FLASH RF gun developments.

Sven Pfeiffer for the LLRF team
FEL Seminar
Hamburg, 19.04.2016

HELMHOLTZ
| GEMEINSCHAFT

DESY

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
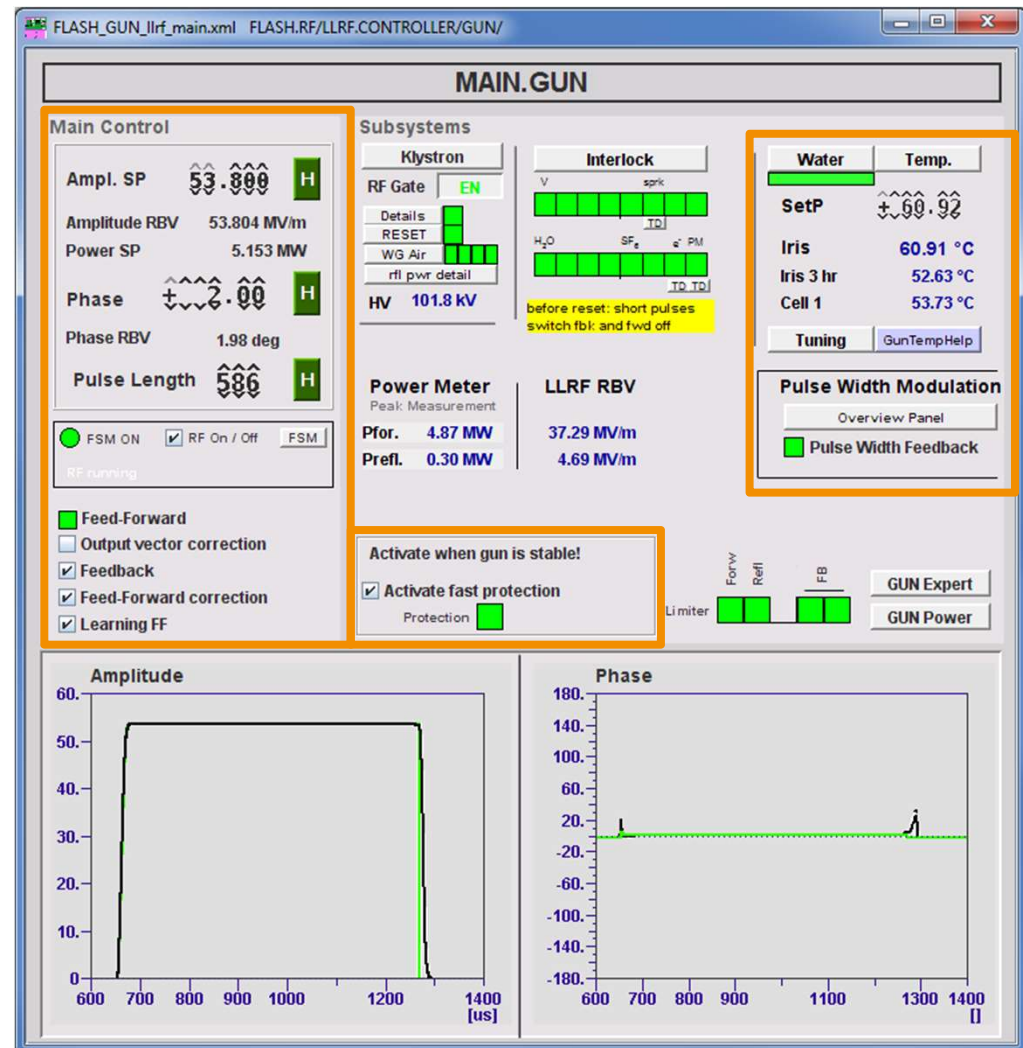
Outline

> **Introduction**

> LLRF

- Feedback & Limitations
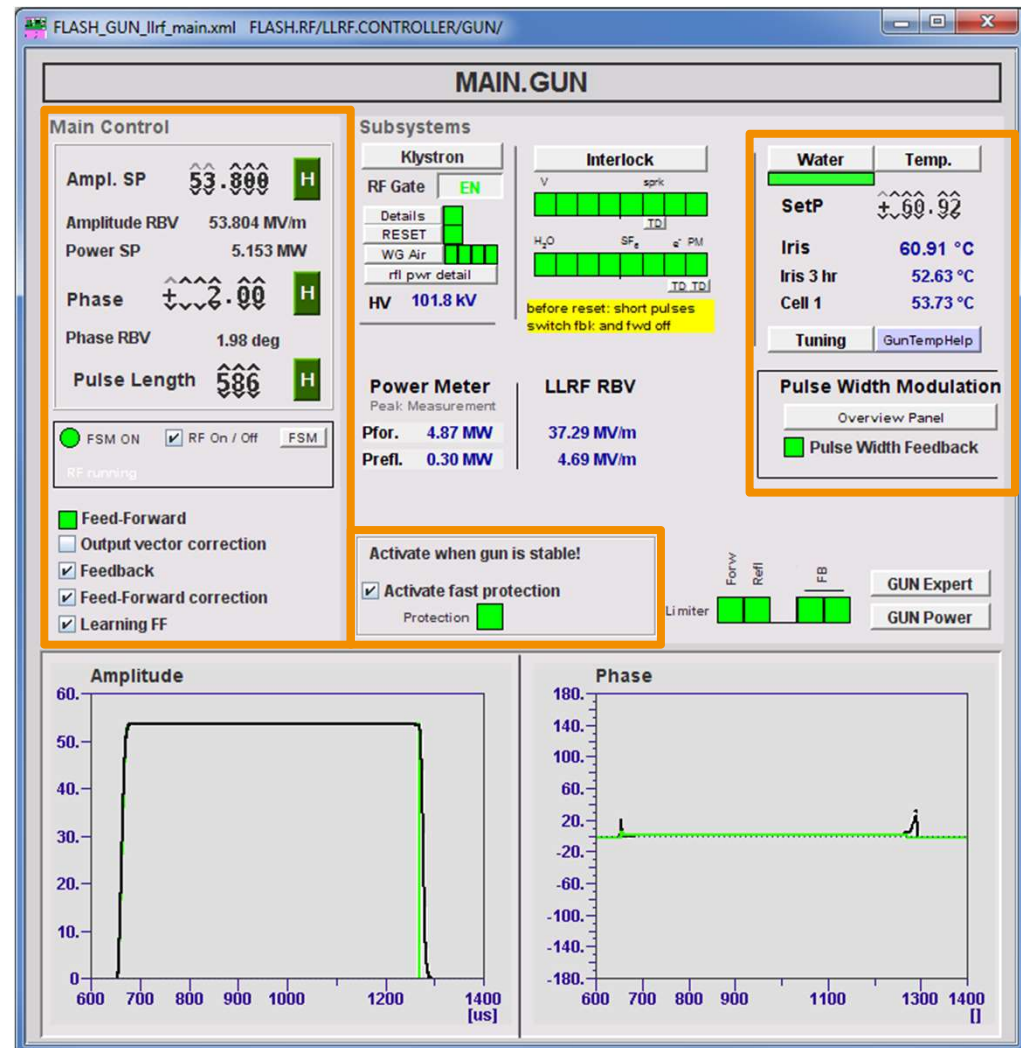
- Learning Feedforward

> Pulse Width Modulation

- RF gun cooling system

- Temperature estimation

- Precision temperature control

> Fast Protection

- The why and wherefore
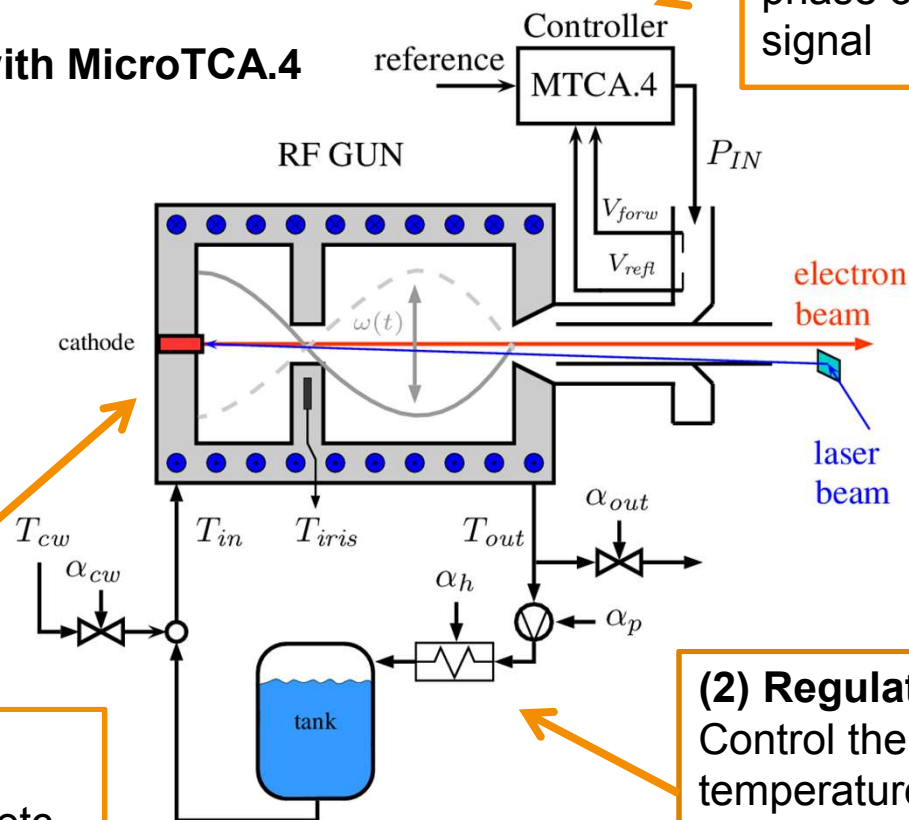
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- After start-up

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

(3) Protection:

Limiter for Output, FB, LFF etc.

Switch off the power to RF gun if necessary, e.g. spark

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

Outline

> Introduction

> **LLRF**

- Feedback Loop
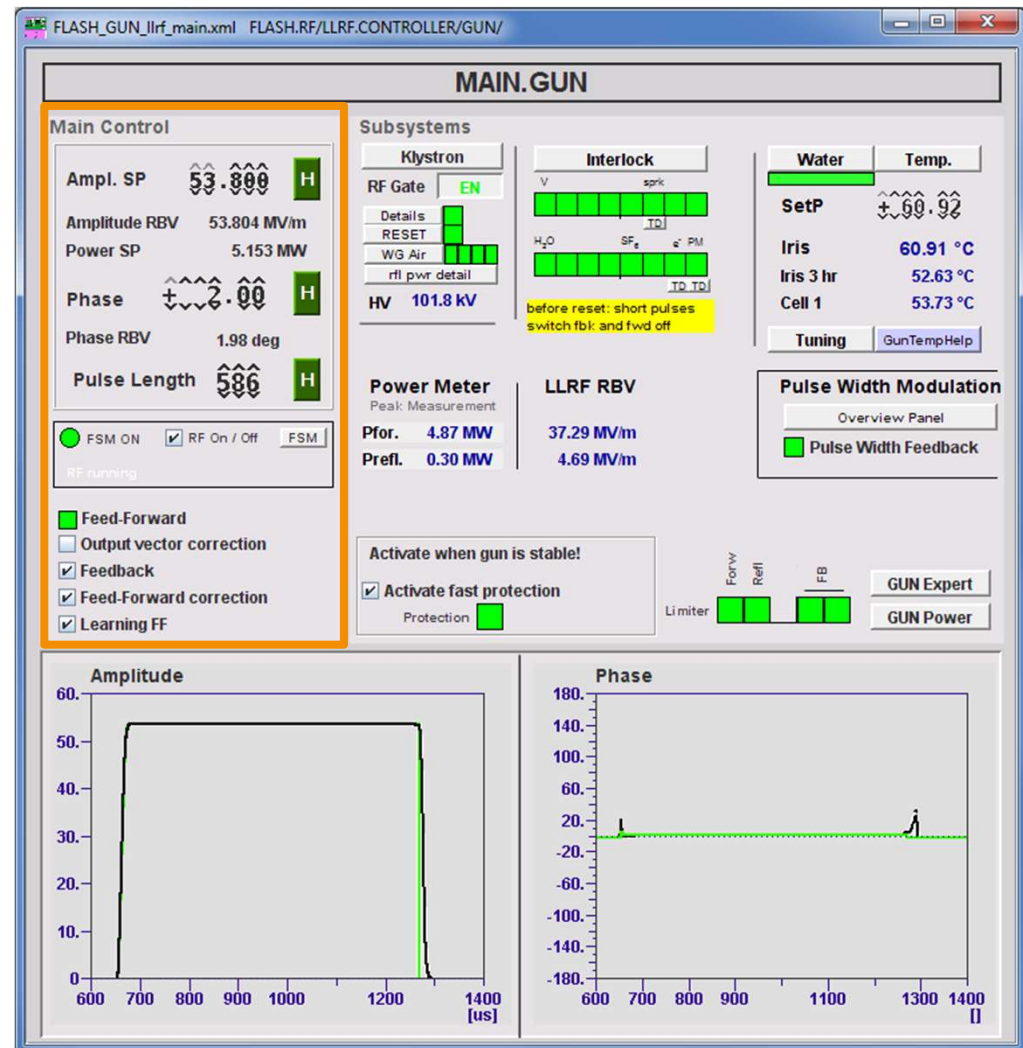
- Concepts & Achievement

> Pulse Width Modulation

- RF gun cooling system

- Temperature estimation

- Precision temperature control

> Fast Protection

- The why and wherefore
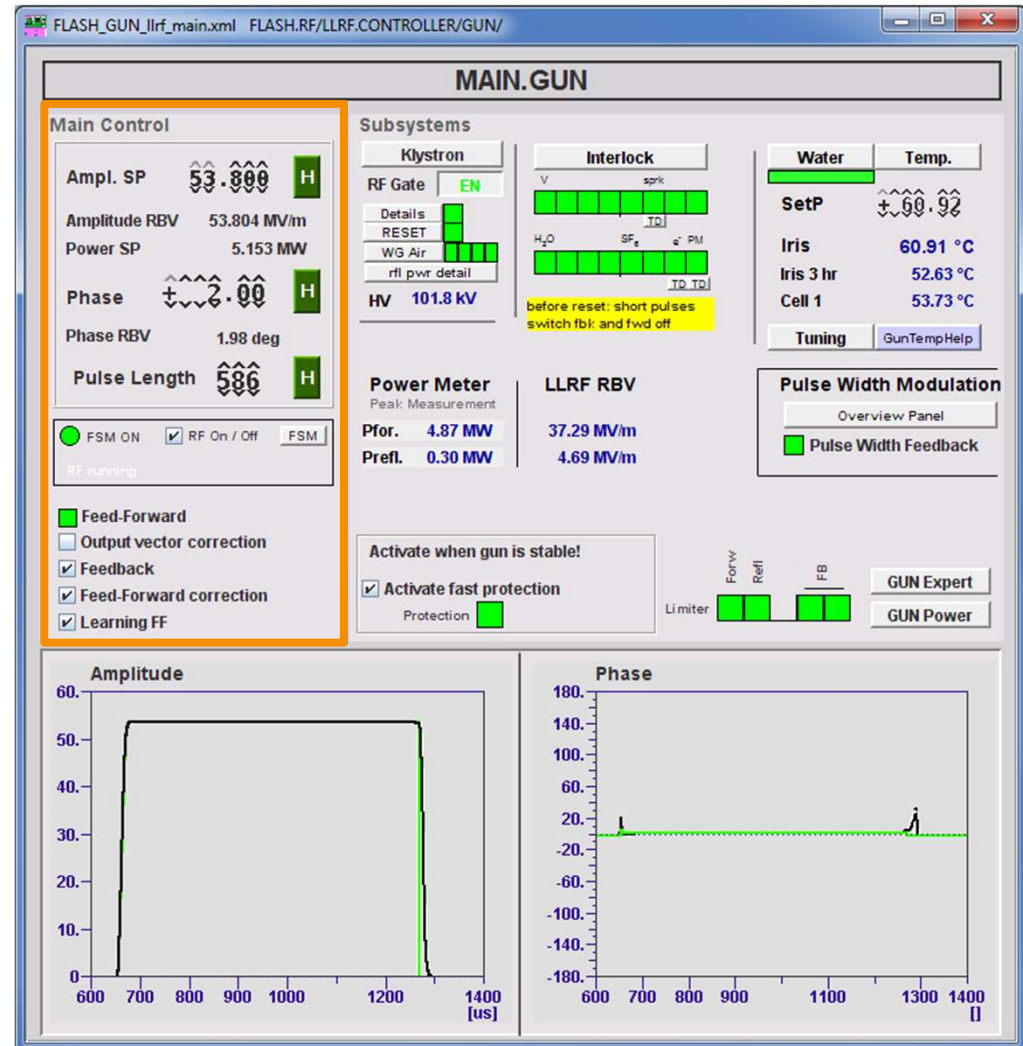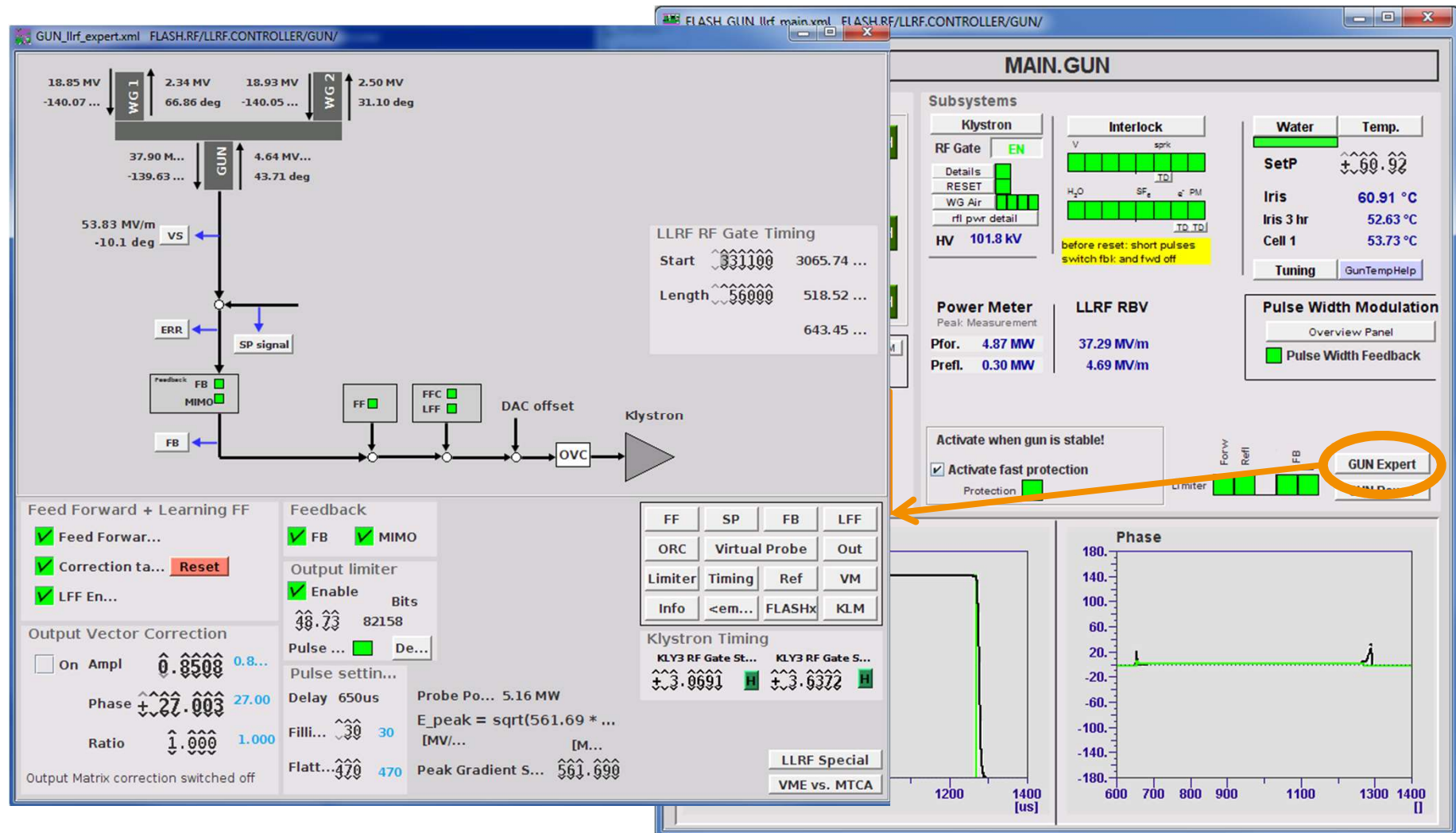
> Current problems

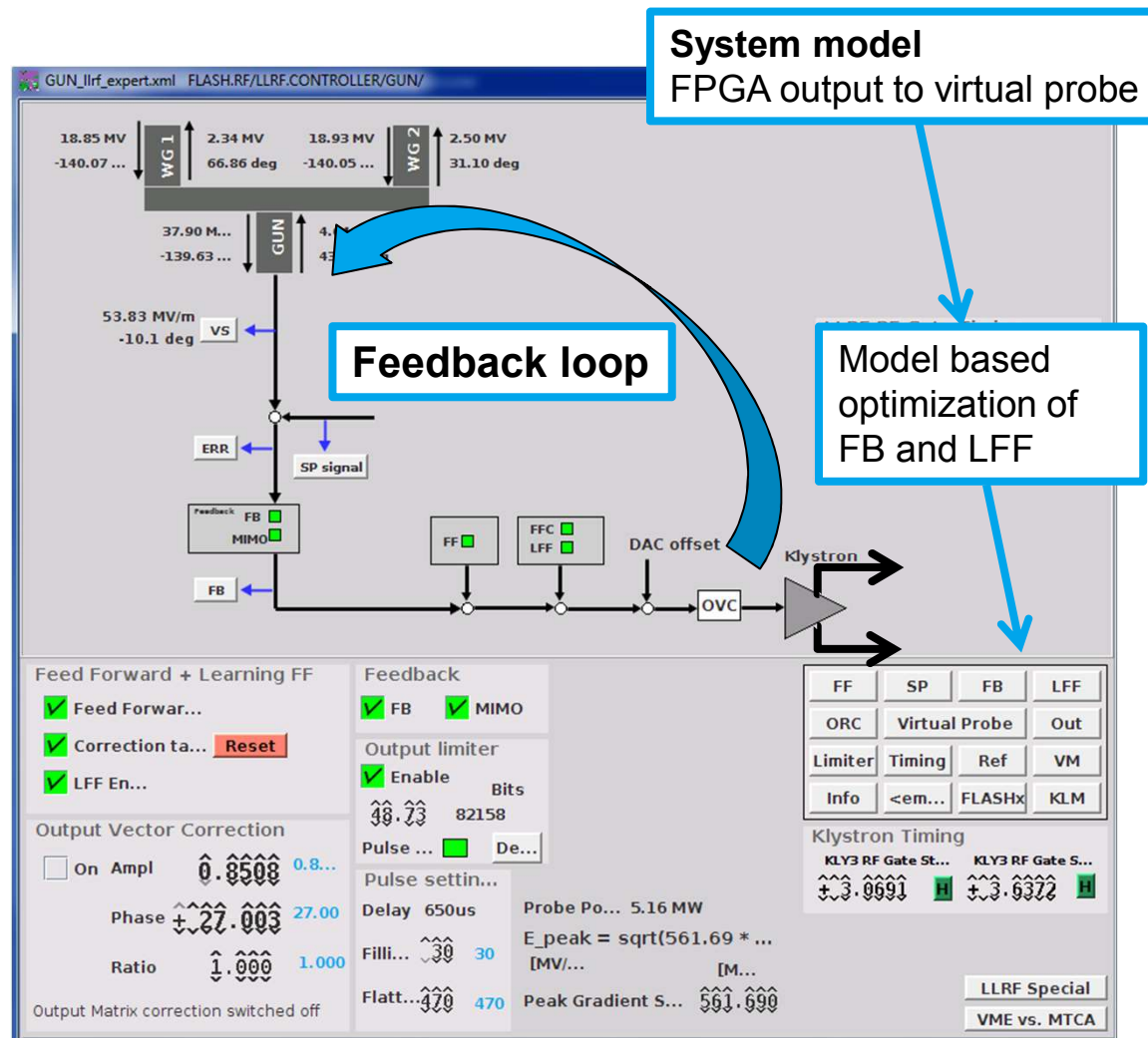- After start-up

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

System model
FPGA output to virtual probe

Feedback loop
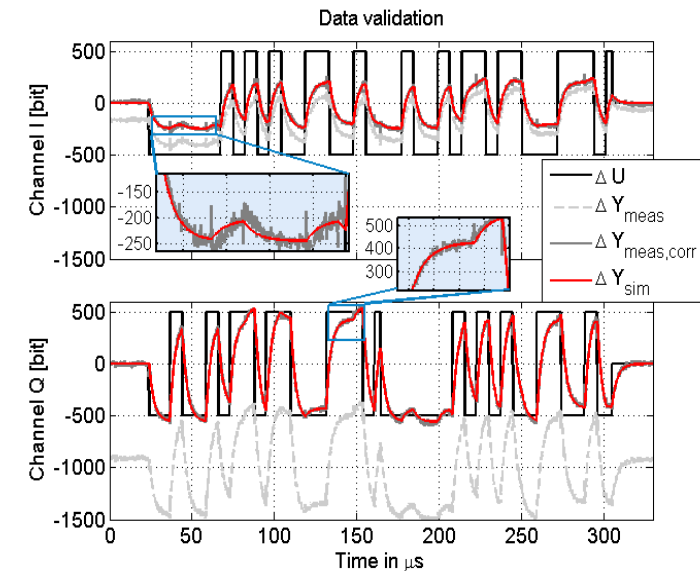
Model based optimization of FB and LFF

Small signal system model

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

Identified parameters:
- I/Q gains as function of frequency
- Cross-couplings
- Bandwidth ~ 52 kHz
- Loop delay ≈ 1.4 µs

LLRF Regulation

Feedback concepts

Goal: dA/A<0.01%
d☐ <0.01 deg (rms)

1) Output-Vector Correction (OVC - Server)

→ Drift compensation

2) Learning Feedforward (LFF - Server)

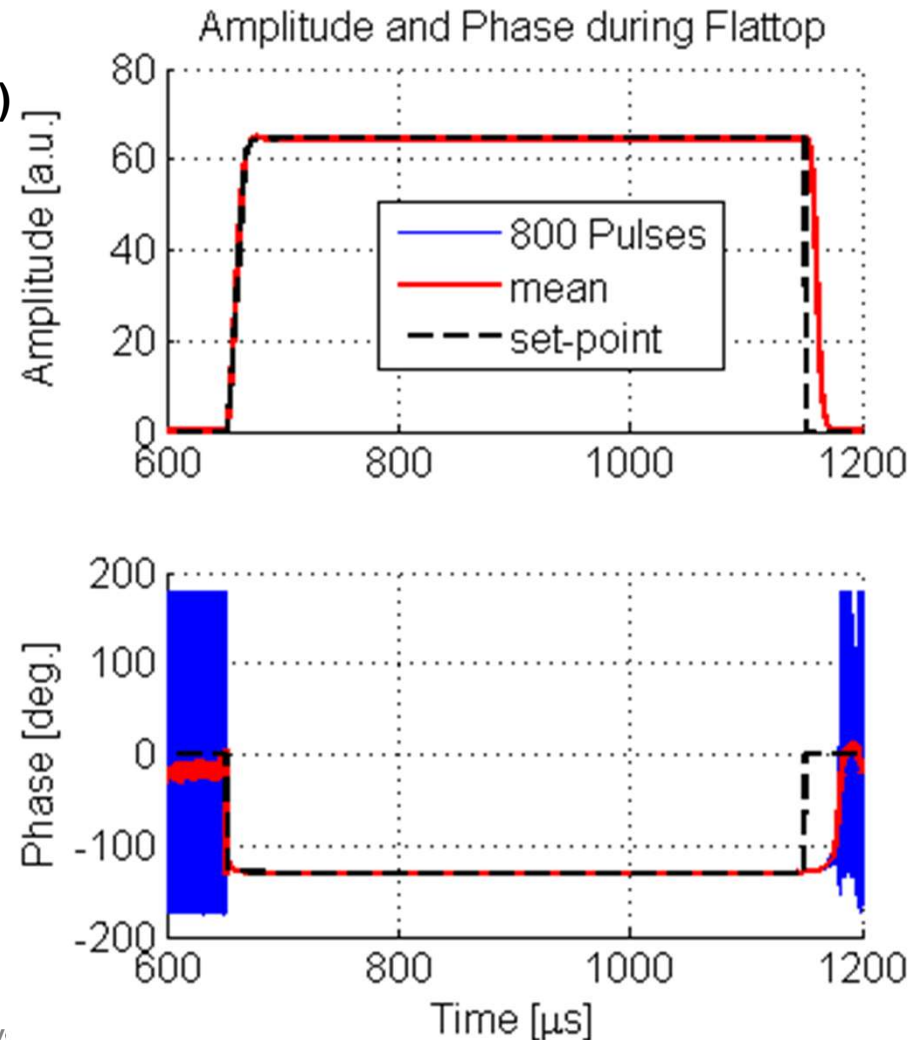→ Minimize repetitive errors from pulse to pulse

3) MIMO feedback (FB - FPGA)

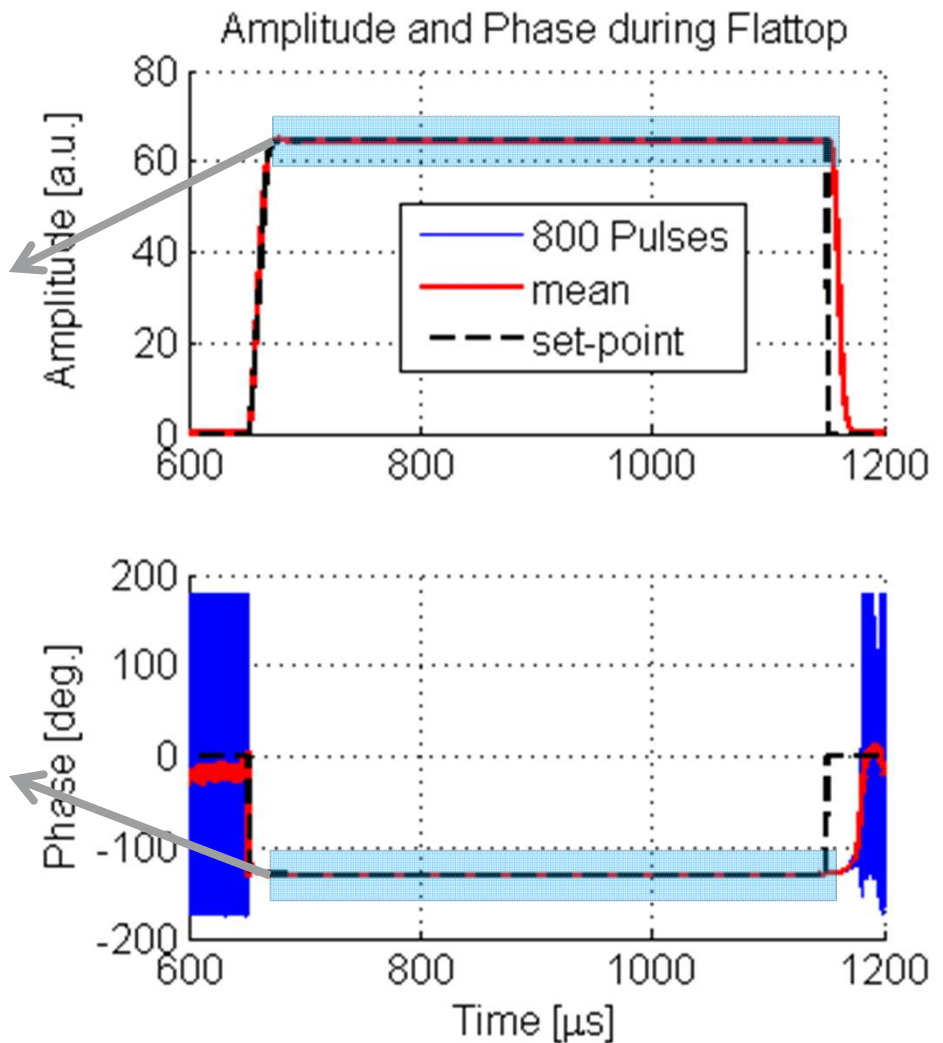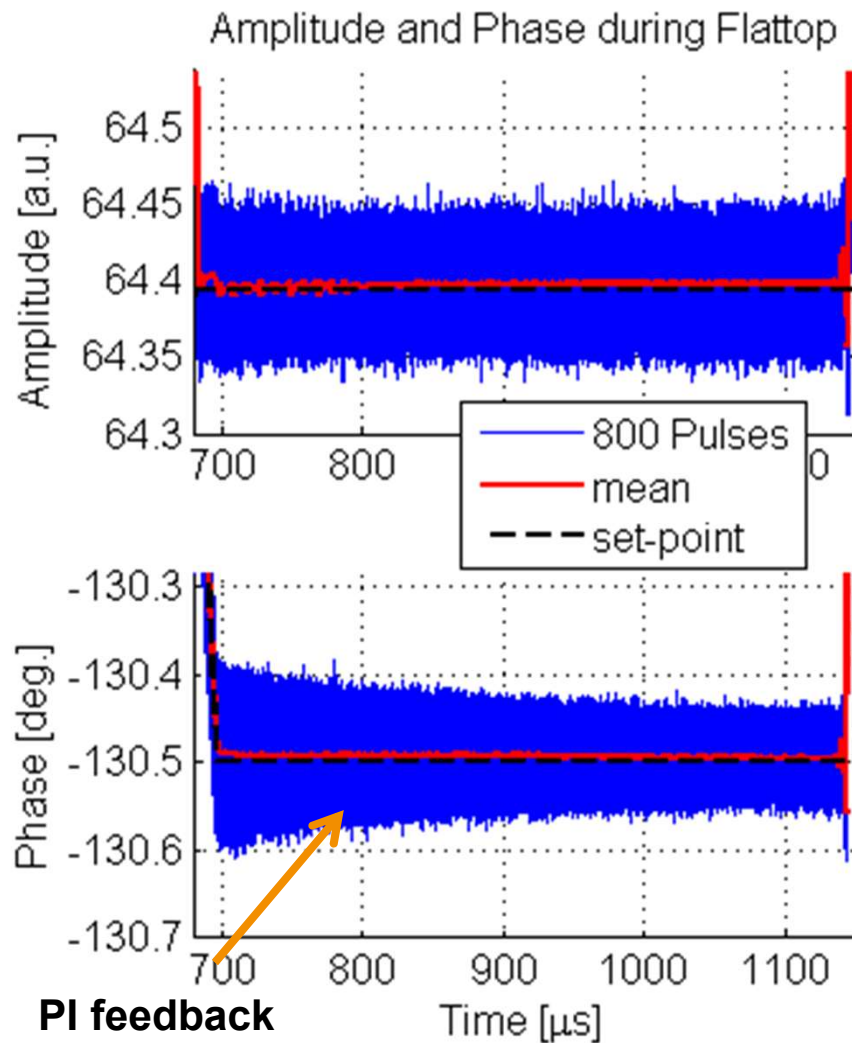→ Intra-pulse feedback

• **Main limitation:** Loop delay ≈ 1.4 µs

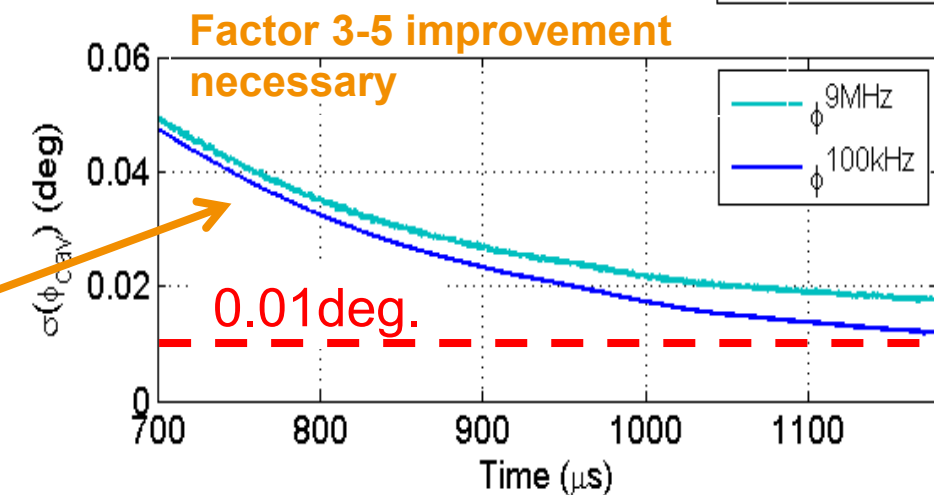→ limits control gain

→ max. FB gain 2-3; SRF ≈ 20-40 (!)

Amplitude and Phase during Flattop

Legend:
- 800 Pulses
- mean
- set-point

Sv

LLRF Regulation

Goal: dA/A<0.01%
        d☐   <0.01 deg (rms)

PI feedback

LLRF Regulation

Goal: **dA/A<0.01%**

d□ <0.01 deg (rms)

Amplitude and Phase during Flattop

Standard Deviation of A/P for RF gun

0.01%   9MHz → 100kHz

Factor 3-5 improvement necessary

0.01deg.
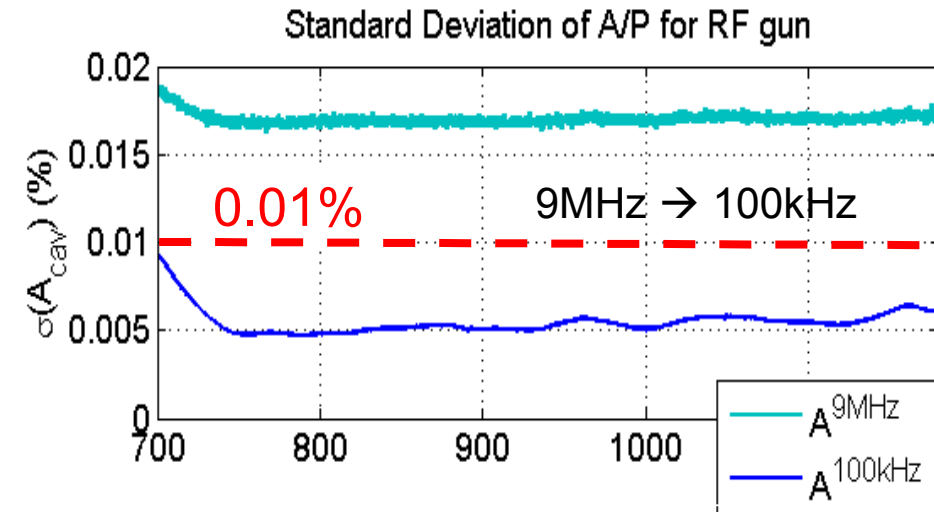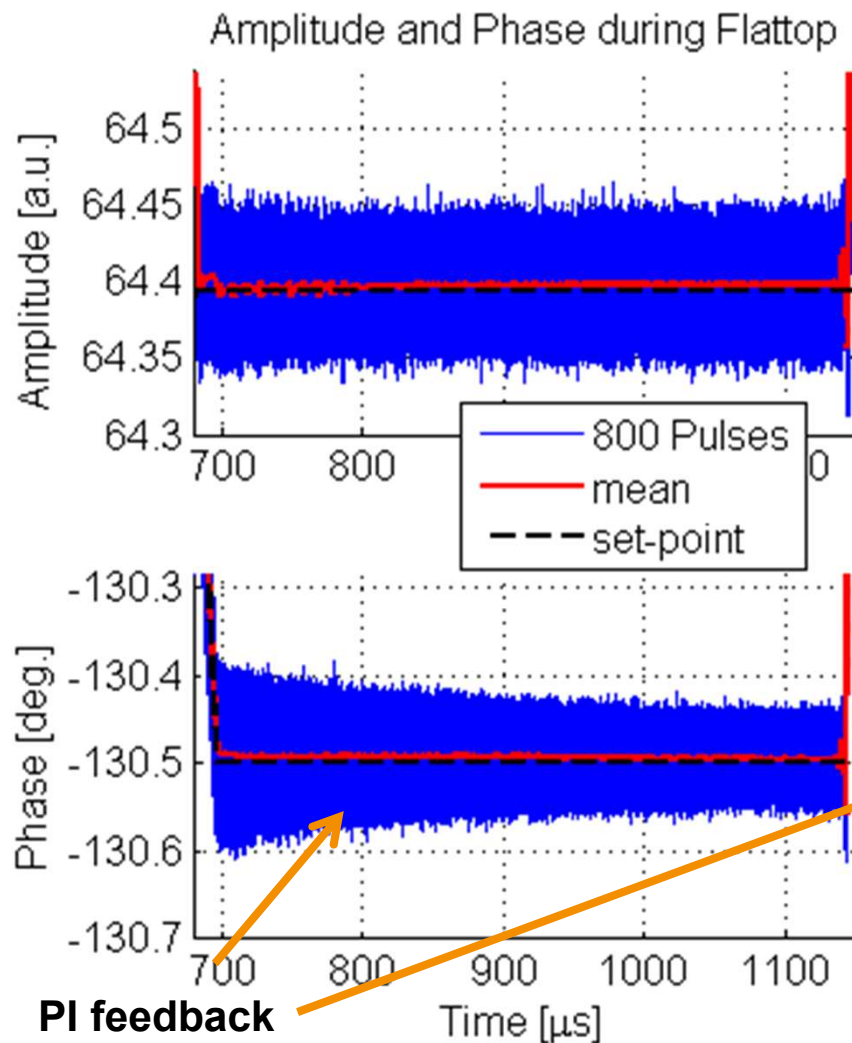
PI feedback

Outline

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> LLRF

- Feedback & Limitations
- Learning Feedforward

> **Pulse Width Modulation**

- RF gun cooling system
- Temperature estimation
- Precision temperature control
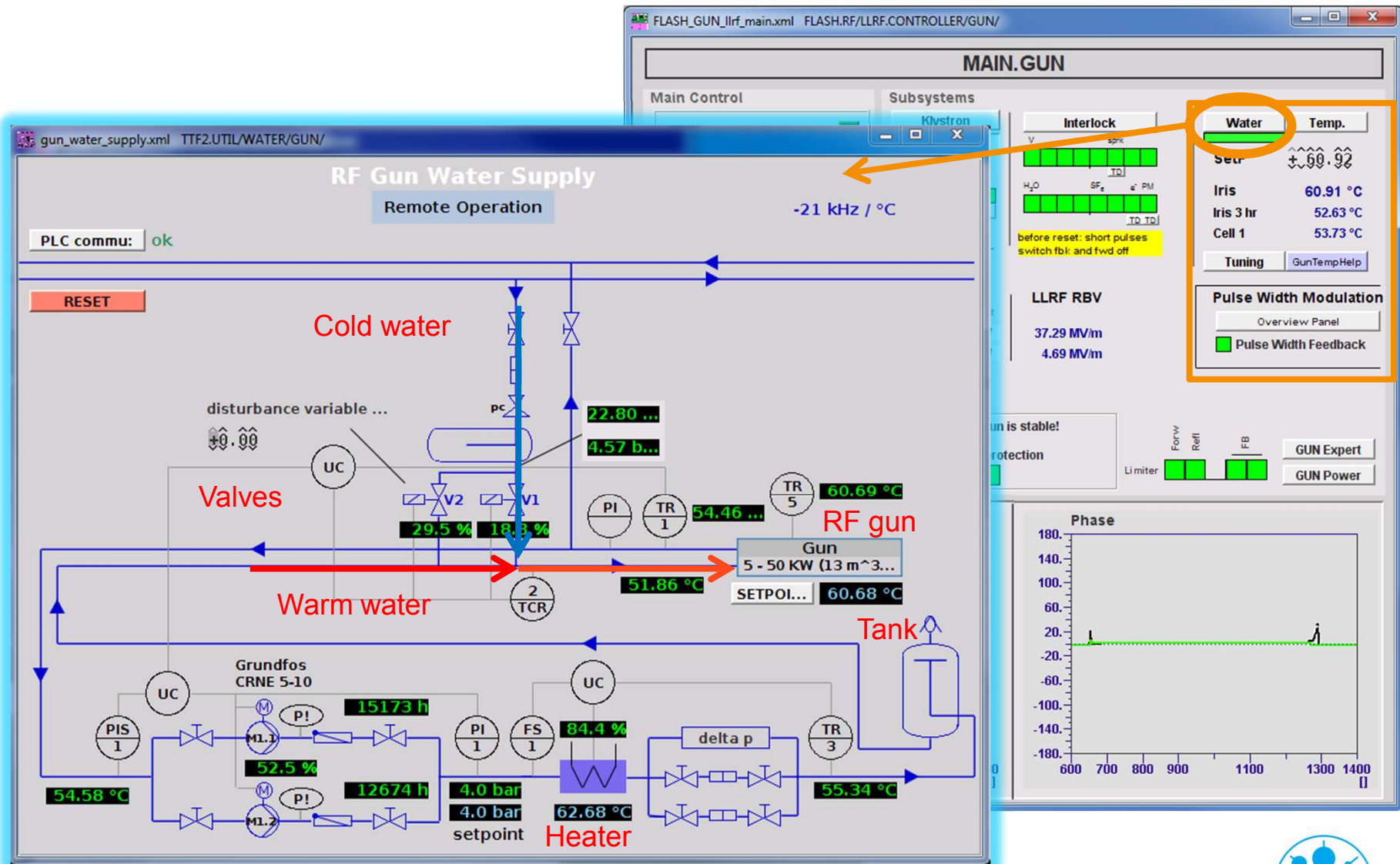
> Fast Protection

- The why and wherefore
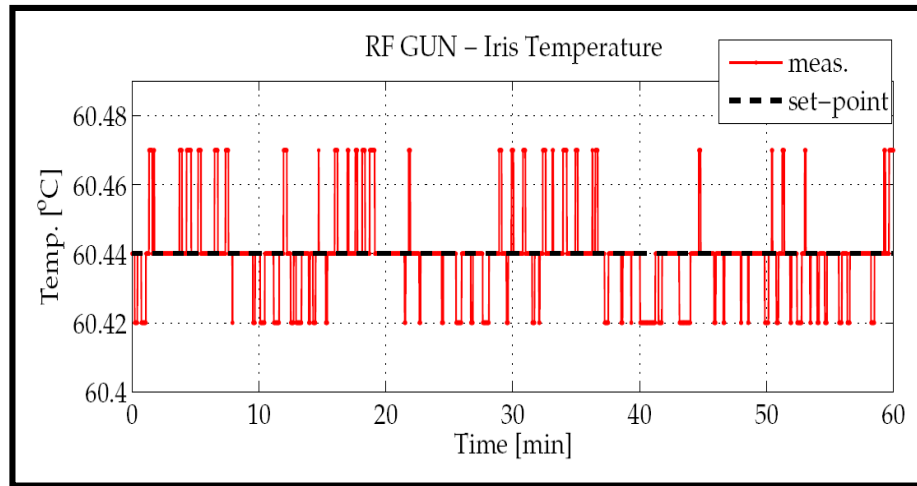
> Current problems

- After start-up

> Outlook

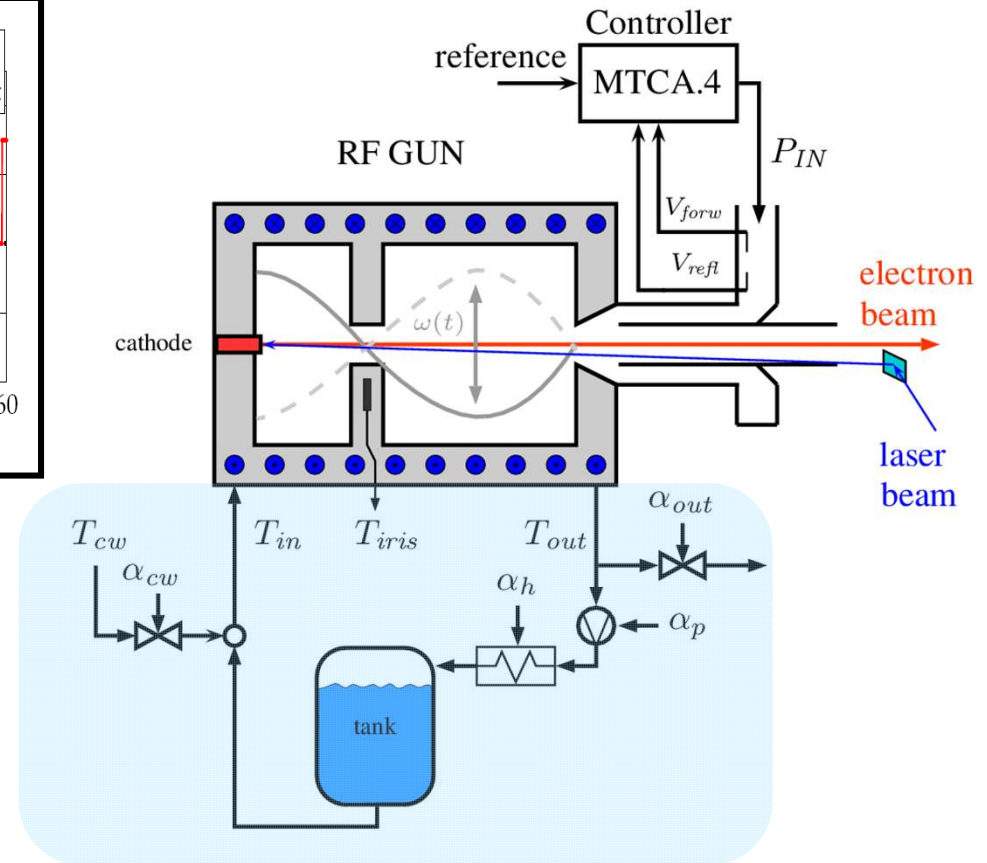# RF gun cooling system

RF gun cooling system

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

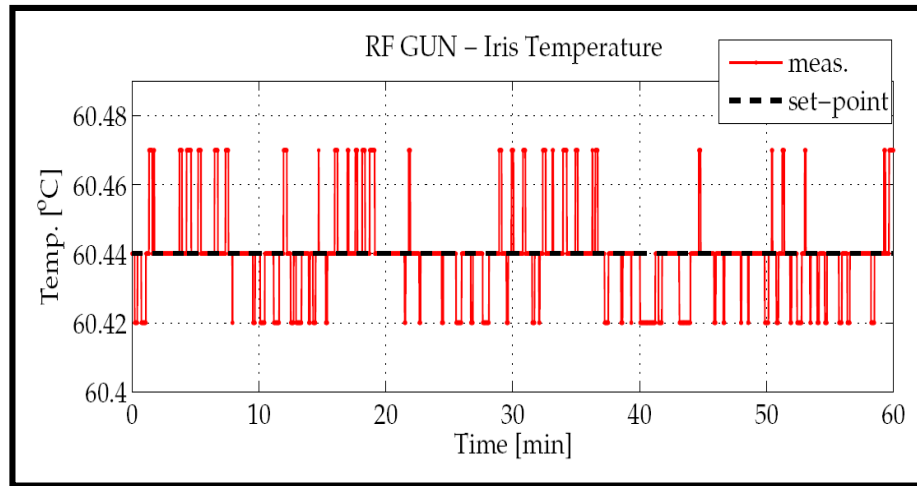@Resolution (12 bit ADC)
  of 0.02 K – 0.03 K

**Required stability for dφ < 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

RF GUN – Iris Temperature

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

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

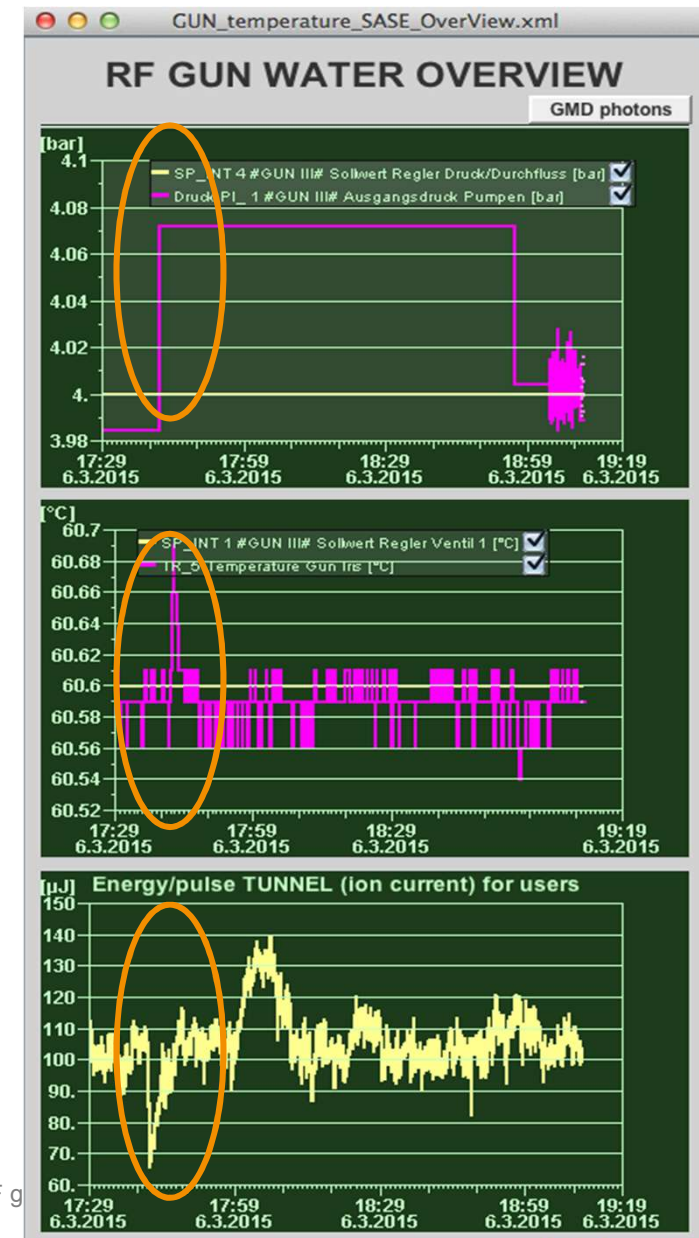**Required stability for dΦ < 0.01 deg without LLRF control:**

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

$(f = 1.3GHz, Q_L = 12000, K_{fT} = -21kHz/K)$

Pressure
+0.09bar

T_{IRIS}
+100mK

SASE
-35uJ

RF GUN WATER OVERVIEW
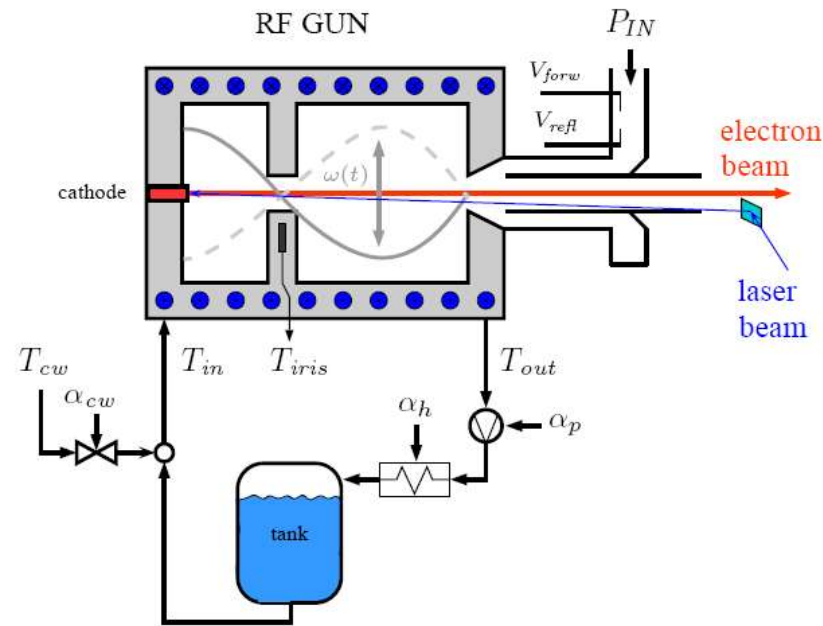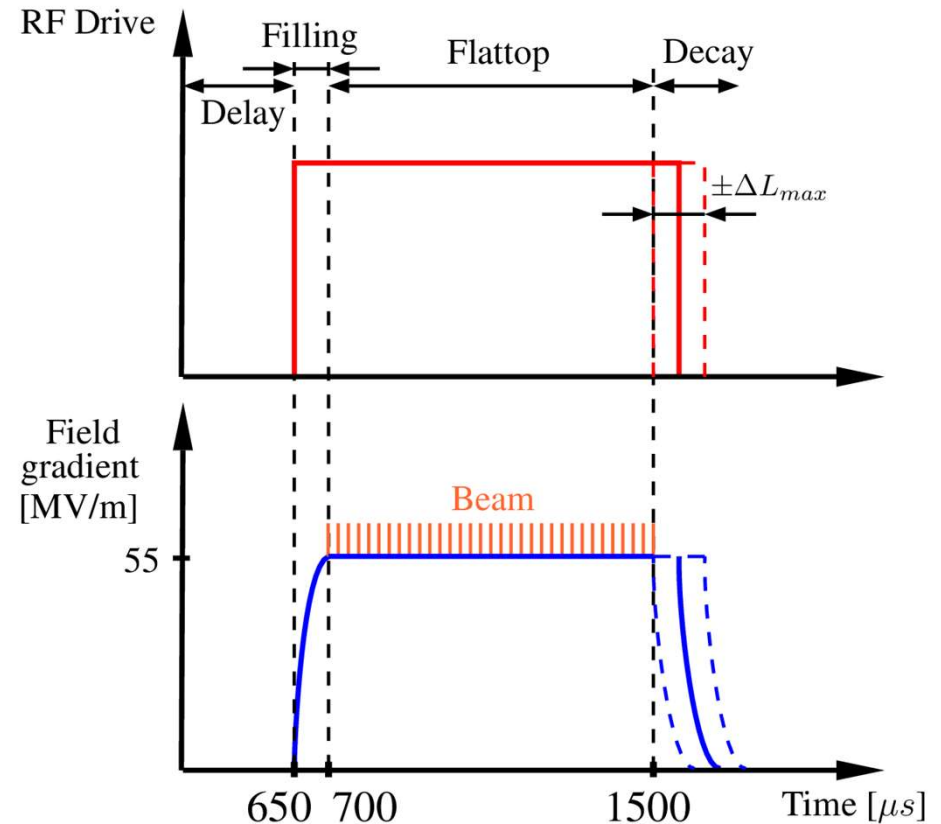
Pulse Width Modulation
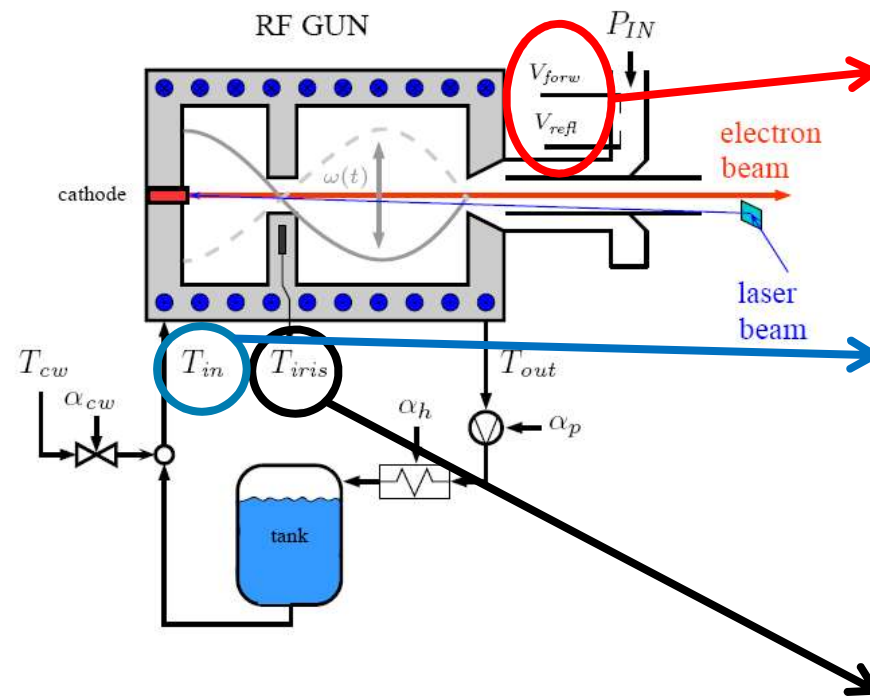
Idea: Usage of LLRF Signals

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
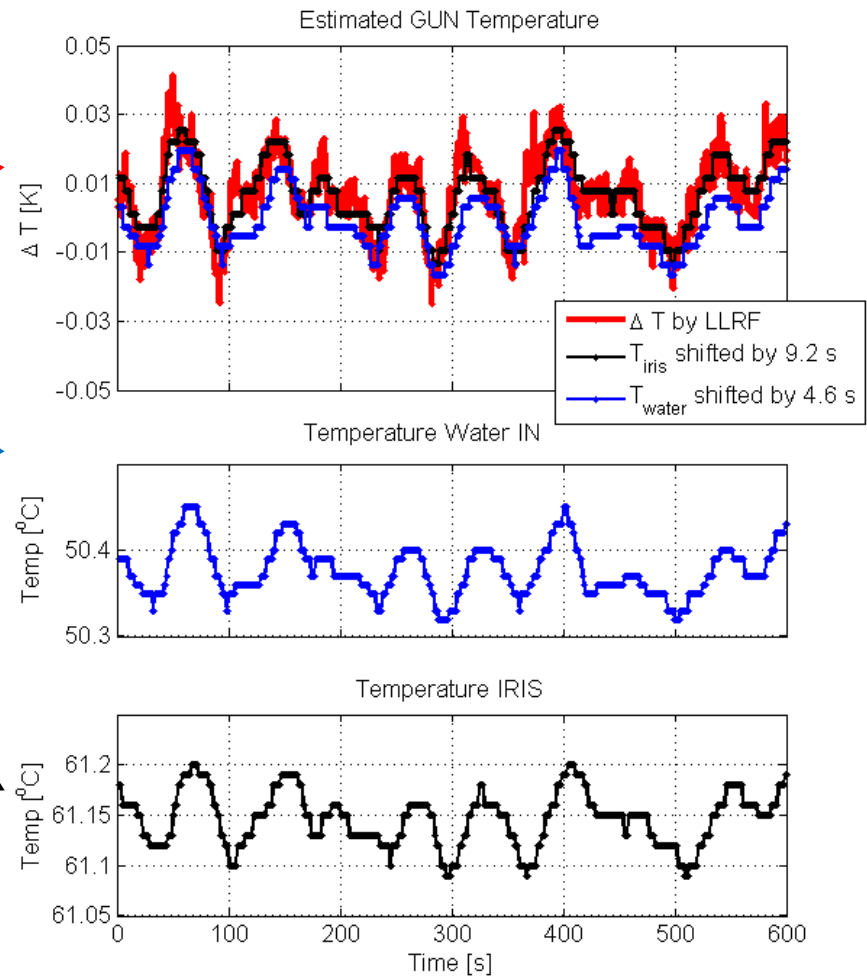
Pulse Width Modulation

Idea: Usage of LLRF Signals

Delayed T_{IRIS} (9s) and T_{IN} (5s) information

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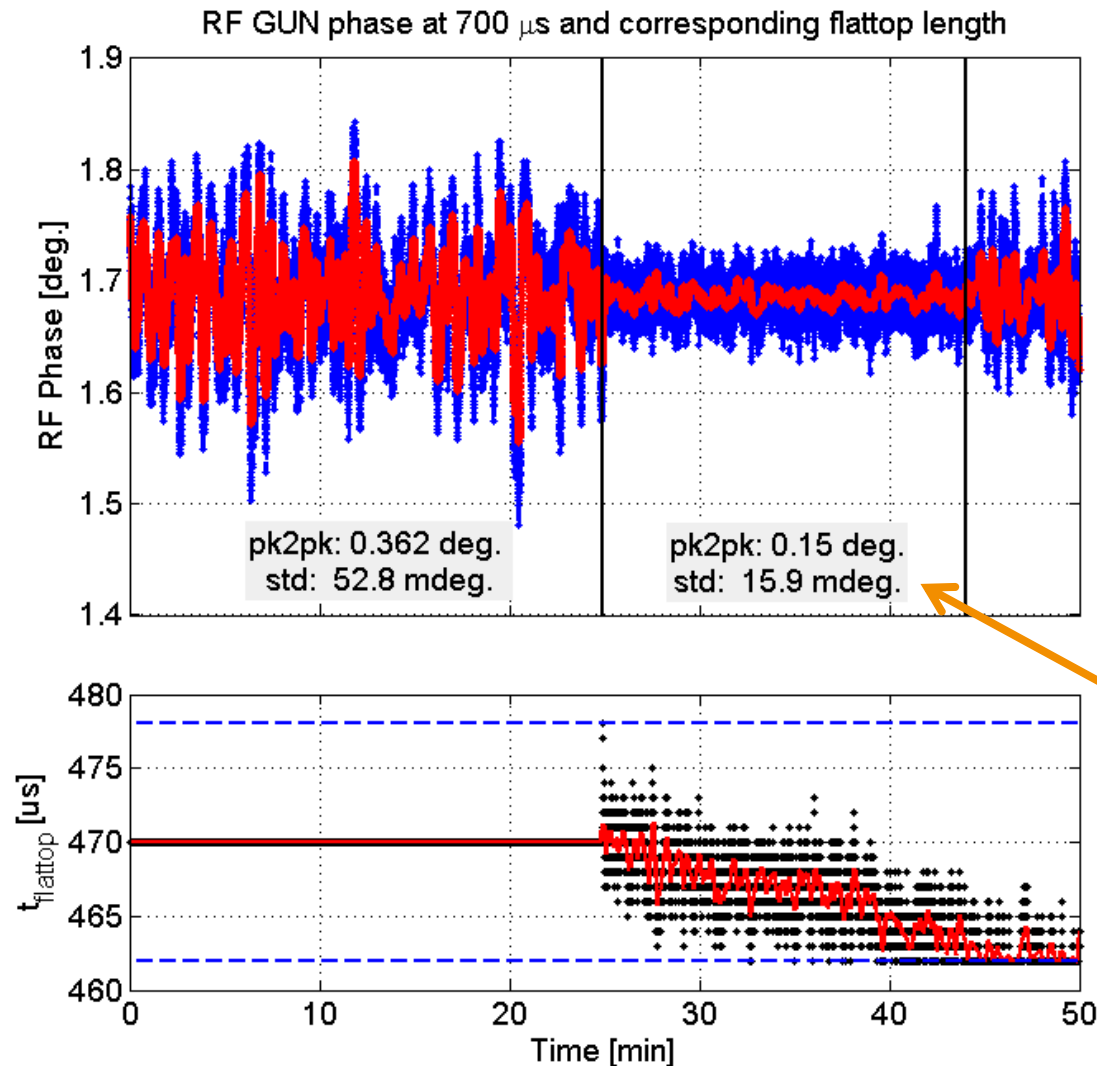- Low pass behavior of temp. sensor

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 700 μs and corresponding flattop length

pk2pk: 0.362 deg.
std: 52.8 mdeg.

pk2pk: 0.15 deg.
std: 15.9 mdeg.

> 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 (dφ = 53 mdeg. → 16 mdeg.)**

> **RF GUN temperature stabilized by x5   (from 14 mK → 3 mK)**

> **Running @ FLASH, PITZ, (XFEL)**

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

Pulse Width Modulation

Goal: **dA/A<0.01%**

dφ <0.01 deg (rms)

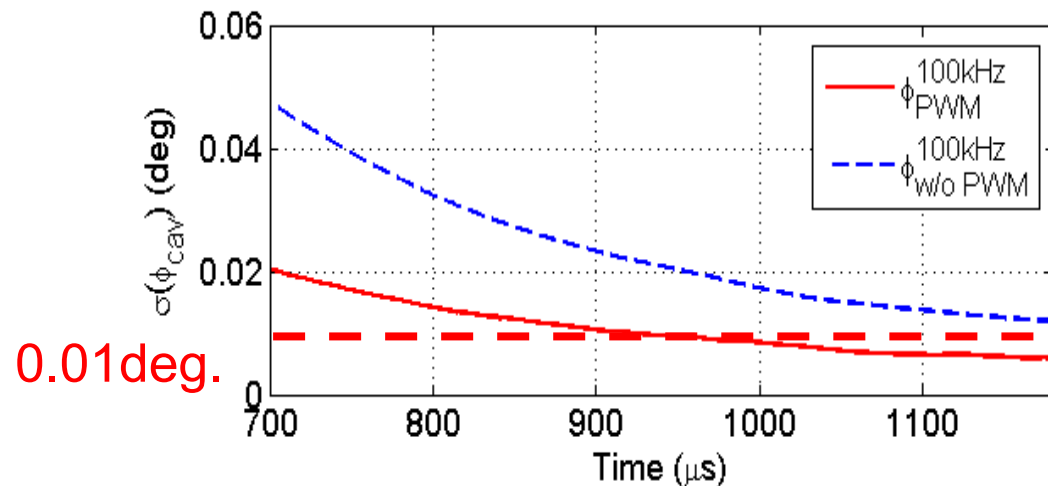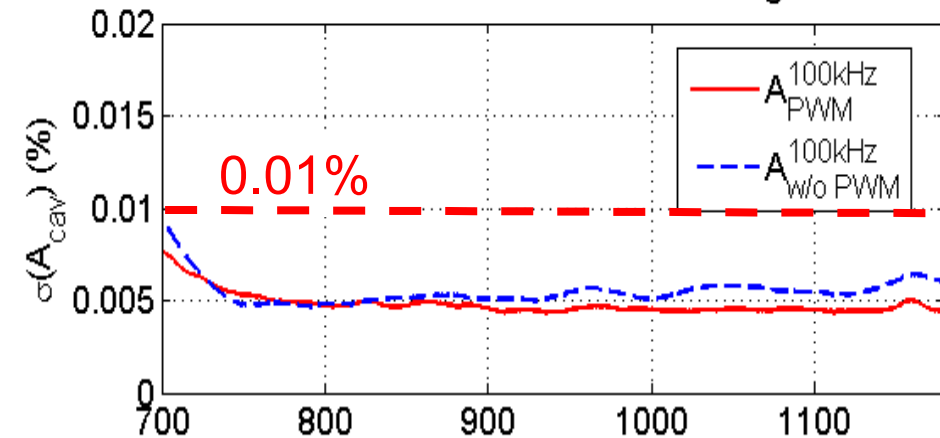**Remember:**

> 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

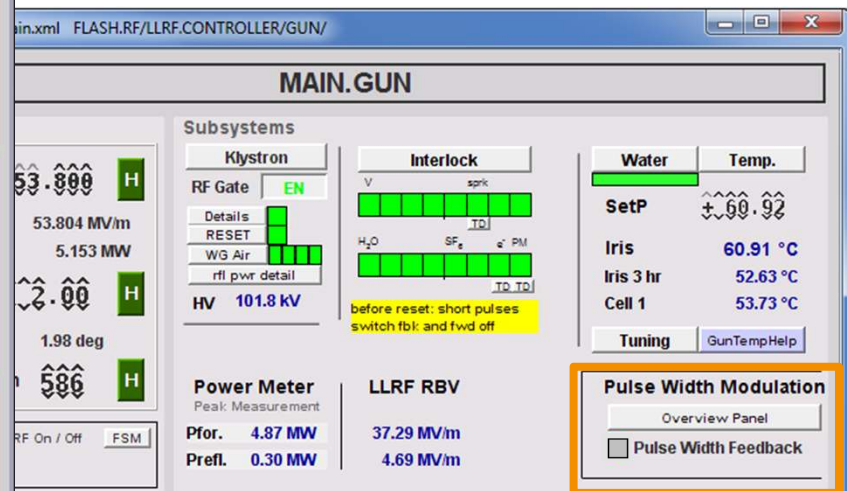> Achieved by using disturbance minimization of detuning with precision temperature control

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

Additional Info

> 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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> **LLRF**

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> **Pulse Width Modulation**

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  ▪ Temperature estimation

  ▪ Precision temperature control

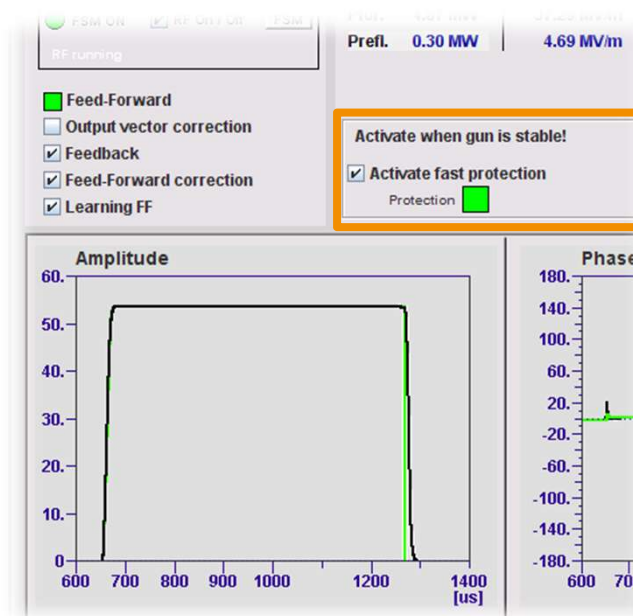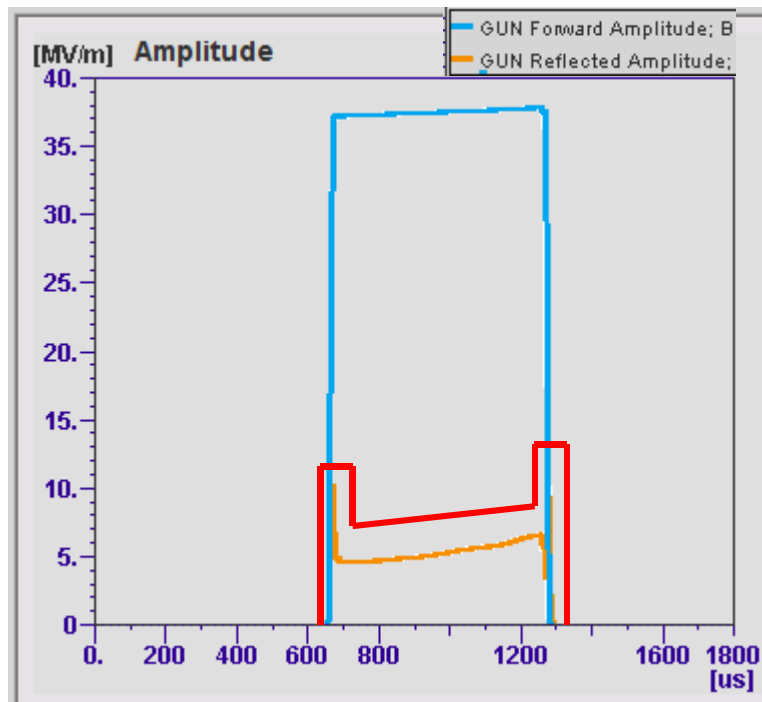> **Fast Protection**

  ▪ The why and wherefore

> **Current problems**

  ▪ After start-up

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

12.04.2016 12:05   S. Schreiber   Hist: FLASH.RF/LLRF.CONTROLL

```
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
     http://ttfinfo.desy.de/elog/XMLlist?file=/TTFelog/data/2016/07/19.02_M/2016-02-19T10:53:12-03.x
event 4:  2-Mar-2016 11:50 h no DAQ data for this event, together with RF-6, could be timing issue
     http://ttfinfo.desy.de/elog/XMLlist?file=/TTFelog/data/2016/09/02.03_a/2016-03-02T17:12:06-07.x
event 5: 18-Mar-2016  9:10 h cooling water pressure oscialltions
     http://ttfinfo.desy.de/elog/XMLlist?file=/TTFelog/data/2016/11/18.03_a/2016-03-18T16:08:07-01.x
event 6: 11-Apr-2016  16:08 h sudden phase jump, also ACC1, llrf issue with reference RF
     http://ttfinfo.desy.de/elog/XMLlist?file=/TTFelog/data/2016/15/11.04_a/2016-04-11T17:36:35-07.x
```
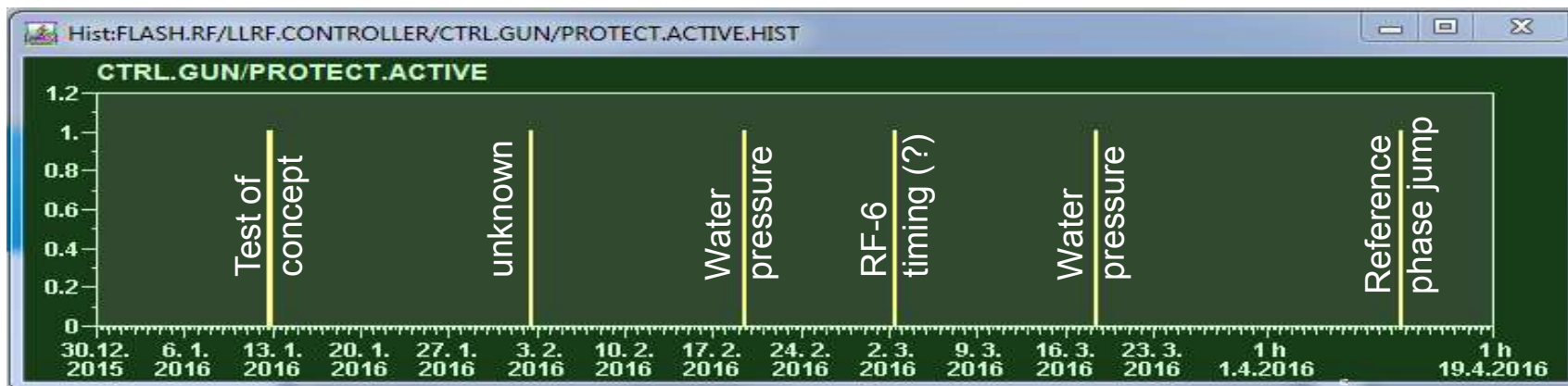
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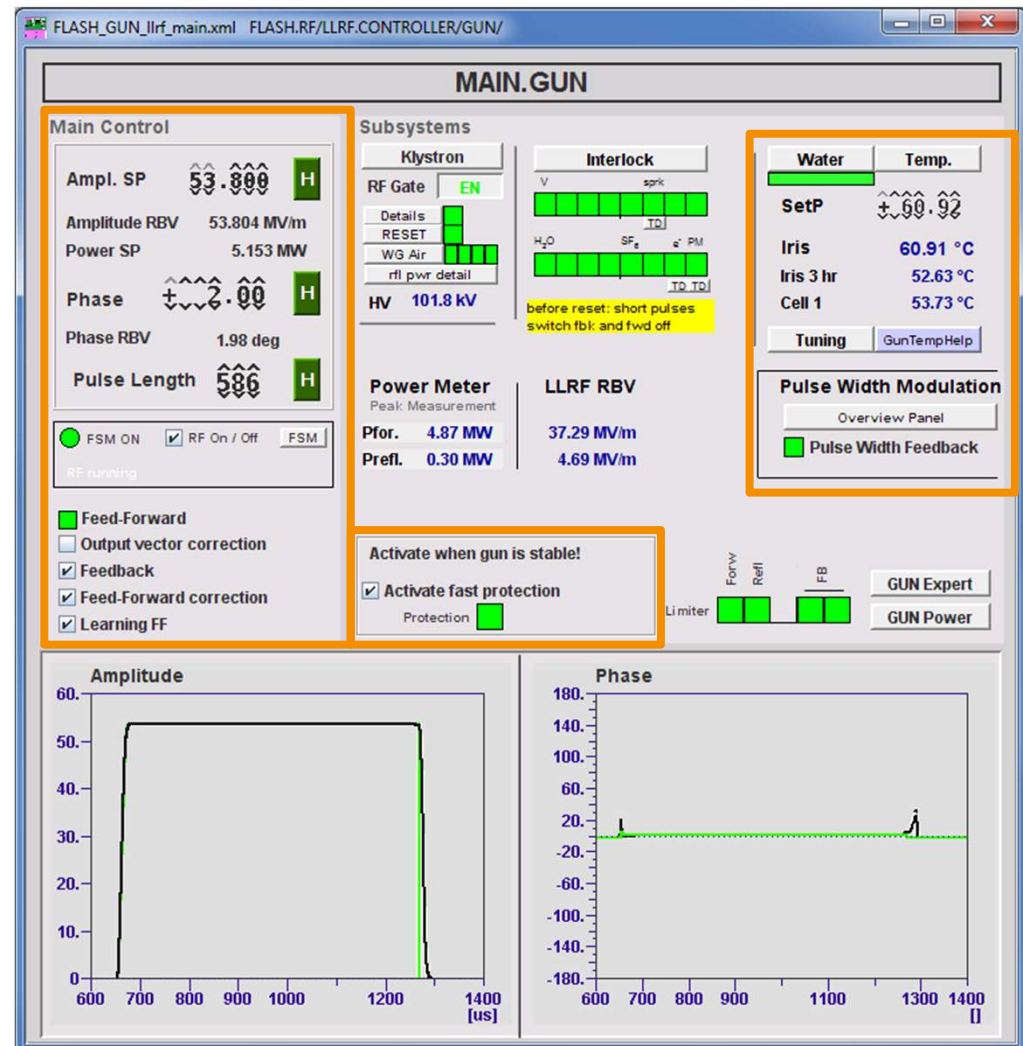- Learning Feedforward

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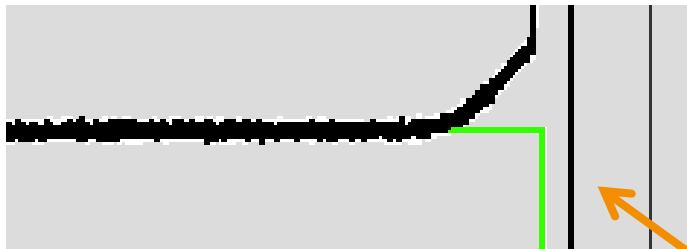- The why and wherefore

> **Current problems**
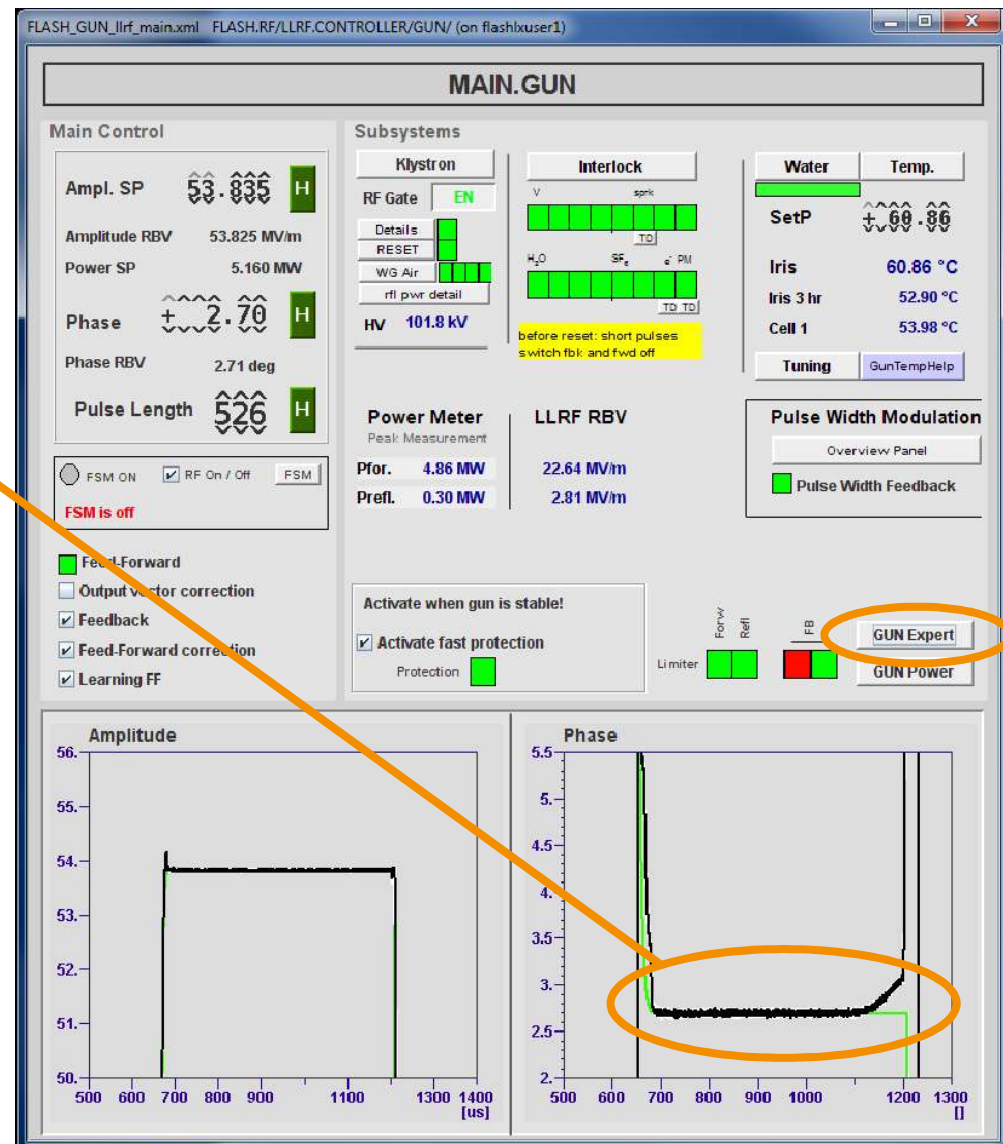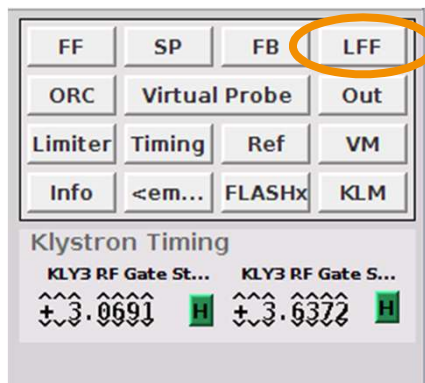
- After start-up

Current Problems

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

> ## How to check?
  - Look in LFF panel

Current Problems

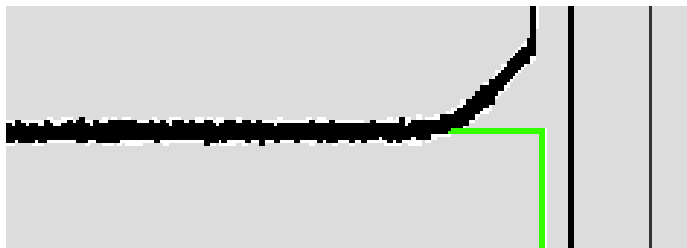> RF gun start-up without FB, LFF

(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
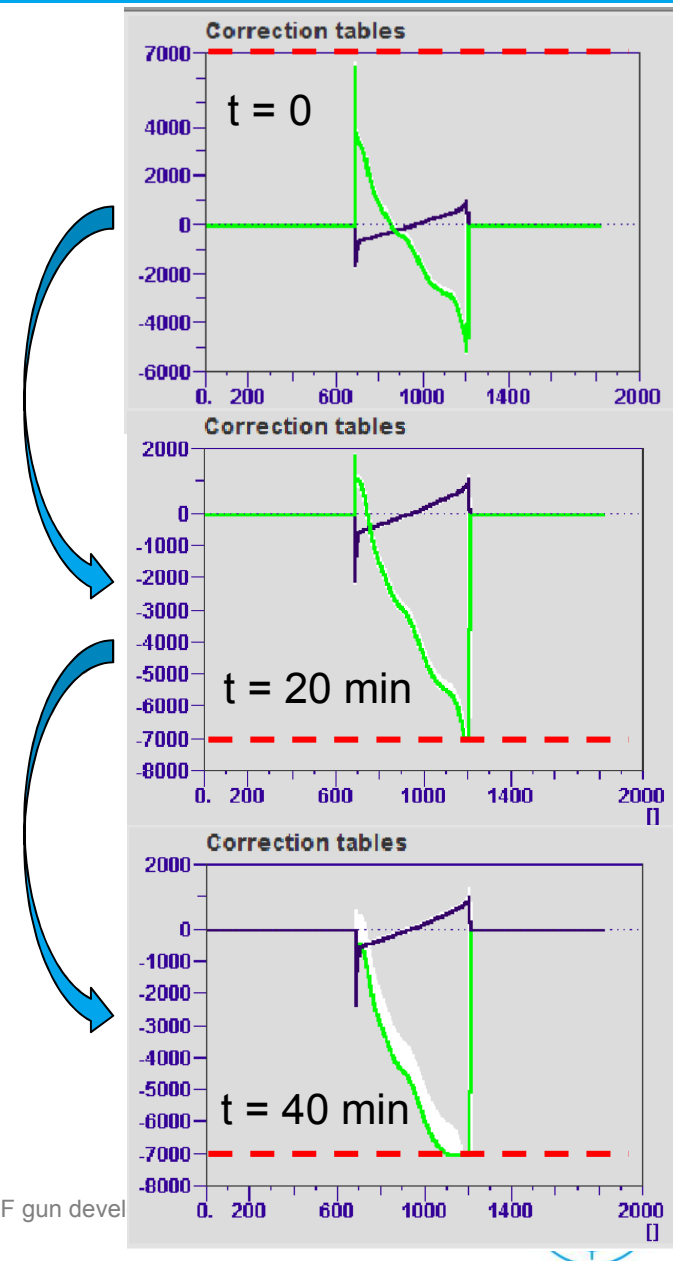
→ t = 0

(3) FF correction tables 20 minutes later

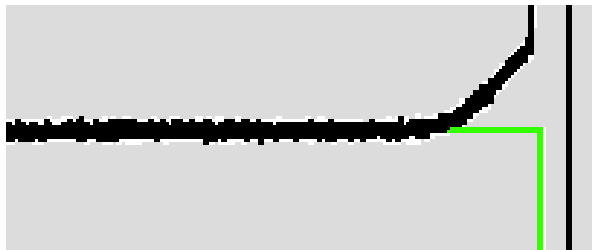(4) After 40 minutes

- FF tables (Q channel) hits limit

Why?
Slowly waveguide heating (guess)

Current Problems

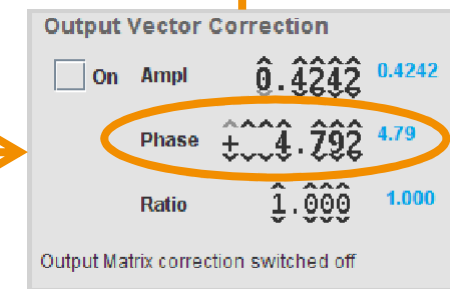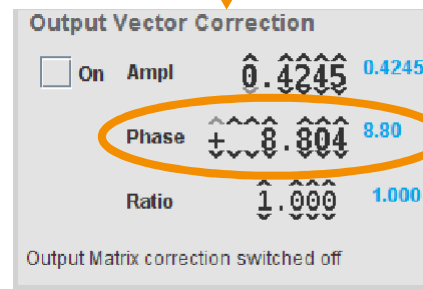> ## After RF gun start-up
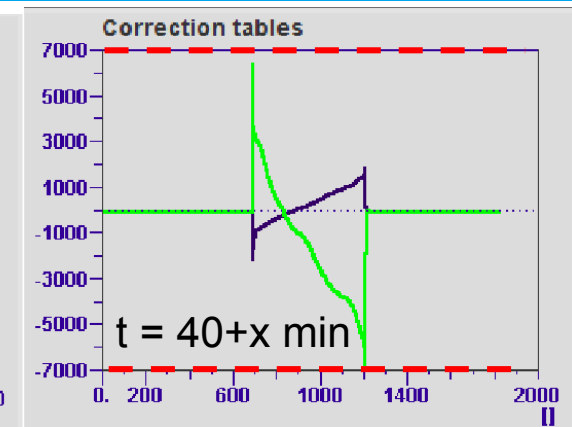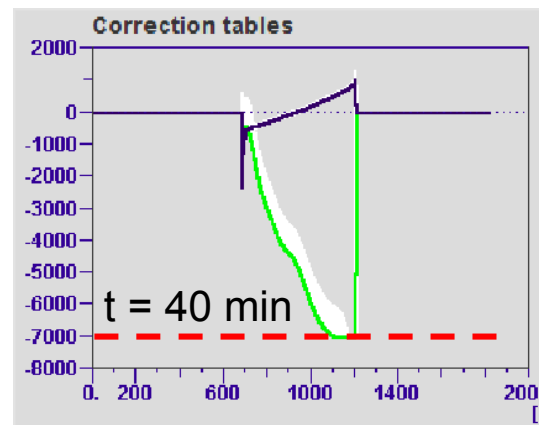
- Phase at end is not on set-point

> ## Why?

- Slowly waveguide heating (guess)

> ## How to check?

- Look in LFF panel
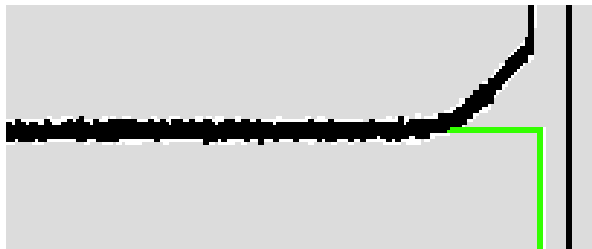
> ## What can I do?

- Adjust OVC phase by ~ -4 deg

Current Problems

> ## After RF gun start-up

- Phase at end is not on set-point

> ## Why?

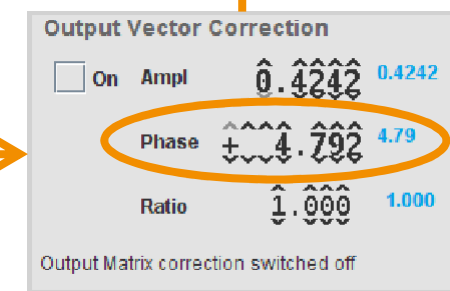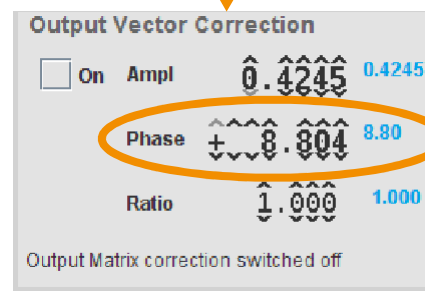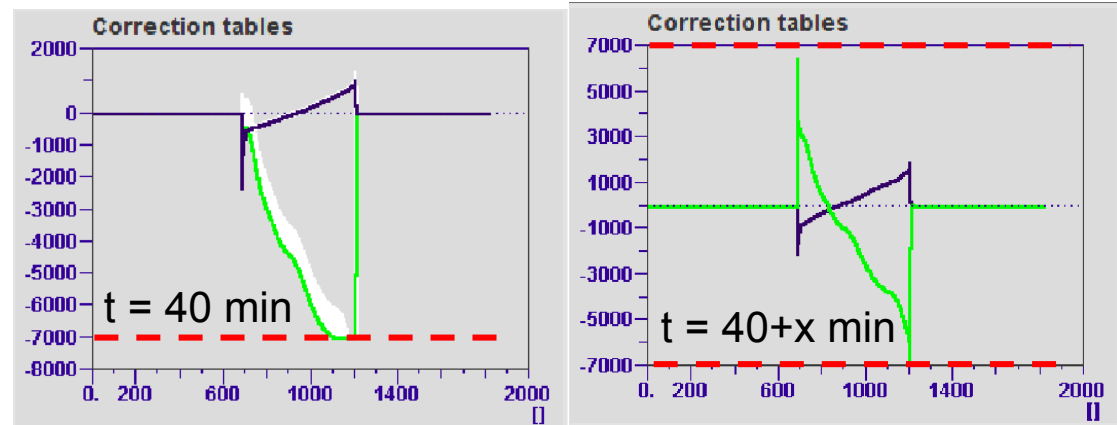- Slowly waveguide heating (guess)

> ## 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!