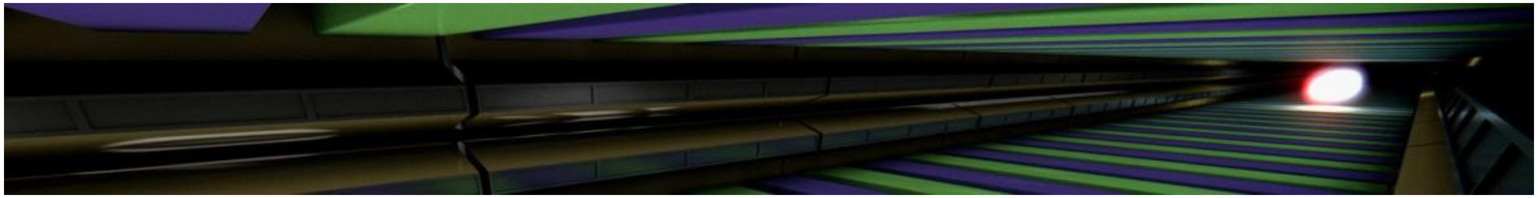


Femtosecond Synchronization

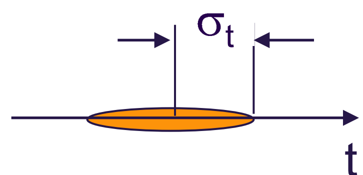
Holger Schlarb

for the optical synchronization team

- Motivation
- Synchronizationsystem
- Komponenten des optischen Synchronisationssystem bei FLASH

Motivation: shorter electron bunch length

- Towards shorter electron pulse duration — 1 ps = 10^{-12} s = 1000 fs = 300 μm/c_0

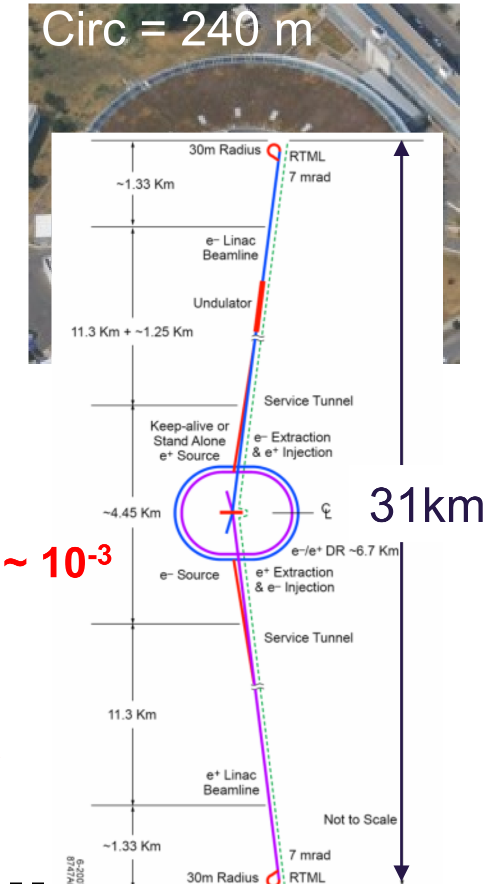


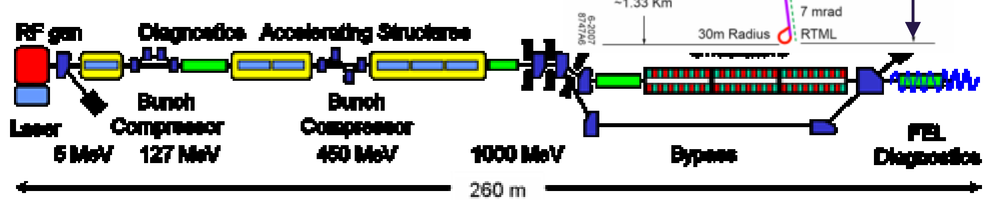
- Synchrotron light sources …BESSY σ_z = 10mm ~ 20 ps
  Low-alpha Multi Bunch Hybrid Modus ~ 2 ps

- Linac driven colliders … SLC σ_z = 2 mm ~ 6 ps
  ILC =0.3 mm ~ 1 ps

- Free Electron Lasers … European XFEL σ_z = 20 um ~ 60 fs
  Short pulse operation modes: FEL pulses < 5 fs

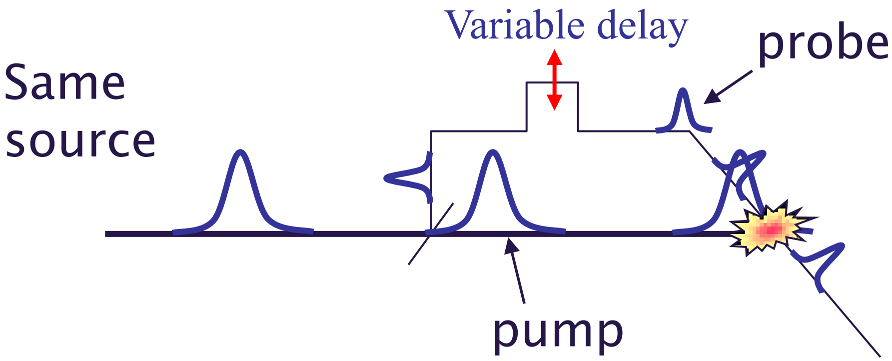
~ 10^{-3}





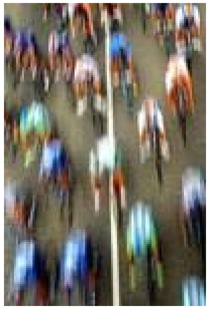
Motivation: Pump-probe experiments

Classical setup:



Probe = flash

Pump



Shot pulses fs ⟸ ps

- Pump pulse initiate reaction, probe pulse records current state.
  Atomic / Molecular Physics/ Solid state dynamics

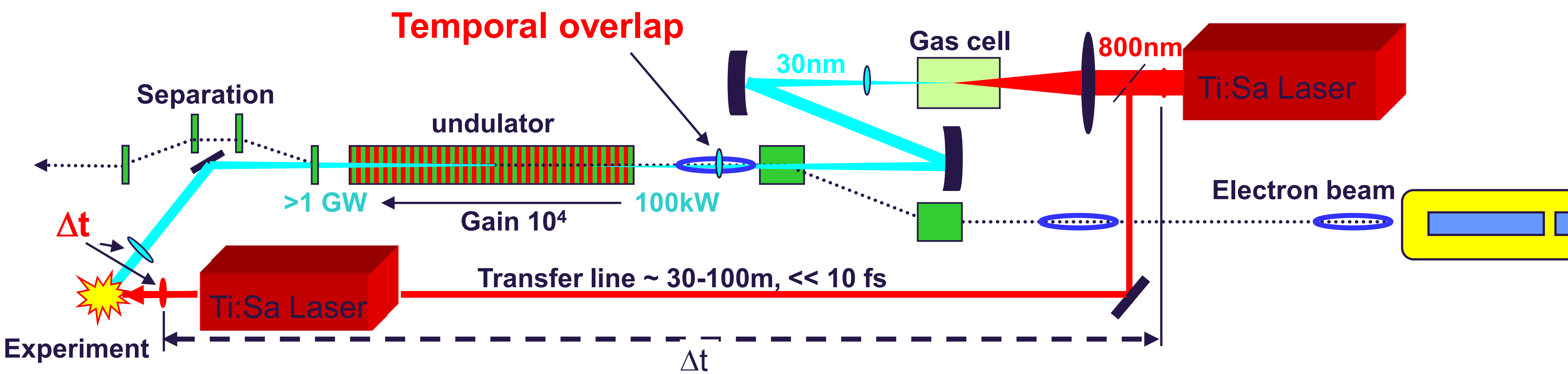
FELs: two different pulse sources: FEL beam and optical laser

Knowledge of time delay is crucial!

Comments: 1) measured at experiment => post analysis
2) for small event rates => not possible

Motivation: seeding with higher harmonics

Generic layout of seeding a single pass FEL



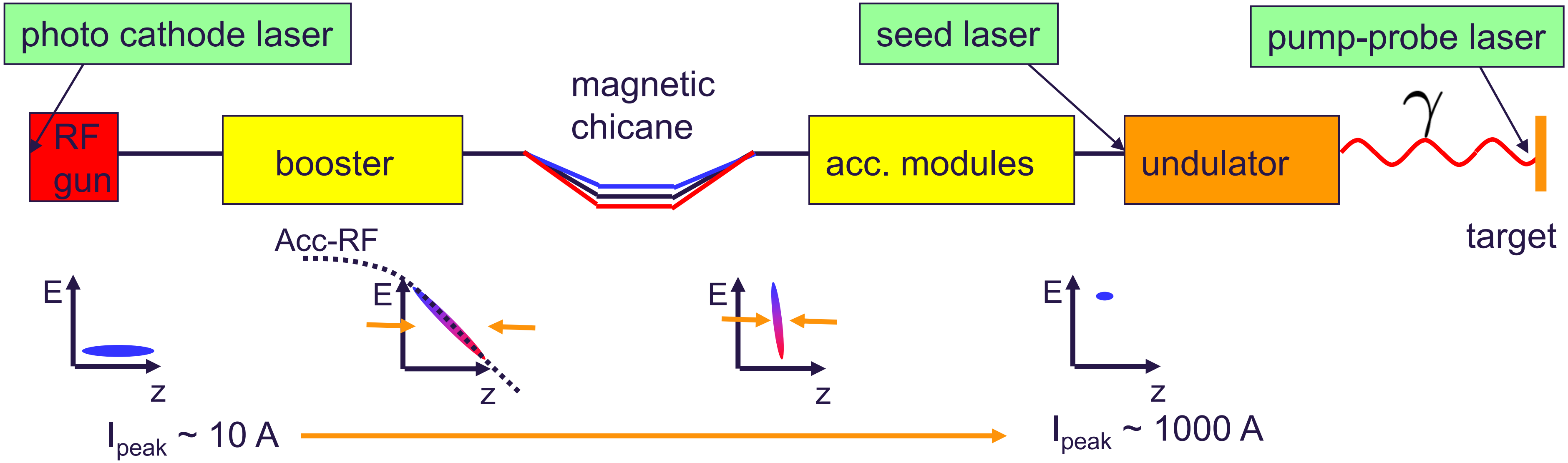
New class of experiments:

- Electron beam is seeded or manipulated using external laser
- Timing of FEL pulse defined by now by seed (laser)

Requirements:

- Temporal overlap between electron bunch & seed pulse essential ~ 10-50 fs
- Particular high demands on synchronization to pump-probe laser ~ 1-5 fs

Motivation: Peak current & arrival time jitter



Compression process & FEL resonance condition

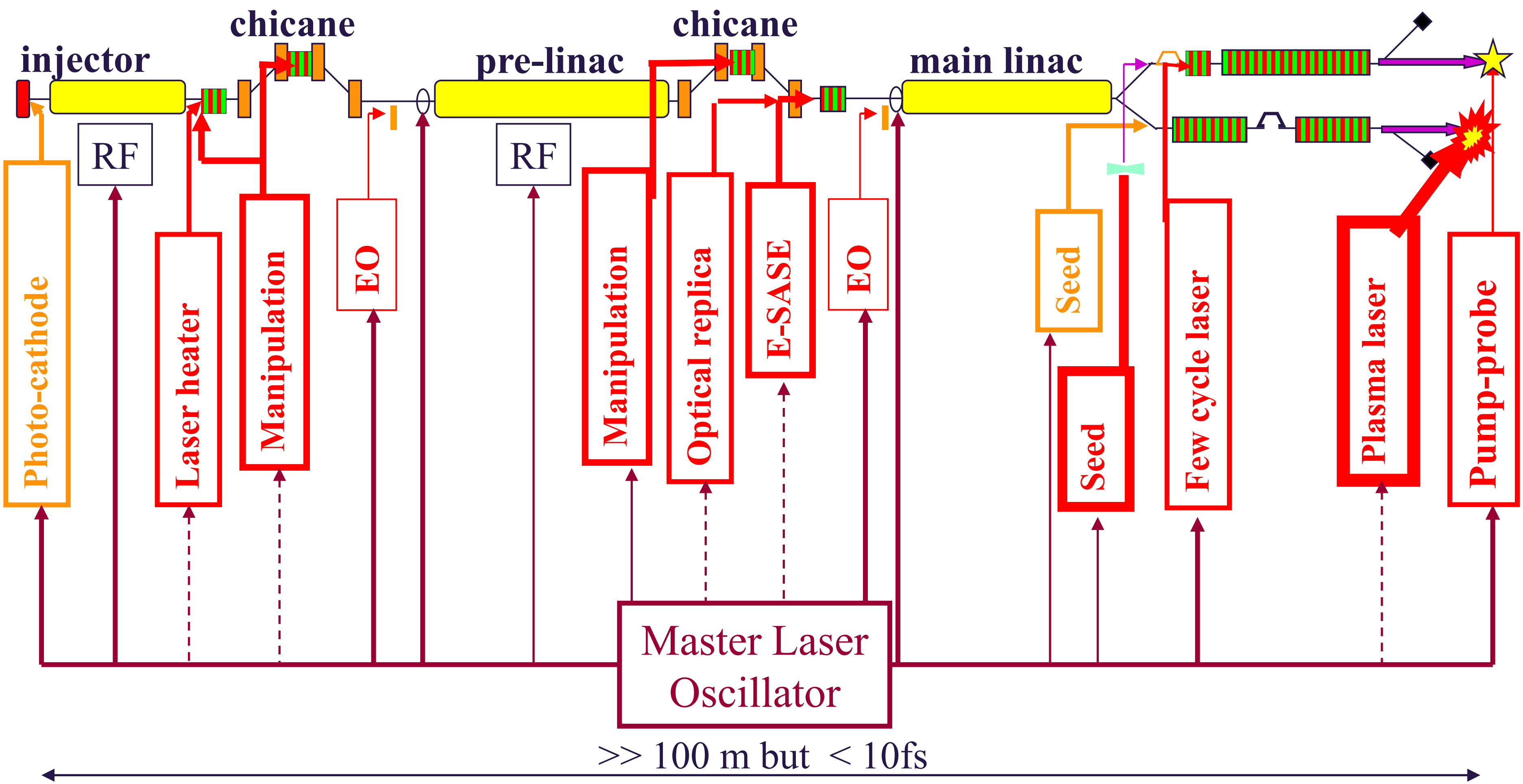
- **stability of peak current** $\Delta I/I$ < 1-10 %
- **control of arrival** Δt < 10-50 fs
- **FEL wavelength fluctuations** $\Delta E/E$ < 10^{-4}

⇒ Increased acceleration RF stability requirements

Phase stability (rel.)	**~ 0.05° …0.005°**	**(~ µH … ~ 1 MHz)**
Amplitude stability	**~ 0.05% …0.005%**	**(~µH … ~ 1 MHz)**

Motivation: Lasers for FELs

Generic layout of single pass FELs



Motivation: summary

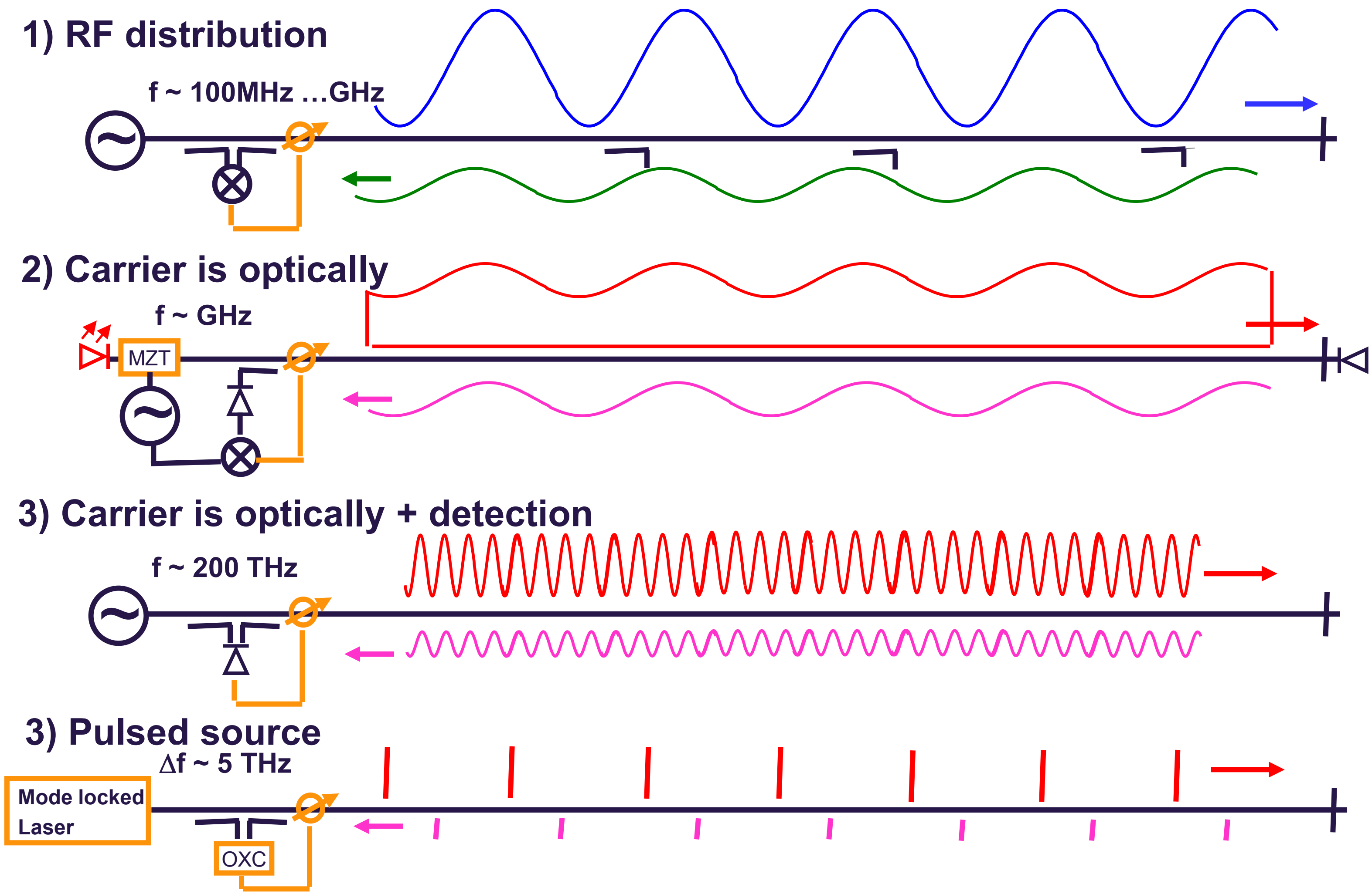
- Accelerator technology advanced from
  picosecond bunch duration → few 10 fs bunches
- Facility length range from ~100 m up to 3.5 km (European XFEL)
- Stability of FELs puts stringent demands on RF requirements
- Optical laser systems become an integral part of FEL facilities
  - for the beam generation,
  - beam diagnostics,
  - beam conditioning/seeding and
  - for user experiments

⇒ Changed the requirements on synchronization from ps to fs precision

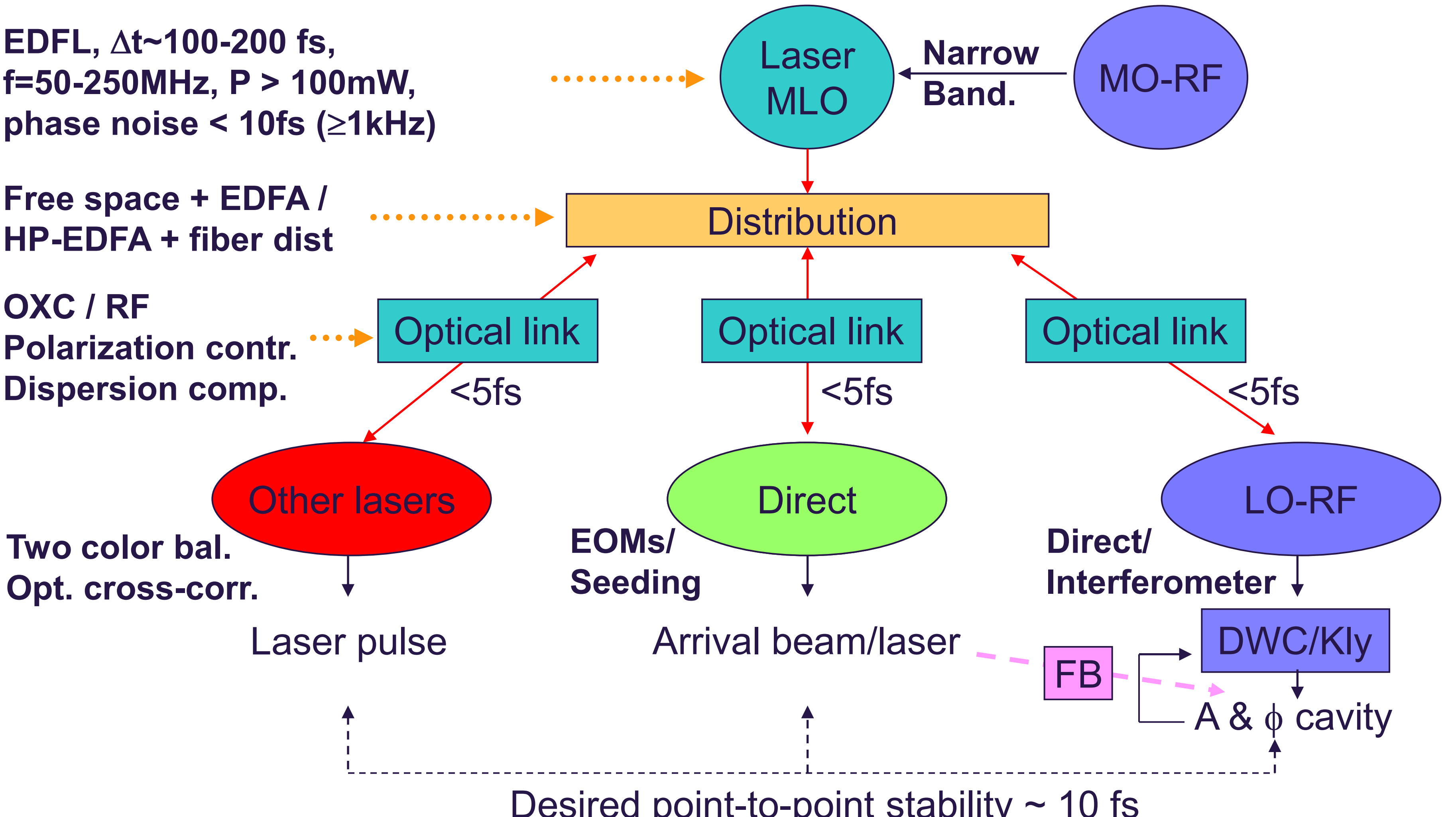
Synchronization

Several scheme on the market!

$$\frac{\Delta t}{t} = \frac{\Delta f}{f}$$



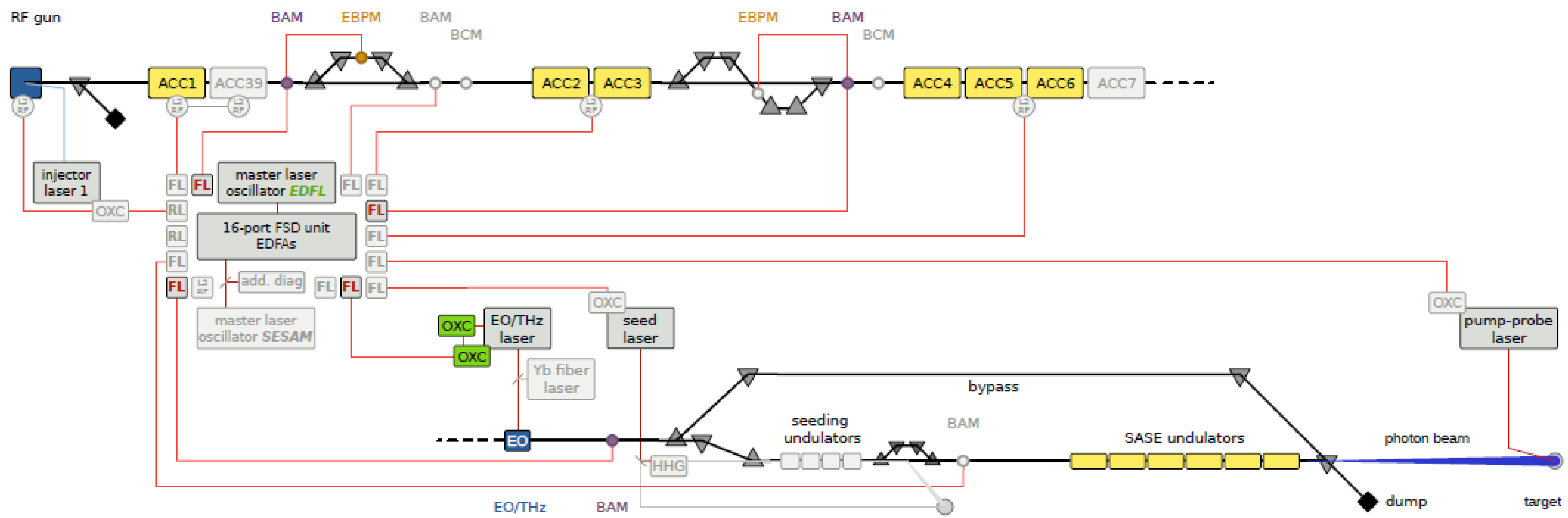
Optical synchronization system



- Main issue: robustness, stability and maintainability ⇒ Prototype at FLASH

FLASH synchronization system (Sep. 2009)

FLASH accelerator and optical end-stations for synchronization:

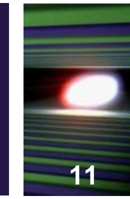


Courtesy: S. Schulz

Master laser oscillator (EDFA) with 4 stabilized optical links to

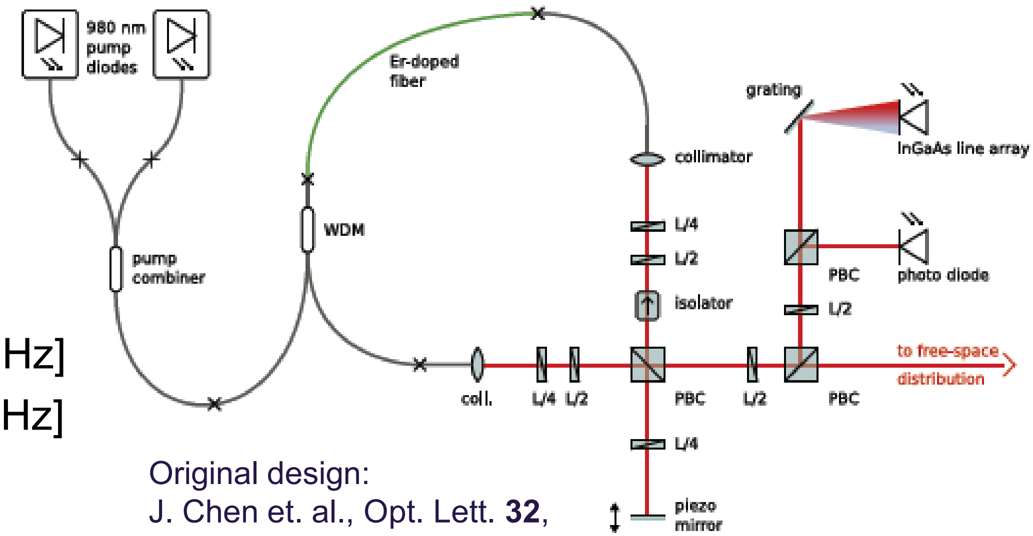
- 3 Beam arrival monitors (BAM)
- 1 cross-correlator for locking diagnostic TiSa laser system (OXC)
- and large aperture BPM for energy measurements (EBPM)

Master laser oscillator (MLO)



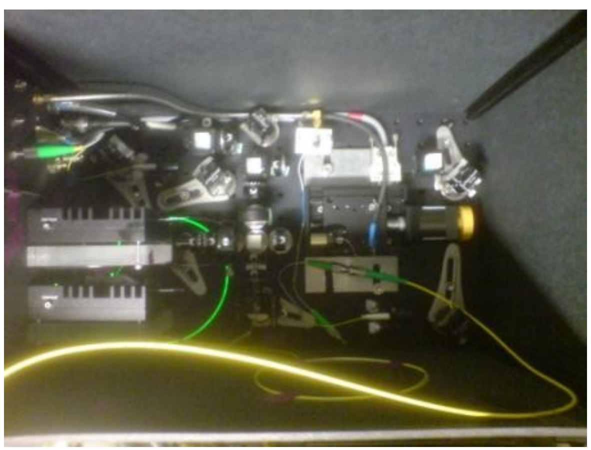
Specification/Requirements

- Mode-locked erbium-doped fiber laser
- Repetition rate of 216.66MHz
- Average power > 100mW
- Pulse duration < 100 fs (FWHM)
- Integrated timing jitter < 10 fs [1kHz,40MHz]
- Amplitude noise < $2 \cdot 10^{-4}$ [10Hz,40MHz]
- Mechanical robust/easy to maintain

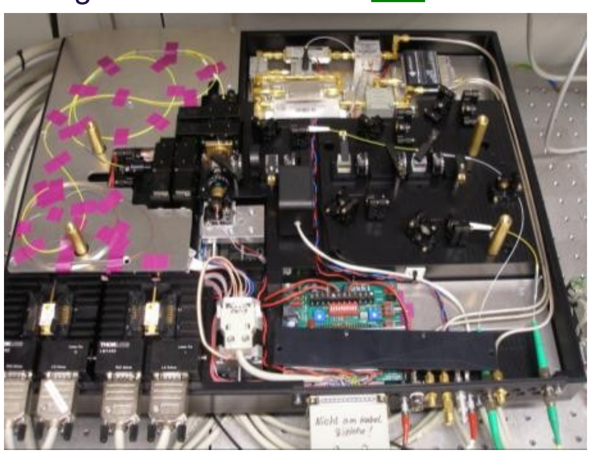


Original design:
J. Chen et. al., Opt. Lett. **32**, 1566-1568 (2007)

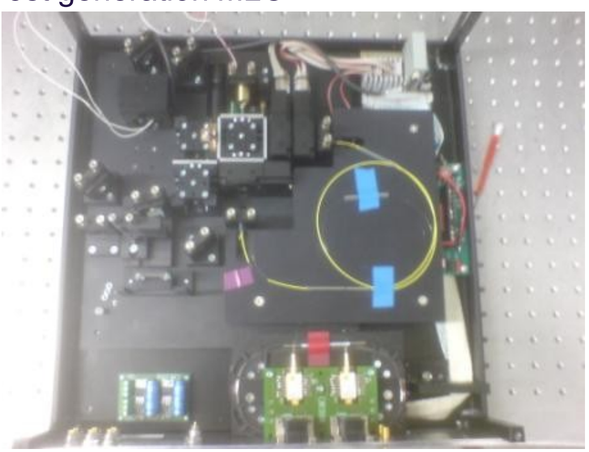
1st generation MLO ✓



2nd generation MLO ☑

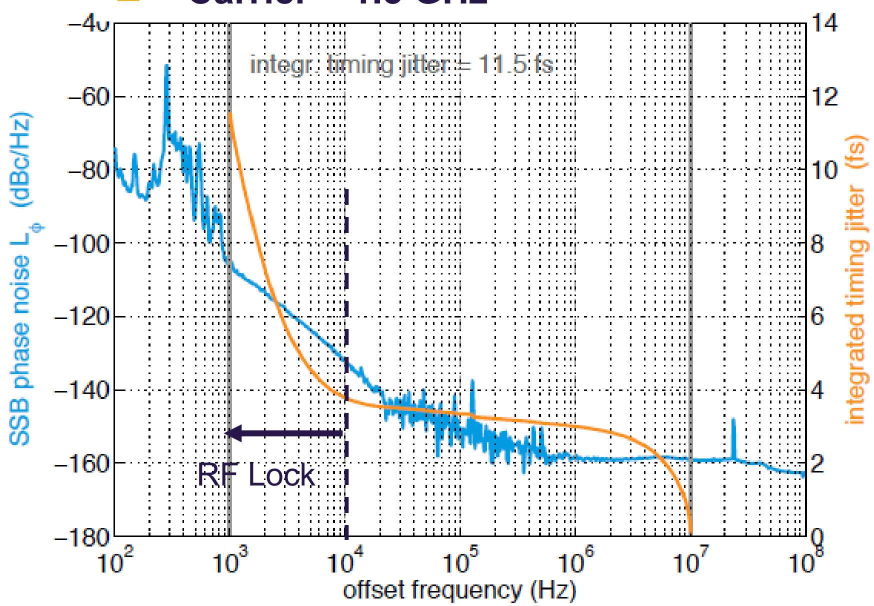


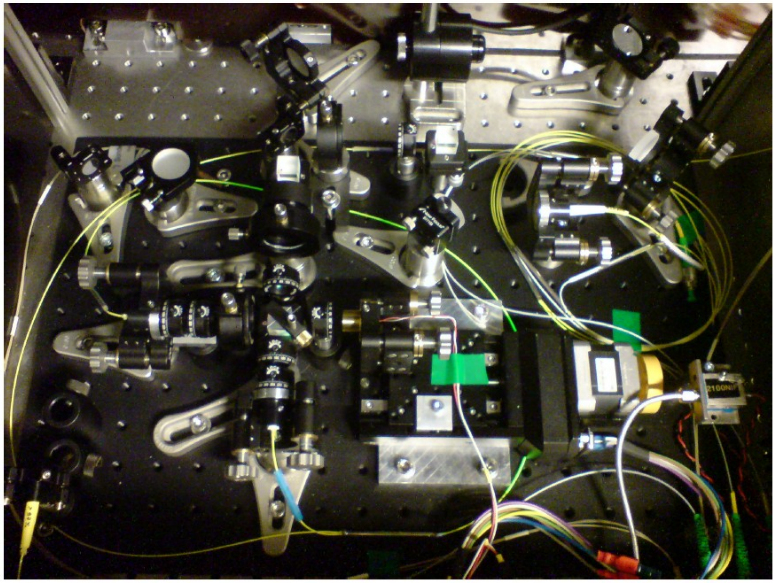
3st generation MLO ✘



Master laser oscillator (MLO)

- **Carrier = 1.3 GHz**





Courtesy: S. Schulz

Performance:

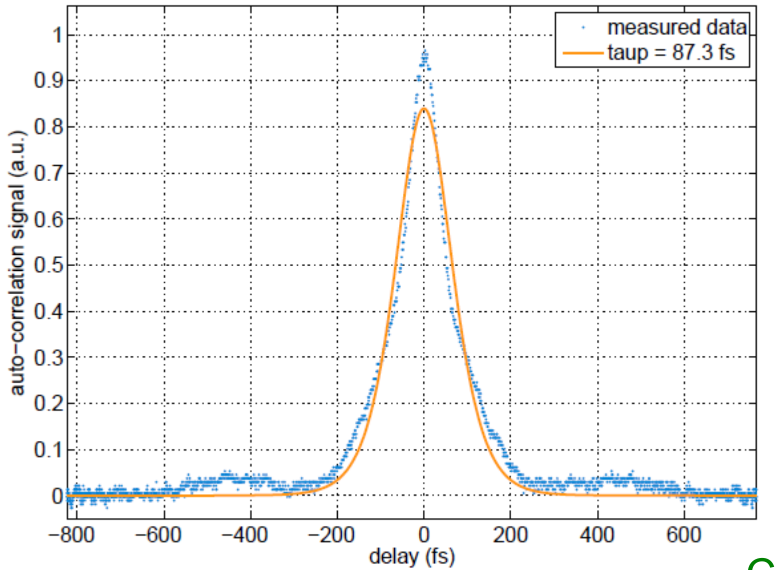
- Integrated timing jitter 11.5 fs @ [1kHz, 10MHz] / 4fs @ [10kHz,10MHz]
- Very short pulses < 90 fs
- Power stability: 2% pkpk and 0.4% rms over 240 hours! (no FB stabilization)

Problems

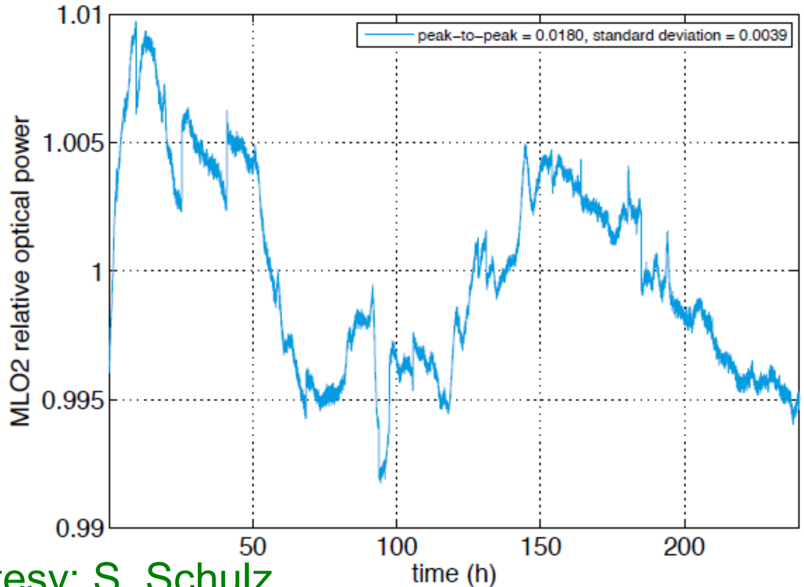
- Output power < 70mW otherwise double pulses
- Reproducibility and maintance

Master laser oscillator (MLO)

- Pulse duration (sech$^2(t/\tau_p)$-fit)



- Output stability



Courtesy: S. Schulz

Performance:

- Integrated timing jitter 11.5 fs @ [1kHz, 10MHz] / 4fs @ [10kHz,10MHz]
- Very short pulses < 90 fs
- Power stability: 2% pkpk and 0.4% rms over 240 hours! (no FB stabilization)

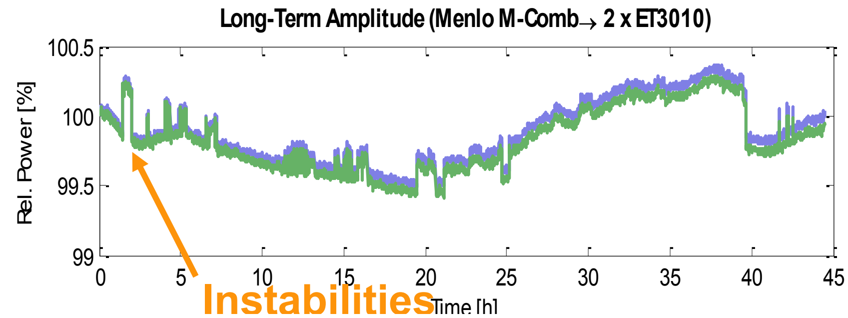
Problems

- Output power < 70mW otherwise double pulses
- Reproducibility (spectrum/pulse duration/phase noise) & maintenance
- Requires special diagnostics and complex exception handling

Master laser oscillator (MLO)

Commercial lasers

- Based on same technology
  - ⇒ After some trouble shooting ok
  - ⇒ High output power > 100 mW
  - ⇒ Similar problems in terms of reproducibility
  - ⇒ Long term measurements: observed instabilities



- New laser based on different mode locking

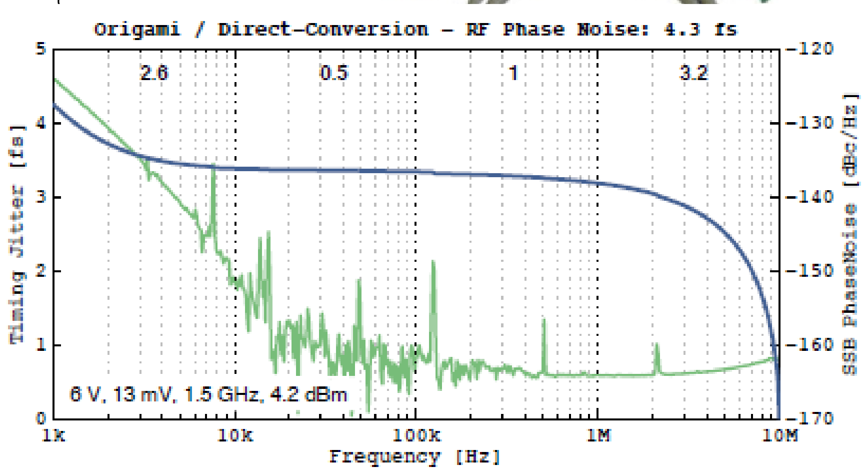
Type: saturable absorber laser (SESAM)

Output power > 100mW

Pulse duration τ_p < 150 fs

Robust mechanics, high reproducibility

Integrated timing jitter **4.3 fs** [1kHz,10MHz]



Inspected at tested at PSI

Changed specification to our purpose

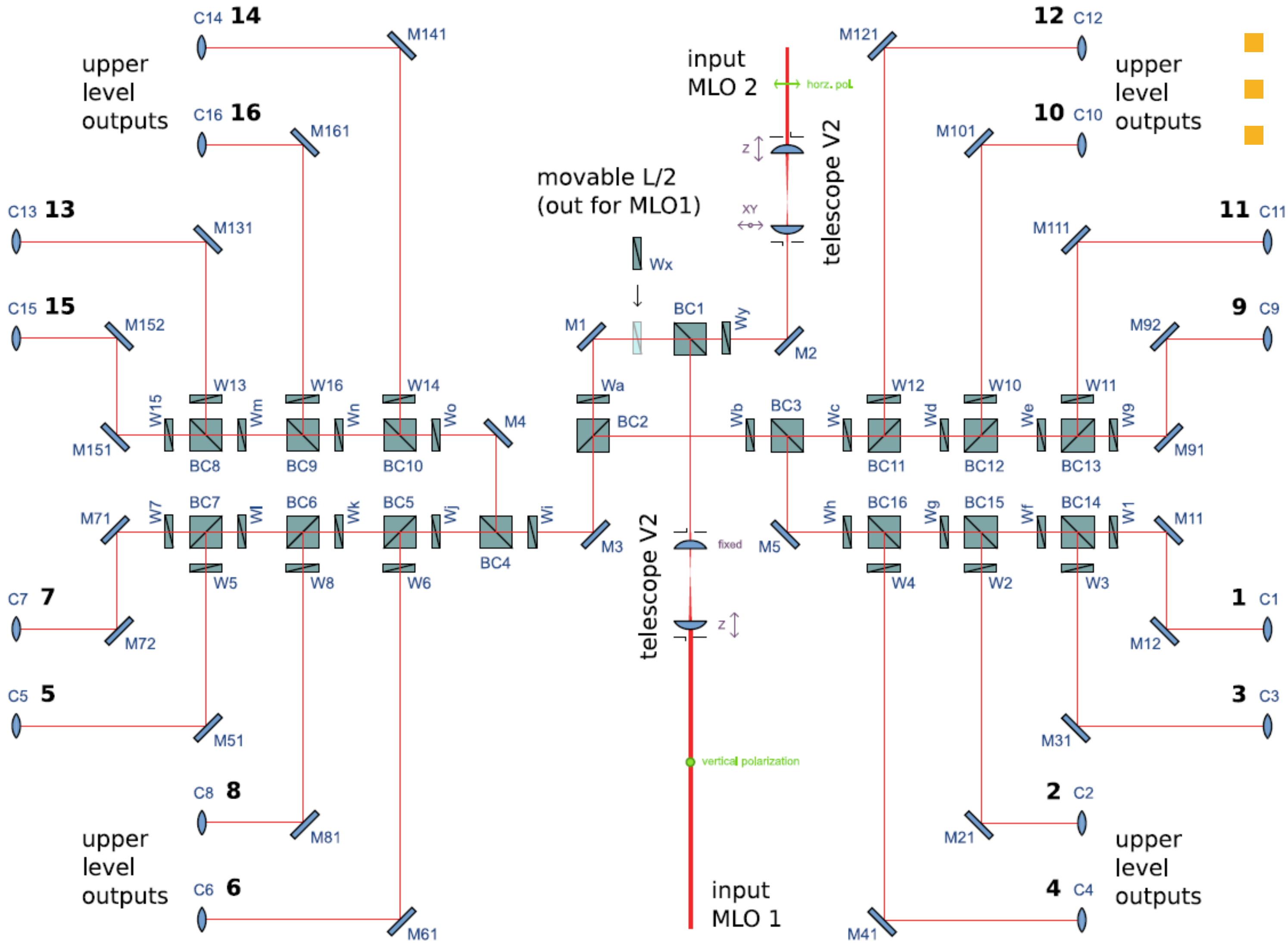
⇒ Delivery April 2010

Problem: long term live time

European XFEL

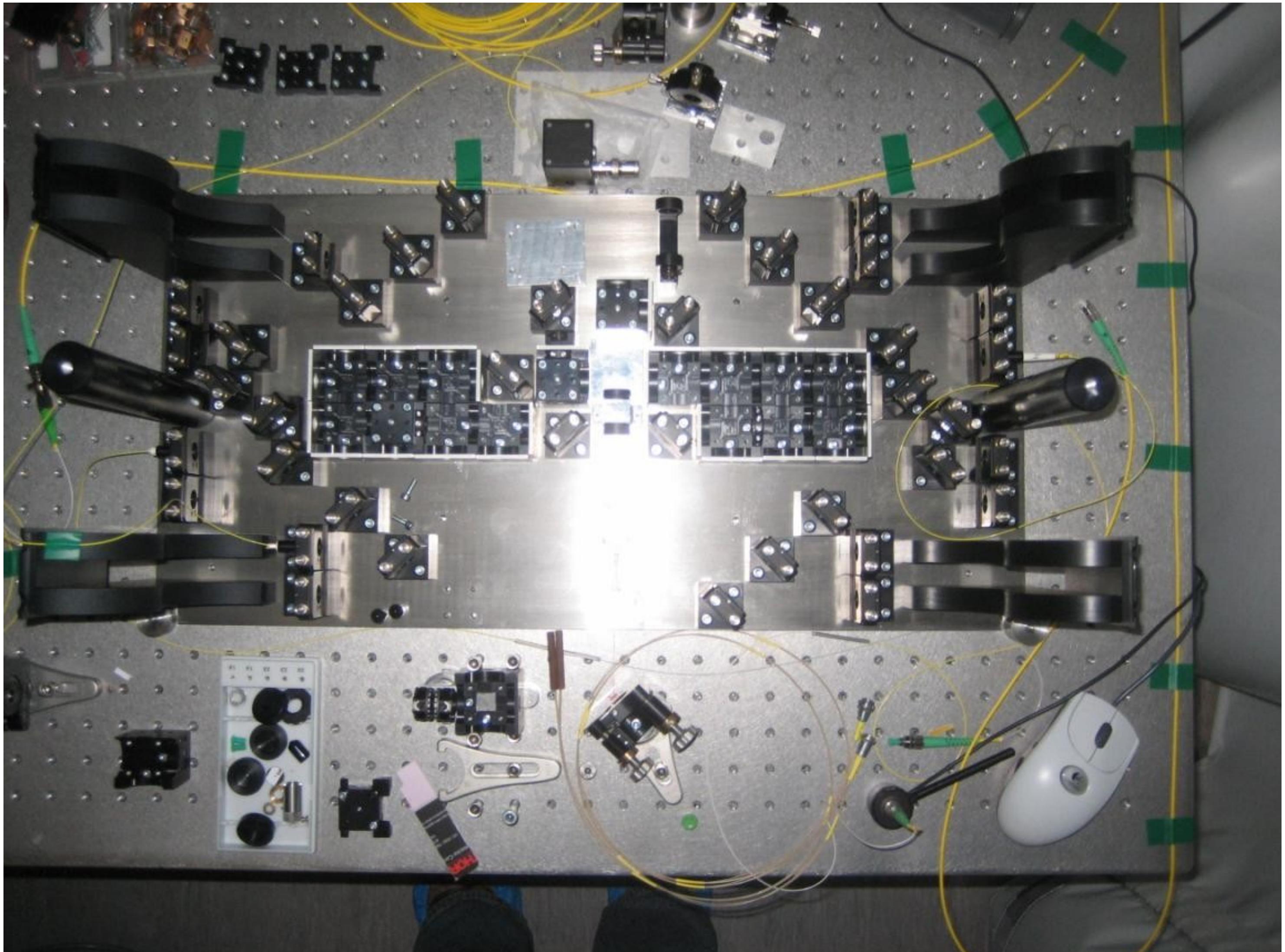
Distribution system

- 120 mW input
- 5 mW out
- 90% incoupling eff.

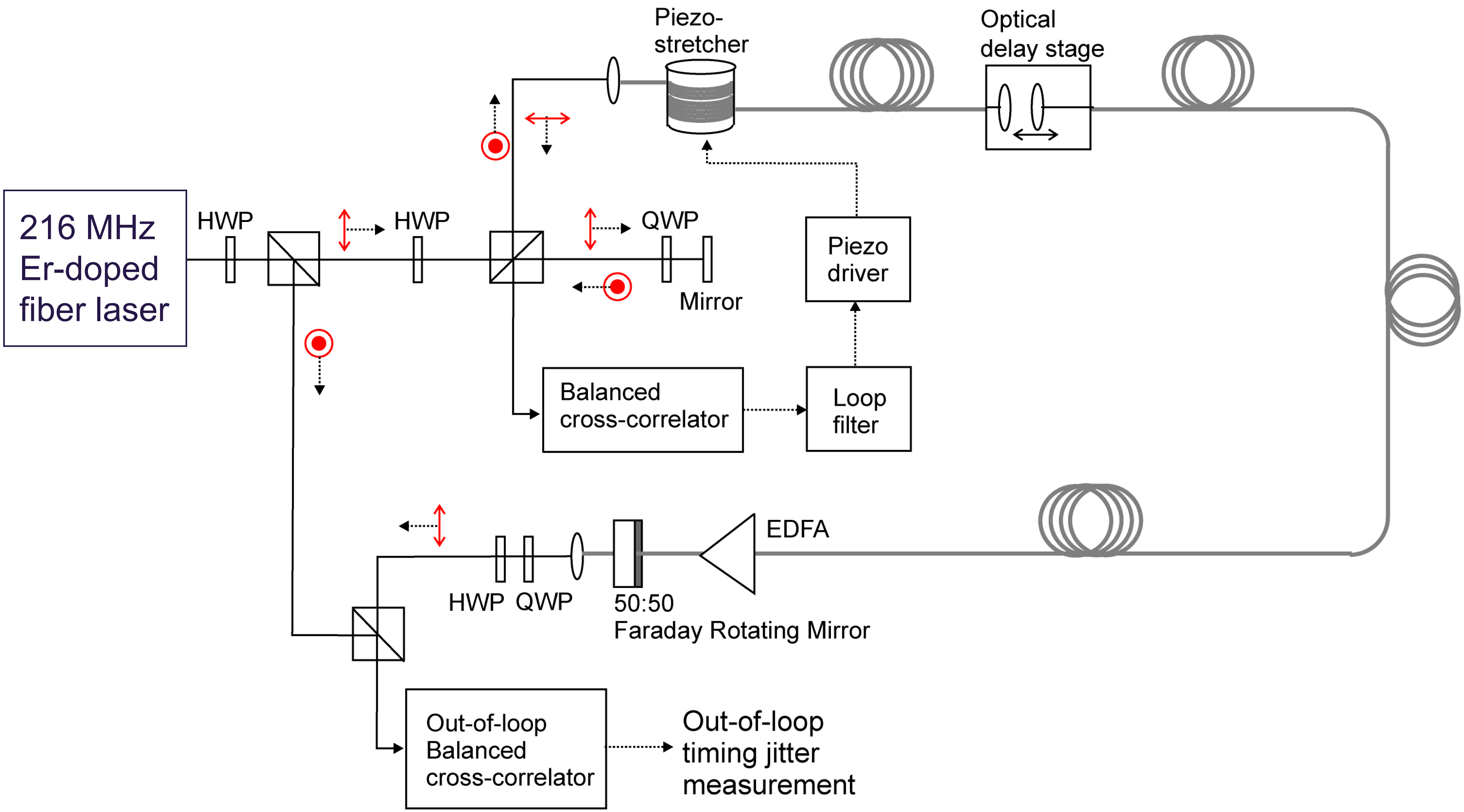


Courtesy: S. Schulz

Distribution system



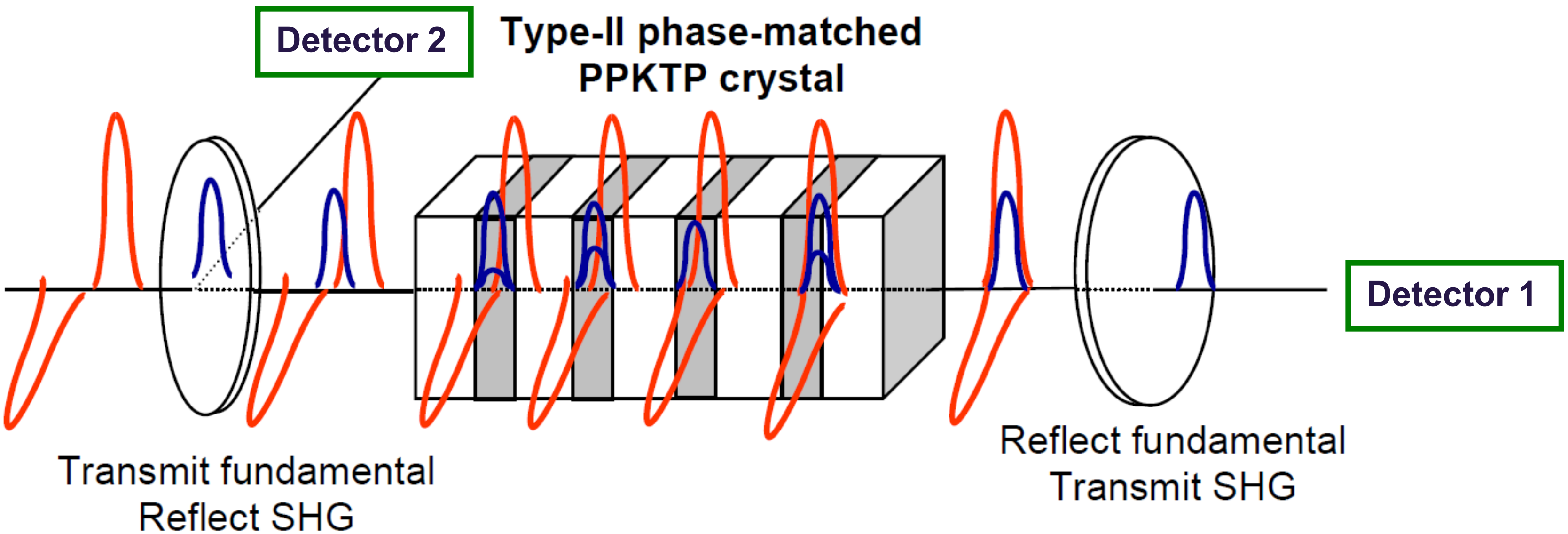
Fiber Link Stabilization



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

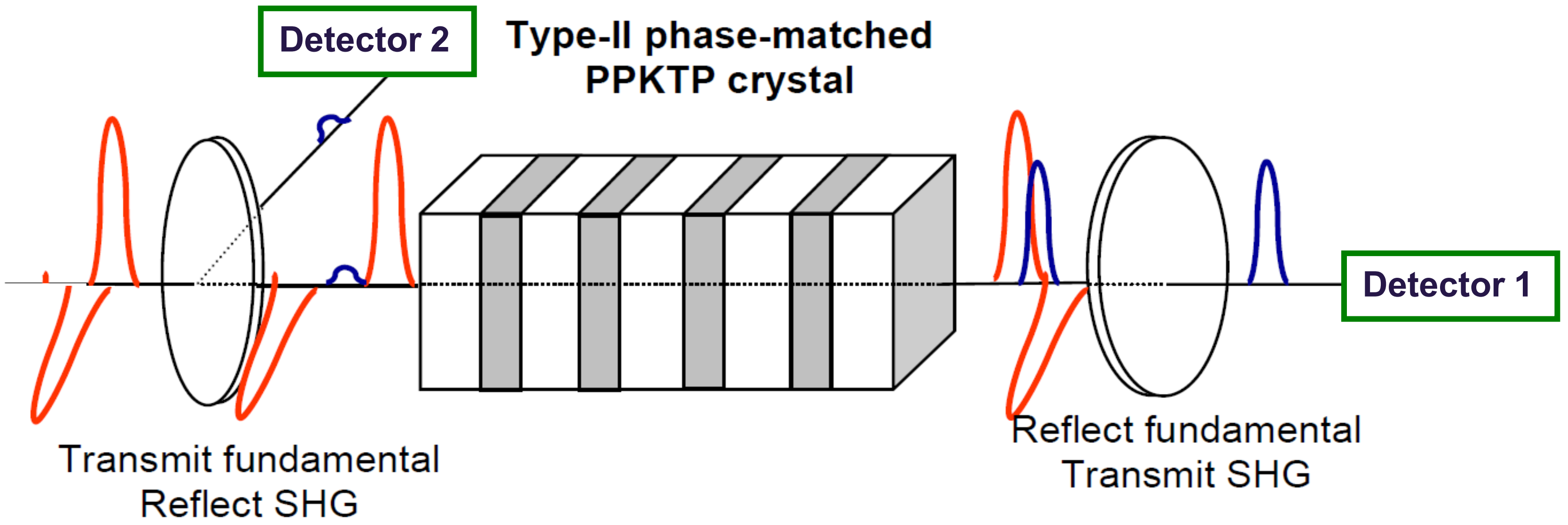
Fiber Link Stabilization

- Single crystal background free optical cross-correlator



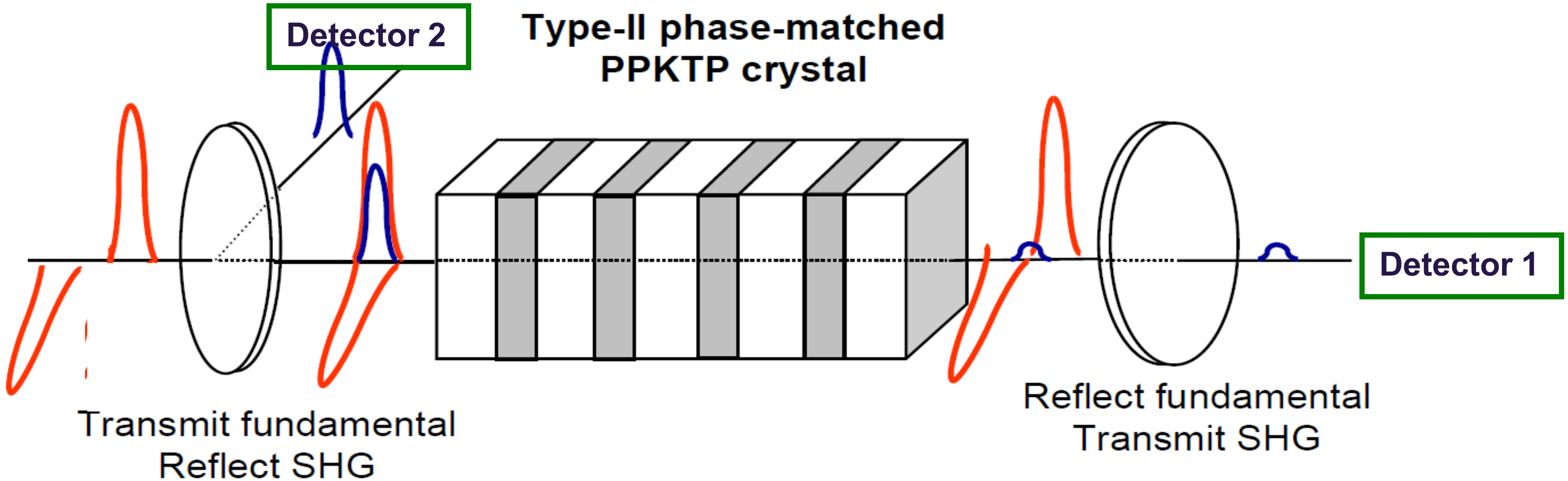
Fiber Link Stabilization

- Single crystal background free optical cross-correlator



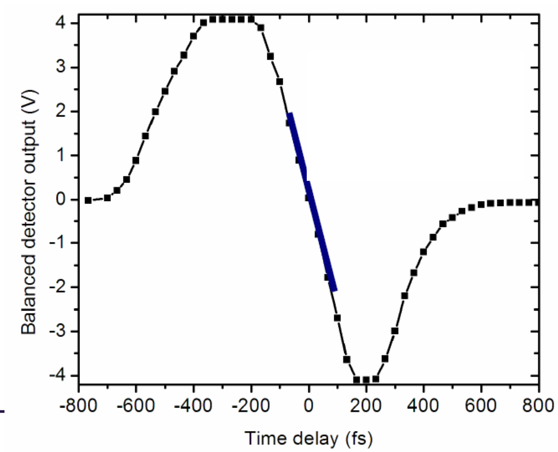
Fiber Link Stabilization

- Single crystal background free optical cross-correlator



⇒ Link is locked at zero crossing

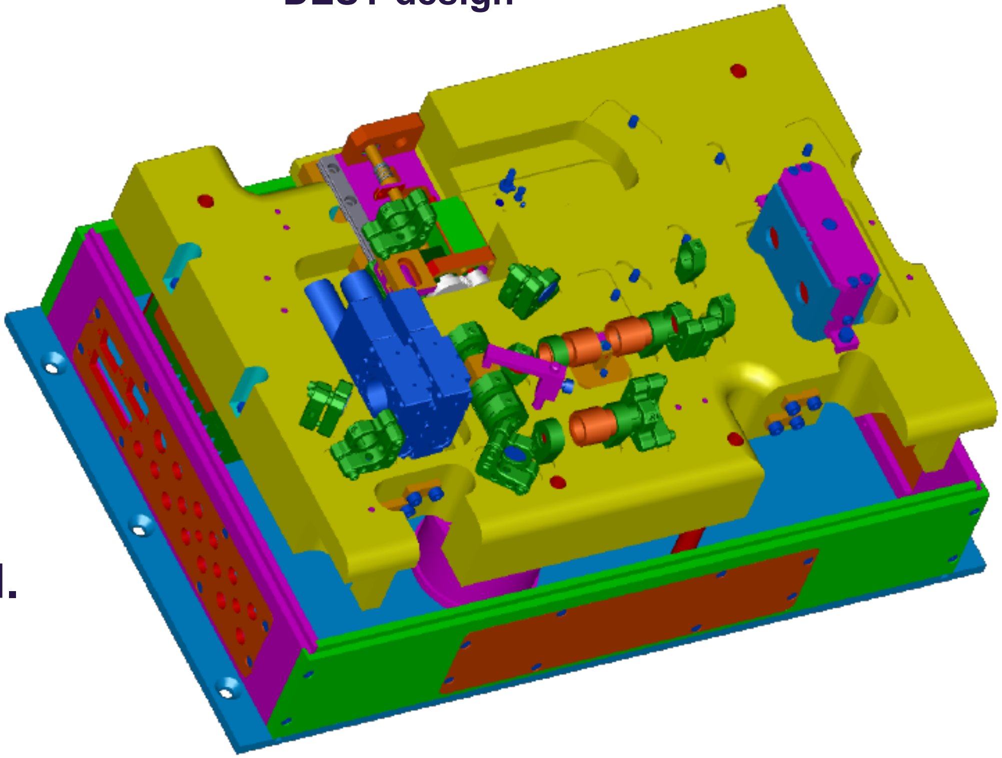
⇒ Amplitude fluctuations are converted to gain fluctuations



Fiber Link Stabilization: engineered version

- Three layer design:
  - -Free space optics with OXC (top)
  - -Fiber layer (middle)
  - -Electronic layer (bottom)
- 5 links completely assembled
- mechanically very robust
- several problems identified
  - -Yawing/pitching of delay line
  - -Some optics holders
  - -Easy to assembly
- **2nd prototype design ready for prod.**

DESY design

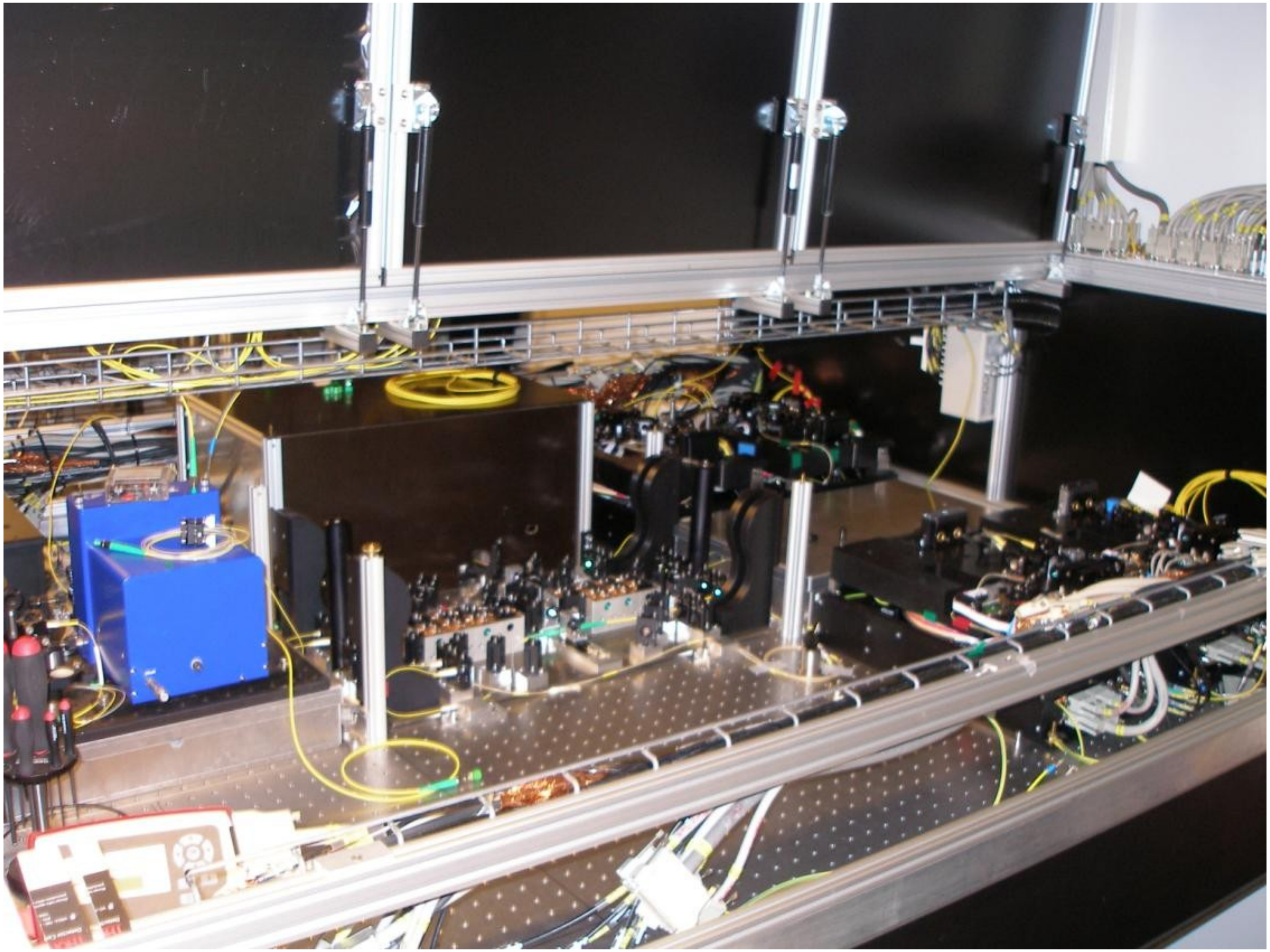


Drawback link stabilization:

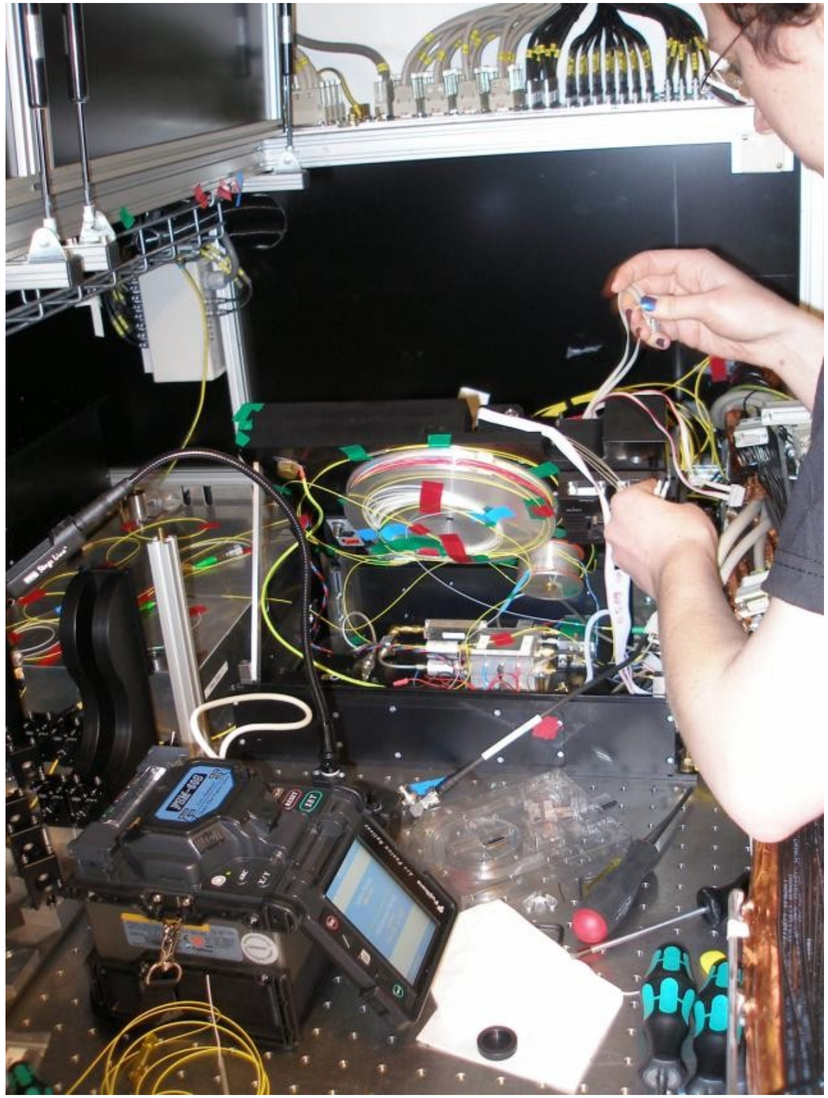
- requires dispersion compensation
- precise overlap of laser pulses
- to cost intensive to supply many end-stations

⇒Room for further improvements (packaging/costs)

Fiber Link Stabilization: engineered version

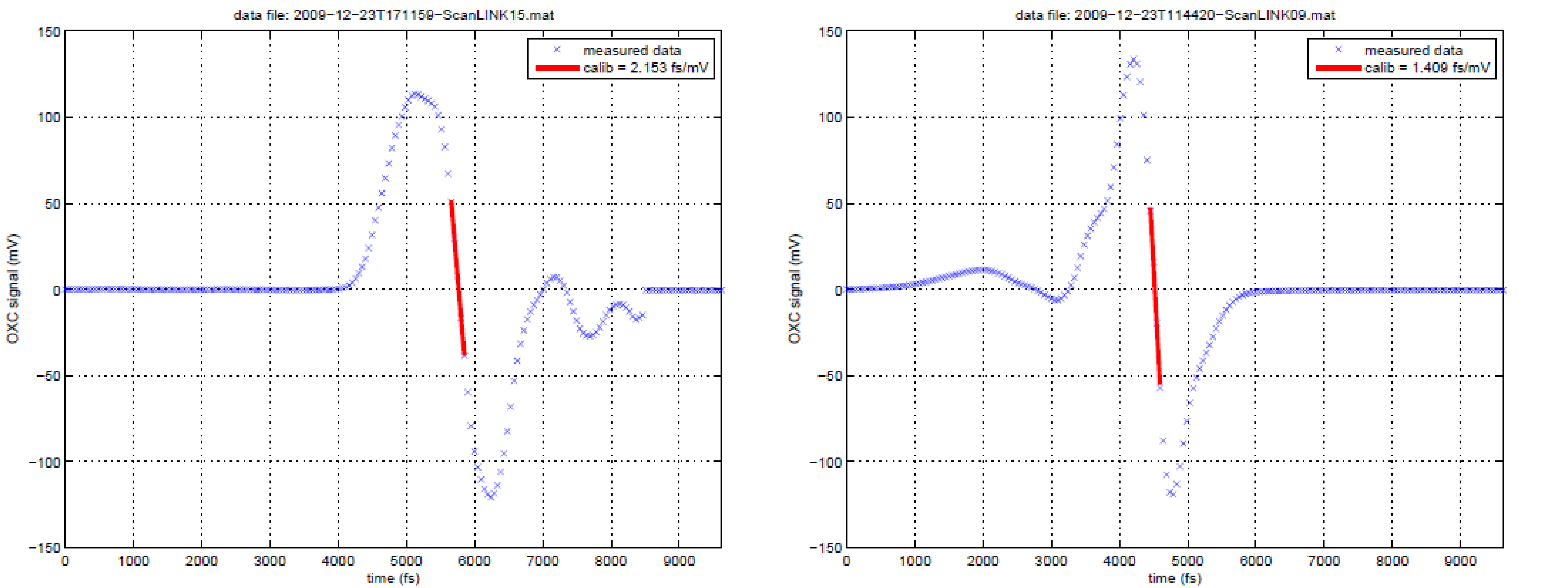


Fiber Link Stabilization: engineered version



Fiber Link Stabilization: cross-correlator

- Calibration of detector signal
  - Still varies from link to link (learning curve …)



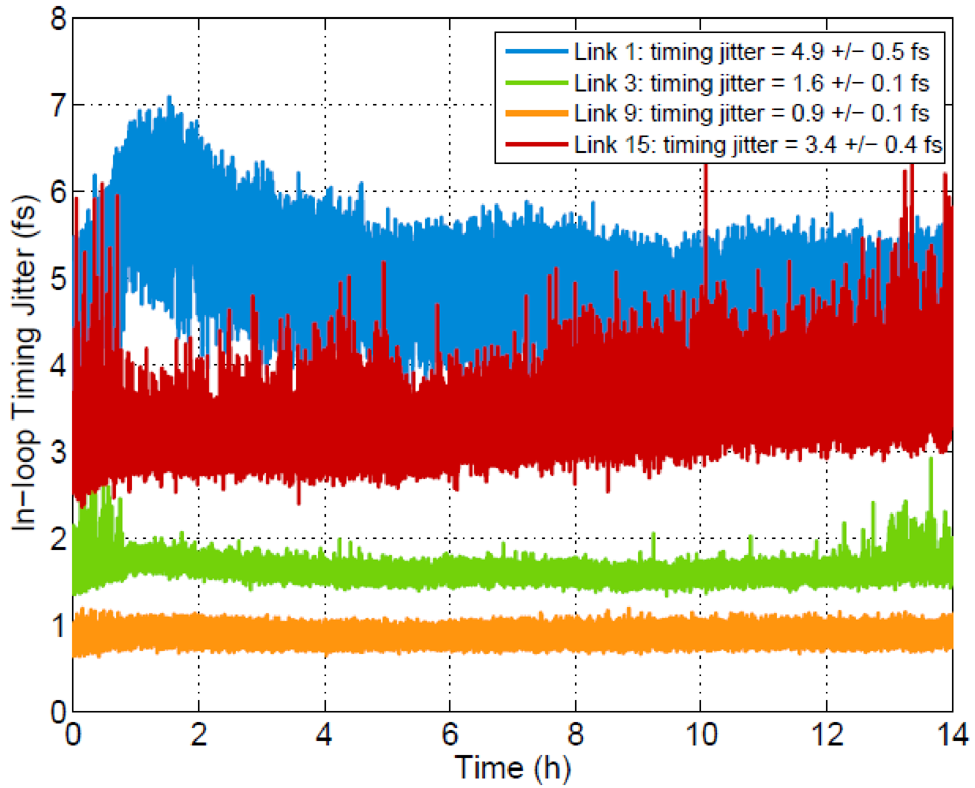
measurements: 2009-12-23

- Varies likely due to dispersion compensation & optical power achieved in link
- Calibration is used to determine remaining in-loop error

Courtesy: S. Schulz

Fiber Link Stabilization: cross-correlator

- Calibration of detector signal
  - Still varies from link to link (learning curve …)

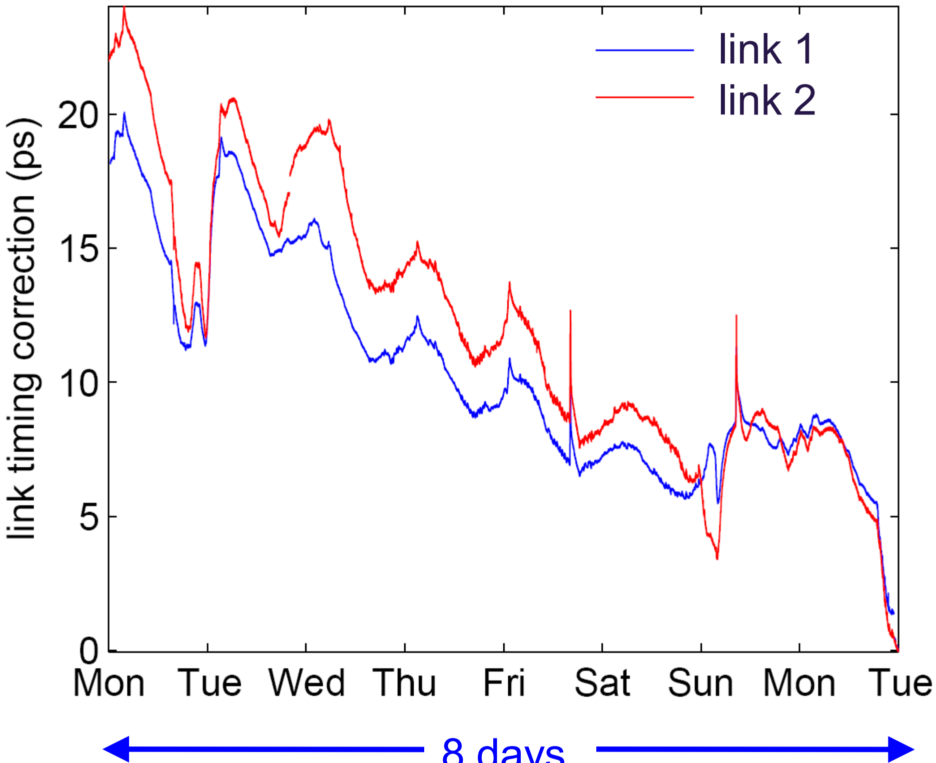


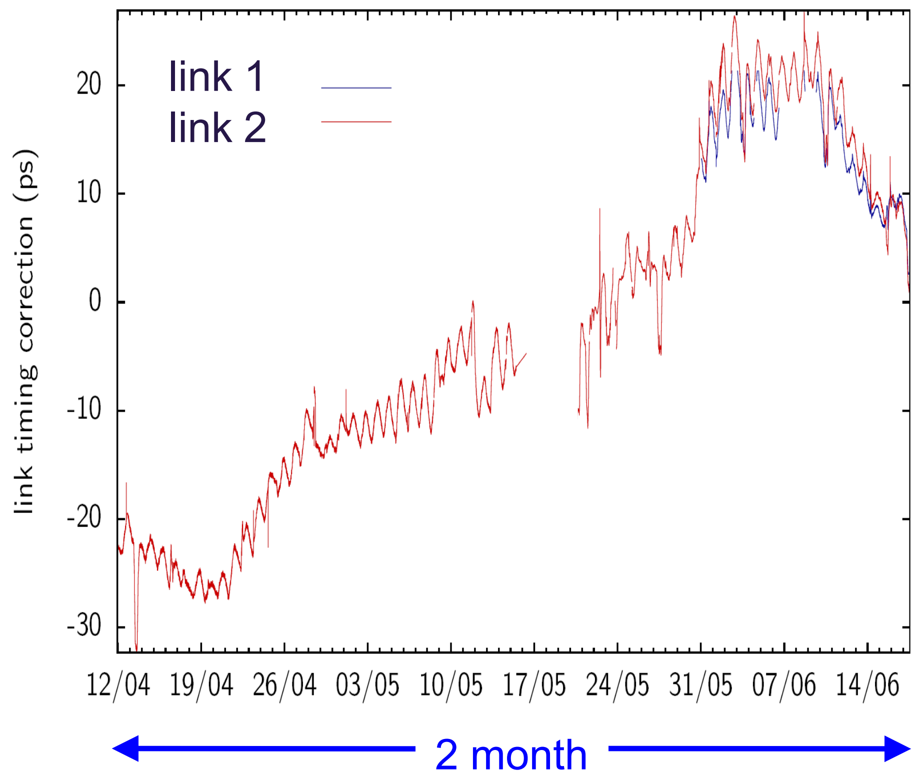
- Out-of-loop jitter cannot be determined easily
- LINK15 uses different link end configuration

Courtesy: S. Schulz

Fiber Link Stabilization: long term behavior

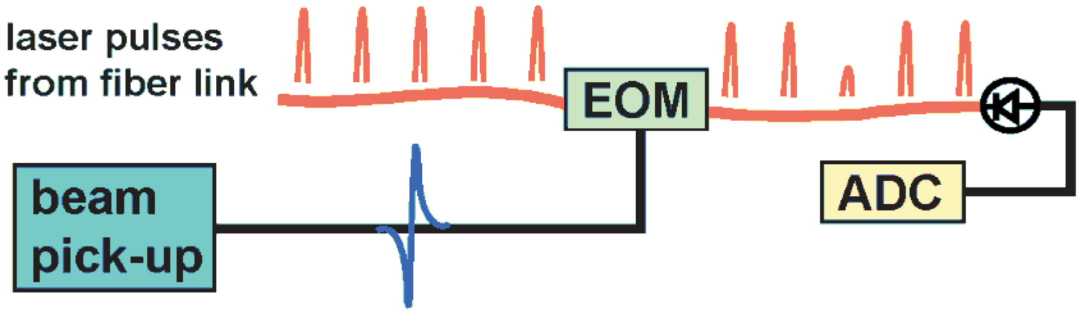
- Installation of two fiber links at FLASH
  - Much smoother correction
  - For 6 month in operation
  - Day/night periods & spring -> summer observable
  - Smooth operation (interruptions understood)

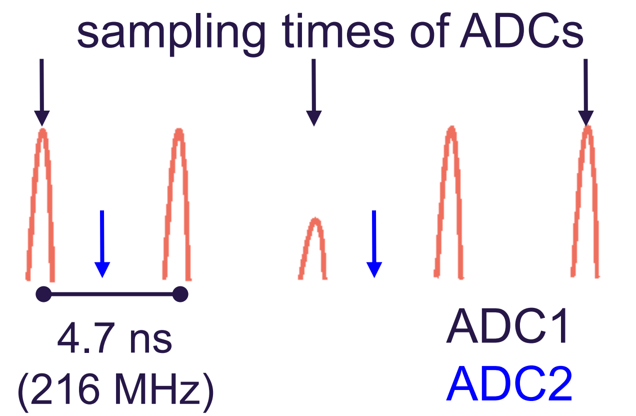




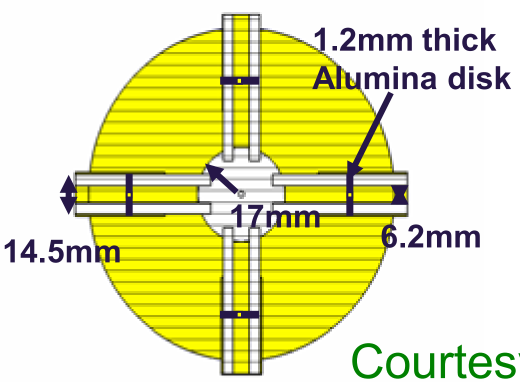
Courtesy: F. Löhl

Bunch arrival time monitor





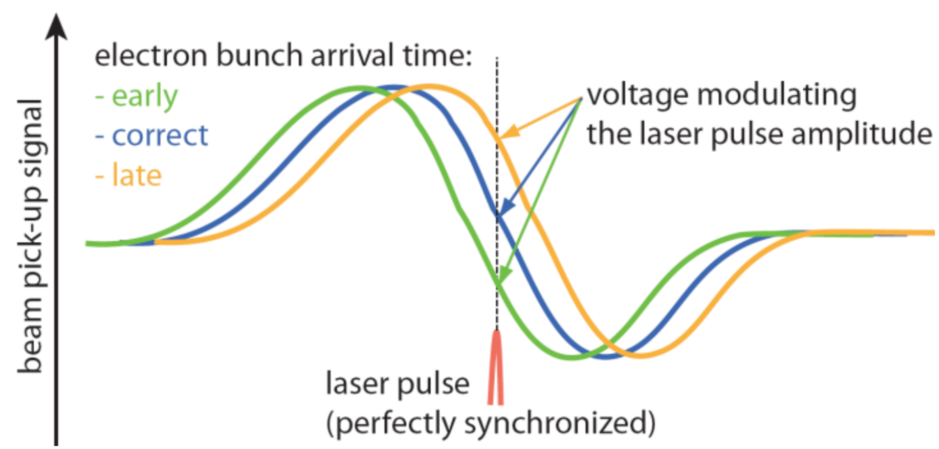
The timing information of the electron bunch is transferred into a laser amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.



New pickup design &
Improved readout

⇒ resolution < 10 fs

Courtesy: K. Hacker



Courtesy: F. Loehl

See: EPAC'06, Loehl et al., p.2781

Bunch arrival time monitor

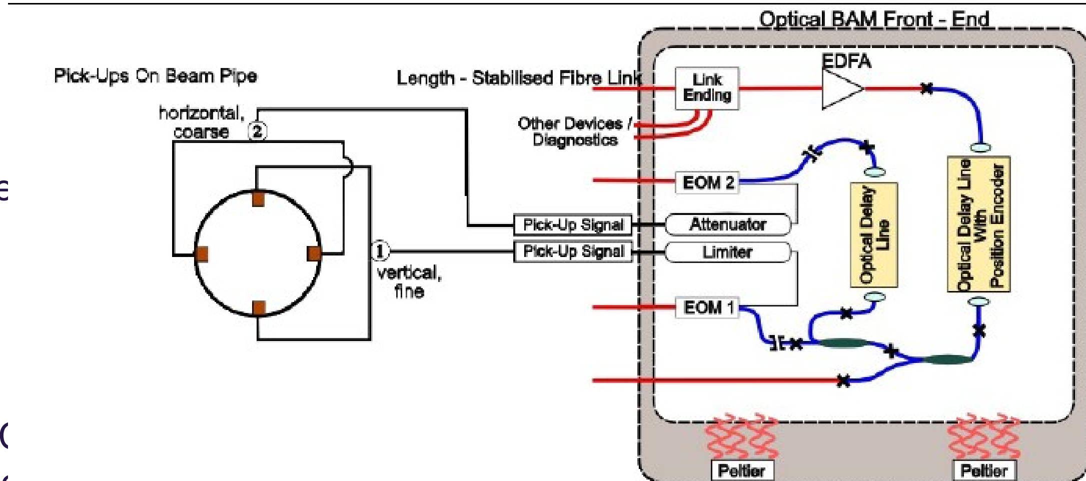
Bunch arrival time monitor (BAM)

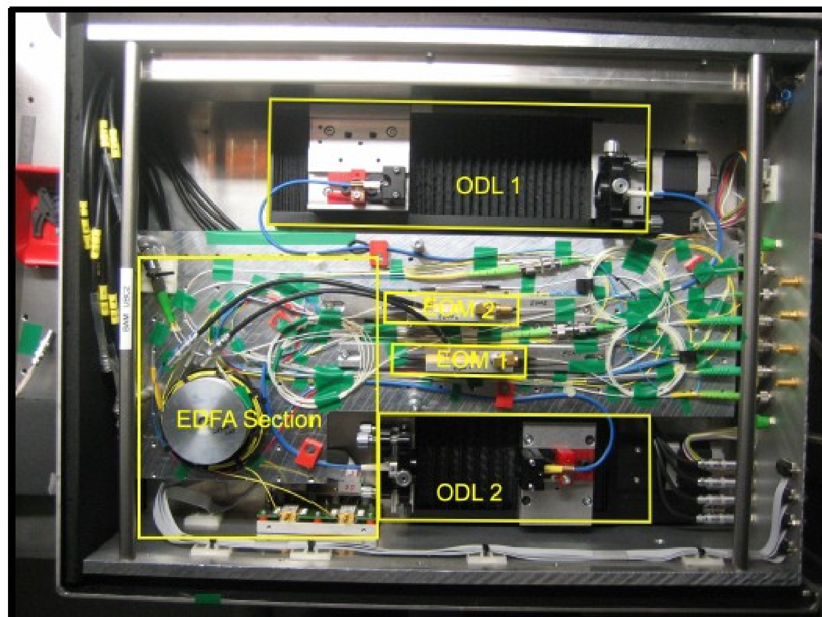
- Coarse and fine measurements
- 10GHz Mach-Zehnder interferometer
- Precision encoder + high duty cycle delay stage
- Controls: Bias, Temp. readout & regulation
- New engineered design (2^{nd} iteration)

Performance & findings:

- Typical resolution: 6-10 fs, (down to 4 fs) @ 1n
- Stable operation after establishing FB on coars
- Assembly + slicing ~ 4 weeks
- Problematic fiber management (too long fibers)
- hardware + firmware + automation software

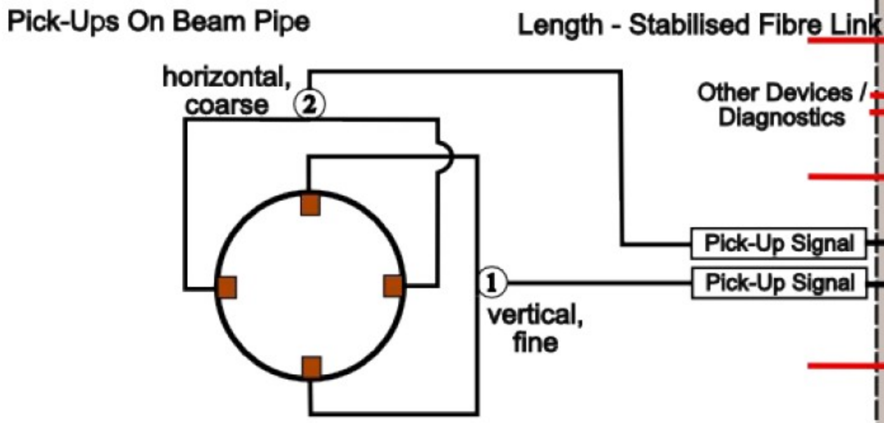
Major Changes of the Latest BAM compared to the BAMs Installed Further Downstream

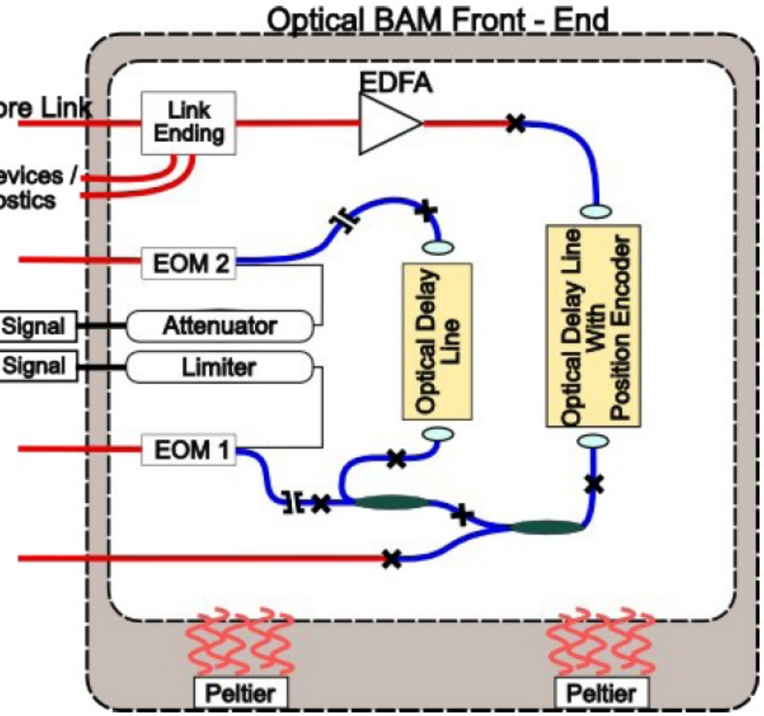


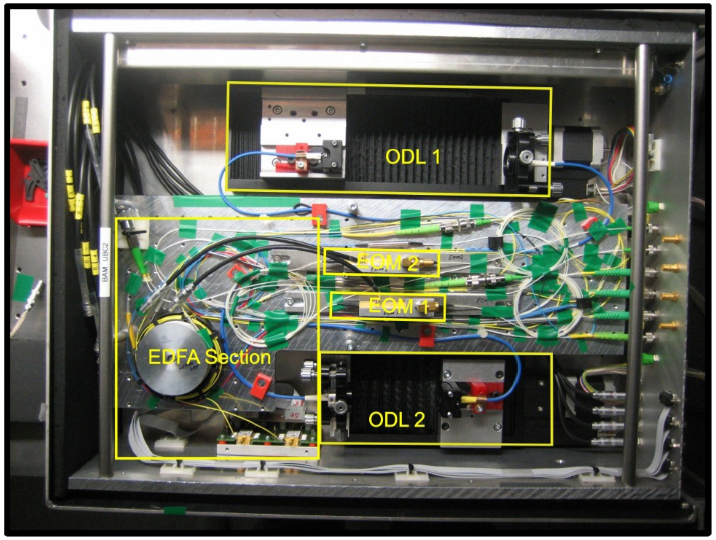


Bunch arrival time monitor

Optical front-end in accelerator tunnel



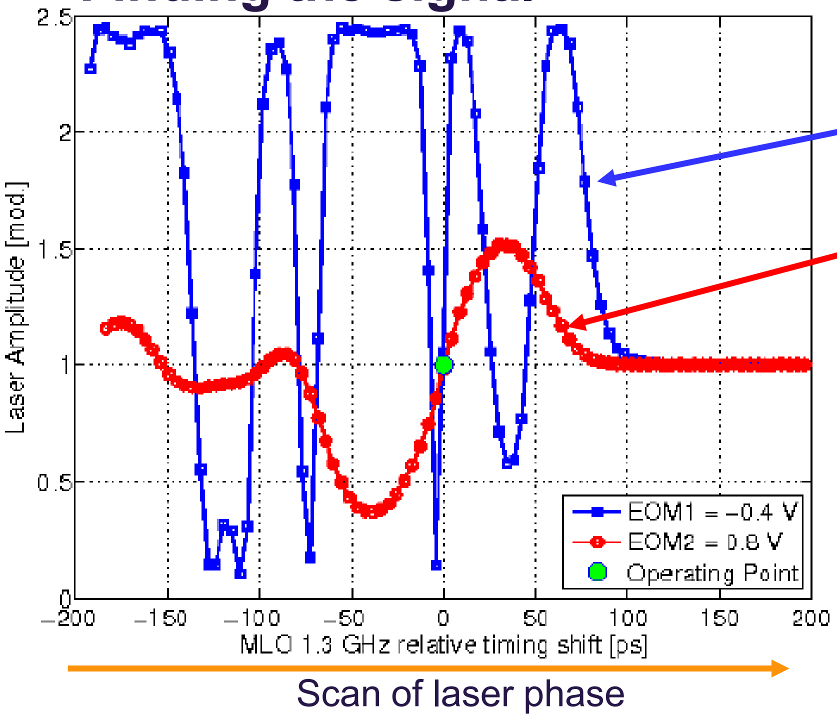




- Temperature stabilized (40mK pkpk)
- High duty cycle optical delay line
- 10GHz Mach-Zehnder modulators
- Coarse/fine channel
- Remote controlled (Bias/Temp/Motors)
- Heidnhain encoder

Bunch arrival time monitor

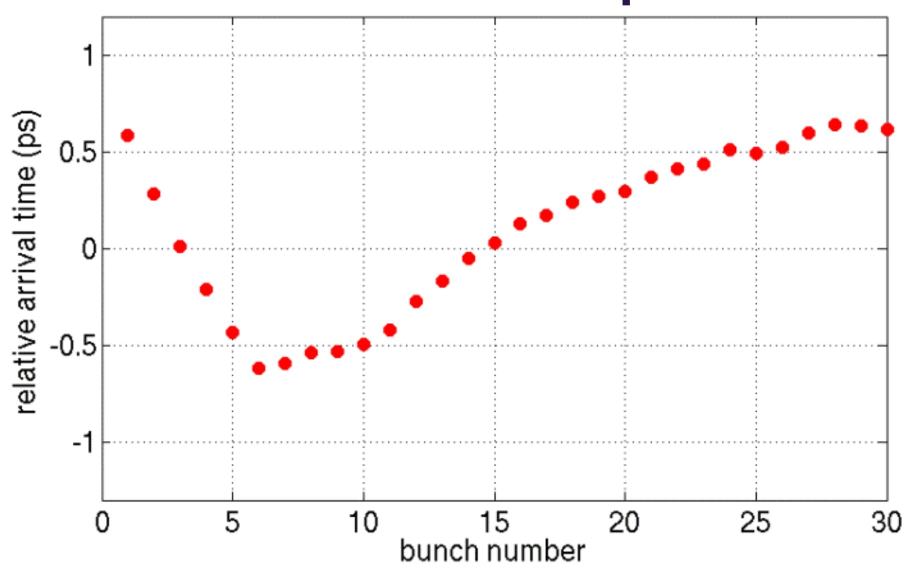
Finding the signal



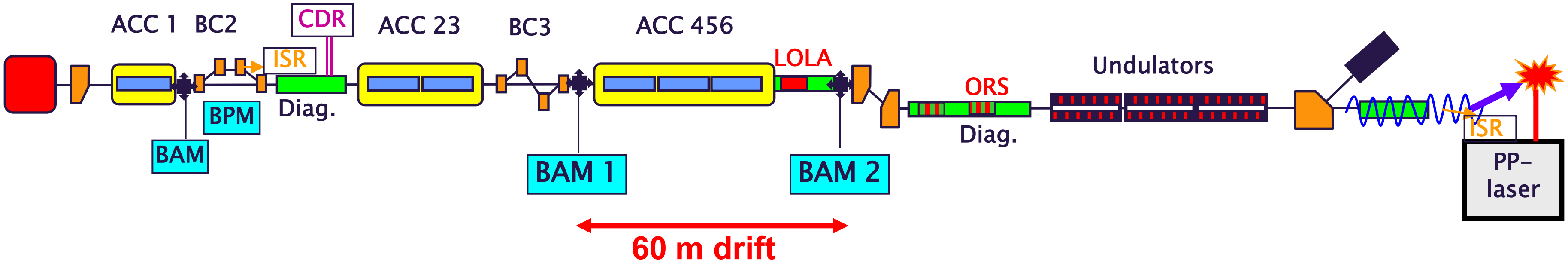
Fine channel, dynamic range ~ 4 ps, intrinsic resolution ~ 4-10fs

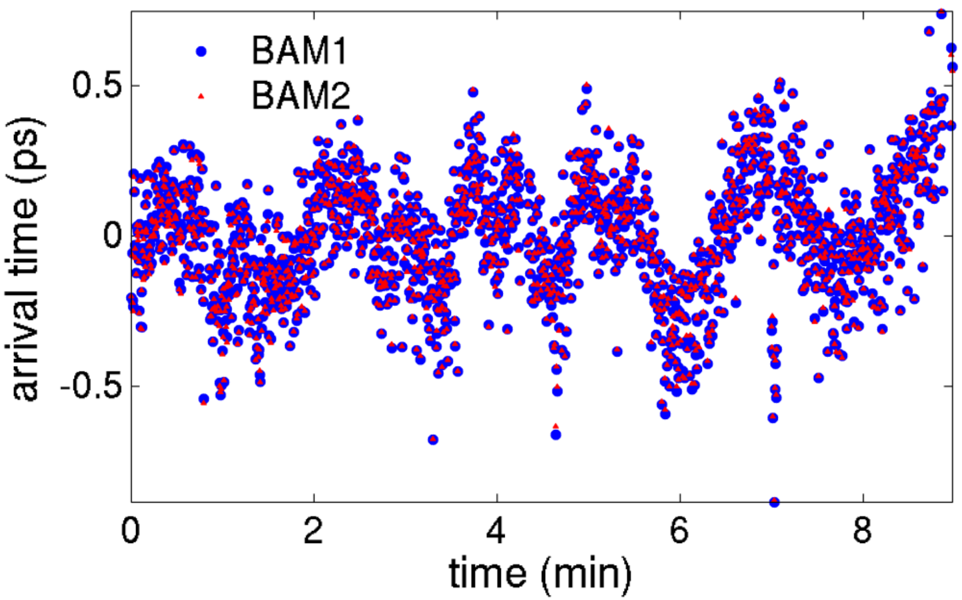
Coarse channel, dynamic range ~ 60 ps, intrinsic resolution ~ 60-100fs

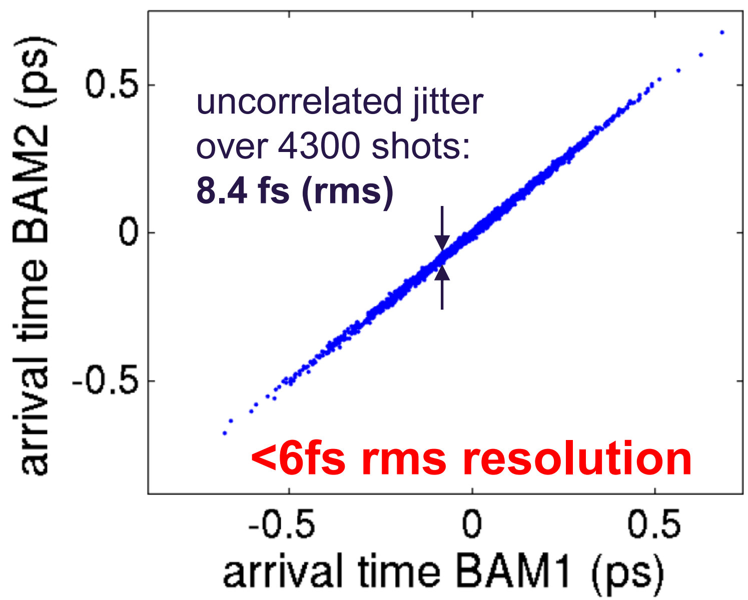
Fluctuations within pulse train



Bunch arrival-time monitor (BAM)



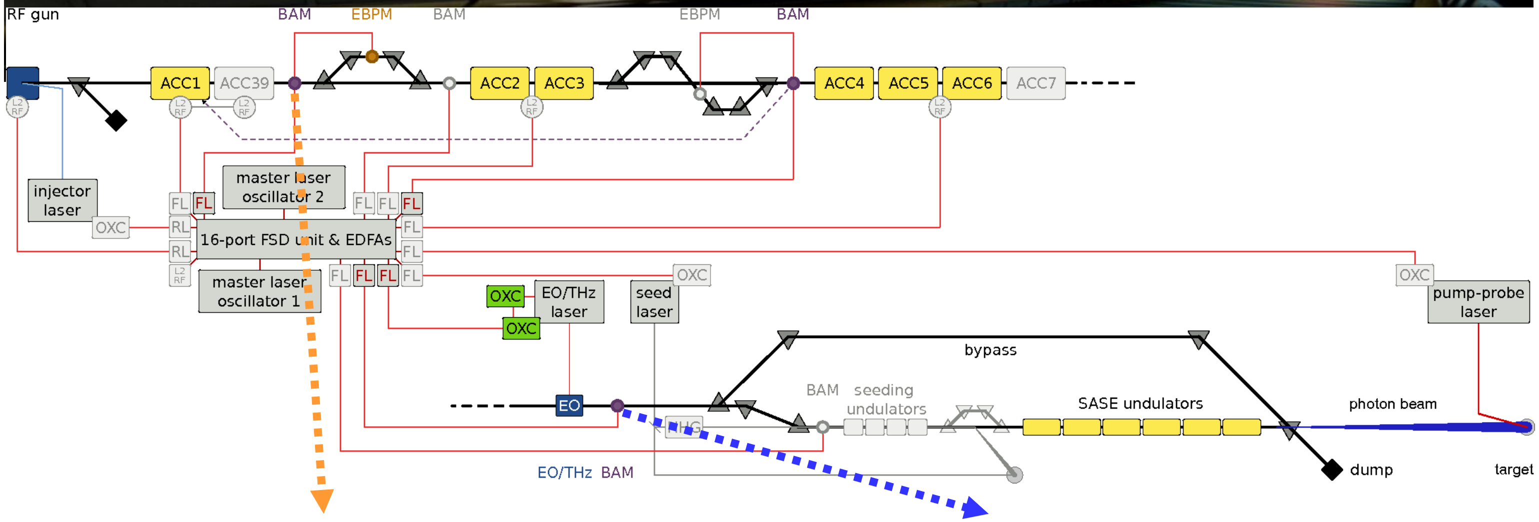




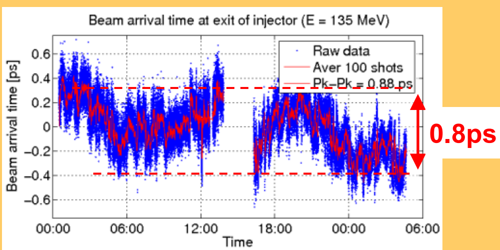
- Complete test: includes timing jitter of MLO & 2*LINK & 2*BAM
- Remark: old configuration (no distribution & bread board type LINK)

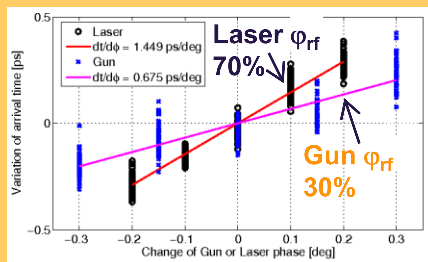
Courtesy: F. Lohl

Some measurements last user run



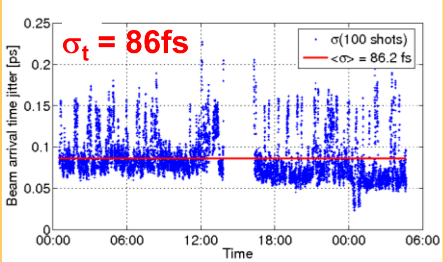
Arrival time drift & jitter from photo-injector

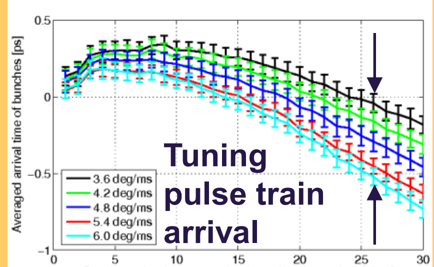




Without FB!

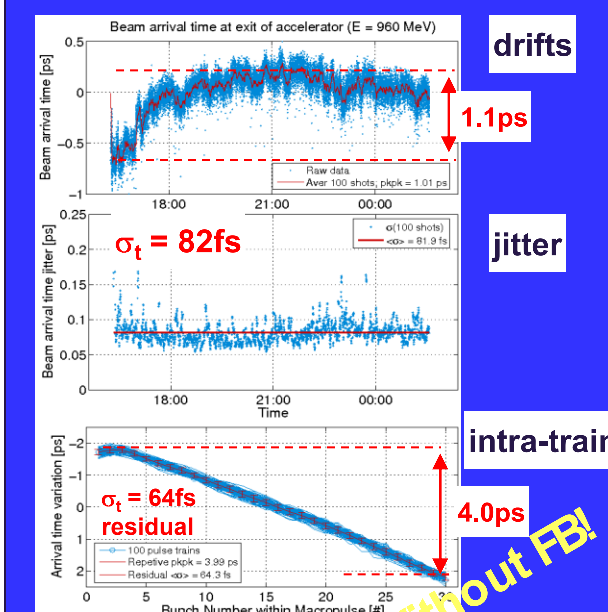
Without AFF!





For FB missing: robust exception handling

& exit of linac



300µs

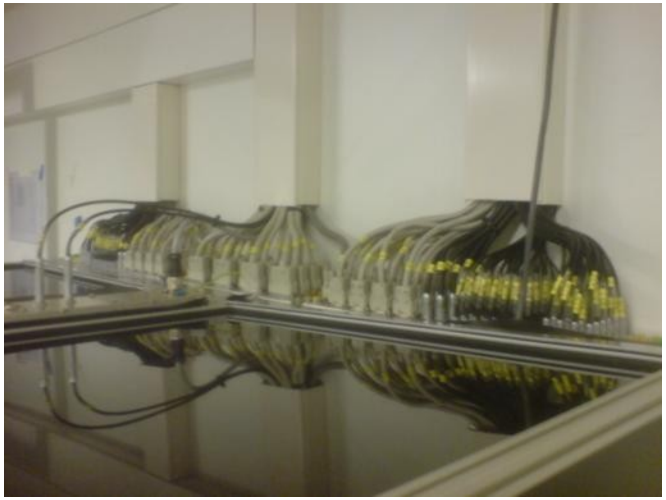
Without FB!

Infrastructure for FLASH optical synchronization

- 300 cables to optical table (including 120 signal cables)
- 58 motors
- 20. . . 24 laser diodes for MLOs and EDFAs
- 16. . . 20 piezo stretchers
- 4 VME crates (change to uTCA in planning)
- optical fibers to all critical end-stations
- 42 temperature sensors, 2 active temperature regulations
- air conditioning and option for water cooling

. . . and almost everything assembled in-house!

Status: ~ 95% done



In house electronics developments:

- VME laser diode driver (FPGA)
- VME ADCs 130MHz, 16bit
- LN Piezo driver ±300V
- DSP regulation (old)
- ADC (9MHz, 14bit)
- DAC (9MHz, 14bit)
- Vector modulator

Status: exist or in productions

Thanks for your attention