SUB-FS REFERENCE TIMING.

Model based optimization of the European XFEL sychronisation system

13th Helmholtz MT ARD ST3 Workshop – DESY Zeuthen

Maximilian Schütte (on behalf of many MSK colleagues)
MSK

26.06.2025

HELMHOLTZ

European XFEL

DESY.

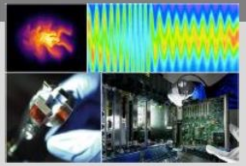
Motivation

ST3 – ADVANCED BEAM CONTROL, DIAGNOSTICS & DYNAMICS

Heart beat of Matter – Faster, more throughput, at highest precision

ARD subtopic 3, MT programme, POF-4: 2021-2027

Control of extreme beams at the forefront of technology



	2015	2020/21	→ 2027
Dynamics code micro-bunching instabilities	OCELOT INOVESA	+ (AI) Artificial Intelligence	
XUV seeding nm	40	20	→ <4
Diagnostic rates Frames/second	k	M	→ G
Synchronization in accelerators fs	15	5	→ <1
Time-resolved fs	10	2	→ <1

Custom & Extreme Beams

Extreme dynamic range

Dynamics 6D phase space

AI agent

Diagnose "every" bunch

Control < 1 fs

Advanced beam control

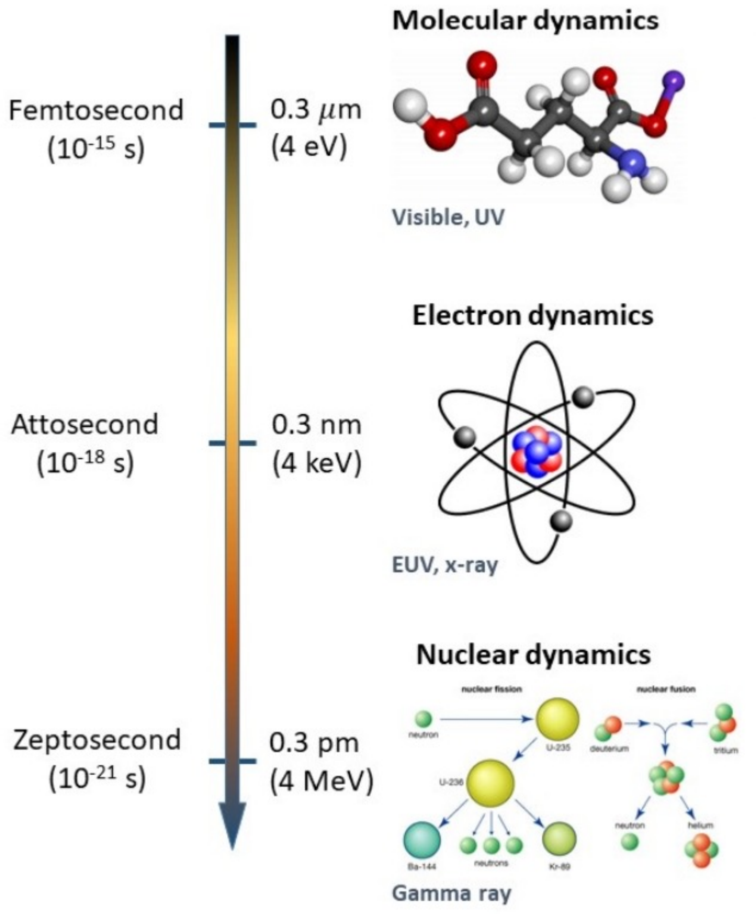
Attosecond metrology

Connecting Sub-Topics and being a hub to DTS and DMA

VISION

Spokespersons: Holger Schlarb (DESY), Erik Bründermann (KIT)

Exploring (Sub)molecular Processes

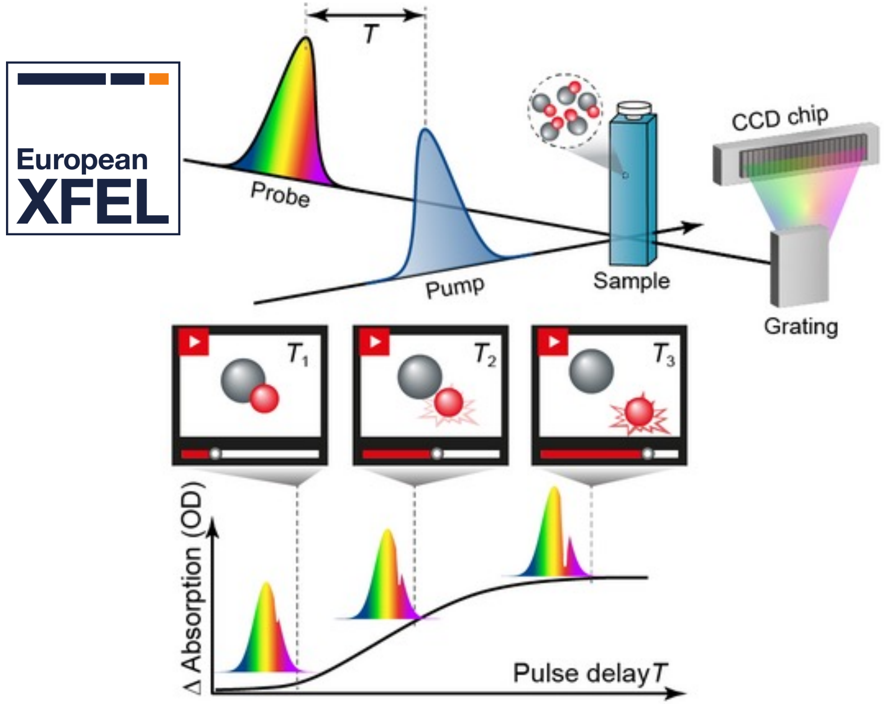


Chemical reactions
Dissociation
Vibration
Rotation

Excitation, HHG, ATI and FTI
Electronic transition
Multiphoton/tunneling Ionization
Electron localization
Double ionization

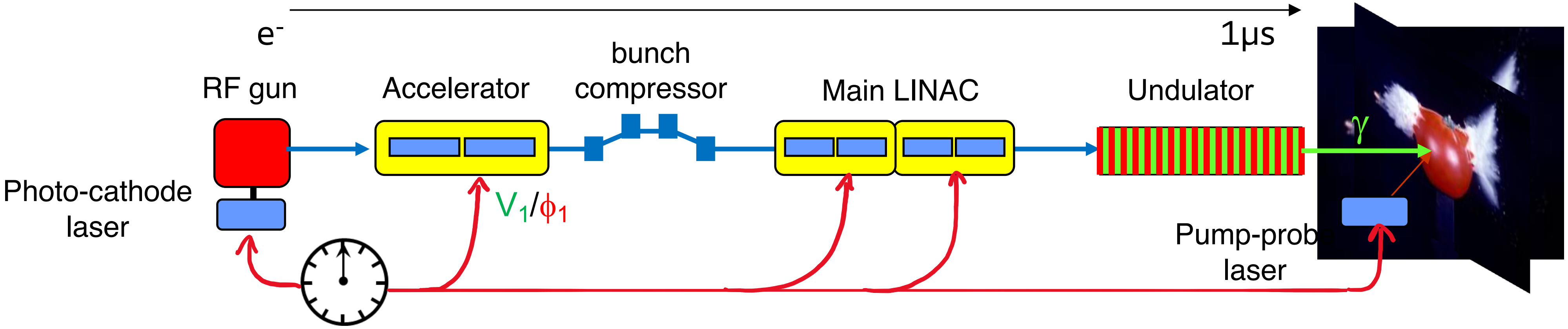
Nuclear collision
Fusion
Fission

Serial Pump-Probe Experimentation



Phase Reference in Free-Electron Lasers

An example related to fs pump-probe experimentation



Voltage | **Phase** | **Init. arrival**

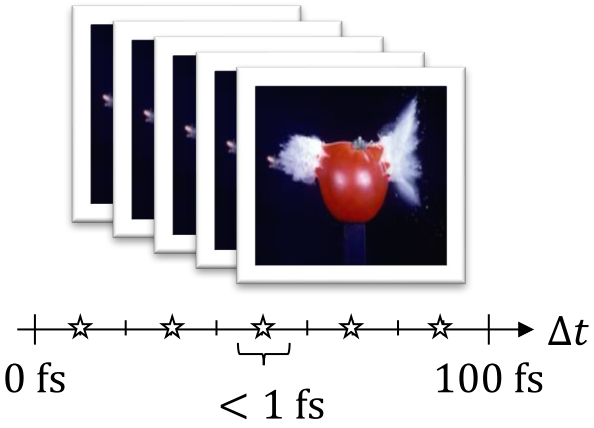
Timing jitter behind BC
C ~5 … 20 typically

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

XFEL: 1.5ps/%
FLASH: 7.0ps/%

2 ps/deg
L-band

0.05 ps/ps
C=20



- Bunch propagation is **absolute** measure of time.
- Phase noise accumulated over this time causes wrong ETA → $\frac{1\ \text{fs}}{1\ \mu\text{s}} = 10^{-9}$.
- Can estimate RF field stability requirements: **0.01% amplitude, 0.01° phase**.

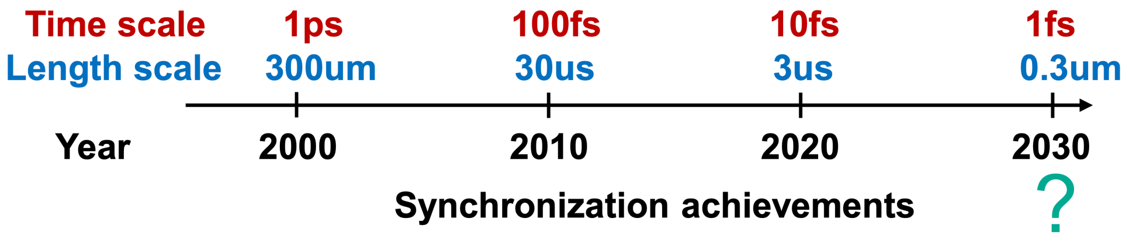
Timing Jitter and Drift Considerations

Overview

time and length scales

duration

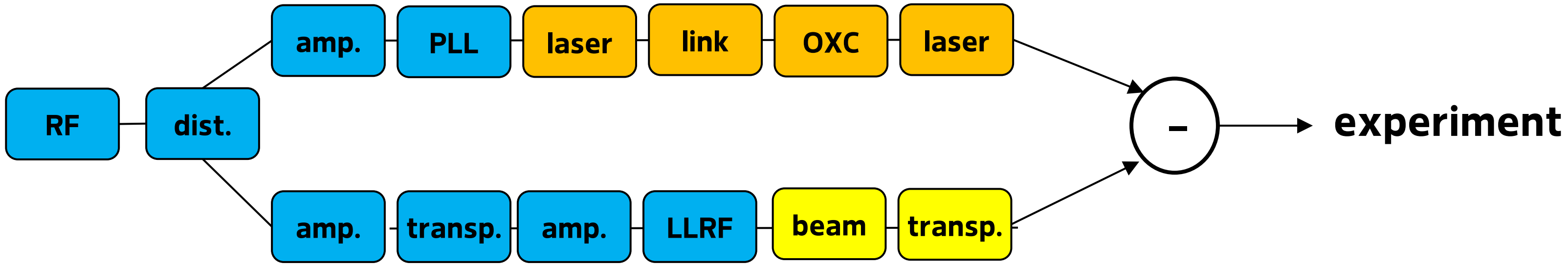
short range	10 µs ... 1 ms	power supplies, EMI, electronics, materials properties
mid range	1 ms ... 10 s	acoustics, seismic activities, air/water flow, fans, ...
long range	10 s ... days	thermal effects, humidity, air pressure, ...

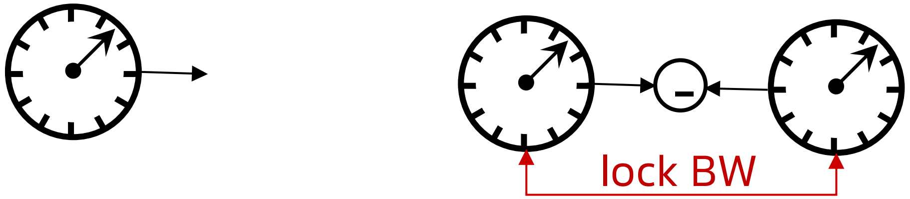


long “chain” of devices

- accelerator
- laser(s)

absolute and **relative timing jitter**

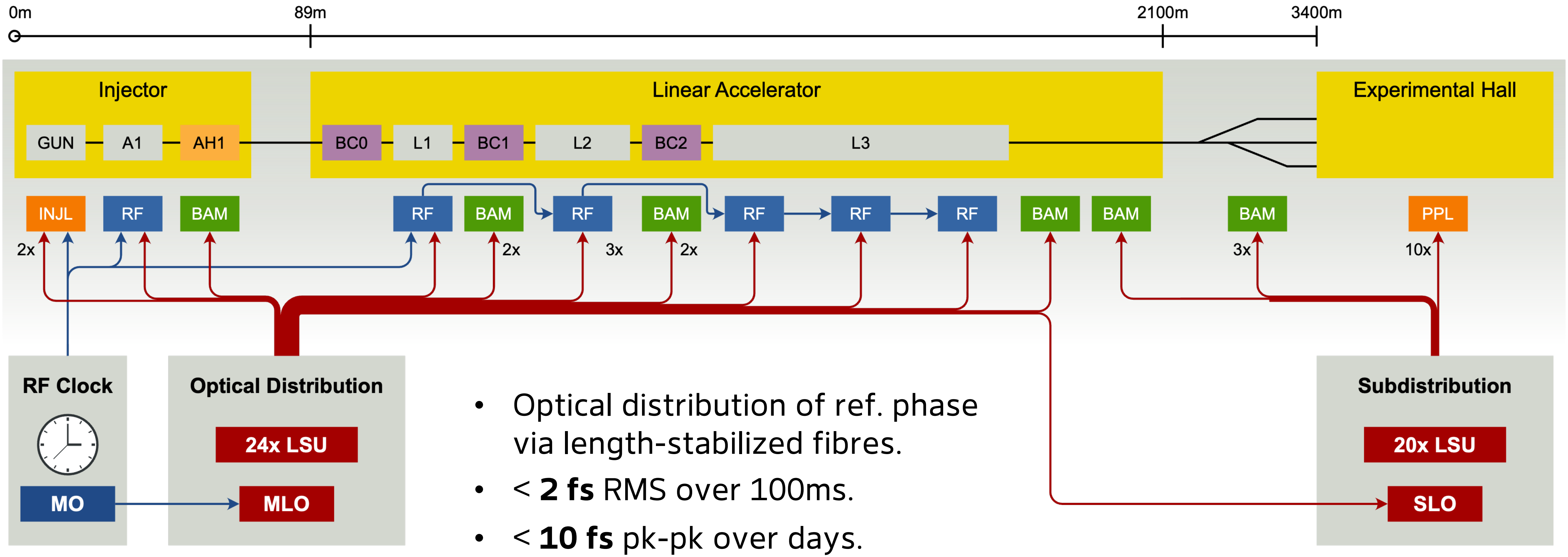




courtesy of H. Schlarb

Synchronisation System and Clients

Optical Synchronisation at European XFEL



- Optical distribution of ref. phase via length-stabilized fibres.
- < **2 fs** RMS over 100ms.
- < **10 fs** pk-pk over days.

System Modeling & Identification

Towards systematic analysis and improvement

Why is the performance as it is?

What can be done to improve it?

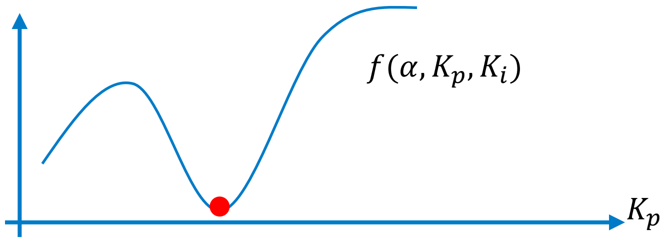
Dynamic Process Model

- Mapping external inputs to process output.
- Consists of relations, e.g.

$$\varphi(t) = \varphi_0 + \int_0^t u(t) \cdot \alpha \, dt \, ,$$

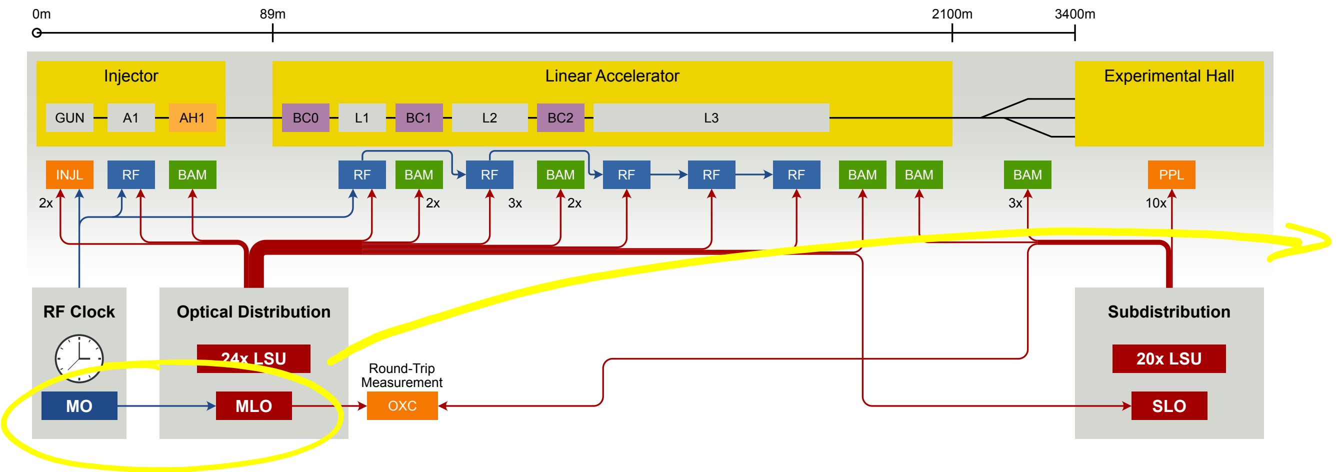
$$u(t) = K_p \cdot e(t) + K_i \int_0^t e(t) \, dt$$

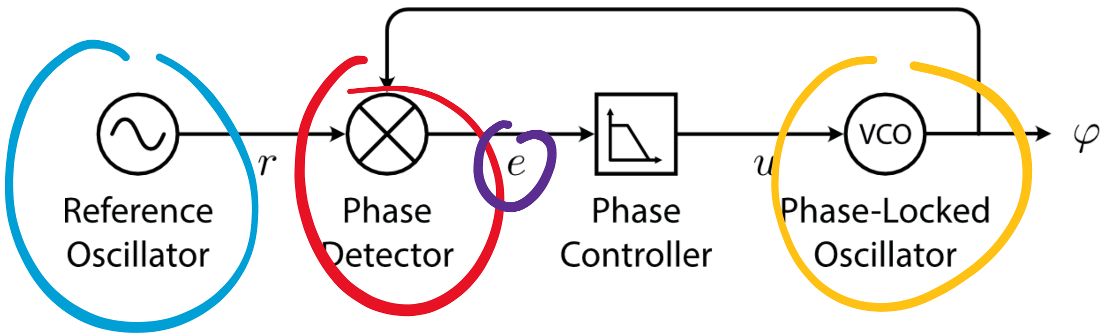
  and set of parameters: α, K_p, K_i.
- Design parameters can be optimized.



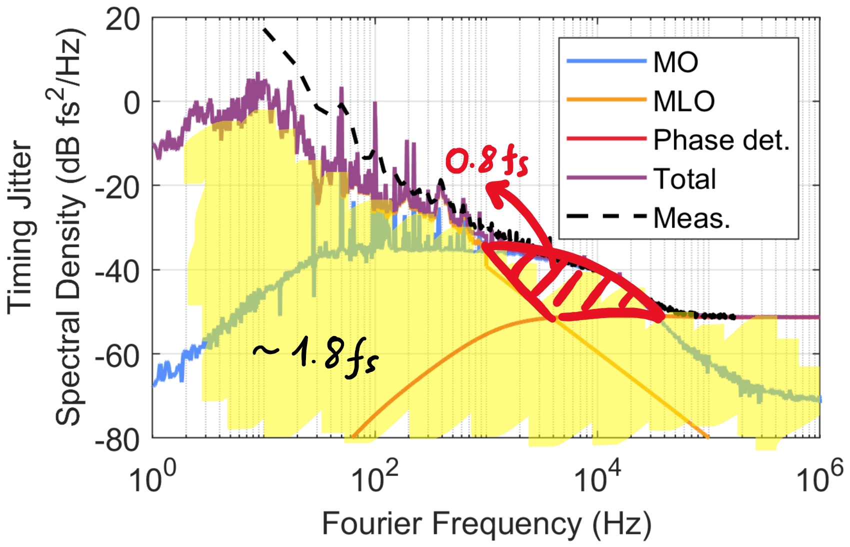
System Modeling & Identification

A simple PLL example





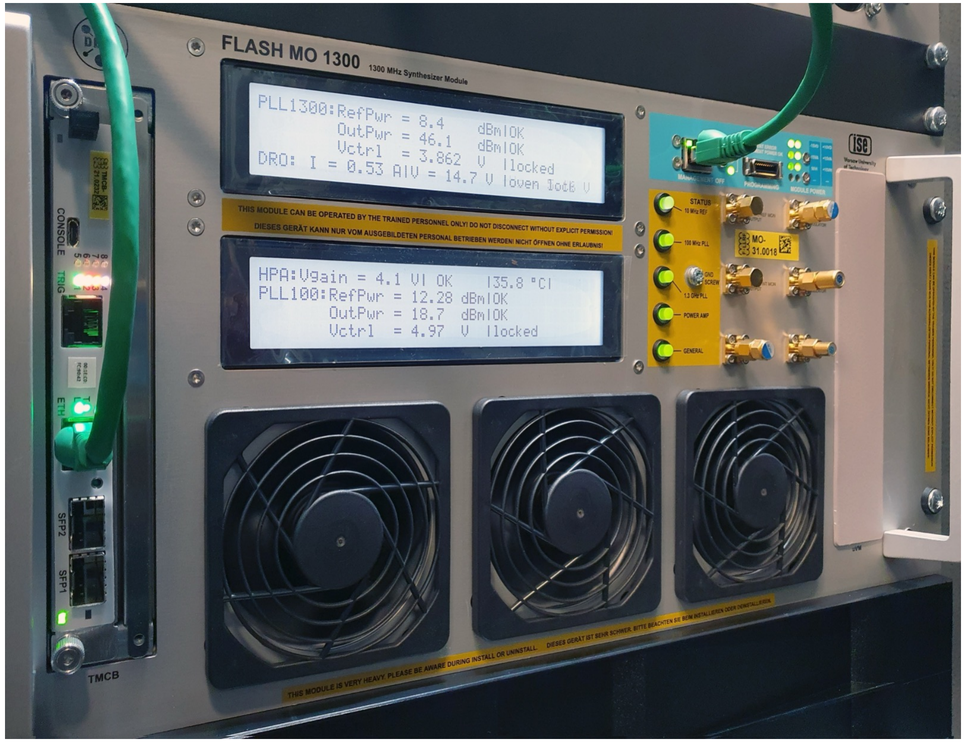
- Inputs:
  - Reference oscillator noise
  - VCO noise
  - Phase detector noise
  - Controller gains
- Output:
  - Relative phase error e



- Linear model.
- Optimization of PI gains minimizes residual jitter.
- „Biggest bang for the buck“: Improve MO btwn 1 – 30 kHz.
- Model validation: Compare simulated & measured totals.

RF Main Oscillator

FLASH's and (Soon) European XFEL's Ultra-low Phase Noise High Power 1.3 GHz Source



Developed together with WUT, industrialised through KVG Quartz Crystal Technology GmbH
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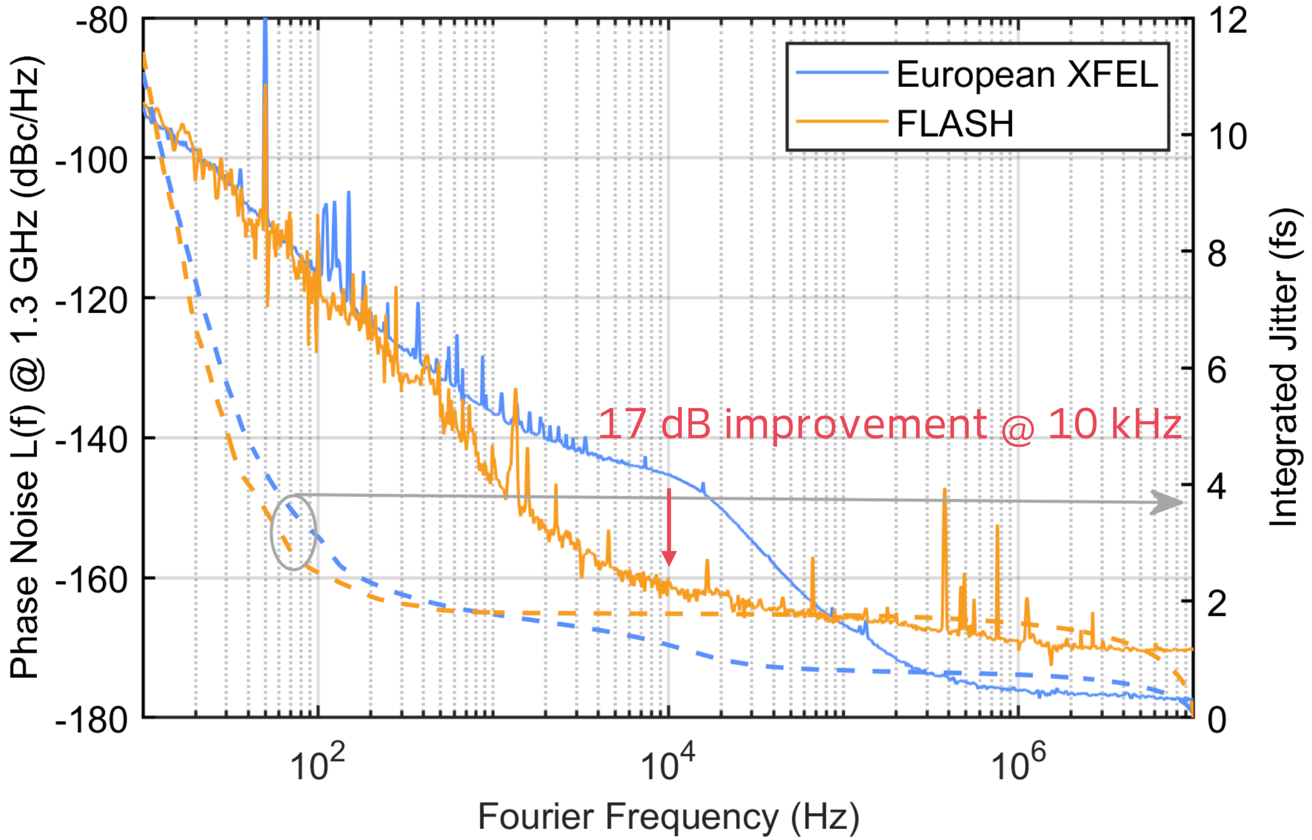
Quartz Crystal Technology GmbH



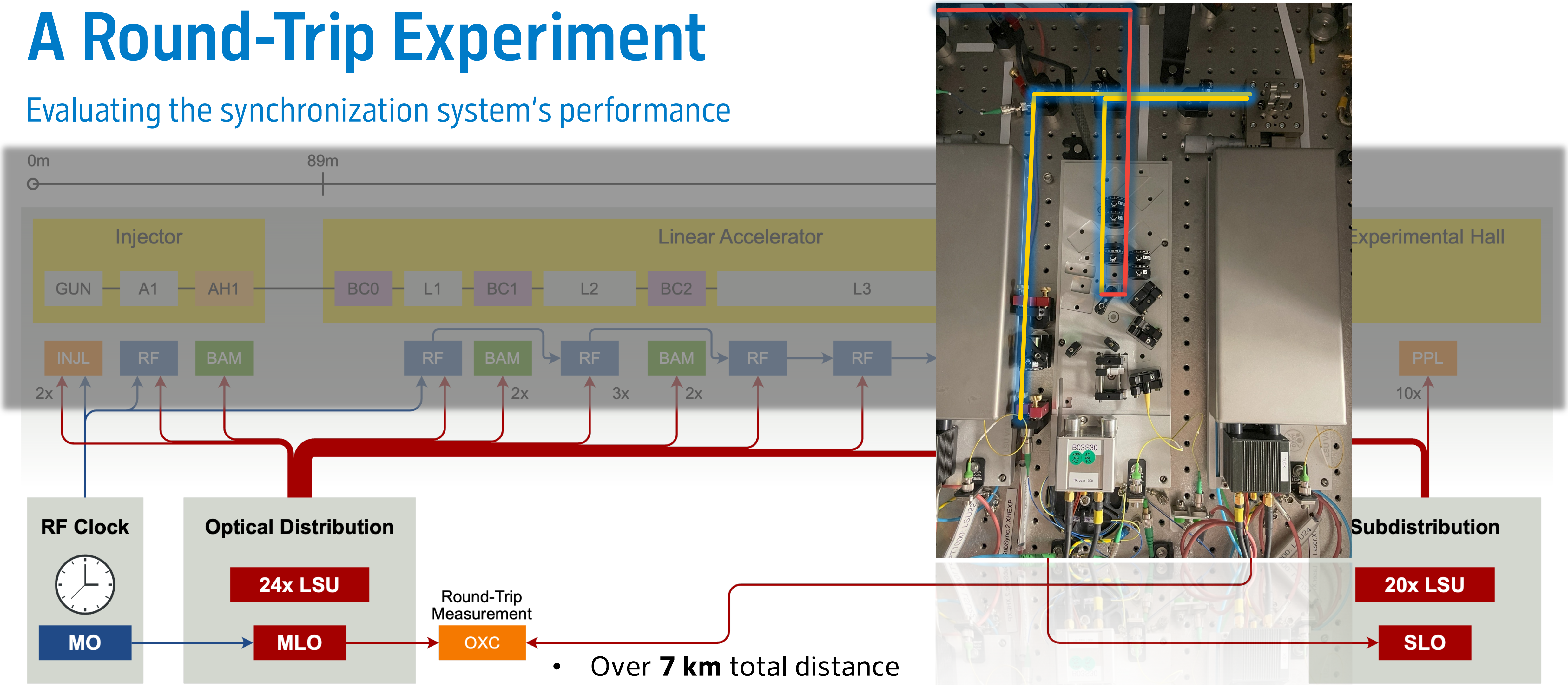
Substantial improvement of integrated jitter
- fs laser systems locked to the reference show significant improvement

courtesy of F. Ludwig, H. Pryschelski, M. Schütte

Performance Evaluation & Optimization

A Round-Trip Experiment

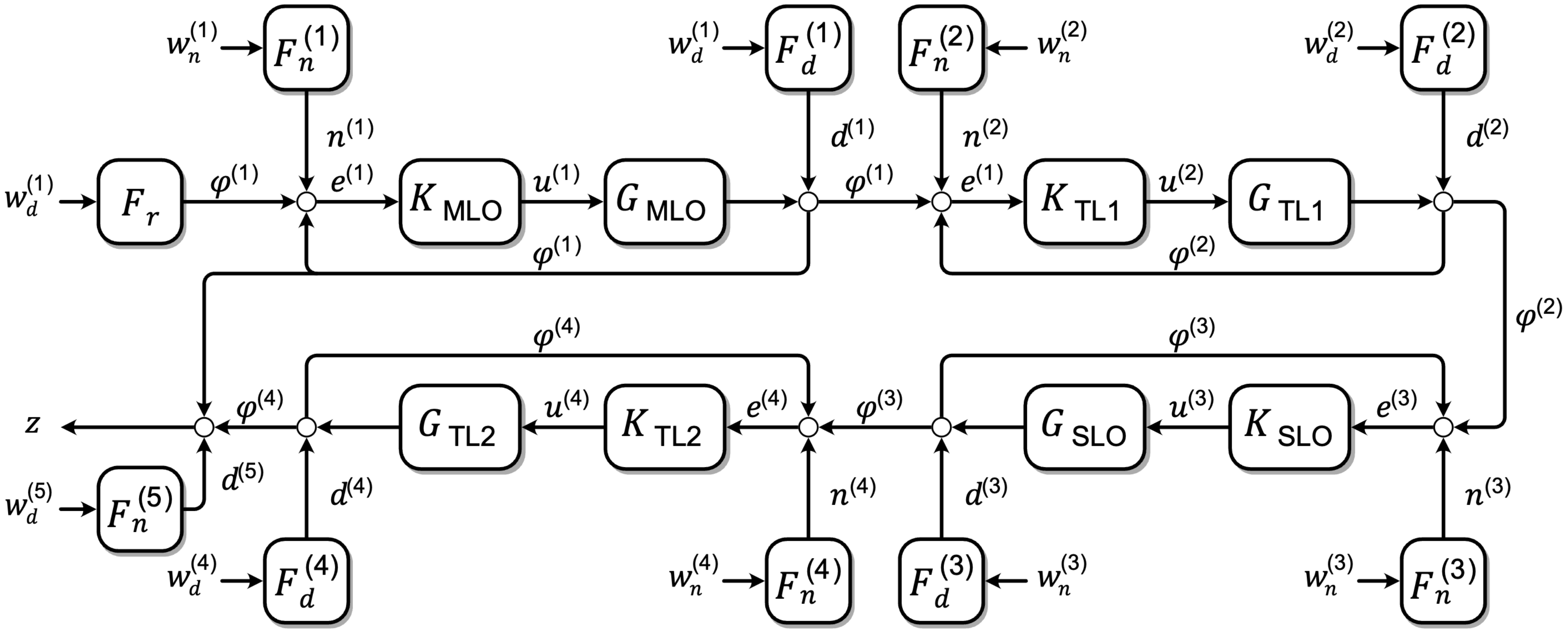
Evaluating the synchronization system's performance



- Over **7 km** total distance
- 10 noise sources
- 8 tunable controller gains
- Heuristic tuning performance: ~ **1.5 fs** RMS

A Round-Trip Experiment

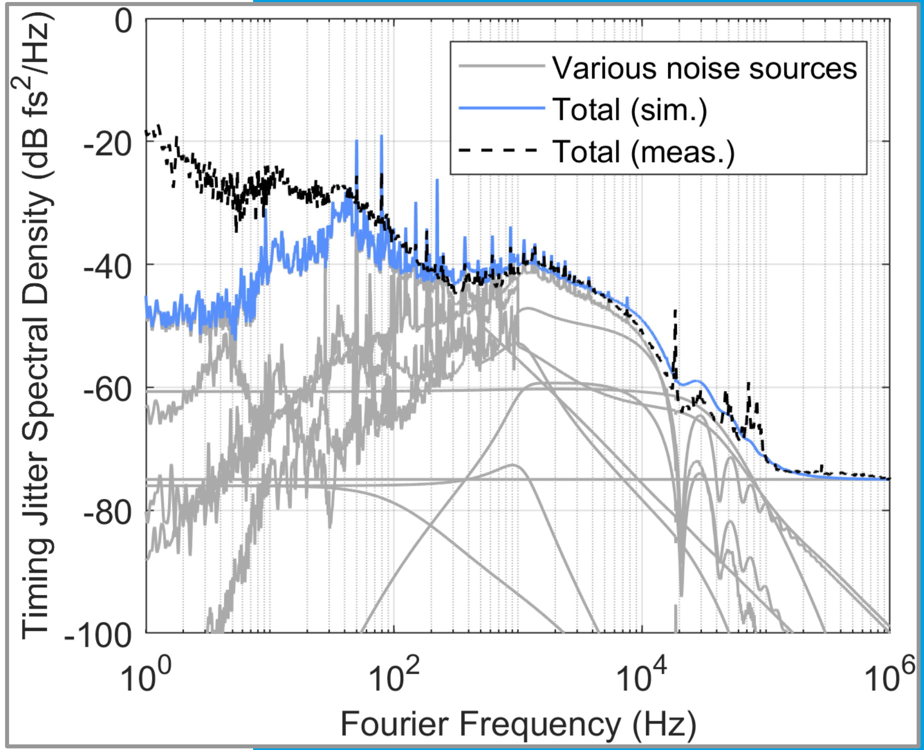
Generalized block diagram



Round-Trip Experiment Results

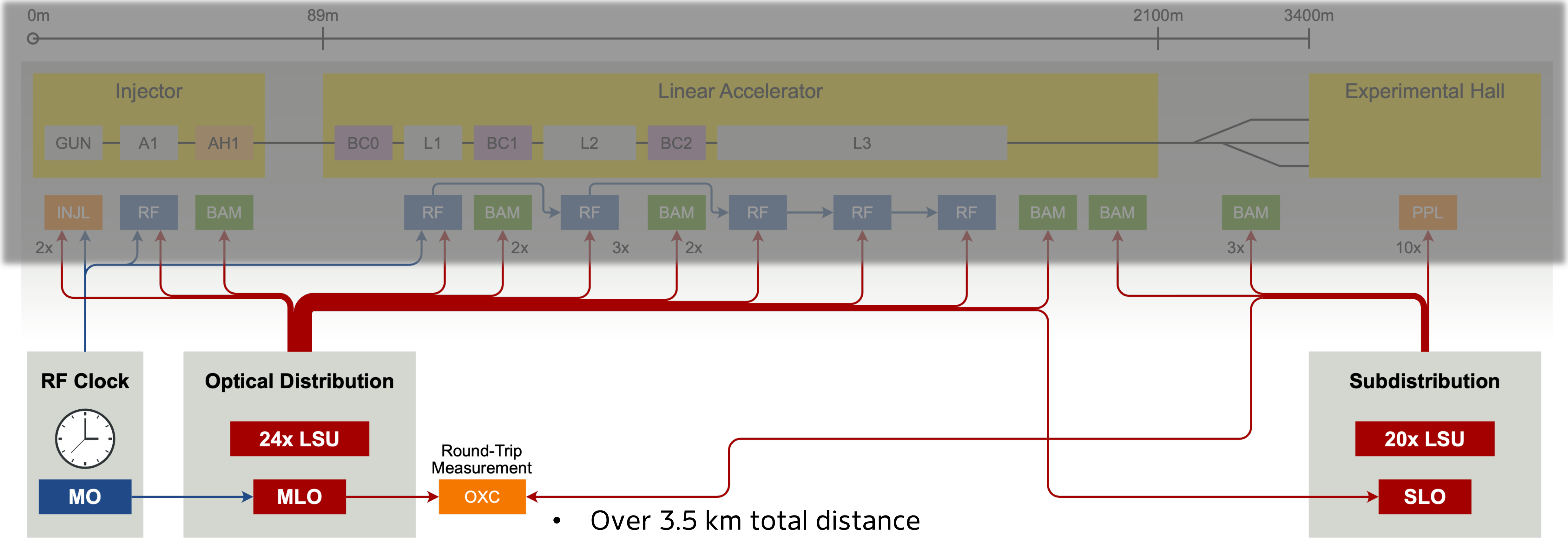
➔ Special thanks to Jannis Lübsen for providing and running the MT-BO optimization.

- Multi-Task Bayesian Optimization allows model-informed optimization of high dimensional parameter spaces.
- Post-BO-optimization performance **0.75 fs** RMS over >7km.
- **50%** improvement over heuristic tuning.
- Model accurately predicts round-trip jitter PSD.
- Dominated by delay-line effect.
  - Improved by making MO more phase stable.
- Outlook: Other controller architectures promise even better performance.



Unpublished results

Pump-Probe System Synchronization



- Over 3.5 km total distance
- 11 noise sources
- 10 tunable PI gains
- Heuristic tuning performance: ~ **1.5 fs** RMS

Pump-Probe Synchronization

→ Results conservative due to delay-line effect.

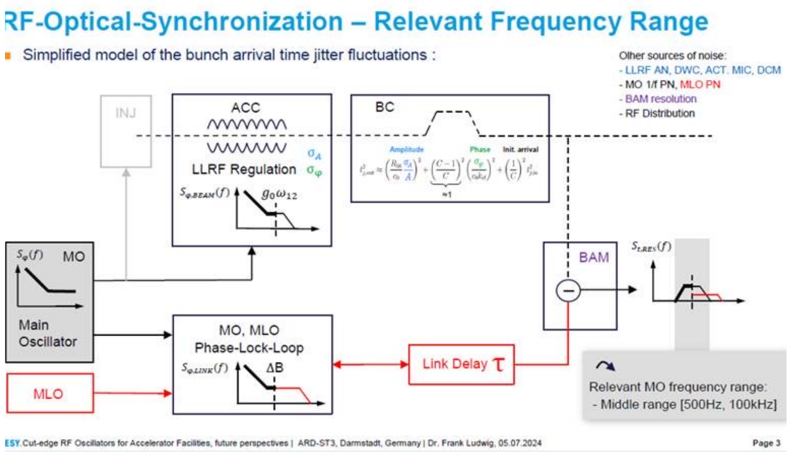
- PPL-XUV jitter can only be measured with PAM (WIP).
- Model predicts < **2.4 fs** RMS residual error PPL – MO.
- Model inferred „next steps" (cf. table).
- **Sub-Femtosecond reference timing is possible with current technology.**

Action	Predicted Perf. Gain	New Performance
Add lead compensator to feedback controllers	~ 12 %	~ 2.15 fs
Reduce loop-latency for PPL seed laser synchronization	~ 7 %	~ 2 fs
Improve MO phase noise (1 – 30 kHz)	~ 48 %	~ 1 fs
Add additional controller interconnections	~ 35 %	~ 0.65 fs

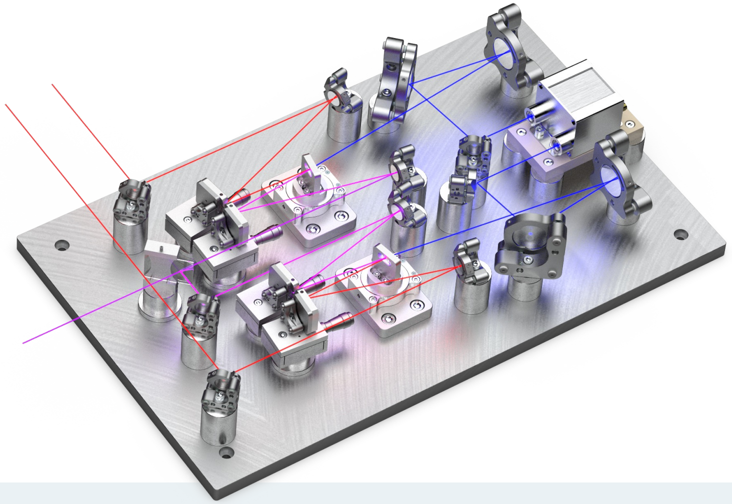
Unpublished results

Outlook & Conclusion

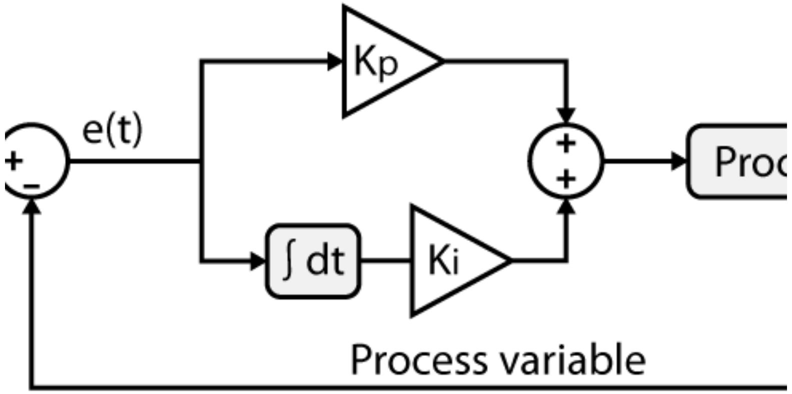
Synchronisation & Longitudinal Stability – An Outlook



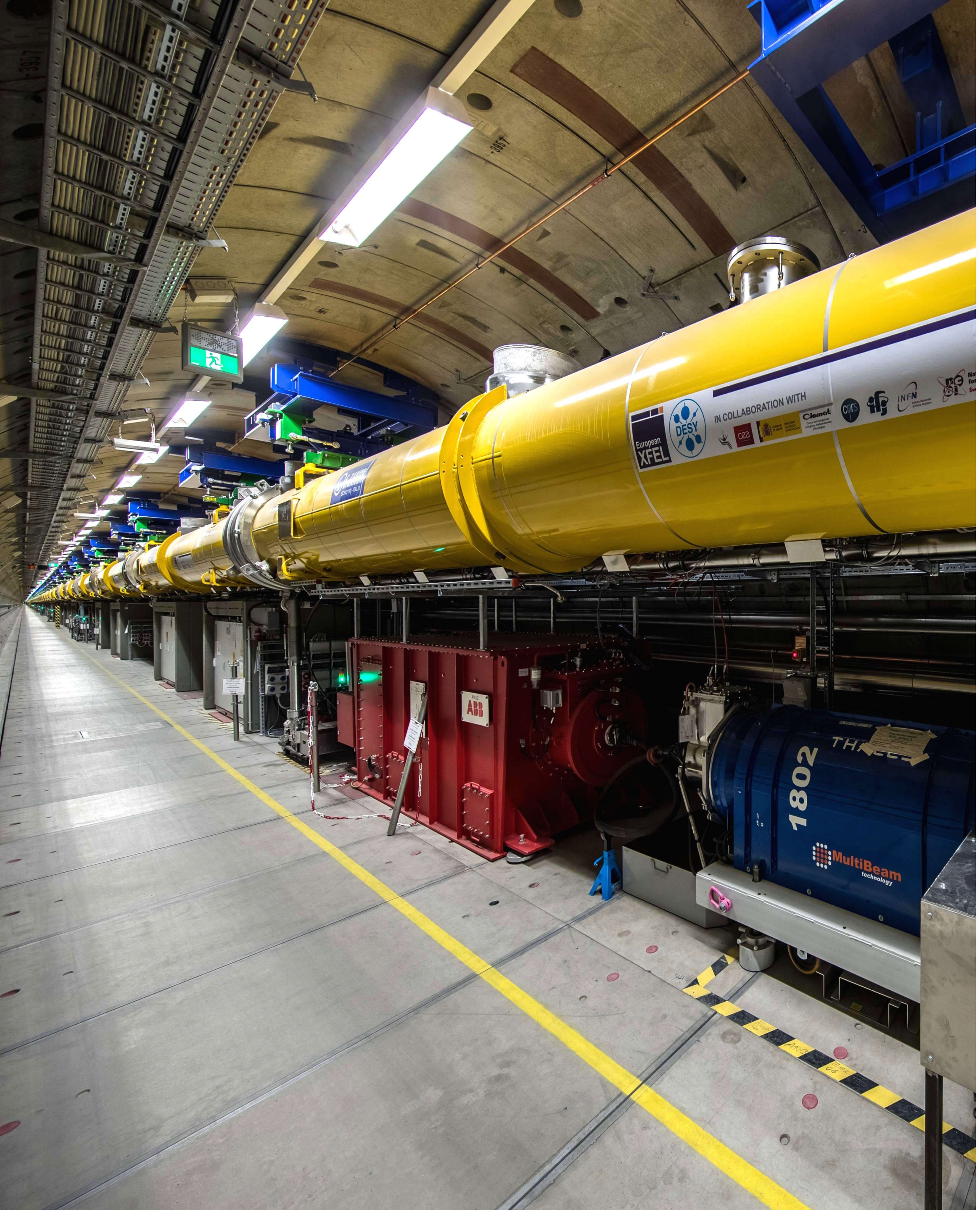
Integration with LLRF and Beam Dynamics Models



Experimental Validation with Laser & Photon Arrival Time Monitors



Model-Based Feedback Design Studies



Take-Aways

- Models let you
  - decompose performance figures into contributions.
  - identify bottlenecks.
  - optimize tuning parameters.
  - cheaply evaluate options.
  - efficiently direct R&D resources.

- Sub-femtosecond facility synchronization is within reach.

Thank You

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