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 $V_{sum}$ and $V_{dac}$ in steady state
- **System Gain**: The amplitude ratio between $V_{sum}$ and $V_{dac}$ 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
  
  \[
  \text{System\_Phase} = \text{angle}(\text{Vector\_sum} / \text{DAC\_out})
  \]
  
  \[
  \text{System\_Gain} = \text{abs}(\text{Vector\_sum} / \text{DAC\_out})
  \]

- 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

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

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

\[ V_e(s) = \frac{1}{1+G(s)H(s)P}V_i(s) \]

\[ = \frac{V_i(s)(s + \omega_{1/2} - j\Delta \omega)}{s + \omega_{1/2} - j\Delta \omega + P\omega_{1/2}ge^{j\theta}} \]

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

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

\[ \Rightarrow \cos \theta > -\frac{1}{Pg} \]

The stable area of system phase is

\[ \left[ -\frac{\pi}{2} + \text{Detuning\ angle}, \frac{\pi}{2} + \text{Detuning\ angle} \right] \]
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

Ten-hour Measurement of ACC1 System Phase

Ten-hour Measurement of ACC1 System Gain

Ten-hour Measurement of ACC1 Amplitude Error

Ten-hour Measurement of ACC1 Phase Error

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

\[
\frac{dV_c}{dt} + (\omega_{1/2} - j\Delta\omega)V_c = C\sqrt{\omega_{1/2}}V_{for} + 2\omega_{1/2}R_LI_b
\]

\[
C = \sqrt{\left(\frac{r}{Q}\right)\frac{\omega_0}{Z_0}}
\]
Forward and reflected signal directivity correction

\[ V_{\text{for}} = aV_{\text{for\_mea}} + bV_{\text{ref\_mea}} \]
\[ V_{\text{ref}} = cV_{\text{for\_mea}} + dV_{\text{ref\_mea}} \]

➢ 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

- Loaded Q at decay part
  - QL: 0.2% RMS

- Detuning at decay part / Hz
  - Detuning: 5 Hz RMS
Beam measurement
-- Calibration of the Toroid signal

\[
\frac{dV_c}{dt} + (\omega_{1/2} - j\Delta\omega)V_c = C\sqrt{\omega_{1/2}}V_{for} + 2\omega_{1/2}R_LI_b
\]

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

\[
R_LI_b = C_b \cdot V_{toroid}
\]
Beam measurement
-- Calibration of the Toroid signal

\[ \text{Beam induced driving signal} = \text{Toroid} \times C_b \]

\[ \times 10^6 \text{Loaded Q measurement with beam} \]

\[ \text{Detuning measurement with beam / Hz} \]
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 inverted 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

- Half bandwidth during the RF pulse / Hz
- Detuning during the RF pulse / Hz
- Gain from DAC to vector sum driving
- Phase shift from DAC to vector sum driving

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

14/10/2008
FLASH Seminar, Zheqiao Geng
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

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

We expect

\[
\frac{dV_{\text{set}}}{dt} + (\omega_{1/2} - j\Delta\omega)V_{\text{set}} = C\sqrt{\omega_{1/2}}V'_d + 2\omega_{1/2}R_L I_b
\]

So the new driving signal can be calculated based on

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