Longitudinal feedbacks for FELs
… at EuXFEL and FLASH

11th Workshop on Longitudinal Electron Bunch Diagnostics

Marie Kristin Czwalinna on behalf of MSK.
June 29th, 2022 to July 1st, 2022, Université de Lille

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FLASH. Free-Electron Laser FLASH

European XFEL

DESY.

our team at DESY

MSK = Group for **beam controls** (Holger Schlarb)

- ~ 70 people (+ master students + PhD students)
- 10 sub-groups

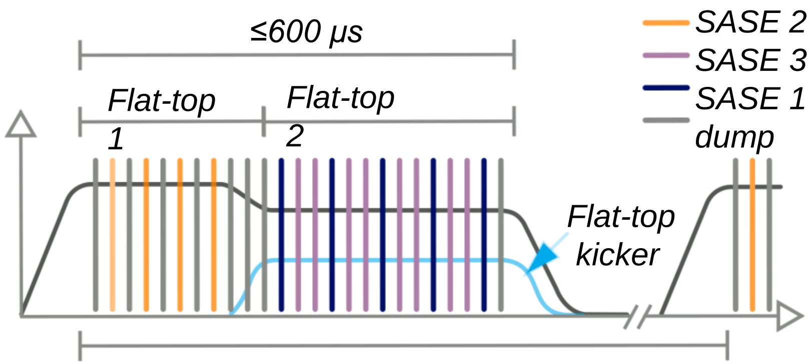
- Analog Electronics Design
- Digital Electronics Design
- Firmware Development
- Software Development
- Optical Synchronisation Systems
- **Longitudinal Diagnostics for Fast Feedbacks**
- Low-Level RF Controls
- Timing for PETRA 3 / PETRA 4
- Fast Orbit Feedback Controls
- Intelligent Process Control (Annika Eichler, Professor at Inst. for Control Sys., TUHH since 05/2022)

Sub-group „**special diagnostics**" (Marie Kristin Czwalinna)
https://confluence.desy.de/display/SDiagPublic/

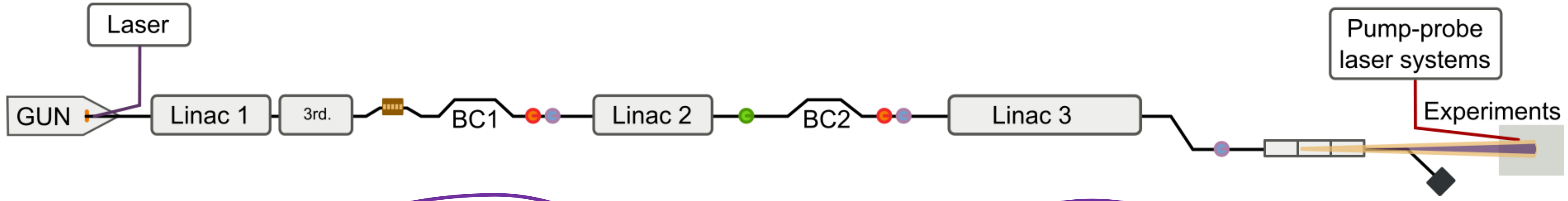
- Jiri Kral : system engineering / hardware design, (BAM)
- Bernd Steffen : electro-optical systems (EOSD)
- Nils Lockmann : coherent radiation diagnostics (BCM, THz Spectrometer)
- Bjoern Lautenschlager : control theory (Beam-based Feedback)
- Jan Roever : mechanical engineering
- n.a. : electrical / RF engineering (>100GHz)

Linac Stabilization
&
Diagnostics suited for Fast Feedbacks

Longitudinal Stability for FELs



- Bunch pattern allows for fast, intra bunch-train corrections
  - 10Hz burst mode
  - Up to 4.5MHz repetition rate within a burst
  - Fixed bunch repetition in the linac
  - User bunch selection only at final beam energy



Energy
- electron bunch energy
→ FEL pulse energy
→ center wavelength
→ bandwidth of the spectrum
- …

Peak current / current profile
- … electron bunch profile and length
- → Intensity of FEL pulses
- → Number of modes / FEL pulse width
- …

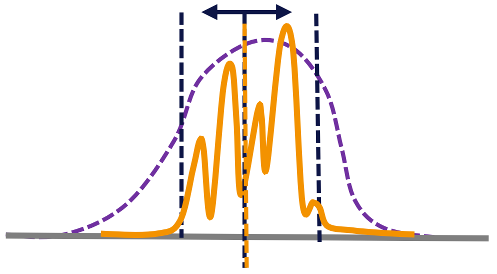
Longitudinal Bunch Properties

Energy/Energy Gain
Compression (Length)
Shape/Profile

Arrival times
- ...electron bunches
- …laser pulses
- …FEL pulses
- .. FEL-to-laser pulses

FEL pulse width at saturation:

$T_{ph}(\mathrm{FWHM}) = \sigma_e(\mathrm{rms})$



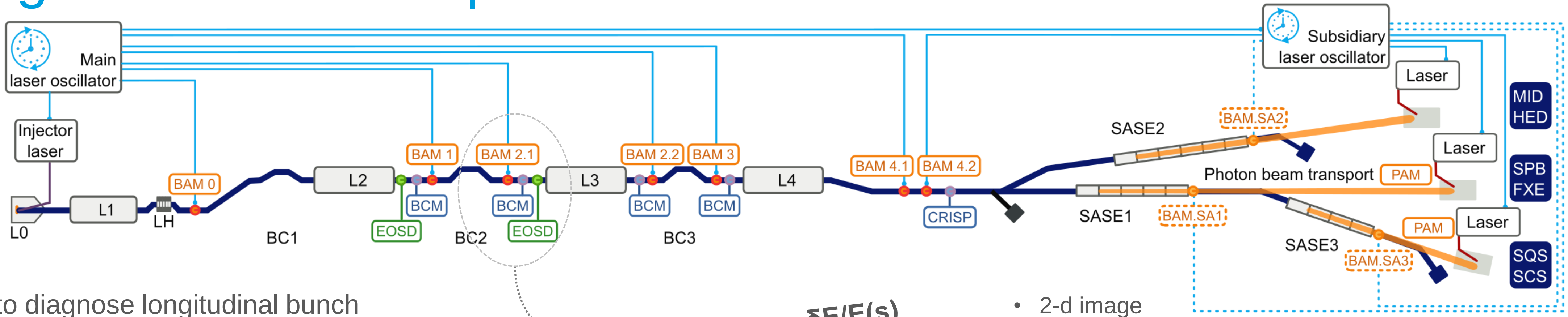
Timing Relation Bunch to FEL

$\langle t_e \rangle \rightarrow \langle t_{ph} \rangle$

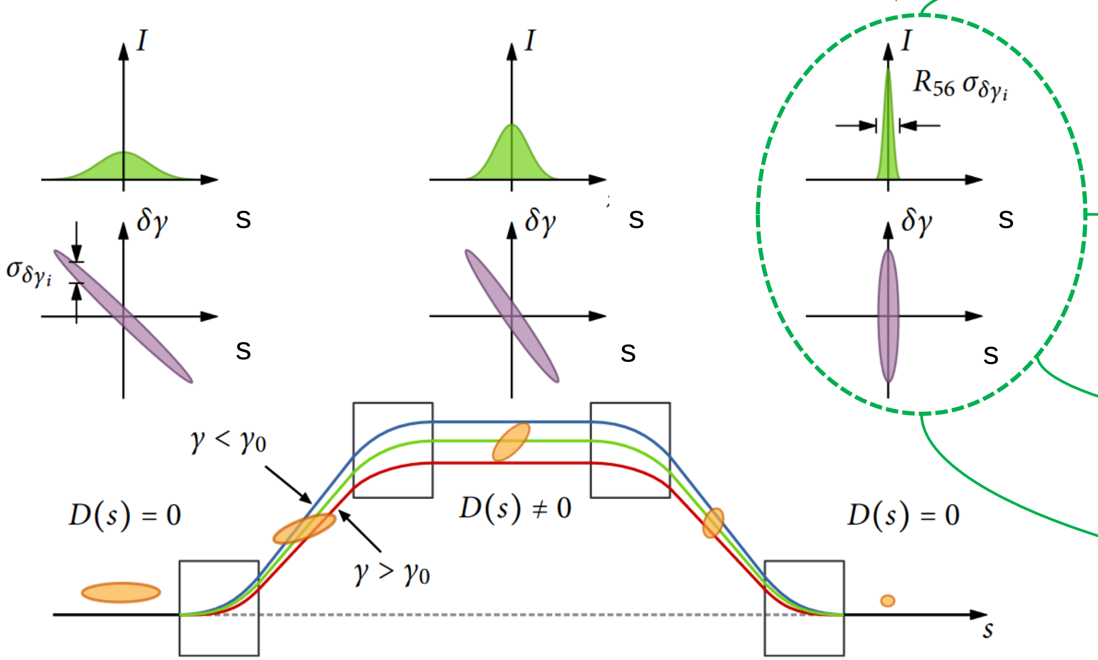
Relative fluctuations in arrival time of the center of mass

$$\sigma_{\mathrm{Arr}} = \mathrm{std}(T_{\mathrm{ph}} - T_{\mathrm{e}})$$

Longitudinal Phase Space



How to diagnose longitudinal bunch properties ?



δE/E(s)

- 2-d image
- longitudinal phase space
  - **TDS** (Transverse Deflecting Structure) + dispersive section (energy spectrometer) + Screen

Q(s)

- 1-d array
- current profiles
  - **CRD** (THz Spectrometer)
  - **EOSD** (Electro-Optical Spectral Decoding)
  - **TDS** (Transverse Deflecting Structure) + Screen

Δt, ΔE

- 0-d properties
  - **BAM** (Bunch Arrival-time Monitor)
    - non-invasive, bunch-resolved
    - 3 - 5fs resolution, **but charge dependent**

C, σ

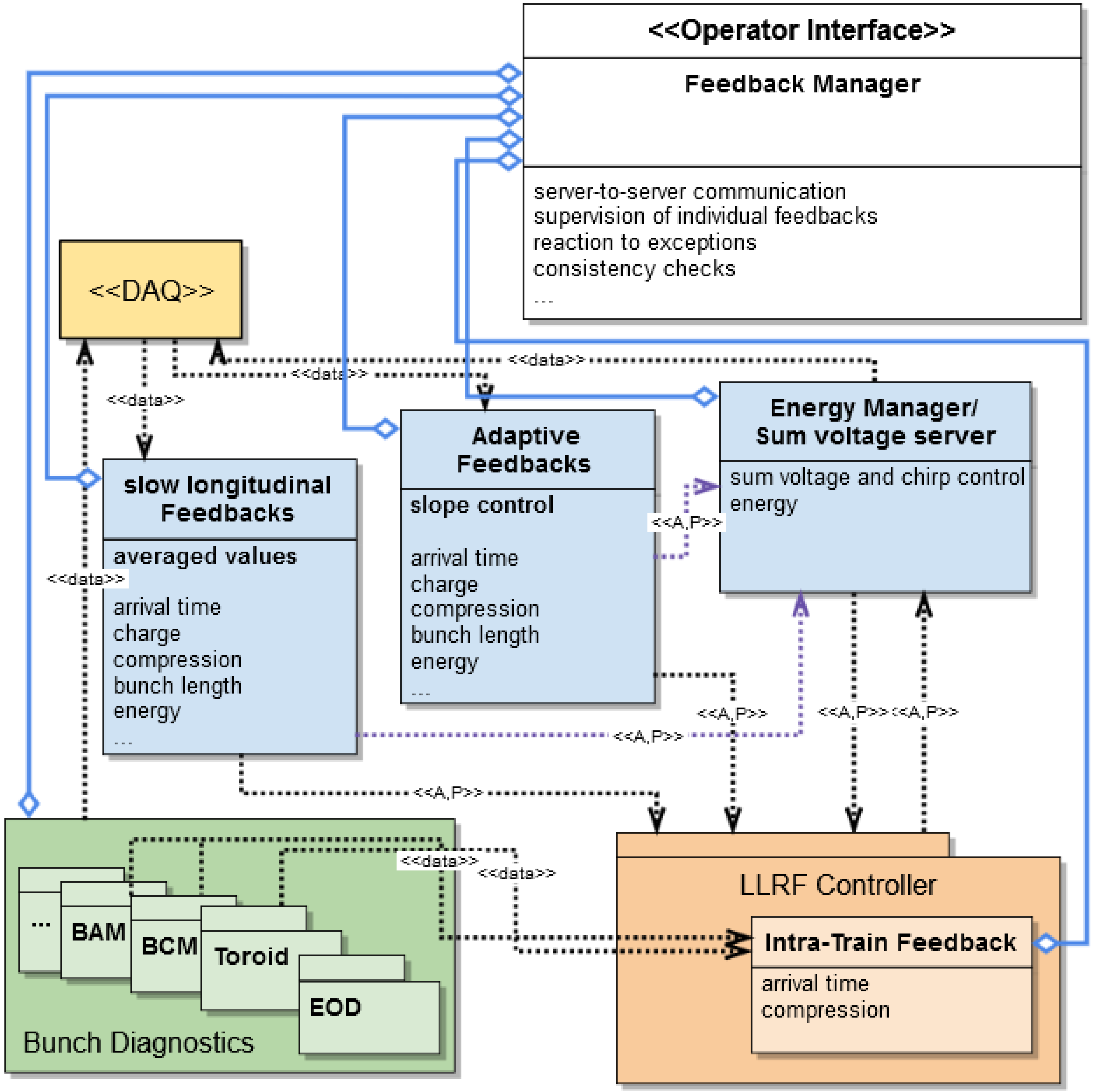
  - **BCM** (Bunch Compression Monitor)
    - non-invasive, bunch-resolved,
    - SNR maybe not sufficient.

Longitudinal Feedbacks on Different Timescales

Overview

Multi-layered system

- Centralized data acquisition system for the whole facility
- Separate server instances
  - inter-server communication
- python or matlab scripts
- Bunch diagnostics
  - Data send to DAQ



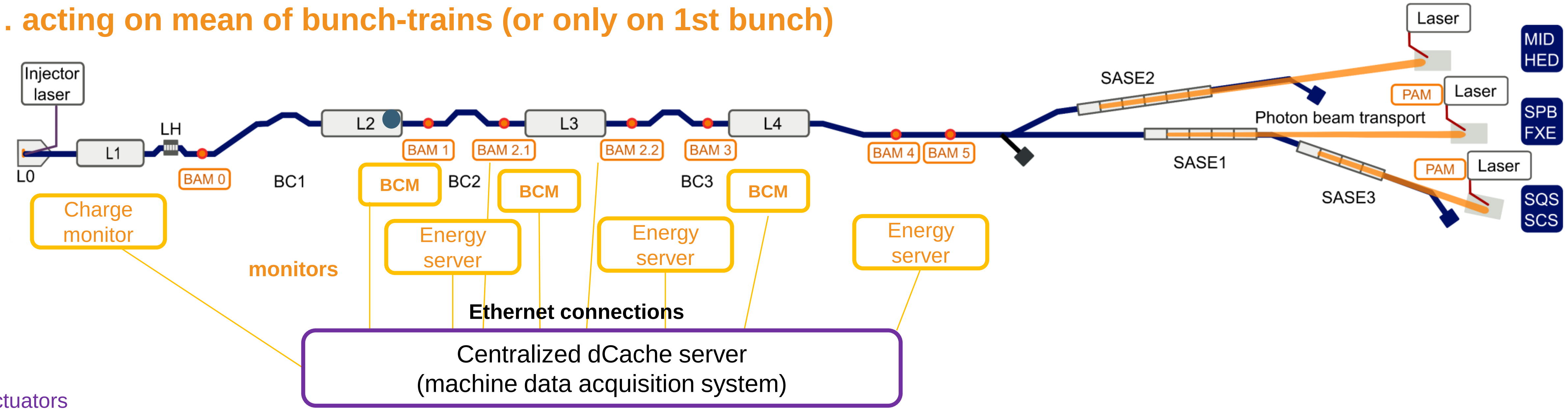
Smart automation of feedbacks:
(work in progress)

- orchestration of all separate tools
- automated configuration
- optimised interplay, especially after exceptional events
- simple user interface on top

joint project with group for control systems (MCS)

Drift Compensation

… acting on mean of bunch-trains (or only on 1st bunch)



actuators

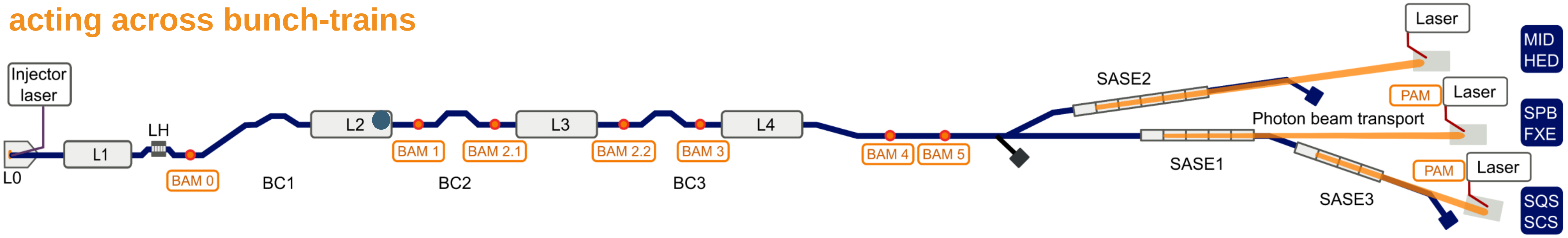
Laser phase,
RF Gun phase,
L1 sum voltage,
L1 chirp,
L2 sum voltage,
L2 chirp,
….

$$\begin{pmatrix} SP.A_{ACC1} \\ SP.P_{ACC1} \\ SP.A_{ACC39} \\ SP.P_{ACC39} \\ SP.A_{ACC23} \\ SP.P_{ACC23} \\ SP.A_{ACC45} \\ SP.P_{ACC45} \\ SP.A_{ACC67} \\ SP.P_{ACC67} \end{pmatrix} = \begin{pmatrix} K_{11} & K_{21} & \cdots & & \cdots & K_{61} \\ & \ddots & & & & \\ & & \ddots & & & \\ & & & \ddots & & \\ & & & & \ddots & \\ & & 0 & & & \vdots \\ & & & & & K_{69} \\ & & & & & K_{610} \end{pmatrix} \begin{pmatrix} BAM_{1UBC2} \\ BAM_{BC2} \\ BCM_{BC2} \\ BAM_{BC3} \\ BCM_{BC3} \\ E_{Dogleg} \end{pmatrix}$$

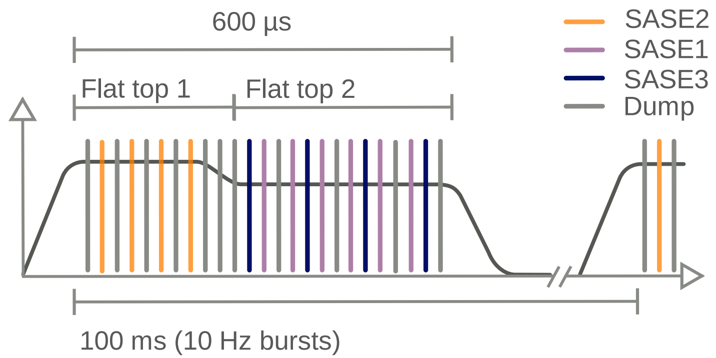
- n x m matrix of monitors and actuators
- measure responses
- SVD algorithm
  - →allows individual weighting factors
  - → ensures causality
  - → offers cross-coupling terms

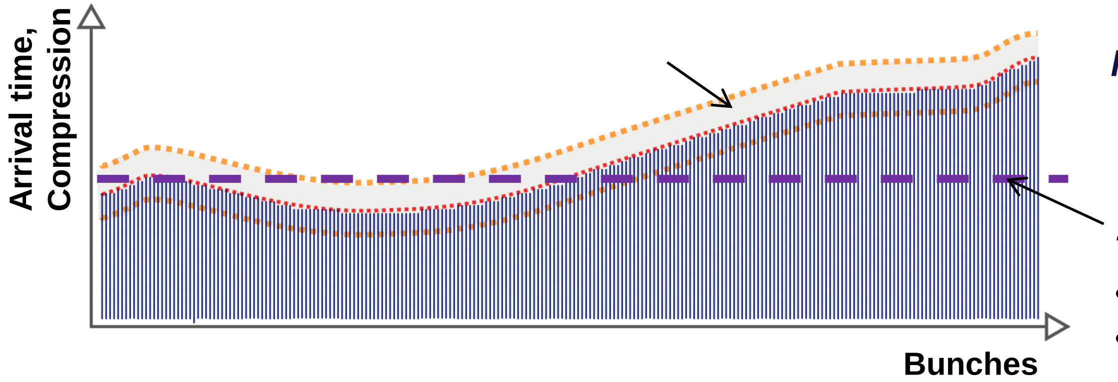
Removal of Repetitive Errors

… acting across bunch-trains



- **Slope removal, adaptive feedforward**
  - uniform arrival time within pulse train
  - learning algorithms
  - final resolution improvement in experiment through post-sorting of data





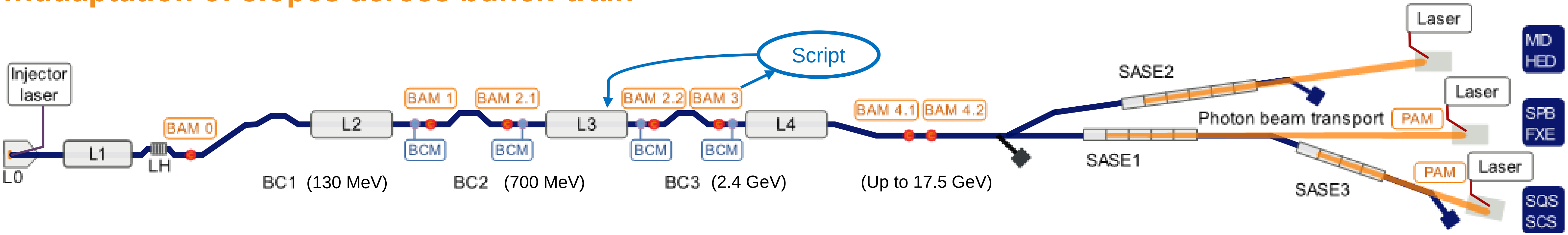
Non-uniformity of properties within bunch-train

Target for adaptive feedforward

- *linear, uniform,*
- *or predefined waveform*

Example: Iterative Learning Control

…adaptation of slopes across bunch-train

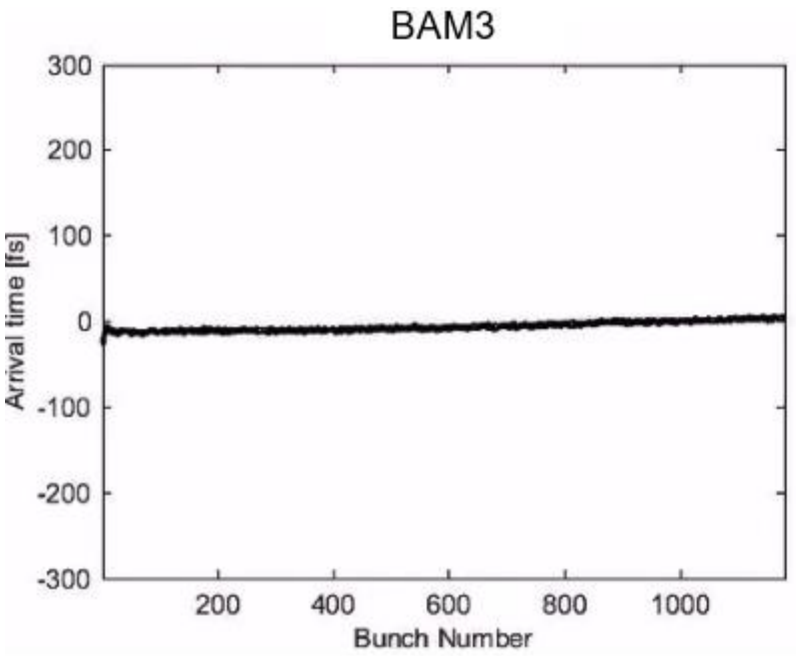


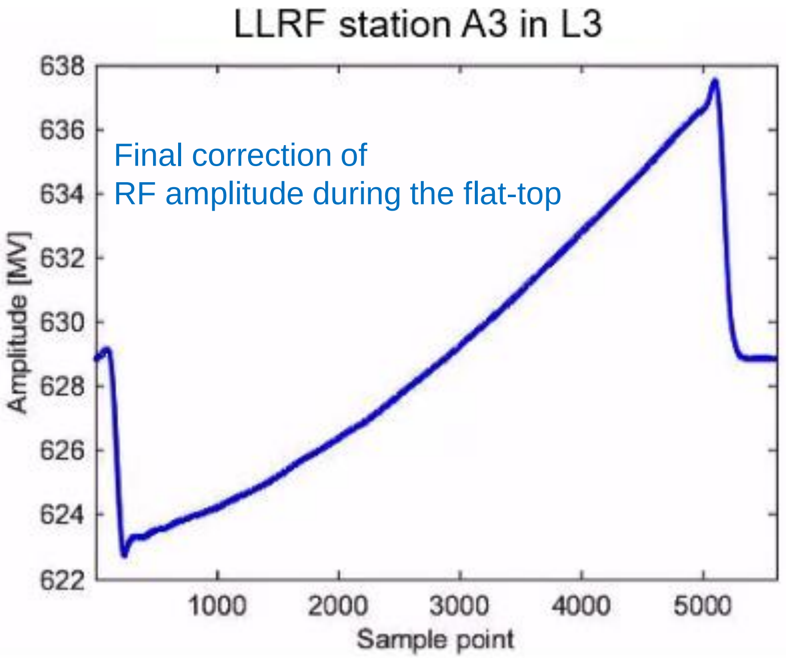
Initial arrival-time slope of ~500 fs

Adaptive algorithm, (matlab script) :

- averaging over 50 bunch-trains,
- calculate correction needed,
- adapt RF amplitude of A3 to reach target at BAM3,
- apply in several iteration.

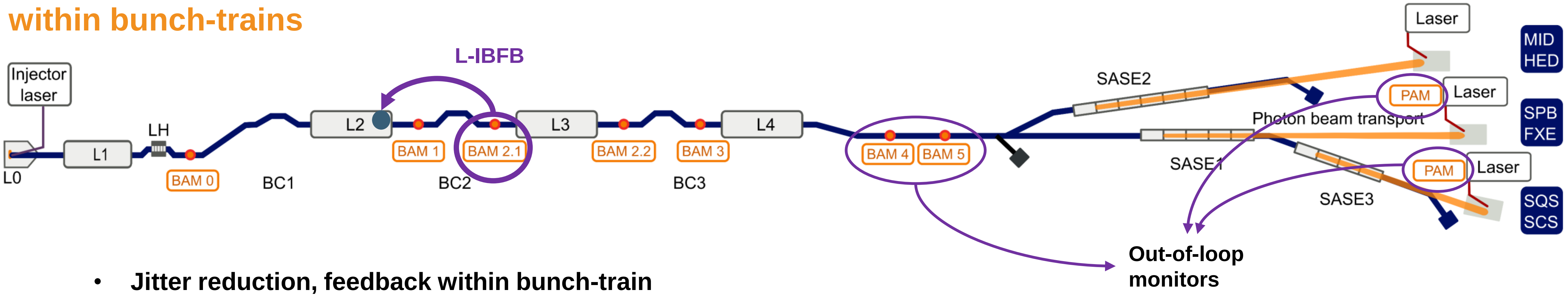
Can be used as static correction after reaching target, or run continuously.



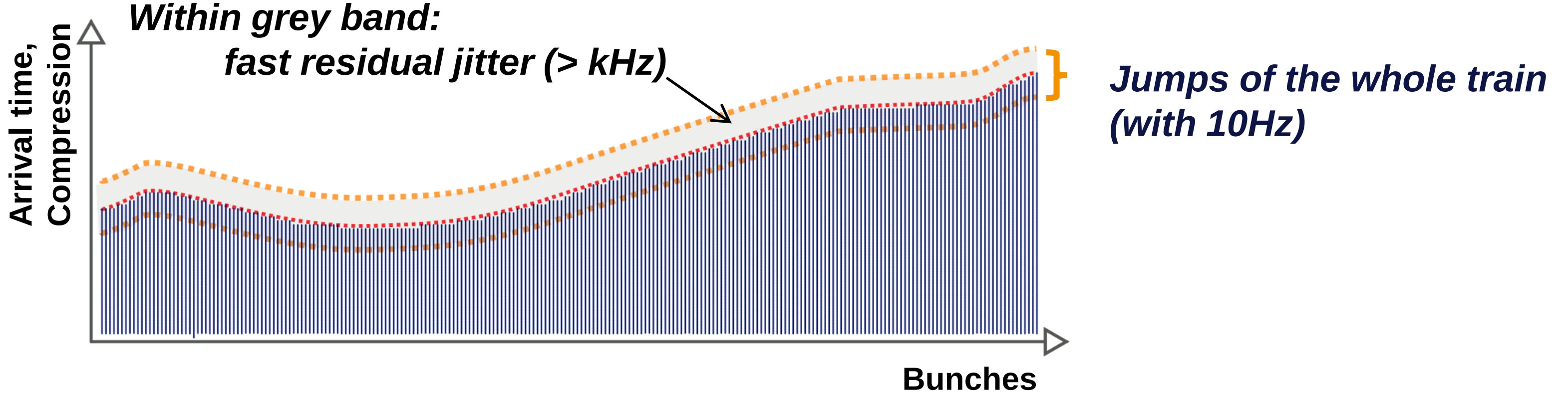


Fast Beam-based Feedback

… within bunch-trains



- **Jitter reduction, feedback within bunch-train**
  - especially critical for arrival-times
  - relevant for high-resolution, single-shot Pump-probe experiments
  - during long averaging runs, which do not allow for post-sorting of data

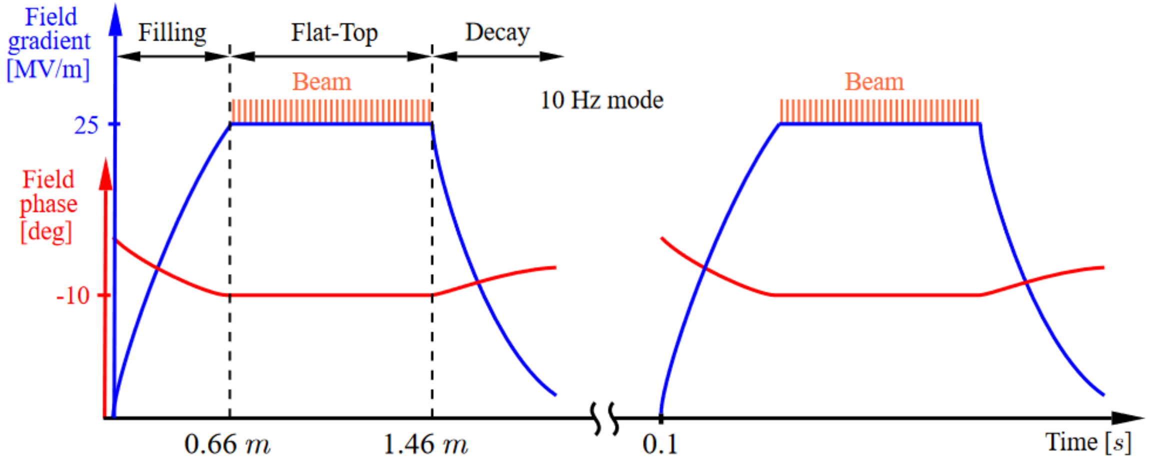


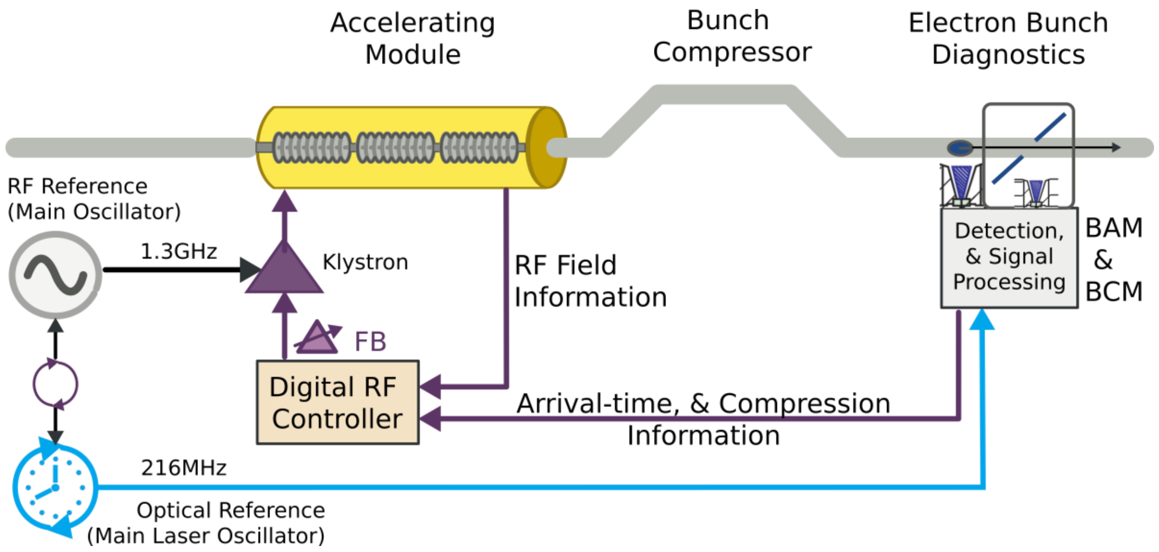
Fast Beam-based Feedback

L-IBFB = longitudinal intra-bunch-train feedback

Requires diagnostics :

- non-invasive,
- single-shot,
- bunch resolved,
- cope with bunch repetition rates up to 4.5MHz.





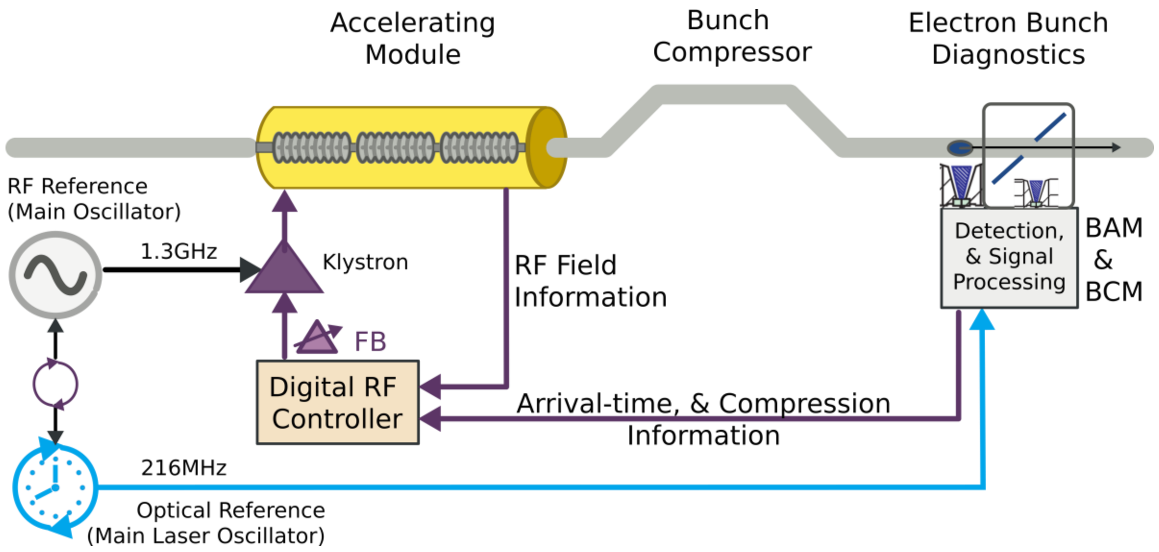
- Feedback as sub-module in LLRF controller on FGPA
- BAM / BCM data sent together via same low-latency link to the LLRF controller
- Time constraints of feedback:
  - < 200ns data processing time in bunch diagnostic,
  - <1us latency of transmission
  - Adaptation times ~10-20us in super-conducting cavities (high Q_L)

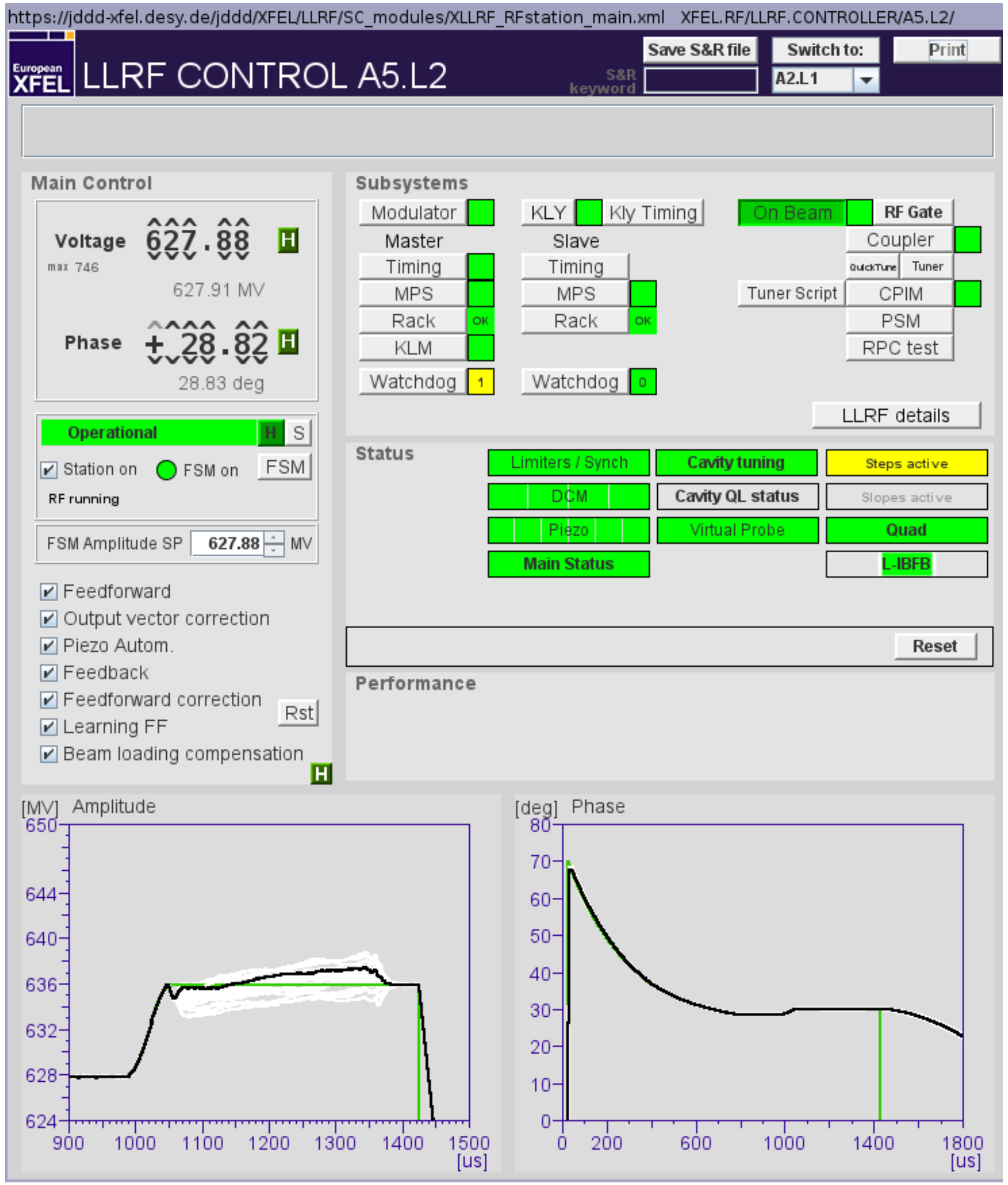
Sven Pfeiffer Phd Thesis http://www-library.desy.de/preparch/desy/thesis/desy-thesis-14-030.pdf

Fast Beam-based Feedback

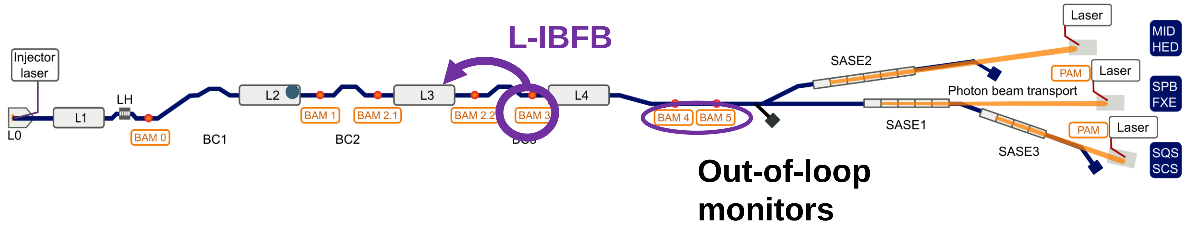
…sub-module of the LLRF controller firmware.

- Arrival time set point → arrival time control error
- LLRF system combines RF field error and beam based error
-
- LLRF controller runs as usual (FF, Feedback, LFF, …)
- All action on firmware level (FPGA)

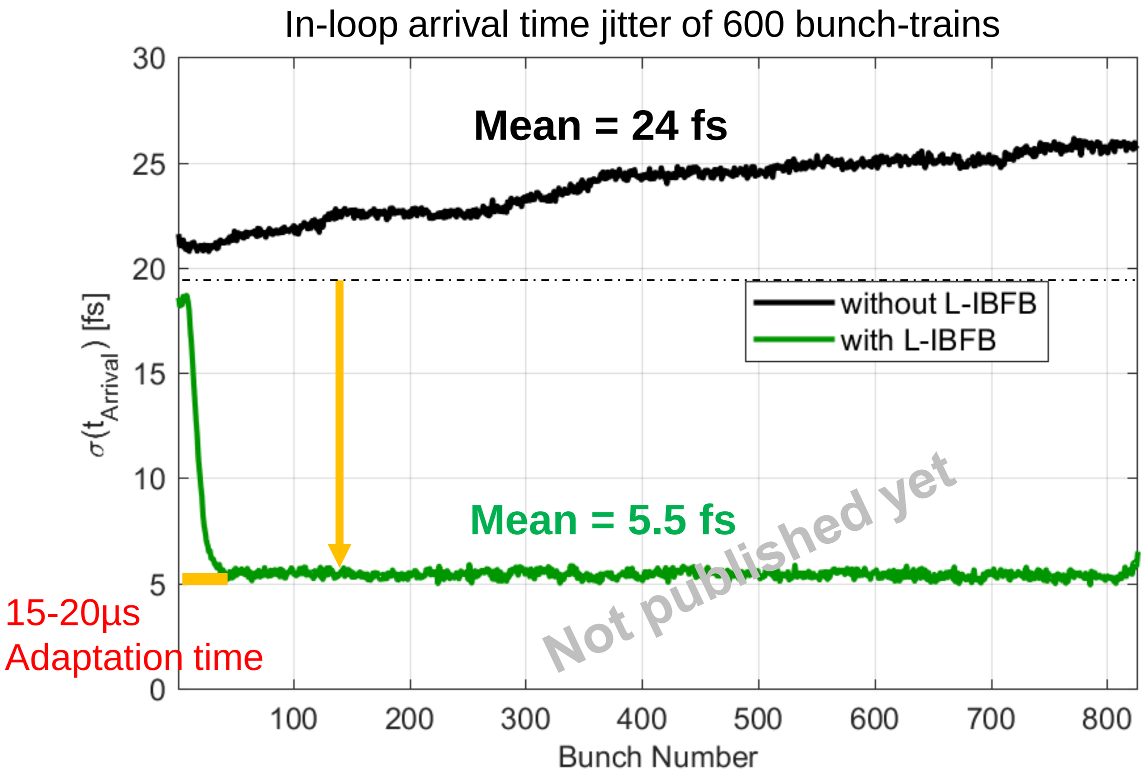


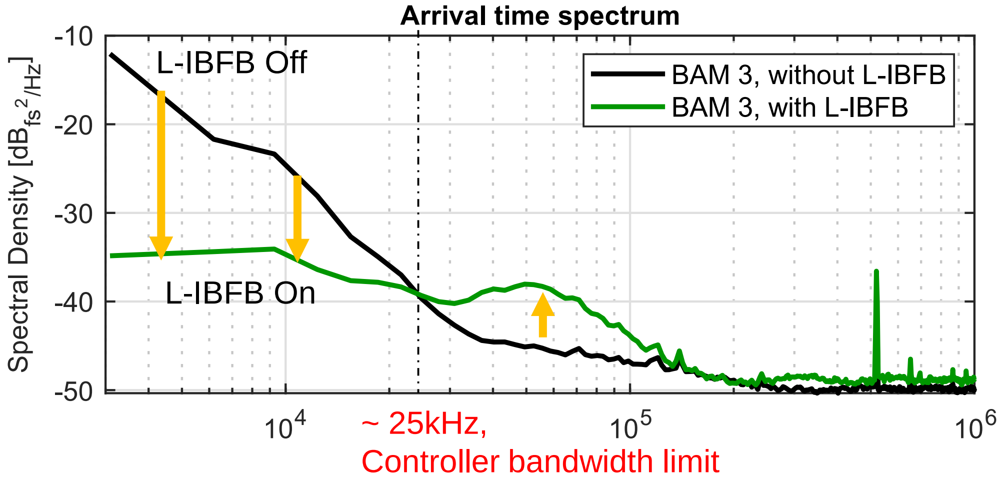


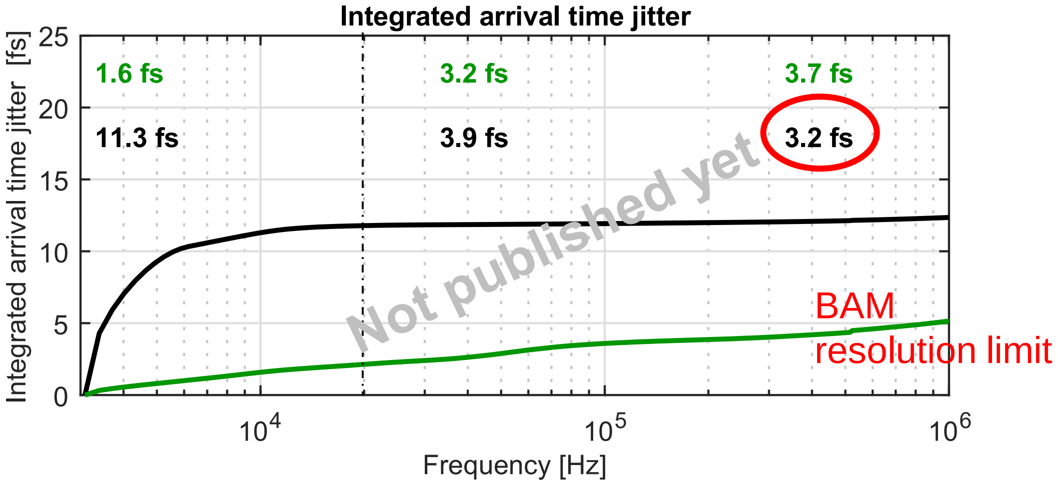
Results from EuXFEL



- The L-IBFB uses BAM No. 5 to act on A5 during the RF flat-top
- Reduction of arrival-time jitter to 5.5 fs
- Steady state value reached after 10-15 µs



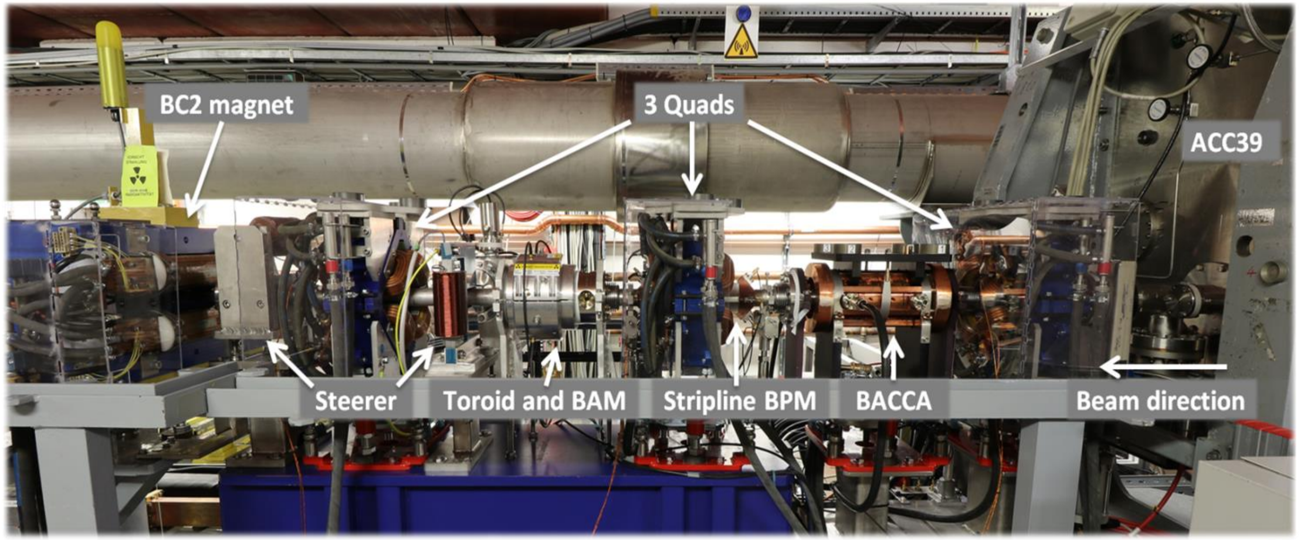




Bunch arrival corrector cavity – BACCA at FLASH

Special cavity for the FLASH facility

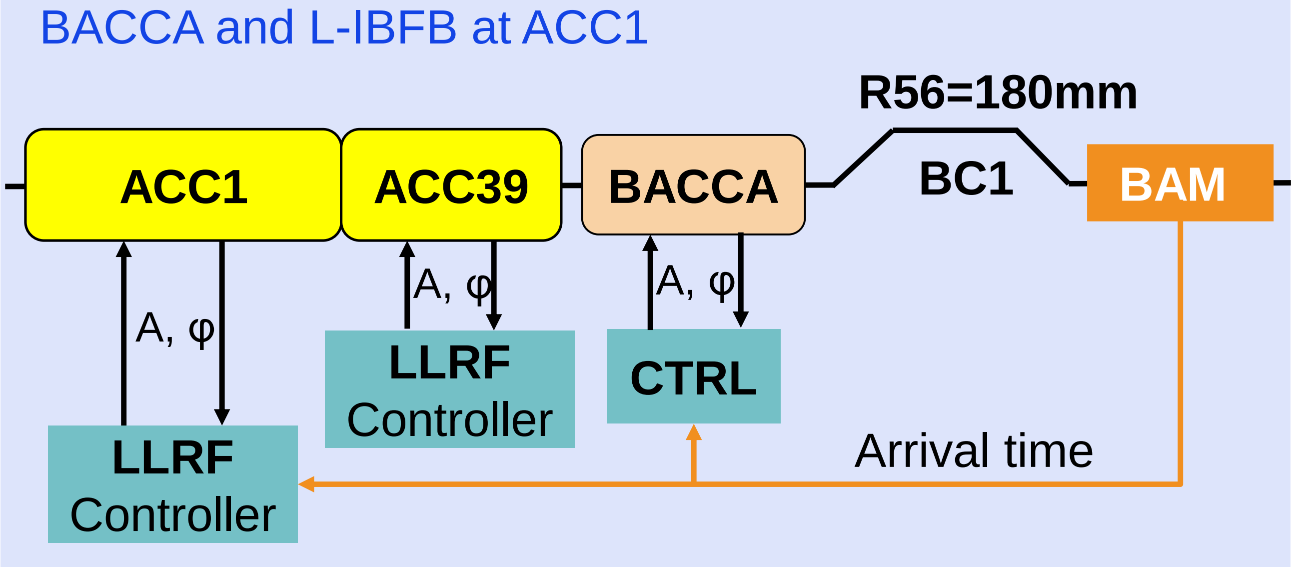
- Normal conducting cavity with 4 cells, 2.9GHz
- Energy modulation range ± 50 keV
- Fast energy (= arrival-time) corrector cavity



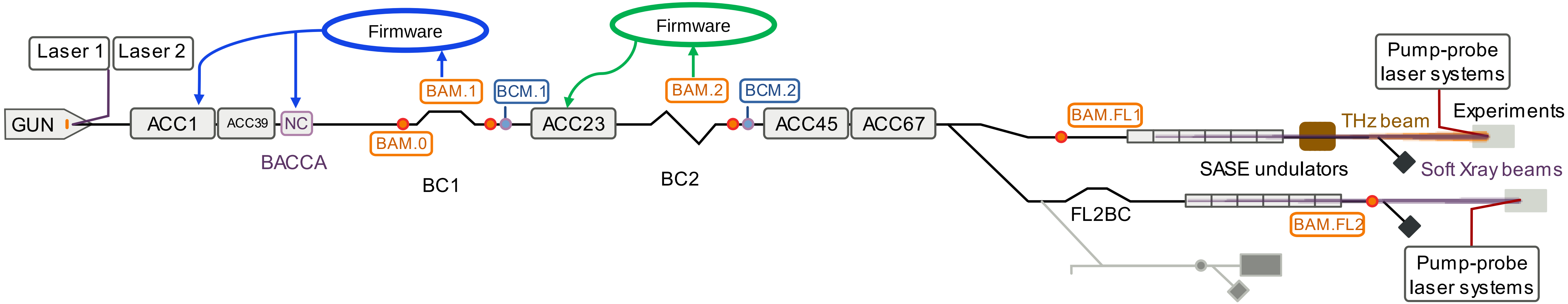
S. Pfeiffer et all, Status Update of the Fast Energy Corrector Cavity at FLASH

Advantage

- ACC1 acts on slow arrival time fluctuations (< 25 kHz) and
- BACCA on the remaining fast arrival time changes

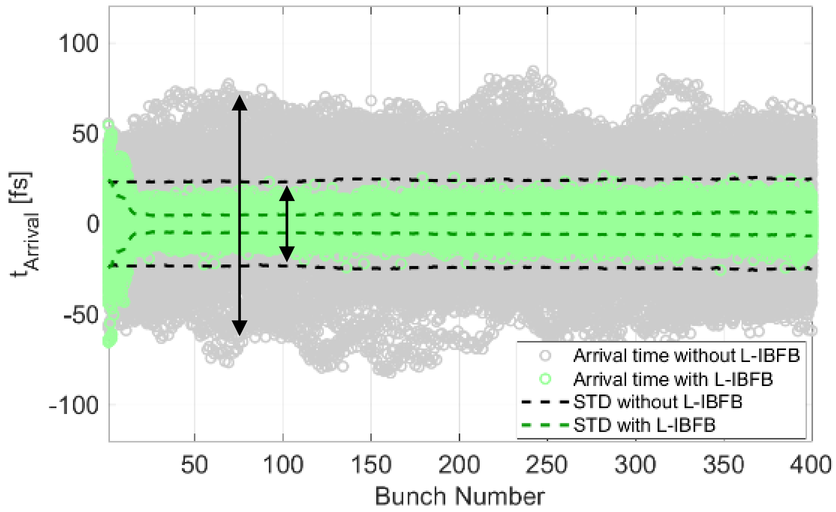


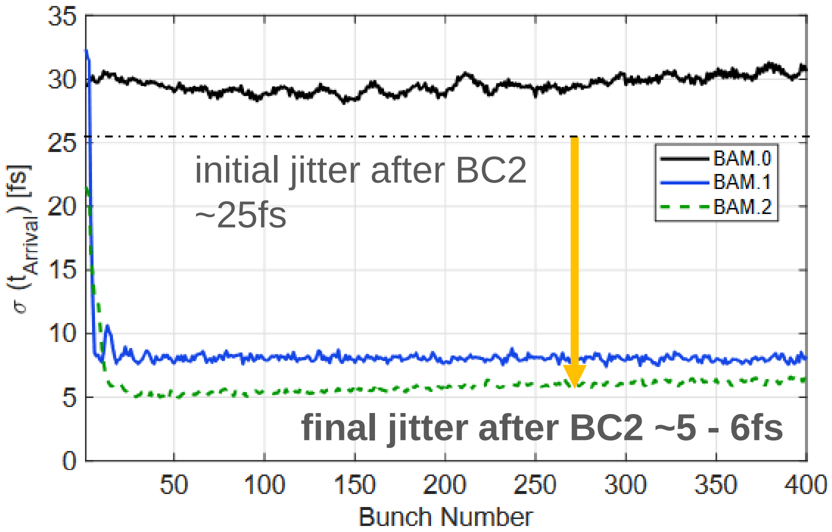
Results from FLASH



Combination of 3 Fast Feedback Loops, acting on RF amplitudes of…

1. 1st SC 1.3GHz module ACC1
2. NC Cavity
3. 2nd/3rd SC 1.3GHz module ACC23





IPAC 2021 https://accelconf.web.cern.ch/ipac2021/papers/tupab302.pdf

Thank You.