ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS028

RECENT IMPROVEMENTS AND FUTURE UPGRADES OF THE J-PARC MAIN RING KICKER MAGNET SYSTEMS

T.Sugimoto*, K.Ishii, T.Shibata, H.Matsumoto, KEK, Tsukuba, Japan

Abstract

J-PARC Main Ring provides a high-intensity proton beam to the long baseline neutrino oscillation experiment (T2K). Increasing the beam intensity to improve the sensitivity of the CP violation study in the neutrino sector, both shorter repetition cycle and higher beam current are required. As a part of the upgrade project, both injection and fast-extraction (Fx) kicker magnet systems have been improved. A new quick charging power supply of the modulator for the Fx kicker magnet was developed and deployed to shorten the charging period from 1.8 sec to 0.2 sec. Non-inductive ceramic resistors are used as the impedance-matching terminator for the injection kicker magnet. A temperature rise of the termination resistor due to the beam induced current was measured, and the average power was estimated to optimize the number of the resistors connected in parallel. Numerical simulation of the thermal behavior of the resistors was carried out, and the results were compared with the measurements. This paper represents the performance of the new charging unit and the design of the termination resistor.

INTRODUCTION

J-PARC (Japan Proton Accelerator Complex) consists of three accelerators, a 400-MeV Linac, a 3-GeV Rapid Cycle Synchrotron (RCS) and a 30-GeV Main Ring (MR). The MR provides a high-intensity proton beam to the long baseline neutrino experiment (T2K) and the hadron experiments. During 2018, the beam intensity provided to the neutrino experiment was 495 kW corresponding to 2.56×10^{14} proton per pulse (ppp) for the repetition rate of 2.48 sec [1]. To achieve the higher precision measurement of the neutrino oscillation and the observation of the CP violation of the neutrino, operation with higher intensity beams is required. In late 2020s, high intensity operation of 1.3 MW beam power will be achieved by both shortening the repetition period from 2.48 sec to 1.16 sec and increasing the number of proton from 2.4×10^{14} to 3.34×10^{14} ppp [2, 3]. Including the margin, the goal of hardware development is to operate with the repetition period of 1 sec. Proton beams are injected into J-PARC MR at 3 GeV by four kicker magnets [4–6] and extracted at 30 GeV by five kicker magnets [7]. The MR stores 2×4 proton bunches extracted from the RCS. Two bunches are deflected by one kicker pulse. After accelerating the injected beam, all bunches are extracted by one pulse of the extraction kicker magnet. To achieve the 1.3 MW operation, both kicker system are required to upgrade.

* takuya.sugimoto@j-parc.jp

NEW CHARGING POWER SUPPLY FOR FX KICKER MAGNETS

A new charging power supply for the modulator of the fast-extraction (Fx) kicker system has been developed to achieve the repetition period of 1 sec. The Fx kicker system is composed of 5 lumped constant kicker magnets powered by pulse forming network (PFN's) [8, 9]. The modulator consists of 60 parallel capacitors which each of them is 20nF, two thyratrons, shunt diodes, and termination resistors. Originally the capacitors were charged in 1.8 sec using an industrial high voltage power supply. However, shorter charging time is required to achieve the acceleration time of 0.58 sec when the repetition period will be shortened to 1.16 sec [3]. Nominal charging voltage is 33kV to extract the beam to the neutrino target. To achieve the charging time to be less than 0.58 sec the output charge must be more than 68.3 mA. Including the margin, the maximum output current is set to 200 mA. Figure 1 shows the block diagram of the new charging power supply of the PFN. The output voltage is controlled by the Pulse Width Modulation (PWM) control. The voltage jitter must be less than 1% and 0.1% for the ramping period and the flat top respectively. A surge blocking diode is introduced to prevent from the break down due to the surge current after switching on the thyratron. There is a functionality to control the output voltage by applying the analog voltage (0-5 V). The charging voltage of the PFN is followed to the ramping pattern of the proton beam energy. The maximum charging voltage is 40 kV and the nominal current is 200 mA. Figure 2 shows the waveform of the voltage of PFN measured by high voltage probe (blue line), the output current (green line) and the pattern voltage (red line). To compare the performance, the waveform of the charging voltage of the old charger was also measured.. The minimum ramping time of the new power supply was measured to be less than 200 msec. We confirmed that the continuous operation for the repetition period of 1 sec had done for several hours without any problem.

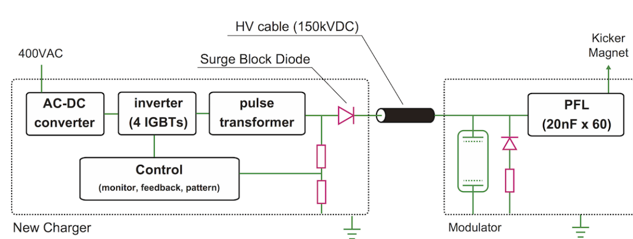

Figure 1: Schematic diagram of the new charging power supply for the Fx kicker magnet.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS028

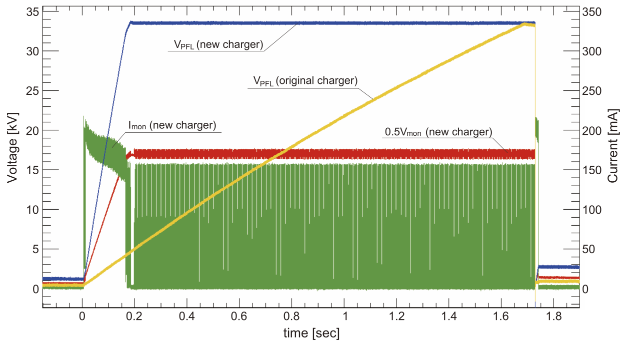

Figure 2: Waveform of the charging voltage measured at the anode of the thyratron in the PFL.

RESISTOR HEATING OF INJECTION KICKER MAGNET

As the beam power increased, a resistor heating problem of the injection kicker magnet has revealed. Figure 3 shows the equivalent circuit of the injection kicker magnet. Impedance matching resistor R_1 is connected to the kicker coil L_1 to reduce the reflection pulse. The resistance is 9.3 Ω optimized by measuring the pulse shape [6]. Fifteen non-inductive ceramic resistors are connected in parallel, which is called as "resistor unit" shown in Fig. 4, to reduce the temperature rise of the resistor. The resistors unit is contained in an individual box settled on the vacuum chamber, which is called "matching box." Resistors (R_2) and capacitors (C_2) are connected to the coil in parallel both to reduce the beam coupling impedance [4, 5] and to match the impedance for high frequency region. The electrodes of the resistor were brazed on both ends of the conductive ceramics to avoid discharge [10]. The nominal current of the pulse is 2640 A, and the pulse width is 1.5 μsec. The pulse energy of the nominal current is about 100 J, and four pulses are fed into the coil during the operation cycle to inject 2×4 bunches to the circular orbit. When the circulating beam passes through the kicker aperture, an electrical current is induced, and it flows in the matching circuit connected to the coil (i.e., R_1, R_2 and C_1). Therefore, the resistor R_1 is heated by both the excitation pulse current and the beam induced current, while the resistor R_2 is heated by only the beam induced current. The temperature rise of the resistor ΔT is estimated as:

$$\Delta T = \frac{1}{N}\frac{Q_{pulse} + Q_{beam}}{hA} \quad (1)$$

$$= \frac{1}{NhA}\left(\int I^2(t)dt\frac{R}{T_{rep}} + \int E_b(t)dt\right) \quad (2)$$

where N is the number of resistors connected in parallel, Q_{pulse} is the power of the excitation pulse of the kicker magnet, Q_{beam} is the power of the beam induced current, h is the convective heat transfer coefficient, A is the surface area of the resistor, I(t) is the excitation current of the magnet, R is the total resistance of the resistors, T_{rep} is the repetition period, $E_b(t)$ is the pulse energy of the beam induced current. Increase of both the diameter of the ceramic cylinder and the number of paralleled resistors is required to expand the total surface area. In addition, a cooling fan is also required to improve the heat transfer coefficient.

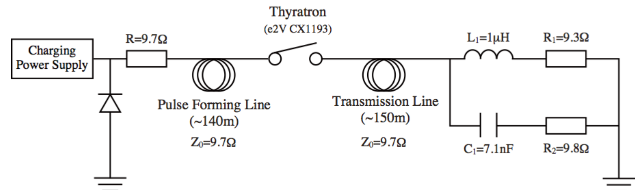

Figure 3: Equivalent circuit of the injection kicker system.

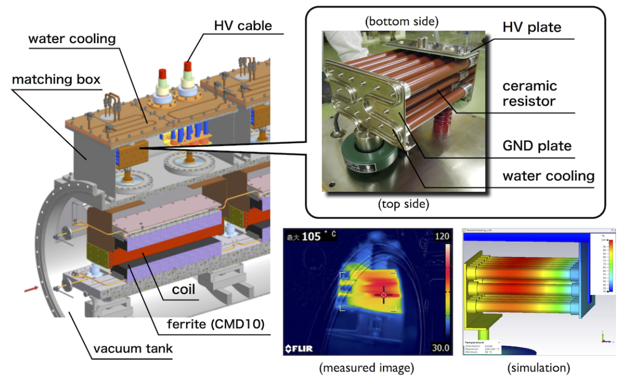

Figure 4: Resistor unit housed in the matching box.

Measurements

Figure 5 shows the temperature variation of the resistor measured by a thermography camera. The resistor unit was pulsed at nominal voltage and the repetition period of 2.48 sec. The time constant of the transient variation is represented as $\tau = \rho Vc/hA$, where ρ is the density, V is the volume, c is the specific heat, h is the convective heat transfer coefficient, A is the surface area. For the resistor, ρ is 2330 kg/m^3, V is 2.72×10^{-5} m^3, c is 730 J/(kg·K) and A is $1.07{\times}10^{-2}$ m^2. Fitting the plot ΔT and τ are estimated as 78.9 °C and 416.2 sec respectively. Therefore, h is calculated as 10.3 W/(m^2·K). This value is reasonable to consider the effect of both the water cooling and natural convection. Considering the 1st term of the equation (2), the temperature rise of the resistor is expected about 270 °C for the input power of 389 W, which is equal to the power of the 1 Hz pulse operation. Figure 6 shows the temperature rise of the resistor as a function of MR beam power. Thermal labels were attached on the surface of the resistors to measure the maximum temperature of the resistors during the continuous beam operation. The solid line shown is a parabolic function because the power consumption of the resistor is proportional to the square of the beam charge. The temperature during the stable operation of both 260kW (1.34×10^{14} ppp) and 440kW (2.27×10^{14} ppp) beam power was measured. The error bar indicates the interval of the indicator of the thermal labels, which is 10 °C step. Extrapolating the fitting function (dotted line), the maximum temperature of the

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS028

resistor is predicted to be 200 °C for 1.3MW (3.34×10^{14} ppp and 1.16 sec repetition) beam circulation. One pulse energy of beam induced current was estimated to 1.37×10^{-3}J when a bunch of 1.3MW equivalent charge passed through the kicker. The total energy of the bunch train (2×4 bunches) circulating in the ring before extraction (1.5×10^5 turns) is 205 J. This corresponds to the average power of 187 W. Hence we obtained the temperature rise of 90 °C, which agrees with the extrapolation. However, the uncertainty of the average power is expected because beam induced current may depend on the distance between the coil and the beam and on the bunch shape. So the maximum power for 1.3MW operation is assumed to 1 kW, including the safety factor of 3 to decide the number of resistors.

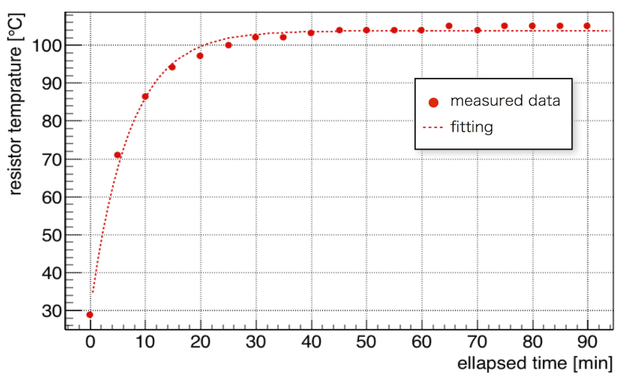

Figure 5: Measured temperature of the resistor for the nominal current and 2.48 sec repetition period.

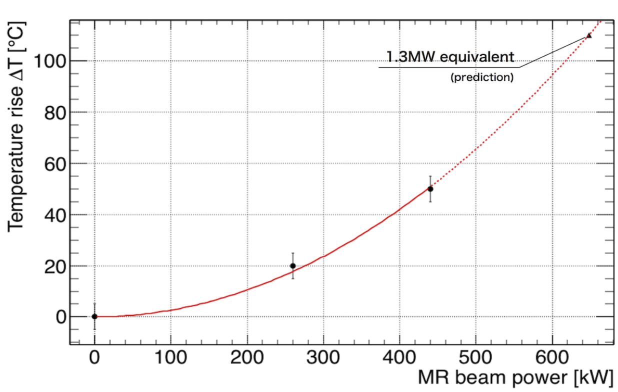

Figure 6: Measured temperature rise of the resistor versus MR beam power.

Numerical Design of New Resistors Unit

A 3D numerical model shown in Fig. 7 was created using the CST [11] to determine the number of resistors. A thermal fluid simulation using the CST Conjugate Heat Transfer (CHT) solver was carried out to estimate the maximum temperature of the resistor T_{max} and optimize the new design of the resistors unit. To improve the cooling of the resistors, forced convection using a fan was tested. The diameter of the resistor cylinder was increased 1.5 times larger than the original, while the length was the same. The number of paralleled resistors was increased from 15 to 30. A cooling fan with the window velocity of 2 m/s was placed to improve the heat transfer coefficient h. Furthermore, an alumina ceramic rod (Al_2O_3) was inserted in each resistor cylinder to reduce the thermal resistance. Simulation results of six conditions are summarized in Table 1. The temperature of case #1 is consistent with a solution of equation (2) for h = 12.5. Instead of alumina, aluminum nitride (AlN) was also tested and the better result was obtained (case #6). However, alumina was chosen to reduce the cost. A further simulation study is still ongoing to determine the best placement of the resistors.

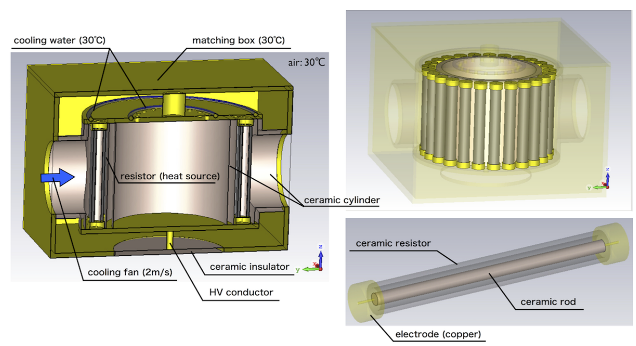

Figure 7: A numerical model of the resistor unit.

Table 1: Simulation Results

case	rod	fan	cylinder	T_{max} [°C]
1	×	×	×	164.8
2	×	×	◯	143.1
3	×	◯	◯	118.4
4	Al_2O_3	×	◯	113.9
5	Al_2O_3	◯	◯	97.9
6	AlN	◯	◯	62.7

CONCLUSION

To achieve a beam power of 1.3MW two kicker magnet systems of J-PARC MR are required to upgrade. A new quick charging power supply for fast extraction kicker magnets have been developed and deployed. Charging time was shortened from 1.8 sec to 0.2 sec. Impedance matching resistor connected to the coil is heated by both the excitation pulse current and the beam induced current. A temperature rise of both 1.16 sec repetition period and the 1.3MW beam circulation was calculated at about 350℃. Improving the number of the paralleled resistor, the surface area of the resistor and cooling is mandatory to reduce the temperature rise. Numerical simulation using CST was carried out to design a new resistor unit. The diameter of the resistor cylinder and the number of resistors were optimized to reduce the temperature rise to be less than 100 °C. The present resistors unit will be replaced by the end of 2021.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS028

REFERENCES

[1] Y. Sato, "High Power Beam Operation of the J-PARC RCS and MR", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2938–2942. doi:10.18429/JACoW-IPAC2018-THYGBF1

[2] T. Koseki, "Upgrade Plan of J-PARC MR - Toward 1.3 MW Beam Power", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 966–969. doi:10.18429/JACoW-IPAC2018-TUPAK005

[3] M. Yoshii *et al.*, "Present Status and Future Upgrades of the J-PARC Ring RF Systems", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 984–986. doi:10.18429/JACoW-IPAC2018-TUPAK011

[4] K. Fan, S. Fukuoka, H. Matsumoto, T. Sugimoto, and T. Toyama, "Coupling Impedance Study of the New Injection Kicker Magnets of the JPARC Main Ring", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper THPPP003, pp. 3725–3727.

[5] K. Fan *et al.*, "Design and Test of Injection Kicker Magnets for the JPARC Main Ring", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper THPPP004, pp. 3728–3730.

[6] T. Sugimoto, K. Fan, K. Ishii, and H. Matsumoto, "Upgrade of the Injection Kicker System for J-PARC Main Ring", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 526–528. doi:10.18429/JACoW-IPAC2014-MOPME069

[7] K. Fan, K. Ishii, H. Matsumoto, N. Matsumoto, T. Sugimoto, and T. Shibata, "Upgrade of J-PARC Fast Extraction System", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 821–823. doi:10.18429/JACoW-IPAC2014-MOPRI089

[8] K. Koseki et al., "The fast extraction kicker for J-PARC with a novel pulse compressin system", *Nuclear Instruments and Methods in Physics Research*, A **739** (2014) 63, http://dx.doi.org/10.1016/j.nima.2013.12.040

[9] K. Koseki, "The fast extraction kicker power supply for the main ring of J-PARC", *Nuclear Instruments and Methods Physics Research*, A **729** (2013) 3, http://dx.doi.org/10.1016/j.nima.2013.06.105

[10] T. Sugimoto, K. Fan, K. Ishii, H. Matsumoto, K. Abe, and S. Fukuoka, "Development of a Non-inductive Ceramic Resistor", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOPWA004, pp. 669–671.

[11] Computer Simulation Technology, https://www.cst.com/