LLRF upgrade status at the KEK Photon Factory 2.5 GeV ring

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KEK PF RF groupe
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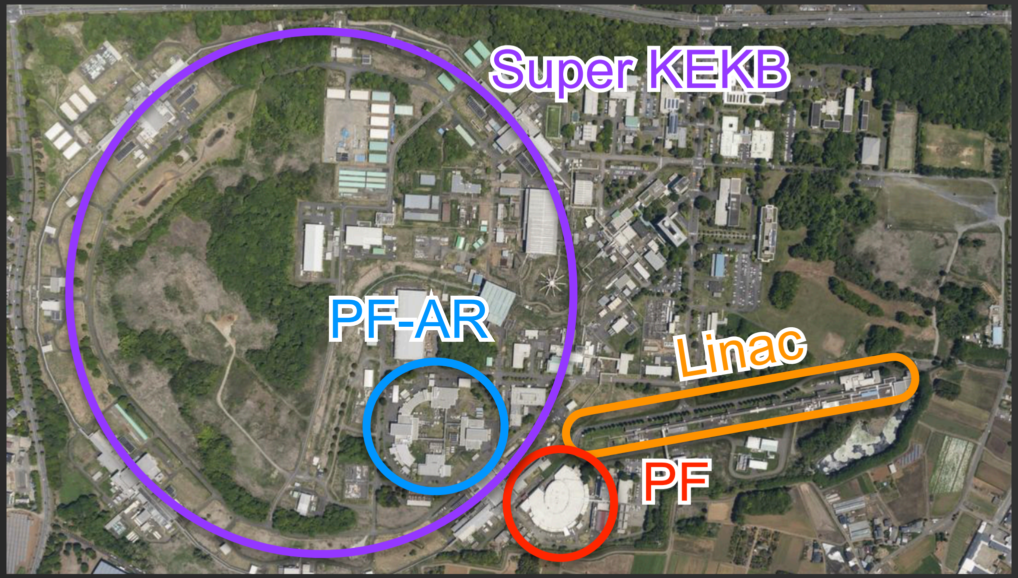
  - Photon factory (PF).
  - PF 2.5 GeV ring RF system.
- Schematic of the new LLRF system.
- Feature of the new LLRF system.
- Performance tests of the new LLRF system
- Summary

Photon factory

- Photon Factory : Synchrotron light source facility in the KEK.
  - -PF Advanced Ring (PF AR) : Single bunch operation (5 or 6.5 GeV, 50 mA).
  - -PF 2.5 GeV ring (PF) : multi bunch mode or hybrid mode.
    <=We are replacing its LLRF (today's topic) .
- We are considering future light source instead of AR and PF.
  - We are preparing short CDR.

<Where KEK?>

<Photo of the KEK>



<Parameters of PF>

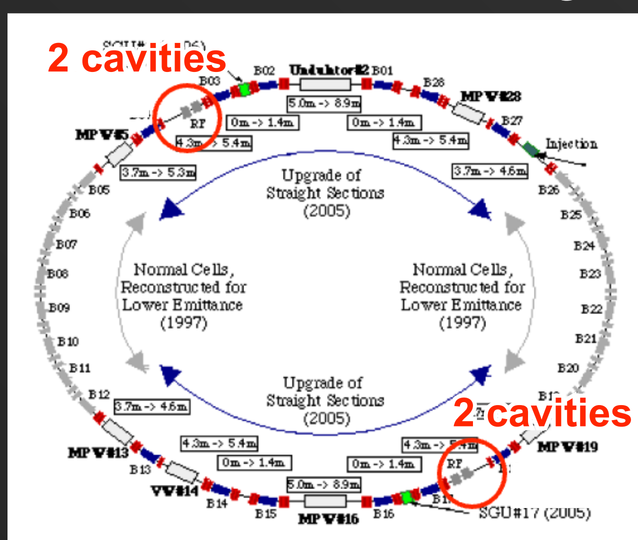
Parameter	Value
Energy	2.5 GeV
Circumference	187 m
Harmonic #	312
Beam current	450 mA
Loss/turn	0.4 MeV
# of beam line	38
Natural emittance	34.6 nm rad

RF system of the PF

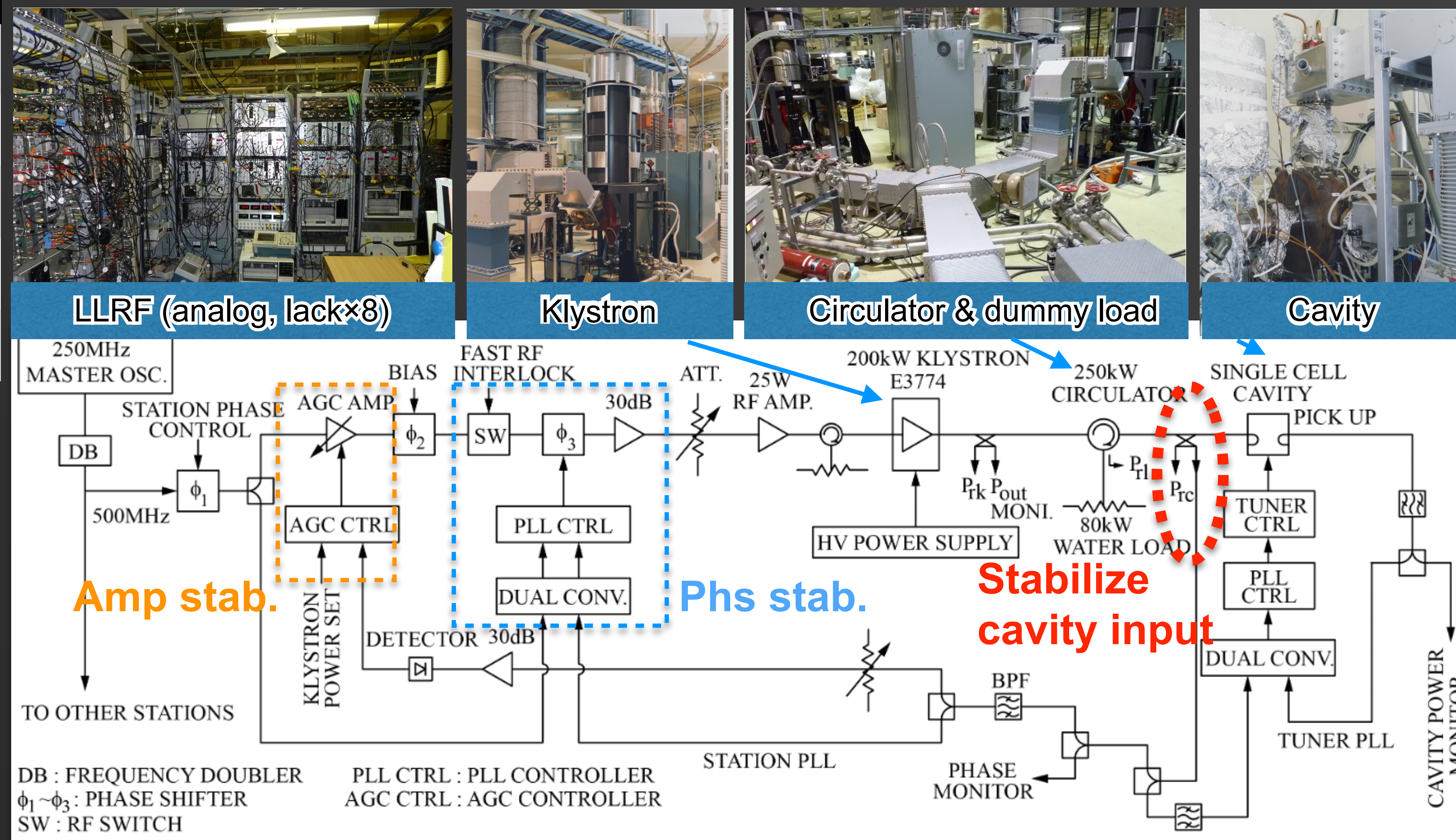
<RF parameter>

Parameter	Value
# of cavity	4
# of klystron	4
RF	500.1 MHz
Total cavity voltage	1.7 MV
Total klystron power	287 kW

<Cavities in the ring>



<Schematic of the single RF station>



- The original LLRF was designed 40 years ago, there are some difficulties to get modules.
- By replacing the analog LLRF to digital LLRF,
  -improve the maintainability.
  -develop technologies for the next generation light source.

Our target :

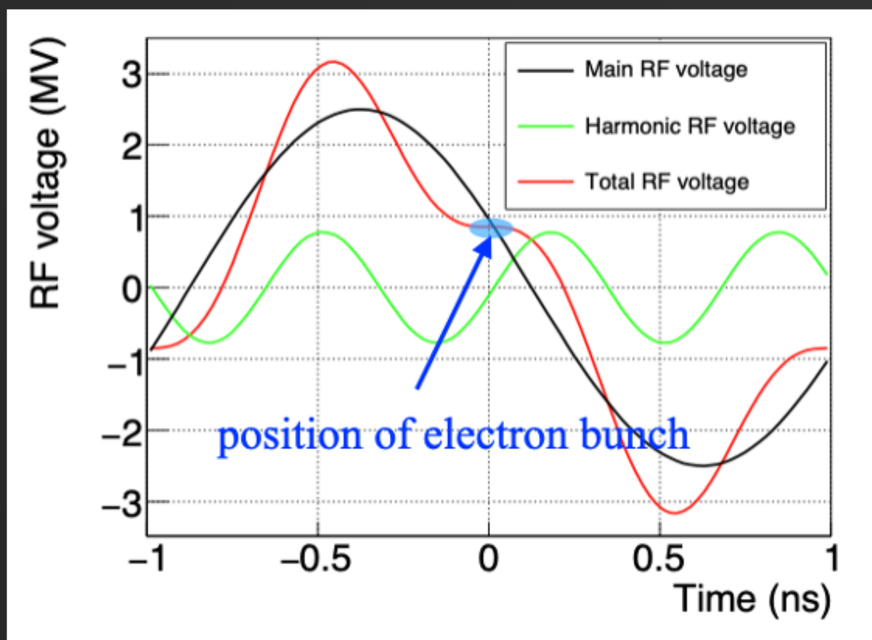
Amplitude stability of the cavity voltage < ± 0.1 %

Phase stability of the cavity voltage < ± 0.1 °

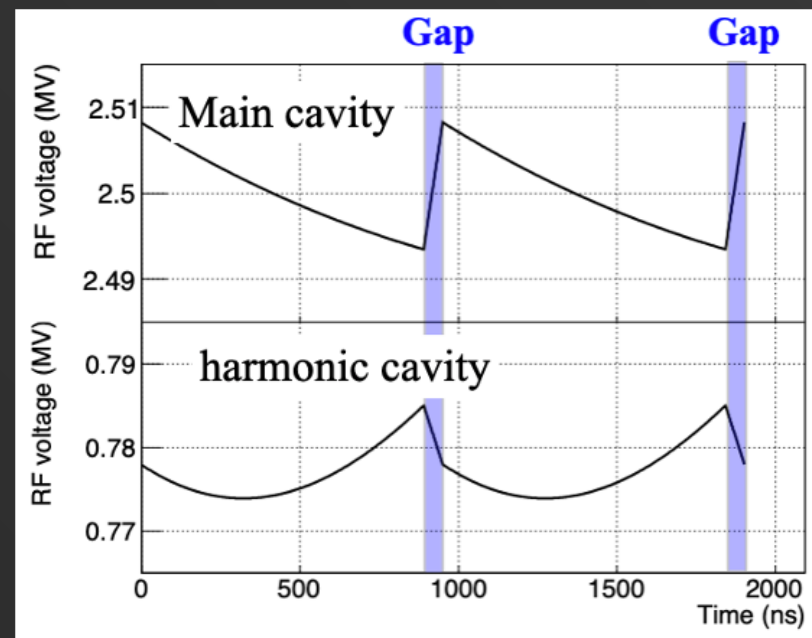
TBL compensation for the future light sources

- When the beam energy is middle (∼3 GeV), intrabeam scattering causes the emittance growth and shortening of the Touschek lifetime.
  => Bunch lengthening using fundamental and harmonic cavities.

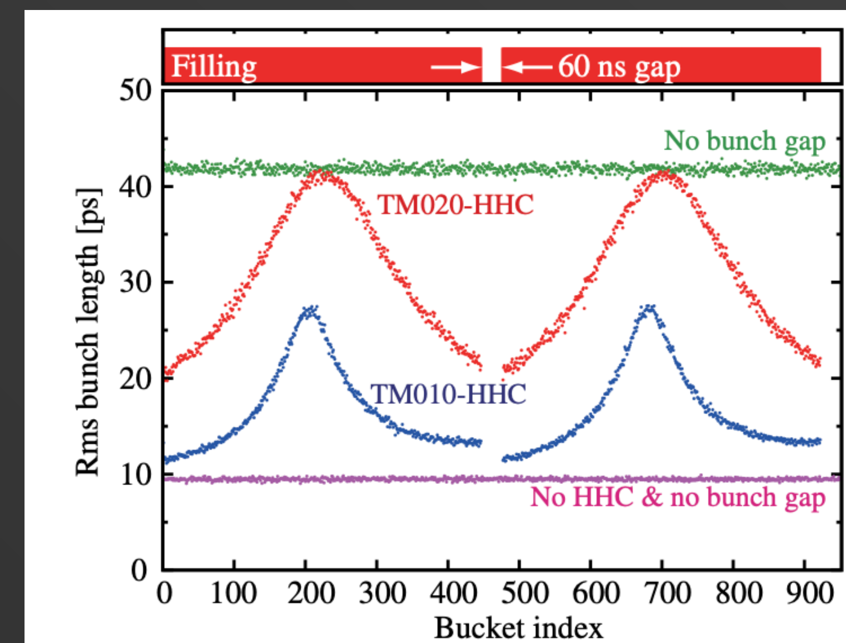
<Double RF wave>



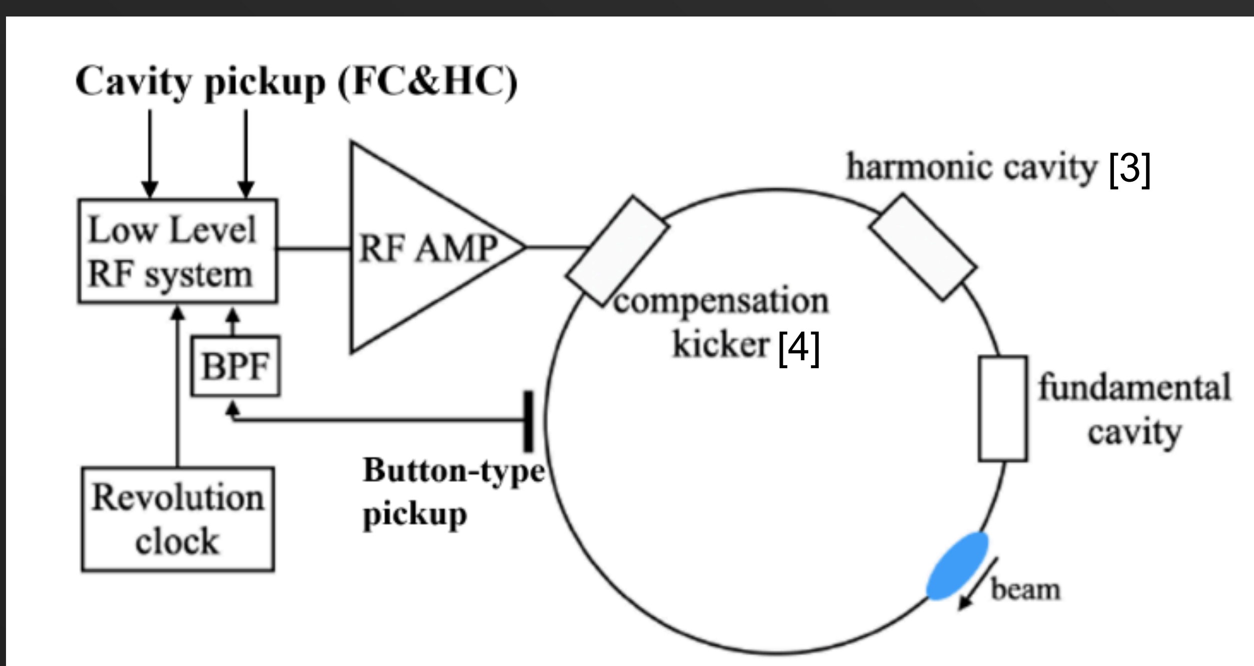
<Transient beam loading>



<Bunch length distribution[2]>



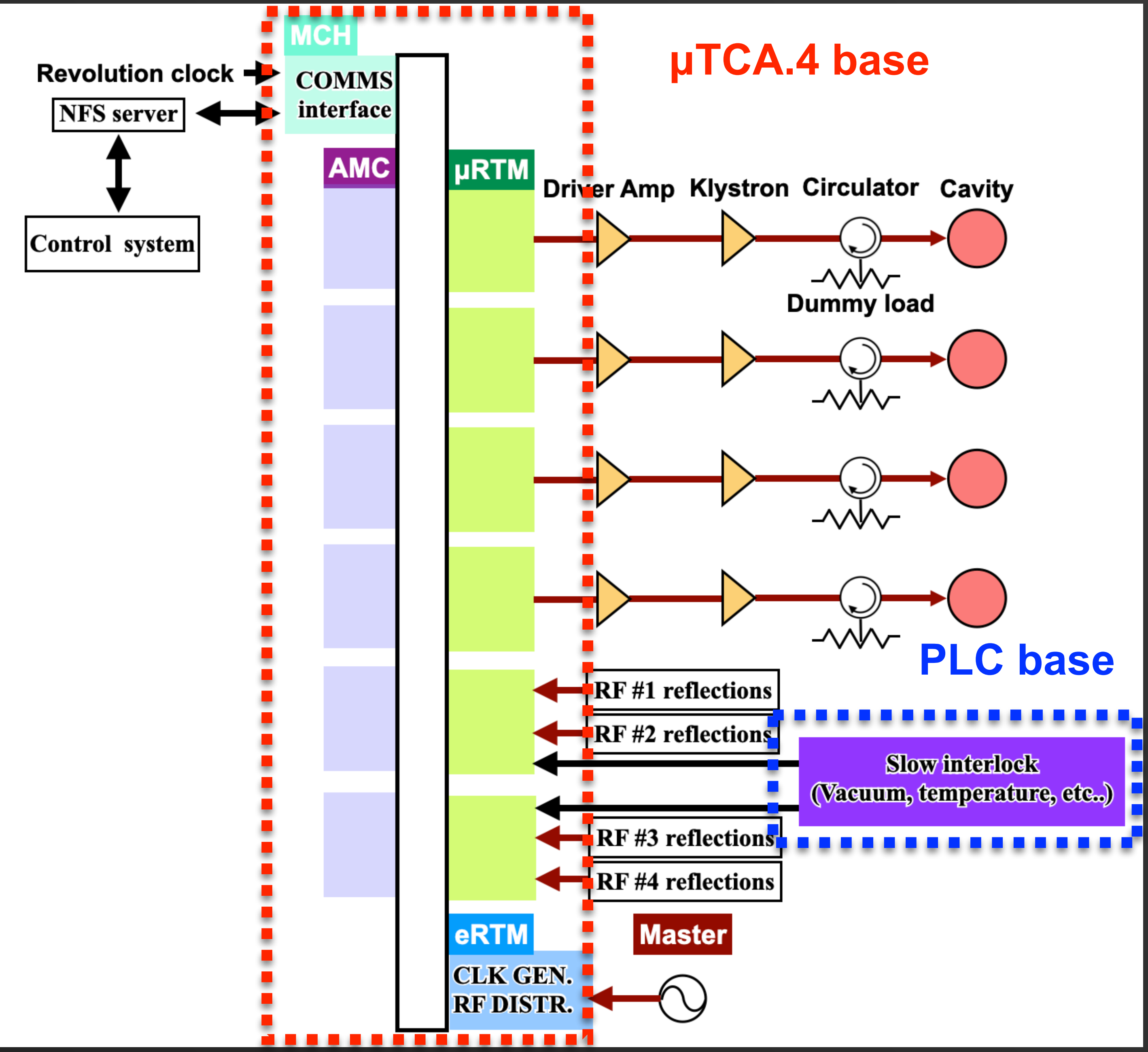
<Proposing system [2]>



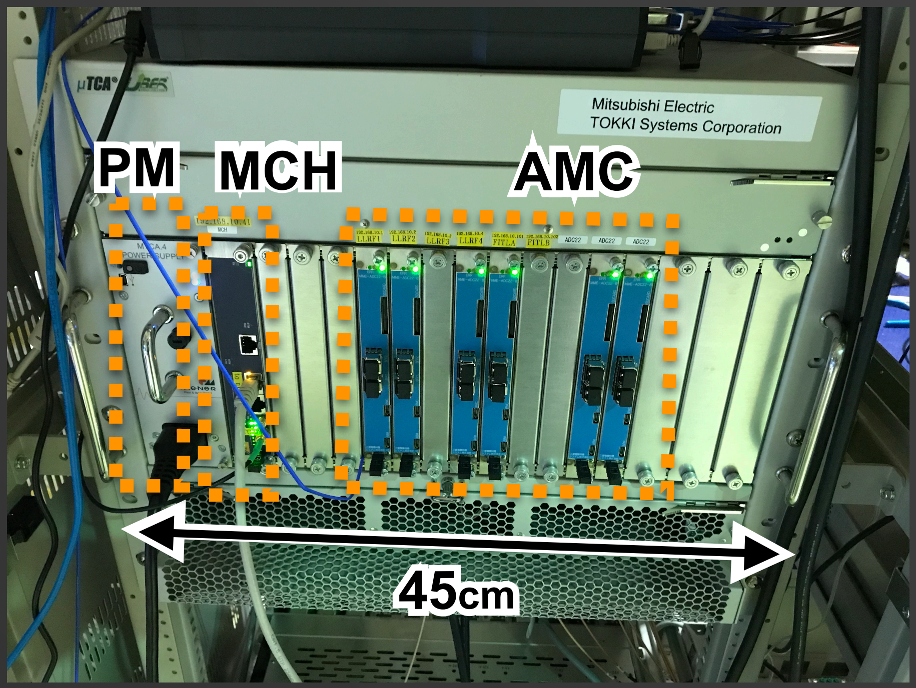
- Detect the phase of the bunch.
- Correct the transient beam loading voltage by wide-band compensation kicker.
- The new LLRF system incorporates advanced technology such as bunch-phase detection and TBL compensation.

[2] N. Yamamoto, *et al.*, PRAB **21**, 012001 (2018)
[3] T. Yamaguchi, *et al.*, NIM A **1053**, 168362 (2023)
[4] D. Naito, *et al.*, Proc IPAC23, WEPA119 (2023)

New LLRF system



<Photo of the µTCA.4 shelf>

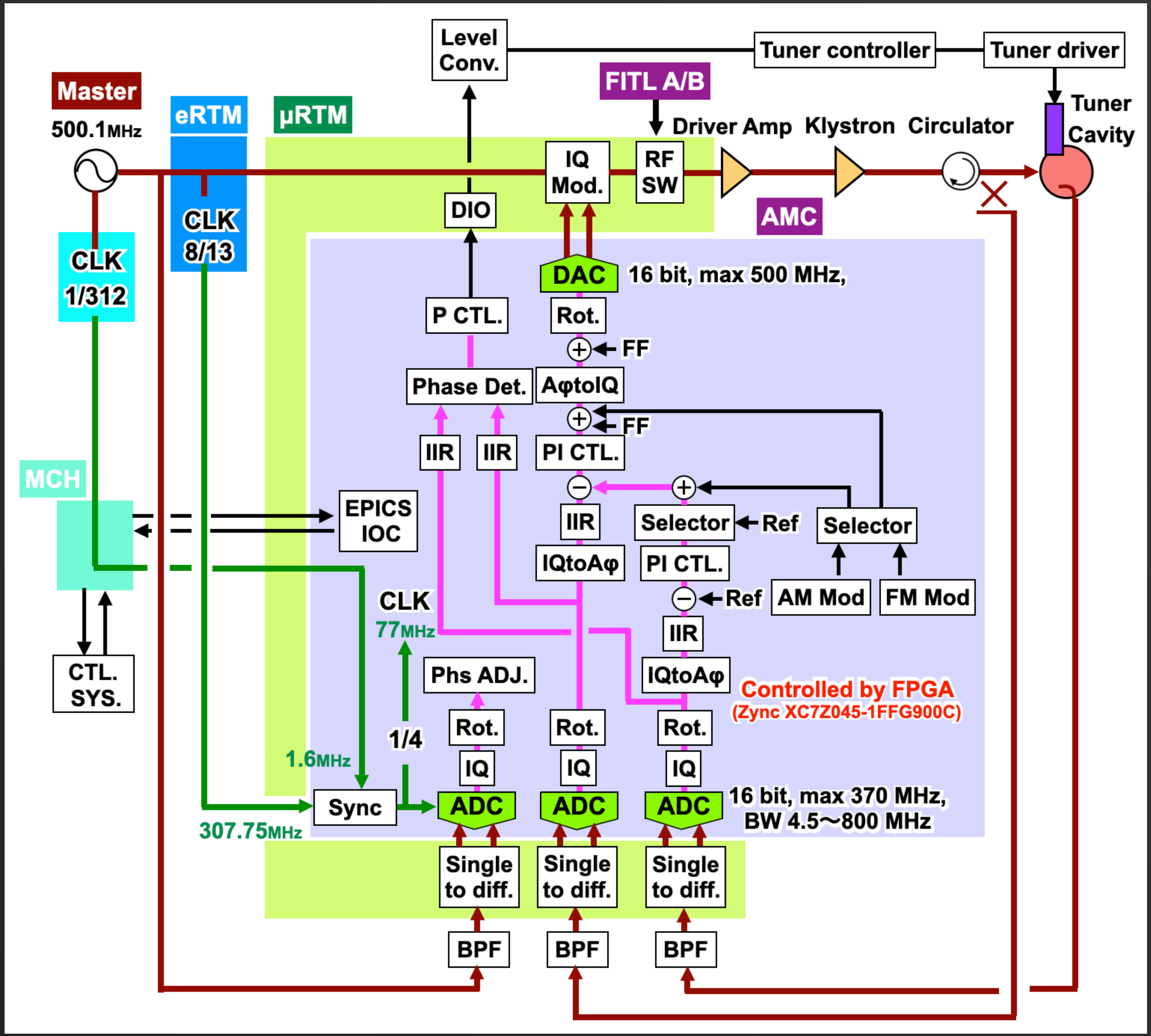


Modul	Development policy
Shelf	use commercial model (nVent)
PM	use commercial model (Wiener)
MCH	use commercial model (NAT)
eRTM	use the module developed at SPring-8
µRTM	modify the module developed at J-PARC LINAC
AMC	modify the module developed at J-PARC MR

Customizing LLRF technologies developed for the SPring-8, J-PARC and SuperKEKB => Minimizing development costs, periods, and risks.

Feature of the new LLRF

<Schematic of the RF control>

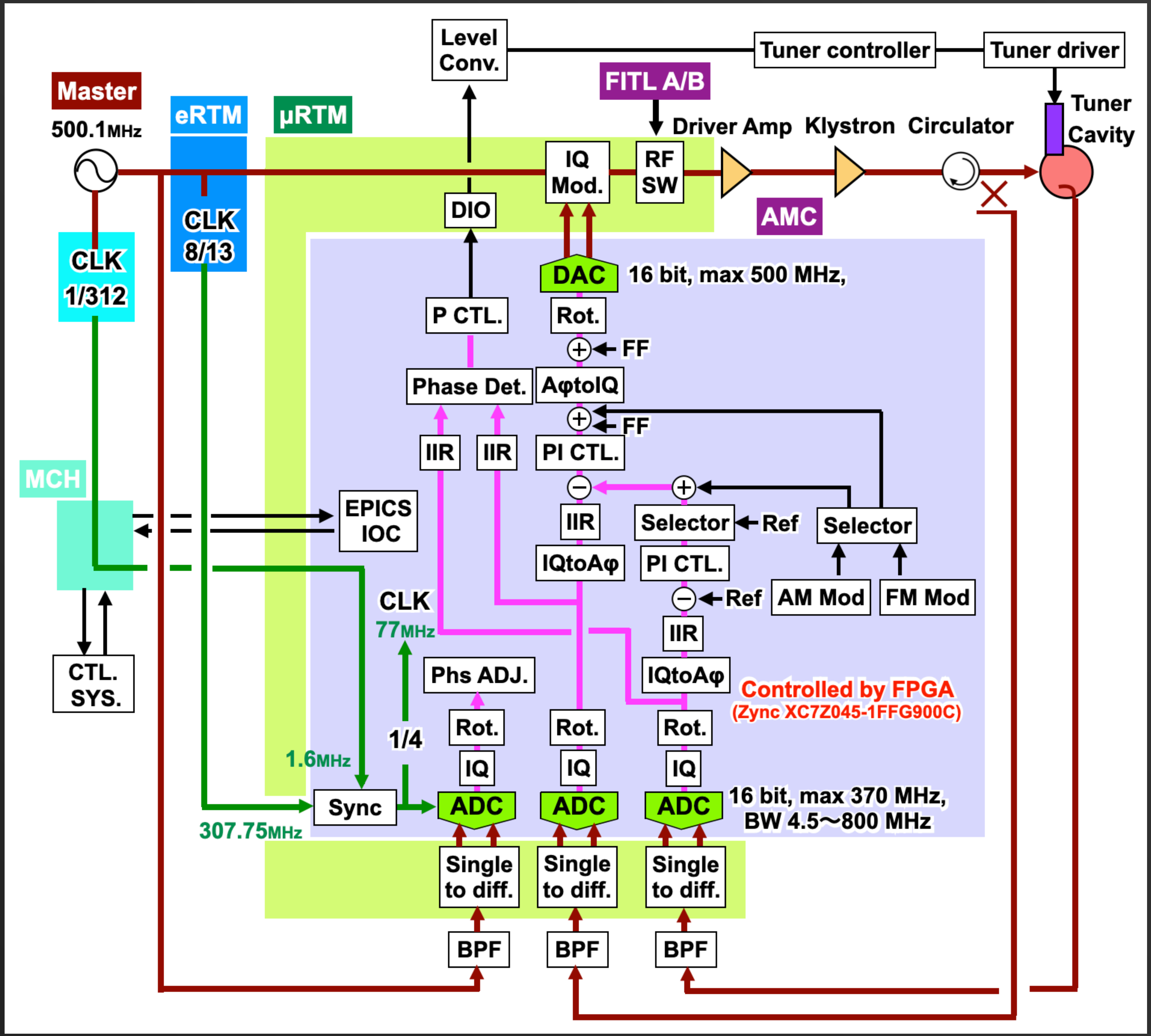


Feature of the new LLRF

1. Non-IQ direct sampling
2. Phase detection in bunch train
3. Amplitude & phase FB
4. AM/FM modulator

Feature of the new LLRF

<Schematic of the RF control>



Feature of the new LLRF

Introduce today

1. Non-IQ direct sampling
2. Phase detection in bunch train
3. Amplitude & phase FB
4. AM/FM modulator

Non-IQ direct sampling and phase detection

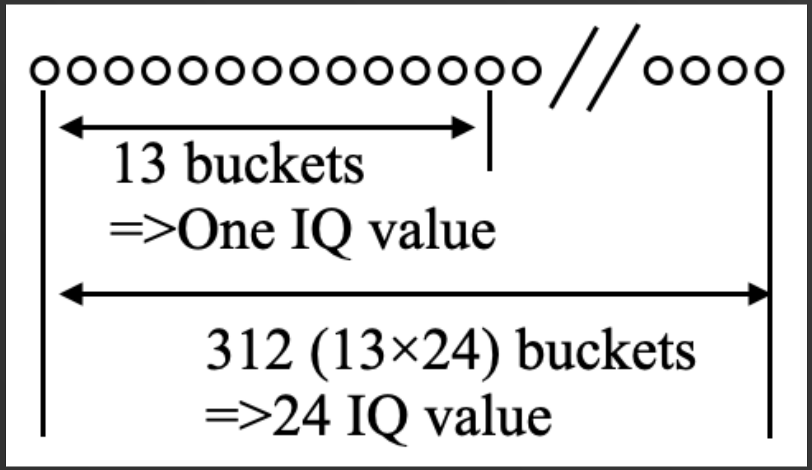
<Definition of the IQ detection >

$$I = \frac{1}{4}\sum_{i=0}^{7} V_i \cos\left(2\pi i \cdot \frac{5}{8}\right)$$

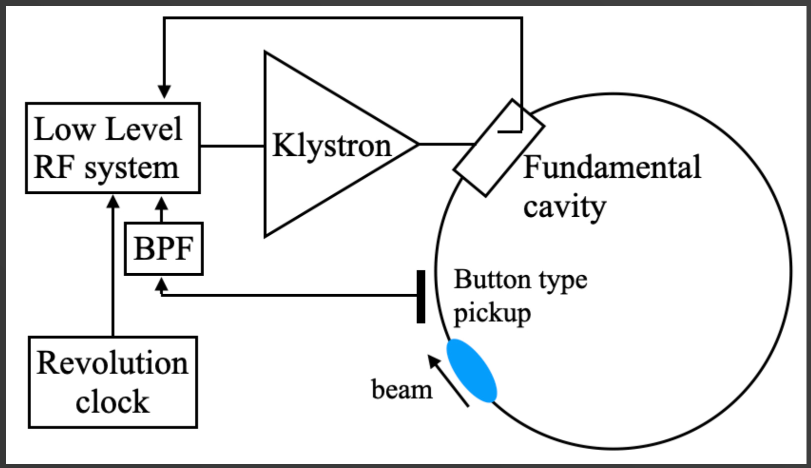
$$Q = -\frac{1}{4}\sum_{i=0}^{7} V_i \sin\left(2\pi i \cdot \frac{5}{8}\right)$$

$$f_s = f_{RF} \times \frac{8}{13}$$

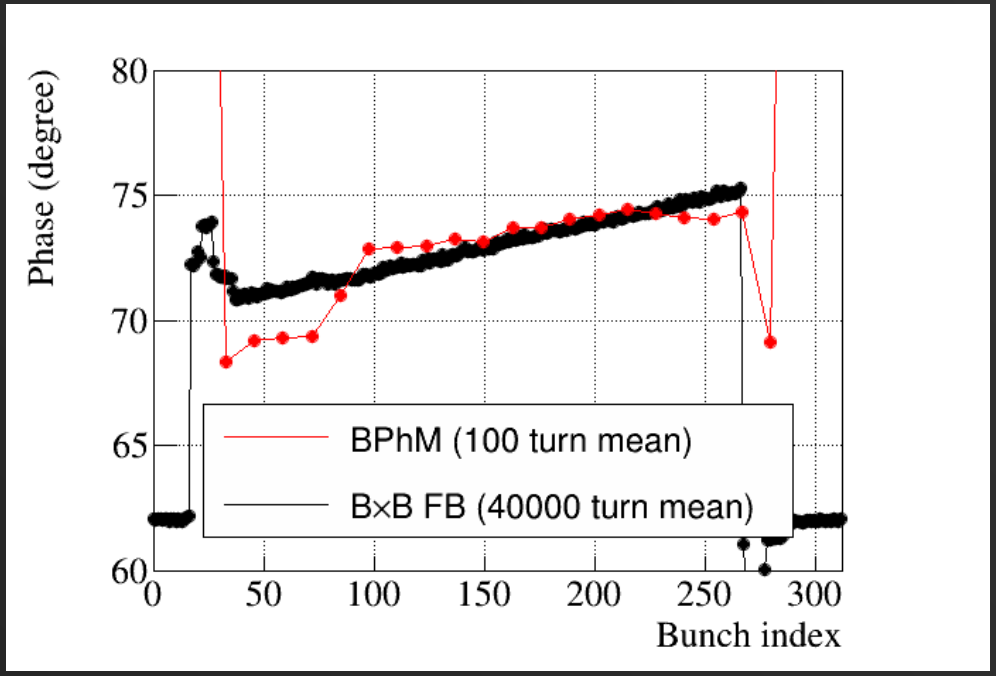
<IQ detection in 1 revolution>



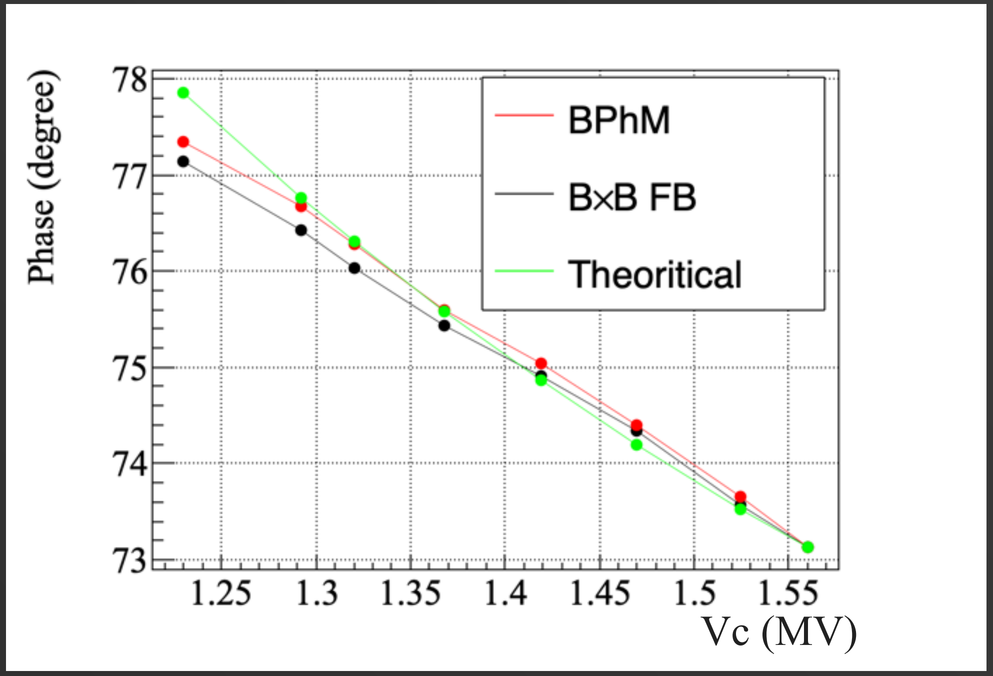
<Bunch detection @ PF>



<Phase detection with using firmware@PF>

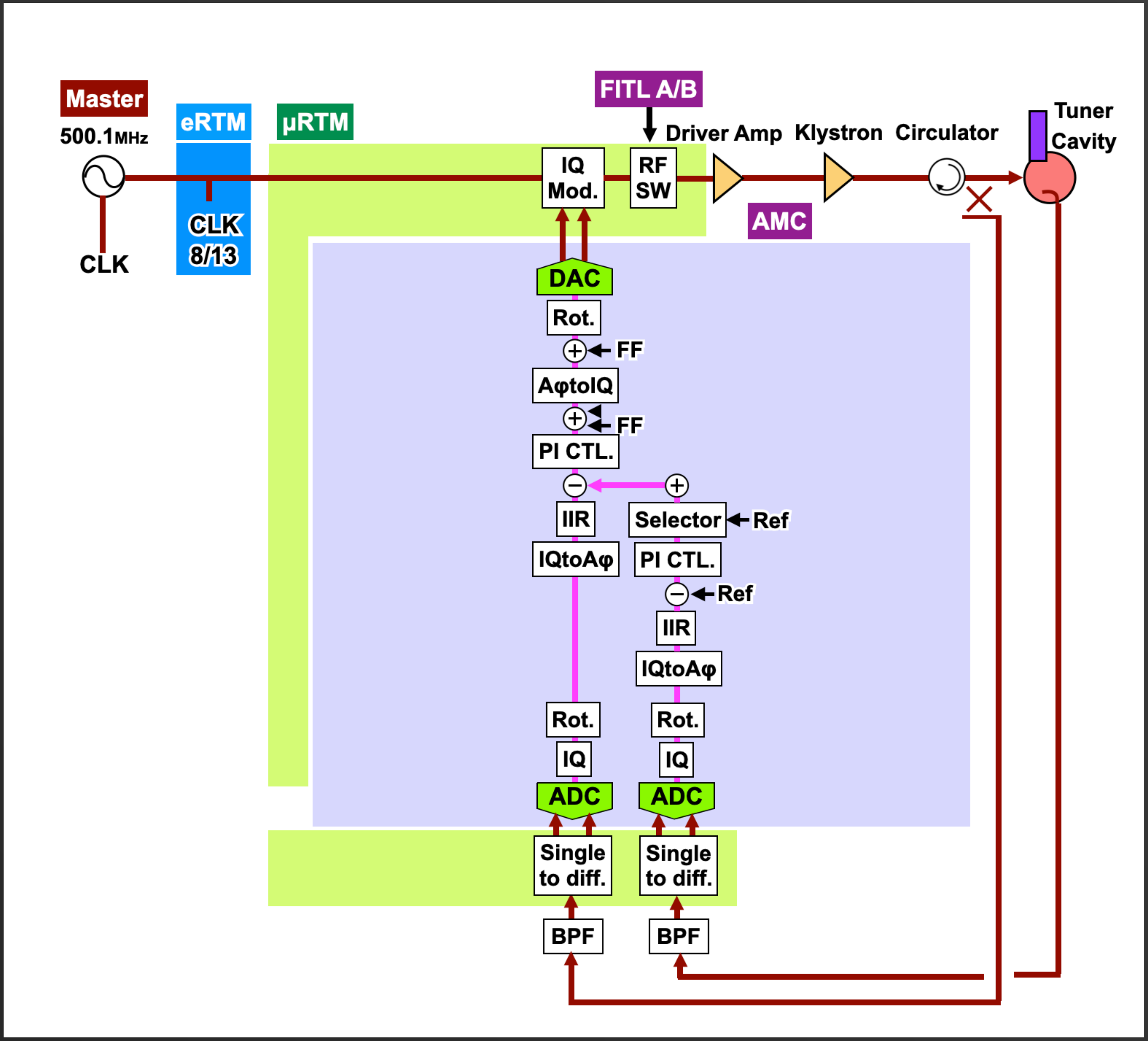


<Phase shift of the 156 bunch vs cavity voltage>



- Adapt non-IQ direct sampling for the RF detection at the ADC.
- Set the sampling clock of the ADC to be 307.75 MHz ($f_{RF} \times 8 \div 13$)
  - -RF detection is synchronized with the revolution clock.
  - **=>Realize the fast calculation of the bunch phase shift in the LLRF system.**
  - -Generate feedforward pattern and correct the phase shift in fundamental cavity (future plan).

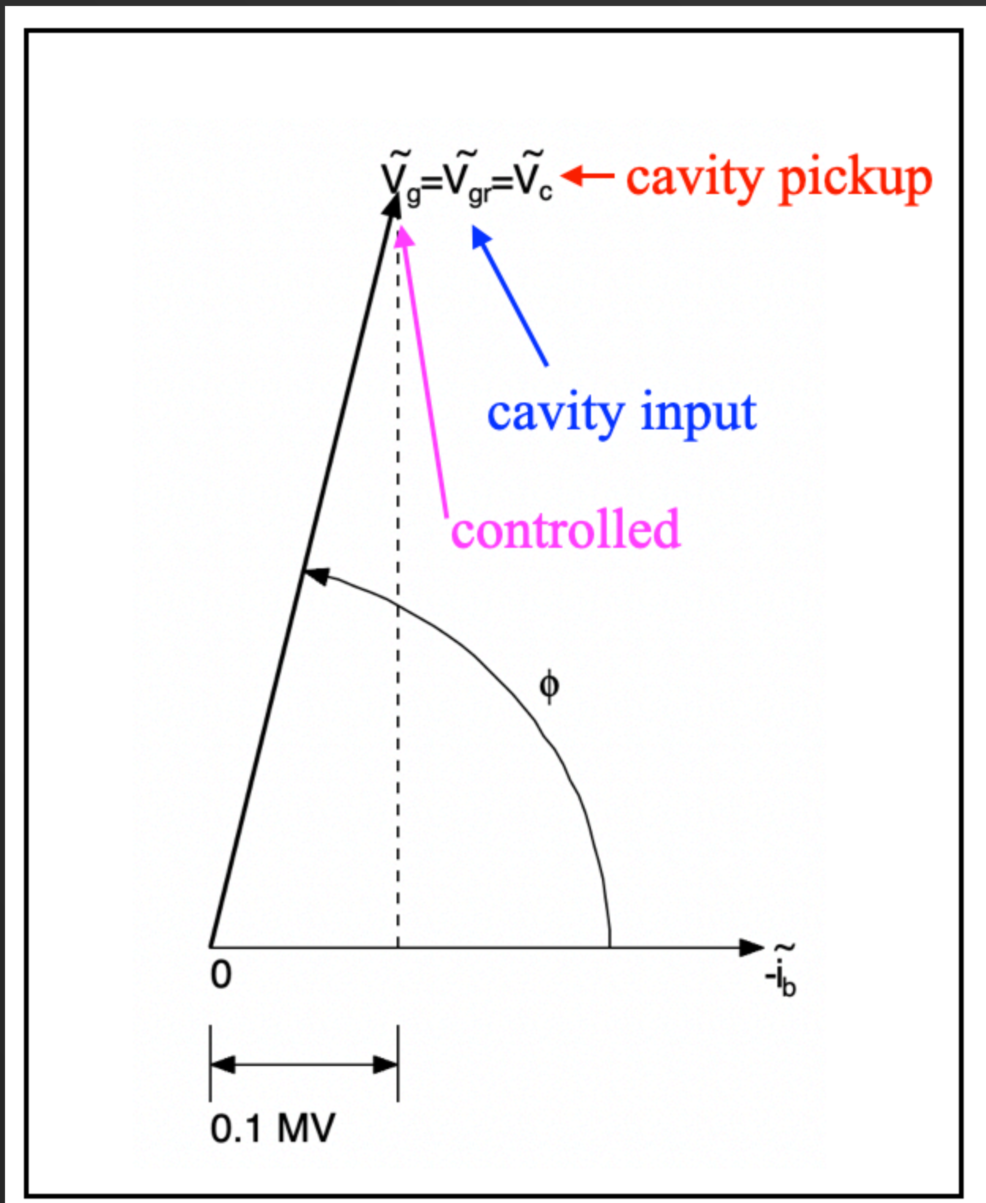
Amplitude and phase control with double loop FB



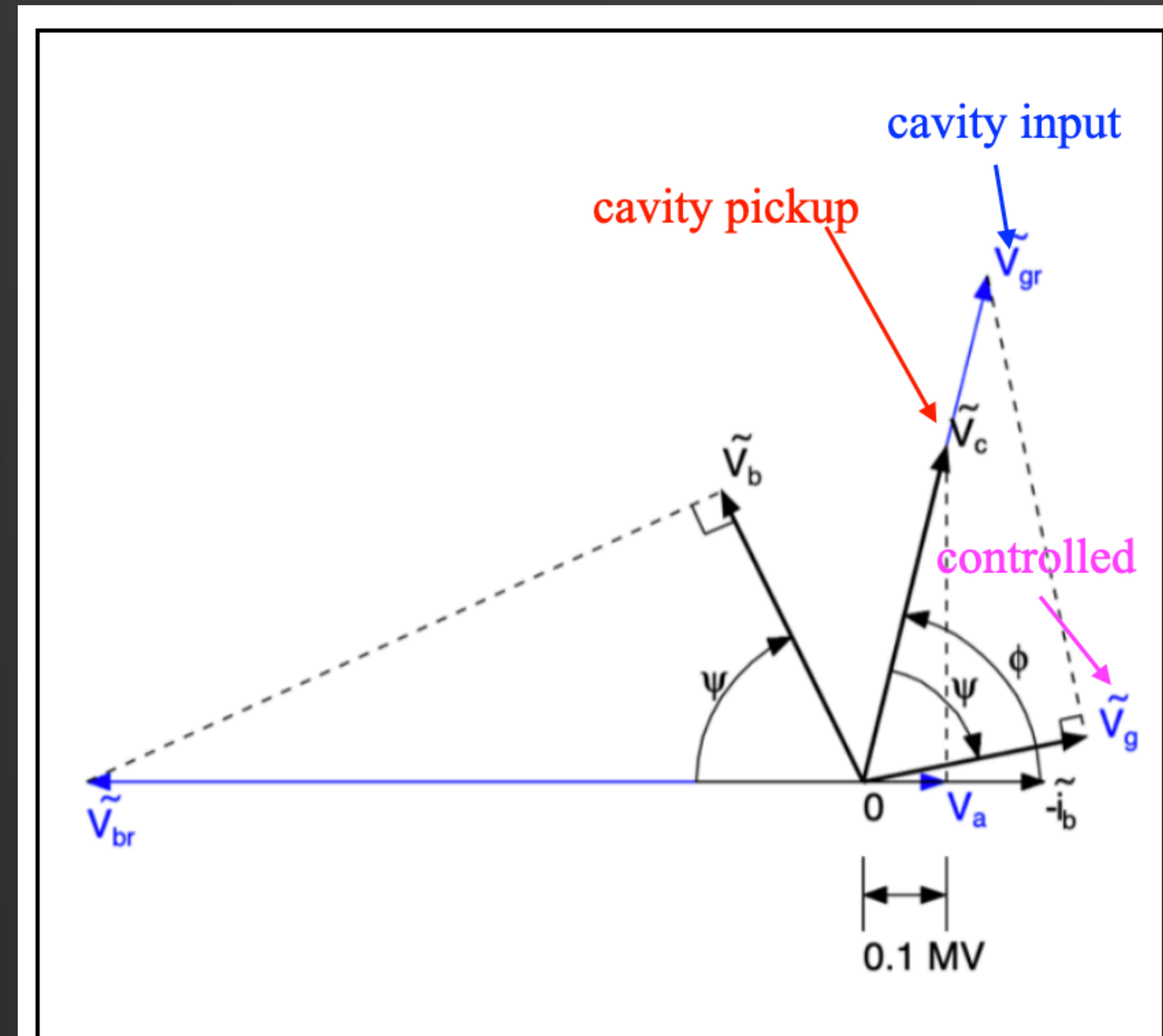
- Using cavity input signal, correct the ripple from the klystron power supply (< 10 kHz).
- Using cavity pickup signal, correct the variation induced by beam loading(∼several Hz).
- The cavity pickup FB output is used as the reference of the cavity input FB (double loop).
- IQ signals are converted to amplitude and phase for the feedback.

Amplitude and phase control with double loop FB

<RF phase at 0mA>



<RF phase at 450 mA>

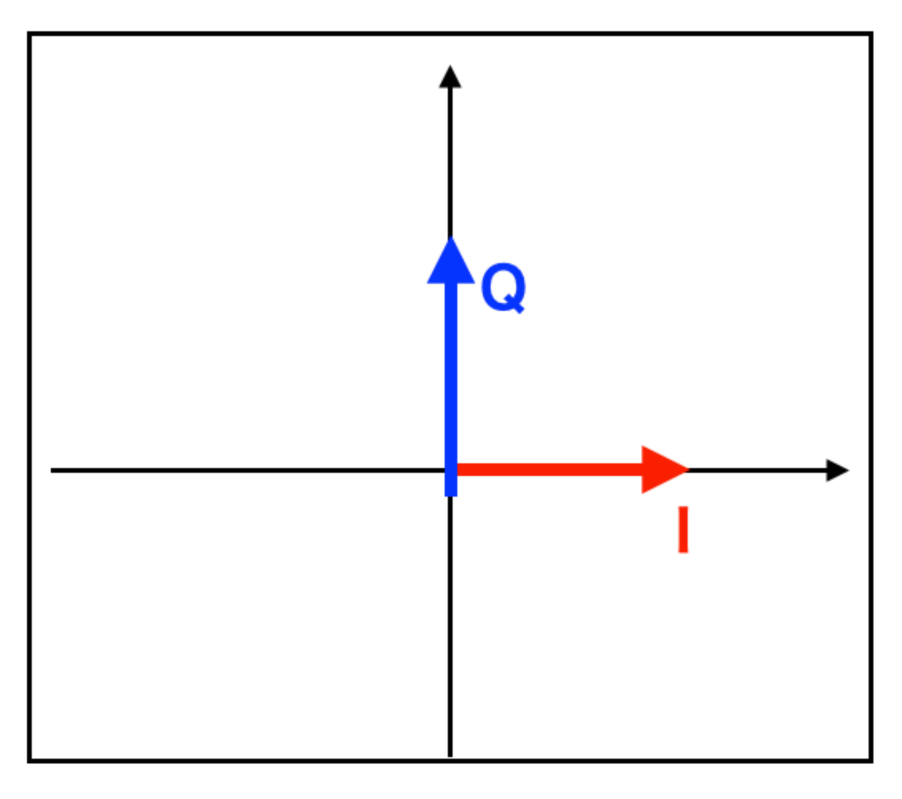


- ψ changes from 0 to 65° (0 mA to 450 mA).
  - The IQ phase also rotates viewed from the generator voltage.
  - The IQ feedback control becomes unstable without phase correction.

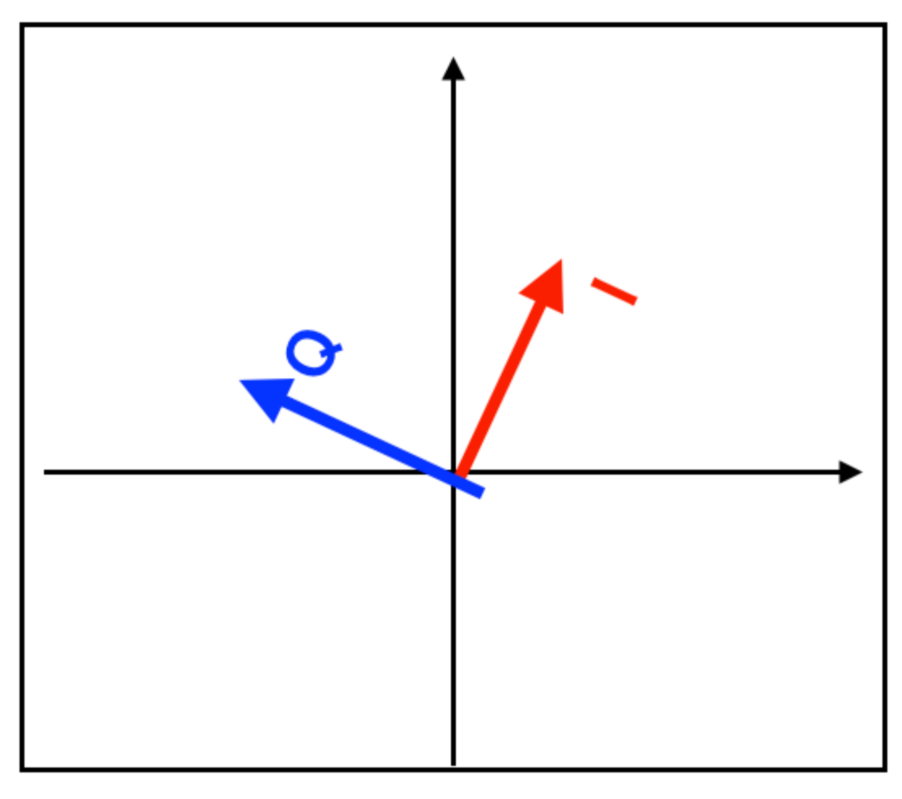
  => Using amplitude and phase control.
  - Advantage : not affected by the phase rotation.
  - Disadvantage : increase of the latency.

Feature of the new LLRF -Amplitude and phase CTL.-

<IQ phase at 0 mA>



<IQ phase at 450 mA>



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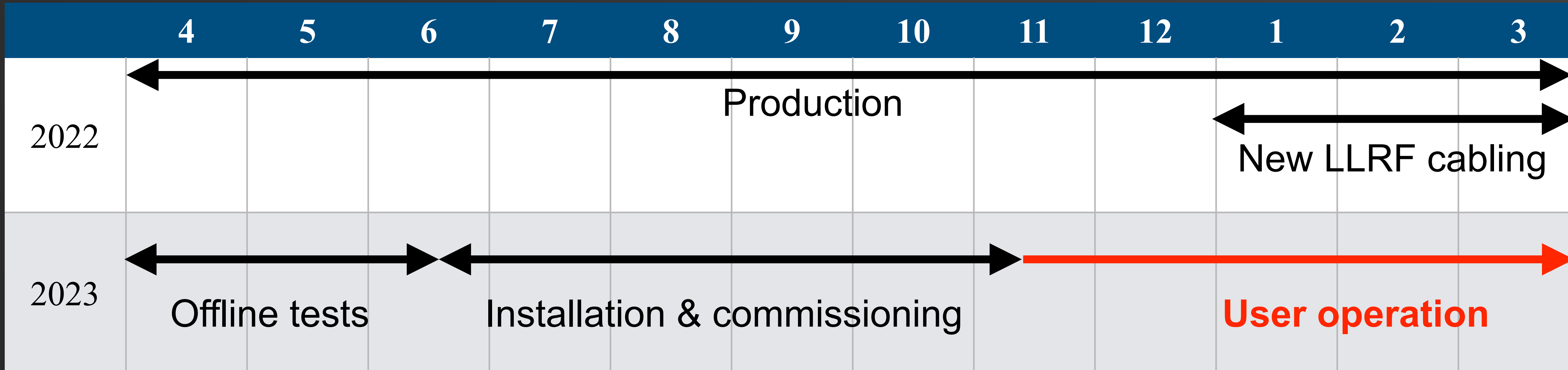
  => Using amplitude and phase control.
  - Advantage : not affected by the phase rotation.
  - Disadvantage : increase of the latency.

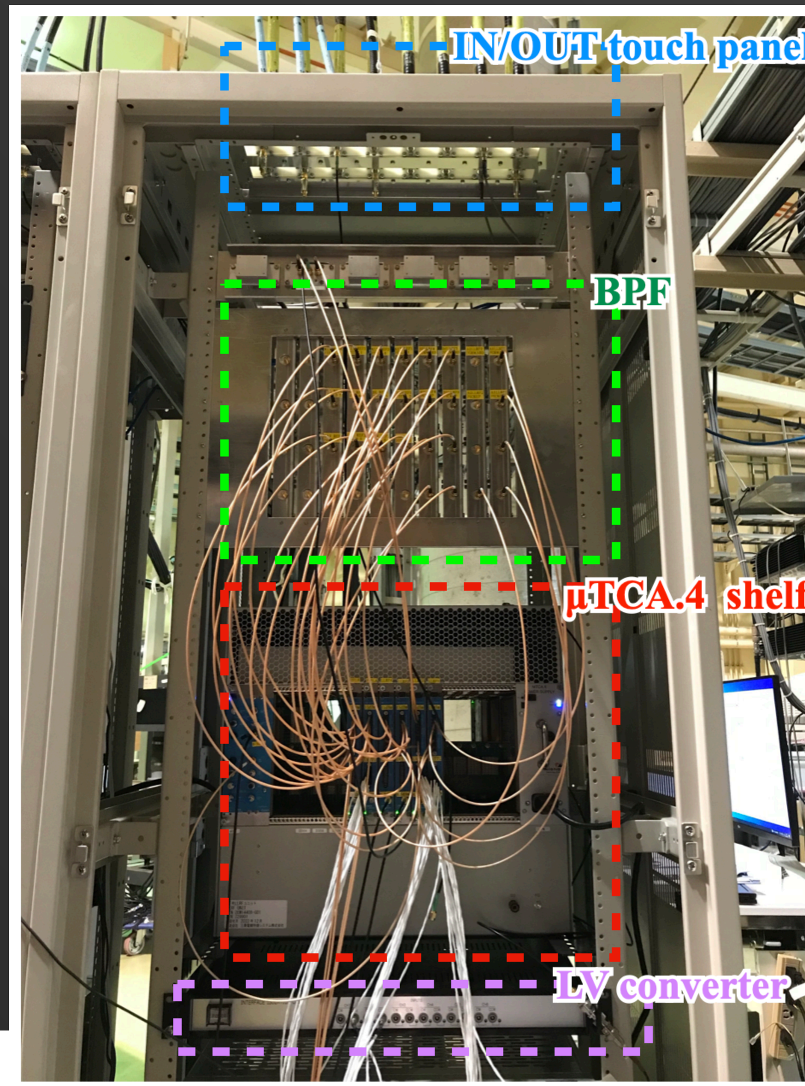
Status of the installation



- Product whole system in 2022.
- All components are installed.
- Performance check of all RF stations were almost completed.
- Currently, under commissioning to establish the control parameters and procedures for the user operation.
  - **We need to finish the commissioning until Nov. 7th!**

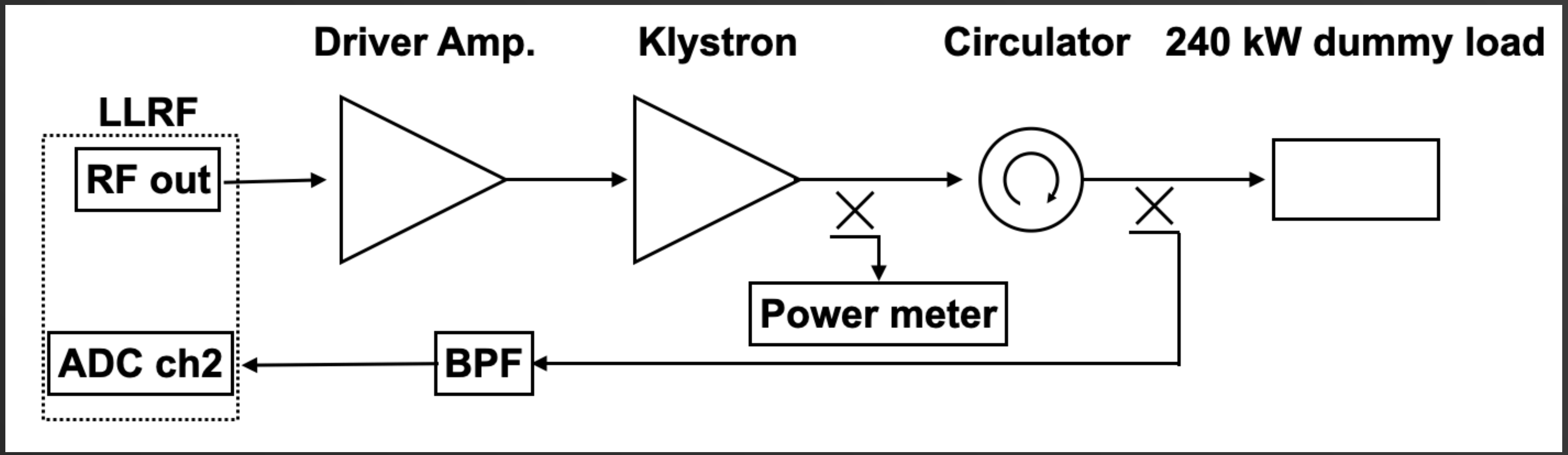
- Highlights of the performance check
  - Comparison of the stability between analog and digital LLRF.
  - Delay measurement.
  - Feedback parameter sweep.
  - Stability check.

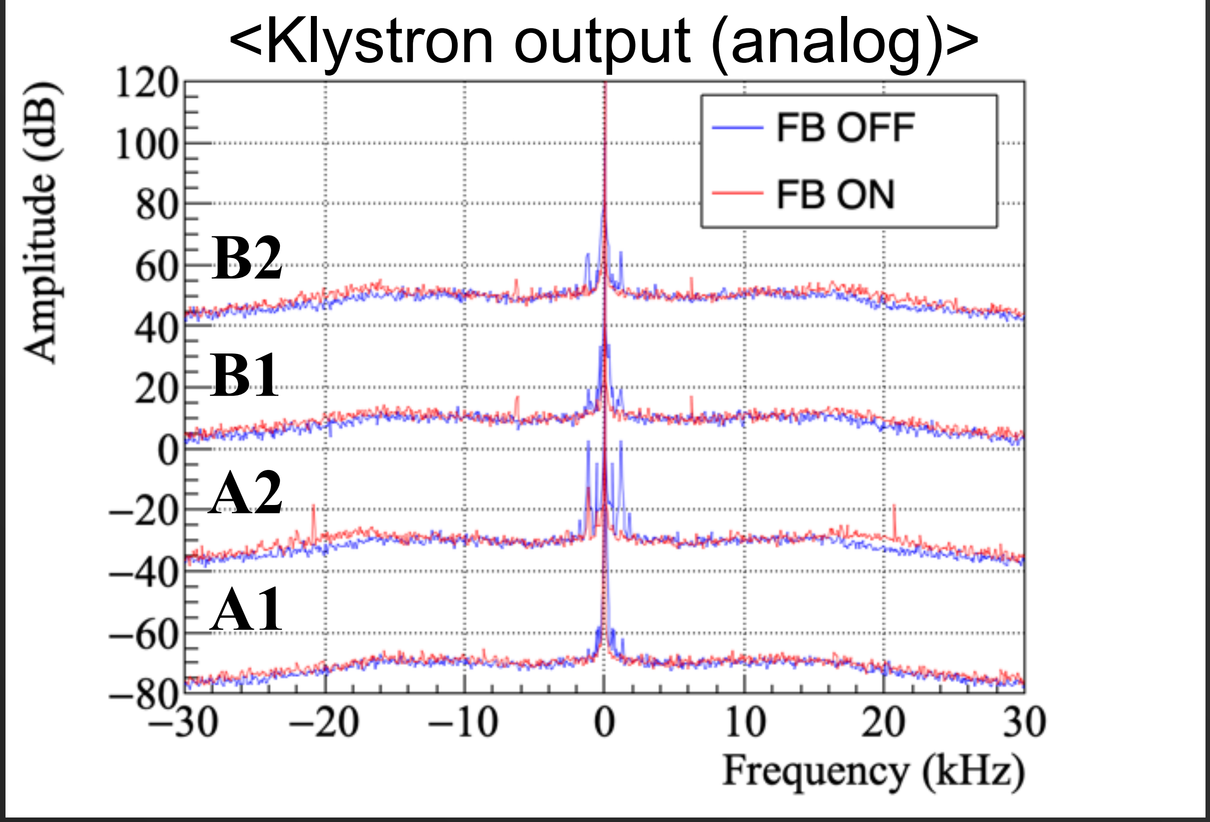
<Photo of the new LLRF>

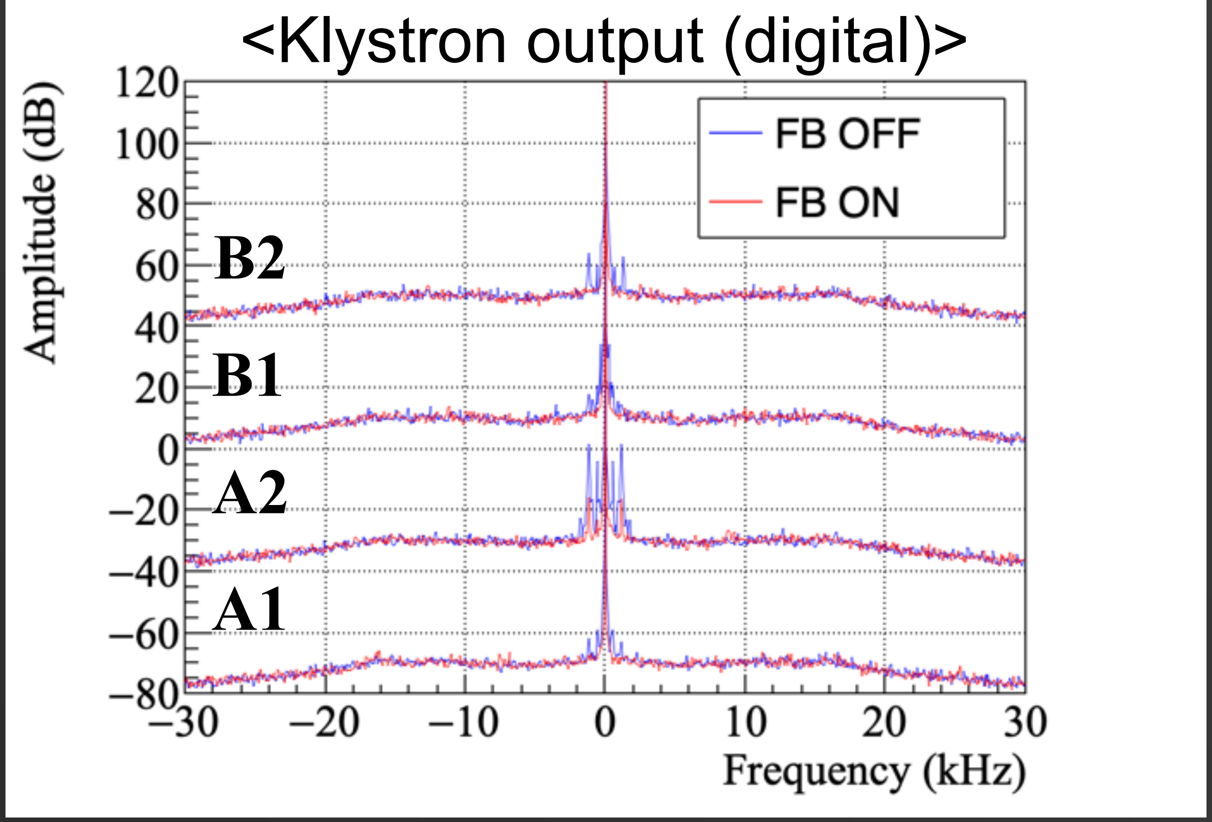


Performance evaluation (1): stability of klystron output

<Experimental setup>



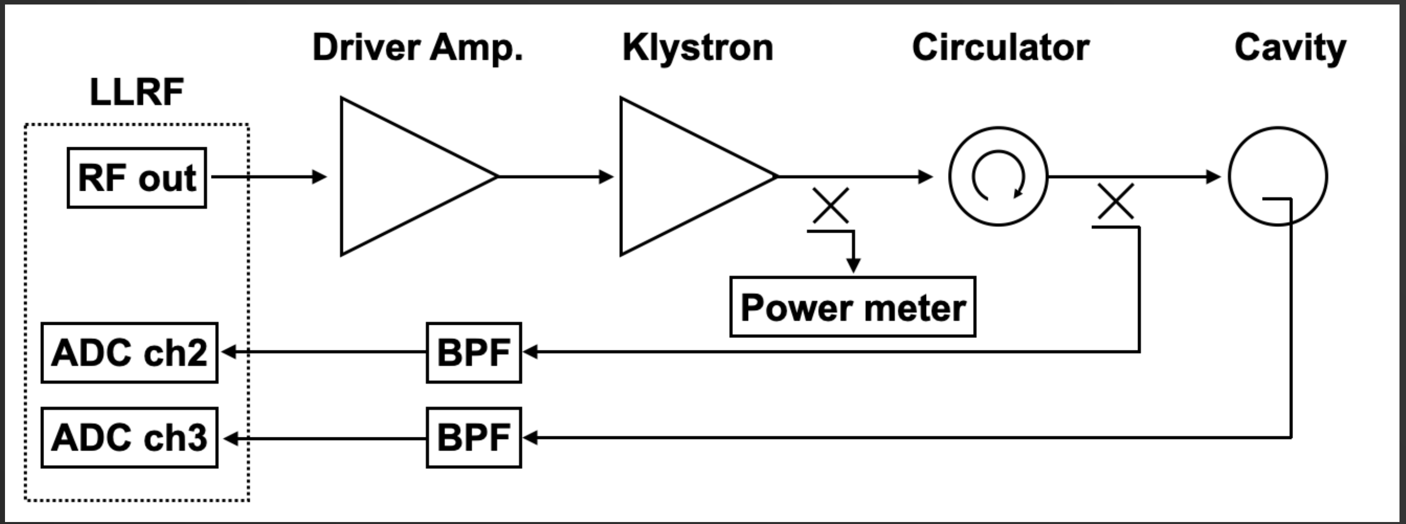




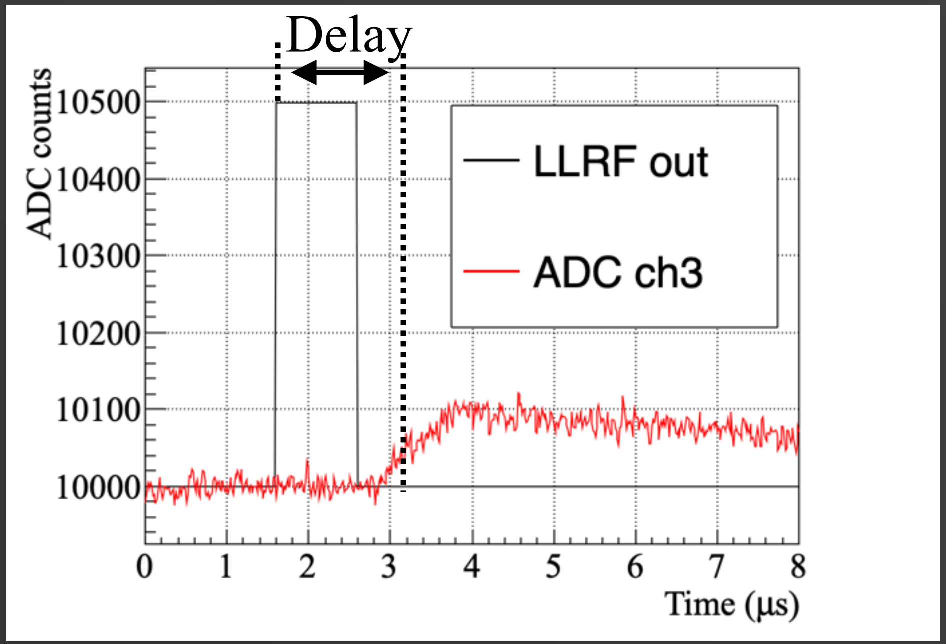
- Control the klystron output only (single loop control).
- Klystron power was set to be 20 kW (1/4 of that at the user operation).
- With the analog LLRF, the feedback amplified some noise.
- The feedback with the digital LLRF was controlled better than that with the analog LLRF.

Performance evaluation (2): Delay time measurement

<Experimental setup>

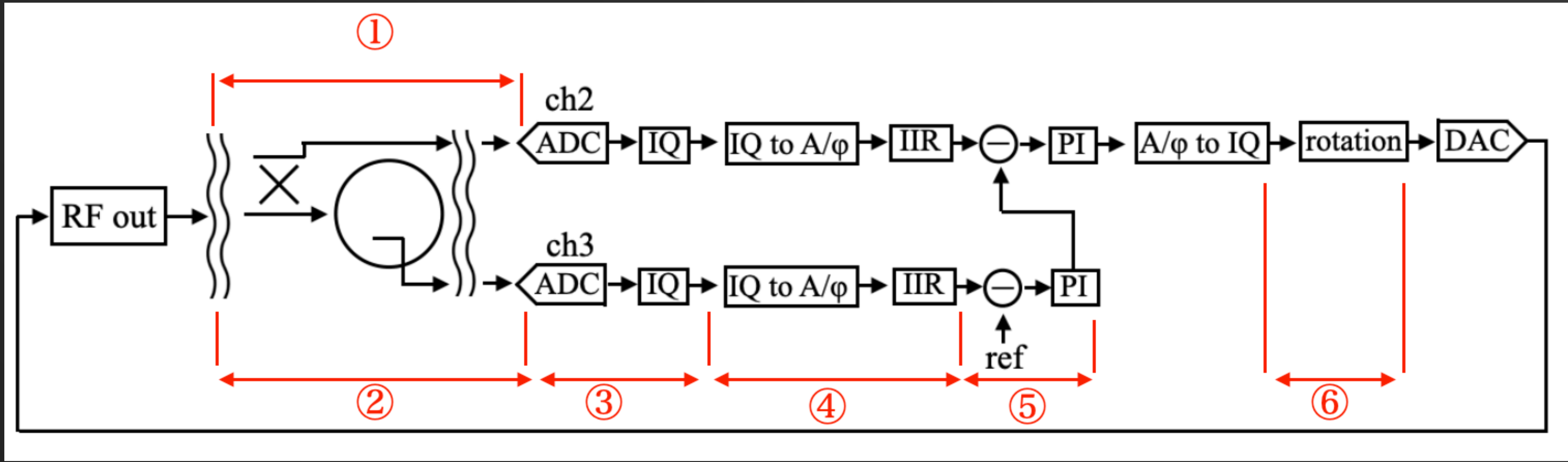


<Impulse pattern>



- Output impulse from the digital LLRF out.
- Measure the waveform at individual process stage in LLRF.

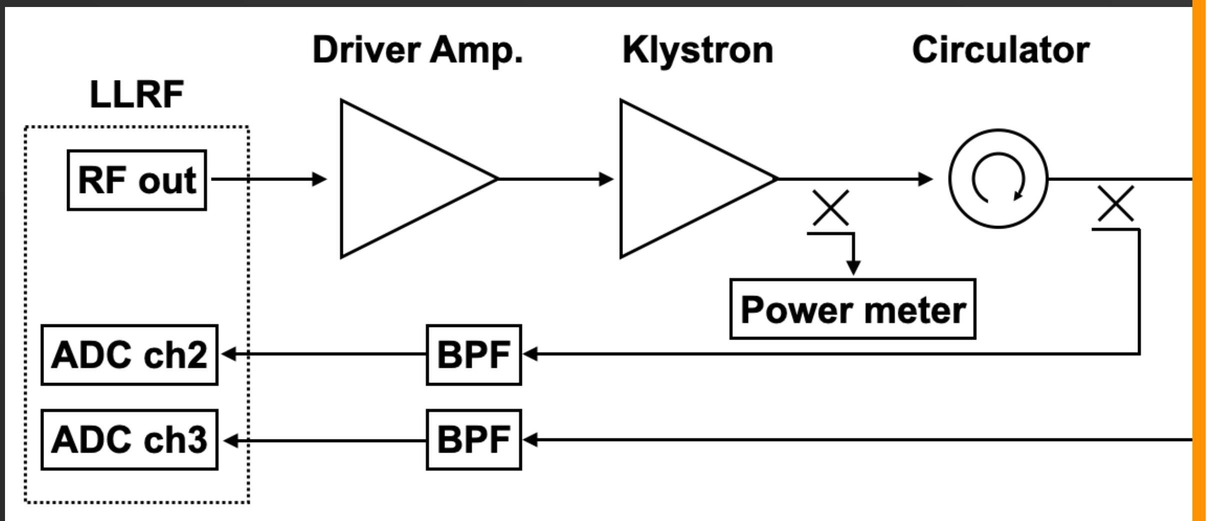
<Definition of the measurement points>



- IQ conversion (data transfer from ADC to FPGA) and A/φ conversion (codec calculation) have large delay in the digital LLRF.
- Total delay is ~ 3 μs => It is acceptable for our situation.

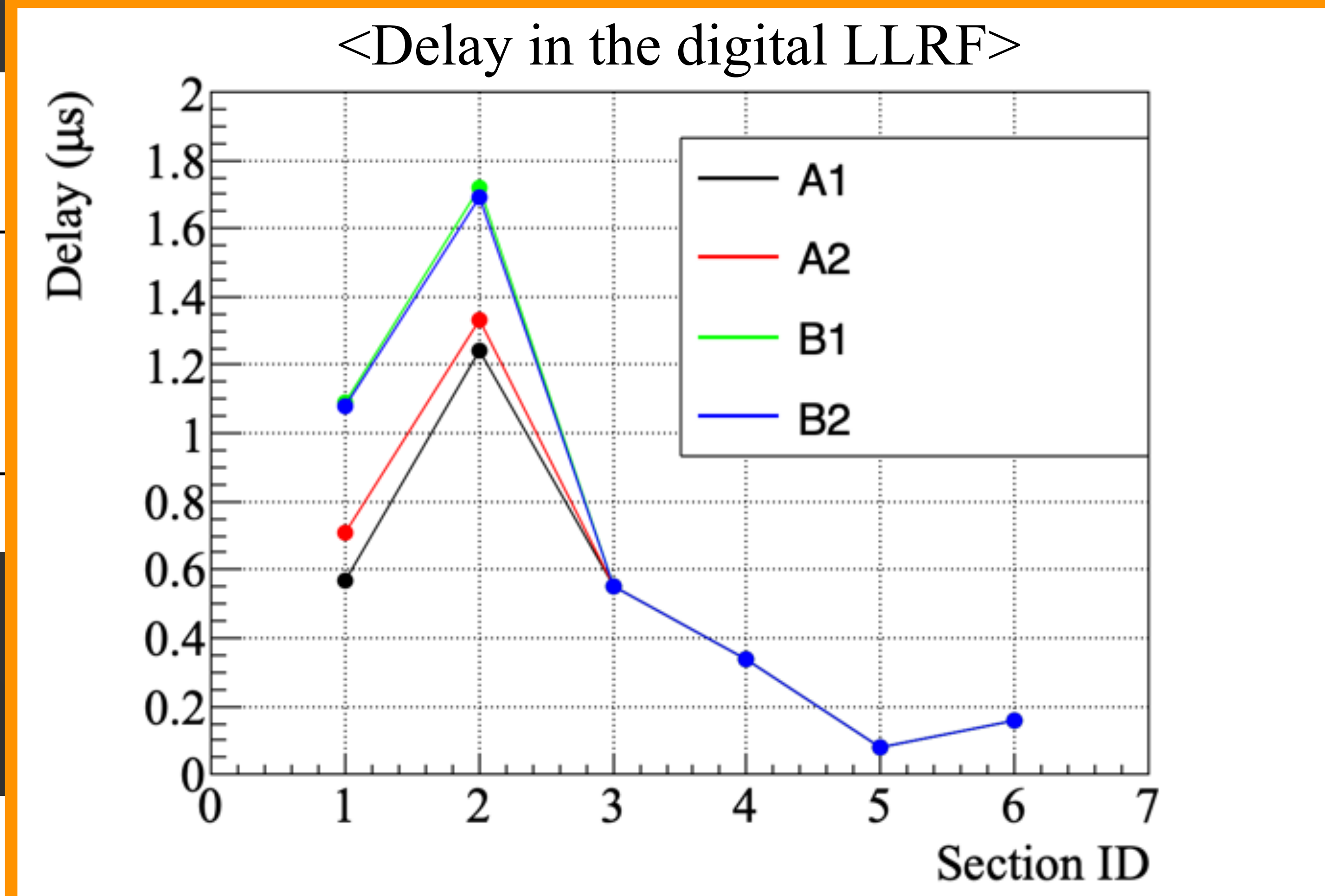
Performance evaluation (2): Delay time measurement

<Experimental setup>

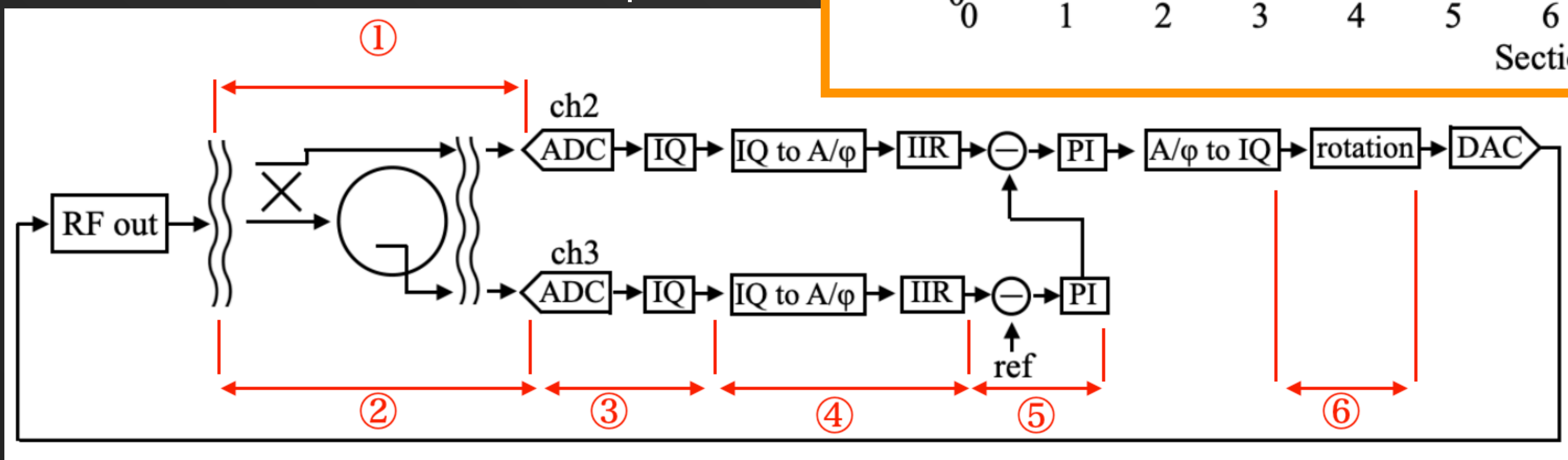


- Output impulse from the digital LLRF out.
- Measure the waveform at individual process

<Delay in the digital LLRF>



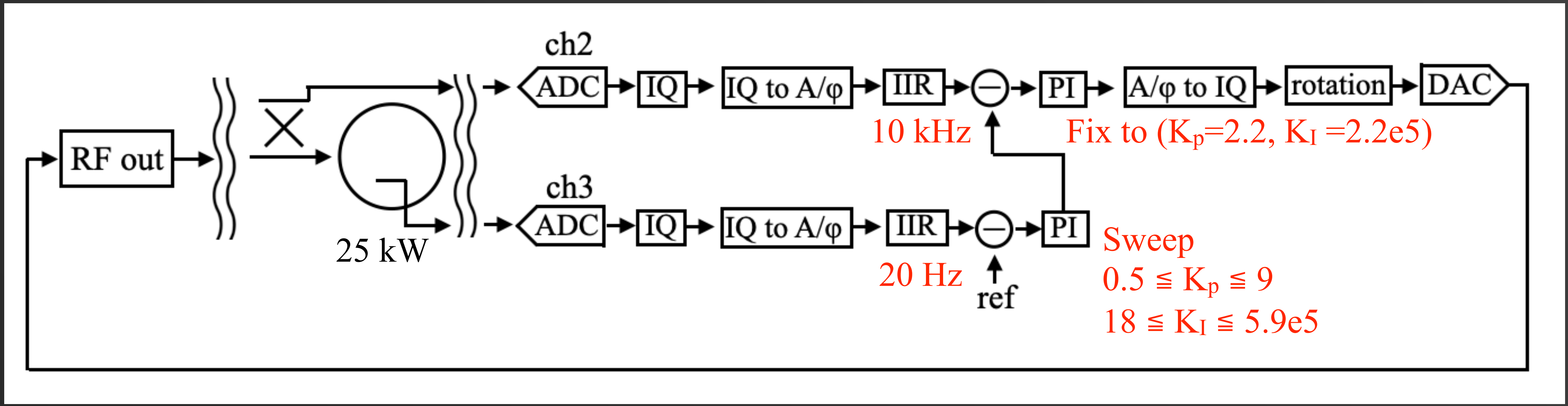
<Definition of the measurement points>



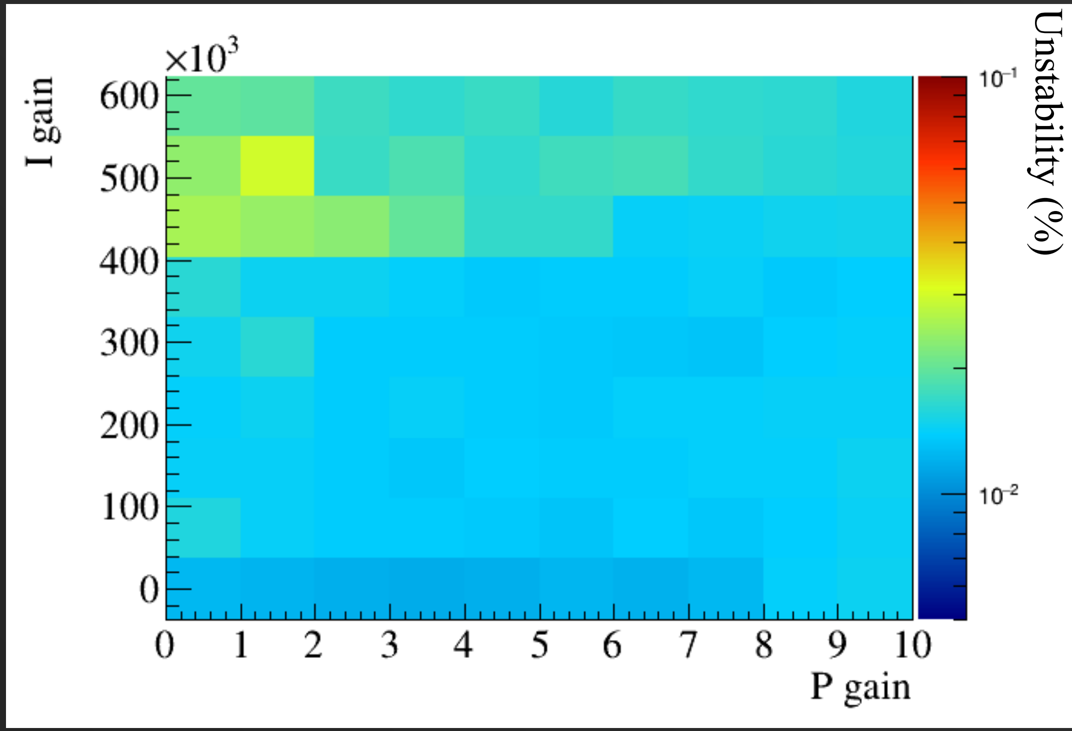
- IQ conversion (data transfer from ADC to FPGA) and A/φ conversion (codec calculation) have large delay in the digital LLRF.
- Total delay is ~ 3 μs => It is acceptable for our situation.

Performance evaluation (3): test of double feedbacks

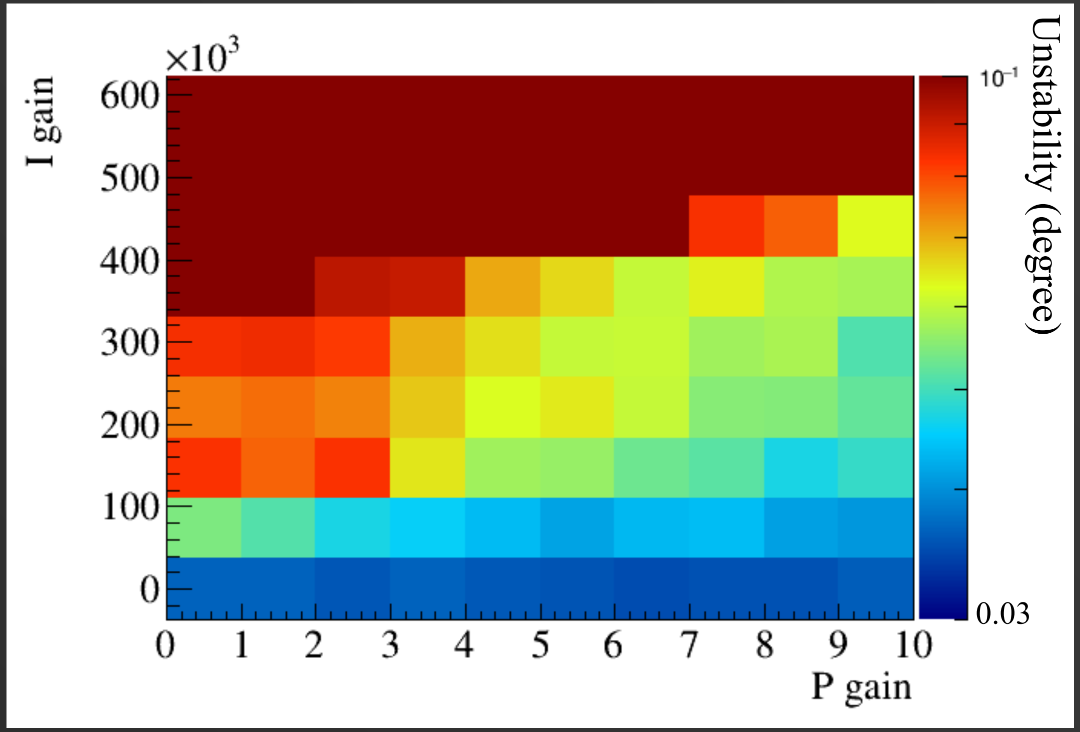
<Experimental setup>



<Stability of cavity voltage amplitude>



<Stability of cavity voltage phase>

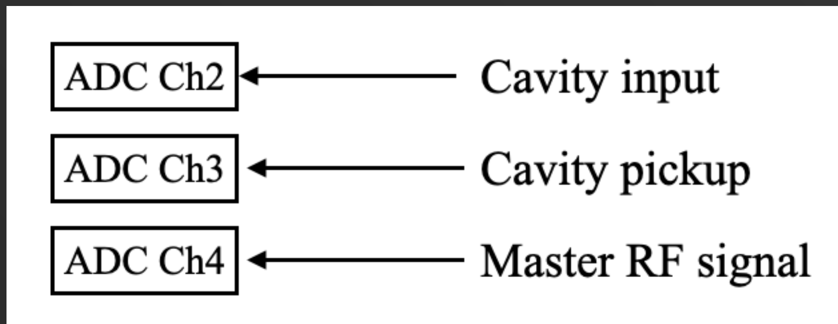


- After fine scan of low gain region, we set the PI parameters to be (K_p, K_I) = (2, 7.3e3).
  - Amplitude stability @ (2, 7.3e3) : ± 0.015 %
  - Phase stability @ (2, 7.3e3) : ± 0.038 °

  => Achieve our goal (< ± 0.1 %, < ± 0.1 °)

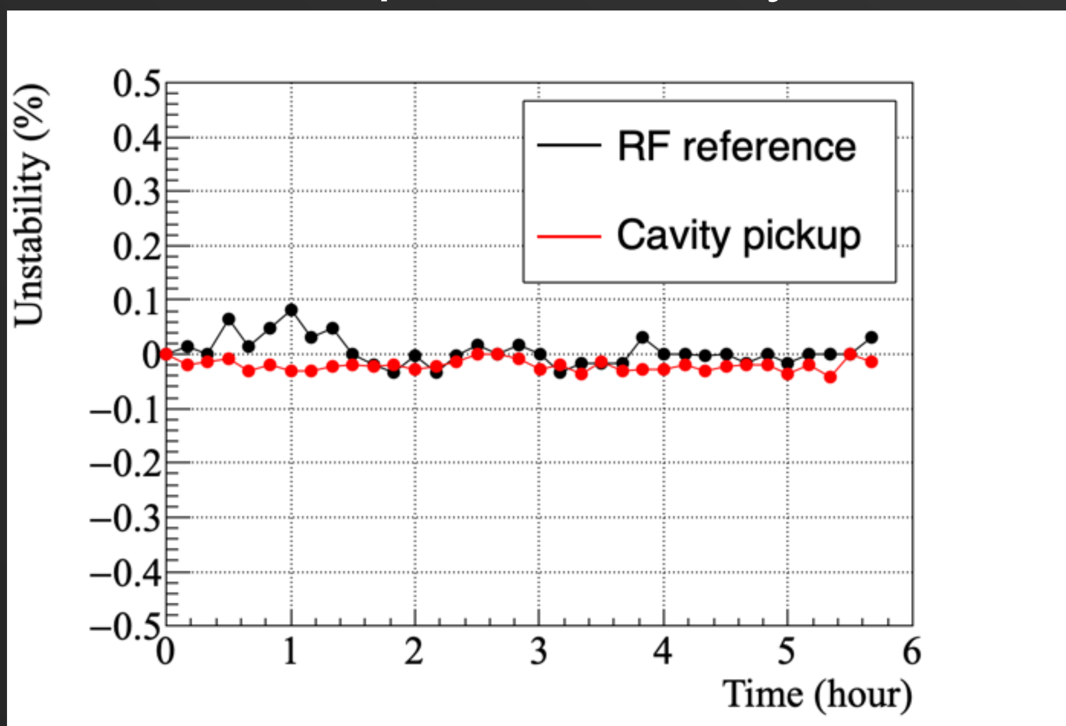
Performance evaluation (4): stability tests

<Experimental setup>

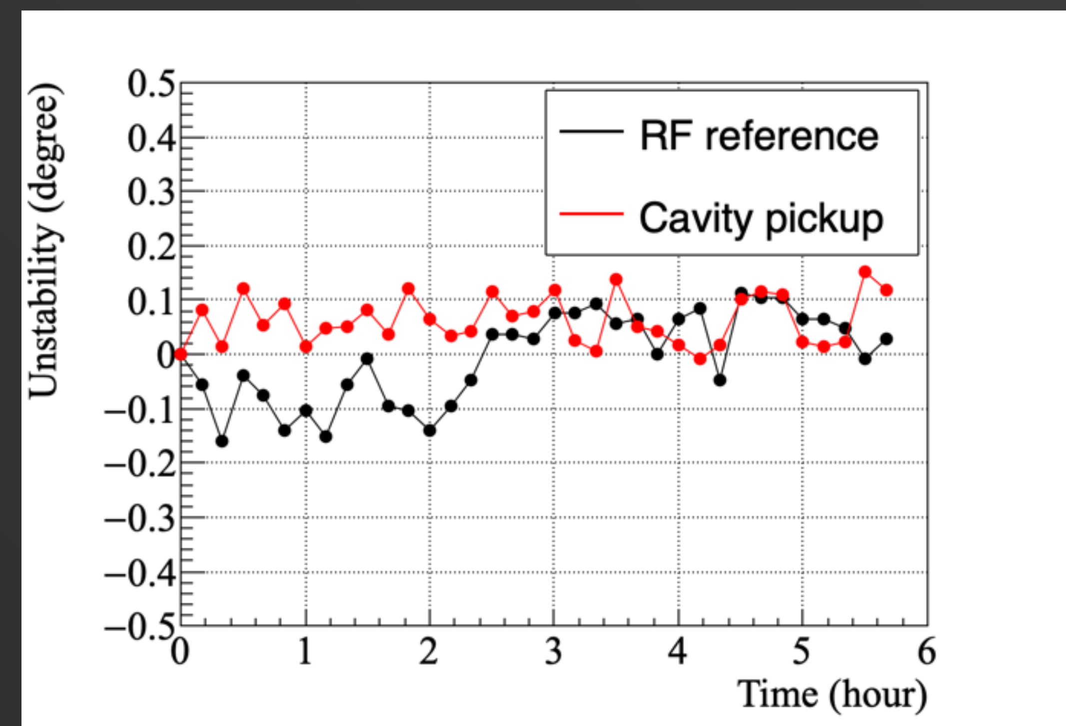


- Set parameters used for the beam operation
- Evaluate the stability of cavity pickup signal (cavity voltage).
- Measure master RF signal to check ADC stability.
- Amplitude and phase were recorded by every 10 minutes.
- Temperature in the shelf was 25.5±0.1 °C.

<Amplitude stability>



<Phase stability>



- Achieved amplitude stability of ±0.011%, phase stability of ±0.044°.
- Assumed that the observed deviation of the master RF came from the ADC unstability.

  -Observed outside of the LLRF, cavity pickup also deviate according to the ADC unstability.

  - Total stability = $\sqrt{(\text{cavity unstability})^2 + (\text{master RF unstability})^2}$

=>**Amplitude stability : ±0.03%, Phase stability : ±0.09°**

The stability was expected to satisfy our goal.

Summary

● We replace the analog LLRF with the digital one
  -Improve the maintainability and develop technologies for the next generation light source.

● Feature of the new LLRF
  - Adopt non-IQ direct sampling
  - Realize fast bunch phase detection to compensate the TBL in the KEK future light sources.

● Installation status of the new LLRF.
  - Completed cabling and hardware install.
  - Checked the performance of the new LLRF.
  - Achieve amplitude stability of ±0.01 %, phase stability of ±0.04° at the tentative tests.
  - Under commissioning to establish the control parameters and procedures for the user operation.
  - Commissioning with storage beam will begin on November 7th.

※ Mitsubishi electric defense and space technology corporation

Acknowledgement

Thanks to the following MEDS* staff for their dedication to producing the new LLRF system:

T. Iwaki, R. Kitagawa, N. Terada, T. Harigae, S. Yamazaki, and M. Ryoshi

Thanks to the following researchers for useful information and discussions:

T. Ohshima (SPring-8), F. Tamura (JAEA), T. Kobayashi, Y. Sugiyama, K. Futatsukawa, T. Matsumoto, and T. Miura (all of KEK).

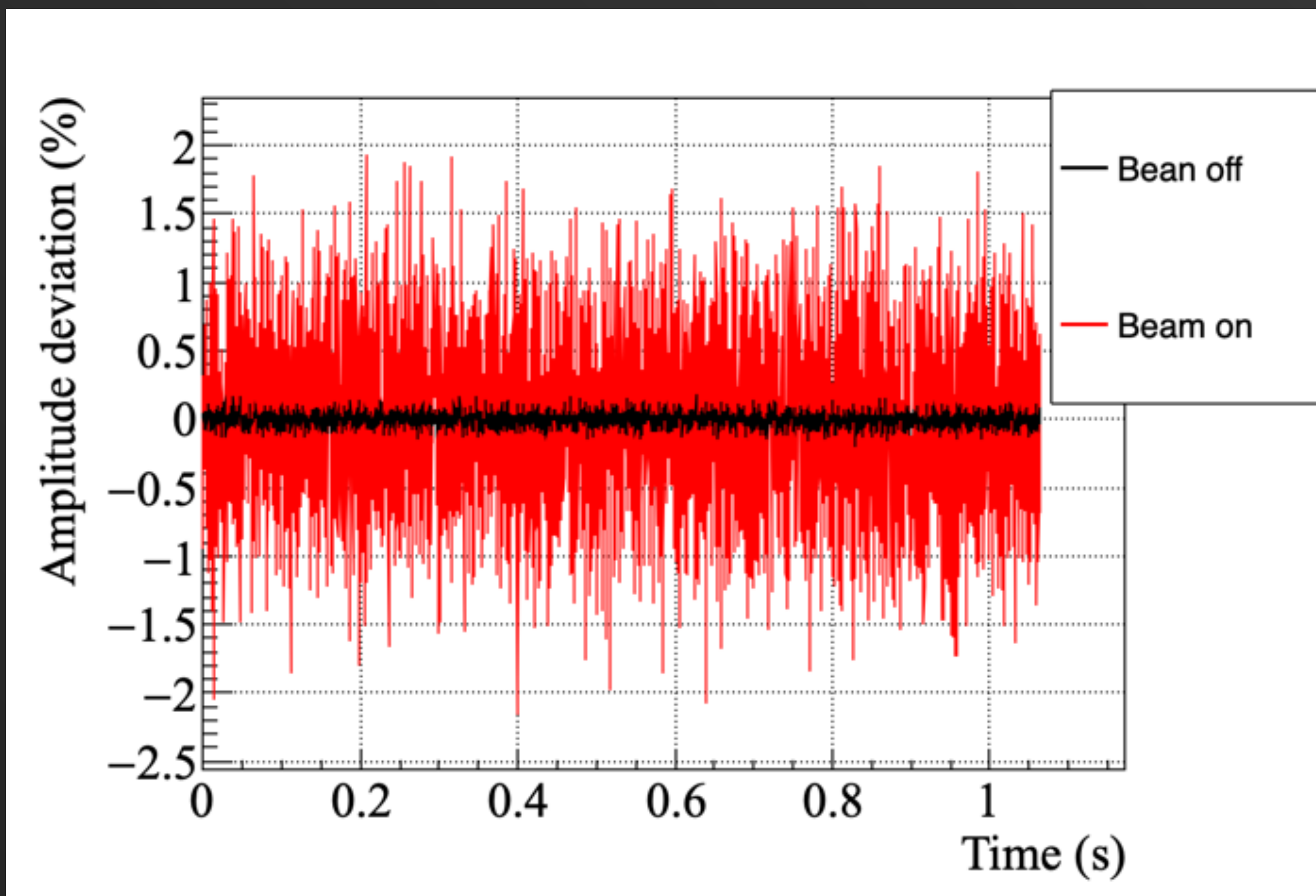
*Mitsubishi electric defense and space technology corporation

Appendix

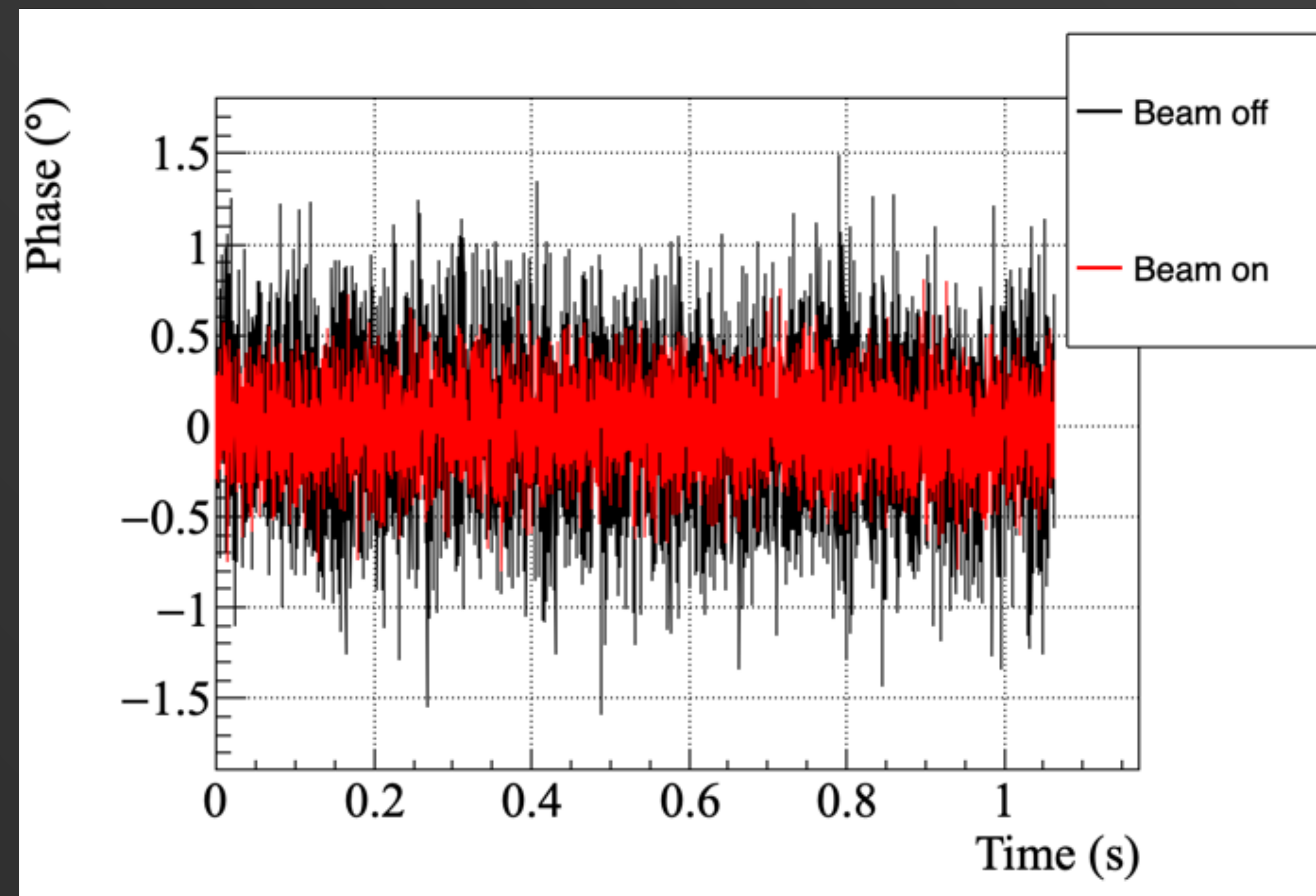
Stability of the analog LLRF system

- Measure the stability of the cavity voltage.

<Amplitude>

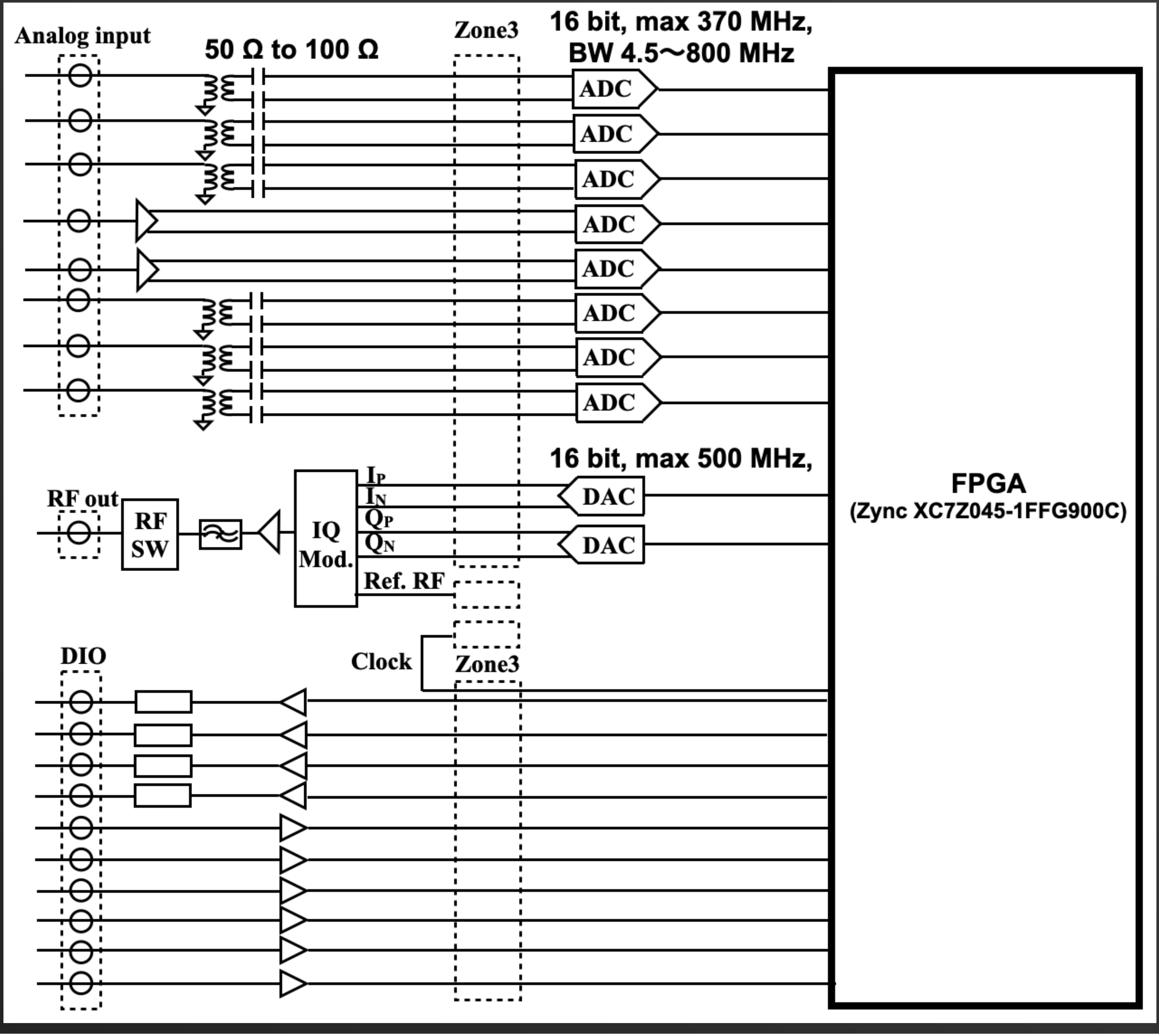


<Phase>

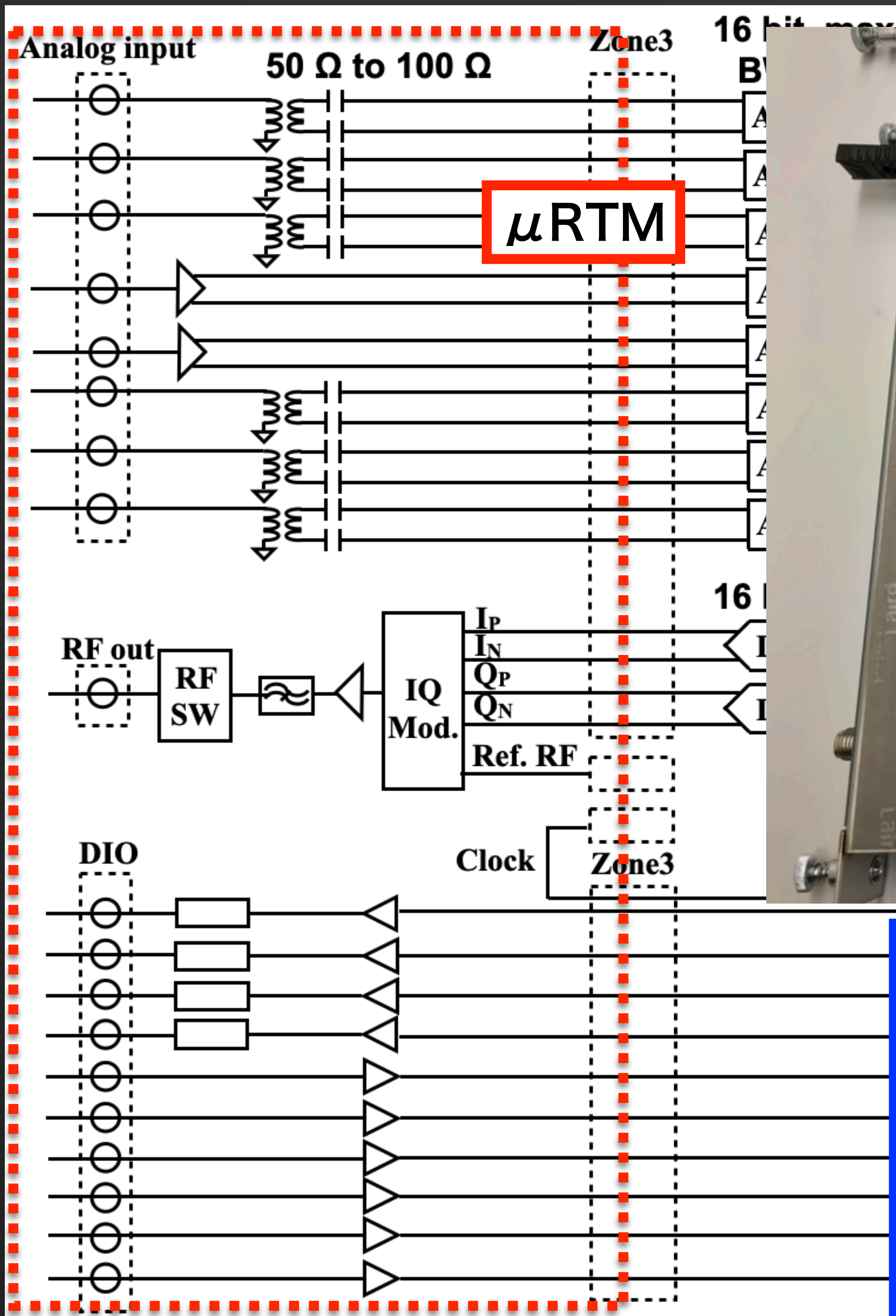


- Amplitude stability changes from ±0.07 to ± 0.52 % (0 mA to 450 mA).
  - Amplitude oscillates with the synchrotron frequency where beam on.
- Phase stability changes from ± 0.55 ° to ± 0.12 ° (0 mA to 450 mA).

Hardware of the LLRF

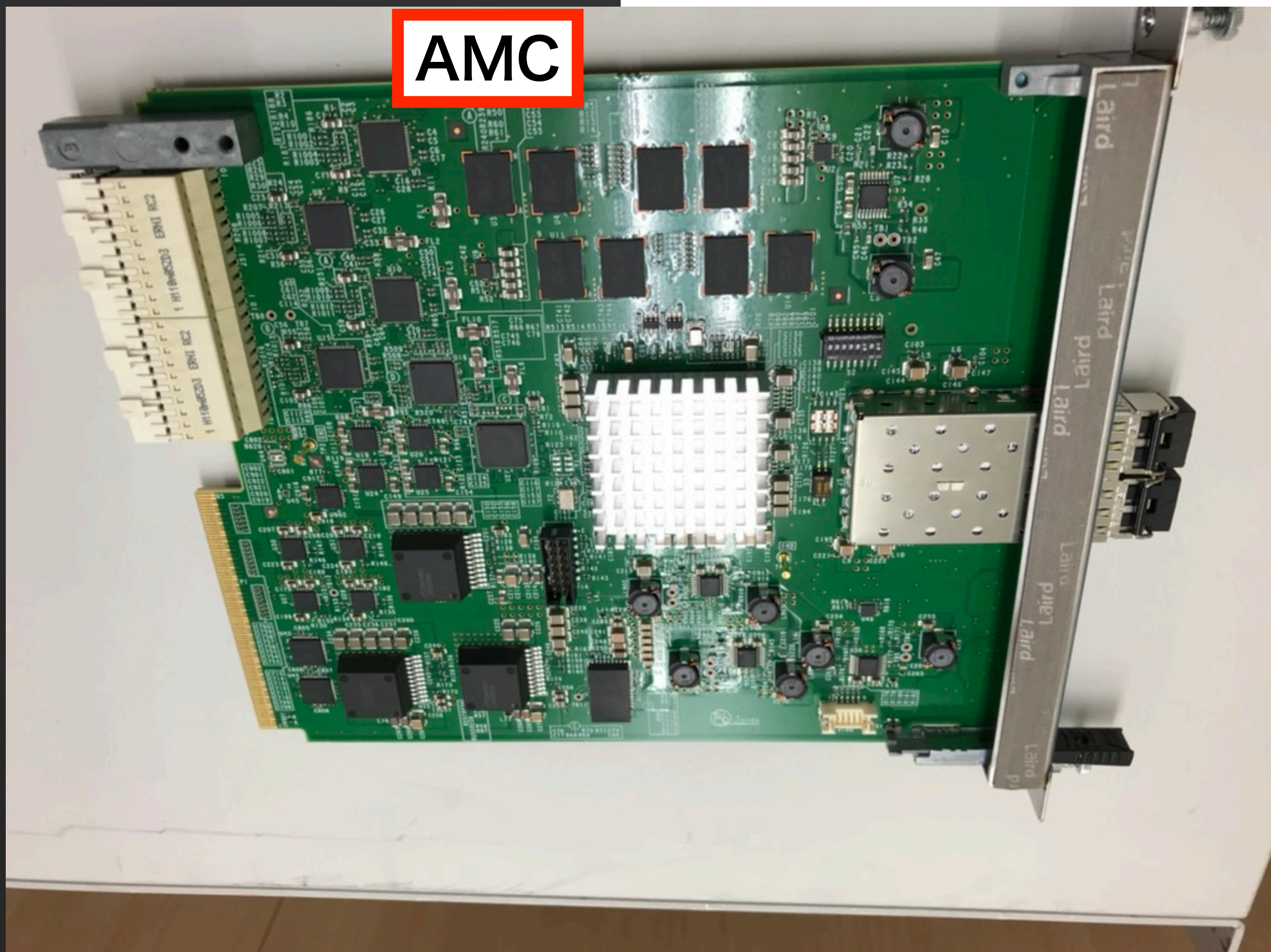


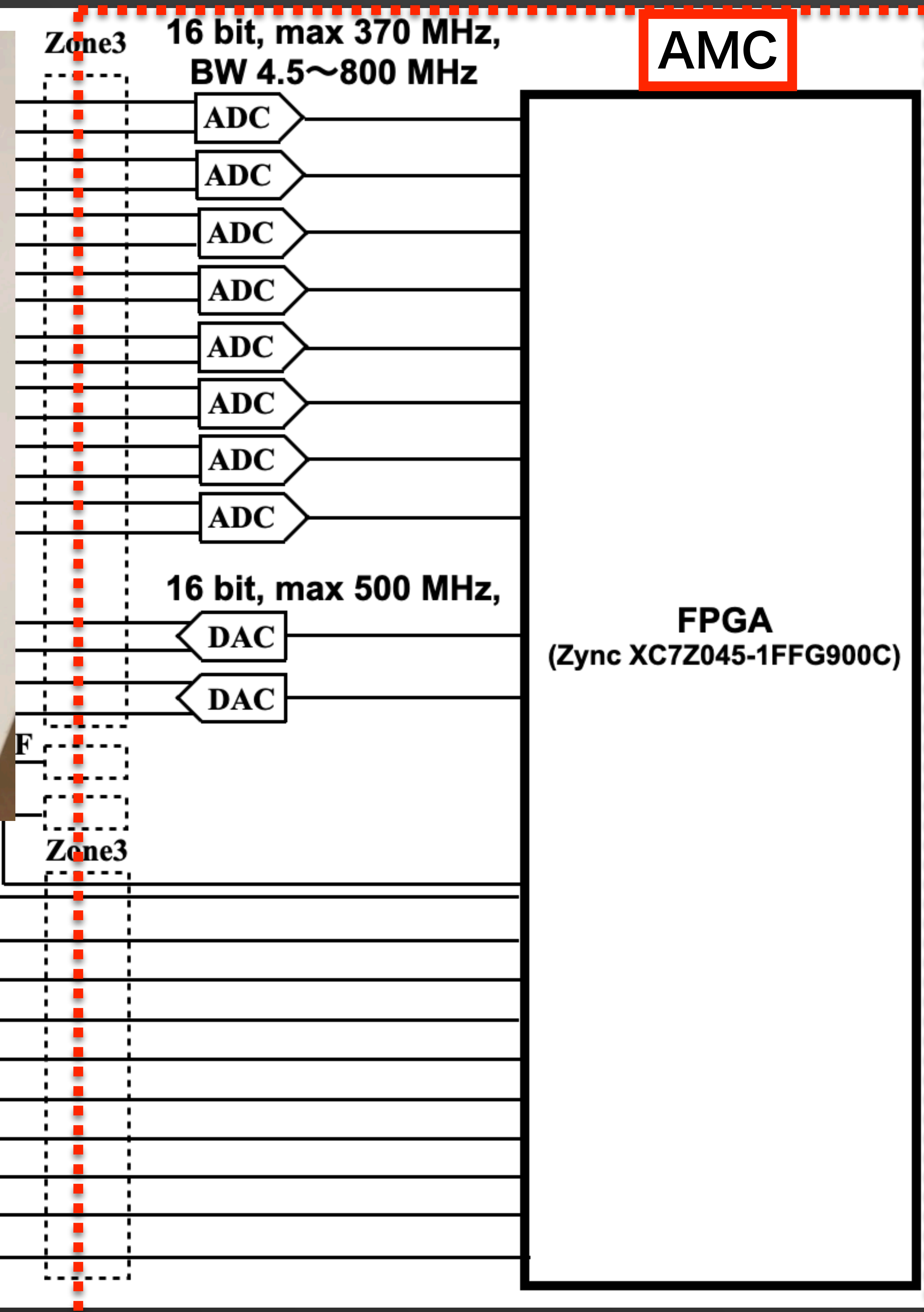
Hardware of the LLRF



Paremeter	Value
# of AC analog inputs	6
# of DC analog inputs	2
# of IQ modulator	1
Maximum RF output	8.3 dBm
# of DIO out	4 (LVTTL)
# of DIO in	6 (TTL or LVTTL)

Hardware of the LLRF





Paremeter	Value
# of ADC	8
Maximum ADC range	15 dBm
Rating of analog circuit	18 dBm
# of DAC	2
# of DIO	10

Hardware of the LLRF

Module	Develop policy	Model No.	Company
Shelf	use commercial model	UB1K-6509 (PICMG MTCA.4 R1.0)	U-ber (nVent)
PM	use commercial model	210113-0133	Wiener
MCH	use commercial model	NAT-MCH0CLK-PHYS	NAT
eRTM	use the module developed by SPring-8	72CGR500A01	Candox
µRTM	modify the module developed by J-PARC LINAC	MME-DSV04-B	MEDS*
AMC	modify the module developed by J-PARC MR	MME-ADC22-B	MEDS*

RF control |

-Stabilization of the cavity voltage | adapt the same control scheme as the SPring-8 system.

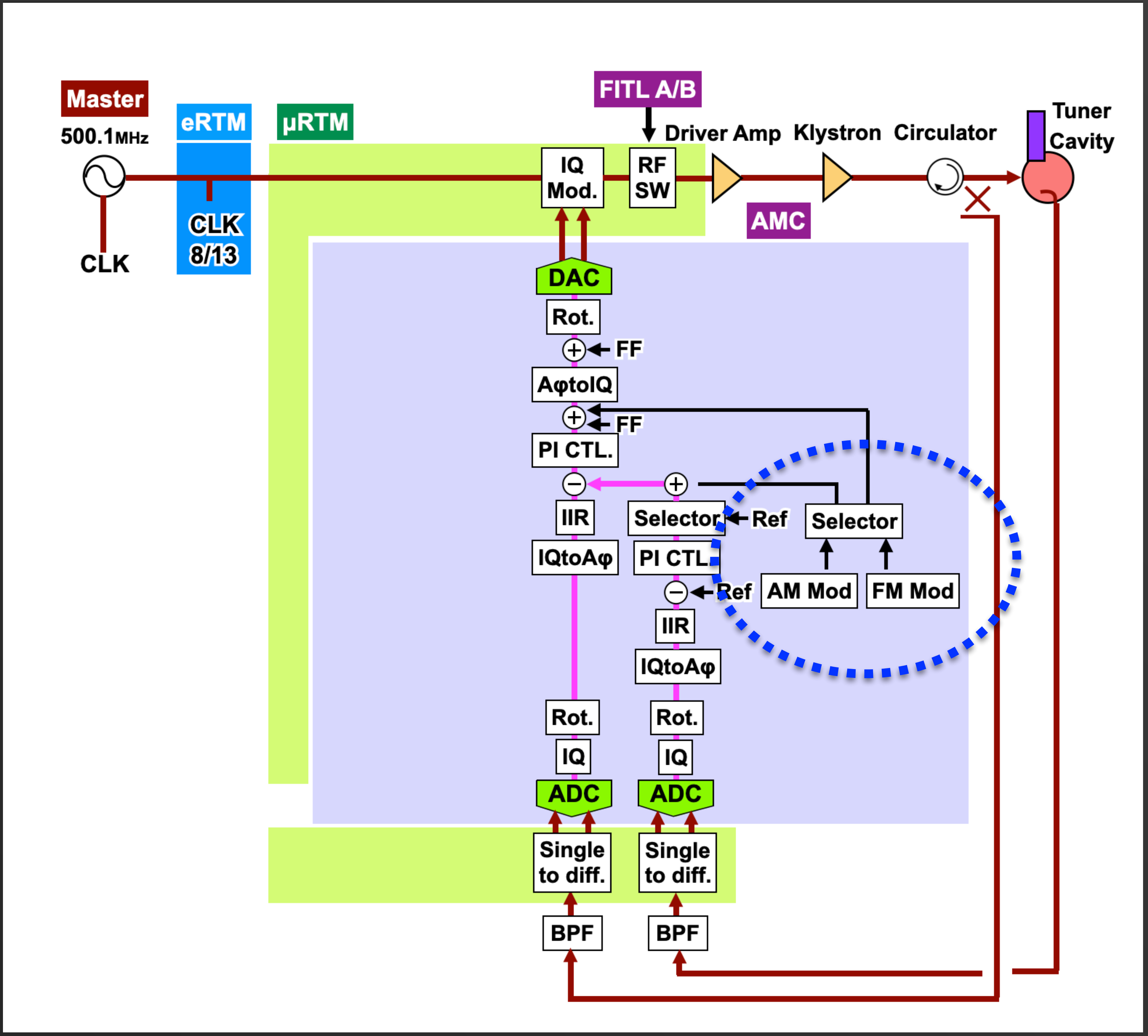
-Control of the cavity tuner | adapt the same control scheme as the Super-KEKB system.

Use and modify modules developed by other institutes
=> Reduce development costs, periods, risks.

Our goal :
Amplitude stability of the cavity voltage < ± 0.1 %
Phase stability of the cavity voltage < ± 0.1 °

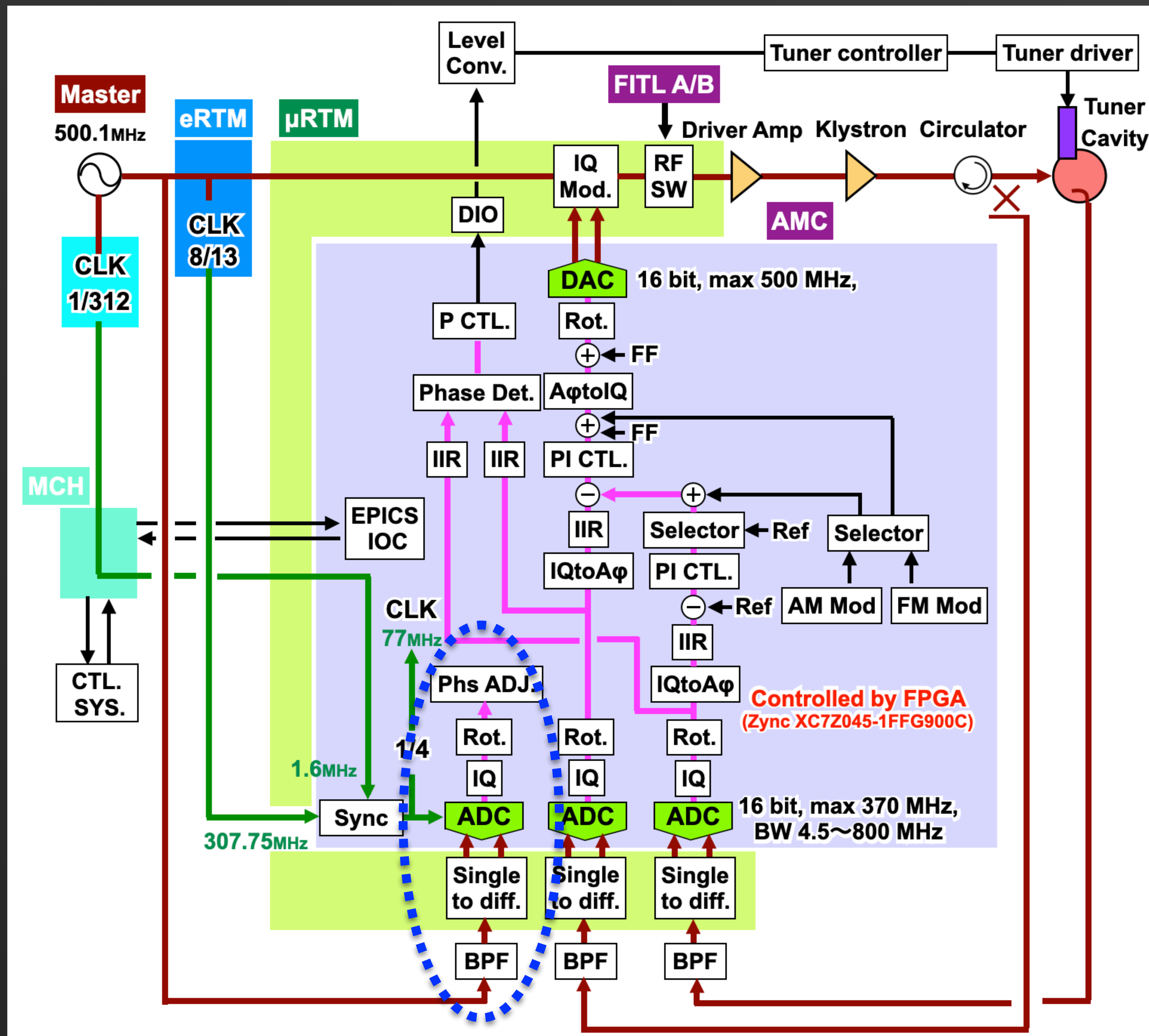
* Old name : Mitsubishi Electric TOKKI Systems

Feature of the new LLRF -FM/AM modulator-



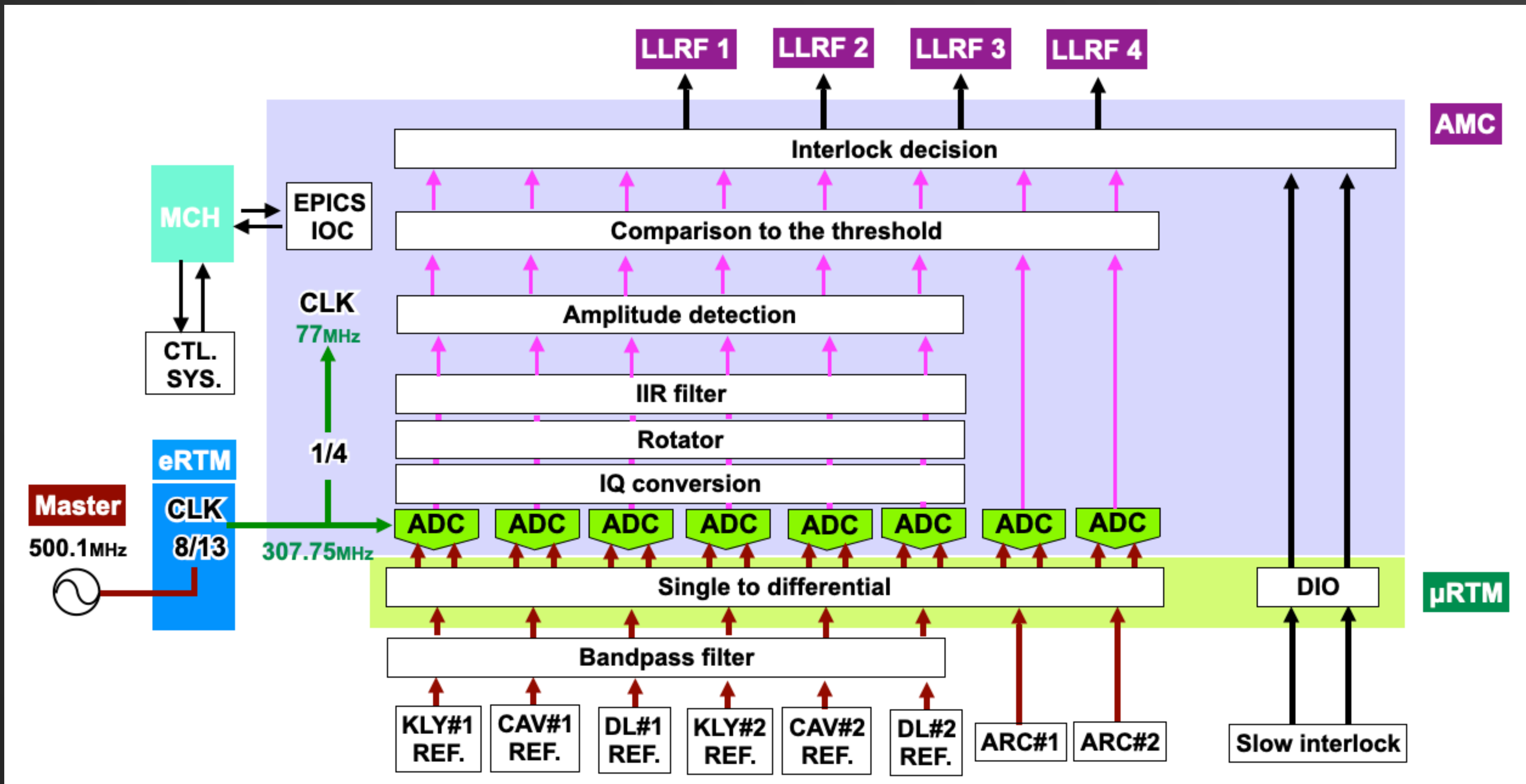
- Adopt FM/AM modulator to mitigate a quadrupole oscillation of the beam.
  - Use NCO and synchronize the modulator in all boards.

Feature of the new LLRF -Phase adjust-



- Adjust phase shift of the AMC board to the master RF signal.
  - Phase shift caused by on/off of the electric power.

Fast interlock boad



Unstability of all RF stations (Amplitude)

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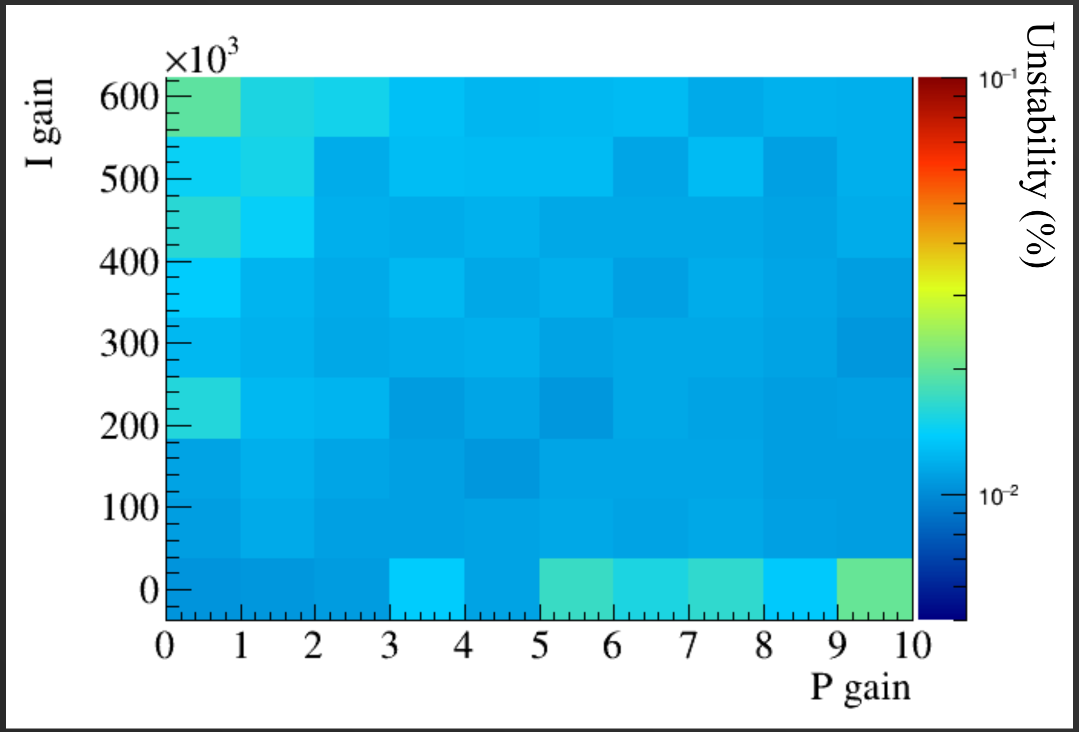

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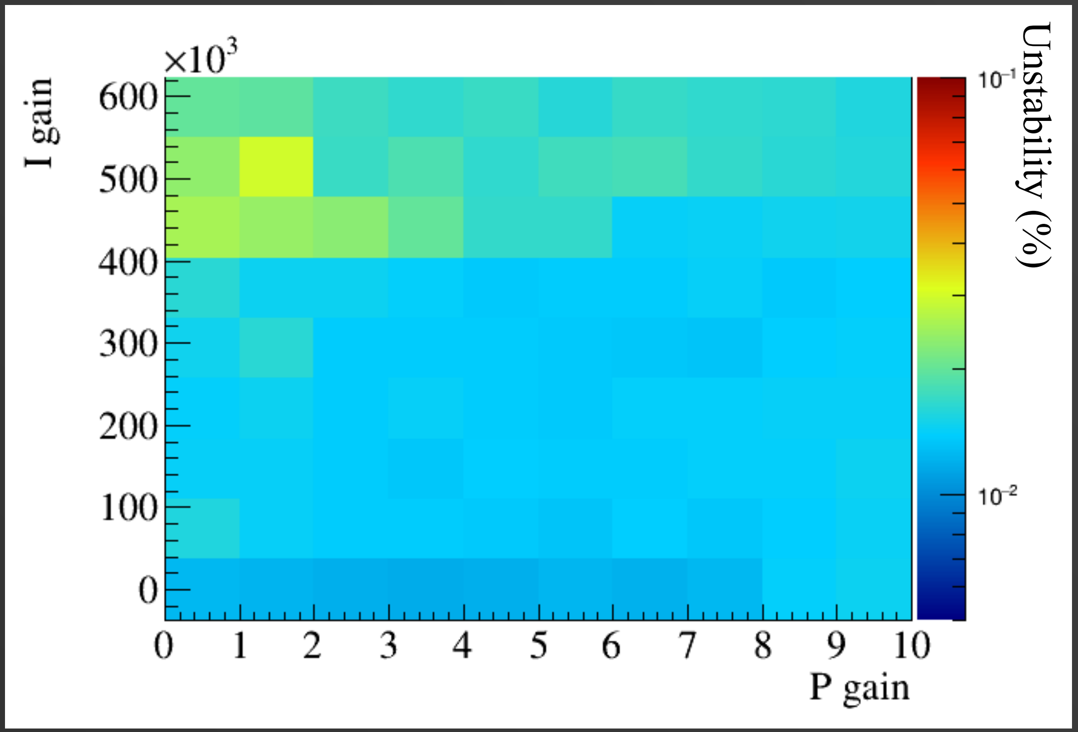

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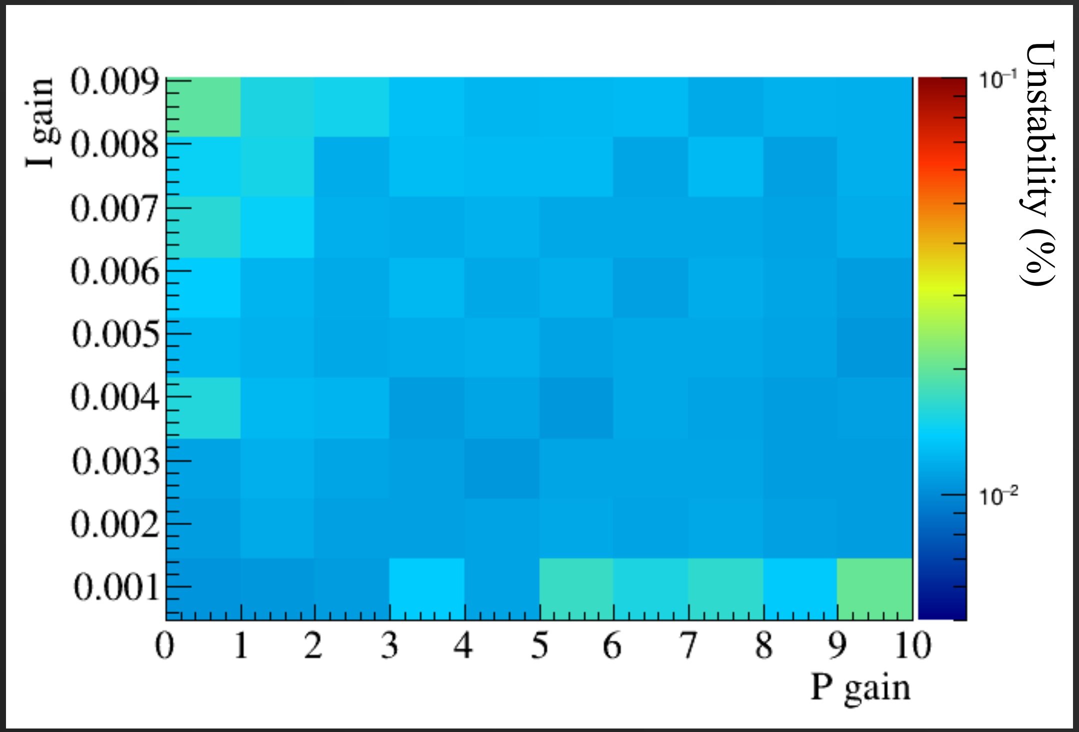

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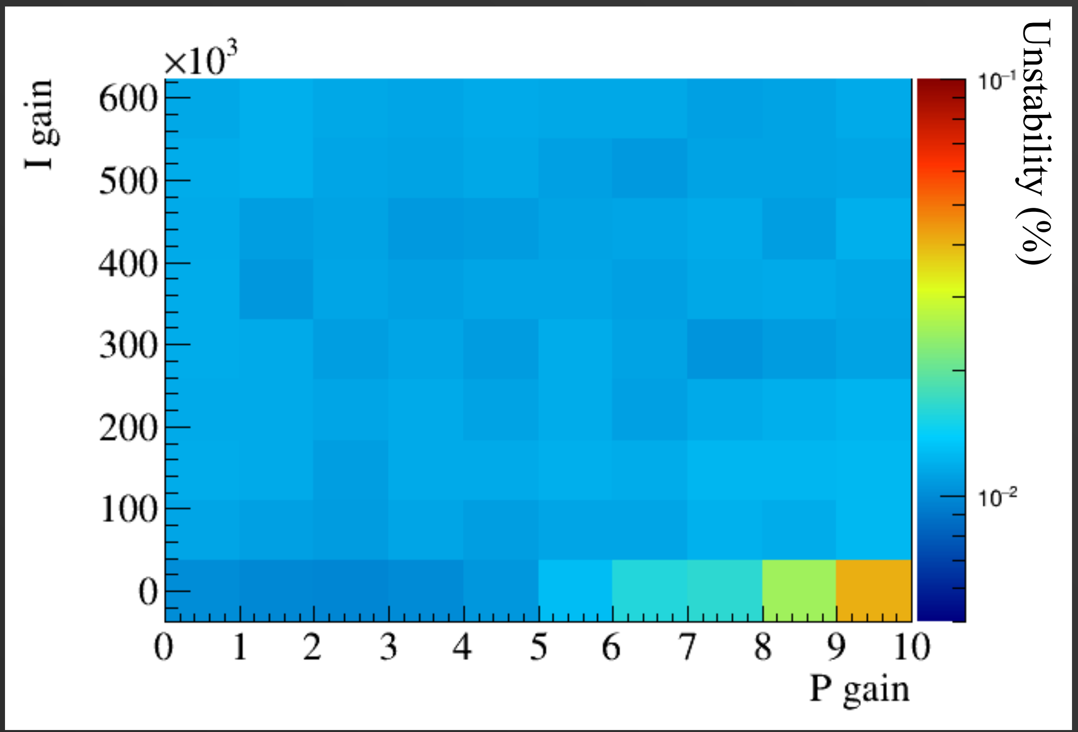

Unstability of all RF stations (Phase)

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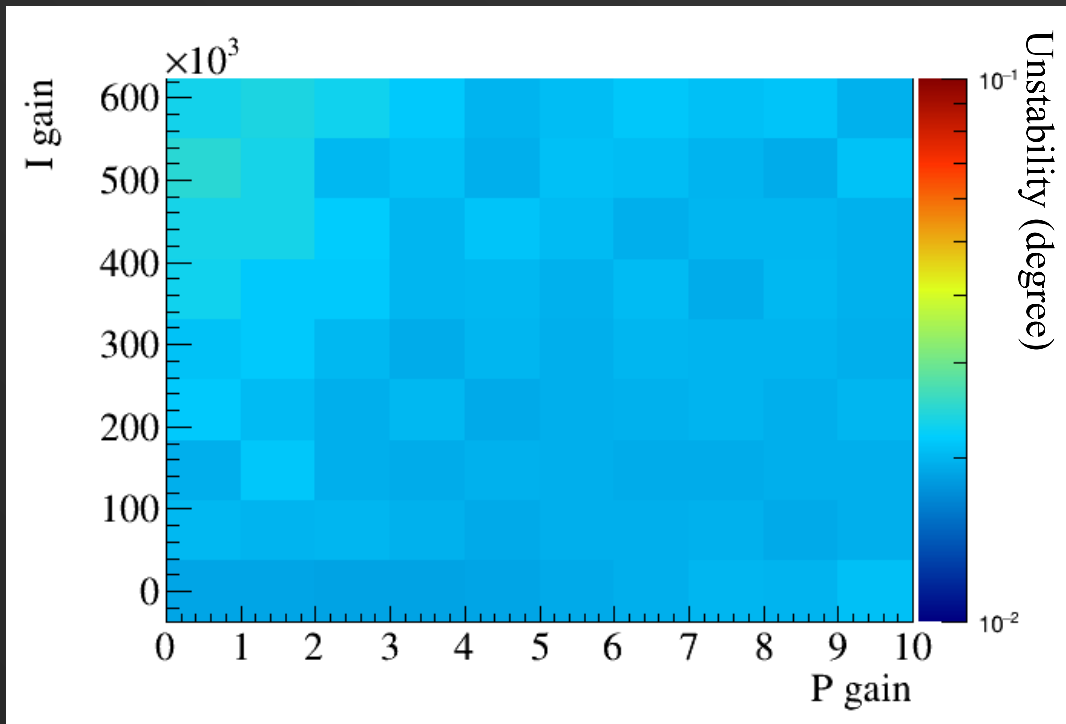

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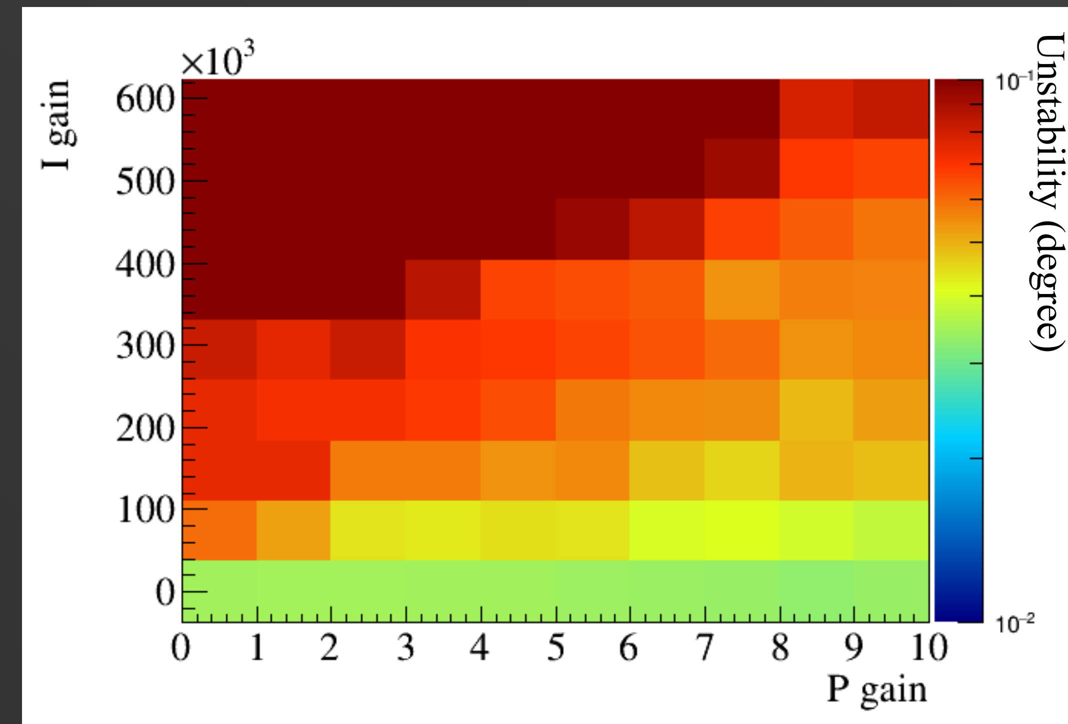

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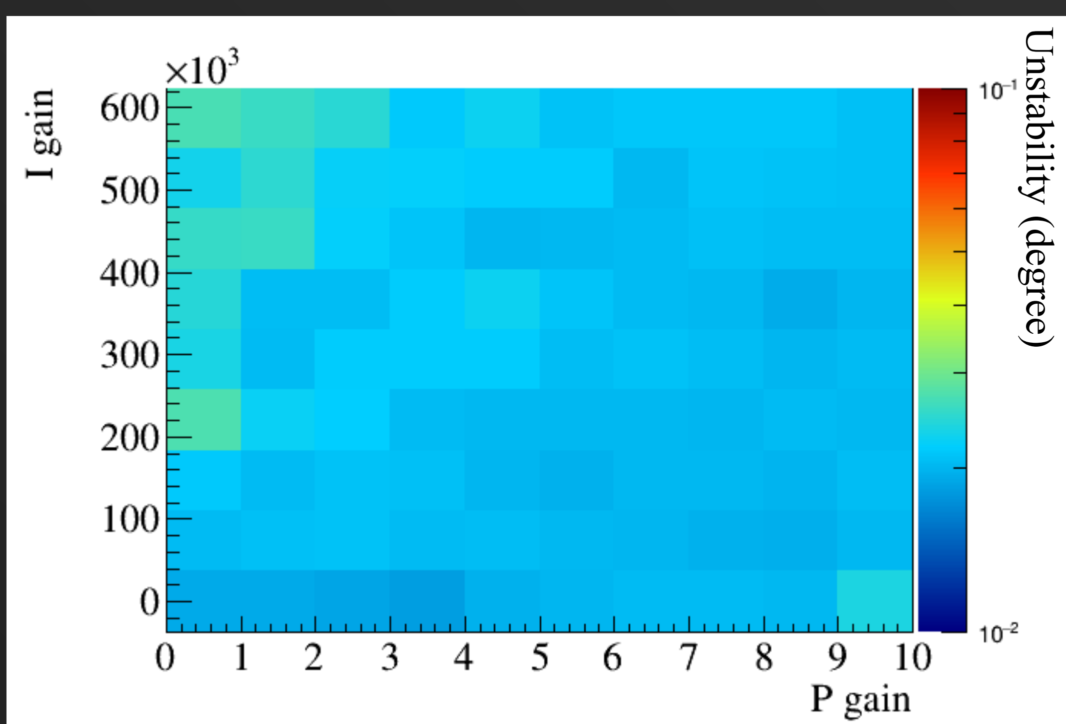

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