Performance of LLRF system

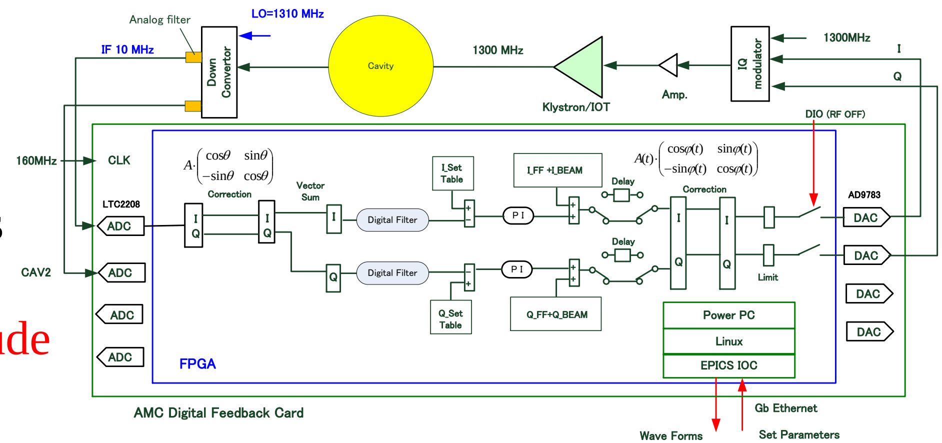
Feng QIU (KEK)

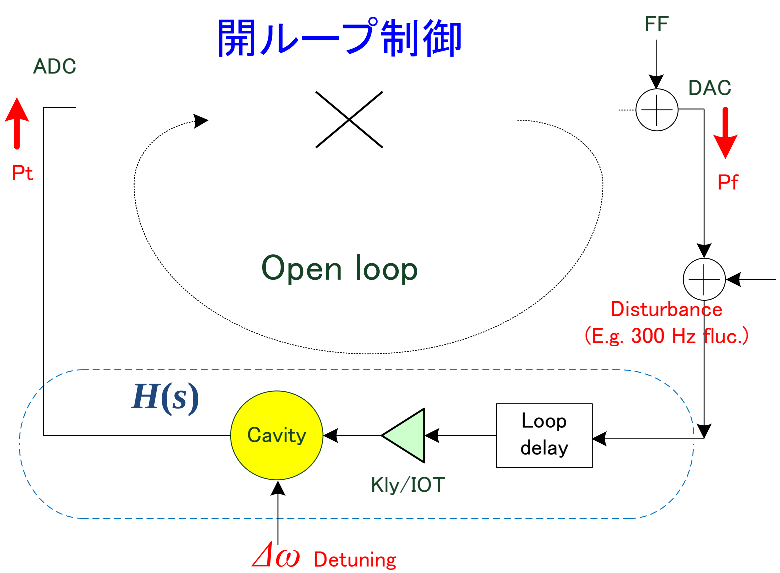
Main Content

- Low Level RF system
- Gain Scanning for Injector
- Experiment on ML cavity
- Summary

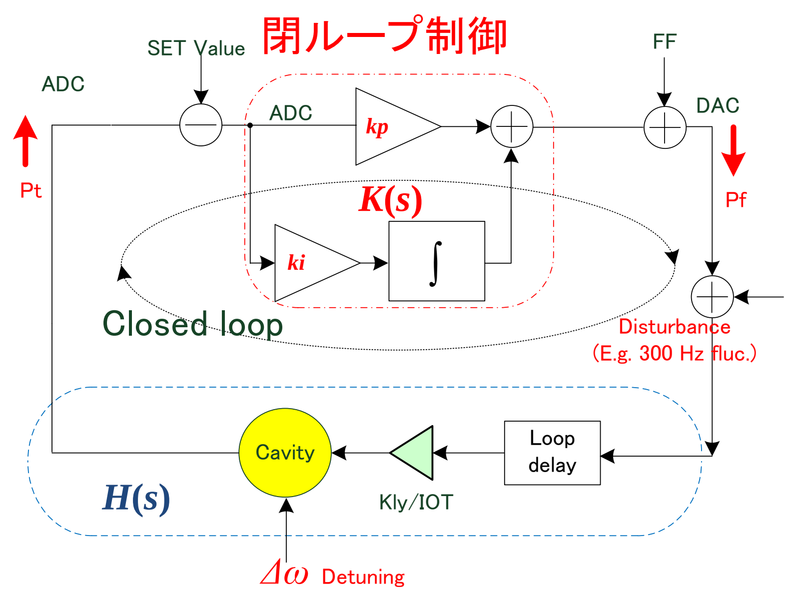
Low Level RF System

- Main function of LLRF systems.
  - I. Stabilize the RF field (I&Q Feedback) .
  - II. Minimize the cavity input power (Tuner Feedback).
- Closed-loop operation (Feedback) is required to stabilize the RF field.
- Requirement: 0.1% RMS for amplitude and 0.1 deg. RMS for phase.





No disturbance suppression!

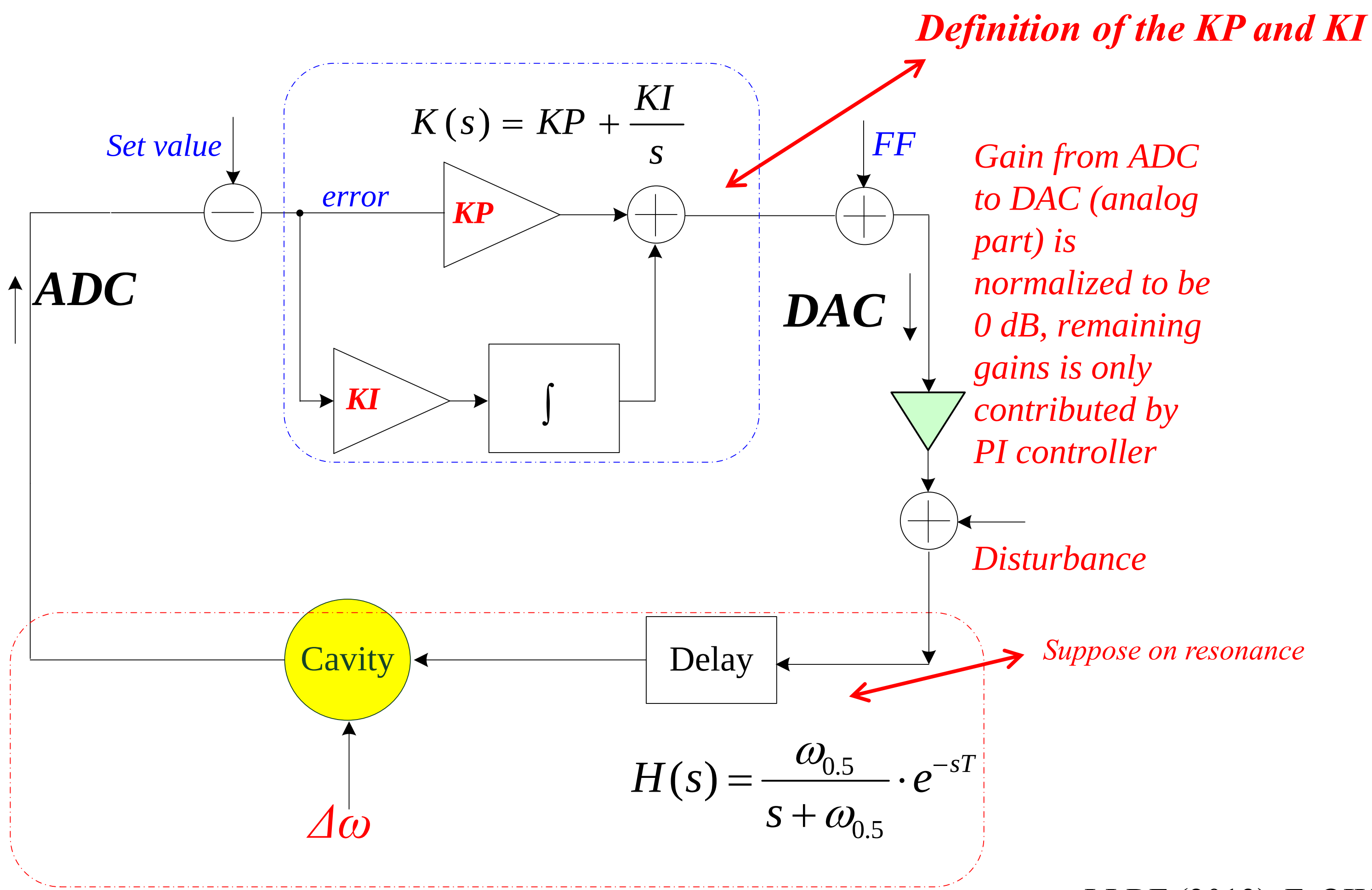


Disturbance suppression: H(s)/(1+K(s)H(s))

Study at cERL (2013), F. QIU

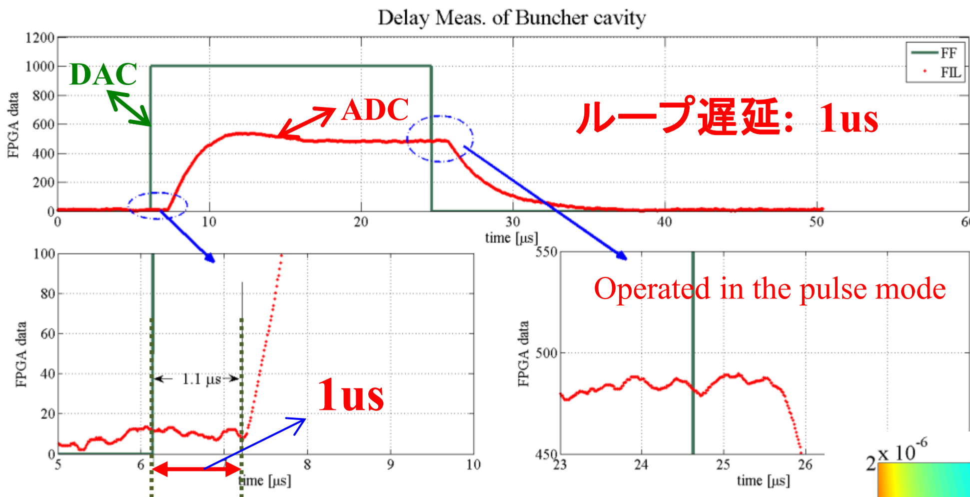
Gain scanning (Definition of Gain)

- Gain-scanning: Scanning different proportional gain KP and integral Gain KI to find out the optimal gains.
- The scanning experiment was carried out at low RF field.

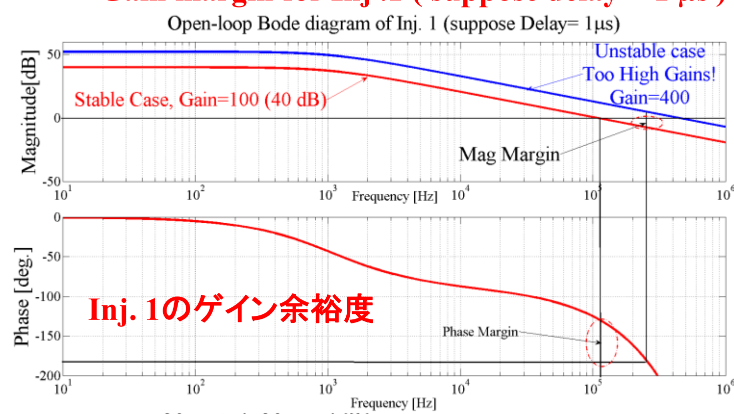


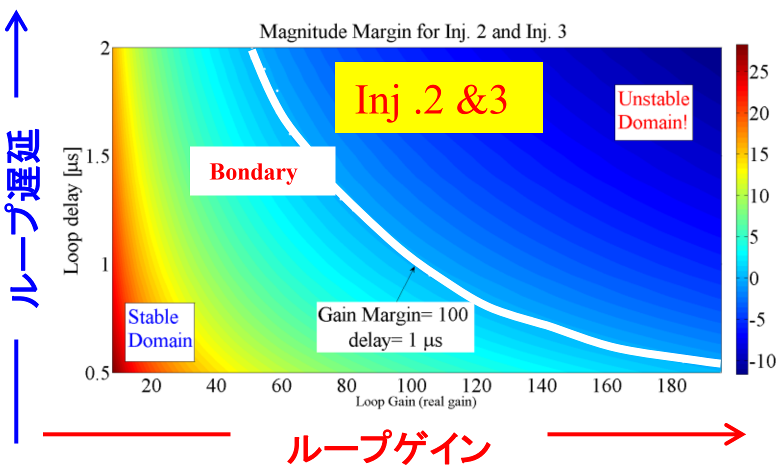
Gain Scanning (Delay measurement)

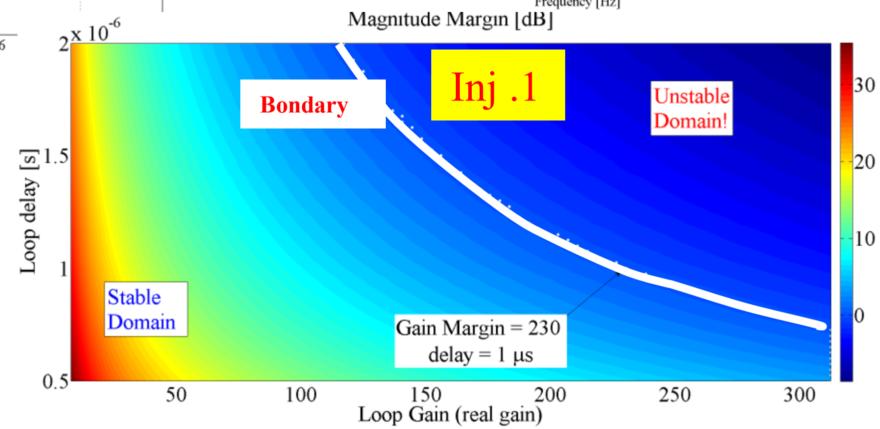
- In order to acquire some priori information about the maximum gain, we have evaluated the loop delay at first due to there is a relationship between the loop delay and the maximum gains.
- Loop delay is measured by exciting the OL system with square wave in the DAC output.



Gain margin for Inj .1 (suppose delay = 1 μs)



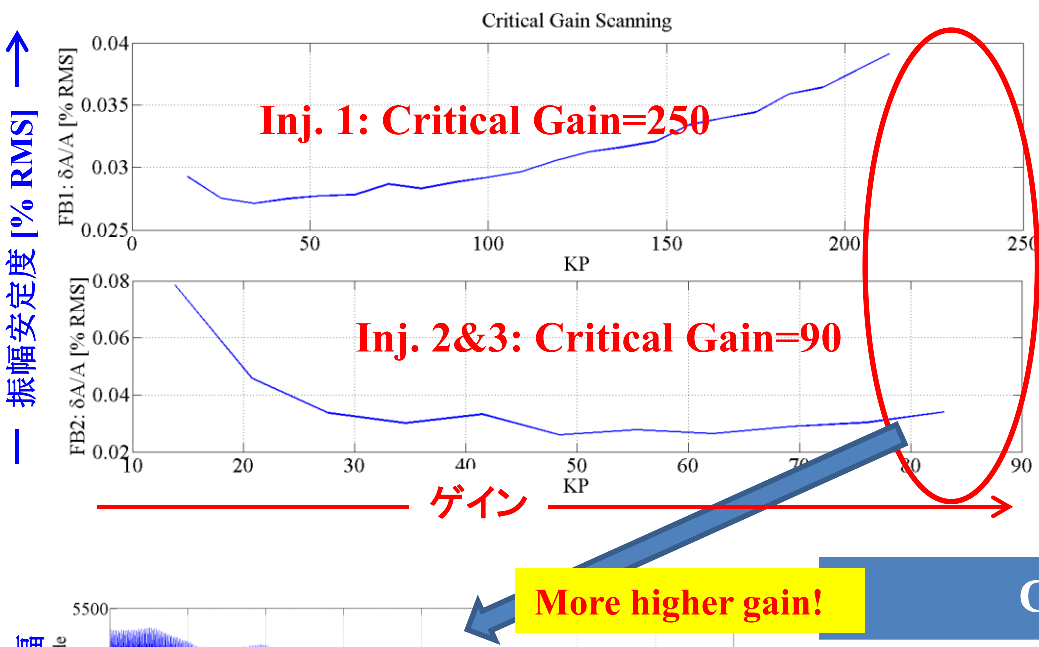




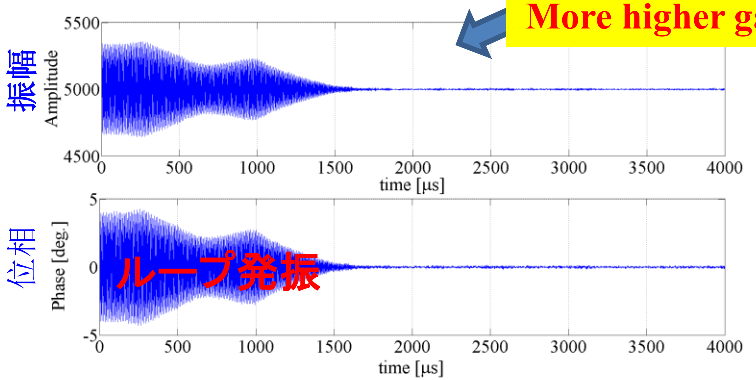
Simulated Gain margin: Inj1=230, Inj. 2&3=100

Gain scanning (Critical gains)

- The Critical gain has measured by the KI=0, KP Scanning.
- If the proportional gain is larger than the critical gain, the loop would be oscillated.



Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	1.2e6	5.8e5	4.8e5
f0.5 [kHz]	58	**0.54**	**1.12**	**1.35**



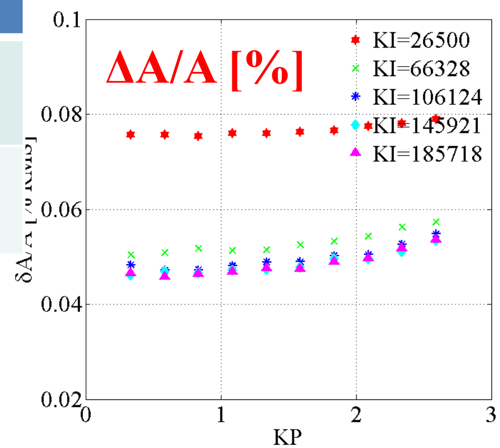
Gain	Inj. 1	Inj. 2&3
	ゲイン余裕度	
Gain Margin (Sim.)	230	100
	測定	
Critical Gain (Meas.)	**250**	**90**

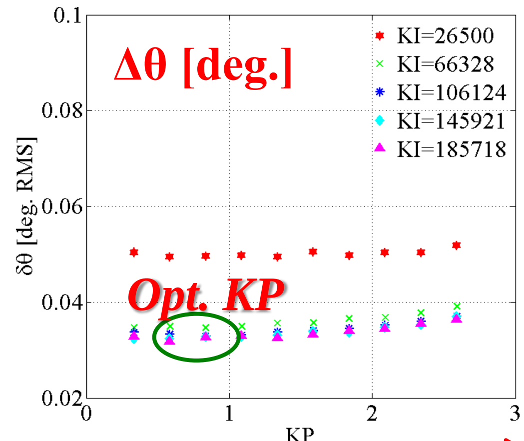
Gain scanning (Buncher)

■ High gain is not available for Buncher cavity (NC) due to its large bandwidth (QL=1.1e4) .

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	**1.1e4**	1.2e6	5.8e5	4.8e5
$f_{0.5}$ *[kHz]*	**58**	0.54	1.12	1.35

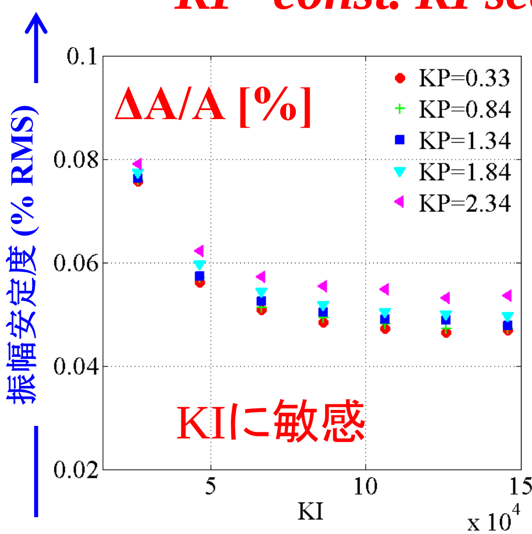
KI=const. KP scanning

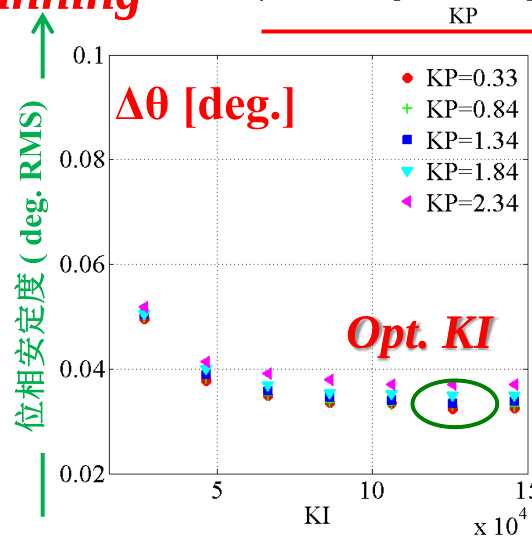




P ゲイン

KP=const. KI scanning





I ゲイン

最適ゲイン:
KP_{opt}=0.8, KI_{opt}=1.2e5.

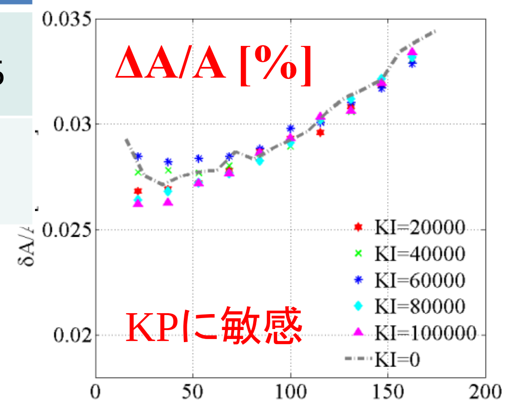
■ It is clear to see that the integral Gain KI is dominant gain for the Buncher cavity because of the limitation of high proportional gain KP (not available！).

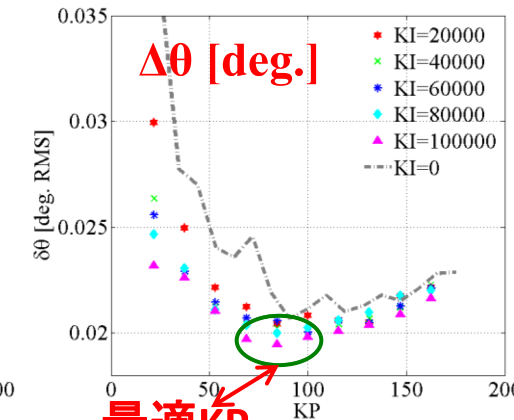
Gain scanning (Inj. 1)

- High gain is available for Inj .1 cavities (SC).

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	**1.2e6**	5.8e5	4.8e5
f0.5 [kHz]	58	**0.54**	1.12	1.35

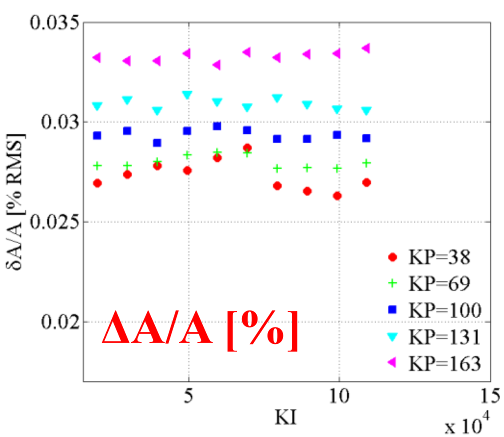
KI=const. KP scanning

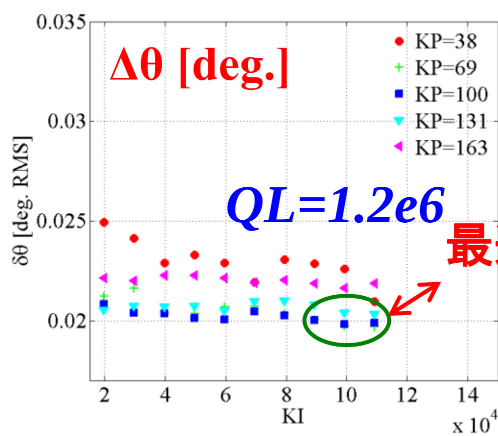




最適KP

KP= const., KI scanning





最適KI

最適ゲイン:
KP_{opt}=84, KI_{opt}=1.0e5.

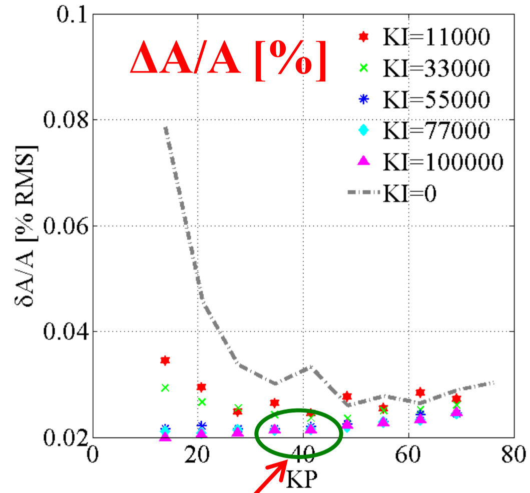
- The dominant gain in Inj. 1 is proportional gain (KP), very common in SC cavity controlling.
- High gain controlling can be realized due to its narrow bandwidth.

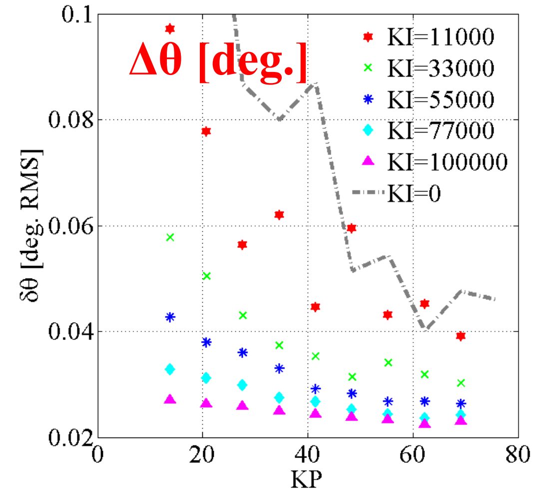
Gain scanning (Inj. 2&3)

- High gain is available for Inj .2 (SC) and Inj .3 (SC).

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	1.2e6	**5.8e5**	**4.8e5**
f0.5 [kHz]	58	0.54	**1.12**	**1.35**

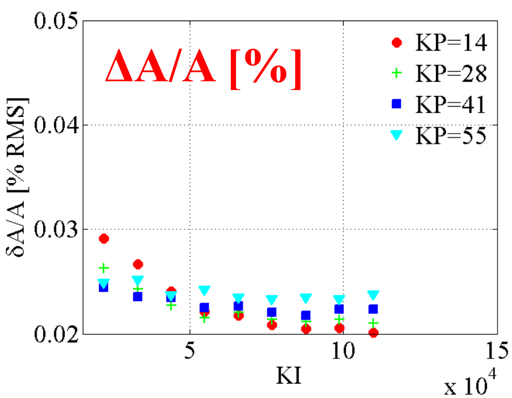
KI=const., KP scanning

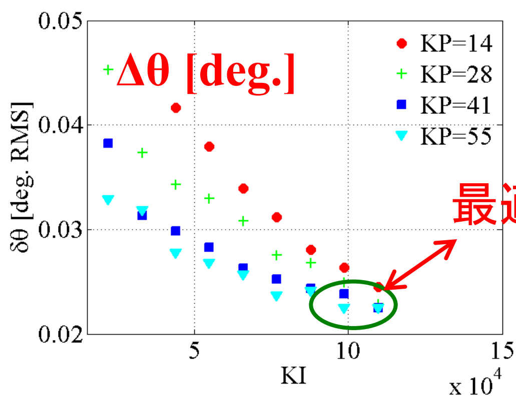




最適KP

KP= const., KI scanning





最適KI

最適ゲイン:
KP_{opt}=41, KI_{opt}=1.1e5.

- Both KI and KP have an effect for Inj. 2&3.
- KI is also significant due to there is an 300 Hz component in the HVPS.

Gain scanning (Conclusion)

Conclusions:

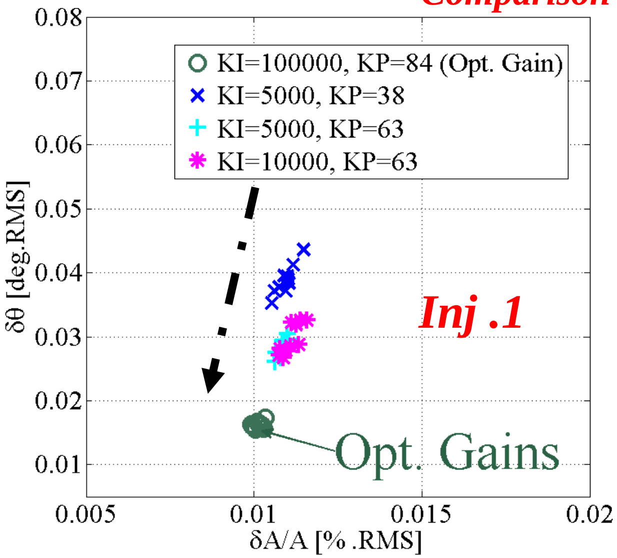
- The proportional gain KP plays an much more important roles in SC cavity and the optimal KP is usually located in the ½ to ⅓ of the critical gains.
- The integral gain KI is significant in normal cavity due to the limitation of the critical gains.

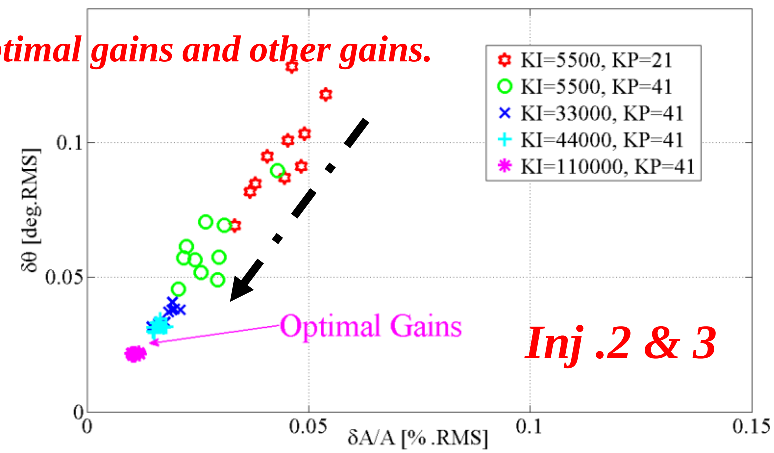
Vector-sum

Gain	Bun.	Inj. 1	Inj. 2	Inj .3
Prop. Gain (KP)	0.8	84	41	
Int. Gain (KI)	1.2e5	1.0e5	1.1e5	
Critical Gain	3	230	90	
$f_{0.5}$ [kHz]	58	0.54	1.12	1.35

About ½ to ⅓

Comparison btw the optimal gains and other gains.



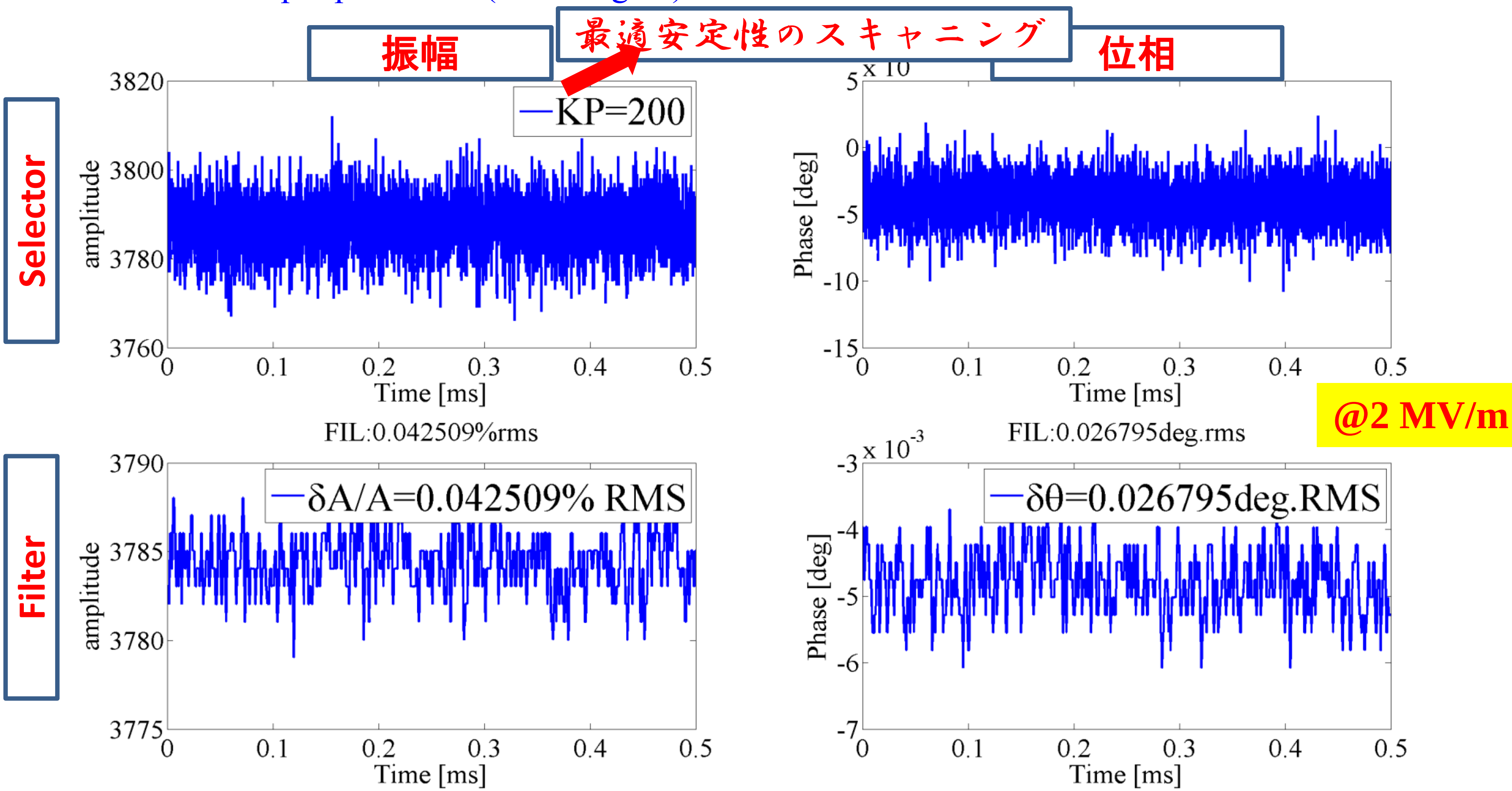


- The performance would be best in the optimal gain case.
- The amplitude and phase stability of Inj. 1 and Inj. 2&3 can be **0.01% RMS** and **0.02 deg. RMS**, respectively.

Experiment on ML (ML1)

- The process of the ML1 gain scanning

Here KP is CSS input parameter (not real gain) !

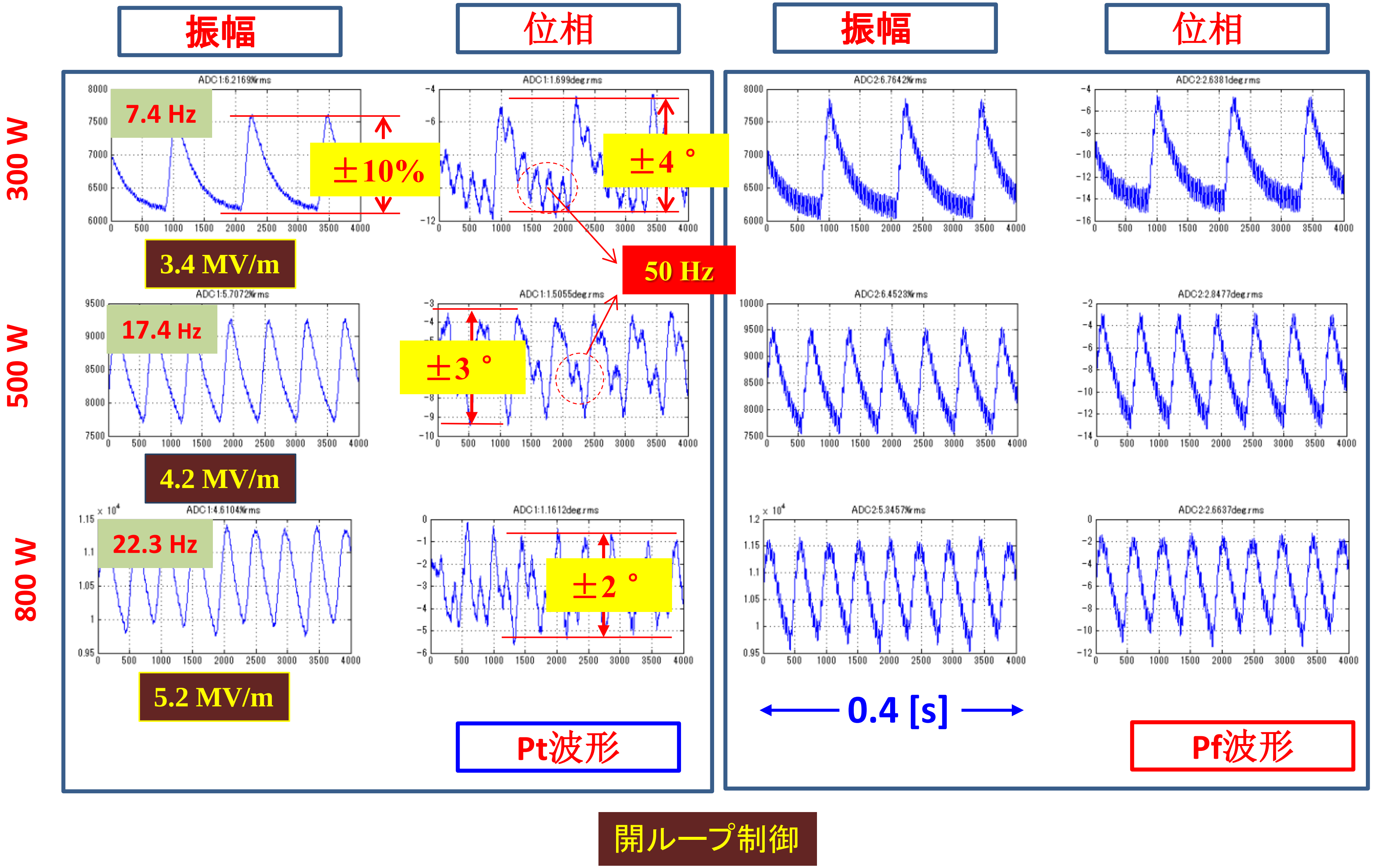


必要な安定度 (0.1%, 0.1 deg.)

Study at cERL (2013), F. QIU

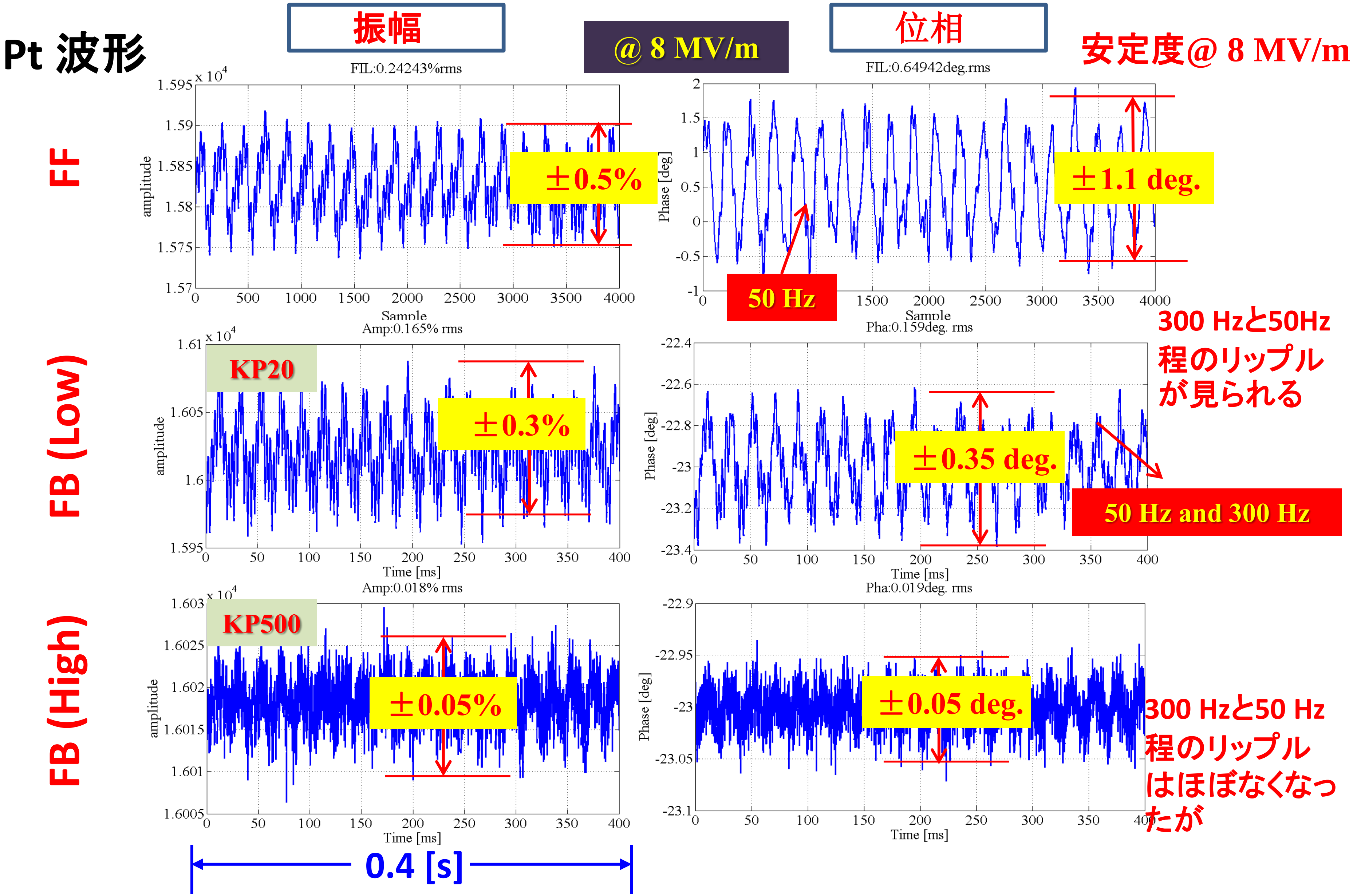
Experiment on ML (ML2 IOT)

- Performance of the IOT in ML2.



Study at cERL (2013), F. QIU

Experiment on ML (ML2)



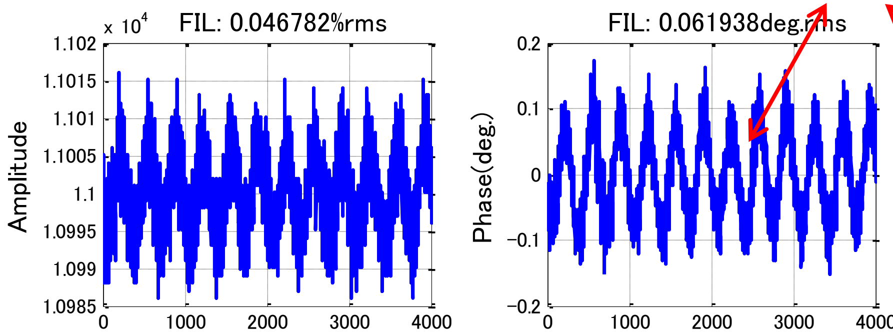
Performance (June)

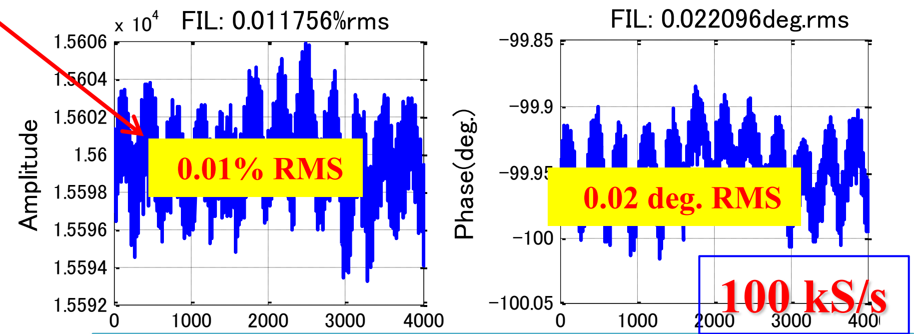
Pt 波形

FB0 (Buncher)

300 Hz fluc. from HV Power Supply

FB2 (Vector-sum of Inj. 2 and Inj. 3)





Amp 0.05% rms, Phase 0.06 deg. rms

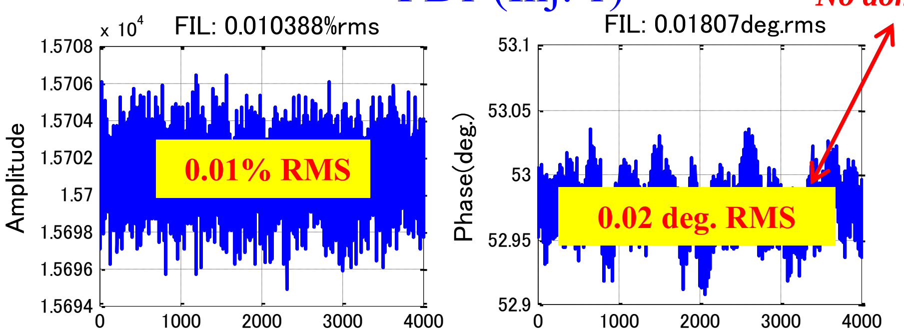
Amp: 0.01% rms, Phase 0.022 deg. rms

100 kS/s

Selections of KP and KI are based on the gain scanning experiment!

FB1 (Inj. 1)

No dominant

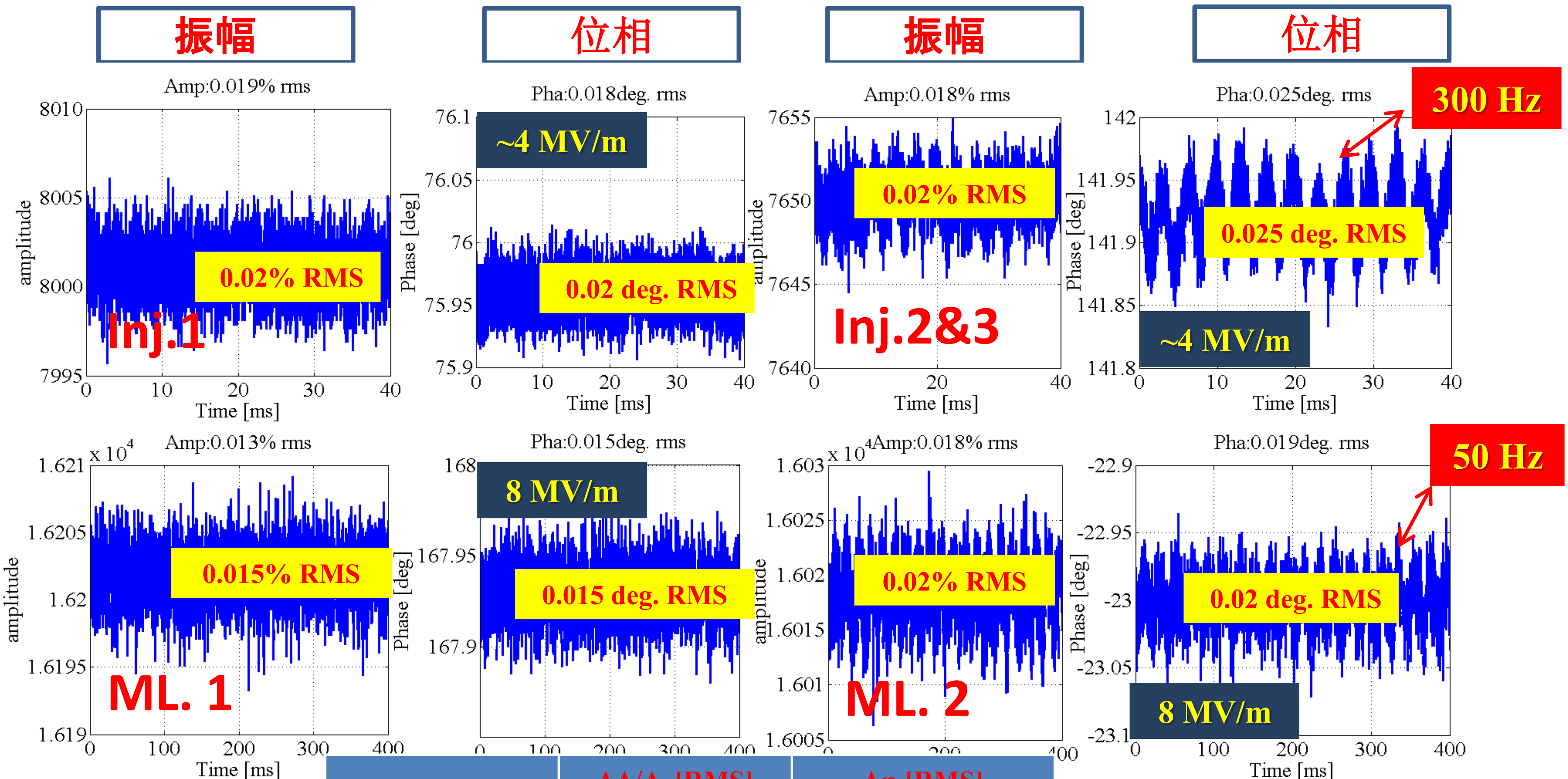


Amp: 0.01% rms , Phase 0.02 deg. rms

	ΔA/A [RMS]	*Δφ* [RMS]	*Loop Delay*
Bun.	0.05%	0.06 deg.	1.1 μs
Inj. 1	0.01%	0.02 deg.	1.1 μs
Inj. 2&3	0.01%	0.02 deg.	1.1 μs

必要な安定度 (0.1%, 0.1 deg.)を満足!

Performance (Dec.)



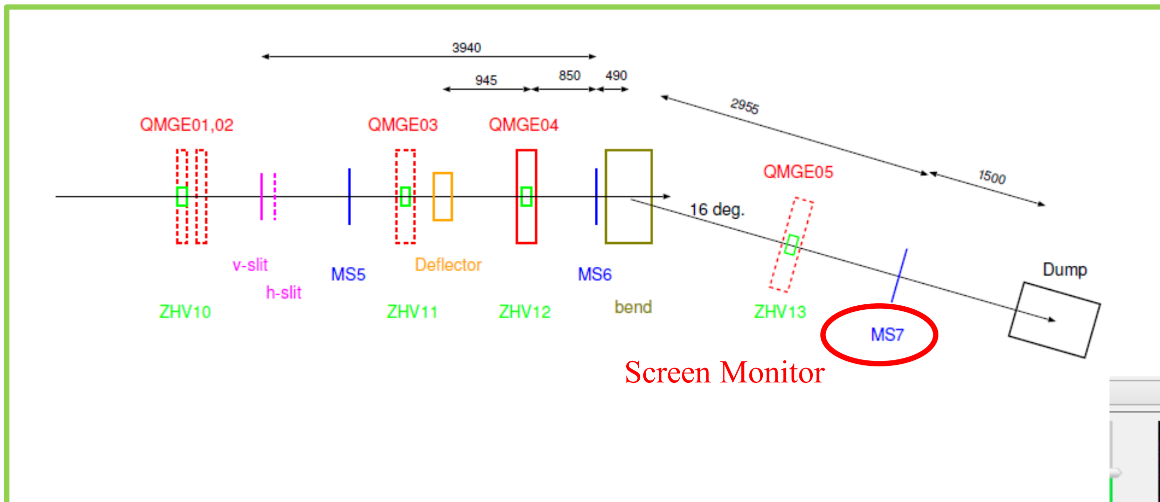
	ΔA/A [RMS]	Δφ [RMS]
Inj. 1	0.02%	0.02 deg.
Inj. 2&3	0.02%	0.025 deg.
ML. 1	0.015%	0.015 deg.
ML. 2	0.02 %	0.02 deg.

必要な安定度 (0.1%, 0.1 deg.)を満足

LLRF (2013), F. QIU

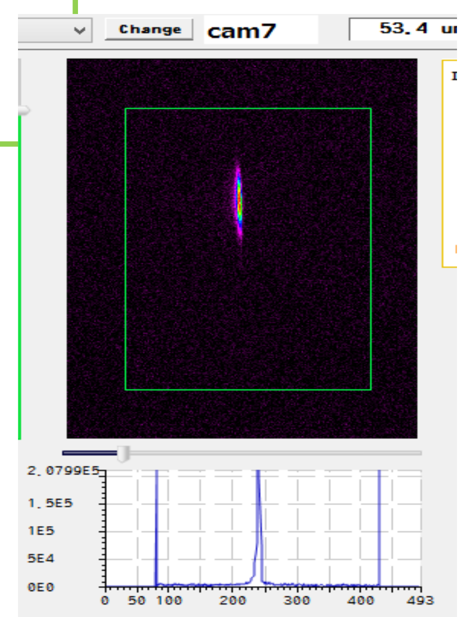
Performance (Screen Monitor@June)

■ The beam momentum is measured by screen monitor and determined by the peak point of the projection of the screen.



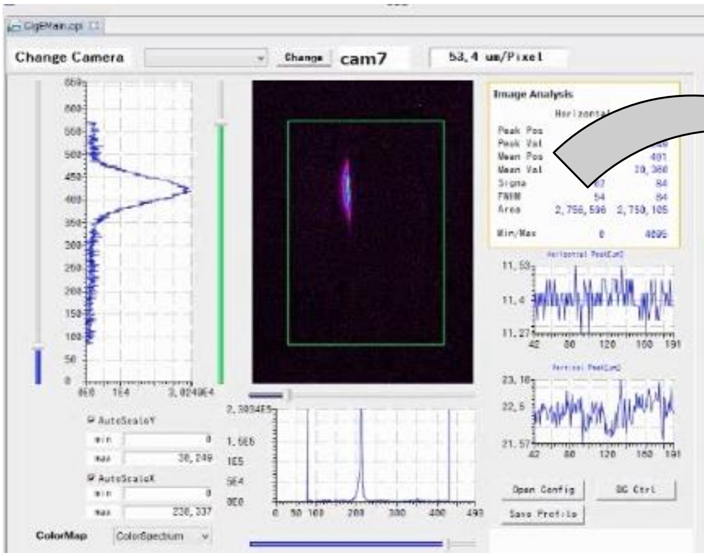
Dispersion @ screen monitor = 0.82m
Resolution = 53.4 µm/pixel
($\Delta P/P$=6.5e-5)

Momentum was determined by the peak point of the projection of the screen.

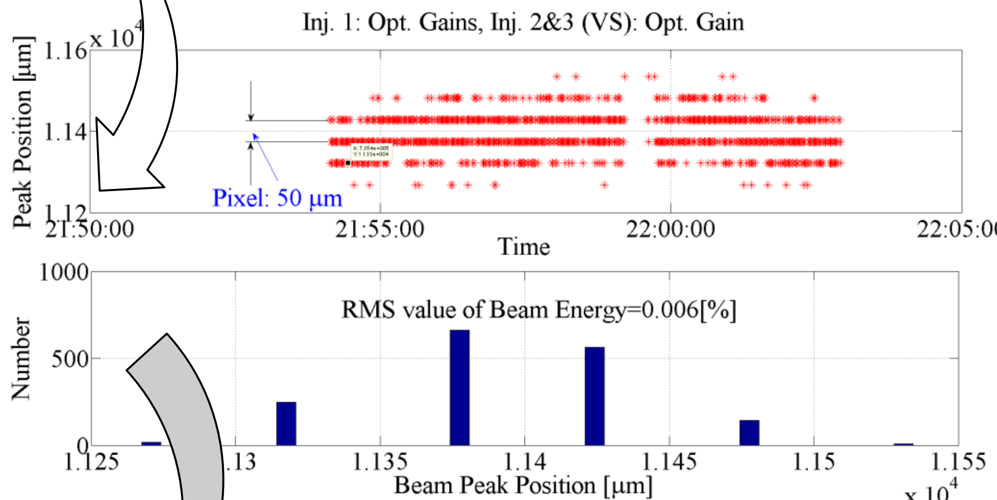


Attention: *Vector-sum error would influence the beam momentum jitter greatly! Thus the phase error btw inj. 2 and inj. 3 should be optimized at first!*

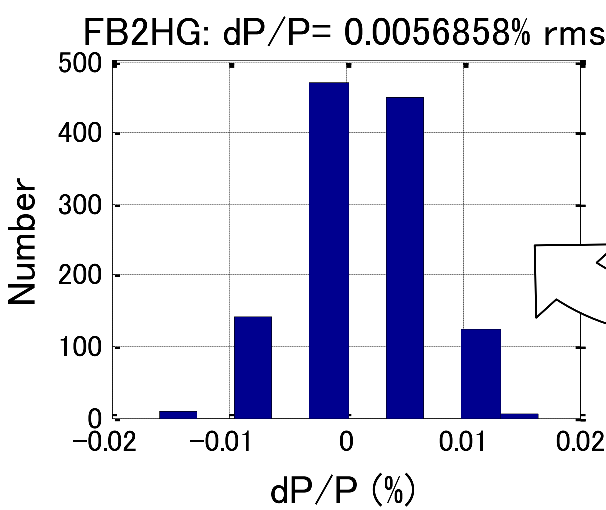
Performance (Beam energy)



Result of the screen monitor



Beam Energy



Momentum Jitter= 0.006% rms

Summary

Summary

- Construction of the RF system for cERL was finished.
- Optimal gains has been determined in the operation for Inj. 1.
- IOT has some oscillation.
- Very good beam momentum.

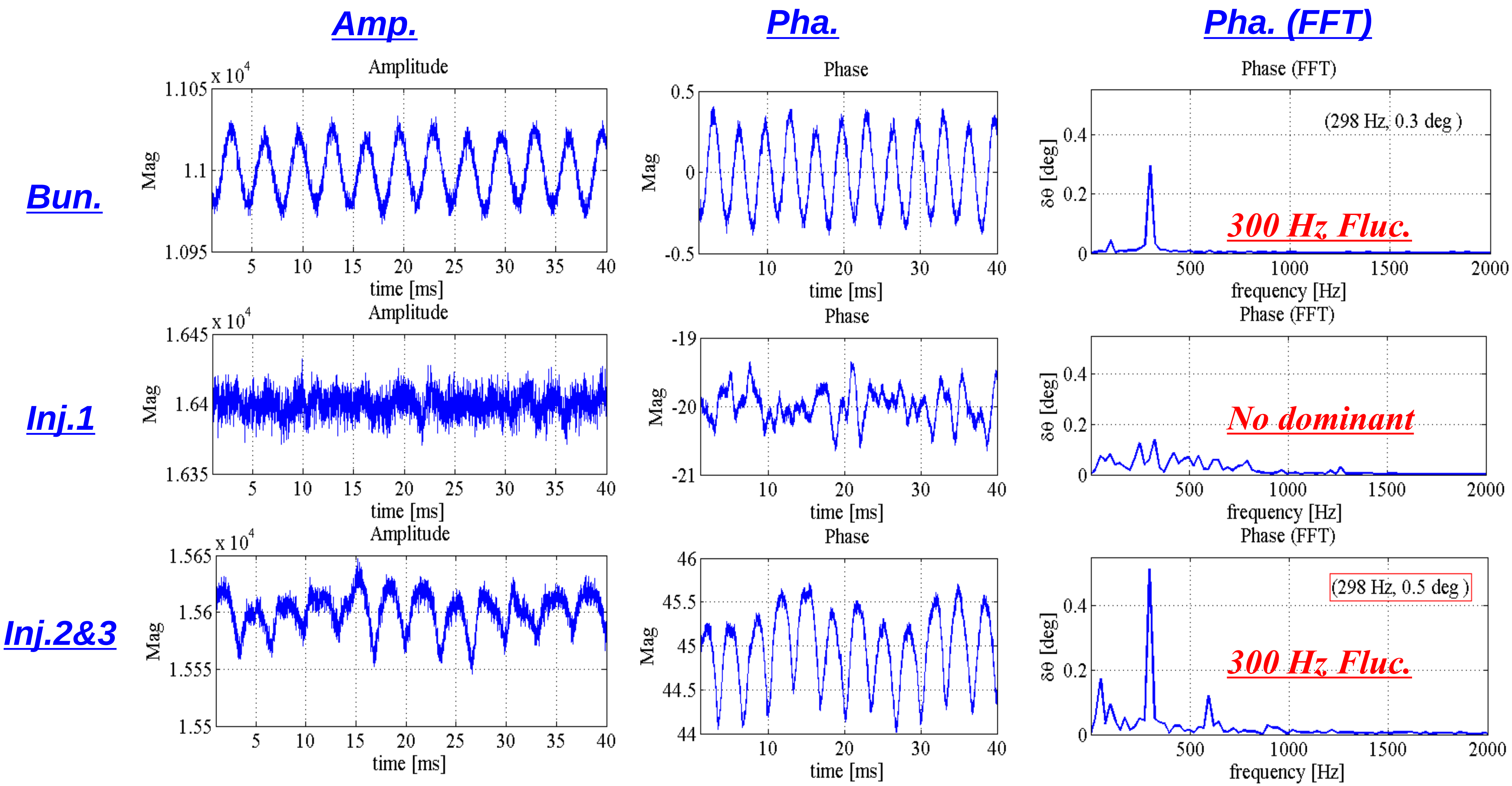
Question?

Thank you very much for your attending

Back up

Performance (300 Hz Fluctuation)

- The 300 Hz fluc. at Inj2&3 and Buncher cavity during CL/OL operation. This 300 Hz fluctuation would influence the system performance.
- The Inj. 1 LLRF system doesn't not has evident dominant components.

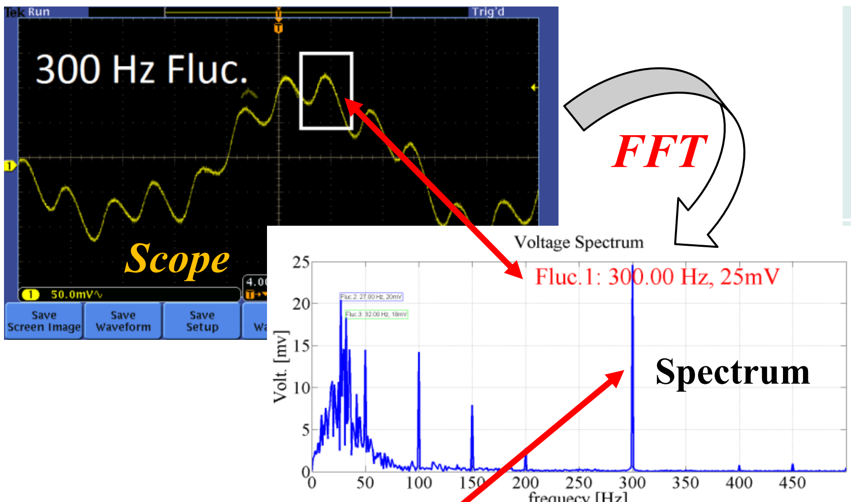


Study at cERL (2013)

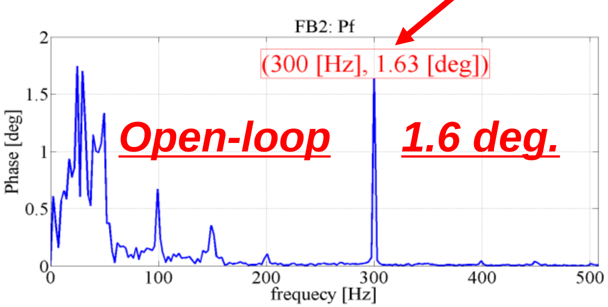
Performance(300 Hz fluc. suppression)

- The Power supply is the main source of the 300 Hz component.
- The RF fluctuation agrees well with the PS fluctuation (suppose 10 deg /HV%, then the 20mV fluctuation in PS will lead to 10 deg×(100×25mv/15V) = 1.67 deg).

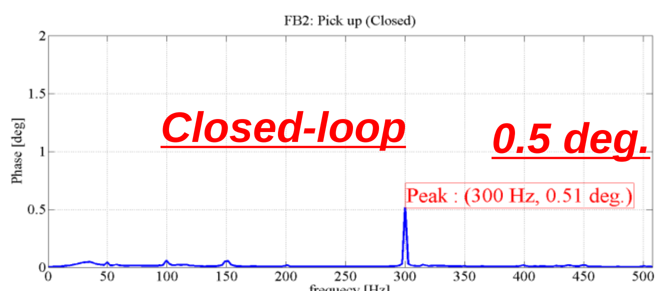
300 KW Kly. High Voltage



Fluc. @ 300 Hz		Buncher	Inj2&3 (VS)
Open loop	*ΔA/A*	-43.5 [dB]	-46 [dB]
	Δθ	0.9 [deg.]	1.6 [deg.]
Closed loop (*KI*=5500, *KP*=0)	*ΔA/A*	-54 [dB]	-56.5 [dB]
	Δθ	0.3 [deg.]	0.5 [deg.]



Cavity input (OL)



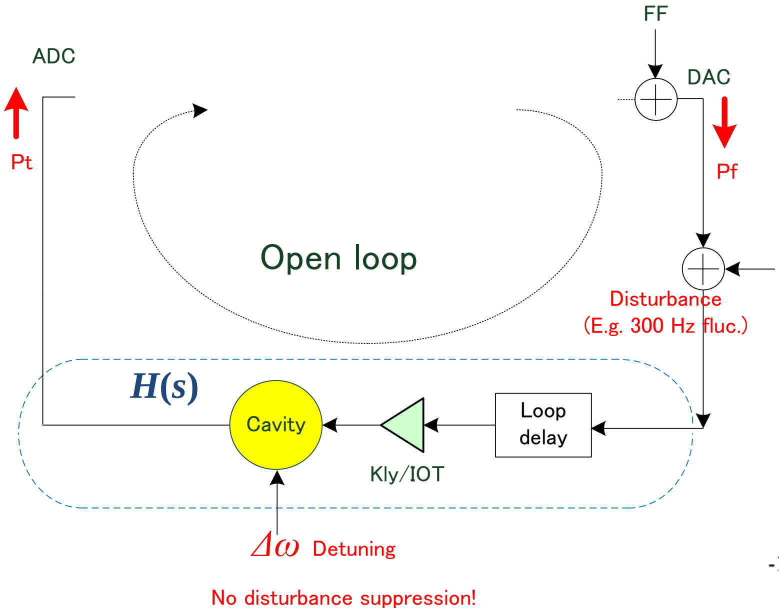
Cavity Pick up (CL)

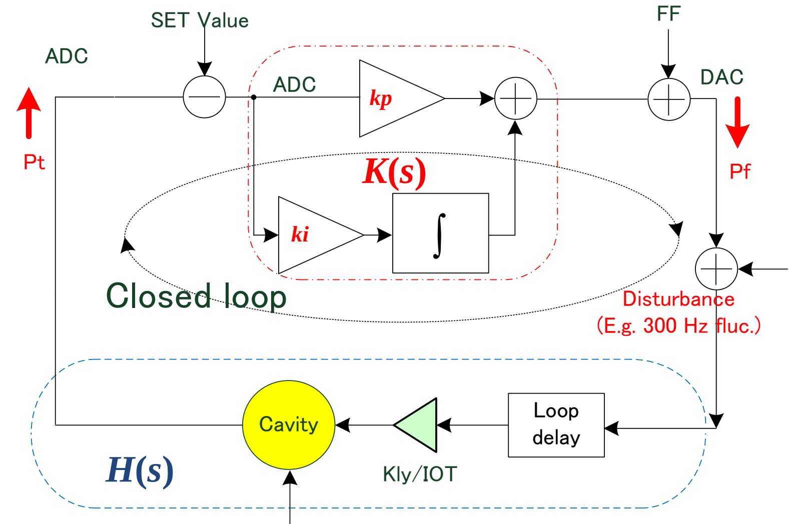
Clear to see that the 300 Hz component is suppressed by CL operation.

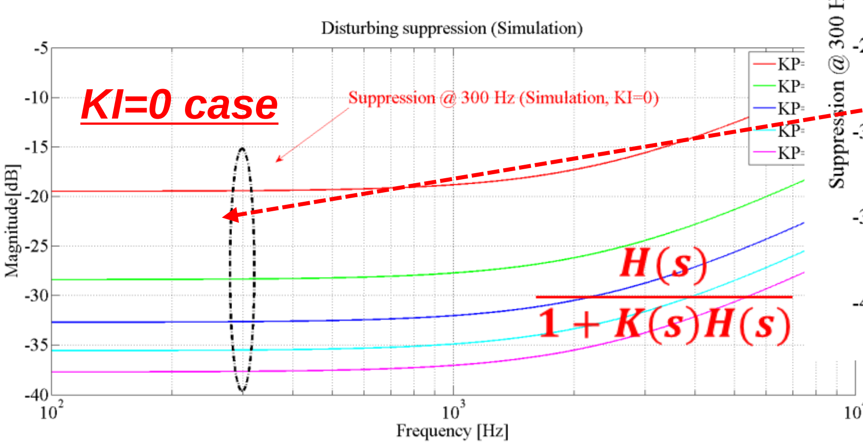
Study at cERL (2013), F. QIU

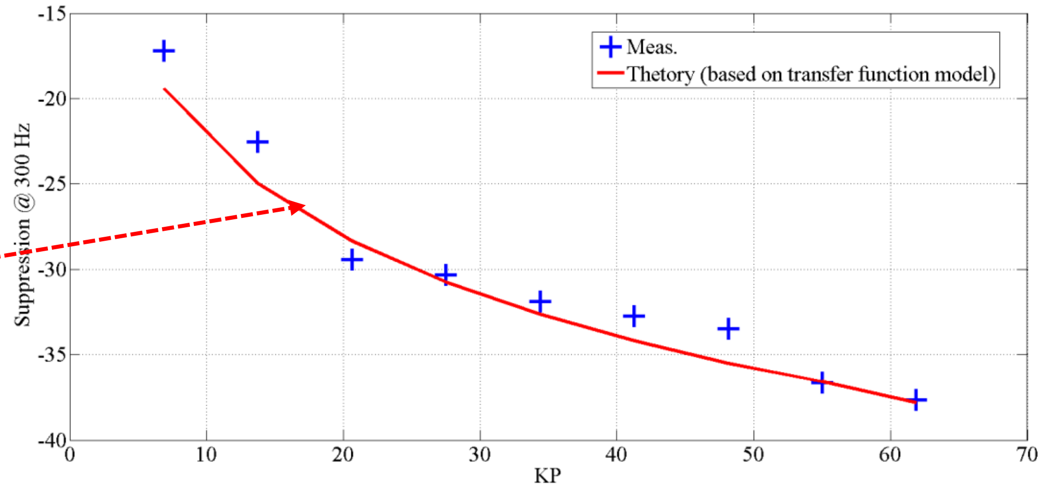
Gain scanning (300 Hz suppression)

- The 300 Hz fluctuation would be suppressed by higher gains.





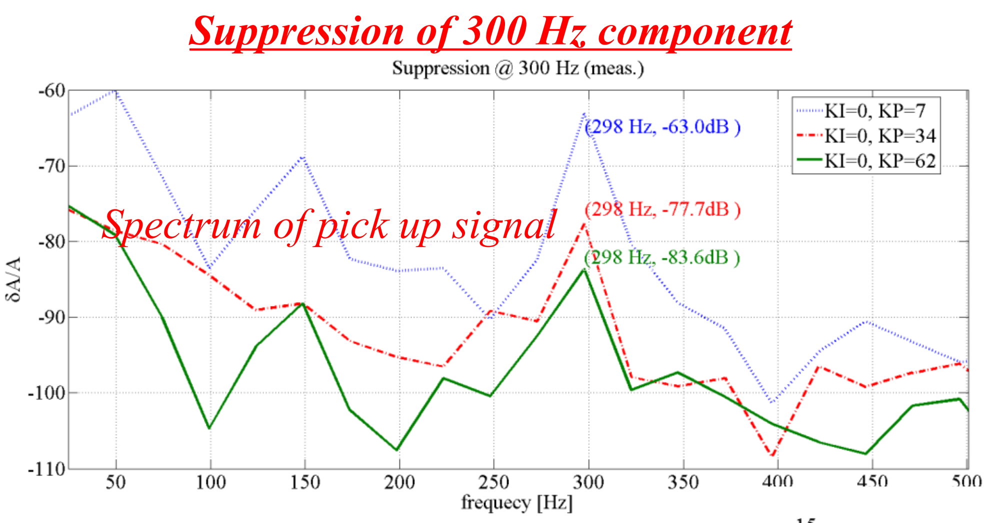




Study at cERL (2013), F. QIU

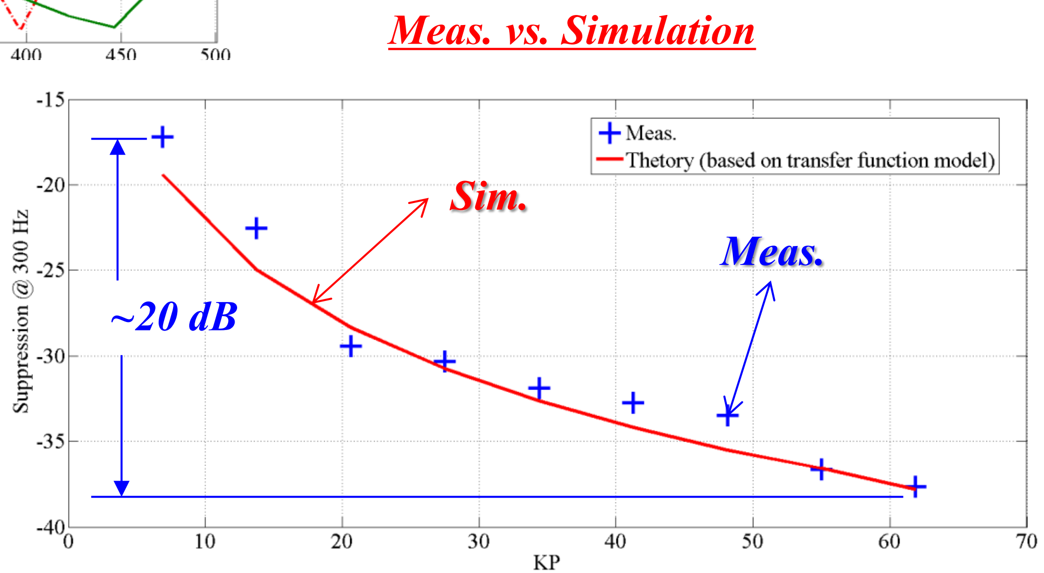
Performance(300 Hz fluc. suppression)

- The 300 Hz component is suppressed by high gains.



About 20 dB suppression when increasing KP by 9 times.

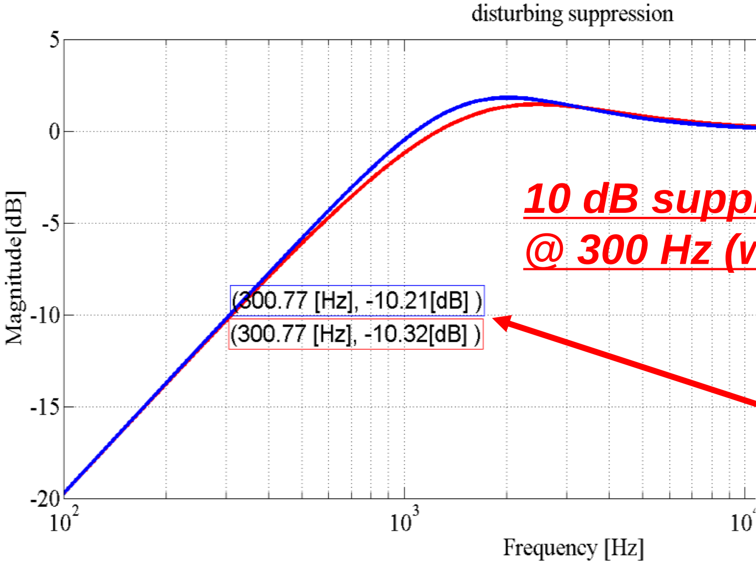
The simulation agrees well with the measured one



Study at cERL (2013), F. QIU

Fluctuation at 300 Hz (Source)

■According to current controlling parameter (KI=10, KP=0), the 300 Hz component is suppressed by ~10 dB (~3 times), not enough.

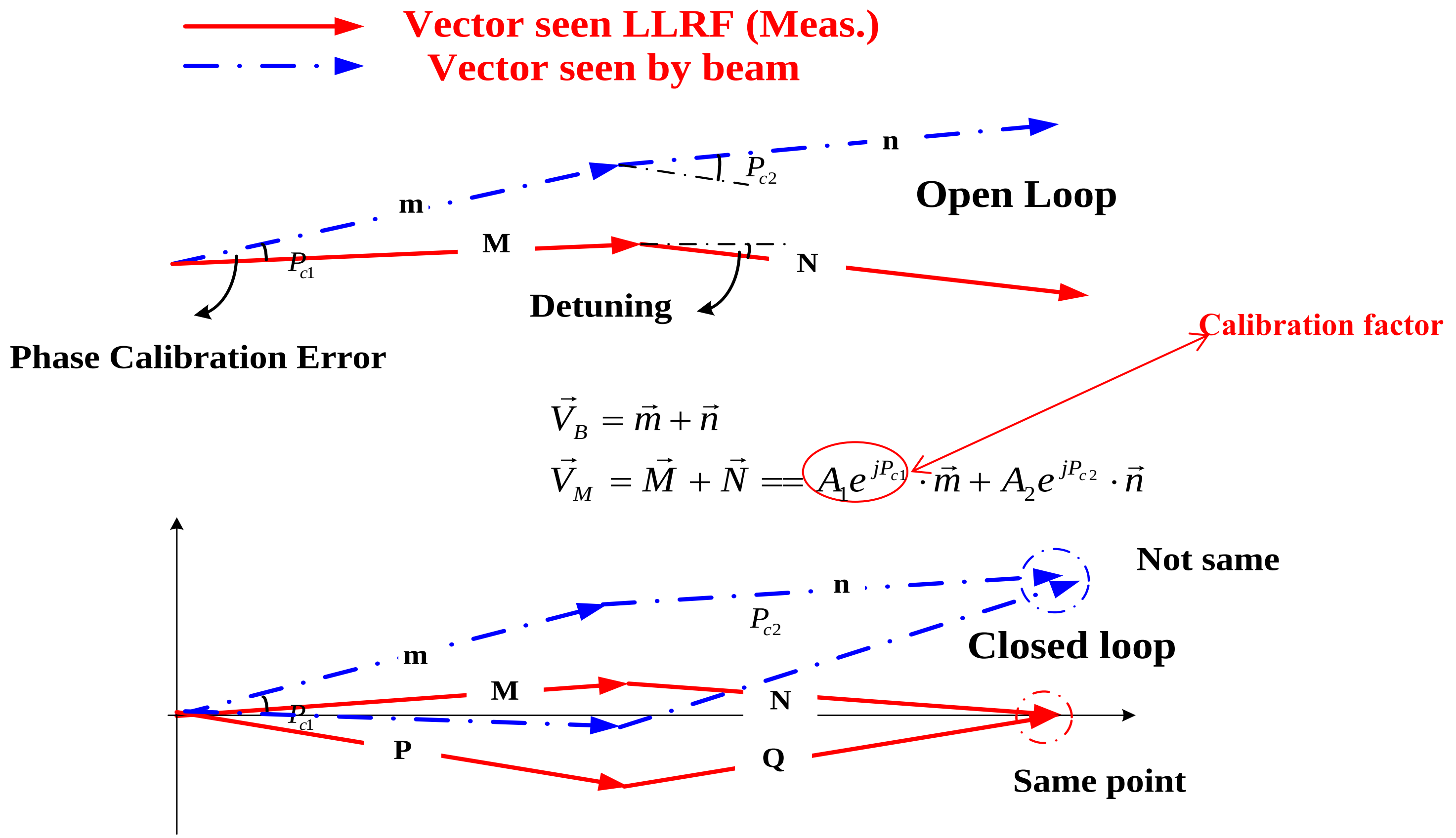


Fluc. @ 300 Hz		Buncher	Inj2&3 (VS)
Open loop	$\Delta A/A$	-43.5 [dB]	-46 [dB]
	$\Delta\theta$	0.9 [deg.]	1.6 [deg.]
Closed loop (KI=10, KP=0)	$\Delta A/A$	-54 [dB]	-56.5 [dB]
	$\Delta\theta$	0.3 [deg.]	0.5 [deg.]

Study at cERL (2013), F. QIU

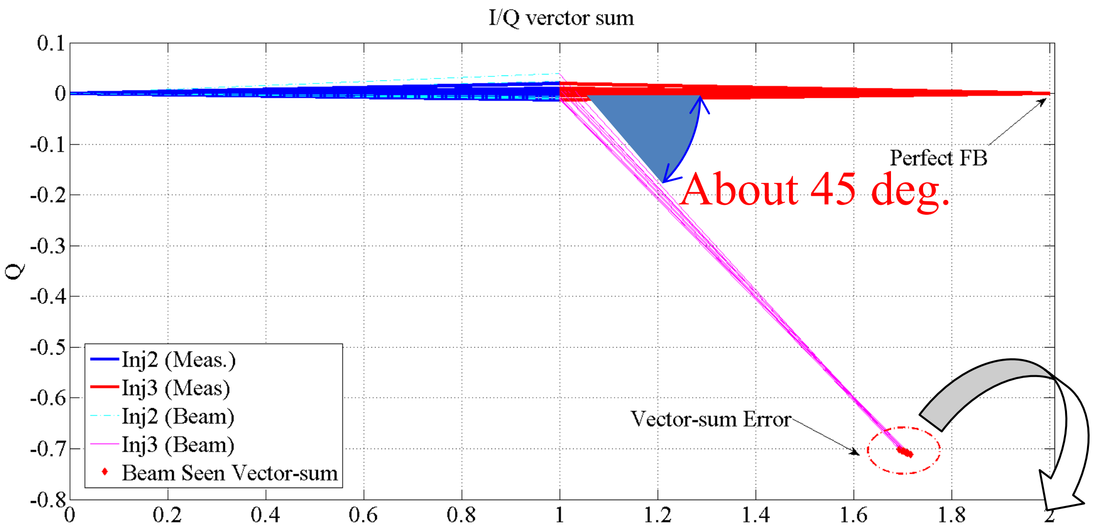
Performance (Vector-sum controlling)

- We have used the vector-sum controlling for Inj. 2 and Inj. 3 (see page 4&5 in this report).
- For vector-sum controlling, the measured vector-sum (***M***+***N***) which is seen by the FPGA or DSP is different from the true accelerating voltage which is seen by the beam (***m***+***n***).
- The calibration (phase or amplitude) error would result of vector-sum error

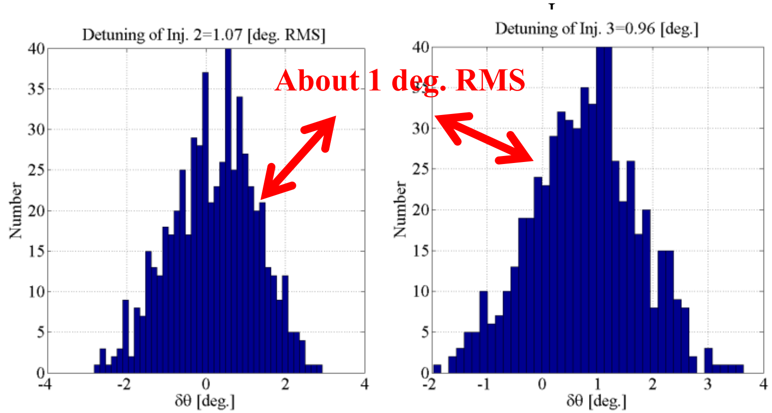


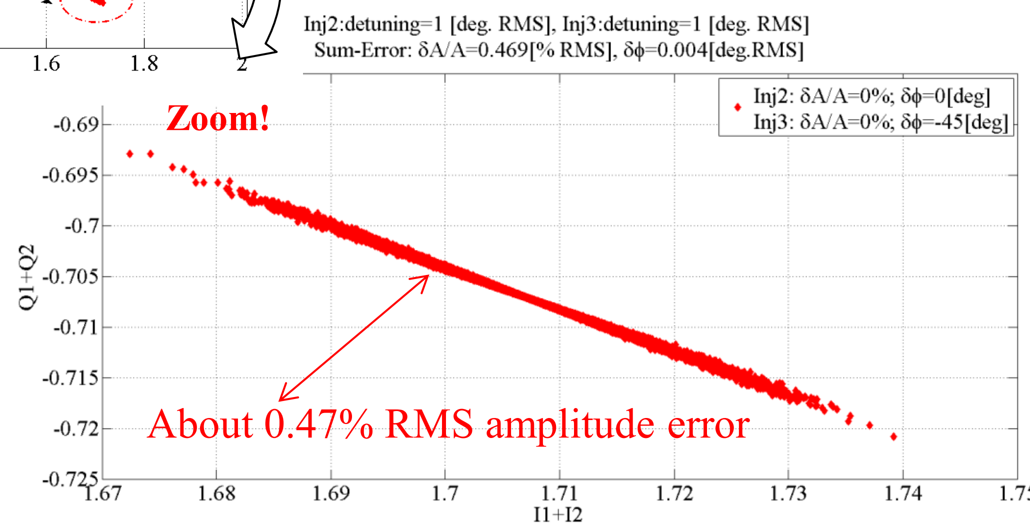
Performance (Vector-sum controlling)

- Suppose the detuning comply with 1 deg. RMS Gauss distribution, similar with the measured result, then the 45 deg. Phase calibration error would result of 0.47% RMS amplitude vector-sum error.



45 deg. calibration error would result of 0.47% RMS vector-sum error!





Distribution histogram of the detuning, similar with Gauss distribution.

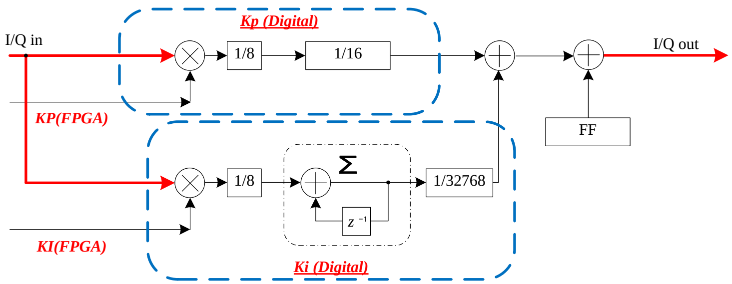
Study at cERL (2013), F. QIU

Gain scanning (definition)

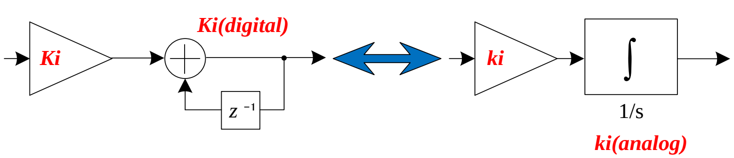
- Gain scanning: determine the optimal controlling gains (@ 2MV).
- Definition of the integral and proportional gains .

I. FPGA input parameter *KP* and *KI*.
II. Digital Gain *Kp* and *Ki*.
III. Analog Gain *kp* and *ki*.
IV. Real Gains: $A_{Set}/(A_{Set}-A_{Meas}.)$

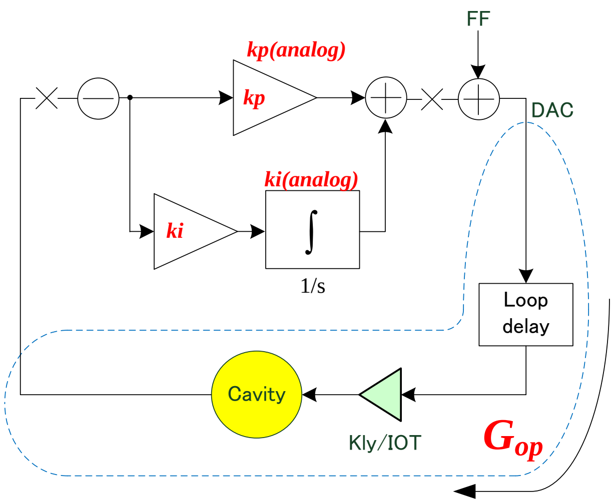
Gains	Integral	Proportional
FPGA	*KI*	*KP*
Dig.	$Ki=KI/2^{18}$	$Kp=KP/2^{7}$
Ana.	$ki=Ki/T_S$ (1)	$kp=Kp$
Real	$\approx ki*G_{op}$ (2)	$\approx kp*G_{op}$



KI&KP **(FPGA) vs.** ***Ki&Kp*** **(dig.)**



Ki **(dig.) vs.** ***ki*** **(ana.)**

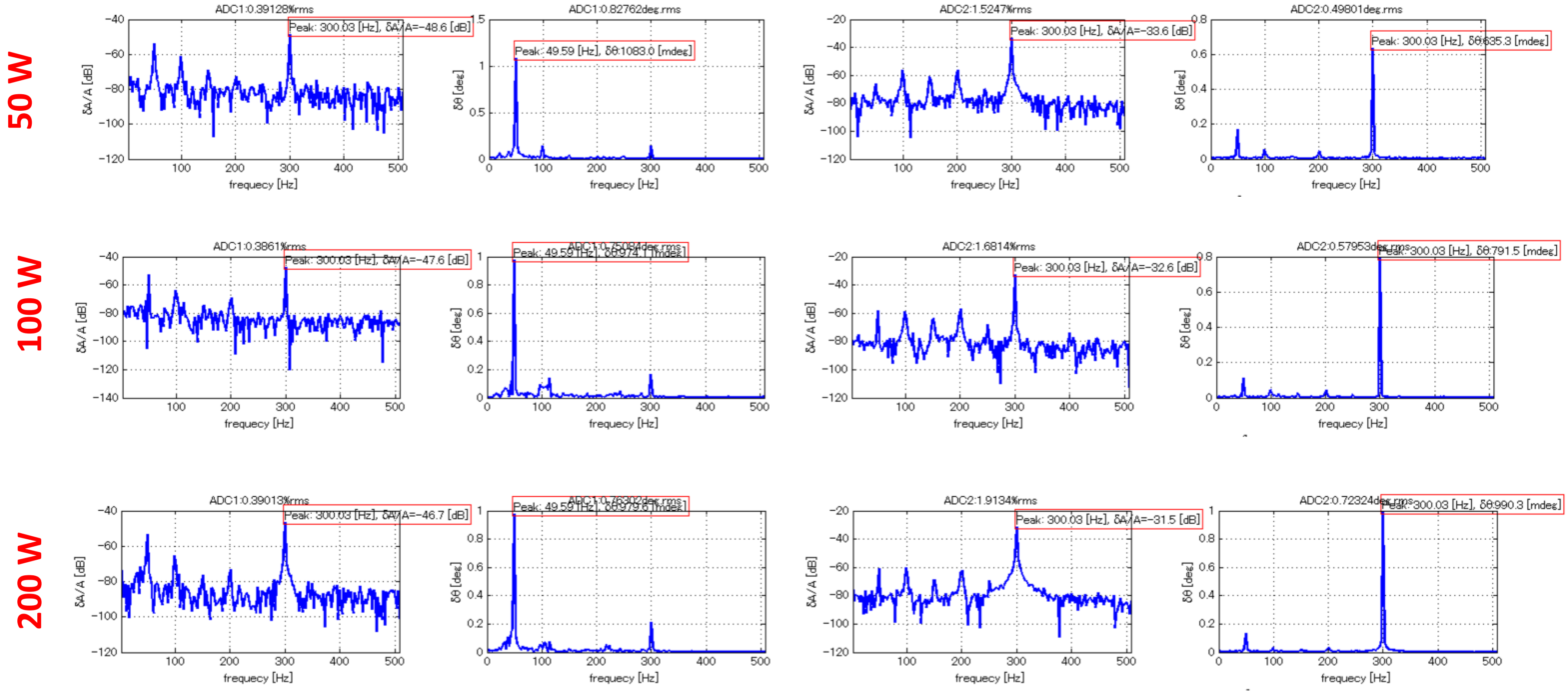


ki&kp **(ana.) vs. real gain** $A_{Set}/(A_{Set}-A_{Meas}.)$

1 . T_S is FPGA sampling clock period (T_S= 1/162.5e6 in cERL LLRF system)
2. G_{op} is the open-loop gain (Gains from FF to SEL(Fil) during the open-loop operation. For the Inj1 and Inj2&3, $G_{op} \approx 1$ (0 dB).)

ML2 IOT test

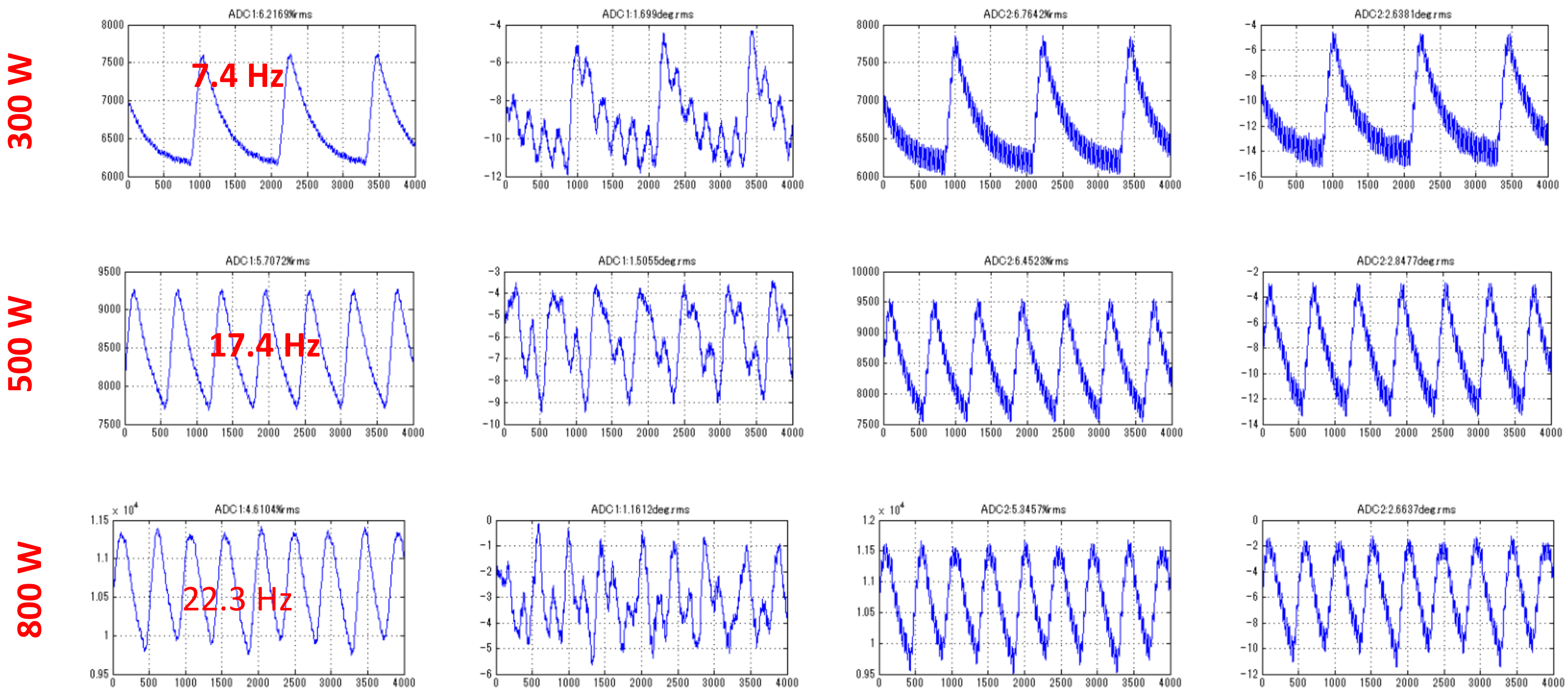
The Spectrum of the IOT (50 W to 200 W)



Study at cERL (2013), F. QIU

ML2 IOT test

The Waveform in the worst IOT output case (300 W to 500 W)



Study at cERL (2013), F. QIU

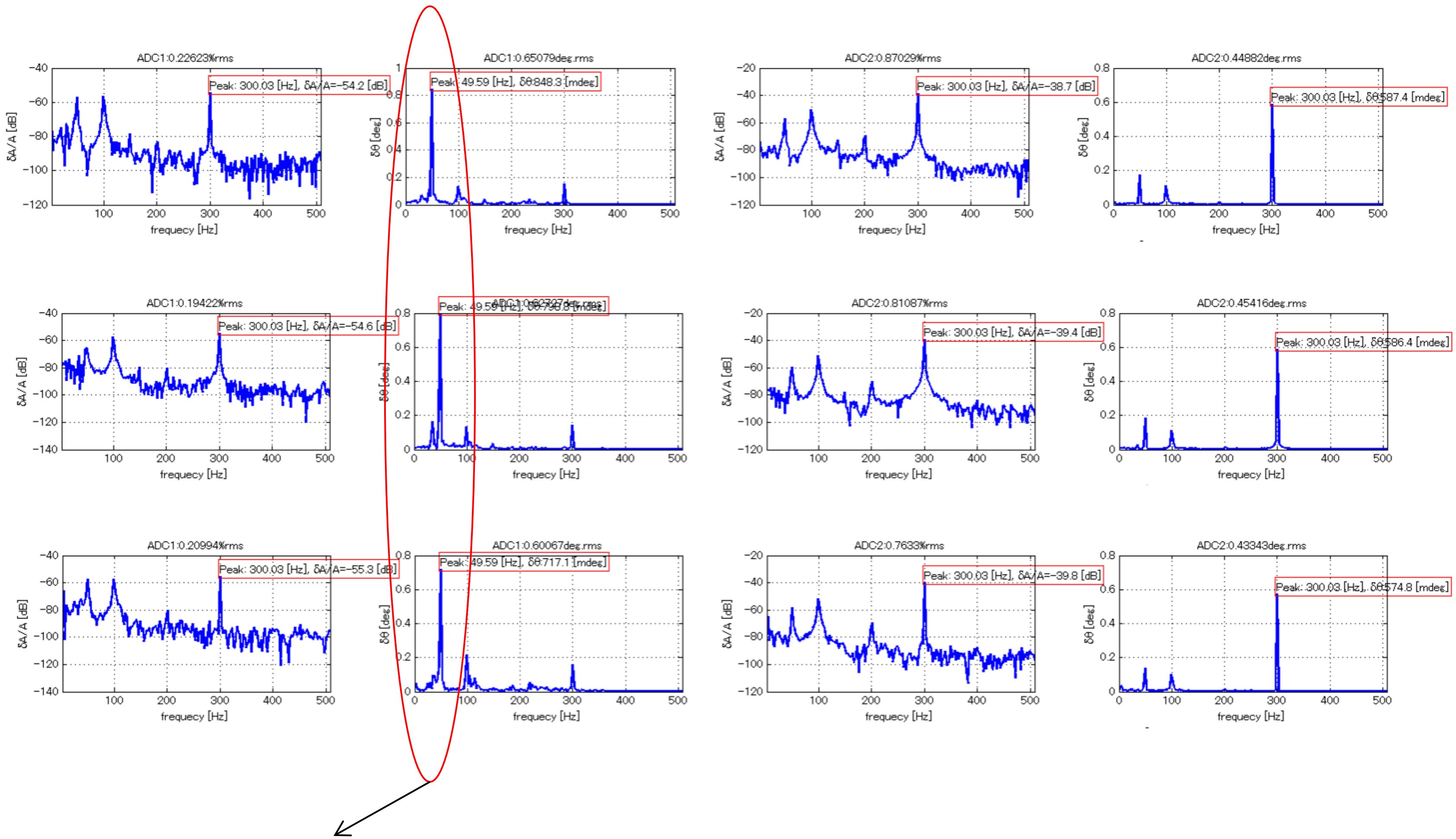
ML2 IOT test

IOT (High power case)

1000 W

1500 W

1800 W

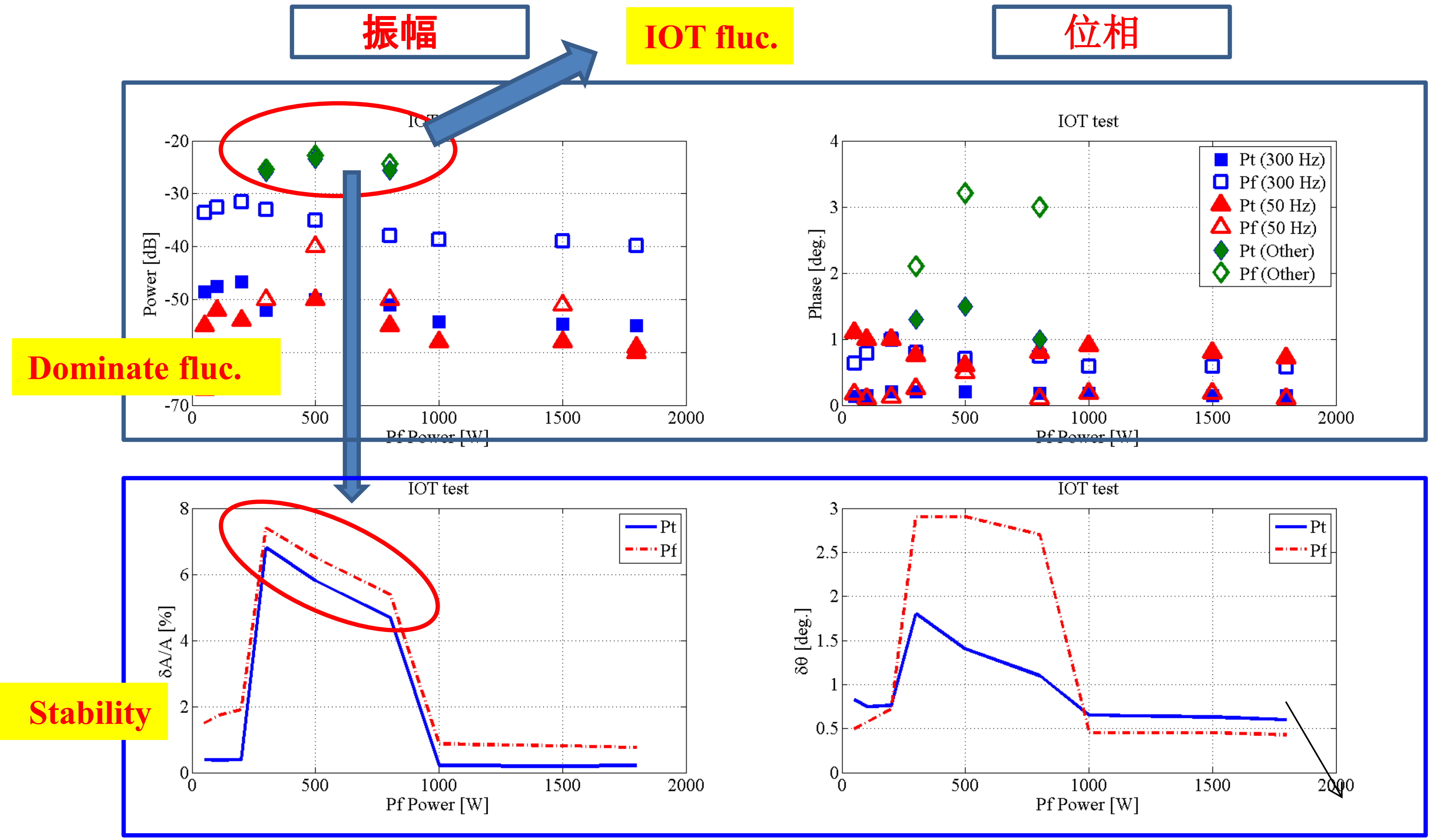


Noted that the 50 Hz component is enhanced from Pf to Pt !

Study at cERL (2013), F. QIU

Experiment on ML (ML2 IOT)

The dominated component in different IOT power

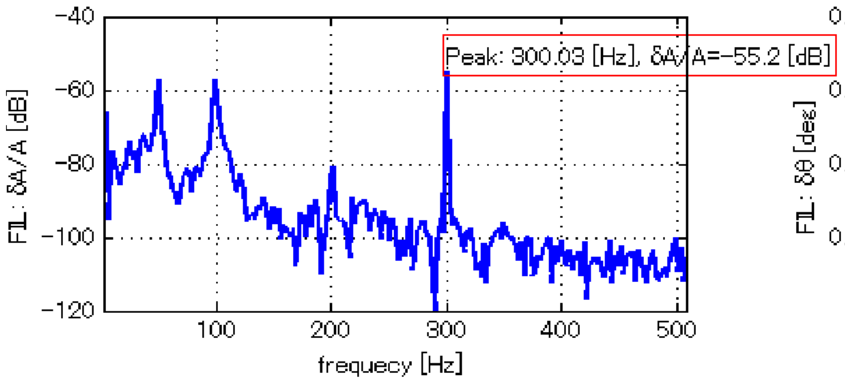


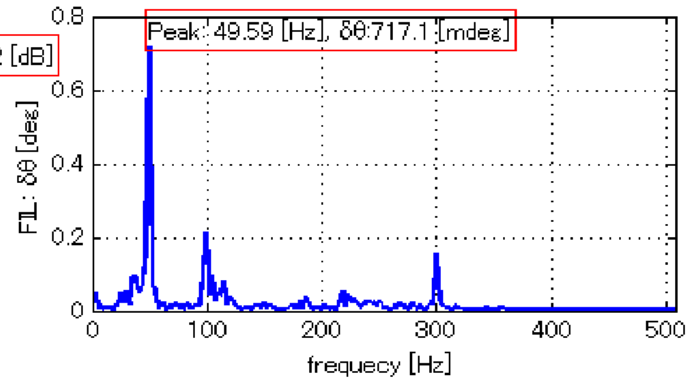
ML2 (Spectrum)

振幅

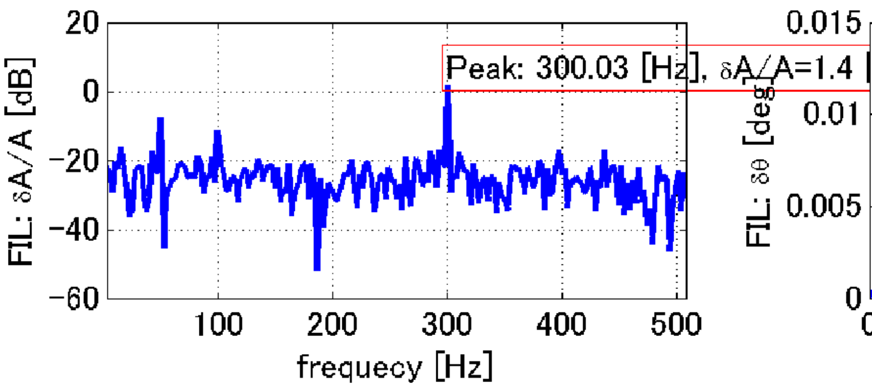
位相

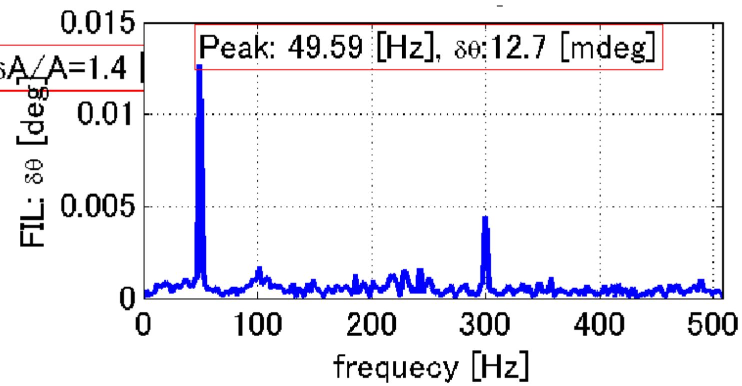
FF





FB





Study at cERL (2013), F. QIU