THE DESIGN OF TRIM-S UPGRADE FOR THIRD-ORDER RESONANCE CORRECTION AT J-PARC MR

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Abstract

At the Japan Proton Accelerator Research Complex (J-PARC) Main Ring (MR), a project involving 24 Trim-S units has been proposed for third-order resonance correction targeted at resonance influence on $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ for on- and off-momentum particles ($\Delta p/p = +0.2\%$ and -0.2%) and unaddressed fourth-order resonance $4\nu_x = 85$ combined by $\nu_x = 21$ and $3\nu_x = 64$. Due to the challenges in estimating the resonance effects on off-momentum particles and the fourth-order resonance, beam studies are being carried out step by step. With 8 Trim-S units already prepared, the next step is a 12-unit configuration for further beam studies. Accordingly, this paper discusses the engineering design of the 12 Trim-S units for user operation, including the specifications of the Trim-S power supplies (PSs) based on consideration of the 1.3 MW beam power, the design of the electrical power system, and the design of control system, i.e. control network, timing sytem, Machine Protection System (MPS), and Personnel Protection System (PPS).

INTRODUCTION

At the Japan Proton Accelerator Research Complex (J-PARC) Main Ring (MR), after the stable operation of 750 kW beam, many efforts are underway to contribute to the next step for a 1.3 MW beam power. Beam loss suppression is one of the major task since we have to keep a hands-on maintenance environment for MR upgrade work. Numerical simulations show that the compensation of the third-order resonances of $3\nu_x = 64$, $\nu_x + 2\nu_y = 64$ and the fourth-order resonance of $4\nu_x = 85$, which is combined by $\nu_x = 21$ and $3\nu_x = 64$, for on- and off- momentum particles ($\Delta p/p = +0.2\%$ and -0.2%) would further suppress beam loss to the ideal level without magnetic filed errors [1]. Hence, a project involving 24 Trim-S (trim coils of sextupole magnets) units is proposed.

This project is conducting step-by-step. In 2015, 4 Trim-S power supplies (PSs) have been installed at D2 Power Supply Building, and the third-order resonances of $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ for on-momentum particles have been successfully corrected [2]. During 2024 and 2025, an System-On-Chip (SoC) Field Programmable Gate Array (FPGA) controller is developed to drive another 4 Trim-S PSs which are located at D3 Power Supply Building [3]. The beam study using individual 4 units and combined 8 units are preformed and compared as well [4]. Results show that their good consistence and agreement on third-order resonance correction at MR. The evaluation of sextupole field error distributed around the whole MR is undergoing and needs to be further investigated for the estimation of resonance effects on off-momentum particles and the fourth-order resonance of $4\nu_x = 85$. As a result, for the next step, considering the resonance correction for $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ on on-momentum particles, the system of 12 Trim-S units is designed and discussed in the aspects of specifications and overall configuration.

This paper is structured as follows. In section 2, the layout of 12 Trim-S units is introduced, and the current setting for each Trim-S unit is calculated based on the beam-study estimation for resonances of $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$. In section 3, using working pattern for 1.3 MW beam power of Trim-S, the specifications of Trim-S PS is derived. The power system is design by considering the power consumption. In section 4, the overall configuration of the Trim-S control system is presented including the design for control network, timing system, Machine Protection System (MPS) system and Personnel Protection System (PPS) system. Finally, a summary and outlook are given in section 5.

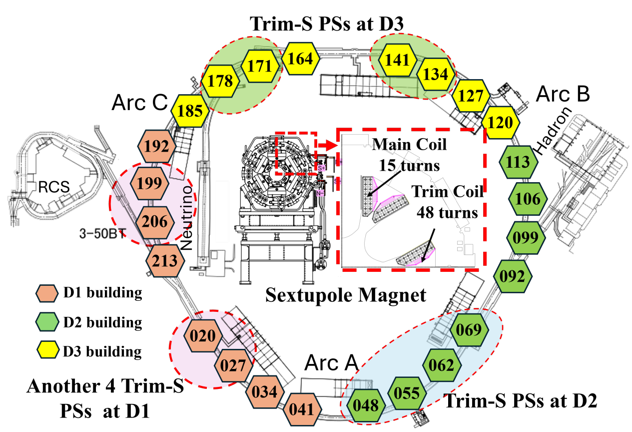

Figure 1: SFA layout and the structure of sextupole magnets at the J-PARC MR. The red circles indicate the locations of 12-Trim-S setup for third-order resonance correction. The numbers inside the the hexagons indicate the addresses of the magnets. The central diagram illustrates the structure of a sextupole magnet, which consists of a main coil and a trim coil.

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MAGNET SELECTION

As shown in Fig. 1, there are totally 24 focusing sextupole magnets (SFA) at J-PARC MR. Each sextupole is equipped a main coil for chromaticity correction and a trim coil for third-order resonance correction. As shown in the left part of Fig. 2, while all main coils are connected in series and powered by a single main PS, the trim coils are excited individually, enabling fine compensation for sextupole magnetic field errors and effective third-order resonance correction.

For the setup of 12 Trim-S units, an additional 4 Trim-S magnets whose coil terminals are located at D1 Power Supply Building need to be selected and excited. The selection of Trim-S magnets for resonance correction is based on two principal criteria:

- The spatial distribution of the driving terms should be as wide as possible to effectively compensate for unclear or diffuse resonance sources.
- The required current settings of the power supplies should be minimized to simplify the design of the PS system.

The third-order resonance driving term is expressed as:

$$G_{3,0,64}e^{j\xi_{3,0,64}} = \sum_{i=1}^{N} \frac{\sqrt{2}}{24\pi}\beta_x(i)^{3/2}[K_2(i)\Delta L] \times e^{j[3\chi_x(i)-(3\nu_x-64)\frac{s(i)}{R}]}, \quad (1)$$

$$G_{1,2,64}e^{j\xi_{1,2,64}} = \sum_{i=1}^{N} \frac{\sqrt{2}}{8\pi}\beta_x(i)^{1/2}\beta_y(i)[K_2(i)\Delta L] \times e^{j[\chi_x(i)+2\chi_y(i)-(\nu_x+2\nu_y-64)\frac{s(i)}{R}]}. \quad (2)$$

Here, the driving term of the resonance is approximately expressed as the sum of the local driving terms of Trim-S units evaluated along the reference orbit length $s(i)$, where N is the number of Trim-S contributed to resonance correction, i represents different Trim-S units. $\beta_x(i)$ and $\beta_y(i)$ are horizontal and vertical betatron functions at $s(i)$, $K_2(i)\Delta L$ is the integrated sextupole strength of Trim-S units, $\chi_x(i)$ and $\chi_y(i)$ are horizontal and vertical phase advances at $s(i)$, R is the average radius of MR, j is the imaginary unit, and ν_x and ν_y are the horizontal and vertical tunes defined by the number of betatron oscillations, i.e., $\nu_{x,y} = \frac{1}{2\pi}\int_s^{s+2\pi R}\frac{ds}{\beta_{x,y}(s)}$.

For the selection of magnets at D1 Power Supply Building, Eqs. (1) and (2) are used with $N = 1$ and $K_2(i)\Delta L = \pm 1$. The choice between -1 and $+1$ for $K_2(i)\Delta L$ depends on the phase position of the driving term, such that all driving terms can be aligned within the same half of the complex plane. Based on the lattice data from the Strategic Accelerator Design (SAD) code and the working point of $(\nu_x, \nu_y) = (21.39, 21.41)$, the driving terms for all magnets are calculated and shown in Fig. 3. Four candidate groups of magnets satisfy criterion 1. Next, by setting $N = 4$, using the $K_2(i)\Delta L$ values derived from the beam-study results of the D2 Trim-S units, and solving the simultaneous equations of Eqs. (1) and (2) for 4 Trim-S units at D1, the required current settings for each power supply are obtained. The 4 candidate groups and their corresponding current settings are listed in Table 1. After comparison, the group consisting of SFA020, SFA027, SFA199, SFA206 is selected due to its lower maximum current requirement. The final current settings of D1, D2 and D3 for the usage of individual 4 Trim-S units, are summarized in Table 2. In the beam study, a scan method [5] with a step size of 0.2 A was used. This means the maximum current setting can reach up to 2.1 A, which is well below the maximum current rating of 5.5 A for the trim coils, and ensures safe operation for the Trim-S design.

Table 1: Magnets Current Setting for Different Group at D1

Magnets	Current [A]
D1 (020, 027, 199, 206)	(0.69, -1.53, 0.20, 1.44)
D1 (020, 041, 192, 199)	(0.95, 2.12, -1.82, -0.10)
D1 (027, 034, 206, 213)	(-1.33, -0.11, 1.73, -0.76)
D1 (034, 041, 192, 213)	(1.12, 2.00, -3.18, -1.66)

Table 2: Current Settings for 12 Trim-S Magnets

Magnets	Current [A]
D2 (048, 055, 062, 069)	(1.71, -0.10, -0.08, 0.25)
D3 (134, 141, 171, 178)	(-1.43, 1.55, 1.70, -1.50)
D1 (020, 027, 199, 206)	(0.69, -1.53, 0.20, 1.44)

SPECIFICATIONS OF TRIM-S PS

In this section, based on requirements of third-order resonance correction, the specifications of Trim-S PS, including the schematic design of Trim-S PS and the design of electrical power system, are derived.

The Design of Trim-S PS

The load parameters of the Trim-S PS, i.e., the parameters of Trim-S magnet, are listed in Table 3. Based on beam study results with acceptable beam loss, the performance specifications of the Trim-S PS are summarized in Table 4. The current ripple is defined as $I_{\text{ripple}} = I_{\max} - I_{\min}$, measured at a 96 kHz sampling rate with a 2 kHz low-pass filter. Gain stability is required to account for potential amplifier gain drift. Long-term stability is evaluated using a moving average of the current, calculated hourly with a 2 Hz sampling rate. The working environmental conditions for the Trim-S system are listed in Table 5.

For third-order resonance correction, the Trim-S PS is designed to operate in DC mode during fast extraction. As shown in Fig. 4, the current of the main coil and the induced voltage in the trim coil are plotted. The 1.2 s operation cycle for 1.3 MW beam power at MR is shown. The current pattern of main SFA PS is specified with a 10% margin (equivalent to dividing by 0.9). The Trim-S PS operates in DC mode with a maximum output current of ±5.5 A, and

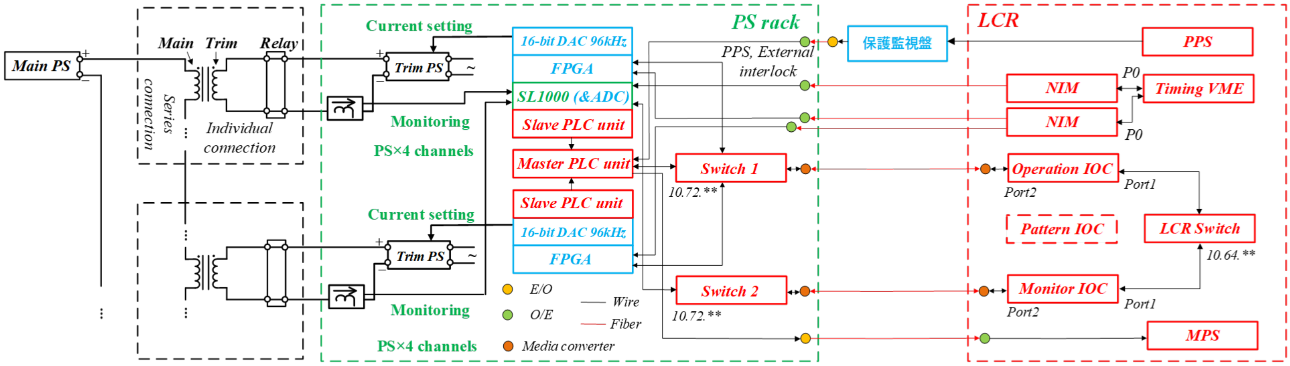

Figure 2: The overall configuration of Trim-S system at one power supply building.

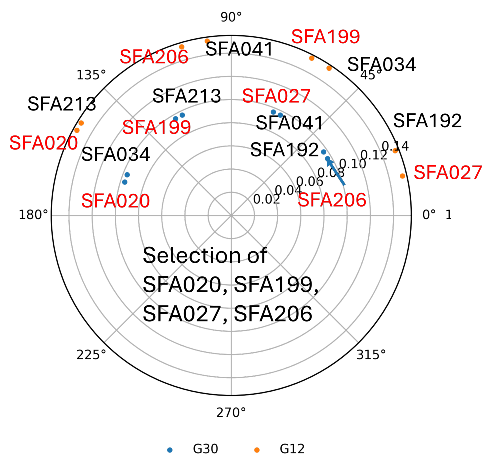

Figure 3: The distribution of driving term at D1 Power Supply Building.

Table 3: Load Conditions of Trim-S PS

Item	Values
Resistance	4.3 Ω
Inductance	0.165 H
Max current	± 5.5 A
Max voltage	150 V
Coupling inductance	14.8 to 16.9 mH

Table 4: Performances of Trim-S PS

Item	Values
Current ripple	< 50 mA
Gain stability	± 100 ppm (8 hours)
Long-term stability	< 5 mA (1 hours)

the corresponding output voltage is ±23.7 V (calculated as $\pm 5.5 \times 4.3 = \pm 23.7$ V).

The Trim-S PS is designed to work in pattern (pulse) mode for slow extraction, because we expect the Trim-S PS works in a lowest effort during the extraction period but effective effort in the injection and ramping period. The working pattern for induced voltage and output voltage are shown in

Table 5: Environmental Conditions of Trim-S PS

Item	Values
Location	Indoors
Surrounding temperature	0 to 40 °C
Relative humidity	10% to 80%

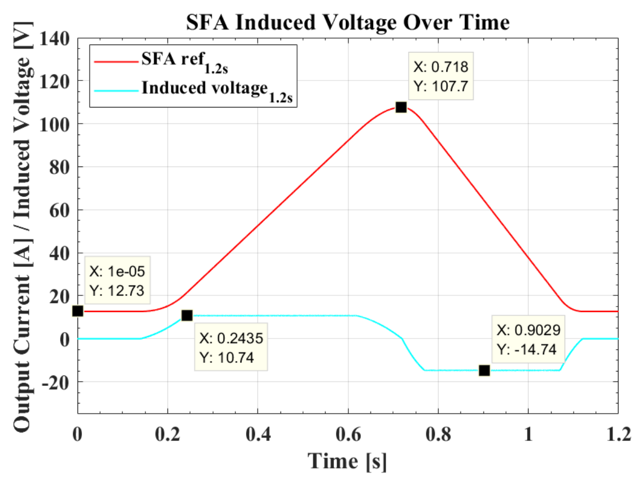

Figure 4: The induced voltage of Trim-S PS for 1.3 MW operation. The pattern of 1.2 s operation for 1.3 MW beam power is presented, in which the output current is specified with a 10% safety margin.

Fig. 5 and in Fig. 6, respectively. A safety margin factor of 10% has been applied to the current pattern of the main SFA PS.

There are mainly two types of PSs suitable for the Trim-S application: linear amplifiers (e.g., the NF4505) and switching amplifiers (e.g., the DP020AS). The NF4505 linear amplifier series offers very low output noise above 2 kHz due to its circuit design. However, this model is no longer available. Given that the load is a magnetic coil, its inherent inductance naturally filtering high-frequency noise. Tests confirmed that when driving the Trim-S magnets, the DP020AS gives acceptable noise levels for stable operation. Therefore, the DP020AS has been selected as the PS for this project.

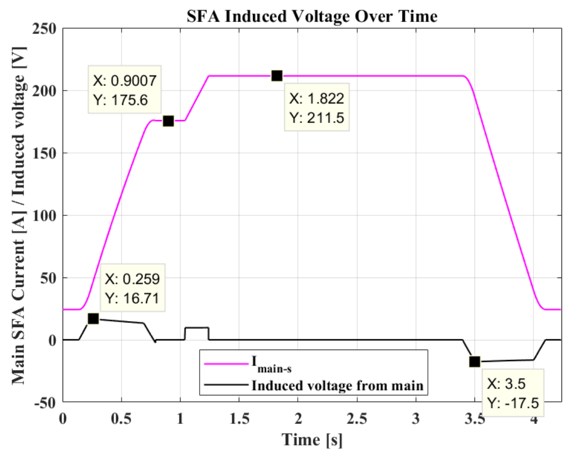

Figure 5: The induced voltage of Trim-S PS in slow extraction. The current of the main PS is scaled up by dividing by a factor of 0.9.

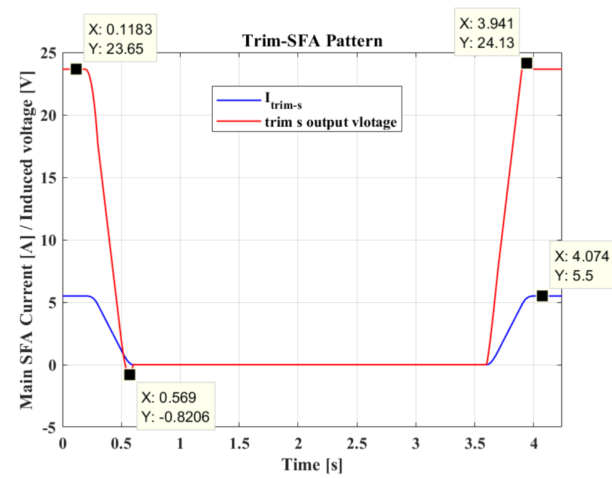

Figure 6: The output voltage of Trim-S PS in slow extraction.

The Design of Power System

For the power system design, the selection of the transformer, MCCBs (circuit breakers), power cabling, and grounding are carefully considered. AC 400 V and AC 200 V / 100 V are available in the power supply building. To minimize the cable size of system, the AC 400 V is used for main power circuit for PS, and the AC 200 V / 100 V is used for the control power supply.

A transformer with a ratio of 400 V / 200 V is used for the main power circuit in each power supply building. Each power supply building accommodates 8 Trim-S PSs for the 24-set setup. Considering the maximum power of these 8 units and multiplying a margin factor of 1.2, the total power requirement is calculated as:

$$2.65 \text{ kVA} \times 8 \times 1.2 = 25.44 \text{ kVA}.$$

Accordingly, a 400 V / 200 V transformer with a power capacity of 30 kVA is selected. For circuit breakers, Table 6 shows that each DP020AS unit has a maximum power of 2.65 kVA and a maximum current of

$$I_{max} = \frac{2650}{200} = 13.25 \text{ A}.$$

Thus, a 15 A circuit breaker is suitable for each DP020AS unit. On the primary side of the transformer, a circuit breaker rated for 40 A is selected, calculated as:

$$I_{primary} = \frac{25440}{\sqrt{3} \times 400} = 36.72 \text{ A}.$$

For the input cables of each PS unit, 2-core (2C) × 2.0 mm^2 copper cables are chosen, capable of carrying 18.9 A (calculated as $27 \times 0.7 = 18.9$ A), which exceeds the 15 A breaker rating. For the primary side of the transformer, 4-core (4C) × 8.0 mm^2 copper cables are selected, rated for 42.7 A (calculated as $61 \times 0.7 = 42.7$ A), safely above the 40 A breaker rating. The power system design for main power circuit of Trim-S PS is illustrated in Fig. 7 (a).

Table 6: The Power Input of DP020AS

Item	Values
Voltage	100 V to 230 V ± 10%
Frequency	50 Hz ± 2 Hz or 60 Hz ± 2 Hz
Phase	Single phase
Power factor	> 0.95
Efficiency	> 80%
Maximum power	< 2.65 kVA

Regarding the power system design for the Trim-S control system, AC 100 V is provided in 3 racks. Each branch in a rack has 8 slots for different devices such as media converters, network switches, controllers, monitoring devices and other user devices. The current for each rack is assumed to be 30 A. The power system design is shown in Fig. 7 (b).

CONTROL SYSTEM DESIGN

The design of control system

The architecture of control system includes the connections between the controllers and the Experimental Physics and Industrial Control System (EPICS) network, the timing system, the Machine Protection System (MPS), and the Personnel Protection System (PPS). The overall configuration of the control system is illustrated in Fig. 2.

An SoC FPGA controller is designed to drive the Trim-S PS. The controller is connected to the EPICS control network and can be operated by users through EPICS. It incorporates a DAC (AD5764) with a resolution of 16 bits and an integral nonlinearity (INL) of ±1 LSB (Least Significant Bit). The DAC output interfaces directly with the DP020AS.

The control system is also connected to the timing system, the Machine Protection System (MPS), and the Personnel Protection System (PPS). The timing system synchronizes the Trim-S PS operation with the accelerator timing, which

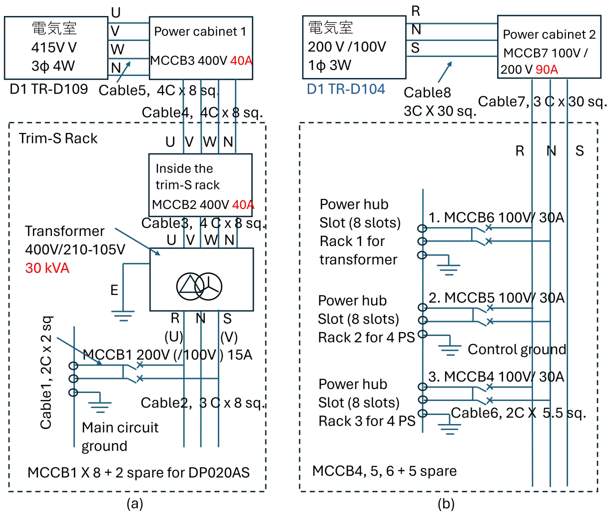

Figure 7: Power distribution for Trim-S system. (a) The power system design for the main power part. (b) The power system design for the control part.

is received in the controller and the monitoring device. The MPS receives signals from the Trim-S system and triggers protective actions for devices such as beam pipes and magnets. The PLC of Trim-S control system receives signals from the PPS and will shut down Trim-S PS to prevent safety incidents involving personnel.

The control system includes three Programmable Logic Controller (PLC) units: one master PLC with a Central Processing Unit (CPU) module for network communication, and two slave PLCs for individual acquisition of statuses. They can be used to control the Trim-S PS for operation, status collection, and interlock functions. Operation commands can be issued either from the EPICS control system or the local control panel. A summary of the operation commands is listed in Table 7. The PLC collects the statuses from PLC terminals, communication such as control I/O of DP020AS, or Analog-to-Digital Converter (ADC) module. Then the interlock logic can be realized based on these statuses. The fault and statuses are summarized in Table 8.

Table 7: The Operation List of Trim-S System

Item	Operation Source
PS reset	Touch Panel / Network
Emergency stop	External signal / bottom
MCCB trip	Network/ MCCB overcurrent
Contactor on / off	Network
Current setting	Network

To achieve an emergency stop, two power switches are employed: a circuit breaker (MCCB8) and a contactor, as shown in Fig. 8. Both devices can be monitored and controlled by the PLC through the control network and internal logic. Upon detecting a fault, the PLC will interrupt the AC power to the DP020AS by using MCCB8 Trip and send an MPS signal to other equipment.

Table 8: The Fault and Status List for Trim-S System

Item	Types
Transformer fault	Fault
Slave PLC failure	Fault
Relay PS fault	Fault
Main SFA PS stop	Fault
PPS	Fault
Magnet fault	Fault
MCCB trip	Fault
Output overcurrent	Fault
PS protection	Fault
PS limiter	Fault
PS output range	Status
PS CV / CC mode	Status
PS power on / off	Status
PS output on / off	Status

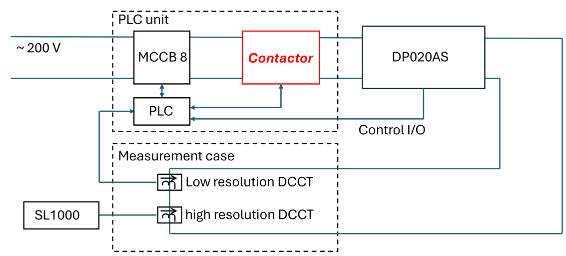

Figure 8: MCCB8 and contactor can be used to stop the AC power of Trim-S PSs.

SUMMARY AND OUTLOOK

In the J-PARC MR, we are planning to upgrade the Trim-S system for third-order resonance correction to futher suppress beam loss towards the target of 1.3 MW beam power. In this paper, we consider and present the design of 12 Trim-S units at D1, D2, and D3 Power Supply Buildings. The current setting for each Trim-S unit is calculated based on the beam study estimation for resonance of $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$. The specifications of Trim-S PS are derived based on the working pattern. The electrical power system is designed based on the specifications of Trim-S PS and the present power system in the power supply building. The control system for user operation is designed to control the Trim-S PS and to ensure the safety of personnel and equipment.

Moving forward, after the experimental evaluation of 12 Trim-S units, we will get the preliminary findings. Such findings would provide the possibility for the design for the whole design of 24 Trim-S units.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Takashi Asami for his help during the beam study and for the valuable discussions.

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