LLRF control system

SRF’21
25th of June 2021

Mathieu Omet
Disclaimer

- This tutorial will give only a rough overview, it is incomplete by its nature
- I have worked mostly on pulsed SRF linacs
- I will answer questions after the tutorial
Contents

- Introduction
- Cavity theory
- LLRF system overview
- Signal detection
- Signal processing and implementation
- Example features of an LLRF system
- Summary
Introduction
What does LLRF stand for? What is it about?

- **Low Level Radio Frequency**
- The goal: control the amplitude and phase of electro-magnetic fields within cavities
  - Required at a wide range of facilities, from small test facilities to large scale accelerators
- These fields can have high amplitudes and high frequencies
- Thus down-conversion to small amplitudes for detection is applied
  - (and in some cases also a down-conversion to low frequencies, while preserving amplitude and phase information, is applied)
Superconducting and Normal Conducting Cavities

• Frequency ranges from MHz to tens of GHz
Modes of Operation

• Pulsed mode
  • Short Pulse mode (SP)
    • Duty factor of e.g. 1%
  • Long Pulse mode (LP)
    • Duty factor of 10% to 50%
  • Only a certain portion of time is usable for beam acceleration

• Continuous Wave (CW)
  • Continuous RF field
  • Duty factor of 100%
  • Beam can be accelerated all the time
Most basic layout of an RF system

- Open loop operation
  - Controller creates drive signal corresponding to a set point
  - Signal is amplified
  - Signal is coupled into the cavity
  - Signal is coupled out of the cavity
  - Signal is detected by the controller
Most basic layout of an RF system

• Closed loop operation
  • Controller creates drive signal corresponding to a set point
  • Signal is amplified
  • Signal is coupled into the cavity
  • Signal is coupled out of the cavity
  • Signal is detected by the controller
  • Controller compares signal to the set point and adjusts the drive signal accordingly
Most basic layout of an RF system

- Let’s take a look at the cavity first
Cavity Theory
Cavity modeling: RCL model

• Electric circuit
  • Resistor R
  • Inductor L
  • Capacitor C

• Forms a harmonic oscillator
Cavity modeling: Quality factor in general

\[ Q = \frac{2\pi \text{ stored energy in cavity}}{\text{dissipated energy per cycle}} = \frac{2\pi f_0 W}{P_{\text{diss}}} \]

- Resonance frequency
- Stored energy
- Dissipated power

Mathieu Omet, 25th of June 2021
Cavity modeling: Unloaded quality factor

- Assumes losses only due to surface resistance

\[ Q_0 = \frac{2\pi}{T} \cdot \frac{1}{2} CV_0^2 \]

\[ Time \text{ period of an RF cycle} \]
\[ Resistance \]
\[ Capacitance \]
\[ Square \text{ of amplitude of oscillating voltage} \]

\[ Q_0 = \omega_0 RC = \frac{R}{L\omega_0} = \frac{\omega_0 W}{P_{\text{diss}}} \]

\[ W = \frac{1}{2} CV_0^2 \]
\[ P_{\text{diss}} = \frac{V_0^2}{2R} \]
\[ \omega_0 = \frac{1}{\sqrt{LC}} \]
\[ \omega_0 = 2\pi f_0 \]
Cavity modeling:
External quality factor

• Accounts for external losses (e.g. via the power coupler)

\[ Q_{ext} = 2\pi \frac{\text{stored energy in cavity}}{\text{dissipated energy in external devices per cycle}} = \frac{\omega_0 W}{P_{ext}} \]

Dissipated power in all external devices
Cavity modeling: Loaded quality factor

- Accounts for all losses

\[ Q_L = 2\pi \frac{\text{stored energy in cavity}}{\text{total energy loss per cycle}} = \frac{\omega_0 W}{P_{\text{tot}}} \]

\[ P_{\text{tot}} = P_{\text{diss}} + P_{\text{ext}} \]

\[ \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} \]

In case of SC cavities \( Q_0 \) is several orders of magnitude larger than \( Q_{\text{ext}} \). Thus, \( Q_L \) is in the same order as \( Q_{\text{ext}} \).
Cavity modeling: Definition of the Loaded Quality Factor

- Add transition line
- Impedance $Z_{\text{ext}}$ is like a parallel resistor to $R$ (characteristic impedance of a coaxial cable: 50 $\Omega$)
- Both can be replaced by the loaded shunt impedance $R_L$

\[
\frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{\text{ext}}}
\]

\[
Q_0 = \omega_0 RC = \frac{R}{L\omega_0} = \frac{\omega_0 W}{P_{\text{diss}}}
\]

\[
\frac{R}{Q_0} = \omega_0 = \frac{1}{\omega_0 C} = \sqrt{\frac{L}{C}}
\]

$R/Q_0$ depends only on $\omega_0$, $C$, and $L$, which means it depends only on the cavity geometry and not the surface resistance.
Cavity modeling: Definition of the Loaded Quality Factor

- The shunt impedance $R_{sh}$ depends on the dissipated power
- Includes factor $\frac{1}{2}$ of the time average

\[
P_{\text{diss}} = \frac{1}{2} \cdot \frac{V_{\text{cav}}^2}{R} = \frac{V_{\text{cav}}^2}{R_{sh}}
\]

\[
R = \frac{1}{2} R_{sh} = \frac{1}{2} \frac{r}{Q} Q_0
\]

- Definition of normalized shunt impedance

\[
\frac{r}{Q} := \frac{R_{sh}}{Q_0} = \frac{2R}{Q_0}
\]
Cavity modeling: Definition of the Loaded Quality Factor

- Coupling between cavity and transmission line

\[ \beta = \frac{R}{Z_{\text{ext}}} \]

\[ \frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{\text{ext}}} \]

\[ R_L = \frac{R}{1 + \beta} \]

\[ r \triangleq \frac{R_{\text{sh}}}{Q_0} = \frac{2R}{Q_0} \]

\[ Q_L = \frac{Q_0}{1 + \beta} \]

\[ \omega_{1/2} = \frac{\omega_0}{2Q_L} \]

\( Q_L \) can be manipulated by changing the coupling \( \beta \)

And with this the cavity bandwidth
Solutions for Changing the Coupling

• Change input depth via movable input coupler antenna

• Change angle of plate of waveguide reflector
Pulsed Operation with Beam Loading

- Without beam

- With beam

Mathieu Omet, 25th of June 2021

LLRF control system
Derivation of Filling and Flattop Powers

\[ I_C + I_R + I_L = I_{cav} \]
\[ \dot{I}_C + \dot{I}_R + \dot{I}_L = \dot{I}_{cav} \]
\[ \dot{I}_C = C\ddot{V}_{cav} \]
\[ \dot{I}_R = \frac{1}{R_L}\dot{V}_{cav} \]
\[ \dot{I}_L = \frac{1}{L}V_{cav} \]
\[ C\ddot{V}_{cav} + \frac{1}{R_L}\dot{V}_{cav} + \frac{1}{L}V_{cav} = \dot{I}_{cav} \]
Derivation of Filling and Flattop Powers

\[
\dddot{V}_{cav} + \frac{1}{R_L C} \dot{V}_{cav} + \frac{1}{L C} V_{cav} = \frac{1}{C} i_{cav}
\]

\[
\frac{1}{R_L C} = \frac{\omega_0}{Q_L}
\]

\[
\frac{1}{L C} = \omega_0^2
\]

\[
\dddot{V}_{cav} + \frac{\omega_0}{Q_L} \dot{V}_{cav} + \omega_0^2 V_{cav} = \frac{1}{C} i_{cav}
\]

\[
V_{\text{hom}} = e^{-\frac{\omega_0 t}{2 Q_L}} \left( C_1 e^{i\alpha t} + C_2 e^{-i\alpha t} \right)
\]

\[
\alpha = \omega_0 \sqrt{1 - \frac{1}{4 Q_L^2}}
\]

One particular solution can be found with

\[
i_{cav} = \hat{I} e^{i\omega t}
\]

\[
V_{cav} = \hat{V} e^{i(\omega t + \phi)}
\]

Φ is the angle between the generator current and the resonator voltage.
Derivation of Filling and Flattop Powers

\[ V_{\text{par}} = \frac{R_L \hat{I} e^{i(\omega t + \phi)}}{\sqrt{1 + \tan^2 \phi}} \]

with \[ \tan \phi = R \left( \frac{1}{\omega L} - \omega C \right) = Q \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right) \]

The particular solution is also called a stationary solution. If the generator frequency \( \omega \) is very close to the resonance frequency \( \omega_0 \), the following approximation can be done:

\[ \dot{V}_{\text{par}}(\Delta \omega) \approx \frac{R_L \hat{I}}{\sqrt{1 + (2QL \frac{\Delta \omega}{\omega})}} \]

where \( \Delta \omega = \omega_0 - \omega \)
The frequency dependency of the amplitude is known as the Lorentz curve.

Bandwidth of the cavity is defined by the -3 dB point.
Derivation of Filling and Flattop Powers

The general solution is:

\[ V_{\text{cav}} = V_{\text{hom}} + V_{\text{par}} = e^{-\frac{\omega_0 t}{2Q_L}} \left( C_1 e^{i\alpha t} + C_2 e^{-i\alpha t} \right) + \frac{R_L \hat{I} e^{i(\omega t - \phi)}}{\sqrt{1 + \tan^2 \phi}} \]

since \( Q_L >> 1 \) One can approximate:

for \( C_1 = C_2 = -\frac{R_L \hat{I}}{2} \)

\[ V_{\text{fill}} = V_0 \left( 1 - e^{-\frac{t}{\tau}} \right) \]

with \( V_0 = R_L \hat{I} \approx 2R_L I_g = \frac{r}{Q} Q_L I_g \) \( \tau = \frac{2Q_L}{\omega_0} \)

\( \hat{I} \approx 2I_g \)

\( \hat{I}_b \approx 2I_{b0} \)

\( I_{\text{cav}} = 2I_g - 2I_{b0} \)

\[ V_{\text{flat}} = \frac{r}{Q} Q_L \left( I_g \left( 1 - e^{-\frac{t}{\tau}} \right) - I_{b0} \cos(\phi_b) \left( 1 - e^{-\frac{t - T_{\text{inj}}}{\tau}} \right) \right) \]
Derivation of Filling and Flattop Powers

We would like to have a constant voltage over the flattop.

\[ \frac{dV_{\text{flat}}}{dt} = 0 \]

\[ \frac{d}{dt} \frac{r}{Q_L} \left( I_g \left( 1 - e^{-\frac{t}{\tau}} \right) - I_{b0} \left( 1 - e^{-\frac{t-T_{\text{inj}}}{\tau}} \right) \right) = 0 \]

\[ \frac{d}{dt} \frac{r}{Q_L} \left( I_g - I_g e^{-\frac{t}{\tau}} - I_{b0} + I_{b0} e^{-\frac{t-T_{\text{inj}}}{\tau}} \right) = 0 \]

\[ \frac{r}{Q_L} \left( I_g \frac{1}{\tau} e^{-\frac{t}{\tau}} - I_{b0} \frac{1}{\tau} e^{-\frac{t-T_{\text{inj}}}{\tau}} \right) = 0 \]

\[ I_g e^{-\frac{t}{\tau}} = I_{b0} e^{-\frac{t-T_{\text{inj}}}{\tau}} \]

\[ I_g = I_{b0} e^{\frac{T_{\text{inj}}}{\tau}} \]
Derivation of Filling and Flattop Powers

\[ V_{fill} = V_0 \left(1 - e^{-\frac{t}{\tau}}\right) \]

\[ V_{flat} = \frac{r}{Q} Q_L I_{b0} \left(\frac{T_{\text{inj}} \omega_0}{e^{\frac{T_{\text{inj}} \omega_0}{2Q_L}} - 1}\right) \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling time</td>
<td>923 (\mu)s</td>
</tr>
<tr>
<td>Beam current</td>
<td>5.8 mA</td>
</tr>
<tr>
<td>(Q_L)</td>
<td>5.44E6</td>
</tr>
</tbody>
</table>

Beam transient time
Derivation of Filling and Flattop Powers

\[ P = \frac{1}{4} \frac{r}{Q} Q_L I_g^2 \]

\[ P_{\text{fill}} = \frac{V_{\text{cav}}^2}{4 \frac{r}{Q} Q_L \left( 1 - e^{-\frac{T_{\text{inj}} \omega_0}{2Q_L}} \right)^2} \]

\[ P_{\text{flat}} = \frac{V_{\text{cav}}^2}{4 \frac{r}{Q} Q_L} \left( 1 + \frac{r}{Q} \frac{Q_L I_{b0}}{V_{\text{cav}}} \right)^2 \]

\[ V_{\text{cav}} = 31.5 \text{ MV/m} \cdot 1.038 \text{ m} = 32.7 \text{ MV} \]

\[ Q_L = 5.44 \cdot 10^6 \]

\[ T_{\text{inj}} = 923 \mu s \]

\[ P_{\text{fill}} \text{ is 190 kW} \]

\[ I_{b0} = 5.8 \text{ mA} \quad \phi_b = 180^\circ \]

\[ P_{\text{flat}} \text{ is 190 kW} \]
Derivation of Filling and Flattop Powers

- One can stay at a single working point of the power amplifier throughout the whole RF pulse.

\[ P_{\text{fill}} \text{ is } 190 \text{ kW} \quad P_{\text{flat}} \text{ is } 190 \text{ kW} \]

Non-linear behavior of a klystron (red curve)

Beam transient time

Actual output

7% power overhead

Desired output

40% power overhead

Output Power \( P_0 \) [MW]

Drive Power \( P_d \) [W]
Derivation of Filling and Flattop Powers

• Set of equations for finding optimal parameters

The optimal coupling $\beta_{opt}$

$$\beta_{opt} = 1 + \frac{r}{Q} \frac{Q_0 I_b}{V_{cav}} \cos(\phi_b)$$

Minimum power for maintaining the cavity voltage

$$P_{min} = \beta_{opt} \frac{V_{cav}^2}{r Q Q_0}$$

Optimum tuning angle

$$\tan(\phi_{opt}) = -\frac{r}{Q} \frac{Q_{L, opt}}{V_{cav}} \frac{I_b}{\cos(\phi_b)}$$

For superconducting cavities one can simplify

$$Q_{L, opt} = \frac{V_{cav}}{r \frac{I_b}{\cos(\phi_b)}}$$

$$\phi_{opt} = -\phi_b$$

$$P_{flat, min} = \frac{V_{cav}^2}{r Q L_{opt}} = V_{cav} I_b \cos(\phi_b)$$

Example set of parameter

$$V_{cav} = 31.5 \text{ MV/m} \cdot 1.038 \text{ m} = 32.7 \text{ MV}$$

$$I_b = 5.8 \text{ mA}$$

$$\cos(\phi_b) = 1$$

$$Q_{L, opt} = 5.44 \cdot 10^6$$

$$P_{flat, min} = 190 \text{ kW}$$
Detuned Cavity with Beam Loading

In reality cavities are detuned by the tuning angle $\Phi$. The sources are Lorentz force detuning and microphonics.

Mathieu Omet, 25th of June 2021
Cavity Differential Equation Continues in Time

Differential equation for a driven LCR circuit

\[
\ddot{V}(t) + \frac{\omega_0}{Q_L} \dot{V}(t) + \omega_0^2 V(t) = \frac{\omega_0 R_L}{Q_L} I(t)
\]

Insertion in equation above and omission of the second-order time derivatives of \( V \) yields...

\[
\omega_0 \ll \omega_0
\]

The cavity is a weakly damped system

\[
\omega_{res} = \omega_0
\]

good approximation, since

\[
\omega_{res} = \omega_0 \sqrt{1 - \frac{1}{4Q_L^2}} \approx \omega_0
\]

Driving current \( I_g \) and Fourier component \( I_b \) of pulsed beam are harmonic with time dependence \( e^{i\omega t} \).

Therefore, we separate the fast RF oscillation from the real and imaginary parts of the field vector.

\[
V(t) = (V_r(t) + iV_i(t)) \cdot e^{i\omega t}
\]

\[
I(t) = (I_r(t) + iI_i(t)) \cdot e^{i\omega t}
\]
Cavity Differential Equation Continues in Time

... the first-order differential equation for the envelope:

\[
\begin{align*}
\dot{V}_r + \omega_{1/2} V_r + \Delta\omega V_i &= R_L \omega_{1/2} I_r \\
\dot{V}_i + \omega_{1/2} V_i - \Delta\omega V_r &= R_L \omega_{1/2} I_i \\
\end{align*}
\]

with

\[
\begin{align*}
\omega_{1/2} &= \frac{\omega_0}{2Q_L} \\
\Delta\omega &= \omega_0 - \omega \\
\end{align*}
\]

cavity bandwidth
cavity detuning

In state space formalism

\[
\frac{d}{dt} \begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L \omega_{1/2} & 0 \\ 0 & R_L \omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}
\]

\[
\dot{x}(t) = A \cdot x(t) + B \cdot u(t)
\]

\[
\begin{align*}
A &= \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \\
B &= \begin{pmatrix} R_L \omega_{1/2} & 0 \\ 0 & R_L \omega_{1/2} \end{pmatrix} \\
x &= \begin{pmatrix} V_r \\ V_i \end{pmatrix} \\
u &= \begin{pmatrix} I_r \\ I_i \end{pmatrix}
\end{align*}
\]
Cavity Differential Equation
Continuous and Discrete in Time

\[
\frac{d}{dt} \begin{pmatrix}
V_r \\
V_i
\end{pmatrix} = \begin{pmatrix}
-\omega_{1/2} & -\Delta \omega \\
\Delta \omega & -\omega_{1/2}
\end{pmatrix} \cdot \begin{pmatrix}
V_r \\
V_i
\end{pmatrix} + \begin{pmatrix}
R_L \omega_{1/2} & 0 \\
0 & R_L \omega_{1/2}
\end{pmatrix} \cdot \begin{pmatrix}
I_r \\
I_i
\end{pmatrix}
\]

\[
\begin{pmatrix}
V_{i,n} \\
V_{q,n}
\end{pmatrix} = \begin{pmatrix}
1 - T \omega_{1/2} & -T \Delta \omega \\
T \Delta \omega & 1 - T \omega_{1/2}
\end{pmatrix} \begin{pmatrix}
V_{i,n-1} \\
V_{q,n-1}
\end{pmatrix} + T \omega_{1/2} R_L \begin{pmatrix}
I_{i,n-1} \\
I_{q,n-1}
\end{pmatrix}
\]
Cavity Simulator Live Demo

• Demo of single cavity in pulsed operation
  • E.g., let’s check the parameter set we have derived earlier
    \[ V_{cav} = 31.5 \text{ MV/m} \cdot 1.038 \text{ m} = 32.7 \text{ MV} \]
    \[ I_{b0} = 5.8 \text{ mA} \]
    \[ \cos(\phi_b) = 1 \]
    \[ Q_{L,\text{opt}} = 5.44 \cdot 10^6 \]
    \[ P_{\text{flat,min}} = 190 \text{ kW} \]
    \[ T_{\text{inj}} = 923 \mu\text{s} \]

• Let’s see for what kind of operation low and high \( Q_L \) values are interesting
LLRF Systems
Types of LLRF Systems

• Analog
  • Designed, optimized and built for a specific purpose
  • Hard to modify
  • Need extra hardware for e.g. data recording

• Digital
  • More flexibility
    • On how to design the system
    • Always possible to add, change, tweak digital algorithms
  • Modern algorithms can be realized
  • Remotely maintainable to a large degree
Example of an Analog LLRF System
Types of Digital LLRF Systems

• 19-inch modules ("Pizza box")
  • Individually developed and built hardware
  • Well optimized

• Crate-based systems
  • Of-the-shelf components
  • Well optimized cards available
  • Highly modular

• Mixed systems
  • Best of both worlds

LCLS-II prototype LLRF system at FNAL CMTS

µTCA.4-based LLRF systems at European XFEL at DESY

µTCA.0-based LLRF system at cERL at KEK

Mathieu Omet, 25th of June 2021
System Architecture Example

- Data acquisition
- Long time archive

Remote PC
Software

- Distribution of data

Control system

Remote PC
Software

- Monitoring
- Change settings
- Data acquisition

Signal acquisition
ADC

From cavity

Communication and algorithms
Software on local CPU

LAN

Signal processing
Firmware on FPGA

Drive generation
DAC

LAN

To amplifier

- Digital filter
- Feedback
- Generation of digital drive signal
- Possibly other algorithms, calculations and functionalities
Signal Sampling
Representation in Quadrature and In-phase

\[ I = A \cos(\phi) \]
\[ Q = A \sin(\phi) \]
\[ A = \sqrt{I^2 + Q^2} \]
\[ \phi = \arctan\left(\frac{Q}{I}\right) \]
Down Conversion in Frequency

• Nyquist-Shannon theorem: \( f_s > 2f_{RF} \)
  • If this is fulfilled, a perfect reconstruction of \( f_{RF} \) is quarantined.

\[
S_{RF}(t) = A_{RF} \cdot \sin(2\pi \cdot f_{RF} \cdot t + \phi_{RF})
\]
\[
S_{LO}(t) = A_{LO} \cdot \sin(2\pi \cdot f_{LO} \cdot t + \phi_{LO})
\]
\[
S_{LO \cdot RF}(t) = \sin(2\pi \cdot f_{LO} \cdot t) \cdot \sin(2\pi \cdot f_{RF} \cdot t)
= \frac{1}{2} \left( \cos(2\pi \cdot (f_{LO} - f_{RF}) \cdot t) - \cos(2\pi \cdot (f_{LO} + f_{RF}) \cdot t) \right)
\]
\[
S_{IF}(t) = \frac{1}{2} \cos(2\pi \cdot f_{IF} \cdot t)
\]

• Preserves amplitude and phase information

Example frequencies

\( f_{RF} = 1.3 \) GHz
\( f_{LO} = 1.31 \) GHz
\( f_{IF} = 10 \) MHz

RF: Radio frequency
LO: Local oscillator
IF: Intermediate frequency
Sampling methods

• IQ Sampling
• Under sampling & Over sampling
IQ Sampling

\[ f_s = 4 \cdot f_{IF} \]

\[ f_{IF}(0) = Q \]
\[ f_{IF}(\frac{\pi}{2}) = I \]
\[ f_{IF}(\pi) = -Q \]
\[ f_{IF}(\frac{3\pi}{2}) = -I \]

\[
\begin{pmatrix}
I \\
Q
\end{pmatrix}_n = \begin{pmatrix}
\cos(\Delta \phi_n) & -\sin(\Delta \phi_n) \\
\sin(\Delta \phi_n) & \cos(\Delta \phi_n)
\end{pmatrix} \cdot \begin{pmatrix}
f_{IF,n+1} \\
f_{IF,n}
\end{pmatrix}
\]
Undersampling and Oversampling

\[ \frac{f_s}{f_{IF}} = \frac{M}{L} = m \]

\[ \Delta \phi = \frac{2\pi}{m} \]

\[ m = 4 \text{ corresponds to the IQ sampling} \]
\[ m < 2 \text{ corresponds to undersampling} \]
\[ m > 2 \text{ to oversampling} \]

\[ \begin{pmatrix} I \\ Q \end{pmatrix}_n = \frac{1}{\sin(\Delta \phi + \phi)} \begin{pmatrix} \cos(n\Delta \phi + \phi) & -\cos((n+1)\Delta \phi + \phi) \\ -\sin(n\Delta \phi + \phi) & \sin((n+1)\Delta \phi + \phi) \end{pmatrix} \cdot \begin{pmatrix} y_{IF,n+1} \\ y_{IF,n} \end{pmatrix} \]

\[ I = \frac{2}{m} \sum_{n=0}^{m-1} y_n \cos \left( \frac{2\pi n}{m} \right) \]
\[ Q = \frac{2}{m} \sum_{n=0}^{m-1} y_n \sin \left( \frac{2\pi n}{m} \right) \]
Undersampling and Oversampling

• Advantages of undersampling
  • Relaxed requirements for ADC due to lower sampling rate (possible cost reduction)
  • Relaxed requirements for FPGA due to lower data rate (possible cost reduction)
  • Possible to detect IF signals with higher frequency than the ADC sampling rate

• Advantages of oversampling
  • More sample points per period
  • Noise reduction due to averaging in the calculation of I and Q values
  • Choice of IF location in the first Nyquist zone is more flexible (corresponding to e.g. an available analog anti-aliasing low pass filter or to the ADC circuit optimization)
Digital Signal Processing and Implementation
Vector Sum Control

• Drive multiple cavities with one power source
Vector Sum Control of 32 Cavities at the European XFEL
Types of Feedback Controller

• Classic feedback controller
  • P: proportional controller output scales with the input error
  • I: integral controller minimizes the steady state error left from the proportional controller correction
  • D: differential controller tries to minimize rapid error changes

• Modern feedback controller
  • E.g. 2x2 MIMO (multiple input multiple output) controller (can do PID and more)
    • Cancellation of a passband mode
    • Cancellation of cross coupling between inputs
How to implement algorithms on an Field-Programmable Gate Array (FPGA)

- Write down the requirements for the firmware
- Make a flow chart and check signal widths
- Create your code
- Create a test bench for your code
- Test and debug your code within the test bench
- Test and debug your code on the target hardware (typically a test setup identical to the production system)
- Deploy the firmware on the production hardware
- If the requirements have changed, revise them and go through all previous steps

Example of Flowchart for a VHDL Algorithm for the FPGA
Ways to Create VHDL Code

- Write directly VHDL source code
  - Absolute control over functionality
  - Allows optimization for different goals (e.g. clock cycles, resources, etc.)
  - Needs good understanding
  - Can take longer to get to the result

```
-- this is a VHDL comment

-- import std_logic from the IEEE library
library IEEE;
use IEEE.std_logic_1164.all;

-- this is the entity
entity name_of_entity is
    port ('IN1' : in std_logic;
          'IN2' : in std_logic;
          'OUT1' : out std_logic);
end entity name_of_entity;

-- here comes the architecture
architecture name_of_architecture of name_of_entity is

-- Internal signals and components would be defined here
begin

    OUT1 <= IN1 and IN2;

end architecture name_of_architecture;
```

VHDL = VHSIC Hardware Description Language
VHSIC = Very High Speed Integrated Circuit

- Use e.g. MathWorks Simulink to create VHDL code
  - Allows quick prototyping
  - Good graphical representation of signal flow
  - Less control
  - Creates VHDL code, which most times cannot be easily debugged by a human
Example Features of an LLRF System
Interlock

• Every facility typically has a Personal Protection System (PPS) and most facilities have a Machine Protection System (MPS)

• Since the LLRF system is a sub-system of a facility, it must have interlock capabilities

• Typically hardwired in hardware or firmware
  • E.g., logical ‘and’ just before the DAC
Exception Prevention and Handling

• The LLRF system should prevent certain exceptions
  • Limiters
    • Maximal setpoint voltage
    • Maximal drive signal amplitude
    • Etc.

• The LLRF system should also include a certain degree of exception handling
  • Algorithms for monitoring or computing parameters and for reacting accordingly
    • Turn off RF drive in case of klystron trip
    • Quench detection
    • Etc.
Operation Close to the Quench Limit

• Quench detection is a common feature of LLRF systems
• If $Q_L$ drops below a predefined limit, the drive is turned off
• Should create interlock for the beam
• RF is turned back on manually or by an automation algorithm
Suppression of Unwanted Passband Modes

- Implement filter (e.g. Notch filter at ADC) in order to suppress frequency of the $8\pi/9$-mode
Detuning

- Detuning lowers the amplitude / requires more power to reach the same amplitude
- Detuning induces change of phase
- The sources are Lorentz force detuning and microphonics
Detuning Compensation

- **Motor tuner**
  - Slow
  - Pre-tune cavity
  - Compensation of static detuning

- **Piezo tuner**
  - Fast
  - Compensation of dynamic detuning (E.g. Lorentz force detuning, etc.)
  - Piezo control is typically part of the LLRF system
Benchmarking the System Performance

- RF stability (VS)
  - Intra train
  - Inter train
- Long term drifts
- Must be better than requirements for (beam) operation

KEK STF: $Q_c = 2 \times 10^7$

KEK STF: $Q_{c,1} = 9 \times 10^6$, $Q_{c,2} = 3 \times 10^6$

European XFEL: overview of VS stabilities, requirements: $\Delta A \leq 0.01\%$, $\Delta \Phi \leq 0.01$ deg.
Summary and Bibliography
Summary

• What you should learn about, when are planning to get involved with LLRF
  • Your facility
    • What are the requirements? (e.g. for short time and long-time stability, etc.)
    • How to integrate the LLRF system (e.g. interlock, communication, etc.)
  • Theory
    • Cavity
    • RF
    • Signal processing
    • Controller
  • Analog hardware
  • Digital hardware
  • Firmware
  • Software
    • E.g. communication, computations, automation, data analysis, data storage, data visualization, user interface, etc.
Thank you very much for your attention! Questions?

• Bibliography
  • S. Pfeiffer, LLRF Controls and Feedback, The CERN Accelerator School, 2016
  • S. Sievers et al., Second-sound measurements on a 3 GHz SRF cavity at low acceleration fields, SRF’13, 2013
  • S. Simrock et al., Cavity Field Control, LLRF Lecture, 5th LC School, 2010
  • M. Omet, Digital Low Level RF Control Techniques and Procedures Towards the International Linear Collider, PhD Thesis, 2014
  • J. Branlard, LLRF controls and RF operations, SRF 2019 Tutorial, SRF2019, 2019
  • J. Branlard, Superconducting cavity quench detection and prevention for the European XFEL, ICAEPCS’13, 2013
  • L. Doolittle et al., High Precision RF Control for SRF Cavities in LCLS-II, SRF2021, 2017
  • J. Branlard et al., Installation and First Commissioning of the LLRF System for the European XFEL, IPAC17, 2017
  • T. Miura et al., Digital LLRF Control System for cERL, 13th Annual Meeting of Particle Accelerator Society of Japan, 2016
  • T. Hellert et al., Detuning related coupler kick variation of a superconducting nine-cell 1.3 GHz cavity, Phys. Rev. Accel. Beams 21, 042001, 2018
  • D. Kostin, Experience with the Eu-XFEL RF Couplers, AWLC’20, 2020
  • S. Fukuda, KEK HLRF Status and S1- global, LCWS’08, 2008
  • C. Pagani et al., Test results of the international S1-global cryomodule, Proceedings of the 8th Annual Meeting of Particle Accelerator Society of Japan, 2011
  • F. Qiu, Tutorial on control theory, 10th International Accelerator School for Linear Colliders, Japan, 2016
  • M. Omet, Status Update of the European XFEL, Seminar at KEK, 2019
  • M. Omet et al., High-gradient near-quench-limit operation of superconducting Tesla-type cavities in scope of the International Linear Collider, Phys. Rev. ST Accel. Beams 17, 072003, 2014