Intra-train Longitudinal Feedback for Beam Stabilization at FLASH

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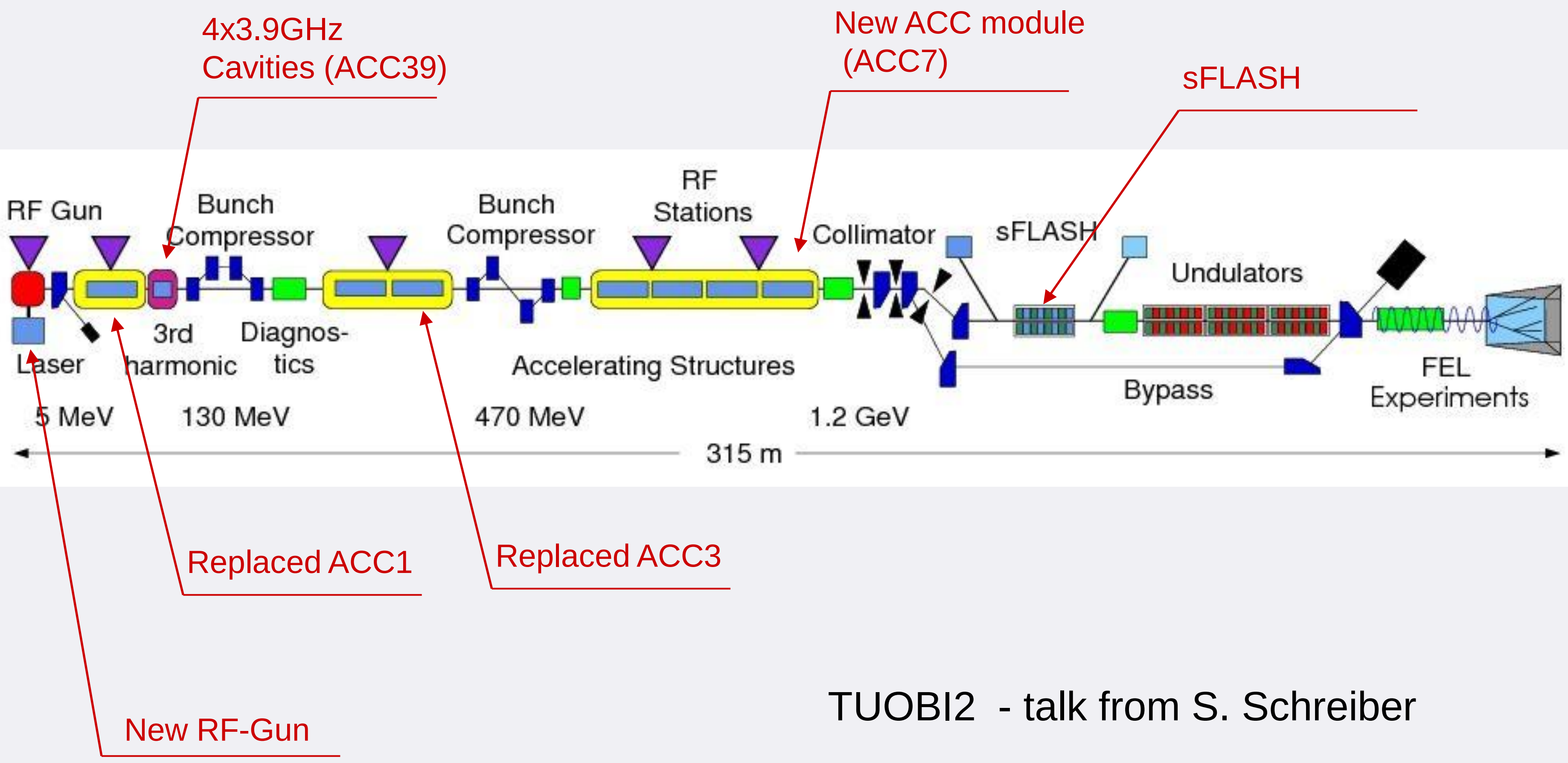
Motivation

Demanding requirements for the bunch train stability at FLASH

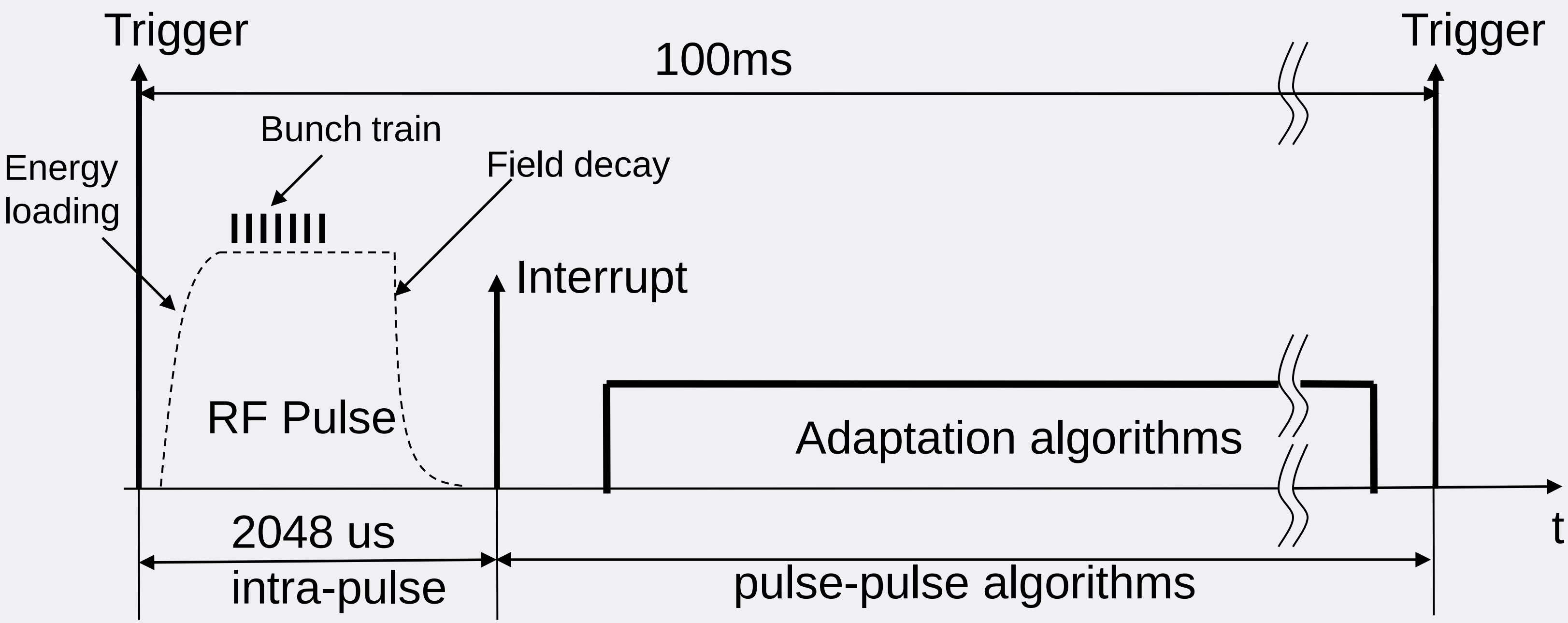
- sFLASH experiment
  - HHG laser pulse length ~ 40 fs
  - longer electron bunches with flat peak current ~ 120 fs
  - bunch arrival time jitter < 40 fs
- Pump-probe experiments
  - Two types of experiments
    - Single shot resolved – mainly interested in measurement of arrival time, repeatability
    - 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)

FLASH
Overview



TUOBI2 - talk from S. Schreiber

FLASH
Pulse Mode Operation



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

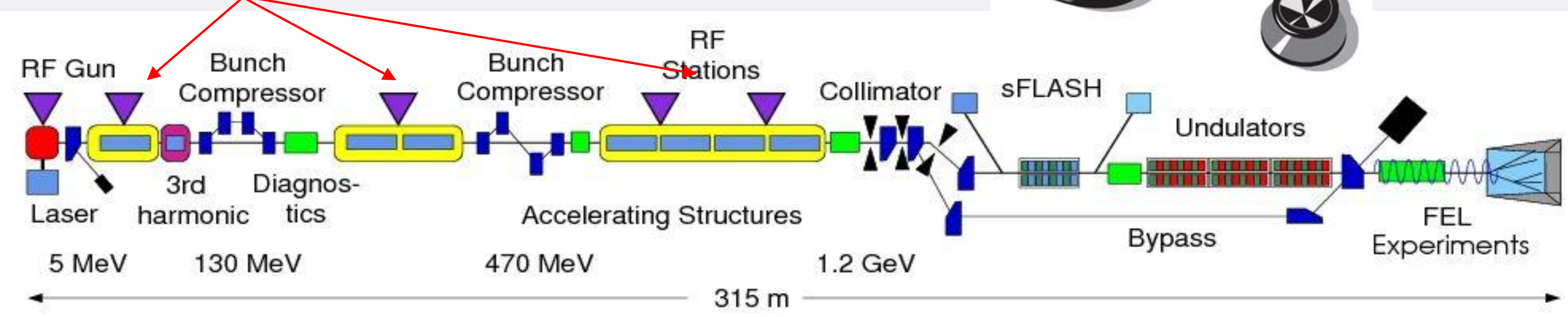
Beam Based Feedback
Implementation Goals

Actuators: LLRF Systems

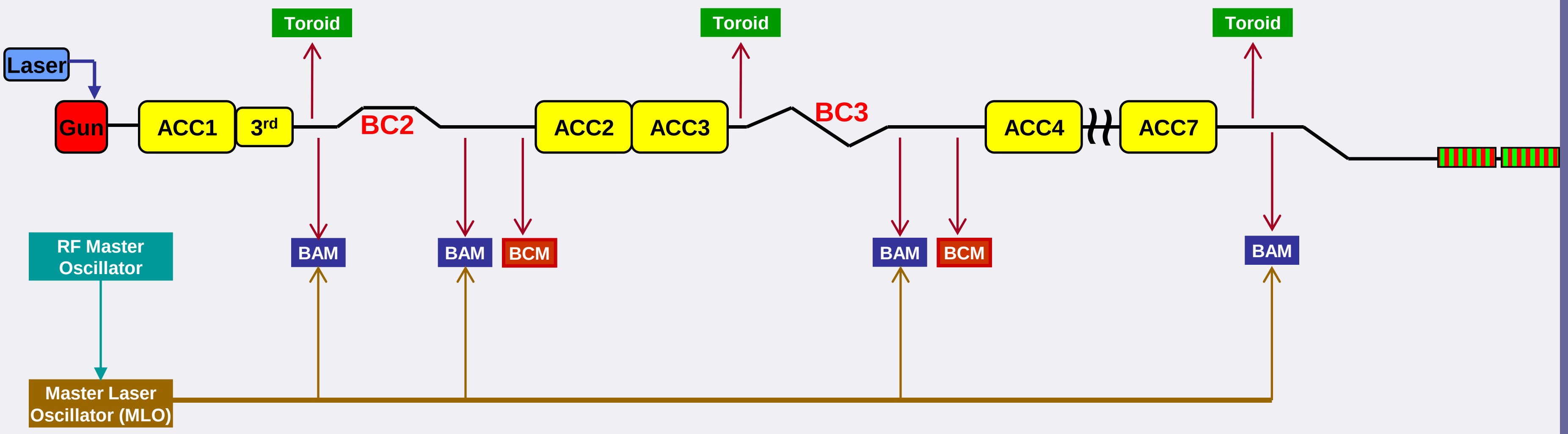
Sensor: Beam diagnostics

fast (intra-bunch)

adaptive (pulse-pulse)

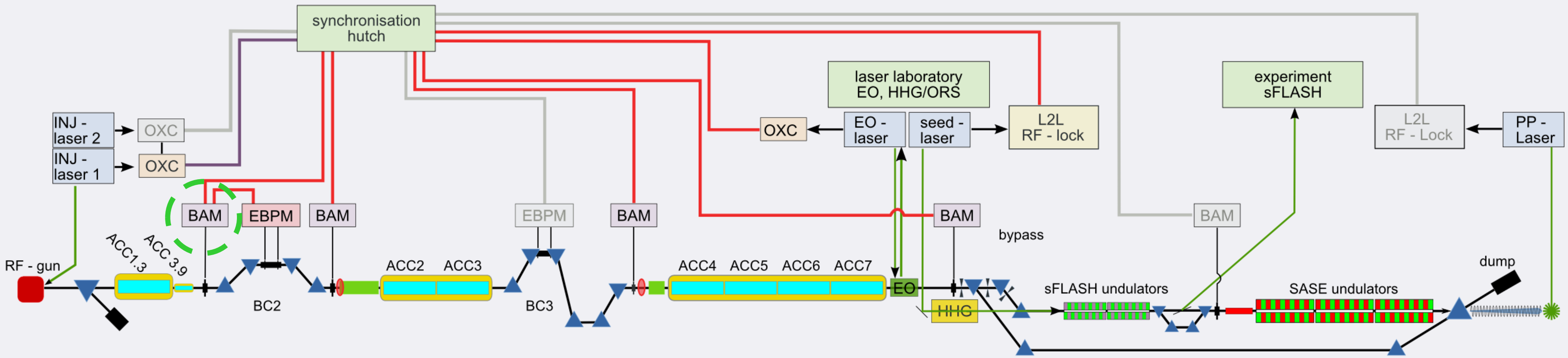


Beam Diagnostic Components



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

Optical Synchronization System
Installation at FLASH



More details in poster from Sebastian Schulz THPA05

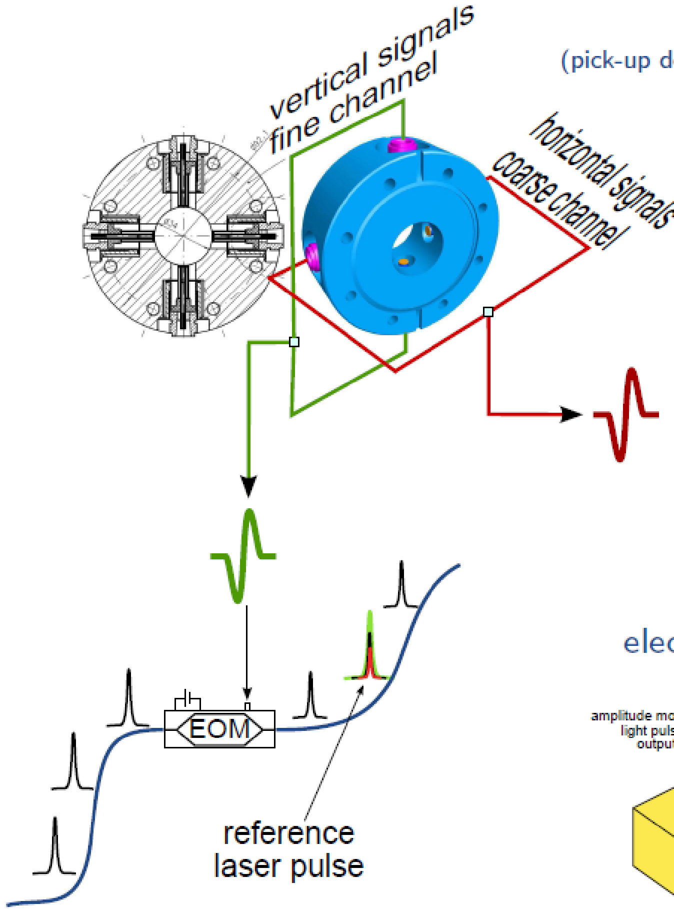
and in the following talk by Matthias Felber

Beam Arrival Monitor
Detector

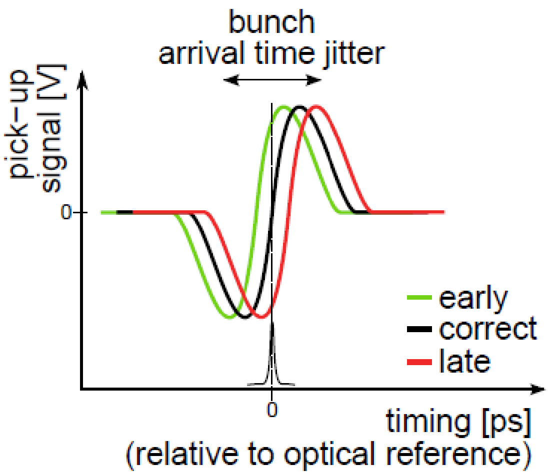
reduced dependency on beam orbit

reduced dependency on bunch charge

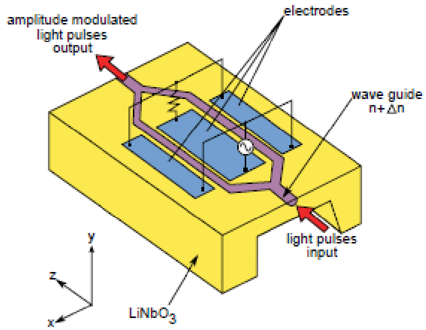
sensitivity in terms of
% modulation per fs timing change



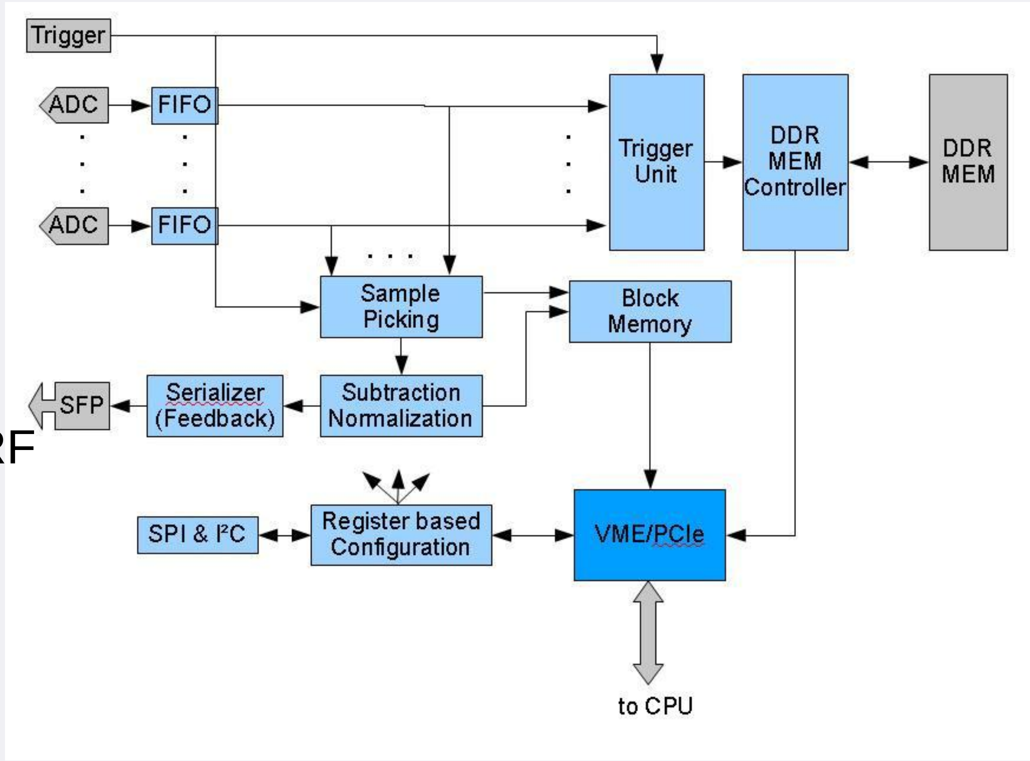
(pick-up design drawing, courtesy: K. Hacker)



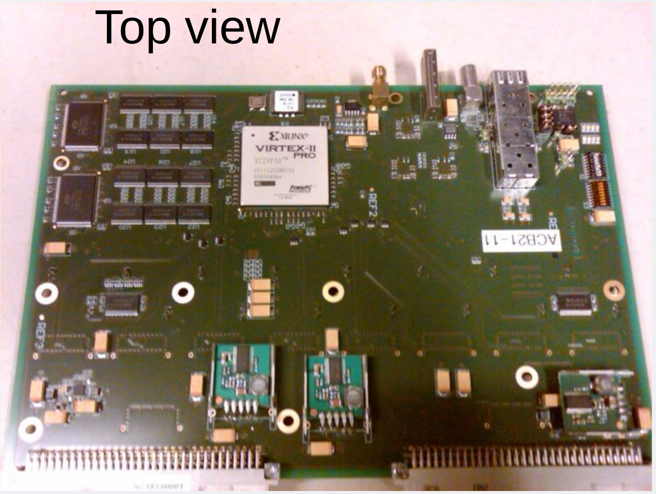
electro-optical modulator

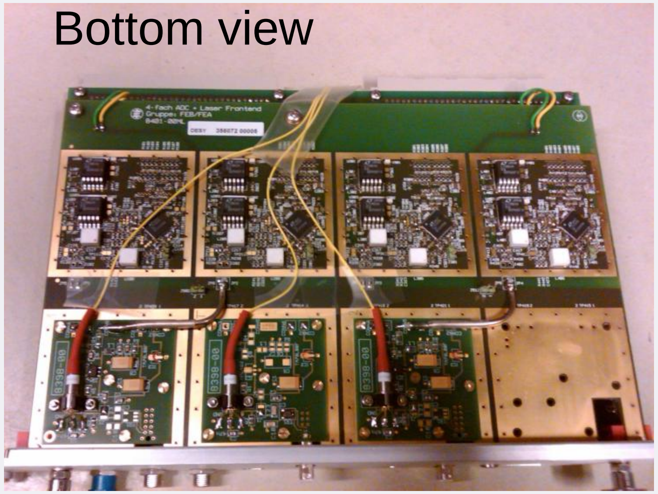


Beam Arrival Monitors
Front-end Electronics



to
LLRF





More details in posters from Patrick Gessler THPA04 and THPA06

Beam Compression Measurement
Detector

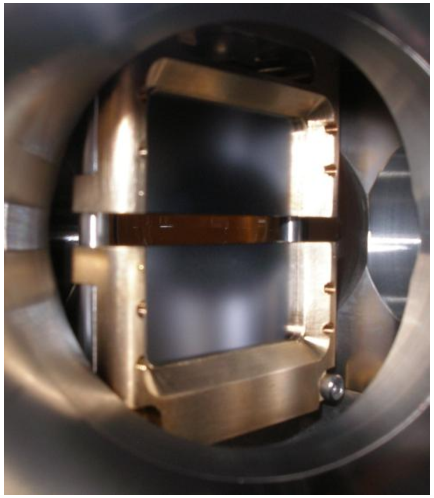
Courtesy of S. Wesch (DESY)

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

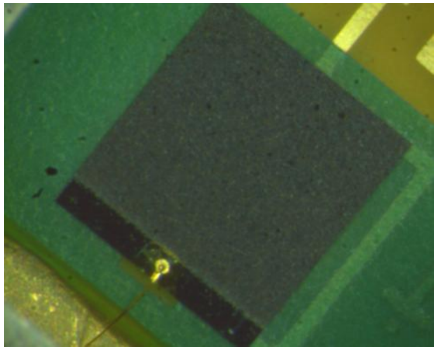
Coherence effect:
- wavelength is comparable or longer than bunch length
- radiated power is inversely propotional to bunch length
- scales quadraticaly in charge

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

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 λ's

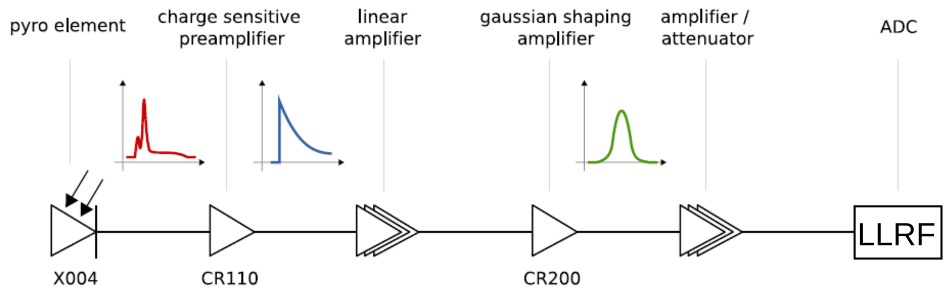


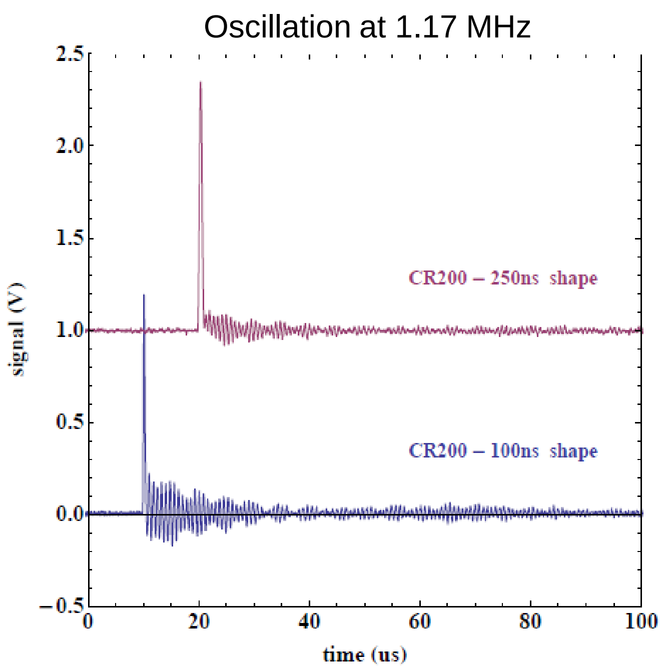
Diffraction radiator (backview)

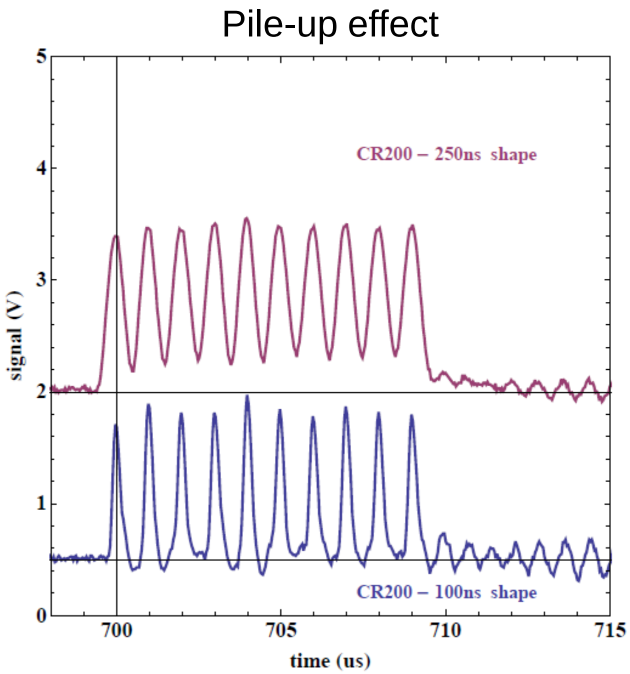


Pyro element

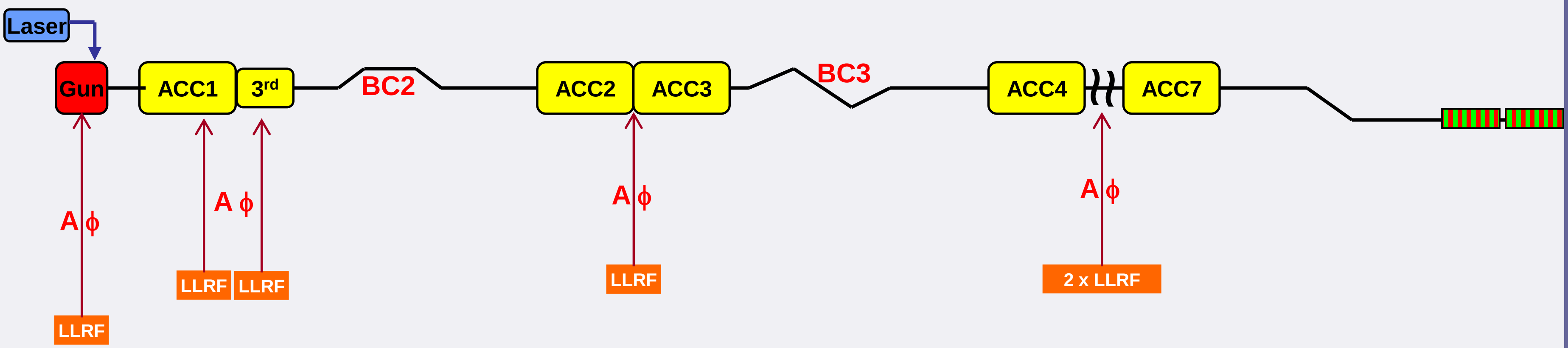
Beam Compression Measurement
Front-end Electronics







Low Level RF Control Systems



LLRF Systems upgrade during FLASH shutdown allowed implementation of the beam based feedback

- All modules controller by the same hardware board SIMCON-DSP
- Unified firmware and software
- Connected signals from beam diagnostic systems

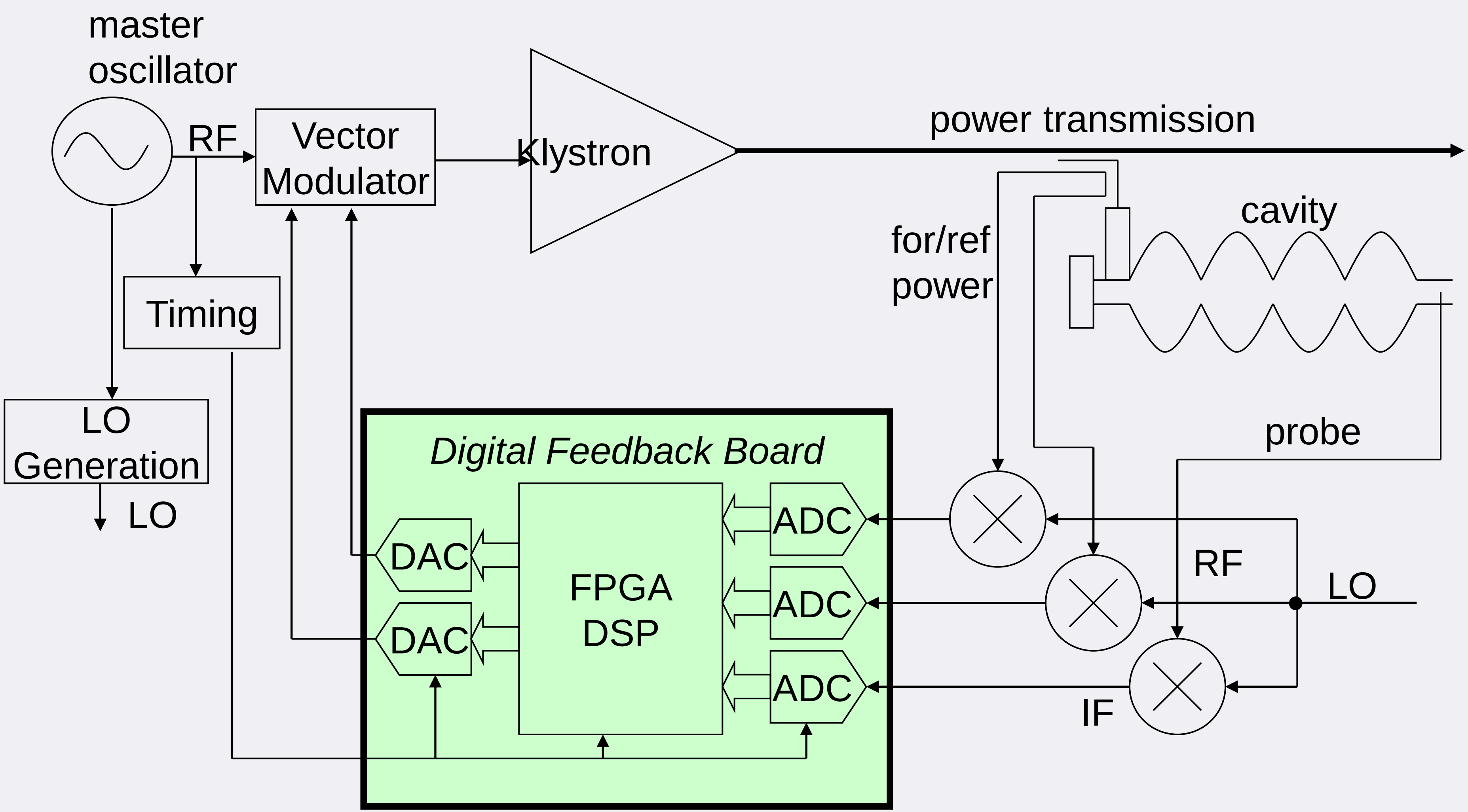
LLRF Control Systems

- Stabilize amplitude and phase of the accelarting 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

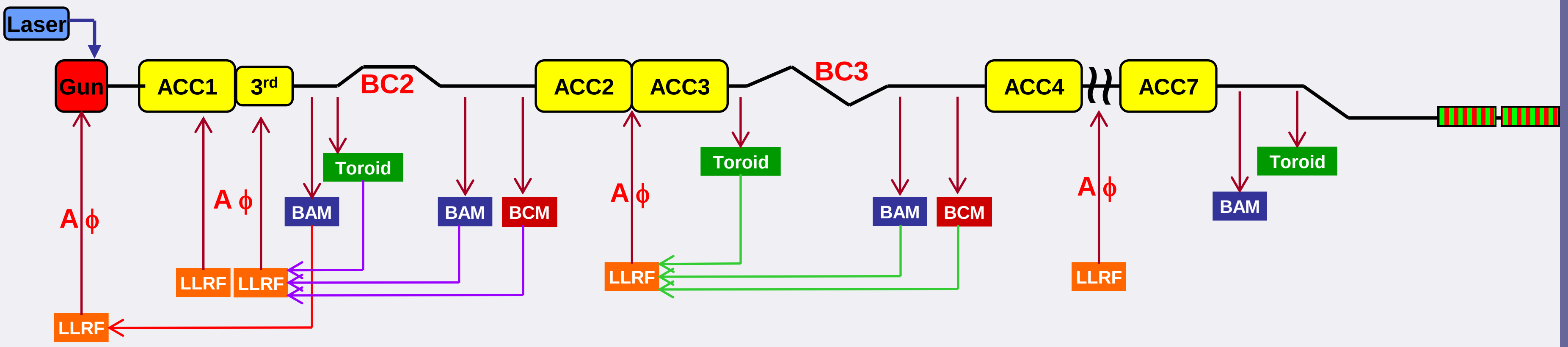
SIMCON-DSP

Low Level RF Control Systems

System setup



Beam Based Feedback
Installation

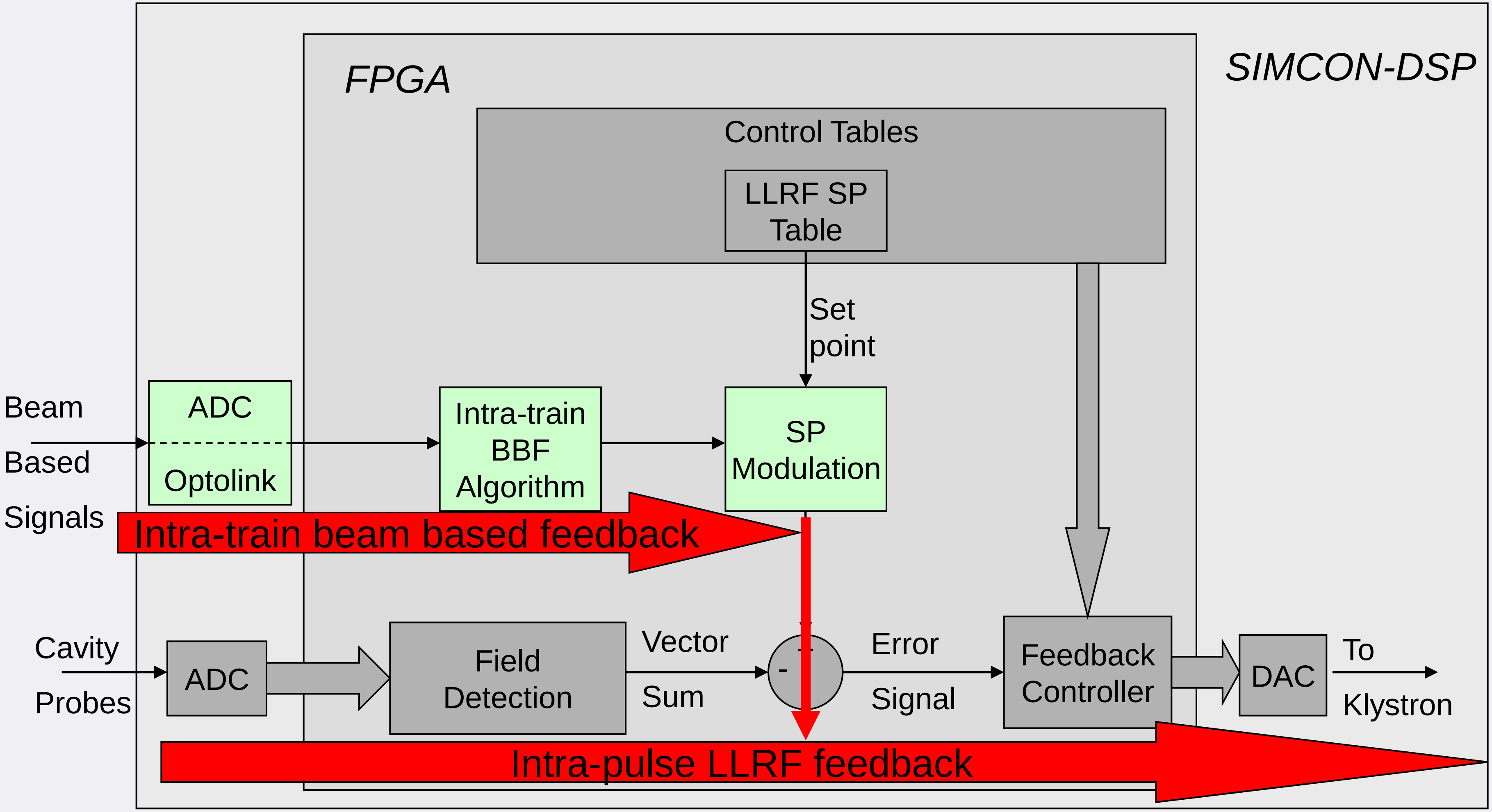


Beam Based Feedbacks:

- 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

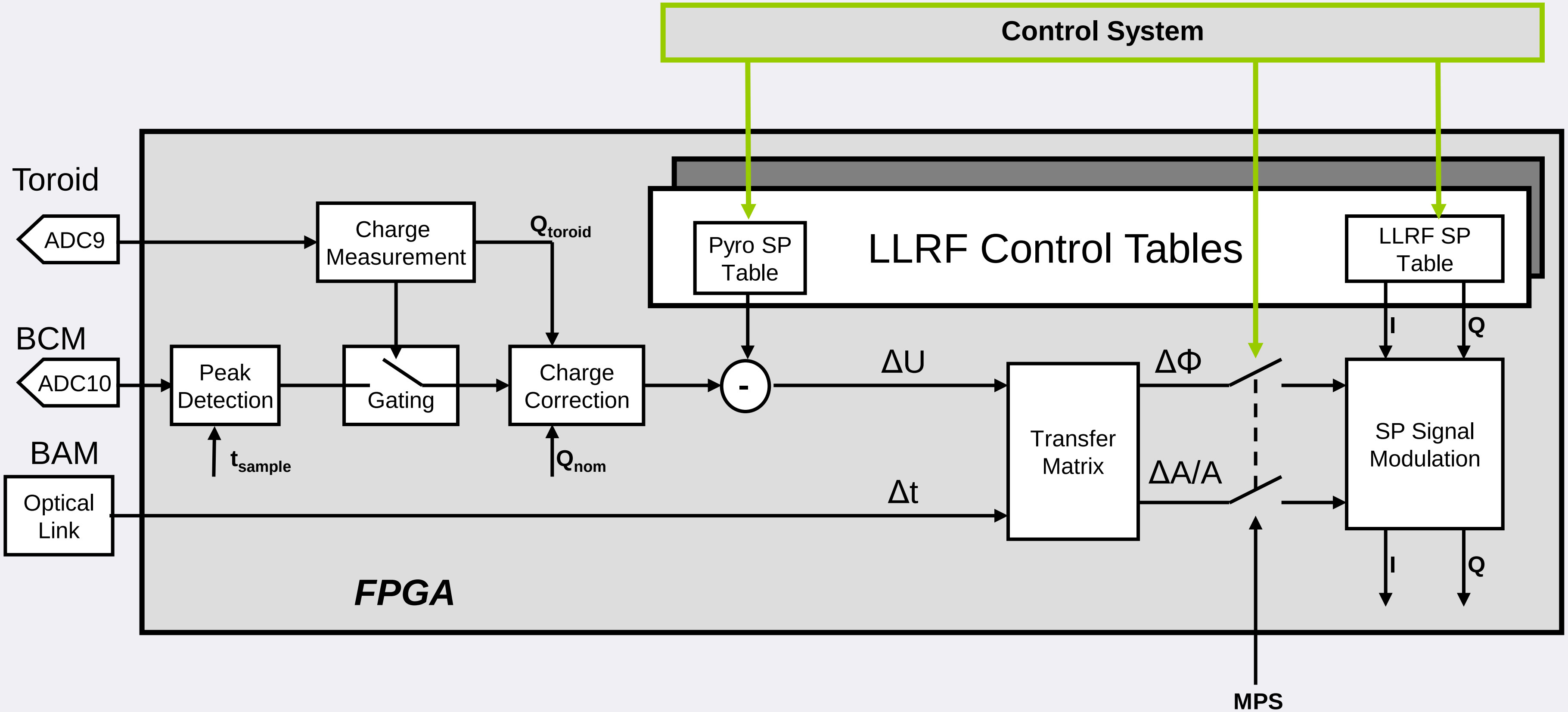
Results from BBF running at BC2

Low Level RF Control Systems
Intra-train BBF Implementation



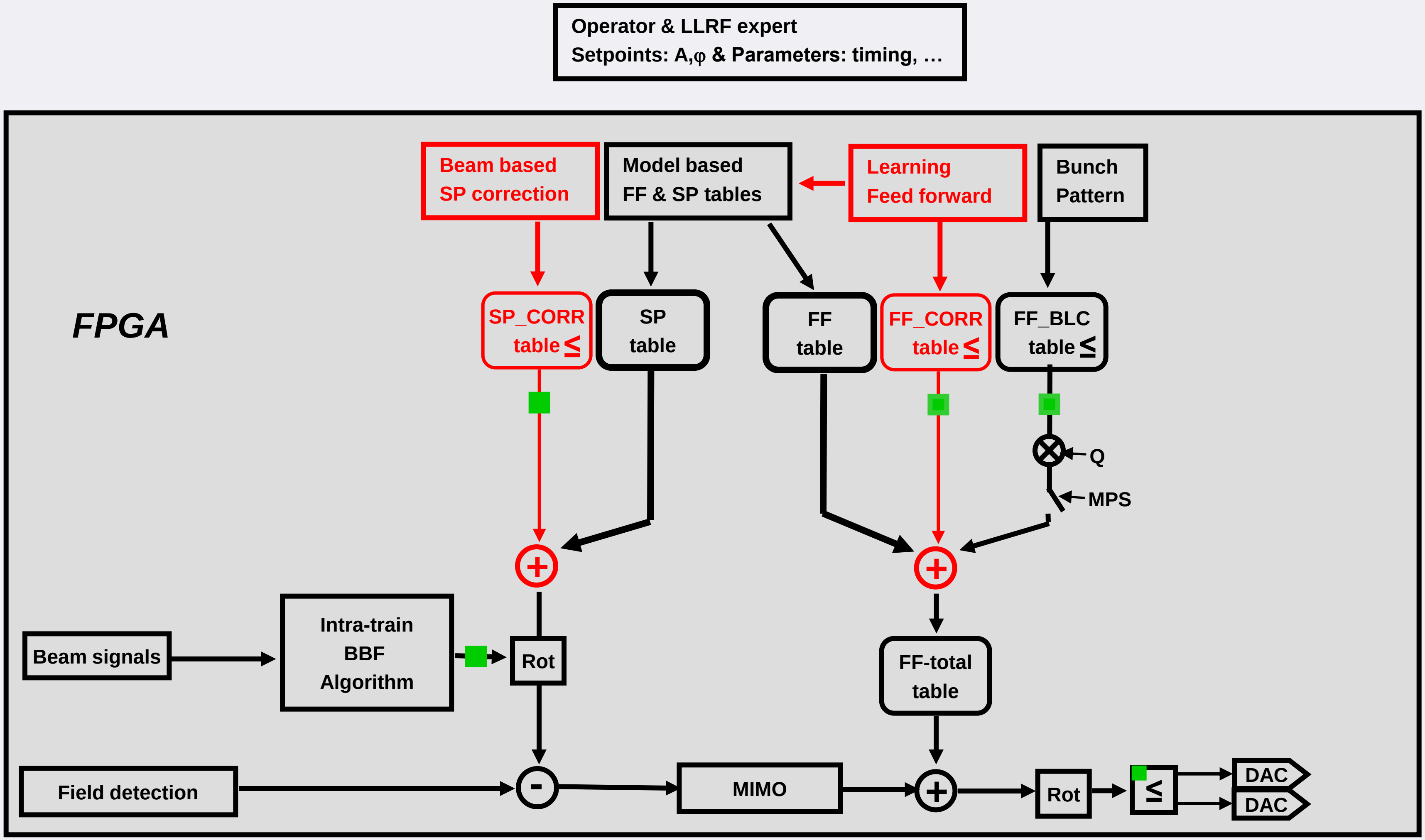
Low Level RF Control Systems

Intra-train BBF Implementation



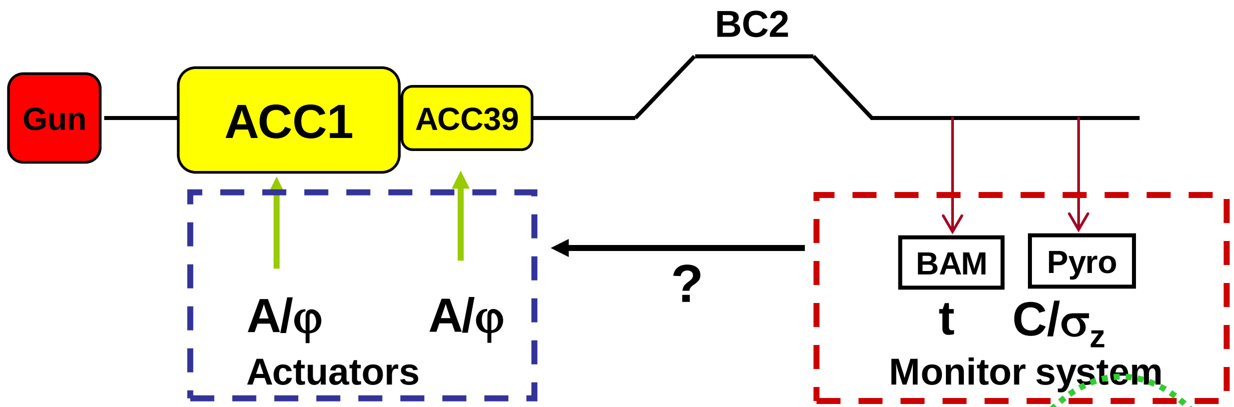
Low Level RF Control Systems

Pulse-pulse BBF Implementation



BBF Calibration

Transfer Matrix Determination



measure

ACC1 ACC39

scanning

$$\begin{bmatrix} \Delta t_{BC2} \\ \Delta C_{BC2} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \end{bmatrix} * \begin{bmatrix} \frac{\Delta A_1}{A_1} \\ \Delta \phi_1 \\ \frac{\Delta A_{39}}{A_{39}} \\ \Delta \phi_{39} \end{bmatrix}$$

calculate

BBF Calibration

Transfer Matrix Determination

off crest

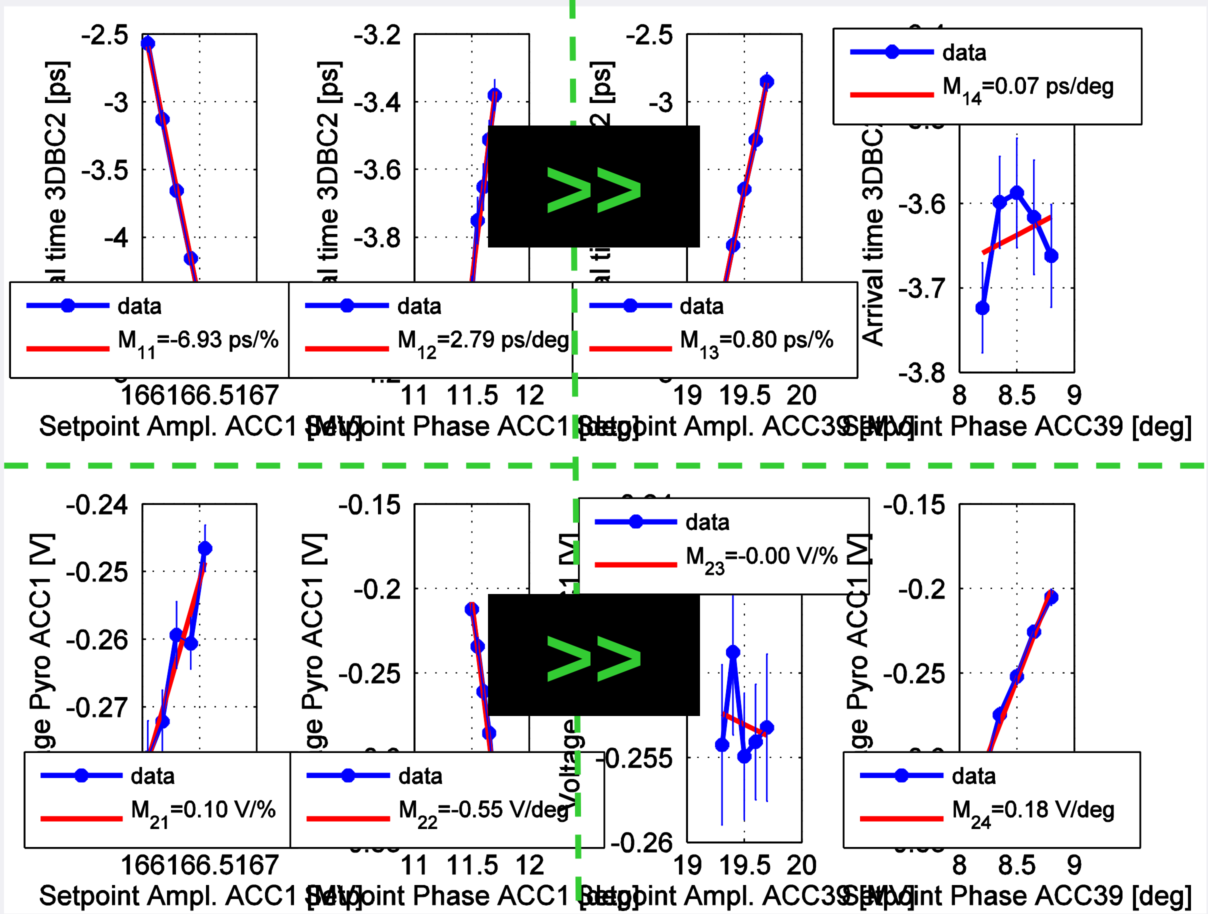
ACC1

ACC39

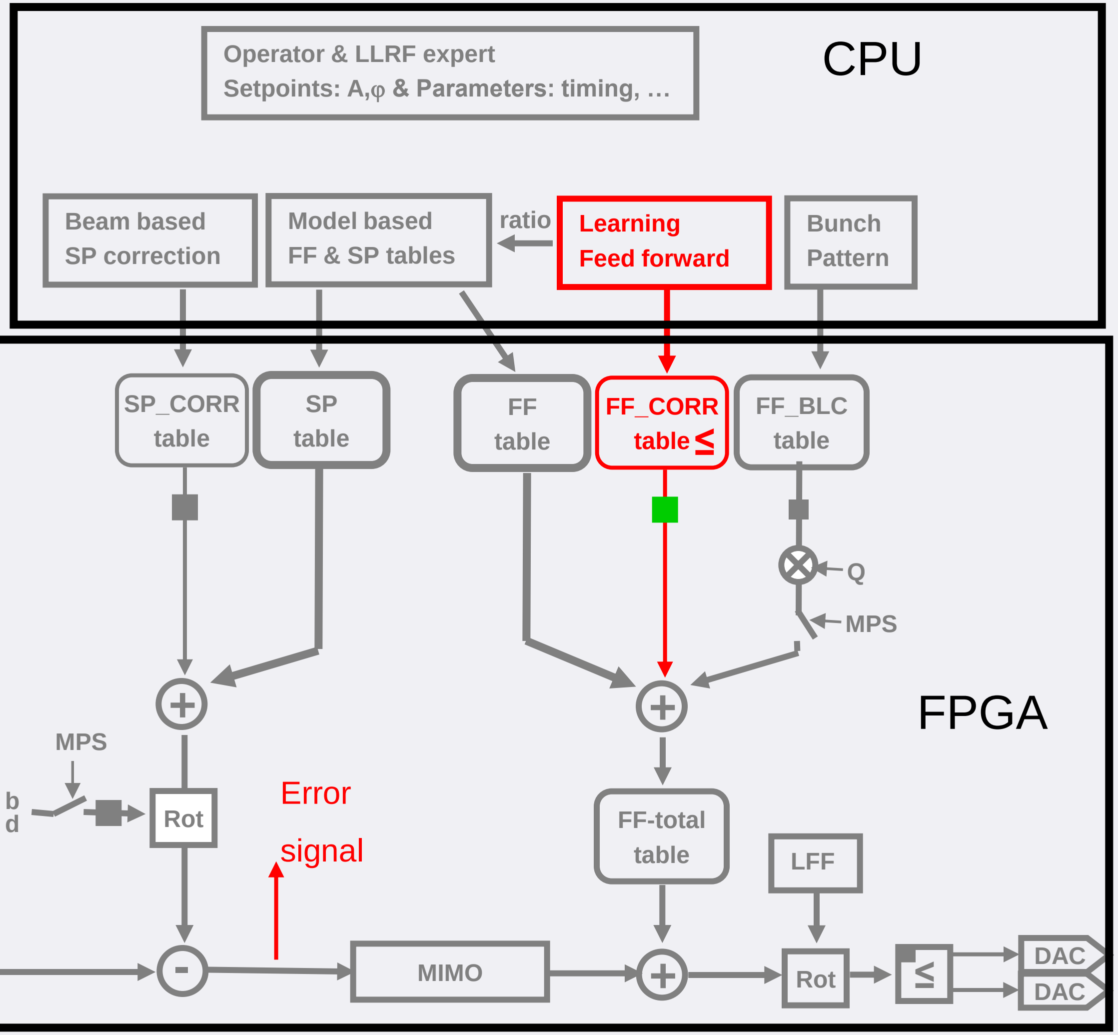
on crest

Beam Arrival Time Change

Bunch Compression Change



Measurements
Learning Feed Forward



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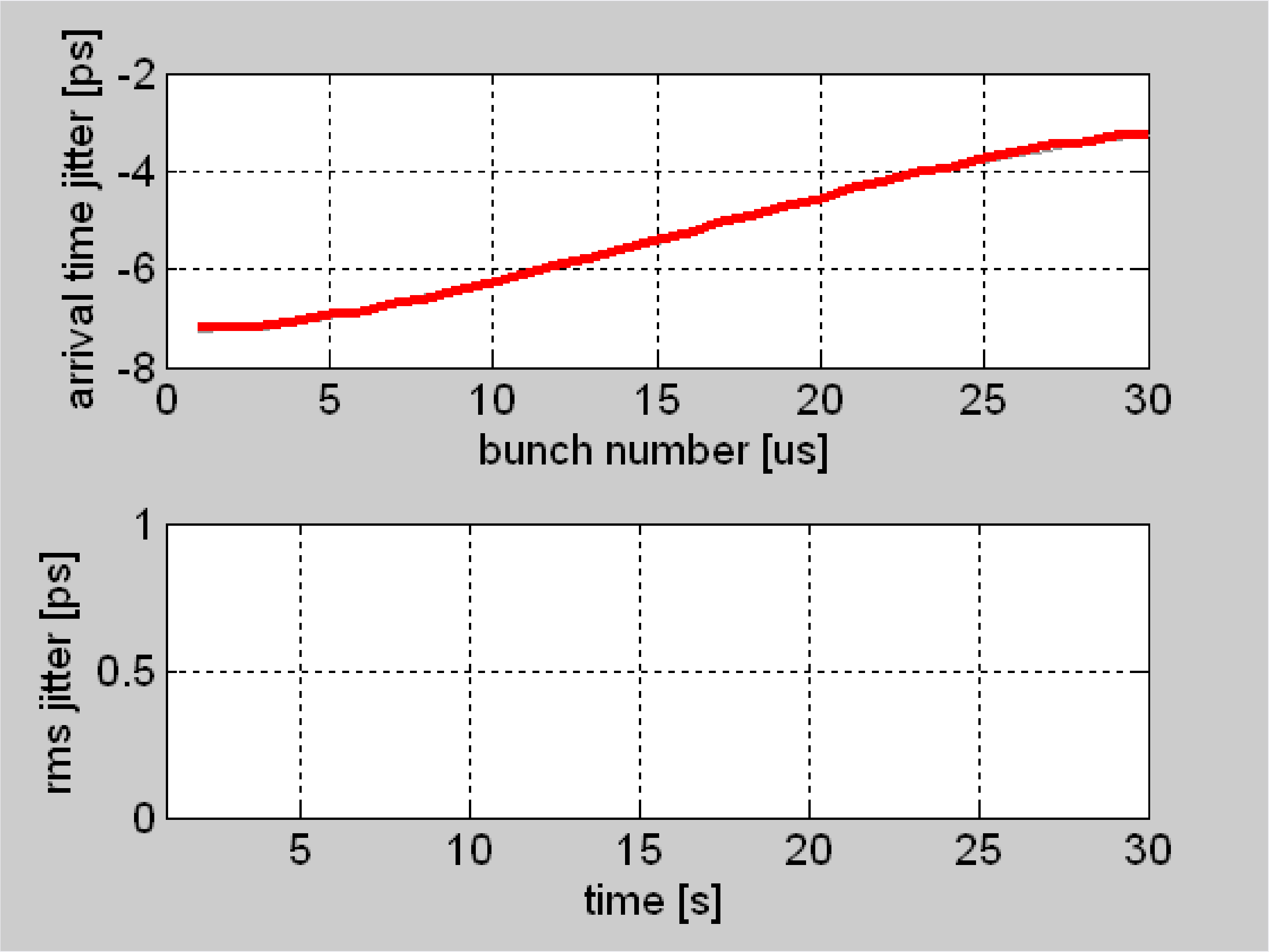
Learning Feed Forward



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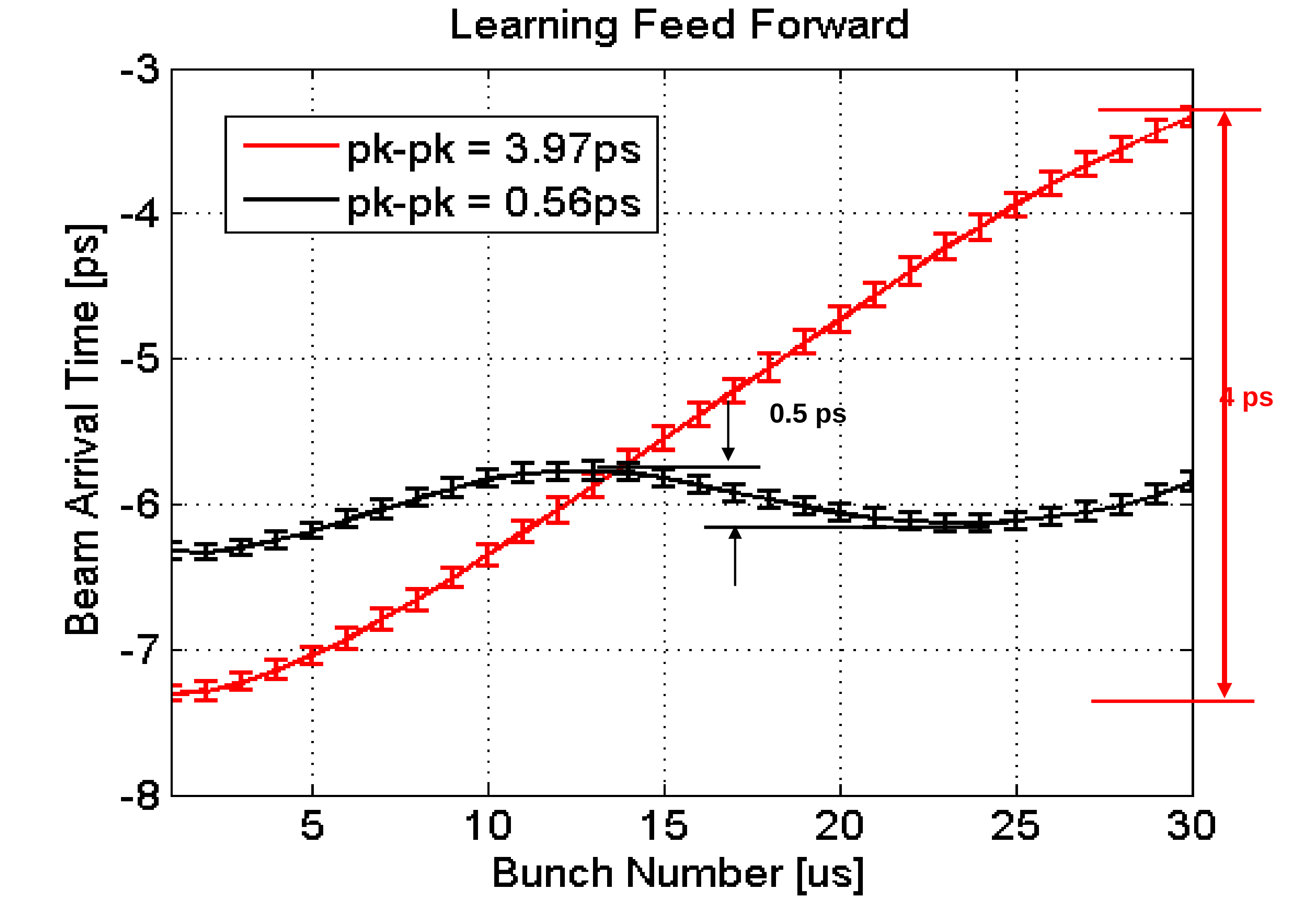
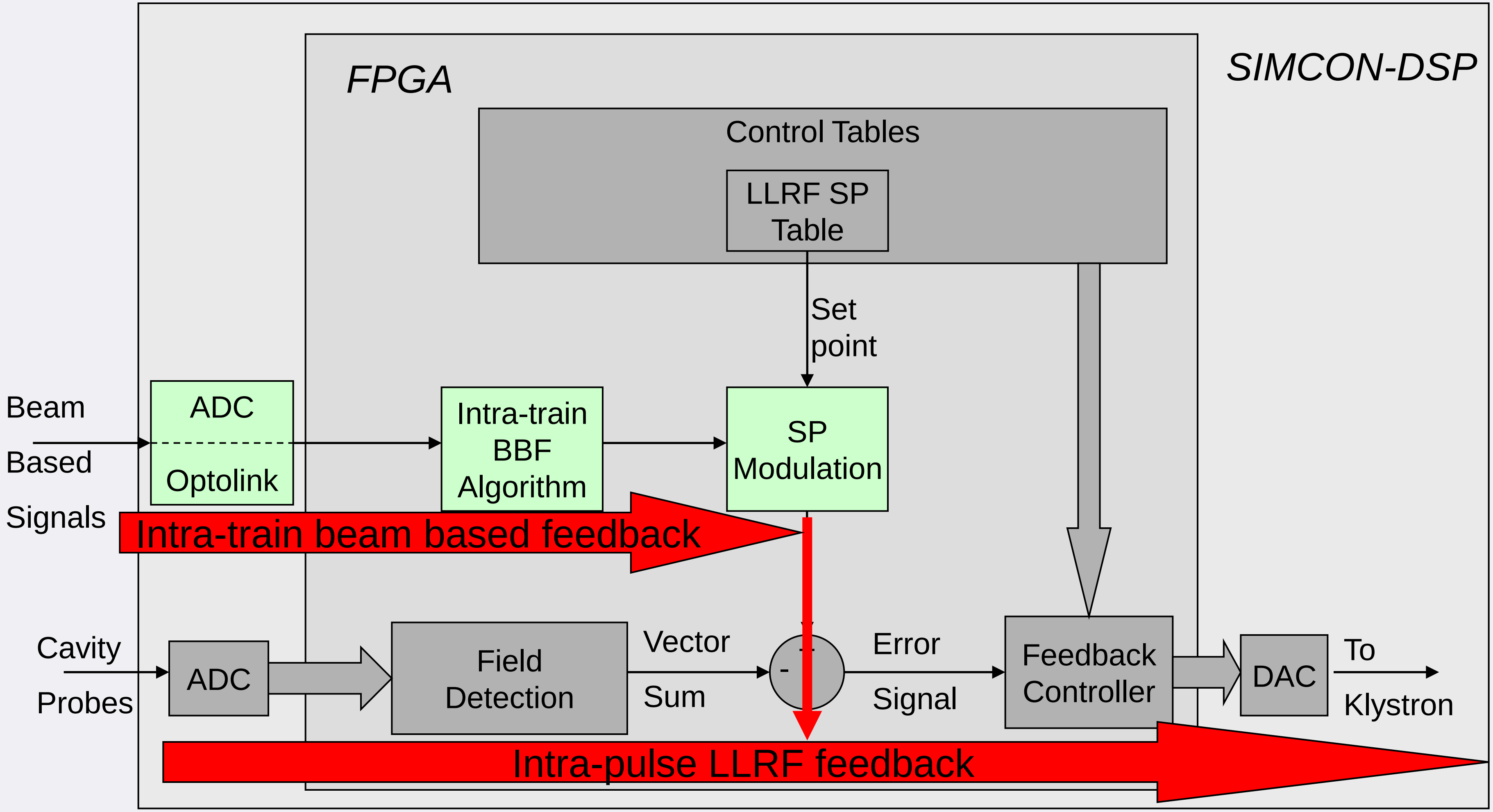
Learning Feed Forward



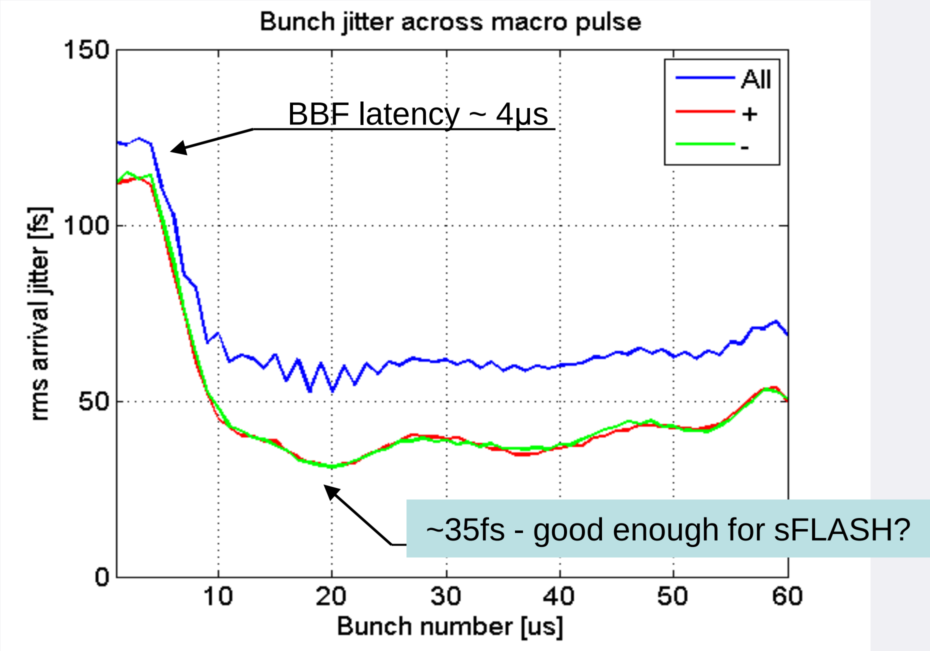
Low Level RF Control Systems

Intra-train BBF Implementation

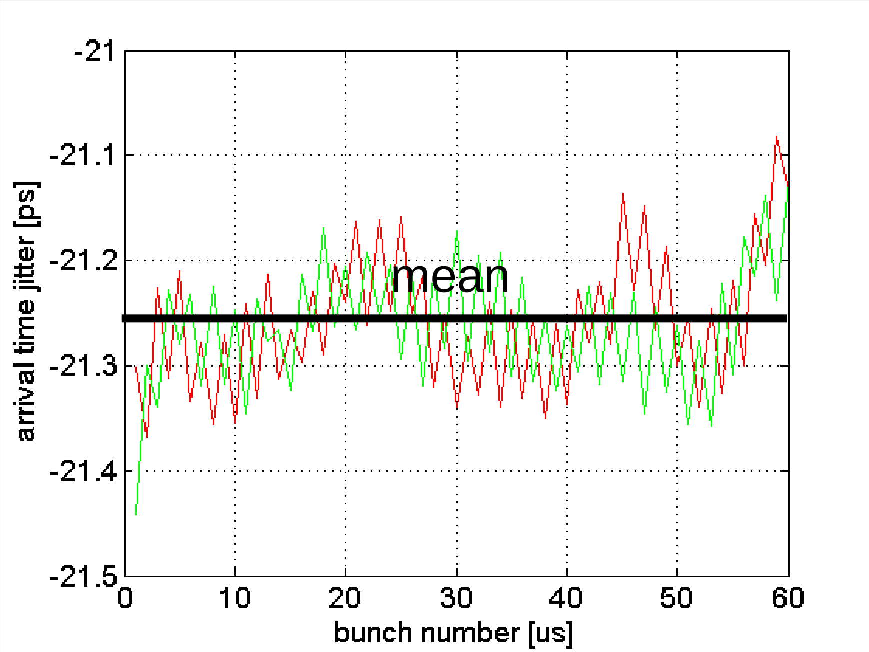


Measurement
Intra bunch train arrival time

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

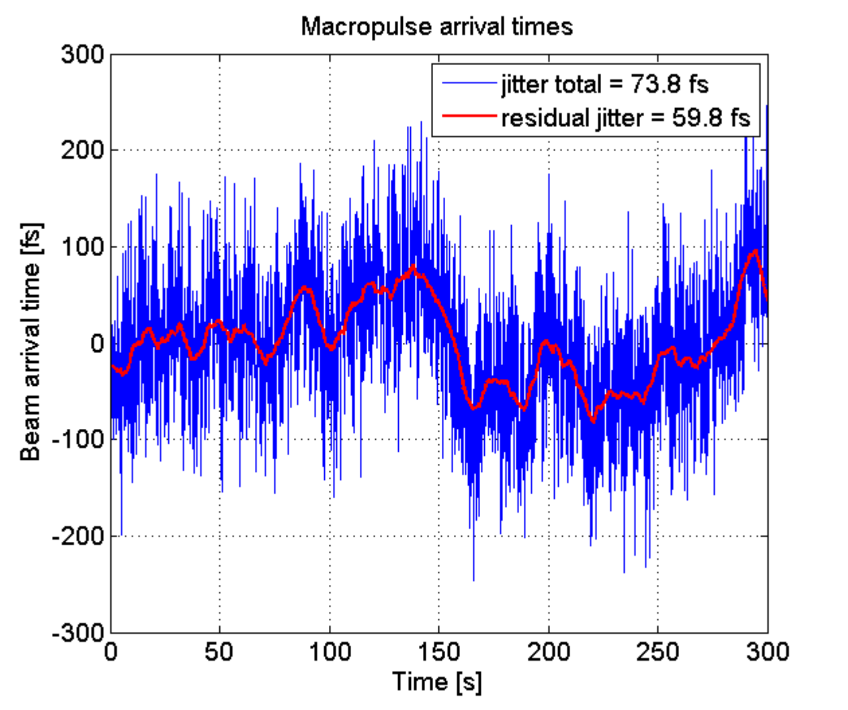


Single RF pulse

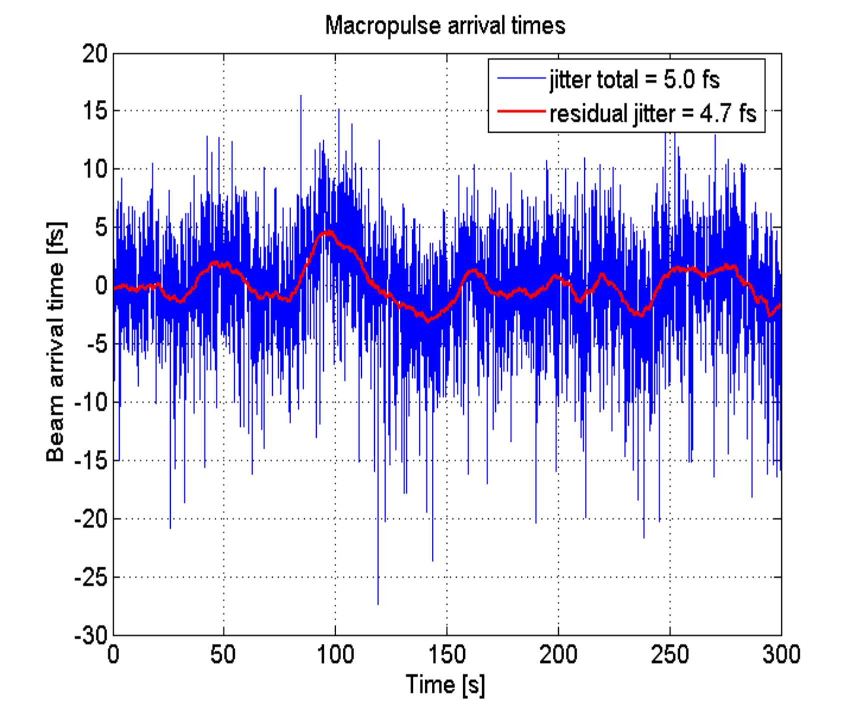


Measurement
Macro pulse arrival time jitter

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 → $\Delta A_1 / A_1 \sim 10e\text{-}4$, $\Delta\varphi_1 < 0.03^{o}$

- rapid fluctuations averaged out
- resolution of BAM ~ 10 fs for single shot can be reduced to ~ fs for macro pulse

Summary

- Commissioned interfaces between LLRF system and beam diagnostic systems
- Well defined and implemented a new concept of the beam BBF in the LLRF systems
  - BBF modules 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”
- M. K. Bock∗, M. Felber, P. Gessler, K. E. Hacker, F. Loehl, F. Ludwig, H. Schlarb, B. Schmidt, J. Zemella, DESY, Hamburg, Germany, S. Schulz, L.-G. Wissmann, University of Hamburg, Germany, “RECENT DEVELOPMENTS OF THE BUNCH ARRIVAL TIME MONITOR WITH FEMTOSECOND RESOLUTION AT FLASH”, Proceedings of IPAC’10, Kyoto, Japan
- F. Löhl, “Optical Synchronizations of a Free-Electron Laser with Femtosecond Precision”, DESY-THESIS-2009-031, 2009
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- 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)”, Proceedins of IPAC’10, Kyoto, Japan