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学位論文題目	Development of Timing Read-Back System toward Stable Accelerator Operation
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(Form 3)

Summary of Doctoral Thesis

Name in full Min YANG

Title Development of Timing Read-Back System toward Stable Accelerator Operation

The Japan proton accelerator research complex (J-PARC) is a high-intensity accelerator facility consisting of a 400-MeV linear accelerator (LI), a 3-GeV rapid cycling synchrotron (RCS), a 30-GeV main ring synchrotron (MR), and three experimental facilities, namely the material and life science experimental facility (MLF), the neutrino experimental facility (NU), and the hadron experimental facility (HD). There are two machine cycles for the accelerators: a 25-Hz rapid cycle used at LI and RCS, and a 2.48-s (or 5.20-s) slow cycle at MR. The J-PARC timing system manages the machine cycles, and distributes delayed-trigger signals to the accelerator components to ensure that each part of the accelerator operates within a specified time. It consists of one transmitter module and several receiver modules. Signals from the transmitter module are distributed to the receiver modules through a fiber-optic network and several optical-to-electrical (O/E) or electrical-to-optical (E/O) modules.

Since the commencement of operation of the J-PARC timing system in 2006, there have been some trigger-failure events during beam operation. For example, an irregular 25-Hz signal event in 2016, a stopped trigger event of the pulsed-bend power supply in 2018, and a missing trigger event of the steering magnet power supply in 2015. These three events seriously affected the regular and stable operation of the J-PARC accelerator. In two of these events, the delayed-trigger signal did not arrive at the device side even when the timing system showed no operational error. Such experiences bring us to the purpose of this thesis: to develop a timing read-back system that can be placed on the device side and be operated independent of the timing system to avoid the same unexpected effect. The system is expected to read back the distributed timing signals and confirm whether the timing signals arrive.

A PLC-type triggered scaler module, which was developed by the J-PARC control group members, is a key module for developing the read-back system. It is a scaler to count the number of pulses per rapid cycle with a relationship to the slow cycle, and stores the count in a momentary array. In 2018, the performance of the module was demonstrated by measuring the accelerator signals: an injection-kicker signal and a low-level radio frequency (LLRF) signal.

Following the early development described above, I started to study a prototype of a timing read-back system with a triggered scaler module in 2020. The software libraries

for the basic input/output (I/O) of the module were developed based on an experimental physics and industrial control system (EPICS). The analysis of possible trigger-failure events was performed, and then the checking routines for the events were developed using a dummy signal. A hardware setup with an injection kicker signal was implemented in the J-PARC MR in June 2020. The study showed that the read-back system can be customized with the EPICS toolkit and is capable of detecting trigger-failure events as we expected.

Based on the above study, customized read-back systems have been developed for important timing signals: a 25-Hz signal corresponds to the start trigger of the rapid cycle, and two delayed-trigger signals for beam control devices. These three signals are related to the past trigger-failure events in the J-PARC MR.

(1) The 25-Hz signal from the RCS is used for the data acquisition of a fast-current transformer (FCT) located between the RCS and MR. The FCT observes the number of protons to MR. An error of the signal causes a critical problem because the number of protons is one of the essential parameters for MR safety.

(2) A delayed-trigger signal for the pulsed-bend power supply controls the beam-switching function between the MR and MLF. The stop of the signal is serious because the miss-controlled beam would go to an undesirable destination.

(3) Because the steering magnet problem in 2015 had been solved, two delayed-trigger signals to start and stop a trim-coil short circuit using a fiber-optic cable (thus called "optical-gate" signal) were selected. The short circuit reduces the magnetic field ripple during beam delivery to the HD. However, a shifted gate signal affects the function of the short circuit and may destroy the circuit fuses.

Three read-back systems were developed and successfully operated. They have been demonstrated as countermeasures against past trigger-failure events. The scheme to use PLC modules and the EPICS toolkit shows high flexibility to fit for different timing signals. The read-back systems enable the operators to find the failure event remotely, and the associated failure information is effective in solving problems in time.

Moreover, read-back systems for non-timing signals, such as a machine protection system (MPS) signal and an LLRF signal, have also been developed and operated with a triggered scaler module. They demonstrated that the triggered scaler module has a wide possibility of being used in various fields.

The read-back systems of this work are already in use at the J-PARC MR, monitoring multiple real signals. Toward more stable operation, there are still important signals to be supervised by read-back systems. A plan to measure approximately 60 of the 200 timing signals in J-PARC MR is discussed. The products of current research contribute not only to the J-PARC operation, but also to other accelerators which have similar timing problems. In the future, with the hardware and software updates, the improved read-back system will be available at other accelerator facilities.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　　名　Min YANG

Title
論文題目　Development of Timing Read-Back System toward Stable Accelerator Operation

本研究の対象である加速器のタイミングシステムは、前段の加速器との同期を取ることによるビームの入射、およびビーム加速のための各機器（電磁石電源、RF、入出射機器、ビームモニタ、など）の同期のためなどに使用される。このタイミングシステムが不調の場合には、ビーム入射、加速、取り出しなどで、さまざまな機能不全が起こる。大強度陽子加速器(J-PARC)での１例を示す：中段加速器(RCS)からのビームを、ビーム輸送ラインにあるパルスベンド電磁石により終段の加速器(MR)行きまたは物質生命科学実験施設(MLF)行きを切替えているが、2018 年 1 月にパルスベンド電磁石の電源へのタイミング信号が届かなかったことにより、本来 MR 行きのビームが来ない事象があった。原因は、タイミングシステムの一部の光送信モジュールの不調であった。

Yang 氏は過去と同様のトラブル発生時にタイミングシステムの不調由来か否かを早期に判断すべく、Timing read-back system を開発した。Triggered scaler という新しいモジュールを評価／改修し、各機器の受け側でタイミング信号を確認し、発生したタイミング不調（故障による信号停止だけでなく稀に起こる一時的なものも）を直ちに検出するようにした。実際にパルスベンド電磁石電源についてこのシステムを運用し、ビーム行き先の不整合となる事象でのタイミング信号の不具合の検証ができるようにした。また、磁場リップル低減のための電磁石のコイルショート回路へのタイミング信号についてもこのシステムを運用し、2020 年 6 月のコイルショート回路の破損の原因がタイミング信号ではないことを証明した。

続いて Yang 氏は将来計画として、別途進行中の次世代タイミングモジュールを用いたパルスベンド電源用の新しい Read-back system の設計、MR 加速器全域のタイミング信号監視系プラン、を示した。これらの提案が実現すれば、タイミングを原因とする運転障害の検出・解析が可能となり、J-PARC 加速器の安定運転に貢献すると考える。さらに、Timing read-back system を他加速器へ展開するためのアイデアを示し、本研究の成果が J-PARC 加速器以外にも波及することが期待される。

本審査会及び公開発表会では、Yang氏は研究内容を明瞭かつ簡潔に発表し、質疑回答を行った。Read-back system の健全性を定期的に確認するシステムが必要との提案があった。日々の研究者どうしの議論は英語で行っていること、本論文の前段階の研究の国際会議での発表があること、などから英語能力は研究開発を進めるにあたり十分であると判断する。また、査読付きの英語論文の投稿を準備中である。論文の主旨及び研究内容は博士論文として妥当であると判断する。

以上のことから本論文は十分に学位授与に値すると認められ、審査員全員一致で合格

とした。