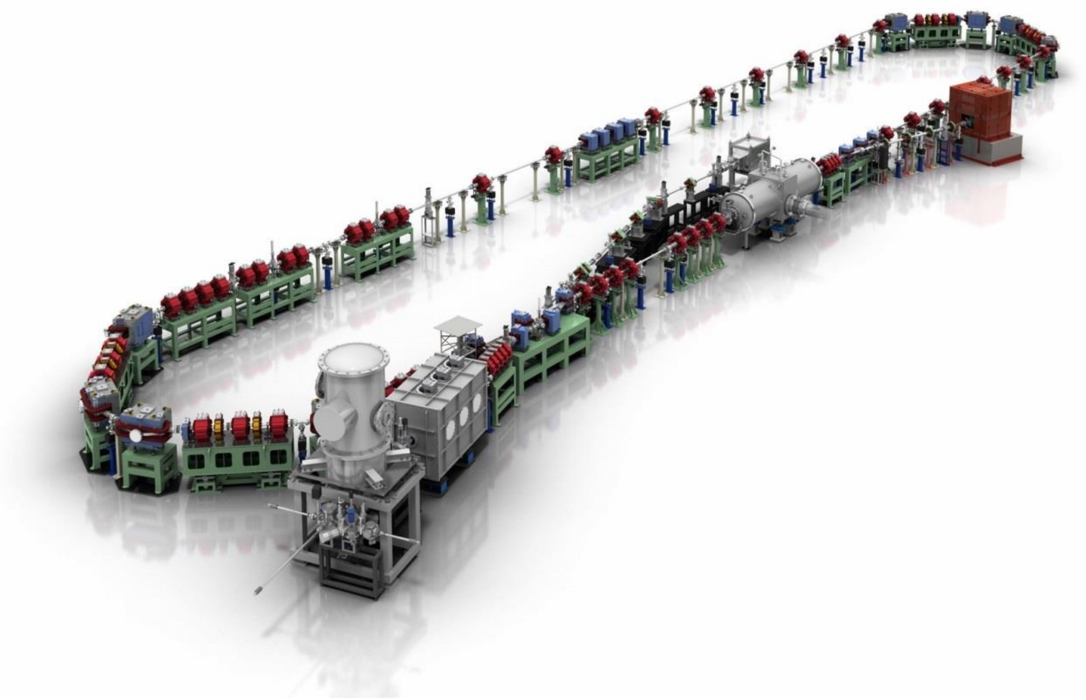
Disturbance observer-based control in LLRF system in a compact ERL at KEK

Feng QIU (KEK) Nov., 03-07, 2015



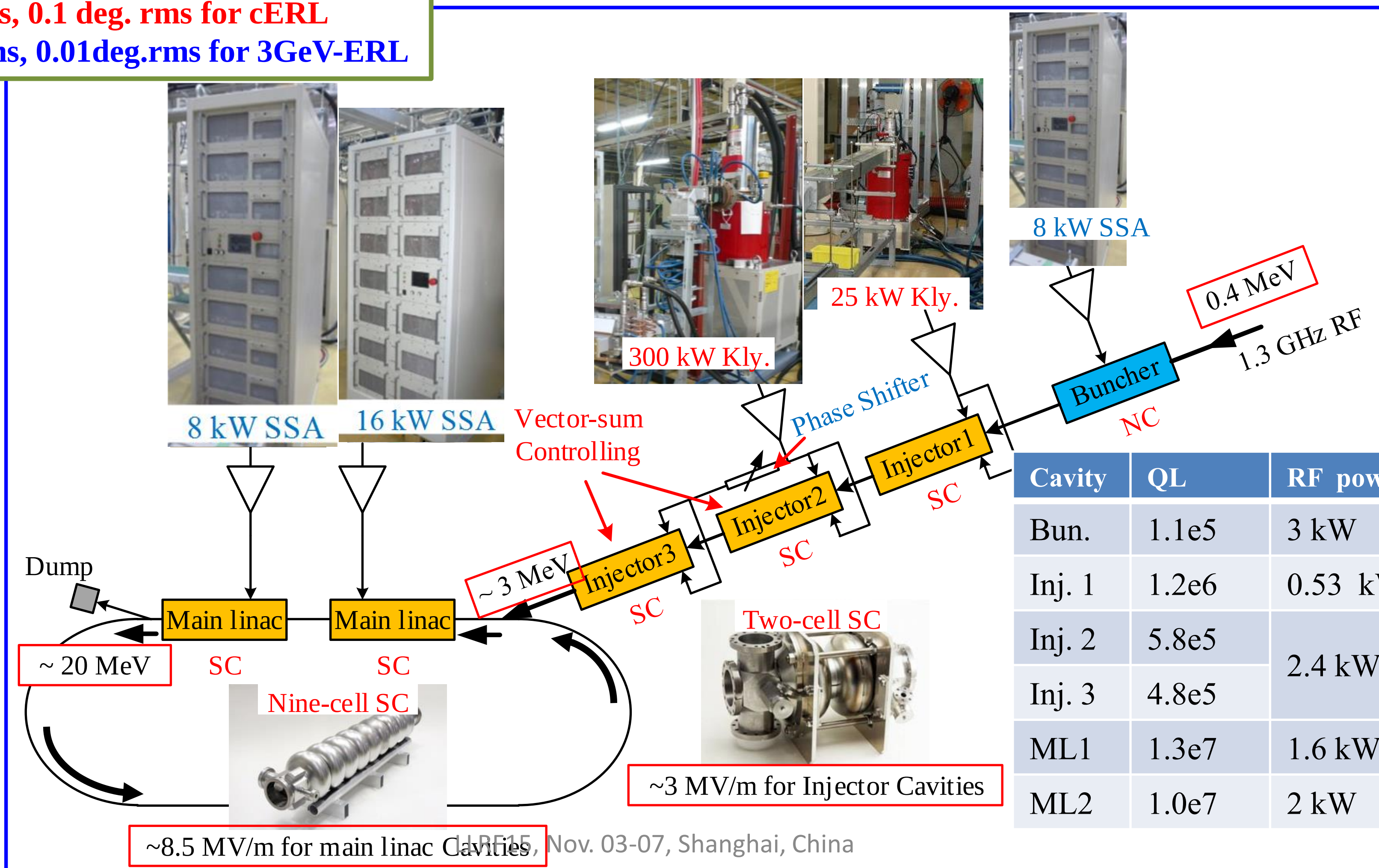
Main content

- Introduction of LLRF systems in the cERL at KEK.
- Idea of disturbance observer-based control.
- Application of disturbance observer-based control.

Introduction

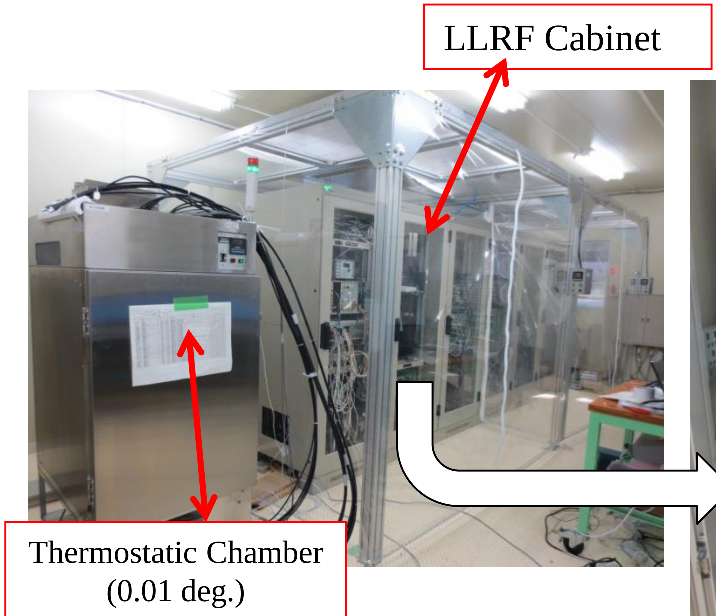
- Compact ERL (cERL) is a test facility for the future 3-GeV ERL project. It is a 1.3-GHz superconducting system and is operated in CW mode.
- April, 2013, injector commissioning. Oct. 2013, main linac commissioning.

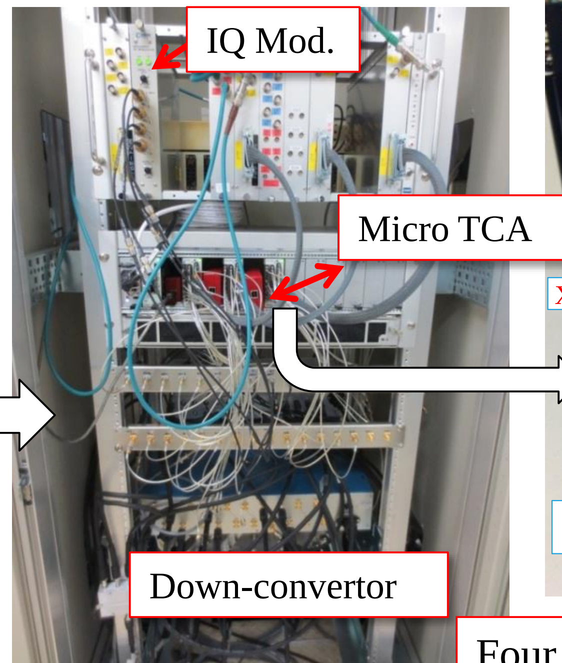
RF requirements
0.1 % rms, 0.1 deg. rms for cERL
0.01% rms, 0.01deg.rms for 3GeV-ERL

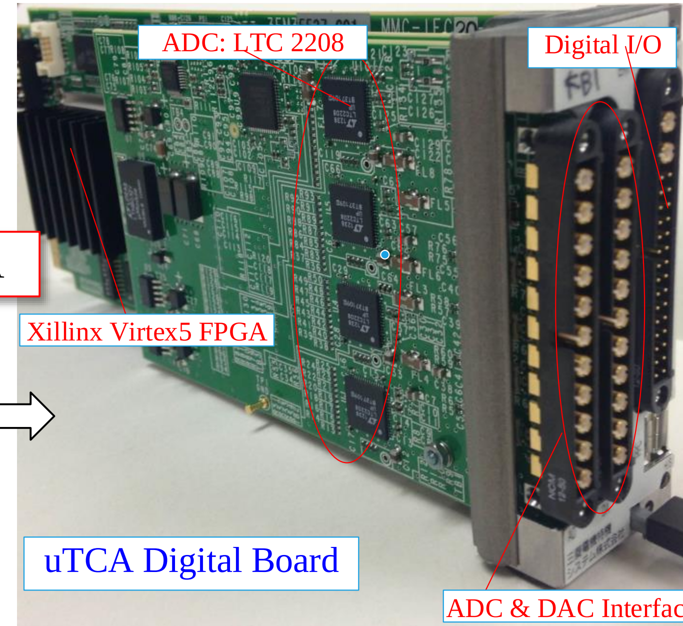


Cavity	QL	RF power
Bun.	1.1e5	3 kW
Inj. 1	1.2e6	0.53 kW
Inj. 2	5.8e5	2.4 kW
Inj. 3	4.8e5	
ML1	1.3e7	1.6 kW
ML2	1.0e7	2 kW

LLRF (Digital Board)



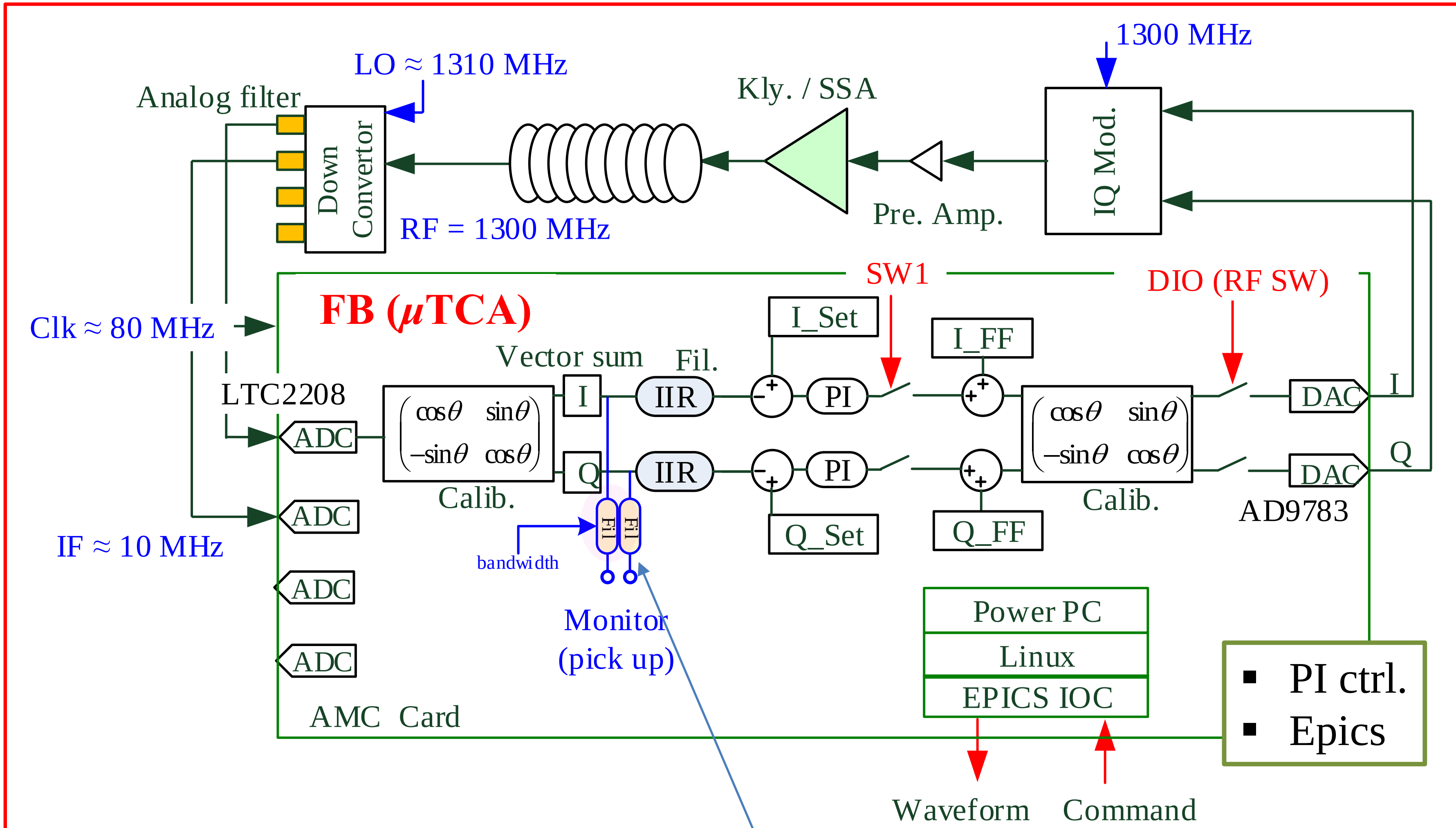




Four channel 16 bits ADCs + four channel 16 bits DACs.

Digital Board	type	Feature
ADC	LTC2208	16 bits, 130 MHz (Max.)
DAC	AD9783	16 bits, 500 MHz (Max.)
FPGA	Virtex 5 FX	550 MHz (Max.), includes a Power PC with Linux, EPICS is installed on the Linux.

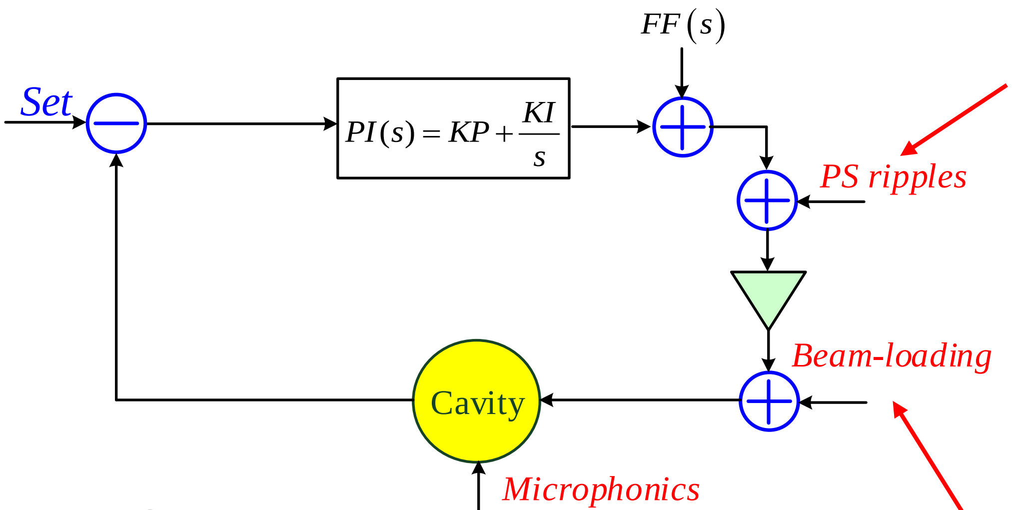
LLRF (schematic)

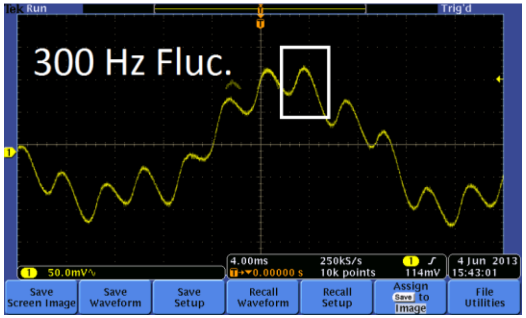


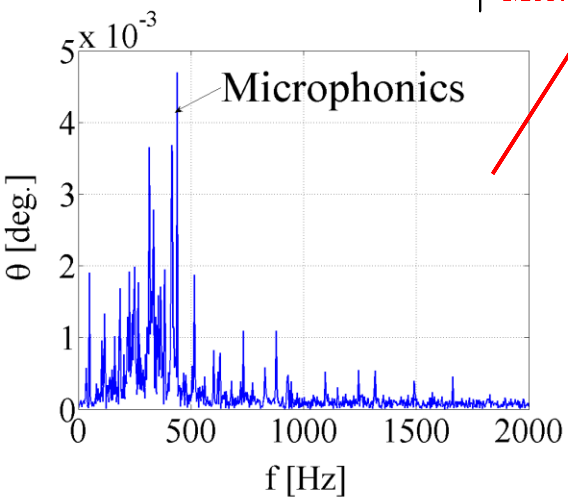
$$IIR: y(n) = \alpha \cdot x(n) + (1-\alpha) \cdot y(n-1), \ \ \alpha << 1$$

Disturbances in RF system

■Main disturbances: High voltage power supply ripples (300 Hz) + burst mode beam-loading (0.5 mA~1mA, 1 ms ~ 2 ms) and Microphonics (DC ~ 500 Hz) [1-3].

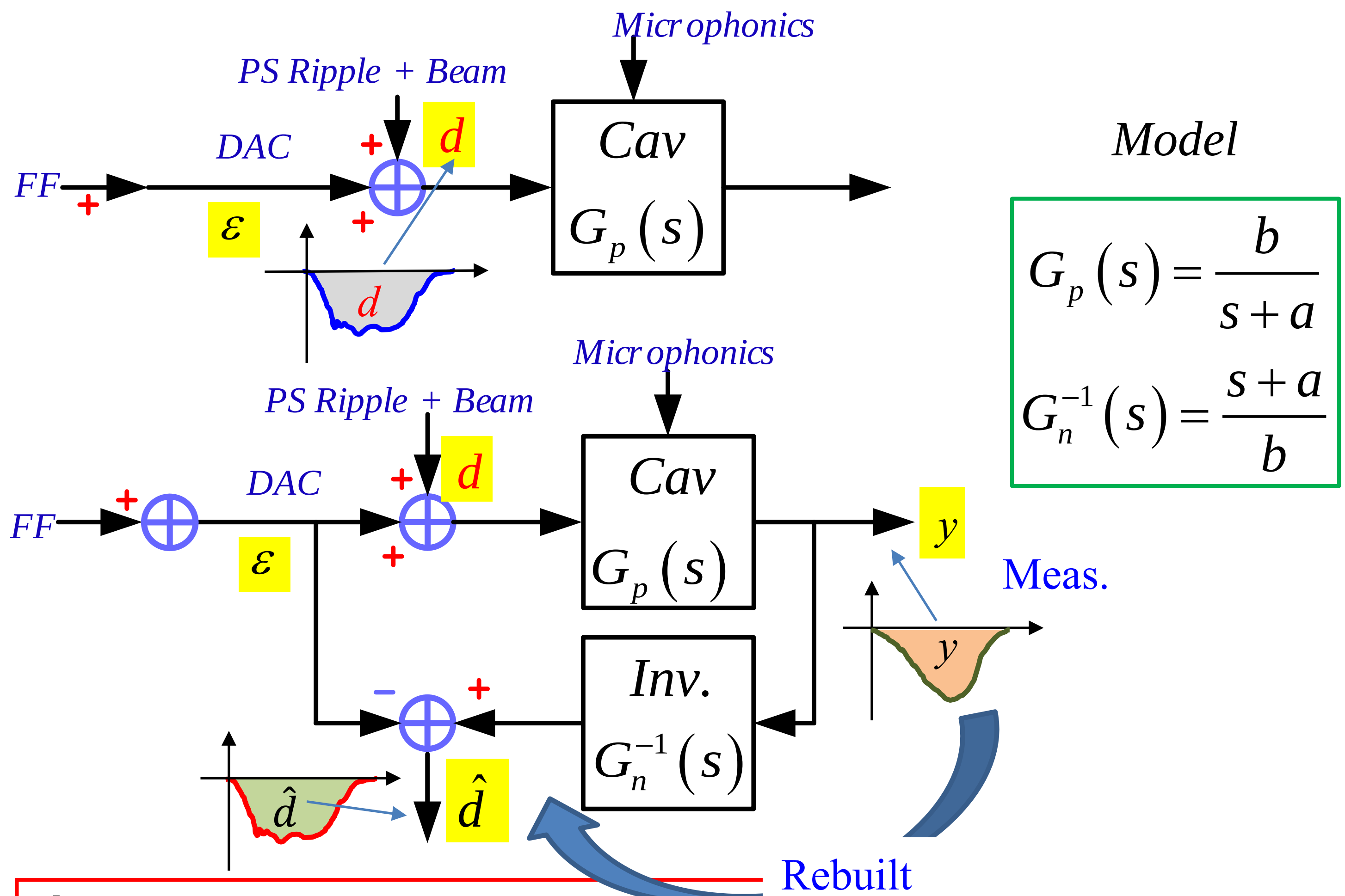






Disturbance Observer (DOB)

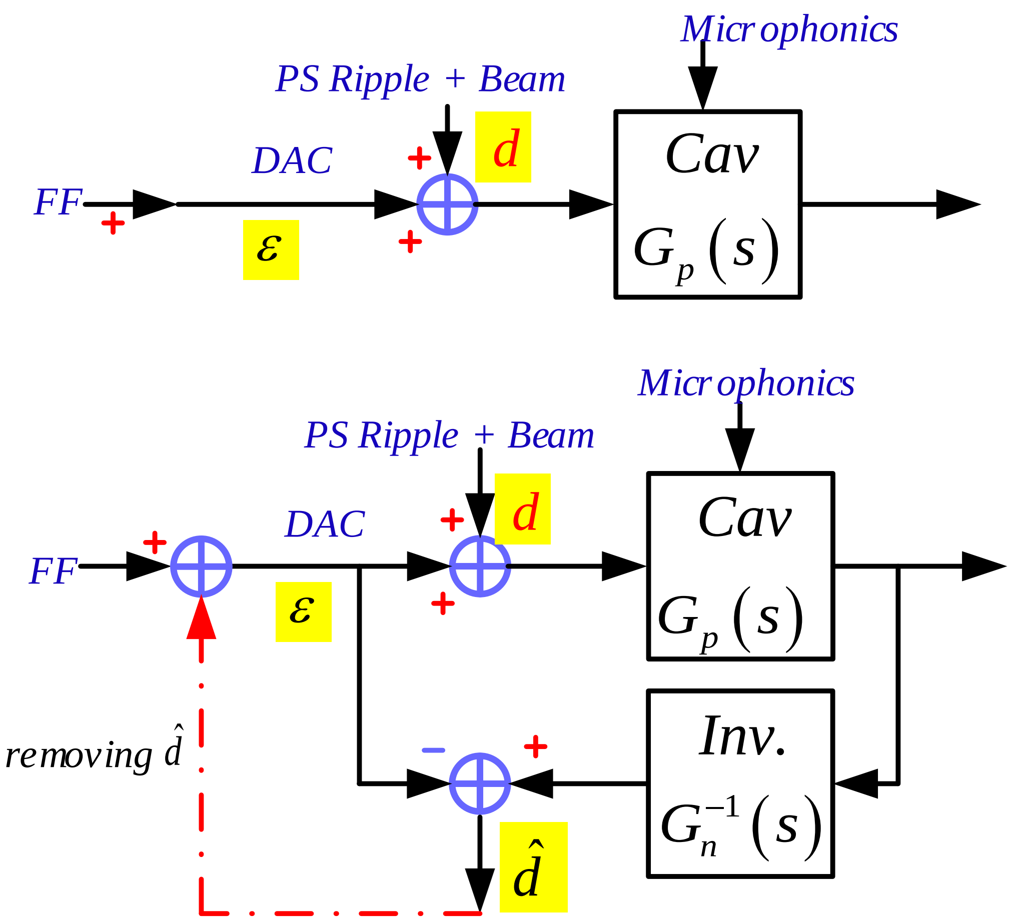
- The disturbances estimate $\hat{d}$ can be evaluated accurately if we "know" the mathematical model of the system (disturbances can be observed).
- Disturbance-Observer-Based control (DOB control) [4-5].



$$\hat{d} = (\varepsilon + d)G_p(s) \cdot G_n^{-1}(s) - \varepsilon = d$$

DOB ctrl (cont'd)

- The disturbances estimate $\hat{d}$ can be removed from FF table, thus the disturbance signal d is rejected.



Model

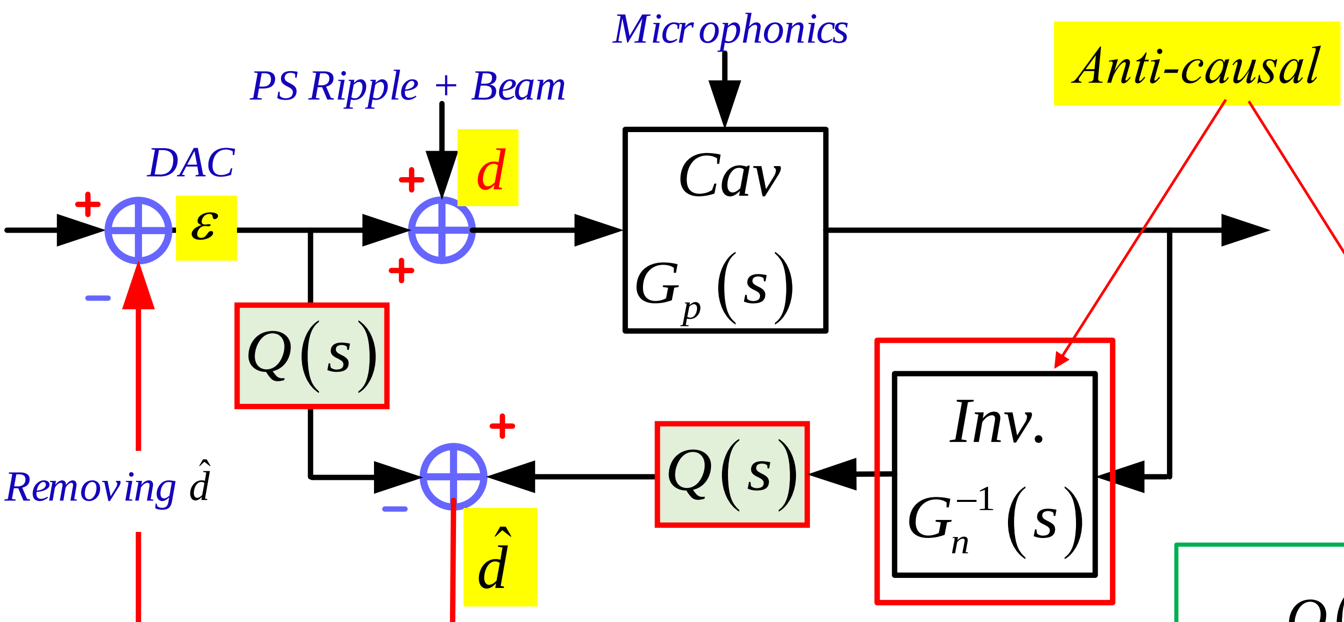
$$G_p(s) = \frac{b}{s+a}$$

$$G_n^{-1}(s) = \frac{s+a}{b}$$

$$\hat{d} = (\varepsilon + d)G_p(s) \cdot G_n^{-1}(s) - \varepsilon = d$$

DOB ctrl (cont'd)

- The low-pass Q filter is required to keep the DOB controller physically realizable.
- The combination of $G_n^{-1}(s)Q(s)$ can be causal.



Model

$$G_p(s) = \frac{b}{s+a}$$

$$G_n^{-1}(s) = \frac{s+a}{b}$$

$$Q(s) = \frac{1}{(\tau s+1)^2}$$

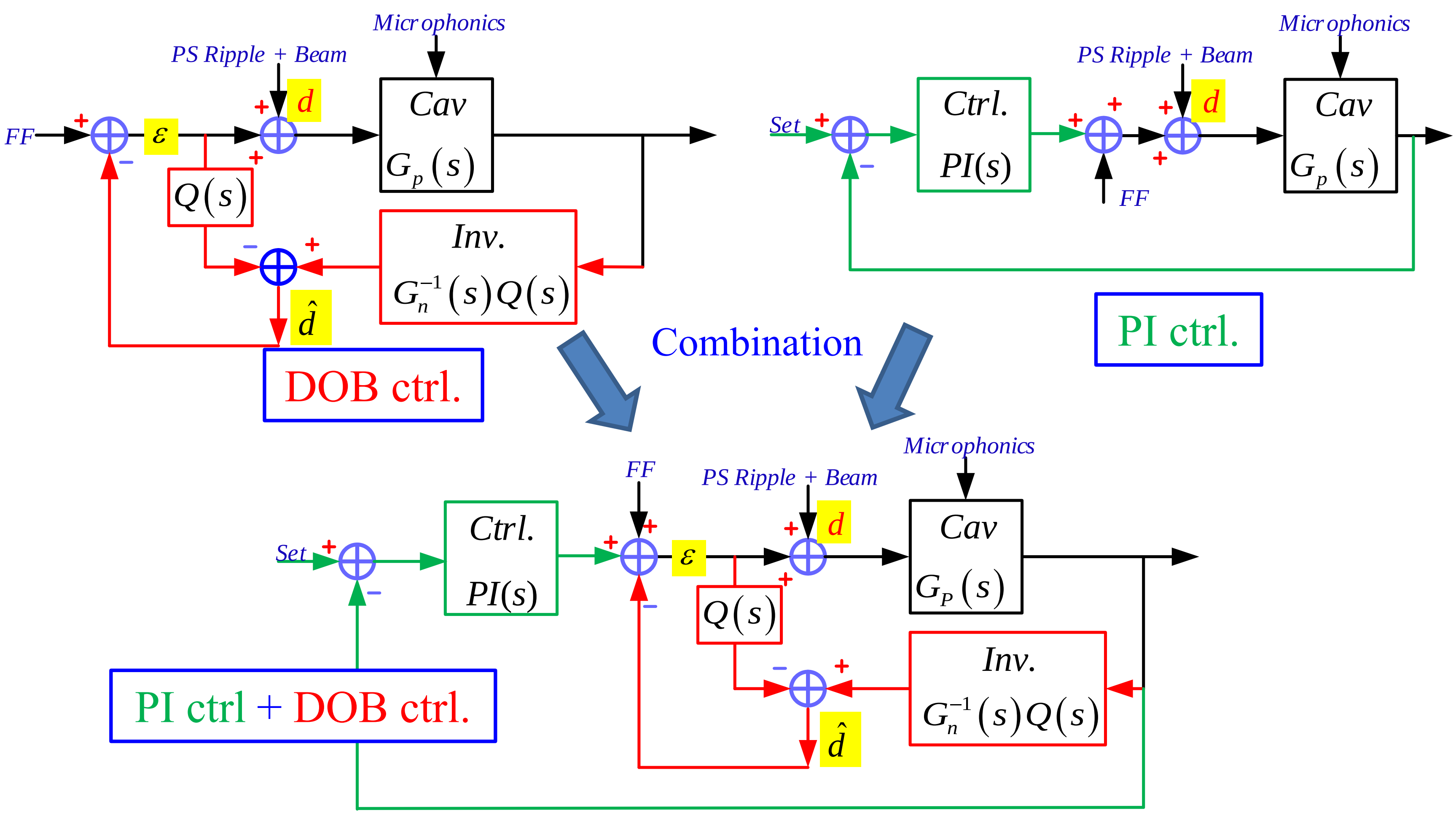
$$G_n^{-1}(s)Q(s) = \frac{s+a}{b(\tau s+1)^2}$$

Causal

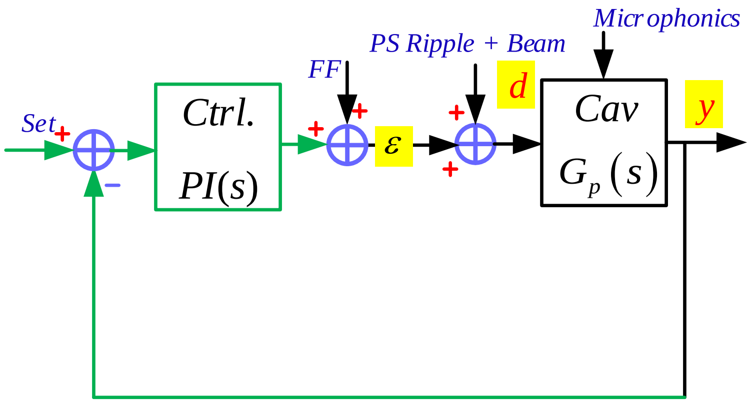
$$\hat{d} = (\varepsilon + d)G_p(s) \cdot G_n^{-1}(s)Q(s) - \varepsilon Q(s) = d$$

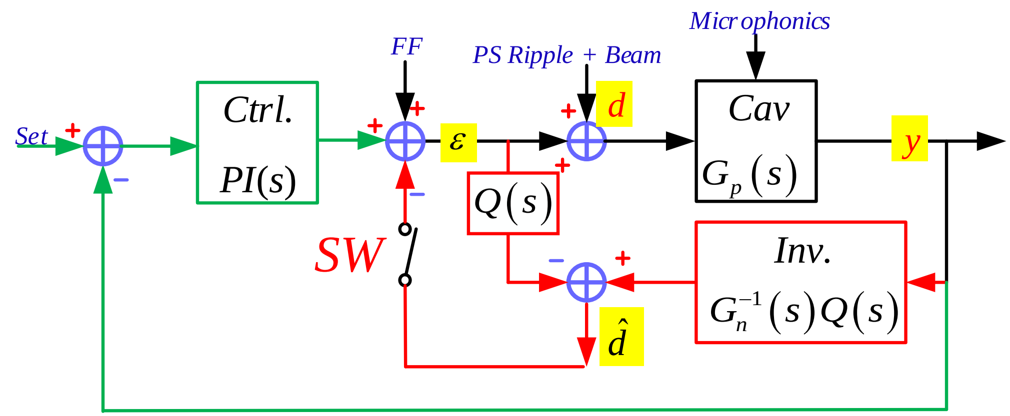
PI + DOB control

- In practical, the combination of DOB control and PI control is applied at cERL LLRF system [1].



Transfer function



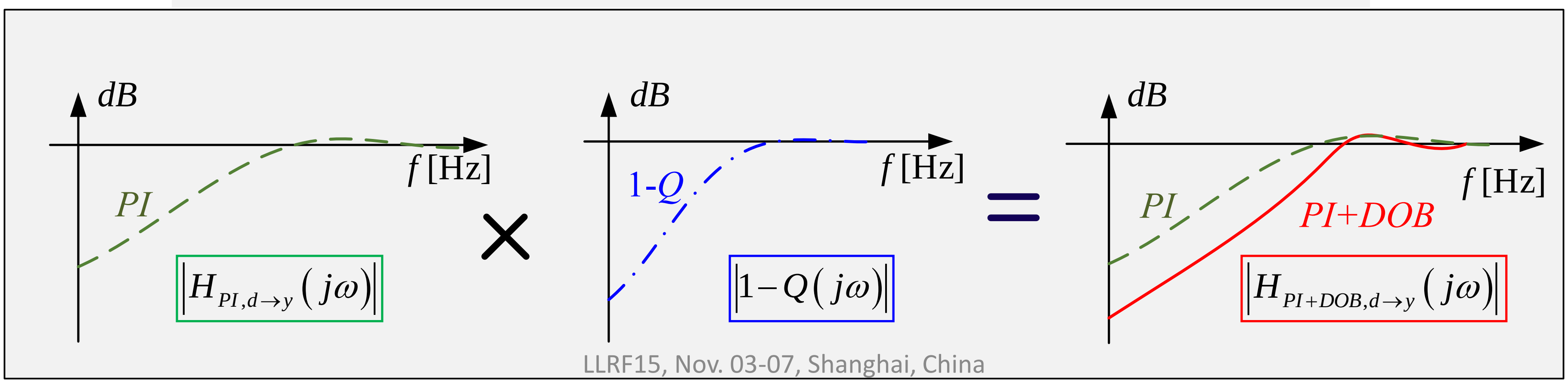


$$H_{PI,d\to y}(s) = \frac{G_p(s)}{1 + PI(s)G_p(s)}$$

$$H_{PI+DOB,d\to y}(s) \approx [1 - Q(s)] \cdot \frac{G_p(s)}{1 + PI(s)G_p(s)}$$

$@\ low\ frequency\colon\ Q(s) \approx 1, then\ 1 - Q(s) \approx 0$

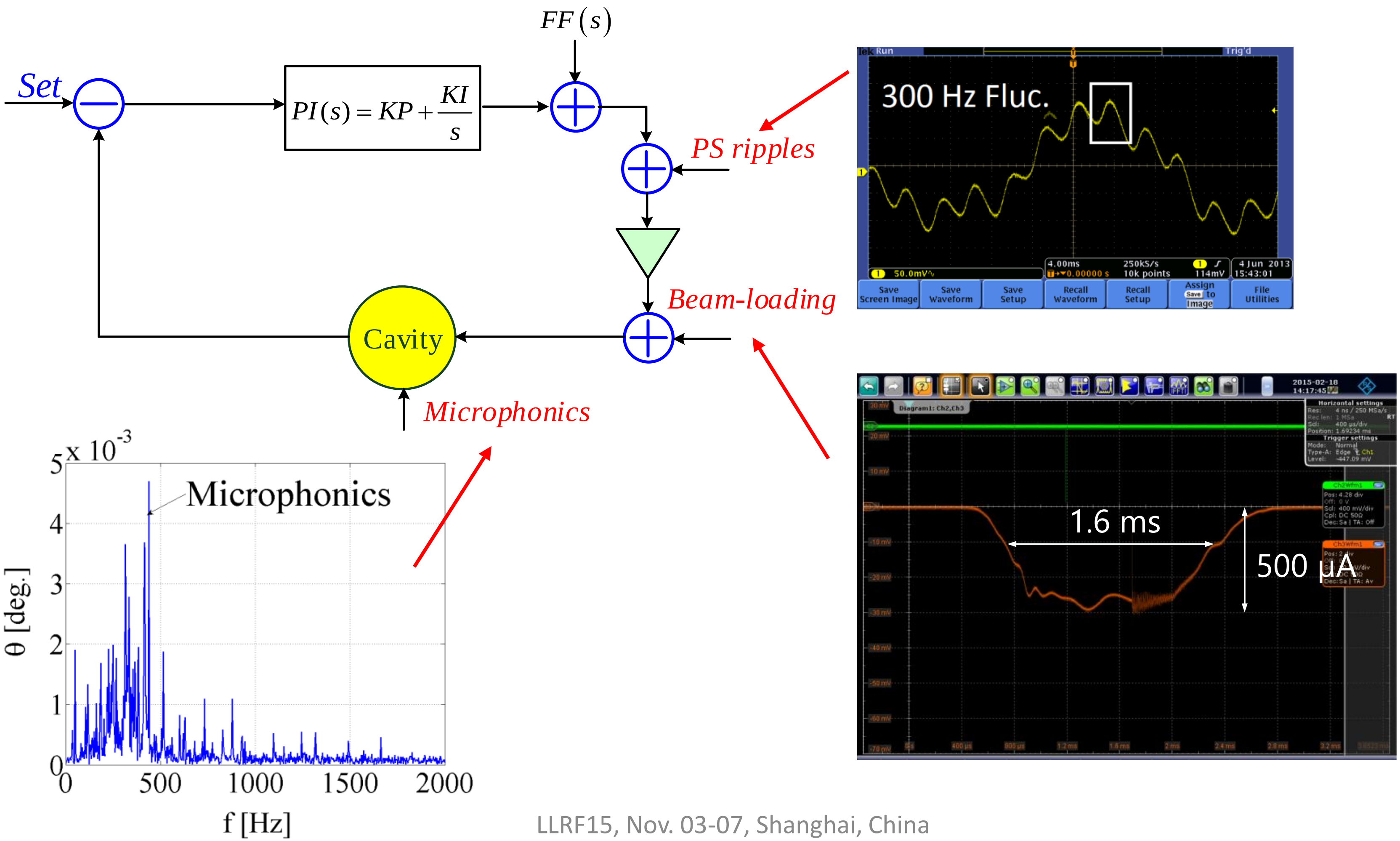
Frequency response from disturbance (d) to cavity pick-up (y)



Application of DOB control

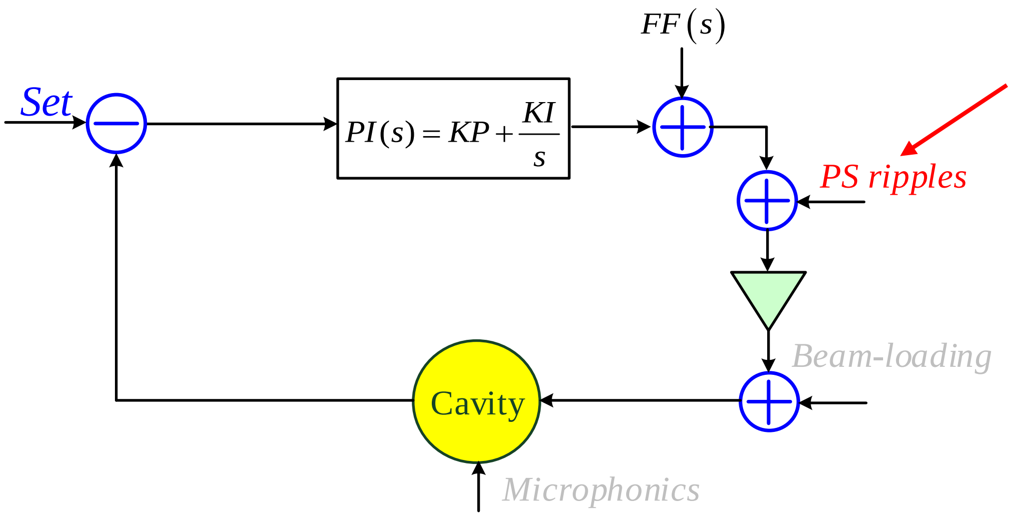
Disturbances in RF system

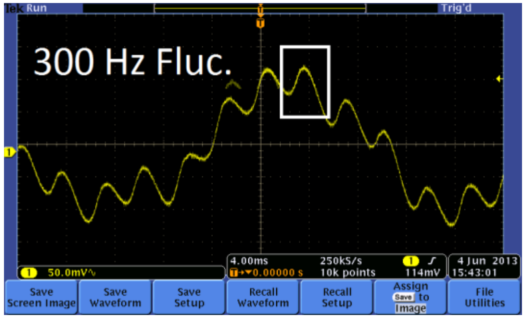
- Main disturbances: High voltage power supply ripples (300 Hz) + burst mode beam-loading (0.5 mA~1mA, 1 ms ~ 2 ms) and Microphonics (DC ~ 500 Hz).



Disturbances 1 (HVPS ripples)

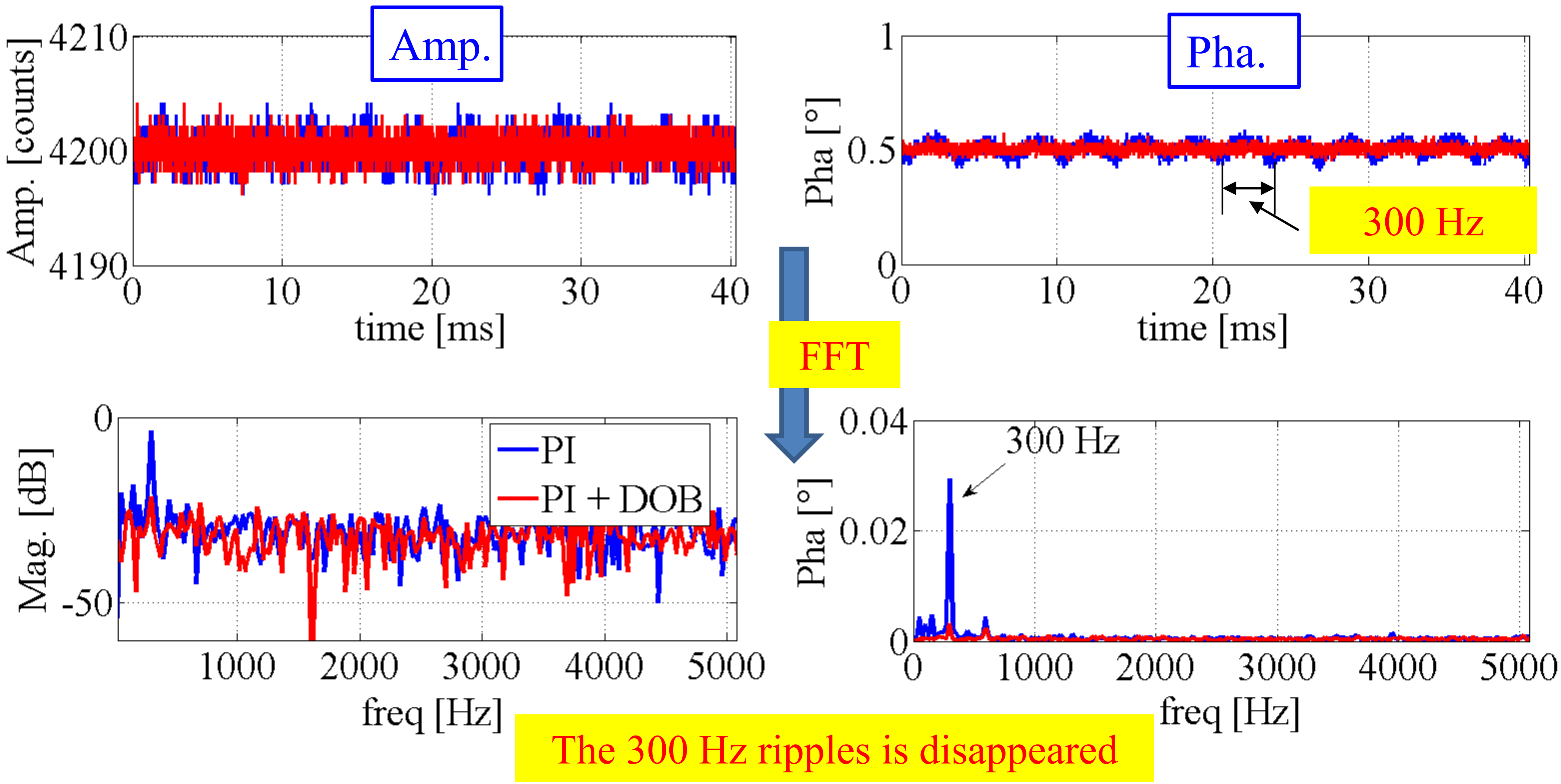
- Main disturbances: High voltage power supply ripples (300 Hz) + burst mode beam-loading (0.5 mA~1mA, 1 ms ~ 2 ms) and Microphonics (DC ~ 500 Hz).





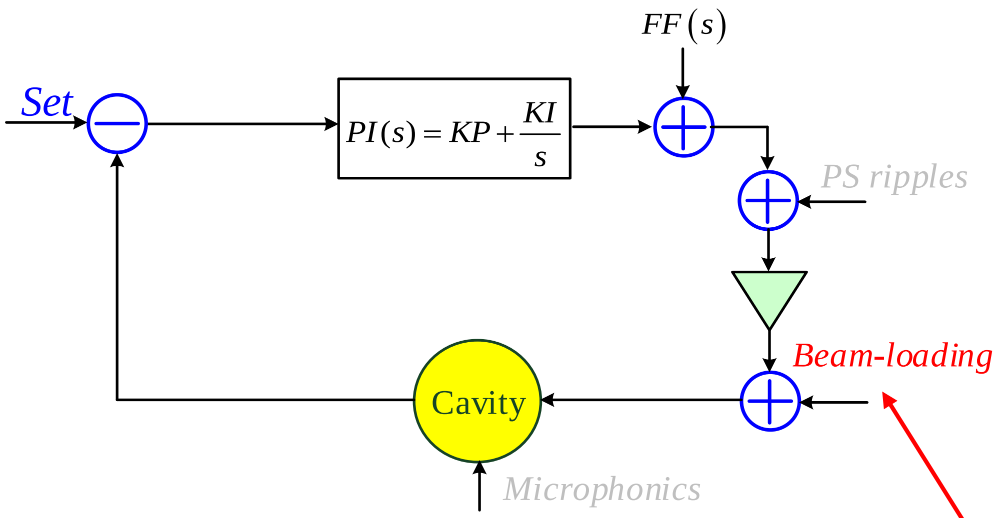
Application 1 (HVPS ripples)

- Disturbances: high voltage power supply ripples (300 Hz ripples).



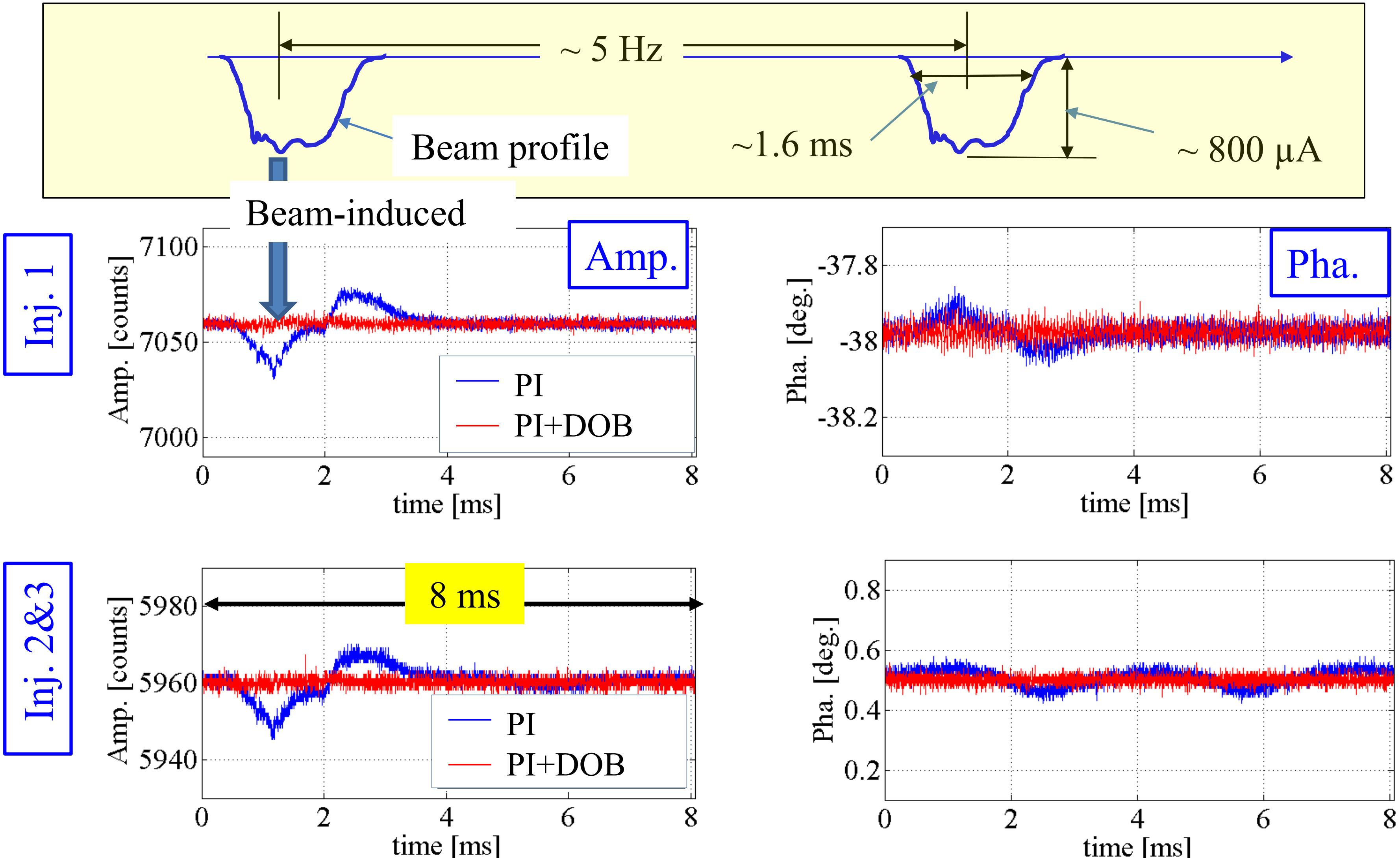
Disturbances 2 (beam-loading)

■Main disturbances: High voltage power supply ripples (300 Hz) + burst mode beam-loading (0.5 mA~1mA, 1 ms ~ 2 ms) and Microphonics (DC ~ 500 Hz).



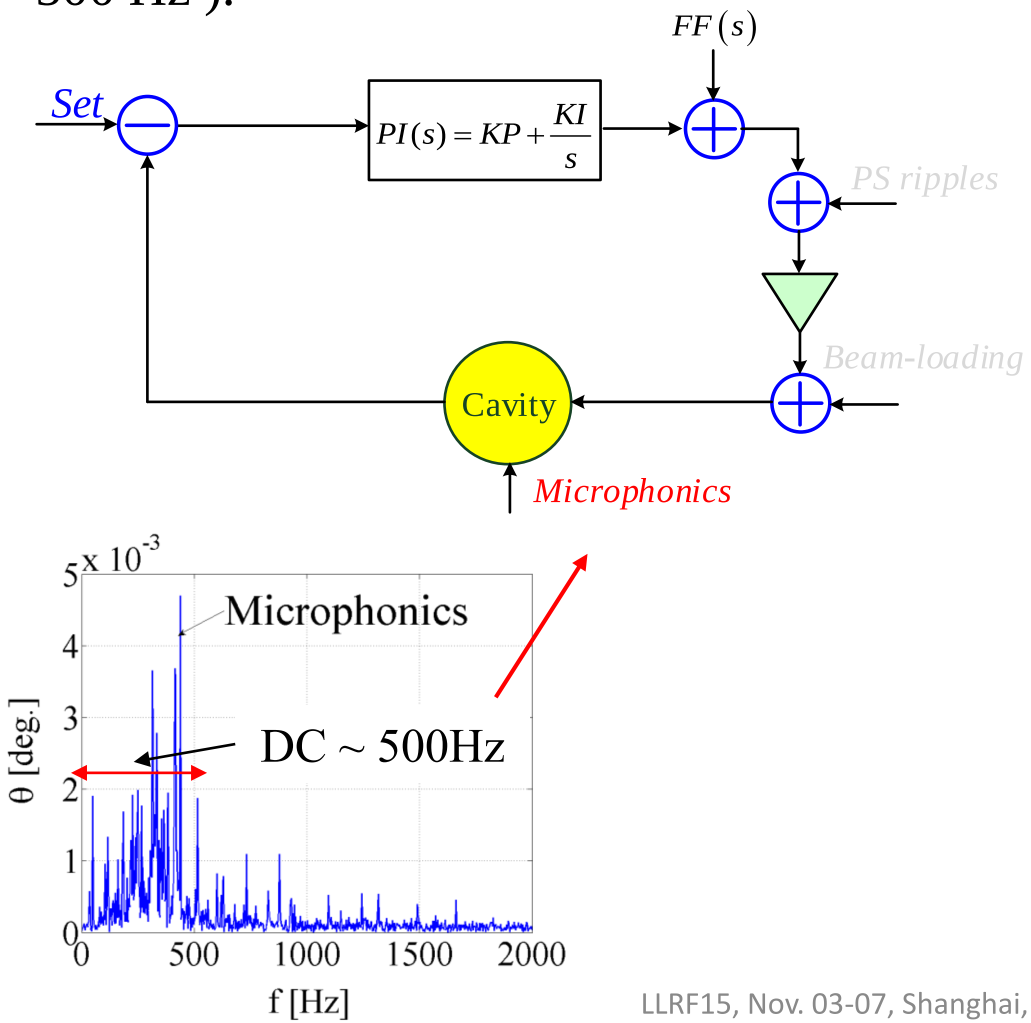
Application 2 (Beam-loading)

- Disturbances: Beam-loading (about 1.6 ms and 800 μA beam current)



Disturbances 3 (Microphonics)

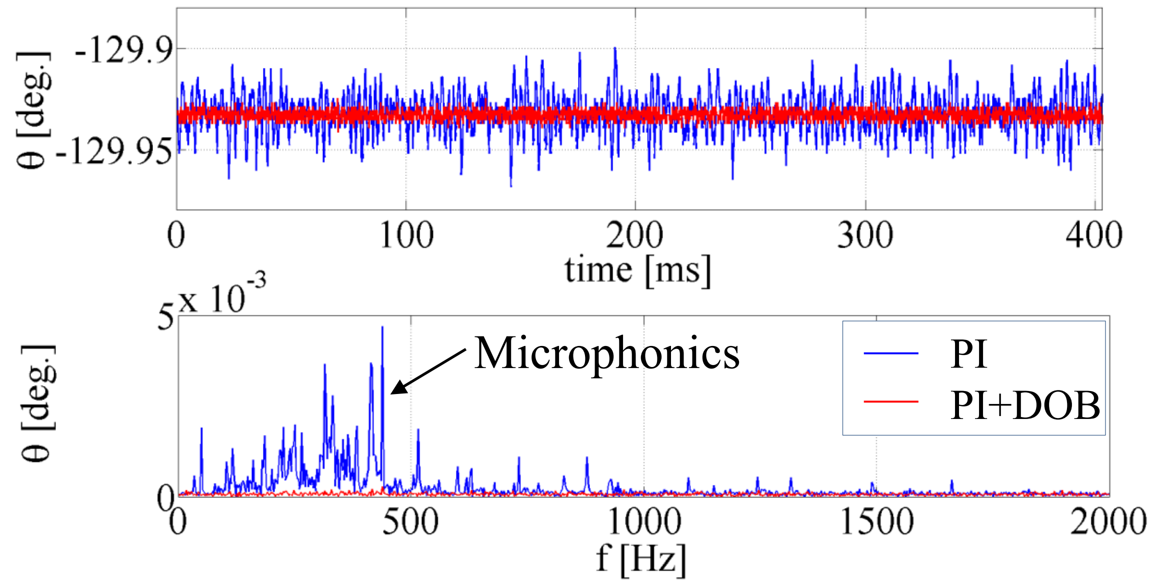
■ Main disturbances: High voltage power supply ripples (300 Hz) + burst mode beam-loading (0.5 mA~1mA, 1 ms ~ 2 ms) and Microphonics (DC ~ 500 Hz).

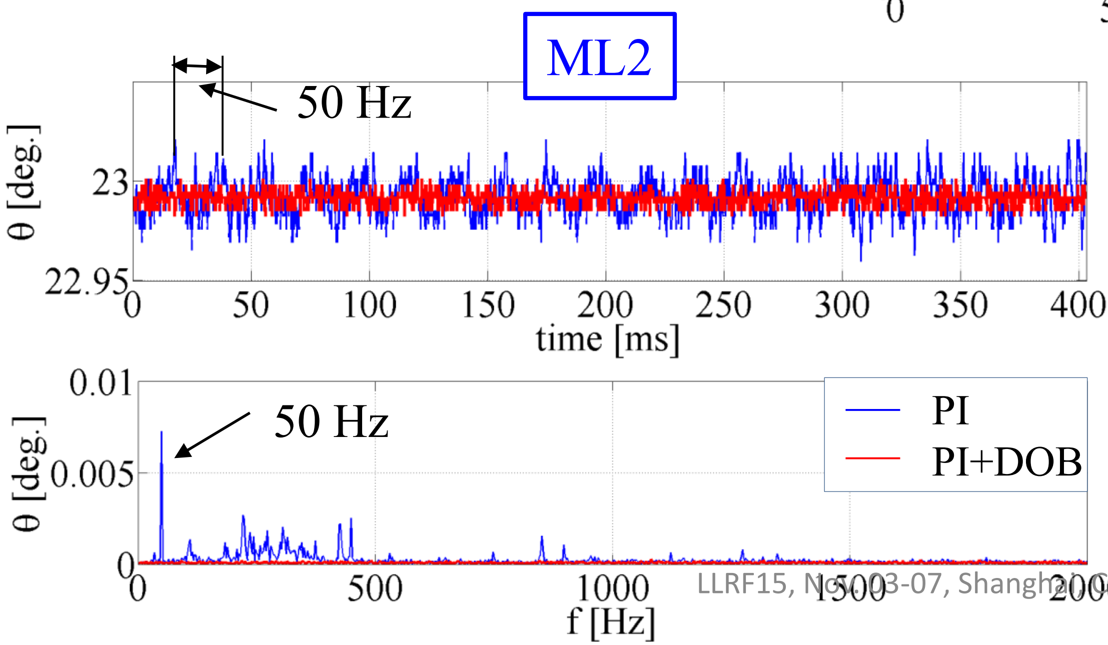


Application 3 (Microphonics)

- Disturbances: Microphonics (DC ~ 500 Hz)
- Even with high feedback gains, the microphonics still exist in the measured RF field.

ML1





The 50 Hz component is disappeared.

ERL (2015), F. QIU

Summary

- Construction of the RF system @ cERL
- Motivation and idea of disturbance control (DOB)
- Successful application of DOB control

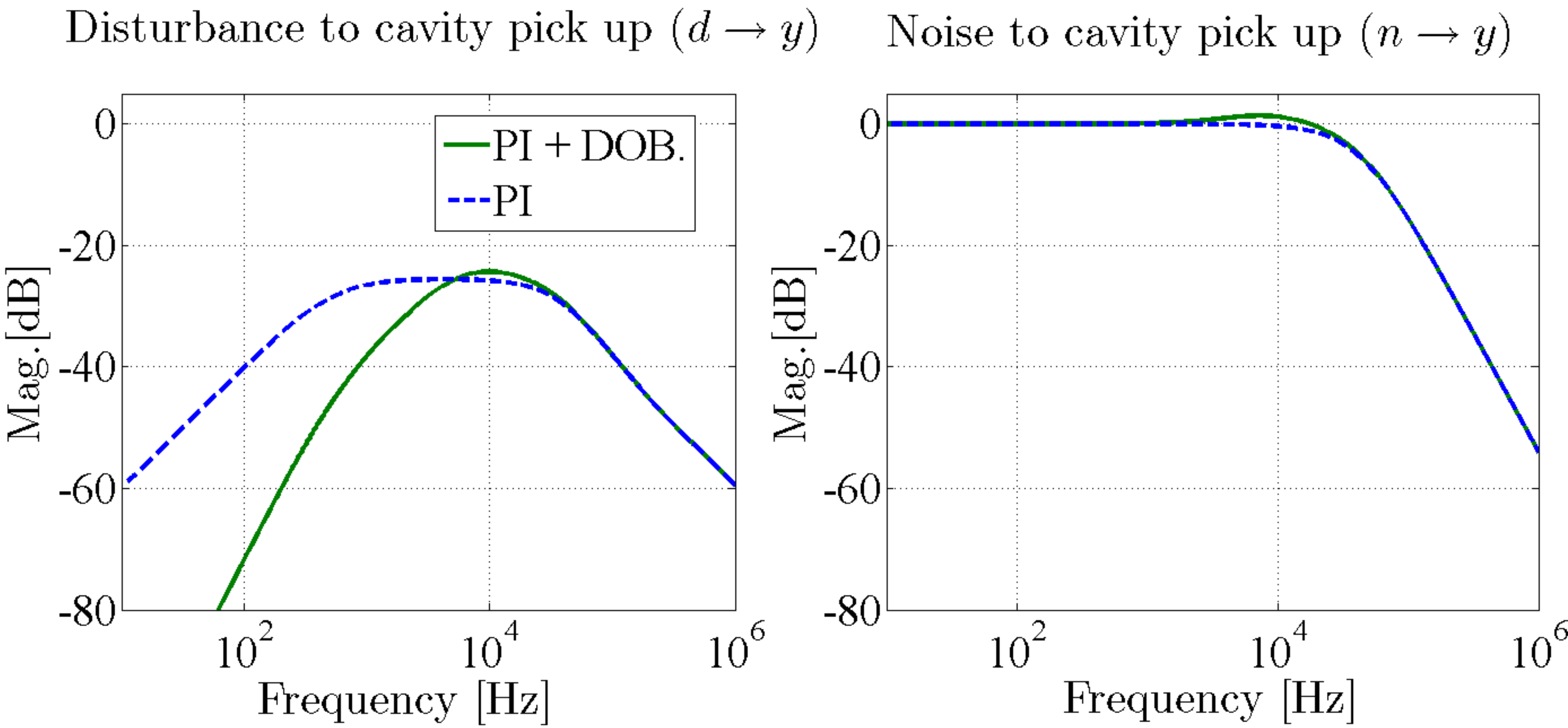
Thank you for your attention

Reference

1. F. Qiu et al., A disturbance-observer-based controller for LLRF systems, in Proceedings of the sixth International Particle Accelerator Conference, IPAC'15, Richmond, USA, 2015 (JACoW, Richmond, USA, 2015), WEPMA054, p. 2895.
2. F. Qiu et al., PERFORMANCE OF THE DIGITAL LLRF SYSTEMS AT KEK cERL , in Proceedings of ERL2015, NewYork, USA, 2015 (JACoW, NewYork, USA, 2015).
3. F. Qiu et al., Application of disturbance observer-based control in low-level radio-frequency system in a compact energy recovery linac at KEK. PRSTAB 18, 092801(2015).
4. X. Chen and M. Tomizuka, Lecture notes for UC Berkeley Advanced Control Systems II (ME233), available at http://www.me.berkeley.edu/ME233/sp14, 2014.
5. Y. Choi, K. Yang, W. K. Chung, H. R. Kim, and I. H. Suh, On the robustness and performance of disturbance observers for second-order systems, IEEE Trans. Autom. Control 48, 315 (2003).

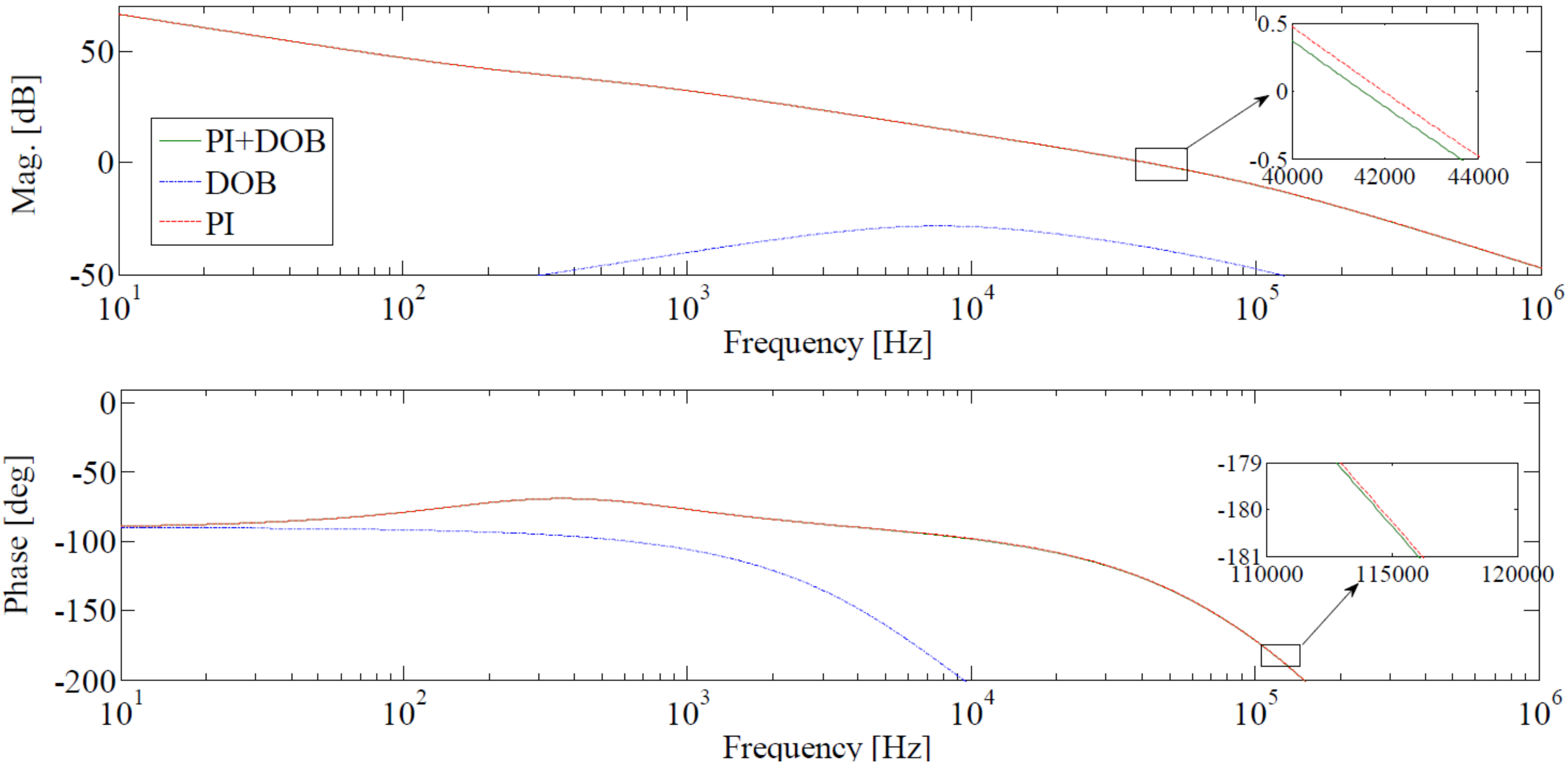
Back up

PI + DOB vs PI



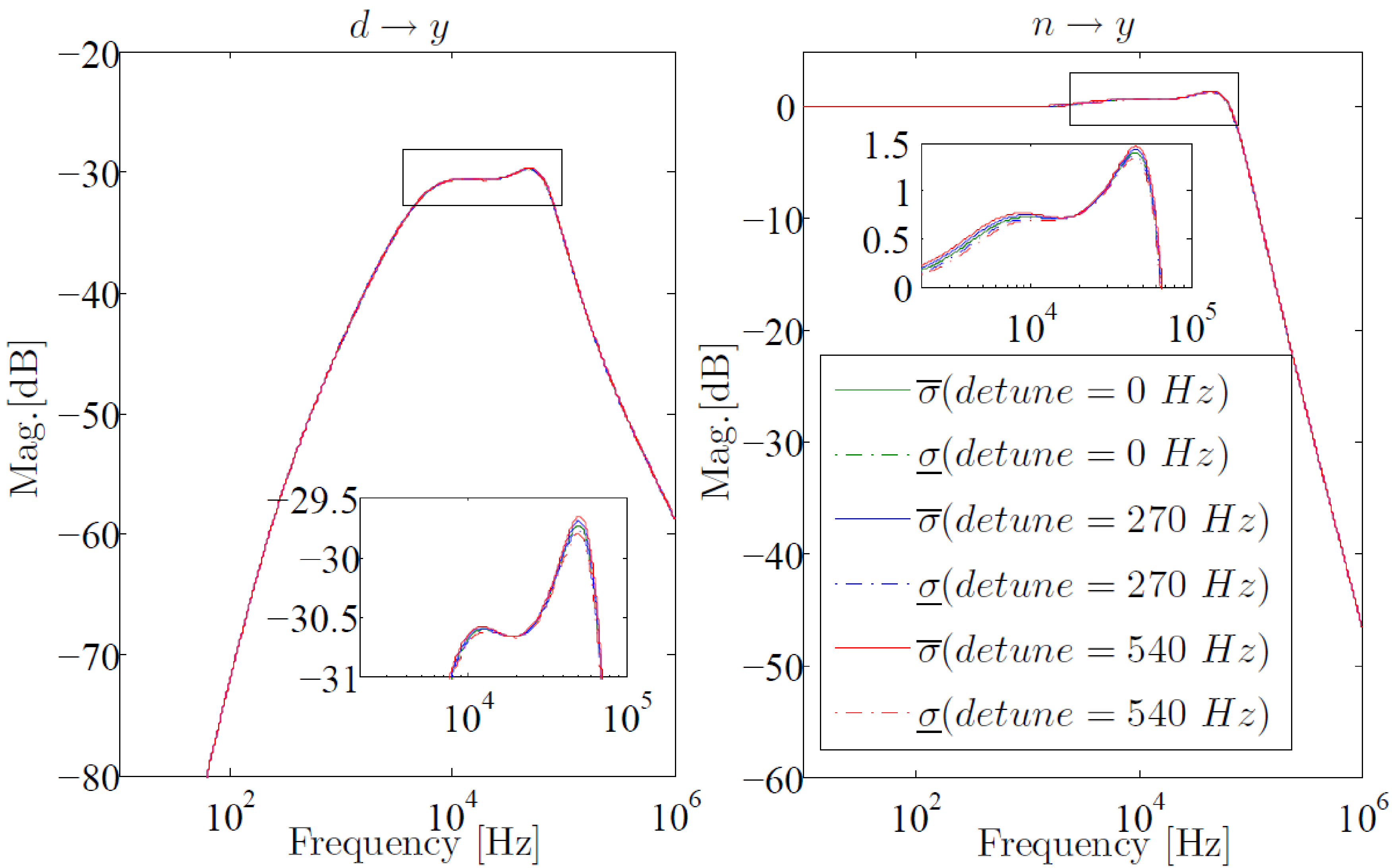
(a) (b)

PI + DOB vs PI



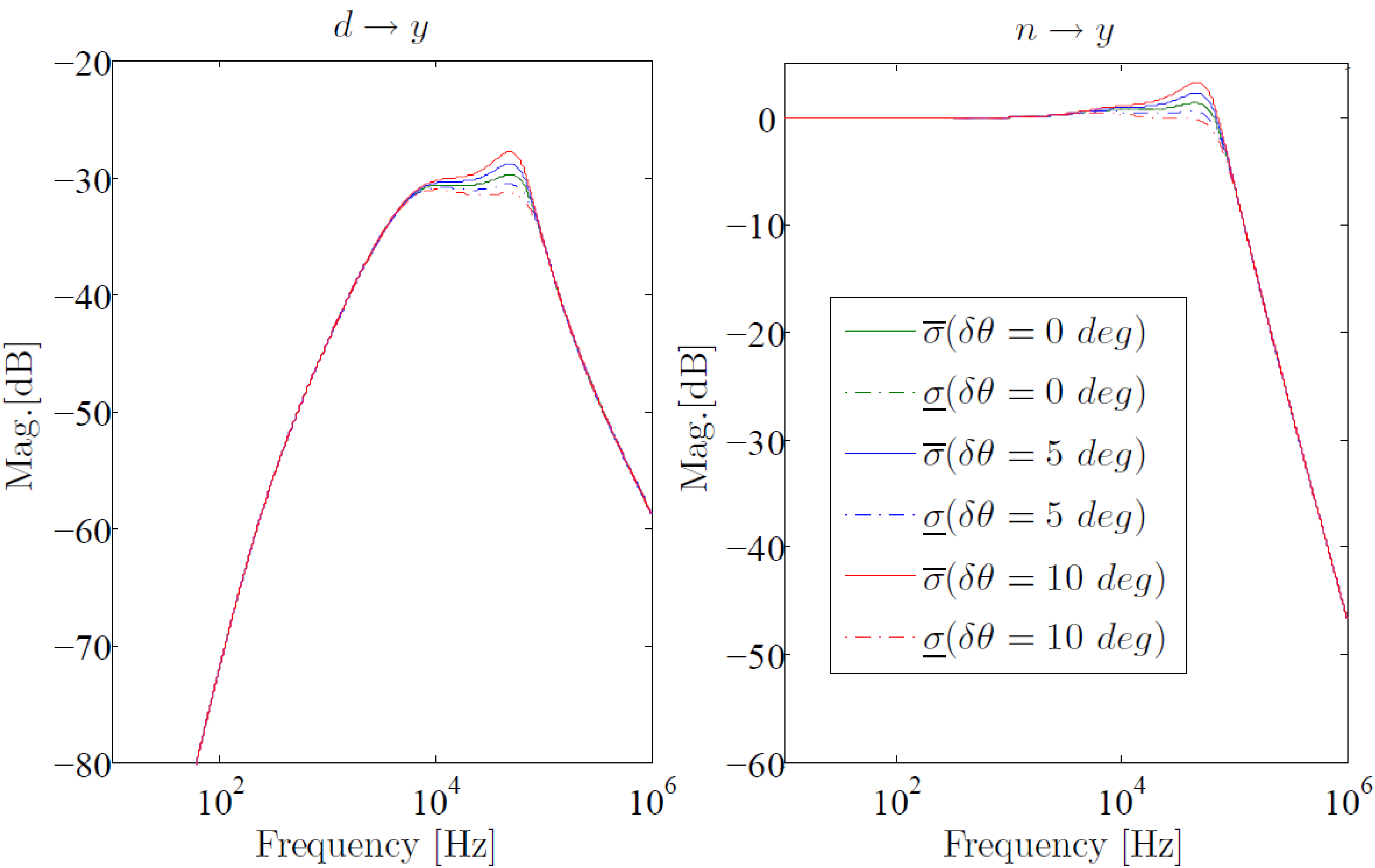
Mag. [dB]
50
0
-50
PI+DOB
DOB
PI
0.5
0
-0.5
40000
42000
44000
10^1
10^2
10^3
10^4
10^5
10^6
Frequency [Hz]
Phase [deg]
0
-50
-100
-150
-200
-179
-180
-181
110000
115000
120000
10^1
10^2
10^3
10^4
10^5
10^6
Frequency [Hz]

PI + DOB vs PI



$d \to y$
Mag.[dB]
Frequency [Hz]
$n \to y$
Mag.[dB]
Frequency [Hz]
$\overline{\sigma}(detune = 0\ Hz)$
$\underline{\sigma}(detune = 0\ Hz)$
$\overline{\sigma}(detune = 270\ Hz)$
$\underline{\sigma}(detune = 270\ Hz)$
$\overline{\sigma}(detune = 540\ Hz)$
$\underline{\sigma}(detune = 540\ Hz)$

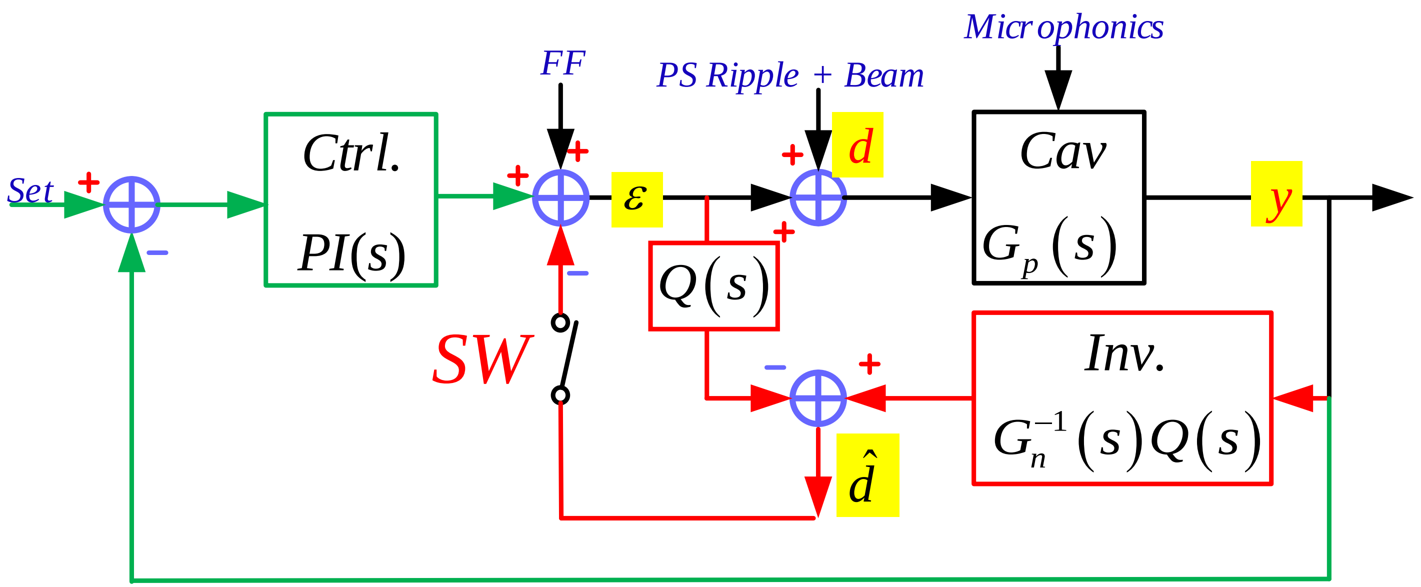
PI + DOB vs PI



$d \rightarrow y$
$n \rightarrow y$
Mag.[dB]
Frequency [Hz]
$\overline{\sigma}(\delta\theta = 0\ deg)$
$\underline{\sigma}(\delta\theta = 0\ deg)$
$\overline{\sigma}(\delta\theta = 5\ deg)$
$\underline{\sigma}(\delta\theta = 5\ deg)$
$\overline{\sigma}(\delta\theta = 10\ deg)$
$\underline{\sigma}(\delta\theta = 10\ deg)$

PI + DOB control

- How to improve the disturbance rejection in the DOB control?



$$H_{PI,d\to y} = \frac{G_p(s)}{1 + PI(s)G_p(s)} (SW\ off)$$

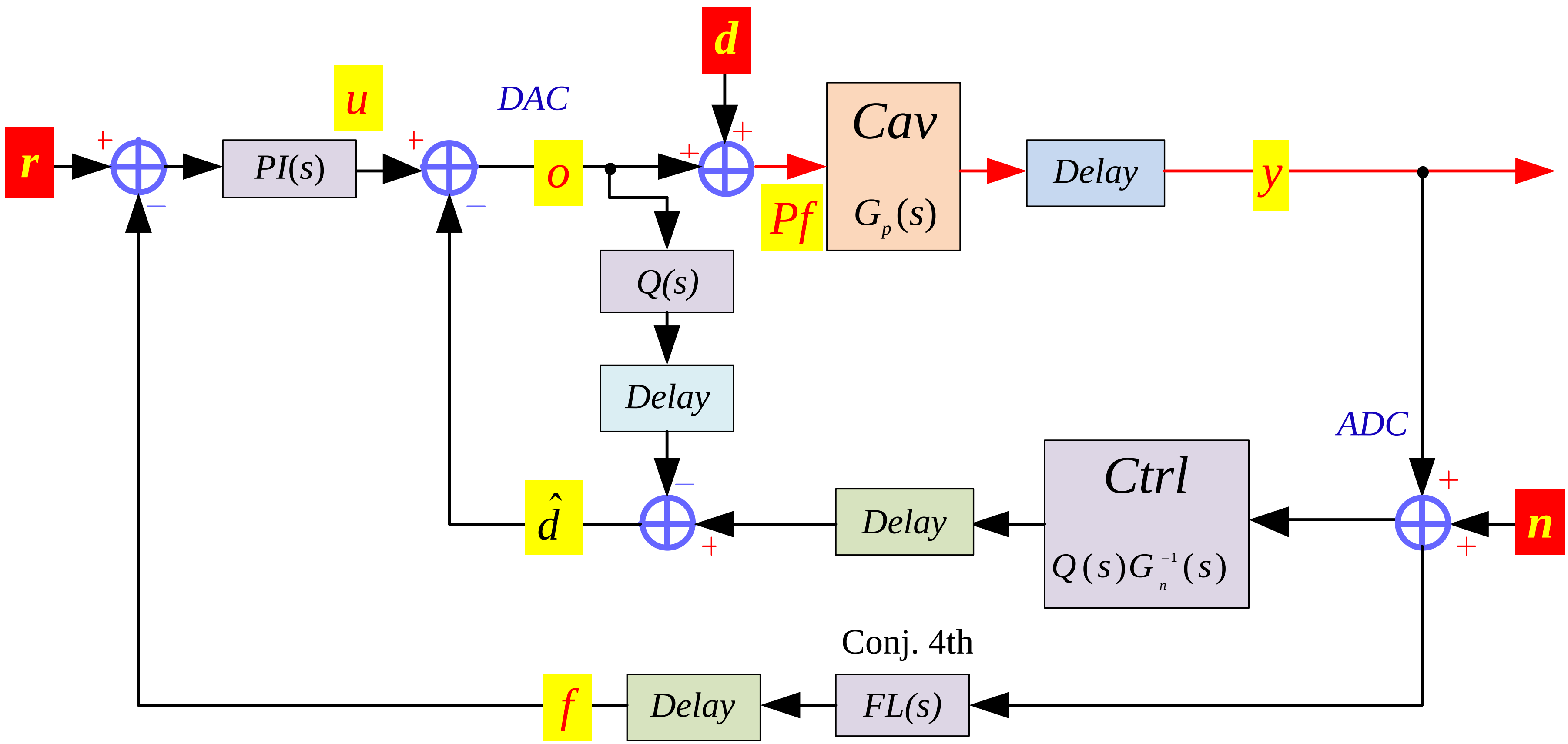
If Q(s) is a low-pass filter, then…

$$H_{PI+DOB,d\to y} = \frac{G_p(s)[1 - Q(s)]}{1 + PI(s)G_p(s) - Q(s) + G_p(s)G_n^{-1}(s)Q(s)} \approx \frac{G_p(s)[1 - Q(s)]}{1 + PI(s)G_p(s)} (SW\ on)$$

$$@\ low\ frequency: Q(s) \approx 1, then\ 1 - Q(s) \approx 0$$

Total LLRF diagram

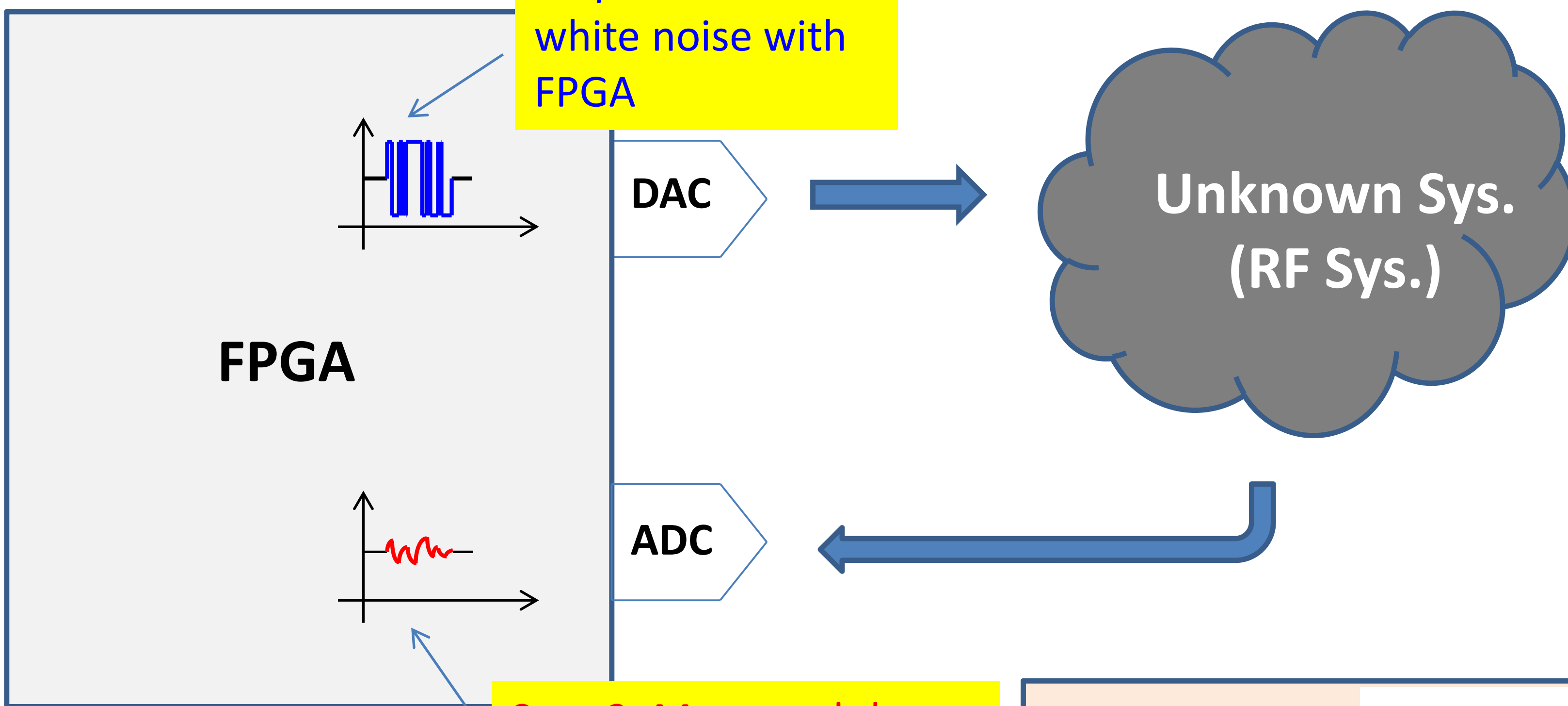
- PI + DOB



System Identification

- Input white noise in the DAC output and read the response from the ADC?

Step 1: Generate white noise with FPGA



Step 2: Measured the response of the white noise

Step 3: Acquire the system model based on the input/output data by system identification method.