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# DEVELOPMENT OF THE POWER SUPPLY CONTROL SYSTEM FOR J-PARC HADRON EXPERIMENTAL FACILITY*

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*Abstract*

The Hadron Experimental Facility is designed to handle an intense slow-extracted proton beam from the 30-GeV Main Ring of the Japan Proton Accelerator Research Complex (J-PARC). We have developed a new control system of a magnet power supply to work with a Programmable Logic Controller (PLC). The control PLC handles the status of the interlock signals between a power supply and a magnet, and monitors the output voltage and the current. The PLC also controls a programmable reference voltage for the DC output current. We have measured the stability of the DC output current of the power supply handled with the control PLC. In addition, we have developed an automatic orbit-correction program, which cooperates with the control PLC. The horizontal position of the proton beam can automatically be adjusted at the centre of the beam dump, and the temperature rise of the copper core during the beam operation can be minimized. The optimized current of a horizontal steering magnet can be corrected with the measured horizontal displacement of the proton beam. As a result of the test of the automatic orbit-correction program with the measured data during the beam operation, the availability of the control system was partially confirmed. The present paper reports the current status of the power-supply control system which can automatically correct the beam orbit to the beam dump.

## INTRODUCTION

The Hadron Experimental Facility [1] (HEF) at the Japan Particle Accelerator Complex (J-PARC), shown in figure 1, is designed to handle an intense slow-extraction proton beam from the 30-GeV Main Ring (MR). The period of beam extraction from the MR to the HEF is 2 seconds and the operation cycle is 5.52 seconds. Eighty-two DC power supplies for the primary and secondary beam line magnets are remotely controlled with the control system based on GP-IB and the Agilent VEE program [2].

We have developed a new control system of magnet power supplies to work with a Programmable Logic Controller (PLC). In addition, we have developed the automatic orbit-correction program which cooperates with the control system. Figure 2 shows schematic diagrams of the present and new control systems.

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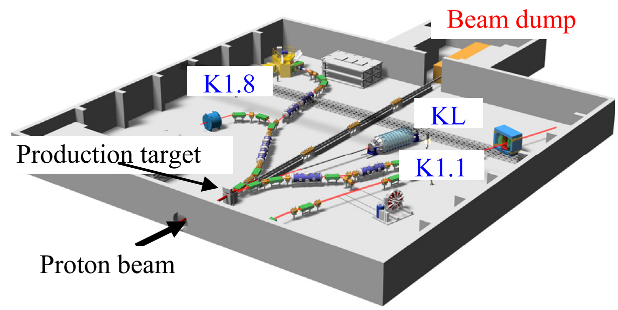
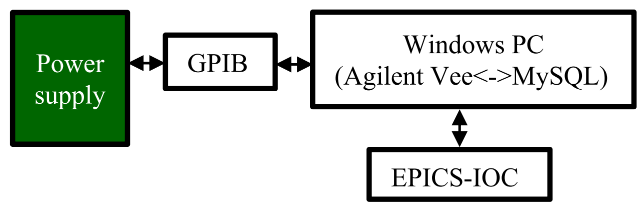
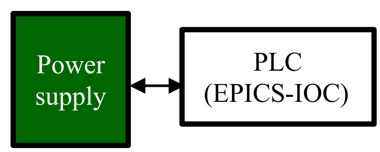



Figure 1: Illustration of the HEF.




(a) Control system of existing power supplies.




(b) New control system with PLC.

Figure 2: Schematic diagrams of power-supply control system.

## CONTROL SYSTEM

The new control system for the magnet power supplies at the J-PARC HEF has been developed to cooperate with the Yokogawa's FA-M3V PLC. The PLC has the merits of its extensibility, portability, and easy transfer to Experimental Physics and Industrial Control System (EPICS) records.

### *The New Control System with Yokogawa FA-M3V PLC*

The test setup with the Yokogawa FA-M3V PLC shown in figure 3 consists of a sequence CPU, a Linux CPU, a relay input, a relay output, an A/D converter and a D/A converter modules. Table 1 shows the model number of the PLC modules. The sequence CPU controls the discrete status of the magnet power supply. The Linux CPU, which is an embedded EPICS IOC on Yokogawa's FA-M3V PLC

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platform [3], transforms the discrete signals and analogue values of the PLC into EPICS records. The 16-bit A/D module measures the DC output current and voltage of the power supply, and the 16-bit D/A module makes a reference voltage to the DC output current. An ethernet-linked touch screen can be connected with the PLC to display the status of the power supply.

The requirements of the control system program are as follows.

- Keep the same configuration of the cabling and connectors as the existing ones between the power supply, the magnet and the control system.
- Keep the same behaviours of the power supply, such as DC-ON/OFF, interlocks, polarity change, ramping up and down of the DC current as the existing system.

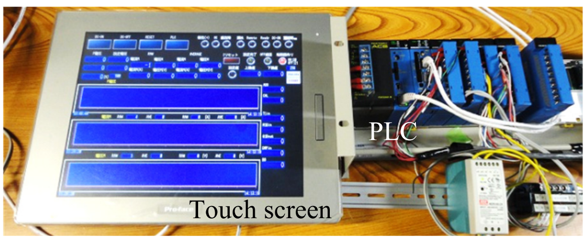


Figure 3: Photograph of PLC and touch screen.

Table 1: Model Number of PLC Modules

| Module | Model number |
|---|---|
| Sequence CPU | F3SP71-4S |
| Linux CPU | F3RP61-2L |
| A/D | F3AD08-5R |
| D/A | F3DA04-6R |
| Input | F3XD16-3F |
| Output | F3YC08-0C |

### *Stability of Current Value*

We have measured the stability of the current of a thyristor power supply to check the performance of the control system. A 50kW DC power supply (rating: 50V-1000A) with a 12 pulse rectifier was operated at 46.2V-907A with a dummy load of water-cooled stainless steel pipes. We have measured output DC current with a KEYSIGHT digital multimeter 34401A at a 440 milliseconds sampling rate. We have also measured ambient temperature with a thermocouple. The photograph of the power supply and the multimeter is shown in figure 4.


Figure 4: Photograph of thyristor power supply and multimeter.

Figure 5 and 6 show the trend graph and histogram of DC output current. The stability of 0.0286 %/3h measured with the PLC was lower than that of 0.05 % on the specification of the 50 kW DC power supply. The ambient temperature rise was 3.7 K. The measured stability is acceptable for the control system of the power supply in the beam line at HEF.

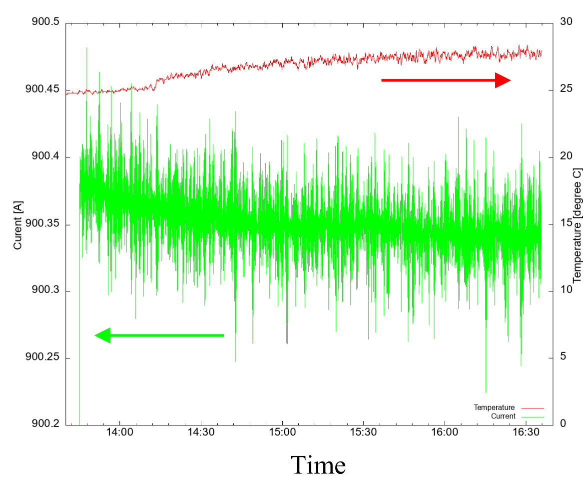


Figure 5: Trend graph of current value.

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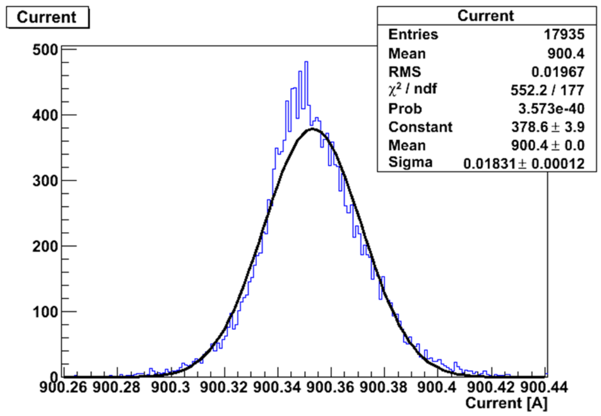


Figure 6: Histogram of current value.

## AN AUTOMATIC ORBIT-CORRECTION PROGRAM

We have developed an automatic orbit-correction program to adjust the beam position at the beam dump in HEF [4].

### *The Method of Automatic Orbit-correction at the Beam Dump in HEF*

Figure 7 shows an illustration of the primary beam line in HEF. The proton beams passed through a production target [5] are guided to the centre of the beam dump. The magnet H18 can be used to adjust the horizontal position of the beam at the beam dump. There are two Residual Gas Ionization Profile Monitors (RGIPMs) [6] in the straight section before the beam dump.

The beam dump is made of oxygen free copper surrounded by iron and concrete shields for radiation. The copper core has a conical hollow ($330^D$ x $4500^H$ mm) to uniformly absorb the heat deposited by primary beam. Forty thermocouples are horizontally aligned at the surface of the copper core. We can continuously measure the transverse beam position and width at the beam dump from the temperature distribution shown in figure 8.

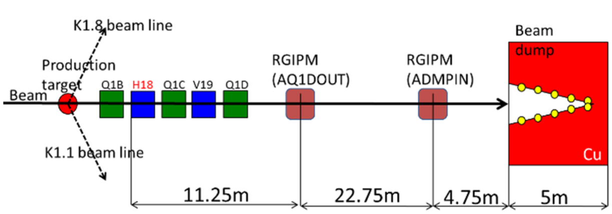


Figure 7: Illustration of the primary beam line at HEF. Red circle, blue, green and dark red boxes illustrate the production target, steering magnets, quadrupole magnets and RGIPMs respectively.

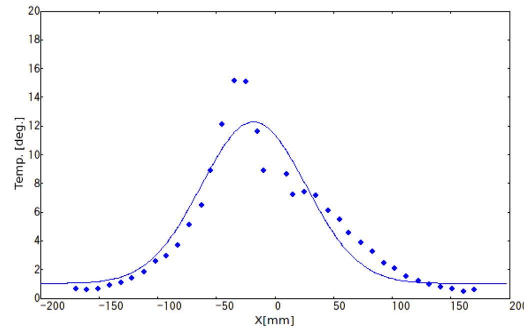


Figure 8: Typical temperature distribution at the beam dump. Its vertical axis is for the temperature rise [K], and the horizontal axis is for horizontal position of thermocouples [mm].

Figure 9 shows a simplified illustration of the incident angle correction at the beam dump. The incident angle ("A" in figure 9) at the beam dump can be calculated from the position information measured with two RGIPMs (AQ1DOUT and ADMPIN). The desirable incident angle ("B" in figure 9) can be estimated from the position at the steering magnet and the centre of the beam dump. The difference (B-A) is the angle to be corrected with the steering magnet. In the estimation of the correction angle, the kick effect in two quadrupole magnets (Q1C and Q1D) is ignored to be small.

The angle correction can be adopted when the following conditions are satisfied.

1. Beam positions at the beam dump with the temperature distribution and RGIPMs are within 165 mm, which is the radius of the conical hollow at the copper core.
2. The transverse beam profile in $\pm 3\sigma_x$ measured with the temperature distribution is within 165 mm.
3. Continuous beam extraction at least five shots.

The desirable kick angle of the steering magnet can be automatically controlled by the programmable voltage for the DC output current through the control PLC.

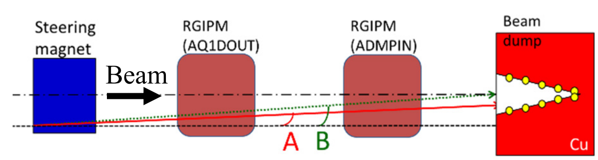


Figure 9: Illustration on the upstream side of the beam dump. The angles of A and B are the incident angle and the desirable incident angle at the beam dump respectively.Test of the Automatic Correction Program with Data during Beam Operation.

### *Test of the Automatic Correction Program with Data during Beam Operation*

We have checked validity of the automatic orbit-correction method with data accumulated during beam operation from June 9th to 14th, 2017. Figure 10 shows a trend graph of three beam positions. Blue and purple points were horizontal positions measured with the AQ1DOUT and AD-

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MPIN, respectively. Red points are the position data calculated by the automatic correction program. The calculated beam positions at the beam dump are about -8mm and stable. The discontinuous periods in figure 8 are due to beam stop.

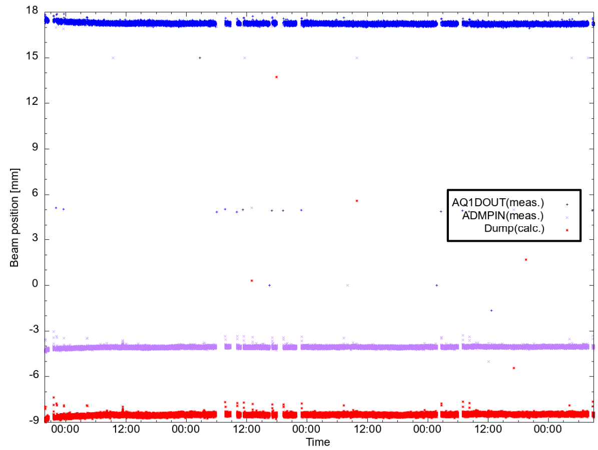


Figure 10: Trend graph of the horizontal beam positions measured with two RGIPMs (blue and purple) and calculated ones (red) by the automatic correction program.

Figure 11 shows a trend graph of the beam positions at the beam dump. The beam positions calculated by the automatic correction program agree well with those measured with the temperature distribution of the copper core. The deviations of the centre positions measured with the temperature distribution are due to decrease of temperatures at the copper core during beam stop. The automatic correction program to adjust the beam position at the beam dump can be useful in the actual beam operation.

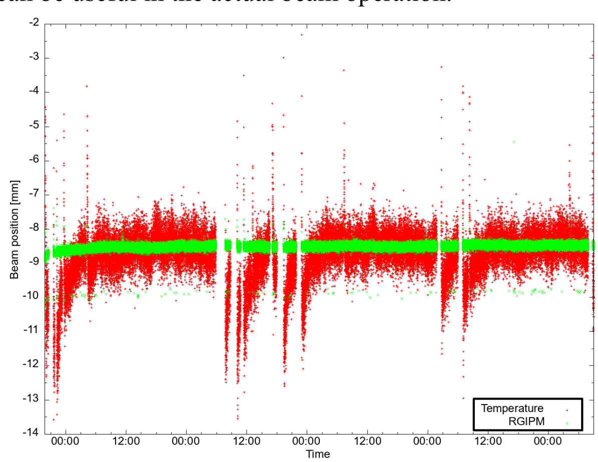


Figure 11: Trend graph of the beam positions at the beam dump. Green points are the position data calculated by the automatic correction program. Red points are the position data measured with the temperature distribution.

Figure 12 shows a trend graph of the optimized current of the horizontal steering magnet. The optimized current was about 24A and stable during the test period of six days.

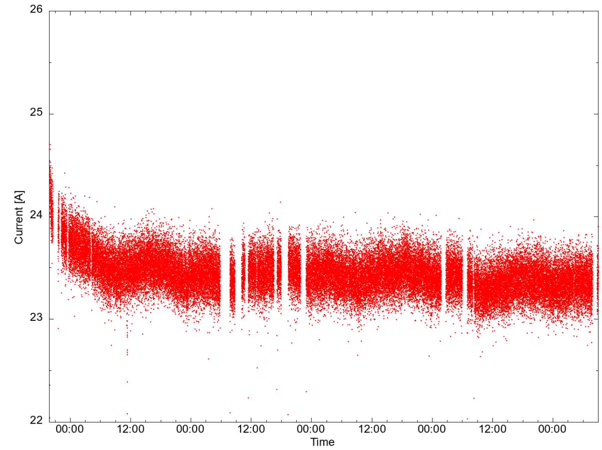


Figure 12: Trend graph of optimized current.

## SUMMARY

- We have developed a remote control system of the magnet power supply with the Yokogawa FA-M3V PLC. The stability of 0.0286 %/3h is measured with the Yokogawa FA-M3V PLC. The measured stability is acceptable for the control system of the power supply in the beam line at HEF.
- An automatic orbit-correction program for the steering magnet, which can adjust the centre position of the beam at the beam dump by using two profile monitors, has been developed and verified to be useful in actual beam operation.

## ACKNOWLEDGEMENT

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