Applications of Timing Read-Back System in J-PARC Main Ring

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5. Future Plan for Pulsed Bending Trigger

6. Summary

1.1 Japan Proton Accelerator Research Complex (J-PARC)

- J-PARC is located in Ibaraki, Japan
- Co-operated by KEK and JAEA

◆Three accelerators:

LI: A 400MeV proton linear accelerator

RCS: A 3GeV Rapid Cycling Synchrotron

MR: A 30GeV Main Ring synchrotron

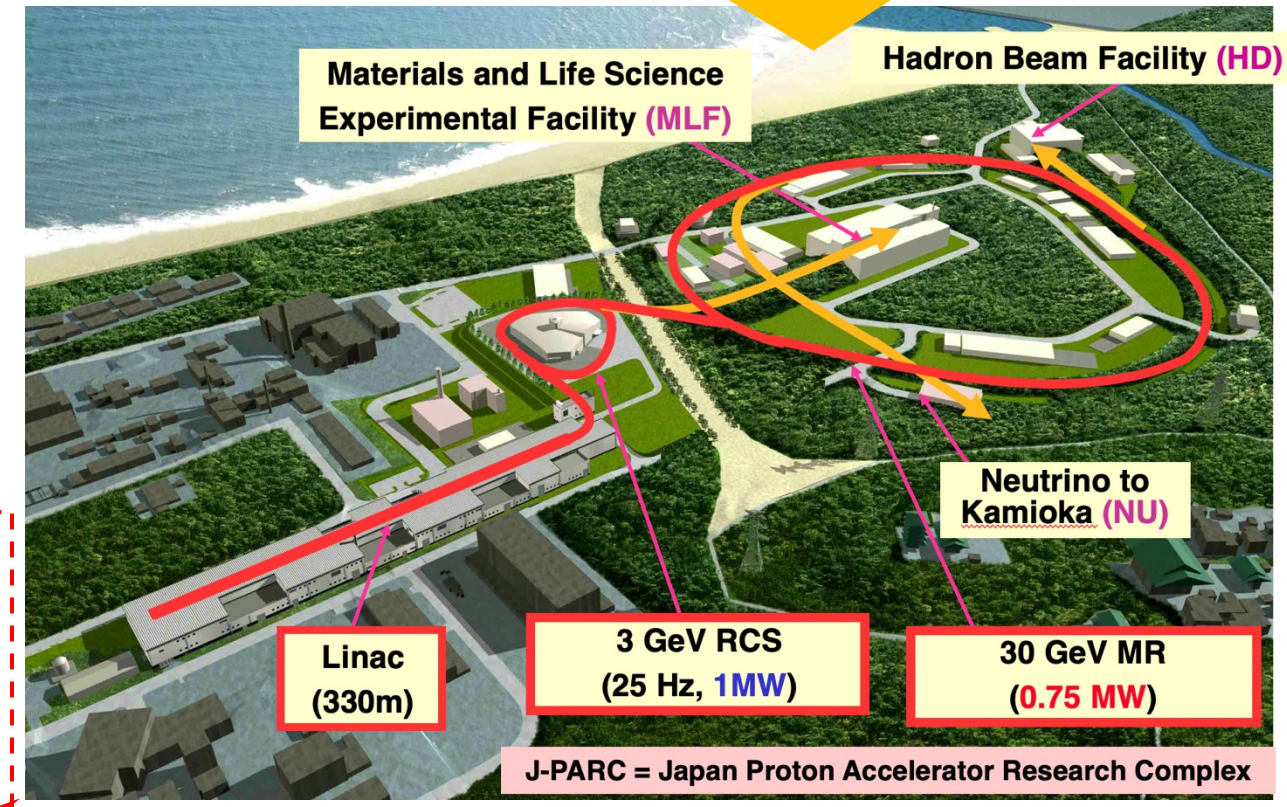
◆Two time cycles:

Rapid cycle: 25Hz is used at LI, RCS

Slow cycle: used at MR

→ to Neutrino Facility: 2.48s

→ to Hadron Facility: 5.2s

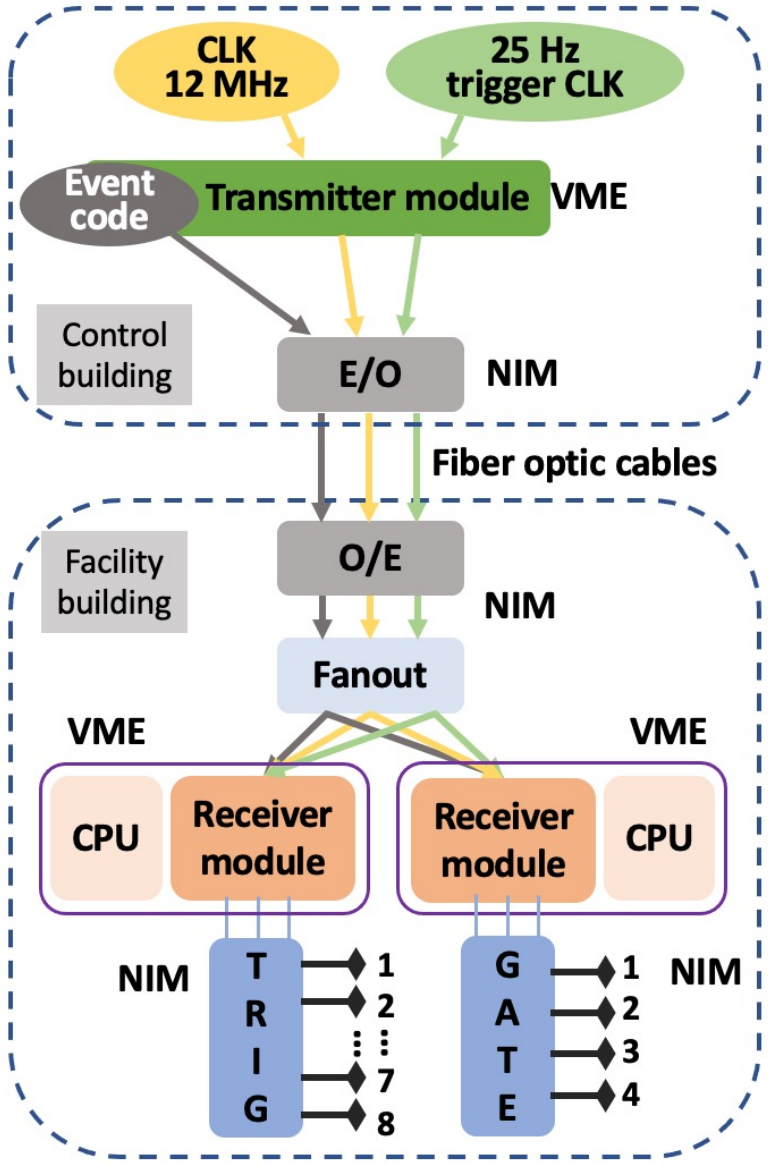


Machine cycle

1.2 J-PARC Timing System

- Timing system is a crucial ingredient for the successful operation of accelerator.
- J-PARC timing transmitter provides following signals:
  - Distribute **25 Hz trigger CLK**.
  - Distribute **CLK 12 MHz** master-RF signal.
  - Distribute **Event codes**, which have information on a beam destination and beam parameters.
- Receiver module generates **delayed trigger / gate** signals that each component of the accelerator runs at the specified time.

What happens if the timing system fails?



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1. Introduction of J-PARC and Timing System

2. Trigger-Failure Events in J-PARC
   Since J-PARC timing system started in 2006, there have been some trigger-failure events during beam operation.

3. Timing Read-Back System and Triggered Scaler Module

4. Applications of Read-Back System

5. Future Plan for Pulsed Bending Trigger

6. Summary

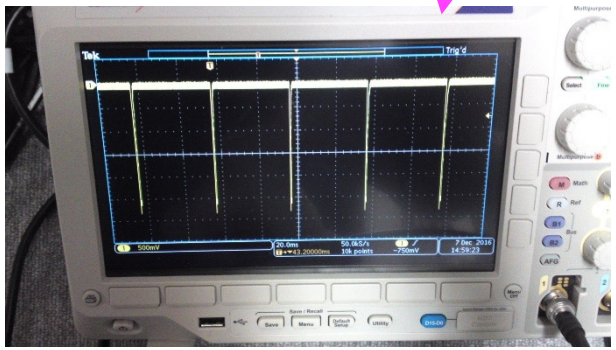
2.1 25 Hz Irregular Trigger Clock Event

Number of beam stops per 8 hours – a few to 10

- In November to December, 2016, the accelerator operation was suspended several times a day, because of the faults of a beam diagnostic system.
- Later investigation showed that **an O/E module** produced irregular signals. → Replaced the O/E module.

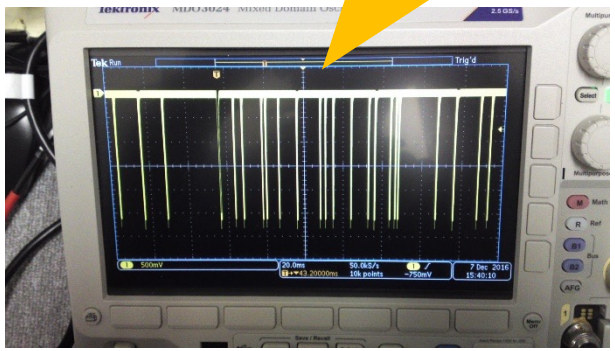
O/E module (RPN-511)

Took ten days to solve!



Normal signal
(25 Hz trigger-clock signals from RCS)

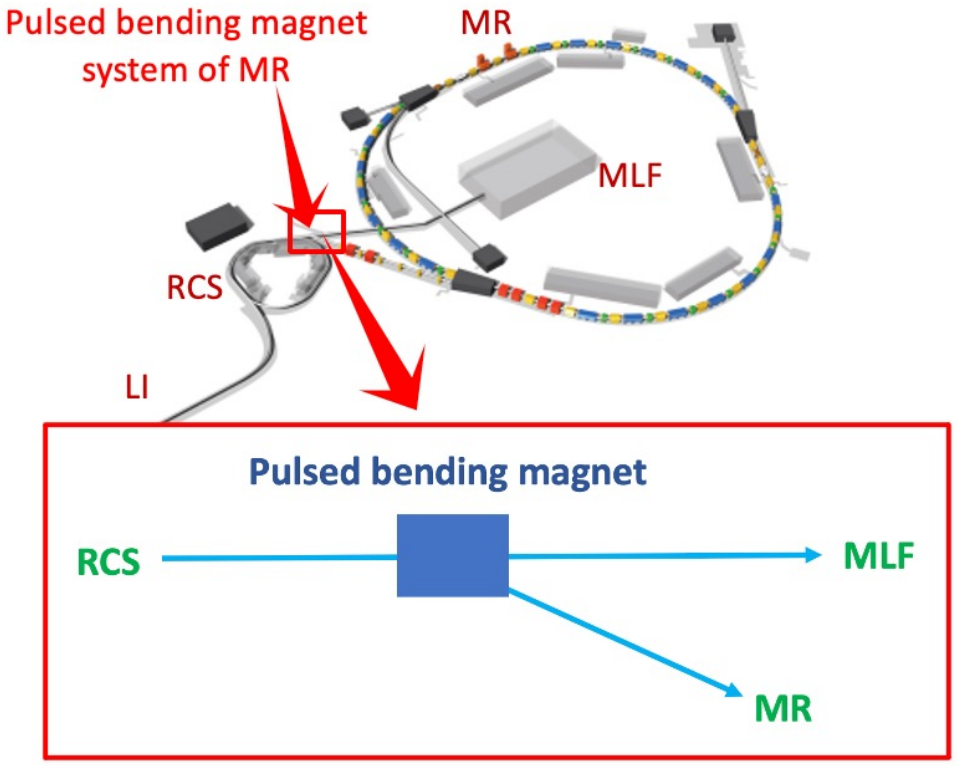
Persistence mode

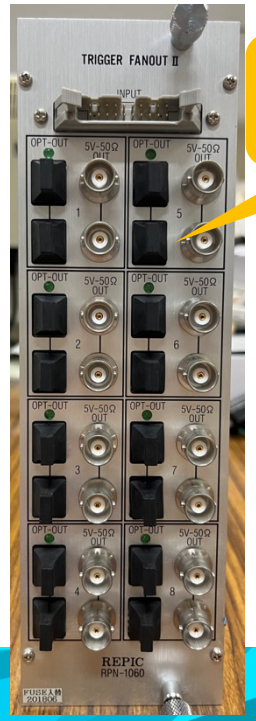


40min later
(Irregular signals appear)

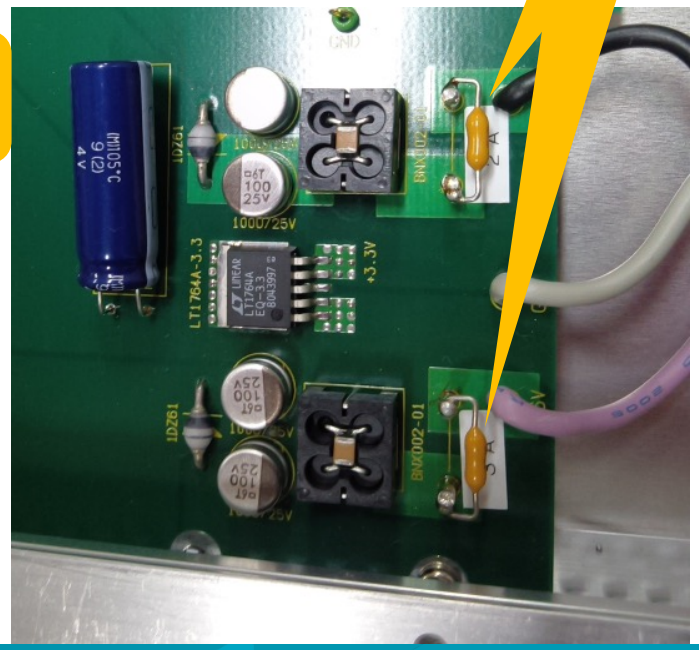
2.2 Pulsed Bending Stopped Trigger Event

- In January 2018, during beam study of MR, the beam that should have reached the MR did not arrive, without any interlock alert.
- Soon we found that a fuse in a **trigger fanout** (NIM optical module) was broken.
  - → Replaced the NIM optical module





RPN-1060



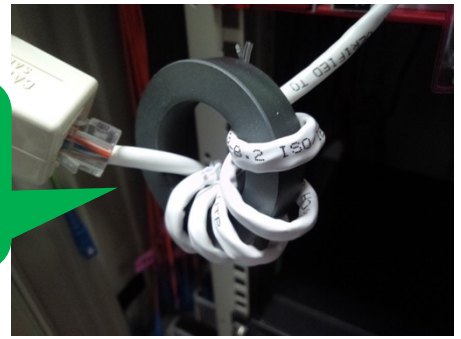
Replaced fuses

2.3 Steering Magnet Missing Trigger Event

- In November, 2015, a bad quality beam appeared during stable beam delivery to Hadron Facility. Such beams appeared a few times per month.
  - In June 2016, we found the **timing receiver module** for MR steering magnets showed momentary errors.

→ Added ferrite cores to metal cables.

This is a very rare event. It took six months to solve!



2.4 Summary of Three Failure Events

Date	Type of Event	Origin	What we did
2017.11- 2017.12	Irregular trigger of 25 Hz trigger clock	An O/E module (generated noisy pulses)	The module was replaced
2018. 01	Stopped trigger of pulsed bending	An O/E module (fuse broken)	The module was replaced
2015.11- 2016.05	Missing trigger of steering magnet	A timing receiver (external noises)	Ferrite cores were added to metal cables

- The first 2 events: serious concerns about the beam-switching function between MLF and MR. Both of them showed no alert from timing system or control system, and it was unable to find them from the control room remotely.
- The 3rd event: really difficult to be detected (low-rate failure) and difficult to find troublesome module among many candidates.

What can we do for them?

2.4 Summary of Three Failure Events

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2015.11- 2016.05	Missing trig	ver rnal noises)	Ferrite cores were added to metal cables

Timing read-back system is the countermeasure!

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What can we do for them?

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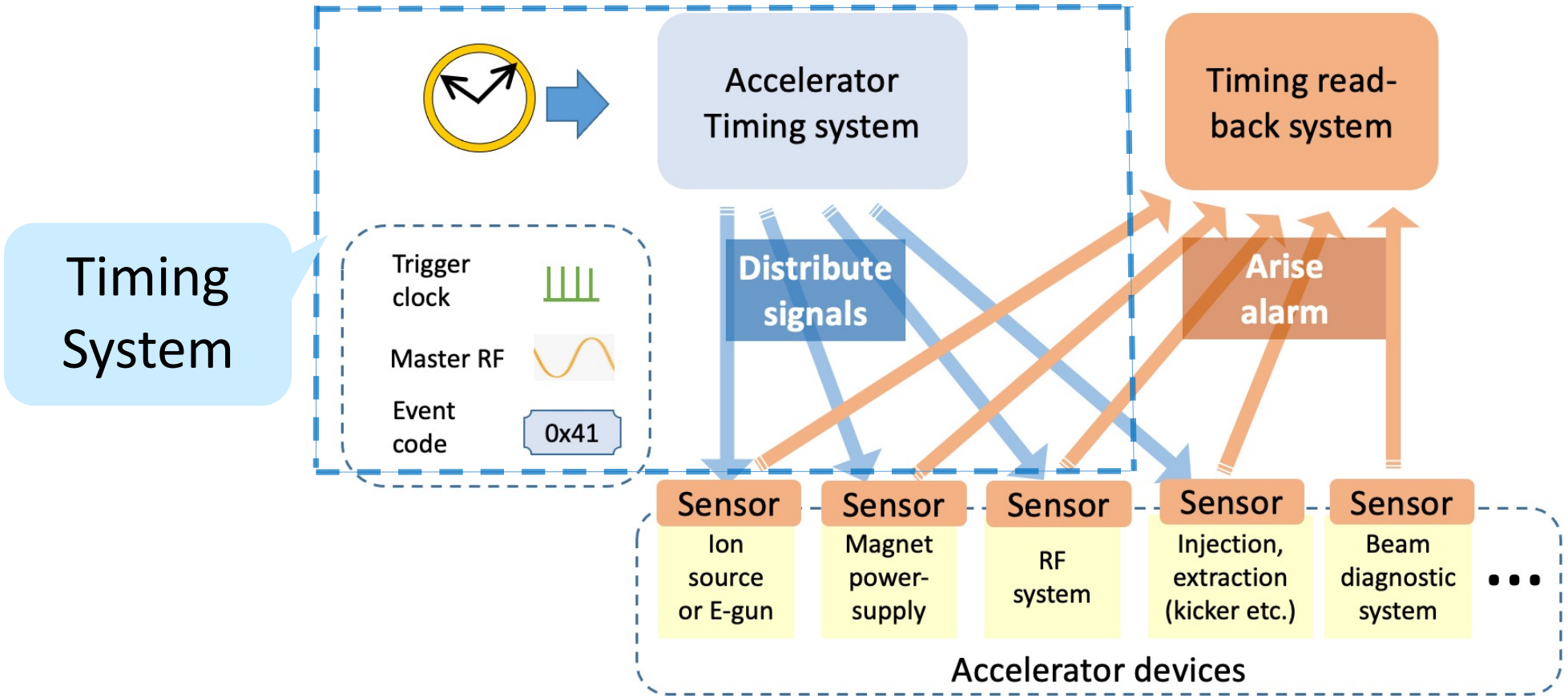
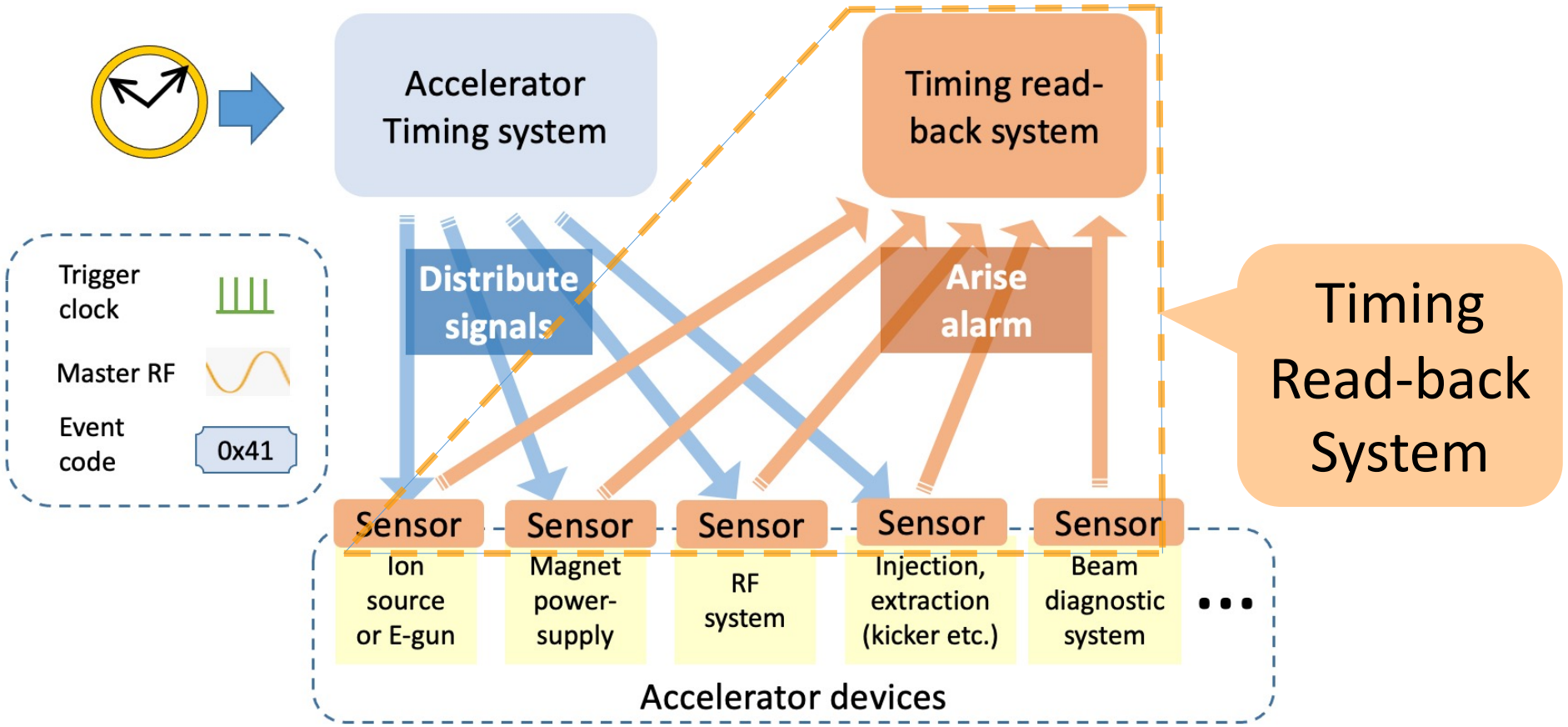
3.1 Timing Read-Back System (1)

- Timing system distributes delayed-trigger signals to accelerator devices.

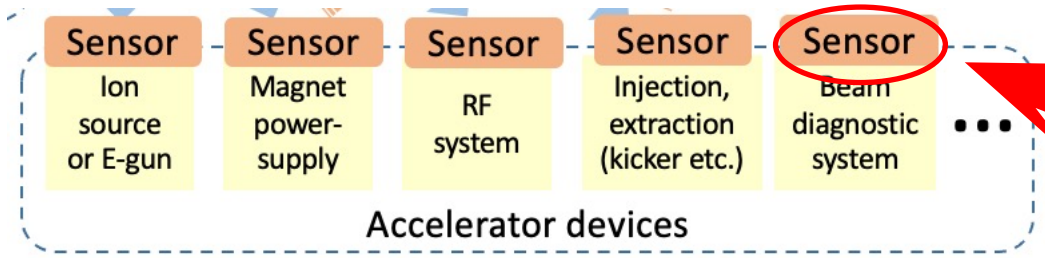


3.1 Timing Read-Back System (2)

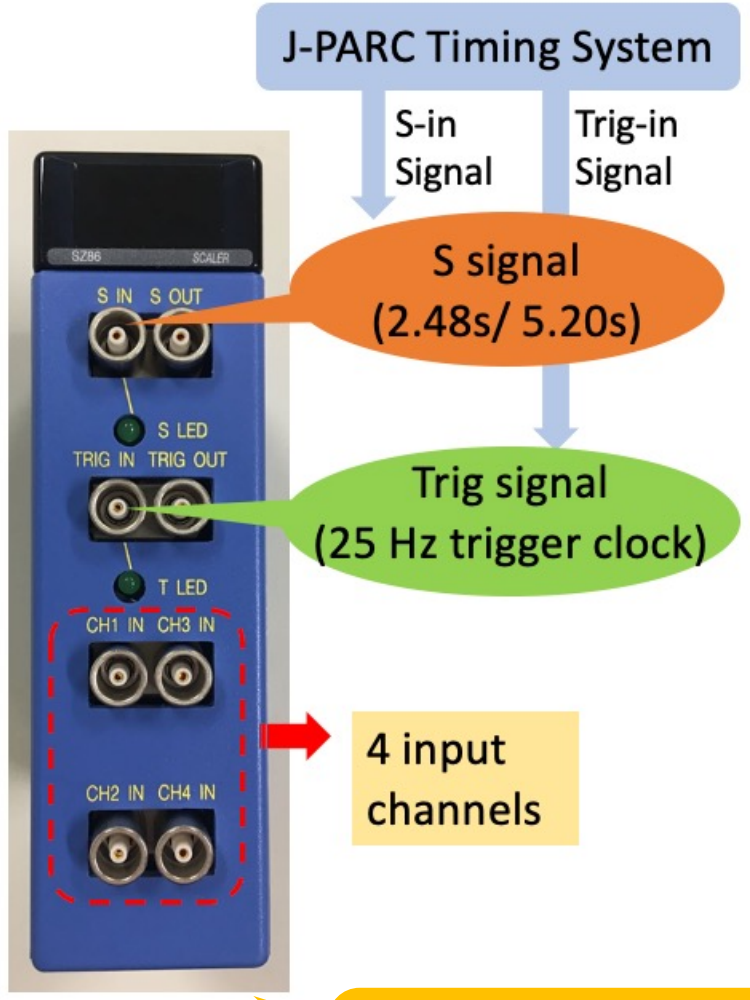
- Timing read-back system
  - Runs independently from the timing system.
  - Observes and confirms delayed trigger signals with sensors.
  - Makes an alert when unexpected trigger-failure event is detected.



3.2 A Triggered Scaler Module - Introduction

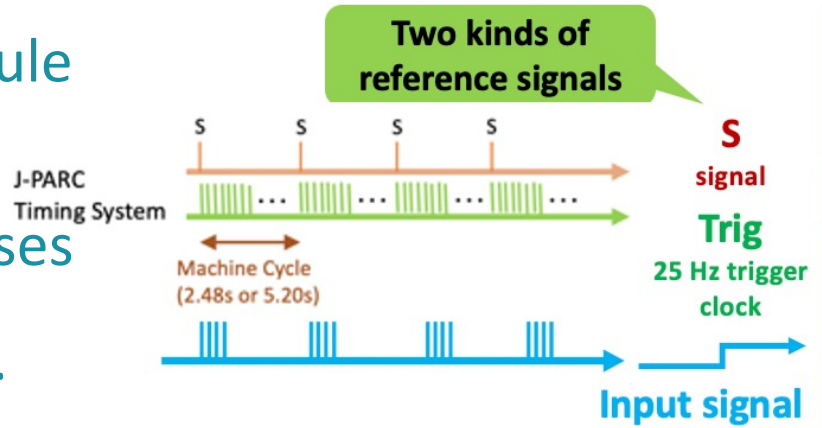


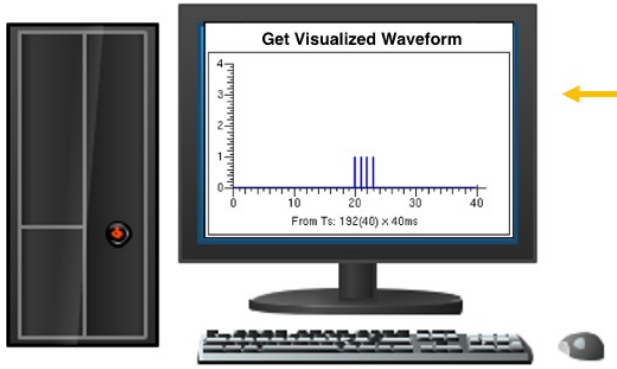
- A new module, triggered scaler, was designed as a sensor of the read-back system for J-PARC timing system.
- Scalers inside the module are used to count number of pulses in 25 Hz (40ms) and stores counts in a momentary array.
- Two reference signals, "S IN" (start of machine cycle) and "TRIG IN" (start of rapid cycle) are needed. They are provided by J-PARC timing system.

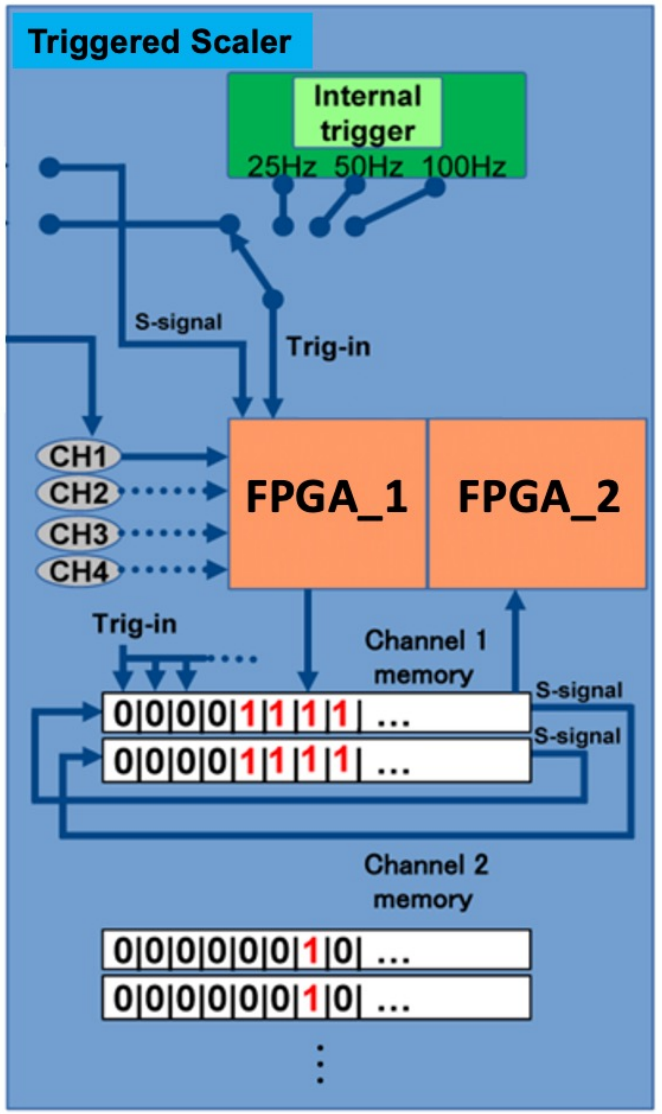


3.2 A Triggered Scaler Module - Working Principle

- Two FPGA logics are inside the module
  - FPGA_1: Counts the input pulses and stores it in a dual ring buffer.
    - a dual memory buffer = two memory buffers, 192 elements x 2.
    - a memory buffer can store 7.68s at maximum with 25 Hz trigger clock.
  - FPGA_2: Reads the memory buffer, detects a trigger failure event, and sets error flags if necessary.



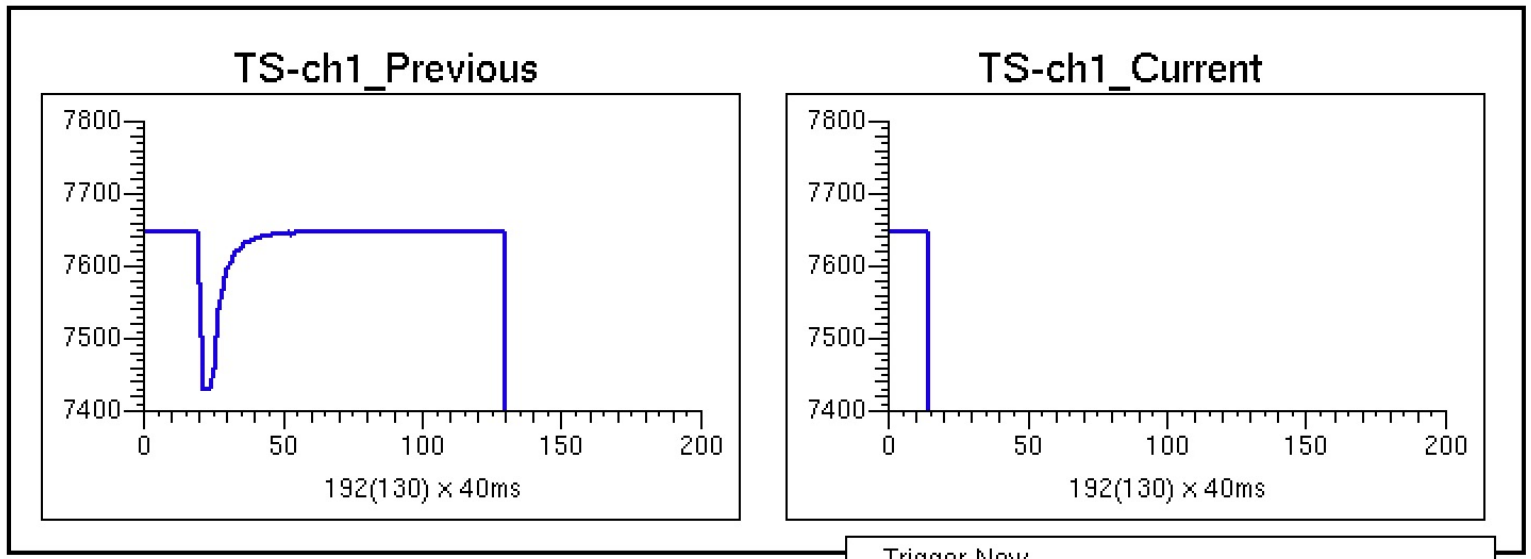


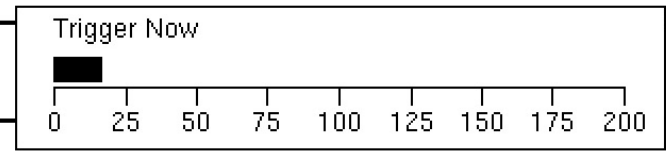


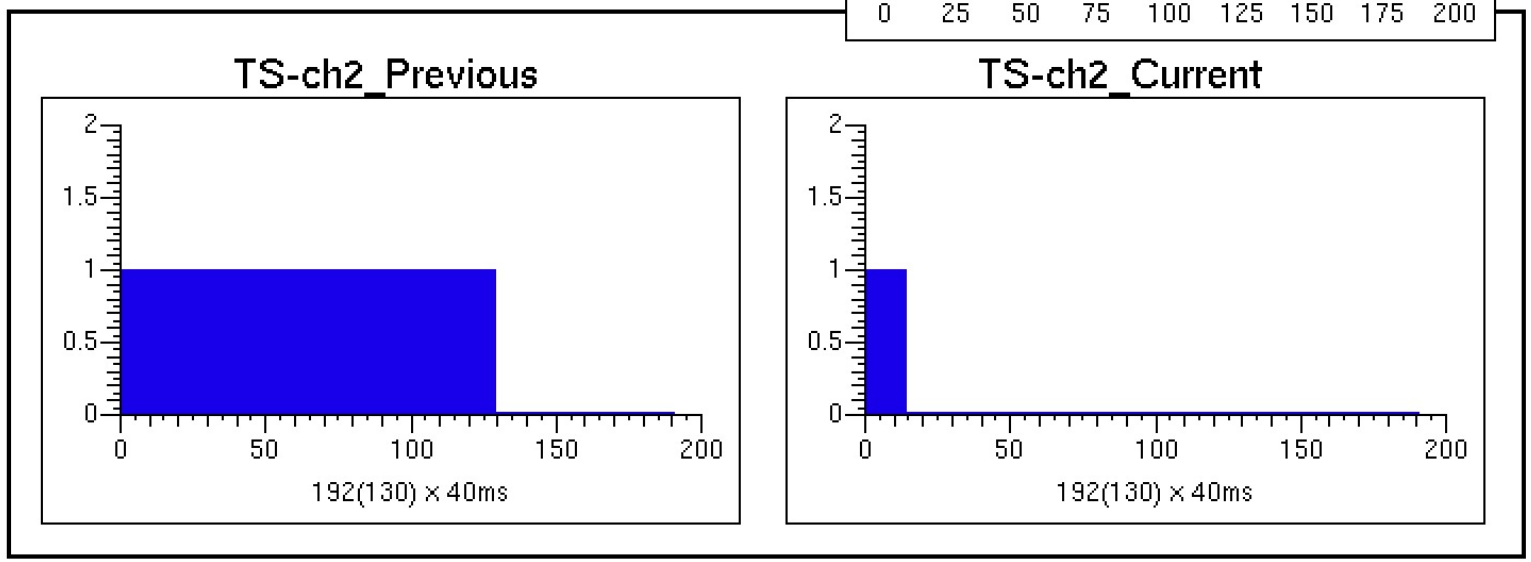
./ts-test-Stat_sz86_2ch.edl

Measured Accelerator Signal by TS

Run No 87
Shot No 592086 21/07/18 14:50:14







Internal Status

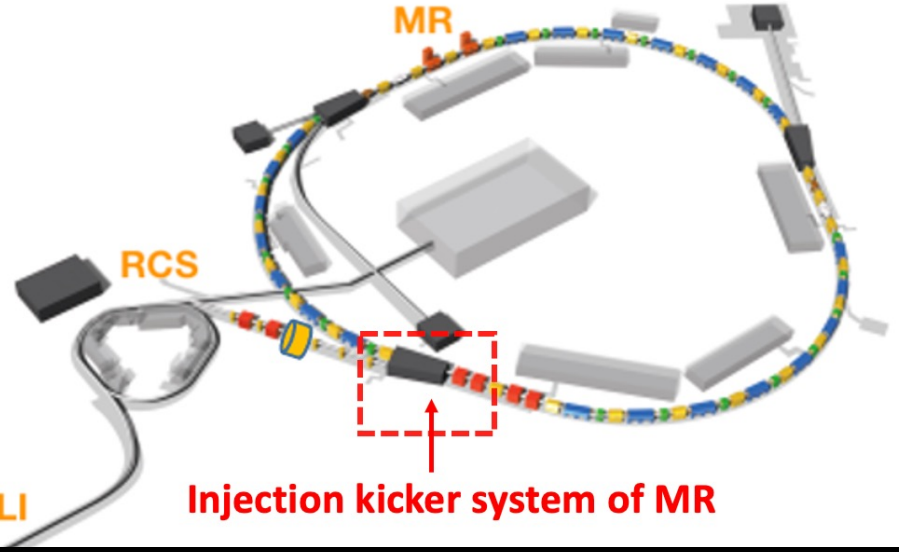
pageNow	0
triggerNow	16
pageSet	0
trigSel	0x14
errSet	0x1
errStatus	0x8d
triggerInCycle	130

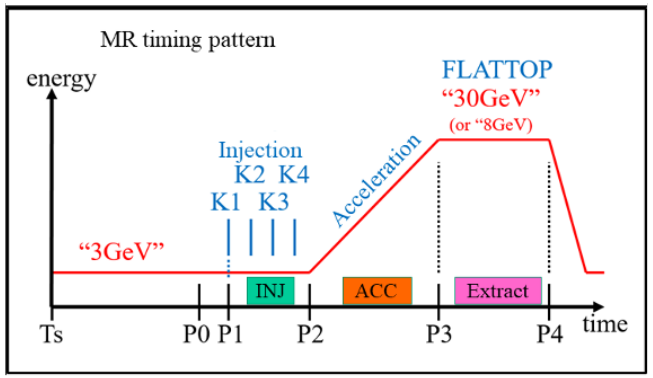
errClear

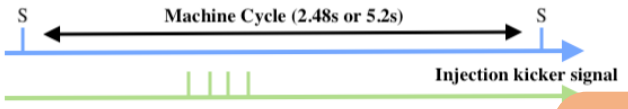
3.2 A Triggered Scaler Module – Performance

- The injection kicker signal was successfully observed in 2018
  - The injection kicker is triggered four times in one machine cycle.

This test was reported in PCaPAC 2018 by Dr. N.Kamikubota








```
opr3@jkjnuc01 [206]% caget MRCO:PIOC_CONT_D3TMG01:TS0:WF:ch3_p
MRCO:PIOC_CONT_D3TMG01:TS0:WF:ch3_p 192 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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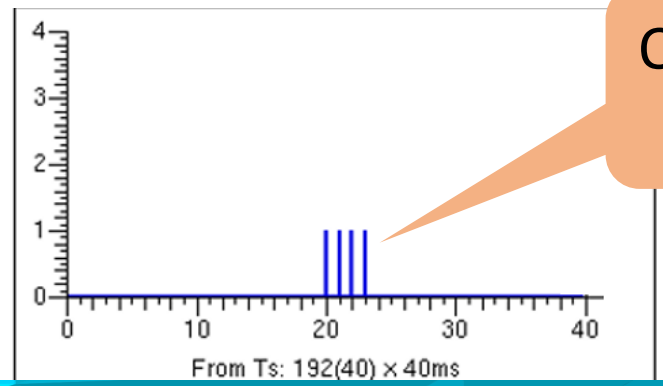
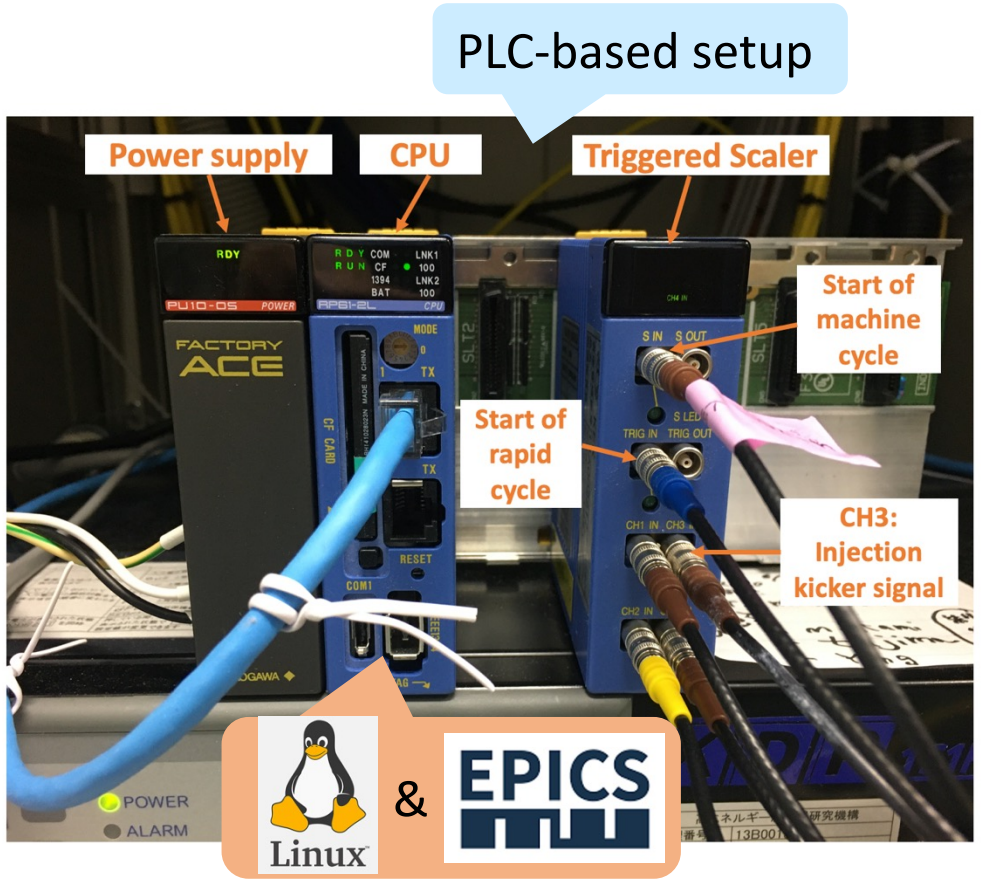


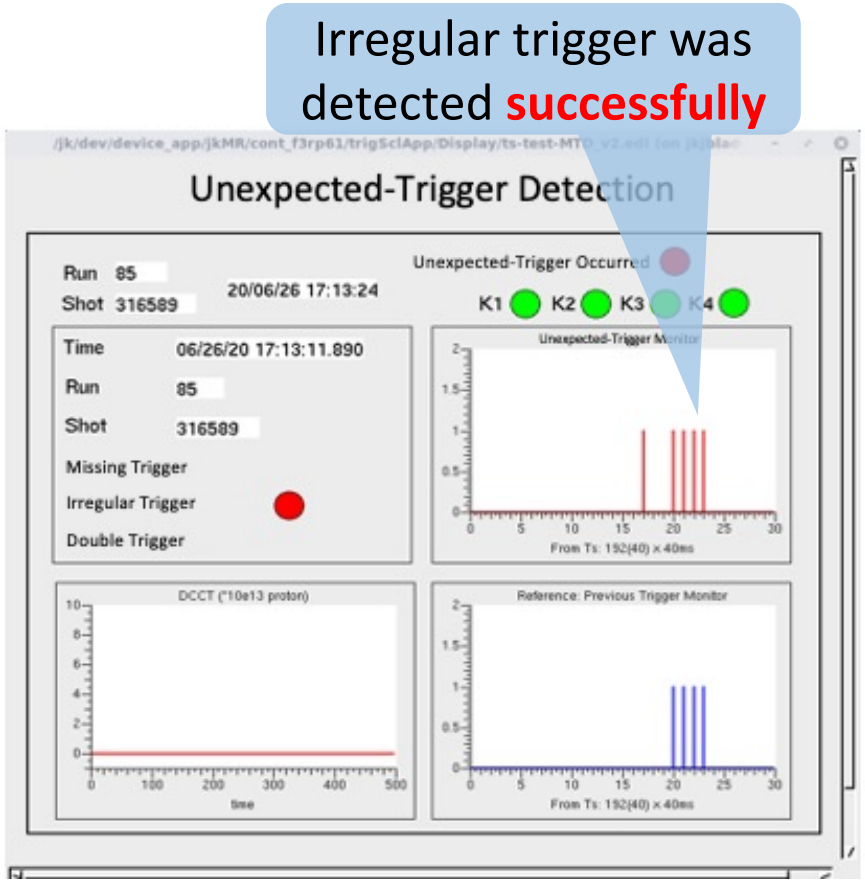
Observed and visualized!

3.3 Prototype Read-Back System

- In 2020, a prototype read-back system was developed and tested using a injection kicker signal
  - Detect a dummy trigger-failure event and identify the failure type successfully



Hardware setup



GUI

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Two timing read-back applications
+ a non-timing read-back application

5. Future Plan for Pulsed Bending Trigger

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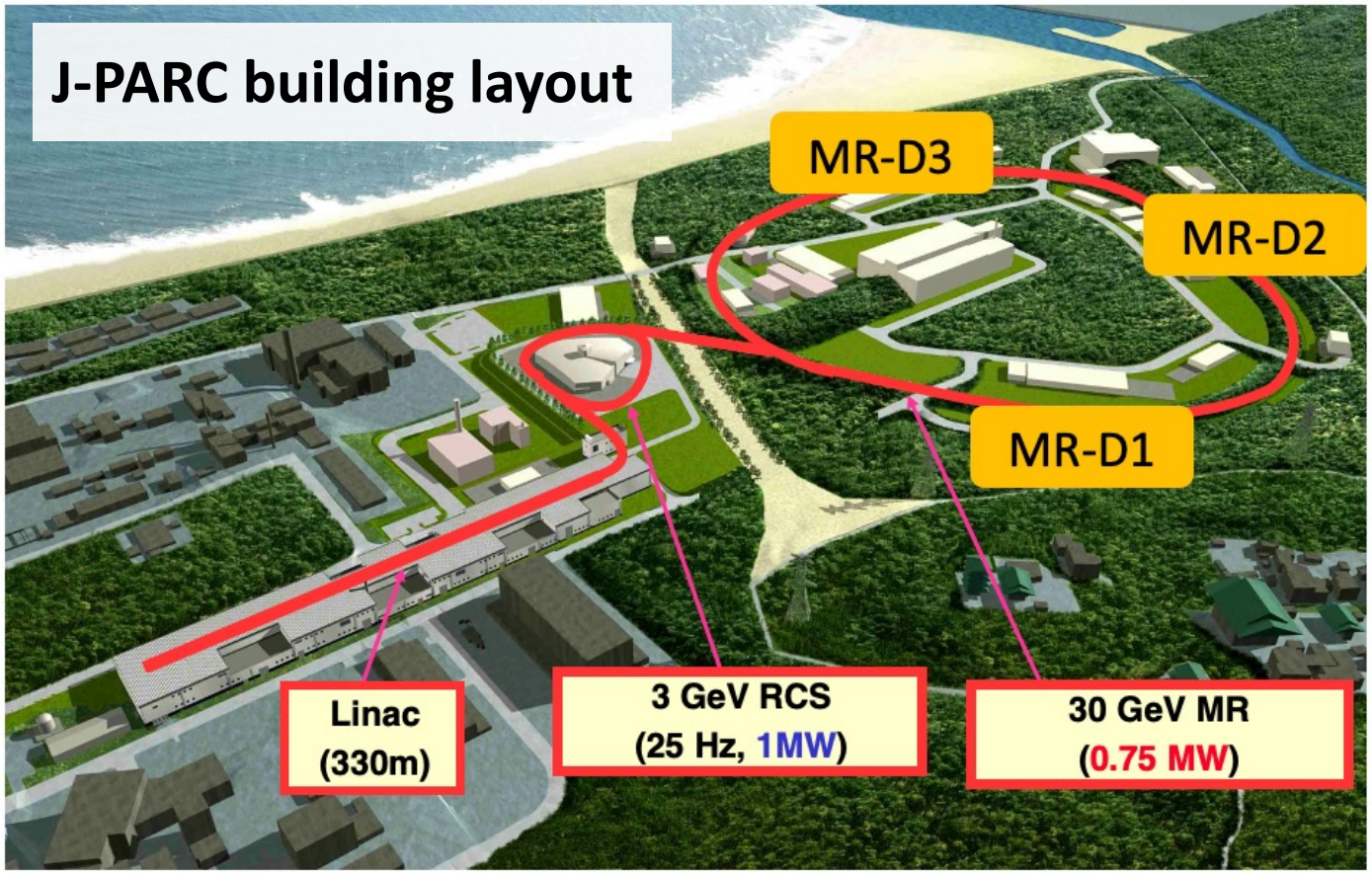
4.1 Read-Back of 25 Hz Trigger Clock & Magnet Power Supply Trigger (1)

- In 2020, the prototype system was located in one building.
- In 2022, new read-back system with three PLC-based setups was developed.



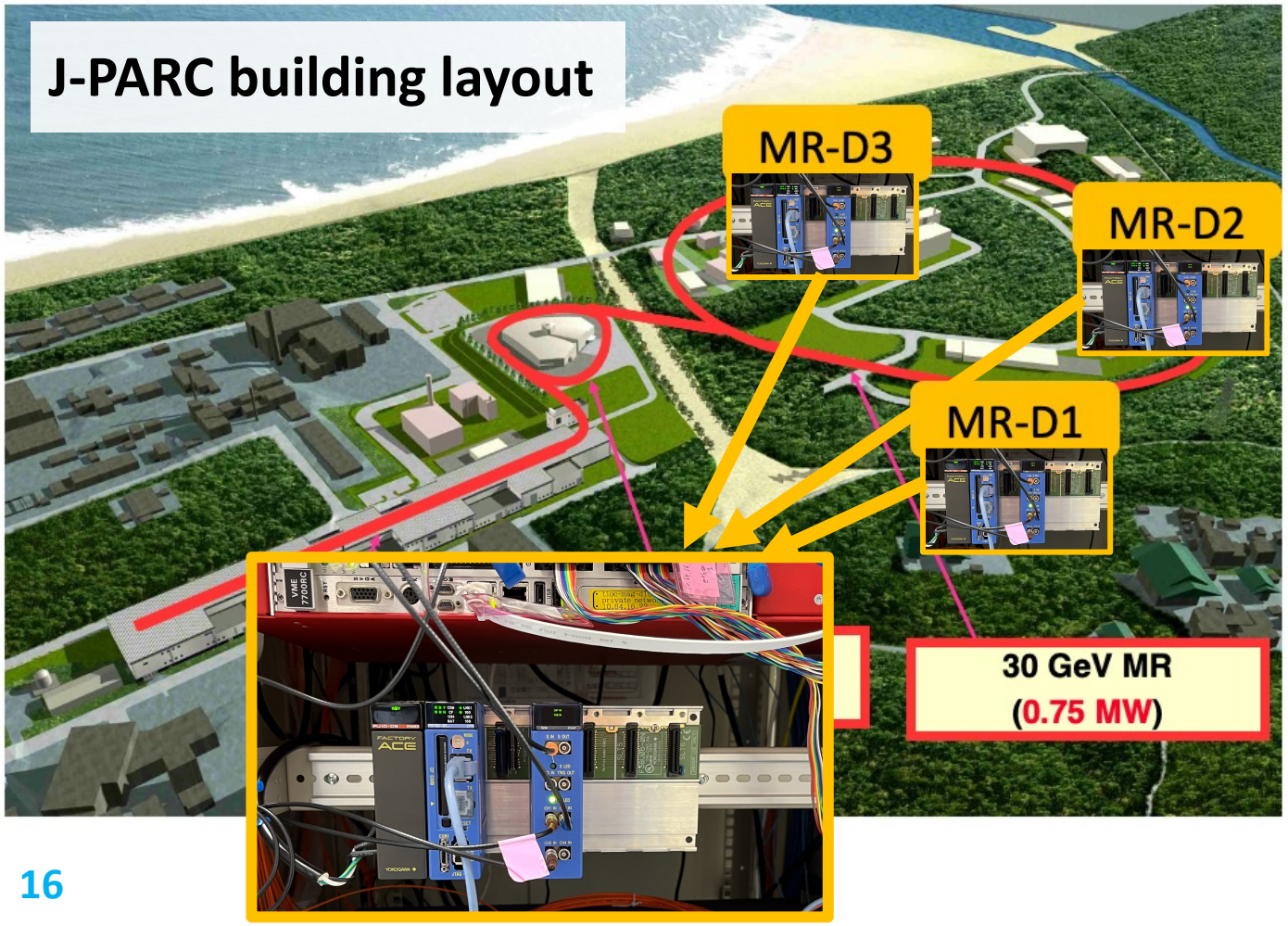
- In MR (Main Ring), there are 3 power supply buildings :

  MR-D1, MR-D2, MR-D3

- Three PLC-based setups with triggered scaler modules are installed at three buildings.

4.1 Read-Back of 25 Hz Trigger Clock & Magnet Power Supply Trigger (2)

- In 2020, the prototype system was located in one building.
- In 2022, new read-back system with three PLC-based setups was developed.



- In MR (Main Ring), there are 3 power supply buildings :

  MR-D1, MR-D2, MR-D3

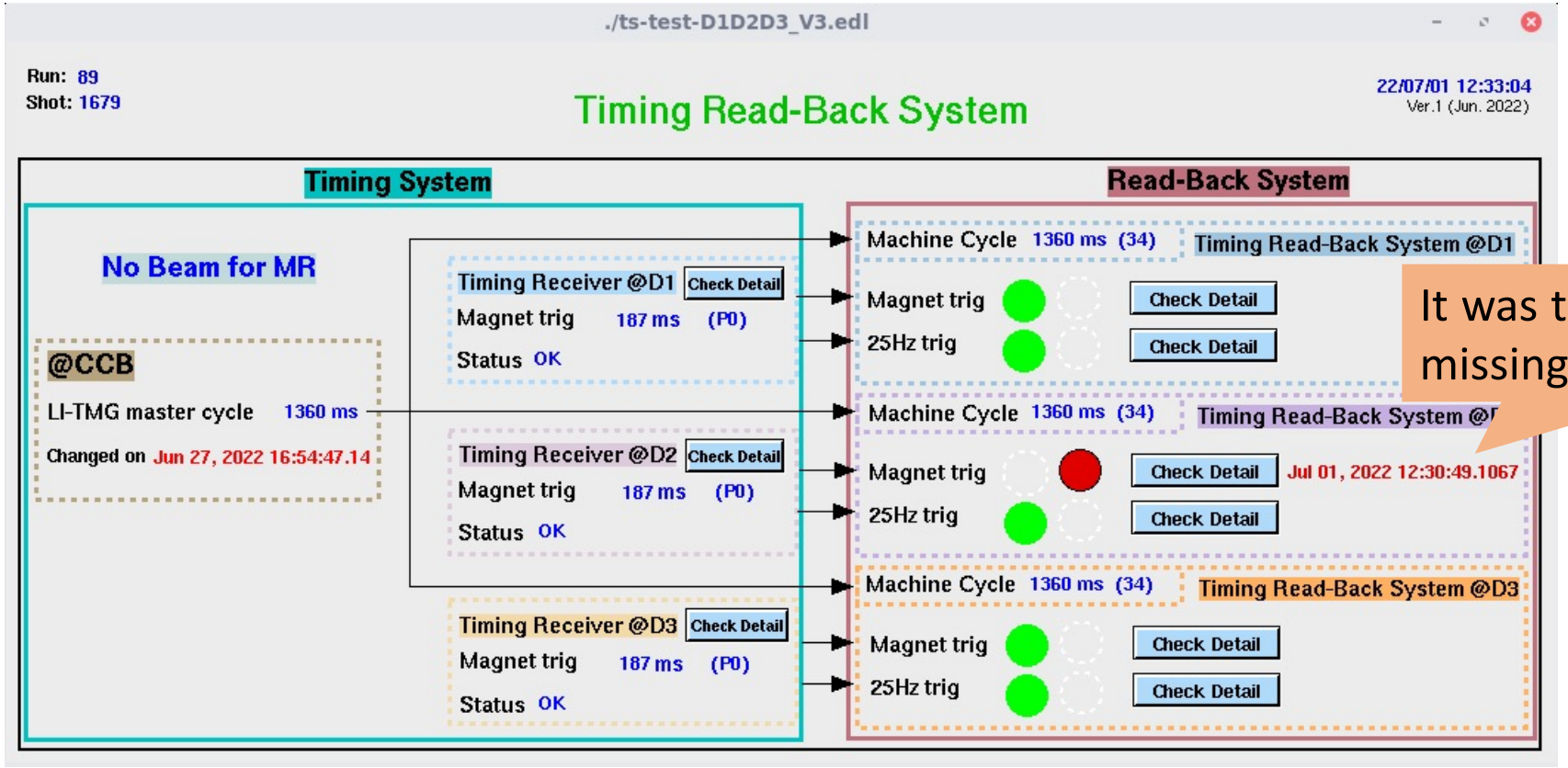
- Three PLC-based setups with triggered scaler modules are installed at three buildings.
- Each setup supervises both signals:

  (a) a 25 Hz trigger clock,

  (b) a magnet power supply trigger.

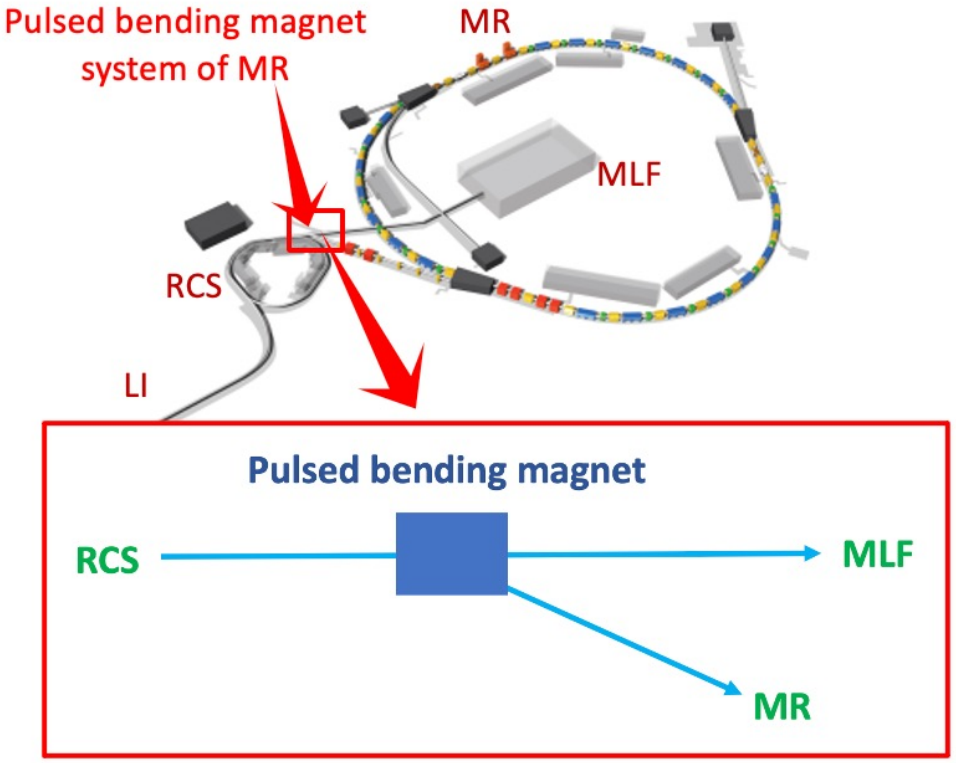
4.1 Read-Back of 25 Hz Trigger Clock & Magnet Power Supply Trigger (3)

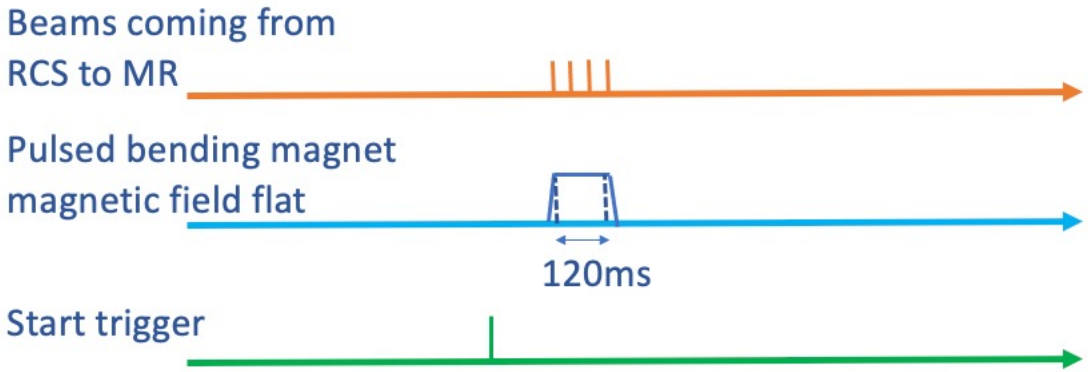
- The read-back application is covering three power supply buildings, and operated during the J-PARC beam operation in June and July 2022. No trigger-failure event was observed.



4.2 Read-Back of Pulsed Bending Trigger (1)

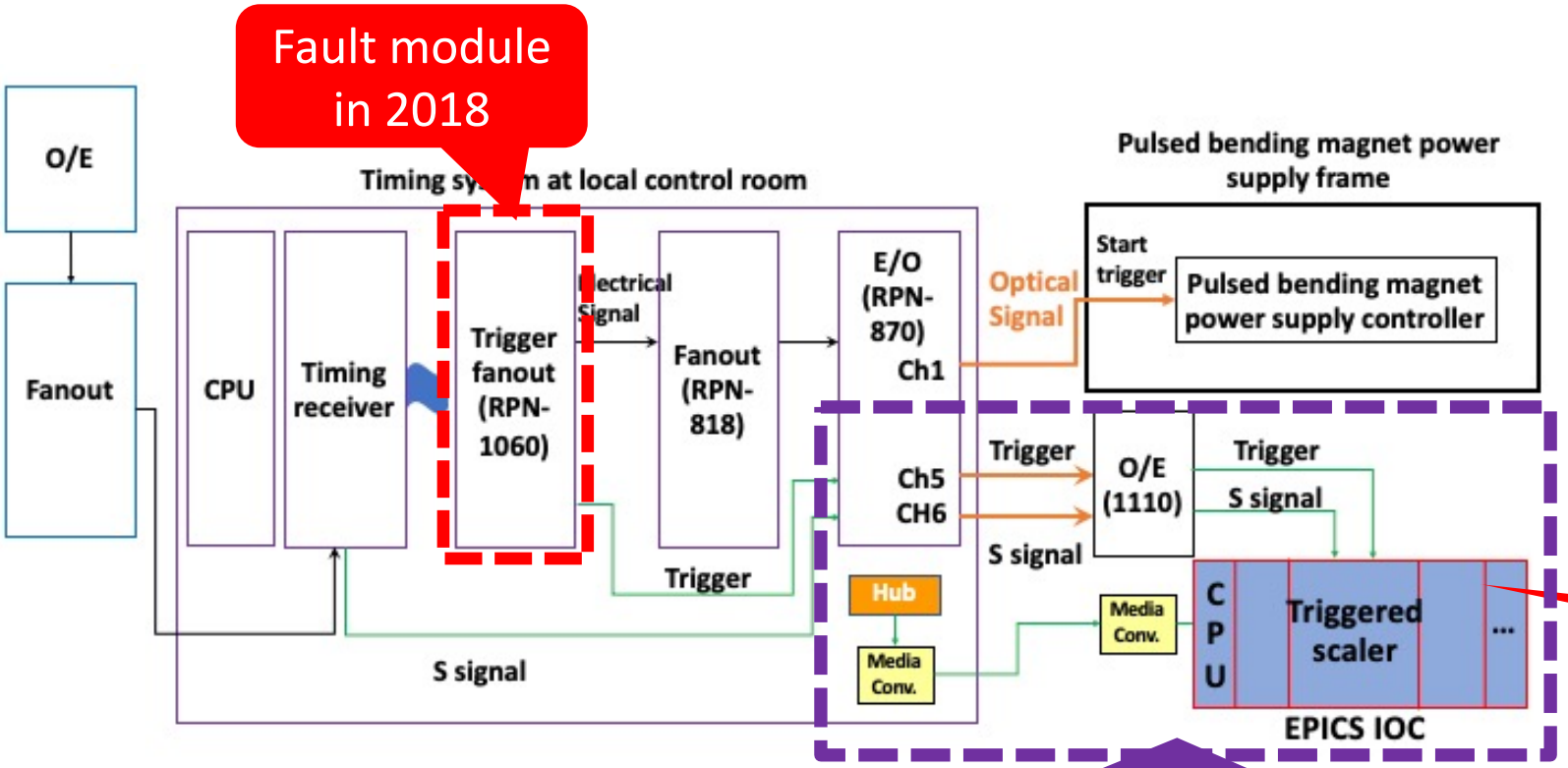
- The pulsed bending magnet switches the beams between MR and MLF.
- The failure of the **start trigger of pulsed bending power supply** is serious because the miss-controlled beam would go to an undesirable destination.

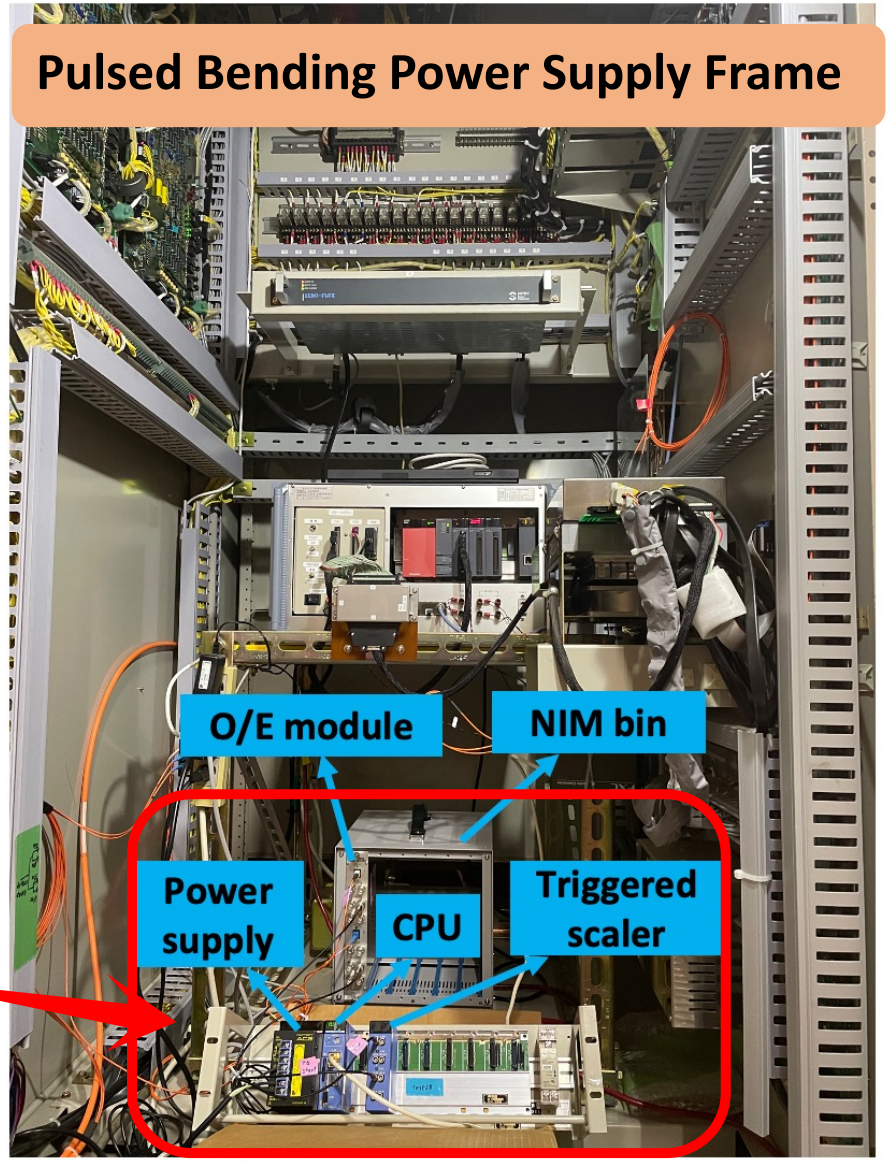




4.2 Read-Back of Pulsed Bending Trigger (2)

- Hardware Setup
  - The EPICS IOC with a triggered scaler module is implemented in the pulsed bending power supply frame.

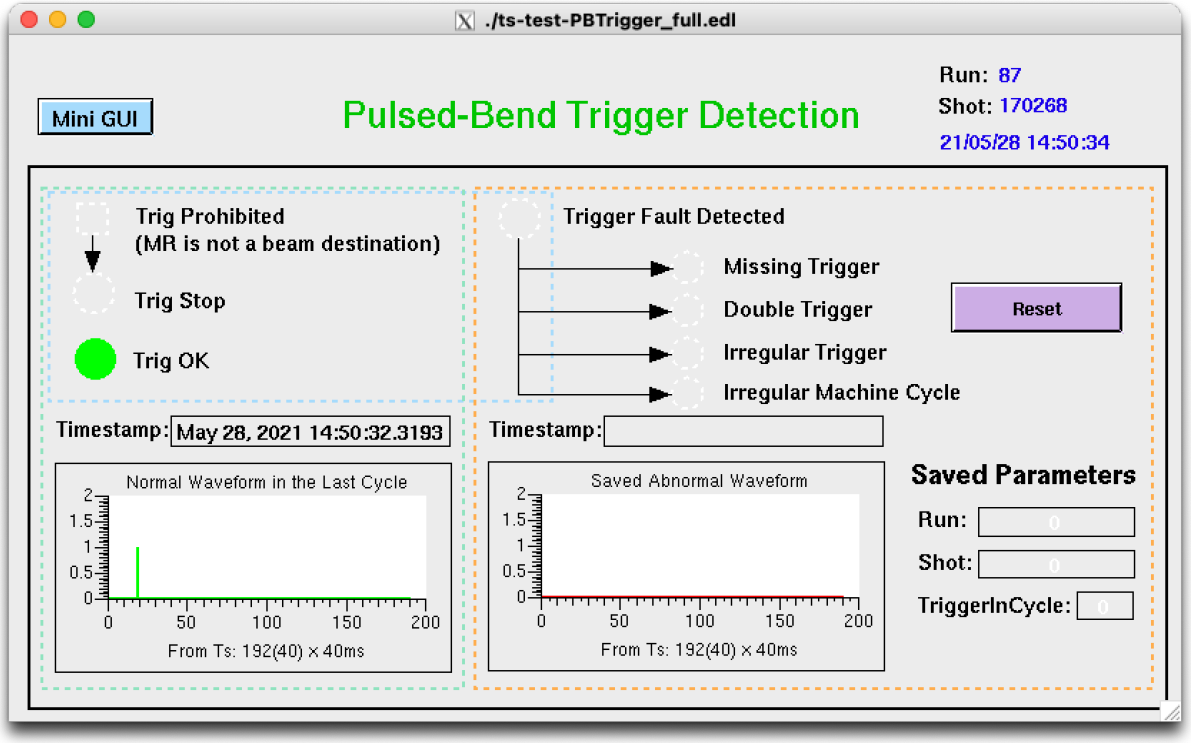




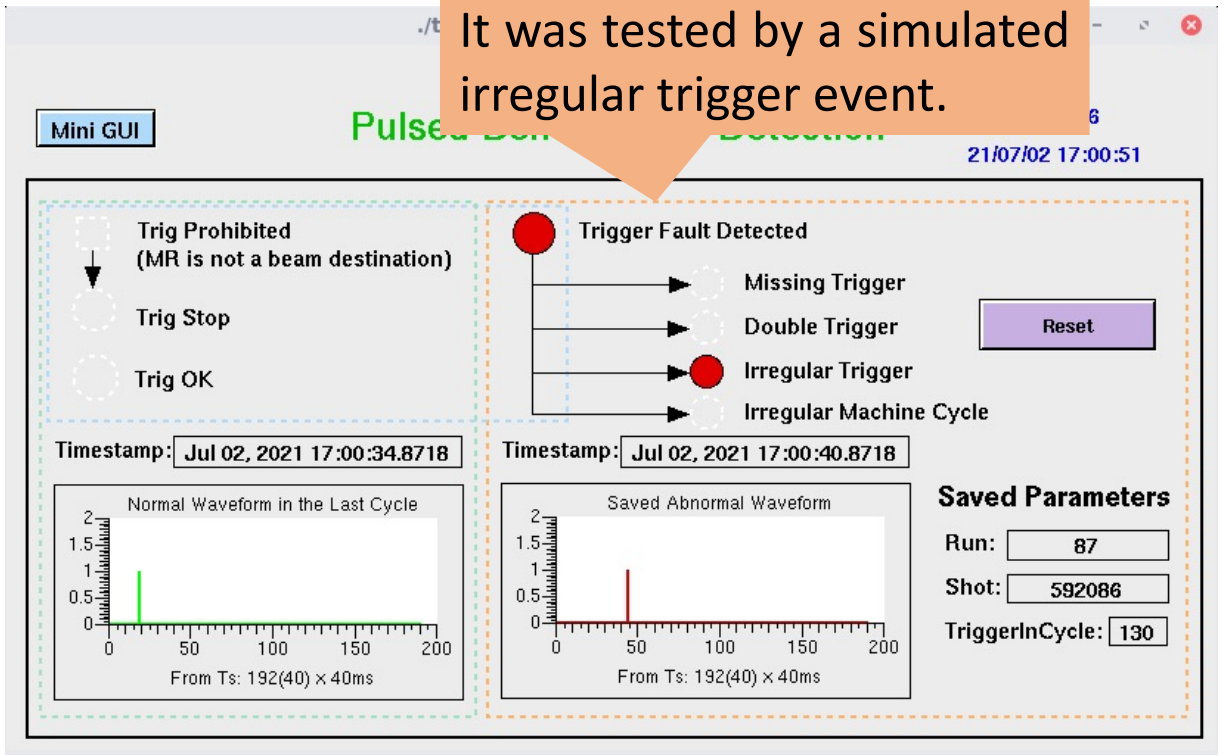
4.2 Read-Back of Pulsed Bending Trigger (3)

- The system has been running in 2021 and 2022 during J-PARC beam operation
  - No trigger-failure events observed so far.
  - It was tested using a dummy signal before and after the operation.

Good for operation, but … -_-!!!



It was tested by a simulated irregular trigger event.

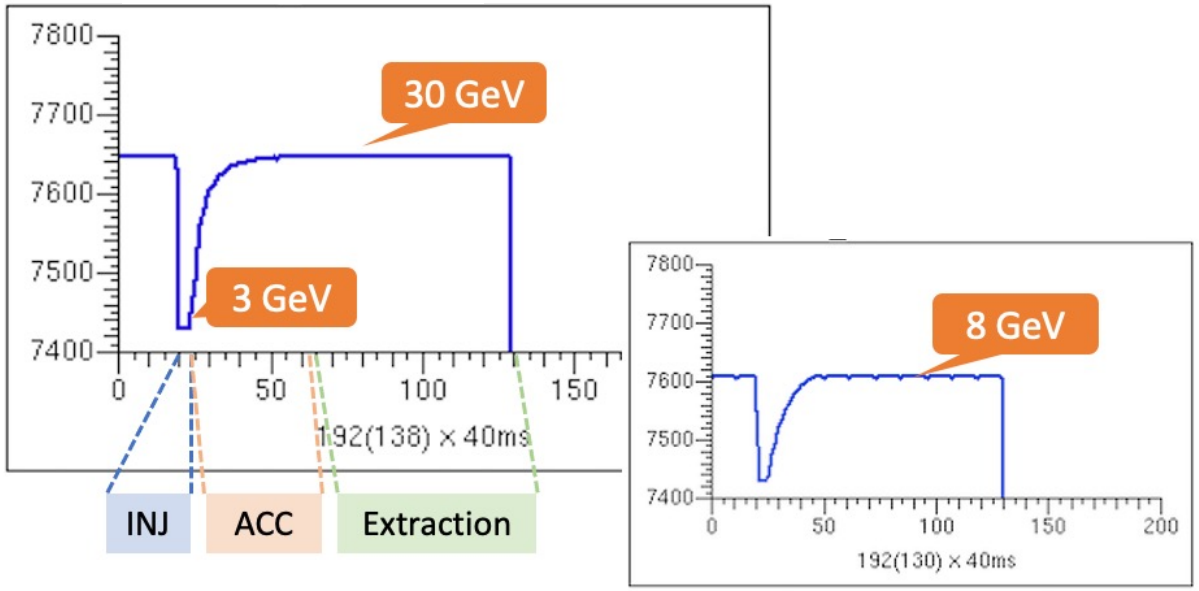


4.4 Read-Back of LLRF Signal

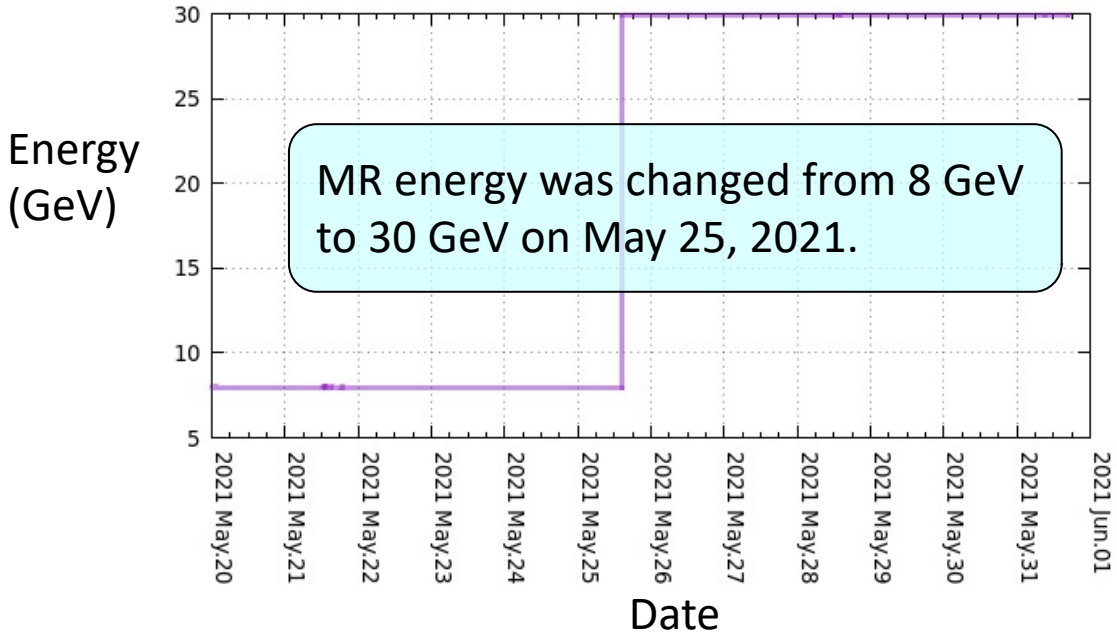
- In 2018, LLRF signal was demonstrated to visualize a LLRF pattern.
- After 2021, this monitoring system has been used in operation.
- Right) a 10-day history of the MR energy, which is deduced from the observed LLRF patterns.

Counts

Observed LLRF Patterns



10-day history of MR energy (from LLRF)



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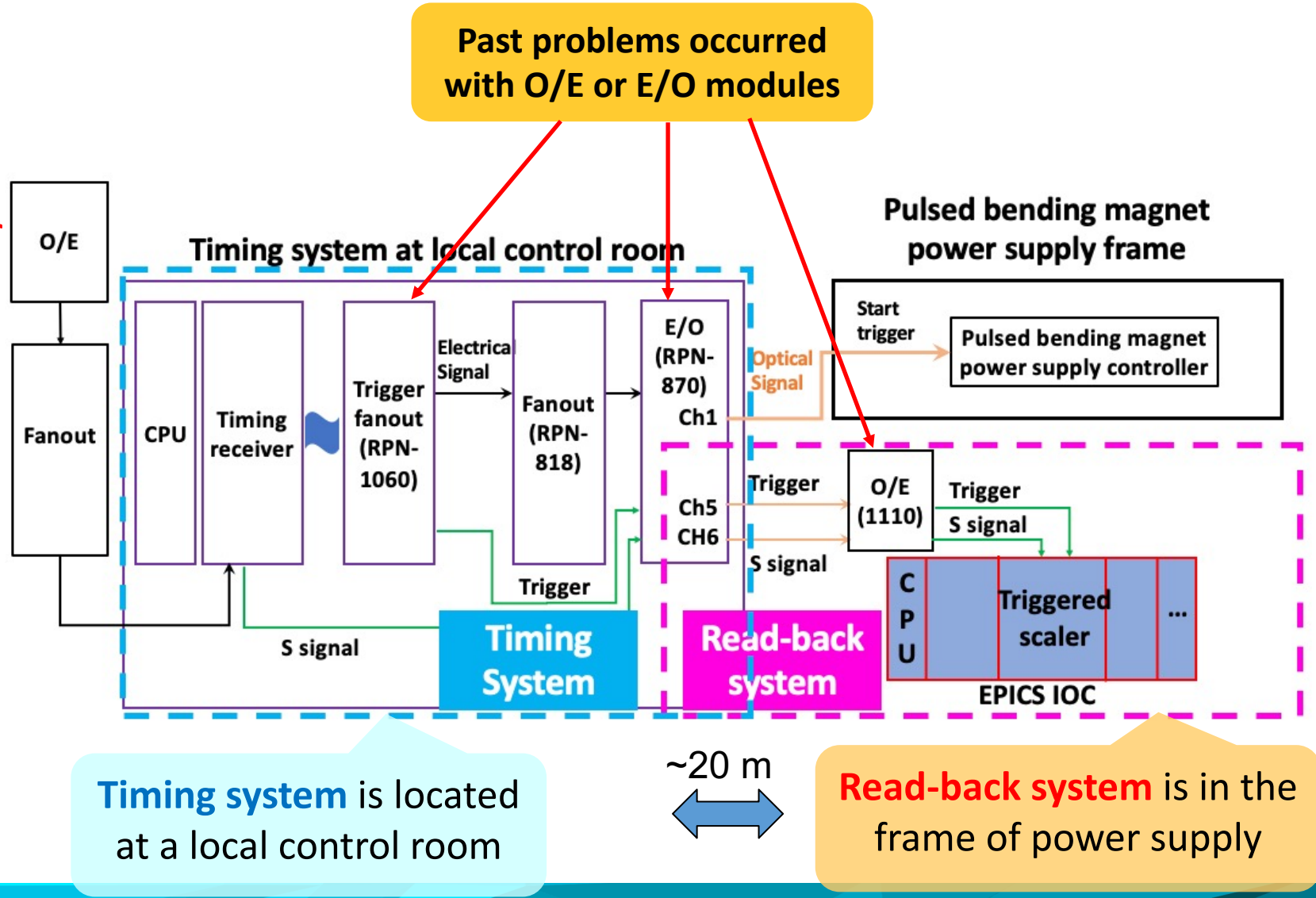
Ongoing plan for pulsed bending trigger

6. Summary

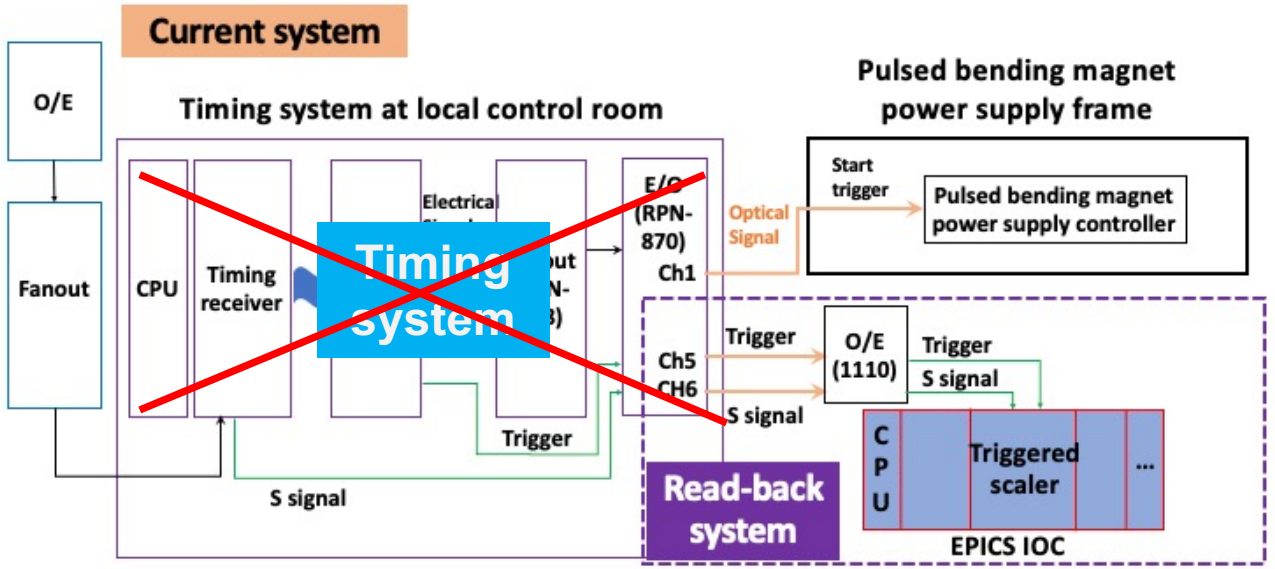
5.1 Ongoing Plan for Pulsed Bending Trigger (1)

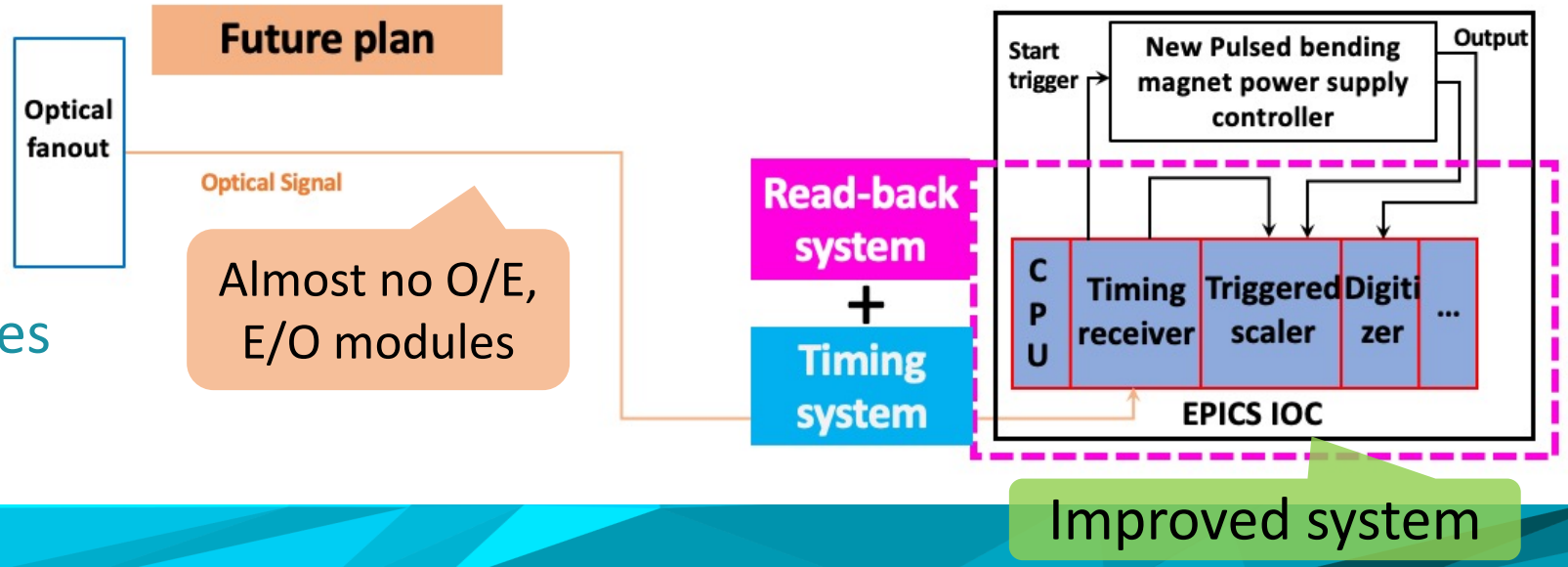
- Current system:
  - Timing system and Read-back system are distant over 20 m.
  - Timing signals are transferred with many O/E and E/O modules over 20m.
  - Aging of modules is potential source of failures.



5.1 Ongoing Plan for Pulsed Bending Trigger (2)

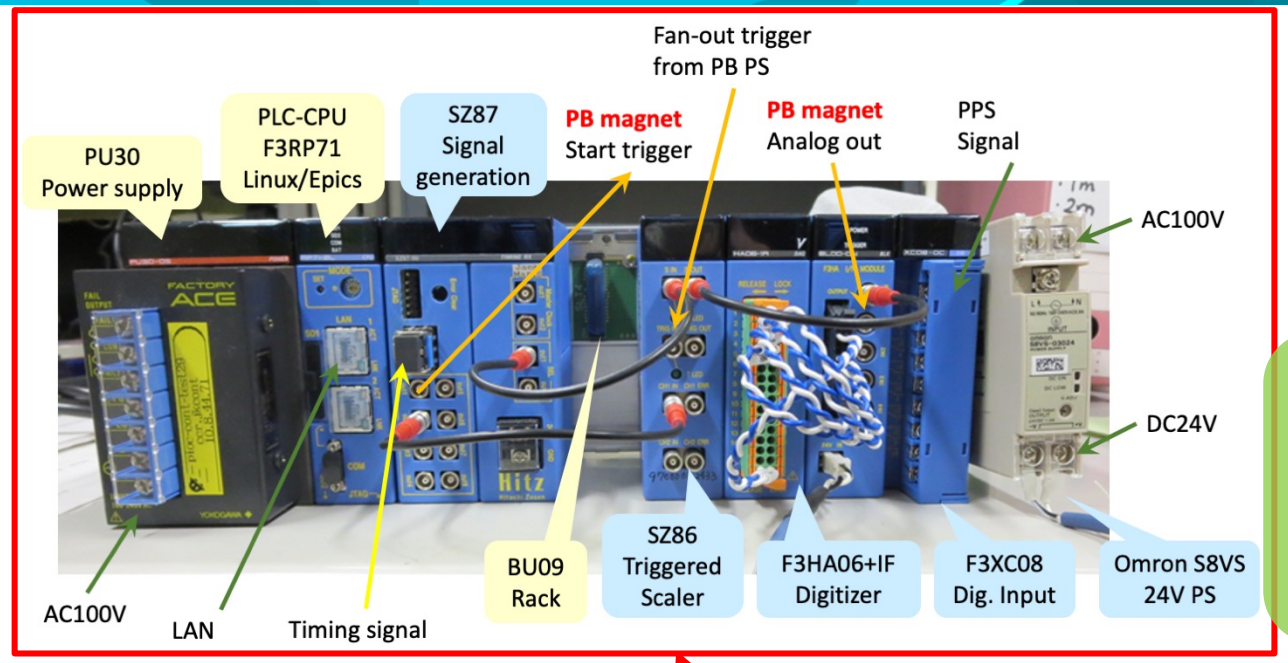
- Future plan
  - New power supply for the pulsed bending magnet is under construction
  - The timing and the its read-back systems will be merged, and embedded inside the frame of the new power supply.
  - Almost no O/E, E/O modules
    -> decrease the failure rate





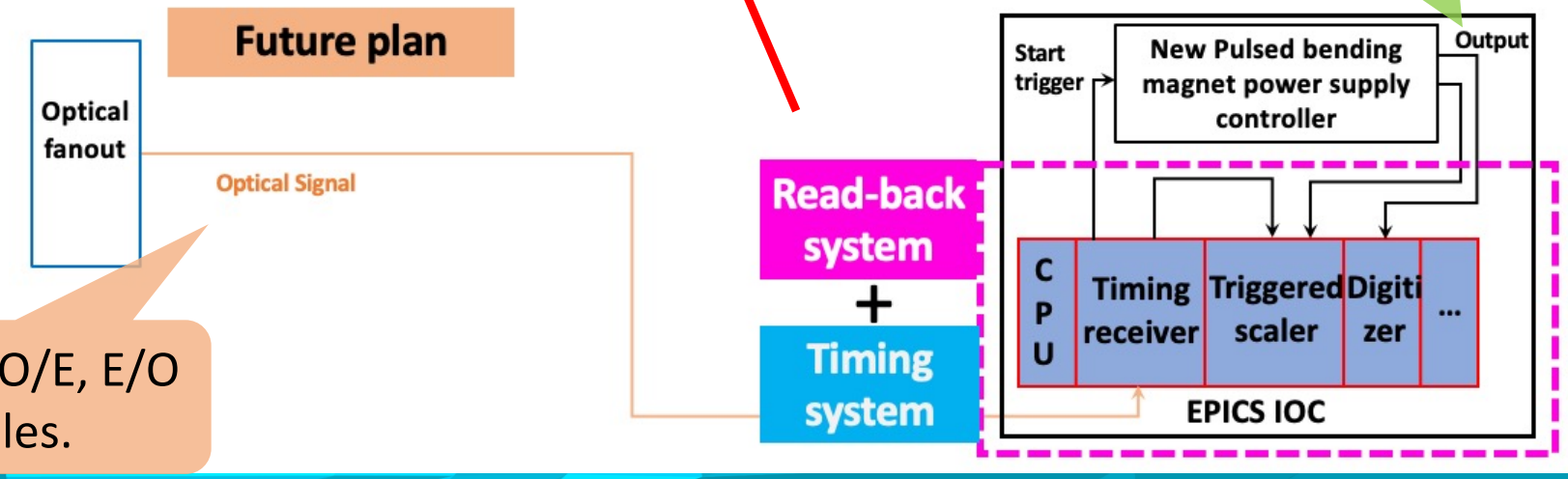
5.1 Ongoing Plan for Pulsed Bending Trigger (3)

- Setup of the improved system:
  - With a new timing receiver → reduce failure rate
  - With a digitizer → supervise analog output
  - Embedded inside the power supply frame



Pulse output and analog output will be supervised

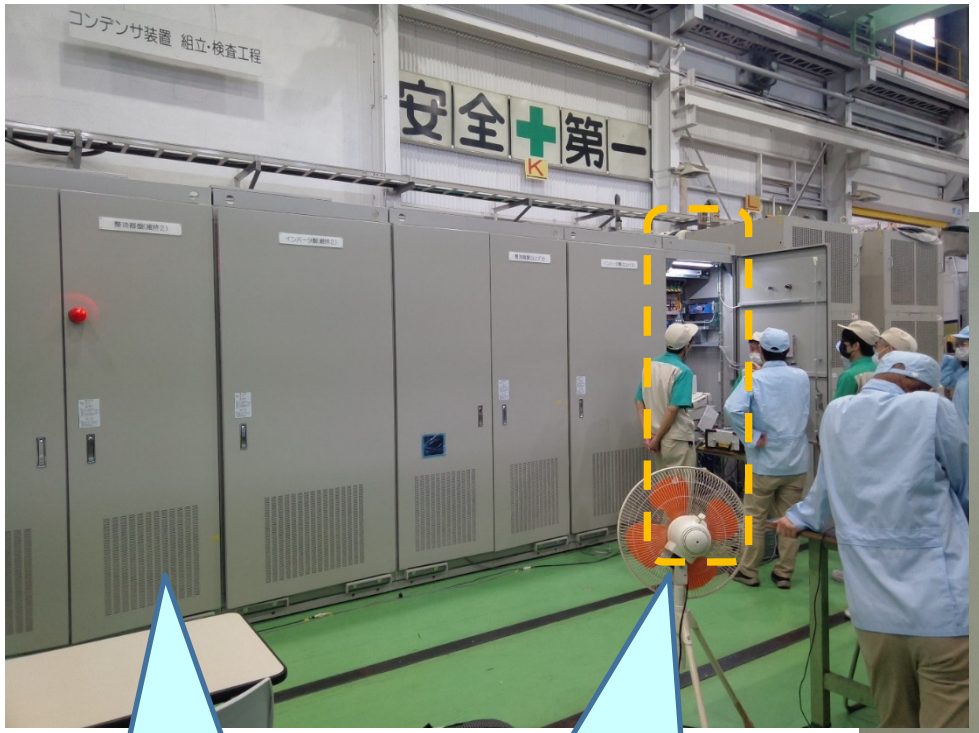
Future plan



Almost no O/E, E/O modules.

5.1 Ongoing Plan for Pulsed Bending Trigger (Photo)

◆New power supply : status on Sept.20, 2022

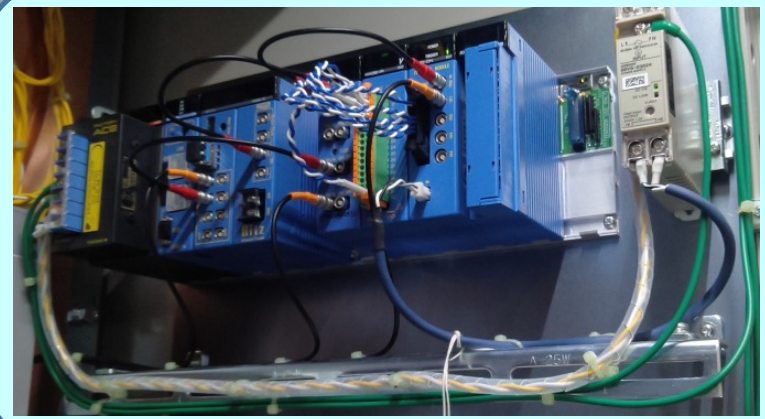


New power supply for the pulsed bending magnet

A control rack, links to the control and the timing systems

The control rack

The improved timing + readback system, embedded inside the power supply (not working yet)



Contents

1. Introduction of J-PARC and Timing System

2. Trigger-Failure Events in J-PARC

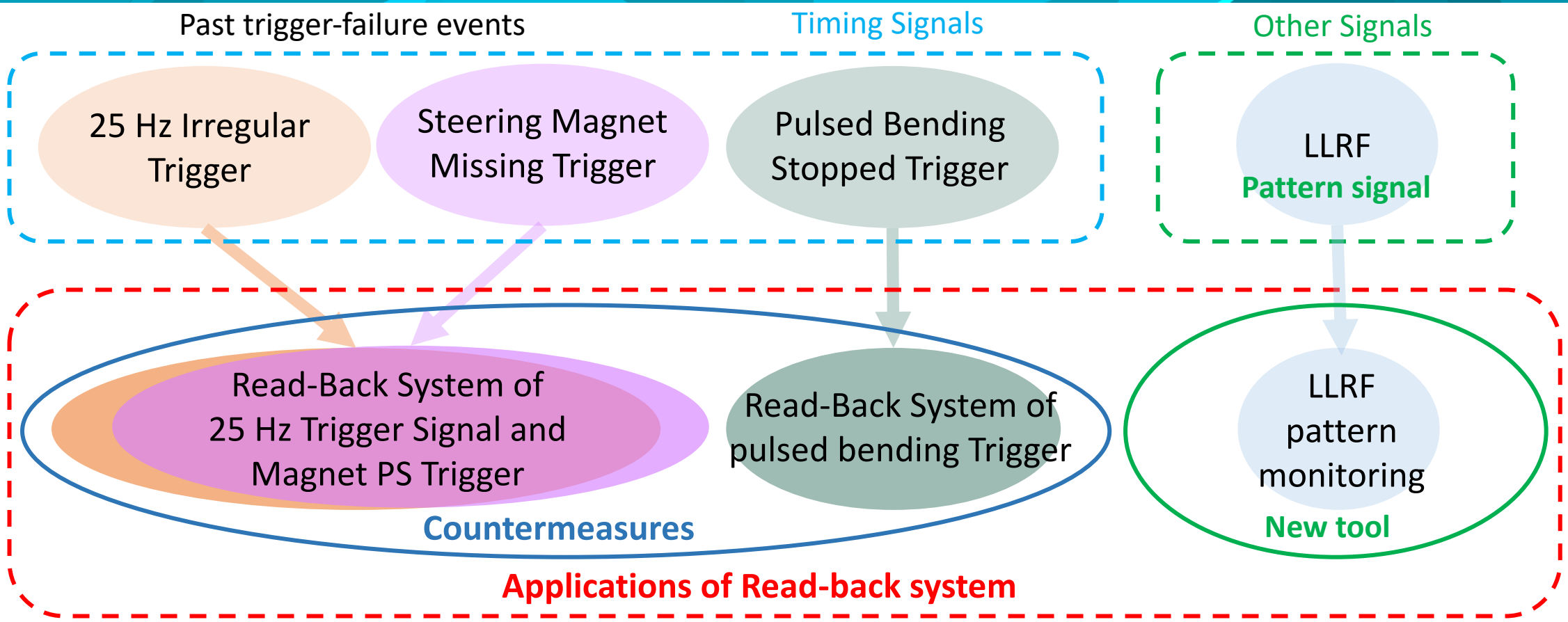
3. Timing Read-Back System and Triggered Scaler Module

4. Applications of Read-Back System

5. Future Plan for Pulsed Bending Trigger

6. Summary

6. Summary



- The applications of timing read-back system were developed, and in operation in J-PARC Main Ring since 2021 and 2022. Triggered Scaler module is the key device.
- New “improved timing and read-back system” is underway for a new power supply.
- These works have contributed to stable operation of J-PARC.

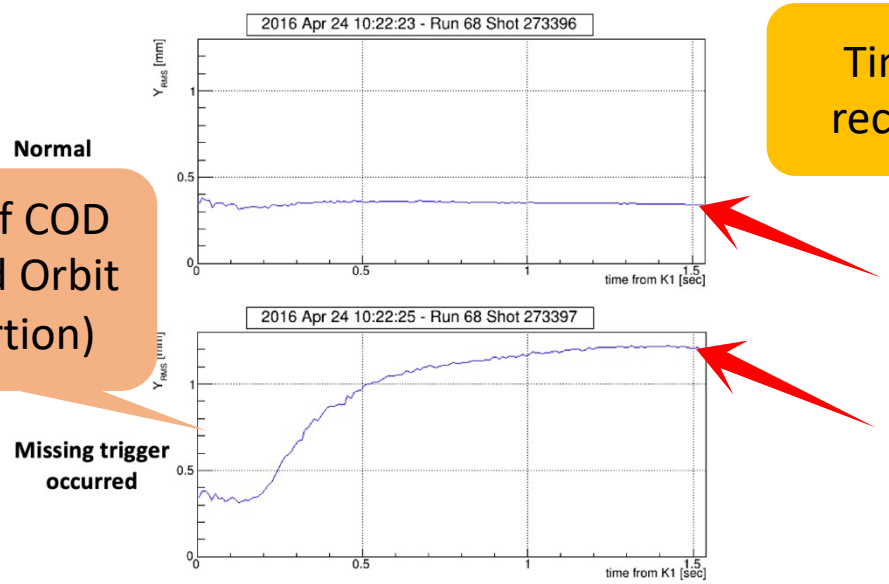
Thank you!

Backup

2.3 Steering Magnet Missing Trigger Event

- In November, 2015, a bad quality beam appeared during stable beam delivery to Hadron Facility. Such beams appeared a few times per month.
  - In June 2016, we found the **timing receiver module** for MR steering magnets showed momentary errors.

→ Added ferrite cores to metal cables.

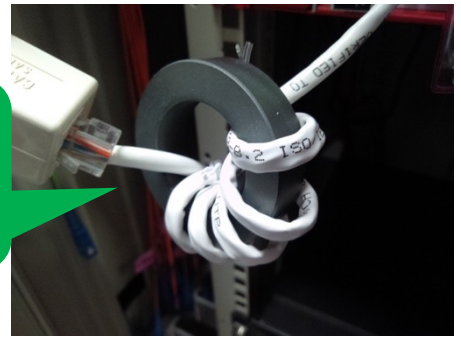


RMS of COD (Closed Orbit Distortion)

Timing receiver

This is a very rare event. It took six months to solve!

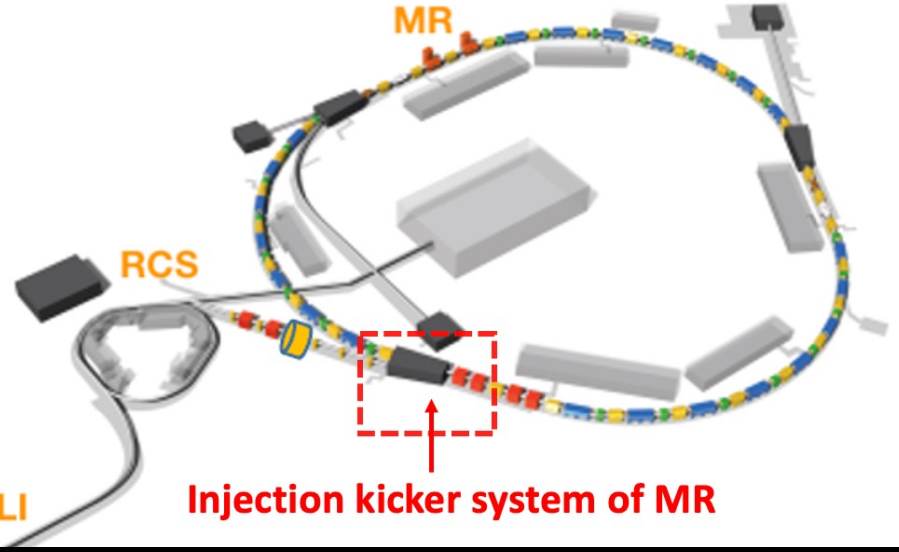
Ferrite core

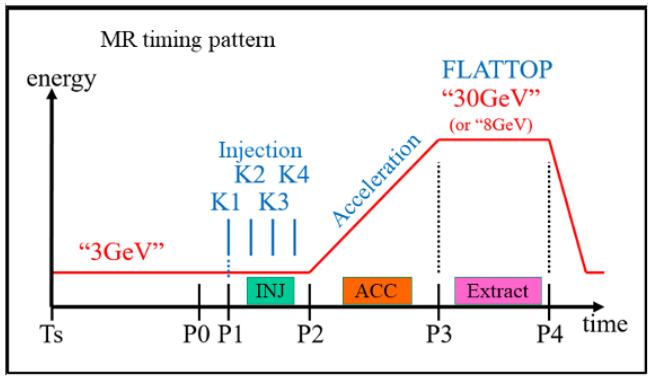


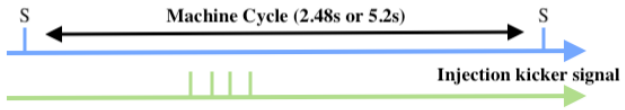
3.2 A Triggered Scaler Module – Performance

- The injection kicker signal was successfully observed in 2018
  - The injection kicker is triggered four times in one machine cycle.

This test was reported in PCaPAC 2018 by N.Kamikubota








```
opr3@jkjnuc01 [206]% caget MRCO:PIOC_CONT_D3TMG01:TS0:WF:ch3_p
MRCO:PIOC_CONT_D3TMG01:TS0:WF:ch3_p 192 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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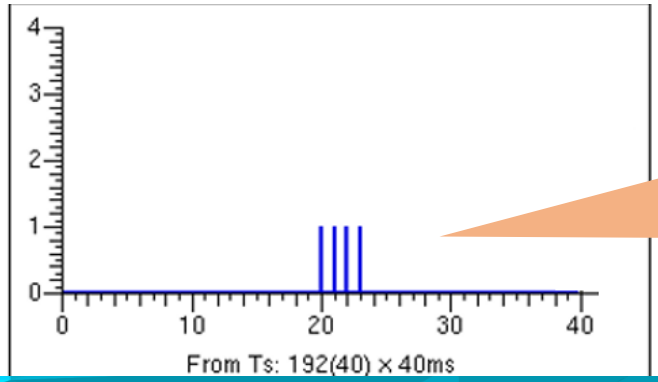
```

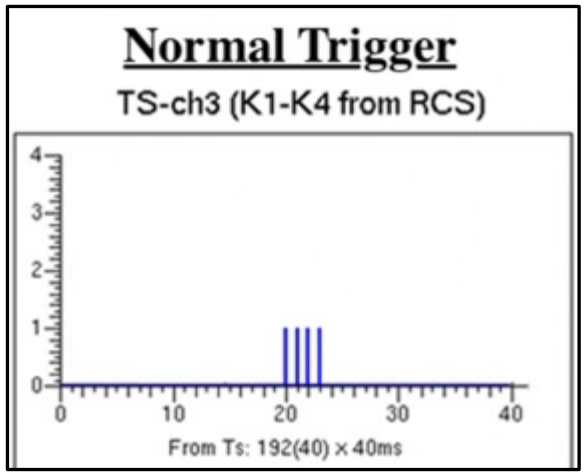


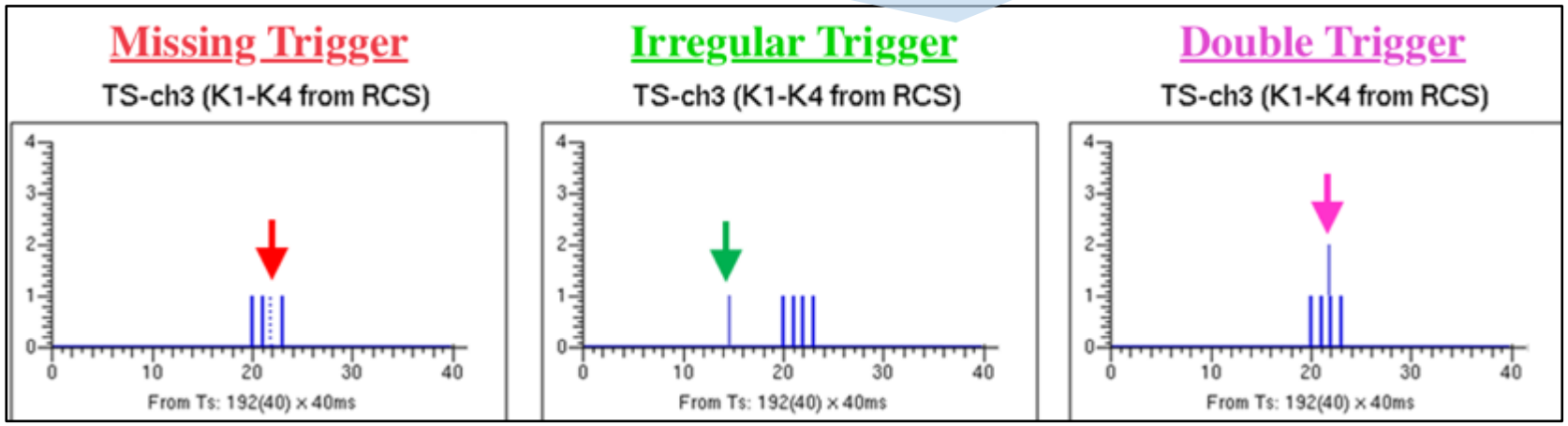
Observed and visualized!

3.3 Prototype Read-Back System (1)

- A prototype read-back system for injection kicker signal was developed.
- Possible failure events of injection kicker signal
  - Missing trigger: one (or more) trigger disappears.
  - Irregular trigger: unexpected triggers are overlapped into the original signal (caused by noise).
  - Double trigger: one (or more) trigger is counted double (caused by bad termination).

The undesirable trigger-failure events are called **"unexpected trigger-failure events"**



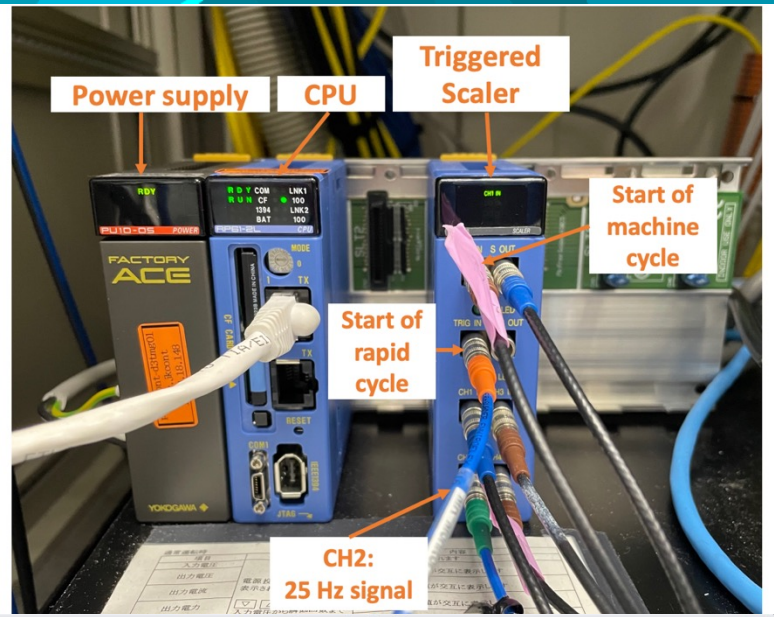


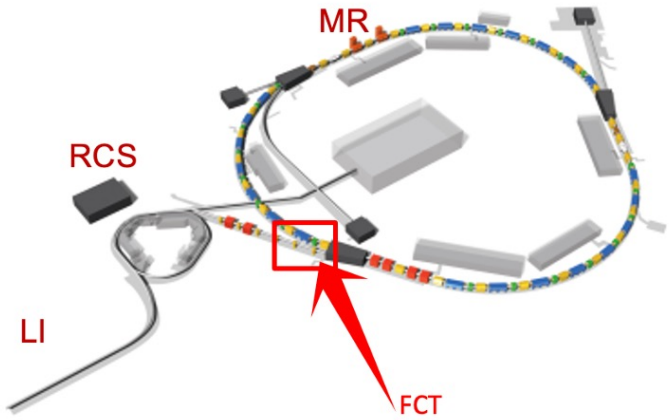
3.4 Summary of Timing Read-Back System & Triggered Scaler Module

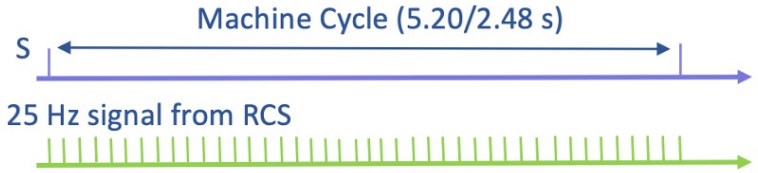
- The prototype system detected unexpected trigger-failure events successfully.
- The triggered scaler module is the key to construct a timing read-back system.
- The EPICS achieves system flexibility.

4.1 Read-Back System of 25 Hz Trigger Clock from RCS

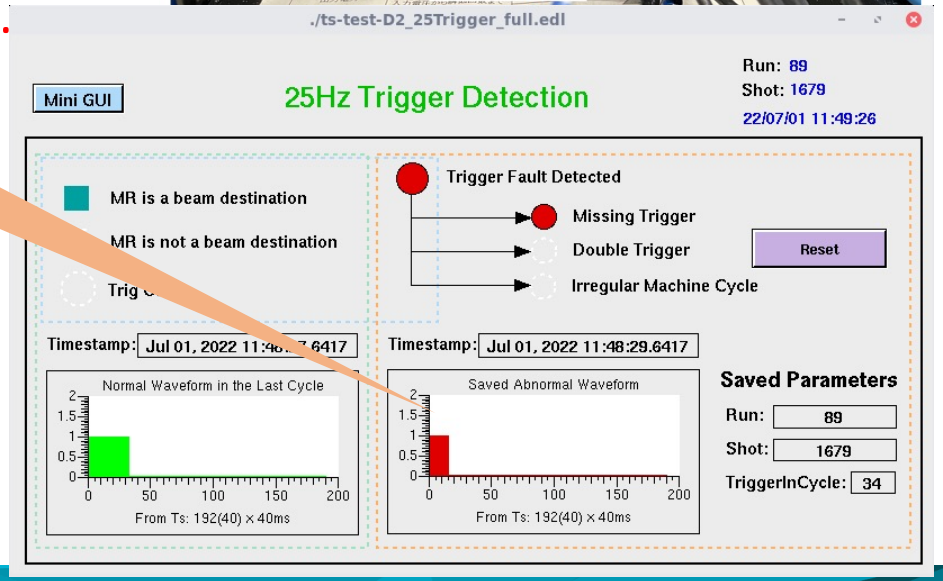
- The 25 Hz trigger clock from RCS is important because ...
  - It is used for the data acquisition of a fast-current transformer (FCT) located between the RCS and MR.
  - The FCT is essential for MR radiation safety. Its error causes a critical problem.
- The read-back system of the 25 Hz trigger clock is available since May 2021. Remote monitoring and trigger detection are realized.







Observed and visualized remotely!



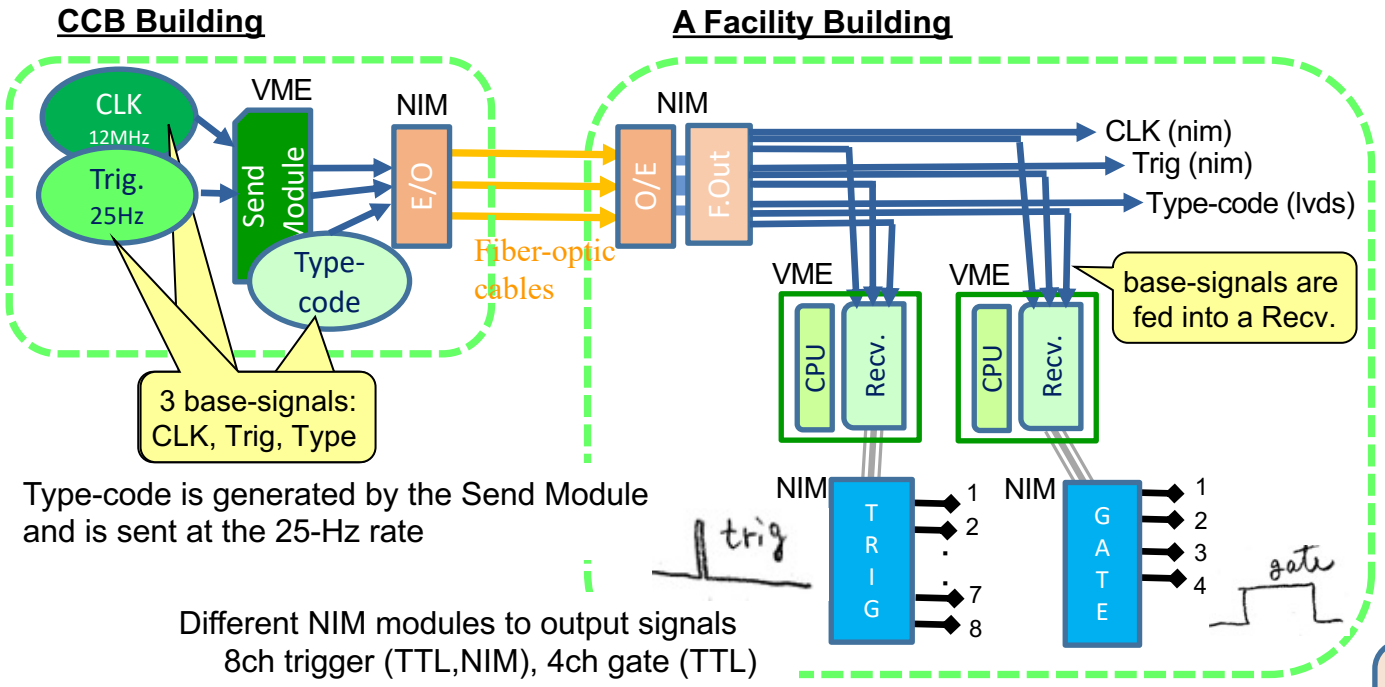
Ref) J-PARC Timing: Facts

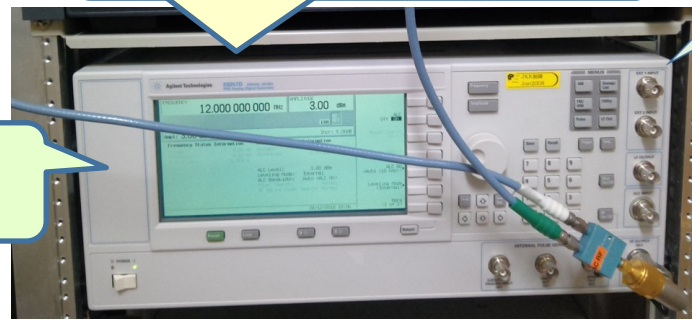
1. J-PARC is an accelerator complex located in Ibaraki, Japan
    1. Rapid cycle: LI(400MeV Linac) and RCS(3GeV) - 25Hz
    2. Slow cycle: MR(30GeV Main Ring) - 2.48s or 5.20s
2. Hardware
    1. Home-design VME modules for control, NIM modules for signal generation (not MRF-based)
3. Software
    1. Developed by ourselves
    2. EPICS and its tools are used in general
    3. Java and python are preferred for table-data handling (epics waveform)
4. Scale of the system
    1. One Send-module (=EVG)
    2. LI/RCS/MR – 118/43/45 VME receiver-modules(EVR), ~540/220/300 endpoints

For more, please refer
"**OPERATION STATUS OF J-PARC TIMING SYSTEM AND FUTURE PLAN**",
N. Kamikubota et.al, at ICALECS2015

Timing: timing hardware - J-PARC

- A Master oscillator to generate 12MHZ Clock
- A send module (timing master, VME) and receiver modules (VME)
- NIM modules to generate trigger or gate signals





Master Osc.

Old timing master
Seq. Pattern 4個

Current timing master
Seq. Pattern 64個

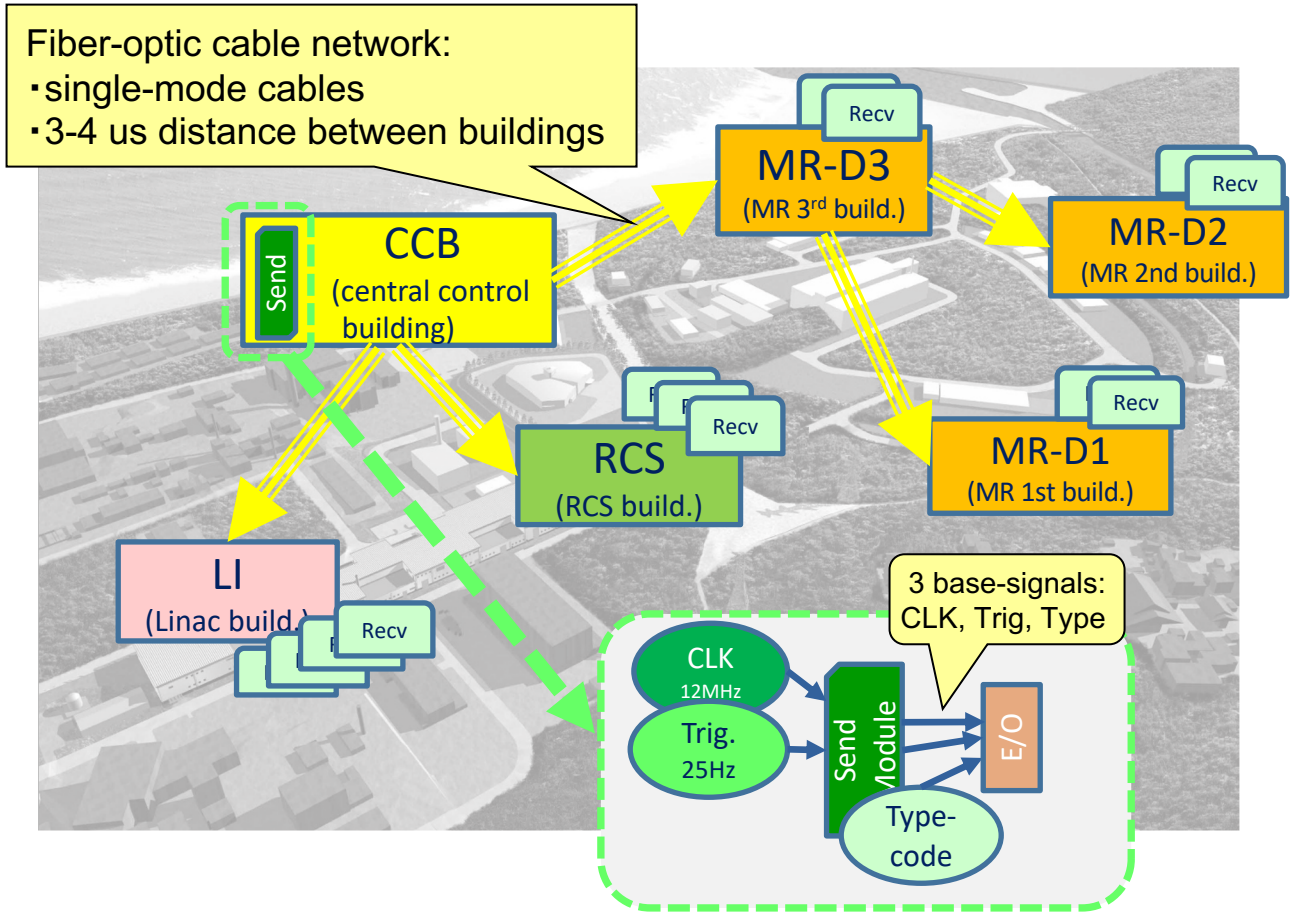
Receiver module
8 setpoints per module

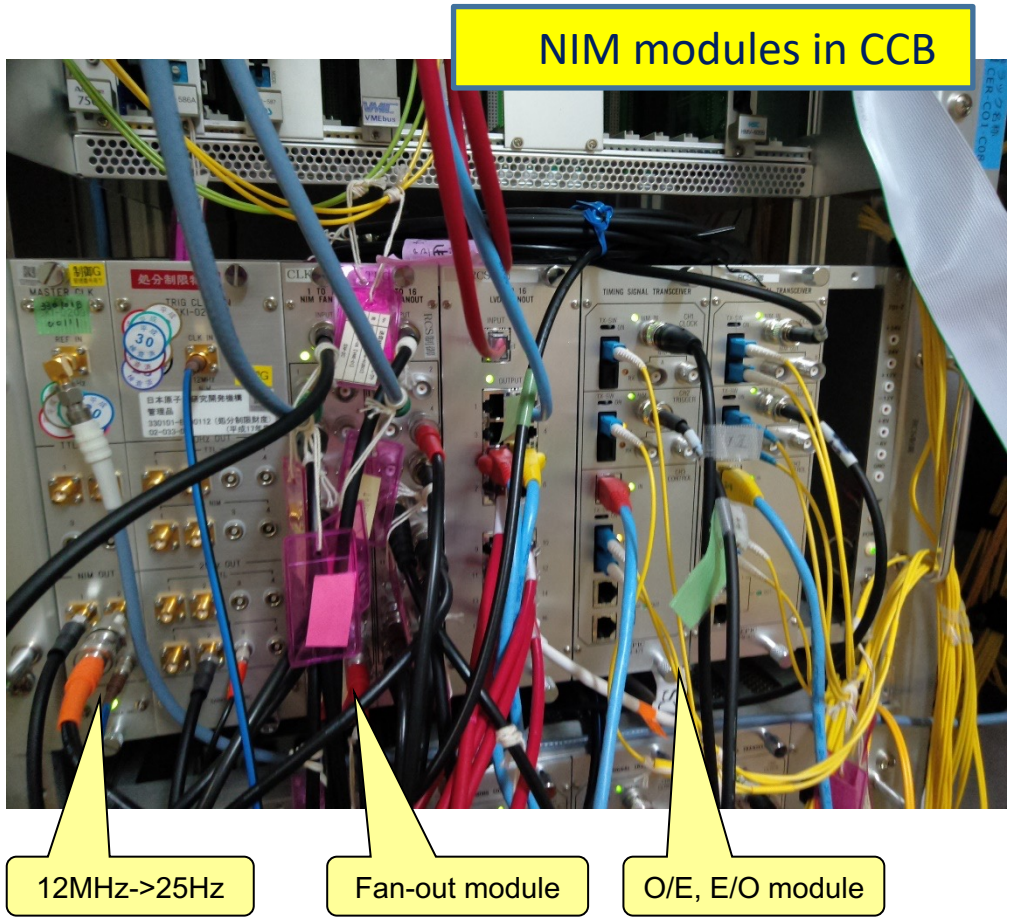
Receiver module

- New timing hardware modules (VME-based master, receiver; PLC-based receiver) are in test

Timing: timing network - J-PARC

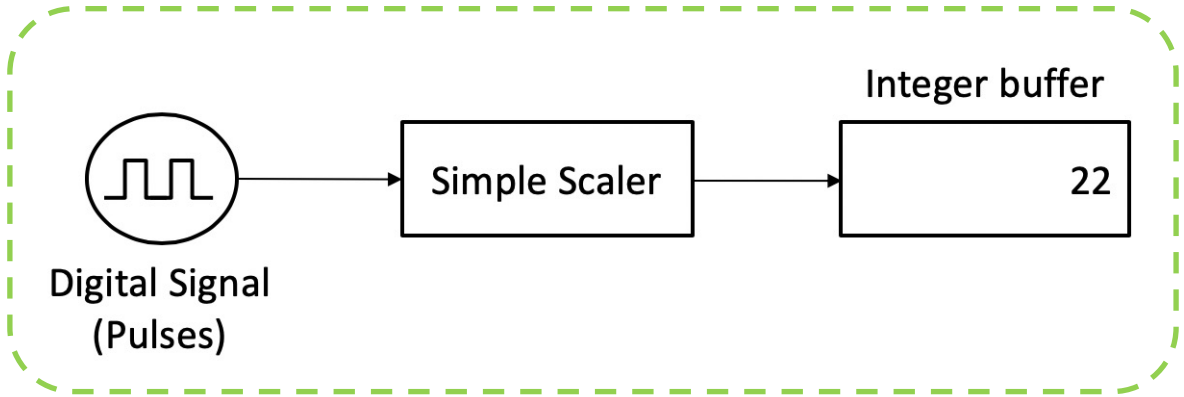
- Fiber-optic cable network between buildings
- O/E, E/O modules (NIM-modules) to form a facility-wide timing network
  - Used to provide 3 base-signals: 12MHz Clock (CLK), 25Hz trigger (TRIG) and sequence of type-codes (TYPE)

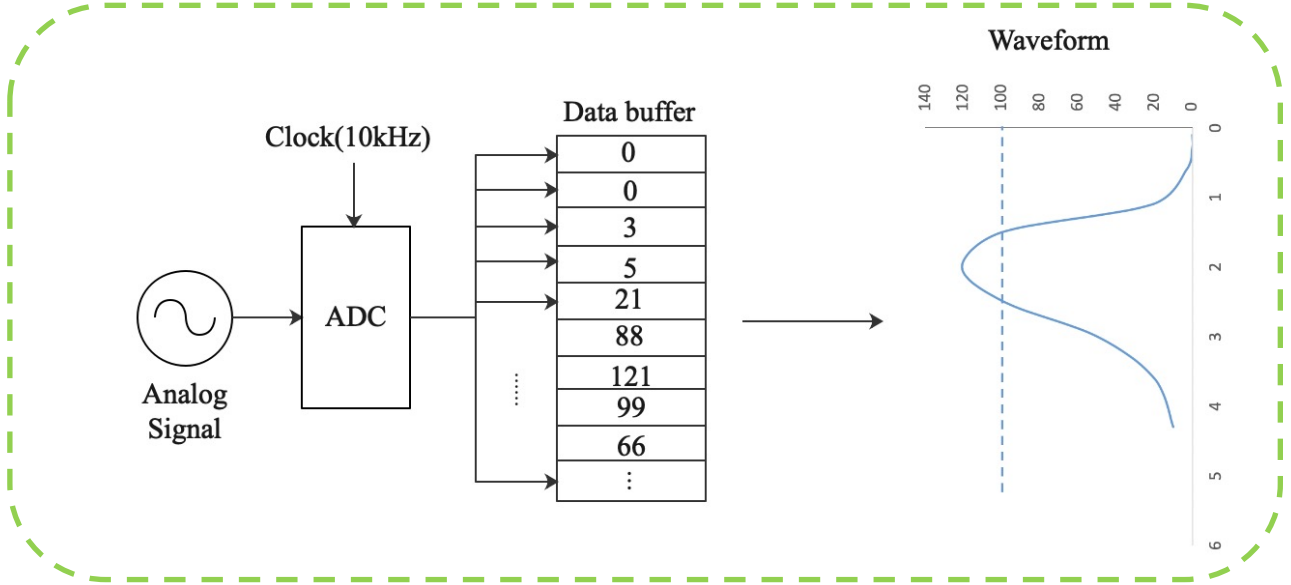


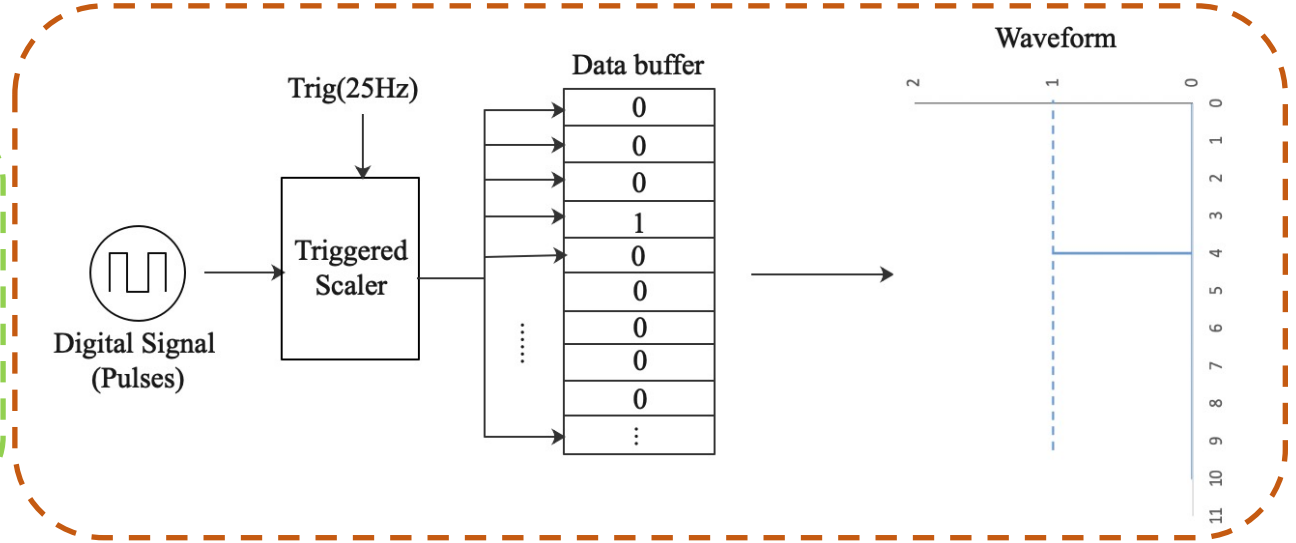


4. Triggered Scaler Module

- Difference Between Digitizer, Triggered Scaler and Simple Scaler
  - Digitizer →
  - Simple scaler →
  - Triggered scaler →

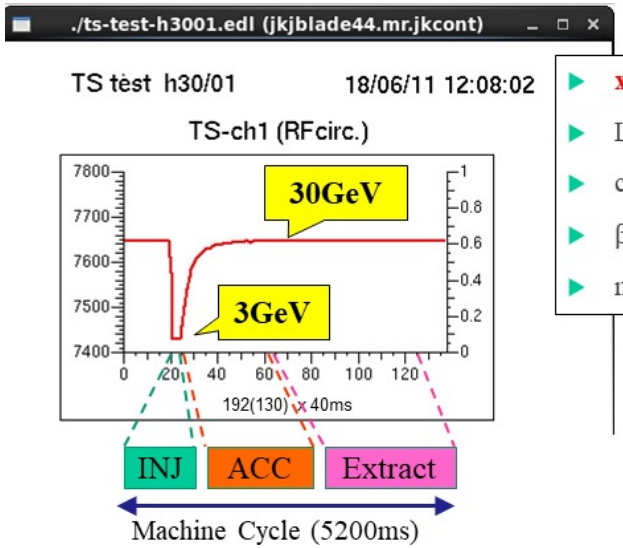






Early Measurement of RF signal

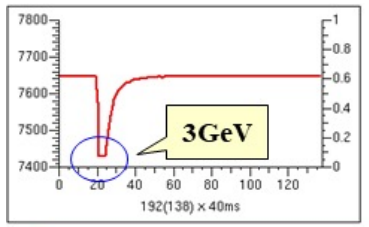
- The number of counts in a 40ms bin were measured.
- Beam energy is 3GeV (8 GeV, 30 GeV), the number of counts 7429 (7608/7609, 7648) was observed.

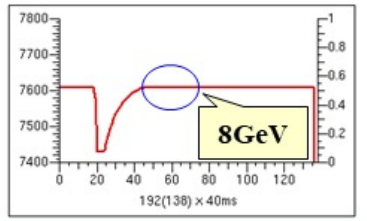


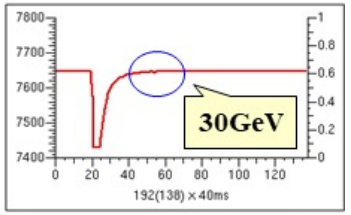
- **x** : RF signal (counts / 40 ms)
- L : Circumstance of MR (1567.5 m)
- c : speed of light (299792458 m/s)
- β : Relative speed
- m_0c^2 : Proton rest mass (0.938 GeV)

$$\beta = \frac{v}{c} = \frac{x}{0.040} \cdot \frac{L}{c}$$

$$E = \frac{m_0 c^2}{\sqrt{1-\beta^2}} - m_0 c^2$$







RF parameters			Observed by a triggered scaler	
Energy	RF(MHz)*	one turn(us)	expected	Number of counts in 40ms bin
30GeV	1.7205	5.231	7647	**7647**
8GeV	1.7118	5.258	7607	**7608 or 7609**
3GeV	1.6717	5.384	7429	**7429**

* revolution frequency with h=9