KEK-JAPAN

第19回 オンライン開催
日本加速器学会年会
The 19th Annual Meeting Particle Accelerator Society of Japan

J-PARCリニアックでの位相ドリフトモニターのインストールと評価

Installation and Test of the Phase Drift Monitor at J-PARC Linac

WEOB09
October 19th
16:30-16:50

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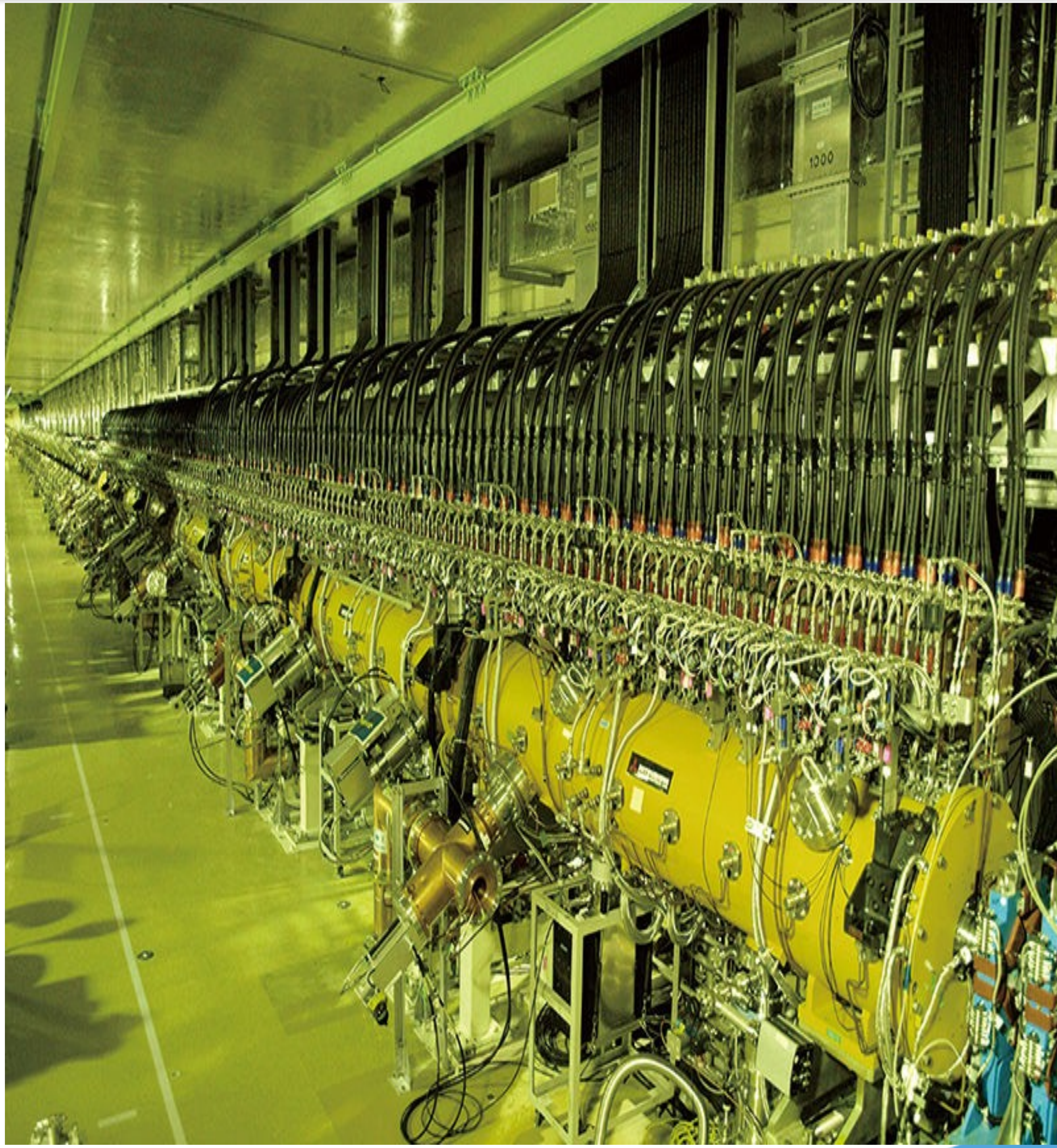
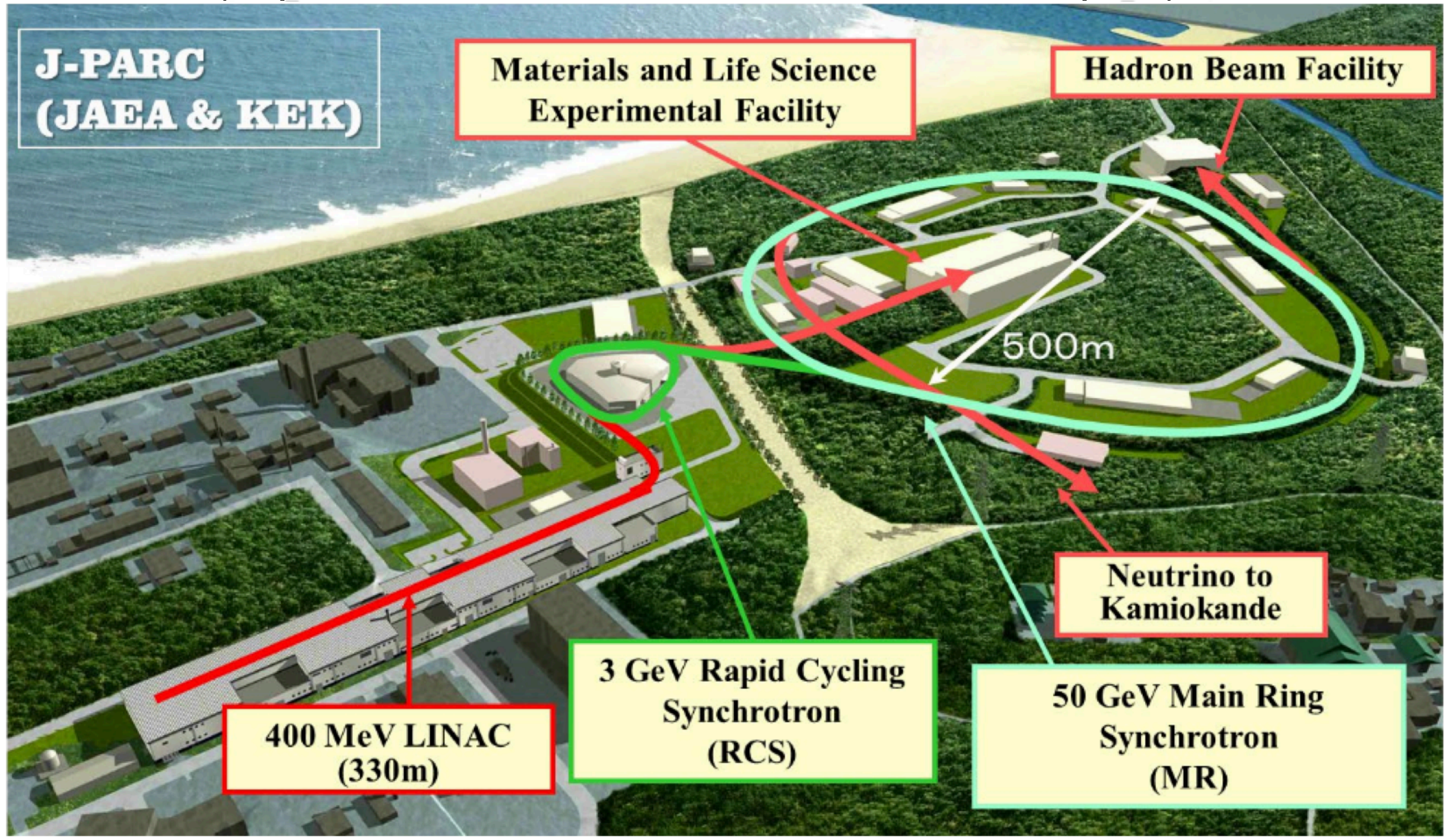
Outline

- Introduction; J-PARC linac
- The phase drift monitor-PDM
  - Introduction: motivation
  - Hardware & software
  - Device installation
  - Long-term RF phase measurements results
- Conclusions



Introduction: J-PARC linac

J-PARC (Japan Proton Accelerator Research Complex)

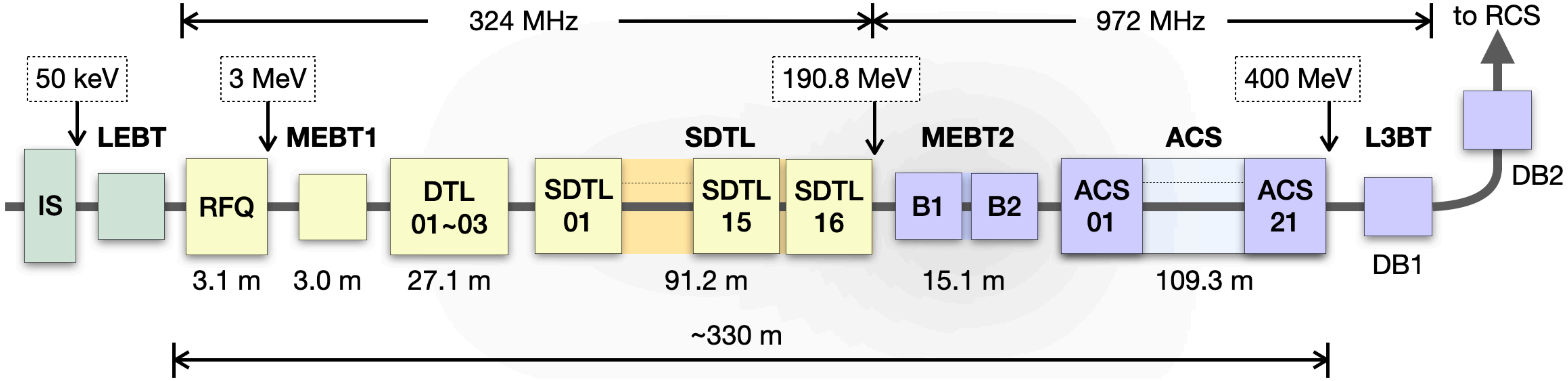


Main parameters of the J-PARC linac	
Particles	→ H^- (negative hydrogen)
Peak current	→ 50 mA
Pulse width	→ 500 μs (Beam), 650 μs (RF)
Kinetic energy	→ 400 MeV
Repetition	→ 25Hz
Acceleration frequency	→ 324 MHz, 972 MHz

- Total of 49 RF stations; **24 (324 MHz) + 25 (972 MHz)**
  - SDTL consists of two cavity tanks: “SDTL**A” and “SDTL**B”:
  - MEBT2B1, MEBT2B2 stations at MEBT2
  - ACS01 → ACS21
  - **LLRF system** with digital feedback (DFB) and feedforward (DFF) at each station.

[3] Z. Fang et al., ”Auto-tuning systems for J-PARC LINAC RF cavities”, Nucl. Instrum. Methods Phys. Res. A., vol. 767, p.135, 2014. doi.org/10.1016/j.nima.2014.08.014

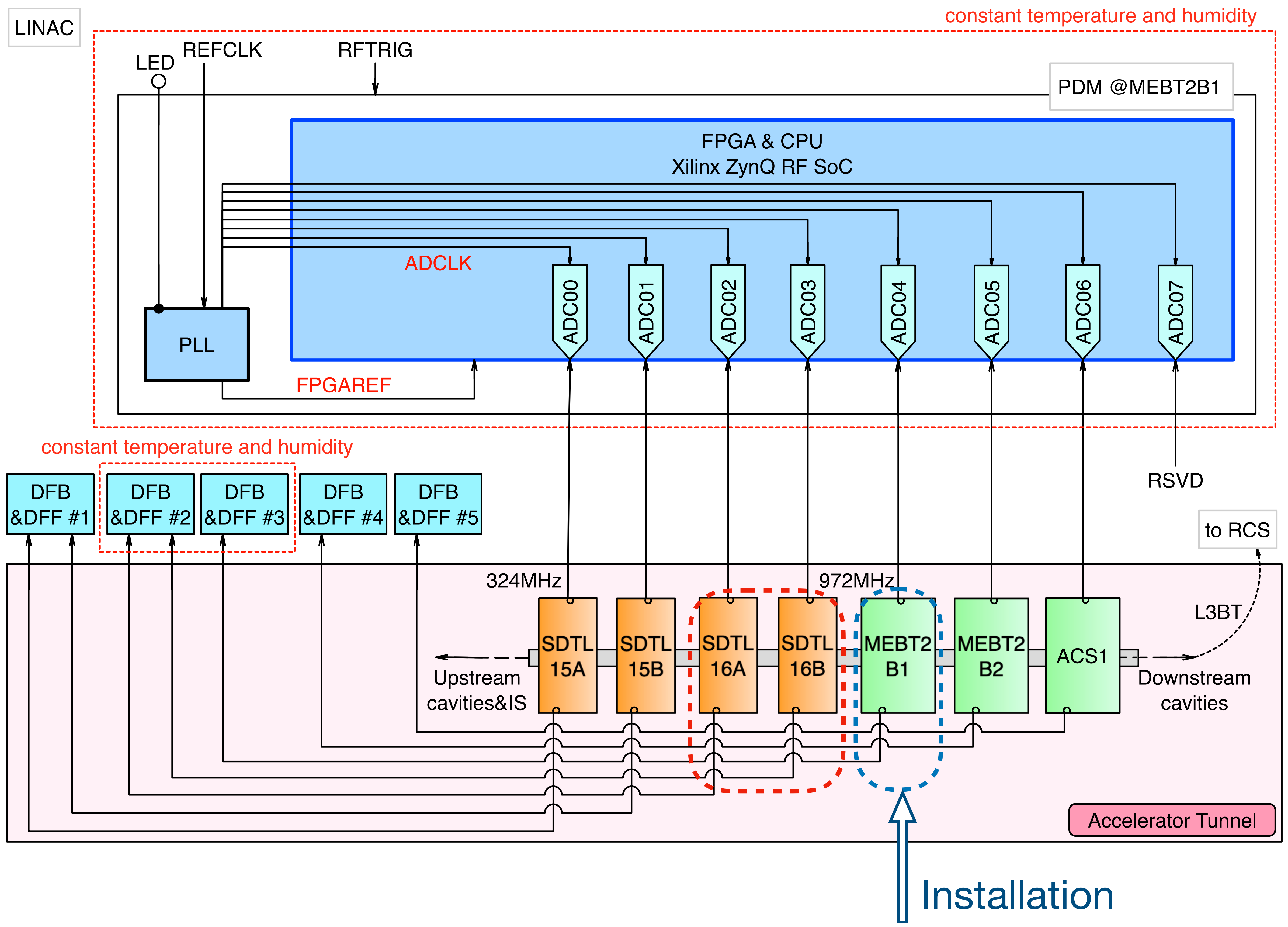
IS	Ion source
RFQ	Radio Frequency Quadrupole Linac
DTL	Drift Tube Linac
SDTL	Separate-type Drift Tube Linac
ACS	Annual Coupled Structure Linac



[1] I. Masanori, “Beam commissioning and operation of the J-PARC linac”, Prog. Theor. Exp. Phys., vol. 2012, p. 02B002, 2012. doi.org/10.1093/ptep/pts019
[2] H. Ao et al., “First annular-ring coupled structure cavity for the Japan Proton Accelerator Research Complex linac”, Phys. Rev. ST Accel. Beams, vol. 15, p. 051005, 2012. doi.org/10.1103/PhysRevSTAB.15.051005

Phase drift monitor

- The drift in the momentum of the injection beam **must be within ±0.05%;**
  - It is essential to stabilize RF field in linac cavities
  - ***Humidity & temperature*** can cause drift in beam injection momentum



- Drift compensation systems;
  - I) Using **cavity phase monitors (CPMs)** located at each RF station (extant).
    - *Two frequencies are individually measured at CPMs.
  - II) A **phase drift monitor (PDM)** installed at MEBT2B1;
    - ❁Xilinx Zynq UltraScale+ RFSoC ZCU111 evaluation platform,
    - ✶Measure phase relationship between **two frequencies simultaneously**✶
    - [a]**Local oscillator is not used.**

Parameters	Extant	Updated
Device	Cavity phase monitor	Phase drift monitor
Technique	Downconverter + IF sampling	Direct sampling
LO	Used	Not used[a]
Frequency	324 MHz* or 972 MHz*	324 MHz✶ and 972 MHz✶
Key point	Conventional	RFSoC❁

Drift compensation scheme:

- SDTL16 and MEBT2B1 RF stations placed in a **constant temperature&humidity environment** are the references,
- Computing the **RF phase differences** with respect to the **reference phases (SDTL16 and MEBT2B1),**
- Compensation for possible drift in RF signals **within the DFB system.**

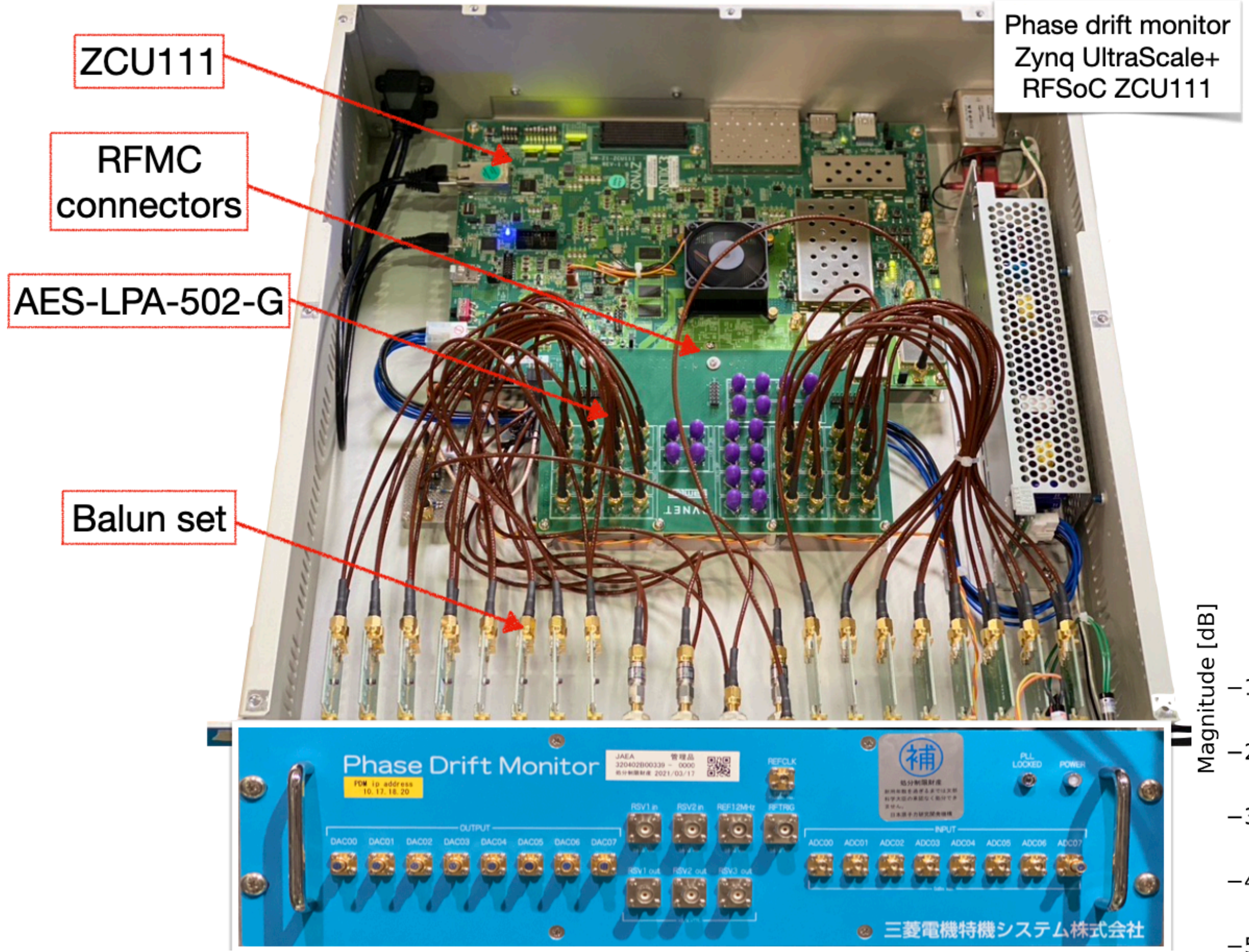
[1] K. Moriya et al., "Energy measurement and correction for stable operation in J-PARC", J. Phys.: Conf. Ser., 2019, 1350, 012140
[2] K. Futatsukawa et al., "Performance of Cavity Phase Monitor at J-PARC Linac", IPAC2013, WEPFI017, Shanghai, China

Hardware & Software

- The PDM architecture, by **M**itsubishi **El**ectric T**O**KKI **S**ystem Co., Ltd (**MELOS**):
  - Xilinx UltraScale+ **RFSoC ZCU111** evaluation board;
    - ❖ **XCZU28DR-2FFVG1517 FPGA**,
    - ❖ **Embedded with EPICS IOC runs on the board** itself.
  - An analog front end; RF differential breakout card (AES-LPA-502-G) and baluns.

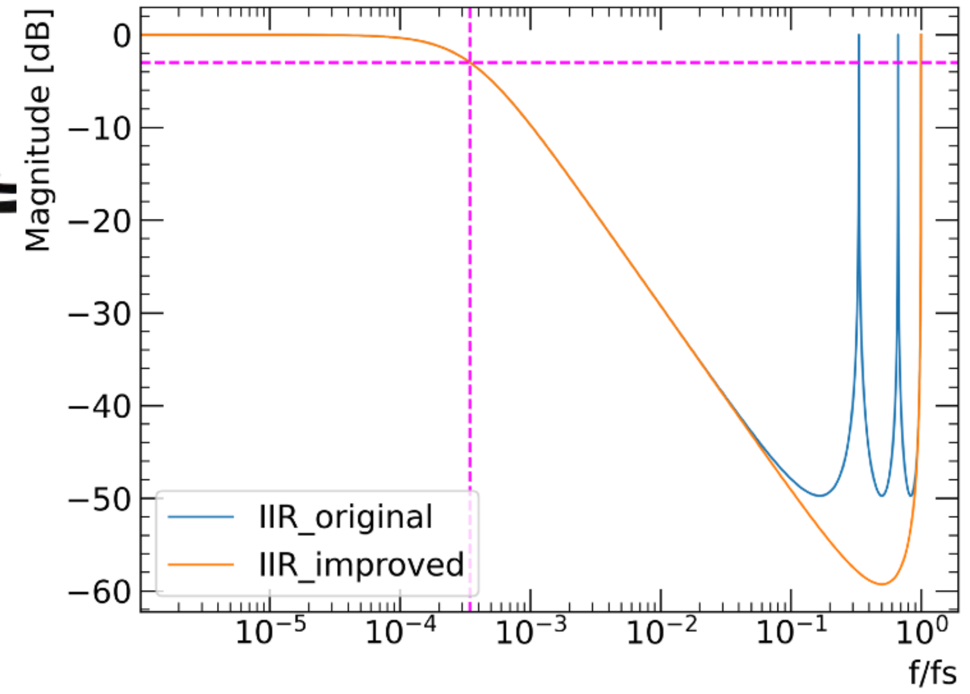
  [3] ES-LPA-502-G, RF Breakout Card for Zynq UltraScale+ RFSoC
  [4] ADC wideband balun board (ADC-WB-BB)

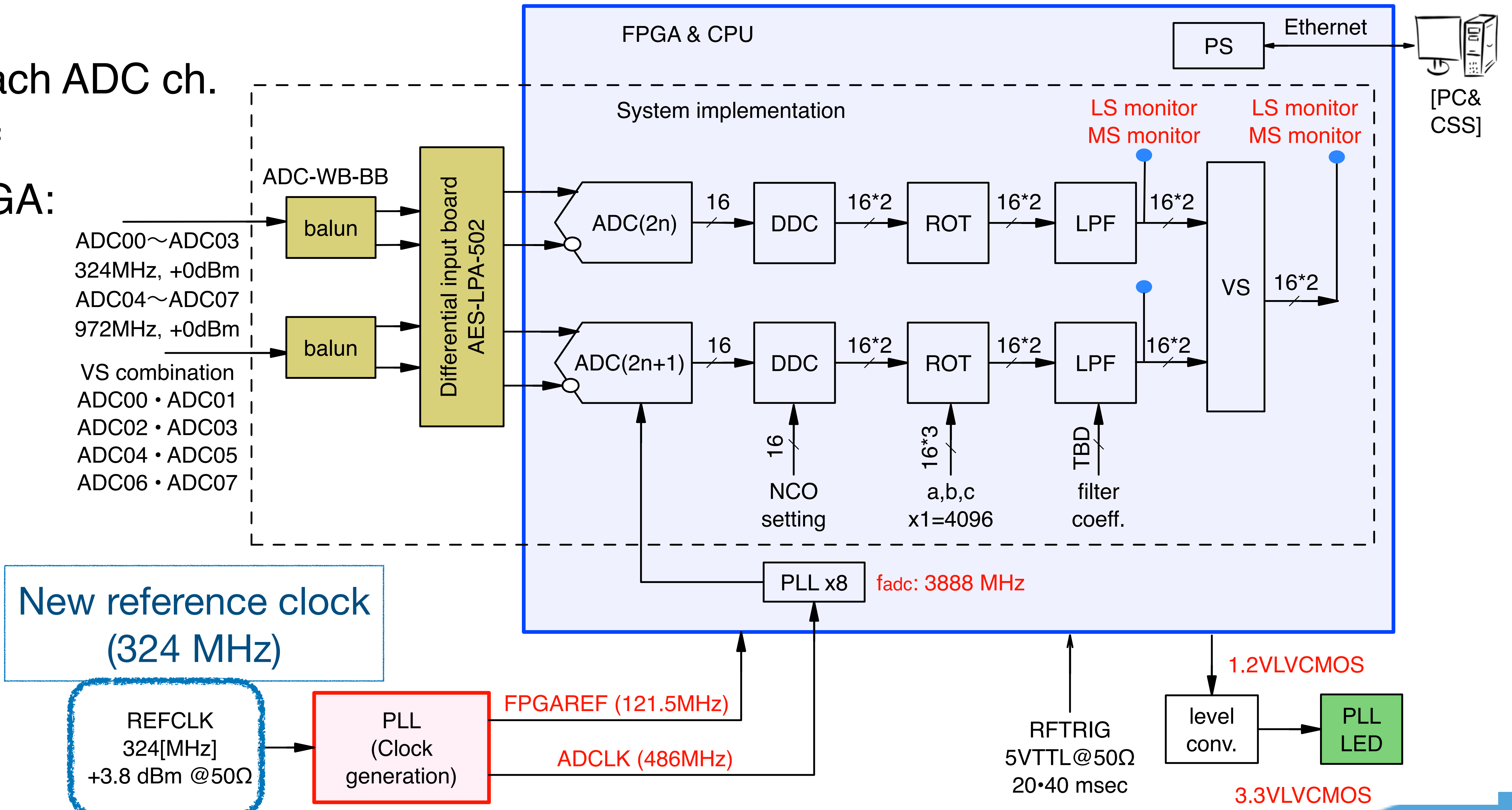
Featuring the Zynq UltraScale+ **XCZU28DR-2FFVG1517E** RFSoC	
RF Data Converter	
# of 12-bit ADCs	8
Max Rate (GSPS) (>1 GHz BW)	4,096
# of 14-bit DACs	8
Max Rate (GSPS)	6,554
Communications & Networking	
USB 3.0, SFP+, RJ45, USB UART/JTAG	1/4/1/1
Expansion Connectors	
RFMC 1.0 → (RFMC (ADC) and RFMC (DAC)	2
Add-on Cards	
XM500 RFMC Balun Add-on Card (AES-LPA-502-G)	1



- FPGA firmware;
  - Data acquisition, DSP function
  - On-board PLL clock generation
  - I/Q calibration (ROT)
  - GUI using CSS software
- The development studies;
  - An individual filter coeff. for each ADC ch.
  - Design and implementation of a cavity-based IIR filter in FPGA: (simplest LPF, α→filter coef)

$y(n)=(\alpha)*[x(n)-y(n-1)]+y(n-1)$





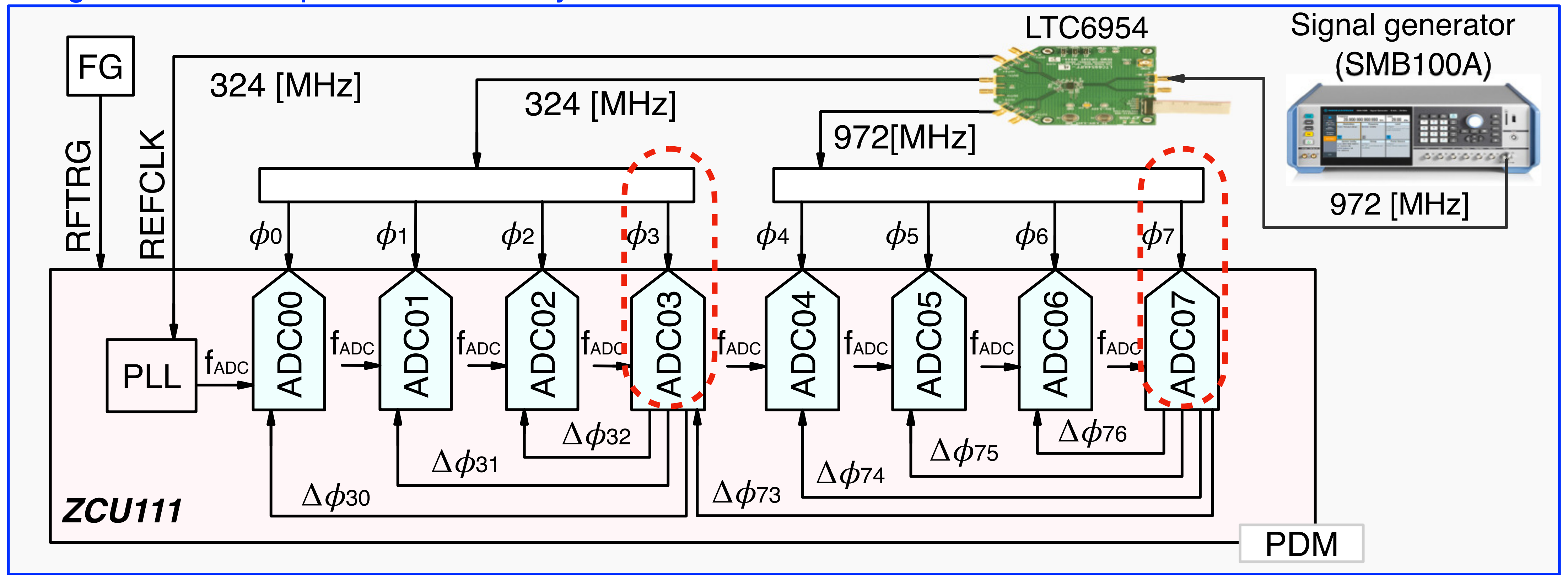
[1] Zynq UltraScale+ RFSoC ZCU111 Evaluation Kit", https://www.xilinx.com/products/boards-and-kits/zcu111.html/
[2] Mitsubishi Electric TOKKI Systems Corporation, http://www.melos.co.jp/english/products/

Performance analysis completion

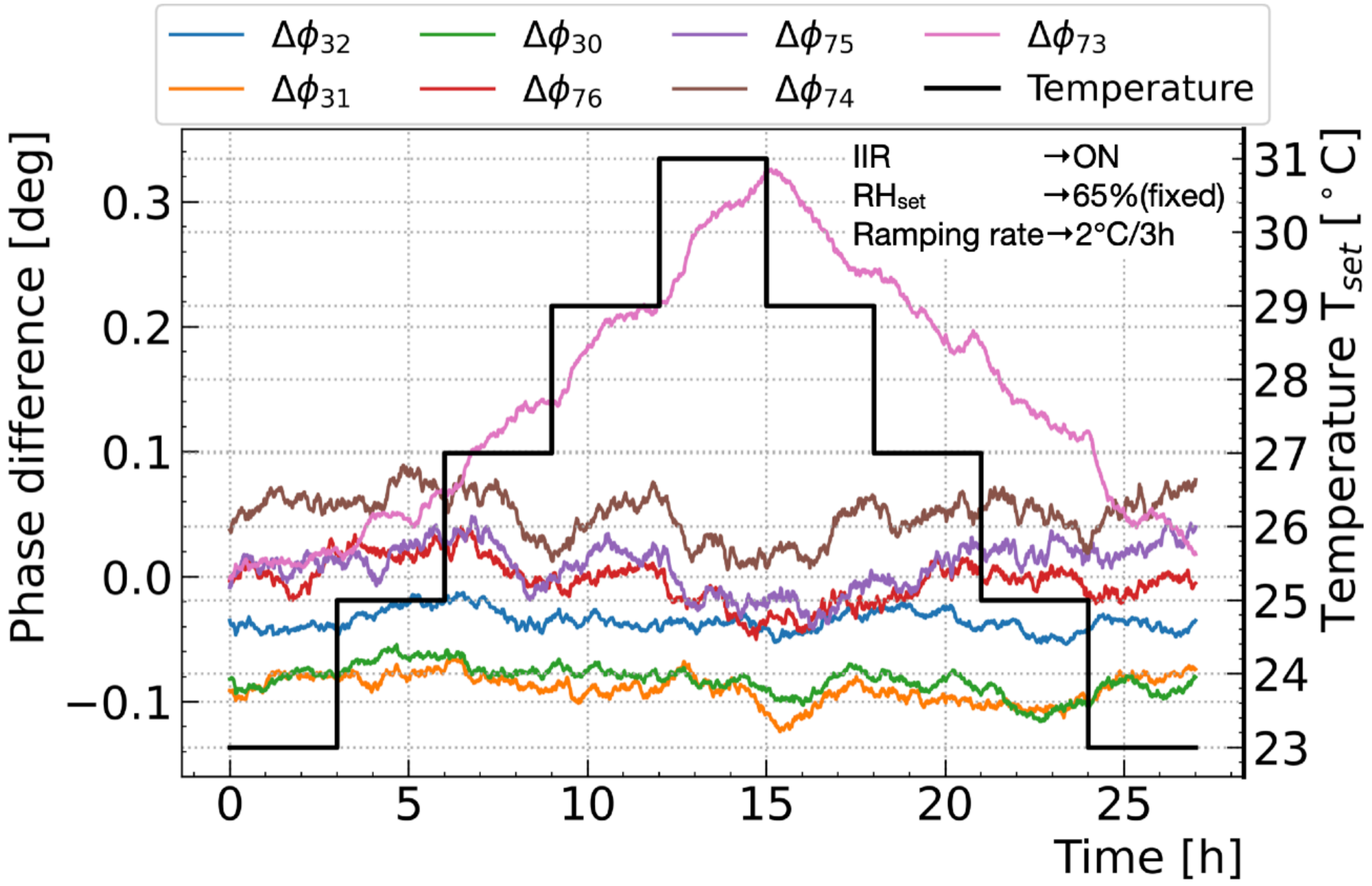
- The first results, amplitude and phase stabilities, crosstalk ADC, etc., were reported.
- To evaluate the drift in phase differences;
  - A commercial environmental **test chamber** (ESPEC PDR-3J),
  - **LTC6954** evaluation board, SMB100A **signal generator**,
  - **Reference phases** ϕ_3 (324 MHz), ϕ_7 (972 MHz).

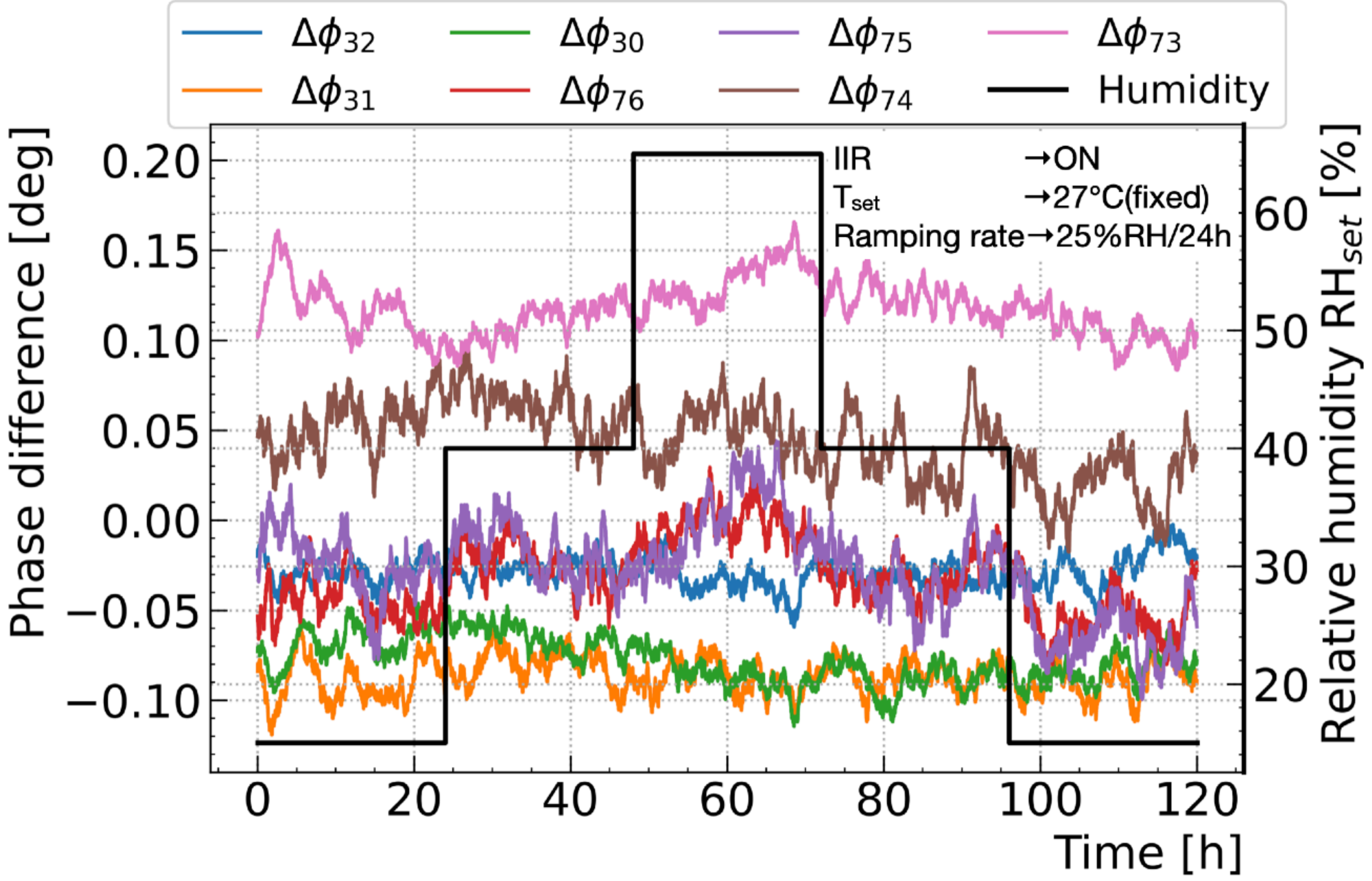
[2] Espec temperature&humidity chamber

Programmable temperature&humidity test chamber



- Providing a stable temperature&humidity inside the MEBT2B1 LLRF control rack:
- ☑ PDM is ideal to be implemented in the LLRF system in terms of temperature&humidity characteristics.



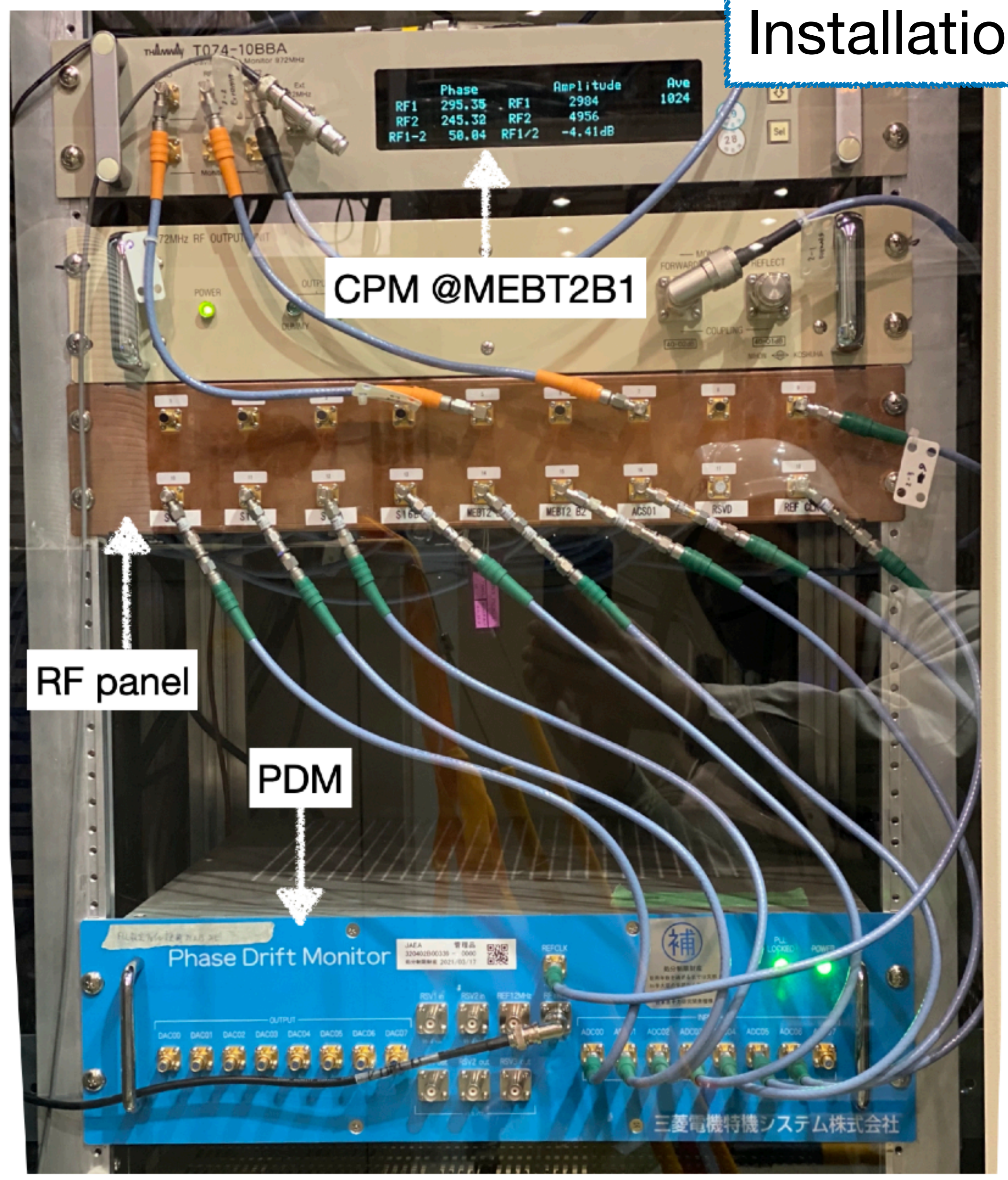


Ramping rate	*Step*	*Phase drift [deg]*			*Remarks*
		$\Delta\varphi_{324}$	$\Delta\varphi_{972}$	$\Delta\varphi_{ref}$	$\Delta\varphi_{324}$ and $\Delta\varphi_{972}$ average drifts in phase differences (pp) of 324 MHz and 972 MHz channels, respectively. $\Delta\varphi_{ref}$:phase drift in relative phase difference
2°C/3 h (fixed 65%RH)	*1°C*	1.23E-03	6.68E-03	*3.75E-02*	
25%RH/24 h (fixed 27°C)	*1%RH*	1.20E-04	*6.63E-04*	4.20E-04	
					Relative phase difference→$\Delta\phi_{73}$=$\Delta\phi_3$-($\Delta\phi_7$/3)

[1] E. Cicek et al., A Recent Upgrade on Phase Drift Compensation System for a Stable Beam Injection at J-PARC Linac, IPAC2021, Campinas, SP, Brazil

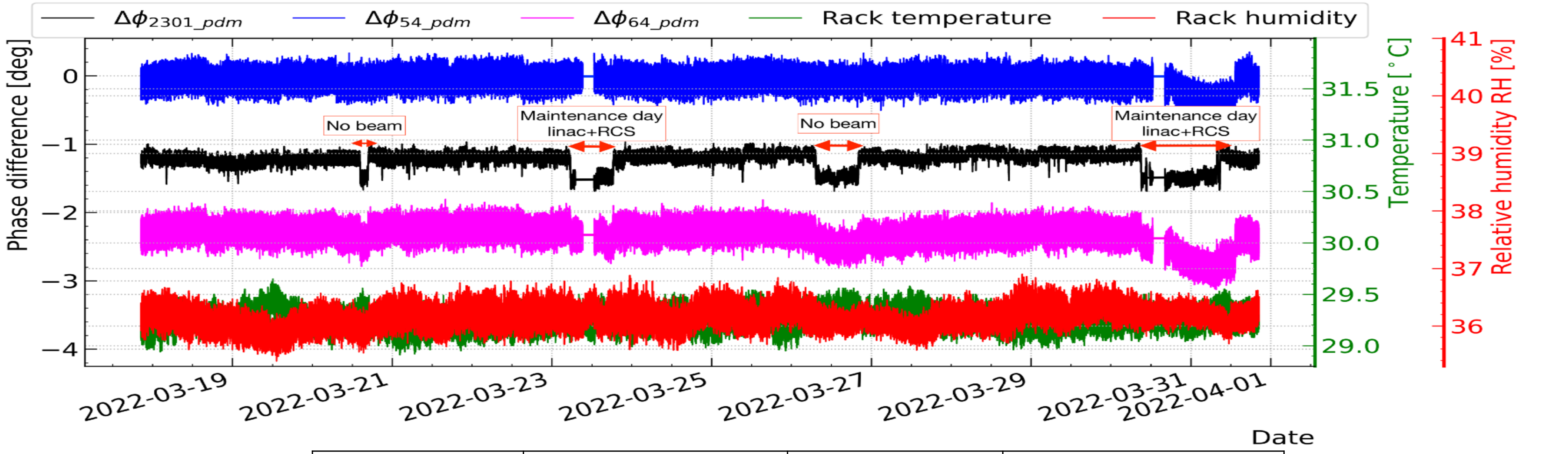
Installation & Long-term RF phase measurement

Installation

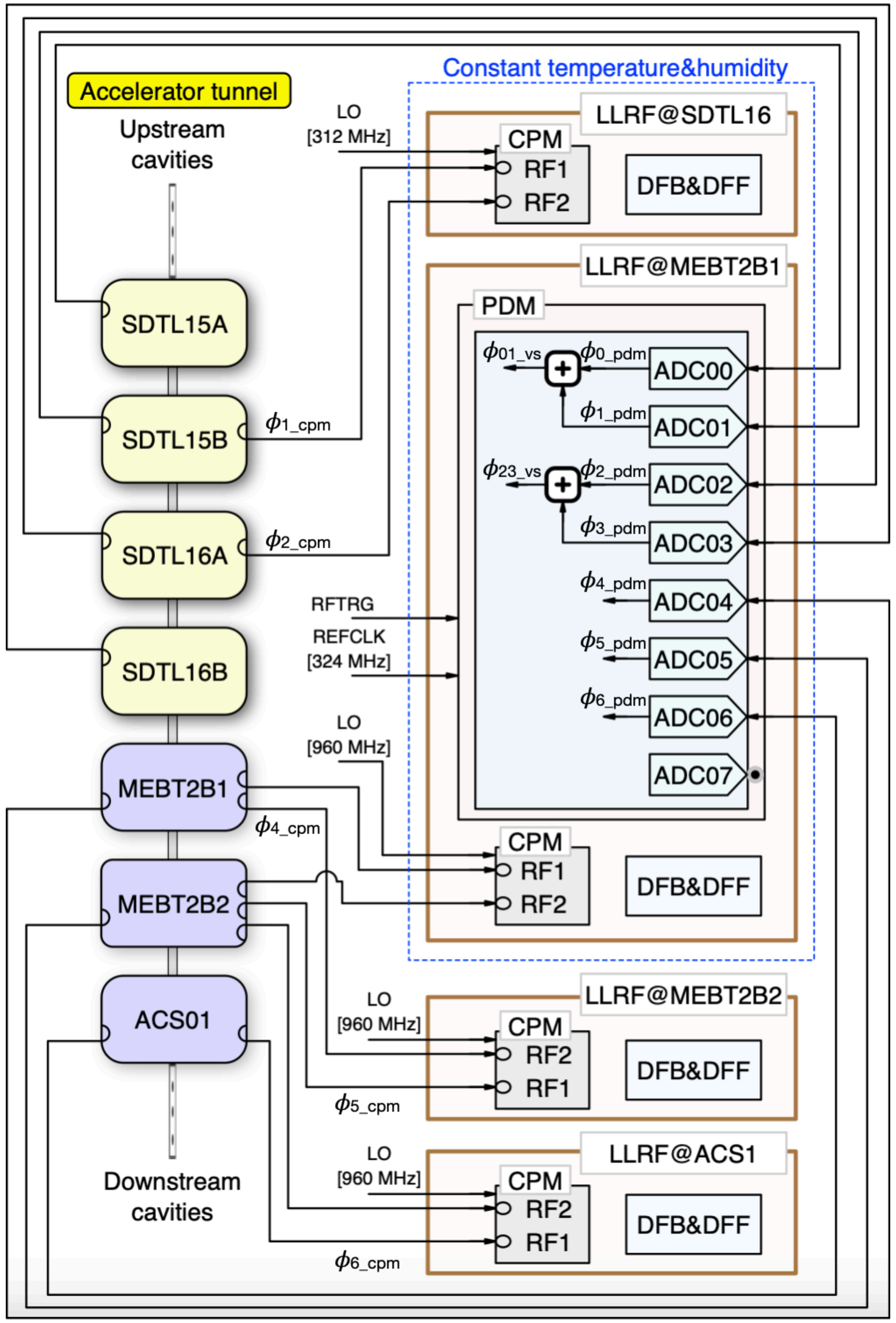


- Installation at the MEBT2B1 LLRF control rack;
  - ☑ ***Constant temperature&humidity*** environment (for SDTL16 and MEBT2B1 RF stations)
  - ☑ 3/8" foam dielectric, phase-stabilized **Andrew Heliax** coax cables,
  - ☑ **Front panel mount SMA cables.**

	f@324 MHz				*f@972 MHz*			
Cavity	*SDTL 15A*	*SDTL 15B*	*SDTL 16A*	*SDTL 16B*	*MEBT2 B1*	*MEBT2 B2*	*ACS1*	*Remarks*
ϕ@PDM	ϕ_{0_pdm}	ϕ_{1_pdm}	ϕ_{2_pdm}	ϕ_{3_pdm}	ϕ_{4_pdm}	ϕ_{5_pdm}	ϕ_{6_pdm}	ϕ_{4_pdm} and ϕ_{23_vs} are the reference phases, and VS: vector sum
VS phase		ϕ_{01_vs} (SDTL15VS)		ϕ_{23_vs} (SDTL16VS)				



	f@972 MHz	*f@972 MHz*	*f@324 MHz*
Cavity phase diff.	*MEBT2B2-MEBT2B1*	*ACS1-MEBT2B1*	*SDTL16VS-SDTL15VS*
Δϕ @PDM	$\Delta\phi_{54\_pdm}$	$\Delta\phi_{64\_pdm}$	$\Delta\phi_{2301\_pdm}$



☆The extant drift compensation system works well…

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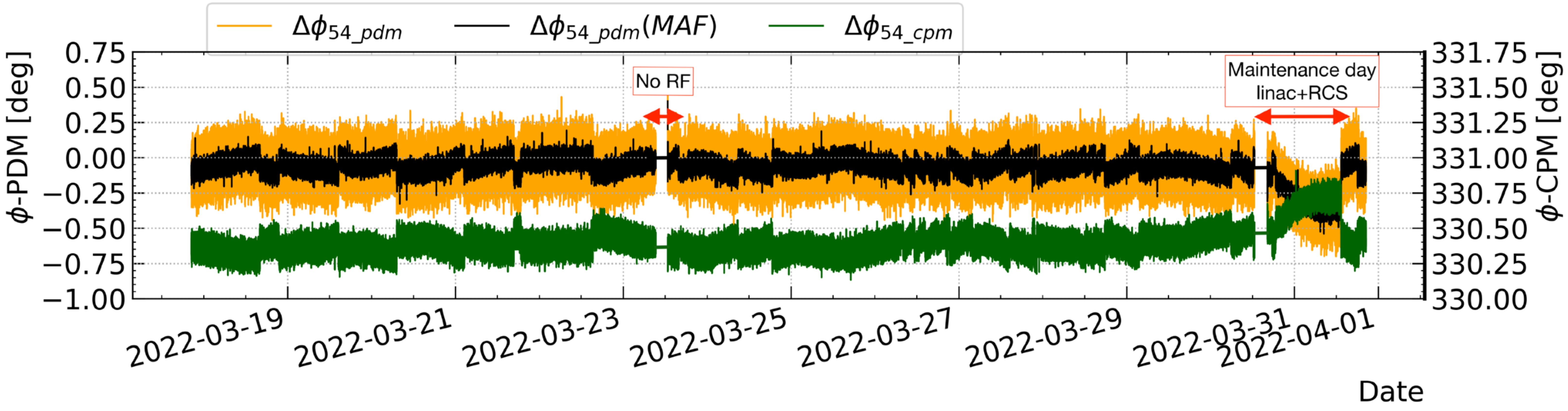
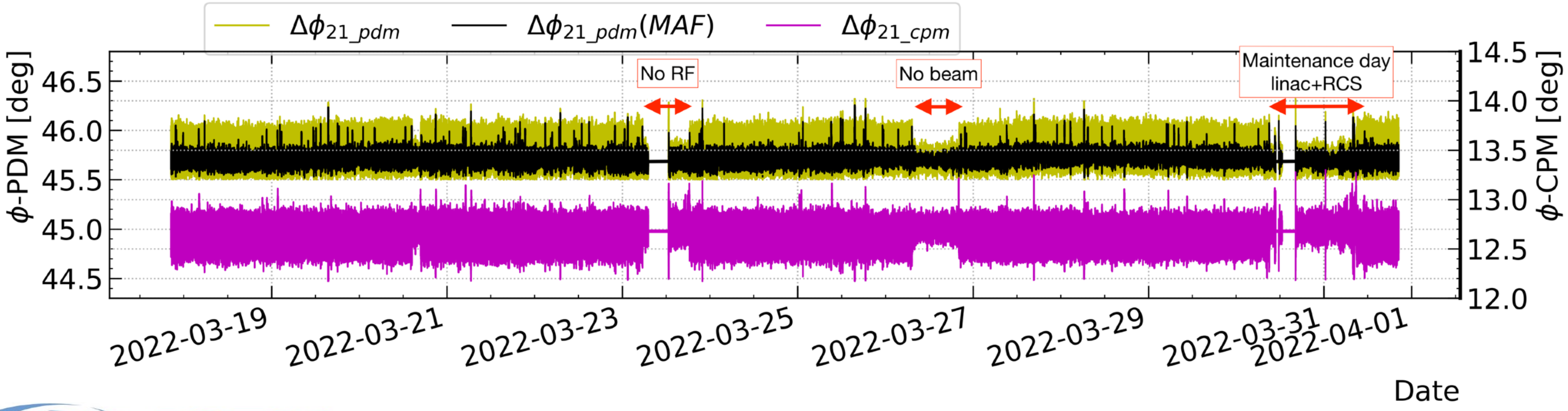
Long-term RF phase measurement cont’d

	f@324 MHz				f@972 MHz		
Cavity	SDTL15A	SDTL15B	SDTL16A	SDTL16B	MEBT2B1	MEBT2B2	ACS1
ϕ @PDM	ϕ_{0_pdm}	ϕ_{1_pdm}	ϕ_{2_pdm}	ϕ_{3_pdm}	ϕ_{4_pdm}	ϕ_{5_pdm}	ϕ_{6_pdm}
ϕ @CPM		ϕ_{1_cpm}	ϕ_{2_cpm}		ϕ_{4_cpm}	ϕ_{5_cpm}	ϕ_{6_cpm}
VS phase		ϕ_{01_vs}		ϕ_{23_vs}			

	f@972 MHz	f@324 MHz
Cavity phase diff.	MEBT2B2-MEBT2B1	SDTL16A-SDTL15B
$\Delta\phi$ @PDM	$\Delta\phi_{54\_pdm}$	$\Delta\phi_{21\_pdm}$
$\Delta\phi$ @CPM	$\Delta\phi_{54\_cpm}$	$\Delta\phi_{21\_cpm}$





- Phase differences compared with permanently installed and successfully operated CPMs:
  - **EPICS archiver appliance for data storage.**
  - ☑ Consistency between PDM and CPMs,
  - ☑ No change in the center of phase differences,
  - ☑ Stable temperature and humidity in the MEBT2B1 rack.

MAF → moving average filter

Relative phase difference

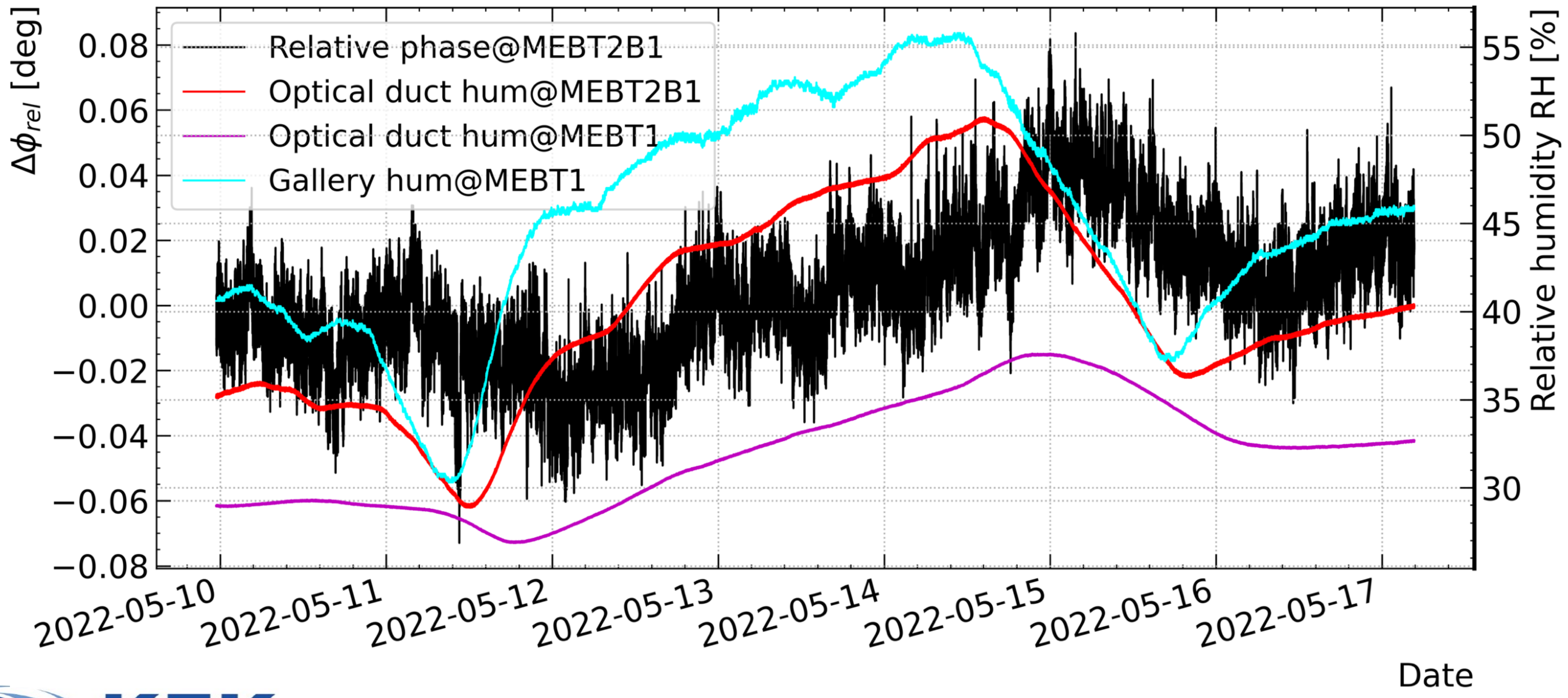
- $\Delta\phi_{rel}$ relative phase difference derived from phase differences between two different frequencies of 324 MHz and 972 MHz;

$$\Delta\phi_{rel} = \Delta\phi_{23\_vs} - (\Delta\phi_{4\_pdm}/3)$$

324 MHz ↑ ($\Delta\phi_{23\_vs}$) 972 MHz ↑ ($\Delta\phi_{4\_pdm}$)

- $\Delta\phi_{23\_vs}$ and $\Delta\phi_{4\_pdm}$ denote phase changes (pp) in the reference channels of ADC03 (SDTL16 VS) and ADC04(MEBT2B1), respectively,
- Data was evaluated on the PDM for about 1-week.

	(Reference @324 MHz) (ADC03 ch.)	*(Reference @972 MHz) (ADC04 ch.)*
Phase difference	*SDTL16VS*	*MEBT2B1*
$\Delta\phi_{rel}$ @PDM	$\Delta\phi_{23\_vs}$	$\Delta\phi_{4\_pdm}$



- The relative phase difference tends to be similar to the;
  - Humidity change in the klystron gallery,
  - Or, humidity change in the optical duct, where RF reference signals are distributed.
- ☑ PDM is a good candidate to compensate for the drift in the relative phase difference.

[1] K. Futatsukawa et al., "Upgrade of the RF Reference Distribution System for 400 MeV LINAC at J-PARC", IPAC2012, WEPPD050, New Orleans, Louisiana, USA

Conclusions

- Phase differences between 324 MHz cavities and their respective reference phase, as well as that of 972 MHz cavities, are measured **to be stable for the long-term on the CPMs and PDM.**

- However, we have found that environmental factors, **particularly humidity changes, cause long-term phase drift in the relative phase difference**, critical information for stabilizing accelerating RF fields through linac cavities operating at two different frequencies.

- The source of variation in the relative phase difference is thought to be **humidity change in the optical duct or klystron gallery.**

➡ **The PDM will be employed within the LLRF system** to compensate for possible phase and amplitude drifts in cavity RF signals by eliminating environmental effects, which is crucial for a stable long-term operation.

- Special thanks the staff members of **Mitsubishi Electric Tokki Systems Co.**, who implemented a perfect phase drift monitor for the J-PARC linac.

- We also thank the **Mitsubishi SC** members for their excellent work during the device installation.

Thank you for your attention.

ご静聴ありがとうございました。