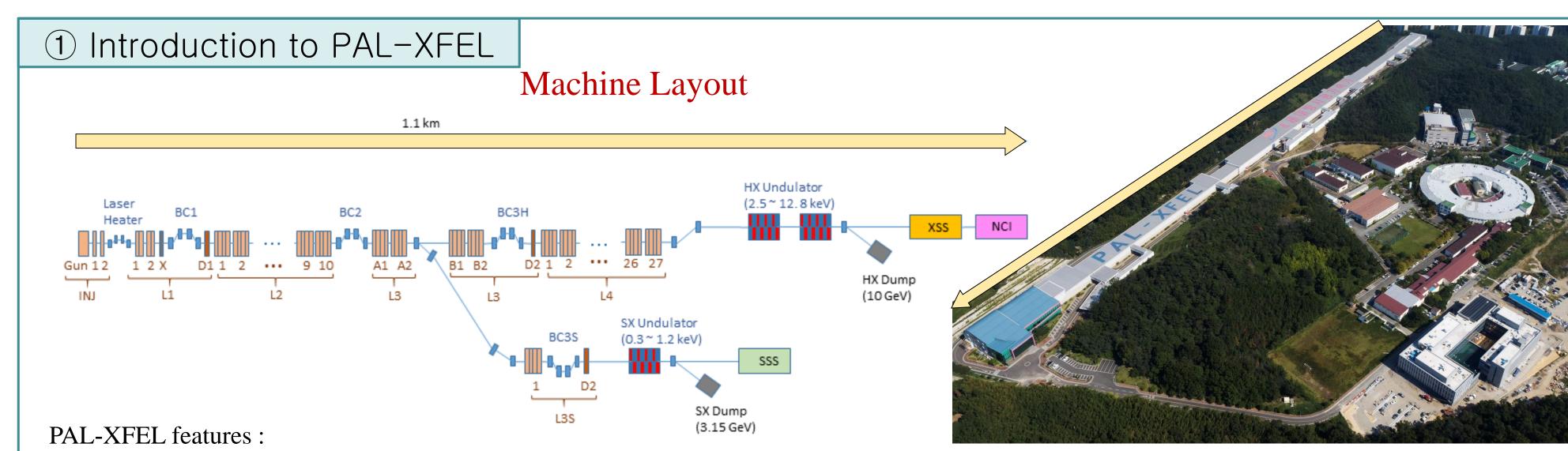# Reliable operation of PAL-XFEL LLRF

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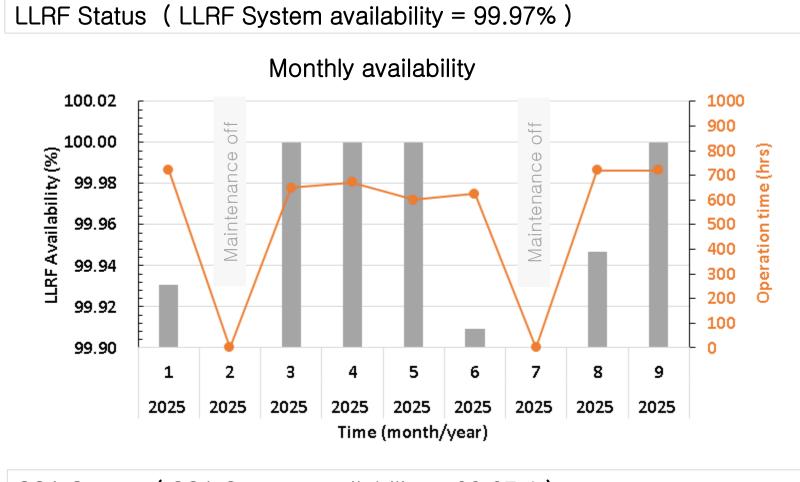
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Id : 13   Poster

Abstract :

The PAL-XFEL(Pohang Accelerator Laboratory X-ray Free Electron Laser) LLRF(Low Level RF) and SSA(Solid State Amplifier) systems have contributed to the stable operation of PAL-XFEL for nearly a decade with their reliability and robustness. Key achievements of these systems include the development of pulse-by-pulse real-time RF switching function for simultaneous operation of the HX and SX beamlines, development of a converter-type X-band LLRF, and development of a function to improve RF amplitude drift. The systems have faced various challenges during their operation, such as the arrival of key component life cycles, the discontinuation of key components, and the need for upgrades to keep pace with technological advances. Therefore, the following activities are being pursued. The PAL-XFEL LLRF and SSA systems have been field-proven, so upgrades are being carried out based on the existing systems. The discontinued processing PCs have been upgraded to higher-performance industrial boards, the RF modules are being redeveloped, and the A/D and FPGA boards are planned to be upgraded with new FPGAs and PCIe. In addition, an updated SSA prototype is in development.
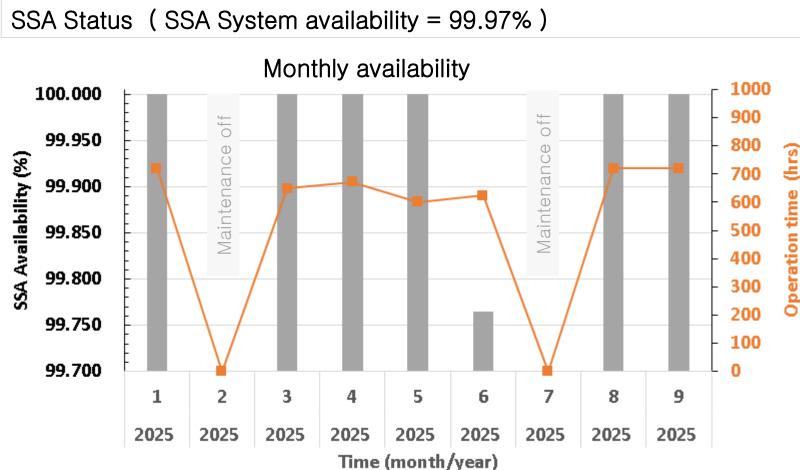
① Introduction to PAL-XFEL

Machine Layout

PAL-XFEL features :
- S-band Normal-Conducting linac (2.856GHz x50, 11.424GHz x1) ➜ total 51 RF stations (51 sets of LLRF / SSA / HV modulator / Klystron)
- Electron-bunch acceleration 10 GeV at up to 60Hz
- 2 Beamlines : One for hard X-ray (HX), the other for soft X-ray (SX) (HX : 2~20keV, SX : 0.25~1.25keV, 2021 update)

② PAL-XFEL LLRF & SSA Status (2025)

LLRF Status (LLRF System availability = 99.97%)

Monthly availability

Cause of Failure (total 7 cases, all recoverable)

No.	RF station	Failure	Treatment
1	L2-07	P-PC frozen	P-PC reboot
2	L4-3	P-PC frozen	P-PC reboot
3	L4-8	LAN bad connection	LAN reconnection
4	L4-10	P-PC frozen	P-PC reboot
5	L4-15	P-PC frozen	P-PC reboot
6	L4-16	P-PC frozen	P-PC reboot
7	L4-22	P-PC frozen	P-PC reboot

※ P-PC := Processing PC

SSA Status (SSA System availability = 99.97%)

Monthly availability
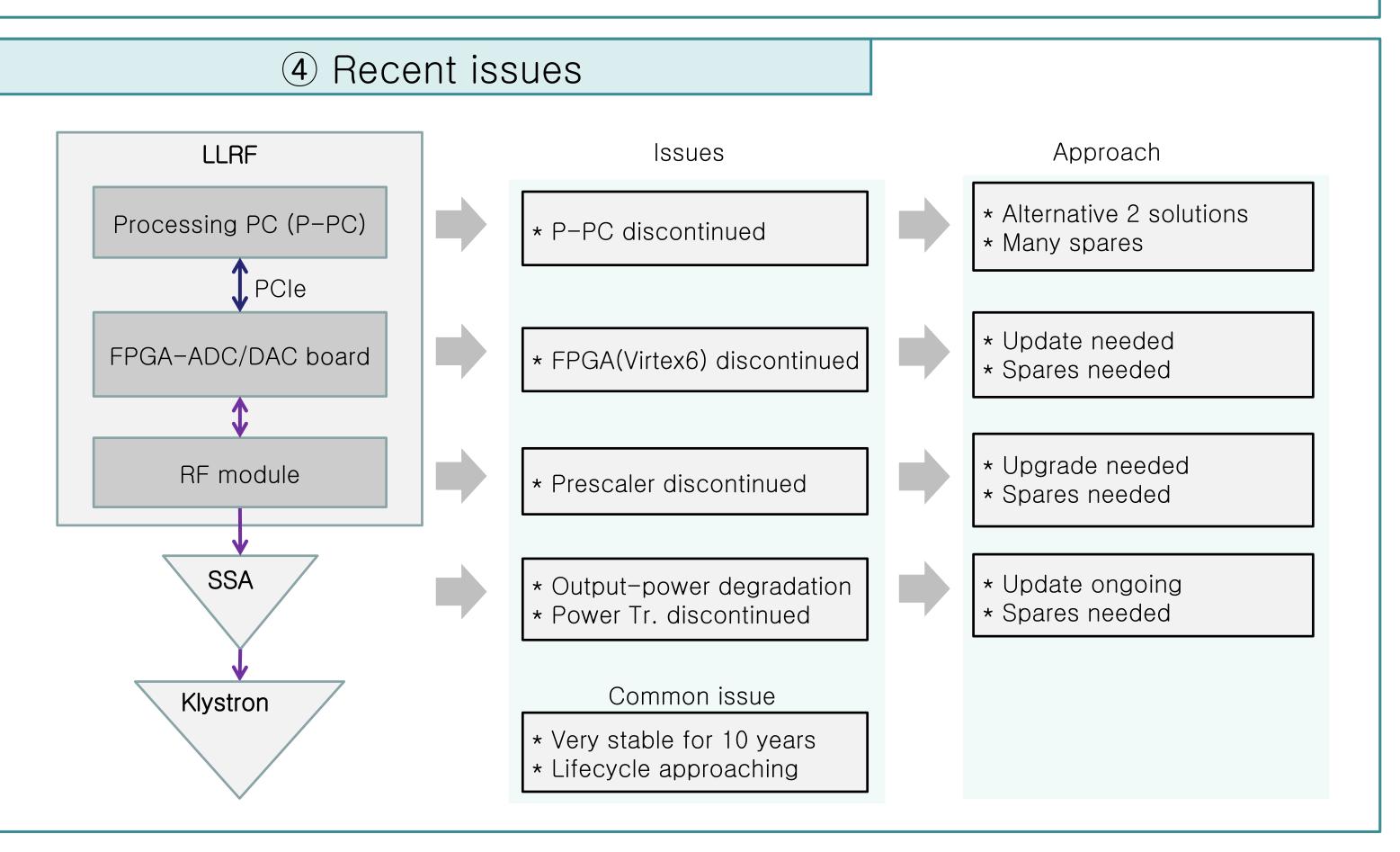
Cause of Failure (total 2 cases, 1 irrecoverable)

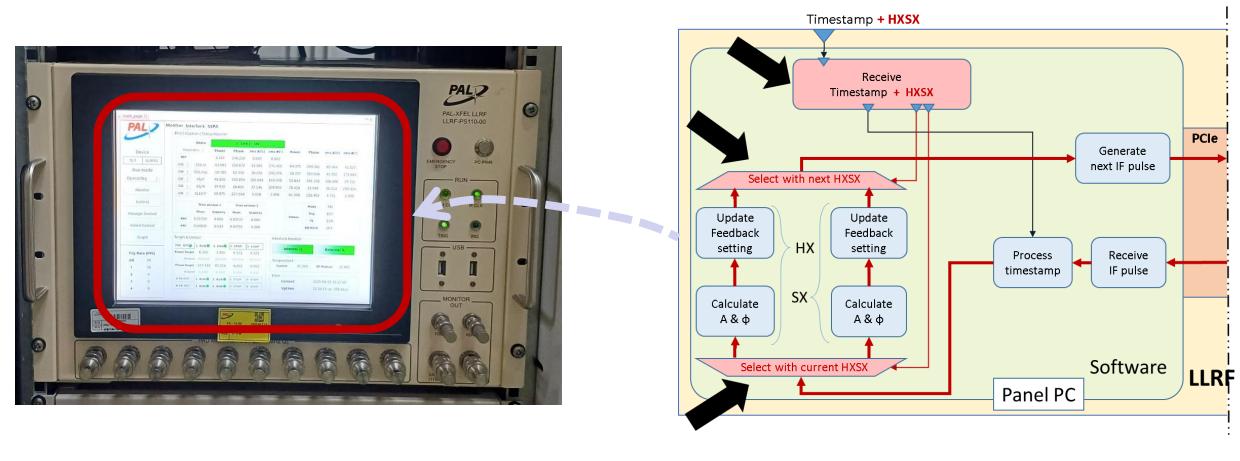| No.	RF station	Failure	Treatment
1	L2-03	SMPS failure	Set replacement (1.4 hrs consumed)
2	L2-06	Over-current interlock	Interlock reset

LLRF + SSA System availability :

99.94%

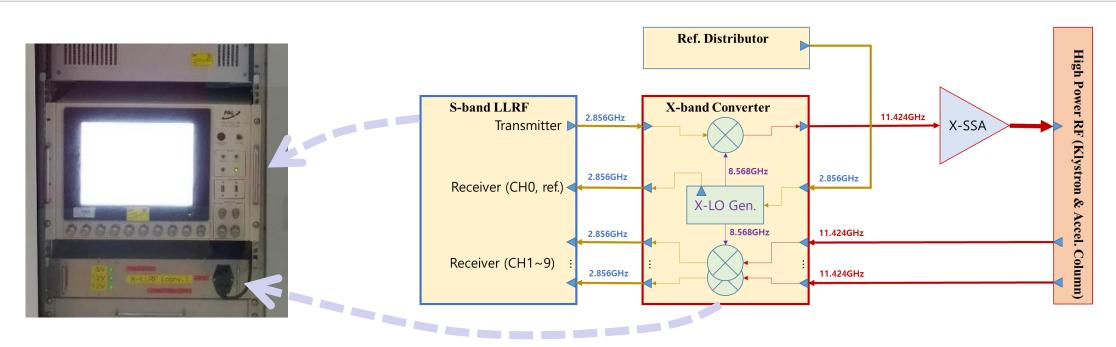※ LLRFs and SSAs on, only the RF outputs turned off during maintenance

③ Past major developments

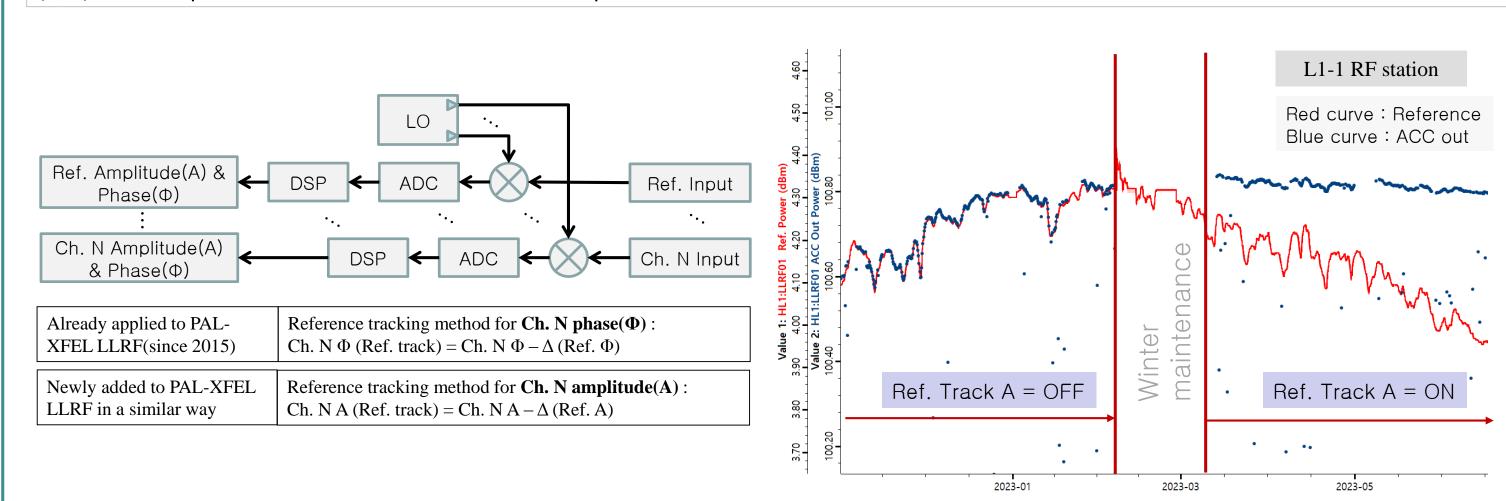**(1/3) Pulse-by-pulse RF switching development**

- Scheme : pulse-by-pulse RF switching for dual beamline operation in mixed-flow way
- Implementation : unique software modifications to the timestamp transmission part and the internal part of the LLRF (Panel PC).
- Contributing to PAL-XFEL operation with high reliability from 2021
- Presented at LLRF2022 under the title "Development of pulse-by-pulse RF switching of PAL-XFEL LLRF for dual-beamline operation"

(2/3) X-band LLRF development

- Two stage superheterodyne structure : S-band LLRF + X-band converter
- Installed in reliable operation on PAL-XFEL since 2023 (improvement up to x2 (jitter) and x7 (drift))
- Presented at LLRF2023 under the title "New development of X-band LLRF for PAL-XFEL Linearizer"

(3/3) Development of a method to reduce RF amplitude drift

Already applied to PAL-XFEL LLRF(since 2015)	Reference tracking method for **Ch. N phase(Φ)** : Ch. N Φ (Ref. track) = Ch. N Φ − Δ (Ref. Φ)
Newly added to PAL-XFEL LLRF in a similar way	Reference tracking method for **Ch. N amplitude(A)** : Ch. N A (Ref. track) = Ch. N A − Δ (Ref. A)

- Extension of the reference tracking method for RF amplitude
- Installed and in stable operation on PAL-XFEL since 2023 (drift improvement up to x5)
- Presented at LINAC2024 under the title "Extension of reference tracking method to reduce RF amplitude drift in particle accelerators"

④ Recent issues

LLRF	Issues	Approach
Processing PC (P-PC)	* P-PC discontinued	* Alternative 2 solutions * Many spares
FPGA-ADC/DAC board	* FPGA(Virtex6) discontinued	* Update needed * Spares needed
RF module	* Prescaler discontinued	* Upgrade needed * Spares needed
SSA	* Output-power degradation * Power Tr. discontinued	* Update ongoing * Spares needed
Klystron		

Common issue
* Very stable for 10 years
* Lifecycle approaching

⑤ Recent upgrade (Processing PC or P-PC)

Current PPC (Panel PC)

New IMB (Industrial Mainboard)

Comparison between current & new P-PC

	Current PPC	New IMB 1	New IMB 2
Board form		Industrial Mini-ITX	Industrial Mini-ITX
CPU	i5-4570TE	i7-10700	i5-14500
RAM	DDR3	DDR4	DDR4
SSD	SATA	M.2 NVME	M.2 NVME
PCIe	Gen2 x1	Gen3 ~x16	Gen4 x16
Product Status	PPC discontinued	IMB in production, CPU discontinued, RAM nearly discontinued	IMB & CPU in production, RAM nearly discontinued
OS	Ubuntu 14	Ubuntu 14	Ubuntu 20
Max. trig.	~200 Hz	480 Hz	540 Hz
Remarks		Upgraded, 18 sets in operation since 2025	Upgraded, Ready to install

The data-processing rate measur. with LLRF

The LLRF set with IMB2 operated stably without pulse dropout at a repetition rate 540Hz for 2 days

Measuring an EPICS PV update rate

Jitter, but 540Hz operation OK!

⑥ Upgrade plan (LLRF & SSA)

LLRF (FPGA-ADC/DAC) update plan (tentative)

	Current	Plan	Remarks
FPGA	Virtex6 (discontinued)	Kintex US+ (KU11P, KU15P), or Zynq US+ (ZU11EG ~)	Soldered chip or field replaceable SOM
PCIe	Gen 2 x1	Gen2 ~ Gen4 x1 ~ x16	The current PCIe sufficient
SFP	–	1 ~ 2	EVR function Optional
Dev. form	Custom	Custom or COTS	

LLRF (RF module) upgrade plan (tentative)

	Current	Plan	Remarks
Phase noise @1MHz	~ −145dBc/Hz	~ −160dBc/Hz	S- & X-band
X-band module	[IF ↔ S ↔ X] : operating [IF ↔ X] : 2 spare sets	[IF↔S↔X] → build a spare [IF ↔ X] → redesign	Coaxial modules
S-band module	[IF ↔ S] : ~ 50 sets operating	[IF ↔ S] → redesign	* Prototype → coaxial * Mass. Product → PCB

SSA upgrade plan (S-band, tentative)

	Current	Plan	Remarks
Final stage RF Tr.	NXP MRF8P29300 (discontinued)	* Replacement to other Tr.s (Ampleon, RFHIC, ···) * Securing for spares	Several manufacturers
Middle stage RF Tr.	FLL120 (discontinued)	Replacement to other Tr.s (Ampleon, RFHIC, ···)	Several manufacturers
Cooling fan	discontinued	Many spares already secured	

Conclusion

- PAL-XFEL has been supported by highly stable and reliable LLRF and SSA systems for about 10 years.

- Even in 2025, the LLRF and SSA systems are still operating very reliably (availability 99.97%).

- Three major developments have occurred over the past decade : Real-time RF switching for dual beamline operation, development of X-band LLRF and drift improvement by amplitude reference tracking method.

- Recently, some issues occurred : discontinuation of main components and approaching lifecycles.

- To address these issues, we developed 2 replacements for the processing PC and successfully applied one to PAL-XFEL.

- Upgrade activities are underway to ensure stable operation of the LLRF and SSA systems for the next 10 years.