Precision Large Scale Synchronization System at the European XFEL

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on behalf of the Lbsync Team

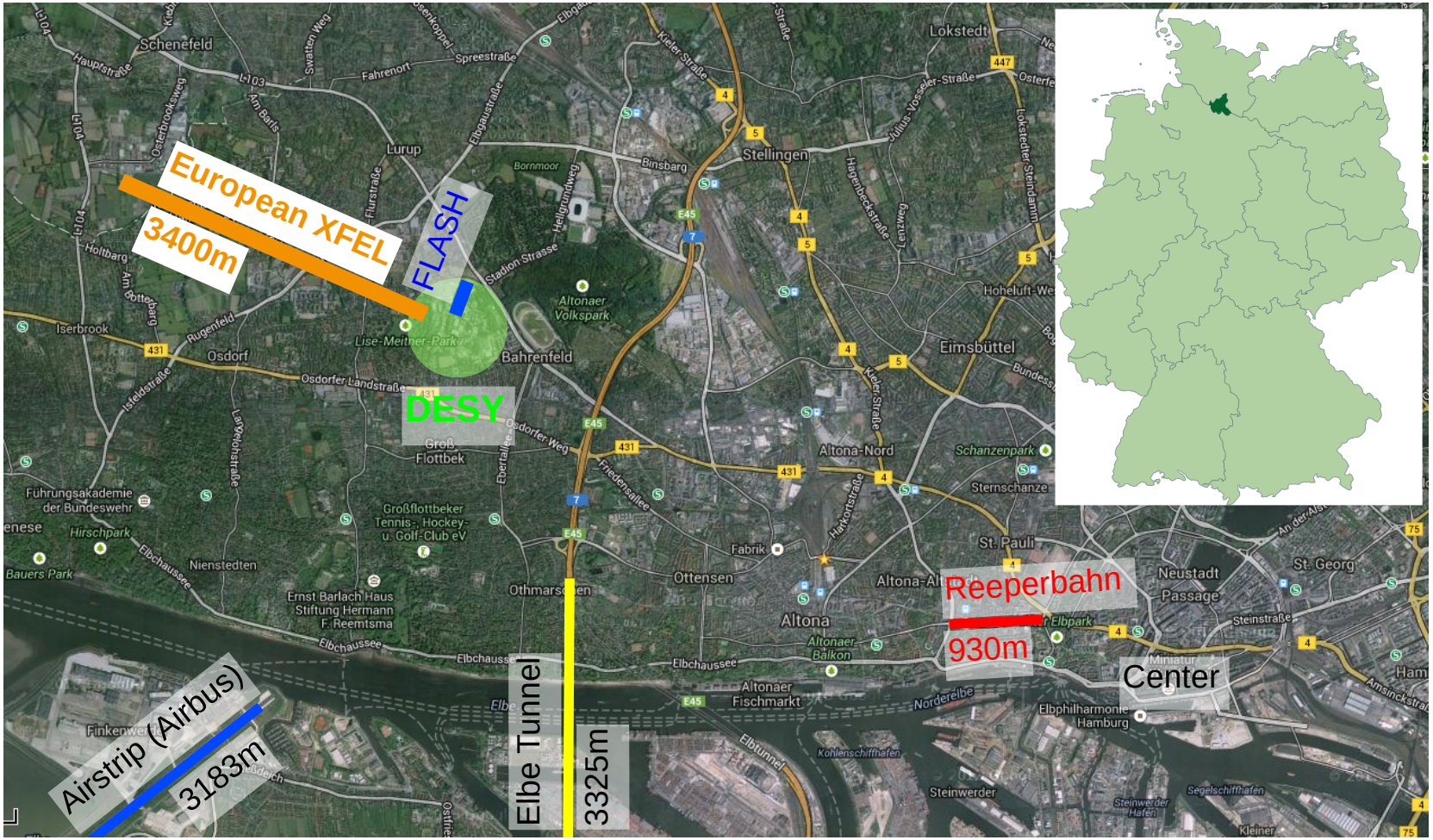
MSK / DESY

Grand Rapids, Michigan, 22th August 2017

Outline

- European XFEL Location and Synchronization Overview
- Optical Reference Distribution
  - Master Laser Oscillator
  - Fiber link stabilization
- Endstations
  - Laser-to-RF: Control RF phase
  - Laser-to-Laser: Control Laser timing
  - Bunch Arrival Monitor: Measure bunch arrival time
- Summary

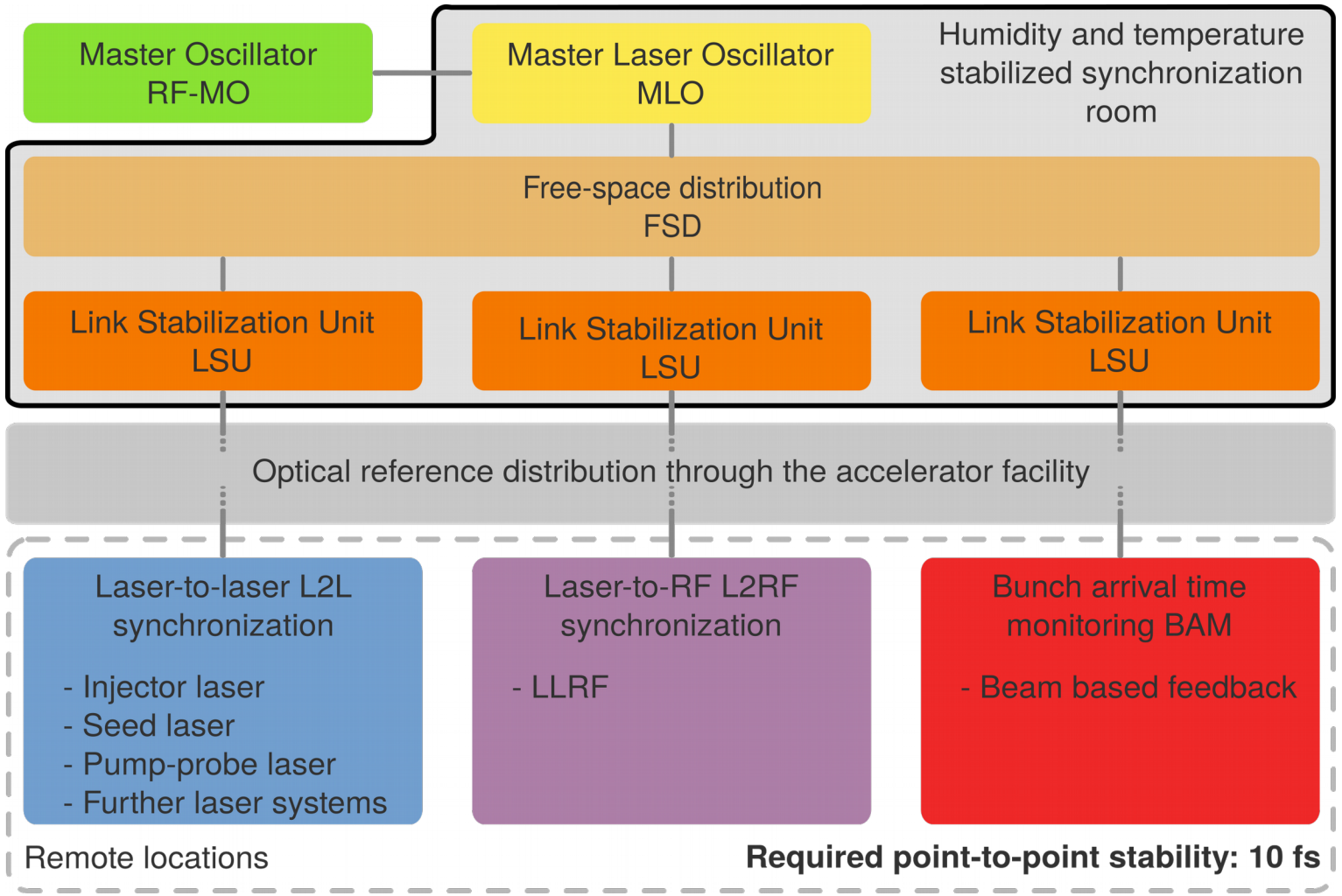
The European XFEL and DESY in Hamburg, Germany



Why is the synchronization optical

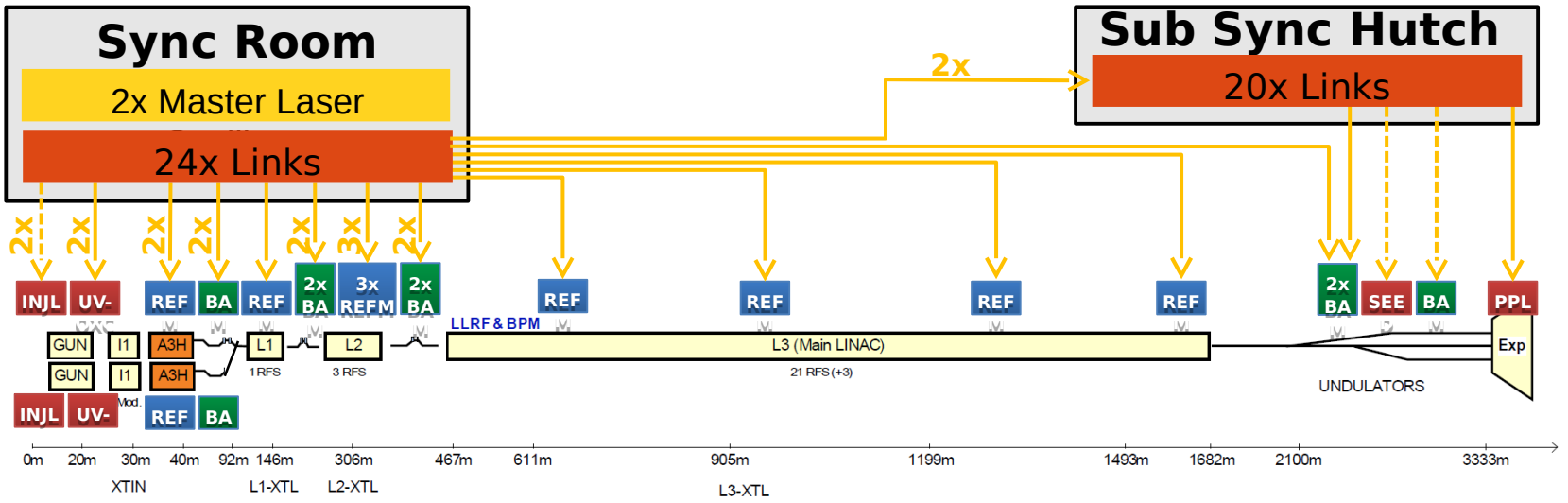
- Ideal for all-optical slave laser locking e.g. pump-probe-laser etc.
- High resolution elektron bunch arrival time measurement available
- High precision laser-to-RF phase comparator available
- Low loss in single mode fibers for long distances ~ 0.3dB / km
- Low loss in polarization maintaining fibers ~ 0.8dB / km
  - 21 km installed at European XFEL, about 6 km at FLASH
  - Quite expensive but …
  - No timing error due polarization mode dispersion
  - No polarization correction necessary

System Overview



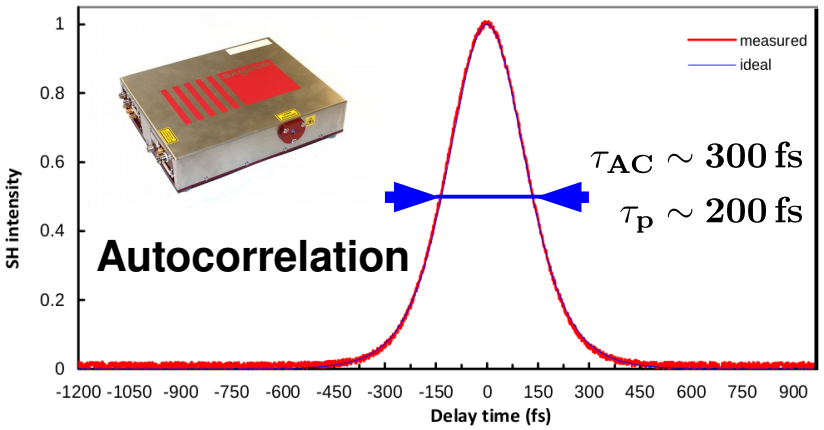
Installation Overview

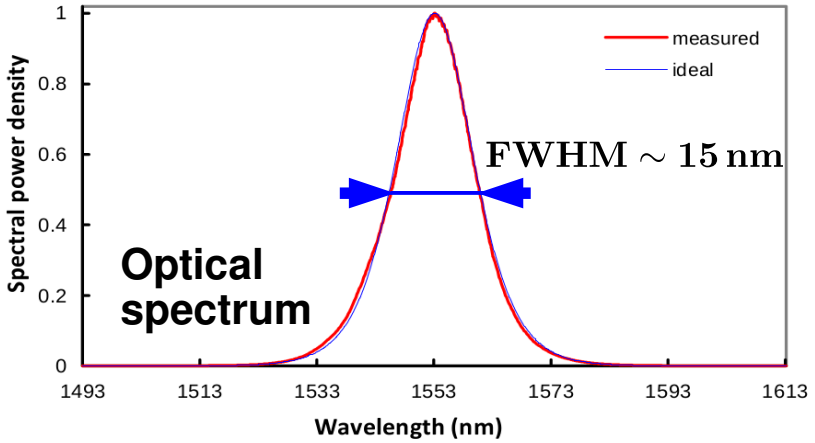
- Master-Synchronization Room
  - Two Master-Laser-Oscillators
    - ► For redundancy
  - Up to 24 Link-Stabilization-Units
- Sub-Synchronization Hutch
  - Synchronized from Master
    - ► By two Links for redundancy
  - Up to 20 Link-Stabilization-Units



Optical Reference Distribution

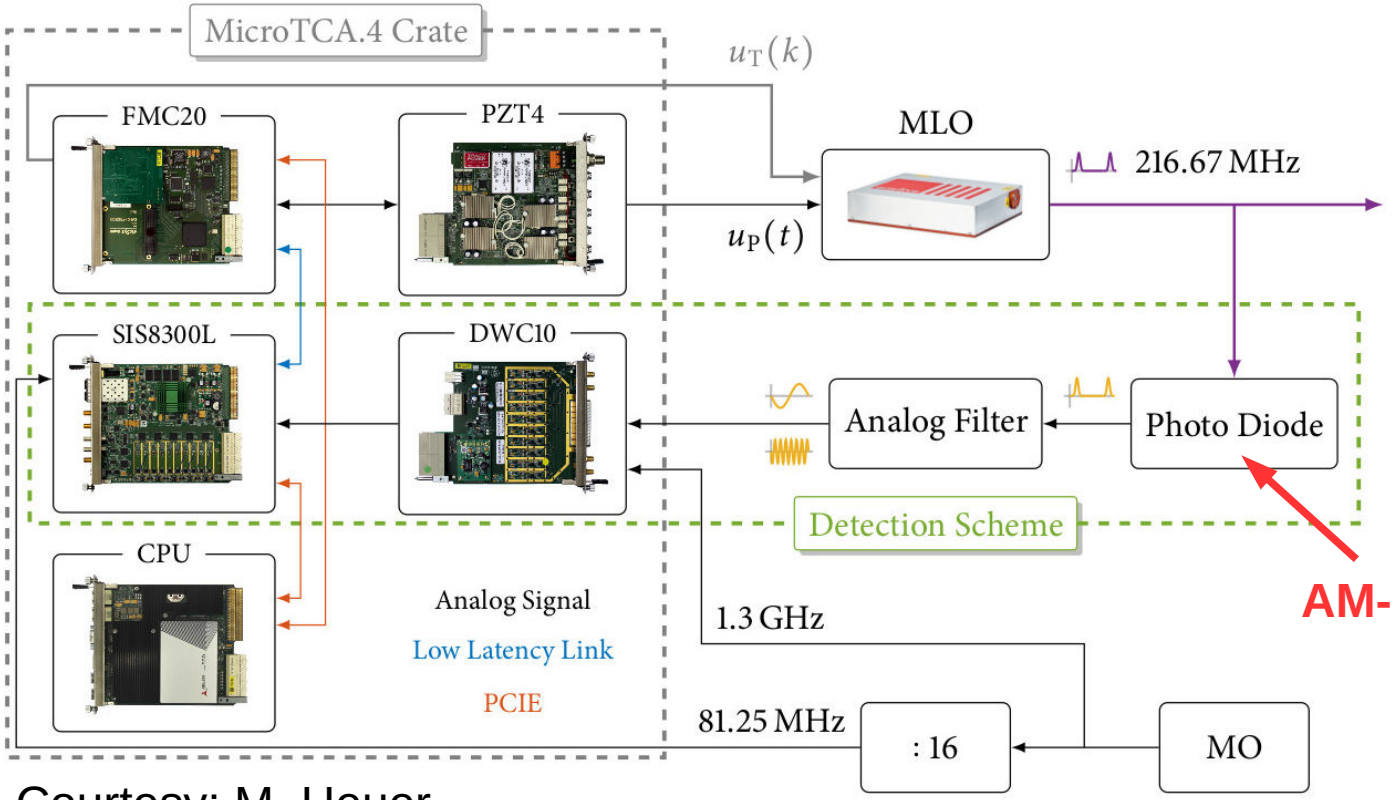
Master-Laser-Oscillator





- Origami 15 from OneFive
  - Compromise between timing resolution and optical bandwidth
  - High repetition rate of 216.667 MHz (1.3GHz / 6)
  - Locked to the Master-Oscillator (1.3GHz with GPS frequency standard)
  - **Low phase noise, low amplitude noise**

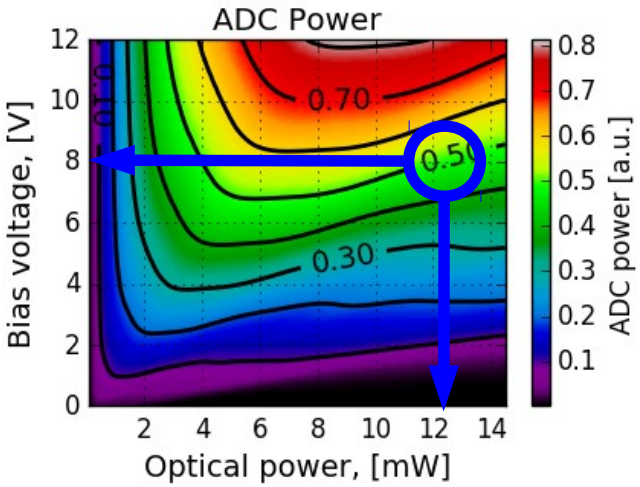
Master-Laser-Oscillator: Overview

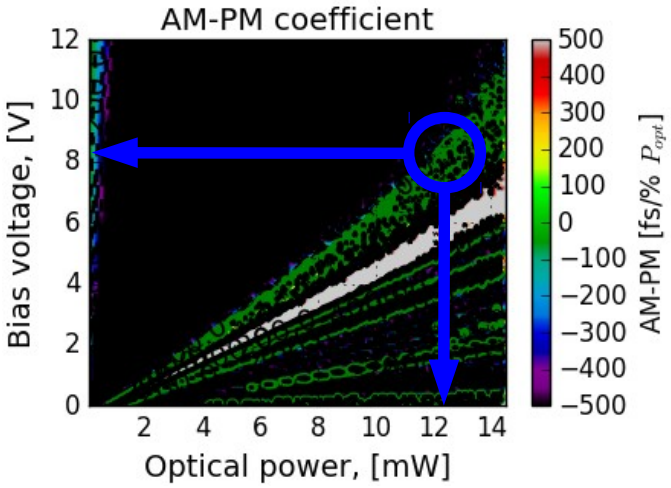


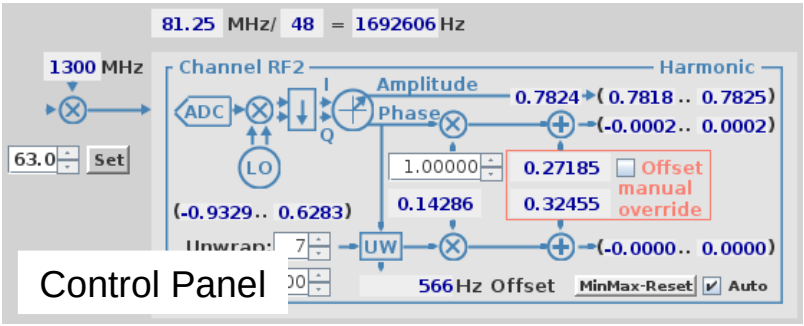
Courtesy: M. Heuer

(Controls & FW)

Master-Laser-Oscillator: Locking

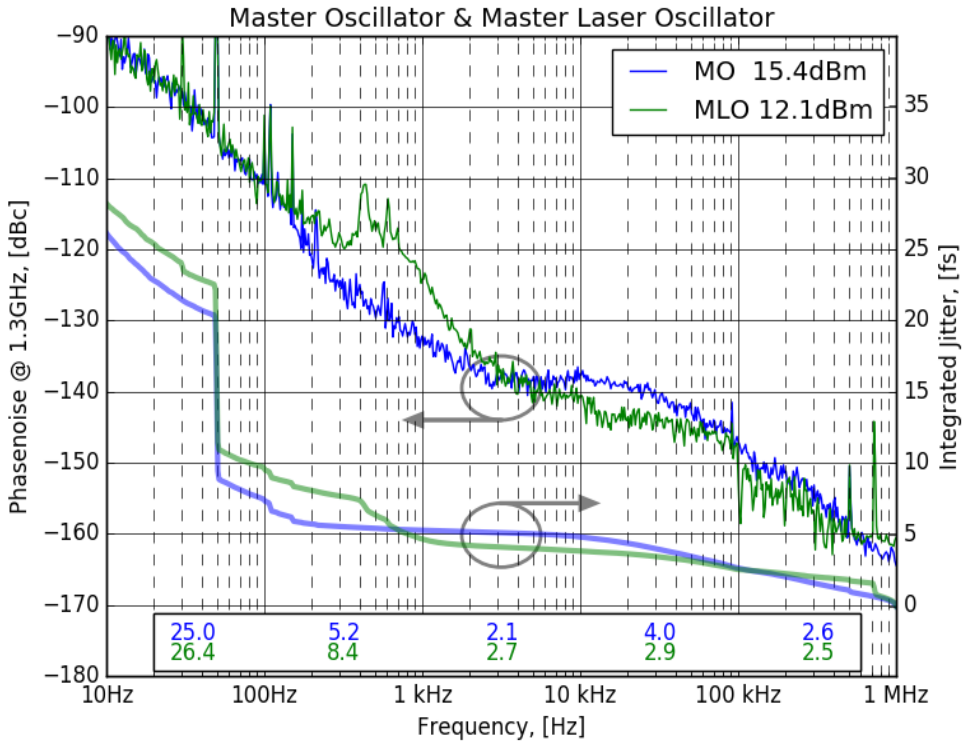






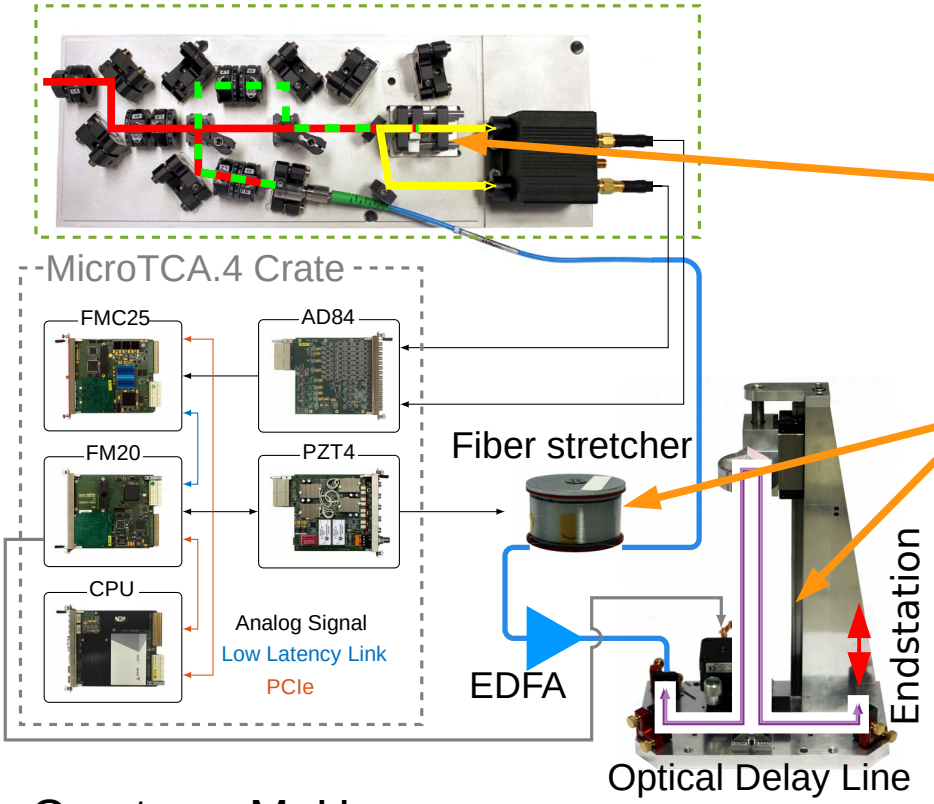
- Locking with a Photodiode
  - Low amplitude noise required
    - ► MLO: Origami 15 ✔
  - Calibrate for AM-PM effect!
- IQ detection in FW => phase shifter
  - Convenient for installation phase
- **Amplitude insensitive set-up** like **Laser-to-RF** in preparation

Master-Laser-Oscillator: Phasenoise



- Integrated Phasenoise
  - 1KHz – 1MHz
    - ► MO: 5.1fs, MLO: 4.1fs
  - 100Hz – 1MHz
    - ► MO: 7.4fs, MLO: 9.6fs
- Next steps
  - Replace MO power-amp
    - ► *DONE on 16.8.*
  - Improve MLO lock

Link-Stabilization-Units: Principle

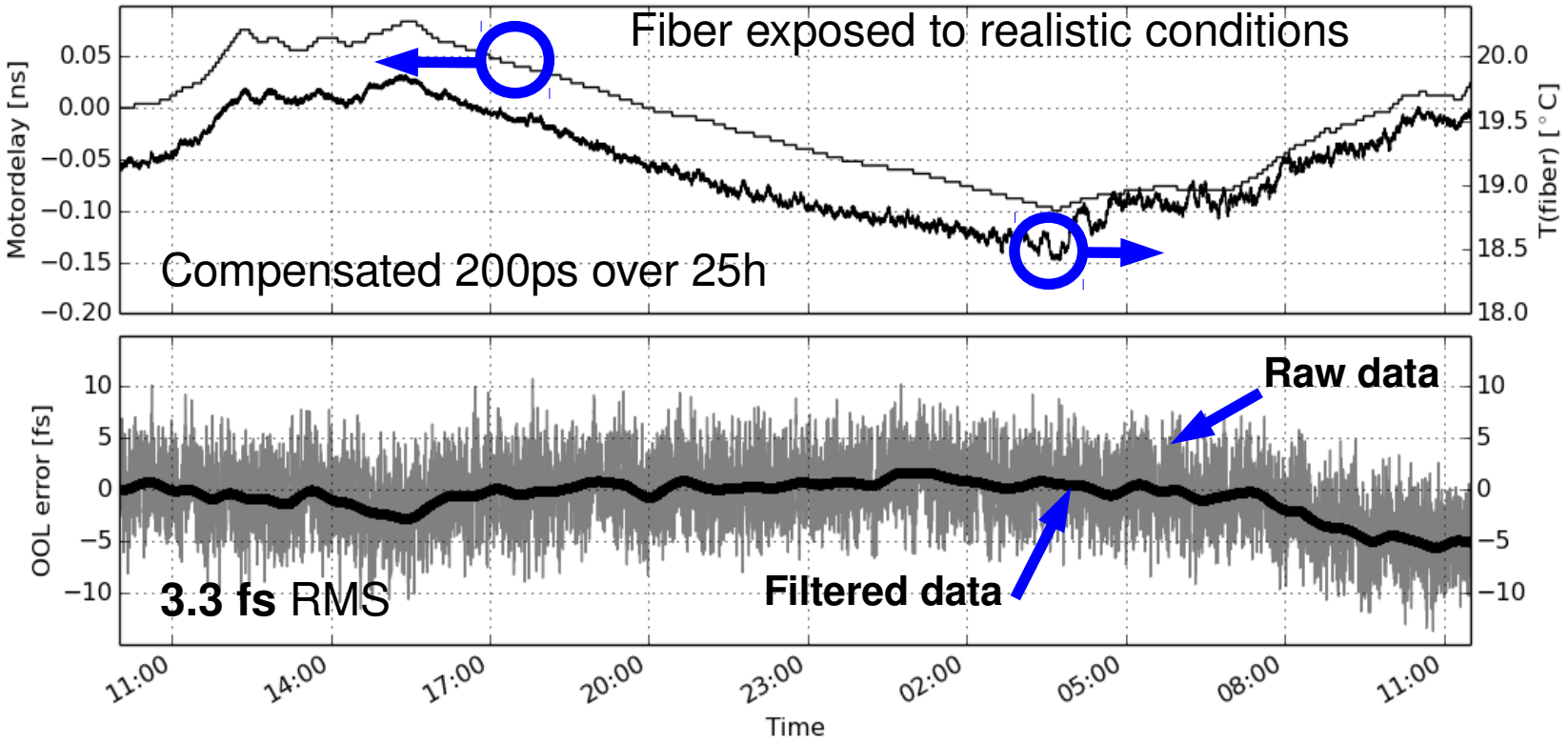


Courtesy: M. Heuer

(Controls & FW)

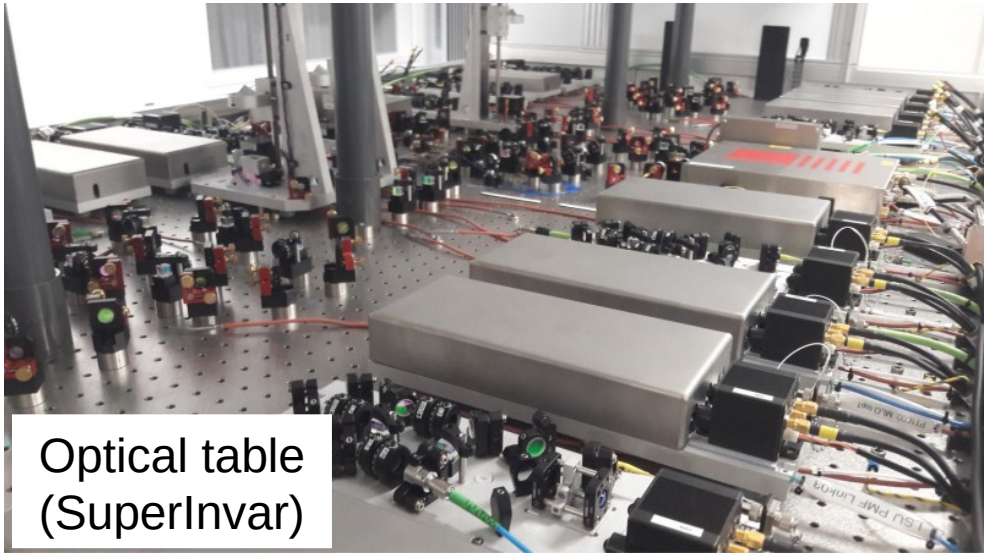
- Installed fibers influenced by temperature, humidity, vibration
- The balanced optical cross-correlator (OXC) detects timing changes
- The pulse propagation time through the stabilized path is held constant by a fiber stretcher and a motorized optical delay line.
- A lot of custom optomechanics
- **Learned a lot from operation at FLASH!**

Link-Stabilization-Units: Out-of-loop measurement



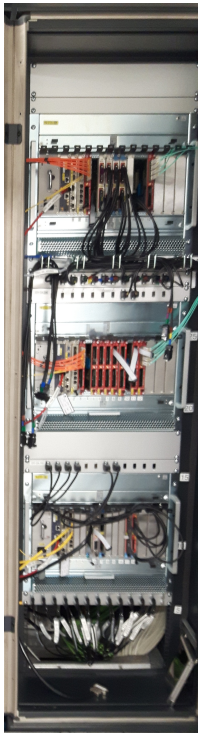
- Prototype tested under **realistic** for meaningful results
  - Partly uncompensated fibers at link end exposed to air flow, vibration, etc
  - **Worst case estimation** for operation of endstations in rack installations

Link-Stabilization-Units: Installation in MasterSyncRoom



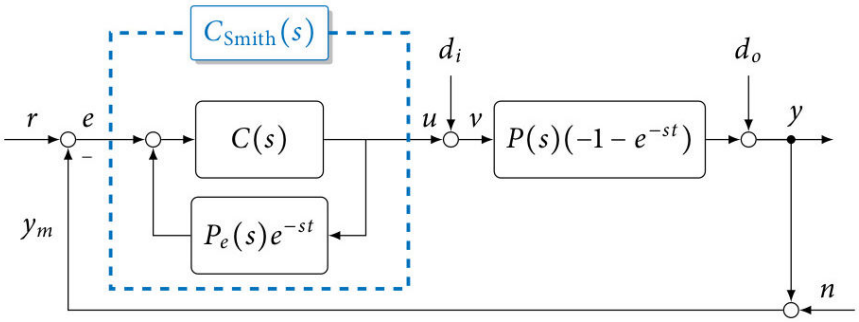
- Reference distribution
  - MLO in operation
  - 13/18 Links in operation (max. 44)
  - 21 km of PMF installed
- Preliminary Results
  - Slope around 5mV/fs ✔
  - Noise 0.1mV RMS 1MHz ✔
  - In-loop jitter < 0.2 fs RMS ✔
  - Observe up to 200 ps/km drift compensation

MTCA based control electronics: Infrastructure footprint



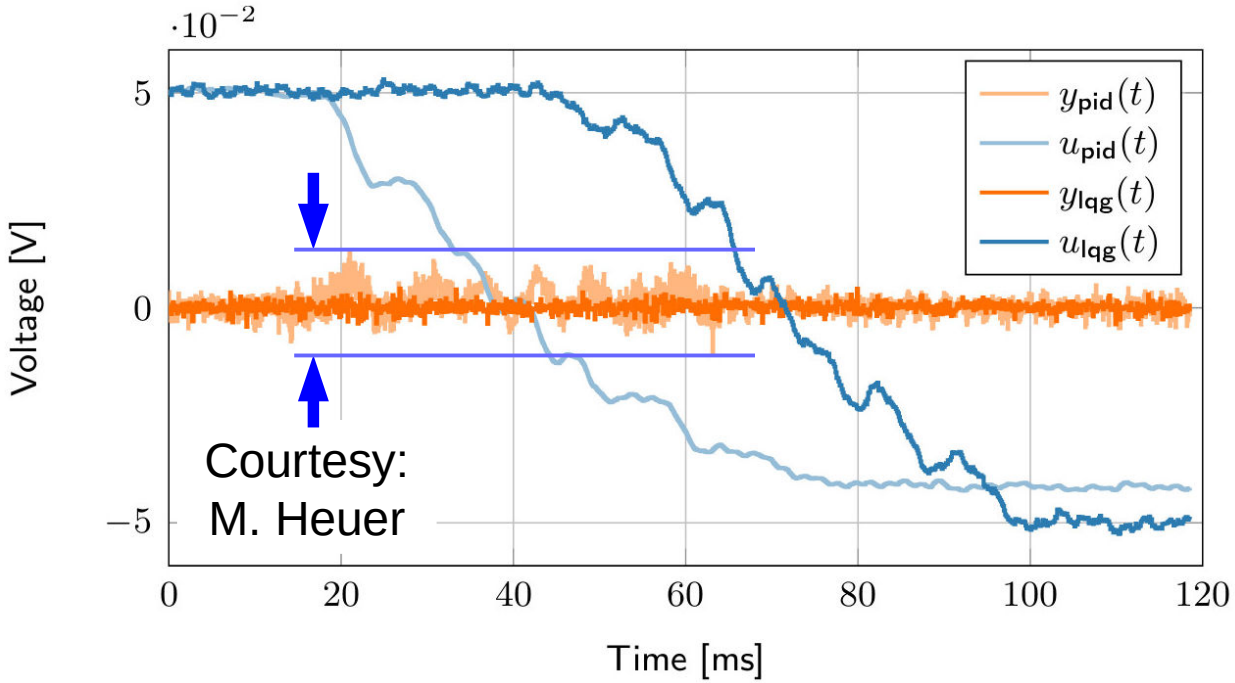
- VME based system at FLASH
  - 4x 42HE racks
  - 2 MLOs + 16 Links
- MTCA based system at XFEL
  - 1x 42HE racks
  - 2 MLOs, up to 32 Links

MTCA based controls: Concept



- Fiber link controls challenging
  - Low piezo resonance frequency of about 18kHz
  - Long response time possible of up to 40 us
- Solution
  - 6th order state space controller
    - ► Can be also useful for lasers
  - Include Smith predictor

MTCA based controls: Results

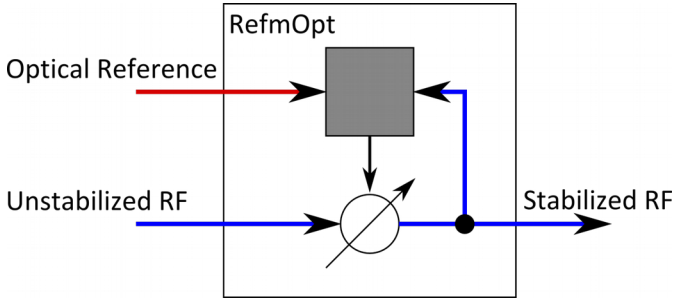


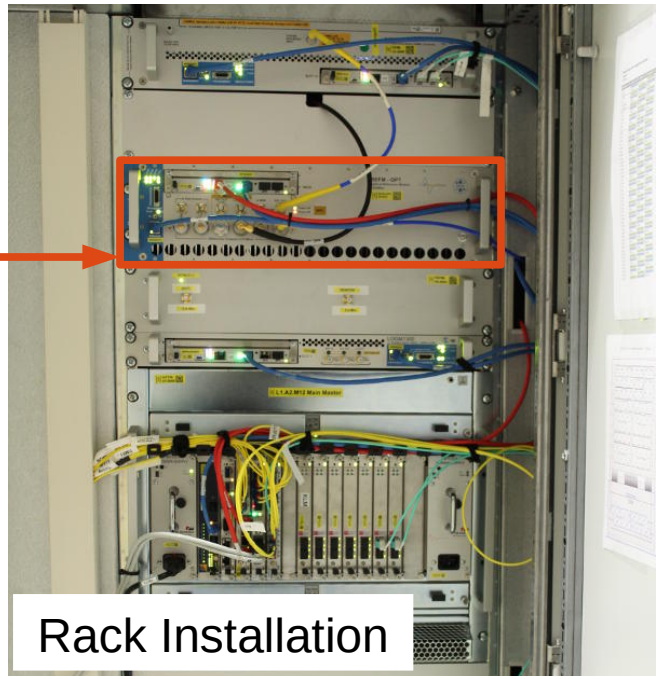
- Example: Coarse tuning step (observed up to 10x / h @ XFEL)
  - When piezo fiber stretcher reaches limits a motorized delay line drives
- LQG implementation in 6th order state-space controller outperforms conventional PID control

Endstations

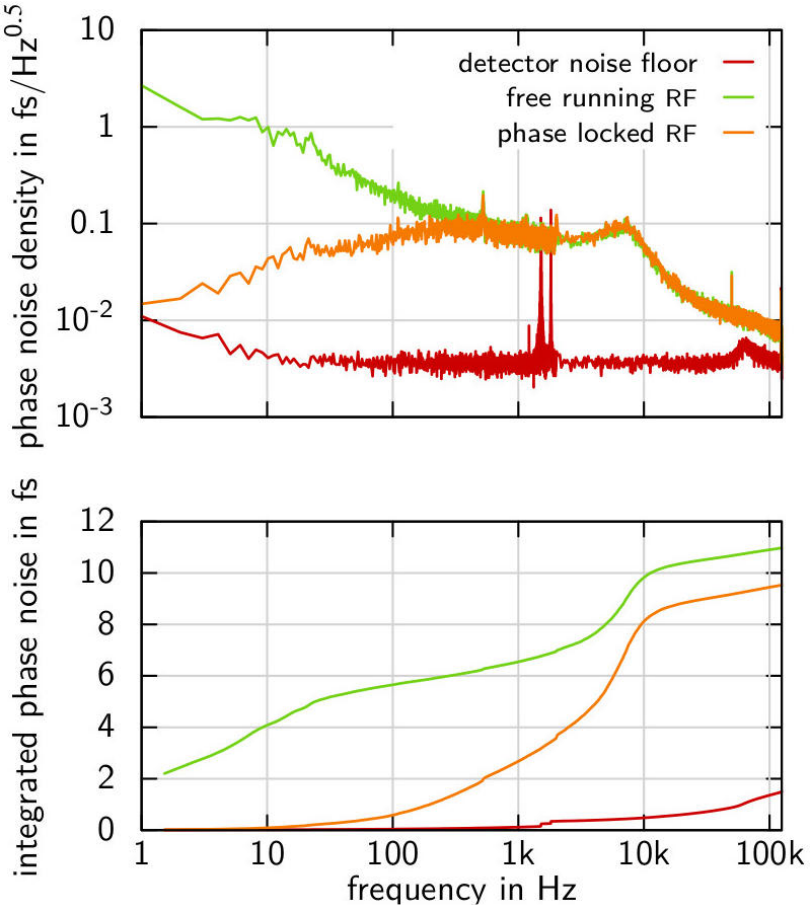
Laser-to-RF: Reference Module Optical (RefmOpt)

- Optical Re-Synchronization of the 1.3GHz for LLRF
  - LLRF cable drift compensation
  - High Resolution
  - Expected Drift < 3fs / 48h
  - 8/9 Units installed (max. 10)





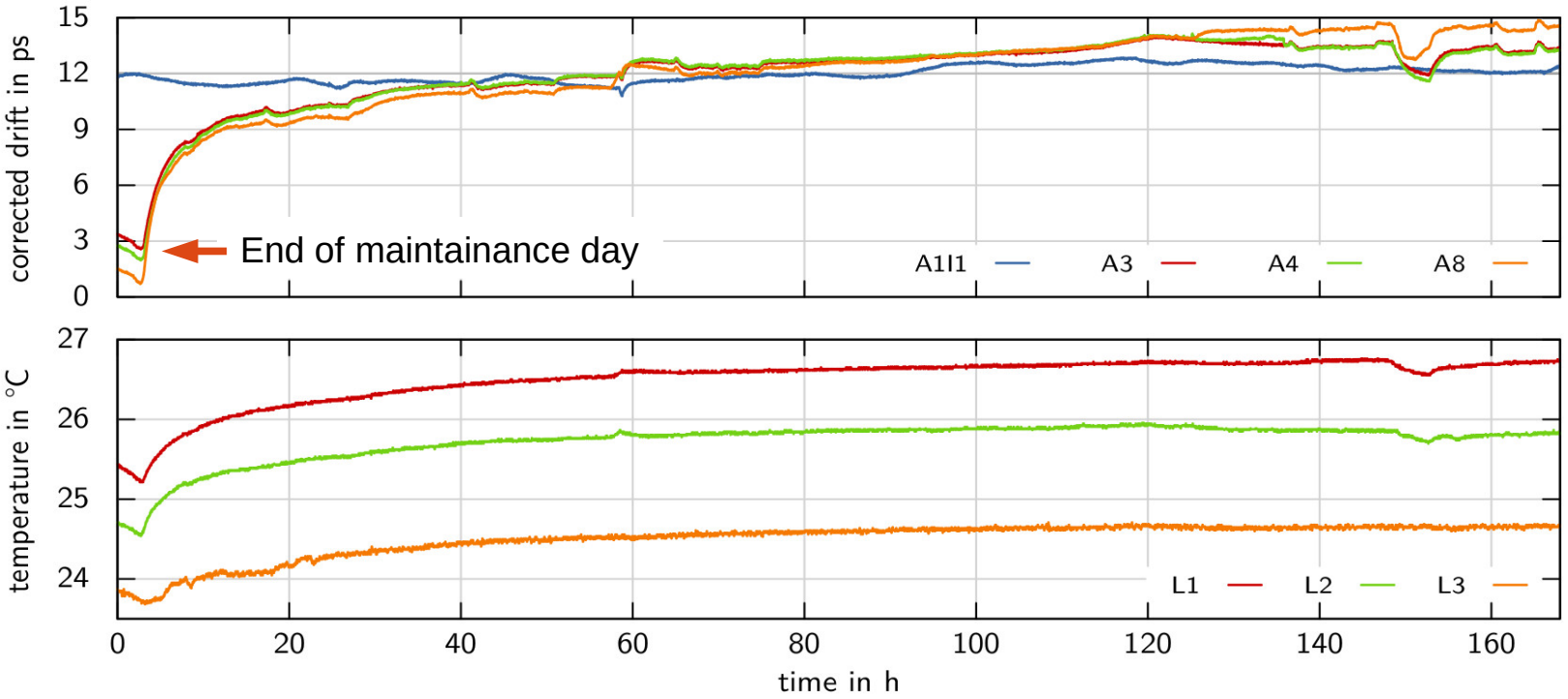
Laser-to-RF: Short term performance at XFEL



REFMOPT.A3M.247.L2

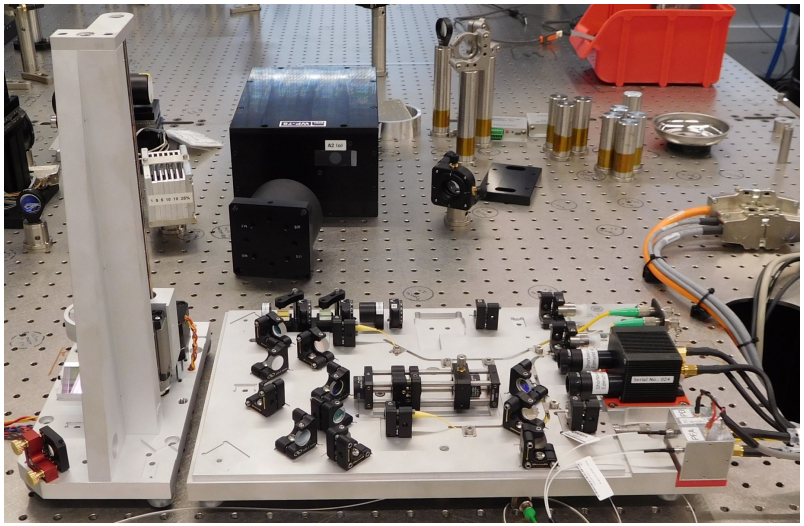
- Detector noise < 2fs (up to 125kHz)
- 11 fs out-of-loop jitter (MO vs. MLO):
  - MLO-to-MO lock (has poor MO power amp)
  - 250m unstabilized RF cable
  - 260m PM fiber link
  - Phase comparator in tunnel
- 9.6 fs in-loop jitter
  - Up to now low bandwidths used
- Need new measurements due to **replaced MO power amp**

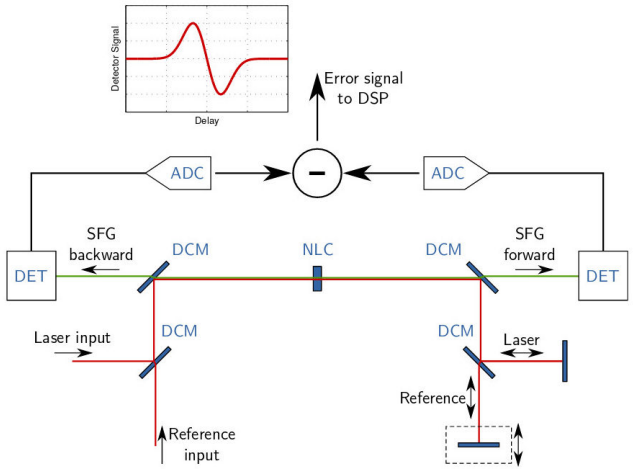
Laser-to-RF: Long term performance at XFEL



- A3 (247m), A4 (295m) and A8 (611) compensate 15ps of RF cable drift !
- All stations are in the main linac tunnel, but experience similar drift
  - Drift dominated by (common) media shaft

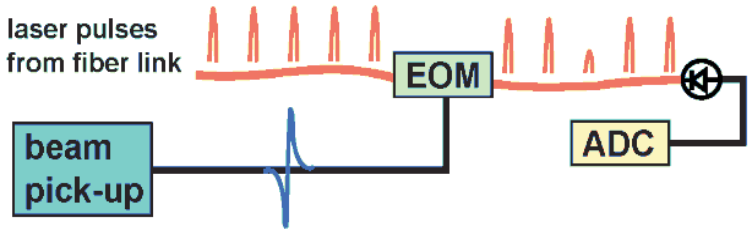
Laser-to-Laser



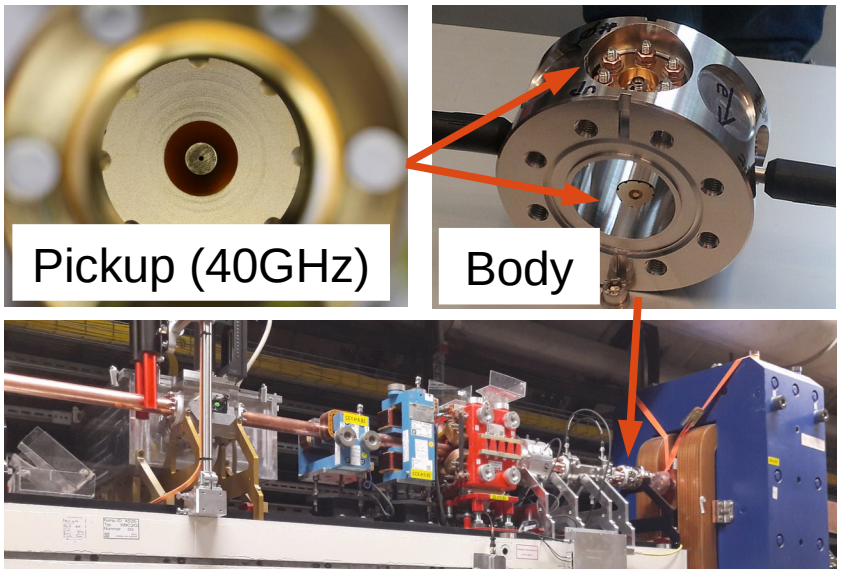


- Synchronization of external Laser systems
  - Injector laser, Pump-probe laser,...
  - Engineered set-up
    - ► “One size fits all”
    - ► Simplified mainainance
  - Balanced cross correlation
  - Sensitivity up to 20mV / fs
  - Out-of-loop jitter < 10fs RMS
  - 2 / 6 installed

Bunch Arrival Monitor from “Special Diagnostics”

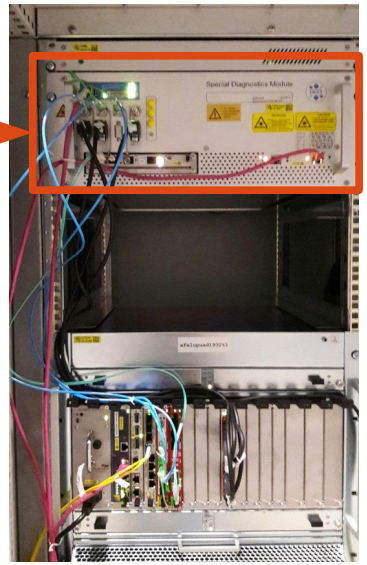


- Bunch Arrival Time Measurement
  - 6/7 Units installed (max. 8)
  - Forseen for arrival time feedback



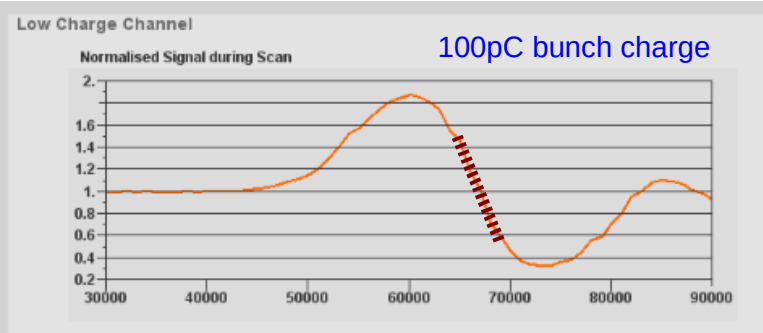
Beamline Installation

BAM Front-End



Rack Installation

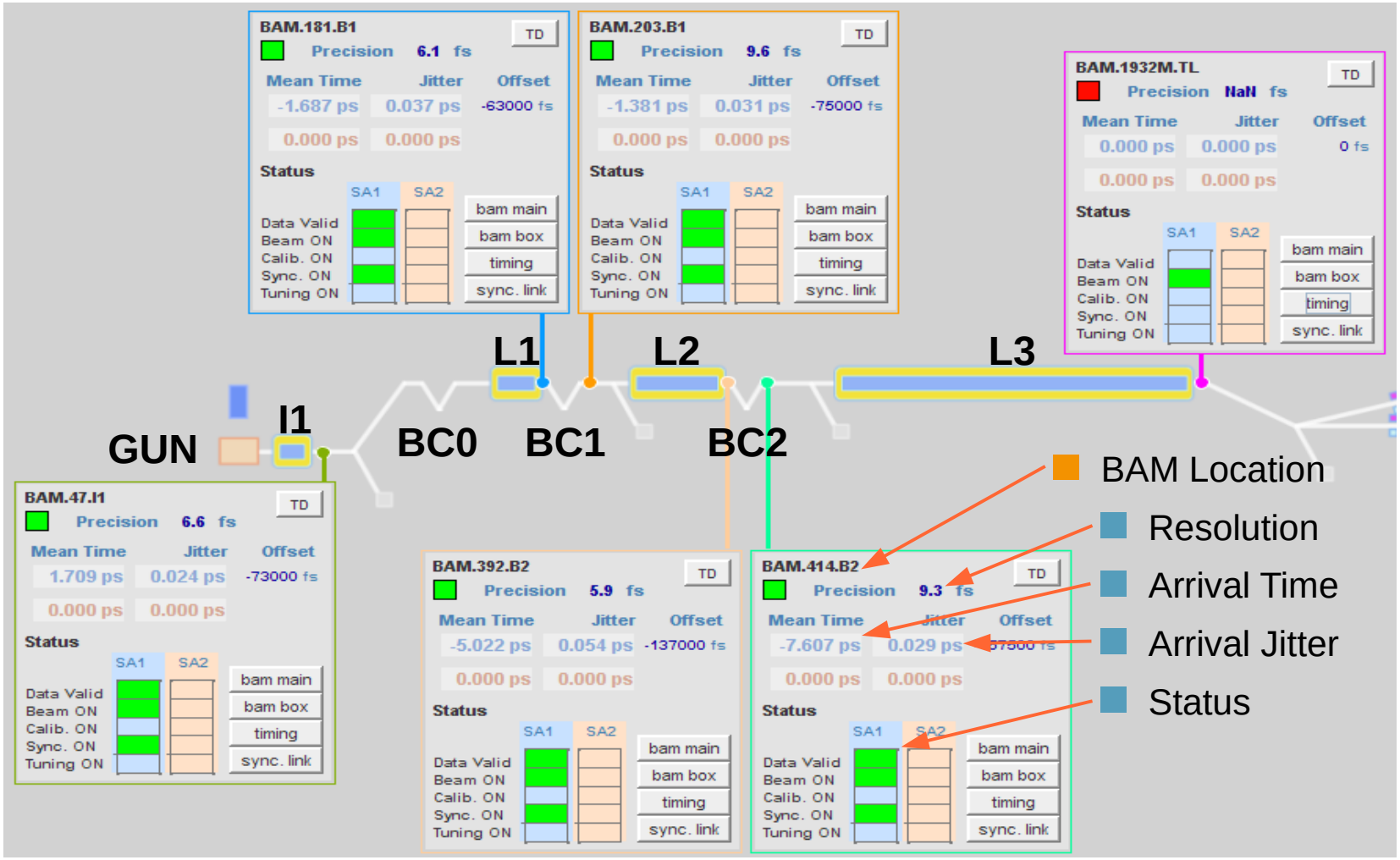
Bunch Arrival Monitor: Resolution



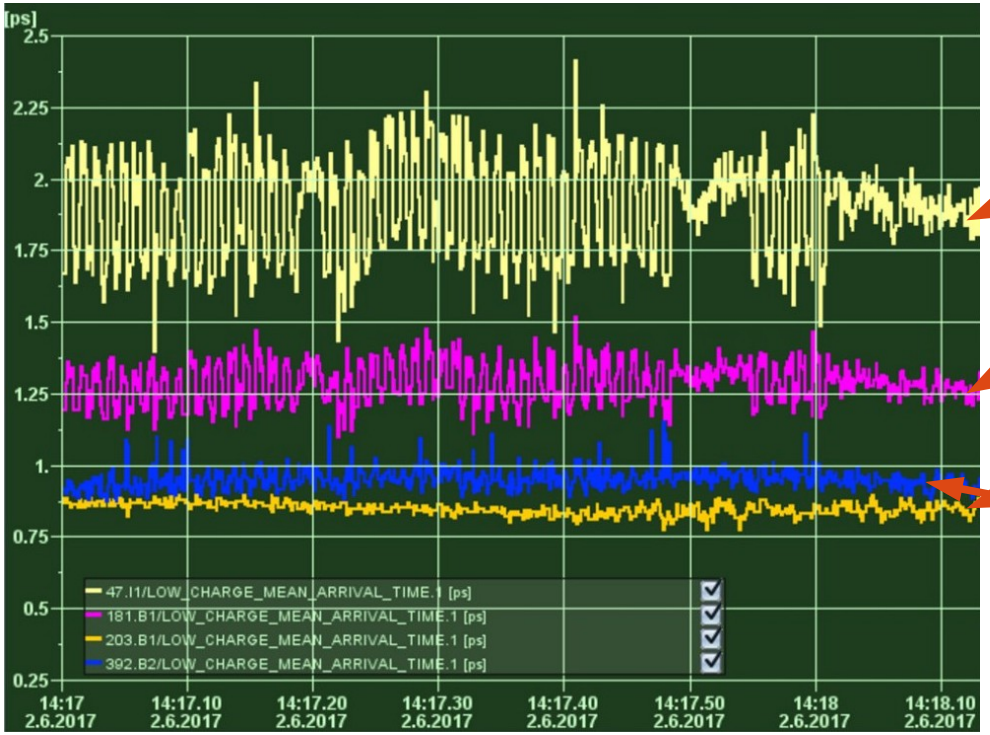
Charge (pC)	Sensitivity (fs/%)	Resolution (fs)
50	120	**24.0**
100	84	**16.8**
140	67	**13.4**
200	38	**7.6**
450	27.8	**5.6**

- Resolution not optimum yet
  - Amplitude noise to high (x2)
  - Electronic noise
    - ► Filters underway
  - Electromagnetic Interference
    - ► Needs improvement
  - Signal too low (x1.5 – x2)
    - ► Changed Rack placing
    - ► Cable about 3dB/m @ 40GHz

Bunch Arrival Monitor: Overview



Bunch Arrival Monitor: Results



- GUN
- **BAM 47m Injector**
- BC0
- **BAM 181m**
- BC1
- **BAM 203m**
- **BAM 393m**

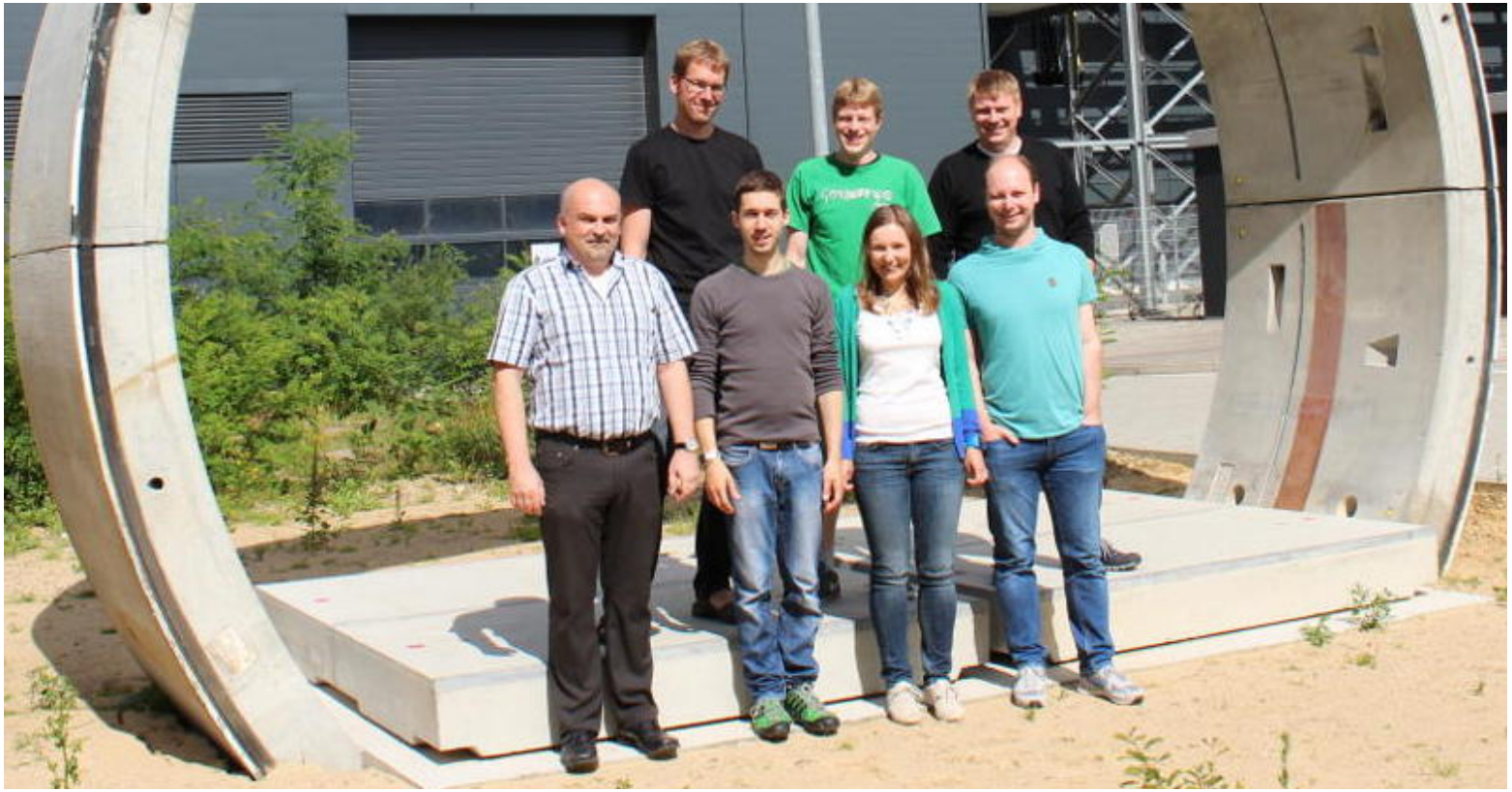
- Expected compressions confirmed
  - BC0: 2, BC1: 8-10, final arrival time jitter is 20 fs RMS **without feedback**
- Helped already to track down a source of unstabilities

Summary

- Optical Synchronization in operation and ready for future expansion
- Still issues come up, get identified and solved
- Sub 10 fs for the synchronization already achieved

- First user experiments in 4 weeks!
- More to come ...

Thank you on behalf of (core) LbSync group (MSK/DESY)



Please visit also the tutorial:
“Integrated Photonics to the rescue of Femtosecond Beam Diagnostics”
by **Franz Kärnter (CFEL) at 11am**