The ESS LLRF Control System

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Outline

- LLRF Introduction and Requirements
- Issues in LLRF Control
- Control Methods Consideration
- Summary
Control and maintain the specified phase and amplitude stability of accelerating field in RF cavity during beam traveling

Also maintain the filling stage of the RF pulse

The stability requirement is from the beam dynamic:

\[ V_{acc,n} = V_c (1 + \delta_v) \cos(\phi_b + \delta_\phi) \]
\[ V_{tot} = \sum_{n=1}^{N} V_{acc,n} \]
\[ \sigma_E \frac{E}{E} = \frac{\langle V_{tot}^2 \rangle - \langle V_{tot} \rangle^2}{\langle V_{tot} \rangle^2} \]

In the case of fixed sync. phase:

\[ \left( \frac{\sigma_E}{E} \right)_{corr.} = \frac{1}{\cos(\phi_b)} \left[ \frac{1}{2} (1 + \cos(2\phi_b)) \sigma_v^2 + \frac{1}{2} (1 - \cos(2\phi_b)) \sigma_\phi^2 + \frac{1}{4} (3\cos(2\phi_b) - 1) \sigma_\phi^2 \right]^{1/2} \]
\[ \left( \frac{\sigma_E}{E} \right)_{uncorr.} = \frac{1}{\sqrt{N \cos(\phi_b)}} \left[ \frac{1}{2} (1 + \cos(2\phi_b)) \sigma_v^2 + \frac{1}{2} (1 - \cos(2\phi_b)) \sigma_\phi^2 + \frac{1}{4} (3\cos(2\phi_b) - 1) \sigma_\phi^2 \right]^{1/2} \]
\[ \left( \frac{\sigma_E}{E} \right)^2 = \left( \frac{\sigma_E}{E} \right)_{corr.}^2 + \left( \frac{\sigma_E}{E} \right)_{uncorr.}^2 \]

Krafft, G ; Merminga, L, Energy Spread from RF Amplitude and Phase Errors, EPAC 96.
The stability requirement varies in different accelerators, determined by specific application.

<table>
<thead>
<tr>
<th></th>
<th>XFEL</th>
<th>ILC</th>
<th>SNS</th>
<th>JPARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp./Phase Stability</td>
<td>0.01%, 0.01°</td>
<td>0.1%, 0.1°</td>
<td>±0.5%, ±0.5°</td>
<td>±1%, ±1°</td>
</tr>
<tr>
<td>(rms)</td>
<td>(rms)</td>
<td>(rms)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The stability is specified in peak to peak rather than in rms in proton machine due to beam velocity is dependent on energy gain.

In some case, the requirement on phase stability differs by time scale, short term (during the pulse), medium term (pulse to pulse), long term (minutes to hours). At XFEL, the requirement is: 0.01° (short term), 0.03° (medium term), 0.1-0.5° (Long term).

The stability at ESS?
Requirements at ESS

- Cavity phase and amplitude stability, frequency control
- Minimize the required overhead power for control
- Automated operation, remote control
- Availability, maintenance, upgradability
- Support Linac commissioning

- High intensity, 50mA
- Long pulse, 2.9ms
- High gradient
- Spoke cavity
- High Efficiency
- High availability; 95%
The ideal cases

- Consider an ideal beam current inject into an ideal superconducting cavity at ideal time
- Ideal beam current: no synchronous phase, continuous current during pulse
- Ideal superconducting cavity: optimized $Q_L$ for beam current, no reflection power at beam duration
- Ideal injection time

Further reading:
The ideal cases
## Perturbations in real world

### Beam Loading
- Synchronous phase
- Beam chopping
- Pulse beam transient
- Charge fluctuations
- Non-relativistic beam
- Pass band modes
- HOMs, wake-field

### Cavity
- Lorentz force detuning
- Microphonics
- Thermal effects (Quench…)

### Power Supply
- Modulator drop and ripple
- Klystron nonlinearity

### Phase reference distribution
- Reference thermal drift
- Master oscillator phase noise

### Electronics crates
- Crates power supply noise
- Cross talk, thermal drift
- Clock jitter, nonlinearity

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Further reading: LLRF Experience at TTF and Development for XFEL and ILC, S. Simrock, DESY, ILC WS 2005
Lorentz Force Detuning

- The radiation pressure on cavity walls
  - cavity shape changes by a volume $\Delta V$
  - cavity resonance frequency is shifted
- Lorentz force detune is repetitive from pulse to pulse
- Lorentz force detuning coefficient $K$ typically a few Hz/(MV/m)$^2$

**Radiation pressure**:

$$P_s = \frac{1}{4} \left( \mu_0 |\overline{H}|^2 - \varepsilon_0 |\overline{E}|^2 \right)$$

**Cavity perturbation theory**:

$$\frac{\omega_0 - \omega}{\omega_0} = \frac{\int_{\Delta V} \left( \varepsilon_0 |\overline{E}|^2 - \mu_0 |\overline{H}|^2 \right) dV}{\int_{V} \left( \varepsilon_0 |\overline{E}|^2 - \mu_0 |\overline{H}|^2 \right) dV}$$

**$TM_{010}$ induced static detuning**:

$$\Delta f = -K \cdot E_{acc}^2$$

Dynamic effects of cavity detuning

Any cavity has an infinite number of mechanical eigenmodes of vibration. A 2nd-order differential equation can be used to describe the dynamics.

2nd-order differential equation of dynamic detuning,
\[
\Delta \dot{\omega}_n + \frac{2}{\tau_{m,n}} \Delta \dot{\omega}_n + \Omega_n^2 \Delta \omega_n = -2\pi K_n \Omega_n^2 \cdot E_{\text{acc}}^2(t) + n(t)
\]
\[
\Delta \omega(t) = \sum_n \Delta \omega_n(t), \quad K = \sum_n K_n
\]
In steady state:
\[
\Delta \omega_\infty = \sum_n \Delta \omega_n\infty = -2\pi \sum_n K_n \cdot E_{\text{acc}}^2
\]

S. Kim, I. E. Campisi, F. Casagrande et al, Status of the SNS Cryomodule Test, PAC07.
Overhead calculation for LFD in elliptical cavity

- It makes calculation easier to discuss detuning according to the rate $\Delta f/f_{1/2}$
- Below $f_{1/2}$, (K~1.5 for high beta, K~2 for med beta), most cavity overhead is <7%.
- 25% or more are required for detuning > 2 $f_{1/2}$ (K~3 for high beta, K~4 for med beta)
- Appropriate pre-detuning for both sync. phase and LFD is assumed
Overhead for LFD in Spoke cavity

Table 3: Overhead estimation under different K for spoke cavity \((E_{acc} = 8.5\,MV/m)\)

<table>
<thead>
<tr>
<th>K ((Hz/(MV/m)^2))</th>
<th>(\Delta f) ((Hz))</th>
<th>(f_{1/2}) ((Hz))</th>
<th>(\Delta f/f_{1/2})</th>
<th>(\varphi_D) (^{(\circ)})</th>
<th>Overhead w/o predetuning</th>
<th>Overhead with predetuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72.25</td>
<td>1174</td>
<td>0.06</td>
<td>3.5</td>
<td>0.09%</td>
<td>0.02%</td>
</tr>
<tr>
<td>5</td>
<td>361.25</td>
<td>1174</td>
<td>0.31</td>
<td>17.1</td>
<td>2.37%</td>
<td>0.59%</td>
</tr>
<tr>
<td>9</td>
<td>650.25</td>
<td>1174</td>
<td>0.55</td>
<td>29.0</td>
<td>7.67%</td>
<td>1.92%</td>
</tr>
<tr>
<td>13</td>
<td>939.25</td>
<td>1174</td>
<td>0.80</td>
<td>38.7</td>
<td>16.00%</td>
<td>4.00%</td>
</tr>
<tr>
<td>17</td>
<td>1228.25</td>
<td>1174</td>
<td>1.05</td>
<td>46.3</td>
<td>27.36%</td>
<td>6.84%</td>
</tr>
</tbody>
</table>

R. Zeng, Power Overhead Calculation for Lorentz Force Detuning, ESS-tech notes, 2012
Klystron droop and ripple

- Perturbations in the cathode voltage results in the change of the beam velocities, and then led to the variations of the RF output phase.
- 1% error in cathode voltage leads to more than 10 deg. variation in RF output phase.
- High frequency ripple with larger amplitude is hard to be eliminated by feedback, especially in normal conducting cavity.

Table 1: Measurement for the phase and amplitude variations in other labs

<table>
<thead>
<tr>
<th>RF freqency /MHz</th>
<th>Cathode voltage change</th>
<th>Phase variation /deg.</th>
<th>Amplitude variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPARC[1]</td>
<td>312</td>
<td>3.40%</td>
<td>25</td>
</tr>
<tr>
<td>SNS [2,3]</td>
<td>805</td>
<td>3%</td>
<td>~50(max)</td>
</tr>
<tr>
<td>PEPII[4]</td>
<td>476</td>
<td></td>
<td>~14° /kV</td>
</tr>
<tr>
<td>SACLAY[5]</td>
<td>704.4</td>
<td>200V@95kV</td>
<td>10° /kV@92kV</td>
</tr>
</tbody>
</table>

Further reading: R. Zeng et, al. The Droop and Ripple’s Influence on Klystron Output, ESS tech-note.

May 4, 2011
The errors can be suppressed in feedback loop a factor of loop gain $G$. The loop gain is limited by loop delay and also by pass-band mode.

Integral gain of $K_i=2\pi f_{HBW}$ is introduced to eliminate the steady errors and reduce low frequency noises.

Assuming that 15 degree phase error is induced by per 1% error from modulator, to control the error to 0.5°, we should restrict the droop and ripple number from modulators:

### Table 5: Noise tolerances of PI feedback closed loop at different frequencies
(Superconducting cavity, $K_p = 20$, $K_i = 2\pi \times 518$)

<table>
<thead>
<tr>
<th>Frequency range /kHz</th>
<th>Gain available</th>
<th>Tolerance in output phase/°</th>
<th>Tolerance in cathode voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.1, or &gt;58</td>
<td>&gt;100</td>
<td>&gt;50</td>
<td>&gt;3.3%</td>
</tr>
<tr>
<td>0.1 ~ 0.4, 15 ~ 58</td>
<td>30 ~ 100</td>
<td>15 ~ 50</td>
<td>1% ~ 3.3%</td>
</tr>
<tr>
<td>0.4 ~ 15</td>
<td>20 ~ 30</td>
<td>10 ~ 15</td>
<td>0.7% ~ 1%</td>
</tr>
</tbody>
</table>

### Table 6: Noise tolerances of PI feedback closed loop at different frequencies
(Normal conducting cavity, $K_p = 1$, $K_i = 2\pi \times 10^4$)

<table>
<thead>
<tr>
<th>Frequency range /kHz</th>
<th>Gain available</th>
<th>Tolerance in output phase/°</th>
<th>Tolerance in cathode voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.1, or &gt;1000</td>
<td>&gt;100</td>
<td>&gt;50</td>
<td>&gt;3.3%</td>
</tr>
<tr>
<td>0.1<del>0.3, 300</del>1000</td>
<td>30 ~ 100</td>
<td>15 ~ 50</td>
<td>1% ~ 3.3%</td>
</tr>
<tr>
<td>0.3 ~ 1, 100 ~ 300</td>
<td>10 ~ 30</td>
<td>5 ~ 15</td>
<td>0.33% ~ 1%</td>
</tr>
<tr>
<td>1 ~ 100</td>
<td>2 ~ 10</td>
<td>1 ~ 5</td>
<td>0.07% ~ 0.33%</td>
</tr>
</tbody>
</table>
The purpose of beam off-crest acceleration by a sync. phase is to minimize the energy spread resulted from wake fields.

By pre-detuning the cavity with motor tuner, the effect of the sync. phase acceleration is compensated.

It can be also compensated by extra power overhead, which was the case in LEP at CERN to avoid ponderomotive oscillation (CW, 8 cavity/klystron)

Further reading: Electroacoustic instabilities in the LEP-2 superconducting cavities, D. Boussard, et, al. 7th RF superconducting workshop, 1995
Beam loading

- One bunch of the beam travelled through an RF cavity will experience the RF voltage, the induced field from previous bunches, and half of the self-induced field (Fundamental Theory of Beam Loading).
- Beam loading effects is not so significant, but get worst when there are charge fluctuation and beam chopping.

\[ I_{DC} = \frac{q}{T_b} = \frac{q\omega}{2\pi} \]
\[ \omega C = \omega_b C = \frac{Q_L}{R_L} = \frac{2}{(R/Q)} \]
\[ V_{b0} = \frac{q}{C} = \frac{1}{2} \frac{\omega(R/Q)}{4} q = \pi(R/Q) \cdot I_{DC} \]

Assume no detune and other perturbation,

\[ V_b(t) = -\left( \frac{1}{2} V_{b0} e^{-(t-nT_b)/\tau} + V_{b0} e^{-(t-(n-1)T_b)/\tau} + V_{b0} e^{-(t-(n-2)T_b)/\tau} + \cdots + V_{b0} e^{-(t-nT_b)/\tau} + V_{b0} e^{-t/\tau} \right) \]

\[ V_{cav}(t) = V_g(t) + V_b(t) = V_{ge} \left( 1 - e^{-t/\tau} \right) + V_b(t), \quad \tau = \frac{2Q_L}{\omega} \]

Further reading: Interaction between RF-System, RF-Cavity and Beam, Thomas Weis, 2005
An beam chopping example in JPARC

Figure 1: Linac beam structure.

Figure 8: The phase variations in the Debuncher2 caused by the chopped beam of the one-bunch and two-bunch operation, respectively.

✓ Non-relativistic beam

✓ HOMs and pass band modes are excited in the cavity during beam loading.

✓ The pass band mode closest to the fundamental mode is to be concerned. It is one of the reasons causes instabilities and limit the loop gain

✓ This mode can be excited by the chopped beam pulses and the switching edges of the rf pulses.

✓ A special filter can be applied to suppress this mode in digital domain

Caused by the mechanical vibrations in the accelerator environment, such as vacuum pumps, helium pressure fluctuations, traffic, ground motion, ocean waves…

It is a slow perturbation, not predictable, and usually of the order of several Hz to several 10Hz

Avoid the domain frequencies in the microphonics spectrum close to the cavity mechanical modes

Figure 3: Typical background microphonics spectrum

Further reading: S. Simrock, M. Grecki, 5th LC School, Switzerland, 2010, LLRF & HPRF.
Thermal drift and crates noise

- Thermal drift in phase reference line and down converter, master oscillator and crate noise are out of the feedback control loop.

- Special cautions should be taken:
  - Temperature-stabilized phase reference line;
  - Low phase noise master oscillator;
  - Down convert board temperature and channels cross talk control;
  - Crate power noise;
  - ADC non-linearization (non-IQ sampling);
  - Drift calibration in digital control;
Feedback

- The errors could be suppressed in feedback loop a factor of loop gain $G$. The loop gain is limited by loop delay and also by pass-band mode.
- Large loop gain will result in more overshoot.
- Average loop gain at SNS is about 50 for superconducting cavity, less than 10 for normal cavity.

$$H_0(f) = GH_{cav}e^{-j\tau f},$$

$$|H_0(f)| = \frac{G}{\sqrt{\left(\frac{f}{f_{hbw}}\right)^2 + 1}},$$

$$\varphi = \angle H_0(f) = -\arctan\left(\frac{f}{f_{hbw}}\right) - \tau f.$$ 

The instability is happening when:

$$|H_0(f)| \geq 1,$$

$$\varphi = -180^\circ + n \cdot 360^\circ, \quad n = \pm 1, \pm 2, \ldots$$
Integral-proportional controller

- Integral gain of $Ki = 2\pi f_{HBW}$ is then introduced to eliminate the steady errors and reduce low frequency noises.
- The PI feedback loop can suppress effectively low frequency noise but the performance degrades as frequency increases, while the far higher frequency noise is filtered by cavity itself.

Further reading: R. Zeng et al. The Droop and Ripple’s Influence on Klystron Output, ESS tech-note.
Feedforward

- Feedforward is to deal with the repetitive errors from pulse to pulse.

- In simplicity, it adds the errors learned to every pulse by feed forward table

\[
\begin{align*}
I_{gr} &= \frac{V_{cav}}{R_L} + I_{br} = \frac{V_{cav}}{R_L} + I_b \cos \varphi_b \\
I_{gi} &= -\frac{V_{cav}}{R_L} \tan \varphi_D + I_{bi} = -\frac{V_{cav}}{R_L} \tan \varphi_D - I_b \sin \varphi_b
\end{align*}
\]

Note here we take \( V_{cav} \) as the reference \( V_{cav} = V_{cav} + i \cdot 0 \)
The oscillation is happening when feedback is applied during beam loading due to loop delay and high loop gain.

Feedforward compensation
The Repetitive perturbations and the system performance may vary slowly with the time (thermal drift, microphonics, cathode voltage variations, component aging).

Adaptive algorithm is crucial here in order to compensate the possible changes of the environmental and operating conditions.
Adaptive feedforward at DESY TTF

- measure the step responses continually to maintain a current system model.
- The step size should be selected carefully.
- It is direct, straightforward, but needs large computation capacity, measurement response not fast.

LLRF Development for TTF II and Applicability to X-FEL & ILC, S. Simrock, ILC WS 2004

May 4, 2011
R. Zeng, SLHiPP-2, Catania
Adaptive feedforward at SNS

1. Q-filter is added to suppress the high frequency component due to that modeling of high-frequency dynamics are difficult and may lead to an inadequate model and unstable behavior.
2. L-filter (self learning filter) that compensates well for low frequencies, and it has the characteristics of PID.
3. A forgetting factor is introduced to put different weights to the past feedforward controller outputs.

A possible scheme: take the current drive signal of the pulse as the feedforward input for the next pulse…Unfortunately, it is unstable

Instead, add a time-reversed low-pass filter: record feedback error signal \( e(t) \), time reverse \( e(t) \rightarrow e(-t) \), low pass filter \( e(-t) \), reverse filtered signal in time again, shift signal in time to compensate loop delay

\[
\text{FF}_{\text{new}} = \text{TRLP}(\text{FB}_{\text{last}}) + \text{FF}_{\text{last}} \\
\ldots \text{is surprisingly stable :)}
\]

Further reading: Alexander Brandt, LLRF Automation and Adaptive Feedforward, FLASH Seminar, 2006
LLRF has to maintain the stability of the RF field, and minimize the required overhead power. Automated operation and easy maintenance should be taken into account, especially in large-scale facilities.

A variety of perturbations can be seen everywhere in the accelerator environment.

PI Feedback is an effective and classical way to deal with the perturbations but at the cost of the more overhead consumption and rising instability.

Feedforward is essential for the repetitive perturbations and need automatically update. We should look into more advanced control methods to be able to achieve better performance.
Thank you for the attention!