Intra-train Longitudinal Feedback for Beam Stabilization at FLASH

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Motivation

Demanding requirements for the bunch train stability at FLASH

• sFLASH experiment
  – HHG laser pulse length ~ 40 fs
  – longer electron bunches with flat peak current ~ 120 fs
  – bunch arrival time jitter < 40 fs

• Pump-probe experiments
  – Two types of experiments
    • Single shot resolved – mainly interested in measurement of arrival time, repeatability
    • Integrating experiments – detectors integrate over entire macro pulses and every bunch must come at the same time – beam arrival time as good as possible (<10fs out of spec)
LLRF control systems stabilize field in the cavities:
- **Intra-pulse** feedback
- **Pulse-pulse** feedback

Beam based feedback stabilize beam properties
- **Intra-train** feedback
- **Pulse-pulse** feedback
Beam Based Feedback

Implementation Goals

Actuators: LLRF Systems

Sensor: Beam diagnostics

fast (intra-bunch)

adaptive (pulse-pulse)
Beam Diagnostic Components

- Beam Arrival Monitors (BAM)
- Bunch Compression Monitors (BCM)
- Charge Measurement (by toroids)
- Master Laser Oscillator (MLO)
Optical Synchronization System

Installation at FLASH
Beam Arrival Monitor

Detector

- Reduced dependency on beam orbit
- Reduced dependency on bunch charge
- Sensitivity in terms of % modulation per fs timing change

Diagram showing the pick-up design drawing, courtesy of K. Hacker.
Beam Arrival Monitors

Front-end Electronics

Top view

Bottom view
Beam Compression Measurement

Detector

Radiation process:
• electron beam passes slitted metallized screen
• expanded electric field from bunch is diffracted
• screen tilt of 45 allows observation

Coherence effect:
• wavelength is comparable or longer than bunch length
• radiated power is inversely proportional to bunch length
• scales quadratically in charge

\[ \frac{dU}{d\lambda}_{\text{bunch}} \approx \frac{dU}{d\lambda}_{\text{e}^{-}} \cdot \left[ N + N^2 \cdot \left| \text{FT}\{I_{\text{norm}}(z)\} \right|^2 \right] \]

Detection:
• pyro electric element LiTaO3 (2mm x 2mm x 27 um)
• deposited heat induces surface charge
• metallization forms a capacitor
• optional black coating increases response at low \( \lambda\)’s

Courtesy of S. Wesch (DESY)
Beam Compression Measurement

Front-end Electronics

Oscillation at 1.17 MHz

Pile-up effect
Low Level RF Control Systems

LLRF Systems upgrade during FLASH shutdown allowed implementation of the beam based feedback
- All modules controlled by the same hardware board SIMCON-DSP
- Unified firmware and software
- Connected signals from beam diagnostic systems

LLRF Control Systems
- Stabilize amplitude and phase of the accelerating field in the cavities
- Intra-pulse feedback with MIMO controller
- Pulse-pulse algorithms (tables adaptation, calibration, ...)
- Frequency control of the cavities using piezo sensors and actuators
Low Level RF Control Systems

System setup

Master oscillator

RF

Vector Modulator

Klystron

Power transmission

LO generation

Timing

Digital Feedback Board

FPGA

DSP

ADC

DAC

ADC

ADC

LO for/ref power

Probe

Cavity

RF

LO

IF
Beam Based Feedbacks:

- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23

Results from BBF running at BC2
Low Level RF Control Systems

Intra-train BBF Implementation

FPGA

Control Tables

LLRF SP Table

Set point

SP Modulation

ADC

Intra-train BBF Algorithm

Beam Based Signals

Intra-train beam based feedback

Optolink

Intra-pulse LLRF feedback

Field Detection

Vector Sum

Error Signal

Feedback Controller

DAC

To Klystron

Cavity Probes

ADC

Intra-pulse LLRF feedback

SIMCON-DSP
Low Level RF Control Systems

Intra-train BBF Implementation

Control System

LLRF Control Tables

Toroid
- ADC9
  - Charge Measurement
  - Pyro SP Table
  - LLRF SP Table

BCM
- ADC10
  - Peak Detection
  - Gating
  - Charge Correction
  - Transfer Matrix
  - SP Signal Modulation

BAM
- Optical Link
- t_{sample}
- Q_{nom}

FPGA

Δt
ΔU
ΔΦ
ΔA/A

MPS
Low Level RF Control Systems

Pulse-pulse BBF Implementation

Operator & LLRF expert
Setpoints: \( A, \varphi \) & Parameters: timing, ...

FPGA

Beam based SP correction
Model based FF & SP tables
Learning Feed forward
Bunch Pattern

Beam based SP correction
SP table
FF table
FF_CORR table
FF_BLC table

Beam signals
Intra-train BBF Algorithm
Rot
Field detection
MIMO
Rot
DAC

Q
MPS

DAC
BBF Calibration
Transfer Matrix Determination

\[
\begin{align*}
\Delta t_{BC2} \\
\Delta C_{BC2}
\end{align*}
\]

\[
\begin{pmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{pmatrix}
\begin{pmatrix}
T_{13} & T_{14} \\
T_{23} & T_{24}
\end{pmatrix}
\]

measure

\[
\begin{pmatrix}
\frac{\Delta A_1}{A_1} \\
\frac{\Delta \phi_1}{\phi_1} \\
\frac{\Delta A_{39}}{A_{39}} \\
\frac{\Delta \phi_{39}}{\phi_{39}}
\end{pmatrix}
\]

scanning

calculate
BBF Calibration
Transfer Matrix Determination

Beam Arrival Time Change

Bunch Compression Change

off crest

ACC1

ACC39

on crest

SP Ampl ACC1        SP Ph. ACC1                    SP Ampl ACC39          SP Ph. ACC39

SP Ampl ACC1        SP Ph. ACC1                    SP Ampl ACC39          SP Ph. ACC39

Waldemar Koprek, DESY
FLASH Seminar, 02.11.2010
Measurements

Learning Feed Forward

Beam based SP correction
Model based FF & SP tables
Learning Feed forward
Bunch Pattern

Operator & LLRF expert
Setpoints: A, φ & Parameters: timing, ...

SP CORR table
SP table
FF table
FF CORR table
FF_BLC table

SP_BBFF table

Beam signals

Field detection

Error signal

DAC

FPGA

CPU

MIMI

DAC
Measurements

Learning Feed Forward
Measurements

Learning Feed Forward

Beam Arrival Time [ps]

Bunch Number [us]

pk-pk = 3.97 ps
pk-pk = 0.56 ps

0.5 ps
4 ps
Low Level RF Control Systems

*Intra-train BBF Implementation*

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**Intra-pulse LLRF feedback**

**Intra-train beam based feedback**

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**FPGA**

- **Control Tables**
  - **LLRF SP Table**

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**SIMCON-DSP**

- **Set point**

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**Beam Based Signals**

- **ADC**
- **Optolink**
- **Intra-train BBF Algorithm**
- **SP Modulation**

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**Intra-train BBF Implementation**

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**Beam Based Signals**

- **ADC**
- **Field Detection**
- **Vector Sum**
- **Error Signal**
- **Feedback Controller**
- **DAC**
- **To Klystron**
Measurement
Intra bunch train arrival time

Conditions:  
Full BBF on ACC1 and ACC39  
Measured after BC3  
3000 macro pulses taken

Single RF pulse

- BBF latency ~ 4μs
- ~35fs - good enough for sFLASH?
Measurement

Macro pulse arrival time jitter

No Beam Based Feedback
Learning Feed Forward ON
rms = 74 fs

With Beam Based Feedback
running in ACC1 and ACC39
rms = 5 fs

LLRF Regulation Performance

$\Delta A_1 / A_1 \sim 10^{-4}$
$\Delta \phi_1 < 0.03^\circ$

• resolution of BAM ~ 10 fs for single bunch
  can be improved to ~ fs for macro pulse
Summary

- Commissioned interfaces between LLRF system and beam diagnostic systems
  - 3DBC2 -> ACC1 and ACC39 - OK
  - 4DBC3 -> ACC39 - OK
  - 1UBC2 -> RF-Gun – installed but not tested

- Well defined and implemented a new concept of the beam BBF in the LLRF systems
  - BBF modules acts on the set point table – no direct interference with the LLRF controller feedback loop
  - Robustness – limiters on the BBF correction signals reduce risk for increased beam losses

- Successful tests with BBF on BC2
  - Prove of the concept
  - Reduction of the intra-train bunch arrival time jitter
  - Significant reduction of pulse-pulse beam arrival time jitter
  - Reduction of the repetitive errors by Learning Feed Forward
Thank you for your attention

References:

- TUOBI2 – S. Scheriber, “FLASH upgrade and first results”
- THOA3 – M. Felber et al., “RF-based Synchronization of the Seed and Pump-Probe Lasers to the Optical Synchronization System at FLASH”
- THPA04 – P. Gessler et al., “Longitudinal Bunch Arrival-Time Feedback at FLASH”
- THPA05 – S. Schulz et al., “Performance of the FLASH Optical Synchronization System Utilizing Commercial SESAM-Based Erbium Laser”
- THPA06 – P. Gessler et al., “Real-Time Sampling and Processing Hardware for Bunch Arrival Time Monitors at FLASH and XFEL”
- C. Behrens, B. Schmidt, S. Wesch†, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany, D. Nicoletti, INFN-Roma, Roma, Italy, “UPGRADE AND EVALUATION OF THE BUNCH COMPRESSION MONITOR AT THE FREE-ELECTRON LASER IN HAMBURG (FLASH)”, Proceedings of IPAC’10, Kyoto, Japan
LLRF Control Tables

Operator & LLRF expert
Setpoints: A, φ & Parameters: timing, ...

Beam based SP correction
Model based ≤ FF & SP tables
Learning Feed forward
Bunch Pattern

SP_BBF table ≤ SP_USER ≤ SP_CORR ≤ SP table
FF table ≤ FF_CORR ≤ FF_BLC ≤ FF_USER table

Beam signals

Field detection

Controller

DAC
Beam Arrival Monitors

Front-end Electronics

- self-spliced Polarisation Maintaing Fibre Section
- 2 Erbium-doped Fibre Amplifiers (EDFA)
- uncompensated fibre length in total: $\approx 5m$
- distance FRM - EOM 1: $\approx 3.5m$

(Design applied for BAM UBC2)
RF amplitude changes
FLASH: \( R_{56} = 180 \, (50) \, \text{mm} \)
XFEL: \( R_{56} = 100 \, (20) \, \text{mm} \)
LCLS: \( R_{56} = 36 \, (22) \, \text{mm} \)

RF phase changes
reduction of incoming timing jitter due to compression

\[
\Sigma_{t}^{2} \approx \left( \frac{R_{56}}{c_{0}} \frac{\sigma_{A}}{A} \right)^{2} + \left( C - 1 \right)^{2} \left( \frac{\sigma_{\phi}}{2\pi f_{RF}} \right)^{2} + \left( \frac{1}{C} \right)^{2} \Sigma_{i,t}^{2}
\]

RF requirements for 10 fs arrival time stability at FLASH:
phase stability \(< 0.005^\circ \) @ 1.3 GHz (\(\approx 10 \, \text{fs}\))
amplitude stability \(< 1.6 \times 10^{-5}\)
Master Laser Oscillator (MLO)

Pulse generation and distribution

- Promising: OneFive ORIGAMI-15
  - Repetition rate: 216.66MHz
  - Average power: > 100mW
  - Pulse duration: \( p < 150 \) fs
  - Integrated timing jitter < 5 fs in the interval [1 kHz; 10MHz]
- Mechanically robust, easy to maintain

More details in poster from Sebastian Schulz THPA05
**Low Level RF Control Systems**

*FPGA Firmware and Software Architecture*

![Diagram of RF control system](image)

- **ADC** to **Field Detection**
- **Cavity Probes**
- **Vector Sum**
- **Error Signal**
- **Feedback Controller** to **DAC**
- **To Klystron**

**Components**:
- Field Detection
- Control Tables and Registers
- VME Interface
- FPGA
- CPU
- DOOCS Server

**Control Flow**:
- ADC
- Field Detection
- Vector Sum
- Error Signal
- Feedback Controller
- DAC

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Low Level RF Control Systems

*Intra-train BBF Implementation*

- **FPGA**
  - Pyro SP Table
  - LLRF SP Table

- **Control Tables**
- **Set point**

- **Beam Based Feedback**
  - Δt
  - ΔA/A
  - ΔΦ

- **SP Modulation**

- **Field Detection**
  - ADC
  - Vector Sum
  - Error Signal

- **Feedback Controller**

- **DAC**

- **To Klystron**

- **Toroid**
- **ADC**
  - Charge

- **BAM**
  - Gigalink
  - SFP
- **BCM**
  - ADC
  - ΔU

- **MPS**
  - Dig. input

- **Cavity Probes**
  - ADC
  - ΔA/A

- **SIMCON-DSP**