

# INJECTION AND EXTRACTION DC MAGNETS POWER SUPPLIES FOR 3GEV RAPID CYCLING SYNCHROTRON OF J-PARC

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## Abstract

Several DC magnets including septum magnets are installed at injection line, beam dump line and extraction section in Rapid cycling synchrotron (RCS), respectively. All the power supplies have been operated stably. In this paper, parameters of their power supplies, and design, calculated and measured ripple current of the extraction septum magnet power supplies are described. For saving the cost and the installation space of the power supplies, a main power supply and three auxiliary power supplies for adjusting the current of extraction septum magnets 1, 2 and 3 are used, respectively. To prevent interferences and keep stabilities, blocking-coils of 100  $\mu$ H, whose value is decided based on calculation of SPICE model, are connected in series with individual auxiliary power supplies. Ripple current of the main power supply are measured. The measured values of it are larger than the calculated one in the model. We guess that they may be coming from several sources such as, superimposing commercial frequency and the higher frequency elements on the ground line of the feedback control system and on DC output of 6-point rectifier thyristors by imbalance of three phase alternating voltage, etc. However, measured ripple current is less than the order of 0.01 % which is required value from view point of the effective beam emittance, therefore fluctuations of the extracted beams have not been observed.

## INTRODUCTION

J-PARC consists of three acceleration systems, Proton Linac, RCS and Main ring (MR) [1]. RCS have successfully accelerated proton beams to the 3 GeV on August 2007. MR have successfully circulated 3 GeV beam and Materials & Life Science Experimental Facility (MLF) have recorded an event of the first neutron production on May 30th 2008.

RCS have the lattice with three-folding symmetry. It has three straight sections; the RF acceleration section, the injection, dump, and collimation section and the extraction section [2,3]. On the injection line, two injection septum magnets (ISEP1, ISEP2) are installed. Two vertical steering magnets and two horizontal steering magnets are installed on the L3BT line to adjust the injected beam orbit from the Linac. On the dump line, several DC magnets, two dump septum magnets (DSEP1, DSEP2), a quadropole magnet, a vertical steering magnet and a horizontal magnet for are installed respectively. The extraction part mainly consists of three extraction septum

magnets (ESEP1, ESEP2, ESEP3), eight kicker magnets as a fast extraction for 3 GeV accelerated beam, two DC kicker magnets as 1/3 circulation extraction for no accelerated beam.

The required flatness of the magnetic field of these DC magnets is less than the order of 0.1 % and also magnetic field must be stable, therefore the power supplies of these DC magnets are required to the stability and the ripple currents of the order of 0.01 % from view point of the effective beam emittance.

## DESIGN OF DC MAGNET AND POWER SUPPLY

Main design parameters of DC magnets and the power supplies for the injection, dump and extraction section are shown in Table 1 and 2. The resistance values calculated by output voltage and current of the power supply are sum of the resistance of the magnet and the cable or the bus-duct. Inductance values at 1 kHz measured by LCR meter are also sum of the magnet and the cable or the bus-duct when they were not connected to the power supplies. Inductance and capacitance of the cable and the bus-duct are sufficiently small compared to that of the magnets and output capacitances except injection steering magnets. Ripple currents against the maximum current at each frequency component are the order of 0.01 % which is different by the power supplies.

The DC stabilized power supplies are dropper-type using transistors except for those of extraction septum magnets which are switching-type using IGBTs. In this paper, system of the dropper-type power supplies is not described because of the limitation of the page length. Extraction septum magnet power supply system is described.

## EXTRACTION SEPTUM MAGNETS POWER SUPPLIES

Excitation currents of the extraction septum magnets need the maximum current of 12.2 kA. For saving the cost and the installation space of the power supplies, we use a main power supply, which excites three extraction septum magnets in series, and three auxiliary power supplies for adjusting the current of the ESEP1, ESEP2 and ESEP3, independently. (Nevertheless, total width of the four power supplies are 17 m.) The maximum current of the main power supply and the auxiliary power supplies are decided to be 9200 A and 3000 A, respectively. When the beams are extracted at the energy of 181 MeV and 400 MeV, the magnets require maximum current of 3000 A, therefore only the auxiliary power

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Table 1: Parameters of DC Septum Magnets and Power Supplies

	P.S. For ISEP1	P.S. For ISEP2	P.S. For DSEP1	P.S. For DSEP2	Main P.S. For ESEP	Auxiliary P.S. For ESEP1	Auxiliary P.S. For ESEP2	Auxiliary P.S. For ESEP3
Max. Magnetic flux density ( $T$ )	0.43	0.48	0.48	1.32	-	0.75	1.47	1.82
Inductance ( $mH$ ) at 1k Hz	0.15	0.028	0.027	0.66	0.18	0.060	0.11	0.13
Resistance ( $m\Omega$ )	8.6	2.9	3.1	20.2	7.4	2.6	3.9	1.4
Max. P.S. current ( $A$ )	3000	6750	6750	3100	9200	3000	3000	3000
Max. P.S. voltage ( $V$ )	43	33	37	75	118	35	55	40
Ripple currents (%)	0.01	0.01	0.05	0.05	0.01	0.03	0.03	0.03

Table 2: Parameters of DC Magnets and Power Supplies

	P.S. For Injection H steer	P.S. For Injection V steer	P.S. For Dump H steer	P.S. For Dump V steer	P.S. For Dump Q	P.S. For DC kicker
Max. Magnetic flux density ( $T$ )	0.035	0.035	0.20	0.1	1.4 ( $T/m$ )	0.27
Inductance ( $mH$ ) at 1k Hz	14.7	14.1	0.8	1.7	1.7	2.4
Resistance ( $m\Omega$ )	490	500	15	22	28	24
Max. P.S. current ( $A$ )	$\pm 22$	$\pm 22$	$\pm 715$	$\pm 450$	1400	660
Max. P.S. voltage ( $V$ )	$\pm 13$	$\pm 13$	$\pm 15$	$\pm 13$	61	24
Ripple currents (%)	0.025	0.025	0.05	0.05	0.05	0.01

supplies can be used by determining these maximum current values.

The equivalent circuit of the extraction septum magnets and the power supplies is shown in Figure 1. The main power supply and the magnets are connected with bus-duct. The auxiliary power supplies and the magnets are connected with cables. These power supplies are connected in series and parallel through the magnets each other. Therefore the power supplies are interfered each other. Although these power supplies have negative feedback control system, stability and ripple current does not satisfy with the required values by SPICE (Micro-Cap) model calculation in the design magnet inductance and resistance. So coils (named blocking-coil) are connected to individual auxiliary power supplies in series. By SPICE model calculation, large ripple current ( $\pm 27 A$ ) of main power supply occurred with blocking-coil of  $35 \mu H$ . When blocking-coil of  $42.5 \mu H$ , ripple current was  $\pm 6.5 A$ . When blocking-coil of  $50 \mu H$ , ripple current was sufficiently suppressed ( $\pm 0.02 A$ ). In these calculations, resistance and inductance of the magnets are  $1.96 m\Omega$ ,  $0.05 mH$  for ESEP1,  $3.36 m\Omega$ ,  $0.079 mH$  for ESEP2 and  $1.00 m\Omega$ ,  $0.077 mH$  for ESEP3 are used. The modelling might be imperfect by stray inductance and/or capacitance etc and also magnet would be just under designing at the same time. Then to avoid the risk of exceeding the required values after the construction, we decided to employ blocking-coils of  $100 \mu H$ . Ripple current of

blocking-coil of  $100 \mu H$  was the almost the same as one of  $50 \mu H$  in the calculation.

The power supplies consist of several unit power supply (800A and 60 V) connected in parallel and in series. Unit power supply is shown in Figure 2. Three phase alternating current of 400V is converted by 6-point rectifier thyristors to direct current which charges a capacitor C2. Charged voltage of C2 is 540 V. The DC voltage is chopped by IGBTs with switching frequency of 17 kHz and stepped down by a high frequency transformer, and then it charges the C1.

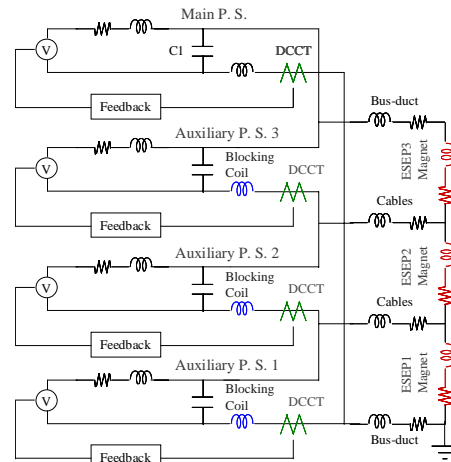


Figure 1: Equivalent circuit of extraction septum magnets power supplies.

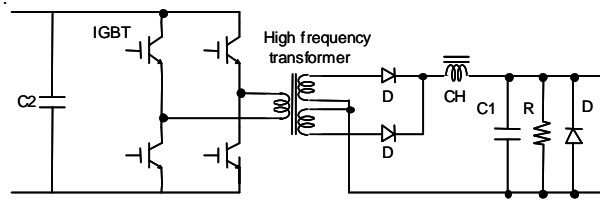


Figure 2: Equivalent circuit of unit power supply.

The auxiliary power supplies consist of 4 unit power supply in parallel. The main power supply consist of 4 power supply panel (not shown) in parallel which consist of unit power supplies with 3 in parallel and 2 in series. Each panel has a thyristors system, therefore converted voltage from thyristors supplies to 6 unit power supplies.

The power supply panel has DCCT (CURACC-type, HITEC Company) of 2300A and the current signals of them are summed in the control panel and same feedback signal is sent them.

Ripple current of the main power supply is measured. Output currents are 8900 A for the main power supply and 3000 A for the auxiliary power supplies, respectively. The output current is detected with DCCT. The detected current of main power supply is converted to the voltage by the amplifier circuit. Current of 10120 A ( $=1.1 \times 9200$  A) are converted into 10 V. As the electromagnetic soft iron block is used for the yoke of the magnet, we are interested in lower frequency components, less than 1 kHz, of the ripple. (The ripple current of 17 kHz component was enough small from measured results.) Frequency components of the output current are measured with Spectrum analyzer (Ono-sokki Company, CF-5220Z). The measured result is shown in Figure 3, where the unit of the measured voltage is in dBV. Conversion expression from the voltage to the ripple current ( $\Delta I_{ripple}$ ) is shown in the following.

$$\Delta I_{ripple} = \sqrt{2} \times (10120/10) \times 10^{(dBV/20)} \quad (1)$$

The maximum value is -65.26 dBV at 50 Hz. 50 Hz is commercial frequency in eastern Japan. The next maximum value is -73.06 dBV at 300 Hz. The -65.26 dBV and -73.06 dBV are converted into  $\pm 0.55$  A and  $\pm 0.225$  A, respectively. These are  $\pm 0.006$  % and  $\pm 0.0025$  % of the maximum current (9200 A) which is less than the required value.

Measured waveform of the ripple current is shown in Figure 4. It seems to be approximately  $\pm 2$  A to the eye. These values are quite different from the results of the SPICE model calculation. Though we calculated again using measurement values of the magnet inductance and resistance, the results of ripple were almost the same with the previous one.

We guess that they may be coming from several sources as follows. Commercial frequency and the higher frequency elements may be superimposed on the ground line of the feedback control system which might causes imperfection of IGBTs switching at the frequency elements. The frequency elements may be also superimposed on DC output of 6-point rectifier thyristors by imbalance of three phase alternating voltage of the

receiving power equipment at J-PARC. There might be errors of fine adjustment of switching timing of the thyristors. It might be difficult to make the model of the circuit including such errors or fluctuations or noises.

Since the ripple current is smaller than the required value, fluctuations of the extracted beams have not been observed.

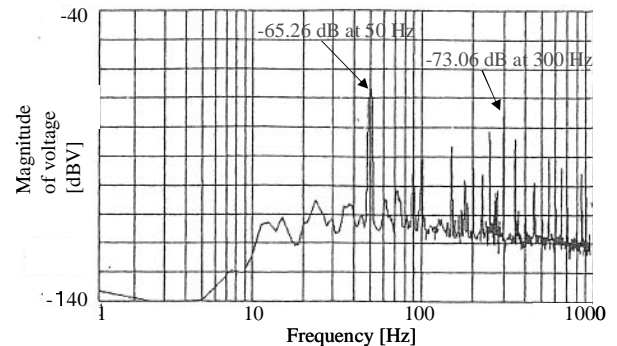


Figure 3: Frequency distributions of the ripple current of the main power supply.

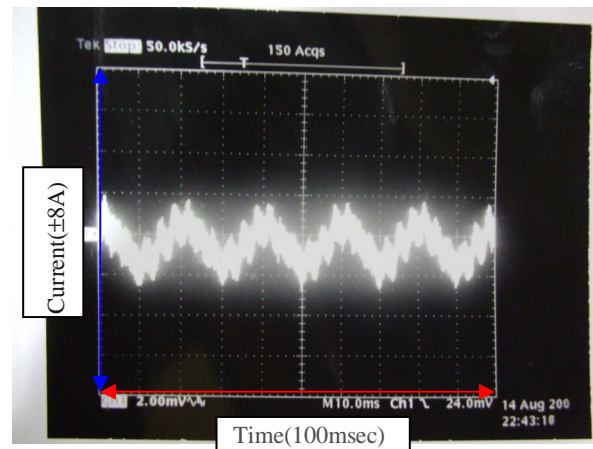


Figure 4: Waveform of the ripple of the current of the main power supply.

## ACKNOWLEDGMENT

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