Progress on LLRF applications development

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FLASH Seminar

07.04.2009

Outline

- Goals of LLRF applications
- Applications studied in January 2009
  - DAC DC offset calibration for LLRF controller
  - Cavity quench detection
  - Adaptive feed forward
- Summary

Goals of LLRF applications

LLRF applications is a group of software for LLRF system in order to:

- ➲ Optimize operating parameters of LLRF controller
- ➲ System Diagnostics
- ➲ Assist operator to simplify operation

Examples for applications

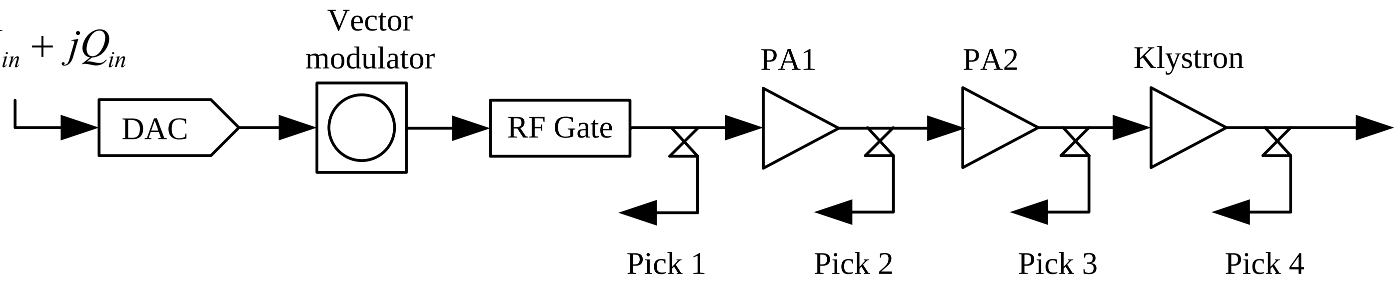
- DAC DC offset calibration for LLRF controller
  - Goal: Assist operator with zero power calibration
- Cavity quench detection
  - Goal: Diagnostic cavity limitation
- Adaptive feed forward
  - Goal: Optimize controller's feed forward parameters

DAC DC Offset Calibration

-- Assist operator with zero power calibration

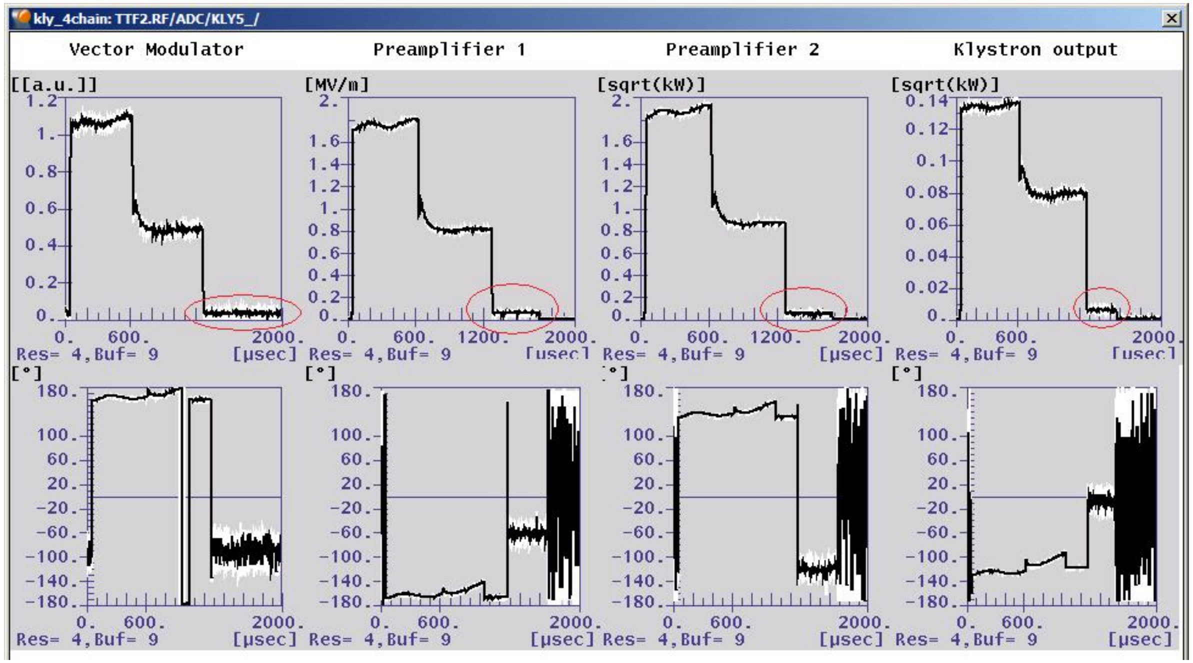
DAC DC offset calibration
-- Introduction

$$V_{in} = I_{in} + jQ_{in}$$

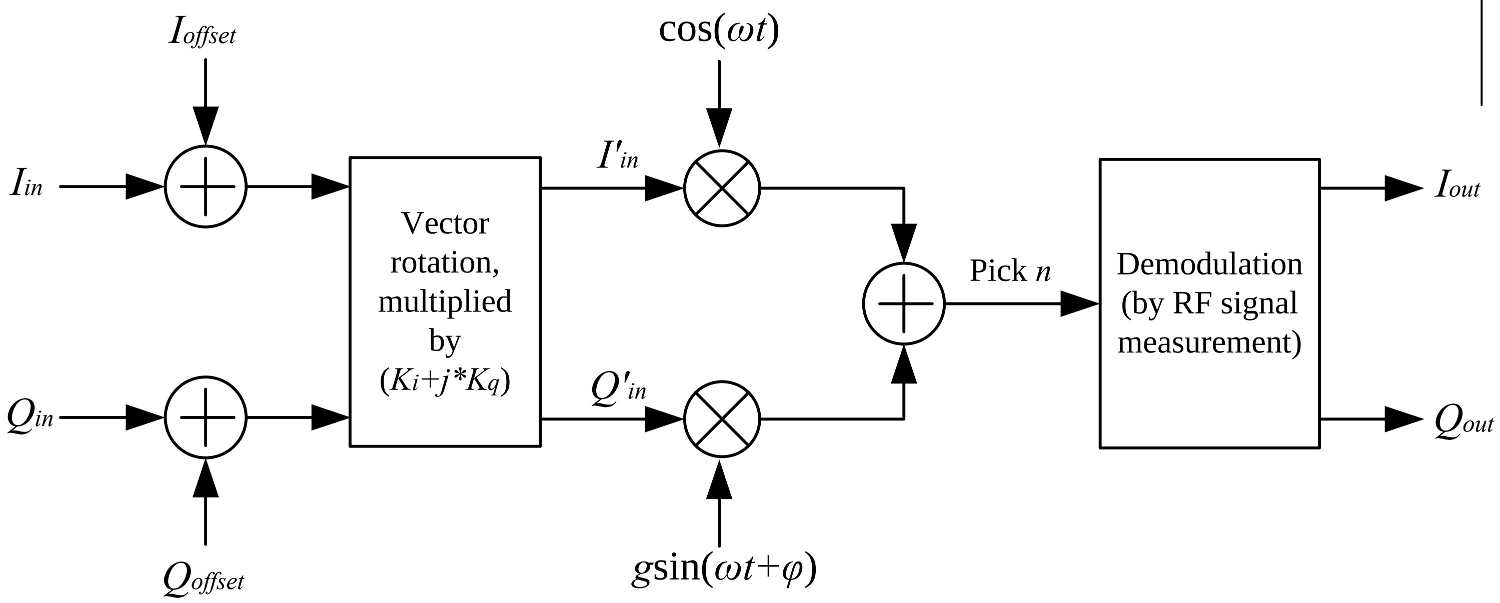


$$V_{out} = I_{out} + jQ_{out}$$

- ➲ DC offset will cause problem to set zero power (gradient)
- ➲ Unknown power offsets will cause error for applications that take the RF decay data (assuming there is no power at the end of the RF pulse)
- ➲ Zero power is obtained by removing the offset at DAC signals (currently by hand)
- ➲ DC offset changes with time, so calibration has to be done from time to time



DAC DC offset calibration
-- Driving chain error model



Unknown parameters: I_{offset}, Q_{offset}, $K_i + jK_q$, g, φ

Known parameters: I_{in}, Q_{in}, I_{out}, Q_{out}, ω

Calibration strategy: Linear fitting

Assumption: RF signal measurement is perfect; System is linear

DAC DC offset calibration

-- Formulas used

Equation for input/output

$$\begin{cases} I_{out} = aI_{in} + bQ_{in} + k \\ Q_{out} = cI_{in} + dQ_{in} + l \end{cases}$$

$$\begin{cases} a = K_i + K_q g\sin(\varphi), \quad b = -K_q + K_i g\sin(\varphi) \\ c = K_q g\cos(\varphi), \quad d = K_i g\cos(\varphi) \\ e = aI_{offset}, \quad f = bQ_{offset} \\ m = cI_{offset}, \quad n = dQ_{offset} \\ k = e + f, \quad l = m + n \end{cases}$$

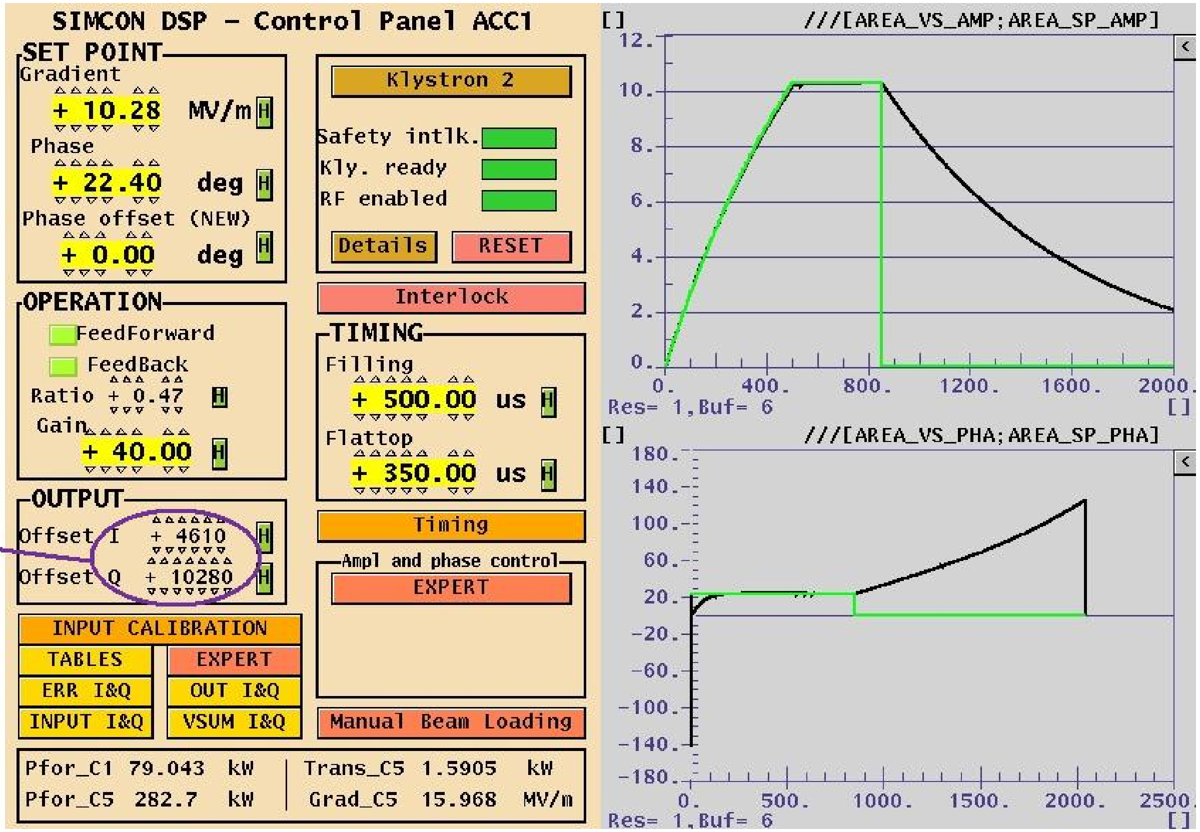
Results

$$\begin{cases} k = aI_{offset} + bQ_{offset} \\ l = cI_{offset} + dQ_{offset} \end{cases}$$

$$\begin{cases} K_i = \dfrac{1}{\left(1 + \dfrac{c^2}{d^2}\right)}\left(a - \dfrac{cb}{d}\right) \\ K_q = K_i \dfrac{c}{d} \\ g\cos(\varphi) = \dfrac{c}{K_q} \\ g\sin(\varphi) = \dfrac{b + K_q}{K_i} \end{cases}$$

At least 3 pairs of input/output points are needed to perform the linear fitting.

DAC DC offset calibration
-- Test results

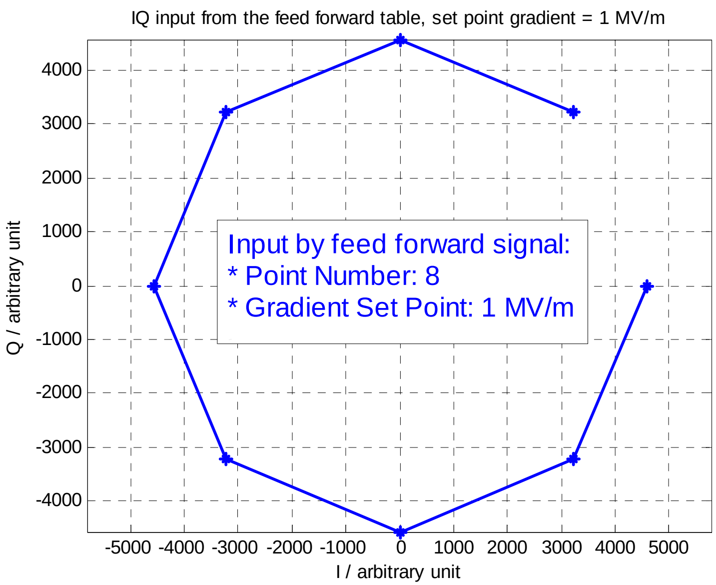


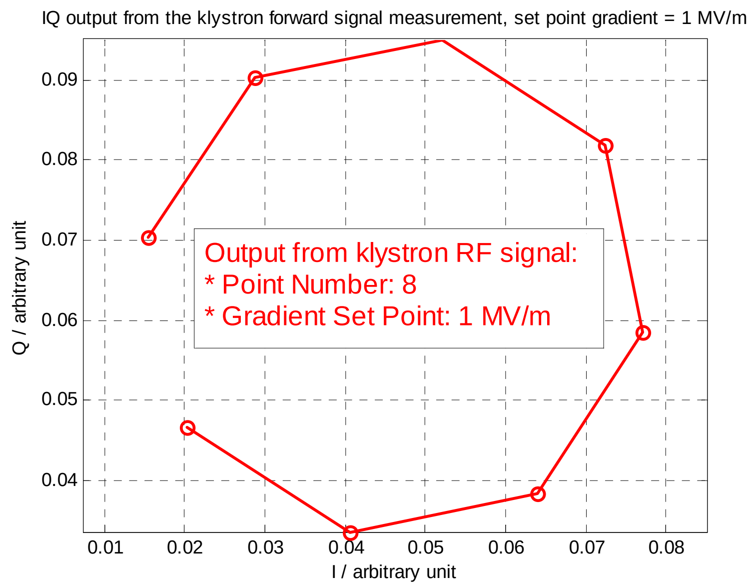
Offset by manual adjustment

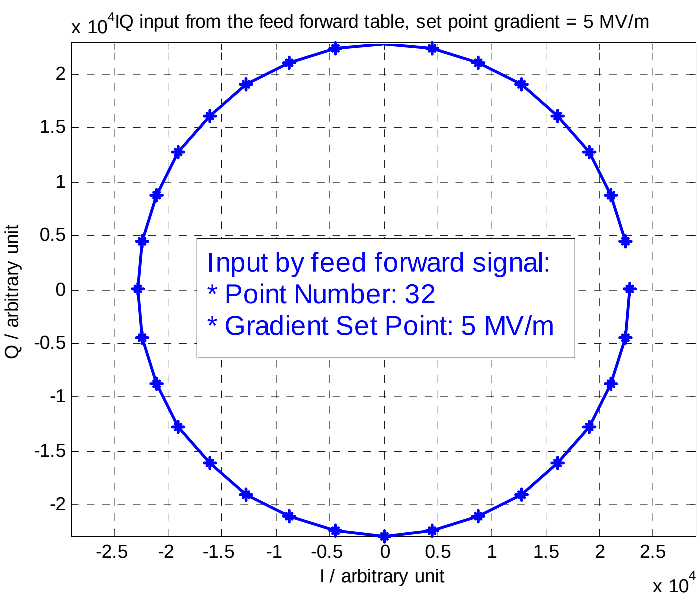
Measured Values

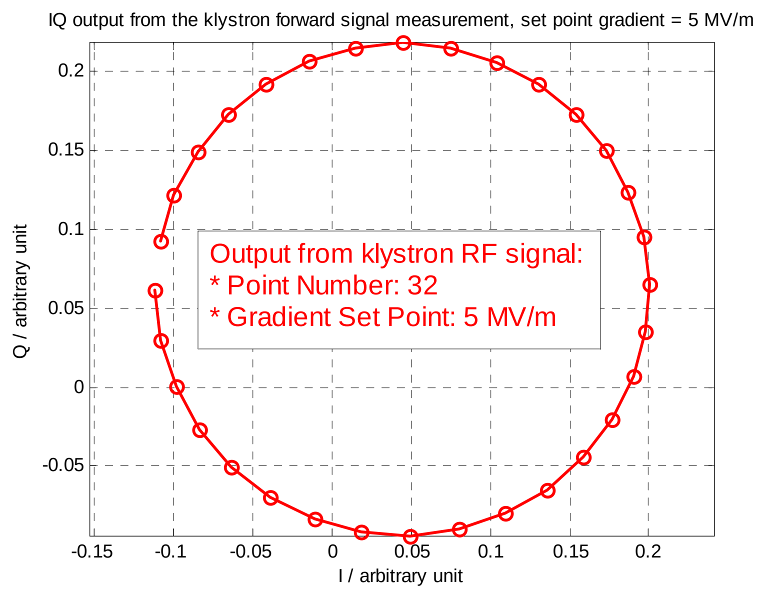
	Gradient / MV/m	I_{offset}	Q_{offset}	K_i	K_q	g	ϕ / deg
3 points	1	4952	10525	-6. 737 e-6	1. 306 e-6	0.9976	-0.77
8 points	1	4875	10505	-6.744 e-6	1.298 e-6	0.9967	-0.16
16 points	5	4937	10255	-6.678 e-6	1.307 e-6	0.9988	-0.16
32 points	5	4936	10276	-6.708 e-6	1.245 e-6	0.9987	-0.11
64 points	1	4847	10467	-6.747 e-6	1.270 e-6	0.9963	-0.01

DAC DC offset calibration
-- Test results







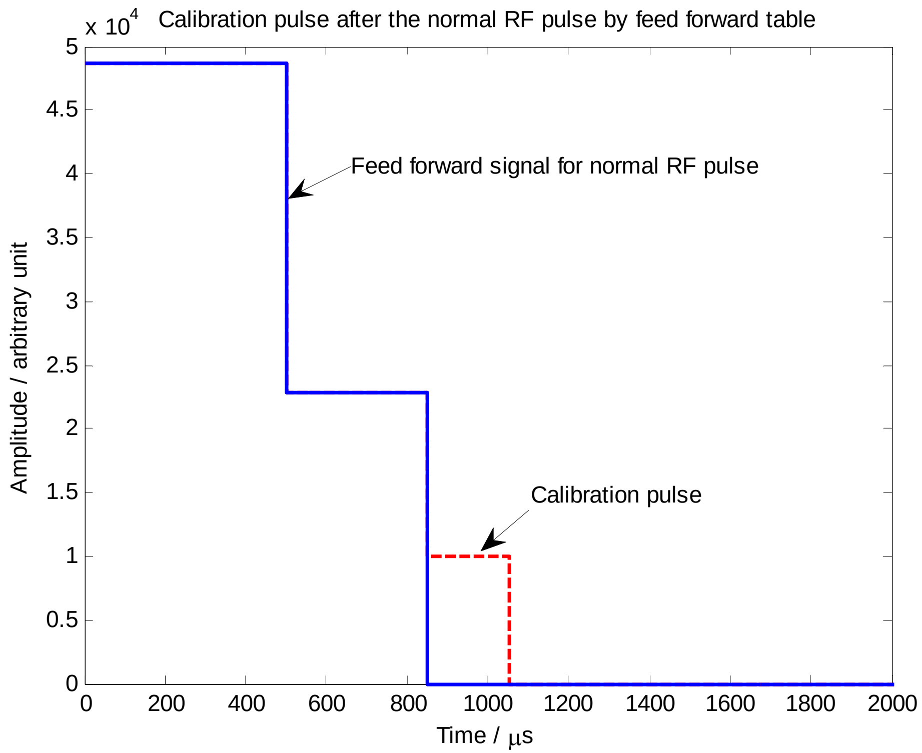


DAC DC offset calibration
-- Summary

➲ The current algorithm need to interrupt the normal operation because it has to change the gradient set point and rotate the feed forward signal

➲ When RF system first start up, offset calibration can be done with klystron off, so that we can avoid klystron interlock trip by unexpected peak driving power

➲ In the future, the calibration can be done without interrupting normal operation by introducing a small calibration pulse after the main RF pulse (see the figure below)



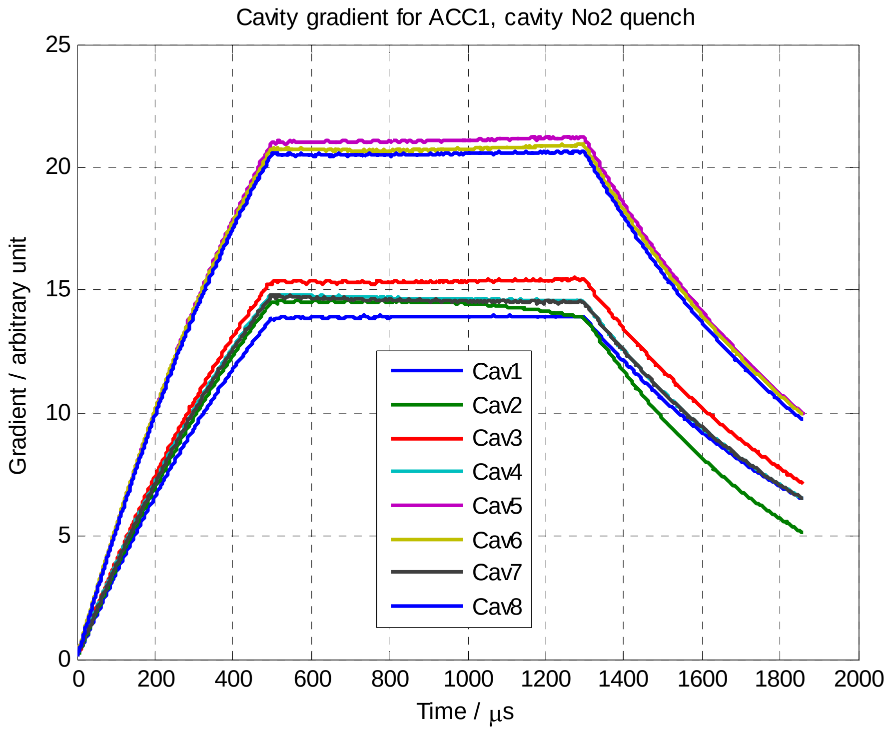
Cavity Quench Detection

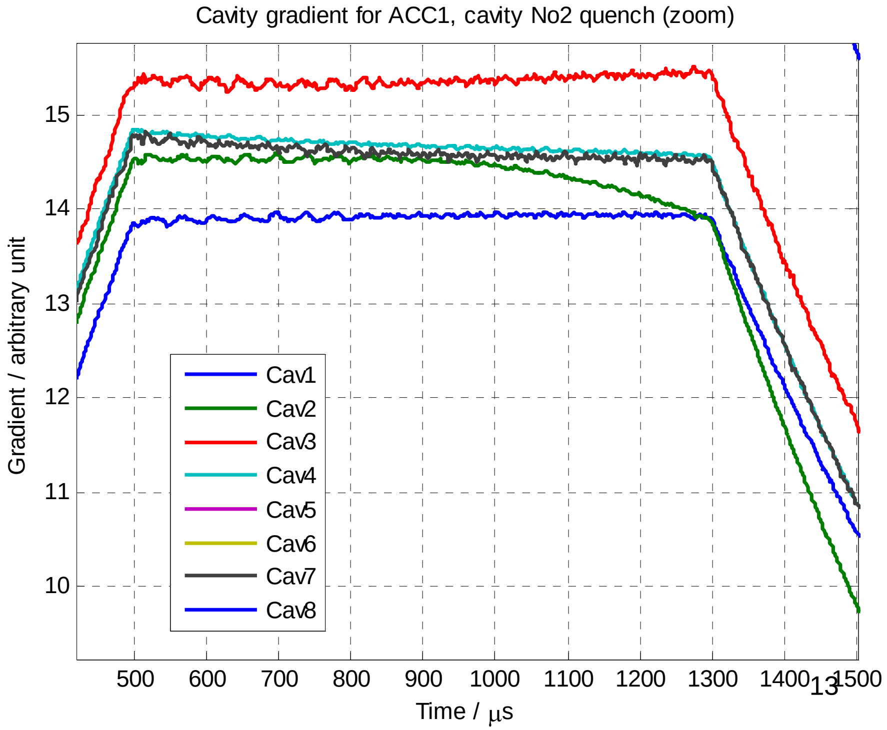
-- Diagnostic cavity limitation

Cavity quench detection
-- Problem description

➲ Cavity quench can cause unstable RF field or even beam loss, and increase the cryo heat load

➲ Goals for this application: Detect quench for each cavity to inform operators and cryogenics





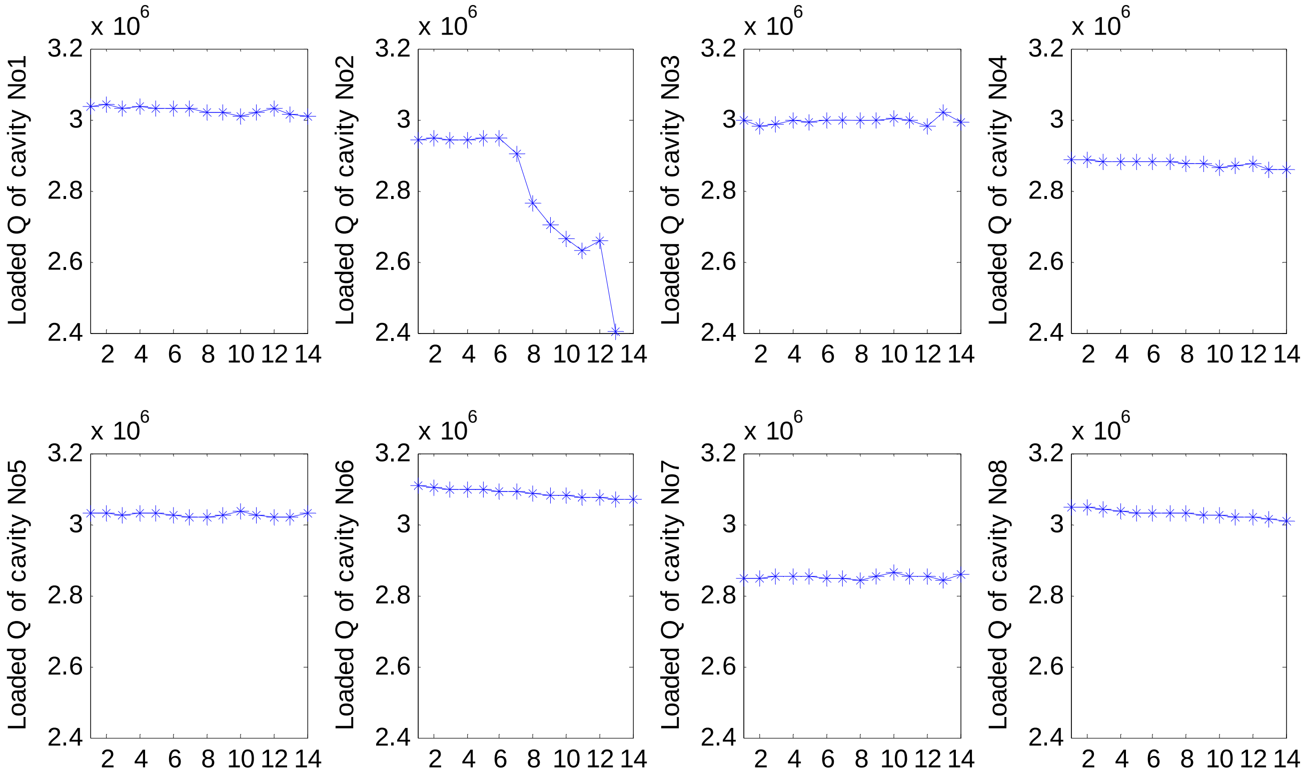
Cavity quench detection
-- Solution

- Existing solutions at FLASH:
  - At the DSP system, quench is detected by monitoring the change of the vector sum pulse shape (work only for vector sum; can not distinguish the pulse shape change by detuning or beam loading)
  - Measure loaded Q of each cavity at the RF pulse decay part (by Valeri Ayvazyan. pulse to pulse quench detection; works for each cavity; precise)
- Solution proposed here: Measure the loaded Q of each cavity during the RF pulse (real time intra-pulse quench detection; precise)
- If the loaded Q drops larger than the threshold, quench event will be generated
- Principle: the cavity equation is used for loaded Q measurement

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

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

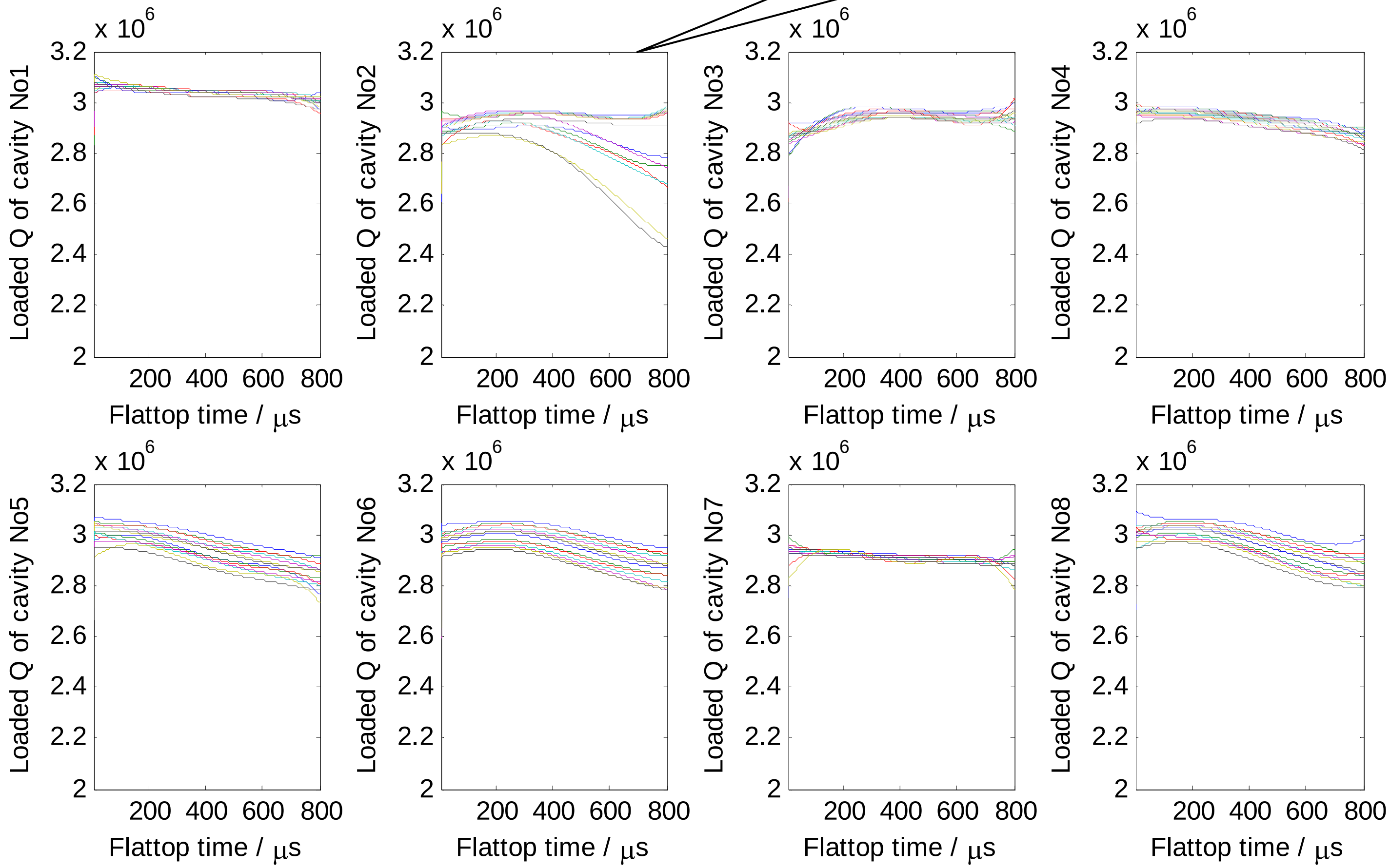
Cavity quench detection
-- Test results



Loaded Q measurement at the RF decay part for each cavity of ACC1, the x number means 14 times measurement with different set point gradient (from 9.3MV/m to 10.6MV/m, 0.1MV/m as increment steps)

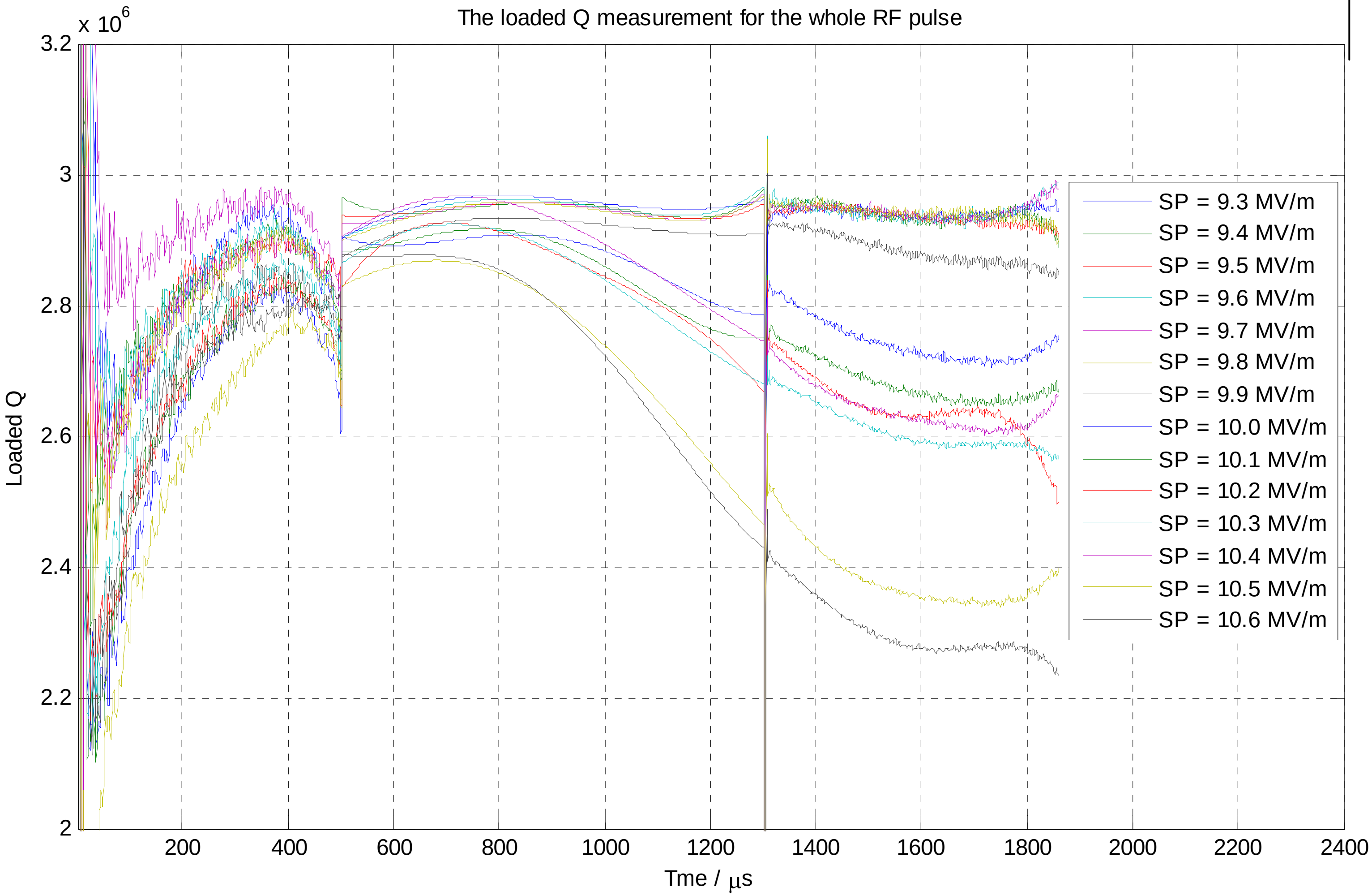
Cavity quench detection
-- Test results

This method also works in presence of beam



Loaded Q measurement during RF flattop for each cavity of ACC1, the curves for each cavity means 14 times measurement with different set point gradient (from 9.3MV/m to 10.6MV/m, 0.1MV/m as increment steps)

Cavity quench detection
-- Test results



Loaded Q measurement of cavity No.2 at ACC1 during the RF pulse with different set point gradient

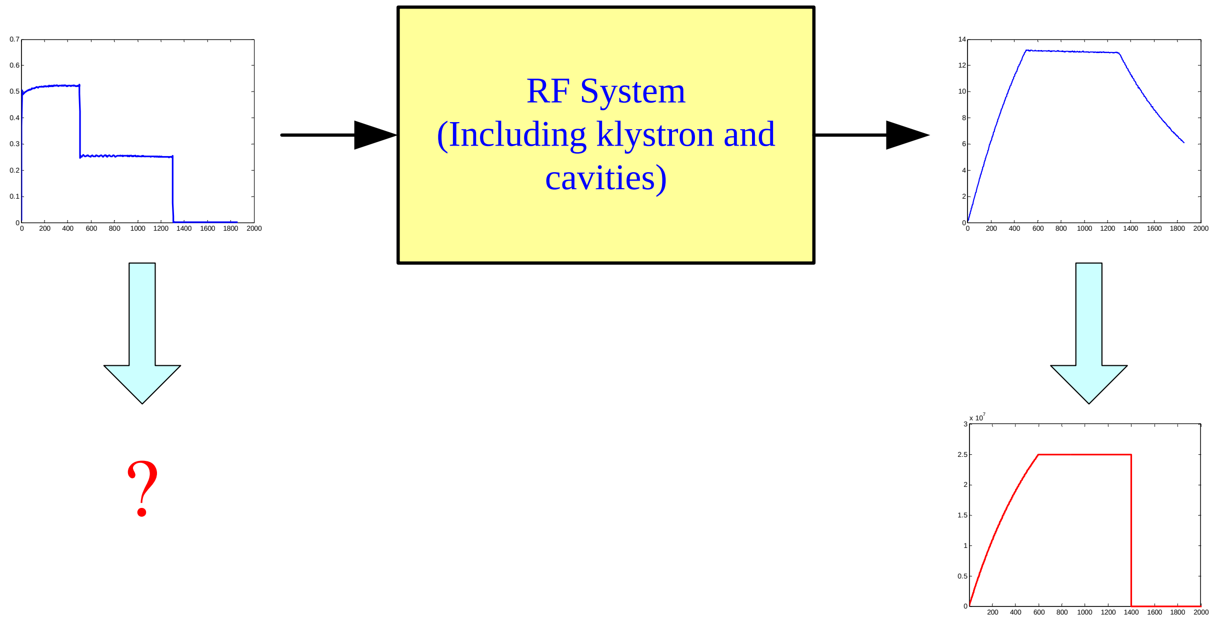
Cavity quench detection
-- Summary

- ➲ The algorithms for the intra-pulse real time quench detection is evaluated, which is currently developed by matlab, and not yet available for operators
- ➲ Quench detection at RF decay is easy, which can be implemented at LLRF ATCA CPU
- ➲ Quench detection during RF pulse in real time is relatively difficult to realize, which must be implemented at faster processors such as DSP or FPGA
- ➲ Whether or not implement the real time quench detection strongly depends on the requirements from the operation group!

Adaptive Feed Forward

-- Optimize controller's feed forward parameters

Adaptive feed forward
-- Problem description



Goals of the application:

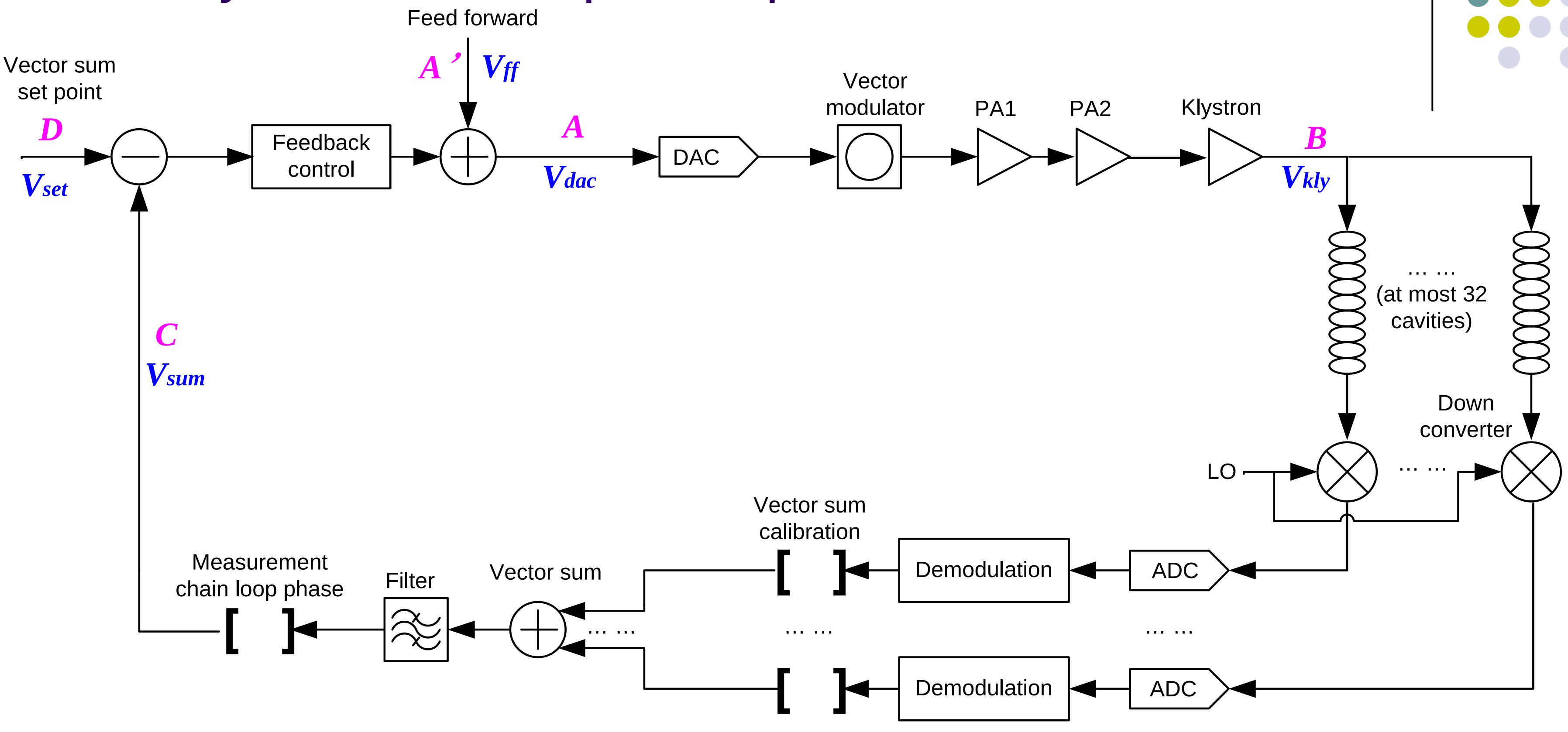
➲ Compensate the repeating errors of the system

➲ When system status changes, such as the gradient or beam condition change, adapt the feed forward table for new working point setting

Adaptive feed forward
-- Solutions

- Time inversed filter based solution
  - By Alexander Brandt
  - The most robust and mature one working for FLASH
  - Easy to implement
- Inversed black box model based solution (learning feed forward)
  - By Christian Schmidt
  - The most precise one
  - The black box model parameters for the RF system have no obvious physical meaning
- Inversed gray box model based solution
  - The topic here
  - The gray box model parameters for the RF system have obvious physical meaning, which will be helpful to understand the system
  - It is possible to predict the required beam compensation signal for the desired beam setting and compensate the beam loading in advance

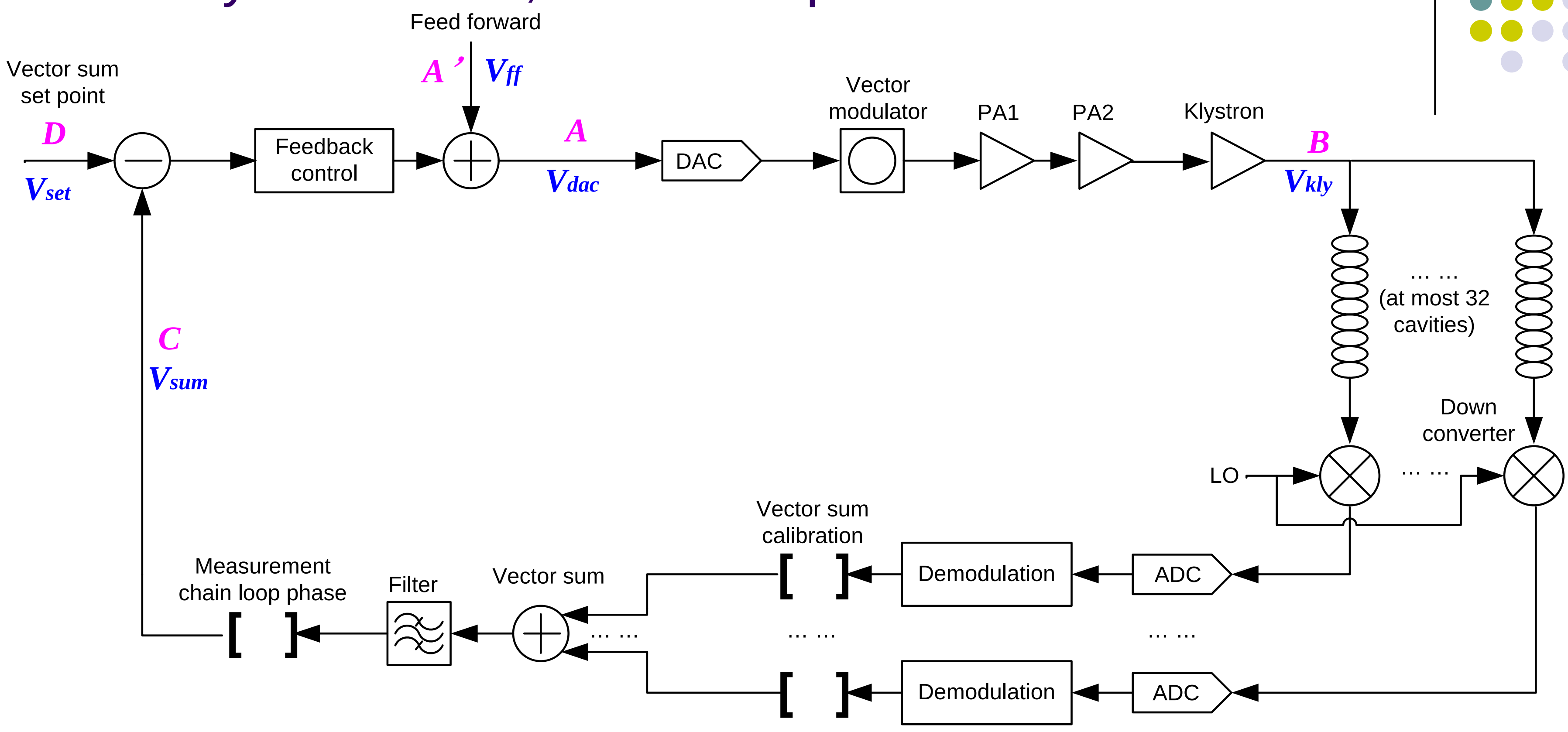
Adaptive feed forward
-- Gray box model, open loop



- *A to B*: modeled as a time varying gain and phase shift, marked as complex gain *G*
- *B to C*: modeled as an effective single cavity, so the open loop model is

$$\frac{dV_{sum}}{dt} + (\omega_{1/2} - j\Delta\omega)V_{sum} = M\sqrt{\omega_{1/2}}C_{kly}GV_{dac}, \qquad M = \sqrt{\left(\frac{r}{Q}\right)\frac{\omega_0}{Z_0}}$$

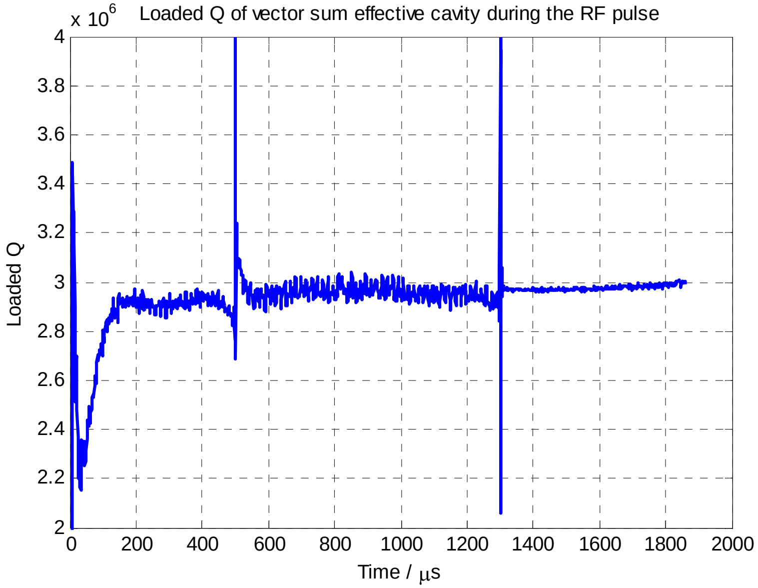
Adaptive feed forward
-- Gray box model, closed loop

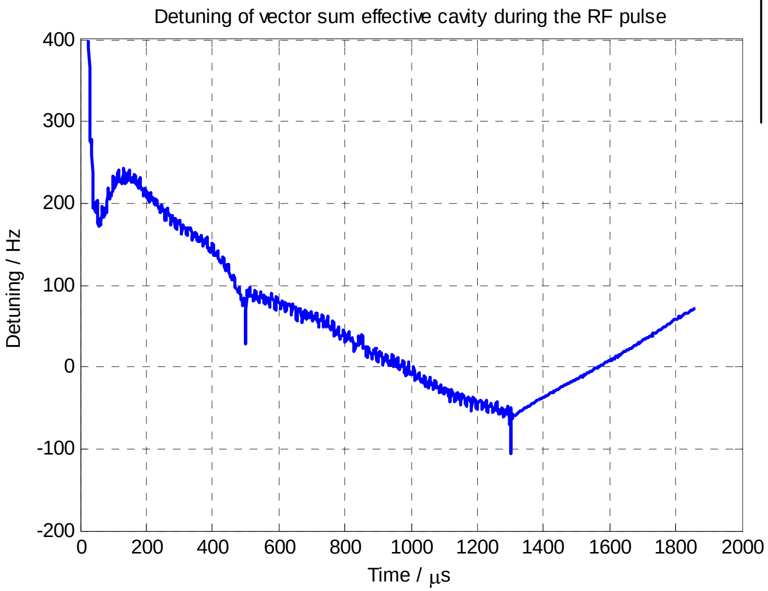


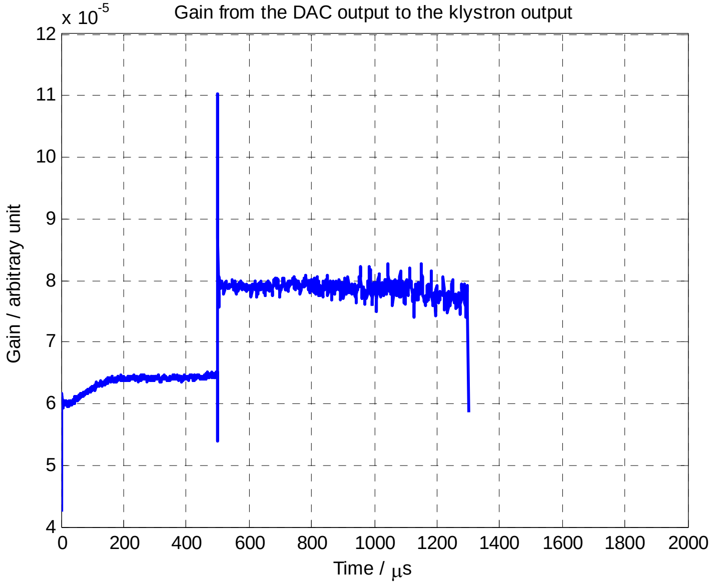
➲ Taking into account the feedback (here is a P controller), the closed loop gray box model is

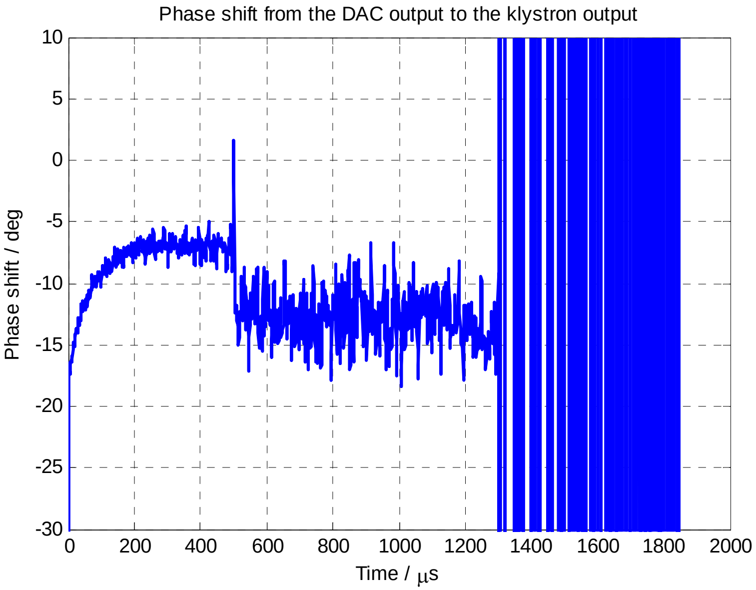
$$\frac{dV_{sum}}{dt} + \left(\omega_{1/2} + M\sqrt{\omega_{1/2}}C_{kly}GP - j\Delta\omega\right)V_{sum} = M\sqrt{\omega_{1/2}}C_{kly}GV_{ff}\,, \qquad M = \sqrt{\left(\frac{r}{Q}\right)\frac{\omega_0}{Z_0}}$$

Adaptive feed forward
-- Test results, the identified model elements

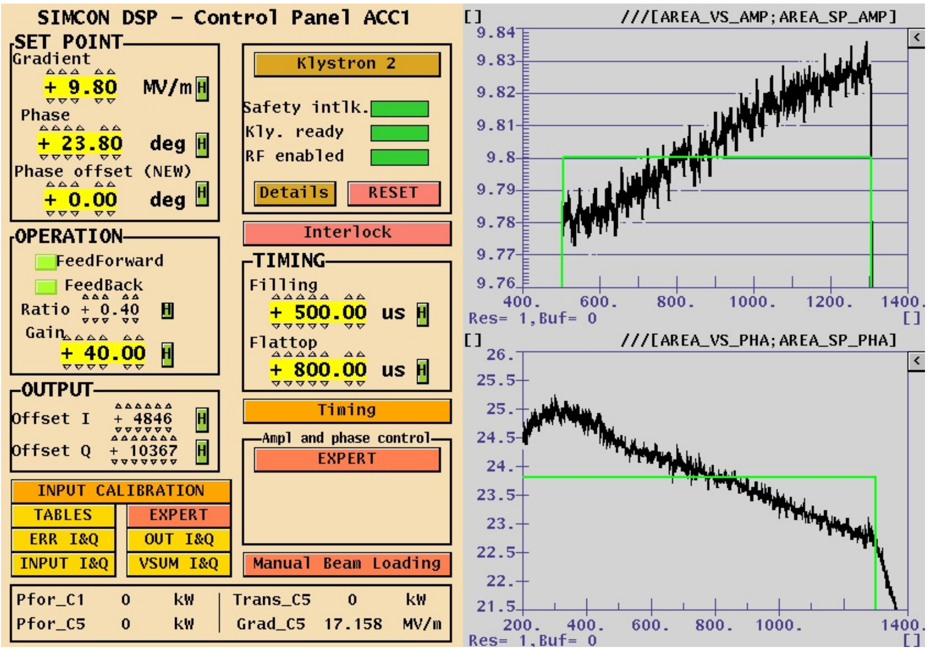


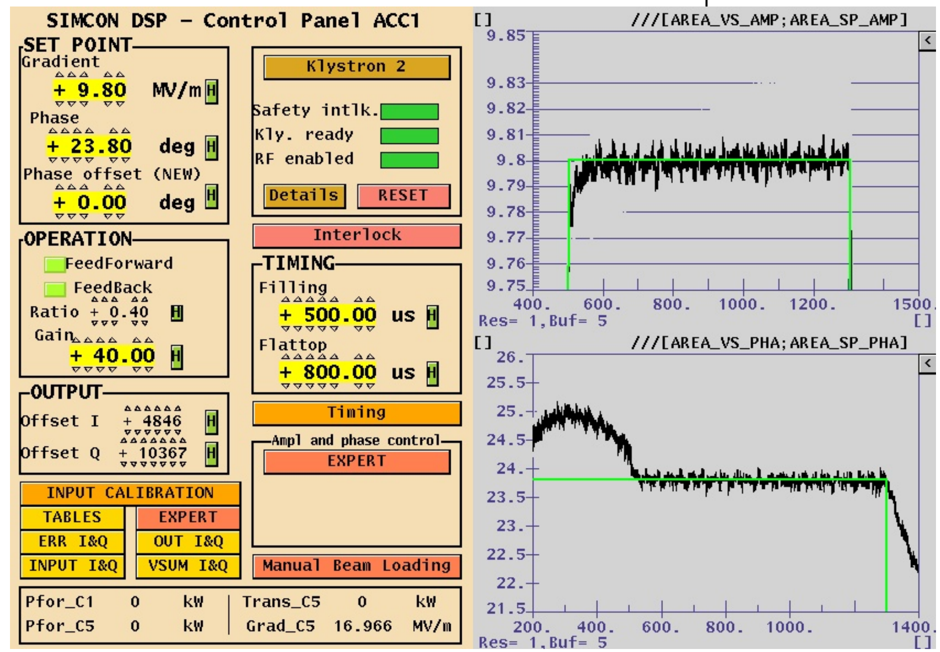






Adaptive feed forward
-- Test results, closed loop AFF

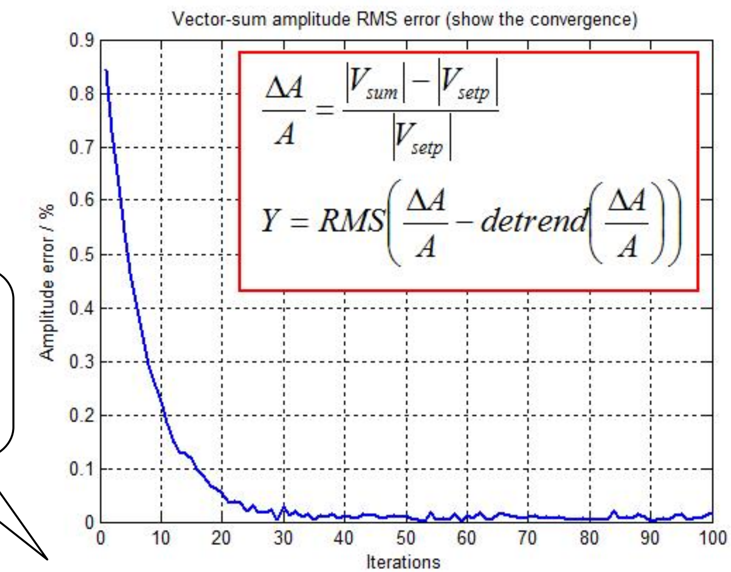


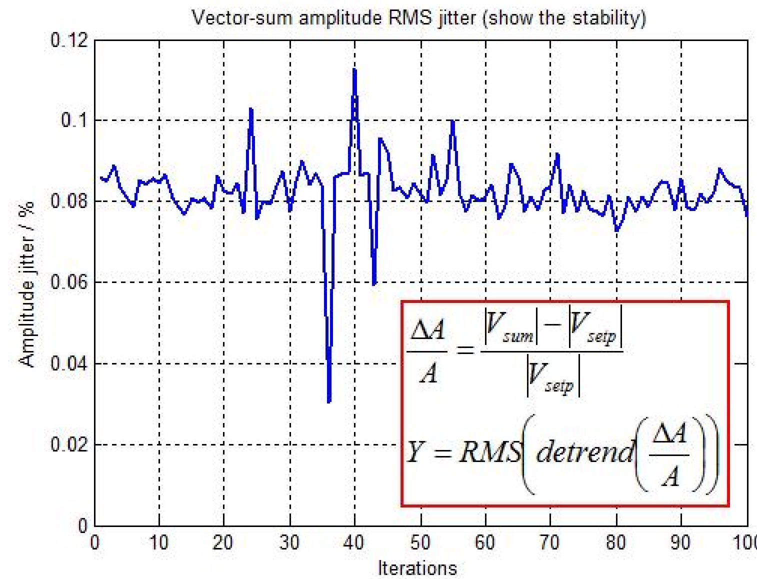


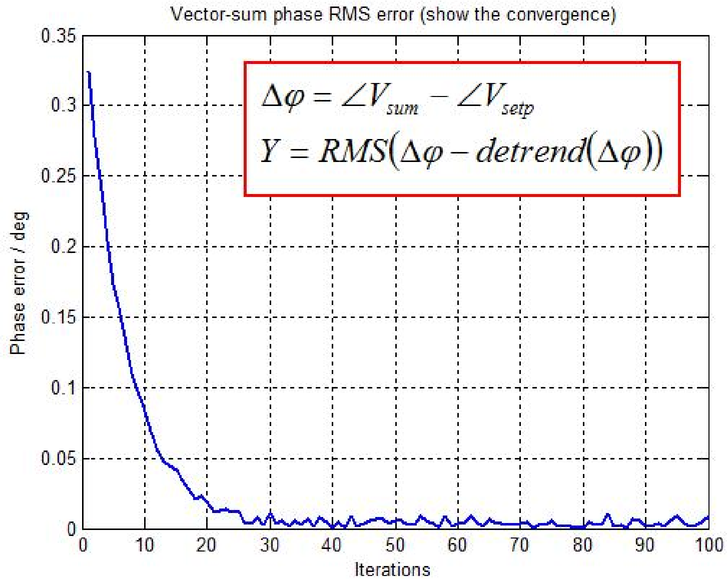
- The adaption is from the start of the flattop
- Transient can be removed by starting the adaption a little earlier than the flattop start point

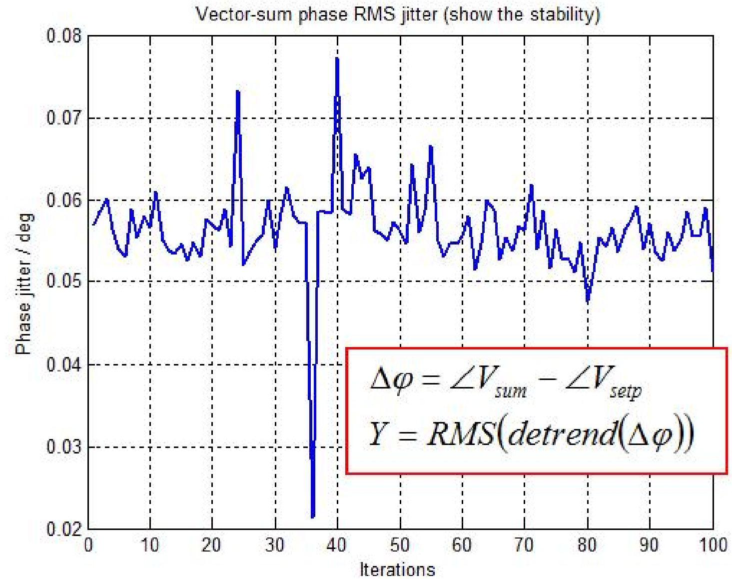
Adaptive feed forward
-- Test results, convergence and stability

Adaption gain = 0.1









Summary

- LLRF applications is part of LLRF system for better performance, system diagnostic and easy operation supporting
- Most applications are based on the RF cavity physical model
- Application development will be on SIMCON DSP development system, but the computation resource is quite limited to implement all necessary applications. Applications will be immigrate to the ATCA system when it is ready.

Thank you!