# Linac Timing, Synchronization & Active Stabilization

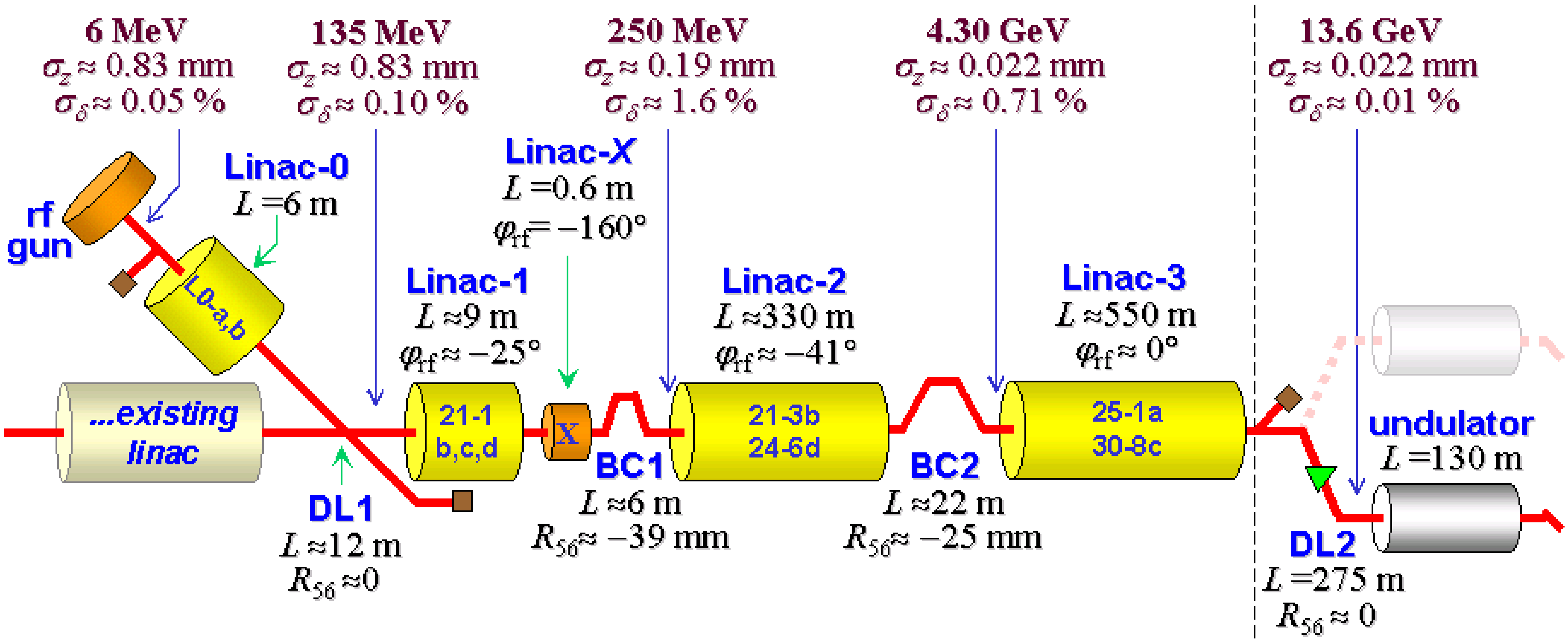
## PAC11 Conference

Florian Loehl, Cornell University

# Outline

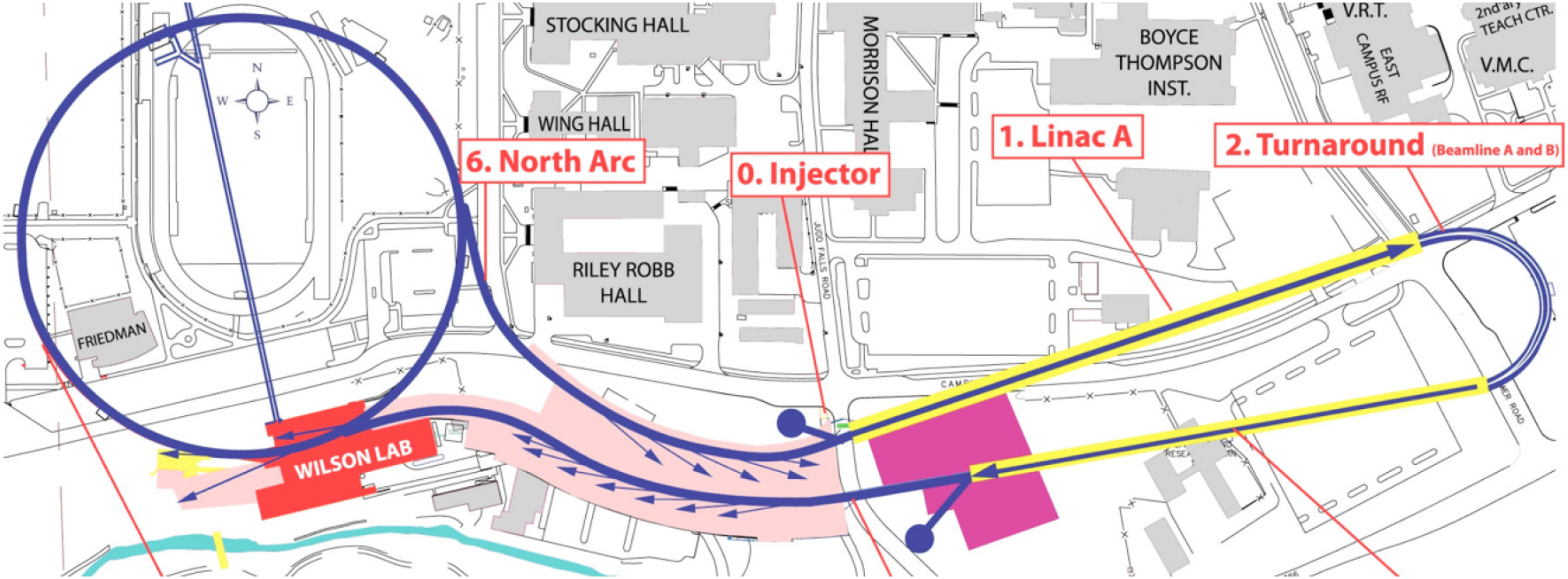
- Femtosecond timing needs in linear accelerators
- Femtosecond stable…
    - …Timing signal distribution
    - …RF signal generation
    - …Laser synchronization
    - …Electron bunch arrival-time detection
    - …Electron bunch shape detection
    - …Active bunch arrival-time and shape stabilization
    - …Photon pulse arrival-time detection

# High gain FEL facilities, like the LCLS



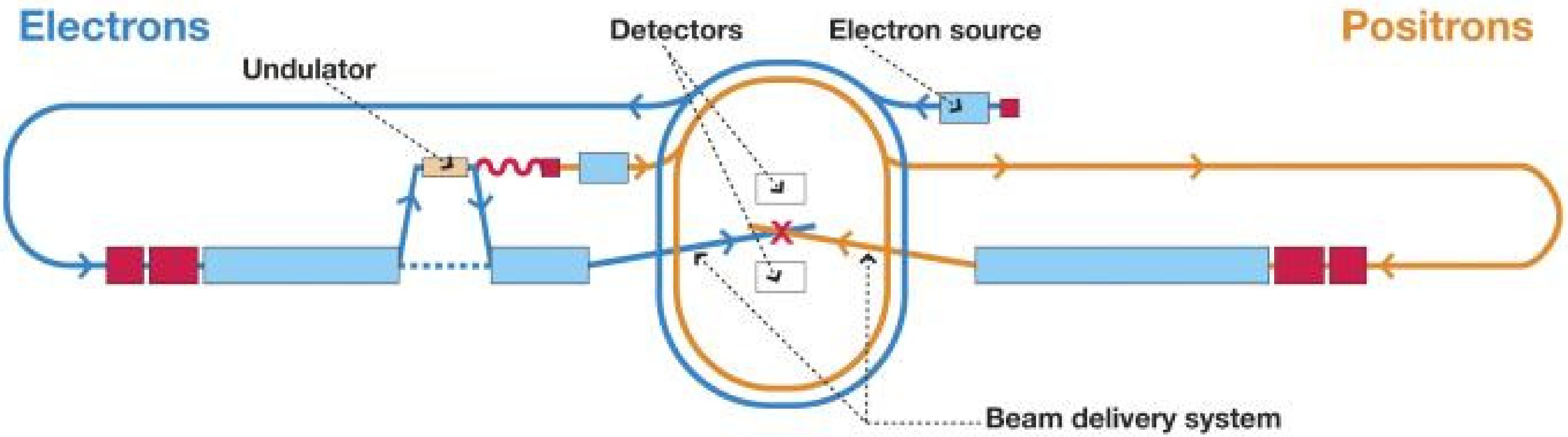
# Linear Accelerators

## ERL facilities, like the Cornell ERL project



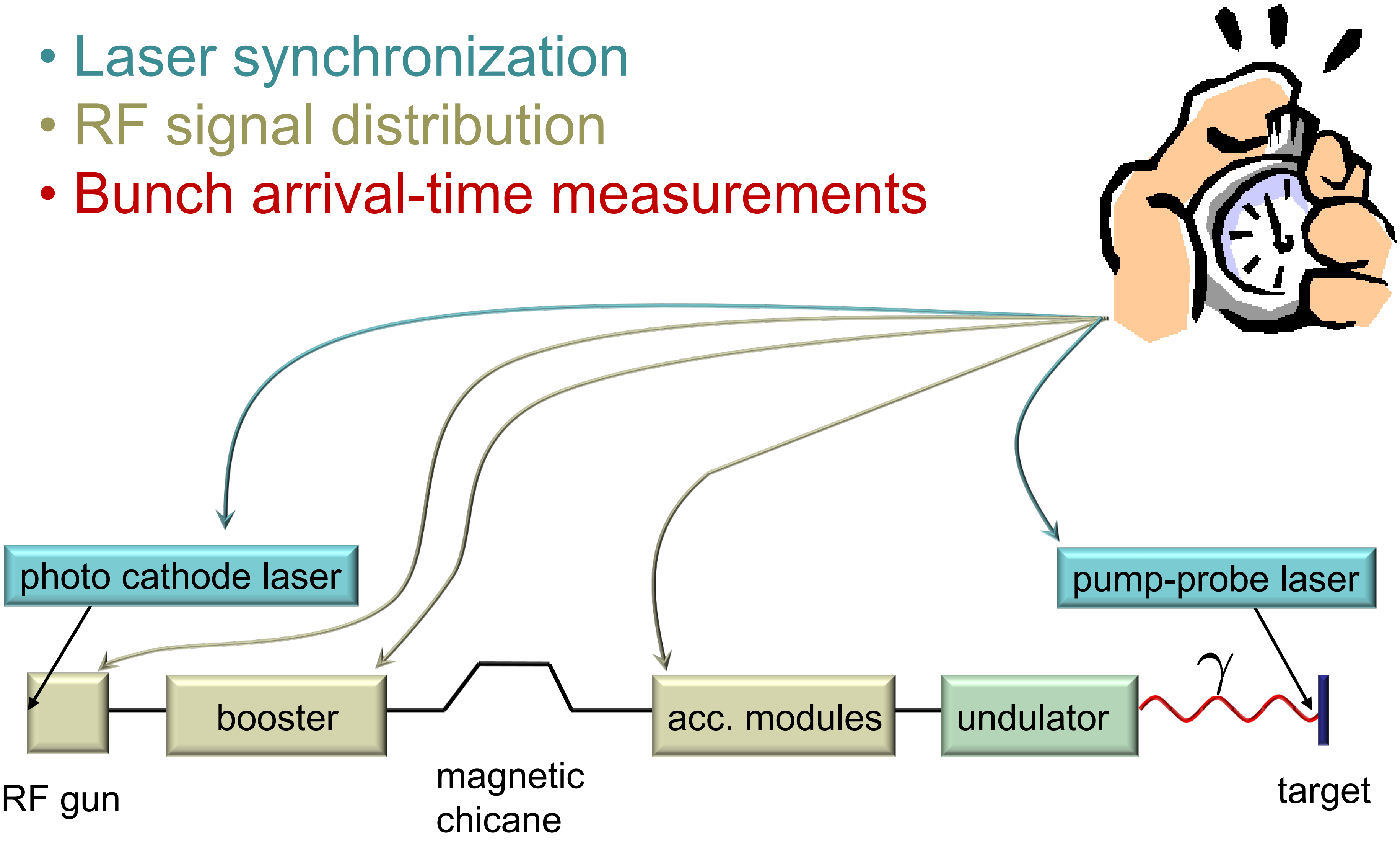
# Linear Collider Projects: ILC & CLIC

## International Linear Collider



# Timing Needs in an X-ray FEL

- Laser synchronization
- RF signal distribution
- Bunch arrival-time measurements



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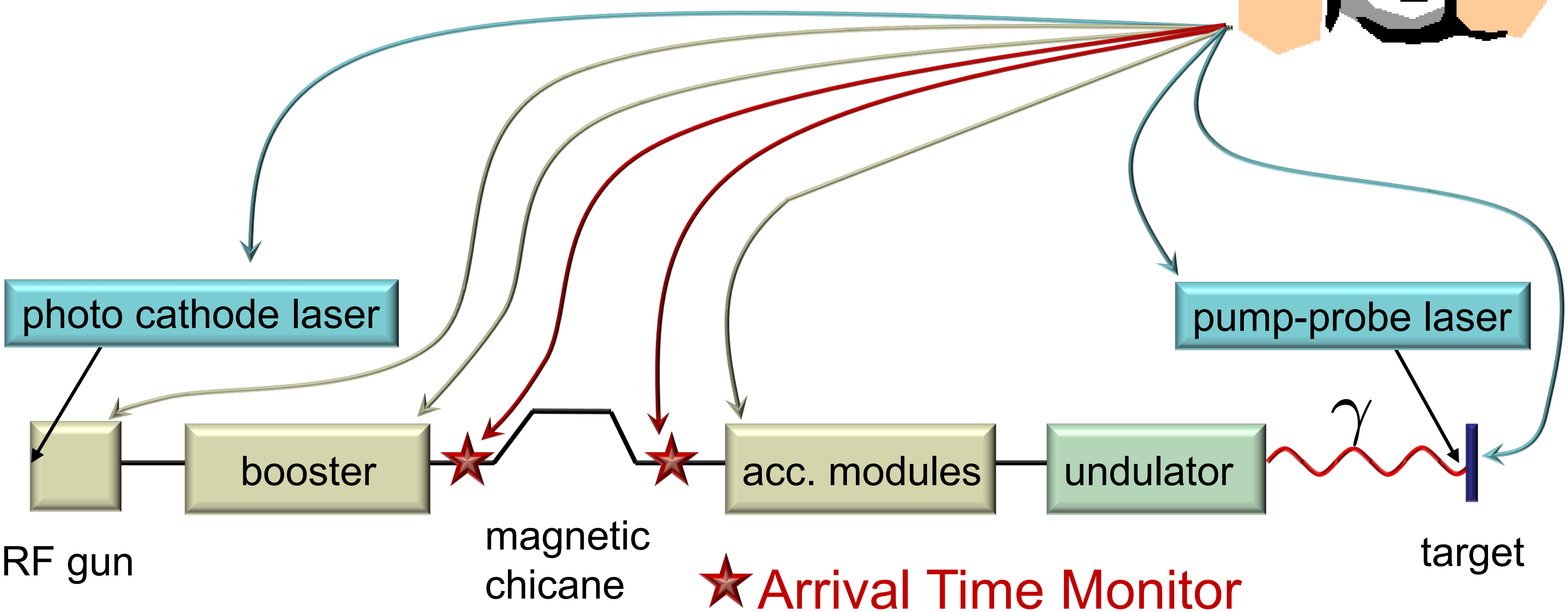

# Timing Needs in an X-ray FEL

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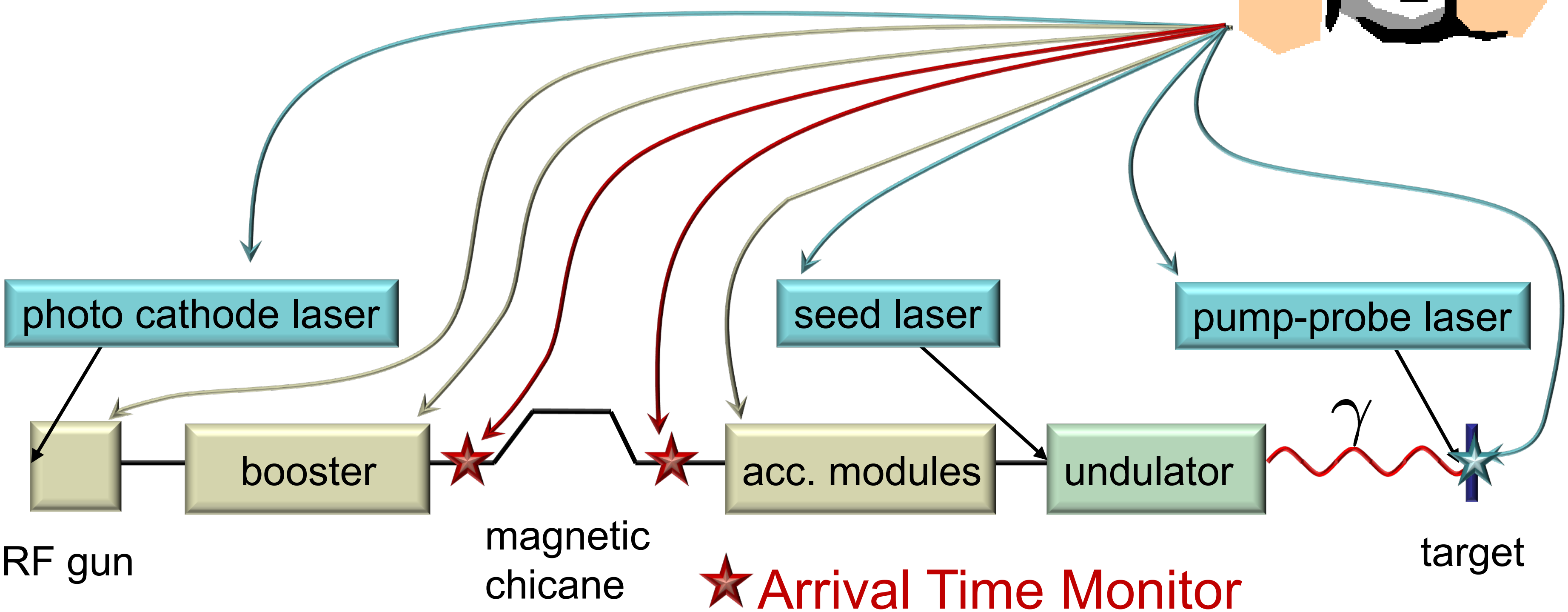





Florian Loehl (Cornell University)
Particle Accelerator Conference 2011 (PAC11)
New York City, USA

# Timing Needs in an X-ray FEL

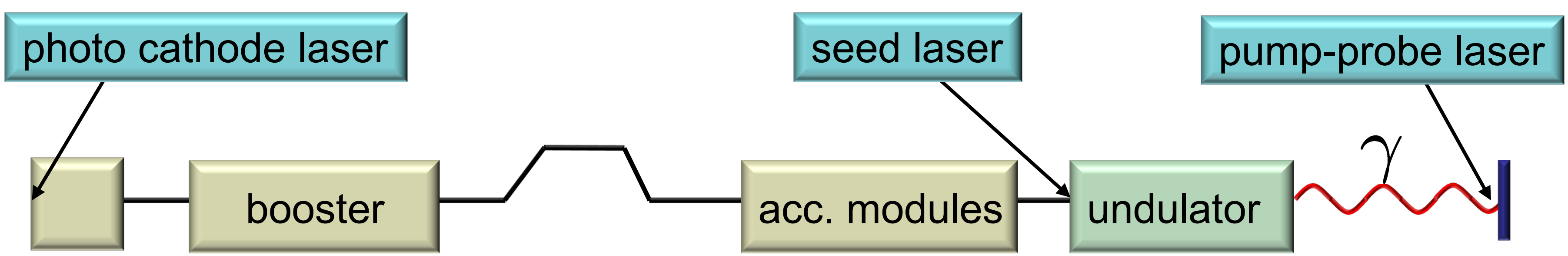
## Which level of accuracy is required?

Ultimate goal:

Arrival-time stability between x-ray pulses and pump-probe laser pulses: fraction of pulse duration

$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{2\pi f_{\mathrm{RF}}}\right)^2 + \left(\frac{1}{C}\right)^2\Sigma_{i,t}^2$$

- $\Sigma_t^2$: timing jitter after compressor
- $\sigma_A / A$: cavity field amplitude jitter
- $\sigma_\phi$: cavity phase jitter
- $\Sigma_{i,t}^2$: injector timing jitter



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Resulting requirements for 10 fs arrival-time stability with FLASH parameters ($R_{56} \approx 180$ mm, $f_{RF} = 1.3$ GHz)

| | |
|---|---|
| $< 1.5\mathrm{x}10^{-5}$ | field amplitude stability of vector sum |
| $< 0.005^{\circ}$ | phase stability of vector sum |

See DESY-TESLA-FEL-2009-08 for detailed timing jitter analysis for FLASH



# Additional Challenges & Differences in X-Ray ERLs and a Linear Collider

**Ultra-short pulse mode in x-ray ERLs:**

- Significant higher repetition rate (~GHz)
  - → Beam stabilization mandatory (instead of just measuring timing variations)
  - → Beam arrival-time monitors can average over many bunches
- A bunch compression at full beam energy leads to a significant larger number of cavities upstream of the bunch compressor

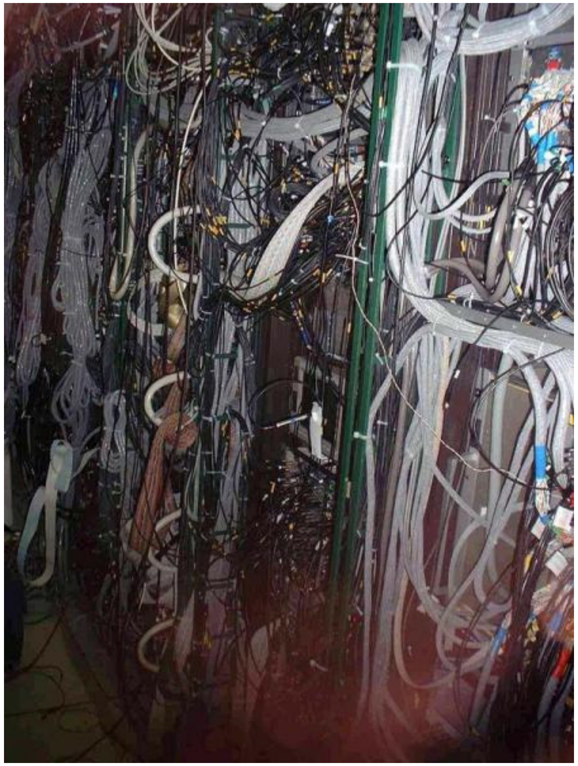
**Linear Collider:**

- Very long distribution distances (tens of kilometers)
- Very large number of cavities
- Timing requirements driven by luminosity loss & requirements can be as tight as in FELs

See, e.g.: D. Schulte and R. Tomas, “Dynamic effects in the new CLIC main linac”, PAC 20009



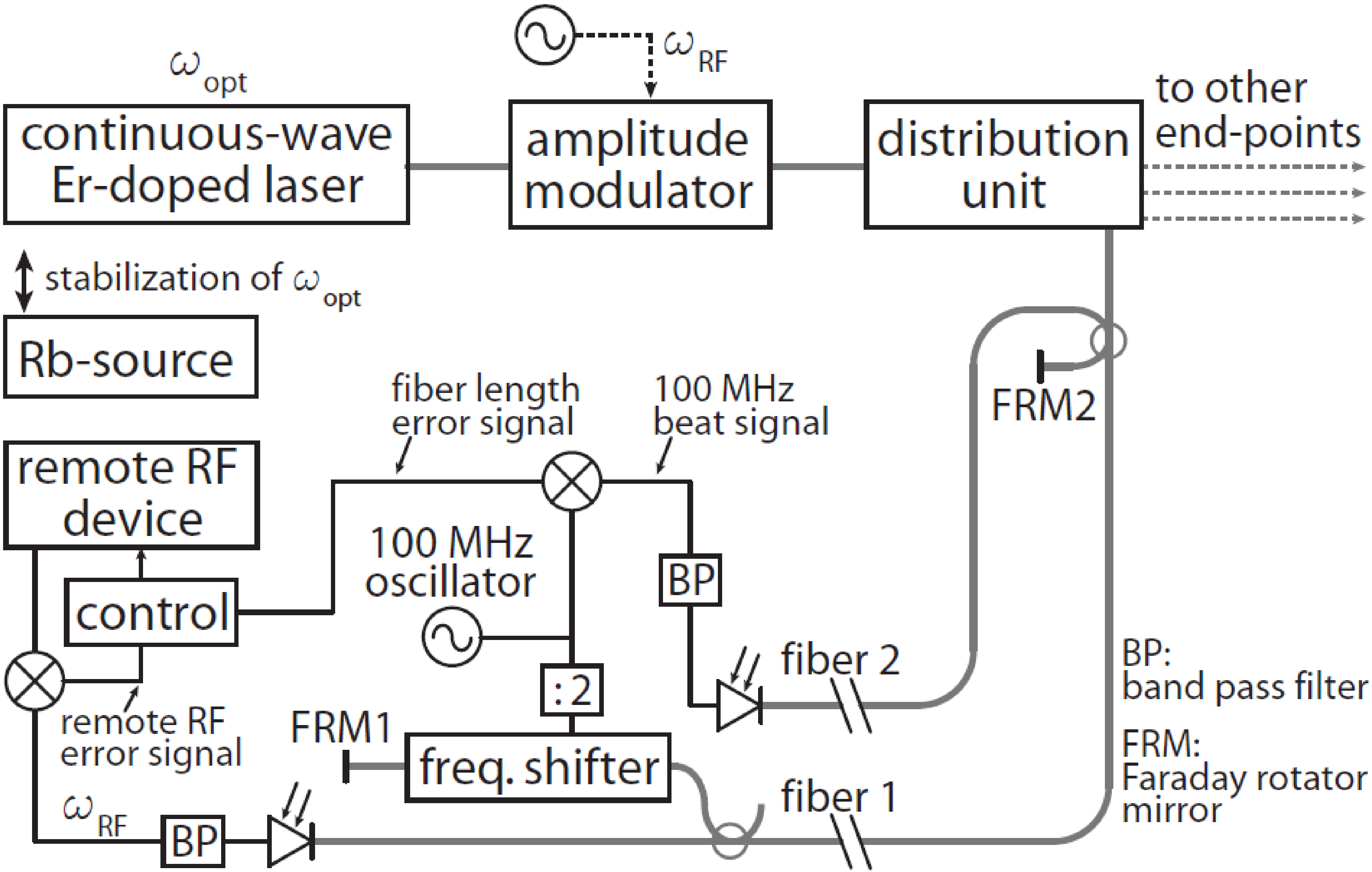
# Optical synchronization schemes
→ Lower transmission loss
→ Higher resolution timing detection



# Femtosecond Stable Timing Distribution CW & Pulsed

<table>
<tr><th>CW</th><th>Pulsed</th></tr>
<tr><td>Transmission of ‘single’ frequency laser light</td><td>Transmission of ~100 - 200 fs long laser pulses</td></tr>
<tr><td>Interferometric stabilization of an optical fiber</td><td>Stabilization of an optical fiber based on cross-correlation techniques</td></tr>
<tr><td>Transmission of RF signal through stabilized optical fiber (by modulating laser amplitude)</td><td rowspan="2">After transmission fiber:<br>• generation of RF signals<br>• direct use of laser pulses for laser based diagnostics / experiments<br>(e.g. bunch arrival-time measurements, beam position measurements, RF phase measurements, …)<br>• locking of lasers by cross-correlation</td></tr>
<tr><td>After transmission fiber:<br>• extraction of RF signal<br><br>WEOBS2</td></tr>
<tr><td>stability: < 10 fs</td><td>stability: < 10 fs</td></tr>
</table>

# CW Optical Synchronization Scheme

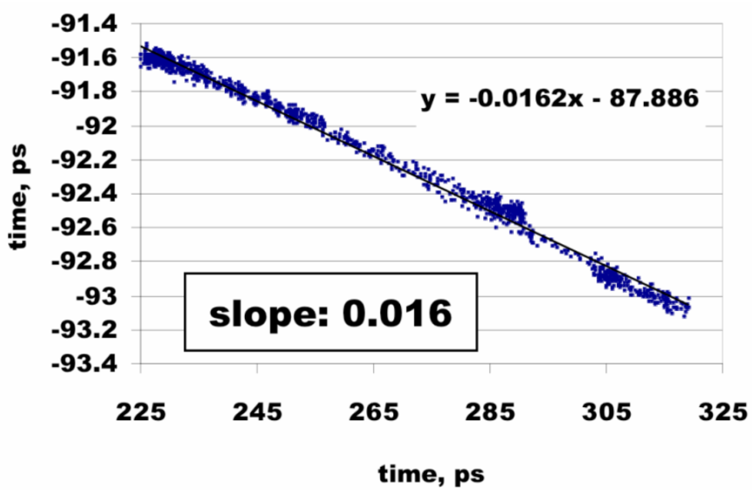


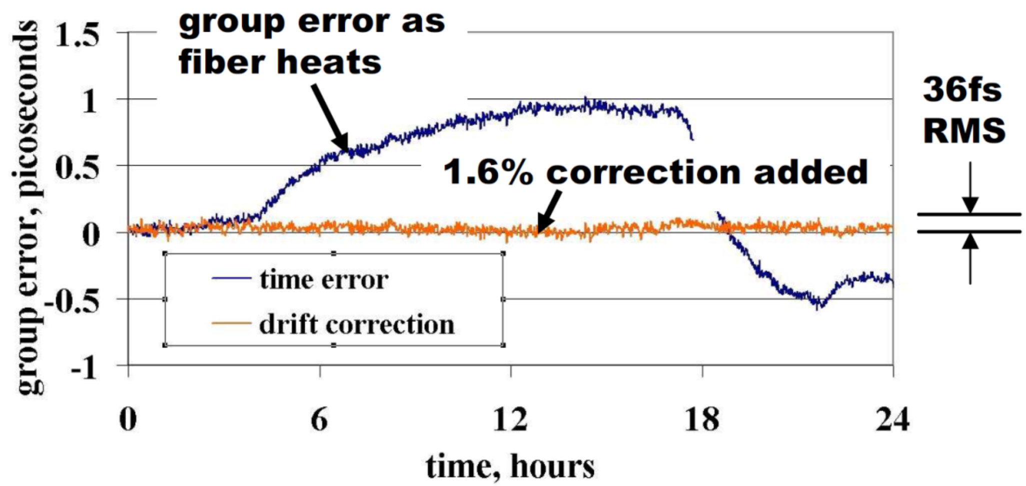

BP: band pass filter

FRM: Faraday rotator mirror

# CW Optical Synchronization Scheme

Difficulty: (temperature dependent) difference between the phase velocity of the optical carrier frequency and the group velocity of modulated RF signal

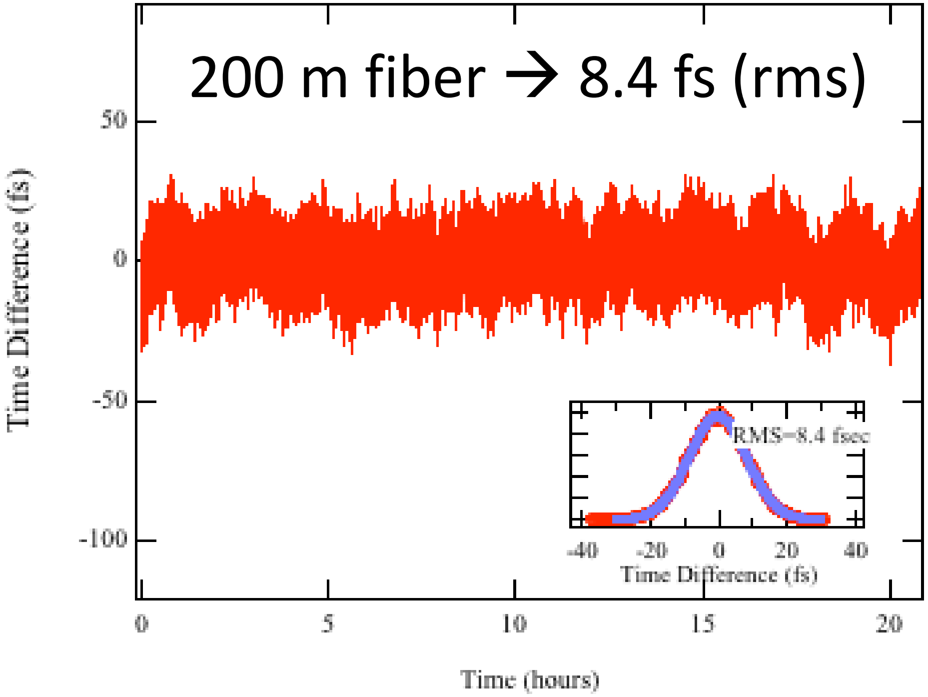


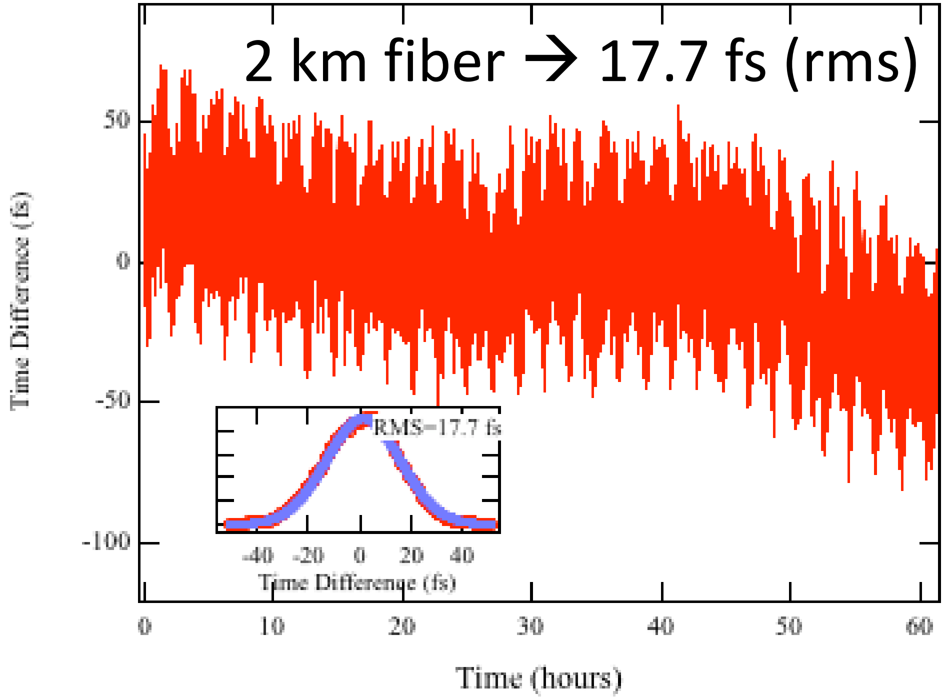




→ Additional feed-forward term added in digital controller to correct for this.

data from R. Wilcox et. al. (Berkeley synchronization team)

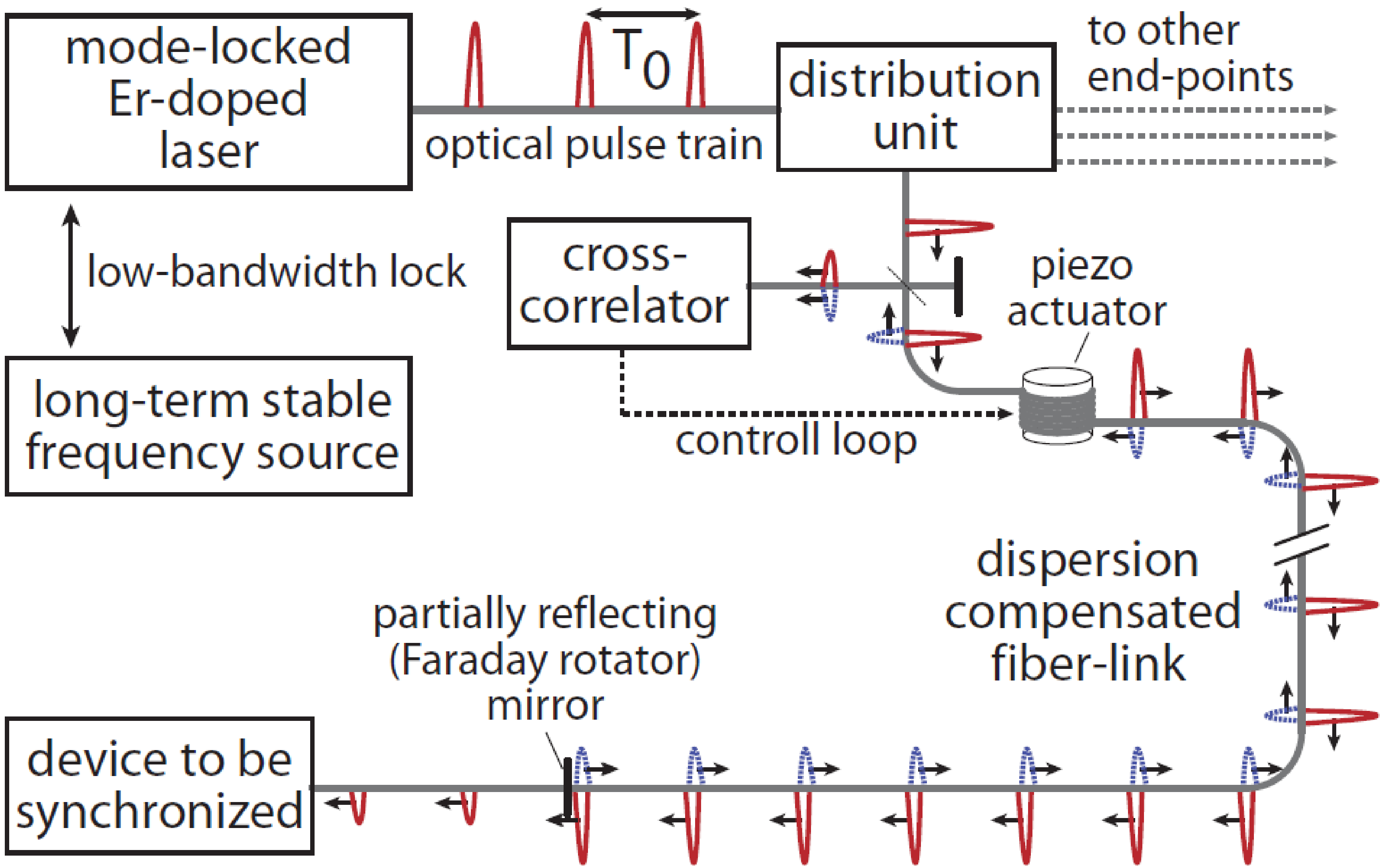
# Stability of RF signal transmission:



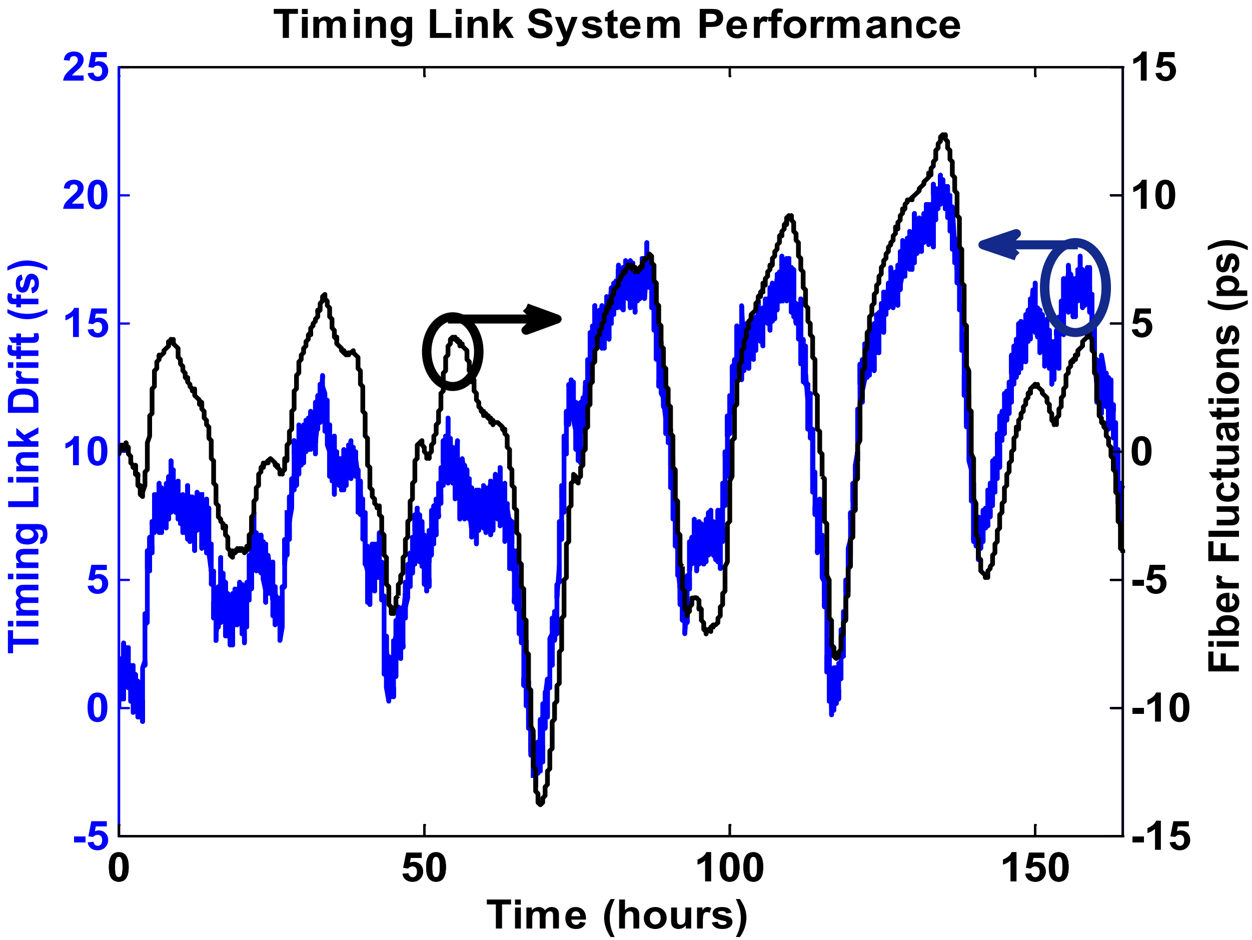

R. Wilcox et. al., Opt. Lett. **34**, 20, pp. 3050-3052 (2009)

# Pulsed Optical Synchronization Scheme
# Fiber Link Stabilization



# Pulsed Optical Synchronization Scheme
# Fiber Link Stabilization (with add. polarization control)

5 fs (rms) drifts over one week of operation

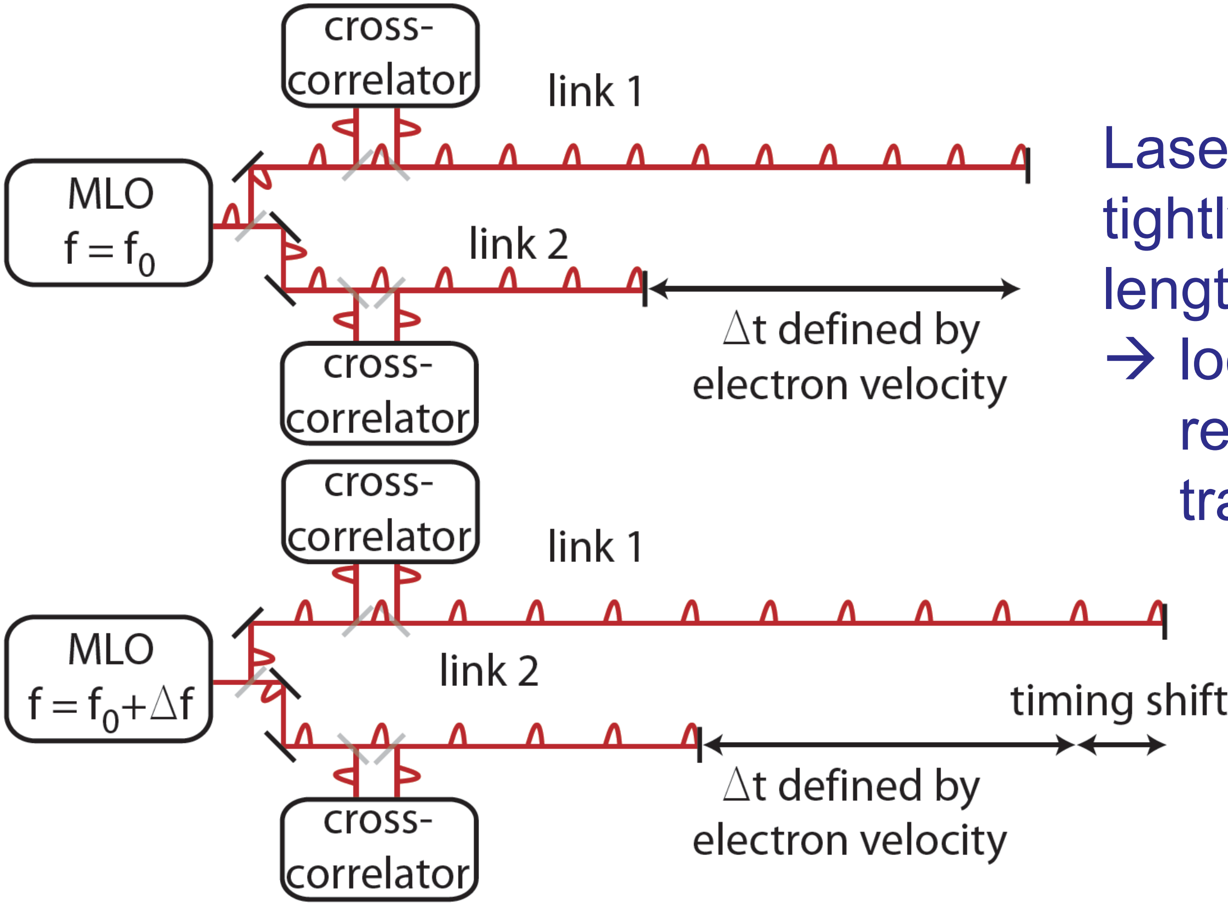



Similar links deployed at FLASH, DESY

5-link system installed at FERMI @ Trieste, 10 days < 10 fs (rms) (IdestaQE and Menlosystems GmbH)

Courtesy of F. X. Kaertner, MIT & CFEL

# Required Frequency Stability of Reference Laser (valid for pulsed & CW scheme)



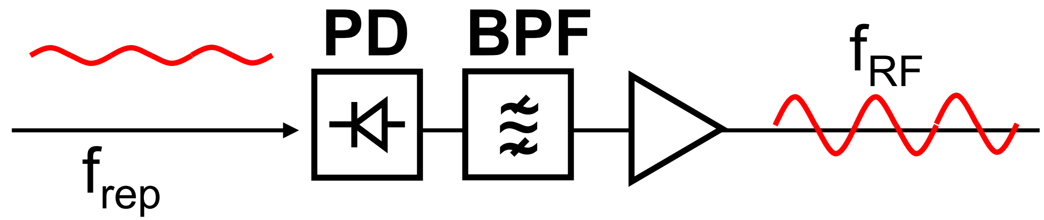

$$\frac{\Delta L}{L_0} \approx -\frac{\Delta f}{f_0}$$

Laser frequency has to be tightly controlled for long link lengths!

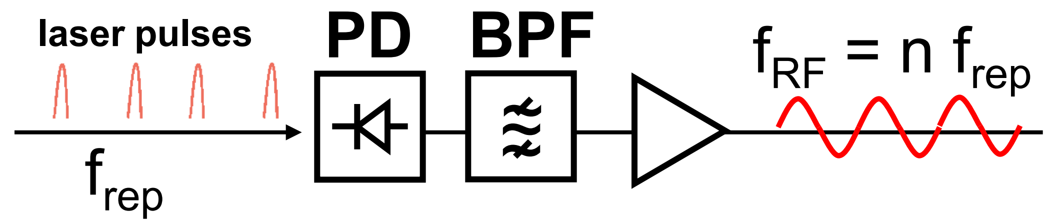
→ locking of laser frequency repetition rate to Rb-transition (or similar)

# (Simple) RF Signal Generation

CW scheme:




Pulsed scheme:




Can deliver sub-10 fs stability for both systems.

Difficulty: RF phase shifts when optical power changes!

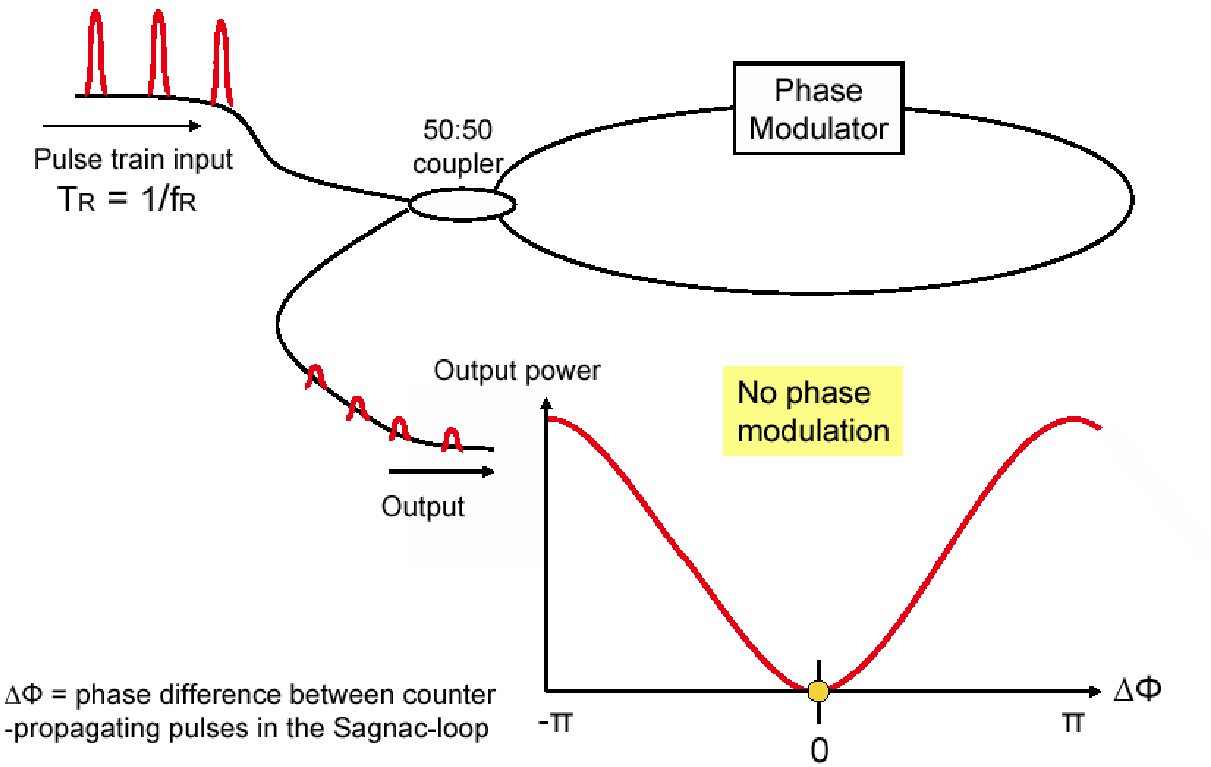
→ Utilize well selected photo diodes

→ Operate photo detectors at optical power where shift is minimum

Alternative: Use more robust RF generation scheme

# RF signal generation and probing

Phase detection in the optical domain:




Courtesy of J. Kim (MIT)

# RF signal generation and probing

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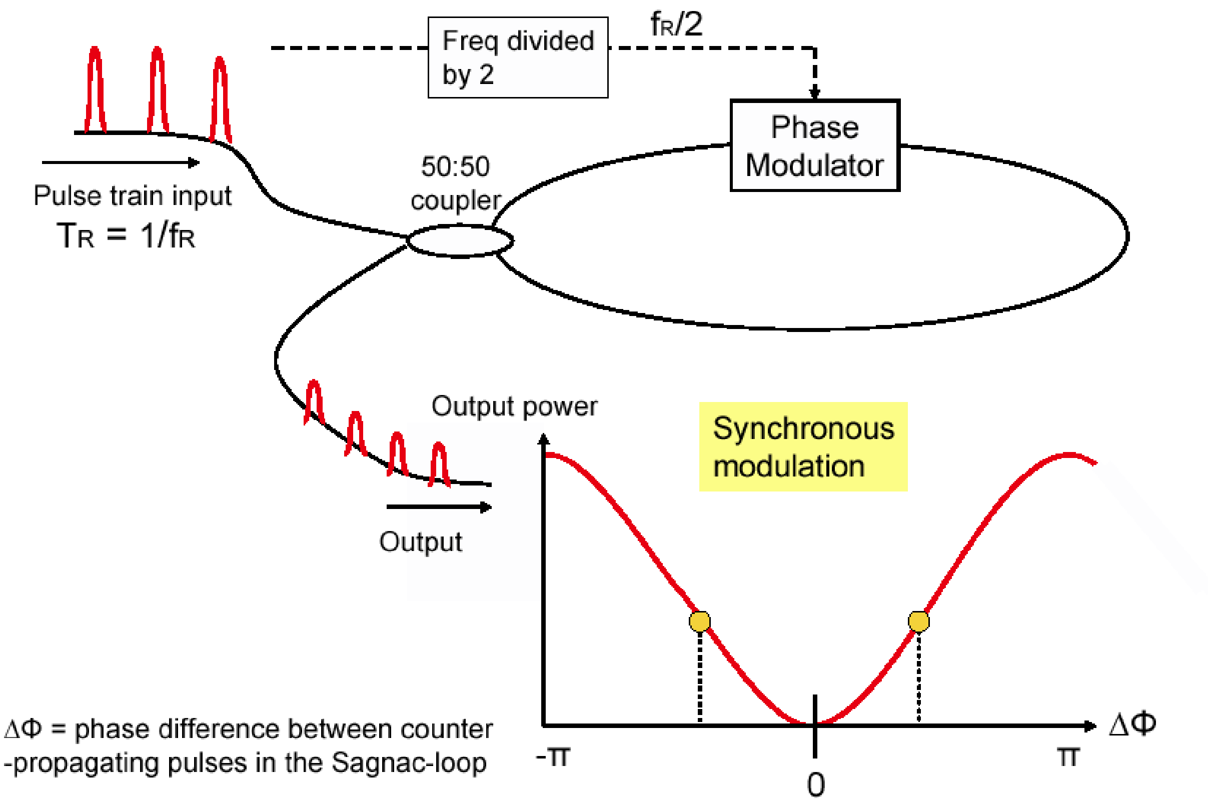


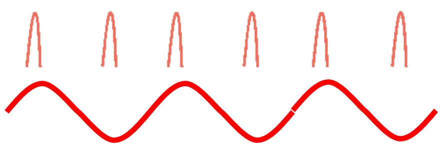

modulation voltage: $f_{rep}$ / 2

Courtesy of J. Kim (MIT)

# RF signal generation and probing

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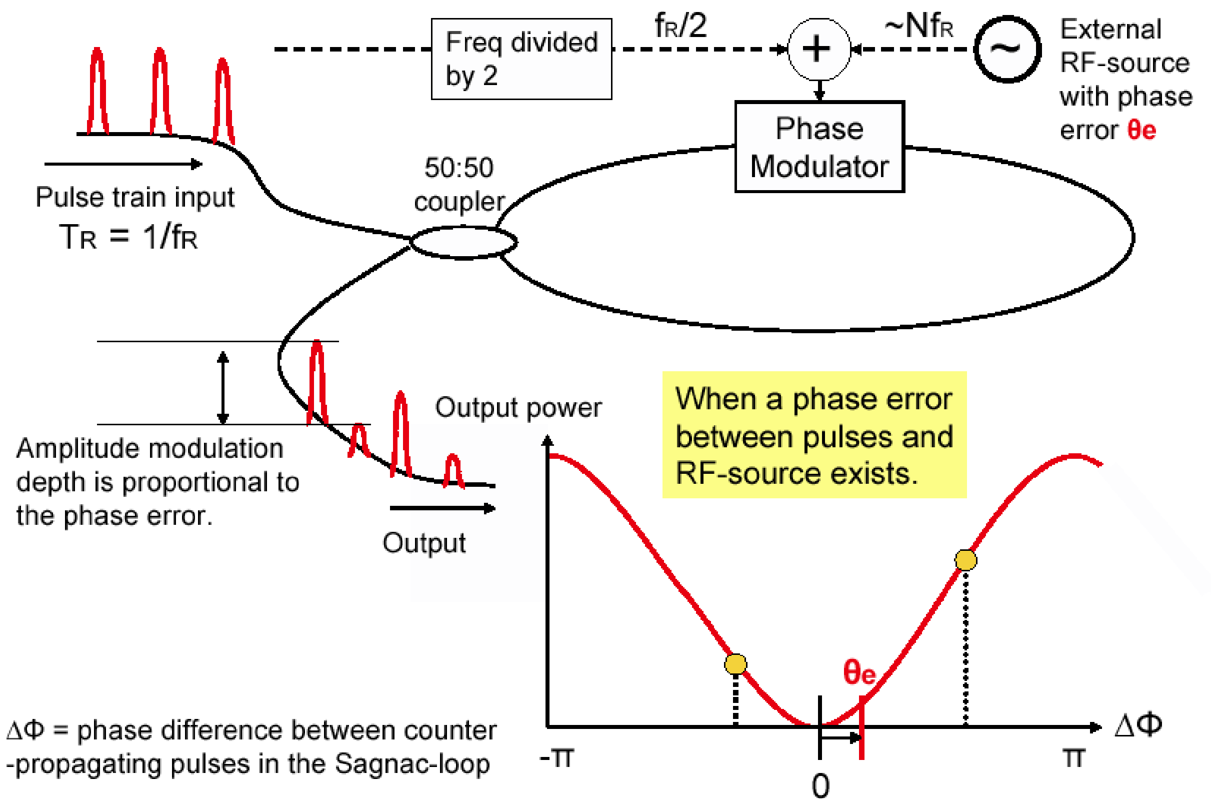
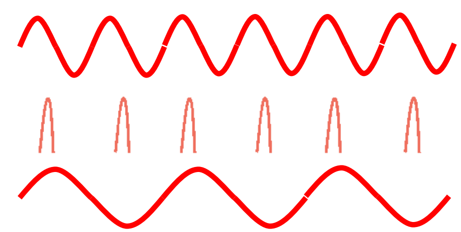



VCO signal to stabilize ($n^*f_{rep}$)



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Courtesy of J. Kim (MIT)

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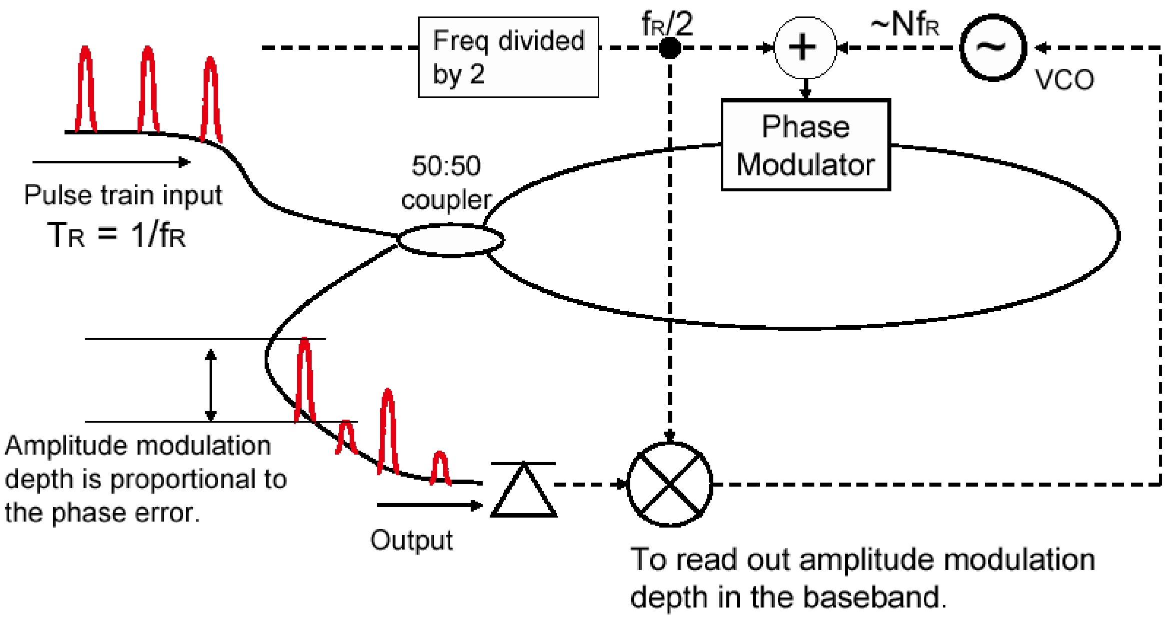


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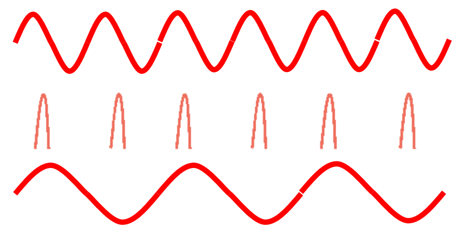
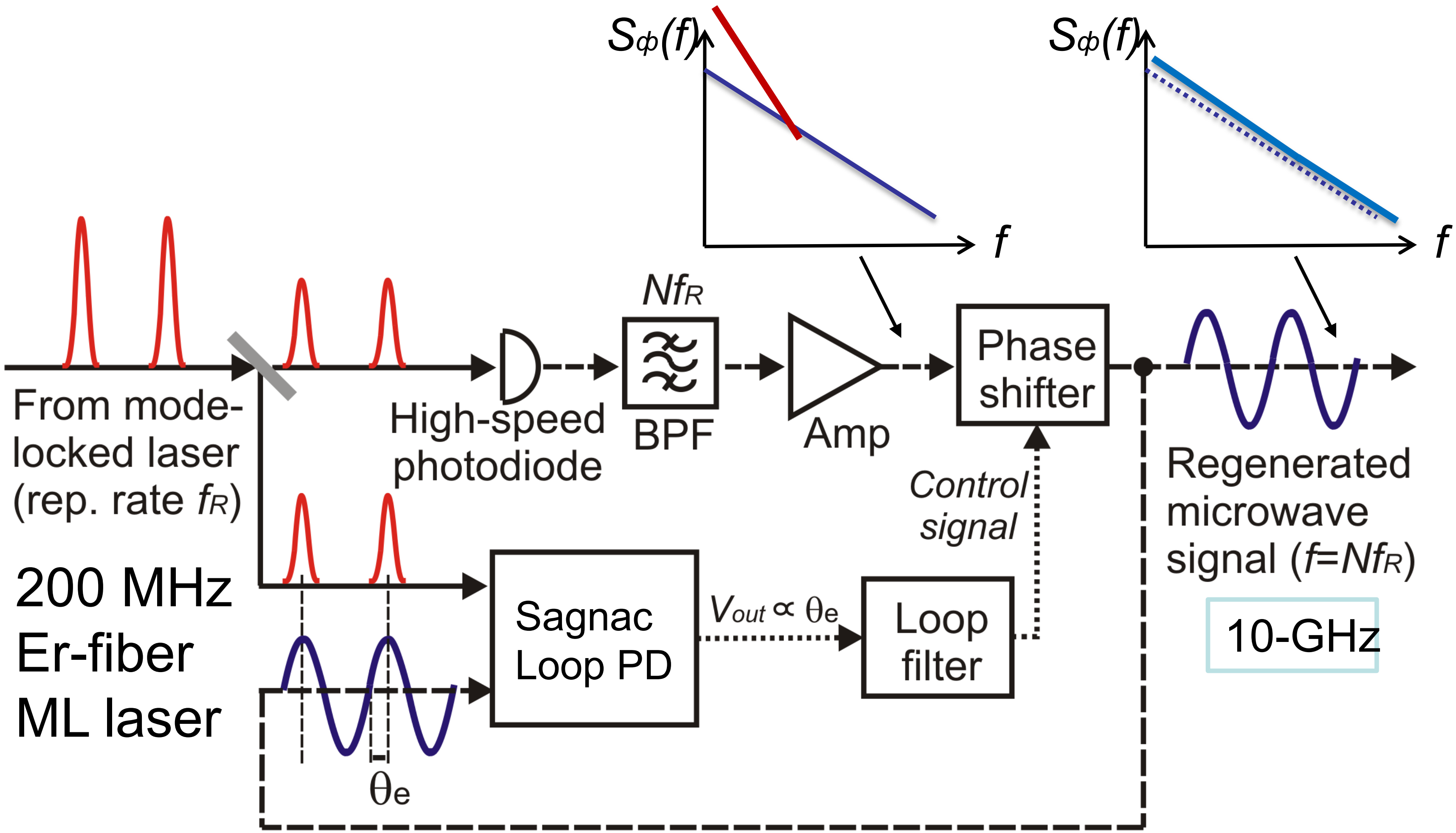


modulation voltage: $f_{rep} / 2$

Courtesy of J. Kim (MIT)

# Sagnac Loop Interferometer

## Delay-locked loop (DLL) for excess noise suppression

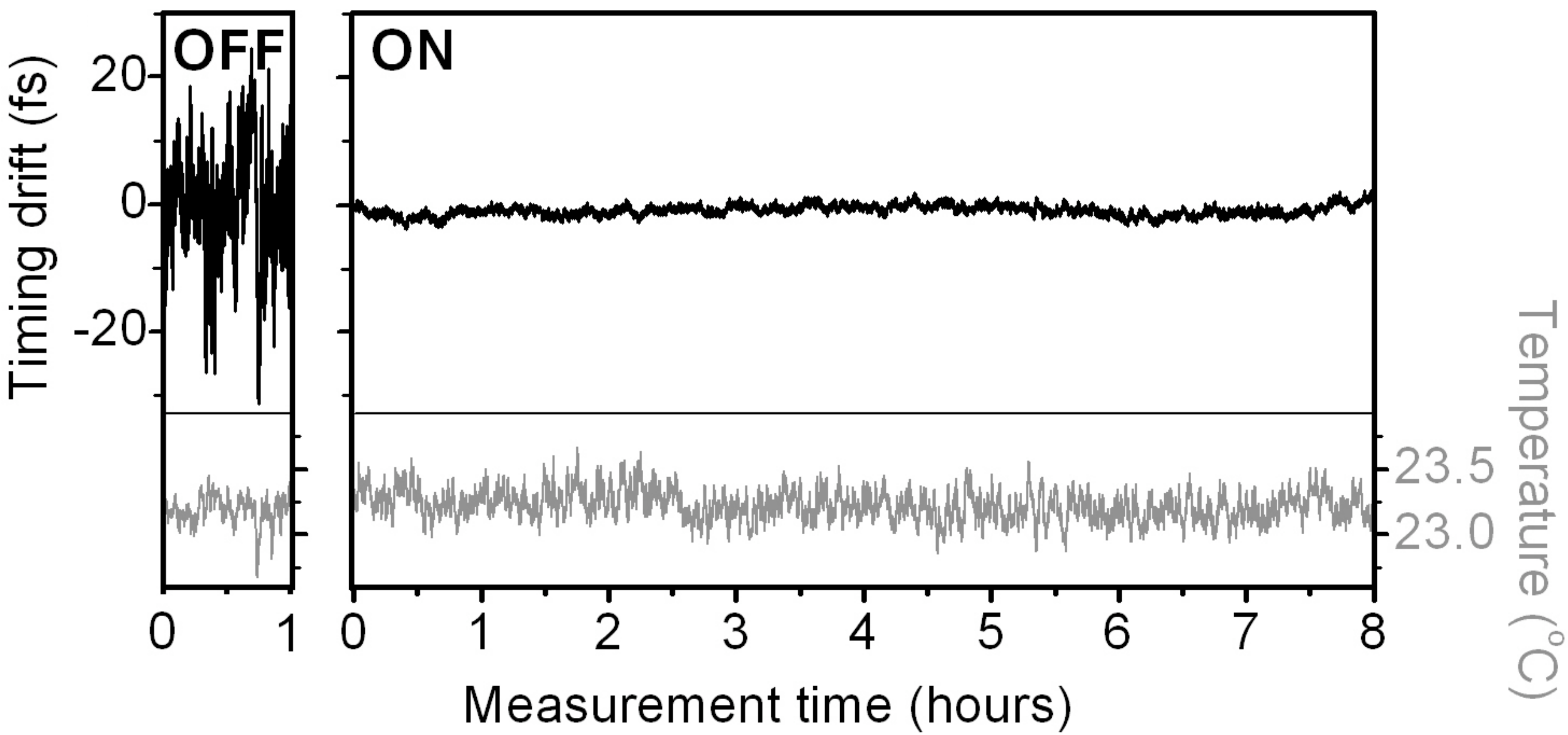



Courtesy of F. X. Kaertner, MIT & CFEL

# Sagnac Loop Interferometer

## Delay-locked loop (DLL) for excess noise suppression

RMS timing jitter integrated in 0.1 Hz – 1MHz: 2.4 fs

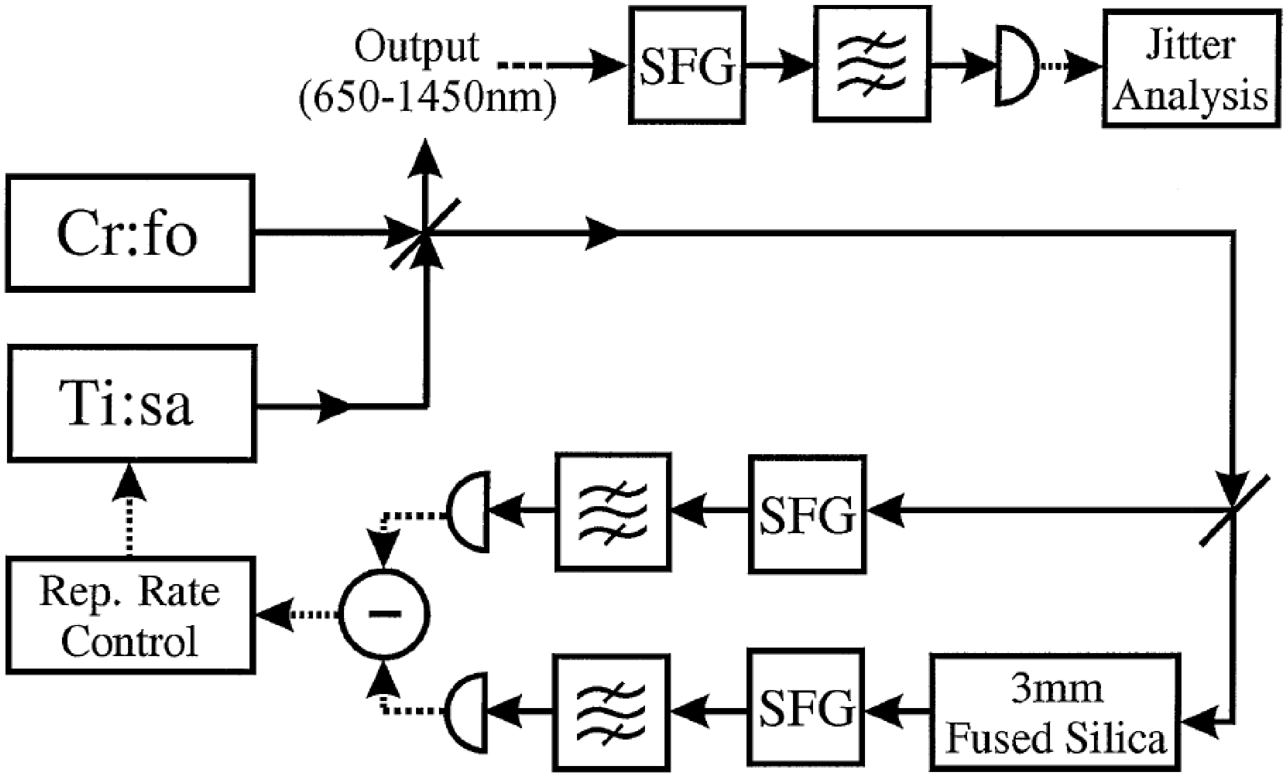



J. Kim and F. X. Kaertner, Opt. Lett. **35**, p. 2022 (2010).

# Synchronization of Lasers to the optical reference

**CW scheme:** See John Byrd's talk: WEOBS2

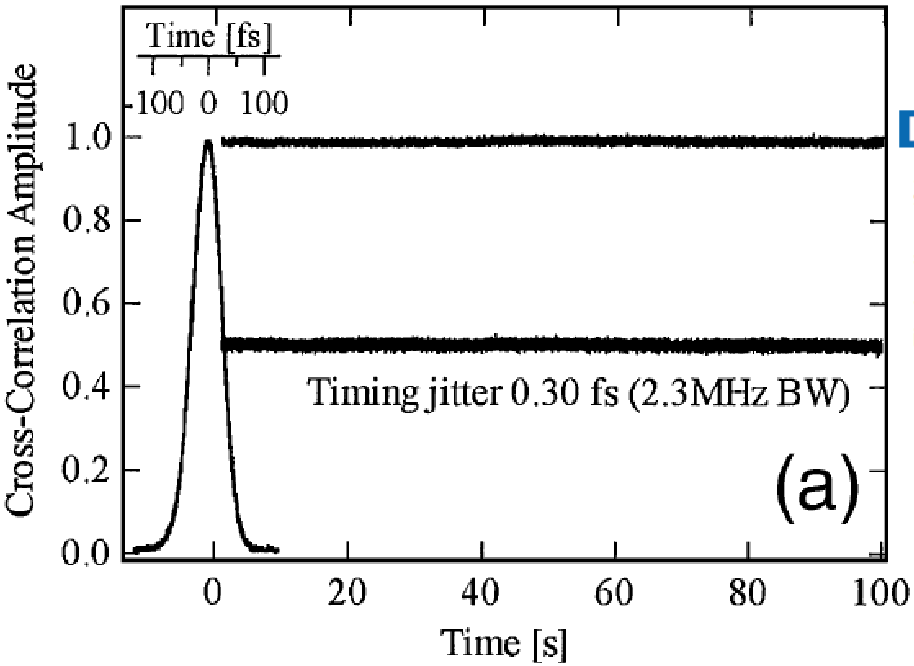
**Pulsed scheme:** Highest precision by performing (two color) optical cross correlation between laser and optical reference




T. R. Schibli et al., Opt. Lett. **28**, p. 947 (2003)

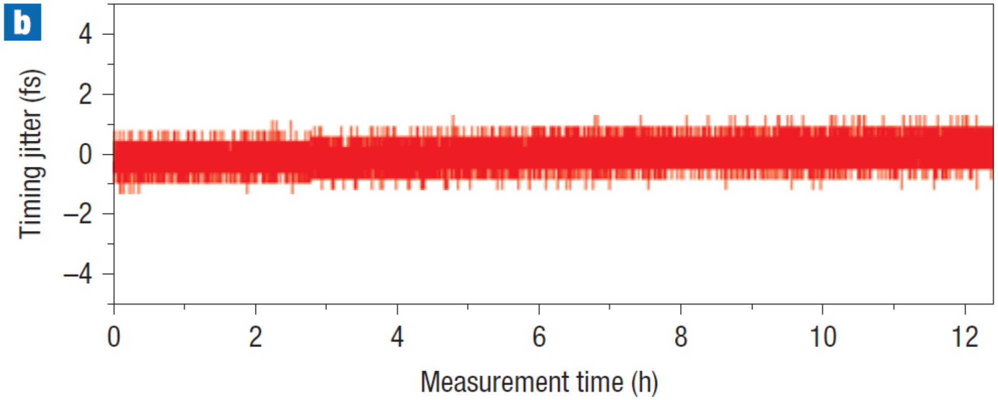
# Synchronization of Lasers to the optical reference

## 0.3 fs stability over 100 s (2.3 MHz bandwidth)




T. R. Schibli et al., Opt. Lett. **28**, p. 947 (2003)

## 0.4 fs stability over 12 h (2.3 MHz bandwidth)




J. Kim et al., Nature Photonics **2**, p. 733 (2008)

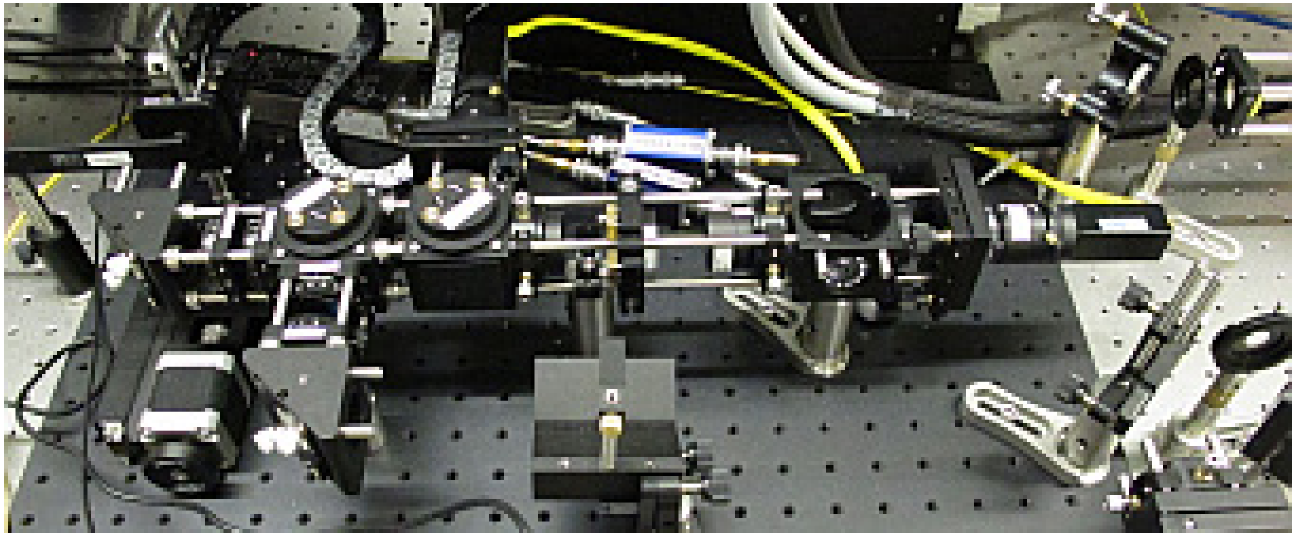
# Synchronization of Lasers to the optical reference

Ongoing efforts to synchronize various types of lasers to the optical reference pulse train at various laboratories like:

**DESY:** S. Schulz et al., PAC09, TH6REP091

**Elettra:** M. Danailov et al., 2nd Timing & Synchronization Workshop

**PSI:**



Courtesy of PSI Timing&Synch Team

# Femtosecond Bunch Arrival-Time Monitors

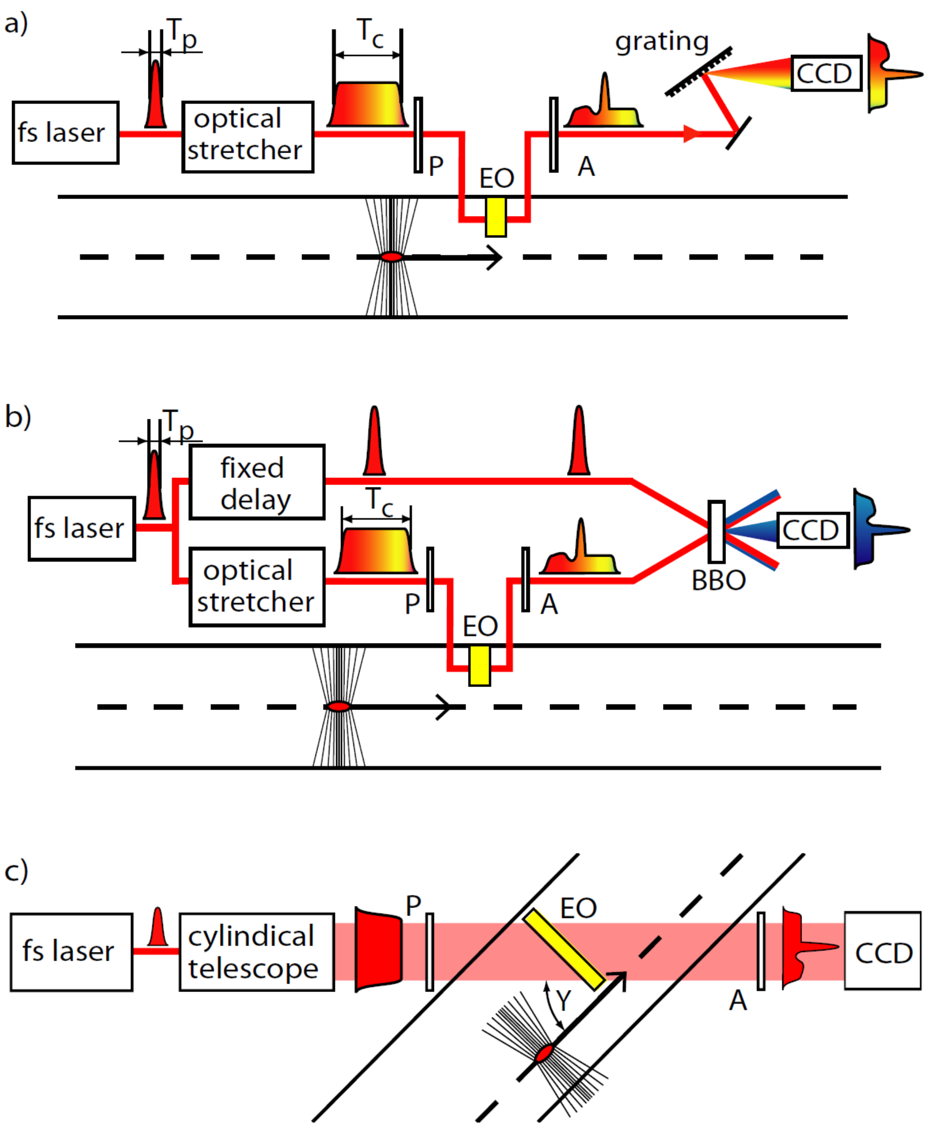
(Sub-10) femtosecond RF based measurements are possible at

- High RF frequencies, see, for example, 30 GHz scheme tested at CTF3:
  A. Anderson et al., MOPAN066, PAC07

- Lower frequencies, when averaging over many RF cycles is possible.
  See, e.g., ‘Phase Cavities’ at LCLS WEOBS2



# Femtosecond Bunch Arrival-Time Monitors
# Electro-optic Beam Profile Monitors

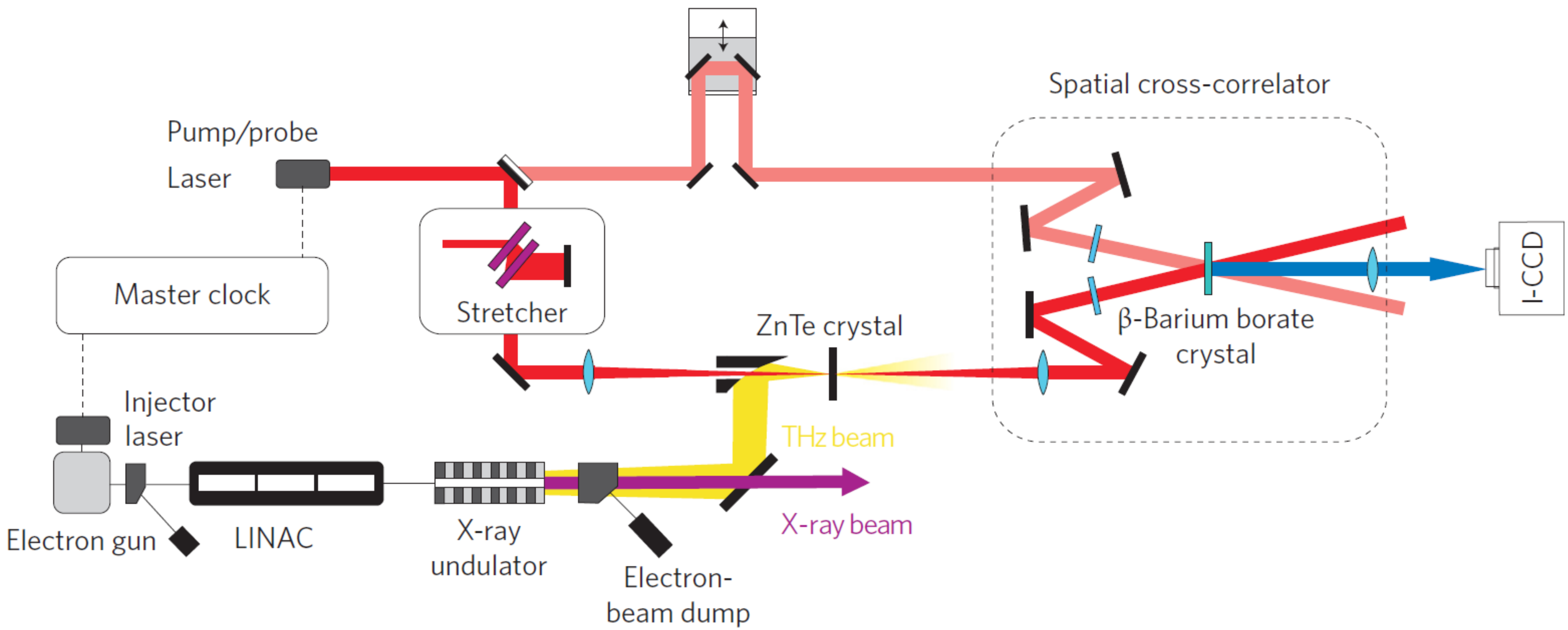



- Single bunch measurements
- Arrival-time measured with respect to a mode-locked laser
- Resolution depends on how precisely the laser is synchronized
- Long. Bunch profile & arrival-time!

But: Monitor data more difficult to analyze and thus less suited as monitors for a fast feedback.

a) I. Wilke et al., Phys. Rev. Lett. **88**, (2002)
b) G. Berden et al., Phys. Rev. Lett. **93** (2004)
c) A. L. Cavalieri et al., Phys. Rev. Lett. **94** (2005)

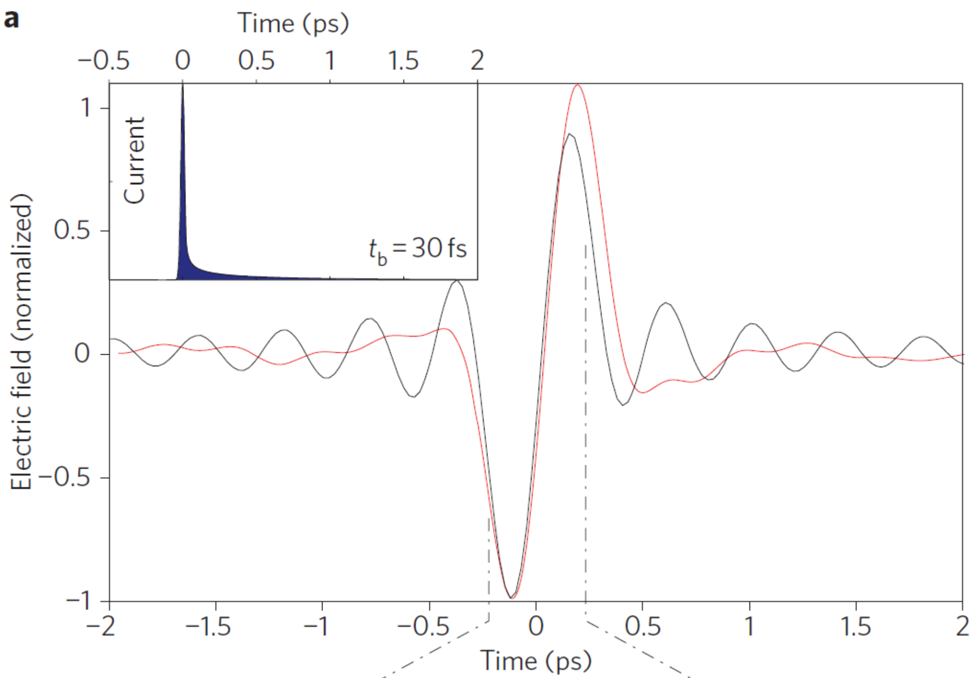
# Femtosecond Bunch Arrival-Time Monitors
# Bunch Arrival-time w.r.t. Pump-Probe Laser

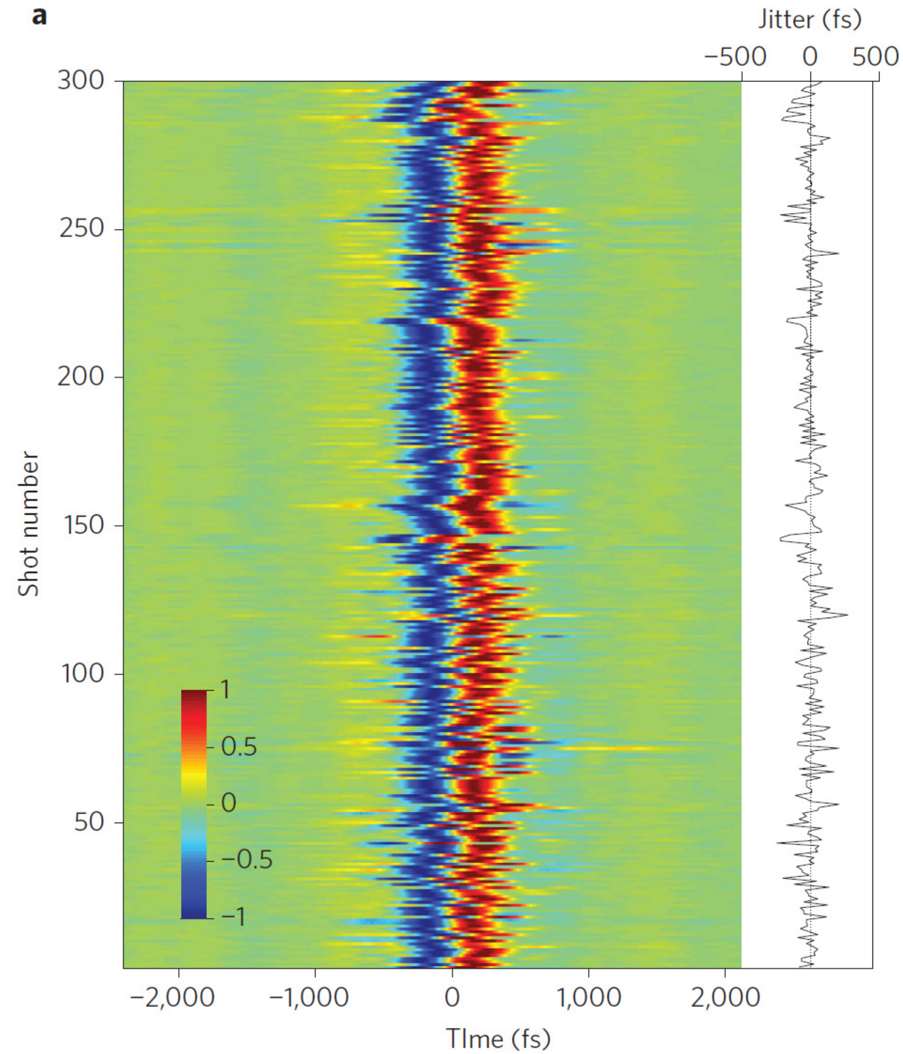



F. Tavella et al., Nature Photonics **5**, p. 162 (2011)

# Femtosecond Bunch Arrival-Time Monitors
# Bunch Arrival-time w.r.t. Pump-Probe Laser

## Electric field of the undulator edge radiation at FLASH

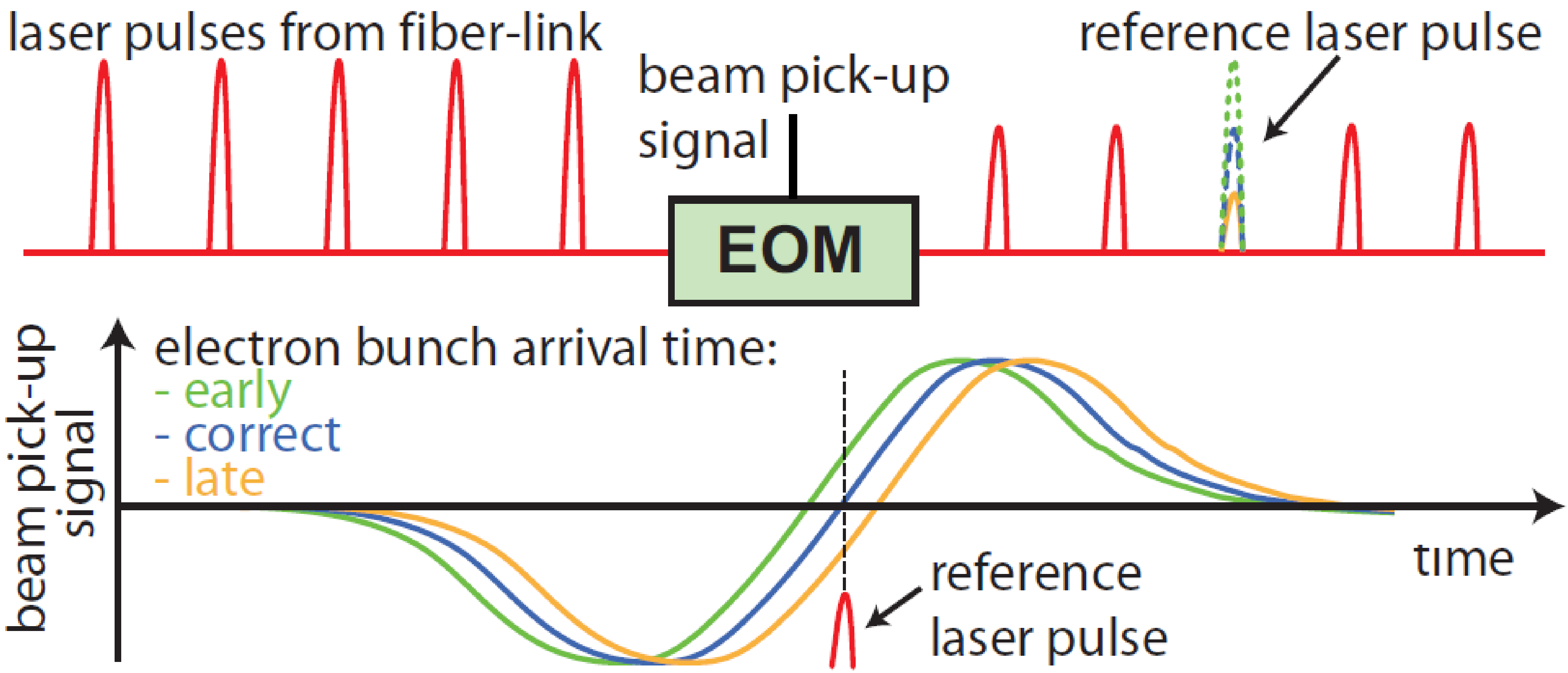



**Measures bunch centroid with a resolution better than 10 fs**

F. Tavella et al., Nature Photonics **5**, p. 162 (2011)

# Femtosecond Bunch Arrival-Time Monitors BAM




Electro-optic scheme utilizing pulses from optical synchronization
→ No additional jitter added

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

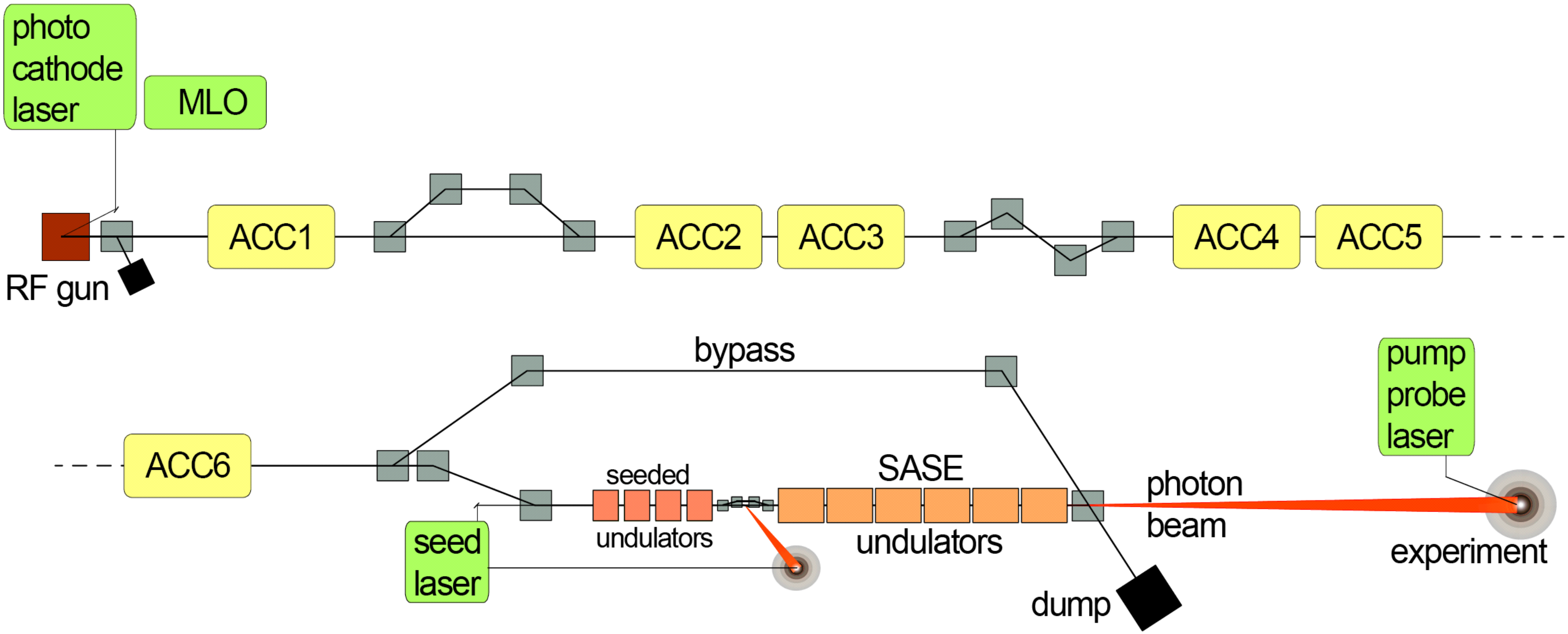
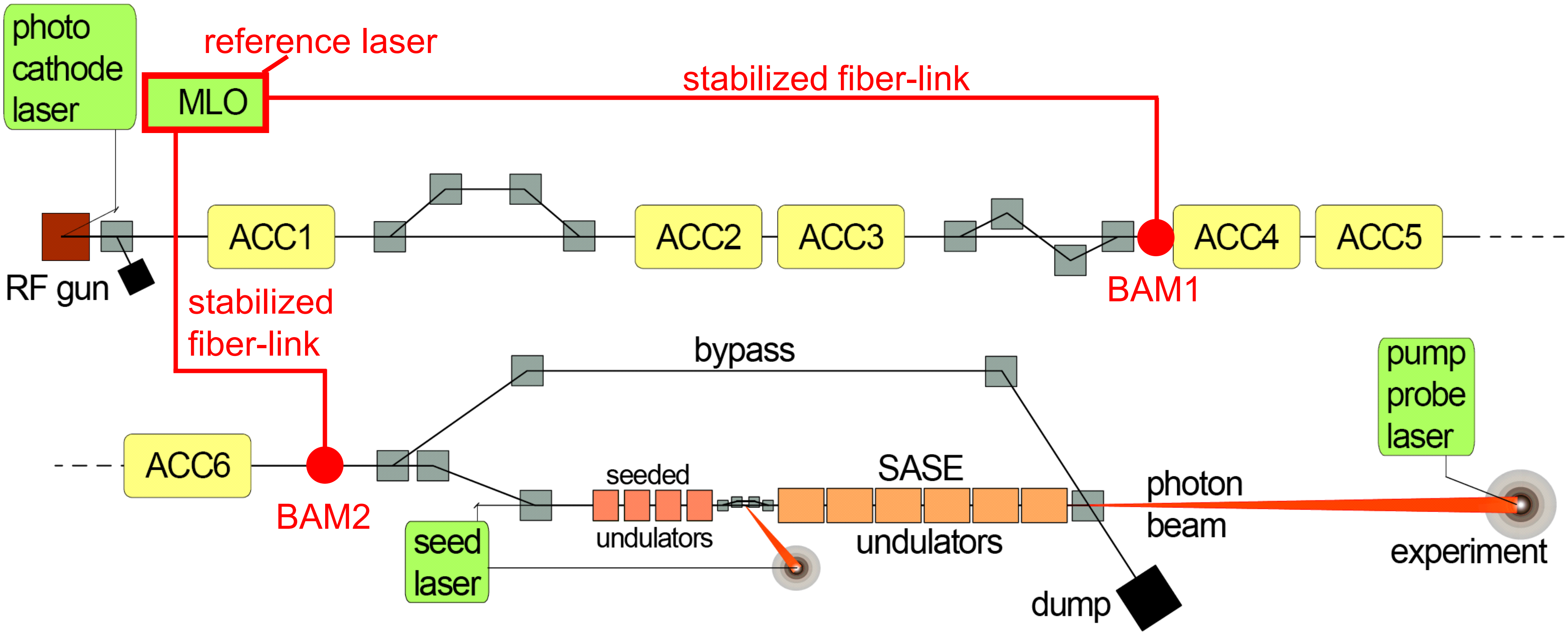


photo cathode laser
MLO
RF gun
ACC1
ACC2
ACC3
ACC4
ACC5
bypass
pump probe laser
ACC6
seeded
undulators
SASE
undulators
photon beam
seed laser
experiment
dump

# Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

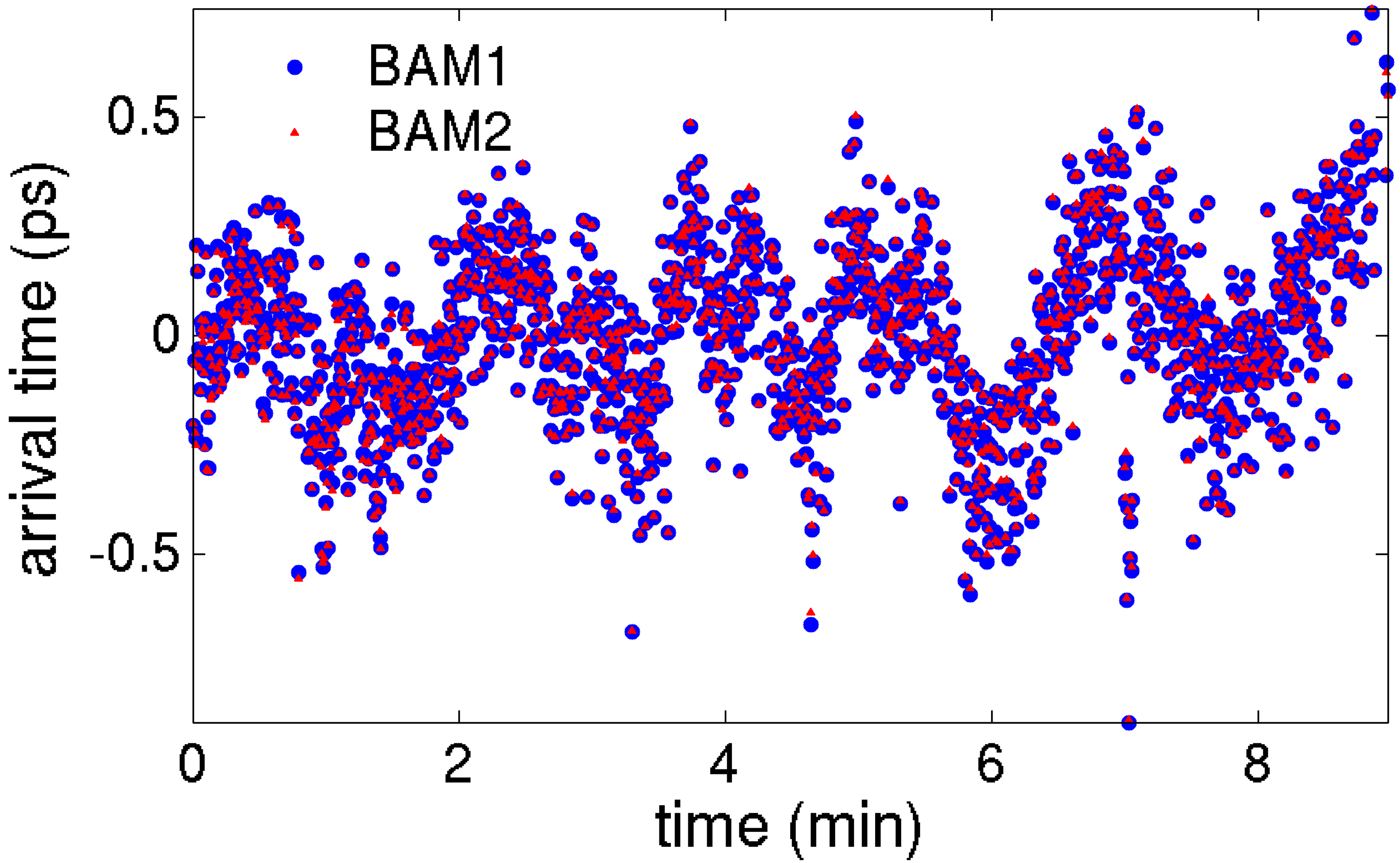



Two independent BAMs measure the arrival time of the same bunches.

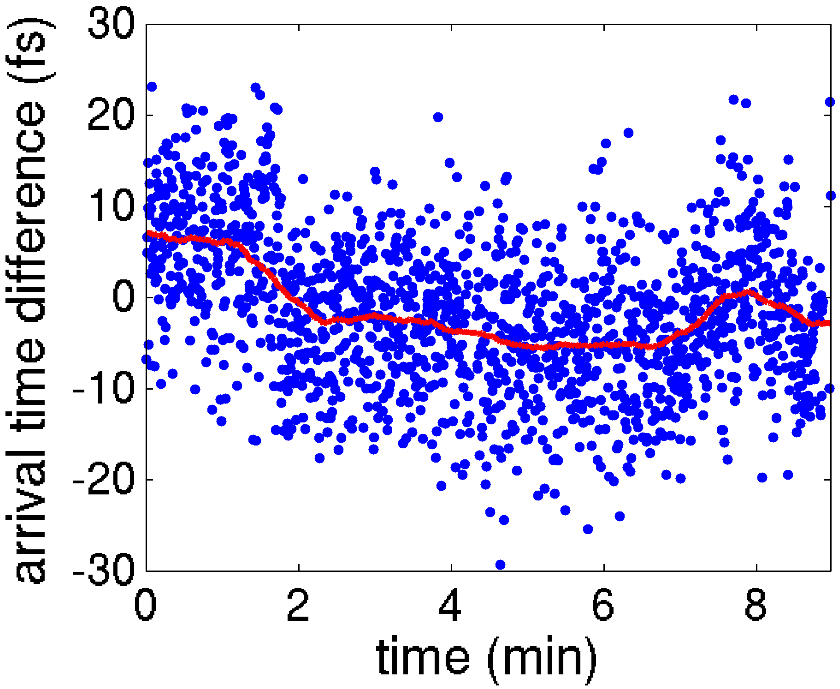
Distance between the two BAMs: 60 m

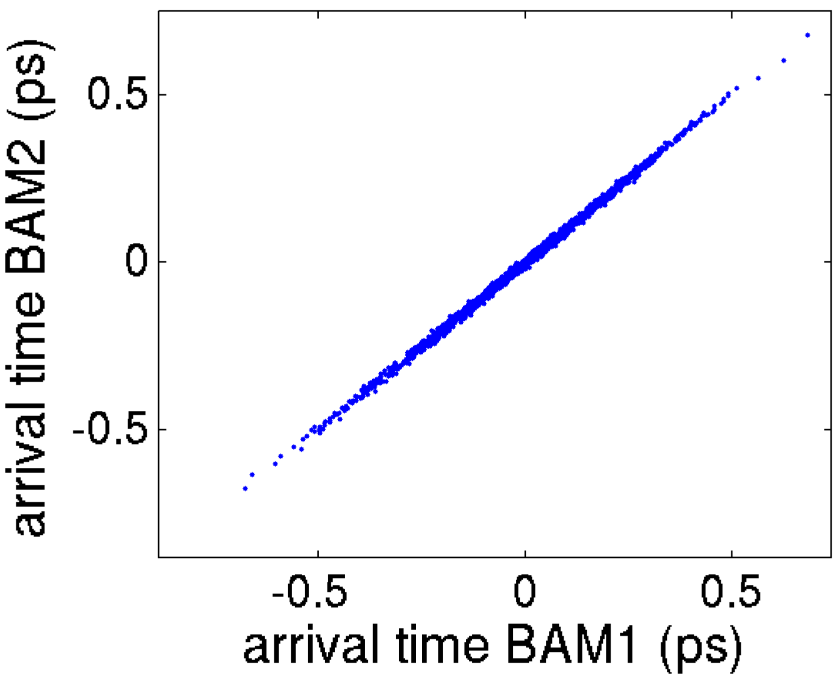
# Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

## Bunch arrival times as measured by both monitors



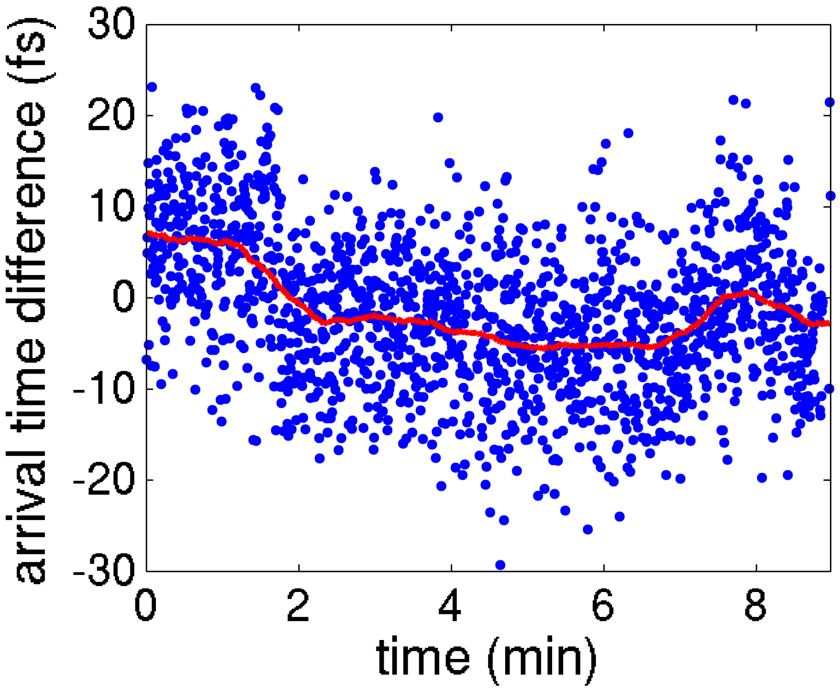
# Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

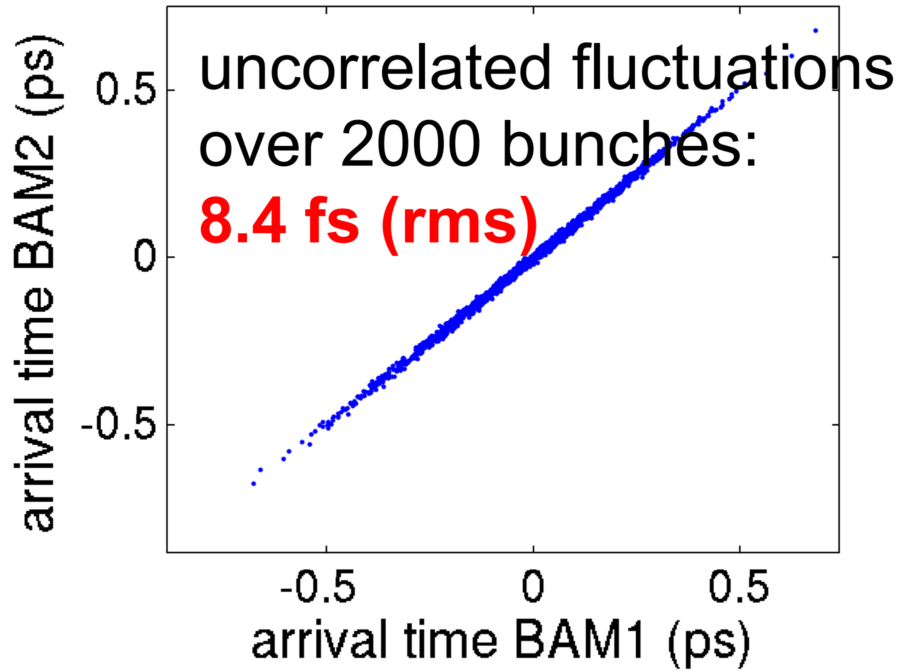



F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

# Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection




Difference between both measurements caused by:

- BAM resolution
- Stability of fiber-links
- Fast laser timing jitter (~3 MHz – 108 MHz)

Stability of a complete measurement chain: **< 6 fs (rms)**

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)



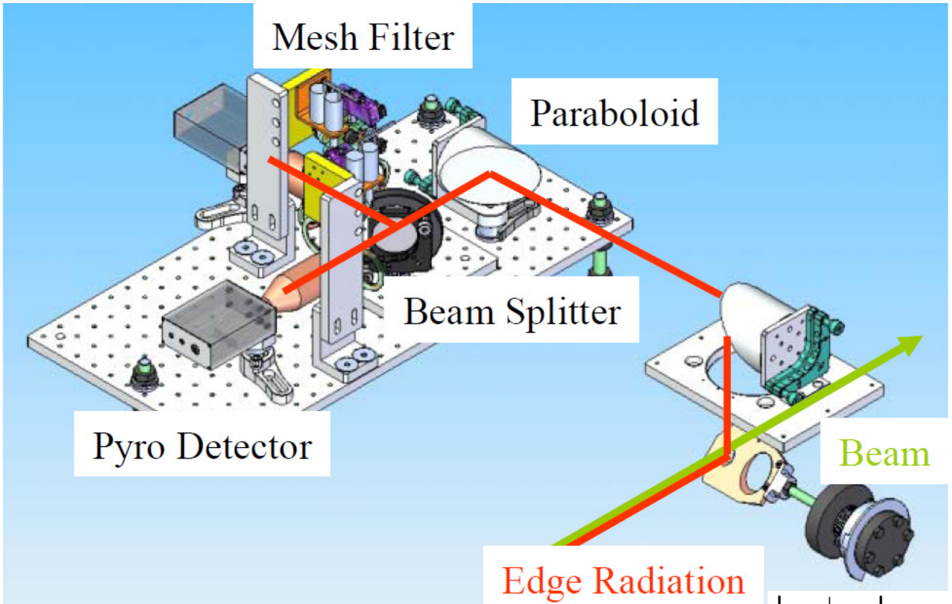
# Detecting Variations of the Bunch Shape

- Possibility of using EO-monitors mentioned before

Ideal monitor for feedback applications:
- Non disruptive
- Fast readout
- Delivers a single number proportional to bunch duration

→Detection of coherent beam induced THz radiation
  - Coherent Diffraction Radiation (CDR)
  - Coherent Synchrotron Radiation (CSR)
  - Coherent Edge Radiation (CER)

# Detecting Variations of the Bunch Shape
# Detection of Integrated THz Power

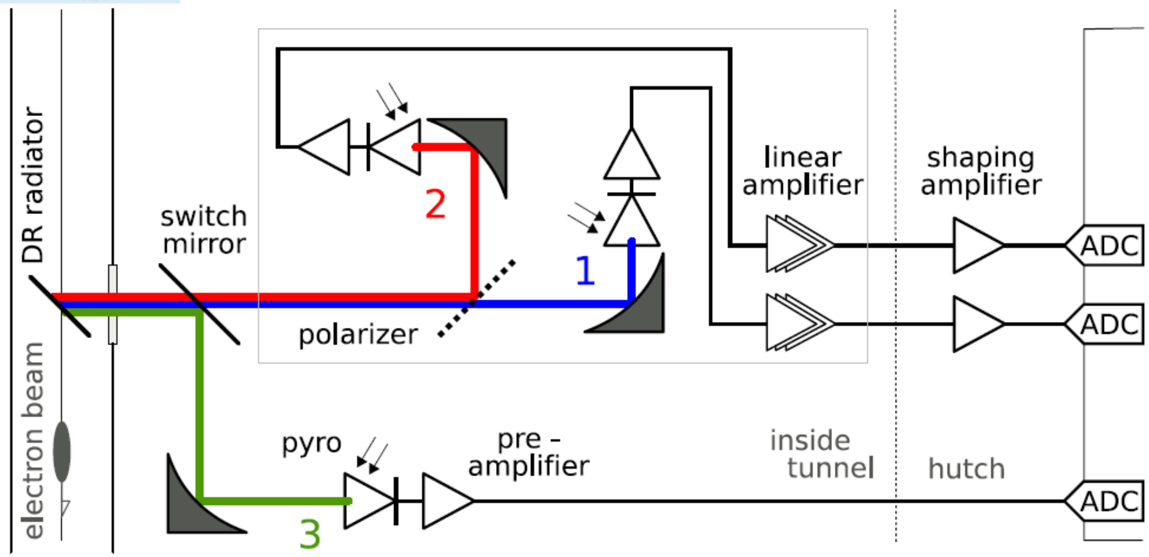



## LCLS edge radiation monitor

H. Loos et al., FRPMS071, PAC07

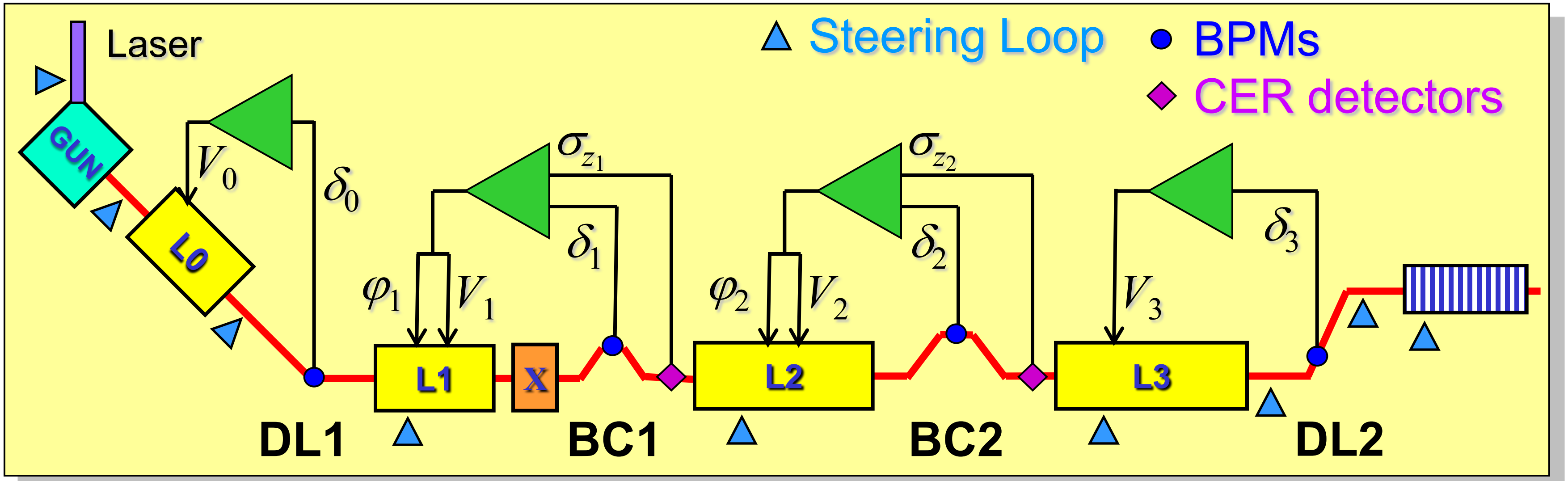
## FLASH diffraction radiation monitor

C. Behrens et al., MOPD090, IPAC10



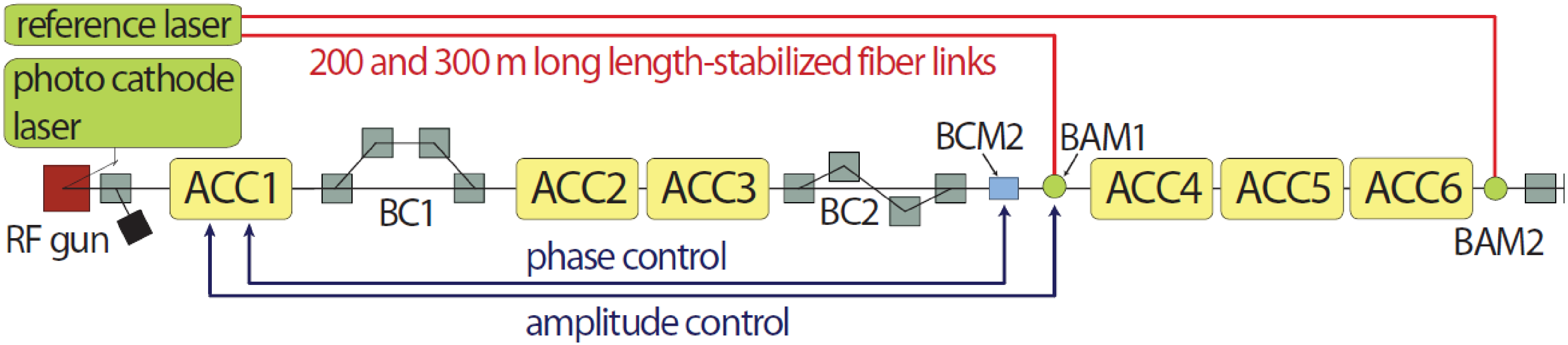
# Active Bunch Shape Stabilization at the LCLS

- Cascaded FB at 5 Hz (Matlab implementation)
- Fixed energy gain in L2 & L3 klystrons
- Change global L2 phase
- Adjust L2 & L3 energy with several klystrons at opposite phases
- Feedback uses orthogonal actuators to separate energy gain and chirp of L2




Courtesy of H. Loos, SLAC

# Active Bunch Arrival-Time & Bunch Shape Stabilization




Fast intra bunch train feedbacks based on the timing reference from the optical synchronization system.

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

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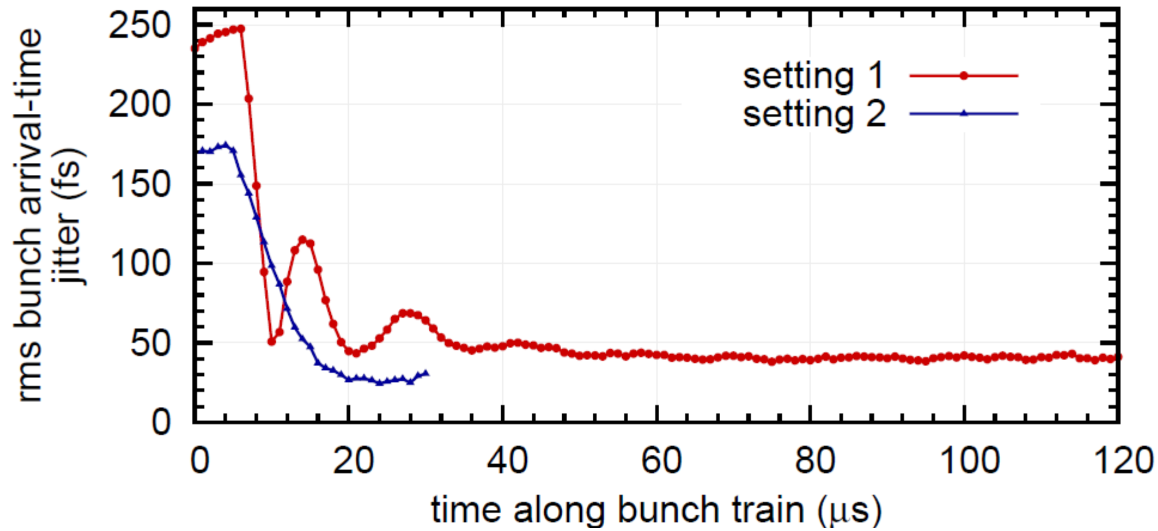
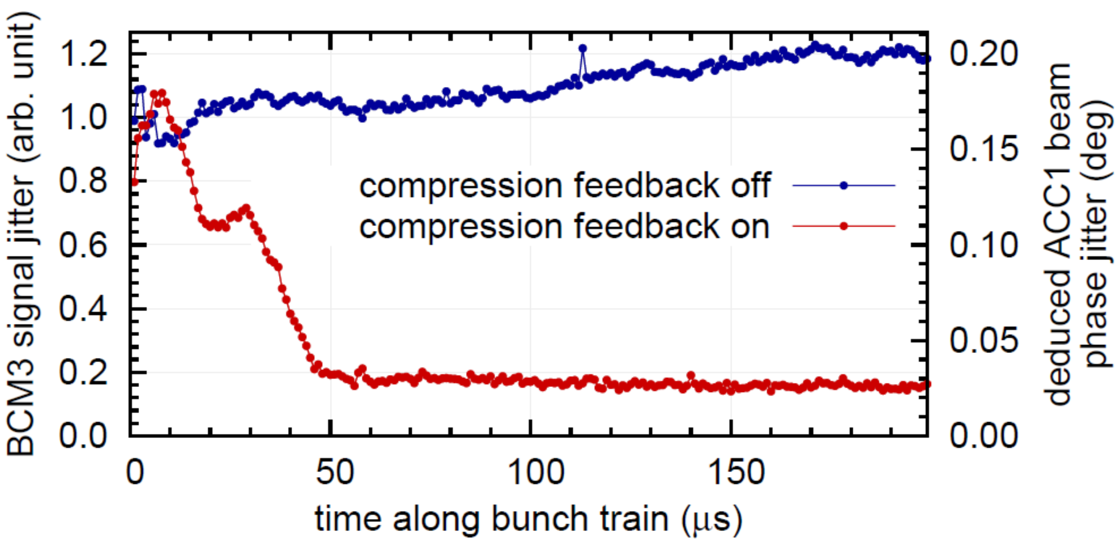



Achieved 25 fs bunch arrival-time stability
→Important for laser based seeding and manipulation schemes
(see WEOCN6)




Achieved 0.025 deg beam phase stabilization

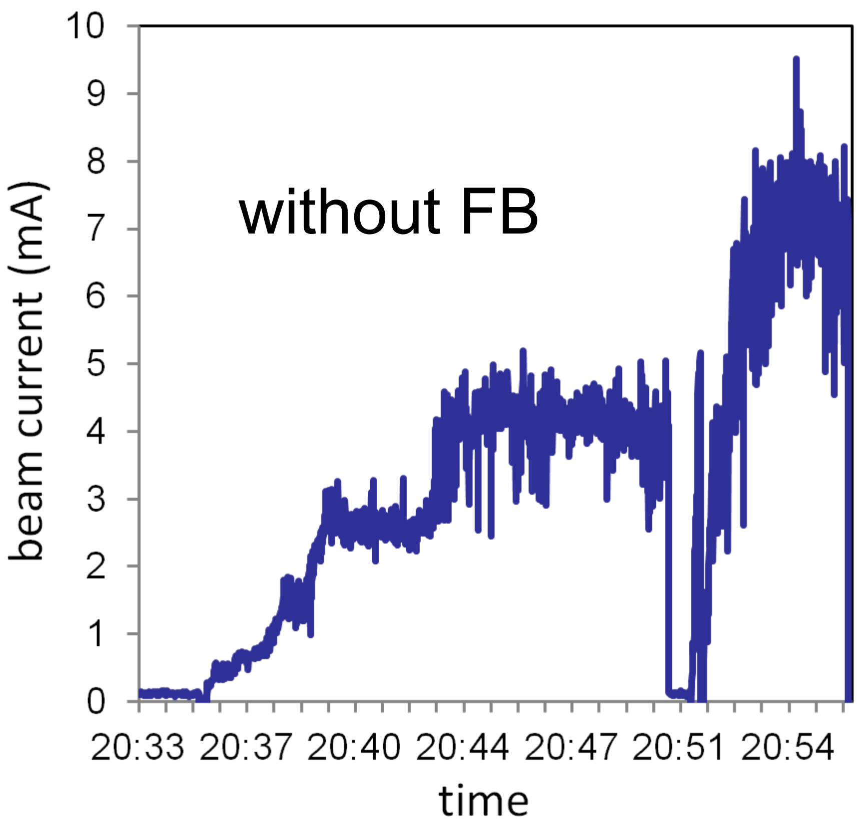
More advanced feedback scheme with more monitors and actuators under way at DESY

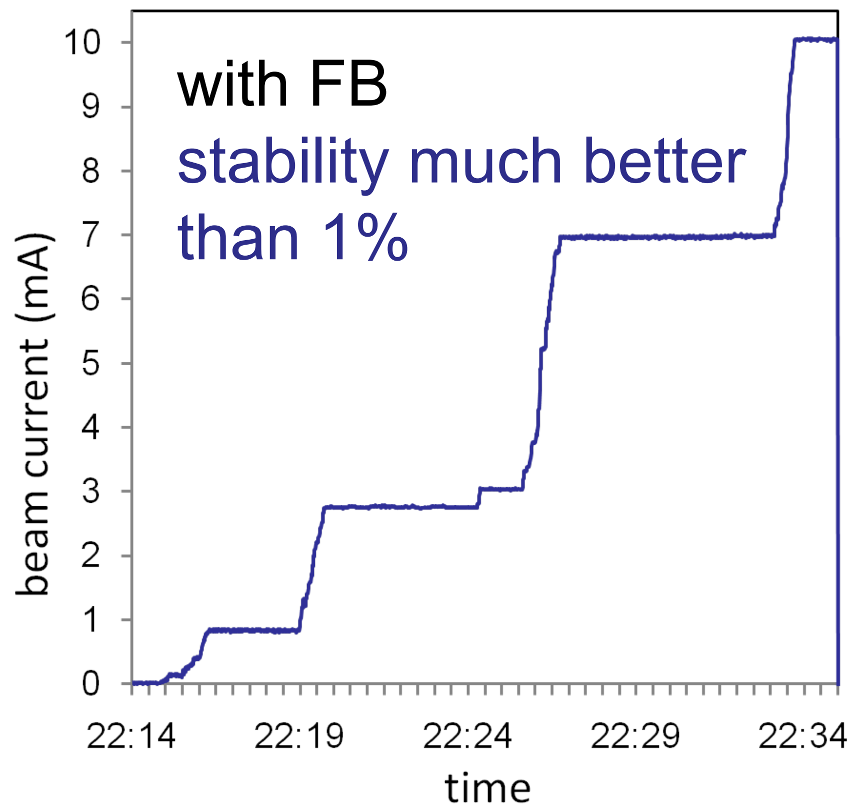
F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

# Bunch Charge Stabilization Example: Cornell CW Injector

Most arrival-time and bunch compression monitors have a dependence on the bunch charge.

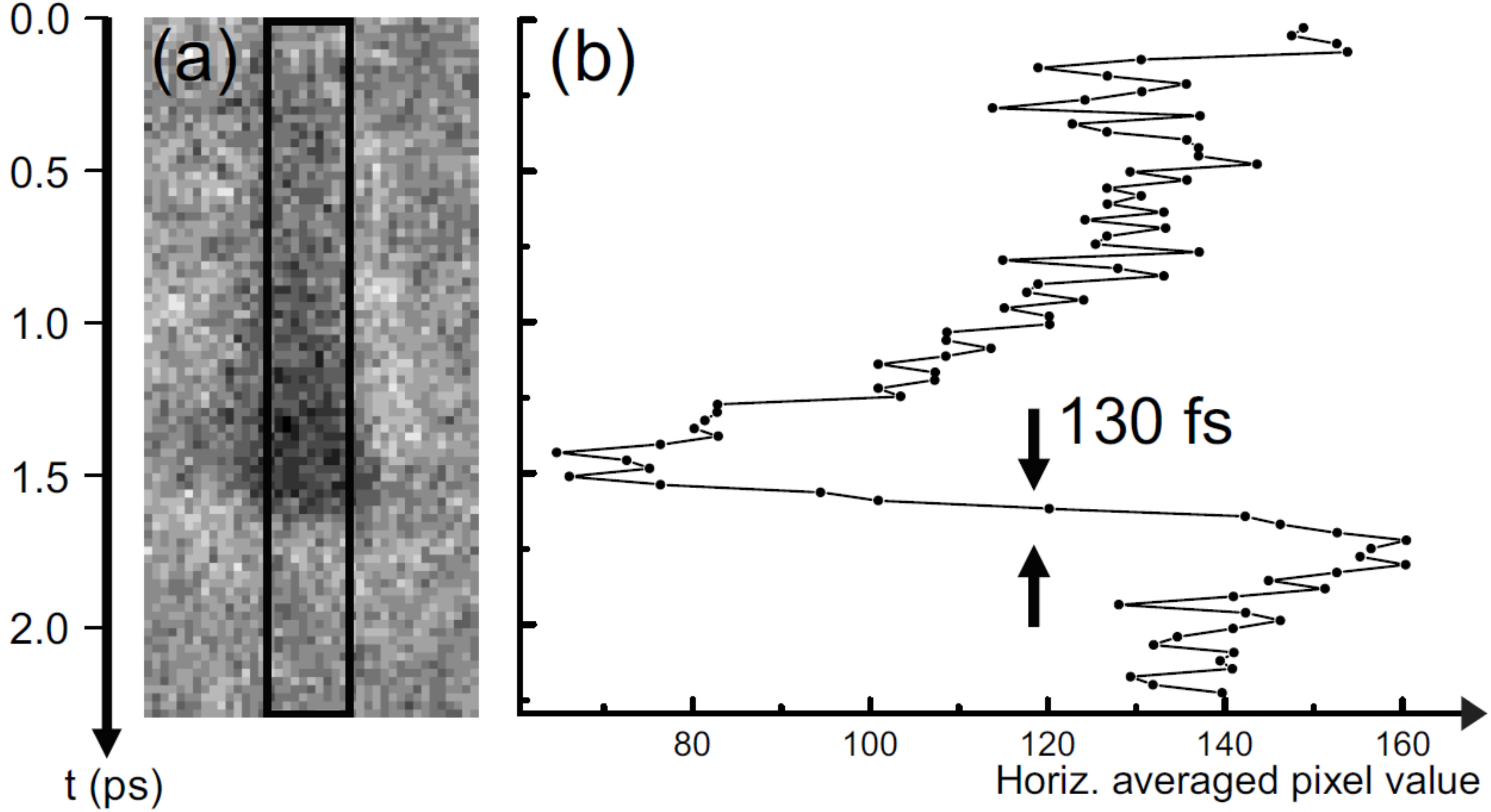
→ Better bunch charge stability can improve the resolution of both of these monitors.



# Photon Pulse Arrival-time Detectors

## 40 – 50 fs arrival-time resolution




T. Maltezopoulos et al., New Journal of Physics **10,** 033026 (2008)
see also: C. Gahl et al., Nature Photonics **2**, pp. 165 - 169 (2008)

# Summary / Outlook

- Femtosecond timing is a very active field of development and many technologies already exist
- 10 fs electron beam stability is almost reached
- Very strong potential for reaching sub-fs photon pulse stability with laser seeding / manipulation schemes
- Still missing: Highest resolution photon pulse arrival-time detectors

Thank you for your attention!