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HIGH INTENSITY CYCLOTRON SYSTEM INTEGRATION AND COMMISSIONING FOR INDUSTRIALIZATION APPLICATION

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Abstract

Up to 430 μA beam intensity was obtained in 10 MeV CRM cyclotron (CYCIAE-CRM) at China Institute of Atomic Energy (CIAE) in 2010. Whereafter, CIAE built a series of 14 MeV high intensity external ion source cyclotrons for medical isotope application and its relevant research. Compared with research cyclotron facility, cyclotron for industrialization application requires higher level of safety, usability and stability. Therefore, mechanical and electrical system integration and optimum are applied in the cyclotron design and commissioning. Electrical devices of cyclotron, including power supply, RF amplifier and PLC controller, are integrated into four standard industrial shielding cabinets with electromagnetic compatibility (EMC) design to improve electromagnetic interference and operation stability. Besides, earthing system is rearranged in regular laboratory maintenance period to minimize electromagnetic coupling of different signal systems. Based on the previous compact system integration, communication system is integrated into each electrical device as well and could be operated in local and remote mode for the convenience of commissioning. Industrial Ethernet standard PROFINET is adopted as communication protocol to improve the efficiency of protocol interaction towards millisecond level. Regarding RF system, start-up sequence of LLRF is optimized to increase uptime and reliability. The commissioning is also presented in this paper.

INTRODUCTION

Cyclotron laboratory of China Institute of Atomic Energy is committed to the research and development of high intensity cyclotron. A 10 MeV CRM cyclotron (CYCIAE-CRM) was developed and 430 μA beam intensity was obtained in 2010 [1, 2]. This cyclotron is featured with external multi-cusp H- ion source, fundamental harmonic buncher [3], half-wave RF resonator [4] and vertically positioned extraction system. It's also the prototype and research platform of high intensity cyclotron CYCIAE-100. Then, CIAE develop a series of 14 MeV high intensity cyclotrons [5, 6] for medical isotope application (CYCIAE-14A) and its relevant research (CYCIAE-14B), based on the experience of CYCIAE-CRM.

In order to provide higher level of safety, usability and stability for industrialization application, system integration and other improvements have been carried out on the design and commissioning of research cyclotron, and thus CYCIAE-14A could achieve better performances.

SYSTEM INTEGRATION

CYCIAE-14A [6] could provide two kinds of injection line for various vaults: for type I, the injection line is installed on the top side of cyclotron, while for type II on the bottom. The latter one is optimized both in mechanical structure and electrical circuits, and then to be applicable for small vault with the advantage of compactness, economy and convenience.

Power Supply

Take the main magnet power supply for example, full bridge resonant soft switching inverter circuit is adopted to decrease switching noise (25 kHz) and its electromagnetic interference. One blocking capacitor is added into the primary circuit of the power transformer to improve the situation of core saturation, which is deduced by the unbalance of volt-second when the power IGBT is on and off. This topology also helps to reduce the volume of power supply.

Figure 1: Power supply integration comparison (Left: discrete power supply for CYCIAE - CRM , Right: integrated power supply for CYCIAE-14A).

Full digital control is used in main magnet power supply to realize the high precision regulation of PWM, and PID parameters could be adjusted locally and remotely. Current ramping rate adjustment is designed and applied for the convenience of field ramping commissioning. By the accurate control algorithm, the current instability of the main magnet power supply (180 A/110 V) is obtained as better than 0.01 % in long term operation (8 h) which meets the requirement of magnet system (Fig. 1).

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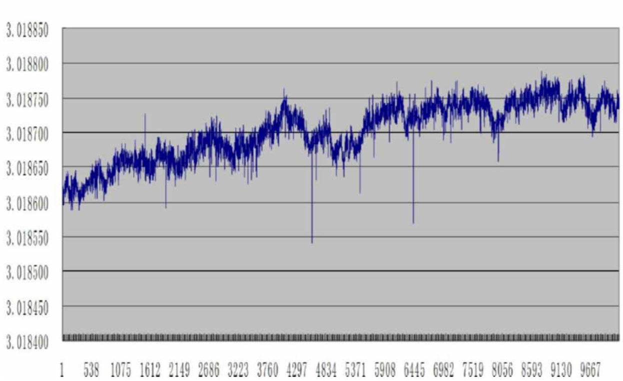

Figure 2: Current instability test of main magnet power supply in long term operation (8 h).

Control System

Main magnet power supply and other power supplies of injection line devices (two quadrupoles, two solenoids and one spiral inflector) are all integrated into one standard industrial shielding cabinet (L800 × W600 × H1800 mm, Fig. 2), and their local control and remote-control systems are integrated as well, which use uniform industrial Ethernet standard PROFINET as communication protocol. In this protocol, control command and state command are configured in the interactive process of communication to realize the functions of adjustment, enable/disable, reset and fault alarm. With the communication protocol integration and optimization, the efficiency of protocol interaction could reach millisecond level, which helps to improve real-time response and failure detection.

ELECTROMAGNETIC COMPATIBILITY DESIGN

Laboratory Earthing System

For the cyclotron laboratory, the earthing system is designed as TN-C-S earthing type (Fig. 3), in which the neutral and earth wires are combined within the supply cable. Due to the separation location of PE and N, the TN-C-S earthing system could provide more effective performances for electromagnetic compatibility (EMC) issues than TN-S earthing system, especially for common mode interference suppression. The TN-C-S earthing system is also featured with low earthing resistance of the PEN conductor. Therefore, the cyclotron could work with a solid reference earthing.

To achieve a much more accurate measurement for beam diagnosis and small signal processing and to minimize the electromagnetic coupling of different signal systems, an additional signal earthing system is applied when the cyclotron is shut down for regular maintenance. The earthing resistance of this signal earthing system is measured as 0.3 Ohms after some necessary improvements.

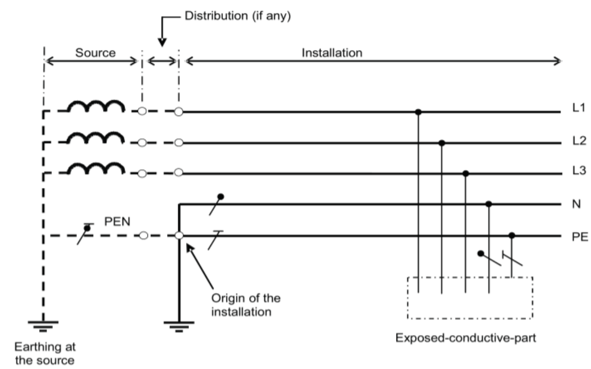

Figure 3: TN-C-S system 3-phase, 4-wire, where the PEN is separated into PE and N at the origin of the installation [7].

Power Supply EMC Design

The cyclotron power supply design complies with the EMC general requirements of IEC 61326-1:2005 applying for electrical equipment for measurement, control and laboratory use. For the immunity requirements, the industrial cabinets are well grounded and shielded to resist electrostatic discharge (ESD) and electromagnetic interference, and the power, signal and control ports are equipped with relevant devices to resist burst, surge and conducted RF interference. For example, the surge protective device (SPD), high-frequency ferrite, varistors and AC EMI filter are inserted in the supply cable in series or parallel between circuit breaker and regulation unit of the power supply. Filter capacitors for DC bus are designed with relatively higher value to compensate voltage dip.

While for the emission requirements, soft switching technology is adopted in the power supply design to reduce IGBT dissipation and electromagnetic emission, especially for the suppression of surge current and spike voltage. Other methods such as differential signalling, shielded cable, varistors, bypassing capacitors and filters are used to improve electromagnetic emission as well.

The EMC design and technology mentioned above have been applied and verified in the magnet power supply of 230 MeV superconducting cyclotron [8] for proton therapy and irradiation, which requires higher level EMC ability. And the power supply passed the internal EMC test referred to IEC 60601-1-2:2004 applying for medical electrical equipment, in which the requirements are much stricter than IEC 61326-1:2005.

The EMC design and integration of RF amplifier and PLC controller are carried out referring to the one of power supply. Thereby, all electrical devices are integrated into four standard industrial shielding cabinets with EMC design to improve electromagnetic interference and operation stability.

RF SYSTEM OPTIMUM

Regarding RF system [5, 9], some significant improvements have been performed to achieve higher reliability. One of the most important issues is concerned with the RF window. Due to heating and multi-pactoring effect, the silver brazing solder between ceramic plate and inner

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conductor is excited and pulled out, and then the solder coated on the ceramic plate of RF window in the vacuum side after long term operation, shown in Fig. 4. Thereafter the leakage occurs and the RF window fails to work. To solve this problem, the RF window was removed 88 mm away from the magnet yoke with the magnet field decreasing from 160 Gauss to 70 Gauss. Air cooling by Teflon tube instead of water cooling is provided to the ceramic plate of the RF window. It's expected to decrease the deterioration possibility of multi-pactoring effect and its coating surrounding the silver brazing region in magnet field. After these modifications, the RF window has been running stably for more than two years.

Figure 4: RF window coated with silver brazing solder.

Meanwhile, the start-up sequence of LLRF is optimized to increase uptime and reliability. In the previous design, the state transition includes four modes: pulse mode (S1), DDS tuning mode (S2), capacitor tuning mode (S3) and DDS tracing mode (S4). In order to improve the start-up sequence efficiency, additional compensating capacitor is added into the cavity and then adjusted to reduce the frequency difference between S2 and S3. Thereafter, the frequency sweeping time of S1 will be decreased.

Due to the good performance of RF cavity cooling system of CYCIAE-14A type II, the DDS tracing mode is proved unnecessary anymore. In the new LLRF design, this mode is replaced by power ramping mode and labelled as S3. This new mode follows the DDS tuning mode (S2) and it is defined as a temporary mode. In this mode, the RF cavity is tuned by capacitor tuning loop, and the ramping rate of S3 is set as a relatively higher value, then the power ramping could be finished in less than five seconds. The original capacitor tuning mode follows the new S3 mode. It is redefined as final normal working mode and relabelled as S4. The only difference between new S3 and S4 lies in the operation power level.

Based on the previous operation experiences, the tuner position monitoring of RF cavity is reserved to detect the possible faults even if the original DDS tracing mode is cancelled. The fact is that the central region may be reinstalled in the period of cyclotron regular maintenance. If the reinstallation is not calibrated by network analyser, the RF cavity could work in the condition without enough tuning range. In other words, the frequency drift due to thermal effect would cause RF cavity tuning failure in long term operation if the tuning range is not covered appropriately. The insufficient RF cavity cooling will cause the similar problems mentioned above. Therefore, the function of tuner position monitoring in LLRF provides the additional method to indicate the possible problems for operators if failure occurs.

With the modifications and improvements, the state transition proceeds faster towards the final working mode, and the operation experience proves the effectiveness and reliability of these improvements.

SUMMARY

To promote 14 MeV high intensity proton cyclotron industrialization applications, system integration and other improvements have been carried out on the design and commissioning of research cyclotron, and thus CYCIAE-14A could achieve better performances. Electrical devices of cyclotron are integrated into four standard industrial shielding cabinets to improve EMC characteristics. Other EMC issues such as earthing system and electrical devices EMC design are presented and discussed. RF window and LLRF start-up sequence are optimized as well. These integrations and improvements help to enhance the stability and reliability of cyclotron for industrialization applications.

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