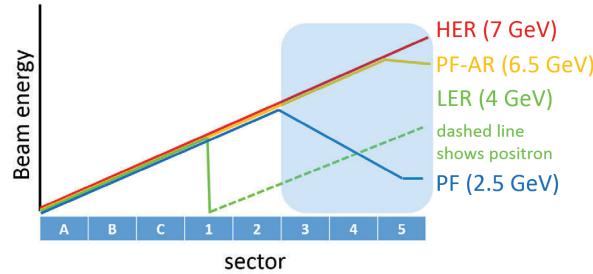


Figure 2: Beam energy along the beam line. Solid line shows electron beam dashed line shows positron beam respectively.

There are 8 (A-C, 1-5) sectors in the linac. Each sector is about 80 m long and the total length of the linac is about 650 m. Figure 2 schematically shows beam energy along the beam line. To minimize the installation of the pulsed magnets, acceleration scheme is carefully adjusted to minimize the length of the beam line where the beam with different energy pass through. The beam for the SuperKEKB HER, it is accelerated all of the sectors. The beam for the PF, it is accelerated in sector A to 2 and decelerated in sector 3 to 5. The beam for the SuperKEKB LER, electrons are accelerated in sector A to 1 and generate positrons at the target located in the middle of the sector 1. Positrons, shown in dashed line, are accelerated rest of the sectors. Since the beam energy is the same in the sector A to C and first half of the sector 1 regardless of the destination, it is not necessary to use pulsed magnets. On the other hand, in sector 3 to 5 shaded by light blue in the Fig. 2, beam with very different energy pass through, magnets in these sectors were completely replaced with pulsed magnets. In sector 2 and a part of sector 1, beam energy of the electron and positron is very different. Magnetic field optimized for the low energy positron beam affect the orbit of the high energy electron beam very little. In these section, DC magnets with compatible setting for both electron and positron beam are used except for several pulsed steering magnets at the moment.

## MAGNET AND SUPPORT

Several types of magnets were installed in the beam lines as summarized in the Table 1. Appearance of these magnets are shown in Fig. 3. In sector 3 to 5, a common unit shown in Fig. 4, which consists of two quad magnets (PM\_32\_4), a horizontal steering magnet (PX\_32\_4), a vertical steering magnet (PY\_32\_4) and a beam position monitor located on a motor controlled movable support, was installed at 13 points.

Table 1: Several Parameters of the Installed Pulsed Magnets

Type	L@1 kHz	R	Max current	Magnetic field	Gap	Installed number
PX_16_5	2.4 mH	71 mΩ	40 A	1040 AT	72 mm	1
PY_16_5	2.4 mH	71 mΩ	40 A	1040 AT	72 mm	1
PX_17_2	2.6 mH	127 mΩ	40 A	1440 AT	39 mm	4
PY_17_2	2.6 mH	126 mΩ	40 A	1440 AT	39 mm	4
PX_32_4	2.9 mH	115 mΩ	40 A	1440 AT	20 mm	13
PX_32_4	2.9 mH	115 mΩ	40 A	1440 AT	20 mm	13
PM_32_4	1.0 mH	8 mΩ	330 A	60 T/m	ϕ 20 mm	28

Other types of steering magnets were installed in sector 1 and sector 2. Two quad magnets (PM\_32\_4) were installed in sector 1 just before the positron production target to focus the electron beam.

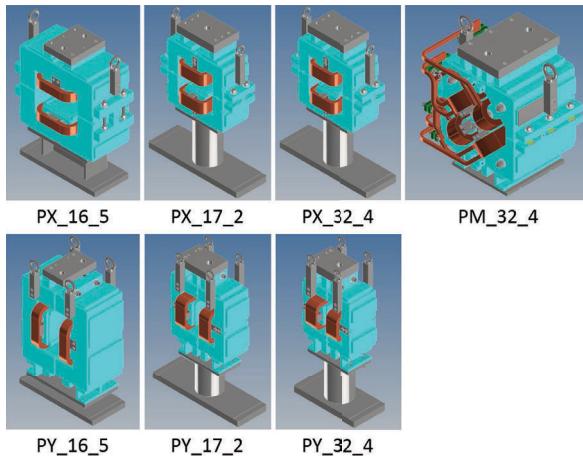


Figure 3: Appearance of installed pulsed magnets.

## PULSED POWER SUPPLY

### Concept and Overview

There are many requirements for the power supply to truly realize the required flexible operation. In addition, since the required number of the power supply is not a few, unit cost, installation space, energy efficiency are crucially important. Trigger rate of our linac is 50 Hz, but injection pattern is not fixed. The destination of the beam is delivered by the EVENT timing system via optical fiber just after the previous pulse. To interpret the information and change setting within 20 ms, fast and intelligent control system is necessary. To realize these requirements with minimum risks and cost, we decide to develop new power supplies by ourselves following the concepts bellows.

- realize high efficiency with energy recovery
- separate power circuit and control system
- use commercially available components as much as possible
- compatible with existent EVENT timing system
- compatible with existent EPICS control system [3]

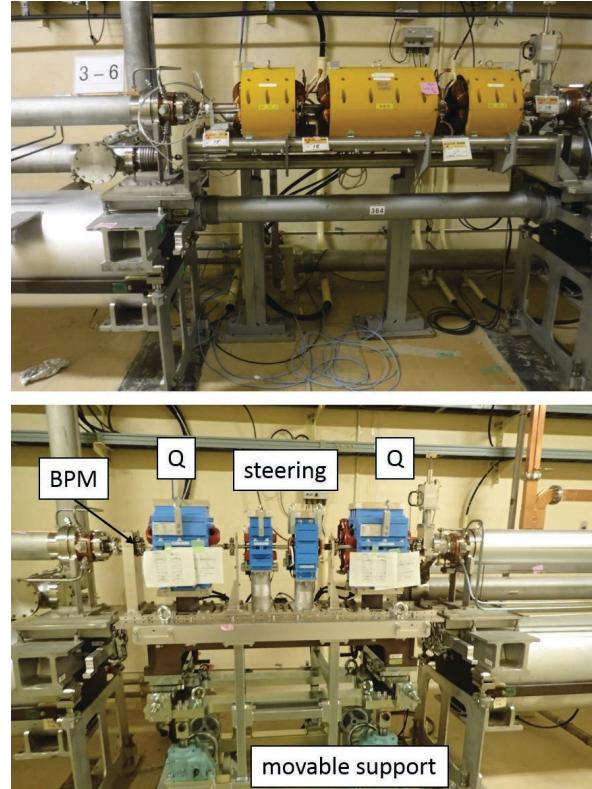


Figure 4: The upper photo shows old DC magnets before replacement. The lower photo shows newly installed unit.

Figure 5 shows a block diagram of the pulsed power supply system [4]. One standard unit which covers 4 quad and 4 steering magnets, shown in Fig. 6, consist of a PXI express unit for fast control, DC power supplies, pulse drivers and NI cRIO unit for interlock and slow data acquisition. There is one computer to control and monitor all of the 64 DC power supplies (DC power supply control server). A CSS archiver and A Network attached storage are used to log various data not only output current of the power supplies but temperature of the IGBT in the pulse driver, status of the DC power supplies and so on. EPCIS channel access protocol is mainly used for the communication among computers. LXI ver 1.3 protocol is used to control the DC power supplies and NI network shared variable is used to send fast waveform data. As for the event timing system, dedicated optical fiber

is directly connected to the module. Most of the software is written by LabVIEW 2016 (32 bit) with NI DSC module and running on Windows 8.1.

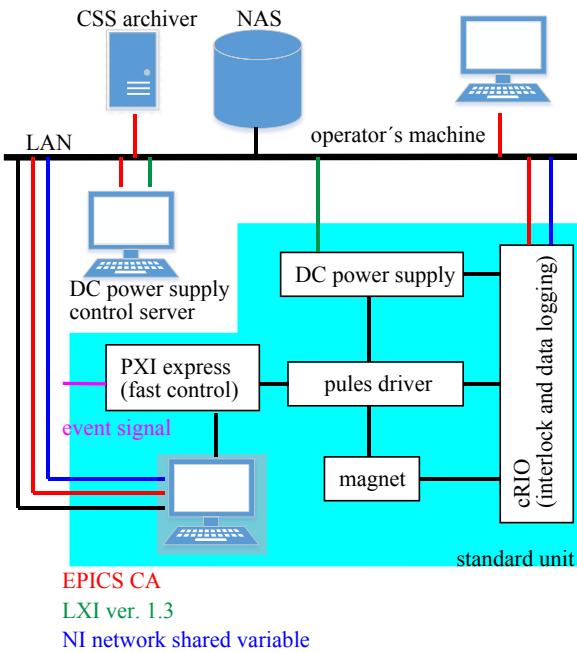


Figure 5: Block diagram of the power supply control and monitor system.



Figure 6: A photo of the standard unit for 4 quad and 4 steering magnets.

### Pulse Driver for Quad Magnet

Design parameters of the pulse driver for the Q magnet is summarized in Table 2. To achieve these values, a novel switching power supply with energy recovery circuit was developed

Table 2: Design Parameters of the Pulse Driver for Quad Magnet

Parameter	Value
max current	330 A
max voltage	230 V
stability	0.1%
cooling	water cooled
power consumption	1500 W
repetition	50 Hz

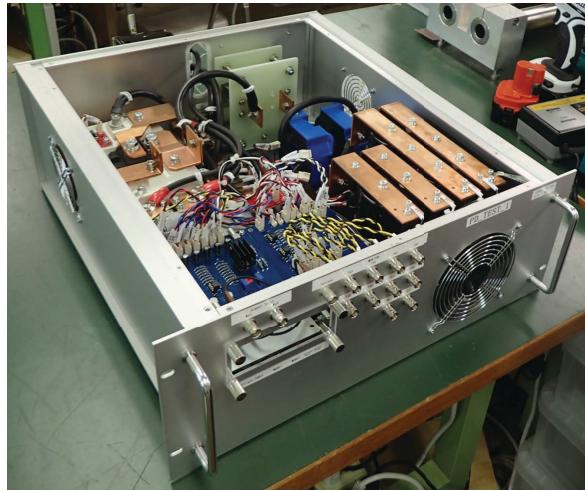


Figure 7: A photo of the pulse driver for quad magnet.

Figures 7 and 8 show an appearance and a conceptual circuit diagram of the pulse driver respectively. The circuit consists of two IGBTs (IGBT 1 and IGBT 2), two capacitors (C\_HV and C\_LV), two DC power supply (VH and VL) and several diodes. After the trigger signal arrives, first, both of the IGBTs turn on and current provided from both of the capacitors pass the load through red lines shown in the upper figure in Fig. 8. When the current reach the set value, IGBT 1 turn off and the gate voltage of the IGBT 2 is controlled to keep constant output current. Finally, after the beam pass through the magnet, IGBT 2 turn off. Stored energy in the load (magnet) is recovered to the capacitor (C\_HV) through the red line shown in the bottom figure Fig. 8.

By combination of such energy recovery mechanism and water cooling system, the outsize dimension of the pulse driver is as small as EIA 3U in height. Output current is monitored and fed back by two independent DCCTs with hall sensor (LEM LF 1005-S) which are calibrated by a more precise external DCCT (Hioki 9709).

### Pulse Driver for Steering Magnet

Design parameters of the pulse driver for steering magnet is summarized in Table 3. Compared with the driver for quad magnet, output power is very small but bipolar output is required. To meet with this condition, power operational amplifier (Apex PA12 [5]) was used for the key device. Although such kind of amplifier is low efficiency compared

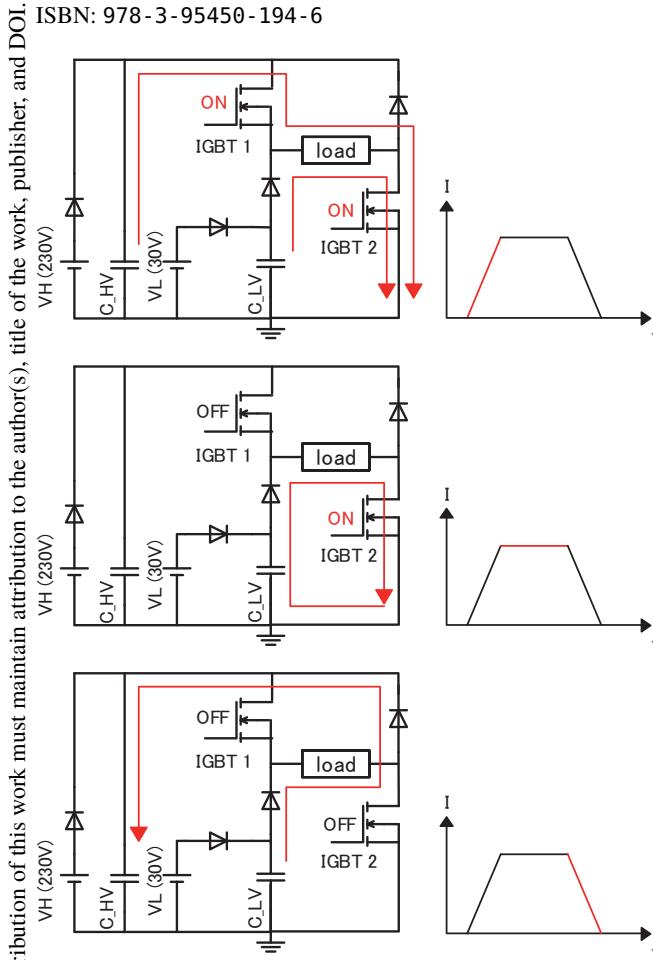


Figure 8: Conceptual circuit diagram of the pulse driver for quad magnet. Red arrows shows the current path. Right side figures shows current profiles at corresponding states.

to switching power supply, the output power is very small compared to the quad magnet above and the low efficiency affect the total power consumption very little.

Table 3: Design Parameters of the Pulsed Driver for Steering Magnet

Parameter	Value
max current	$\pm 10$ A
max voltage	$\pm 40$ V
stability	0.01%
cooling	air cooled
power consumption	750 W
repetition	50 Hz

Figure 9 shows an appearance of the pulse driver for the steering magnet. Air cooling was adopted for the simplicity and cost. Usually steering magnets are used in a pair of horizontal and vertical magnets, there are two circuit in one box of JIS 2U height (99 mm). Output current is monitored and fed back by two independent precision resistor of 1 ohm which are calibrated by more precise external DCCT (Hioki 6862).



Figure 9: A photo of the pulse driver for steering magnet.

### Control and Monitor System

For the fast control, PXI express unit plays major role. The unit shown in Fig. 10 consists of a PC and a PXI express chassis (NI PXIE-1082) with four cards, a controller board (NI PXIE-8381) to connect to the PC, an event receiver board (EVR) (MRF PXI-EVR-230), a DAC board (NI PXI-6733), and a ADC board (NI PXI-6356), which can set and monitor output current up to 8 pulsed power supply independently in 16 bit resolution with 1 MSa/s sampling or update rate. They are placed in the same rack and connected by a metal cable.

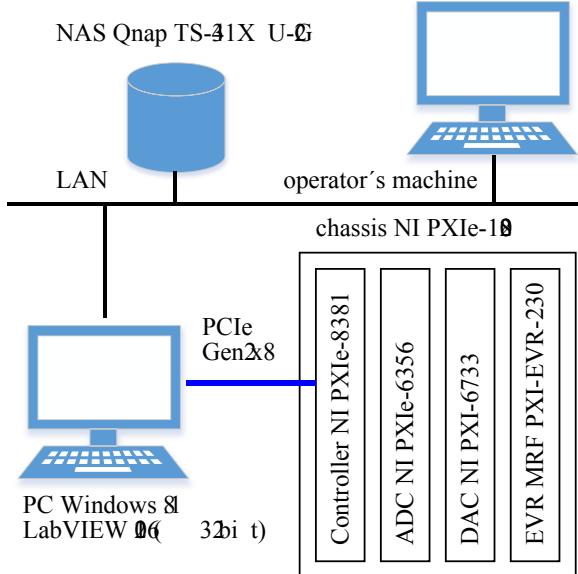


Figure 10: Components of the fast control system.

For the slow data acquisition and interlock system, NI compactRIO (NI cRIO-9063) unit is used. One unit consists of a 32 ch 250 kSa/s/ch ADC module (NI 9205), a 32 ch TTL digital I/O modules (NI 9403) and two 4 ch relay output modules (NI 9482). It covers 4ch of the pulsed power supply, namely for one PXI express unit (8 ch), two cRIO units are needed. To realize robust interlock system, cRIO is working not in a scan engine mode but in a FPGA mode. On the upper

layer, EPICS CA server is running on the NI RT Linux. Not only the PVs for the ADC and DIO data, but the PVs for the high and low threshold, average number to control data acquisition are also prepared which can be set and read using EPICS CA protocol.

### Trigger System

An EVR board in PXI form factor is used to integrate the timing system to the linac timing system. In our linac, event timing system by Micro-Research Finland Oy (MRF) is adopted. The EVR receive not only the timing information but also the mode number and shot ID. The mode number is used to determine the next output setting. The shot ID is used to tag the monitored information. The trigger timing is precisely (8.77 ns step) adjusted 3 ms before the beam arrival. Since the rising and falling time of the magnet current is in the order of ms, pulse shape of the power supply does not important as long as the reproducibility is assured.

## PERFORMANCE EVALUATION

### Efficiency

Power consumption of the pulsed power supply for quad magnet was calculated and measured by a power meter (Hioki, PW3335). Blue bars in Fig. 11 shows calculated power consumption from measured resistance and inductance of the magnet and cables when one magnet was operated at 300 A and 50 Hz without energy recovery. About 15% of energy is lost by ohmic heating of the coil and cable but 85% are stored in the inductance of the coil. It is in principle possible to recover the latter part of the energy to capacitors. Green bar in Fig. 11 shows measured power consumption in total including DC power supply. The red arrow corresponds to recovered energy. The energy recovery efficiency compared with stored energy in inductance and total energy are as high as 80.1% and 68.5% respectively.

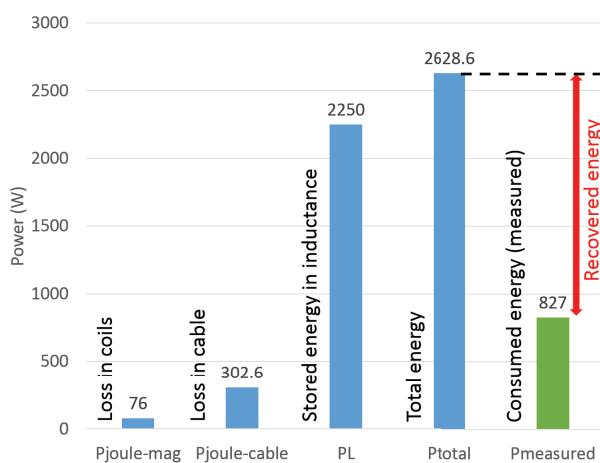


Figure 11: Energy balance of pulsed power supply for Q magnet.

### Stability

Figure 12 shows a stability measurement result of pulsed power supply of quad magnet for 24 hours. Horizontal axis shows the measured output current and vertical axis shows the number of entry. Bin width is 0.2 mA. Output current was set to alternate between 0 A and 166 A at 50 Hz. Measured mean value and standard deviation of the output current were 165.946 A and 14.578 mA respectively which corresponds to 88 ppm (0.0088%) relative stability at this current. This is much smaller than design value (see Table 2).

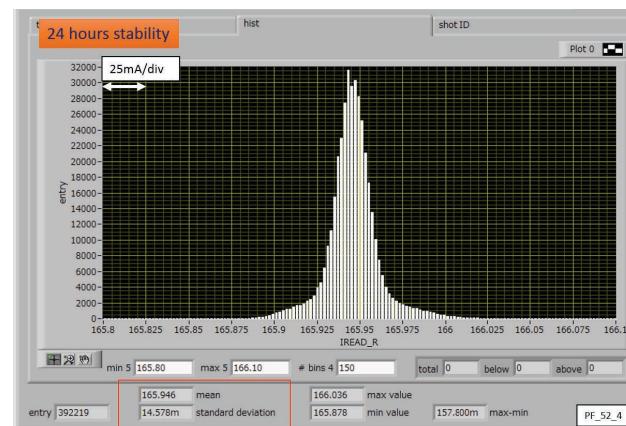


Figure 12: A histogram of the stability measurement of pulsed power supply for quad magnet.

## OPERATION

After four months installation work from May, comprehensive test was done for a month in September in 2017. In November, simultaneous injection using the newly installed pulsed magnets were demonstrated successfully. Since the SuperKEKB phase two operation start from March in 2018 and light source rings restart in May, real simultaneous injection operation started in the middle of May and ended July in 2018 for summer shutdown. During entire period, there was no severe problem and the beam was delivered to all of the four rings stably.

## CONCLUSION

Large number of DC magnets was replaced with new pulsed magnets in 2017 for the pulse-to-pulse beam modulation for 4 storage rings. Two kinds of pulsed power supplies for quad and steering magnet respectively were developed. Installation and commissioning of the system were successful and they are now working in the KEK electron positron injector linac without any severe trouble for about 1 year.

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