J-PARC LINAC/Synchrotron LLRF System

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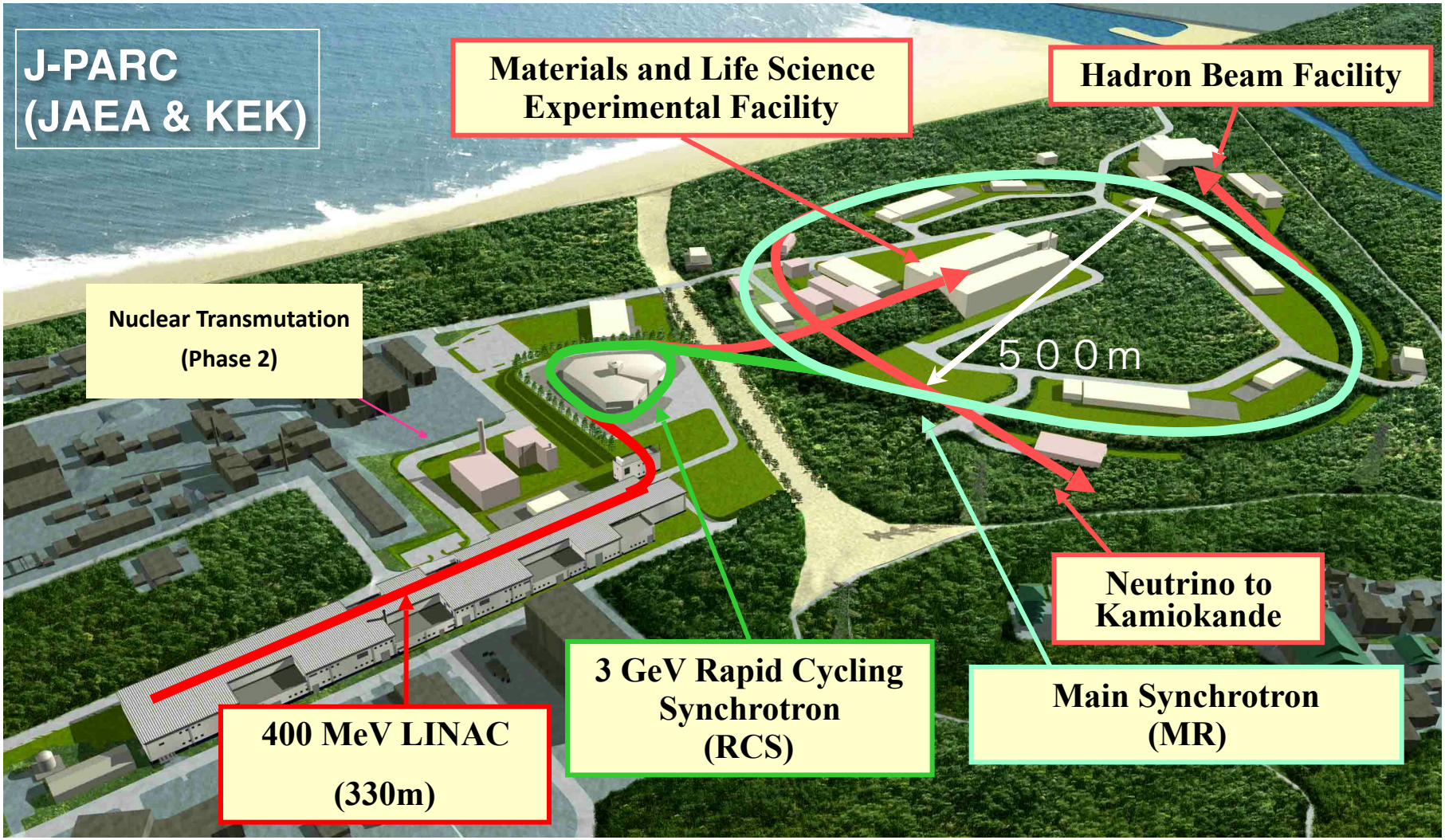
J-PARC

Joint Project between KEK and JAEA

J-PARC (Japan Proton Accelerator Research Complex)

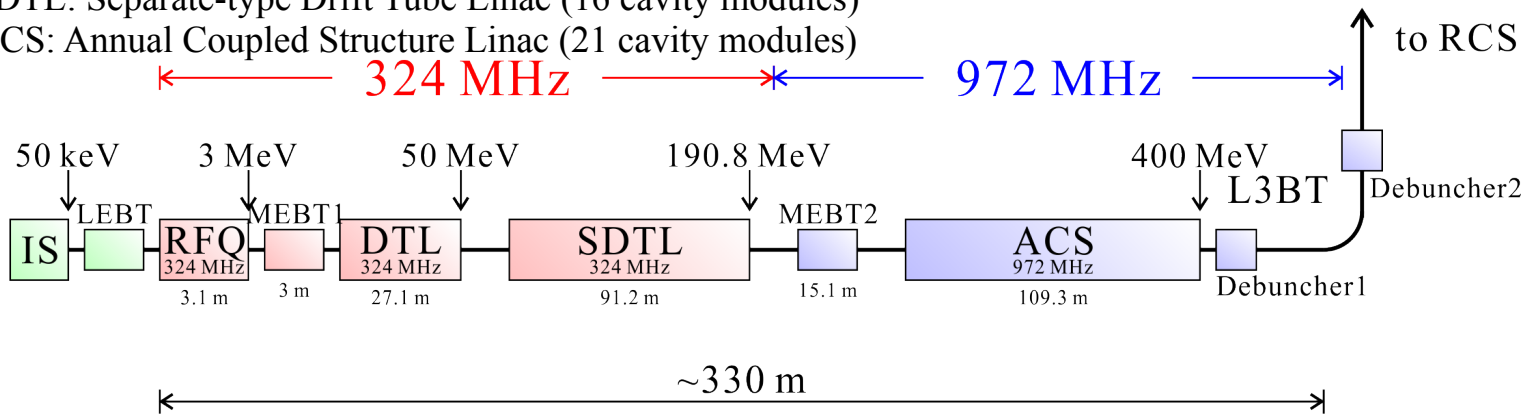


J-PARC Linac

- Particles: H⁻ (negative hydrogen)
- Kinetic Energy: **181 MeV → 400 MeV at 2013**
- Peak Current: **Max 30 mA → 50 mA at 2014**
- Acceleration Frequency: **324 MHz → 324 MHz + 972 MHz at 2013**
- Pulse Width: 500 μs (Beam), 650 μs (RF)
- Repetition: 25 Hz

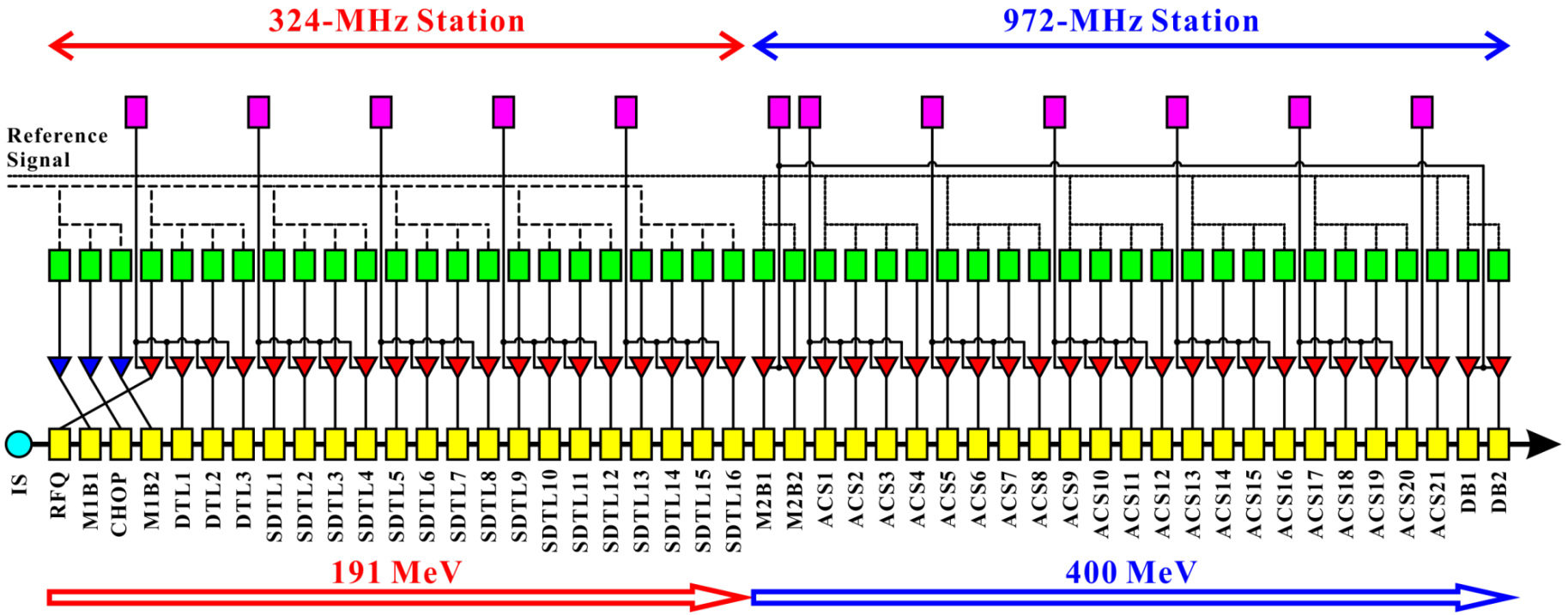
IS: H⁻ Ion Source
RFQ: Radio Frequency Quadrupole Linac
DTL: Drift Tube Linac (3 cavity modules)
SDTL: Separate-type Drift Tube Linac (16 cavity modules)
ACS: Annual Coupled Structure Linac (21 cavity modules)

Cavity Type: NC



Required Gradient Stability : ±1% in amplitude, ±1 deg. in phase
→ digital FB & FF : ±0.3% in amplitude, ±0.3 deg. in phase
→ Reference Distribution System : ±0.3 deg. in phase

Linac RF System

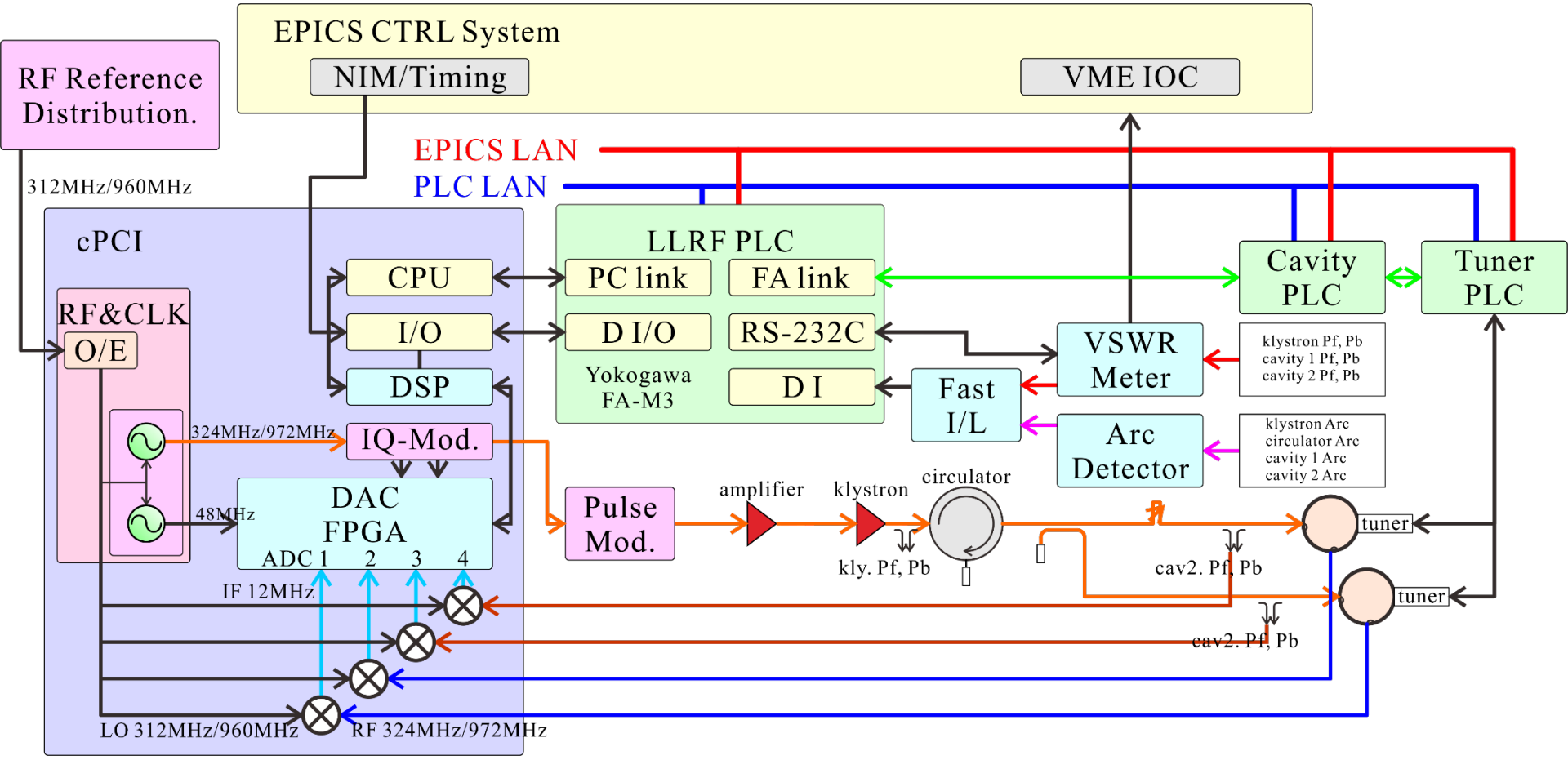


#Components	HVDC PS	LLRF	Klystron	Solid-State Amplifier	Cavity Module
324MHz	5	24	20	4	39
972MHz	7	25	25	0	25

※ One klystron supplies the RF power to two SDTL cavities.

※ One high-voltage power supply drives four klystrons.

Block diagram of J-PARC Linac LLRF



Basic requirements of J-PARC LINAC LLRF:

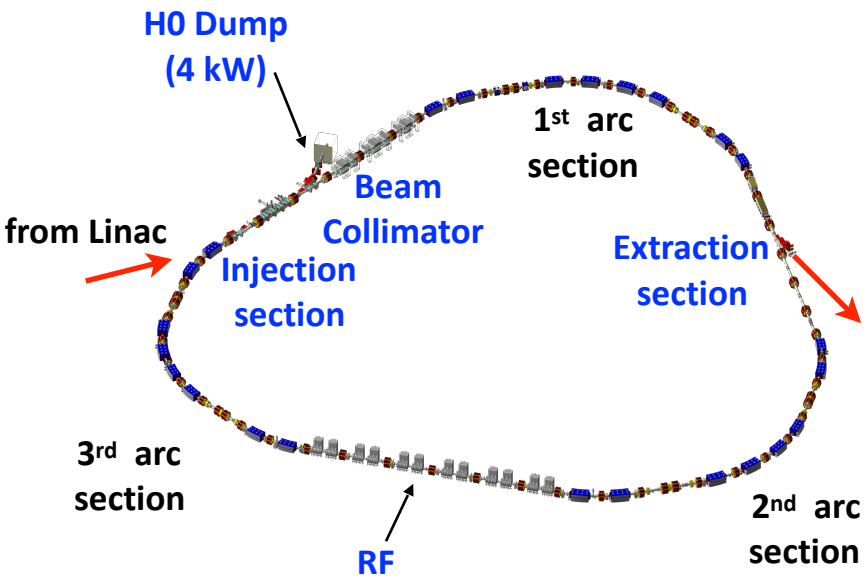
- ➢ Stabilities of RF field: ±1% in amplitude and ± 1° in phase.
- ➢ Auto-tuning of rf cavity.
- ➢ Interlock system.
- ➢ Operation system with a great convenience, high reliability, and fast response.

3GeV rapid cycling synchrotron (RCS)

Features

- High transition gamma: a missing bend structure
- Magnetic Alloy loaded cavity, high accelerating gradient, conbined function,,,
- Beam delivary to MR and MLF with 25Hz rapid cycling

Circumference	348.3 m
Injection energy	400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Output beam power	1 MW
Harmonic number	2
Tune (x/y)	6.45/6.42
Transition gamma (γ_t)	9.14

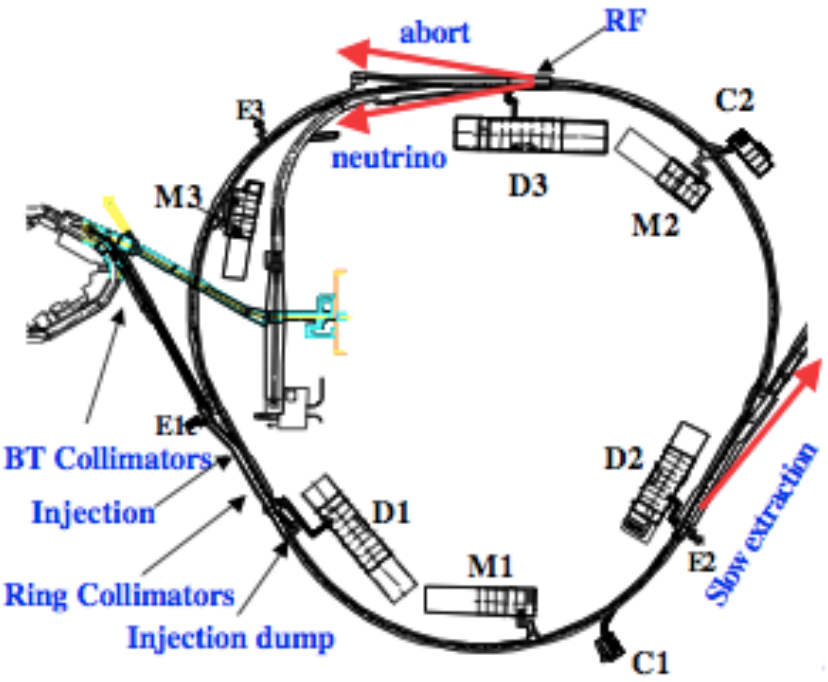


Main synchrotron Ring (MR)

Features

- Imaginary Transition gamma: the missing bend structure
- Magnetic Alloy loaded cavity, same as the cavities in the RCS, separated function
- deliver to two facilities w/ low and fast extractions for nuclear/particle physics experiments

Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 GeV
Repetition rate	0.3 Hz
Output beam power	0.75 MW
Harmonic number	9
Tune (x/y)	22.4/20.8
Transition gamma (γ_t)	-34.5

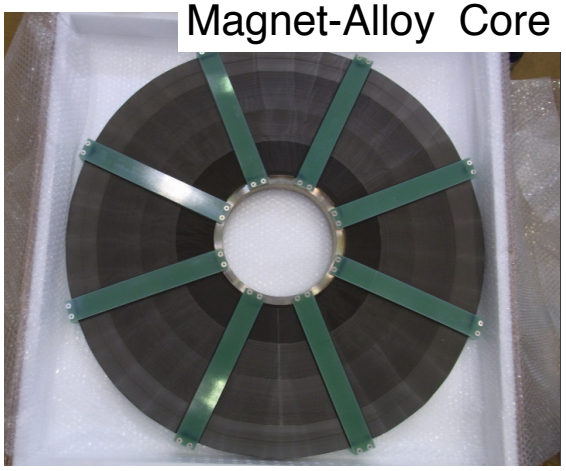


Ring RF Systems

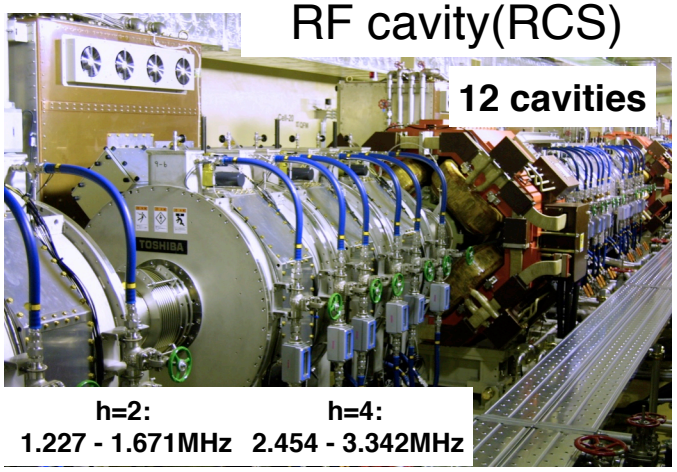
※ Wide-band Magnetic Alloy loaded RF cavities. (no tuning system provided)
※ High power amplifier with two tetrodes operated in a pusu-pull supplies the RF power to each cavity
※ Solid-state amplifer uses as an driver amplifer.

ring	frequency (MHz)	Anode DC PS	Tetrode AMP	MA Cavity
RCS (h2/h4)	1.22 - 1.67, 2.44 - 3.34	12	12	12
MR (h9)	1.67 - 1.72	7	7	7
MR (h18)	3.34 - 3.44	2	2	2

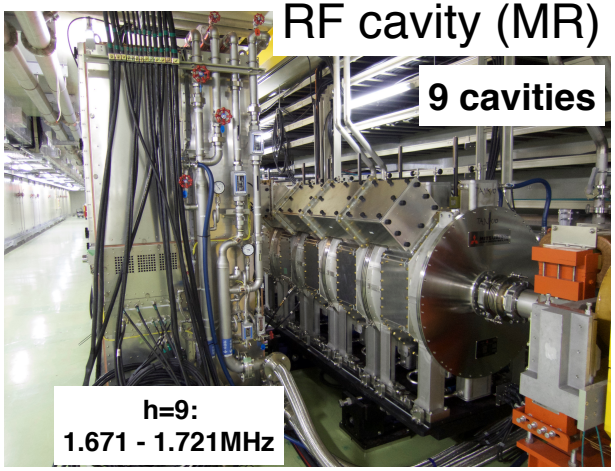
Magnet-Alloy Core



RF cavity(RCS)



RF cavity (MR)



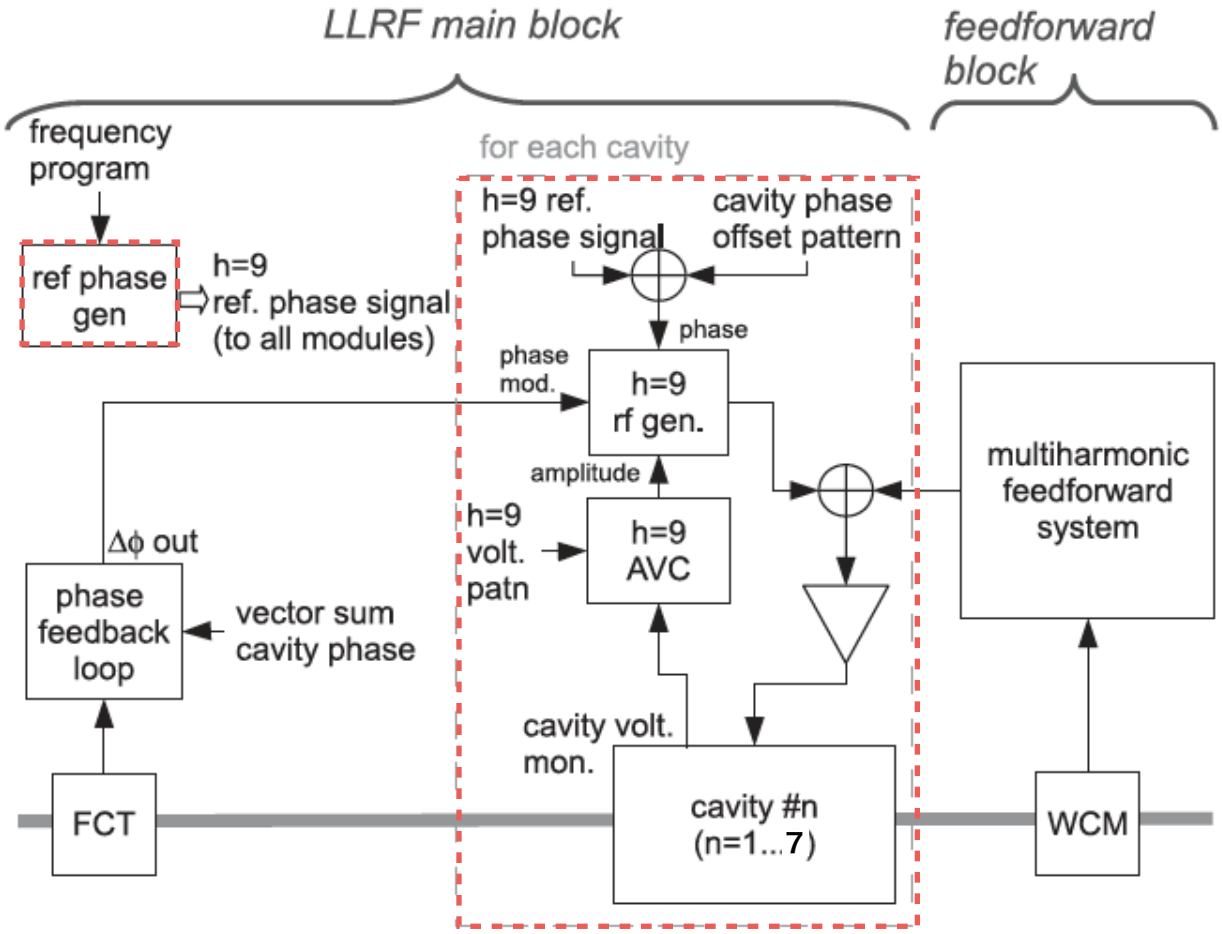
LLRF for Ring RF Systems

※ LLRF is a full digital system based on DDS.

※ Functions

- Reference phase generation
- Auto voltage control for the fundamental and 2nd harmonic RF
- Beam-phase feedback loop
- Δr feedback (not used)
- multi-harmonic feedforward beam loading compensation

LLRF for Ring RF Systems



Phys. Rev. ST Accel. Beams 16, 051002 (2013)

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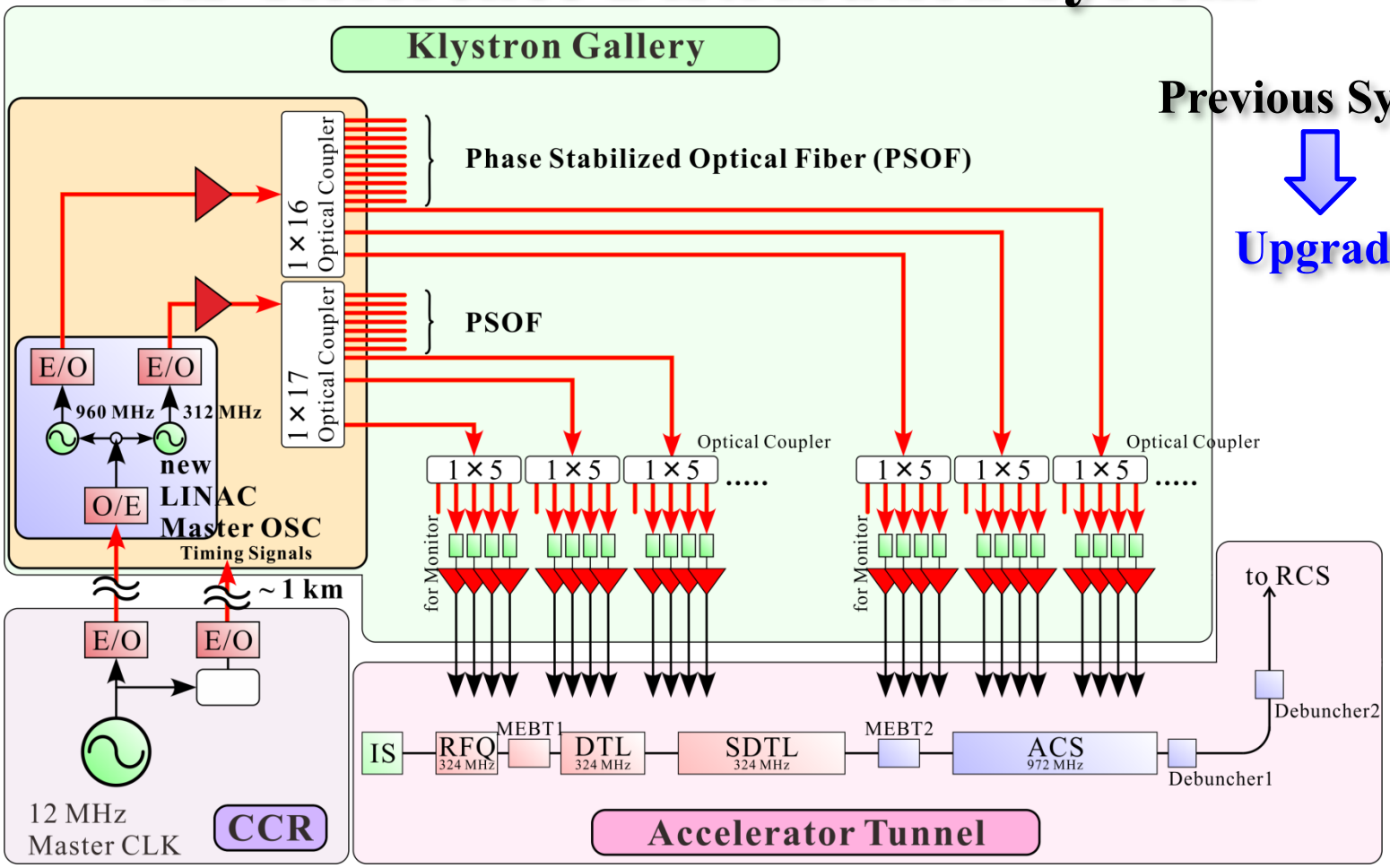
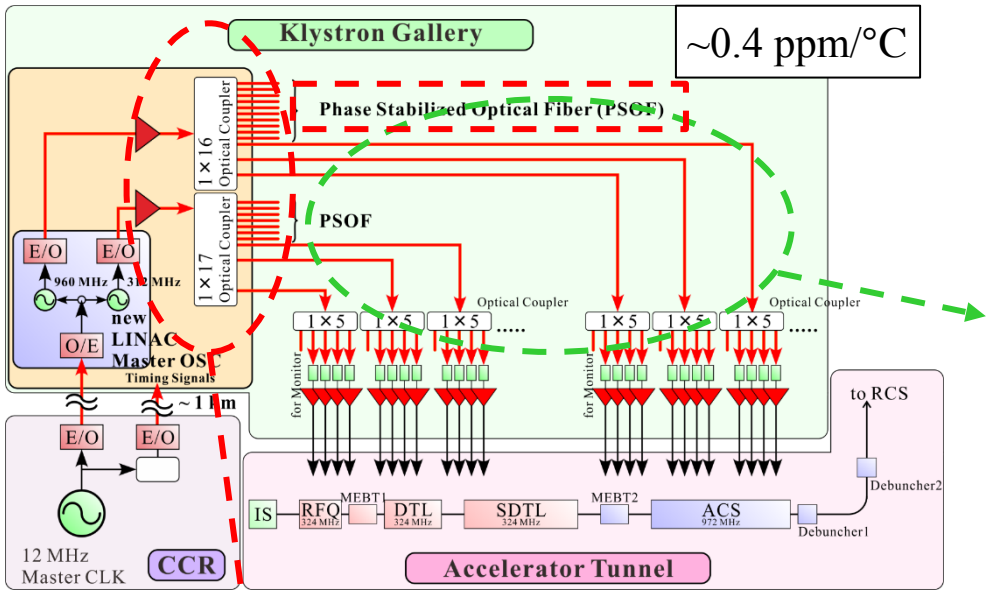
RF Reference Distribution System

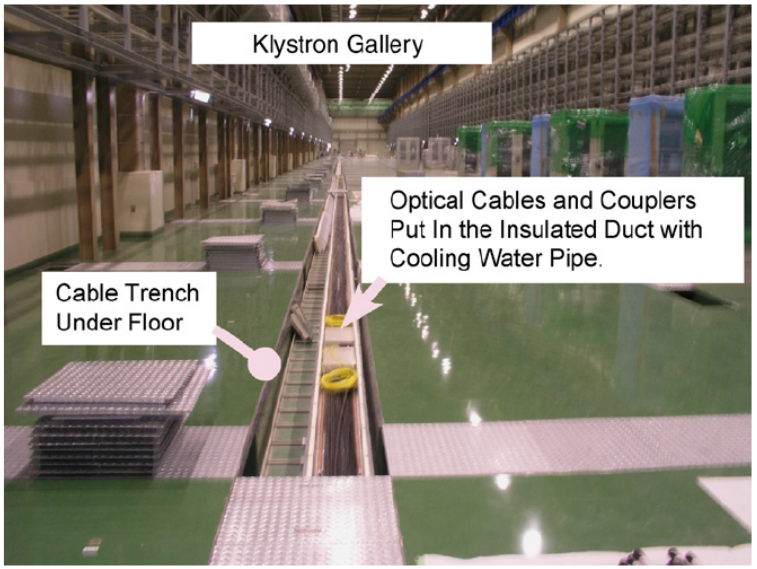


- **The 12MHz Master CLK comes from the central control room (CCR).**
- **The 312MHz and 960MHz RF reference are generated by LINAC Master OSC.**
- **The 312MHz RF reference signals go through the same lines as the previous system. The 960MHz RF reference signal is optically amplified and divided into 16 lines, then furthermore divided into 5; one of the five is returned back to the front end for phase monitor.**

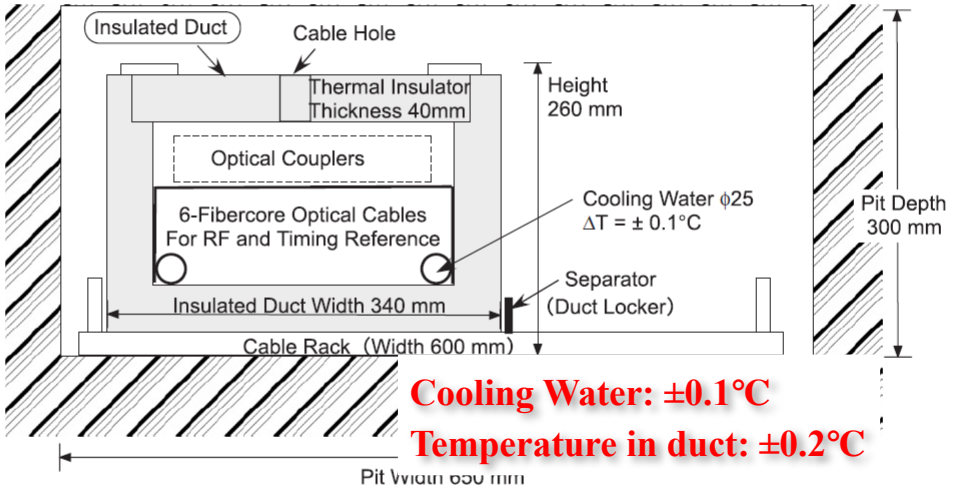
Optical Signals on Distribution System



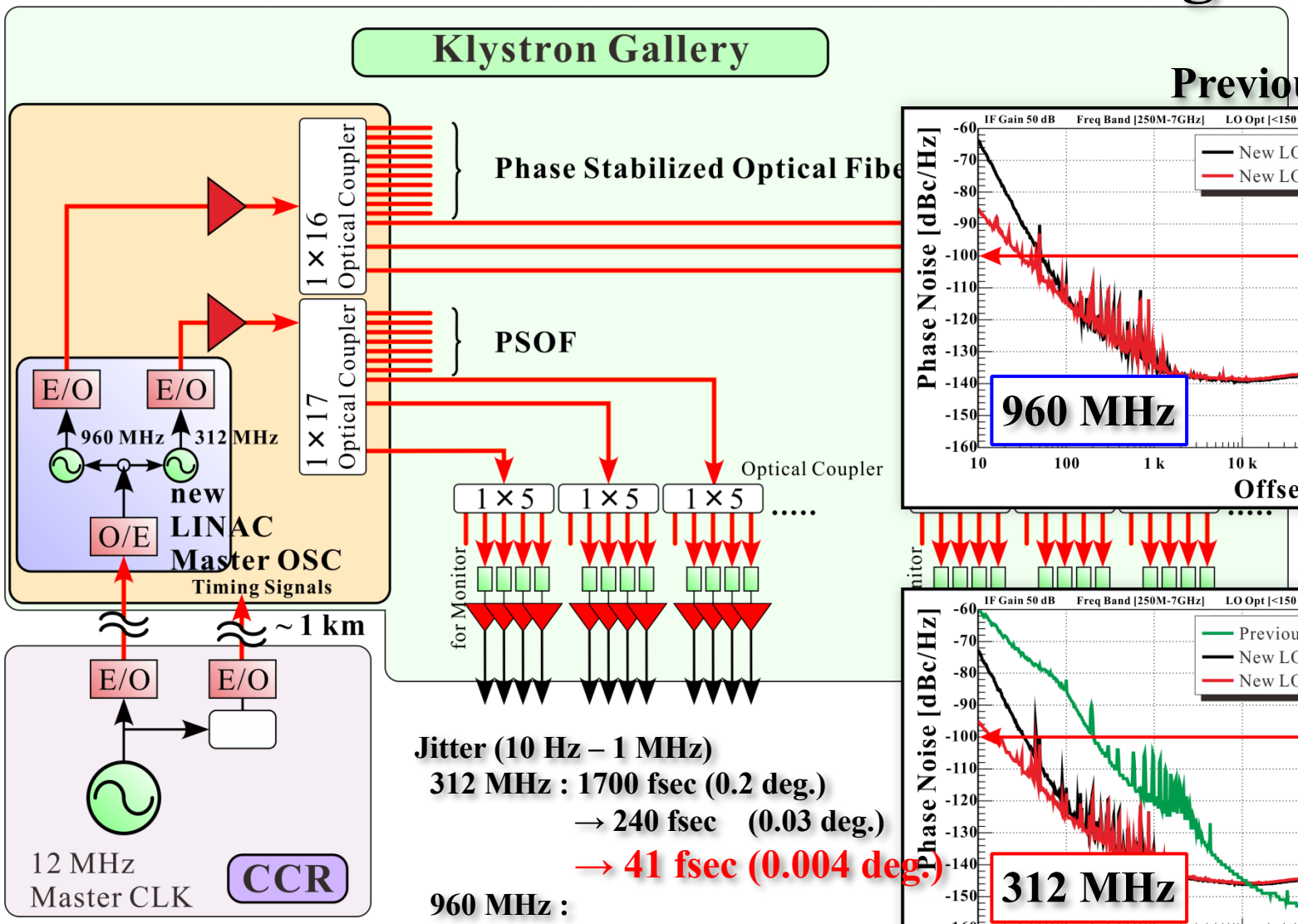
Installation of the optical cables and optical couplers in the insulated duct.



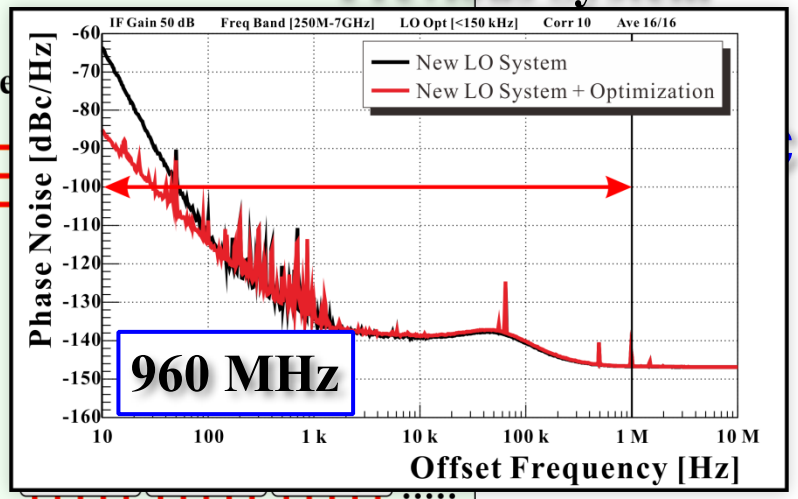
Optical coupler in the temperature control oven

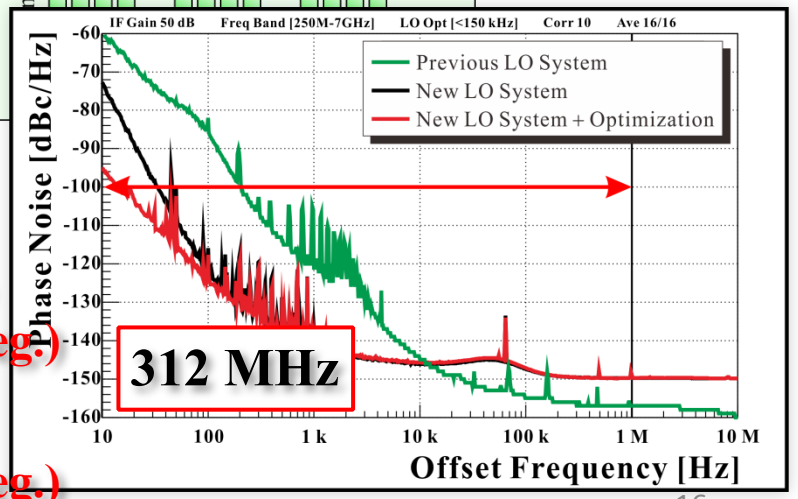


Performance of RF Reference Signals



Previous System





Jitter (10 Hz – 1 MHz)

312 MHz : 1700 fsec (0.2 deg.)

→ 240 fsec (0.03 deg.)

→ 41 fsec (0.004 deg.)

960 MHz :

→ 240 fsec

→ 41 fsec (0.014 deg.)

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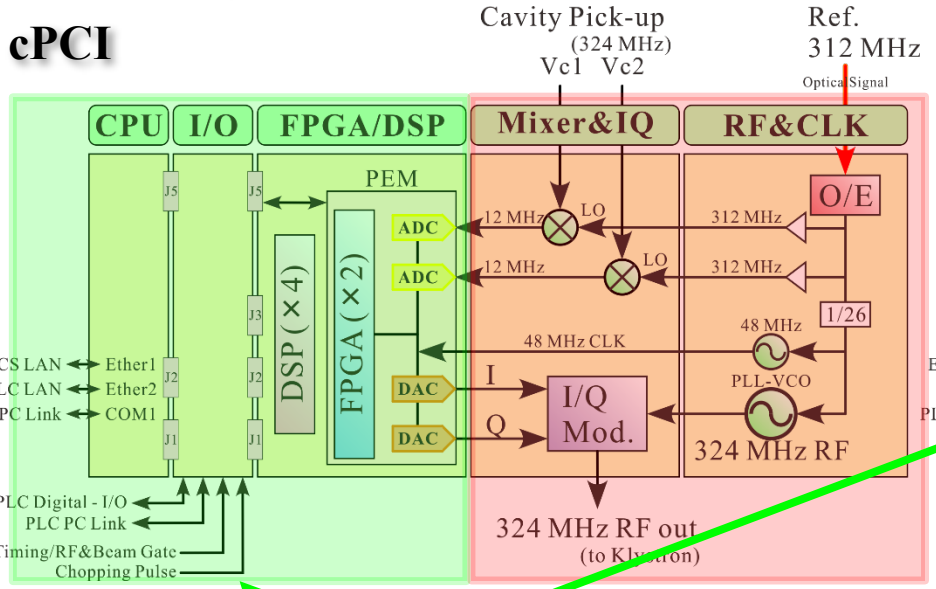
Digital Control

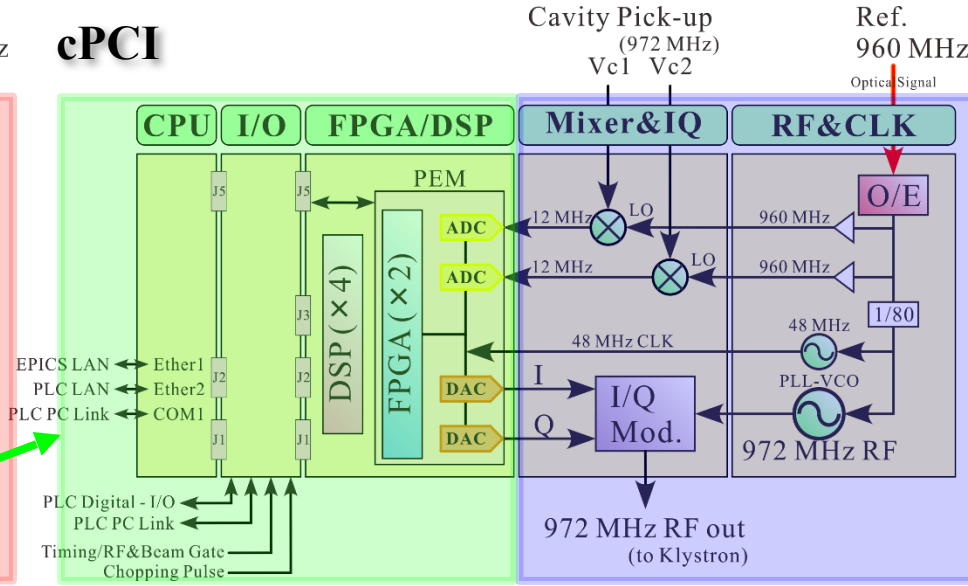
324MHz System

RF : 324MHz, LO : 312MHz
IF : 12MHz, CLK : 48MHz



972MHz System

RF : 972MHz, LO : 960MHz
IF : 12MHz, CLK : 48MHz

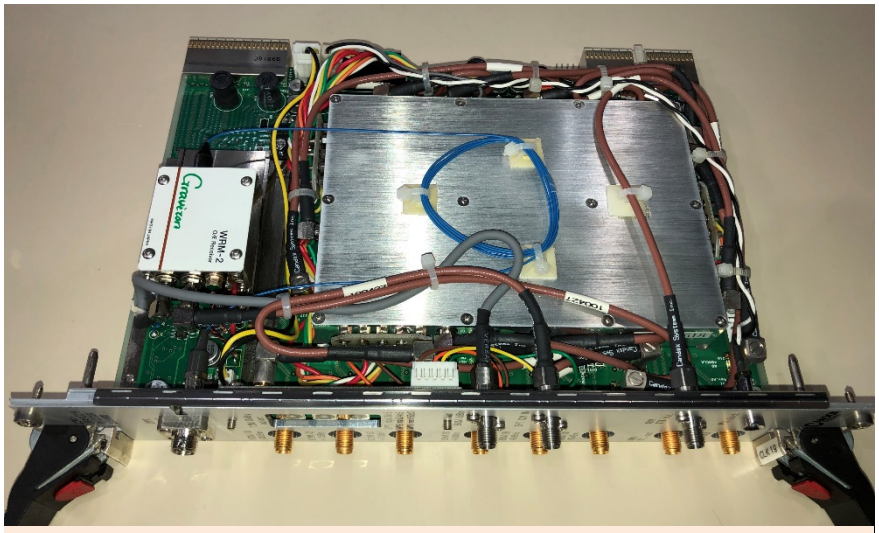


. digital modules of the 324MHz system and the 972MHz system are same.

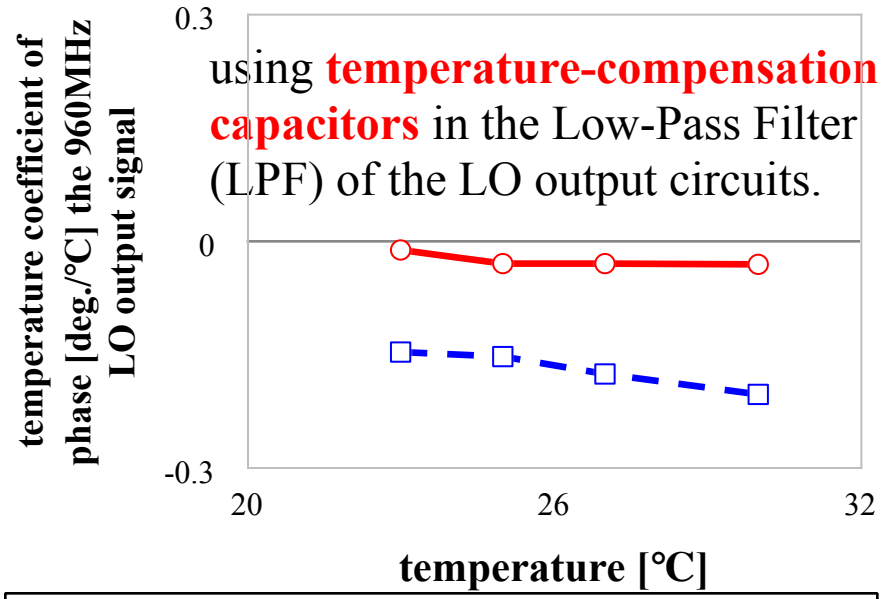
- The 312MHz/960MHz optical signal is received by the RF&CLK module as the phase reference.
- The 324MHz/972MHz RF signal is generated by a PLL-VCO.
- The cavity signals are down-converted to 12-MHz IF signals by mixers and sampled by 48-MHz ADCs.

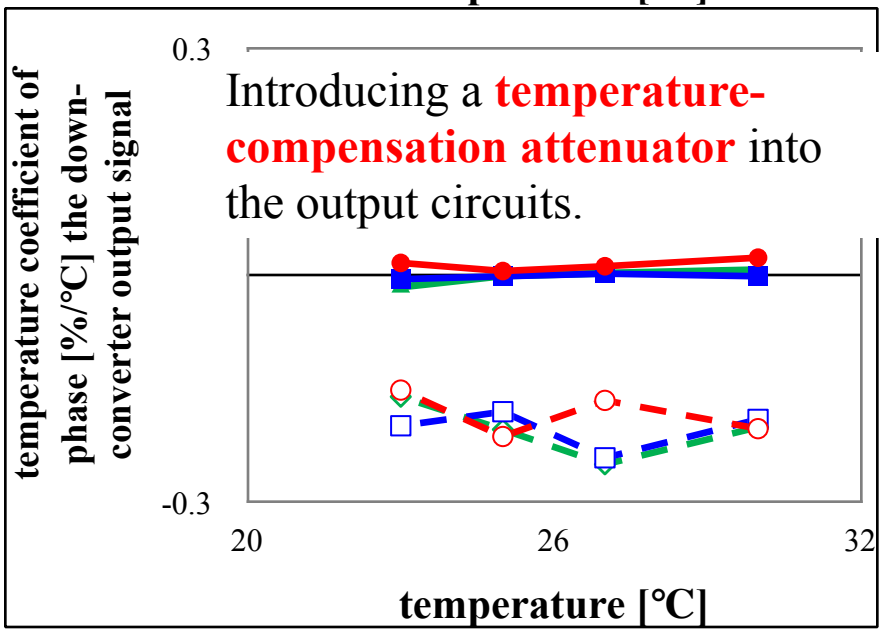
Improvement of Analog Device

RF&CLK board



Mixer&IQ-Mod. board





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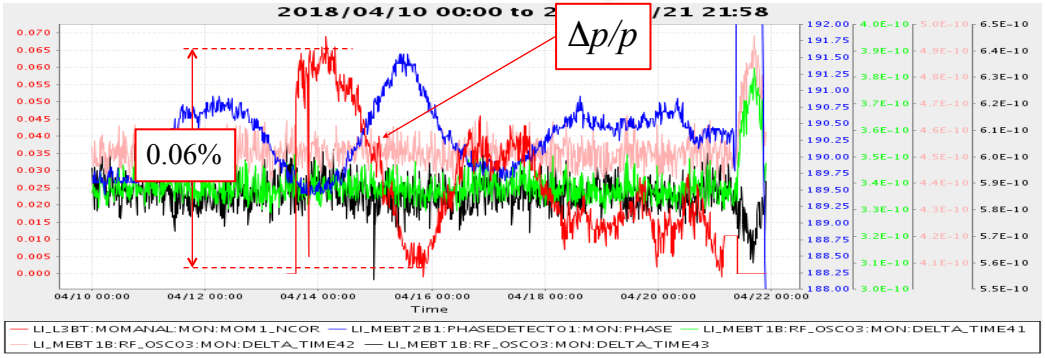
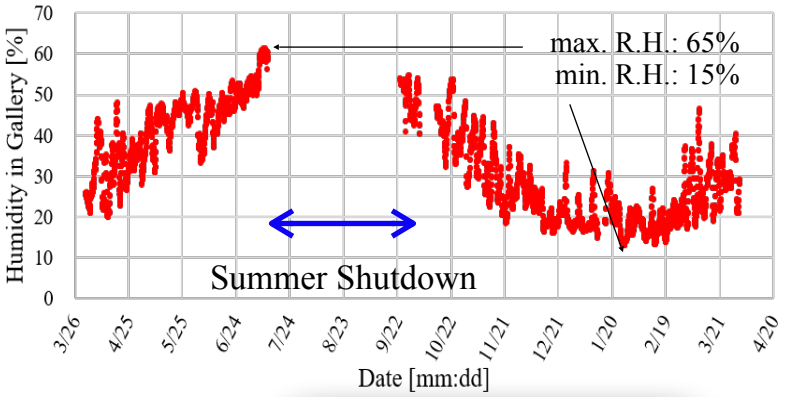
Humidity Effect

- ✓ The inject momentum to RCS drifted with humidity of the klystron gallery.
- ✓ In the J-PARC linac, the air conditioning system is not designed for humidity and varies from 15% to 65% throughout the year.

Inject momentum drift



trend of humidity at gallery



✓ The humidity dependence of some RF modules.

:Preliminary results (30%-65%):

- Master OSC: ~1.5 deg.(312MHz), ~4.0 deg.(960MHz)
- 324MHz RF&CLK board: ~1.0 deg.
- 972MHz RF&CLK board: ~2.0 deg.

⇒ larger source of momentum shift

precision air conditioner
19" rack

✓ We will install the local precision air conditioner in this summer shutdown

at MEBT1 : installing RF reference oscillator
at SDTL16 section : downstream of the 324MHz stations
at MEBT2 B1 section : upstream of 972MHz station

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Motivation

Almost all modules (Linac/Rings) were developed more than ten years ago and have been used *since the beginning*. Very difficulty in the maintenance due to discontinued modules and outdated FPGA. And, need more functionalities for higher intensities and stability.

Present Status:

NIM(analog) + cPCI (digital): Linac RF

- ✓ FPGA board: discontinued
- ✓ DSP board: discontinued
- ✓ CPU board: discontinued, but fungible

Specialized 9U VME: Ring (RCS&MR)

- ✓ FPGA: Xilinx ISE Ver 6.2i

VME: Ring (RCS BPM controller)

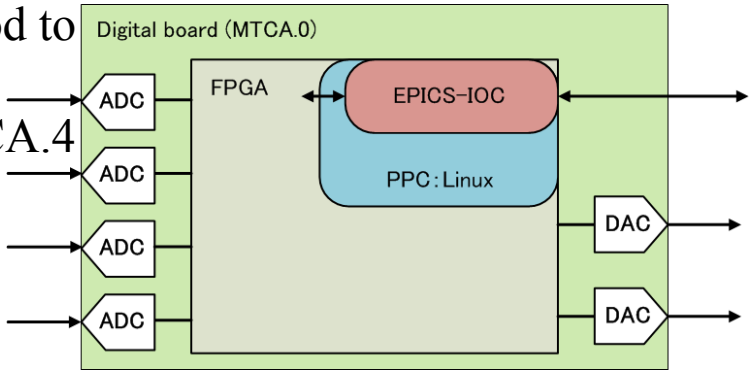
- ✓ DSP: TI Code Composer Studio Ver 2.1

VME + NIM: Timing system

We choose "µTCA.4 as next platform!"

μTCA.4 in KEK

- Module made by **Mitsubishi Electric TOKKI systems Co.,Ltd**
  - EPICS-IOC is running on the LINUX installed on the CPU in the FPGA.
- In 2008, the development of digital board based on MTCA.0 was started for the aim of common use at RF control among SuperKEKB, cERL, and STF in KEK.
  - **Type1**:used for cav-voltage regulation and cav-tuning
  - **Type2**: used for RF direct (under) sampling method to monitor the slow (narrow band) phase change.
- In 2013, the development of the module based on MTCA.4 for the LLRF system of STF
  - **Type3**: SFP on the RTM is used to communica



Newly developed board based on MTCA.4

Type1

- FPGA (Virtex 5 FX),
- 4 x 16-bit ADCs (Max. 130MSPS)
- 4 x 16-bit DACs
- Digital I/O

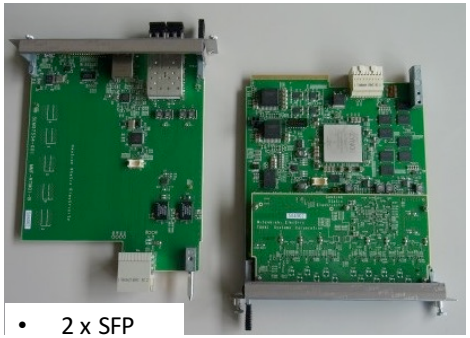
Mitsubishi Electric TOKKI System Co., Ltd.

Type2

- FPGA (Virtex 5 FX),
- 2 x 14-bit ADCs (Max. 400MSPS)
- Digital I/O

Mitsubishi Electric TOKKI System Co., Ltd.

Type3



- 2 x SFP
- 1 x RJ-45
- Digital I/O
- 2 FPGAs (Zynq-7000, Spartan 6)
- 14 x 16-bit ADCs
- 2 x 16-bit DACs

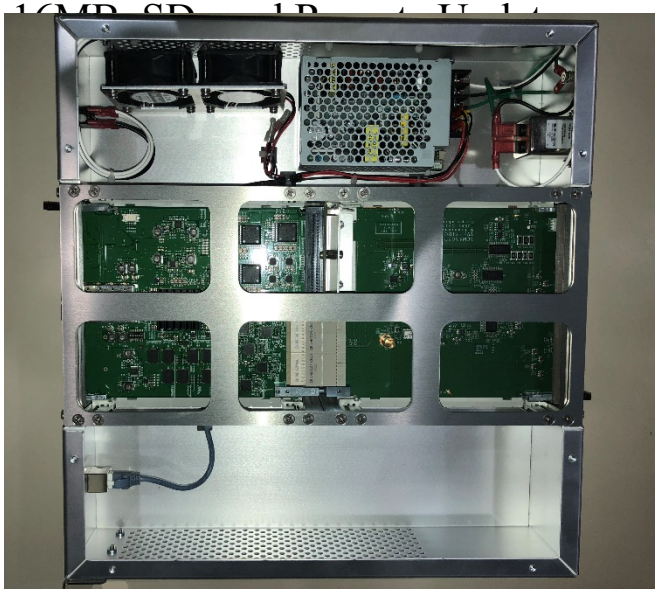
Mitsubishi Electric TOKKI System Co., Ltd.

Linac LLRF upgrade

- A new digitizer, instead of the digital boards of cPCI.
- The AMC board having FPGA, ADC and DAC for DFB and DFF is specialized to use the bus of the μTCA.4 standard.
- On the other hand, the RTM one is temporary. In the 1st stage, the shelf of μTCA.4 with the bus and the RF backplane will not be utilized an ARM on a Zynq FPGA will be used instead of a CPU board.

A/D-D/A signal processing board of AMC producing by Mitsubishi Electric TOKKI Systems Corporataion

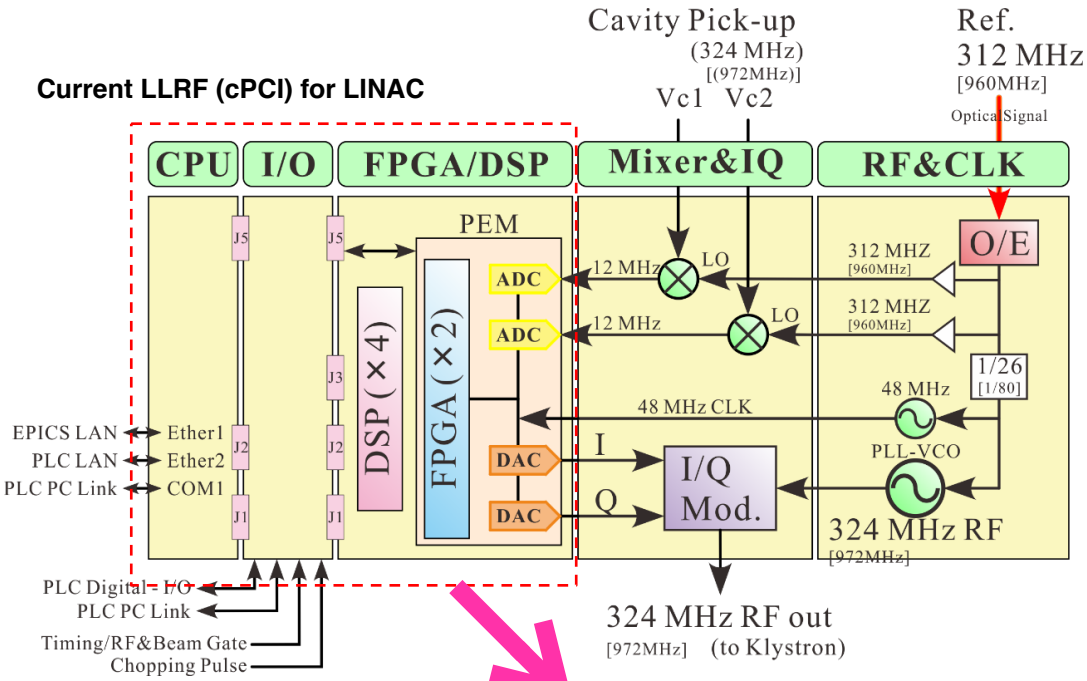
platform: μTCA.4 AMC
FPGA: Zynq XC7Z045-1FFG900C, QSPI FLASH-ROM
RAM: DDR3-SDRAM 1GB×2 (PL, PS)
OS: Xilinx Linux (EPICS-IOC)
ADC: 8ch 16bit 370MSPS(max.), BW: 800MHz
DAC: 2ch 16bit 500MSPS
SFP: 2ports



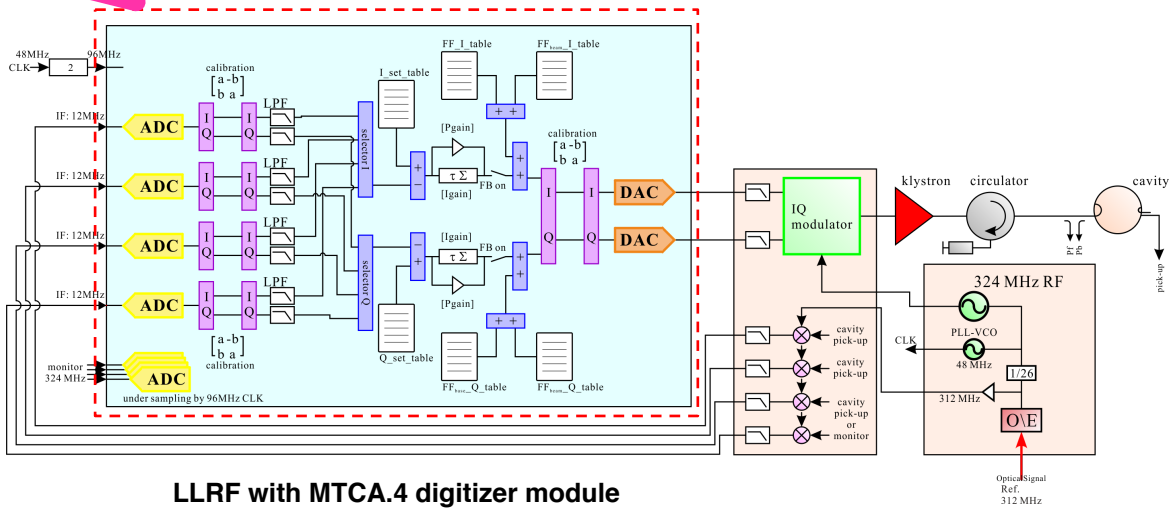
→ The μTCA.4 RTM of the J-PARC linac LLRF is produced.
(Just level converter. As the 1st step, the analogue modules of cPCI are used.)

µTCA.4 board (Linac)

Current LLRF (cPCI) for LINAC



Replace with MTCA module



LLRF with MTCA.4 digitizer module

Schedule for New Digitizer (Linac)

✓ **FY2020:**

- ➢ Installation: 17 (RFQ, SDTL1~16)
- ➢ Production:
  - digitizer box : 3 (for DTL1~3)
  - μRTM, AMC set : 4 (for MEBT1)

    μRTM : new exploitation using a μTCA.4 shelf

    → present system:

    One cPCI shelf was used for one cavity.

    → future system:

    One μTCA.4 shelf will be used for several cavities.

    ex. MEBT1 buncher1, buncher2, chopper1, chopper2

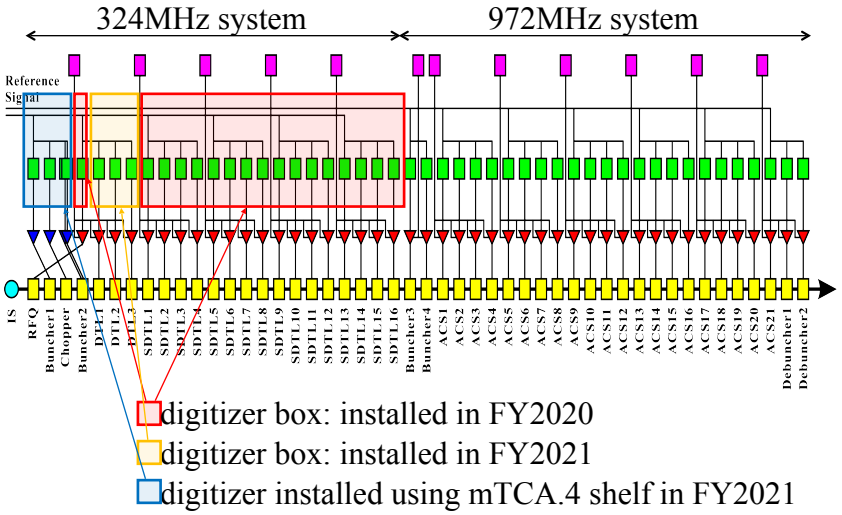
    In addition, a digitizer for beam monitor will be installed in the same shelf.

✓ **FY2021:**

- ➢ Installation:
  - digitizer box : 3 (DTL1~3)
  - μTCA.4 system for MEBT1

    one eRTM, four sets of AMC + μRTM
- ➢ New exploitation ? (depending on budget):
  - for 972MHz ACS cavities

    → shorter loop delay

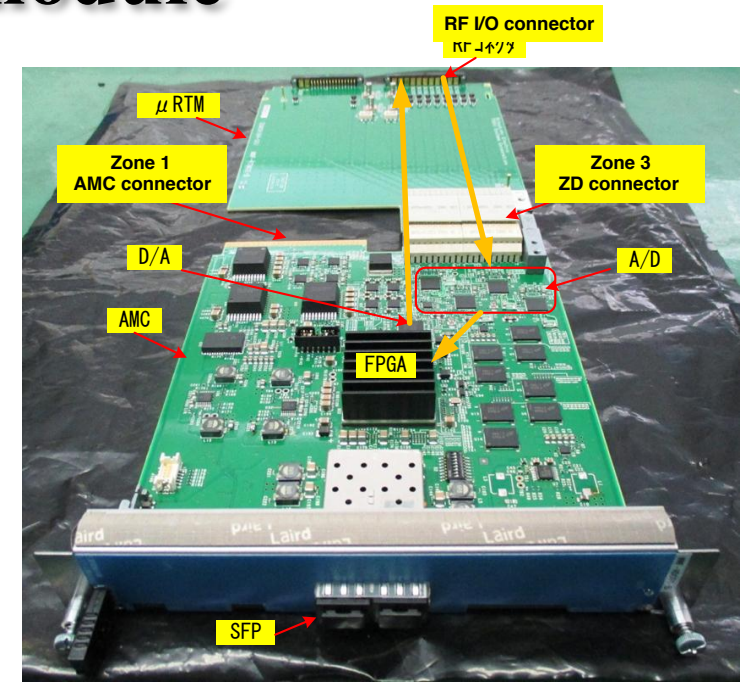


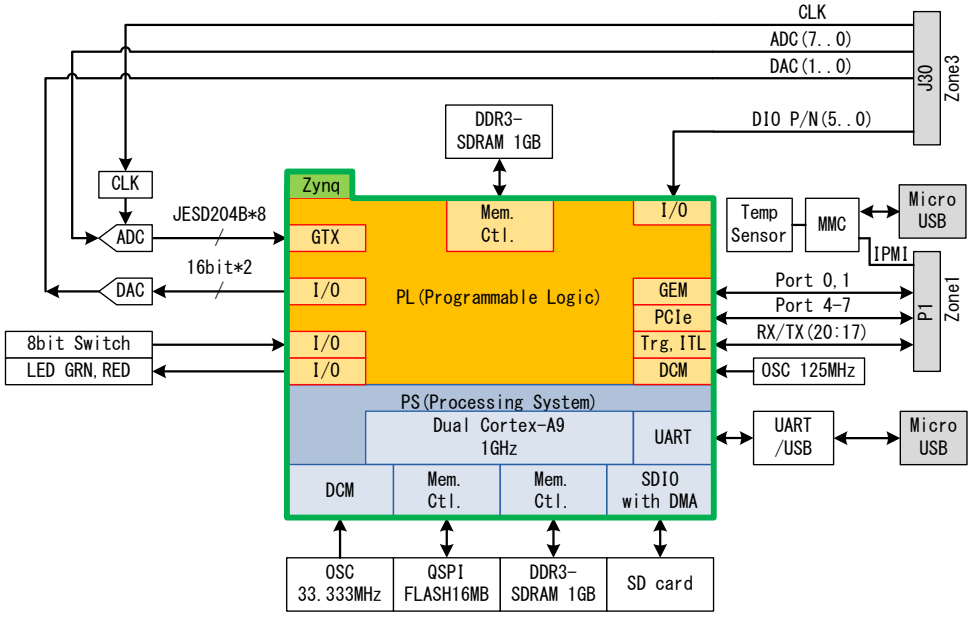
RCS/MR LLRF upgrade

- J-PARC synchrotrons use the wide-band MA loaded cavity systems.
  - Beam loading compensation is necessary to achieve the high intensity operation.
- Required Function for LLRF.
  - **RF common function:**
    - Frequency pattern, Freq. &Phase FB
      - Vector Sum of Cavity Voltage
  - **Cavity Voltage Driver**
    - I/Q pattern generation and FB for Cavity
    - multi-harmonic Feedforward for the beam loading compensation
    - multi-harmonic vector rf voltage control is implemented (New)
- Development status with μTCA.4
  - new LLRF system for RCS
  - longitudinal oscillation FB for MR

A/D-D/A AMC module

- based on the **Mitsubishi Electric TOKKI System Co.,Ltd**.
  - 8 ADC and 2 DAC
  - Analog signal through Zone3 (ClassA1.1) Connector
- PCI-Ex and GbE through Zone1 AMC Connector
- EPICS-IOC running on embedded Linux on Zync FPGA
  - Enables the remote control and the easy integration into the current control system.





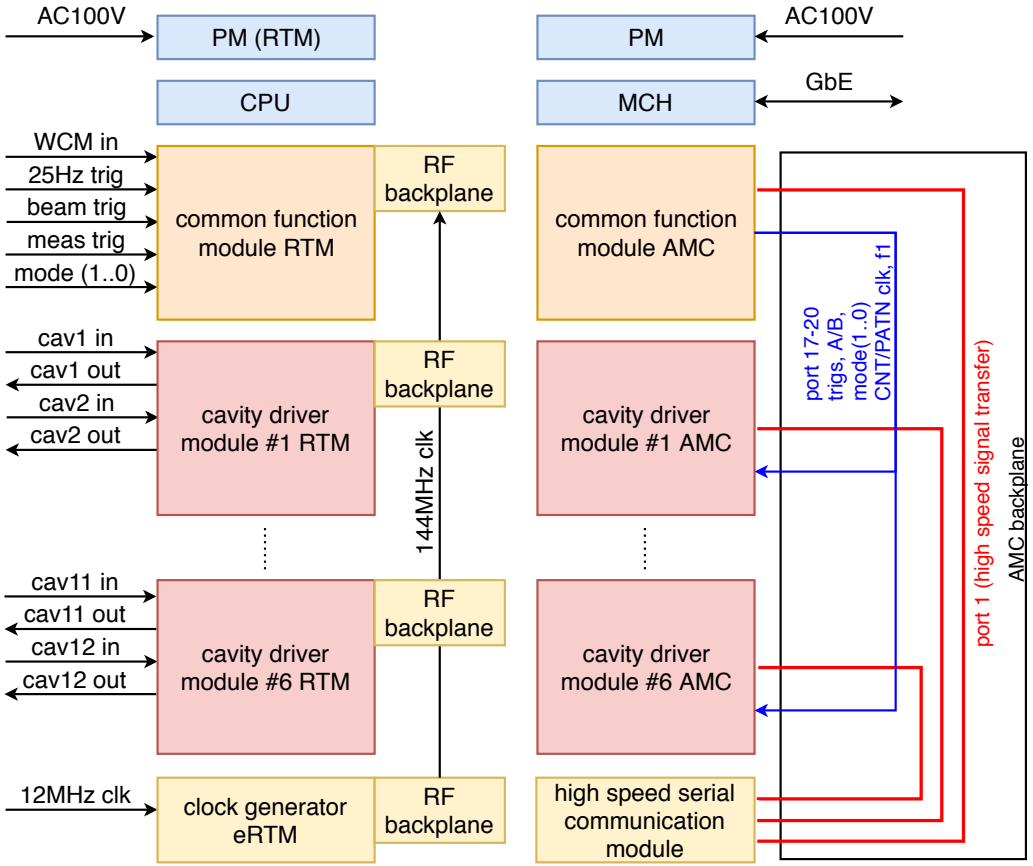
FPGA	Zynq XC7Z045-1FFG900C
OS	Xilinx Linux (EPICS-IOC)
RAM	DDR3-SDRAM 1GiB×2 (PL, PS)
FPGA Config	QSPI FLASH-ROM 16MiB, SD Card, Rer
ADC	8ch, 16bit, 370MSPS max., BW 800MHz
DAC	2ch, 16bit, 500MSPS max.

new LLRF for RCS

- Single MTCA.4 shelf can supports modules for the all the 12 cavities for RCS.
- Separate modules with functions
  - Common Function and cavity driver.
- Vector Sum is done by special module (High Speed Serial Com. module) in MCH2 slot

- Shelf and Modules are fabricated in FY2018 and under debug for the installation during this summer.

F. Tamura et.al., Phys. Rev. Accel. Beams 22, 092001 (2019)



Schedule for New LLRF for Rings

- ✓ **FY2019:**
  - ➢ Installation: 12 LLRF modules for RCS RF systems
- ✓ **FY2020:**
  - ➢ Developement:
    - LLRF modules for MR RF system
      → shorter loop delay
    - μTCA.4 system, same as RCS LLRF system
  - ➢ Manufactoring:
    - for MR RF systems (9+2 systems)
      → shorter loop delay
- ✓ **FY2021:**
  - ➢ Complete Manufactoring and Installation:
    for 9 fundamental RF systems
    and 2 second harmonic RF systems

Contents

1. Introduction
2. RF Reference Distribution System
3. Digital Feedback System
4. Humidity Effect
5. Developing System
6. Summary

Summary

- ✓ We introduced the performance and our experience of the LLRF systems in J-PARC linac/Ring.

Linac

- ✓ To reduce an RF jitter, Linac master oscillator was modified.
- ✓ To stabilize RF signals, the temparature-compensation devices are used in the analog module.
- ✓ Humidity control becomes more important to stabilize proton momentum for RCS.

New developement

- ✓ μ**TCA** based modules are considered as the new LLRF systems for the replacement in Linac and Rings(RCS and MR).
- ✓ LLRF system for RCS with RTM RF backplane has been tested and their installation are on going.