LLRF study in cERL

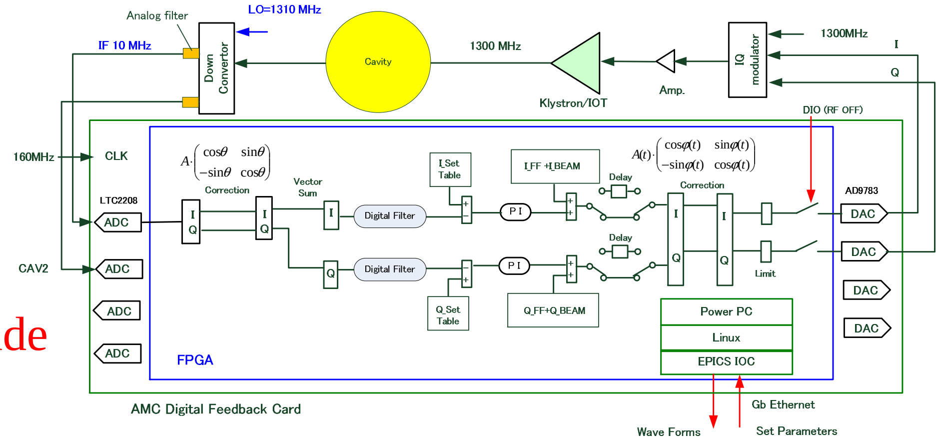
Feng QIU

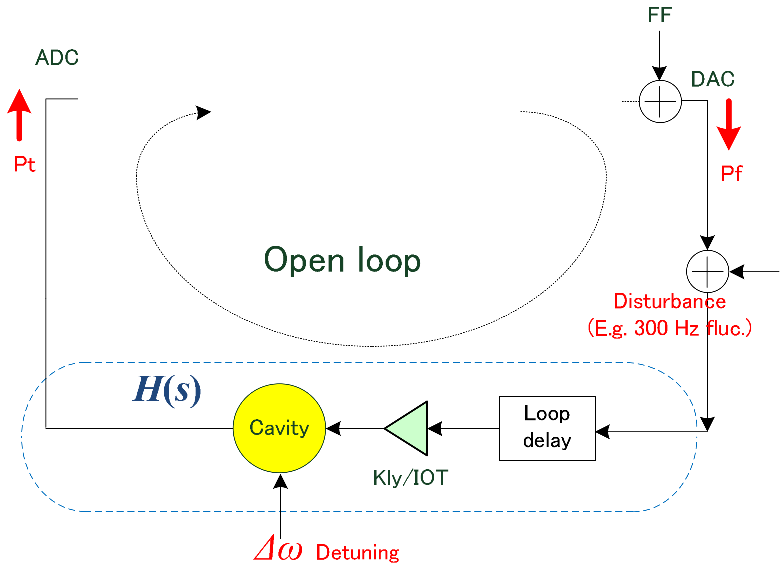
Main Content

- LLRF system
- The 300 Hz Fluctuation
- Gain Scanning
- Future Plan

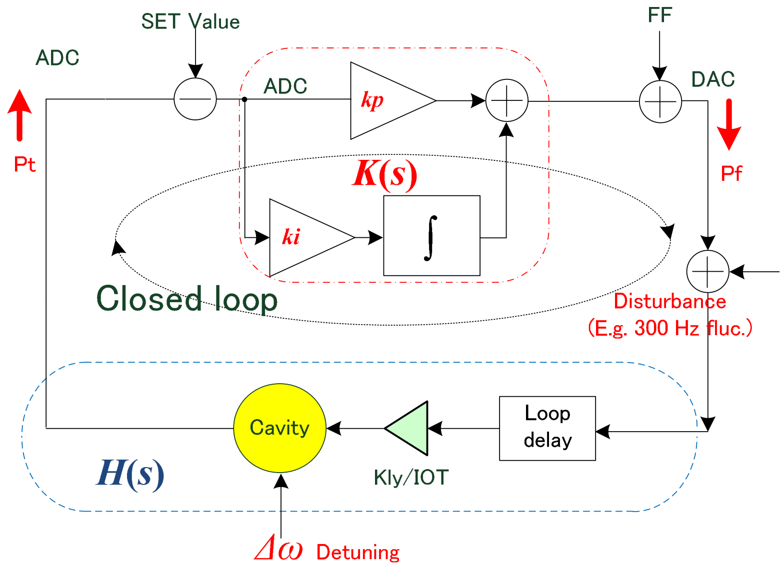
LLRF system

- 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 [1].





No disturbance suppression!



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

1 .Higher gain (Larger K(s)) corresponds to higher disturbance suppression. However, too high gains may result of unstable.

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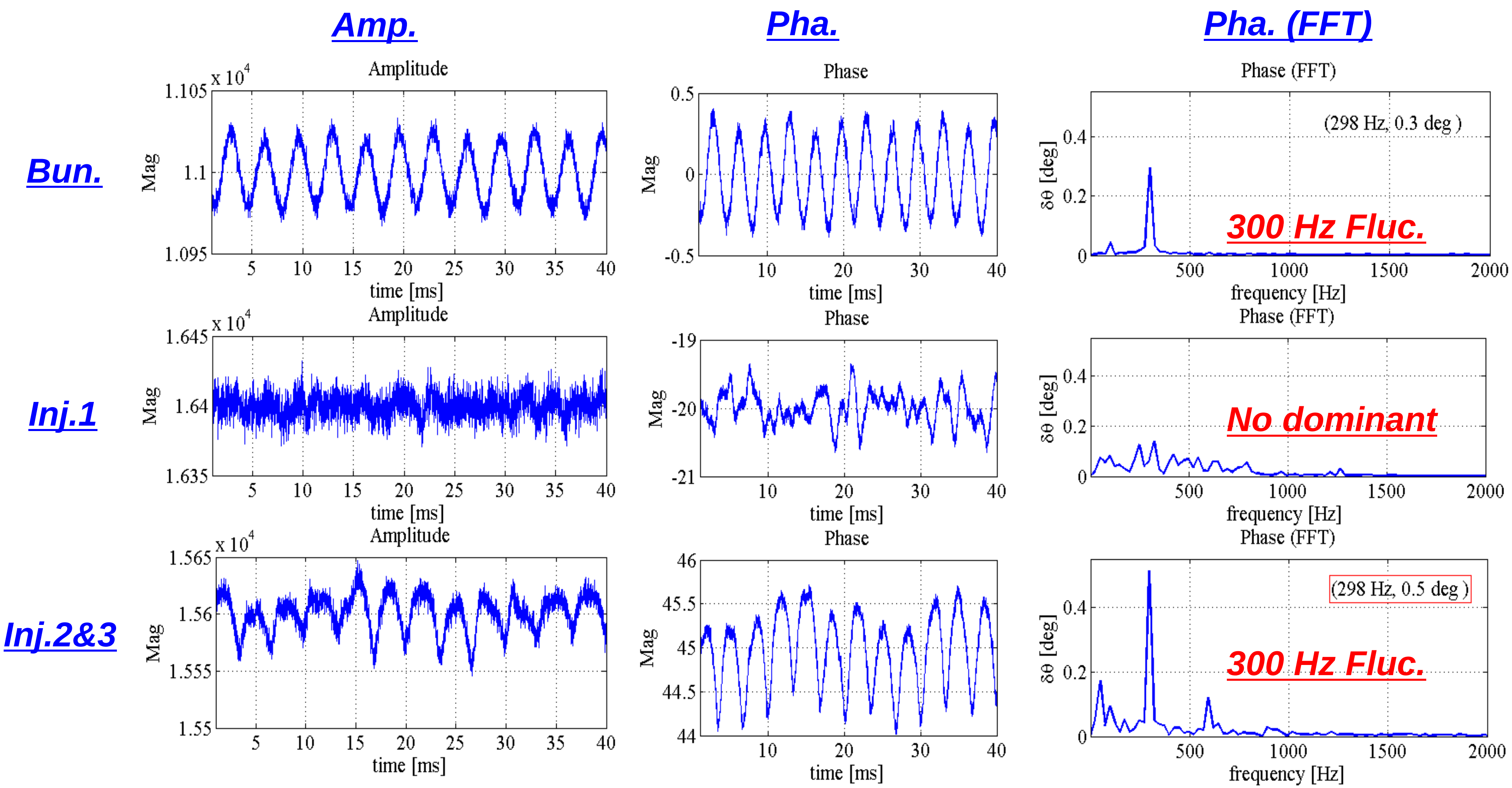
300 Hz Fluctuation (Inj. 2&3, Buncher)

- The 300 Hz fluc. at Inj2&3 (FB2) and Buncher (FB0) cavity during CL/OL operation.
- The Inj1 (FB1) LLRF system doesn't not has evident dominant components.



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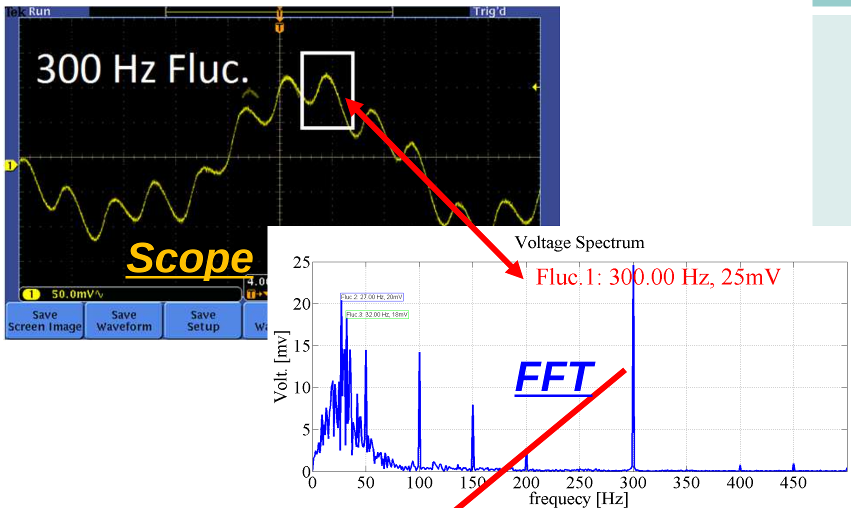
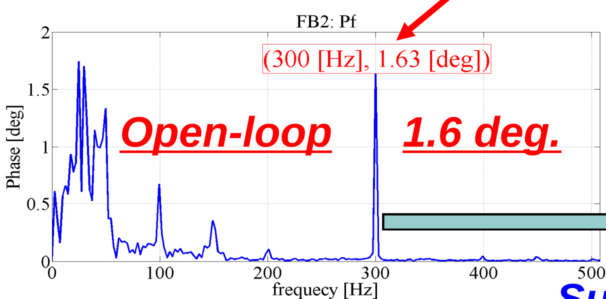
Fluctuation at 300 Hz (Source)

- The Power supply is the probable 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).
- According to current controlling parameter (KI=10, KP=0), the 300 Hz component is suppressed by ~10 dB (~3 times), **not enough**.

300 KW Kly. High Voltage

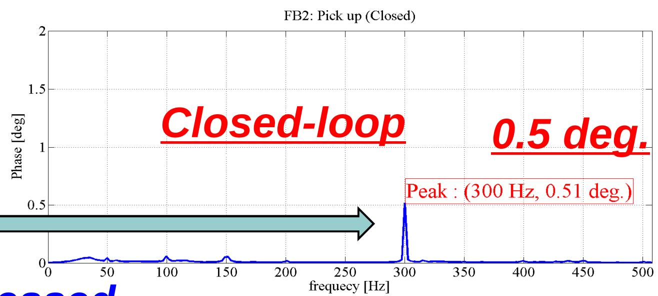


Fluc. @ 300 Hz		Buncher	Inj2&3 (VS)
Open loop	$\Delta A/A$	-43.5 [dB]	-46 [dB]
	$\Delta\theta$	0.9 [deg.]	1.6 [deg.]
Closed loop KI=10, KP=0)	$\Delta A/A$	-54 [dB]	-56.5 [dB]
	$\Delta\theta$	0.3 [deg.]	0.5 [deg.]



Cavity input (OL)

Suppressed



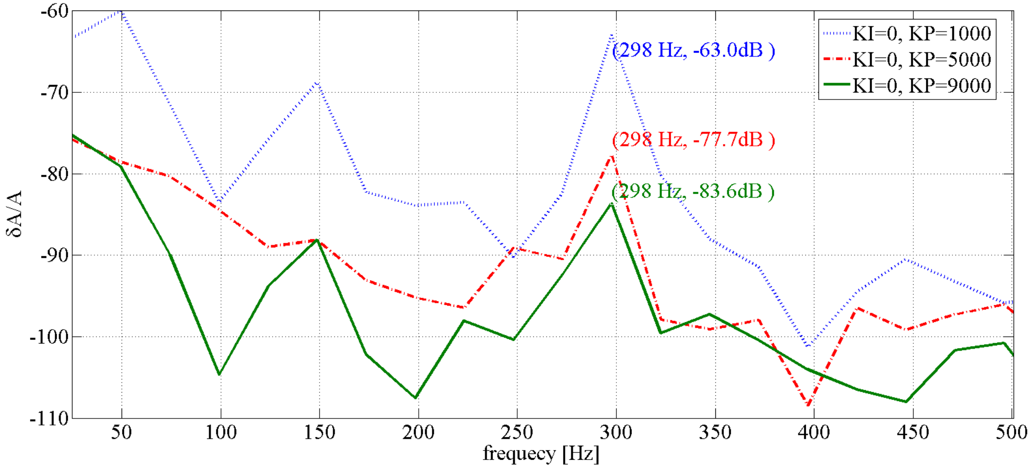
Cavity Pick up (CL)

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

Gain scanning (300 Hz suppression)

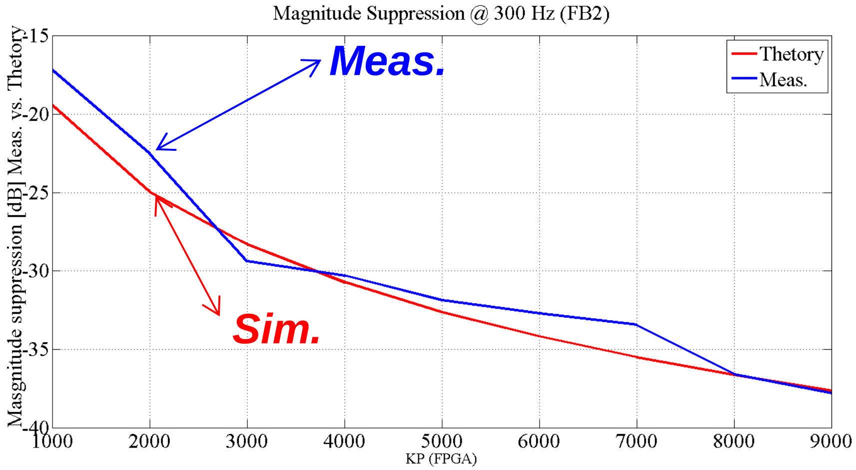
- Gain-scanning: Scanning (changing) different proportional gain KP and integral Gain KI (@ 2 MV/m for security) to find out the optimal gains .
- The 300 Hz component is suppressed by high gains.

Suppression of 300 Hz component



About 20 dB suppression when increasing proportional gain KP by 9 times (KI=0).

Meas. vs. Sim.



We can also analyze the suppression of the 300 Hz component by simulation, the results agree well with each other.

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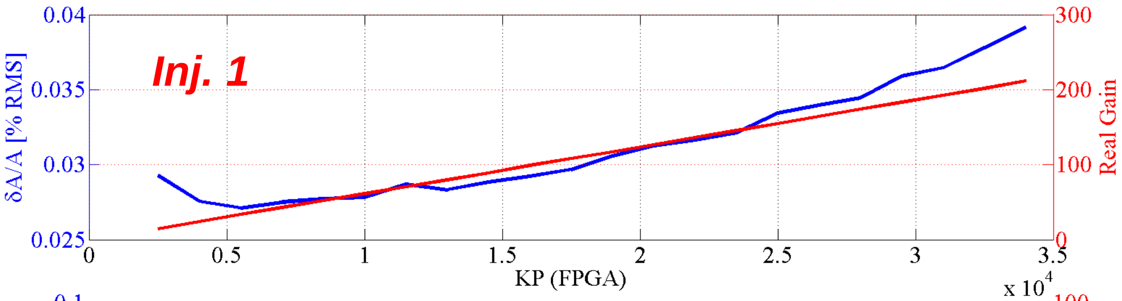
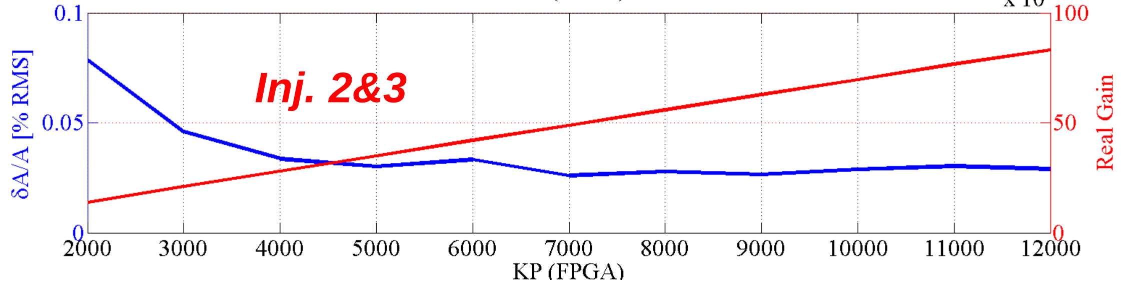
Gain scanning (Critical gains)

- Too high gains would result of loop-unstable. We can evaluate the critical (Maximum) gain by both KI=0, KP gain-scanning.

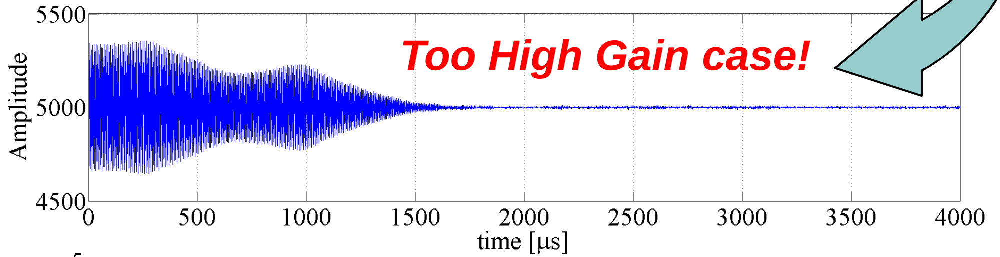


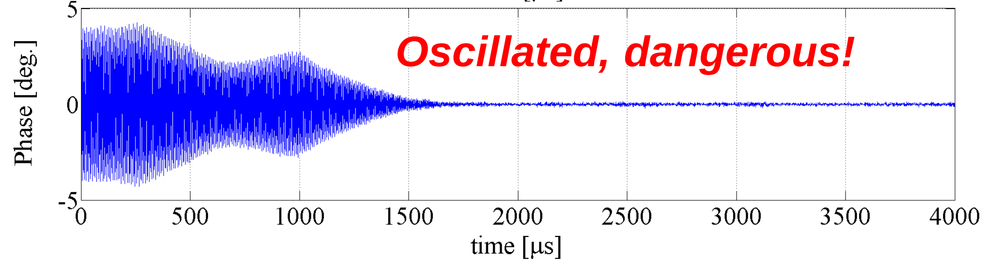


Critical Gain of FB1 is about 250 (**Oscillation @ Gain 250**)
Critical Gain of FB2 is about 90 (**Oscillation @ Gain 90**)

The difference of the critical gain is main dominated by the bandwidth of the cavity.

Stb	Inj1	Inj2	Inj3
QL [2]	1.2e6	5.8e6	4.8e6
Bandwidth [kHz]	1.1	2.25	2.7





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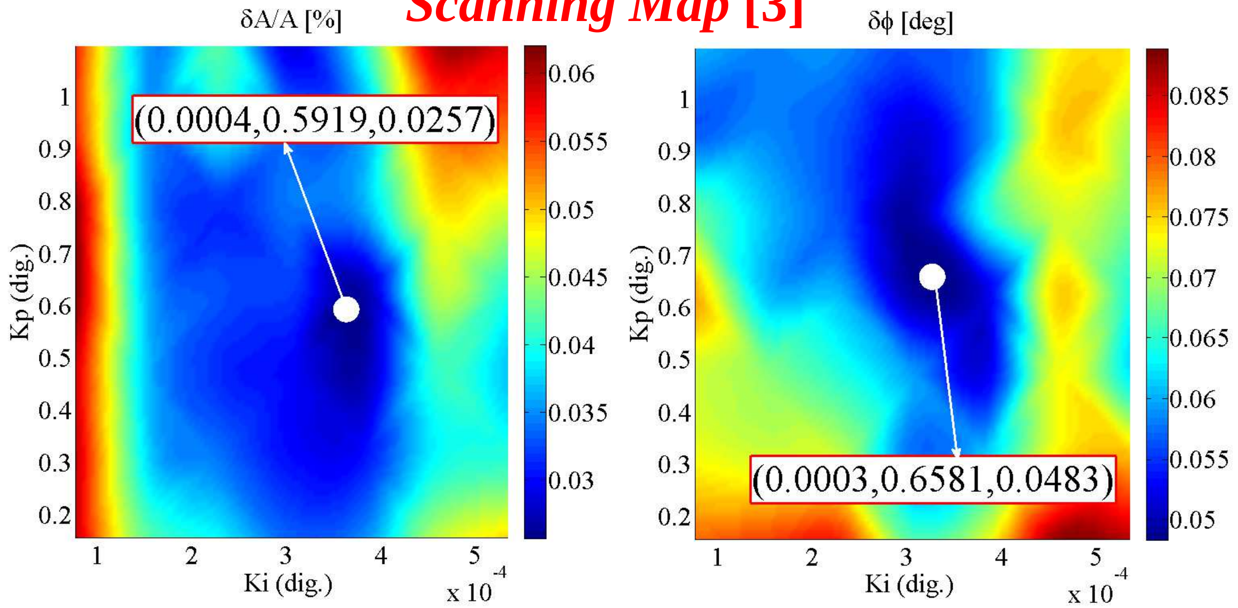
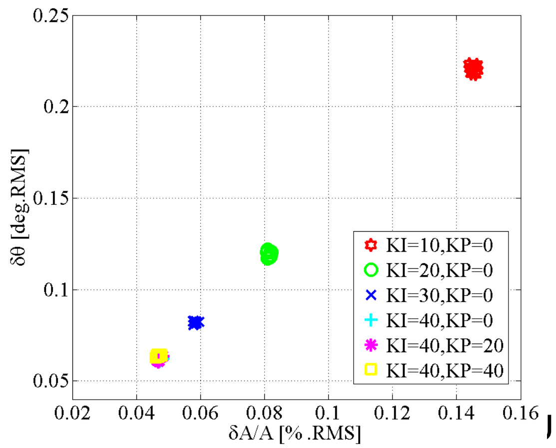
Gain scanning (Buncher)

- It is clear to see the optimal gains (optimal KP and KI) of the buncher cavity according to the scanning map.
- For the buncher cavity, the performance is dominated by the integral gains (KI) due to it is normal cavity (QL=2.1e4 [2]).

Scanning Map [3]



Performance @ 7MV/m

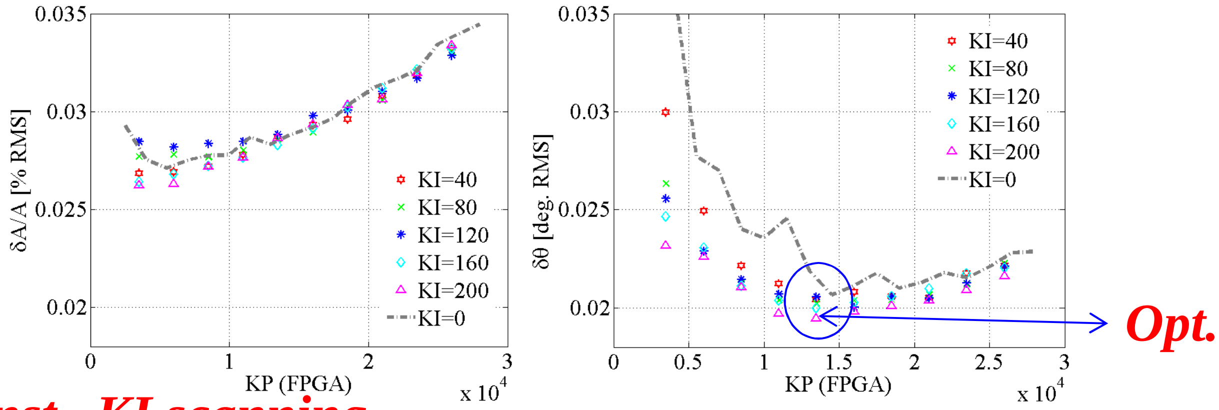


The amplitude and phase stability can be 0.045% RMS and 0.055 deg. RMS, respectively.

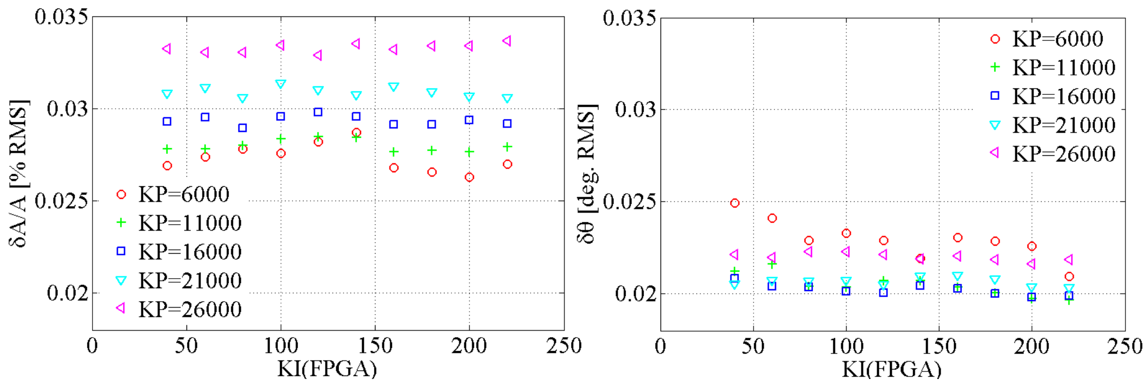
Gain scanning (Inj. 1)

- The dominant gain in Inj1 is proportional gain (KP).
- High gain controlling can be realized due to its narrow bandwidth.

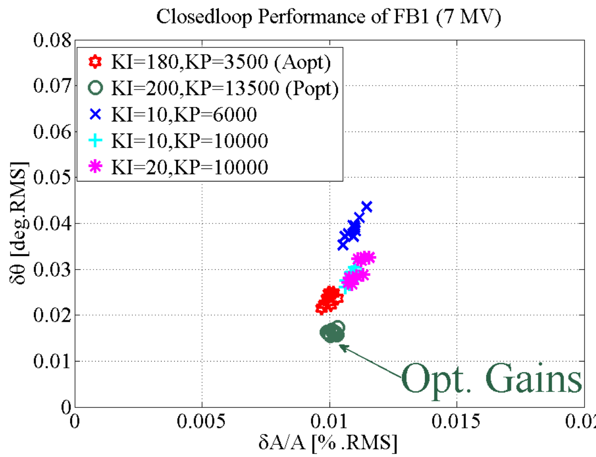
KI=const., KP scanning



KP= const., KI scanning



Performance @ 7MV



The amplitude and phase stability of Inj1 can be 0.01% RMS and 0.02 deg. RMS, respectively.

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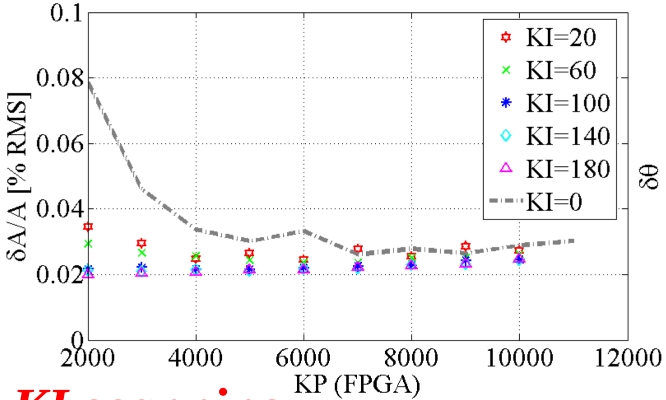
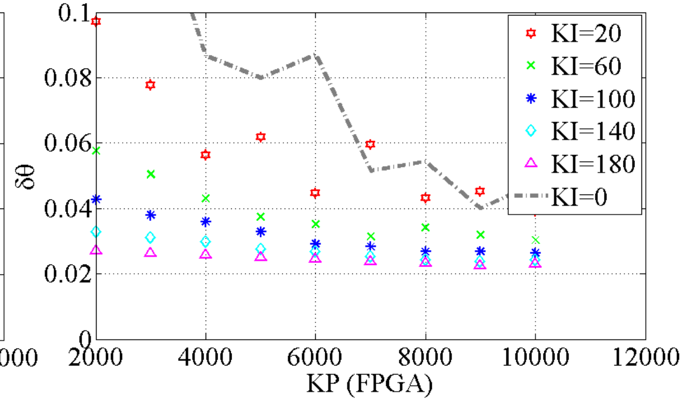
Gain scanning (Inj. 2&3)

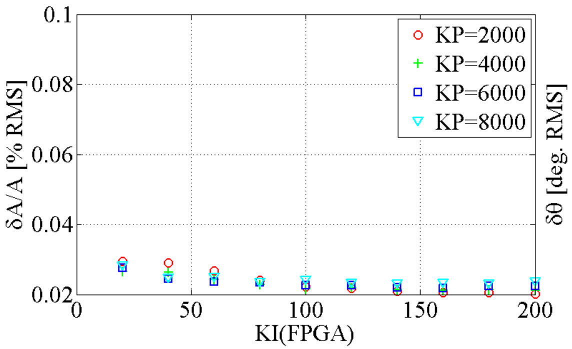
- Both KI and KP have influenced the performance.
- Because there is 300 Hz component in Inj. 2&3, Higher KI would suppressed the 300 Hz more effective.

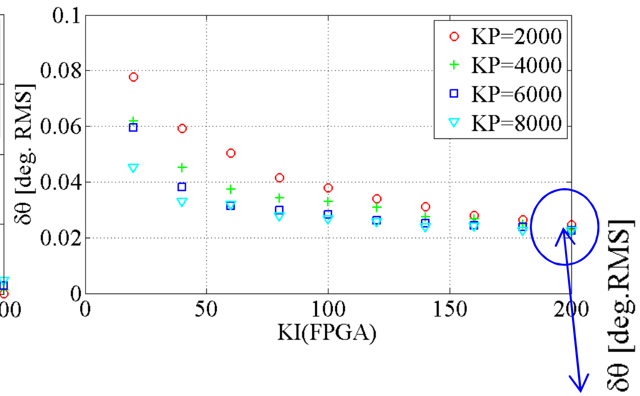
KI=const., KP scanning





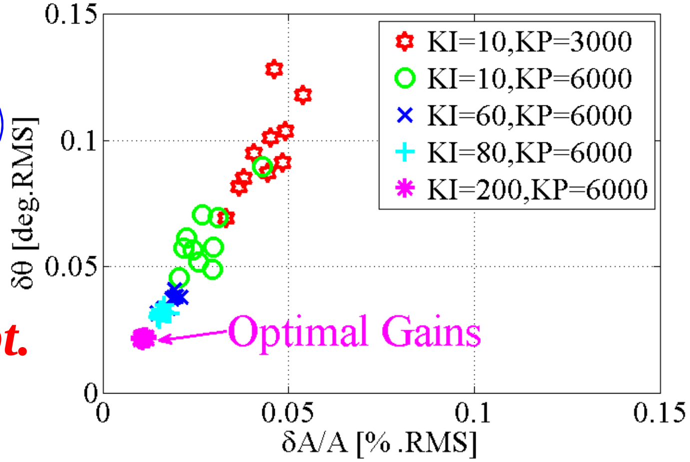
KP= const., KI scanning





Opt.

Performance @ 7MV



The amplitude and phase stability of Inj1 can be 0.012% RMS and 0.02 deg. RMS, respectively.

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Future Plan

- How to eliminate the 300 Hz fluctuation in the power supply (not by increasing the controlling gain but by hardware itself).
- How to change the controlling parameter safely (KI, KP, SETA, SETP, etc.)? What is the limitation of every parameter?
- Vector-sum controlling problem in the Inj. 2&3 (FB2).

Reference

[1] T. Miyajima, “Beam Commissioning of Energy Recovery Linacs”, IPAC’13, Shanghai, May 2013, FRXBB201

[2] S. Sakanaka et al. “Progress in Construction of the 35-MeV Compact Energy Recovery Linac at KEK” IPAC’13, Shanghai, May 2013, WEPWA015

[3] F. QIU et al. “Evaluation of the Superconducting LLRF System at cERL in KEK”. IPAC’13, Shanghai, May 2013, WEPEM015

Question?

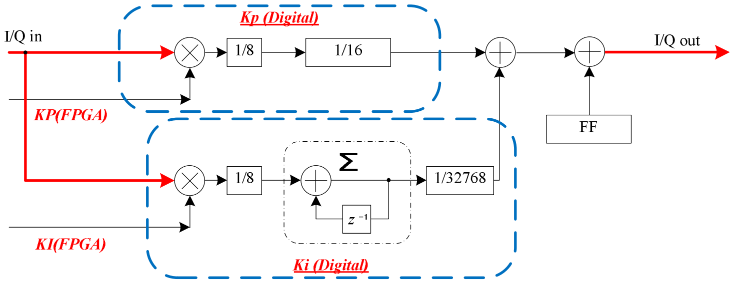
Thank you very much for your attending

Gain scanning (definition)

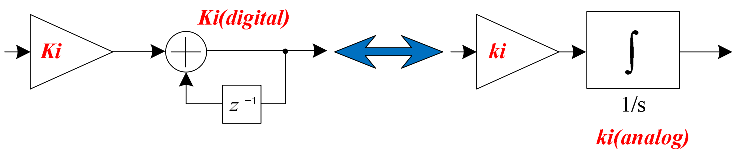
- Gain scanning: determine the optimal controlling gains (@ 2MV foe security).
- Definition of the integral and proportional gains .

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

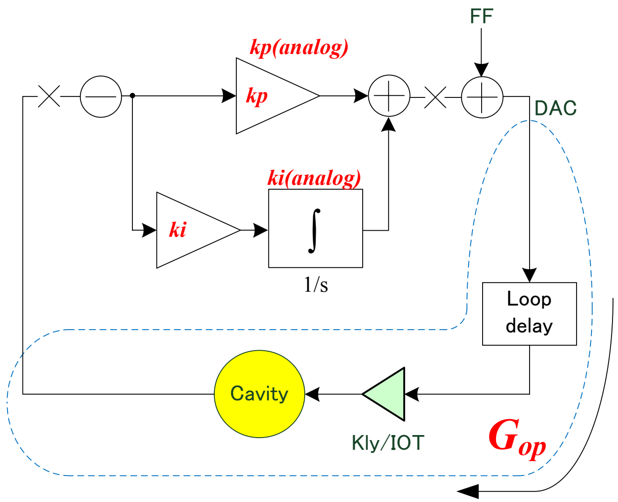
Gains	Integral	Proportional
FPGA	KI	KP
Dig.	$Ki=KI/2^{18}$	$Kp=KP/2^{7}$
Ana.	$ki=Ki/T_S$ (1)	$kp=Kp$
Real	$\approx ki*G_{op}$ (2)	$\approx kp*G_{op}$



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



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

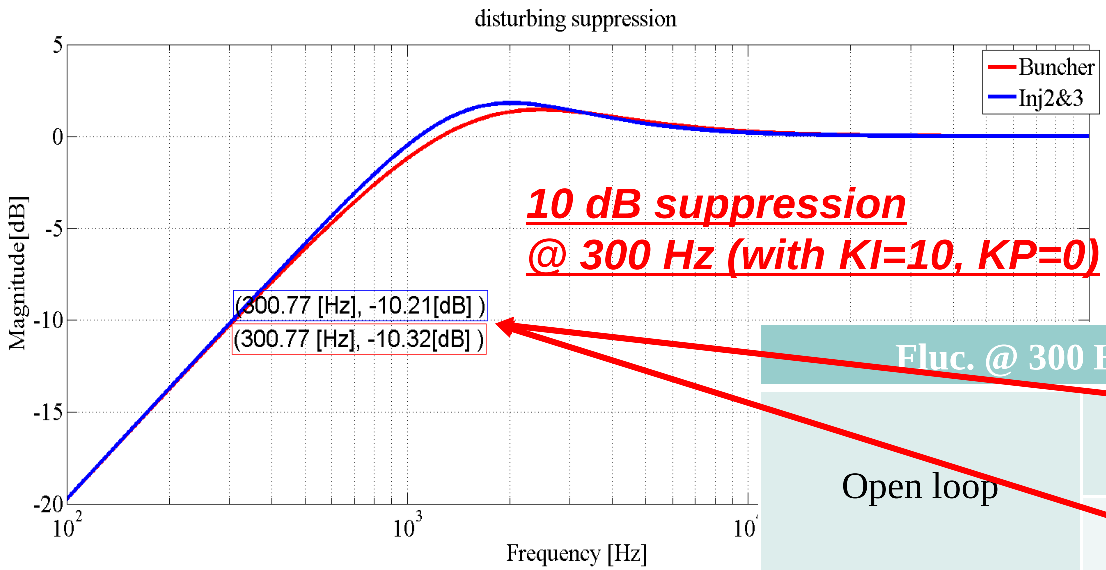


ki&kp **(ana.) vs. real gain** $A_{Set}/(A_{Set}-A_{Meas}.)$

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).)

Fluctuation at 300 Hz (Sim.)

■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]
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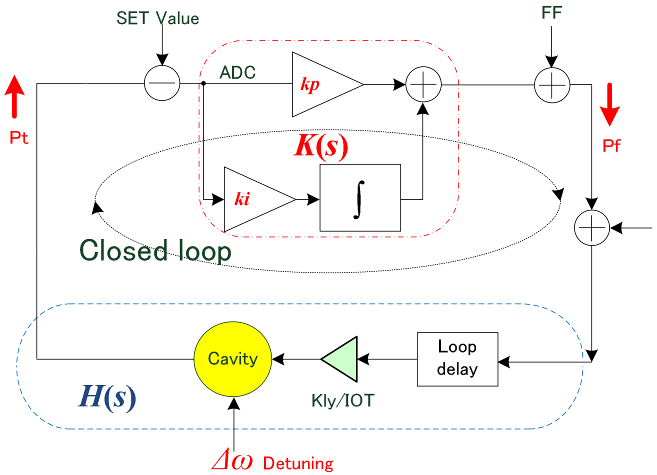
	$\Delta\theta$	0.3 [deg.]	0.5 [deg.]



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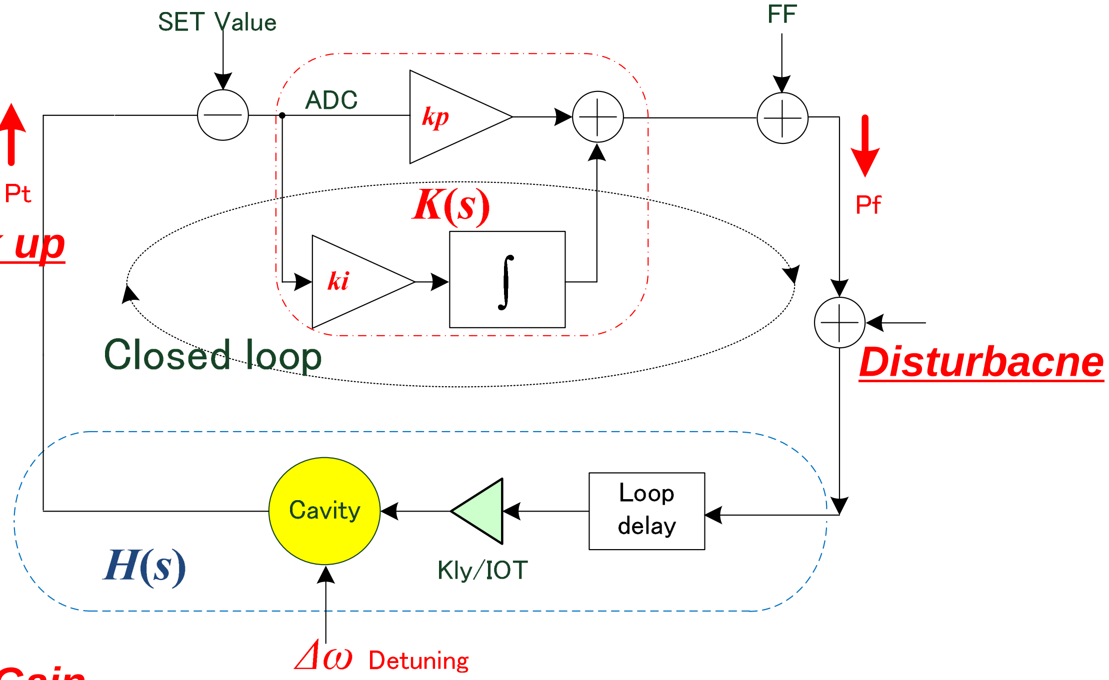
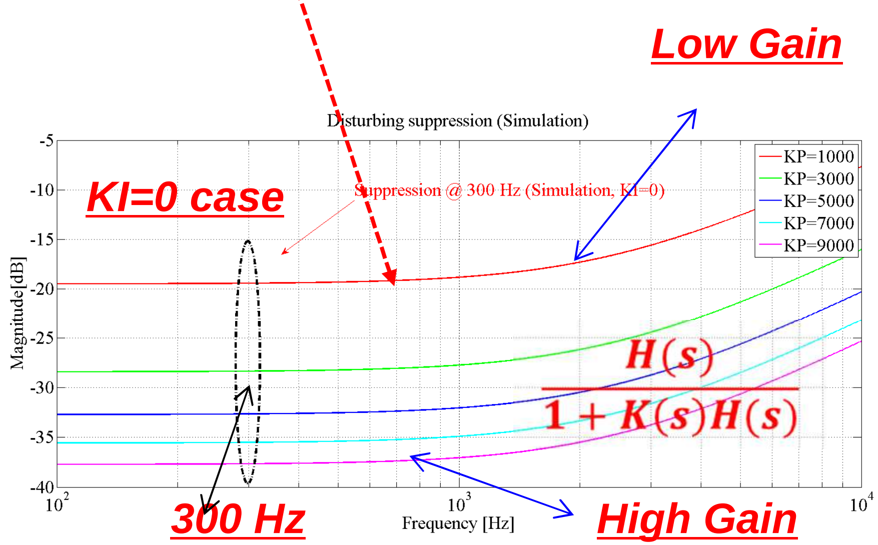
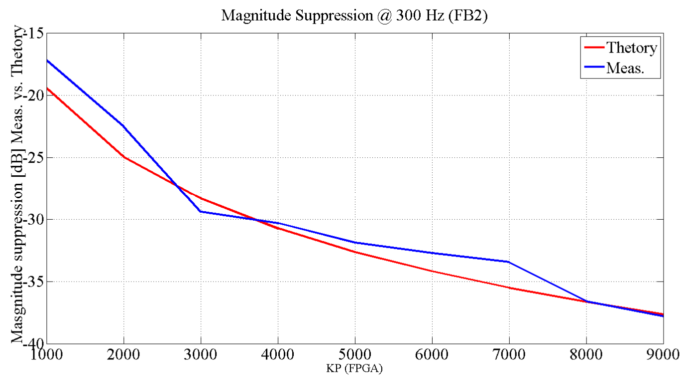
Gain scanning (300 Hz Sim.)

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



The transfer function from the disturbance to the Pcik up in the closed loop





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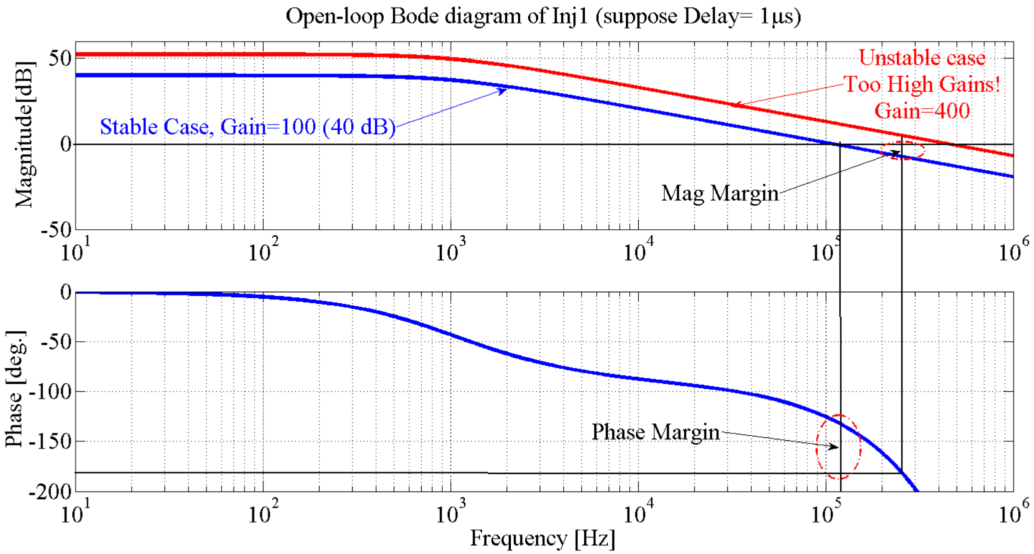
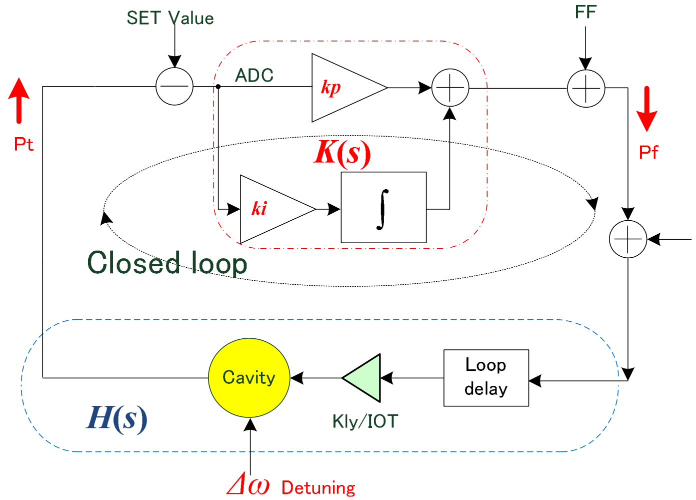
Gain scanning (High Gain Sim.)

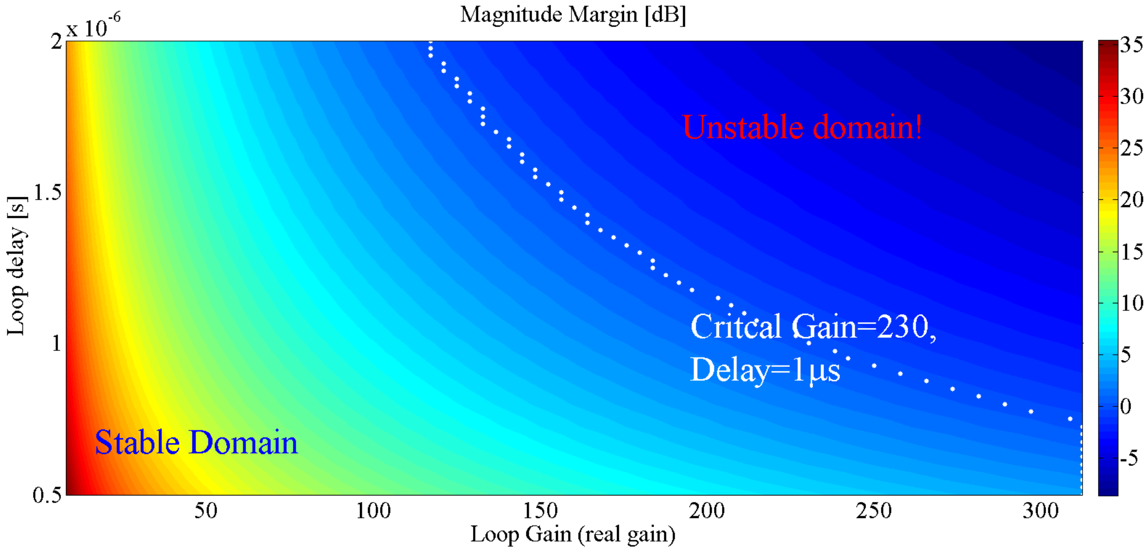
■ Too high gains would result of loop-unstable. We can evaluate the critical gain by both KI=0, KP gain-scanning and bode diagram simulation.



Critical Gain of FB1 is about 250 (**Oscillation @ Gain 250**)
Critical Gain of FB2 is about 90 (**Oscillation @ Gain 90**)

Stb	Inj1	Inj2	Inj3
QL	1.2e6	5.8e6	4.8e6
BW [kHz]	1.1	2.25	2.7





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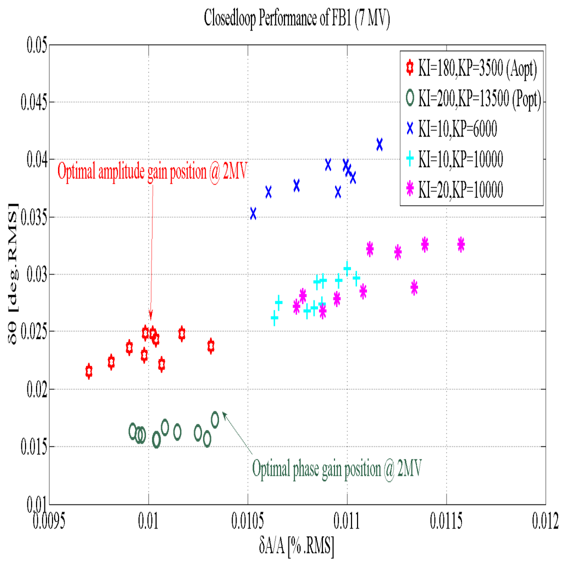
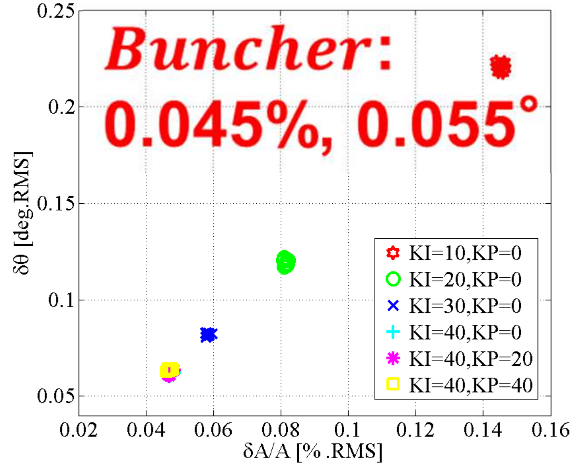
Gain scanning (Performance)

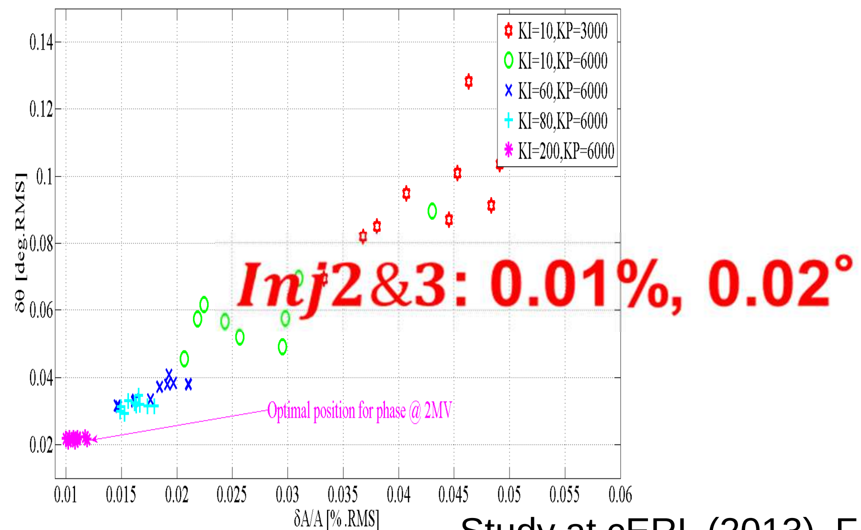
- Gain-scanning experiment is implemented in 2MV/m condition, it is also in agreement well with 7 MV/m case.
- Our requirement: 0.1% for amplitude, 0.1 deg for phase. *Satisfying (FB0&1&2).*



Inj1: 0.01%, 0.02°



Stb	Bun.	Inj1	Inj2&3 (VS)
ΔA/A [%]	0.045	0.01	0.012
Δθ [deg]	0.055	0.02	0.02



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