Femtosecond Optical Synchronization System for FLASH

Short Overview

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On behalf of the LbSyn Team

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SINAP FEL-Collaboration Workshop, Hangzhou

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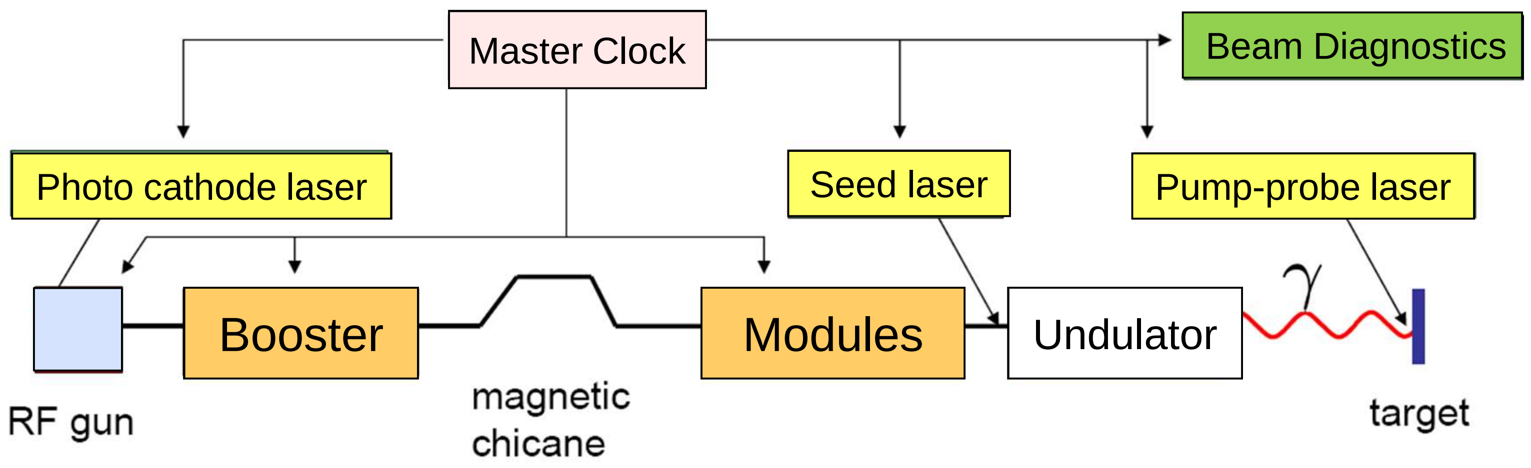
Agenda

- Synchronization needs and system layout
- Optical synchronization at FLASH
- The basic components of the system
  - Master Laser Oscillator (MLO)
  - Link stabilization units
  - Bunch Arrival-time Monitor (BAM)
- Beam-based feedback
- Synchronization of external lasers

Synchronization needs in a (seeded) FEL facility

- Goal
  - Measure and stabilize (feedback) timing jitter + drifts
  - Lock various lasers (pump-probe, diagnostic, seed, …)
  - Provide extremely stable RF reference signals

  } on a 10 fs scale

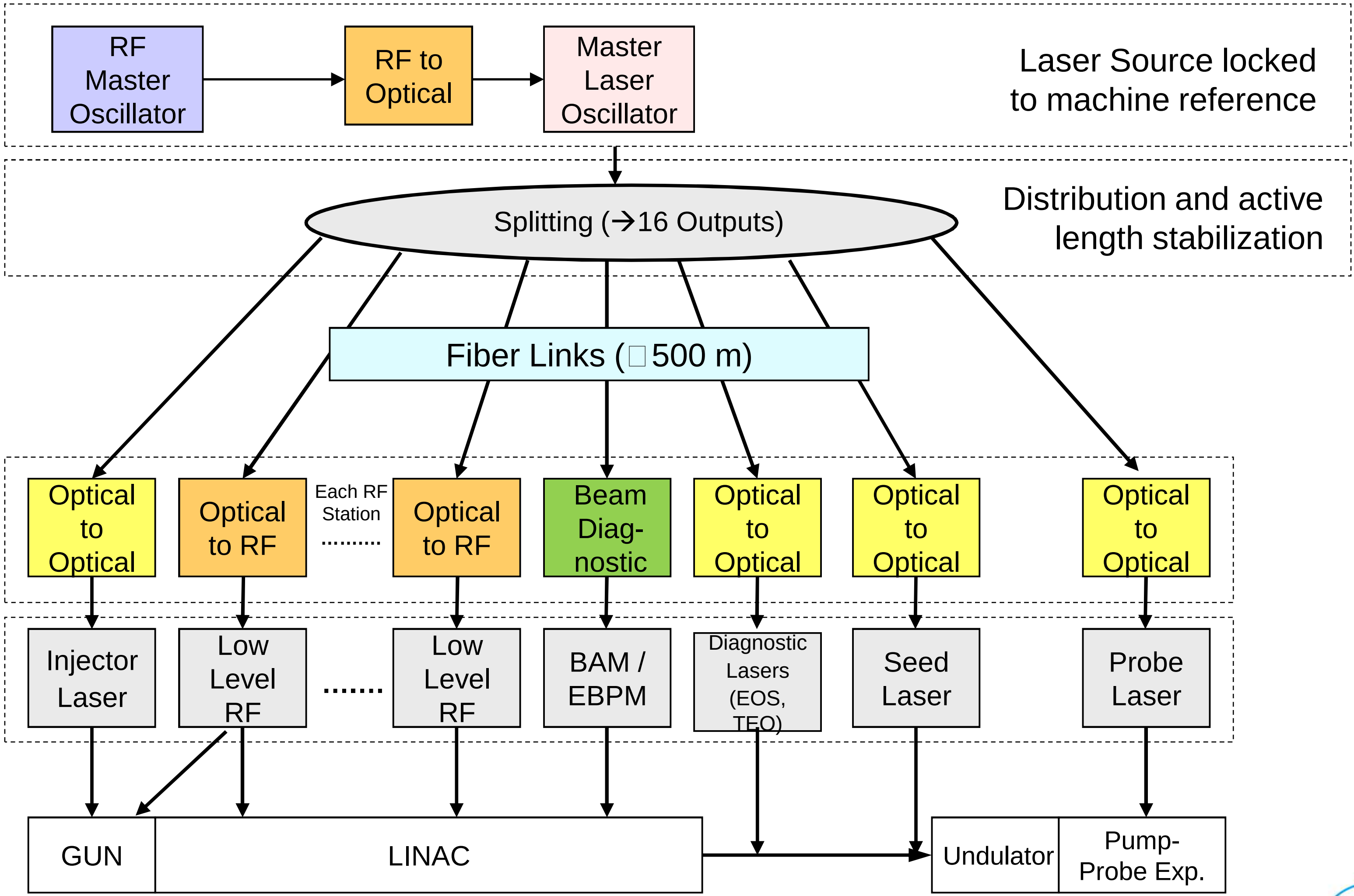


- Main sources for arrival-time changes
  - Arrival-time of the photo cathode laser pulses
  - Phase of the RF gun
  - Amplitude and phase of the booster module(s)

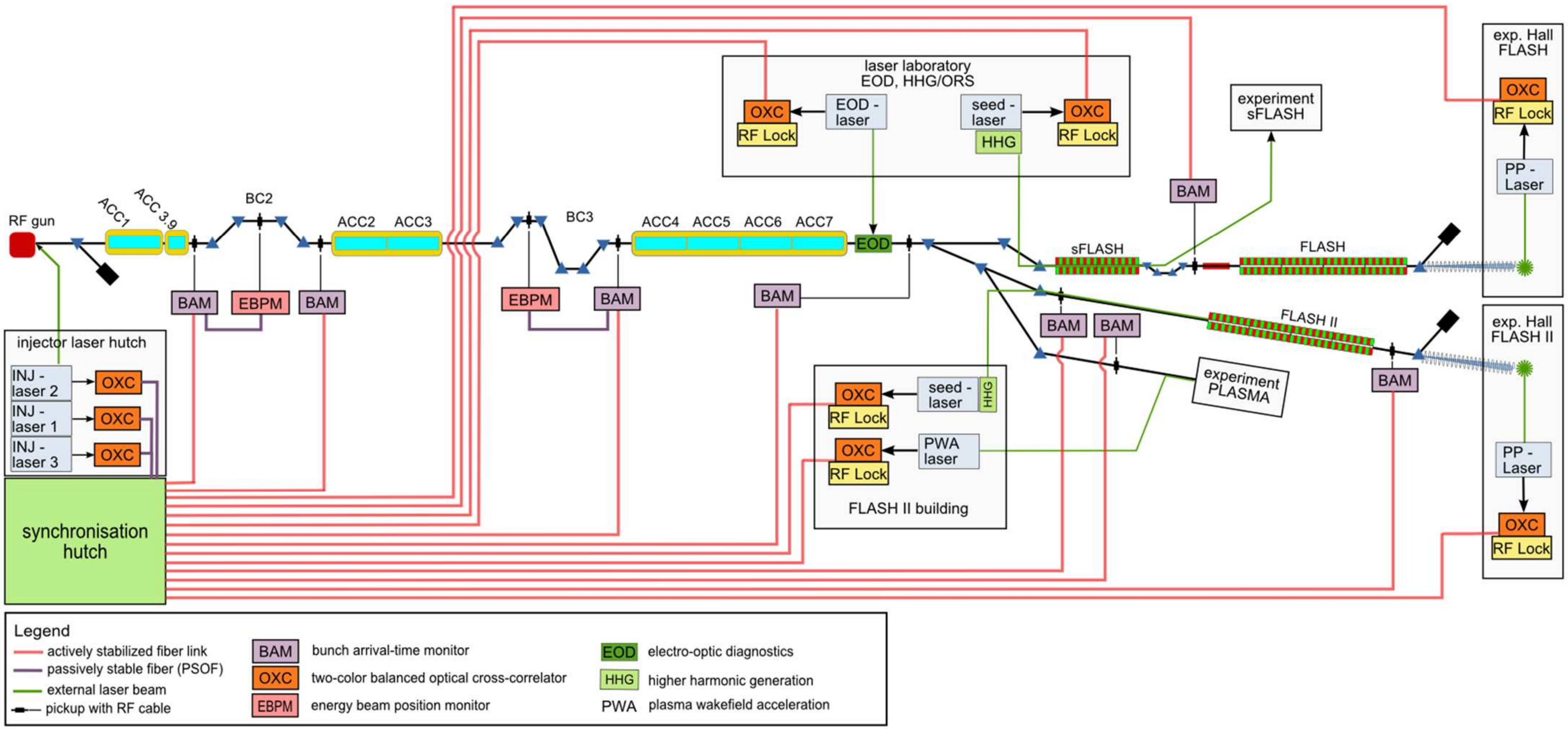
RF requirements for 10 fs arrival stability:
$\Delta\varphi < 0.005°$ @ 1.3 GHz
$\Delta A/A < 1.6 \cdot 10^{-5}$

Layout of the synchronization system

The reference timing information is encoded in the precise repetition rate of an optical pulse train

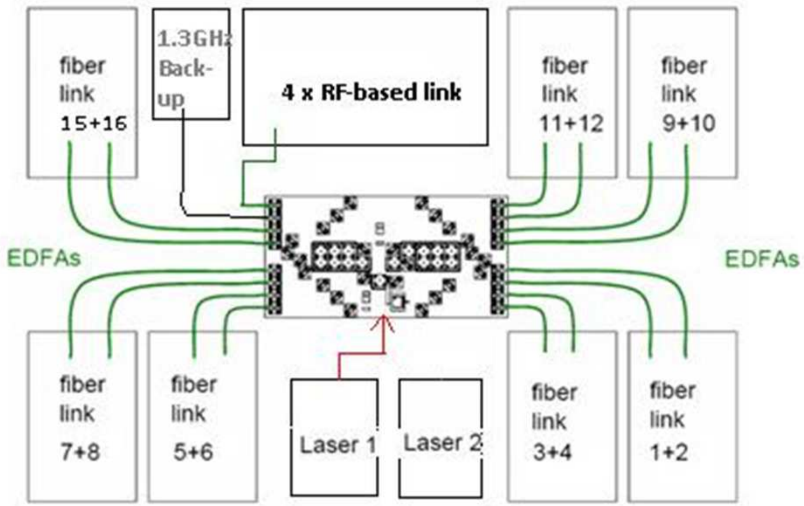


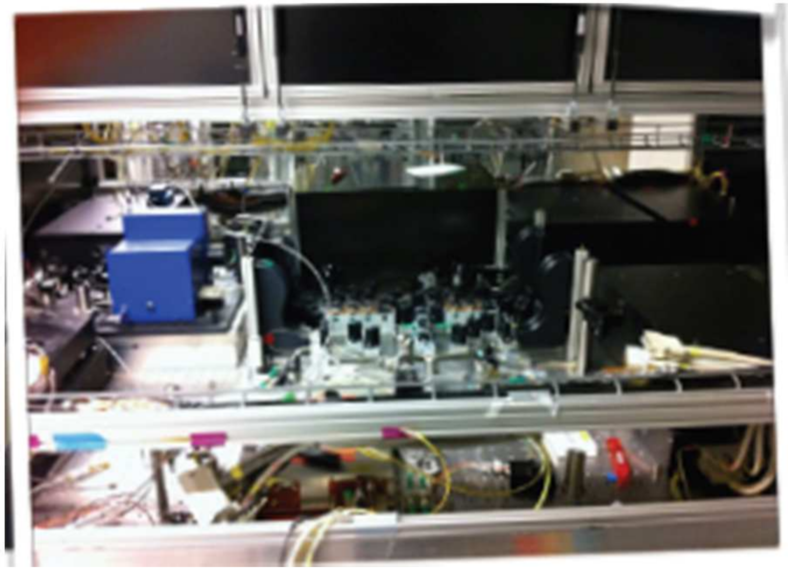
Schematic of full expansion state at FLASH (2015)



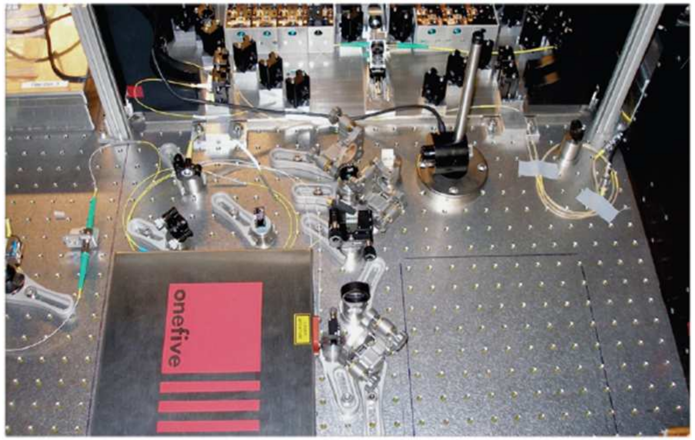
The synchronization hutch at FLASH

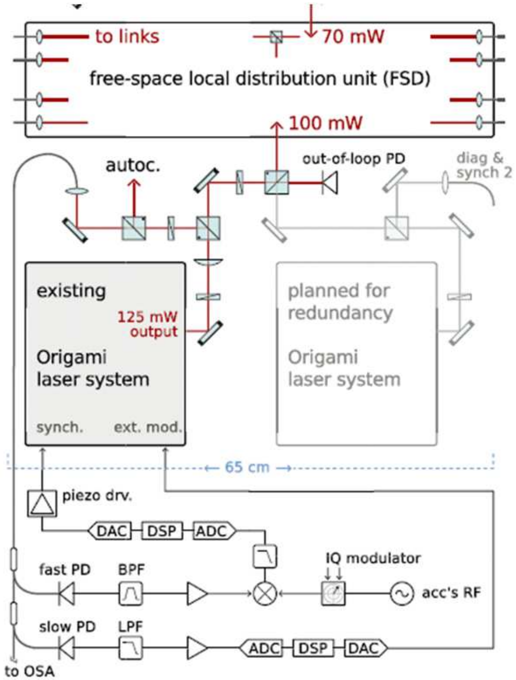
- Optical table - full expansion state
  - 2 lasers (for redundancy)
  - 16-port free-space distribution
  - 16 fiber amplifiers (EDFAs) in 4 boxes
  - 14 link stabilization units based on OXC
  - 4 RF based link stabilization units
  - 1.3 GHz backup
  - Diagnostics…
- Four electronic racks
  - 5 VME crates (in future µTCA)
  - 22 feedback loops (DSP, FPGA)
  - 18 piezo drivers (± 300 V)
  - 15 (or 30?) laser-diode drivers
  - 50 stepper motor drivers
  - > 40 temperature readouts
  - tons of monitor signals
  - ~ 300 cables to/from optical table

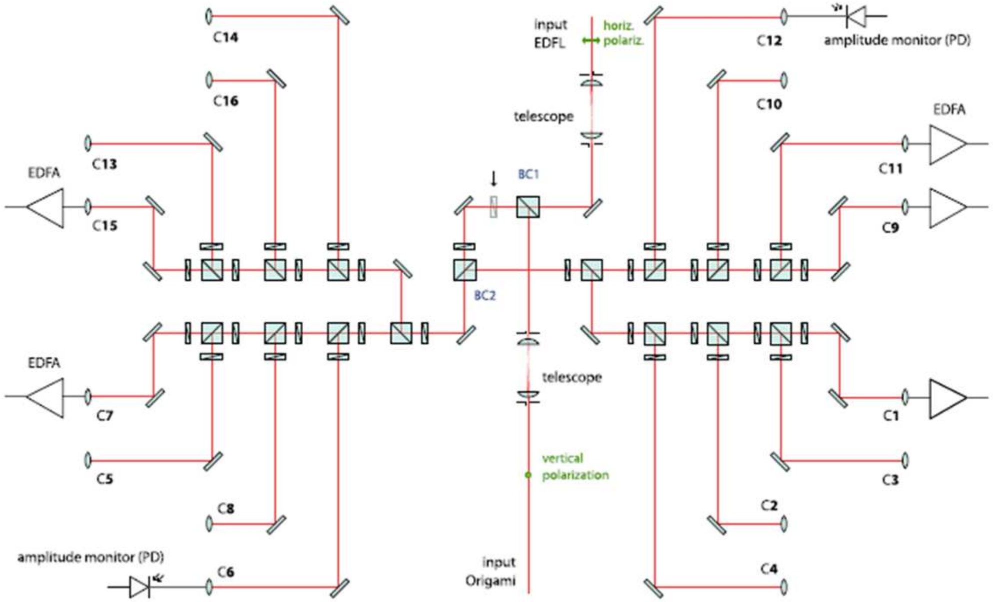


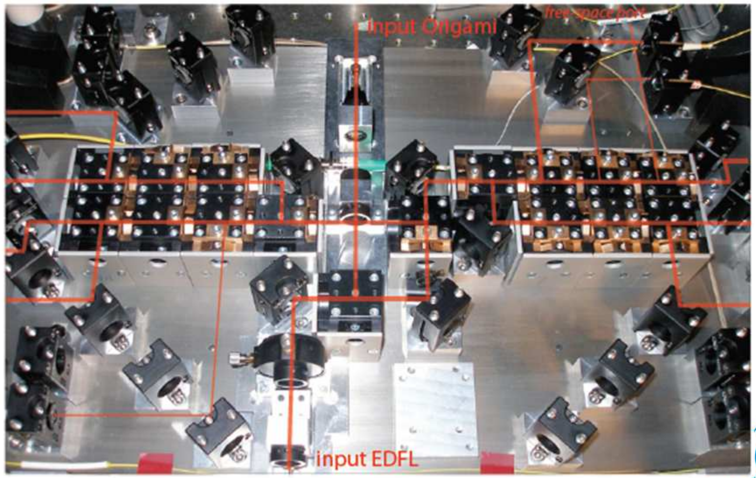


Master laser oscillator (MLO) + Distribution



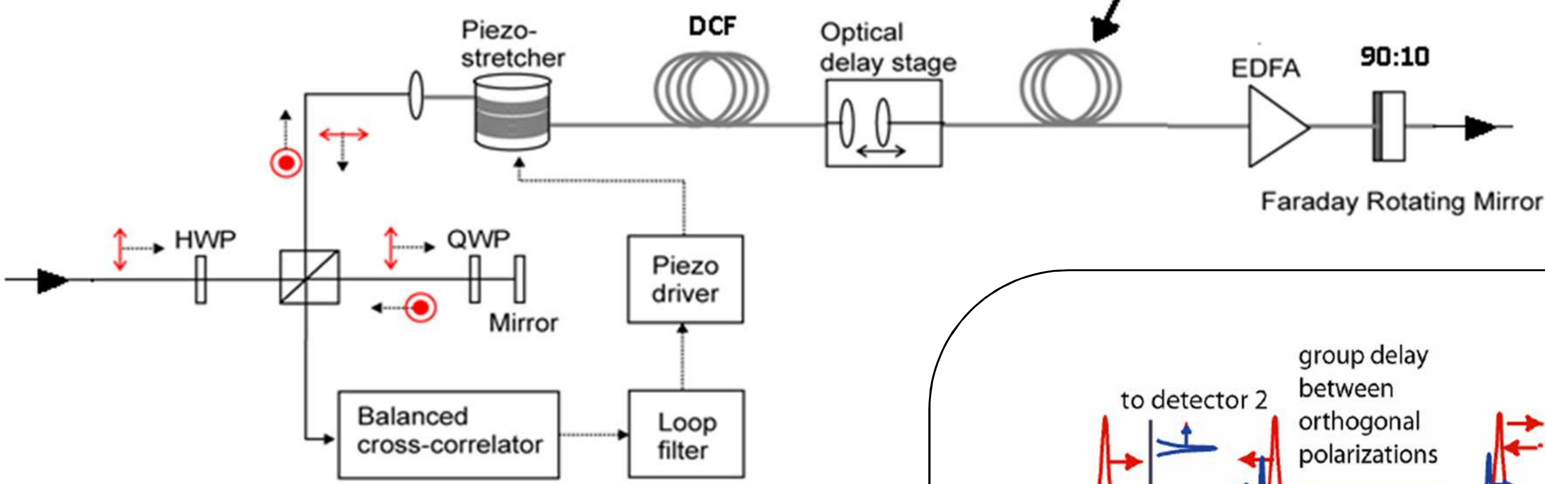


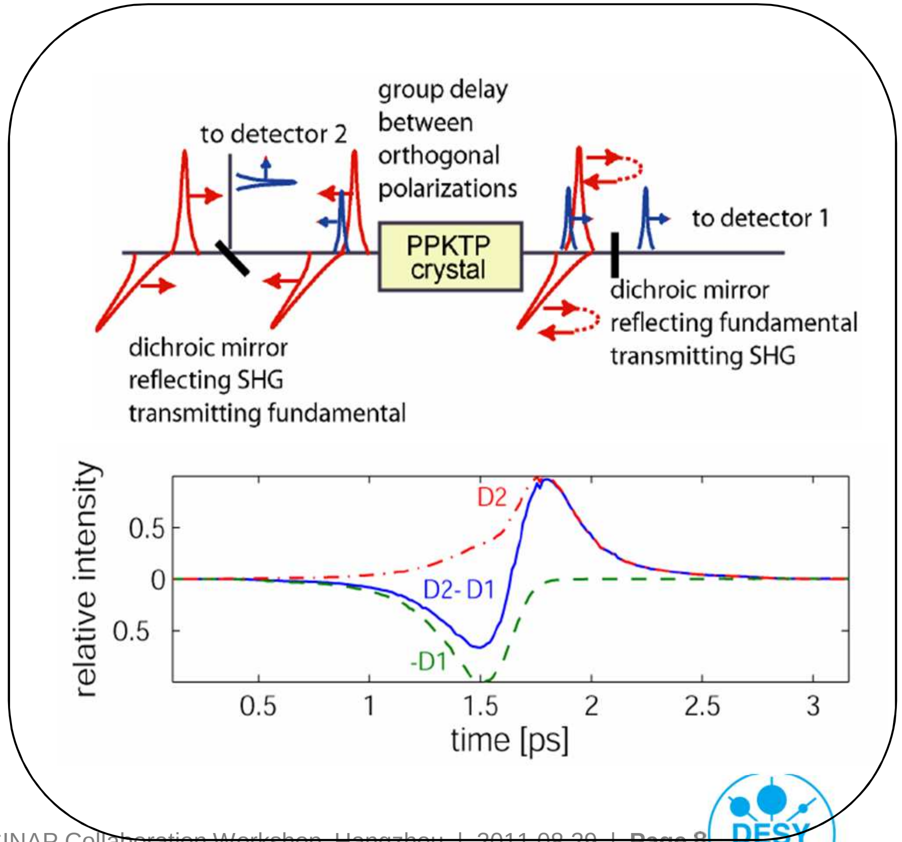




Fiber link stabilization by balanced optical cross-correlation

J. Kim et al., Opt. Lett. ***32****, 1044-1046 (2007)*

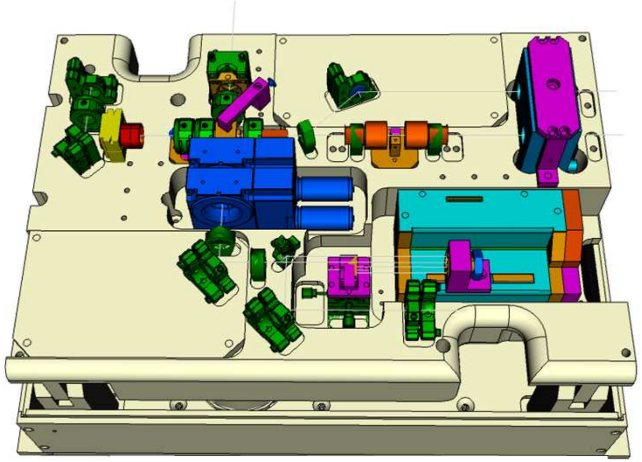


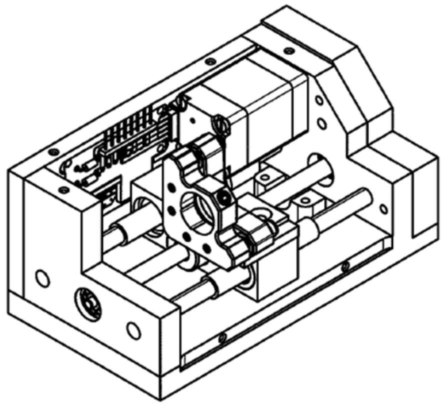


…a different scheme will be presented by Thorsten Lamb

Link stabilization setup: in-house “industrialized” design

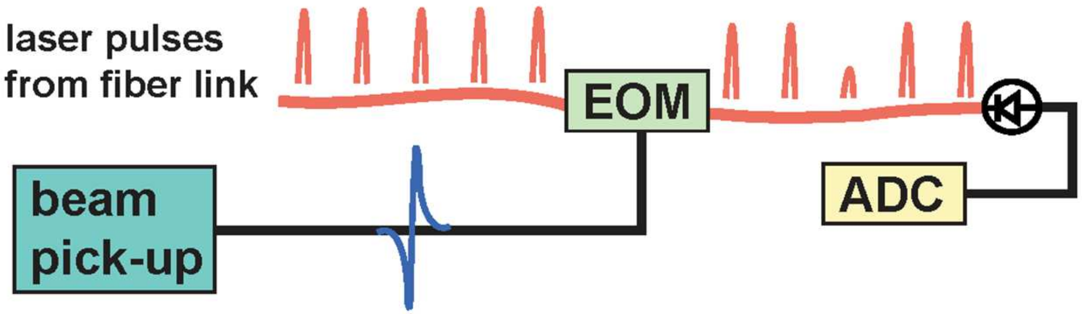
3rd iteration of mechanical layout

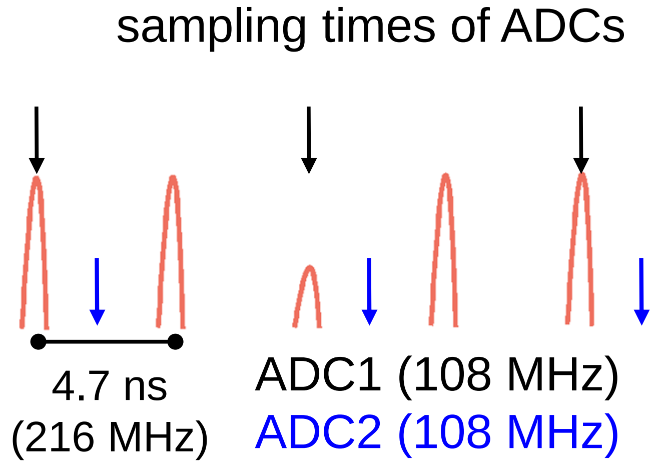


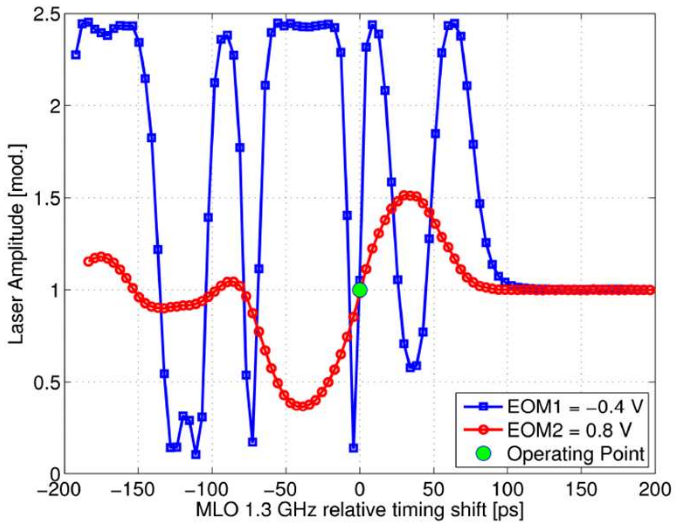


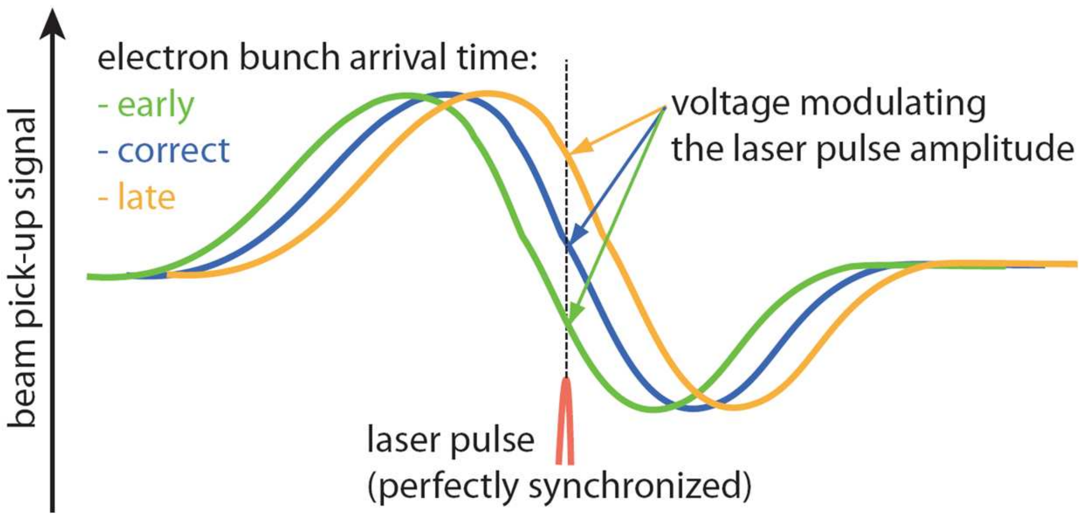
Sometimes noise on signal,
origin is under investigation…

Beam arrival-time monitor (BAM)









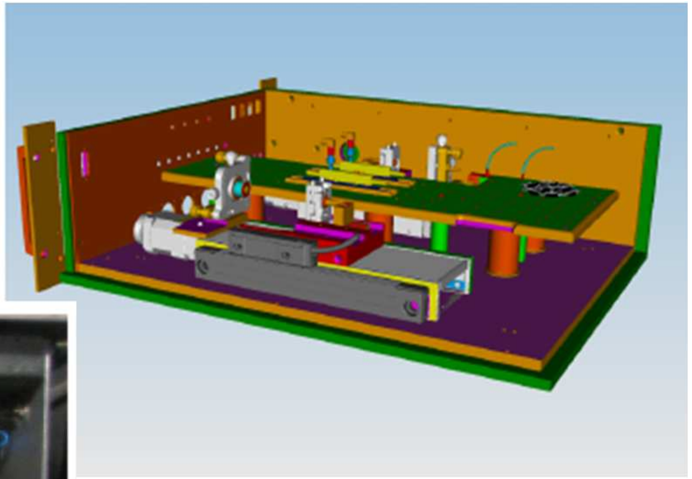
M. Bock, FEL09, WEPC66

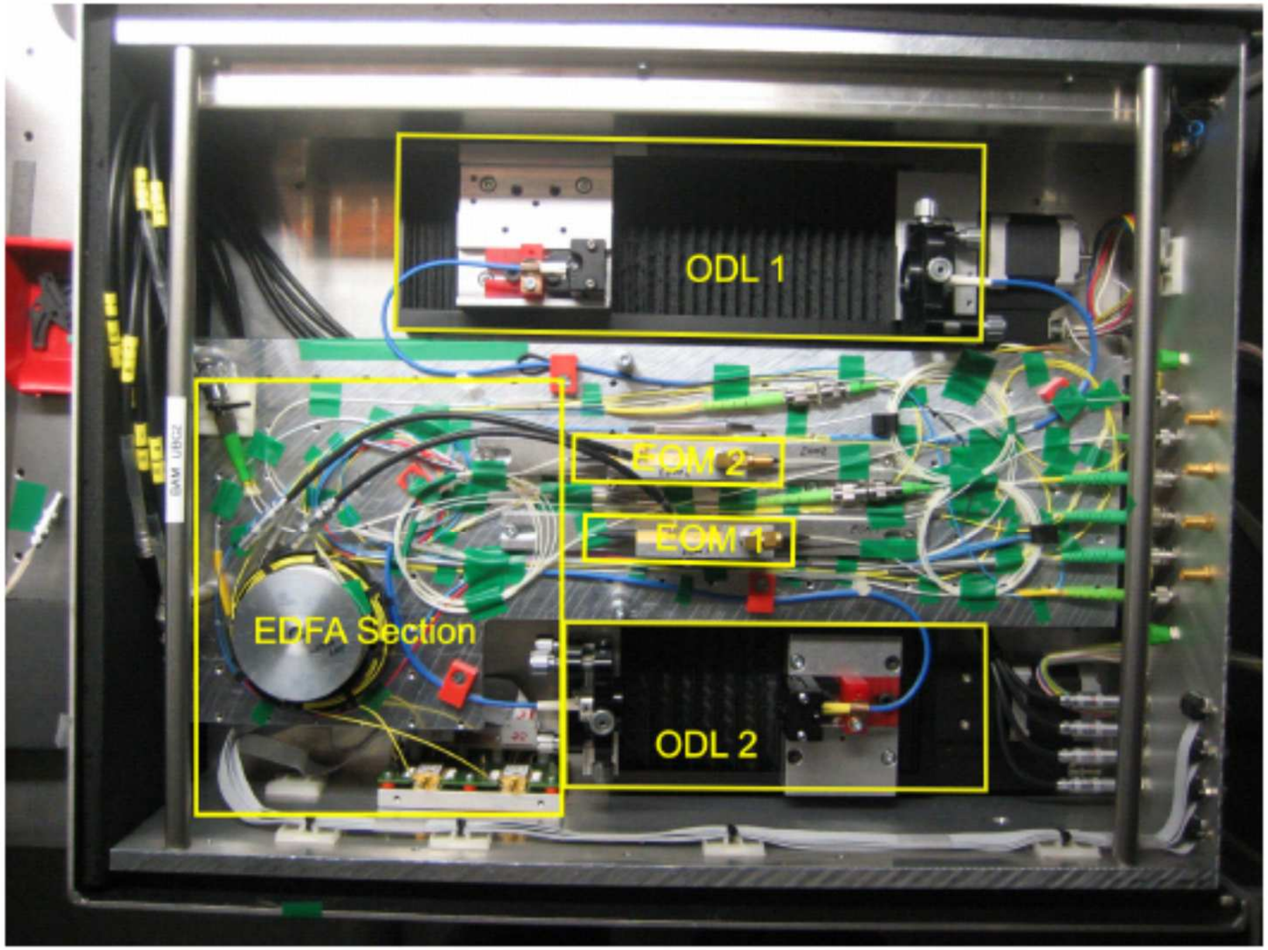
F. Loehl, PhD thesis, DESY-THESIS-09-031, 2009

Patented 2006 by DESY

BAM frontend

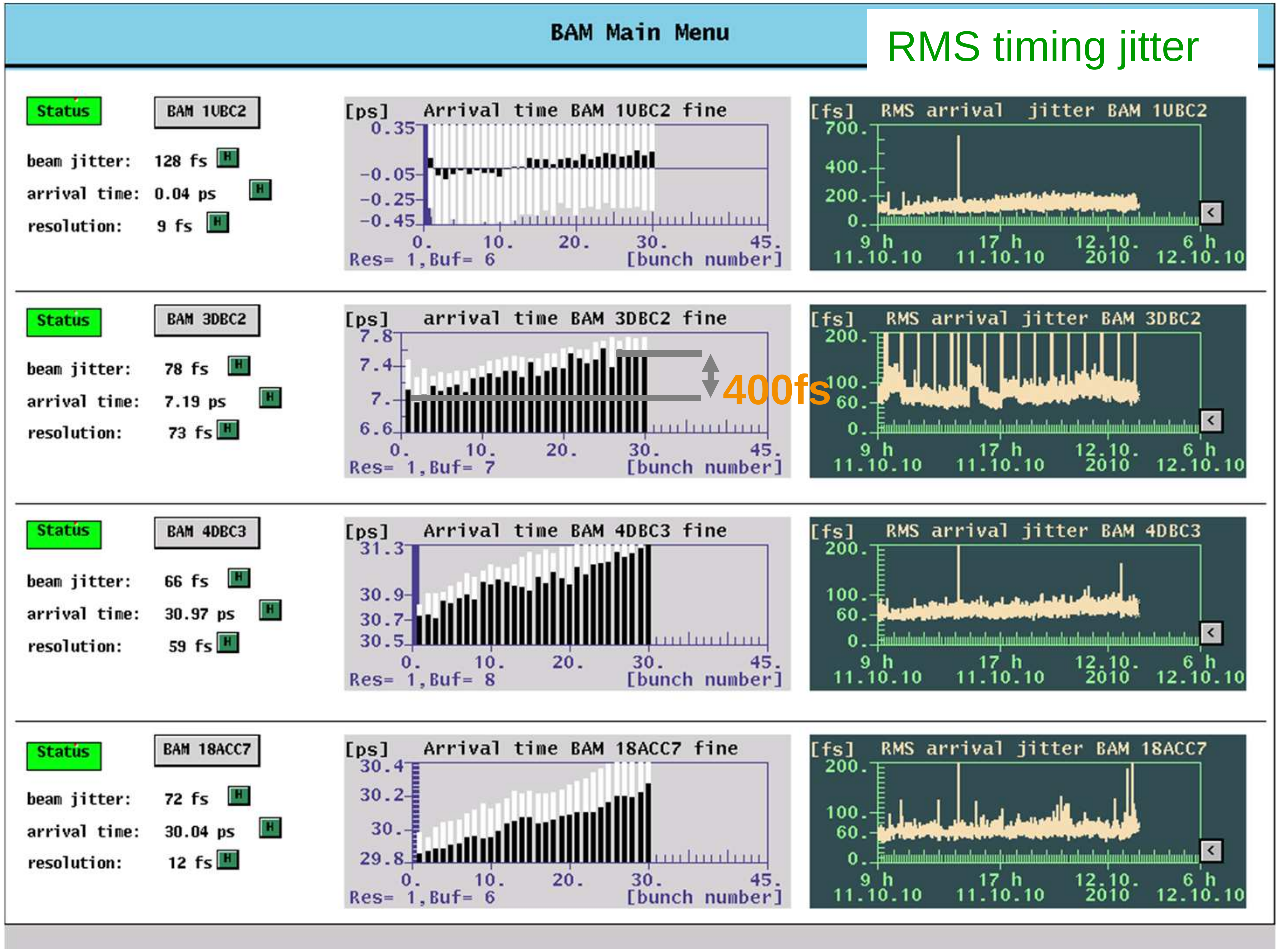
Shown here: 2nd iteration,
3rd iteration is in progress…





Example: arrival stability after LLRF upgrade

Arrival time measurements



Typically values

60-100 fs rms from injector

60-80 fs rms behind BC2

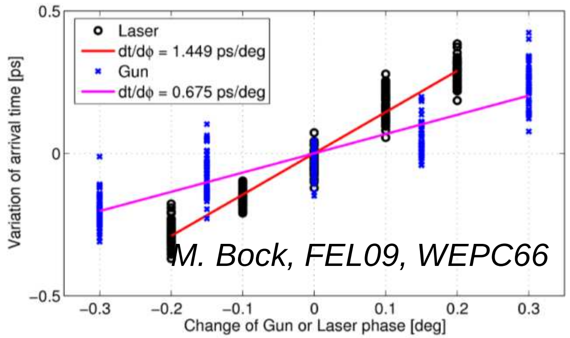
50-60 fs rms exit LINAC

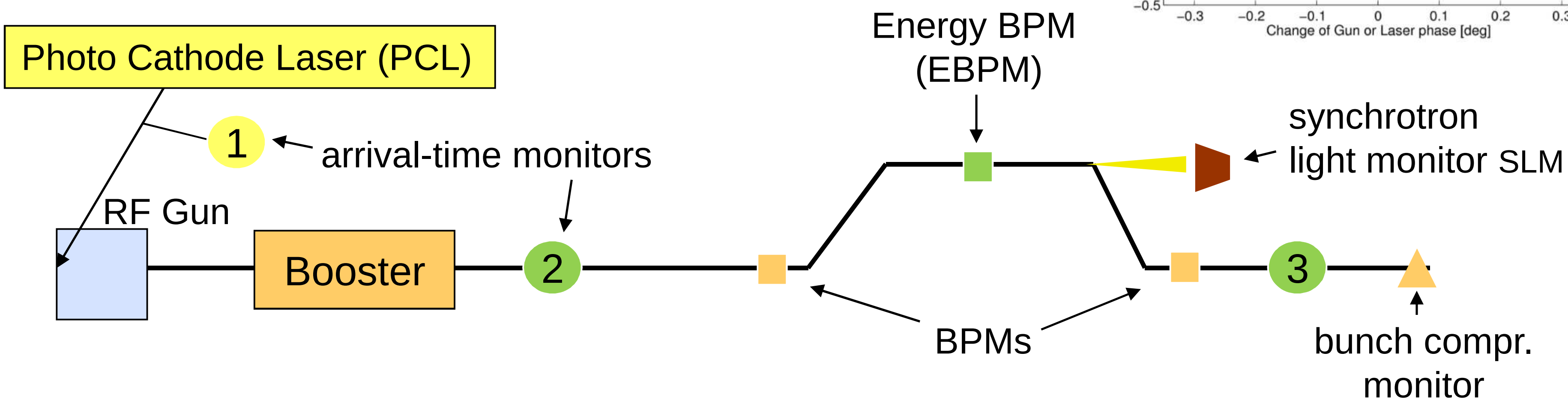
Pulse to pulse about factor of 2 better than last year

Across bunch train
dA/A ~ 7e-4
(LFF was off
250 kHz @ 0.5 nC)

Beam-based injector feedback

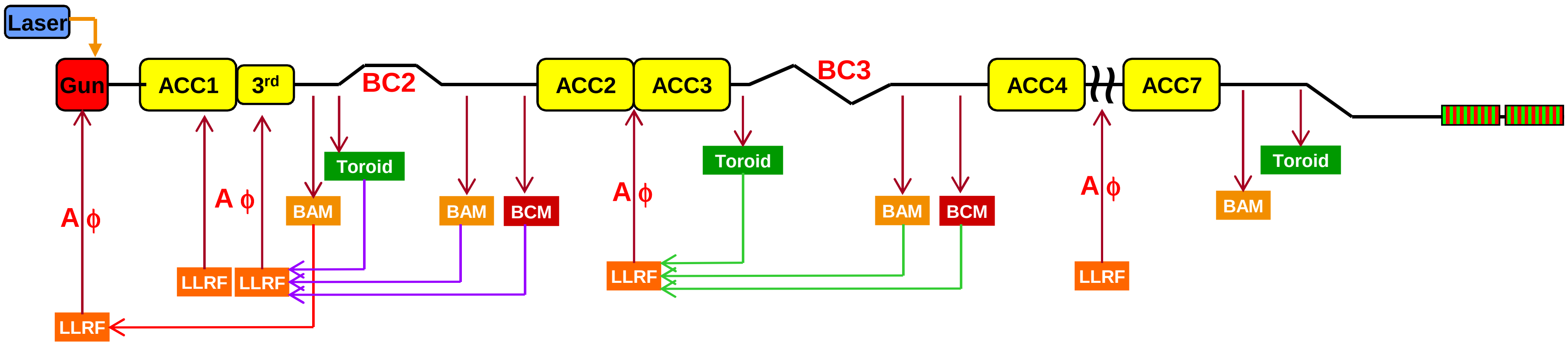
- Goal: Achieve stable arrival time, energy and compression
  slow: pulse-to-pulse & fast: intrapulse
- Need: - Many (different) monitor systems
  - complex algorithms and fast (<10 us) regulation





Machine parameter:	*Monitor:*
Arrival-time of PCL	1st arrival time monitor
Phase of RF gun	difference 1st and 2nd arrival-time monitor
Amplitude of booster	EBPM + BPMs / difference 3rd and 2nd arrival-time monitor (/ SLM)
Phase of booster module	(bunch compression monitor / fiber laser + EO)

Beam-based feedback: topology at FLASH

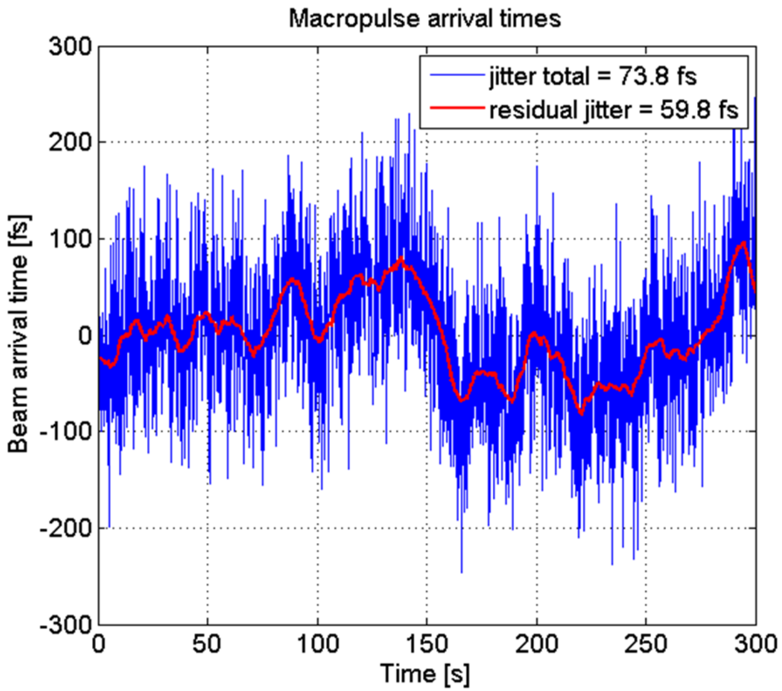


Beam Based Feedbacks:

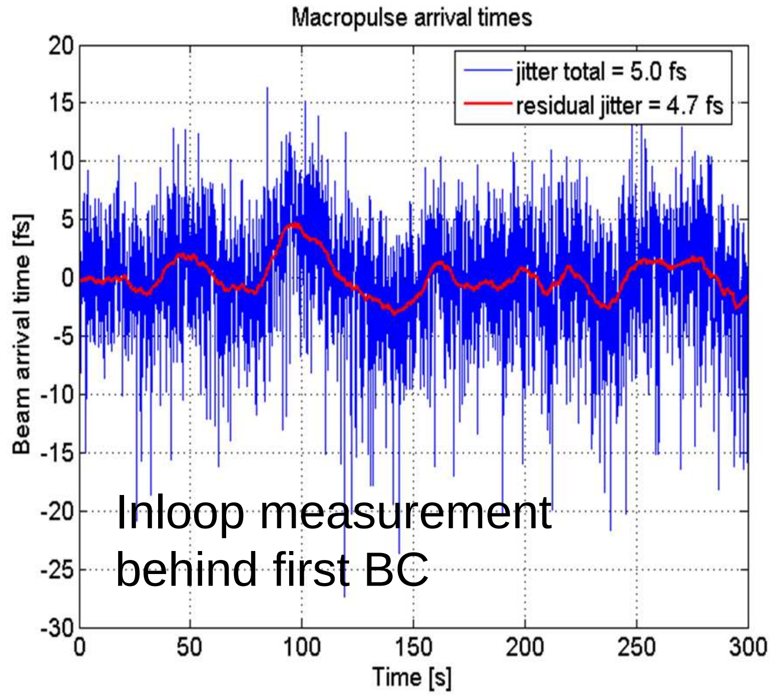
- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23

Slow (several 10 Hz macropulses) beam-based feedback

No Beam Based Feedback
Learning Feed Forward ON
rms = 74 fs



With Beam Based Feedback
running in ACC1 and ACC39
rms = 5 fs



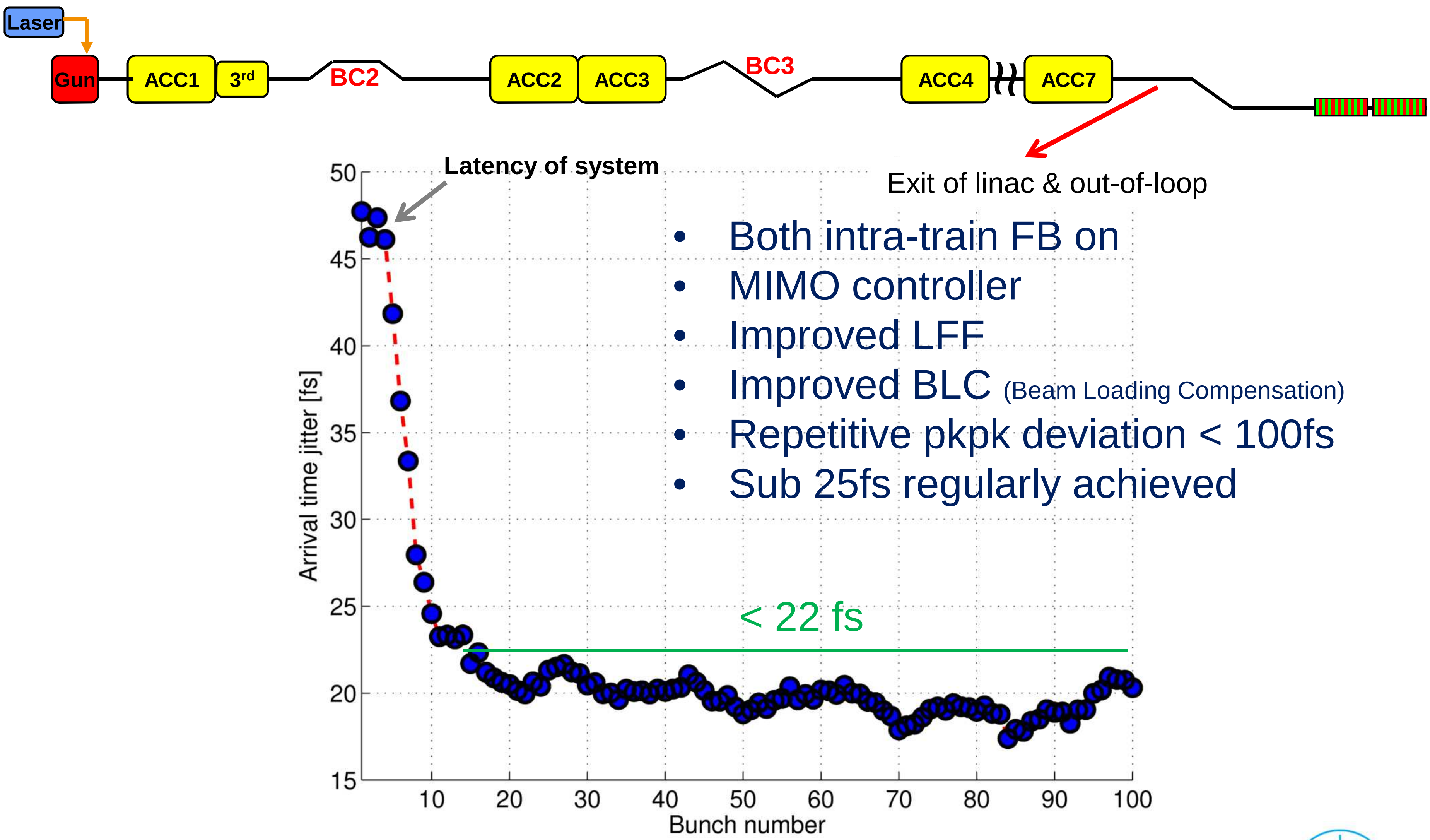
LLRF Regulation Performance → □A_1/ A_1~10e-4

□□$_1$< 0.03°

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

Courtesy: W. Koprek

Fast (intrapulse) beam-based feedback

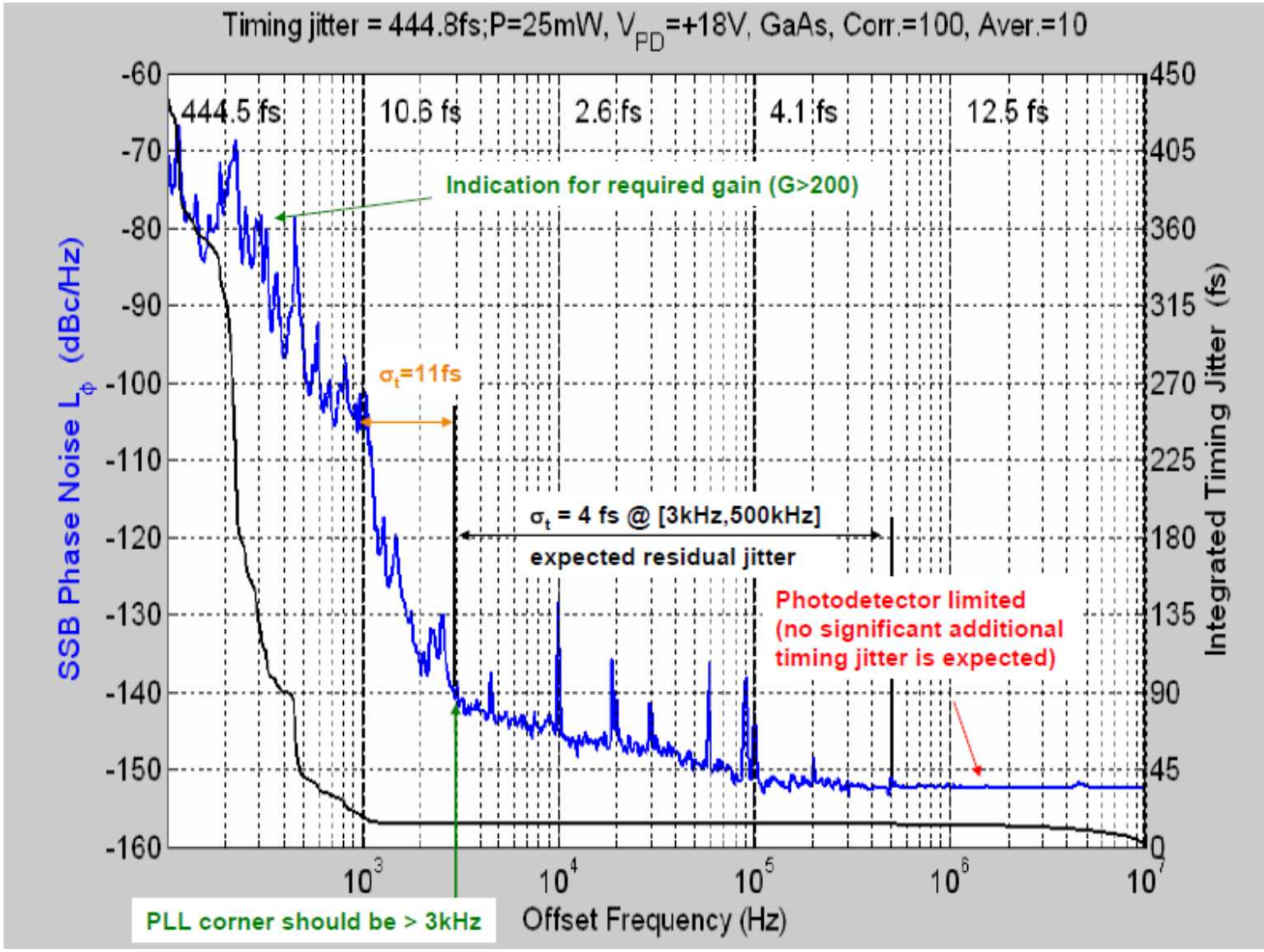


- Both intra-train FB on
- MIMO controller
- Improved LFF
- Improved BLC (Beam Loading Compensation)
- Repetitive pkpk deviation < 100fs
- Sub 25fs regularly achieved

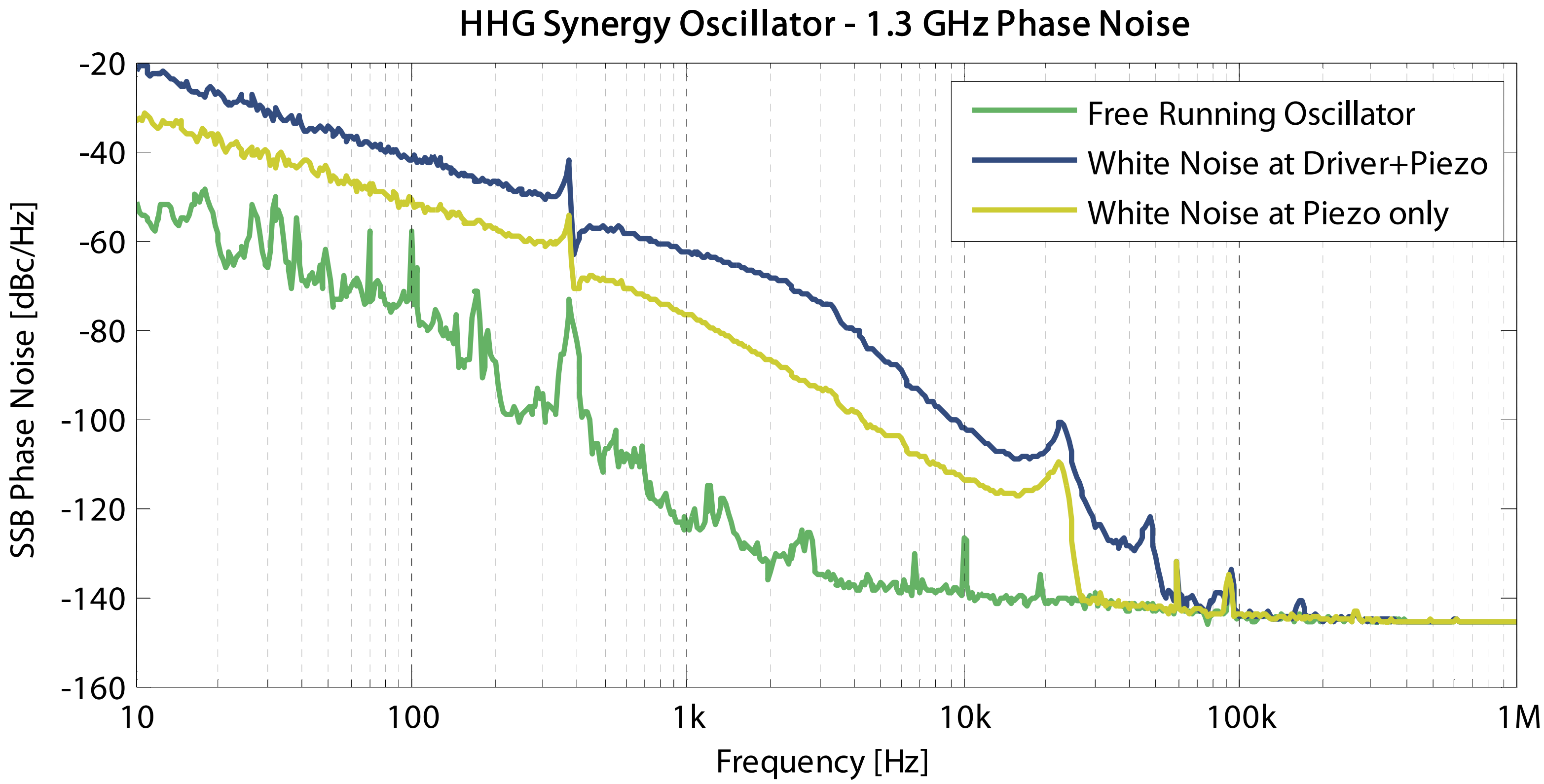
Courtesy: Ch. Schmidt

Laser-to-Laser (L2L) synchronization

Typical phase noise and timing jitter of a Ti:Sa at 1.3 GHz



Dangerous pitfall: piezo resonance



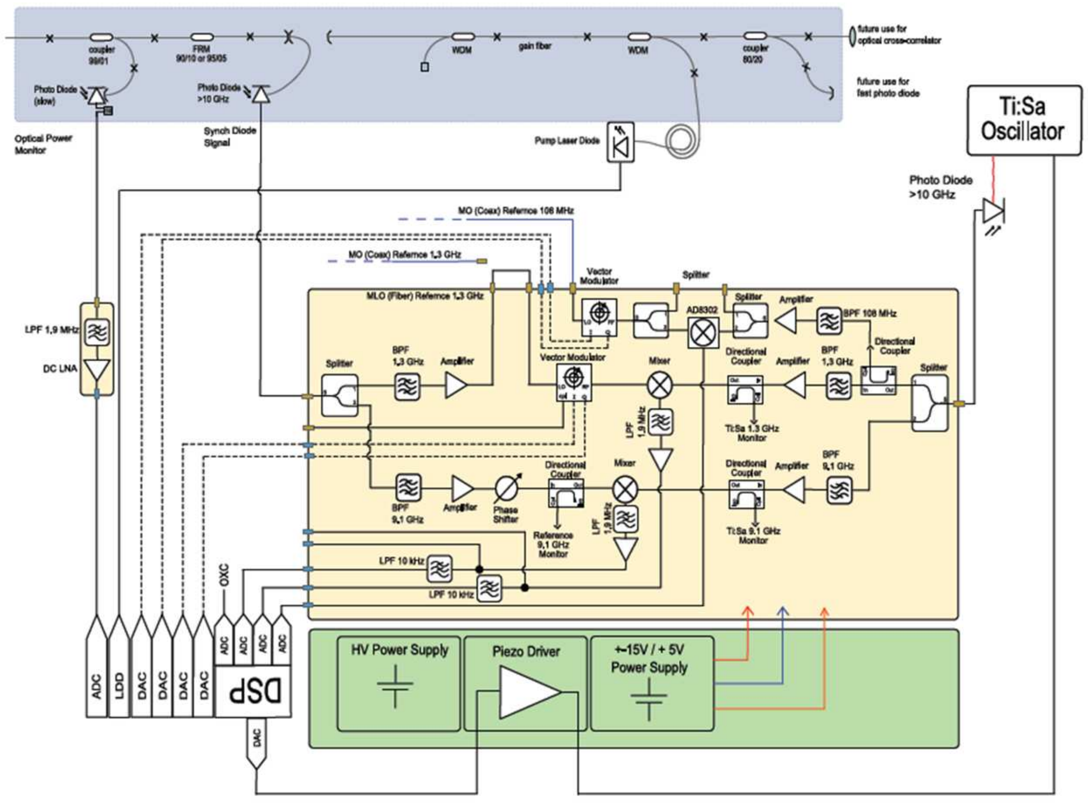
Laser-to-laser synchronization: RF PLL

Principle of Operation for Control and Measurement

traditional synchronization:

- based on a RF down-mixing scheme
- reference either RF from MO or generated from "link pulse train"

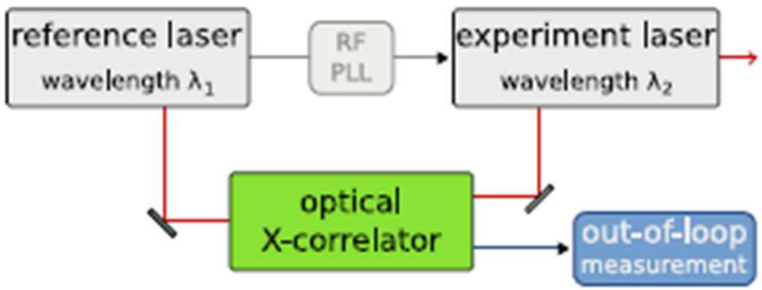
jitter $\sigma_{lock} \gtrsim 30$ fs



PP-Synch, M.Felber, 20.01.2011

Laser-to-laser (L2L) synchronization: RF PLL and o-o-l OXC

Principle of Operation for Control and Measurement



traditional synchronization:

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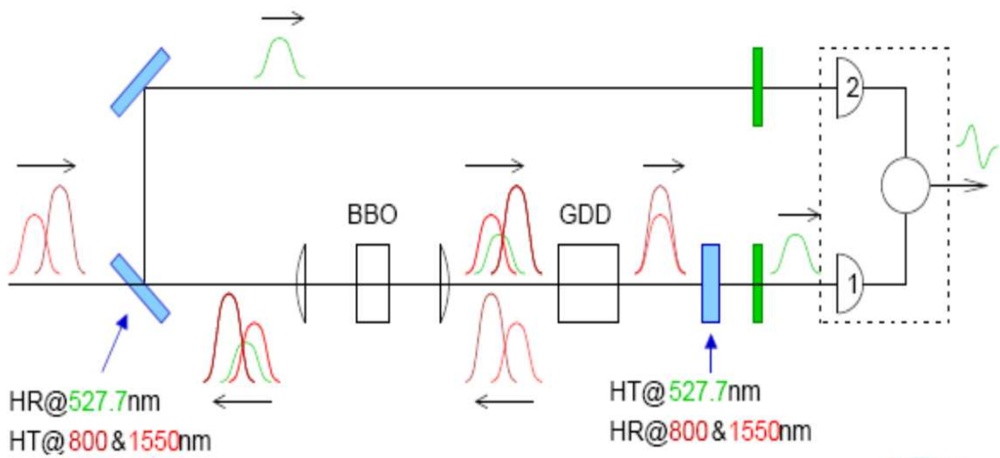
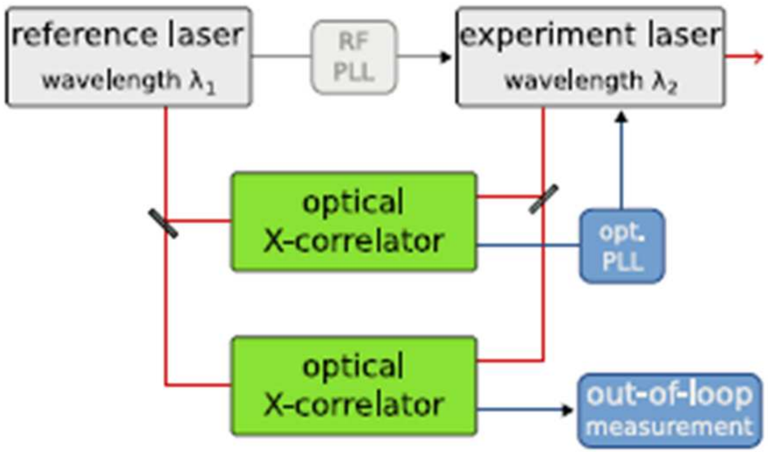
out-of-loop measurement:

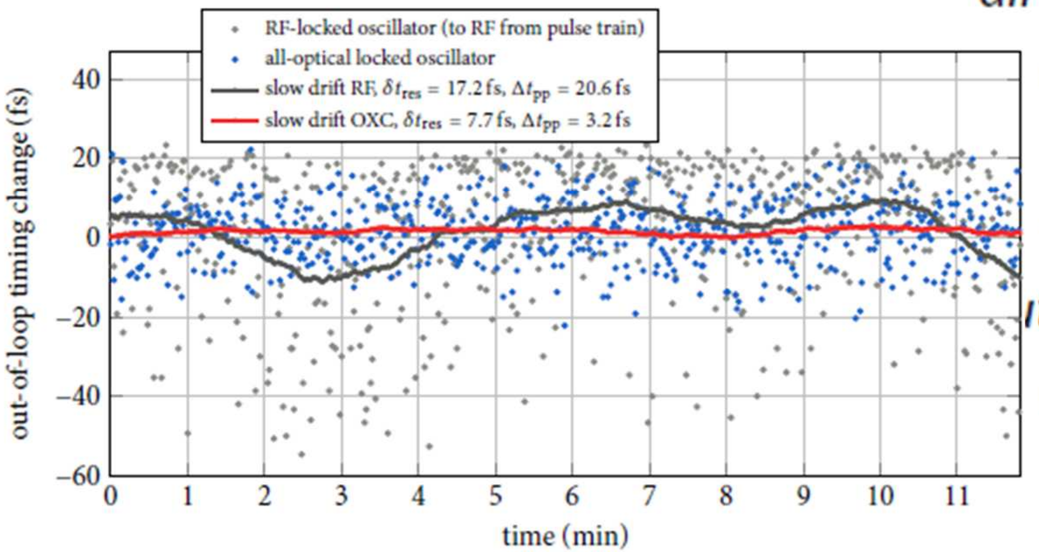
- optical cross-correlator



L2L synchronization: RF vs. OXC PLL – drift & jitter

Principle of Operation for Control and Measurement





traditional synchronization:

- based on a RF down-mixing scheme
- reference either RF from MO or generated from "link pulse train"
- timing jitter $\sigma_{lock} \gtrsim 30$ fs
- prerequisite for optical lock

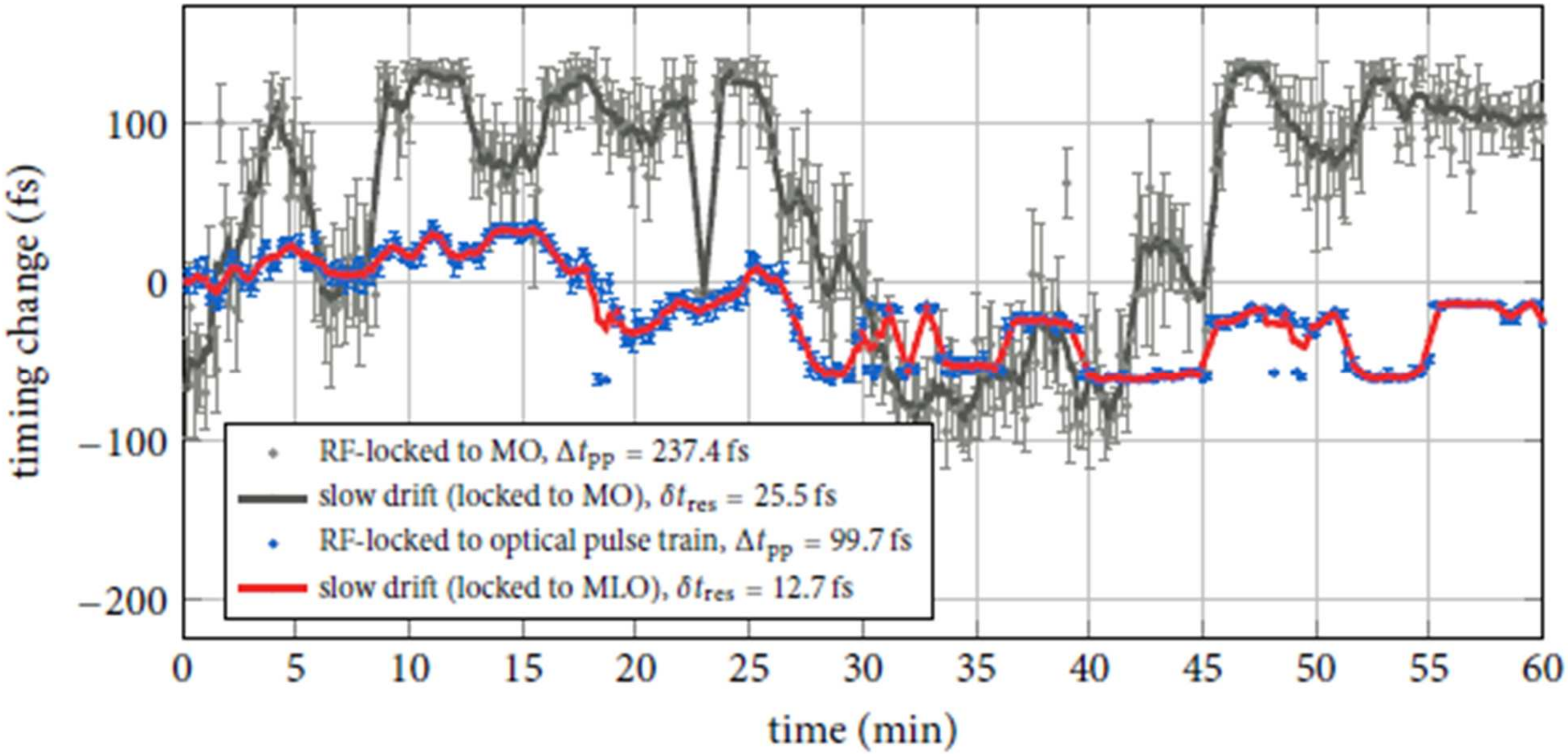
all-optical synchronization

- lock to cross-correlator signal at zero-crossing
- expected jitter < 10 fs

ıt-of-loop measurement:

- optical cross-correlator

L2L synchronization: RF distribution & lock vs. OXC PLL



Requirements for developing a synchronization system

- Infrastructure
  - Environment

    Temperature stabilization
    Vibration suppression
    EMI shielding

  - Typical laboratory equipment

    Optical spectrum analyzer
    Autocorrelator
    RF phase- and amplitude noise analyzer
    Baseband analyzer
    Fast scopes (□8 GHz)
    RF spectrum analyzer (□10GHz)
    Splicer + PM splicing equipment
    etc…

- Engineering skills

  Optics (Free space- and fiber)
  Electronics (low noise analog / fast digital)
  FPGA programming
  Software (Control system integration / feedback)
  Mechanical (small and precise / big and robust)
  RF

- Time, Money and **Manpower**

During the past years many fruitful collaborations contributed to the progress

Thank you for your attention!