Outline

> Introduction

> LLRF
  - Feedback & Limitations
  - Learning Feedforward

> Pulse Width Modulation
  - RF gun cooling system
  - Temperature estimation
  - Precision temperature control

> Fast Protection
  - The why and wherefore

> Current problems
  - After start-up
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Introduction

1.3 GHz SWS, Pulsed mode @ 10 Hz,
Forward power ≈ 5 MW (average power ≈ 50 kW)
Pulse length up to 800 μs → 1% duty cycle

Since 01/2015 operated with MicroTCA.4

(1) Regulation - LLRF:
Control the amplitude and phase of virtual probe signal

(2) Regulation - Water:
Control the RF gun temperature → keep it on (slightly below) its resonance frequency

(3) Protection:
Limiter for Output, FB, LFF etc.
Switch off the power to RF gun if necessary, e.g. spark
Outline

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> LLRF
  - Feedback Loop
  - Concepts & Achievement

> Pulse Width Modulation
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LLRF Regulation

Main.GUN Panel

LLRF

- Ampl. SP [MV/m]
  - (new: before power SP [MW])
- Phase SP [deg]
- Pulse length [μs]
- Feedforward
- Feedback
- OVC, LFF etc.
LLRF Regulation
LLRF Regulation

Small signal system model

\[
\begin{bmatrix}
\Delta Y_I(z) \\
\Delta Y_Q(z)
\end{bmatrix}
= \begin{bmatrix}
G_1(z) & -G_2(z) \\
G_2(z) & G_1(z)
\end{bmatrix}
\begin{bmatrix}
\Delta U_I(z) \\
\Delta U_Q(z)
\end{bmatrix}
\]

Identified parameters:
- I/Q gains as function of frequency
- Cross-couplings
- Bandwidth \( \sim 52 \, \text{kHz} \)
- Loop delay \( \approx 1.4 \mu s \)

Feedback loop

System model
FPGA output to virtual probe

Model based optimization of FB and LFF
Feedback concepts

1) Output-Vector Correction (OVC - Server)
   → Drift compensation

2) Learning Feedforward (LFF - Server)
   → Minimize repetitive errors from pulse to pulse

3) MIMO feedback (FB - FPGA)
   → Intra-pulse feedback
   • **Main limitation:** Loop delay ≈ 1.4 μs
   → limits control gain
      → max. FB gain 2-3; SRF ≈ 20-40 (!)

**Goal:**

\[
\frac{dA}{A} < 0.01\% \\
\frac{d\phi}{\phi} < 0.01 \text{ deg (rms)}
\]
LLRF Regulation

Goal: \( \frac{\Delta A}{A} < 0.01\% \)

\( \Delta \phi < 0.01 \text{ deg (rms)} \)
LLRF Regulation

Goal: \( \frac{dA}{A} < 0.01\% \)

\( d\phi < 0.01 \text{ deg (rms)} \)

Factor 3-5 improvement necessary

Standard Deviation of A/P for RF gun

\( \sigma(A_{\text{Cum}}) \) (deg)

\( 0.01\% \quad 9\text{MHz} \rightarrow 100\text{kHz} \)

\( 0.01\text{deg.} \)
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> Outlook
RF gun cooling system

- Cold water
- Warm water
- Valves
- RF gun
- Tank
- Heater
RF gun cooling system

Long term error ± 1 bit (about 14mK rms)

@Resolution (12 bit ADC) of 0.02 K – 0.03 K

Required stability for \( \Delta \theta < 0.01 \) deg without LLRF control:

\[
\Delta T = \frac{\tan \psi \cdot f}{2 \ Q_L K_{fT}} \approx \frac{d\phi \cdot f}{2 \ Q_L K_{fT}} < 0.45mK,
\]

\((f = 1.3GHz, Q_L = 12000, K_{fT} = -21kHz/K)\)
RF gun cooling system

Long term error ± 1 bit (about 14mK rms)

@Resolution (12 bit ADC) of 0.02 K – 0.03 K

Required stability for $d \varphi < 0.01$ deg without LLRF control:

$$\Delta T = \frac{\tan \psi \cdot f}{2 Q_L K_{FT}} \approx \frac{d \phi \cdot f}{2 Q_L K_{FT}} < 0.45mK,$$

($f = 1.3GHz, Q_L = 12000, K_{FT} = -21kHz/K$)
Idea: Usage of LLRF Signals

Use pulse width modulation to control the dissipated power (heat balance) to the RF gun body within pre-defined limits.

Needed is a high precision temperature estimation with no time delay for pulse to pulse feedback.
Idea: Usage of LLRF Signals

- **Transition from cavity body to sensor**
- **Low pass behavior of temp. sensor**

**Delayed** $T_{\text{IRIS}}$ (9s) and $T_{\text{IN}}$ (5s) information:

- Flash RF Gun data
  - Temp. sensor (12 bit ADC)
Pulse Width Modulation

Blue: single pulse, Red: mean 100 pulses (10s@10Hz)

RF GUN phase at 1st beam position (700µs) for 50 minutes

- Without and with modulation to minimize disturbances from cooling water circuit
- Pulse to pulse compensation (10 Hz)
- Improvement for phase x3 
  \[ d\phi = 53 \text{ mdeg.} \rightarrow 16 \text{ mdeg.} \]
- RF GUN temperature stabilized by x5 
  \[ \text{from 14 mK} \rightarrow \text{3 mK} \]
- Running @ FLASH, PITZ, (XFEL)

* Under review @ Physical Review Special Topics - Accelerators and Beams
Pulse Width Modulation

Goal: \( \frac{dA}{A} < 0.01\% \)

\( d \varphi < 0.01 \text{ deg (rms)} \)

Remember:

- Factor 3-5 improvement in phase is necessary using only LLRF control

Applying PWM:

- No improvement of RF amplitude
  - Detuning affects mainly the RF phase
- Great improvement in standard deviation of RF phase
- Achieved by using disturbance minimization of detuning with precision temperature control
Pulse Width Modulation – Panel

- PWM Feedback check box
- Set-point (automatically computed)
- Status indicator
- Initialization (settings before PWM)
- Manual (set-up, problem handling)

With Pulse Width Modulation
- Start-up of RF gun → next slide

Without Pulse Width Modulation
Using pulse width modulation – panel for start-up of RF gun

Direct response
RF gun is in resonance, to cold or to warm

→ Relative detuning / temperature information

→ What is the current optimal Iris set-point etc.
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Fast Protection

- Implementation in FPGA (L. Butkowski, C. Schmidt et al.)
- Threshold for reflected signal is defined (scaled by forward signal)
- Cut RF pulse if reflected signal is too high (sparks, detuning, etc.)
Fast Protection

> 6 Events since 01/2016 → no known false alarms

<table>
<thead>
<tr>
<th>12.04.2016 12:05</th>
<th>S. Schreiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hist: FLASH.RF/LLRF.CONTROLL</td>
<td></td>
</tr>
</tbody>
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rf gun fast protection: events where the fast protection triggered

- event 1: 12-Jan-2016 16:03 h tests, rf was off
- event 2: 2-Feb-2016 9:59 h unknown reason
- event 3: 19-Feb-2016 10:52 h increase of cooling water pressure
- event 4: 2-Mar-2016 11:50 h no DAQ data for this event, together with RF-6, could be timing issue
- event 5: 18-Mar-2016 9:10 h cooling water pressure oscillations
- event 6: 11-Apr-2016 16:08 h sudden phase jump, also ACCL, llrf issue with reference RF
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Current Problems

> After RF gun start-up
  - Phase at end is not on set-point

> How to check?
  - Look in LFF panel
Current Problems

> RF gun start-up without FB, LFF

(1) Adjust OVC before FB and LFF is enabled
(2) Enable FB, LFF
  - FF correction are centered after a while
  - FF correction limits: 7000 bits
→ t = 0
(3) FF correction tables 20 minutes later
(4) After 40 minutes
  - FF tables (Q channel) hits limit

Why?
Slowly waveguide heating (guess)
Current Problems

> After RF gun start-up
  - Phase at end is not on set-point

> Why?
  - Slowly waveguide heating (guess)

> How to check?
  - Look in LFF panel

> What can I do?
  - Adjust OVC phase by ~ -4 deg
Current Problems

> After RF gun start-up
  - Phase at end is not on set-point

> Why?
  - Slowly waveguide heating (guess)

> How to check?
  - Look in LFF panel

> What can I do?
  - Adjust OVC phase by ~ -4 deg

> Why is it not done automatically?
  - Most of the time OVC is OFF…
  - OVC ON does not mean that its active…
  - Active limiter deactivate OVC
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Thank you for your attention!