Beam-based Stability Evaluation in the LINAC of European XFEL.

Feedback & Monitoring Systems.

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On behalf of :

group for accelerator beam controls (DESY, MSK)

HELMHOLTZ

DESY.

Agenda

1 Introduction

2 Typical Stability

3 Enhanced Stability

4 Beam-based Monitoring & Failure Detection

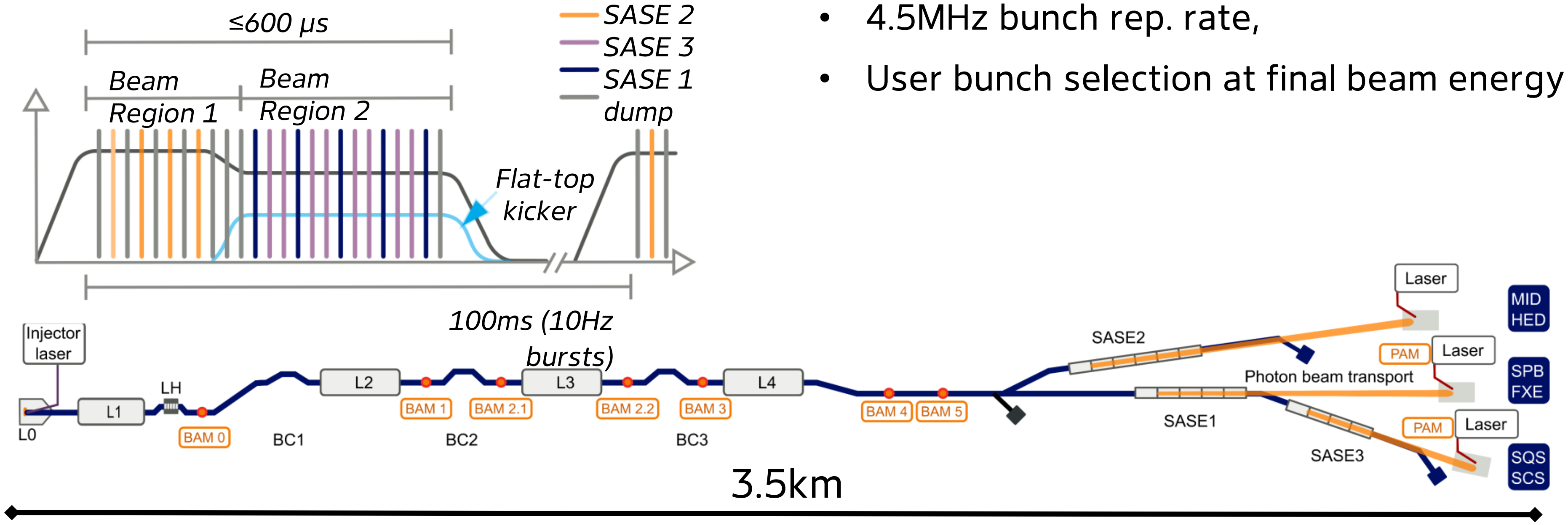
5 Summary & Outlook

Introduction

European XFEL

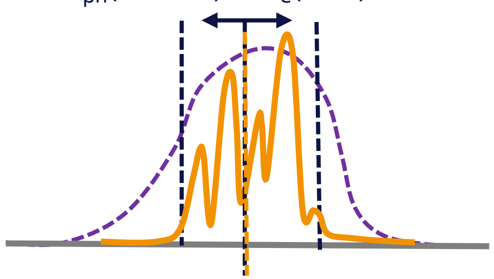
Operated in burst-mode, 10Hz, 600us.

- 10Hz burst mode,
- 4.5MHz bunch rep. rate,
- User bunch selection at final beam energy



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 Bunch Properties

Peak current,
Bunch Current profile

- Intensity of FEL pulses
- Number of modes / FEL pulse width
- …

Beam Energy

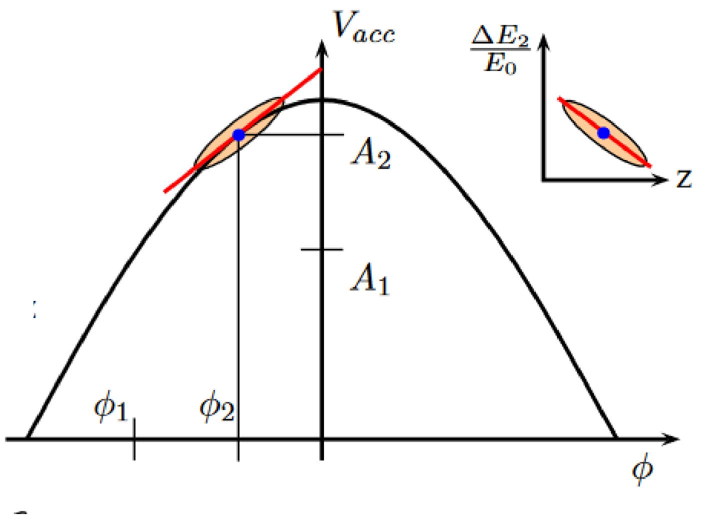
- FEL pulse energy → center wavelength
- Bandwidth of the spectrum

Arrival times

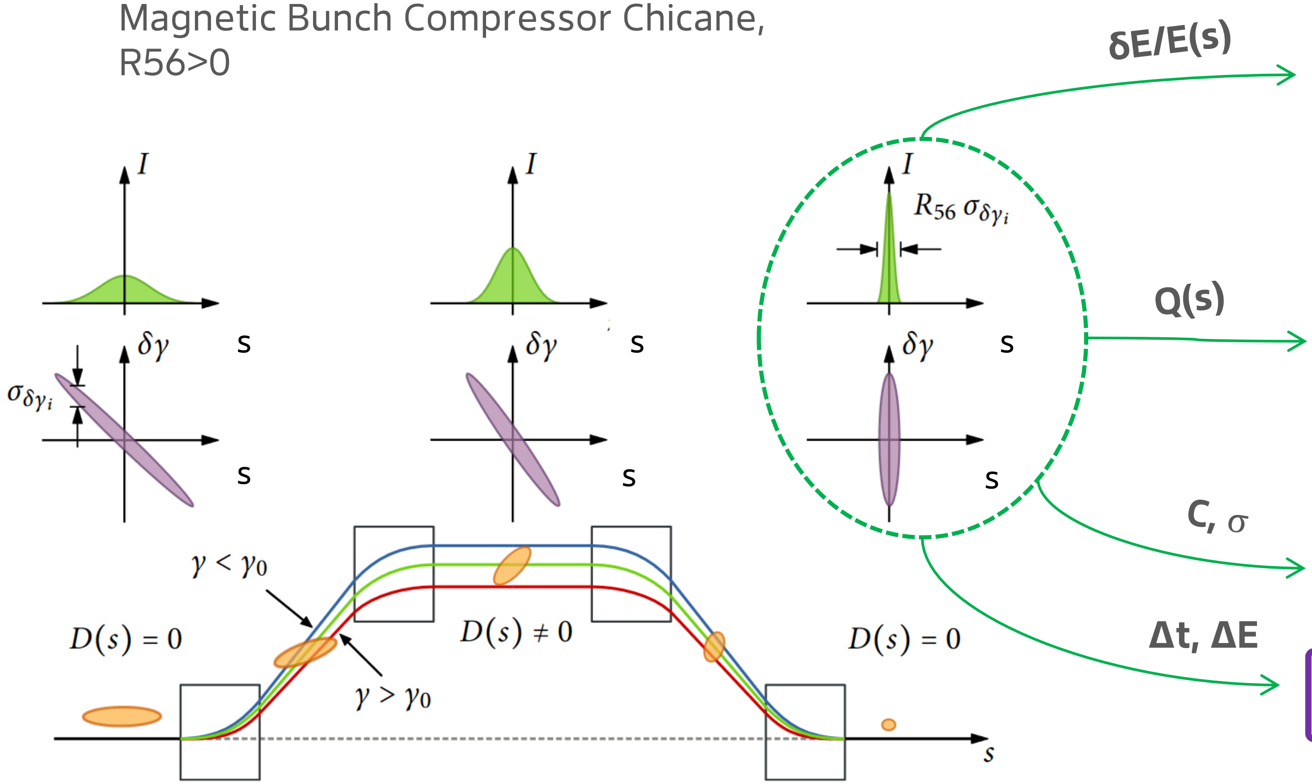
Sections with Longitudinal Dispersion

→ Beam Monitoring & Evaluation of RF Stability.

Off-crest acceleration



Magnetic Bunch Compressor Chicane, R56>0

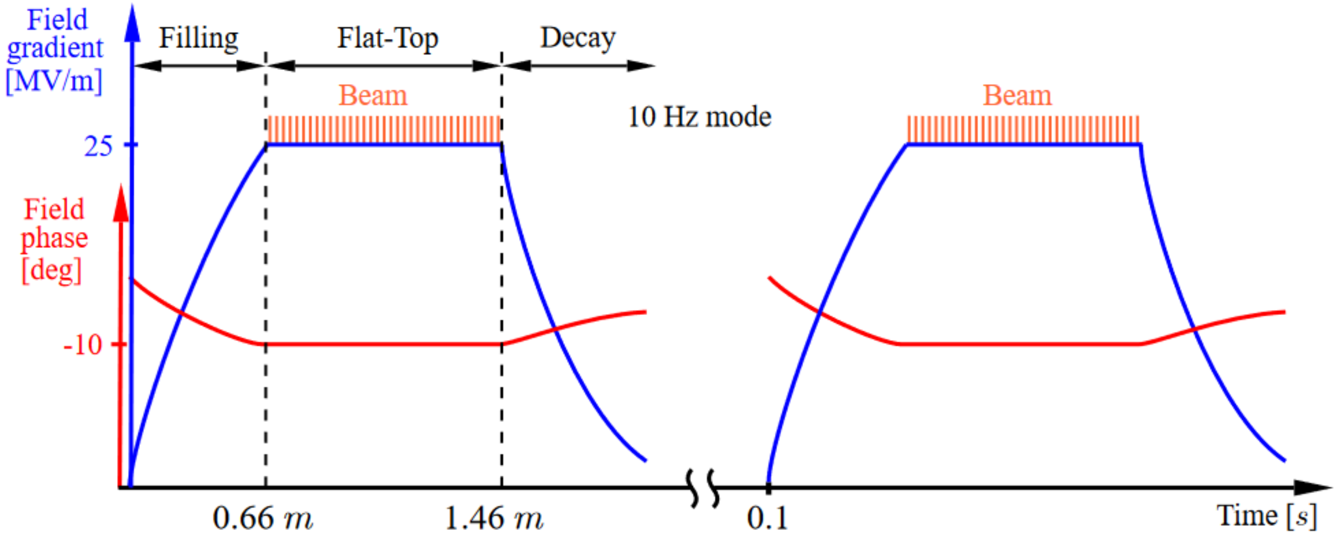


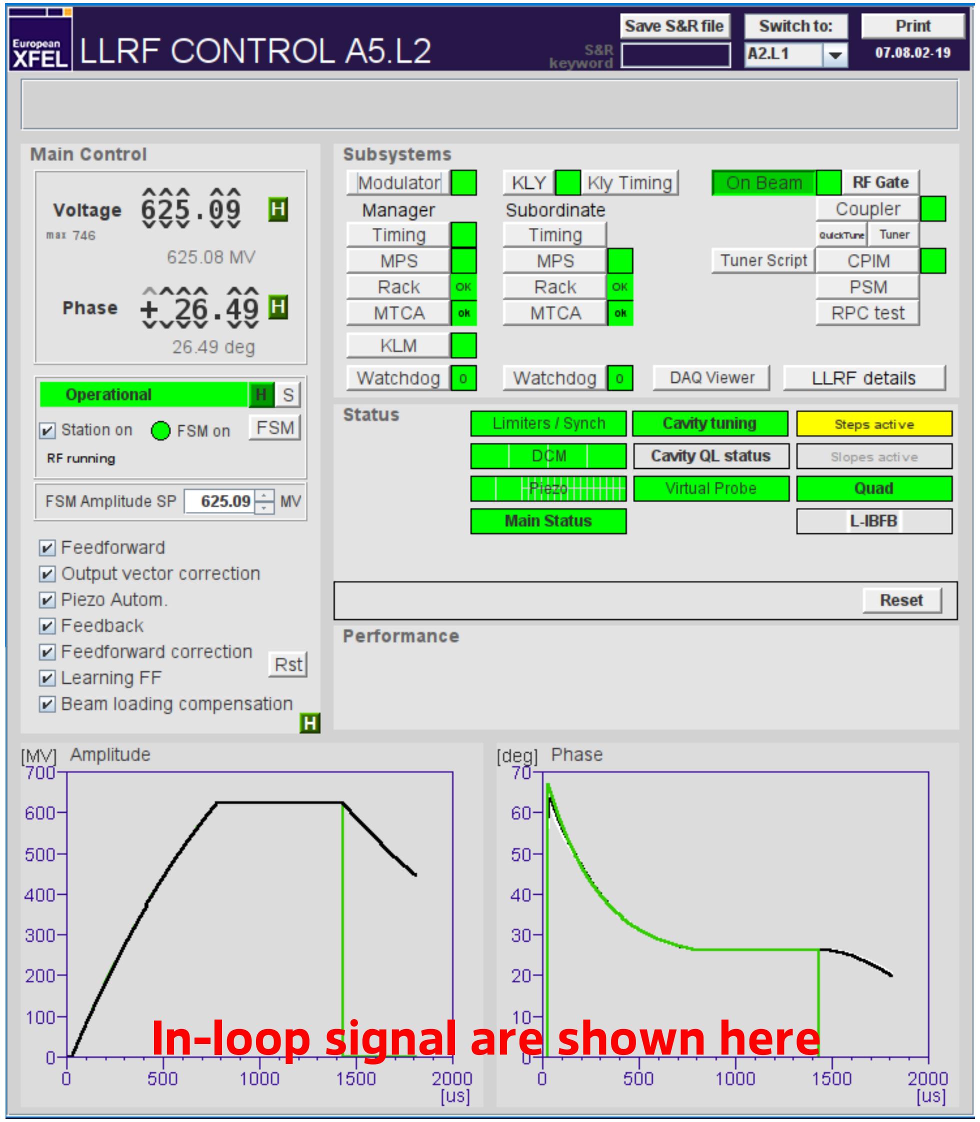
- longitudinal phase space
- current profiles
- bunch compression
- **bunch arrival-time**

Burst-Mode Operation with 600us RF Pulses

LLRF Vectorsum Regulation & Multi-Cavity Controller.

- LLRF: Control → Amplitude A and Phase φ
- Calculates drive signal for high power provided by the klystron
- Three different parts
    - Filling
    - Flat-tops, bunches are accelerated
    - Decay
- **Complex System:** Different controller types combined : MIMO, PI, or learning feedforward



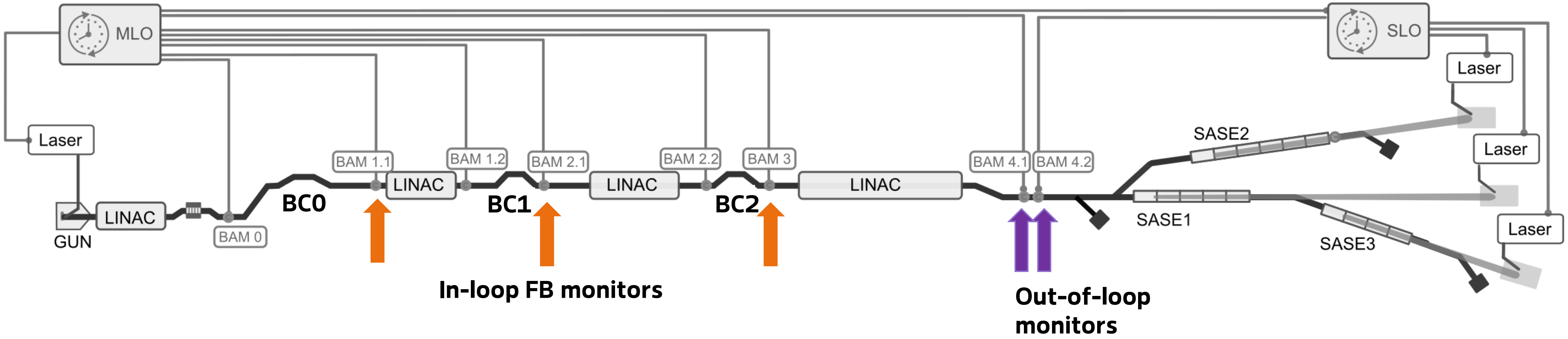


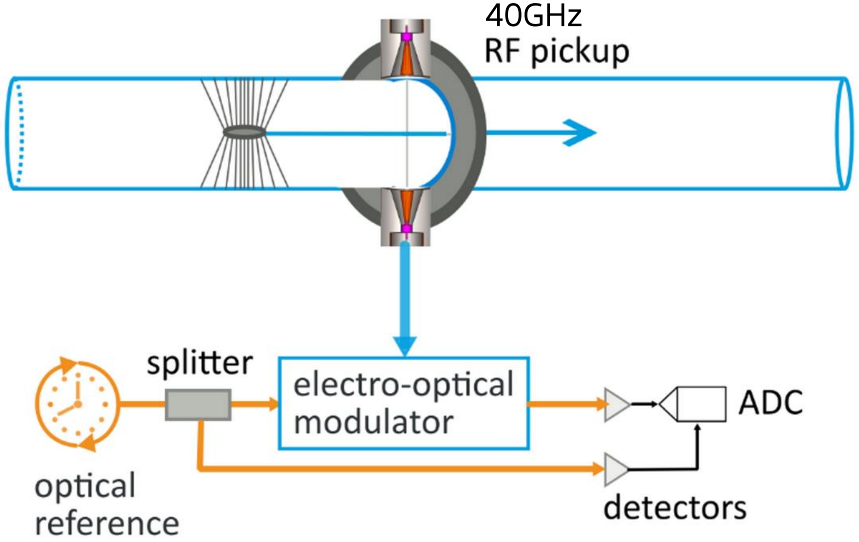
Typical Performance

Energy <—> Arrival-time Stability

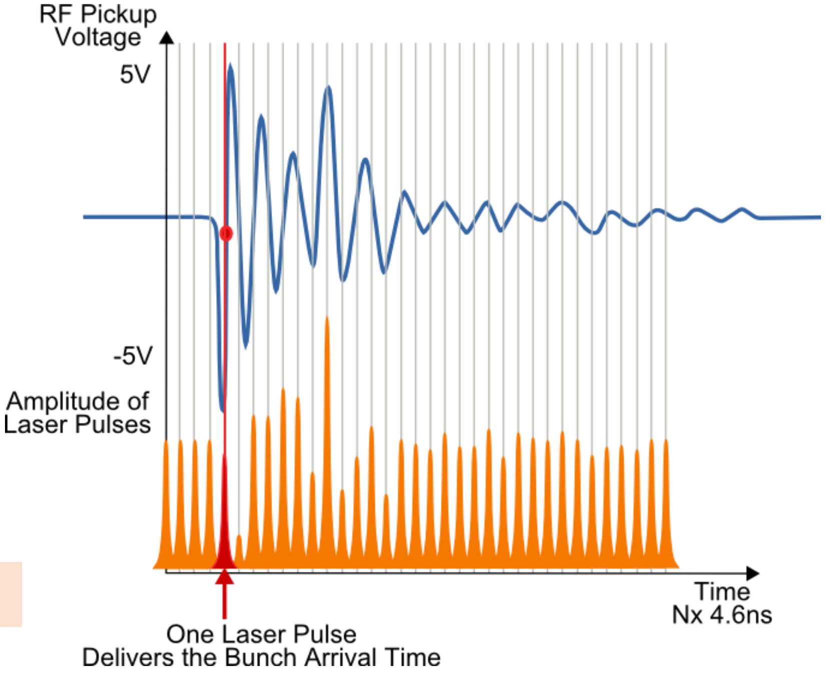
Electro-optical Bunch-Arrival-time Monitors

Measures Deviation from Expected Arrival-Time with Femtoseconds Resolution.





Typical resolution **3 fs** (100…250pc)

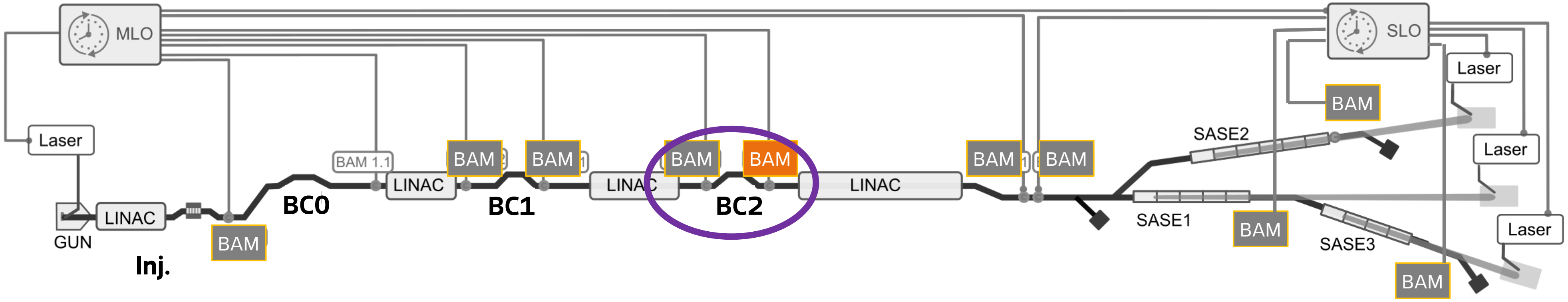


Arrival-time Deviation
→ Measure for Energy Deviations

ΔT ~ ΔE/E

Requirements on RF Stability

Arrival-time Jitter? → Ultimately Limits Performance in Timing-Sensitive User Experiments.



Derived from a **linear compression**,
the timing jitter after BC dependents on

Goal = 10 fs rms

$$\Sigma_{t,f}^2 = \left(\frac{R_{56}}{c_0}\right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left(\frac{C-1}{C}\right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2} + \left(\frac{1}{C}\right)^2 \cdot \Sigma_{t,i}^2$$

Relative amplitude noise $\frac{\sigma_v}{v}$

RF phase jitter σ_ϕ

Initial jitter $\Sigma_{t,i}$

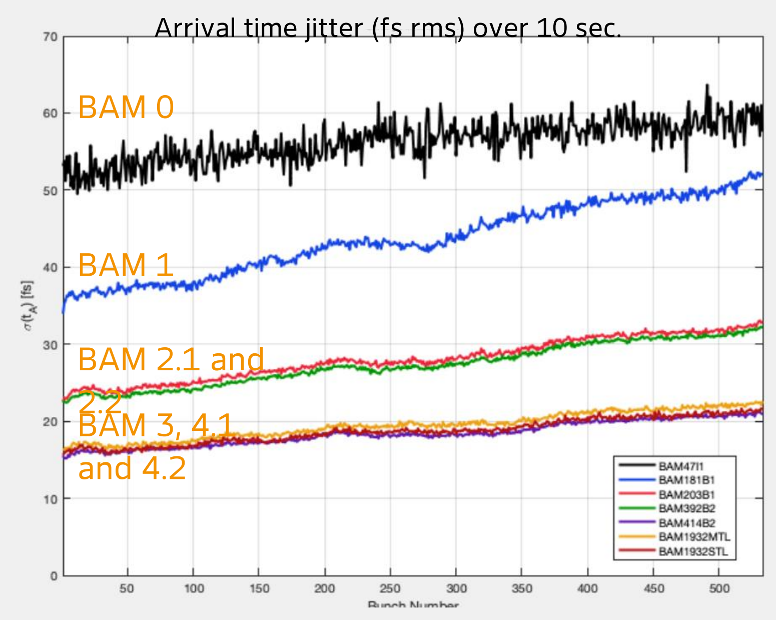
Typically **<0.01%** rel.Amp. & **<0.01deg** Phase

Inj. : 55 fs

BC0 : 45 fs

BC1 : 2 8fs

BC2 : 20 fs



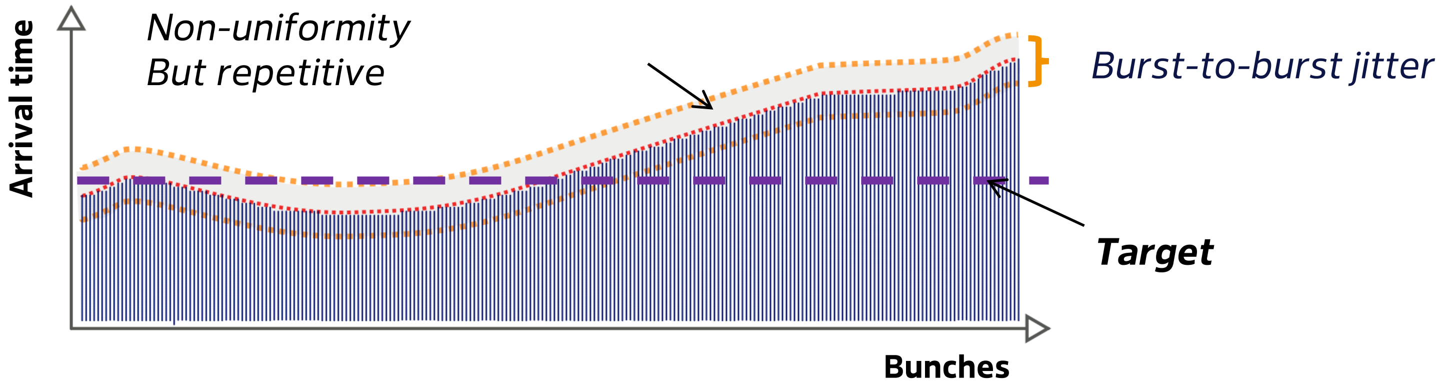
Bunch numbers 1 to 550 per train

Enhanced Stability
→ Using Beam-based Feedbacks

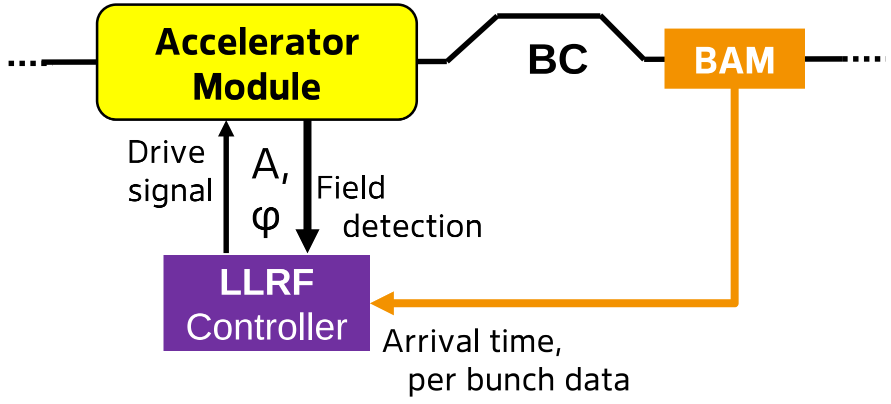
Beam-based Feedback Loop as Integral Part of the LLRF Controller

Intra-burst Stabilization & Removal of Repetitive Errors.

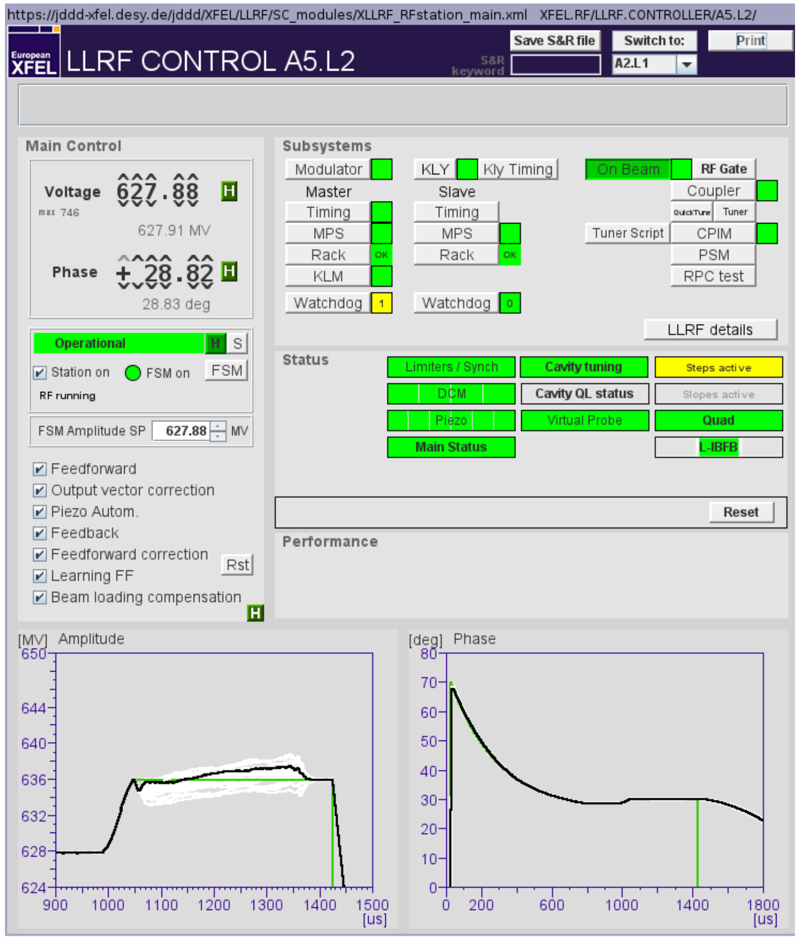
1. **Slope removal, adaptive feedforward**



2. **Jitter reduction, feedback within bunch-train**



Basic feedback loop:
Error signal combination in the LLRF controller.

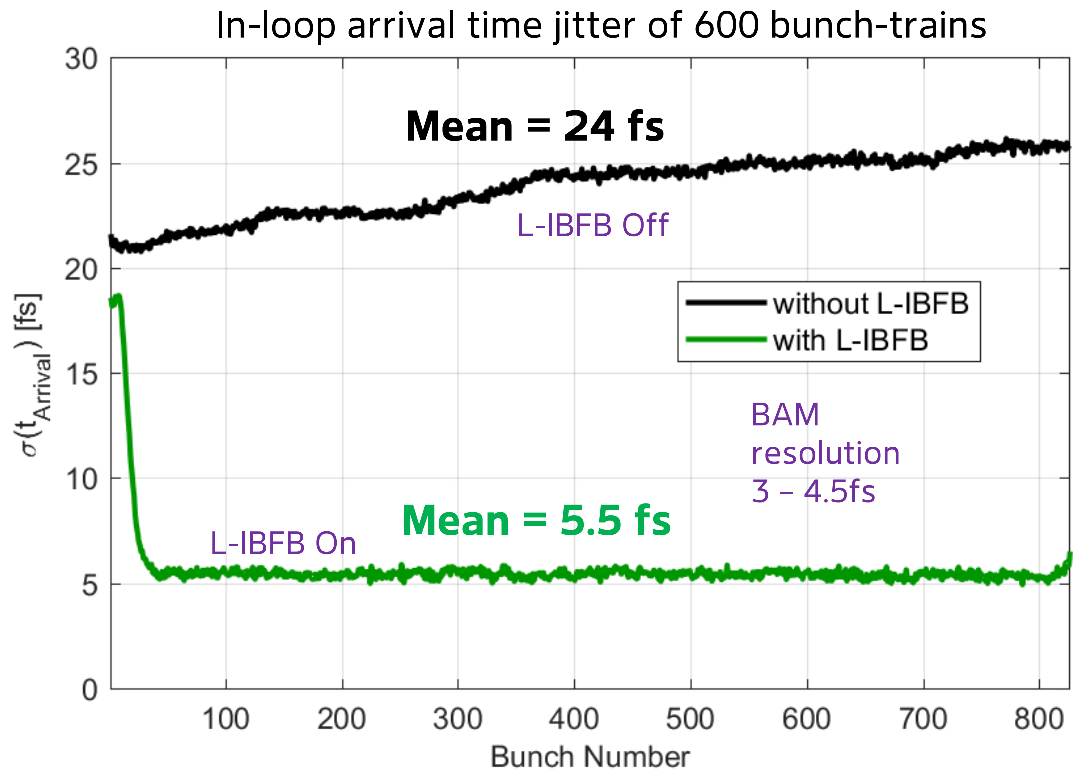


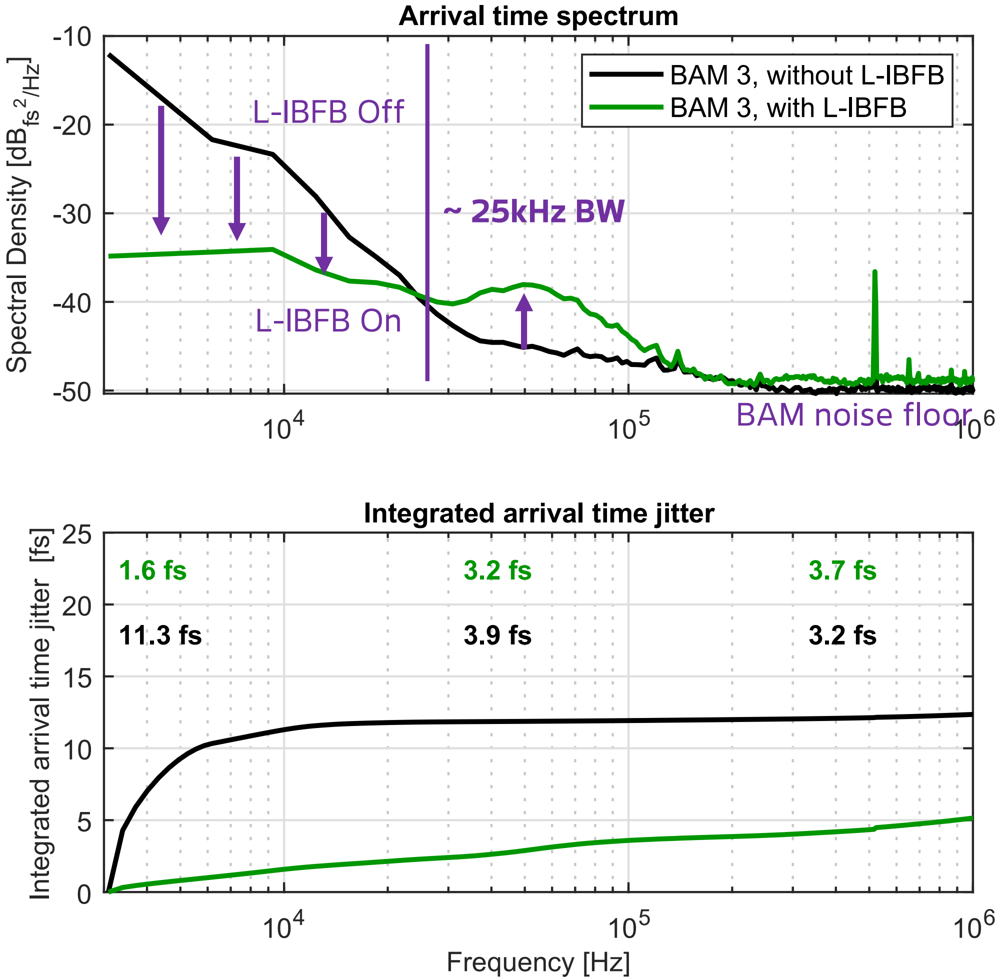
Intra-Train Stabilization

Suppression of RF field fluctuations within 25kHz BW.

- Energy corrections ~ 10^{-6} (e.g. **±5MeV @2.4GeV**),
- Adaptation time ~ 10-15 µs,
- Operation stable over days,
- Limited regulation range → offset correction by slow feedbacks.

Facility	Best	Daily
EuXFEL	3.3 fs	**~ 4…5 fs**
FLASH	4.7 fs	**~ 6 fs**

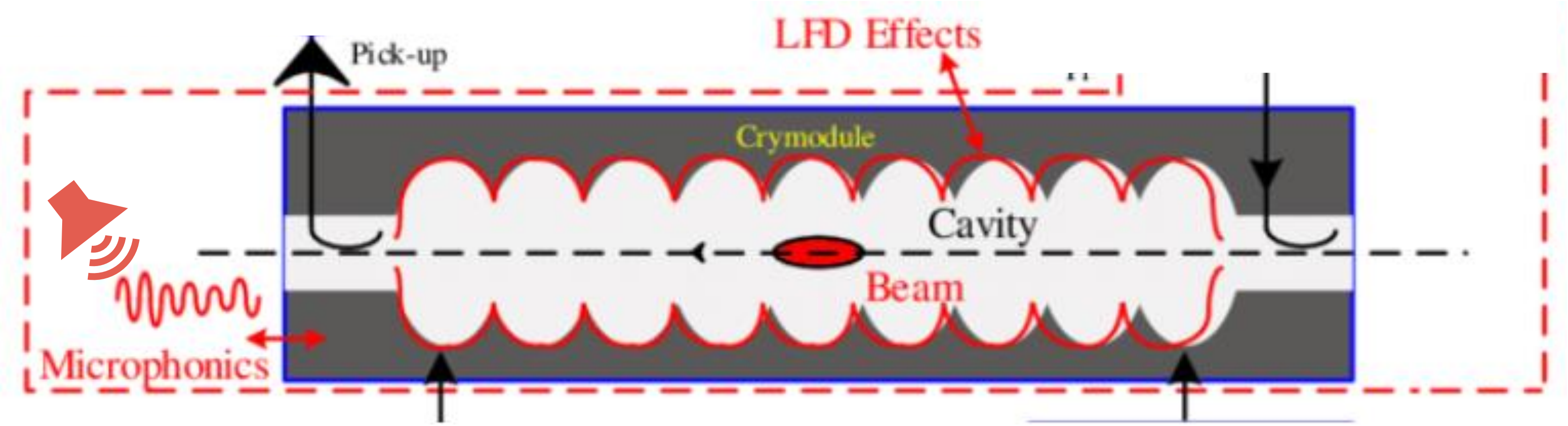




Beam-based Monitoring & Failure Detection

Example 1, Dynamic Cavity Tuning

Automation with Piezo Actuators (DC + AC Voltage)



Dynamic cavity tuning (piezos)

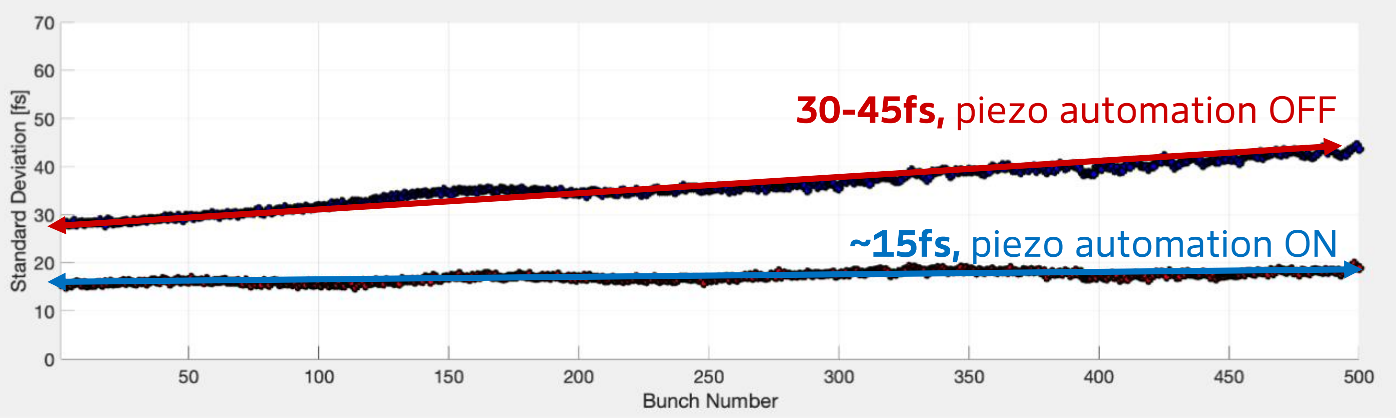
- detuning of individual RF cavities
- Compensates microphonics
- high degree of automation

→ Essential component in multi-cavity control

when absent,

- increased energy, thus timing jitter
- deterioration of field stability within the burst

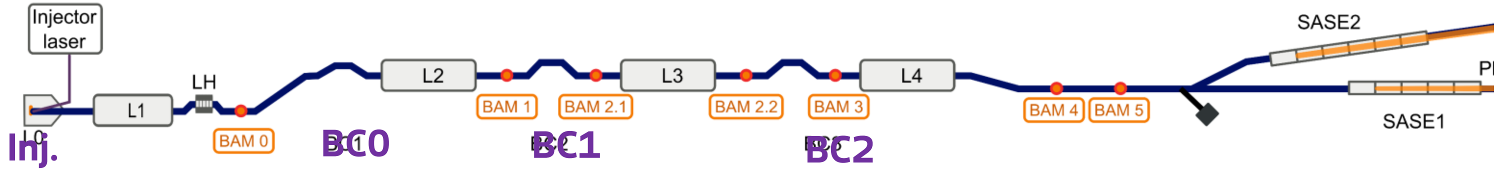
Arrival time jitter [fs] ,100 shots



Bunch No.

Example 2, Observe Unusual Behavior of Beam

Beam-based Monitors as Possibility for Detecting LLRF Control Errors



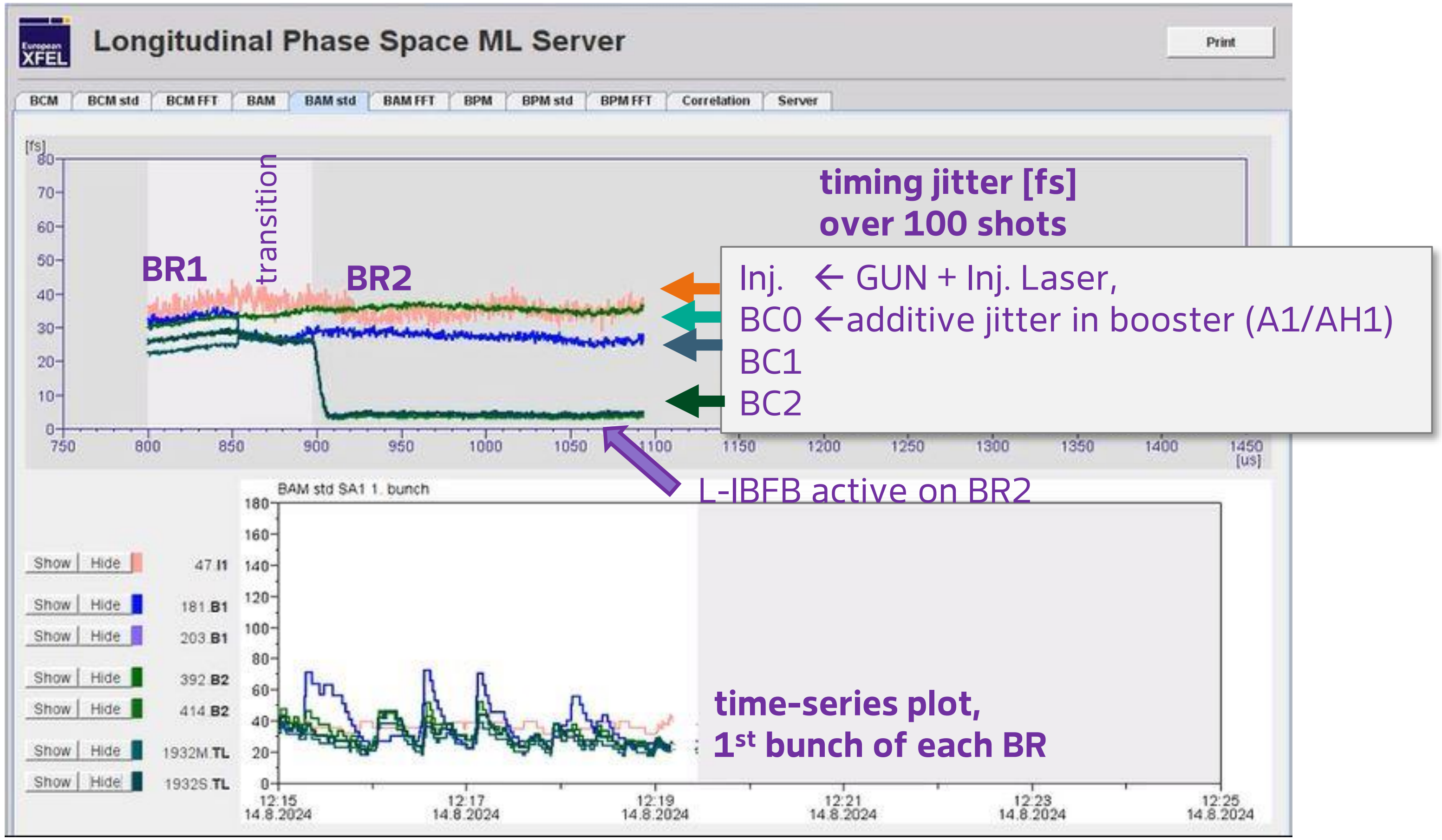
1. High complexity of HPRF + LLRF controllers
2. Lack of out-of-loop monitoring in RF controls

→ valuable information from beam

→ continuous monitoring

- Uses single-shot beam monitors (timing, energy, compression, …)

- Implemented as middle-layer server
  - **Online statistics (mean, std, slopes,…)**
  - **When thresholds exceeded → alarm**



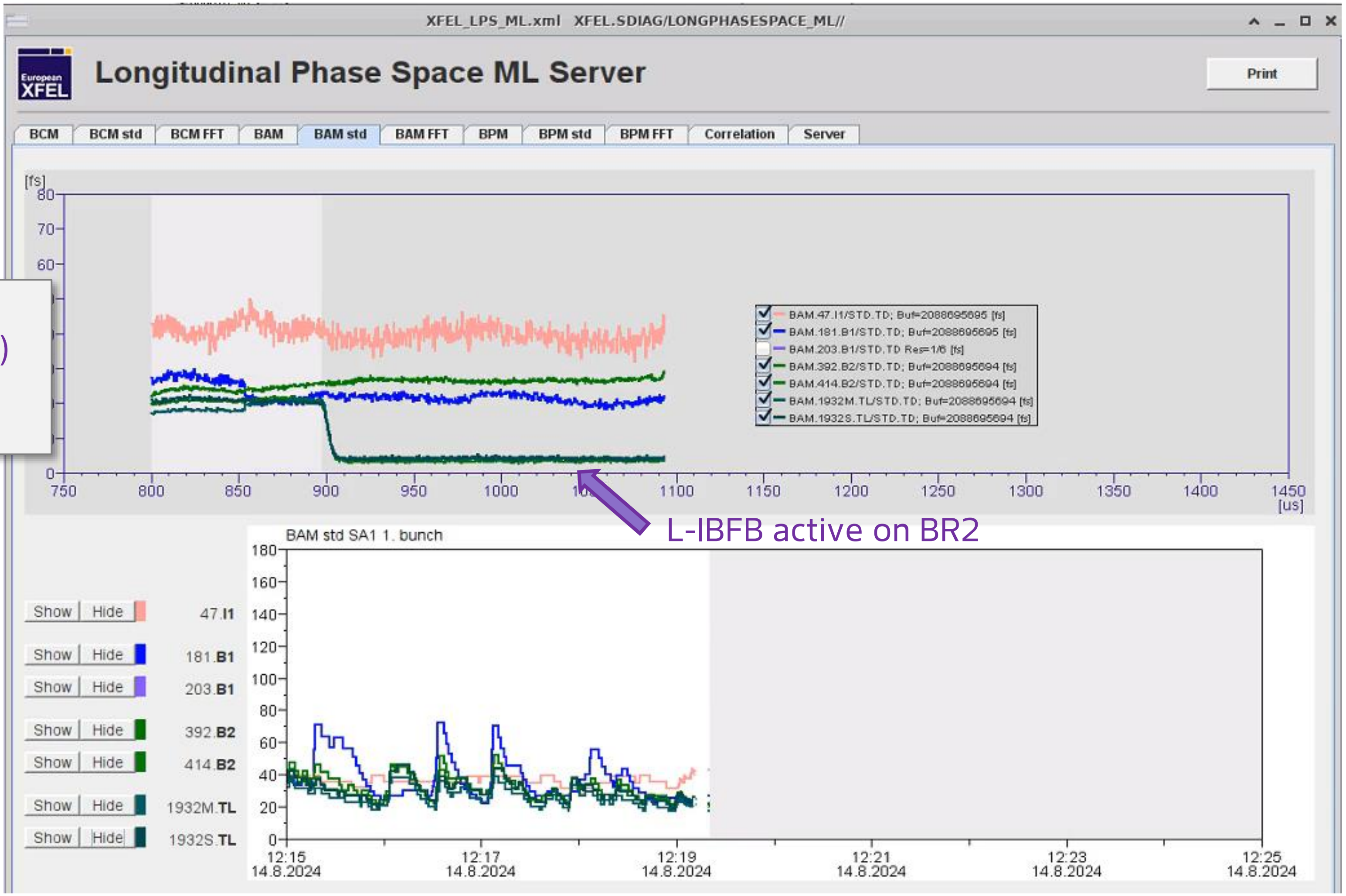
Example 2, Observe Unusual Behavior

Requires expert knowledge to investigate → Capability to add Data-driven Fault Diagnosis

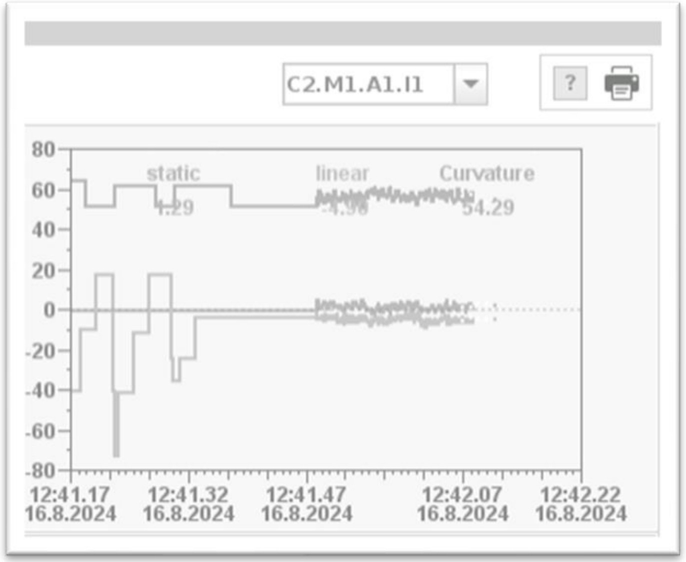
Identified Cause:
Oscillation in detuning automation

Solved:
reduction of gain in regulation loop (piezo AC voltage)

- Injector → sees GUN + Inj. Laser,
- BC0 → sees Booster (A1/AH1)
- BC1
- BC2



L-IBFB active on BR2

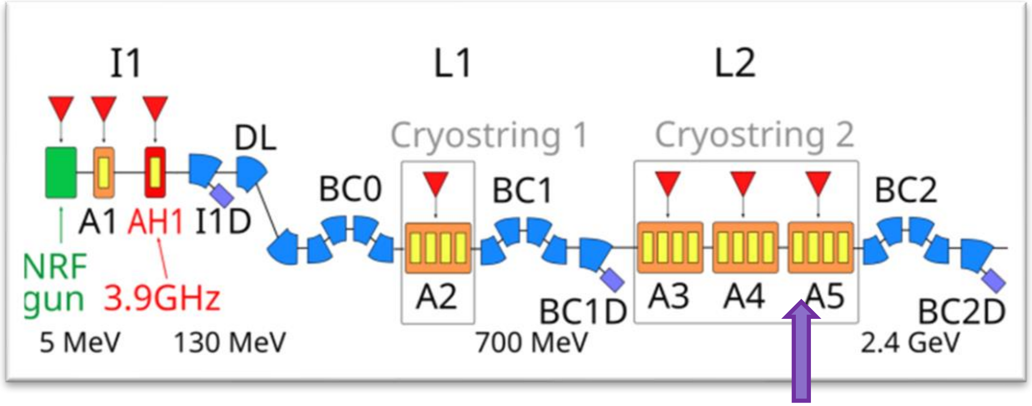


Example 3, Short-circuited Cavity Probe

Disturbance introduced on beam → Thorough Investigation to Find a Solution

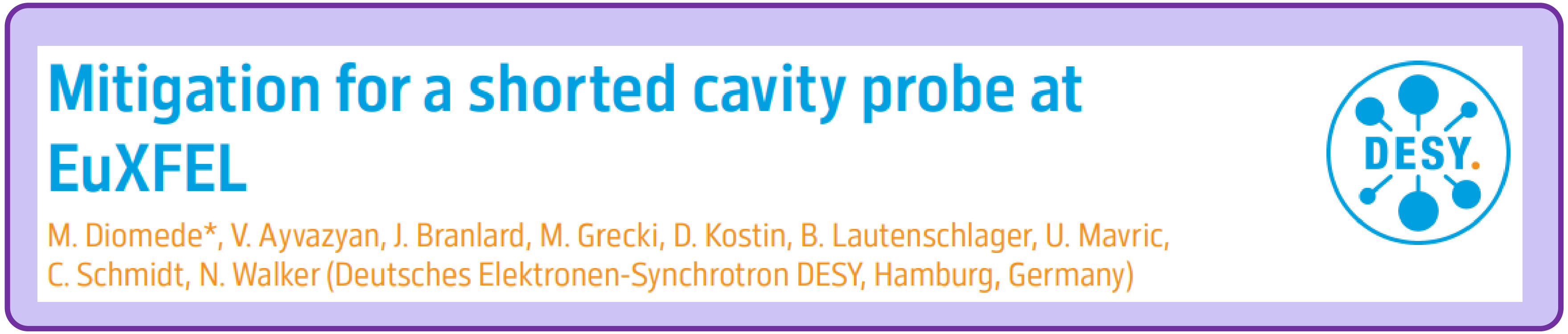
Identified Cause:

- Cavity with faulty probe connector
  but still requires to be included in vector sum regulation
- Large effect on beam
  ~ 300fs unwanted arrival-time slope (over 600us)



... Details see Poster today,

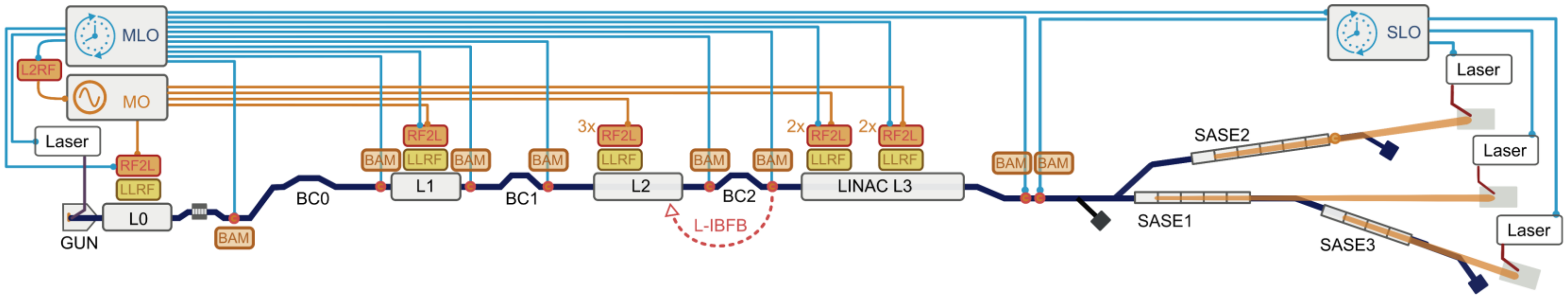
Possible way for mitigation.



Summary & Outlook

Conclusion & Outlook

Importance of Monitoring Systems.



Achieved :

- RF Field Stability → ΔE/E ~ 10^{-6}
- Active beam stabilization [10Hz…100Hz] < 5 fs

Beam-based Information for
Fault Detection & Fault Diagnosis of LLRF Systems

- Requires sufficiently precise beam monitoring
  - Resolve energy deviation ~ 1E-6
  - Resolve phase deviation ~ 10mdeg

Thank you.

Contact

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