# LLRF Low Level Applications Study

FLASH Seminar

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# Outline

- Introduction to low level applications (LLA)
- System phase and system gain
- Cavity parameters measurement
- Adaptive feed forward
- Future plan for LLA

# Introduction to low level applications

# LLA Introduction

Low level applications is a collection of work concern to the software of

- Locating near front end hardware (in FPGA, DSP or front end CPU)
- Running fast (intra-pulse or pulse-pulse)

# Two focuses of LLA

- Algorithms: Principle to perform measurement and optimization
- Implementation: Multi-processor, distributed software, real time

# Algorithm Study:
# System phase and system gain

# Goals

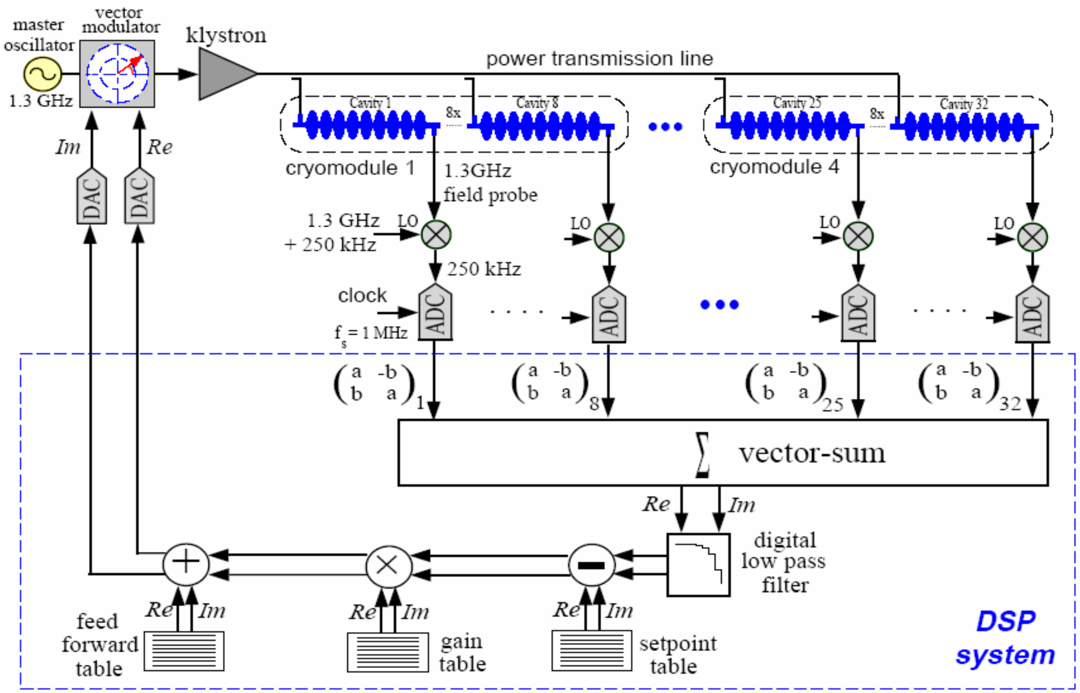
- Measure the system phase and system gain
- Study the influence to the feedback system by the system phase

# Definition

- System Phase: The phase difference between *Vsum* and *Vdac* in steady state
- System Gain: The amplitude ratio between *Vsum* and *Vdac* in steady state
- With P controller

  Loop Phase = System phase

  Loop Gain = System Gain * Feedback Gain
- Assume the system is Linear



# Measurement of system phase and system gain

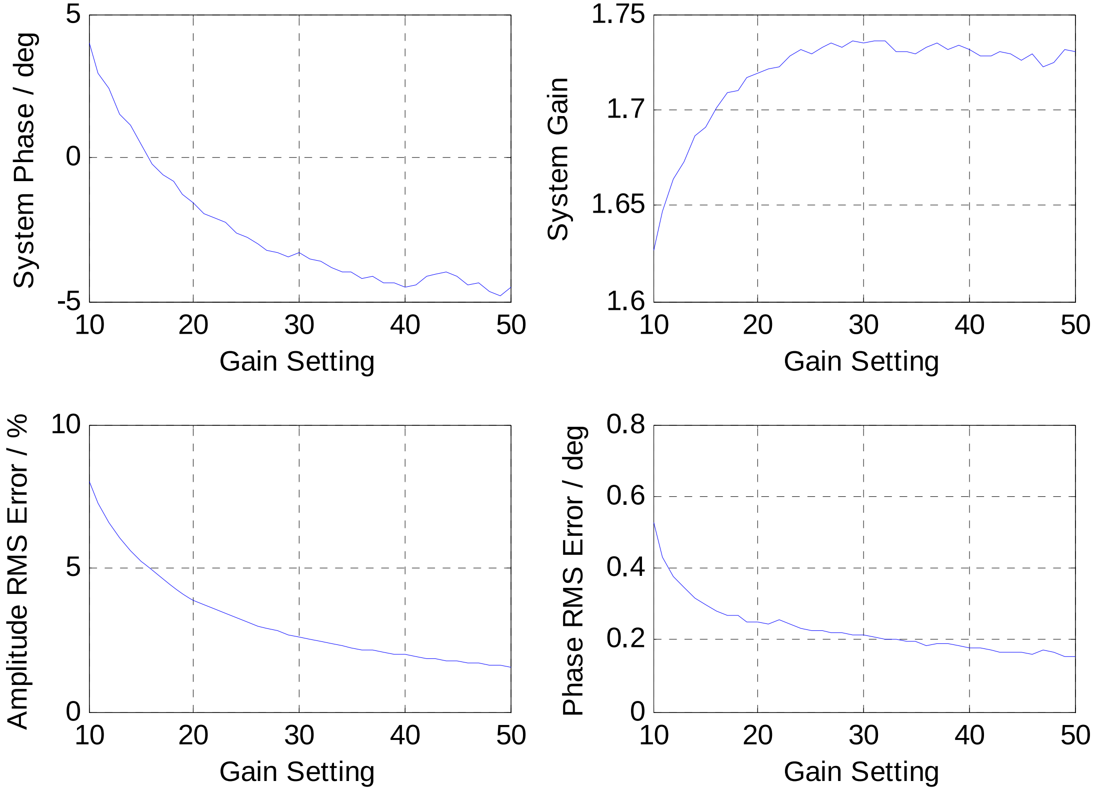
- During RF flattop, the cavity is approximately in steady state, so

$$System\_Phase = angle(Vector\_sum / DAC\_out)$$

$$System\_Gain = abs(Vector\_sum / DAC\_out)$$

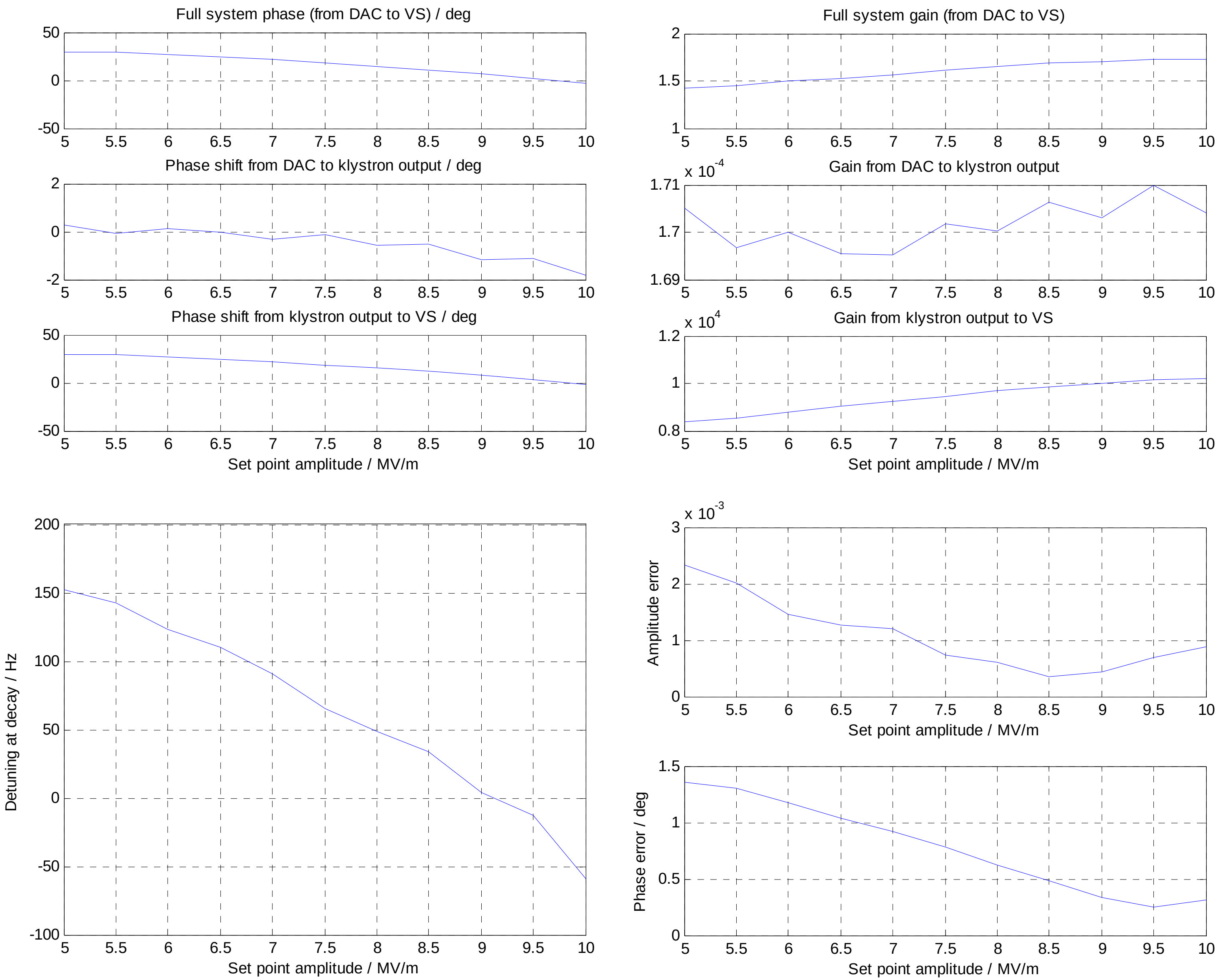
- This method only works when there is no beam
- The RF flattop should be flat (close to steady state)
- System phase and system gain change during the flattop due to the cavity detuning changes

# Measurement at ACC1
# -- Change the feedback gain



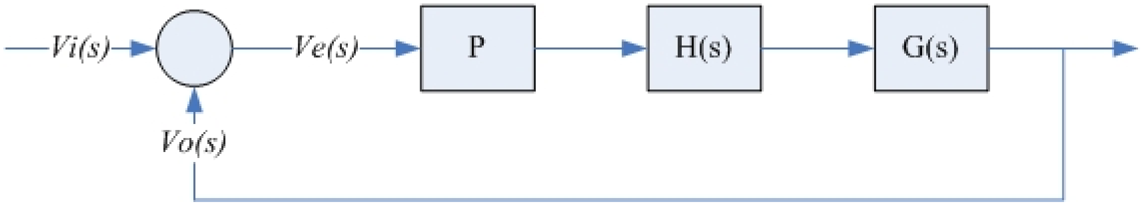

- With only feedback, without feed forward
- System phase and system gain are measured by averaging the flattop
- With smaller gain, the flattop is bad, approximation to steady state will have larger error

# Measurement at ACC1
# -- Change the set point gradient




- ➢ With feedback and feed forward
- ➢ The klystron of ACC1 is quite linear
- ➢ The definition of system phase and system gain includes the cavity detuning effect

# System phase and feedback stability




$$H(s) = ge^{j\theta}$$

$$G(s) = \frac{\omega_{1/2}}{s + \omega_{1/2} - j\Delta\omega}$$

$$V_e(s) = \frac{1}{1 + G(s)H(s)P} V_I(s)$$
$$= \frac{V_I(s)\left(s + \omega_{1/2} - j\Delta\omega\right)}{s + \omega_{1/2} - j\Delta\omega + P\omega_{1/2} ge^{j\theta}}$$

$$\mathrm{Re}\left[\omega_{1/2} - j\Delta\omega + P\omega_{1/2} ge^{j\theta}\right] > 0$$

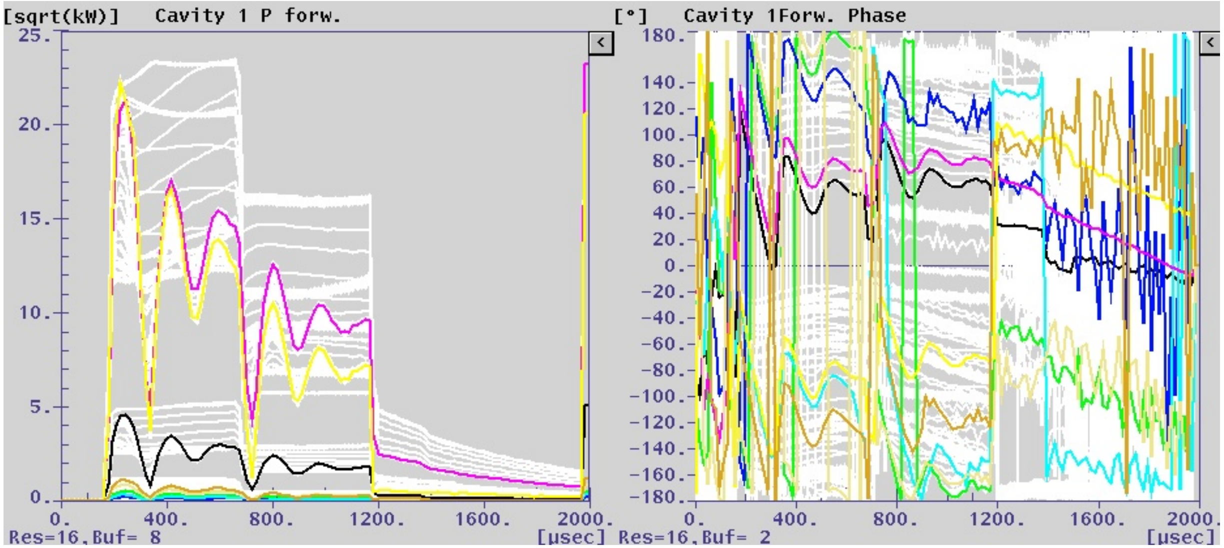
$$\omega_{1/2} + P\omega_{1/2} g \cos\theta > 0$$

$$\Rightarrow \quad \cos\theta > -\frac{1}{Pg}$$

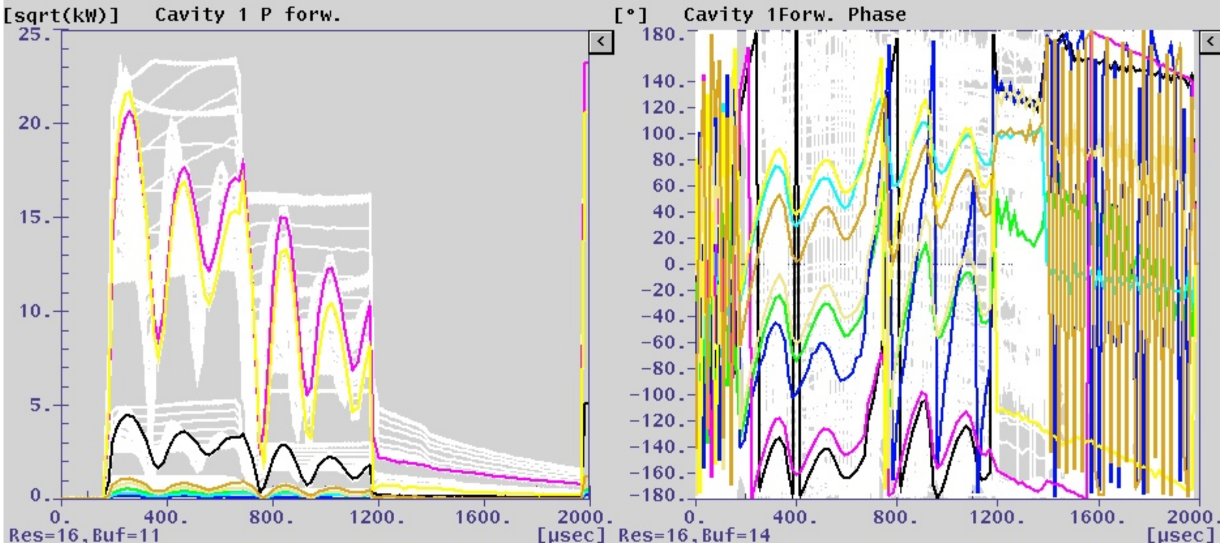
The stable area of system phase is

$$\left[-\frac{\pi}{2} + Detuning\_angle, \frac{\pi}{2} + Detuning\_angle\right]$$

# Measurement at ACC1
# -- System phase and feedback stability

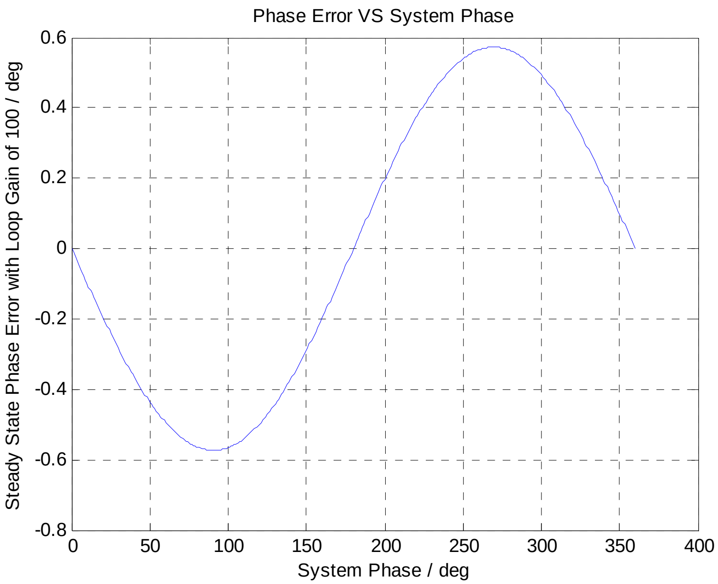


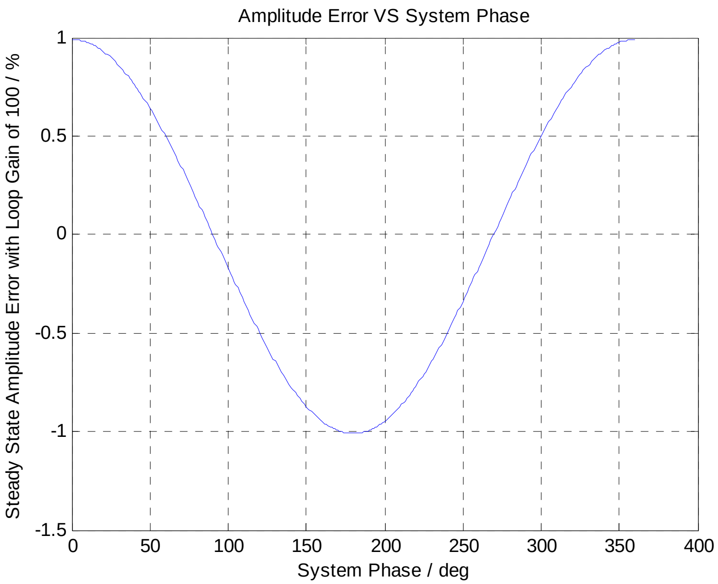

- ➢ With feedback and feed forward on
- ➢ The loop phase is changed in negative way by about 70 degree




- ➢ With feedback and feed forward on
- ➢ The loop phase is changed in positive way by about 80 degree

# System phase and steady state error

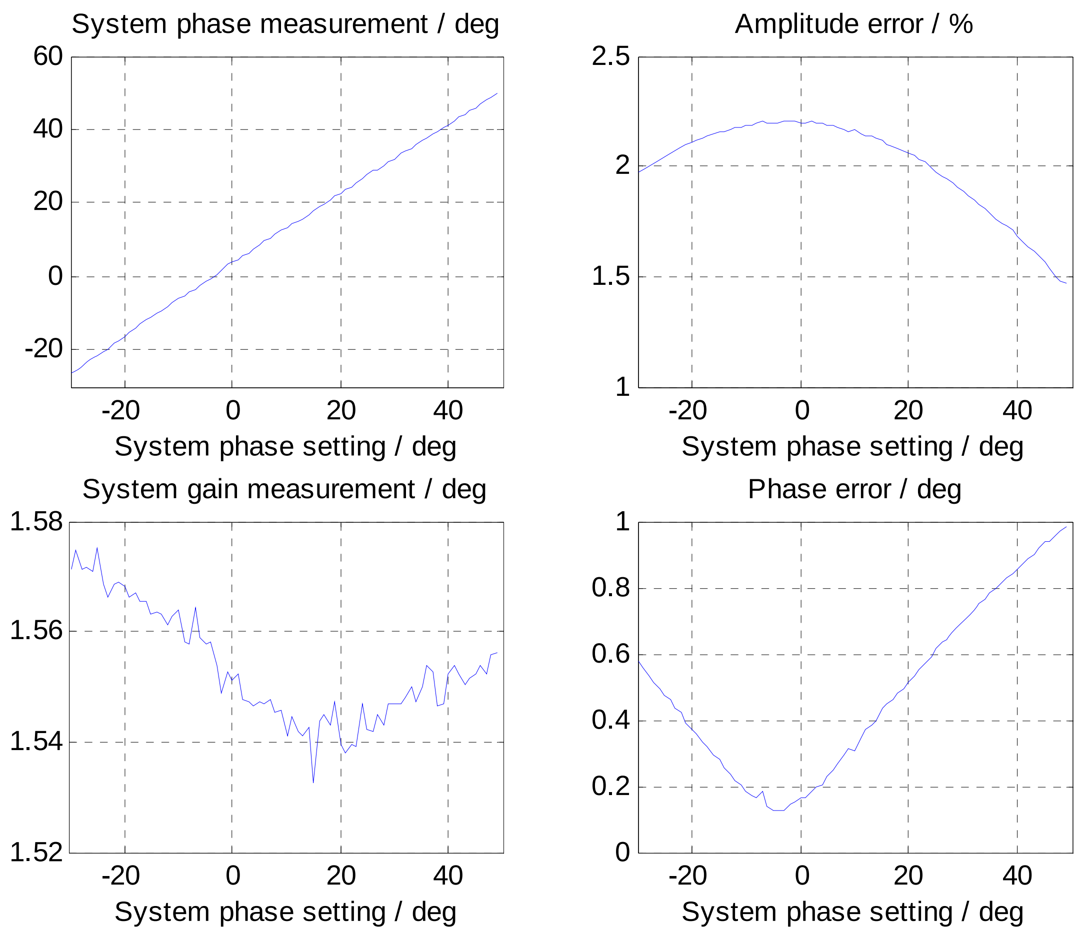



System Phase Optimization:

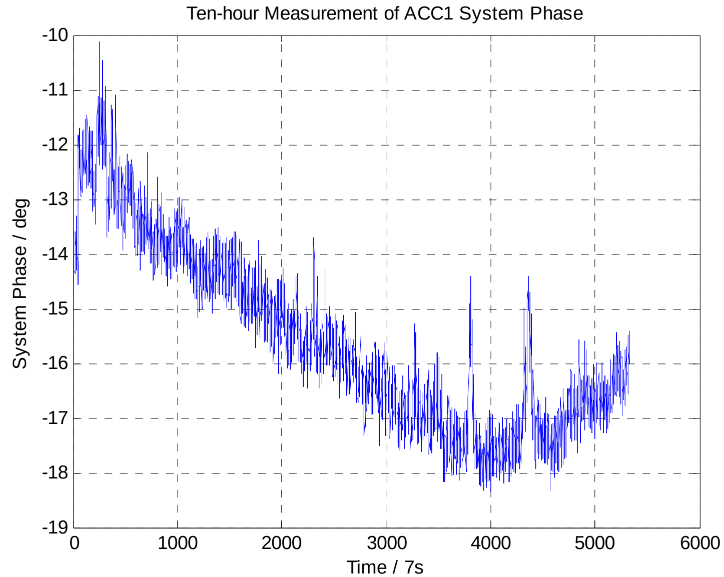
- Keep system phase in the stable range
- Select system phase to be 0 for minimizing the steady state phase error (amplitude error is non-avoidable for feedback but can be compensated by feed forward)

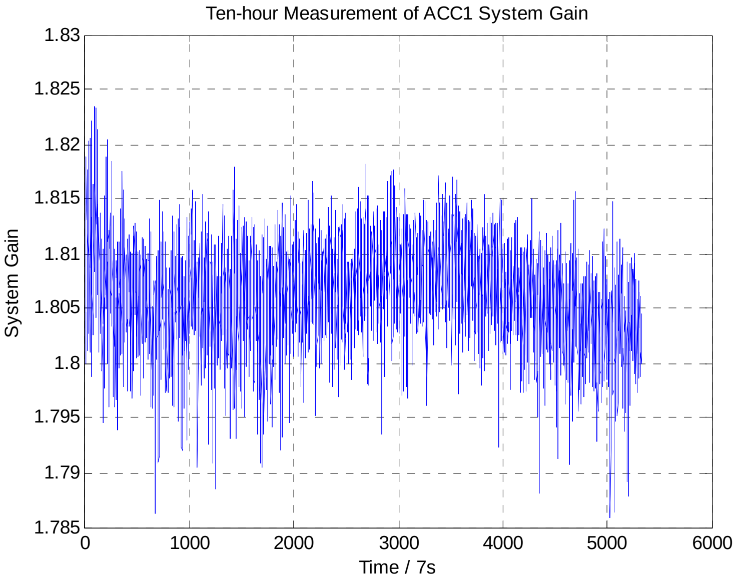
# Measurement at ACC1
# -- System phase and steady state error

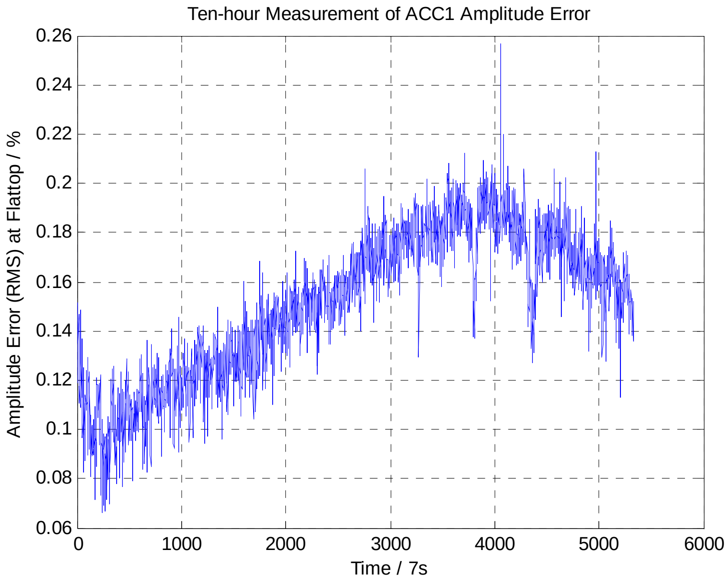


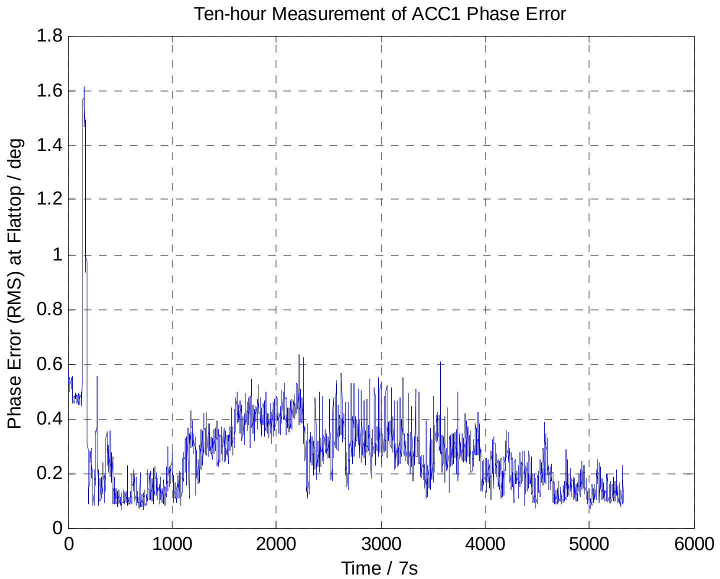

- With only feedback, without feed forward

# System phase and system gain drift






Measured during 1:00am, 17.08.2008 to 11:00am, 17.08.2008.

# Algorithm Study:
# Cavity parameters measurement

# Goals

- Measure loaded Q of the cavity
- Measure detuning of the cavity
- Measure beam phase and amplitude in each cavity

# Cavity equation used for parameters measurement

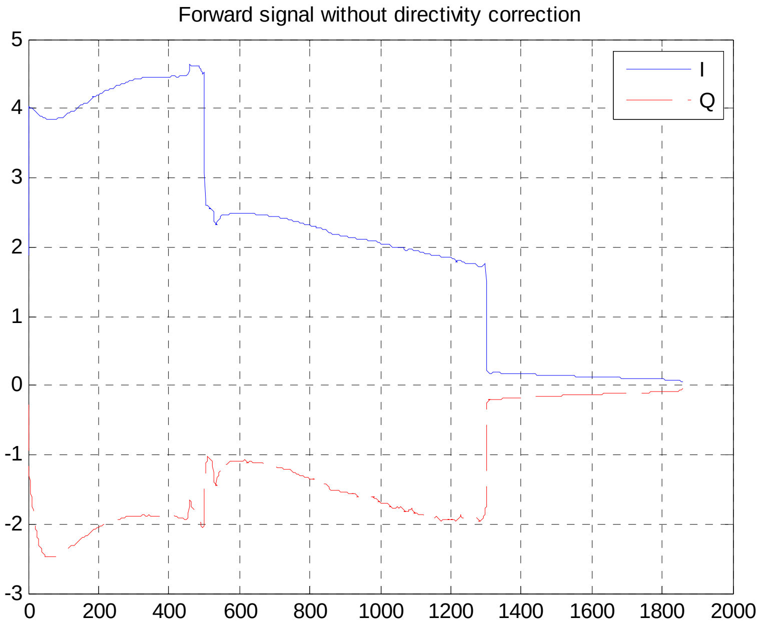
$$\frac{dV_c}{dt} + (\omega_{1/2} - j\Delta\omega)V_c = C\sqrt{\omega_{1/2}}V_{for} + 2\omega_{1/2}R_L I_b$$

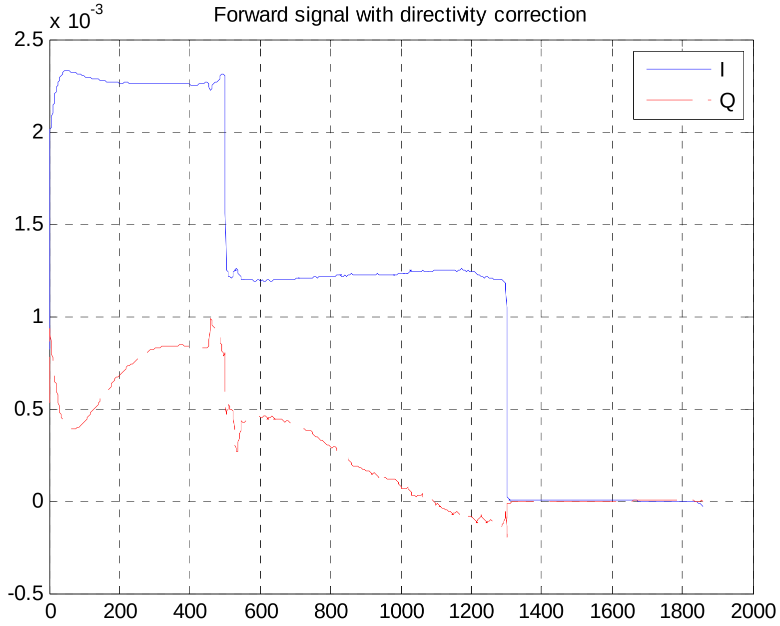
$$C = \sqrt{\left(\frac{r}{Q}\right)\frac{\omega_0}{Z_0}}$$

# Forward and reflected signal directivity correction

$$V_{for} = aV_{for\_mea} + bV_{ref\_mea}$$

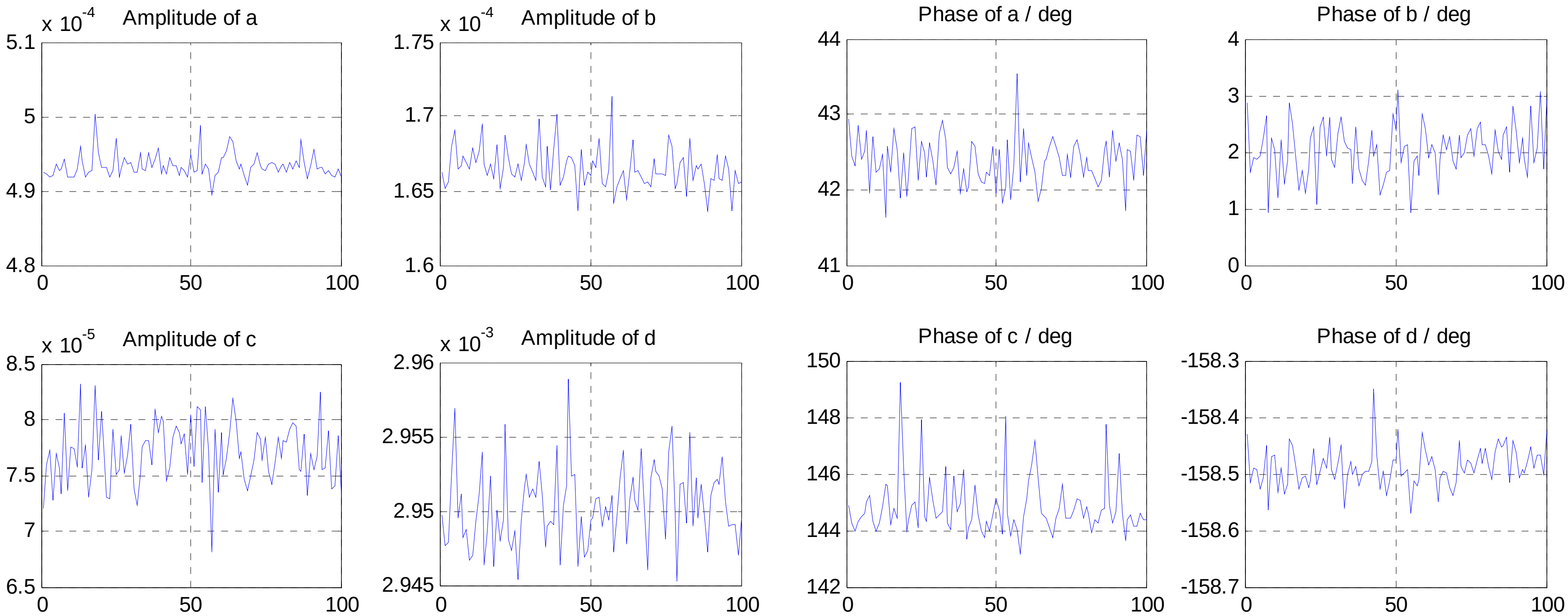
$$V_{ref} = cV_{for\_mea} + dV_{ref\_mea}$$



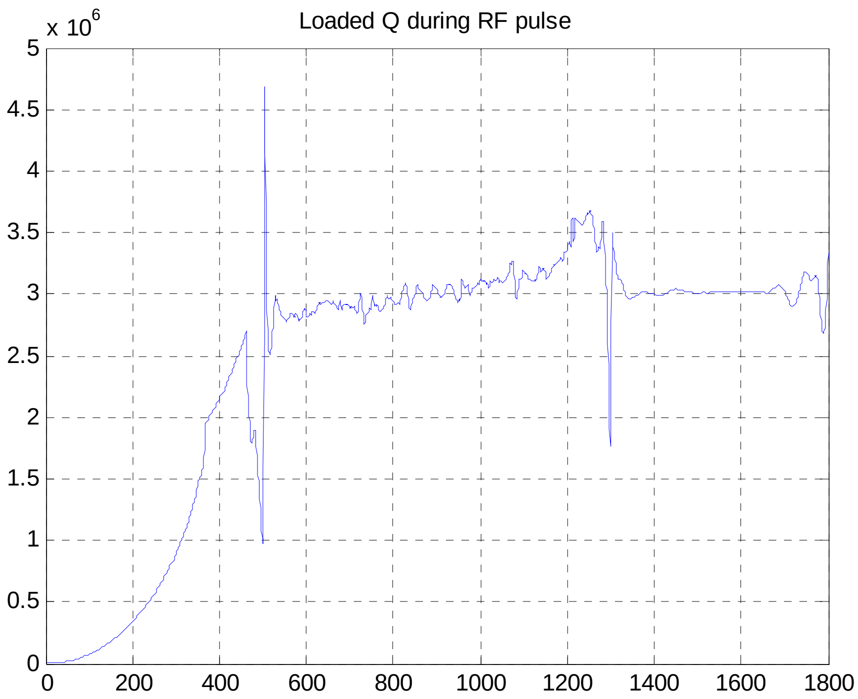

➢ The forward signal with directivity correction will be used as the cavity driving signal in the cavity equation

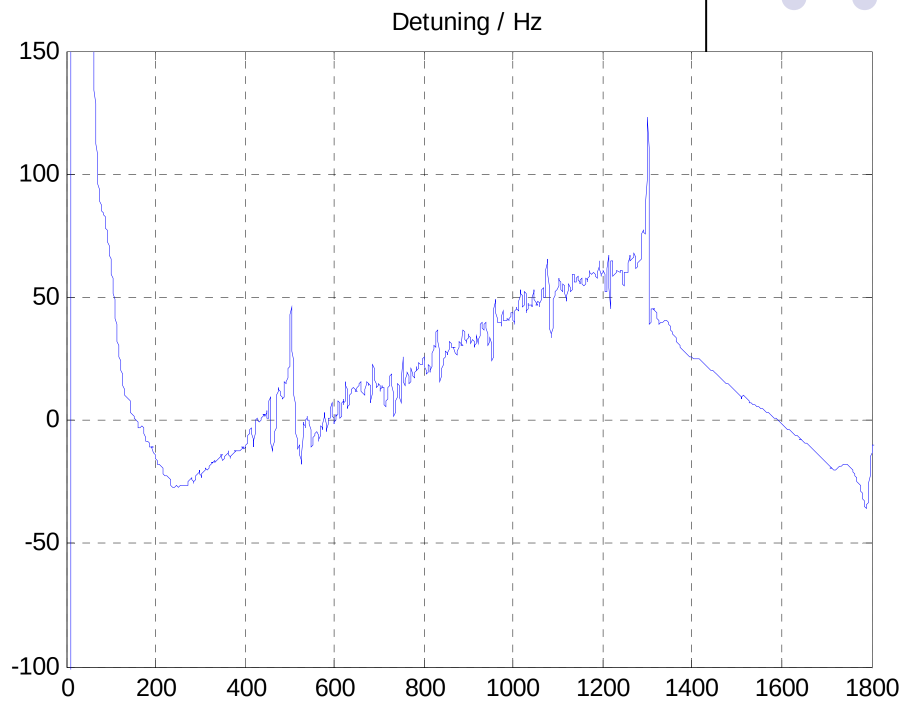
# Forward and reflected signal directivity correction




- 100 times calibration of the directivity coefficients

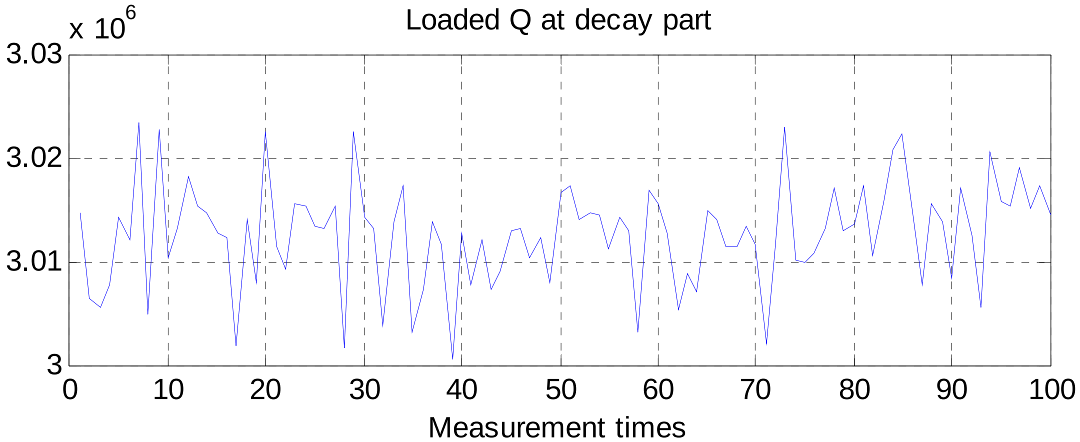
# Loaded Q and detuning measurement -- Intra-pulse, without beam

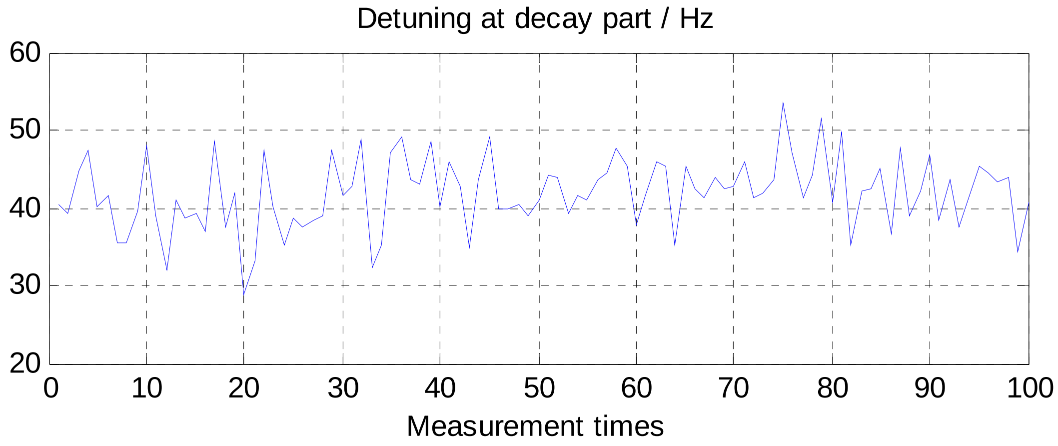



- Measurements are sensitive to the cavity driving signal calibration
- Large error during the filling time
- Relative measurements can be used to detect the system status change

# Loaded Q and detuning measurement -- Pulse to pulse, at RF decay




- QL: 0.2% RMS
- Detuning: 5 Hz RMS

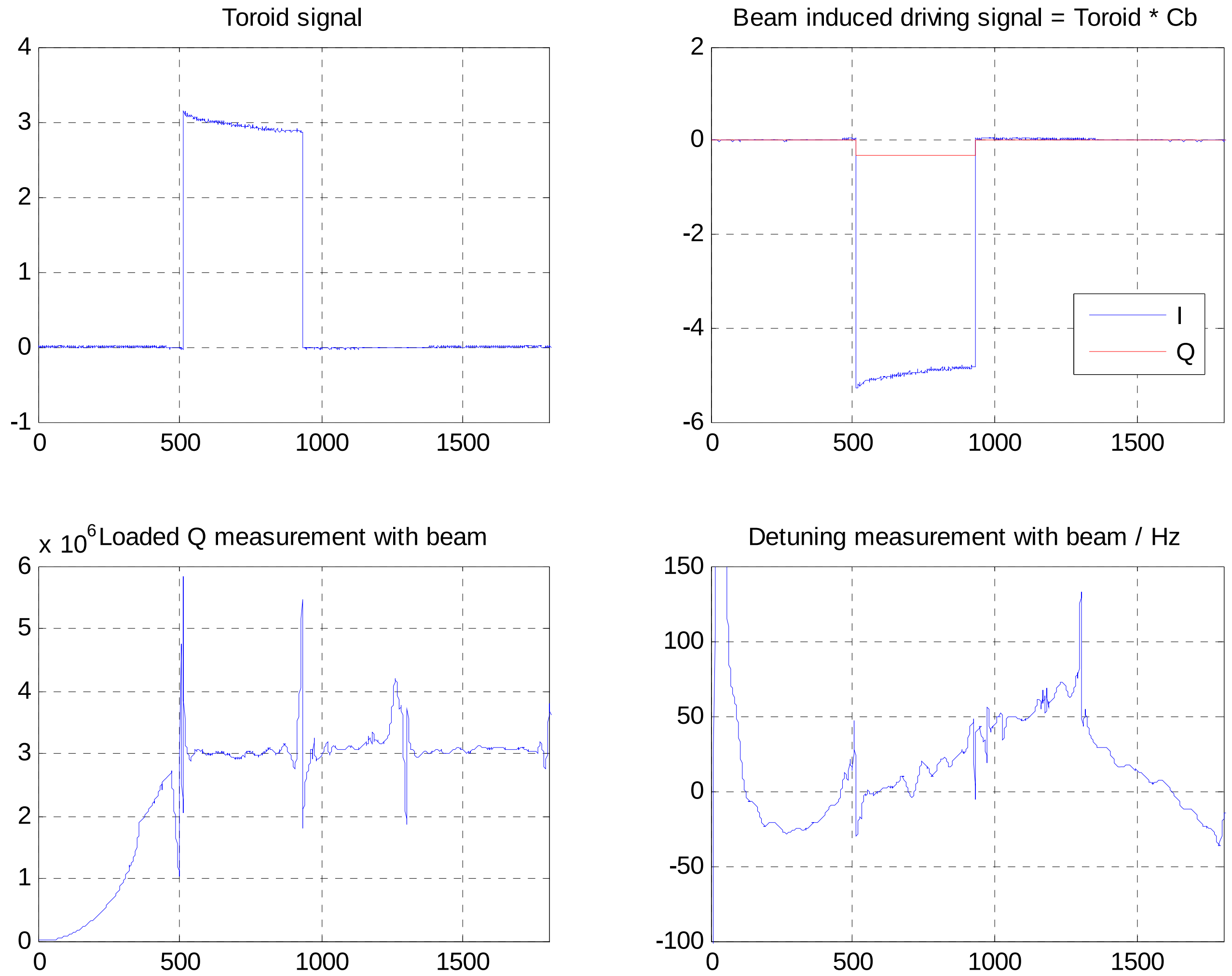
# Beam measurement
# -- Calibration of the Toroid signal

$$\frac{dV_c}{dt} + (\omega_{1/2} - j\Delta\omega)V_c = C\sqrt{\omega_{1/2}}V_{for} + 2\omega_{1/2}R_L I_b$$

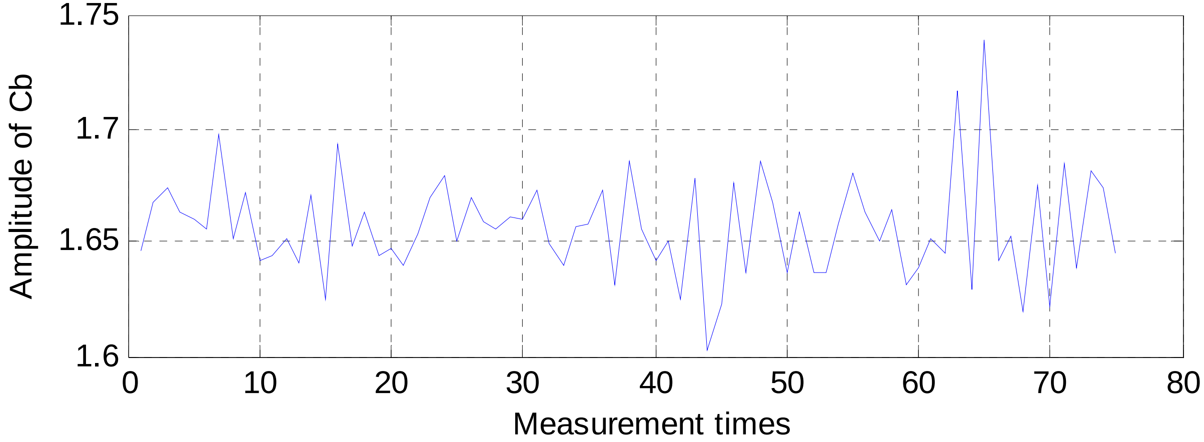
- The beam induced cavity driving voltage can be derived by the Toroid signal multiplied by a complex coefficient

$$R_L I_b = C_b \cdot V_{toroid}$$

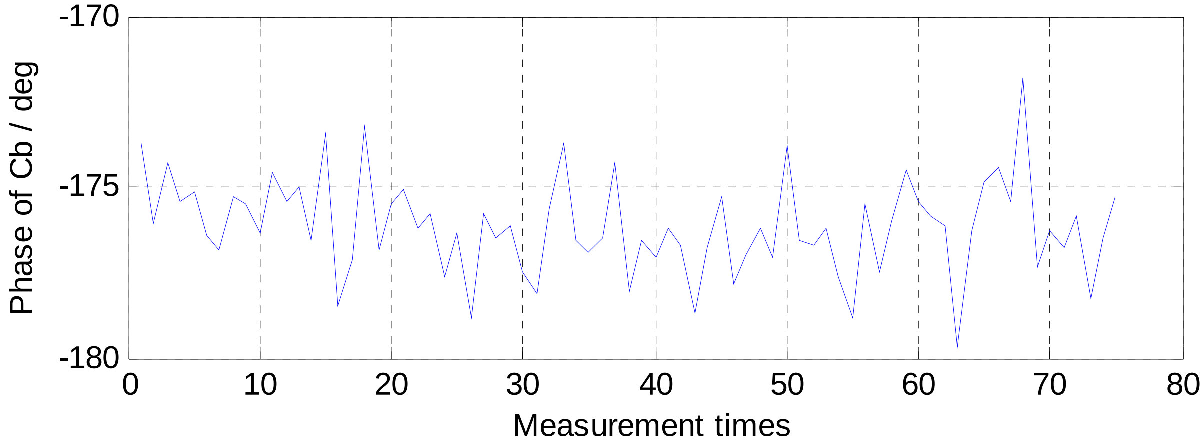
# Beam measurement
# -- Calibration of the Toroid signal



# Beam measurement
# -- Pulse to pulse fluctuation




- 1.3% RMS




- 1.4 degree RMS

# Use cases of cavity parameters

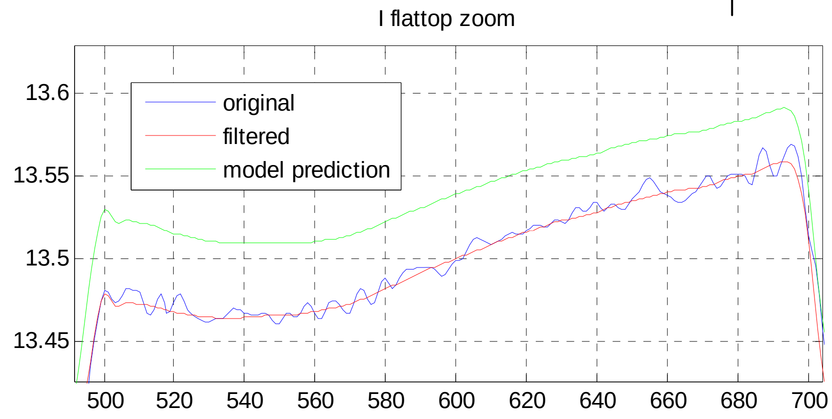
- Detect the QL exceptions, such as quench
- Provide detuning information to piezo control
- Detect the detuning exceptions
- Calibrate the vector sum
- Denoise the cavity probe signal in real time
- …

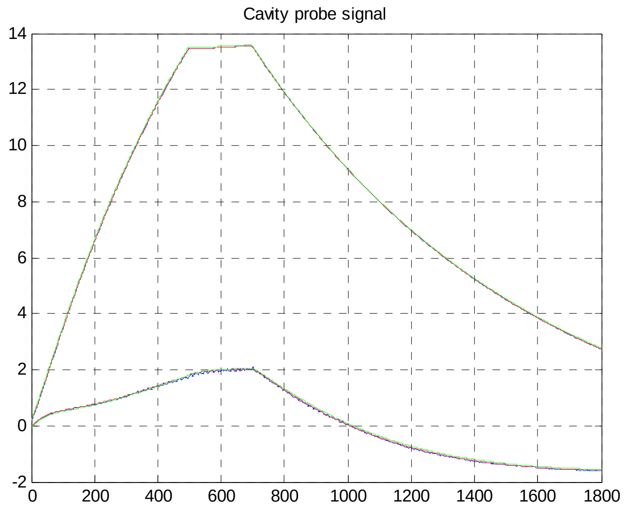
# Denoise the cavity probe signal with Kalman filter in real time

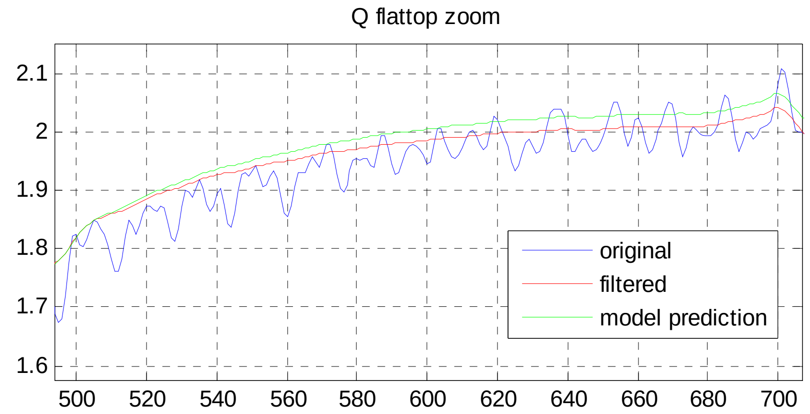
The cavity model are formed by:

- Loaded Q curve during the RF pulse
- Detuning curve during the RF pulse
- Beam curve during the RF pulse
- Cavity equations

The model is linear and time varying.



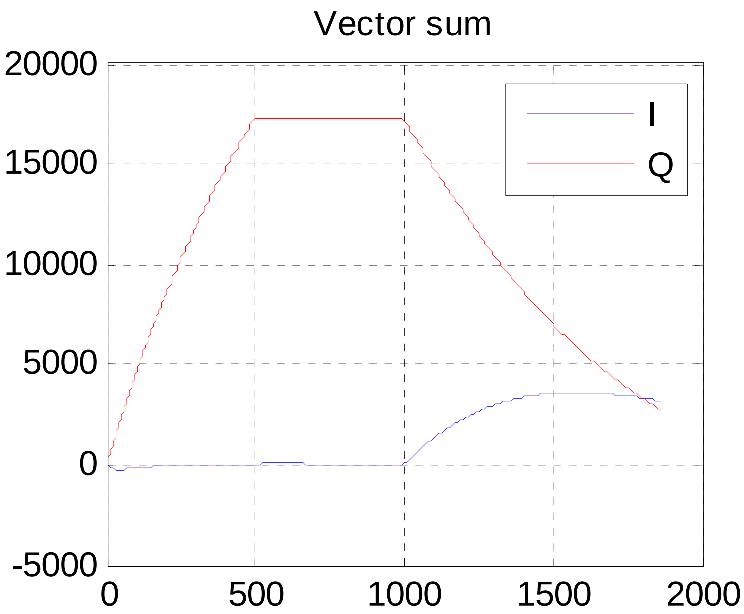
# Algorithm Study:
# Adaptive feed forward

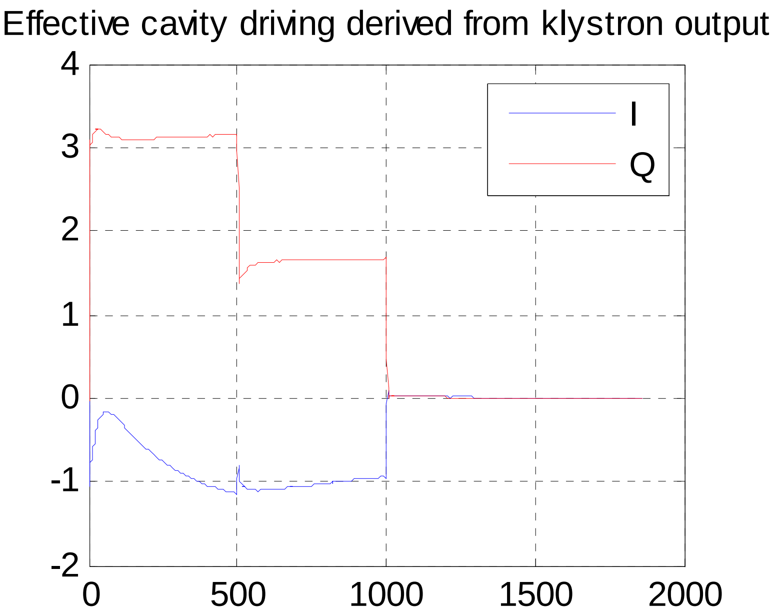
# Goals

- Identify the system
- Study the adaptive feed forward algorithm based on inversed system model

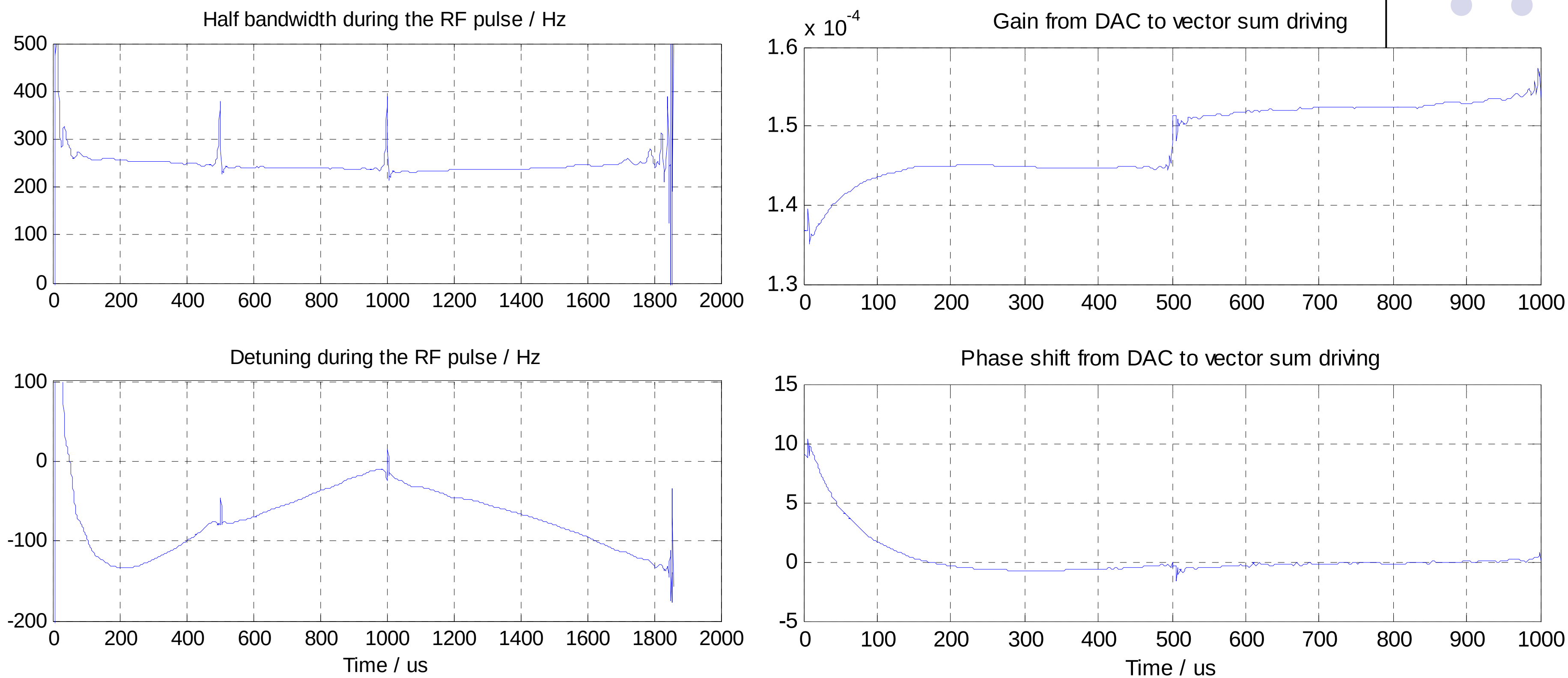
# Calibrate the klystron signal as vector sum effective driving signal

- The vector sum can be viewed as the output of an effective single cavity
- The cavity equation will still work for the effective single cavity
- The driving signal to this effective single cavity can be derived from the klystron output signal by multiplying a complex constant



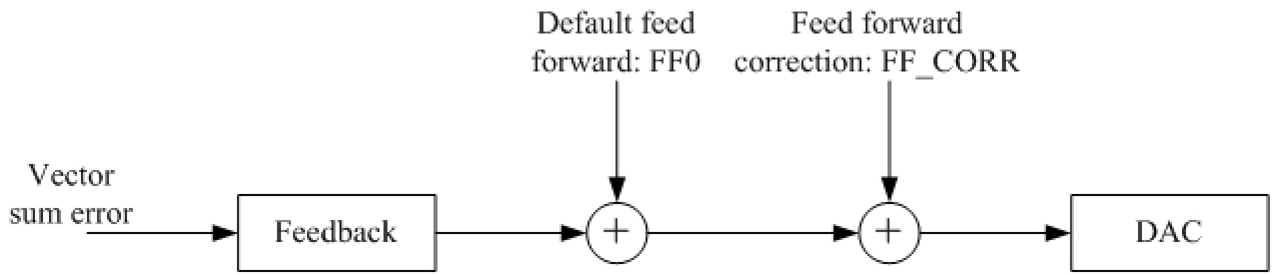
# Vector sum effective single cavity model




AFF:

- Vector sum error → Driving signal correction (system model)
- Driving system correction → Feed forward correction (DAC to driving signal gain)

# Adaptive feed forward algorithm -- Procedure




For each iteration:

- Get the initial feed forward correction table from last pulse: FF_CORR0 = DAC – FF0
- Measure the vector sum error of this pulse
- Inverse the system model, calculate the corresponding feed forward correction signal FF_CORR1
- Get and update the new feed forward correction table of this iteration: FF_CORR = FF_CORR0 + FF_CORR1

Analysis:

- With open loop operation: normal adaptive feed forward algorithm
- With closed loop operation: feedback signal will also be taken into account

# Adaptive feed forward algorithm -- Principle

Cavity equation

$$\frac{dV_{sum}}{dt} + (\omega_{1/2} - j\Delta\omega)V_{sum} = C\sqrt{\omega_{1/2}}V_d + 2\omega_{1/2}R_L I_b$$

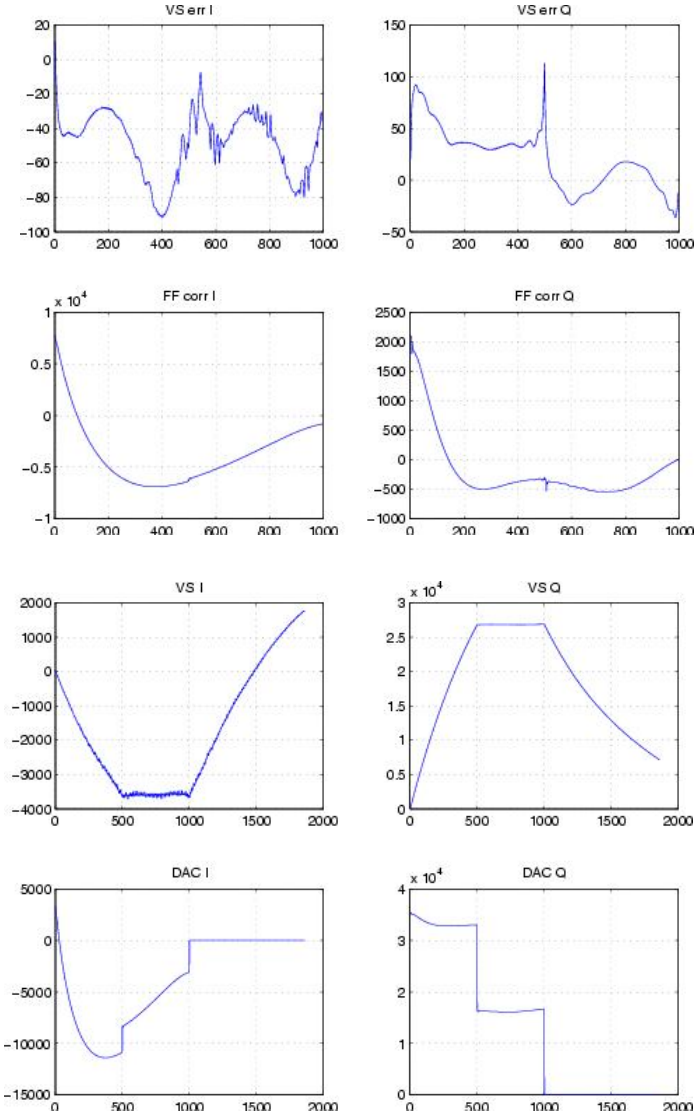
We expect

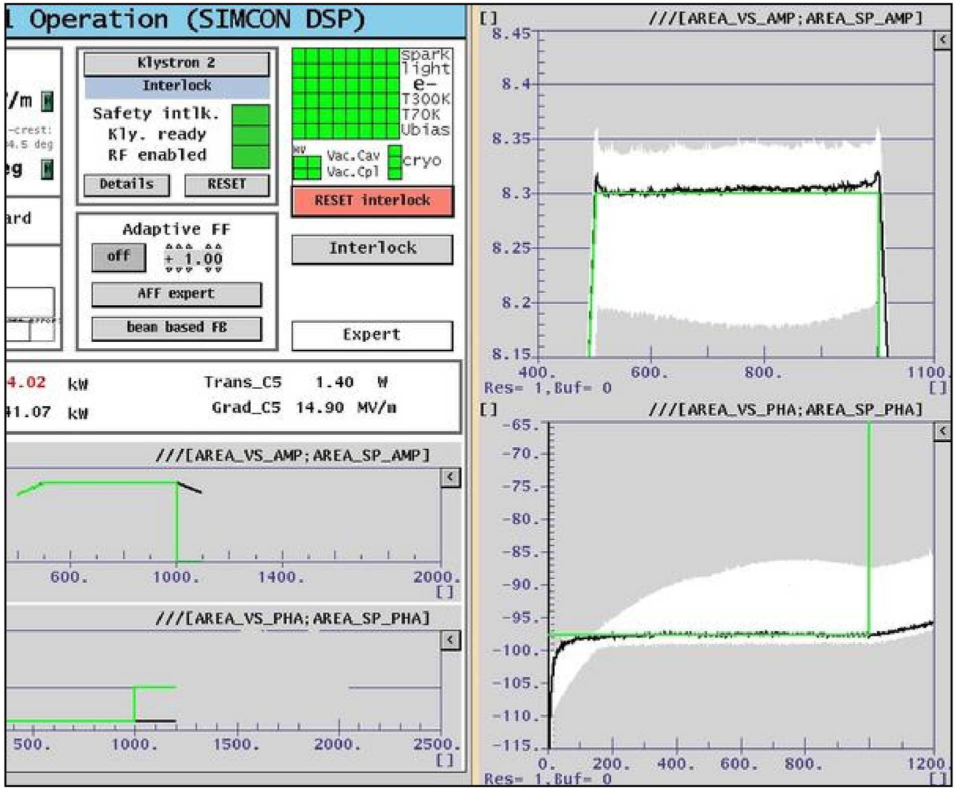
$$\frac{dV_{set}}{dt} + (\omega_{1/2} - j\Delta\omega)V_{set} = C\sqrt{\omega_{1/2}}V_d' + 2\omega_{1/2}R_L I_b$$

So the new driving signal can be calculated based on

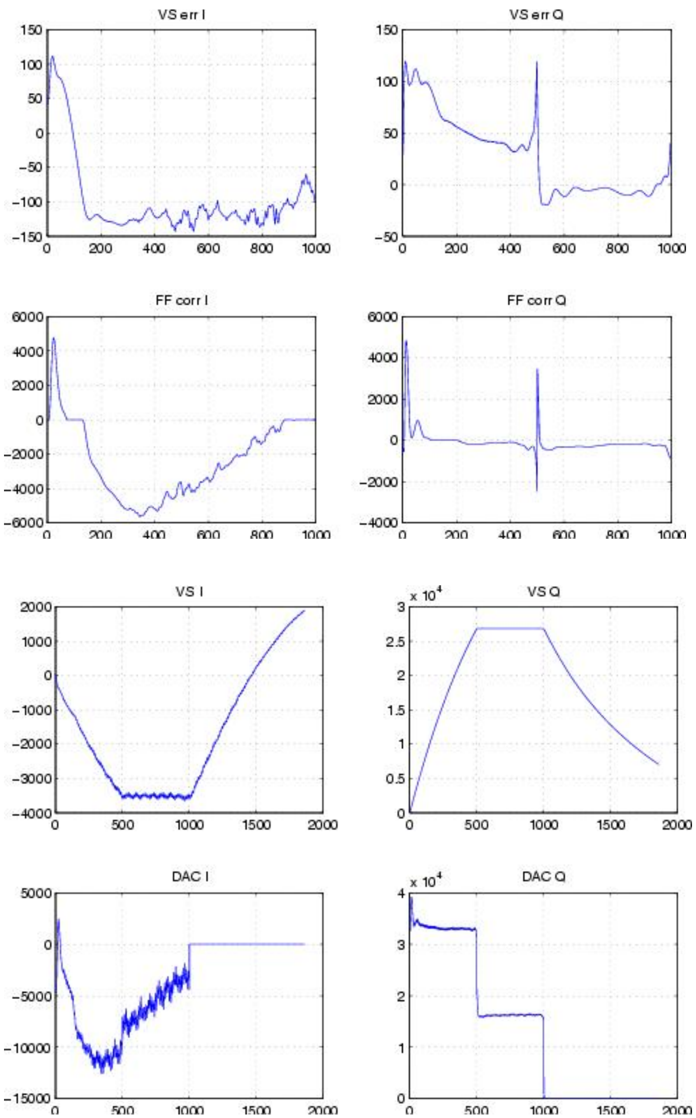
$$\frac{d\Delta V_{sum}}{dt} + (\omega_{1/2} - j\Delta\omega)\Delta V_{sum} = C\sqrt{\omega_{1/2}}\Delta V_d$$

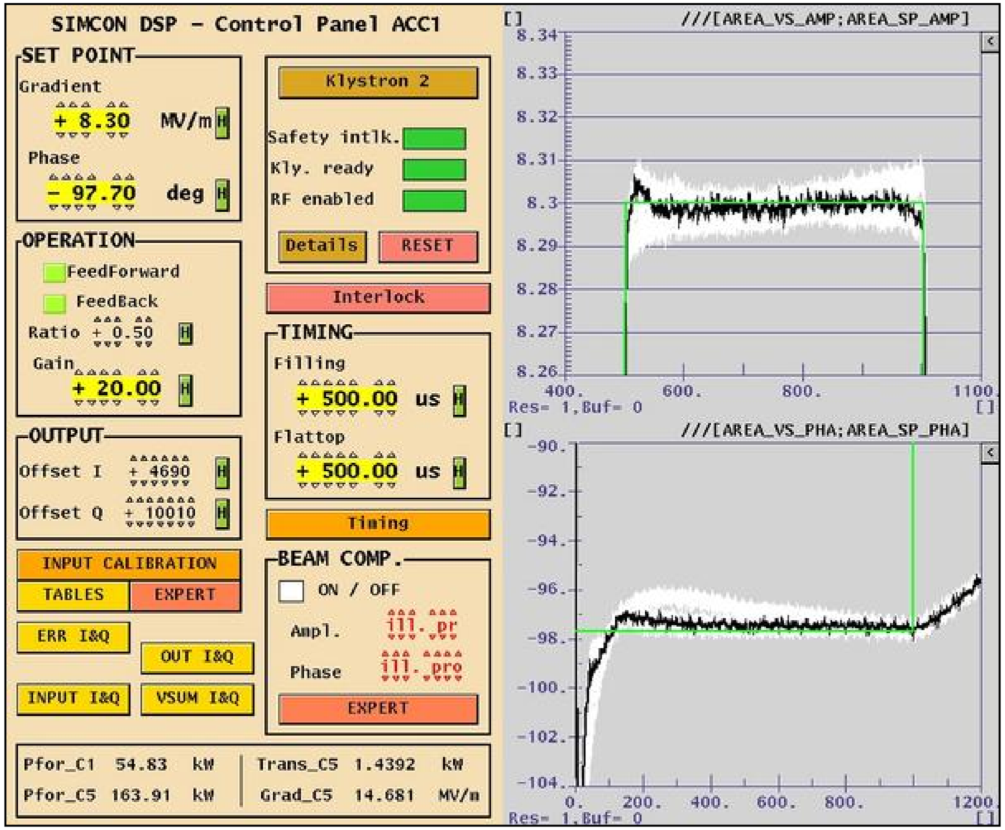
# AFF test at ACC1 (Open loop)



# AFF test at ACC1 (Closed loop)



# Future plan for LLA

# Plan for LLA work

- Continue developing algorithms
  - System phase and system gain
  - Cavity parameters measurement
  - Adaptive feed forward
  - System status analysis
  - Exception detection and handling
  - System performance estimation
- Implement and test the LLA algorithms in the SIMCON development system at ACC1

# Thank you for attention!