**FLS Meeting**
**March 7, 2012**

# Status on Pulsed Timing Distribution Systems and Implementations at DESY, FERMI and XFEL

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# Acknowledgement

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**DESY:** Holger Schlarb and Sebastian Schultz

**FERMI:** Mario Ferrianis

**European XFEL:** Michael Bousonville

# Outline

- Synchronization System Layout for X-ray FELs
- Timing Jitter of Femtosecond Lasers
  - Fiber Lasers
  - Solid-State Lasers
- Timing Distribution Over Stabilized Fiber Links

  Influence of Polarization Mode Dispersion
- Implementations at DESY, FERMI and plans for the European XFEL

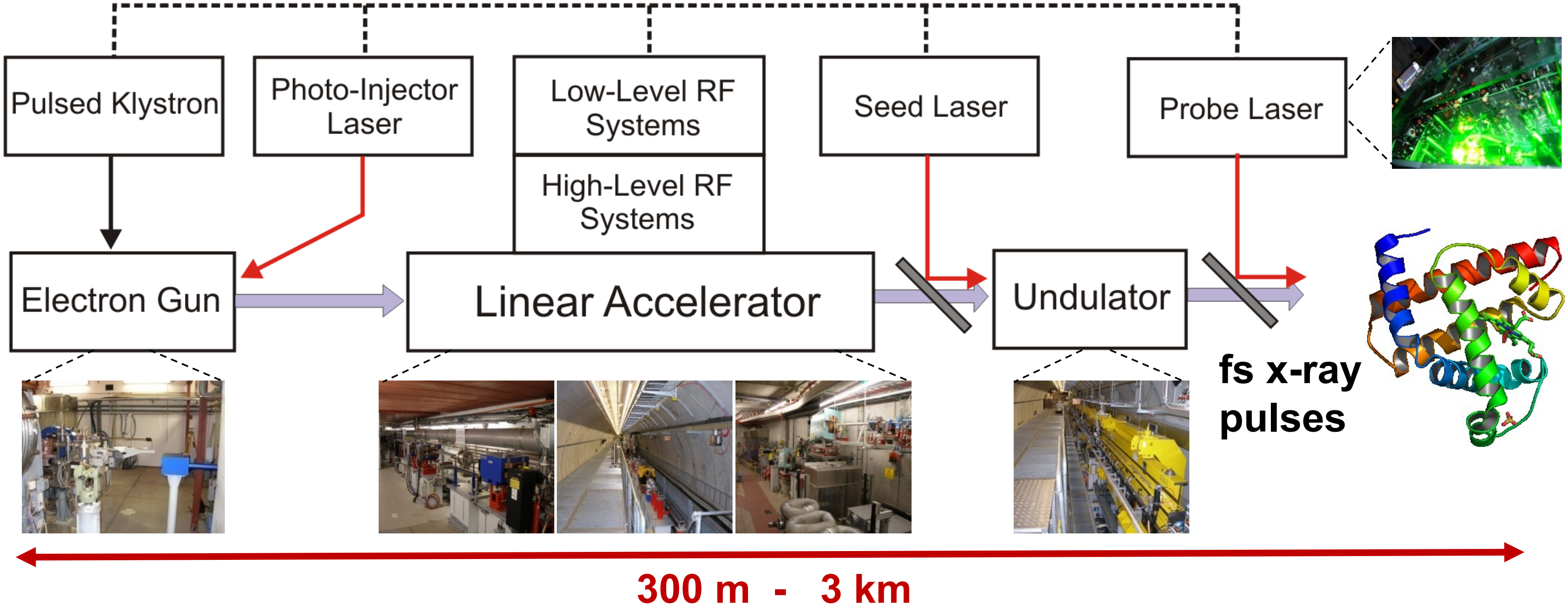
# Timing of X-ray Free Electron Lasers

**FLASH, FERMI and the European XFEL**

**LCLS in Stanford is operating since April 2009**

**Today, we have long-term stable pulsed sub-10 fs timing available**

**Tomorrow sub-fs timing will be required.**



Pulsed Klystron

Photo-Injector Laser

Low-Level RF Systems

High-Level RF Systems

Seed Laser

Probe Laser

Electron Gun

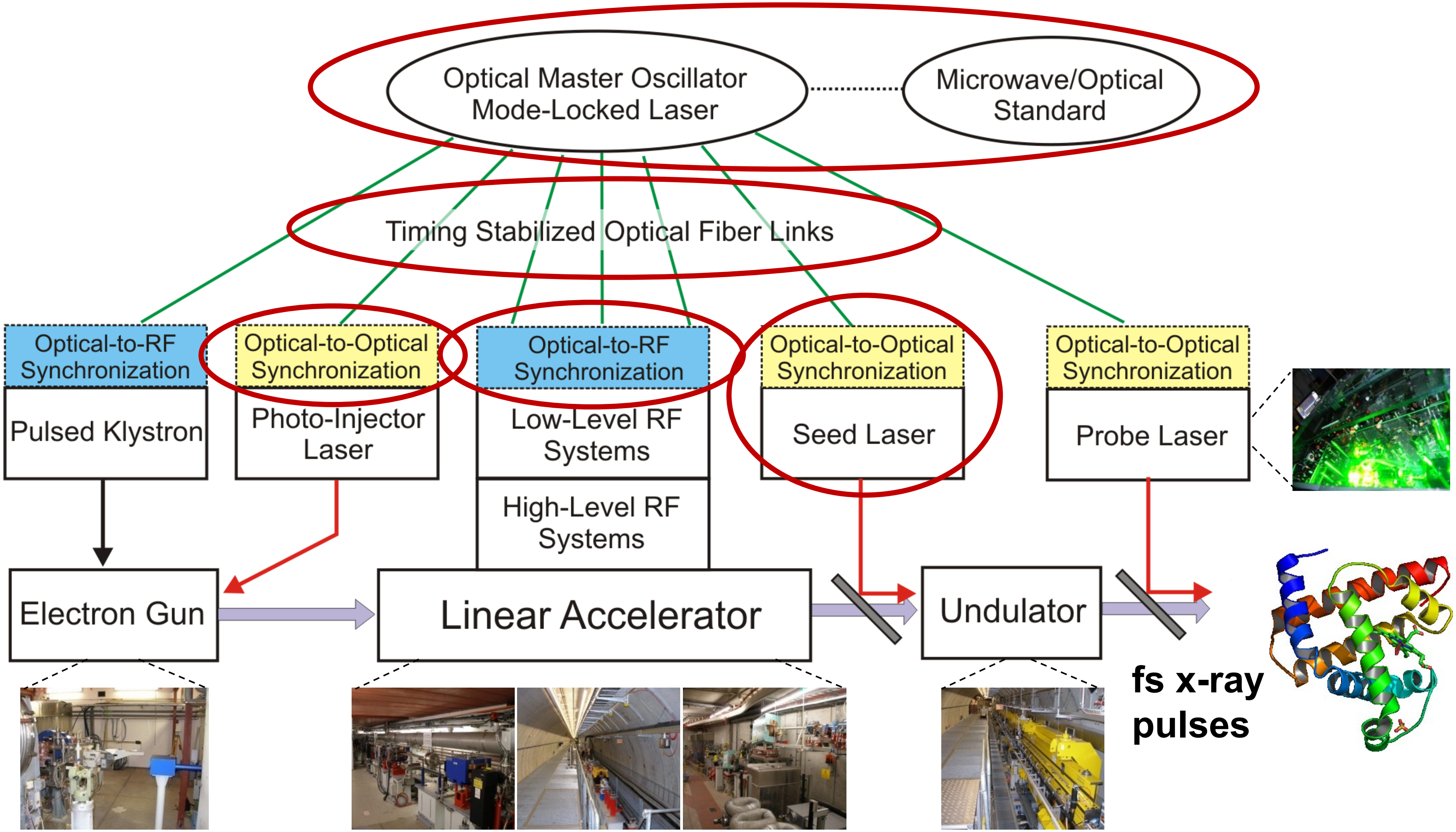
Linear Accelerator

Undulator

**fs x-ray pulses**

**300 m - 3 km**

# Timing Distribution and Synchronization



Optical Master Oscillator Mode-Locked Laser

Microwave/Optical Standard

Timing Stabilized Optical Fiber Links

Optical-to-RF Synchronization

Pulsed Klystron

Optical-to-Optical Synchronization

Photo-Injector Laser

Optical-to-RF Synchronization

Low-Level RF Systems

High-Level RF Systems

Optical-to-Optical Synchronization

Seed Laser

Optical-to-Optical Synchronization

Probe Laser

Electron Gun

Linear Accelerator

Undulator

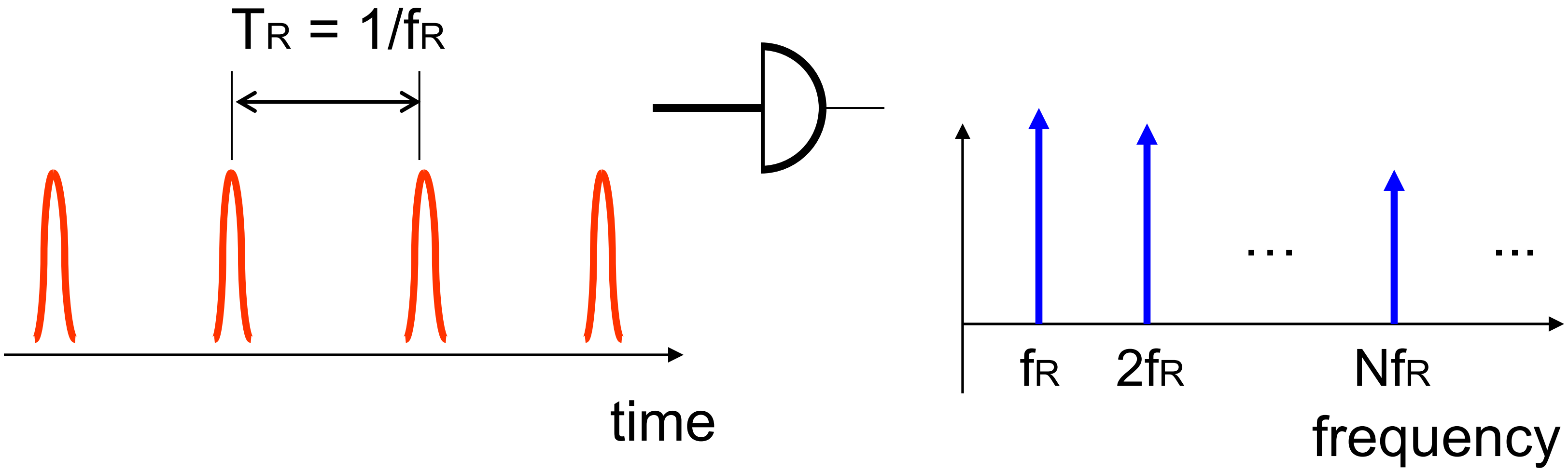
**fs x-ray pulses**

**J. Kim et al, FEL 2004.**

SCIENCE

**Other approaches : R. Wilcox, LBNL, cw-distribution**

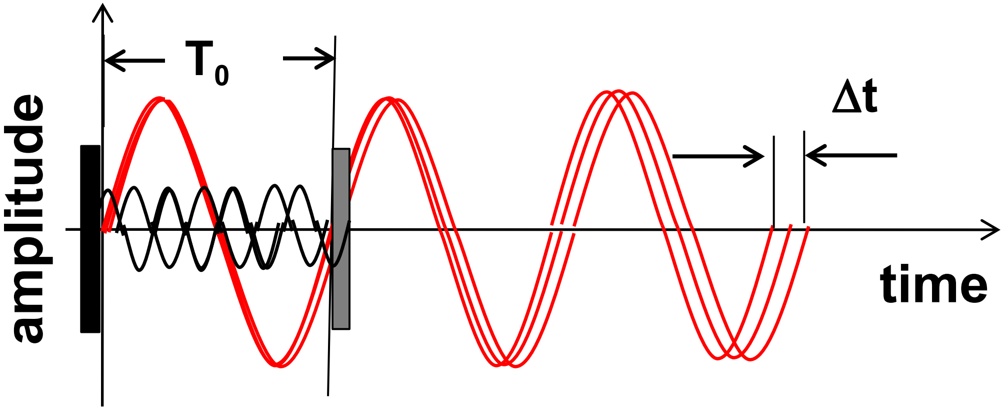
# Why Optical Pulses (Mode-locked Lasers)?



- **Real marker in time and RF domain**, every harmonic can be extracted at the end station.
- Suppress Brillouin scattering and undesired reflections.
- **Optical cross correlation** can be used for link stabilization or for optical-to-optical synchronization of other lasers.
- Pulses can be directly used to **seed amplifiers, EO-sampling**, ….
- **Group delay is directly stabilized,** not optical phase delay.
- After power failure system can **auto-calibrate!**

# Timing Jitter of Femtosecond Lasers

**Electronic Oscillator**



**Dissipation-Fluctuation Theorem**

$$\frac{d}{dt} < \Delta t_{RF}^2 > \approx T_0^2 \cdot \frac{1}{W_{mode}} \cdot \frac{kT}{\tau_{cav}}$$

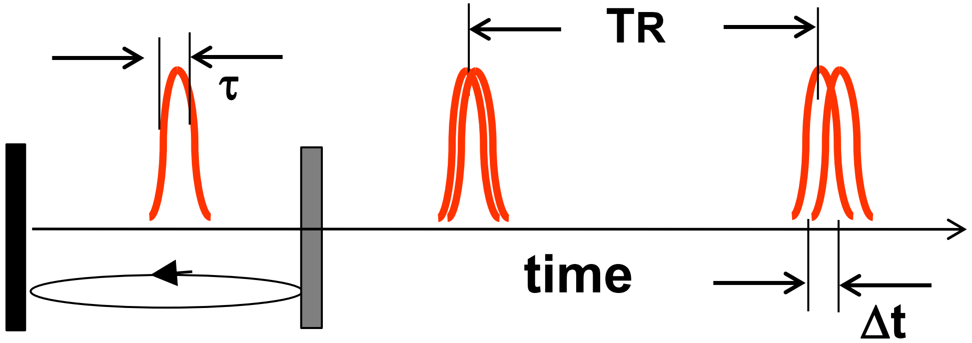
**period ~100ps**

**cavity lifetime**

**$10^{-6}$**

**pulse width ~100fs**

**Femtosecond Laser**



**Optical Cavity**

$$\frac{d}{dt} < \Delta t_{ML}^2 > \approx \tau^2 \cdot \frac{1}{W_{pulse}} \cdot \frac{\hbar}{\tau_{cav}}$$

$$\hbar\omega_c \sim 50kT$$

$W_{mode/pulse}$ = mode / pulse energy

$\tau_{cav}$ = cavity decay time

kT = thermal energy

$\hbar\omega_c$ = photon energy

H. A. Haus and A. Mecozzi, IEEE JQE *29, 983* (1993).

J. Kim and F. X. Kärtner, Laser & Phot. Rev., 1–25 (2009).

# How Do We Measure Low Jitter?

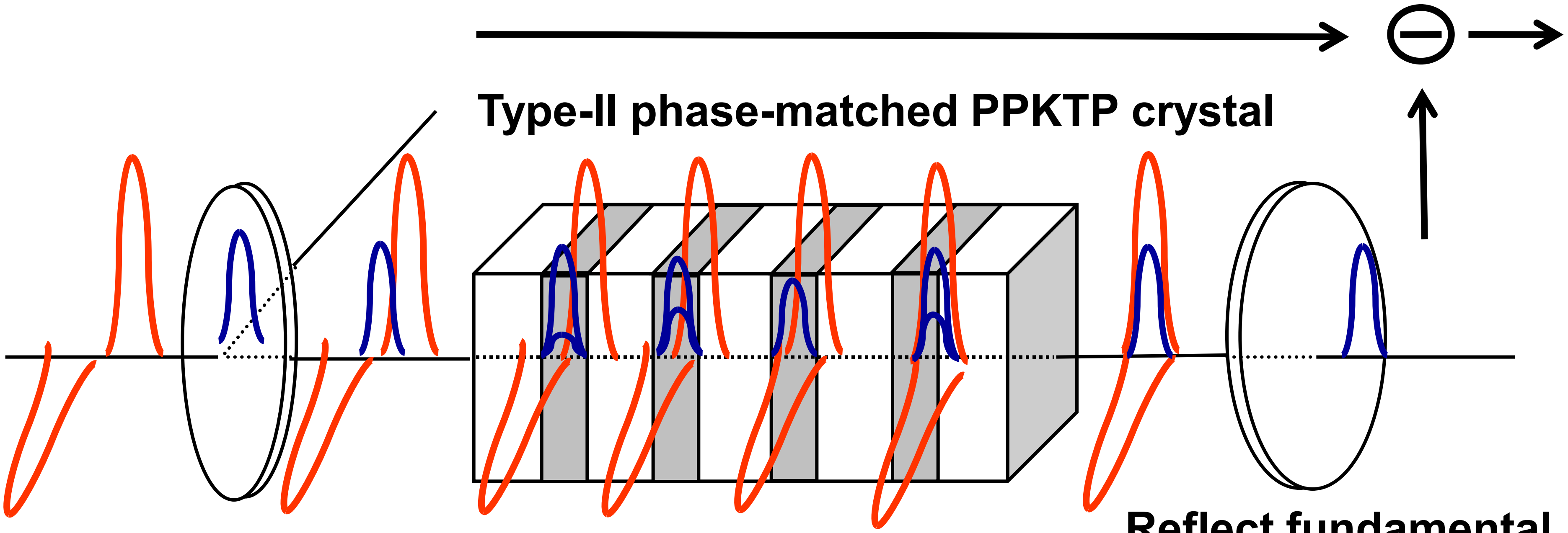
**Sensitive Time Delay Measurements**

**by**

**Balanced Optical Cross Correlation**

# Single-Crystal Balanced Cross-Correlator

T. Schibli et al, OL 28, 947 (2003)



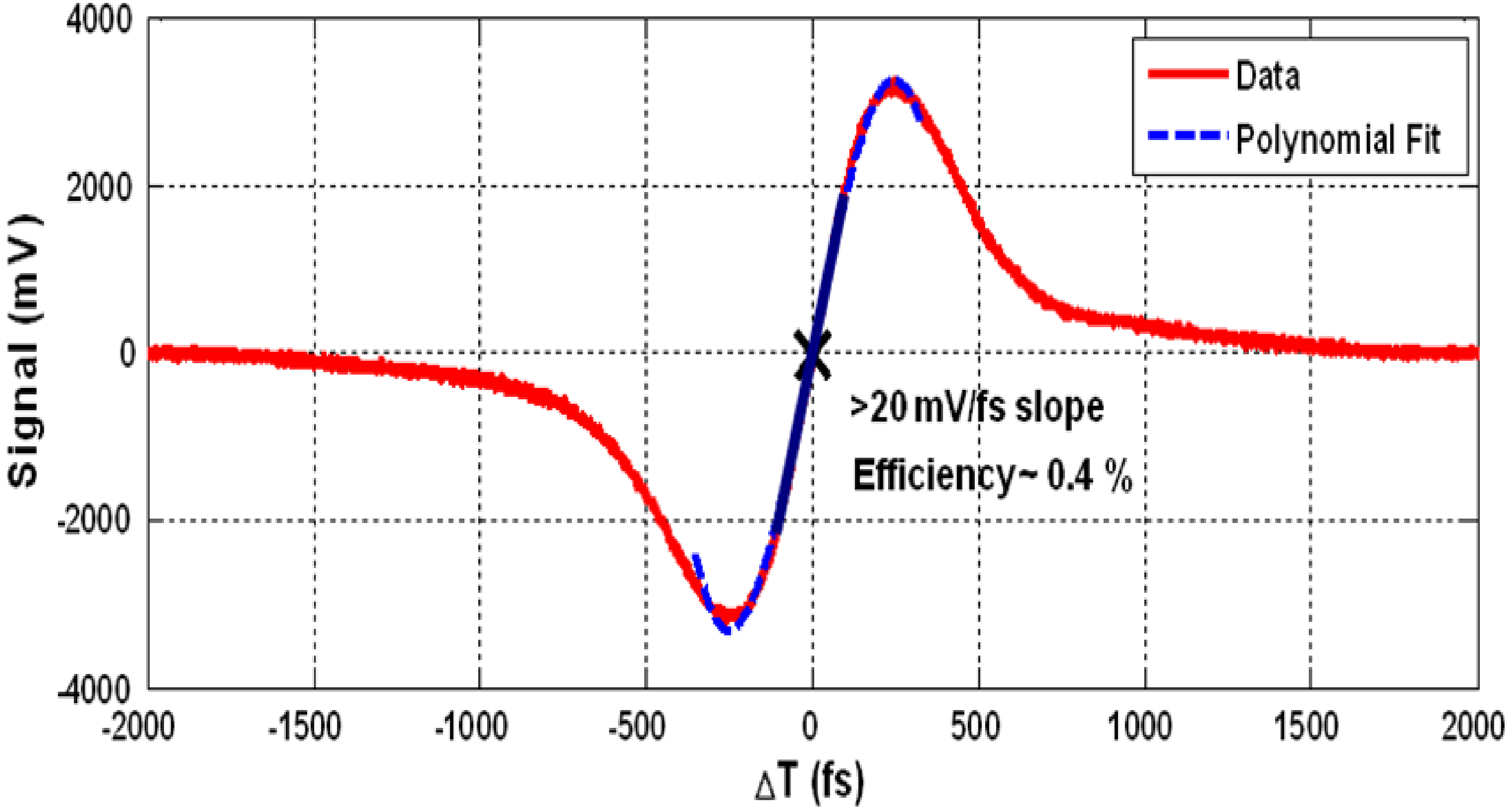
Type-II phase-matched PPKTP crystal

Transmit fundamental
Reflect SHG

Reflect fundamental
Transmit SHG

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

# Single-Crystal Balanced Cross-Correlator

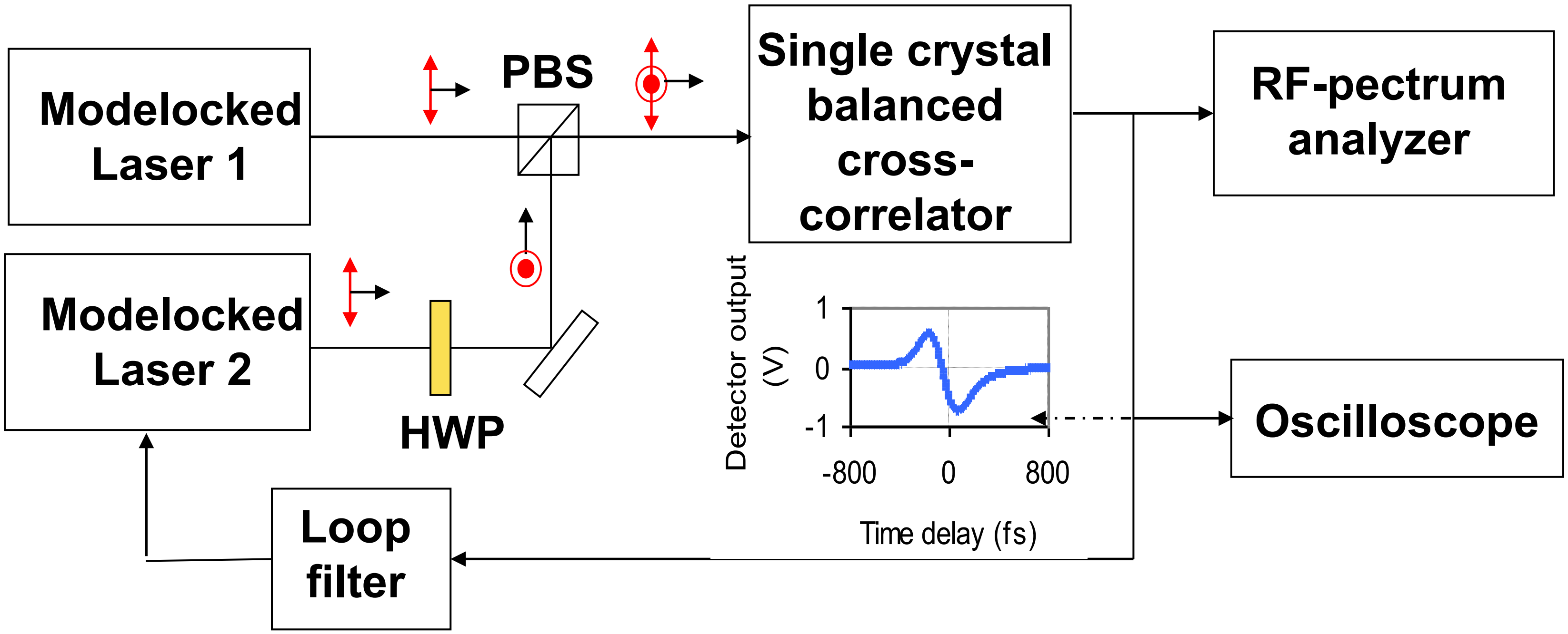


**80 pJ, 200 fs**
**1550nm input pulses**
**at 200 MHz rep. rate**

**In comparison:**
**Typical microwave mixer**
**Slope ~1 μV/fs @ 10 GHz**
**Greatly reduced thermal drifts!**

# Timing Jitter of Fiber Lasers

## Phase detector method → Timing Detector method



Modelocked Laser 1

PBS

Single crystal balanced cross-correlator

RF-pectrum analyzer

Modelocked Laser 2

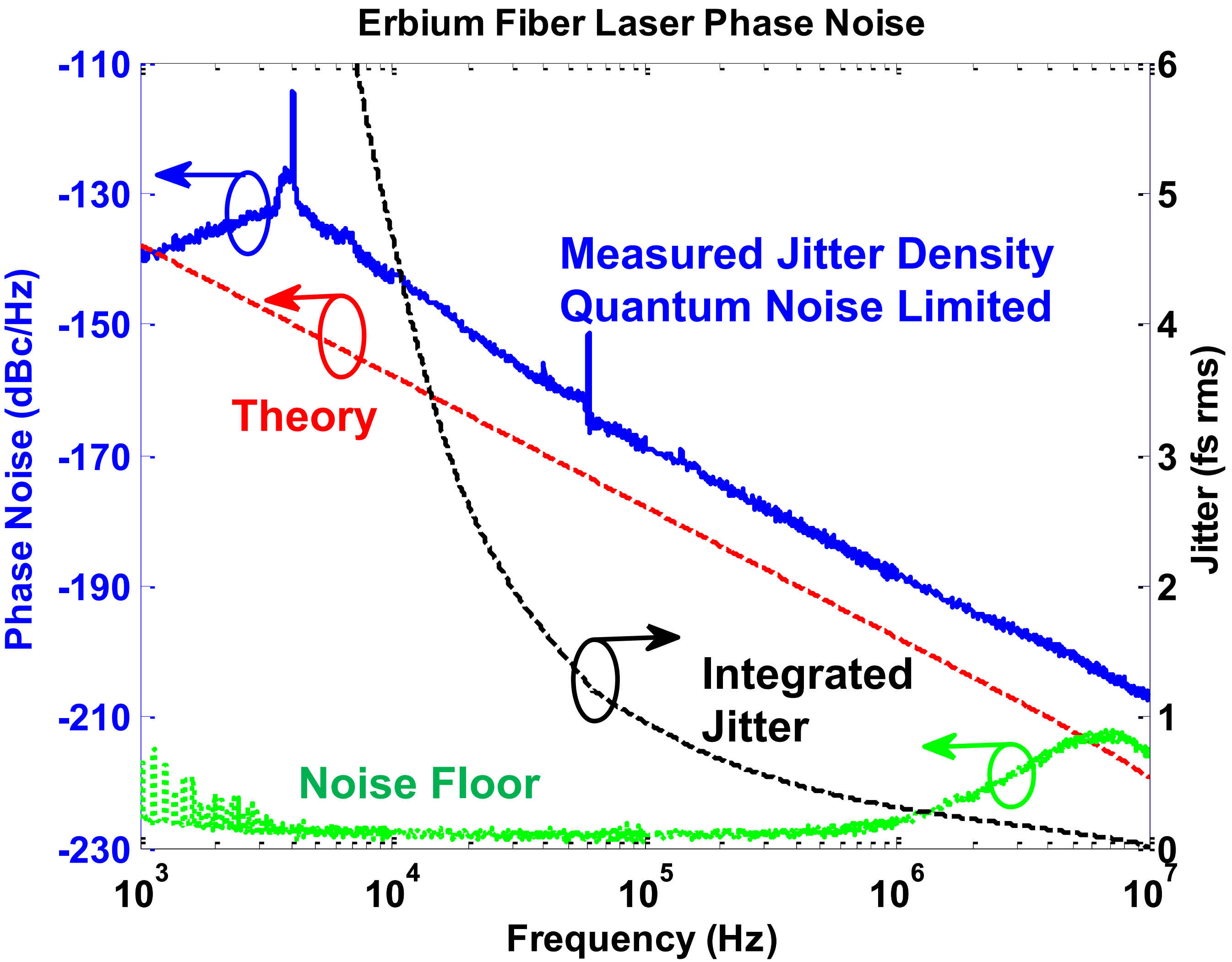
HWP

Oscilloscope

Loop filter

J. Kim, et al. , Opt. Lett. 32, 3519 (2007).

# Timing Jitter of Fiber Lasers



Low timing jitter (<1 fs) in the high frequency range [100 kHz, 10 MHz]

J. Cox et al. Opt. Lett., 35, 3522 (2010)

# Attosecond Jitter and Below?

## How do we get to Attosecond Jitter Lasers?

$$\frac{d}{dt} < \Delta t_{ML}^{2} > \approx \tau^{2} \frac{1}{W_{pulse}} \cdot \frac{\hbar}{\tau_{cav}}$$

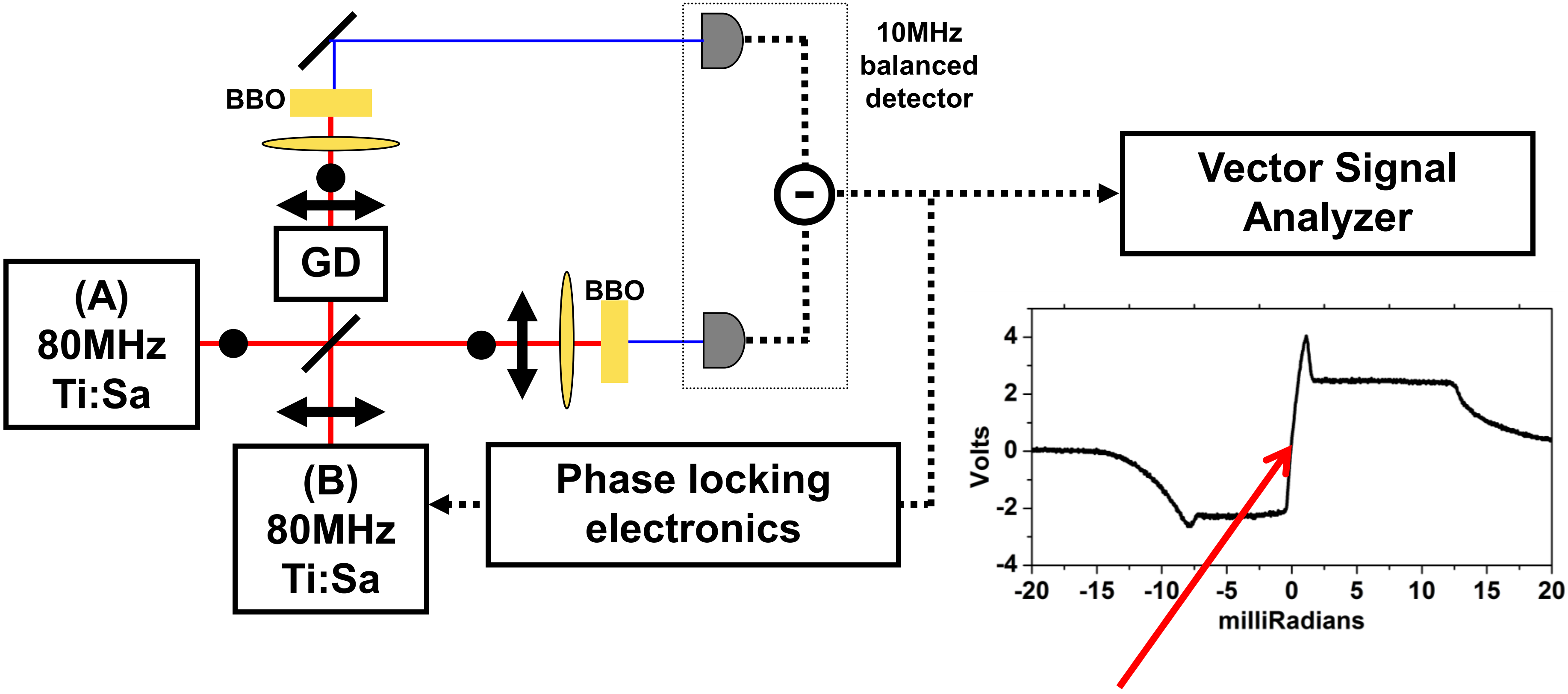
**Intracavity losses down (Factor of 50)**

**Intracavity energy up (Factor of 50)**

**10-fs pulses (Factor of 100)**

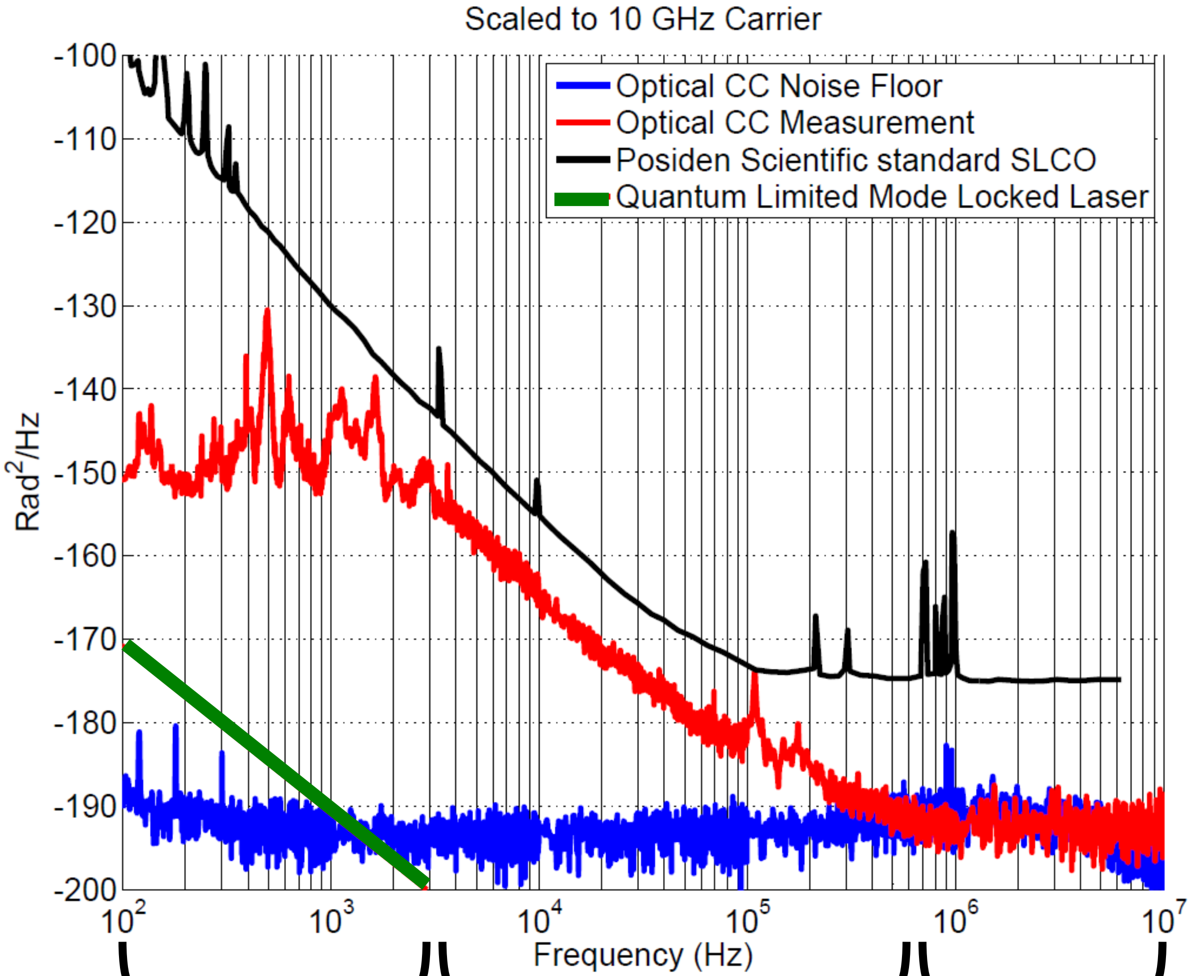
**~ $10^6$ Is it true?**

# Timing Jitter of 10 fs Ti:sapphire Lasers



~ 1V / fs

# Timing Jitter of 10-fs Ti:sapphire Lasers

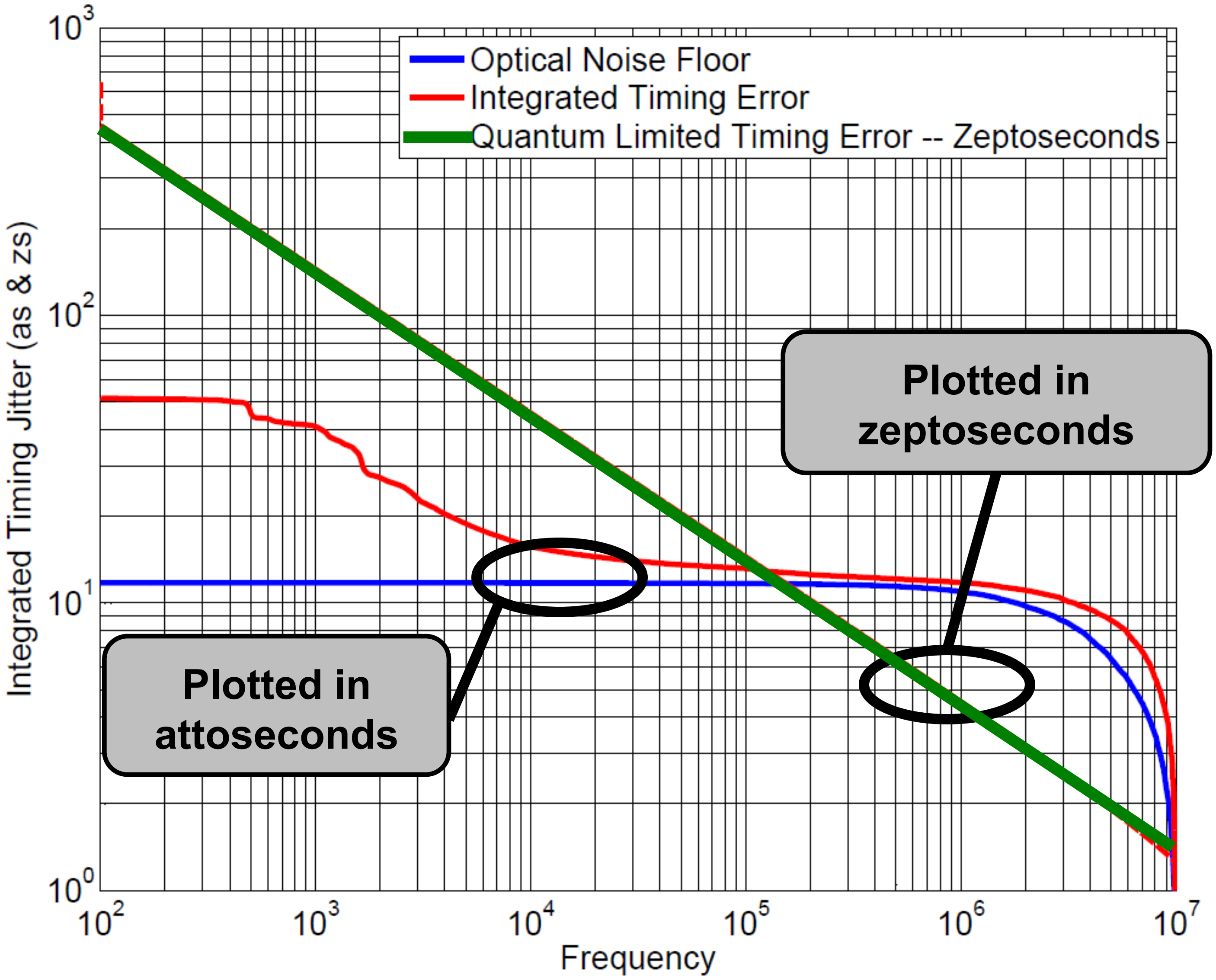


**Environmental noise suppressed by feedback loop**

**Pump laser intensity noise converted to phase noise**

**Nearly shot noise limited**

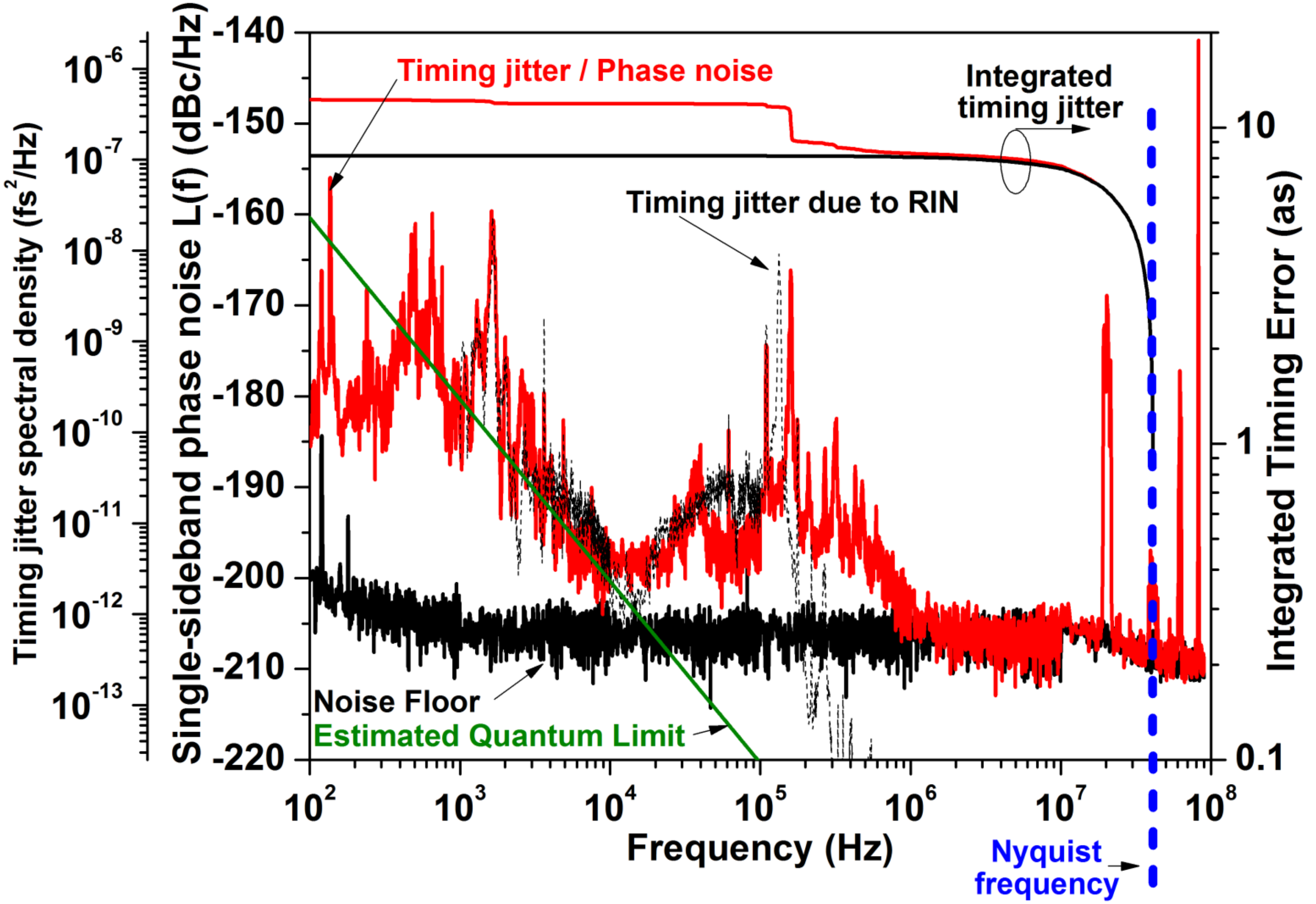
# Integrated Timing Jitter



**Plotted in zeptoseconds**

**Plotted in attoseconds**

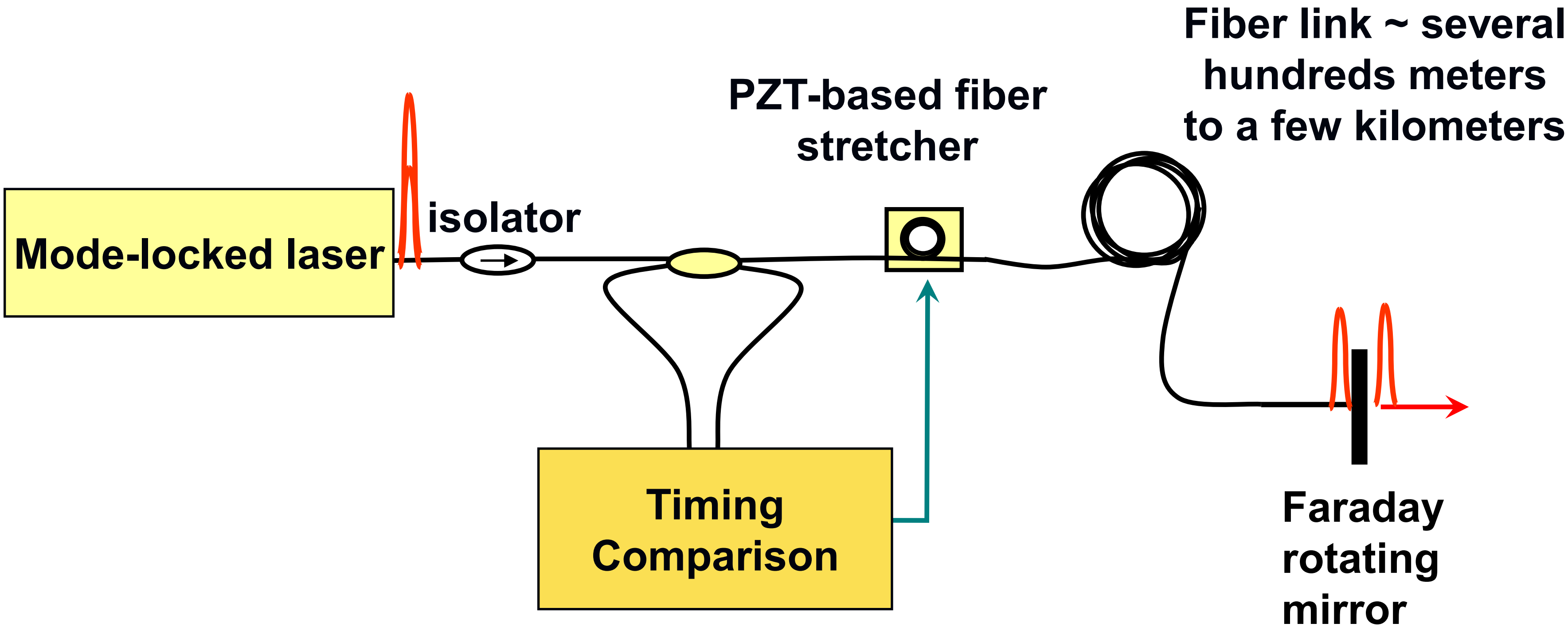
# Two-Laser Synchronization with 100 kHz BW



A. Benedick, et al. Nat. Photonics 6, 97-100, 2012

# Timing - Stabilized Fiber Links

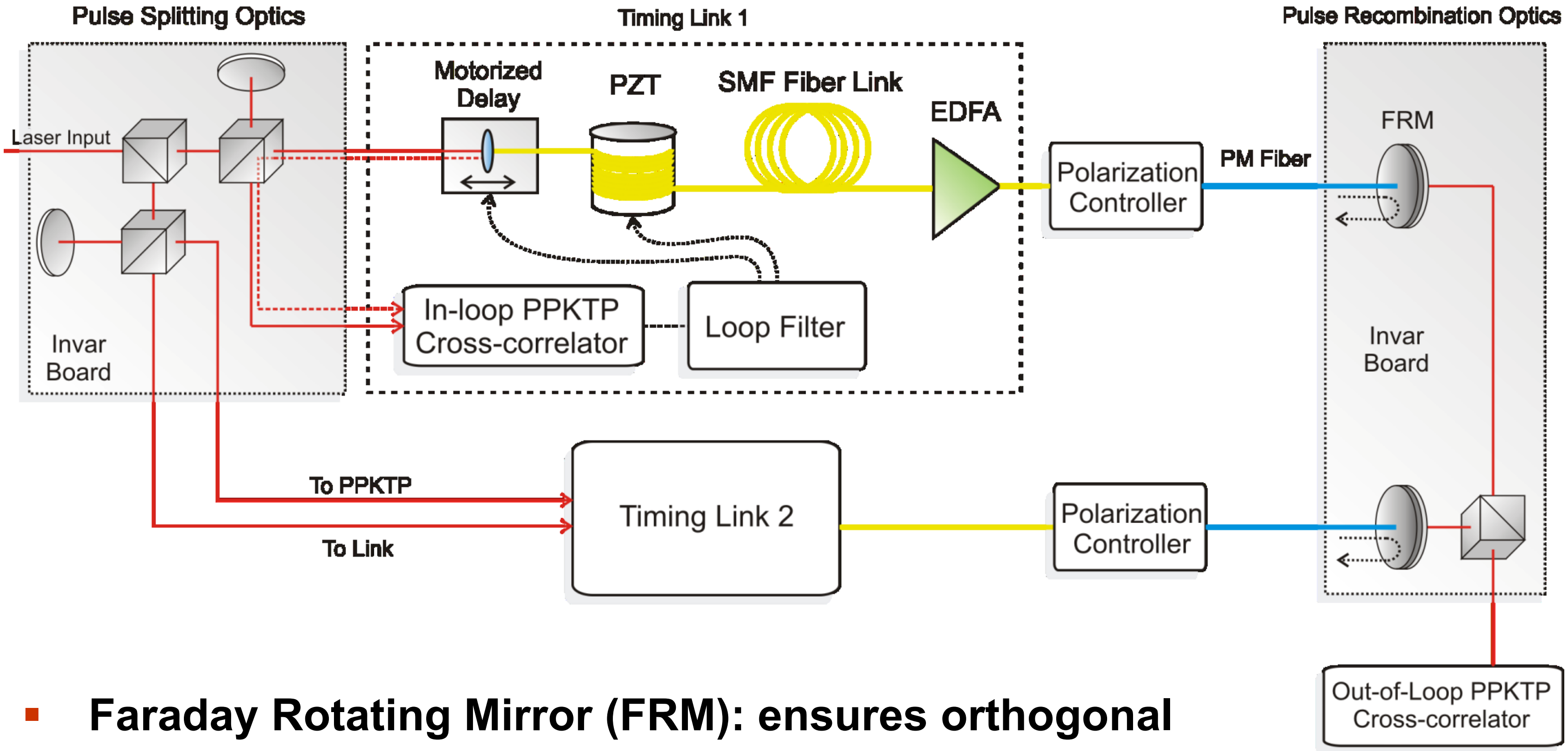
# Timing-Stabilized Fiber Links



Cancel fiber length fluctuations slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 μs → ~100 kHz BW

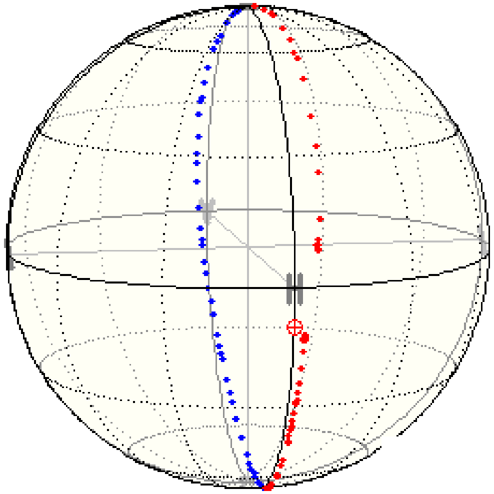
# 2 Link Test System



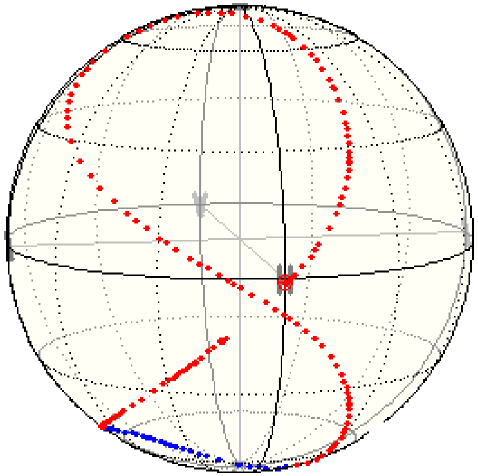
- **Faraday Rotating Mirror (FRM): ensures orthogonal polarization upon return**
- **Polarization controller eliminates polarization drift at output**

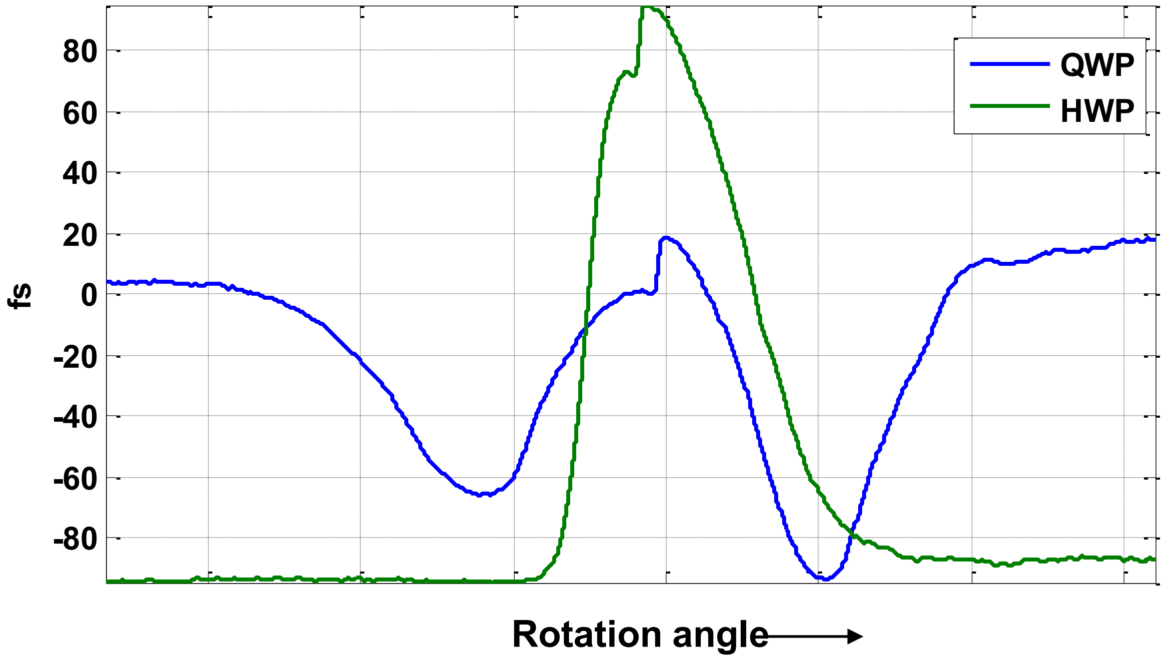
# Limitations by PMD

**HWP**



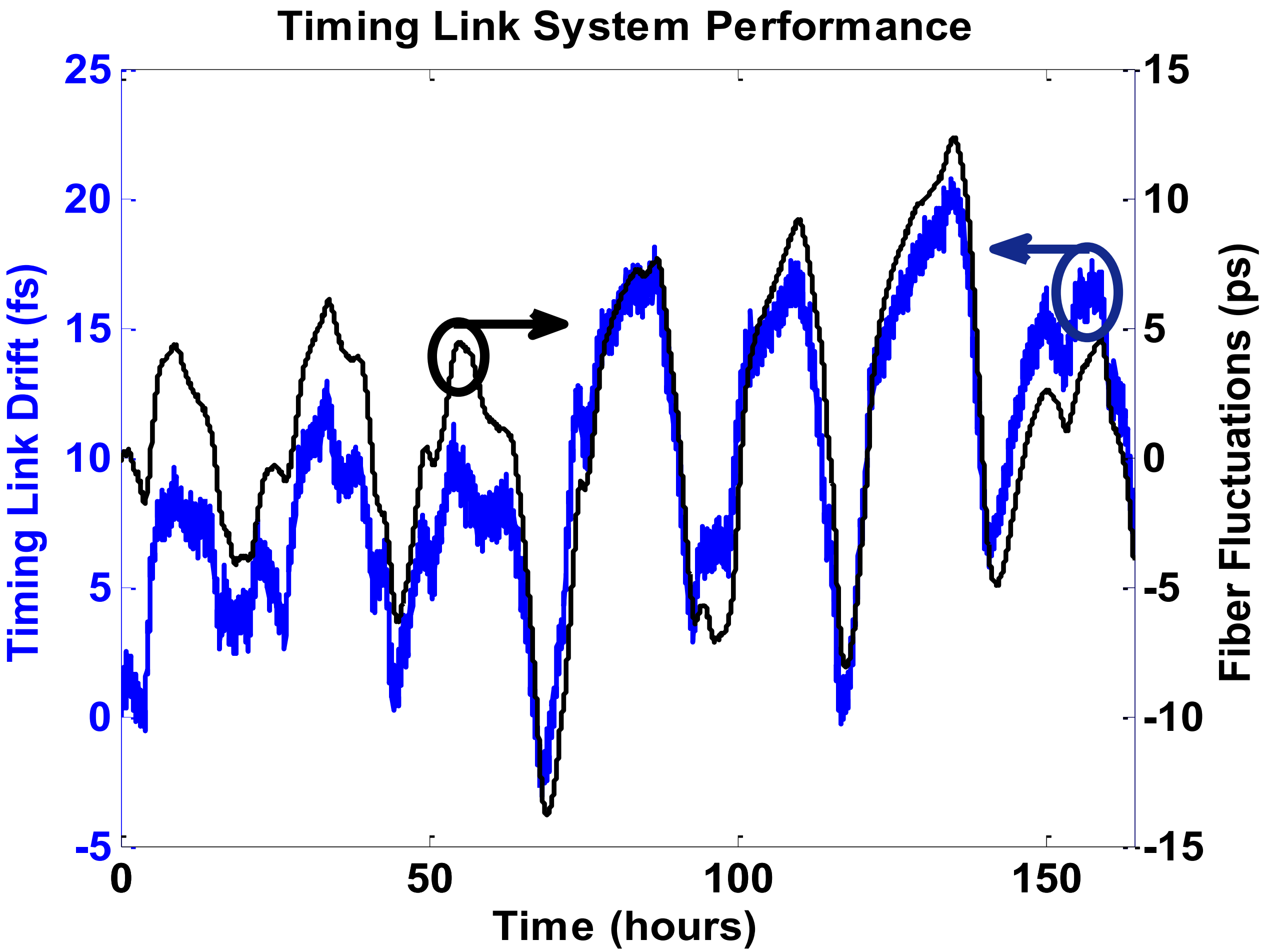
**QWP**





- Stress of fiber link critical to PMD
- PZT stretcher → ~80 fs PMD
- Longterm solution: PM-Fiber Link

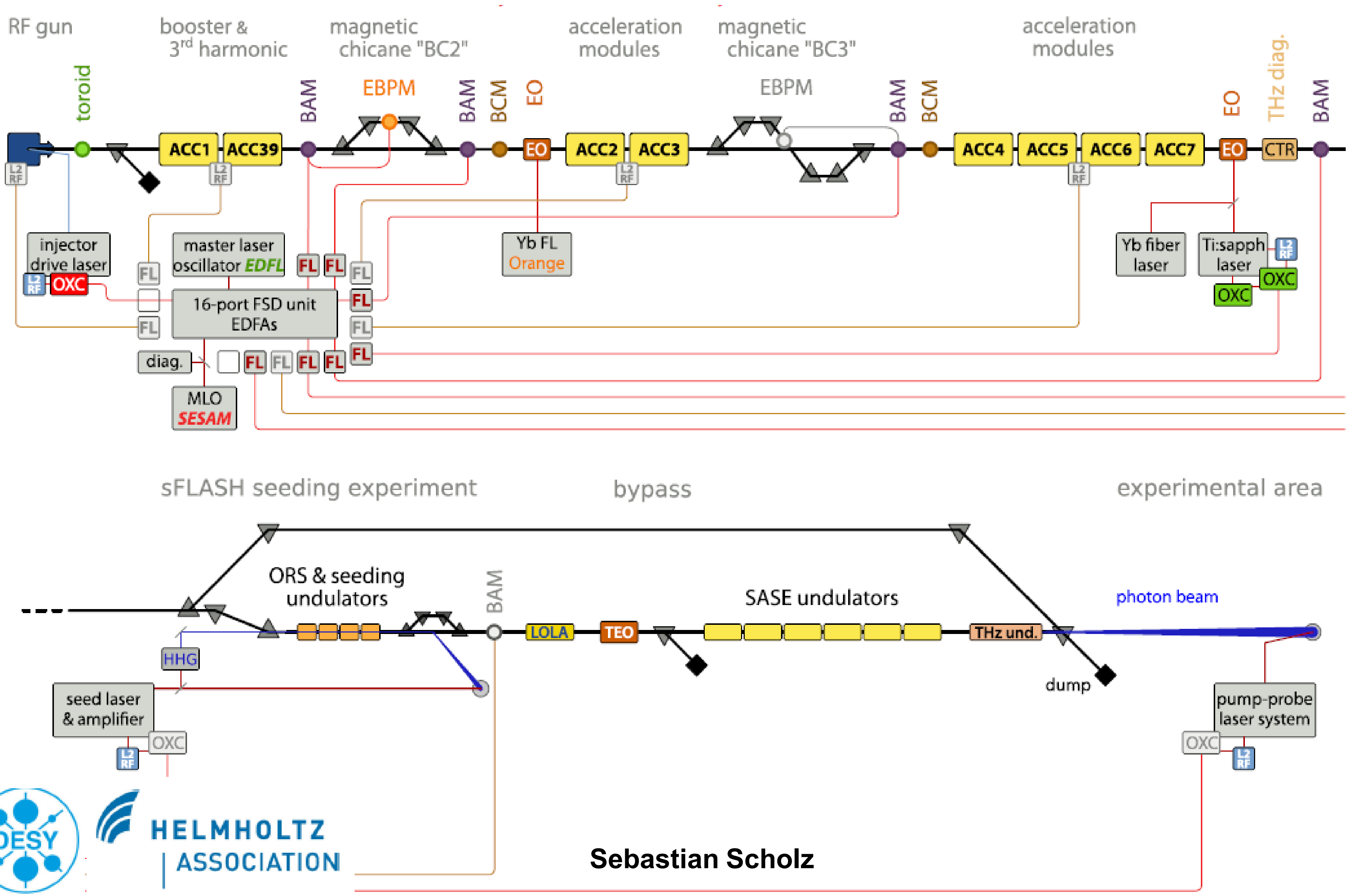
# 1-week operation w/ Pol. Control



**5 fs (rms) drifts over one week of operation**

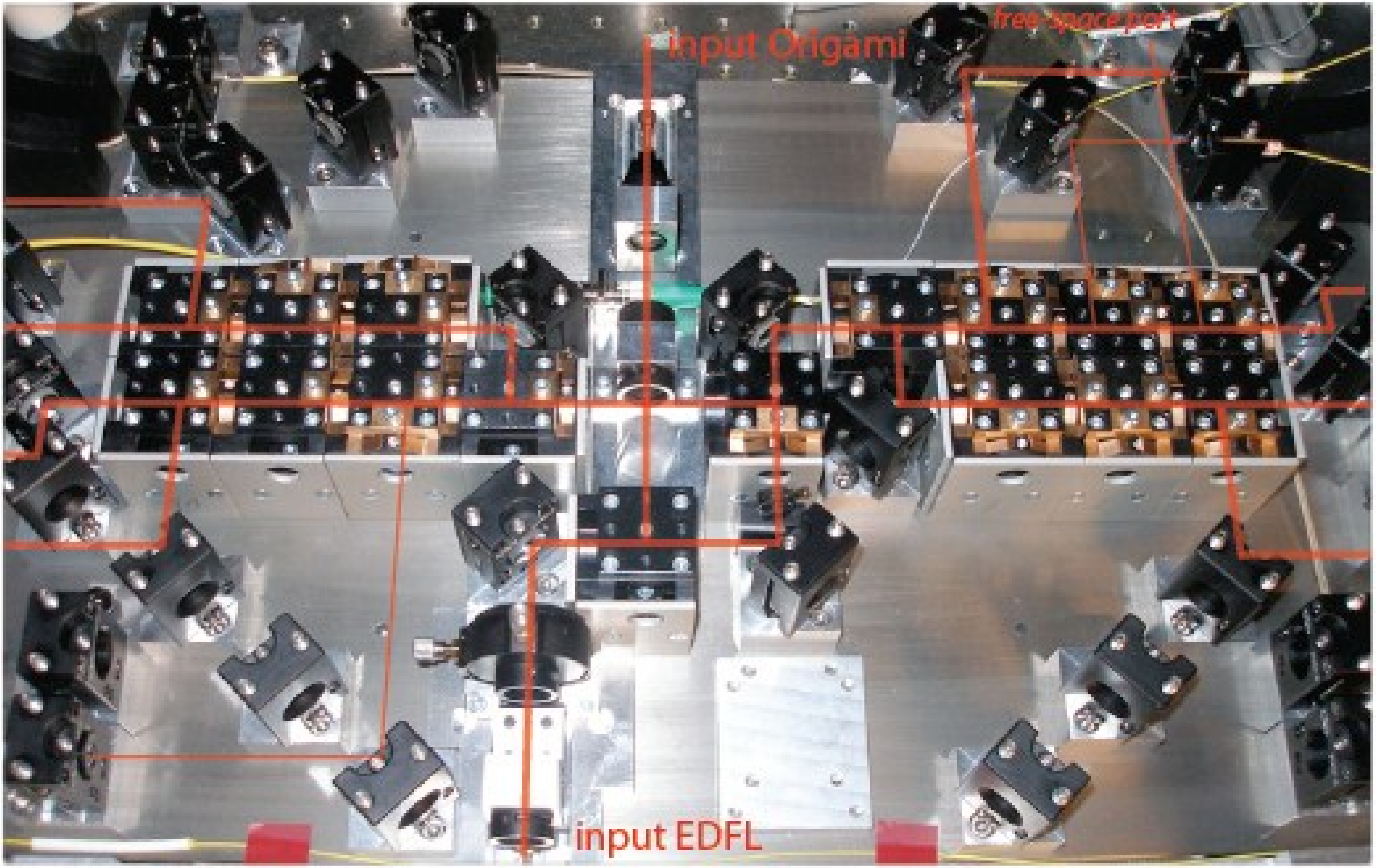
**Residual drifts: Thermal expansion in X-correlators**

# Implementation at FLASH - DESY

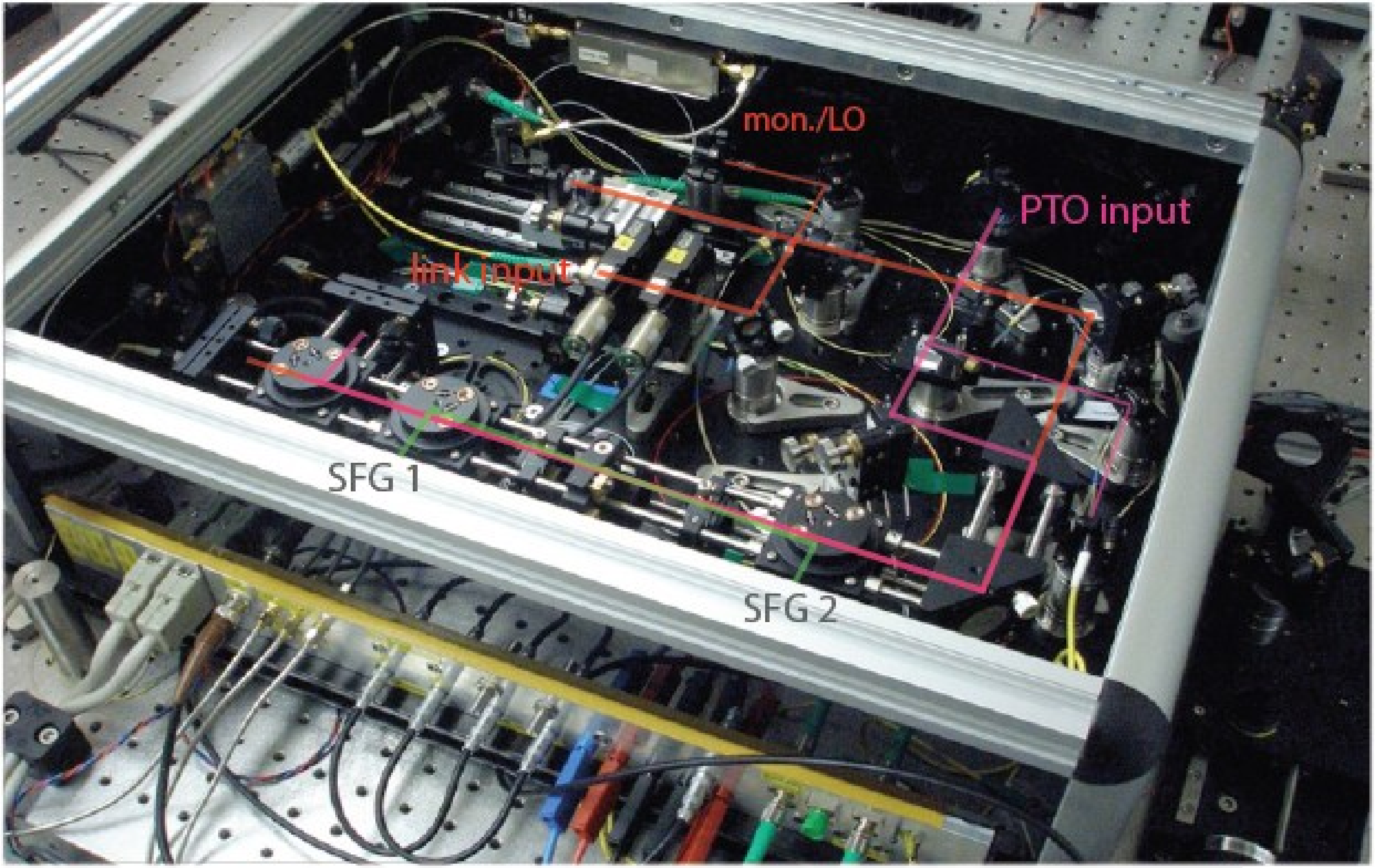


**Sebastian Scholz**

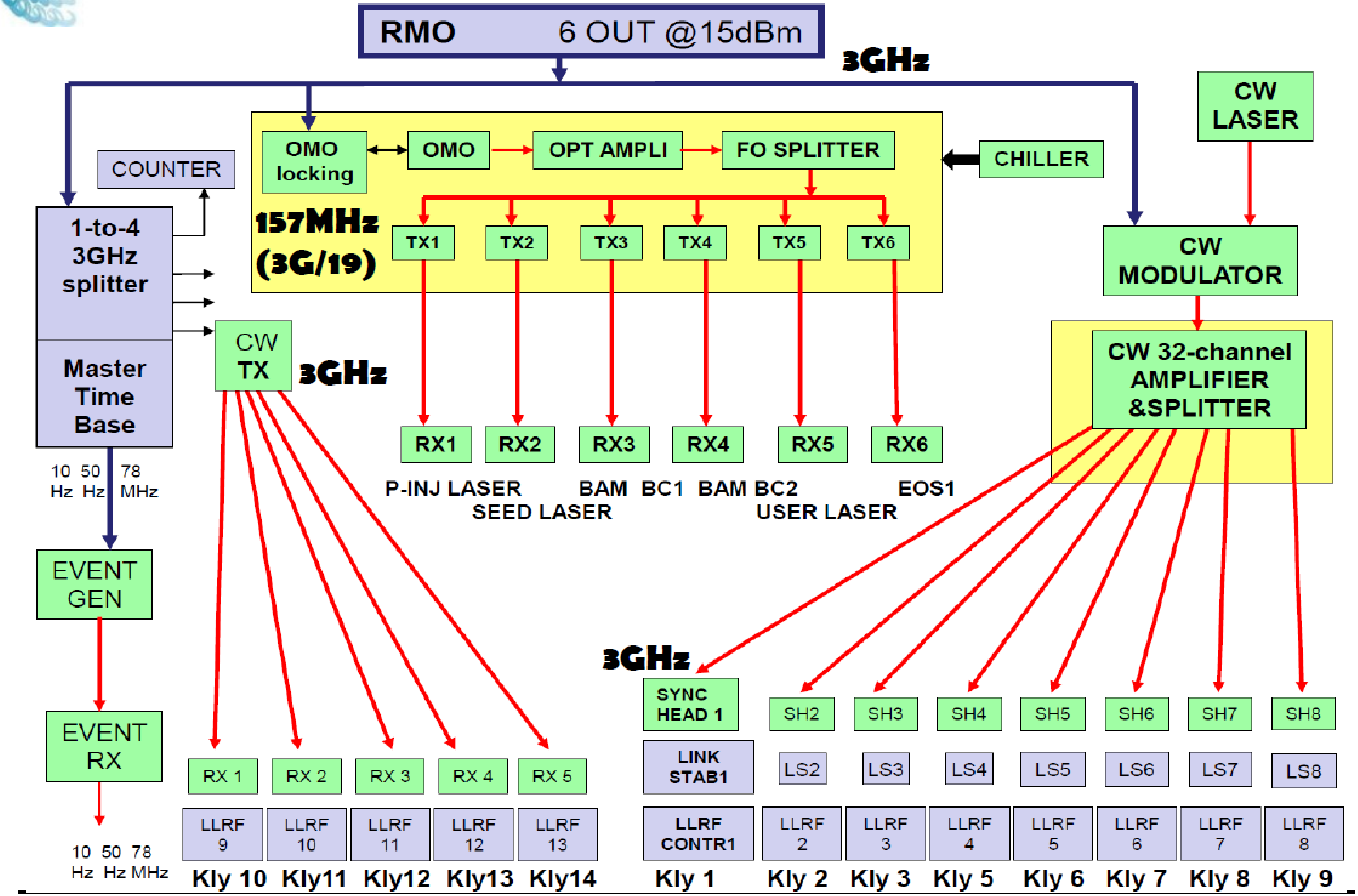
# Reference Pulse Distribution to 16 Fiber Links



# Optical Cross-Correlator for Photo Injector Laser



# FERMI@Elettra timing system: current status



RMO 6 OUT @15dBm

3GHz

COUNTER

1-to-4 3GHz splitter

Master Time Base

10 Hz 50 Hz 78 MHz

EVENT GEN

EVENT RX

10 Hz 50 Hz 78 MHz

OMO locking

OMO

OPT AMPLI

FO SPLITTER

CHILLER

157MHz (3G/19)

TX1 TX2 TX3 TX4 TX5 TX6

RX1 RX2 RX3 RX4 RX5 RX6

P-INJ LASER

SEED LASER

BAM BC1

BAM BC2

USER LASER

EOS1

CW LASER

CW MODULATOR

CW 32-channel AMPLIFIER &SPLITTER

CW TX

3GHz

RX 1 RX 2 RX 3 RX 4 RX 5

LLRF 9 LLRF 10 LLRF 11 LLRF 12 LLRF 13

Kly 10 Kly11 Kly12 Kly13 Kly14

3GHz

SYNC HEAD 1

LINK STAB1

LLRF CONTR1

Kly 1

SH2 SH3 SH4 SH5 SH6 SH7 SH8

LS2 LS3 LS4 LS5 LS6 LS7 LS8

LLRF 2 LLRF 3 LLRF 4 LLRF 5 LLRF 6 LLRF 7 LLRF 8

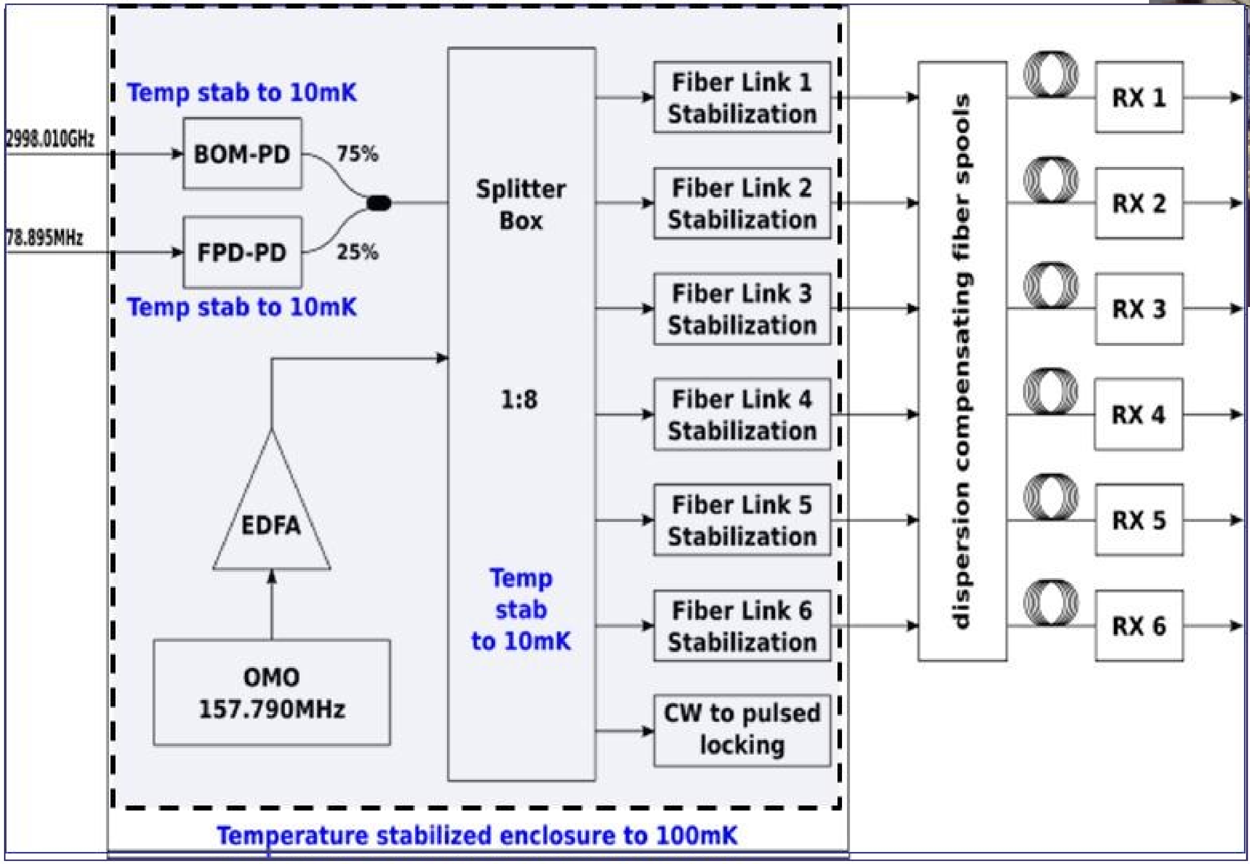
Kly 2 Kly 3 Kly 5 Kly 6 Kly 7 Kly 8 Kly 9

M. Ferianis

# Pulsed optical timing

Pulsed optical timing system has been engineered and built by MENLO Systems, Gmbh & IdestaQE

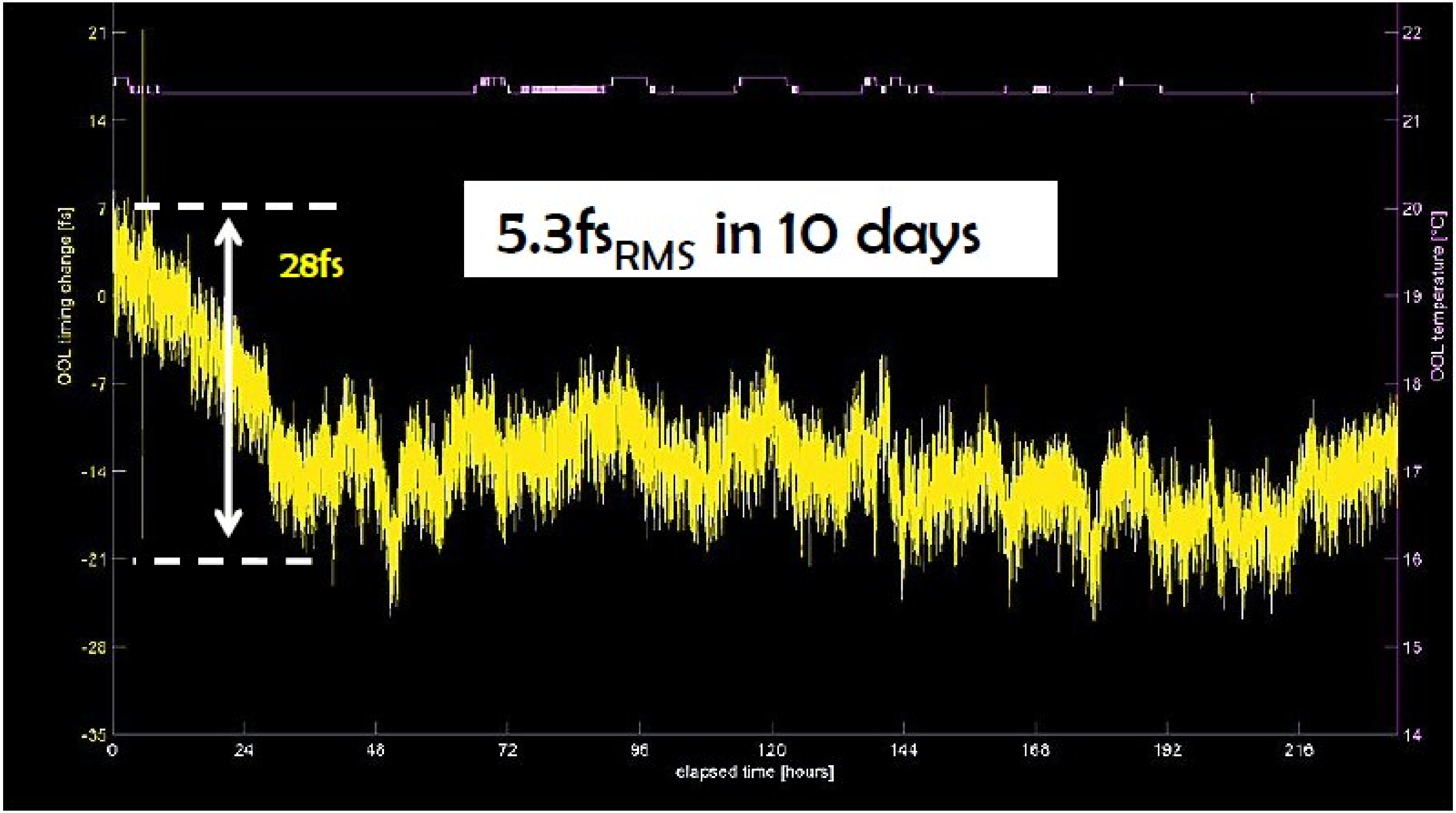
A 2 year project, with on-site installation and testing included



Pulsed optical timing system components installed in the FERMI timing hutch

# Pulsed optical timing

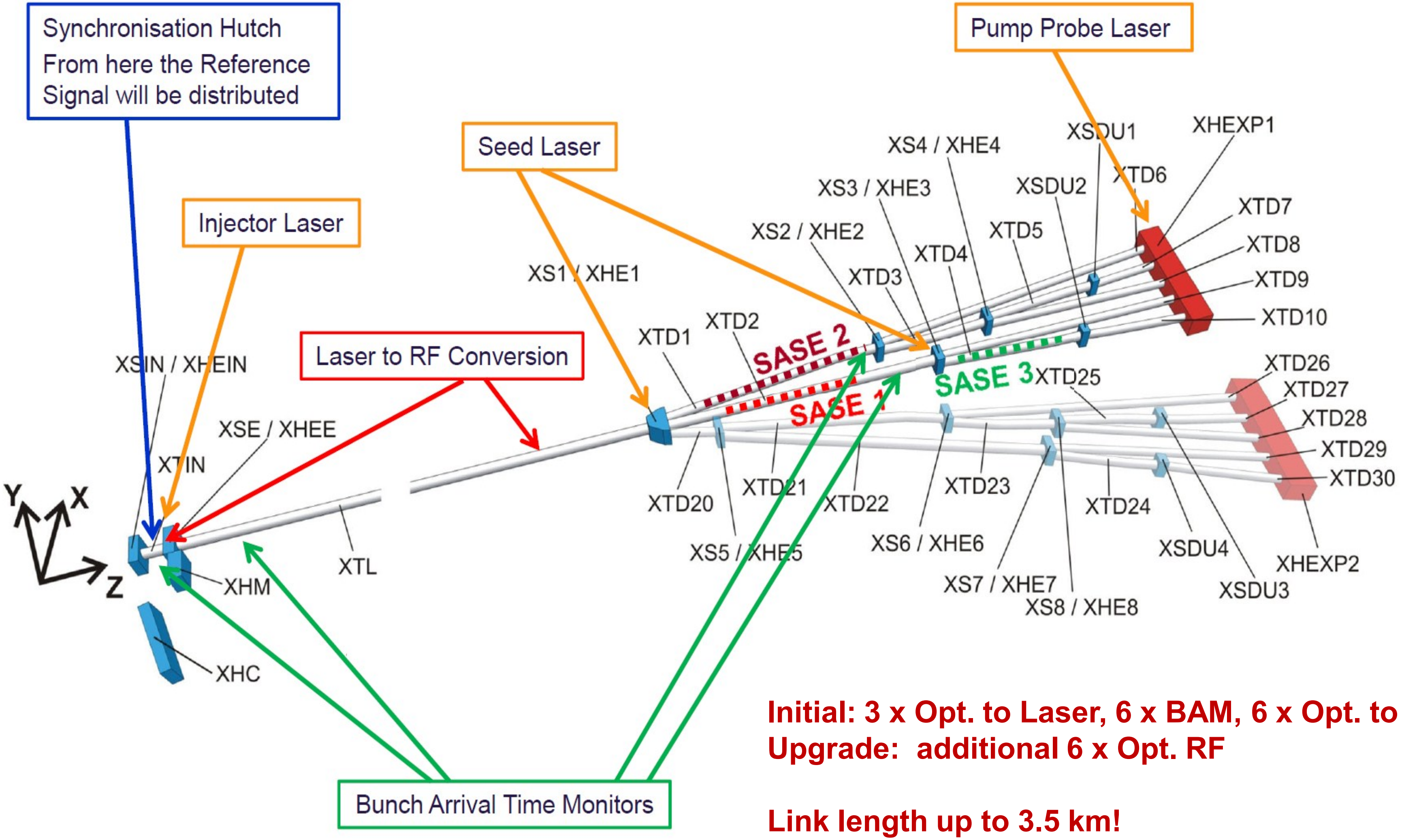
## out-of-loop long term (10 days) drift measurement; local optical reference vs. 150m loop-back stabilized link



28fs

$5.3\text{fs}_{\text{RMS}}$ in 10 days

# European XFEL Timing Overview



**Initial: 3 x Opt. to Laser, 6 x BAM, 6 x Opt. to RF**
**Upgrade:  additional 6 x Opt. RF**

**Link length up to 3.5 km!**

# Conclusions

- Fundamental jitter in modelocked lasers is really low!
- Typical fiber lasers ~ 1 fs jitter for frequencies > 10 kHz
- Solid-state lasers ~ 10 as jitter for frequencies > 10 kHz (pump noise limited)

  Potential for < 1 as jitter!

- Pulsed timing distribution systems can give long term stable timing to X-ray FELs: < 10 fs over ~ a week.
- Increase long term stability, robustness and < 1fs stability:
  PM – Fiber Links + Integrated Balanced Cross Correlators.
- Systems at the 10 fs level have been successfully implemented at FLASH – DESY, FERMI and are also considered for timing of the European XFEL.