# Long-distance optical stabilization with femtosecond resolution

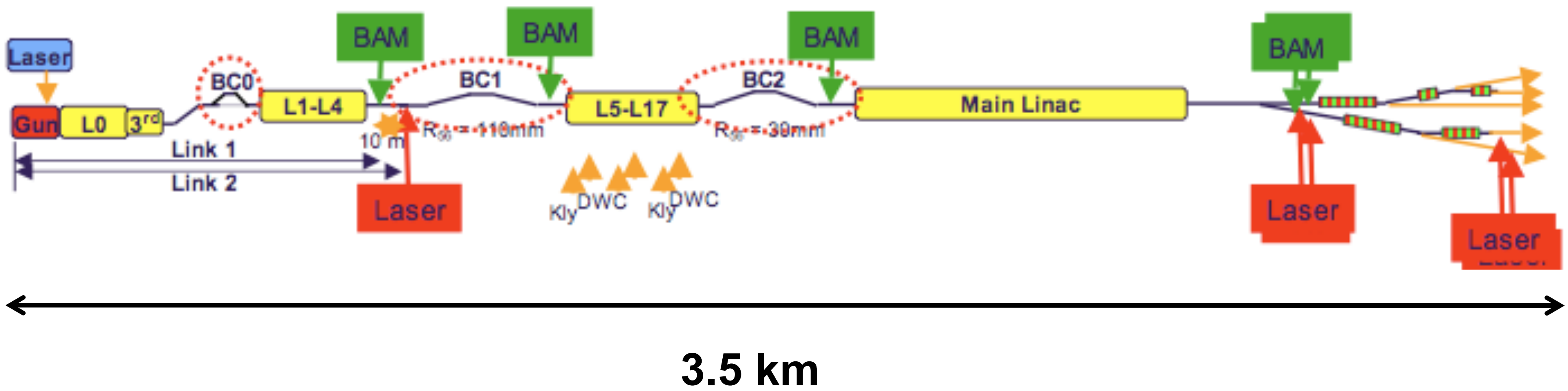
F. Ömer İlday

Physics Department

Bilkent Üniversitesi

# Motivation for use in light sources

- Next-generation light sources (e.g., DESY) will generate few-fs x-ray pulses
- X-rays and lasers must be synchronized at a level shorter than pulse duration.
- Precision required (**few fs over several km**) is beyond RF-distribution capabilities.

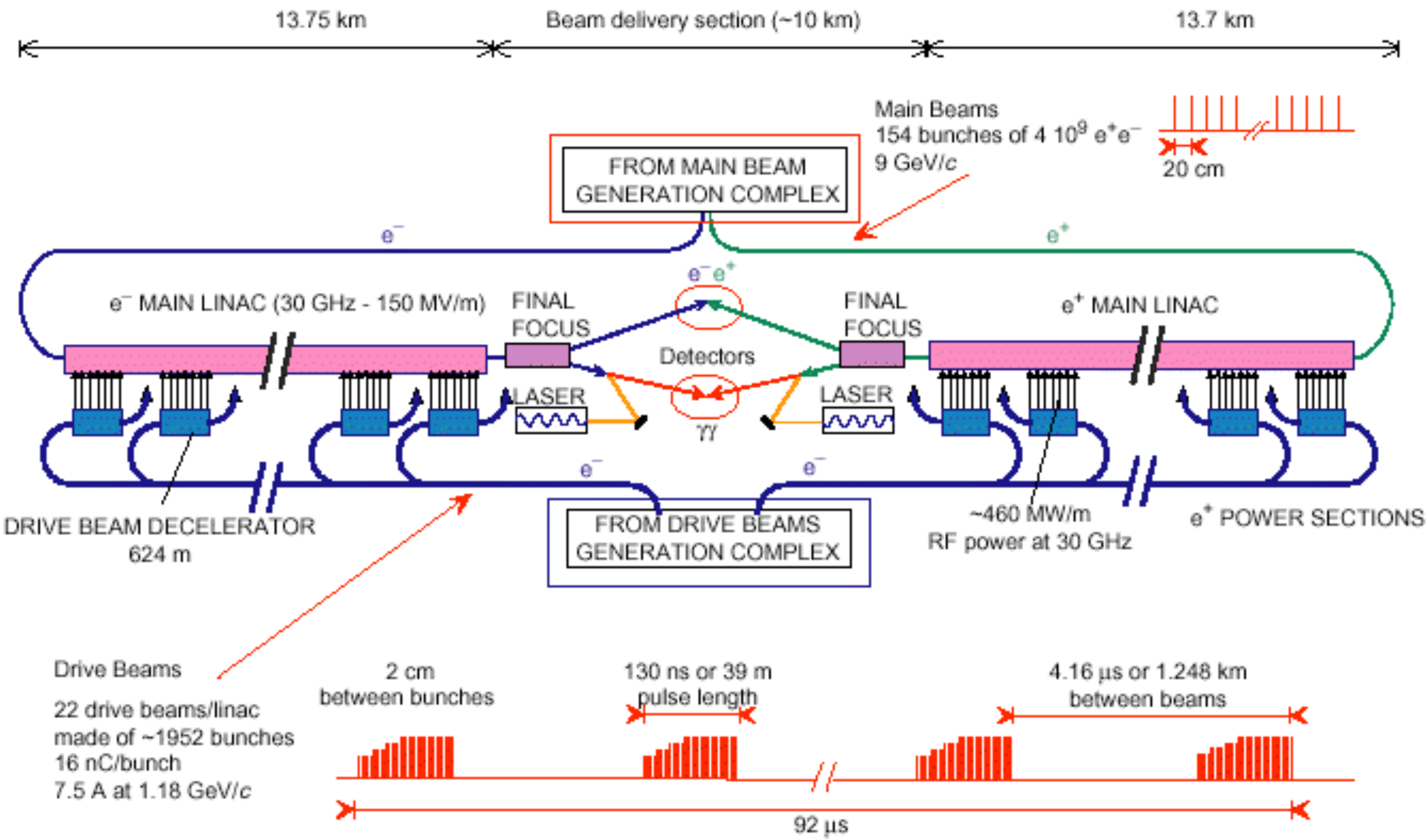


# An ongoing effort dating back to ~2005

- DESY: FLA Group
  - Holger Schlarb, Bernhard Schmidt, Peter Schmüser,
  - Axel Winter, Florian Löhl, Frank Ludwig, Matthias Felber and others …
  - *Talk by Felber at 12:00 describes the DESY system in detail.*
- Prof. Franz Kärtner's Group @ MIT
  - Jeff Chen, Jung-Won Kim, …
- Many other contributors…

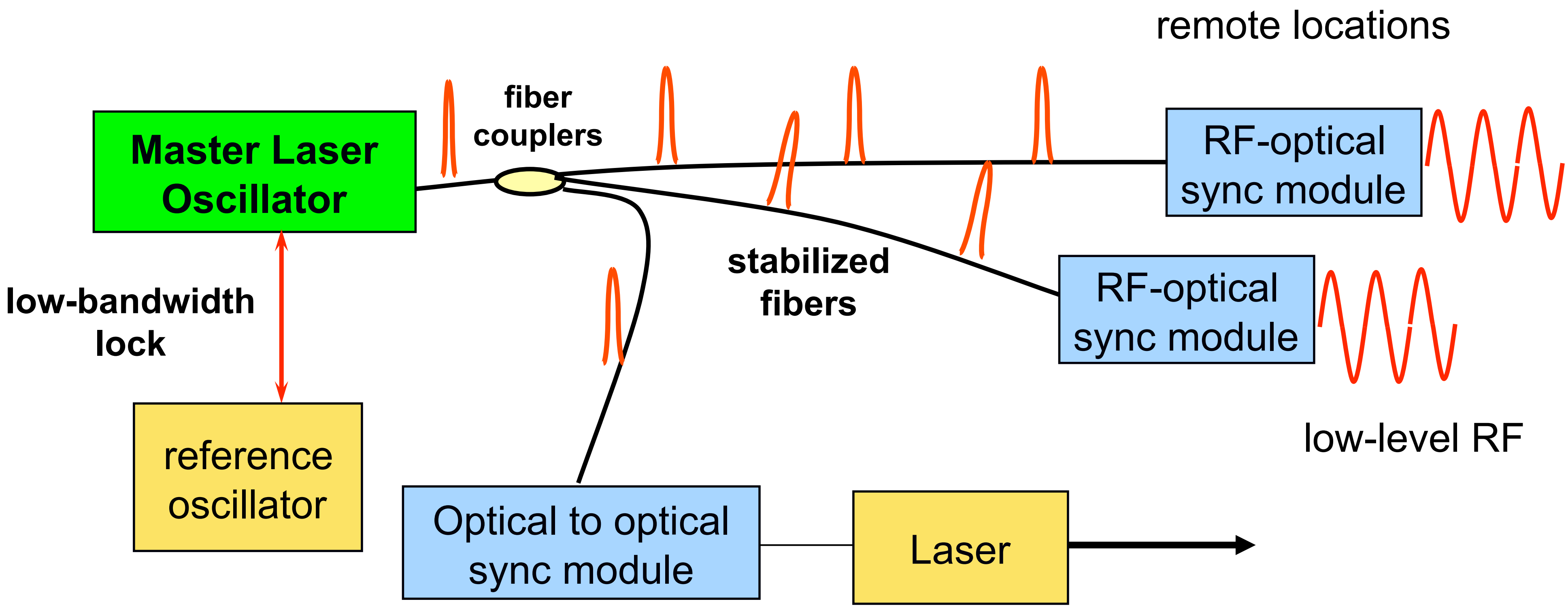
# Motivation for applying optical sync to a particle collider

- At the collision point, the arrival time of the particles must be precisely controlled to locate the collision point right in the center of the detector module.
- About 10 fs variation in arrival time corresponds to 30 μm shift of the collision point.

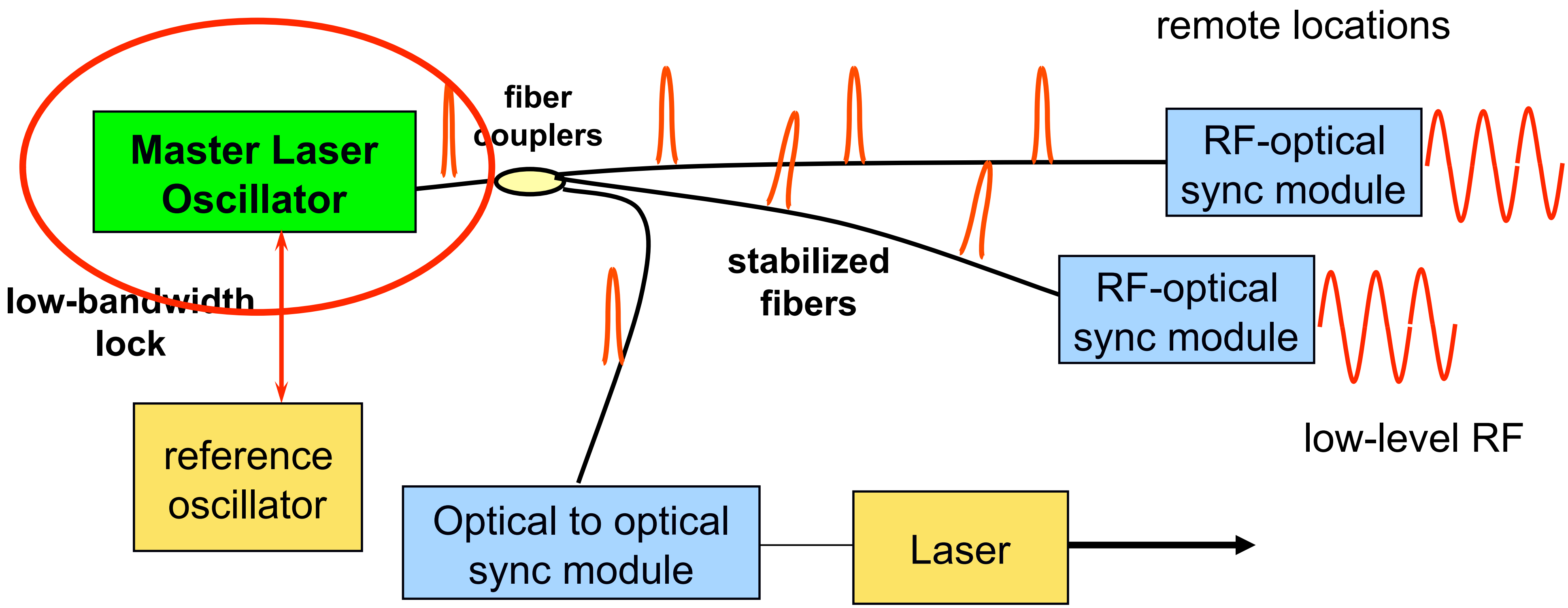


# Optical Synchronization Scheme

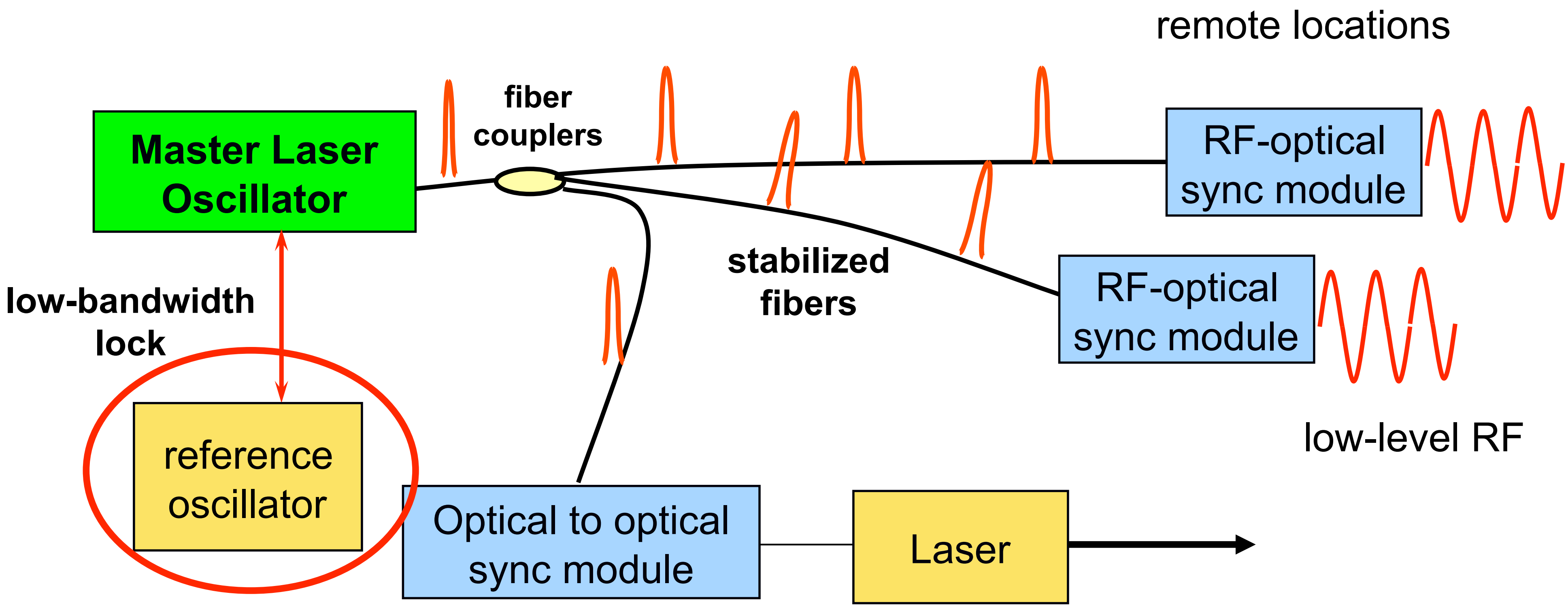
# Synchronization system layout



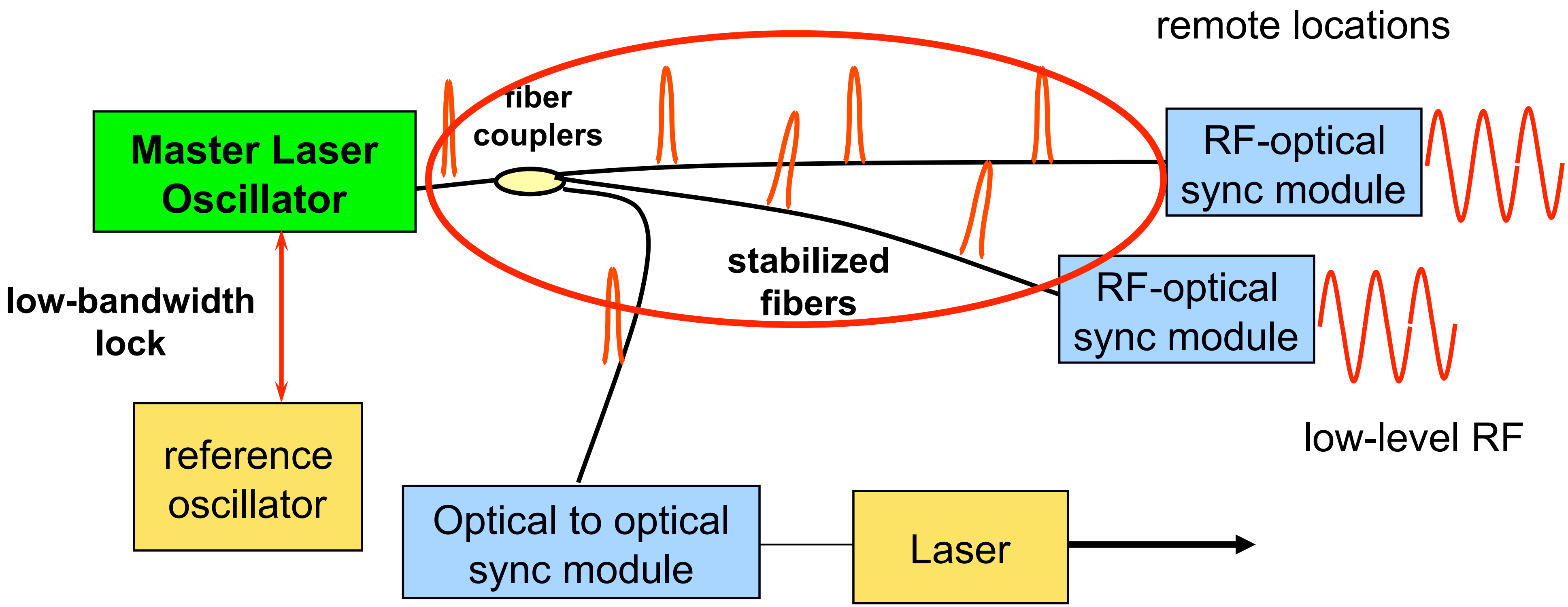
# Synchronization system layout



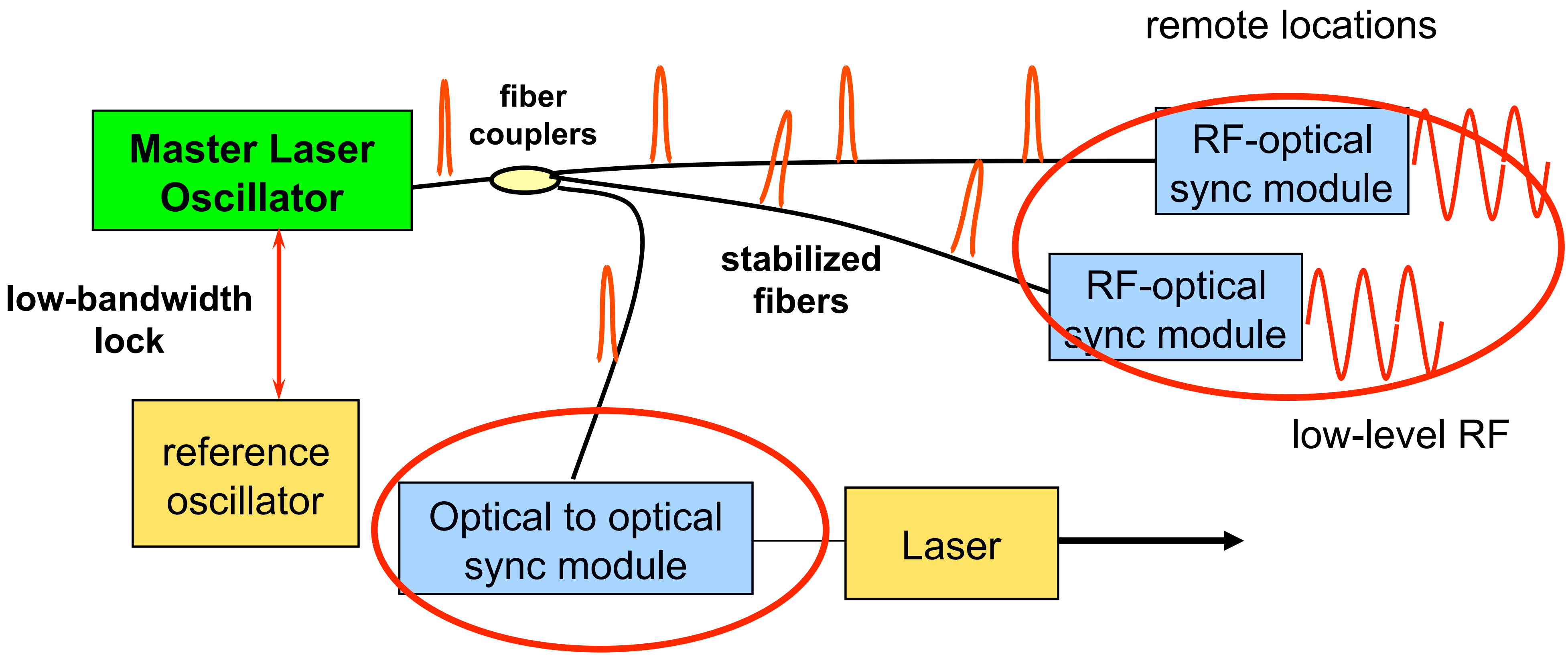
# Synchronization system layout



# Synchronization system layout



# Synchronization system layout



# Optical Synchronization Scheme:

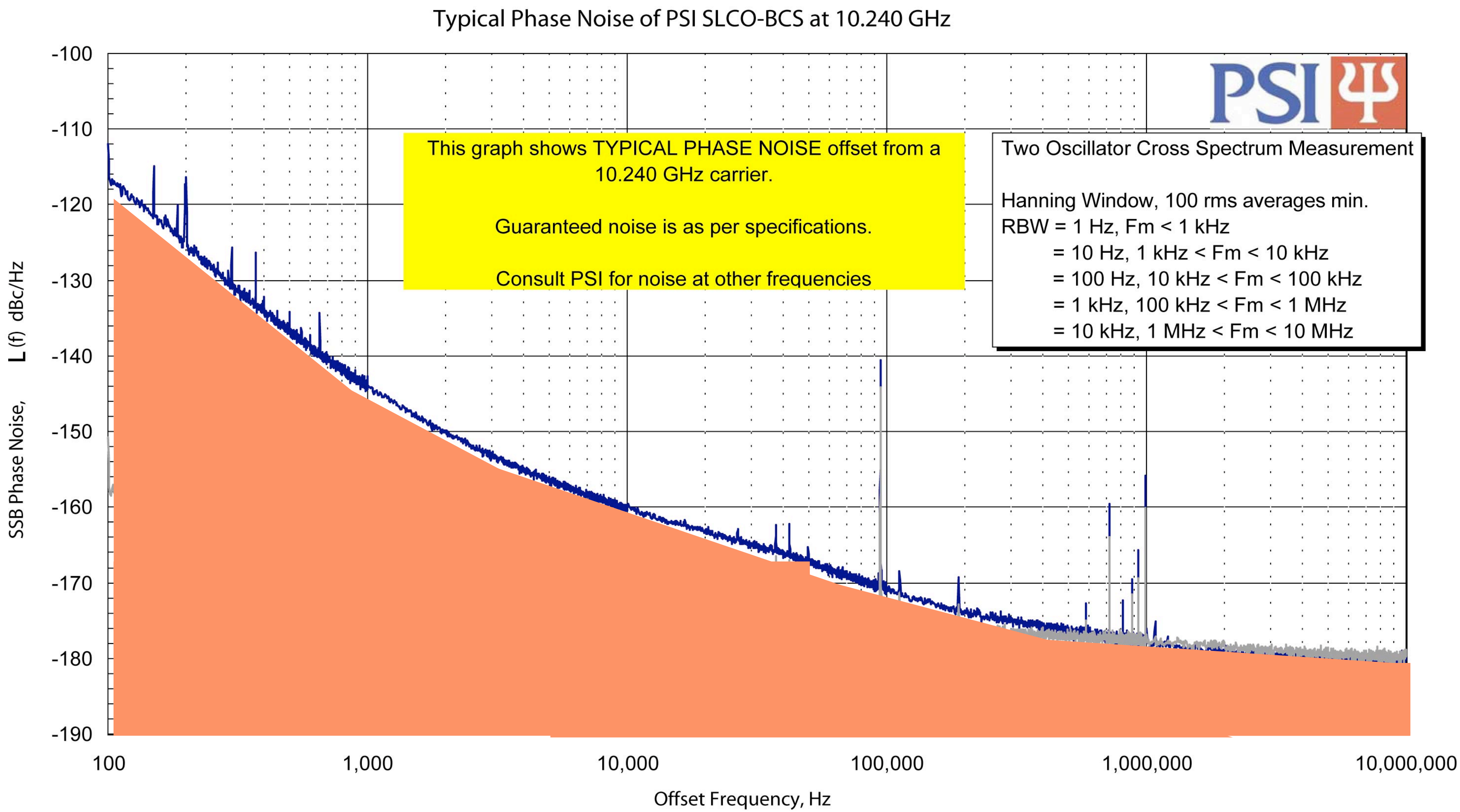
1 - Highly stable reference

2 - Optical master oscillator

3 - Conversion to RF

4 - Timing stabilized fiber links

# Extremely stable microwave/RF oscillators exist




Timing jitter: $$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)df}}{2\pi f_0}$$ < 6fs

## Optical Synchronization Scheme:

1 - Highly stable reference

2 - <u>Optical master oscillator</u>

3 - Conversion to RF

4 - Timing stabilized fiber links

# Robust, low-noise mode-locked laser

- **Internal timing jitter of the master laser has to be absolutely minimal**

- Passively mode-locked lasers offer excellent high-frequency (short-term) stability

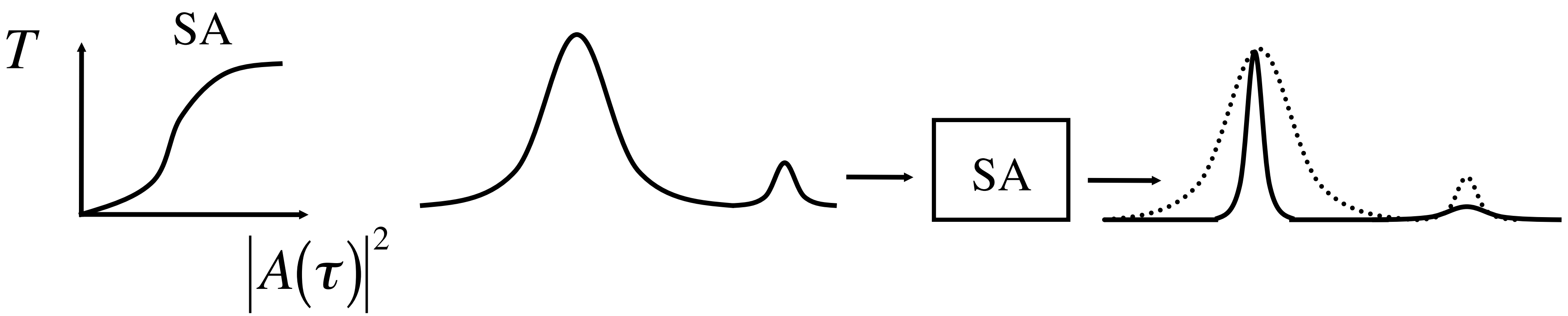
- Er-doped fiber lasers:

  - sub-100 fs to few ps pulse duration
  - 1560 nm wavelength - use telecom components
  - reliable, weeks-long uninterrupted operation
  - can use multiple lasers for redundancy

# Mini-tutorial on Mode-locking

Mode-locked operation is self-initiated from noise fluctuations:

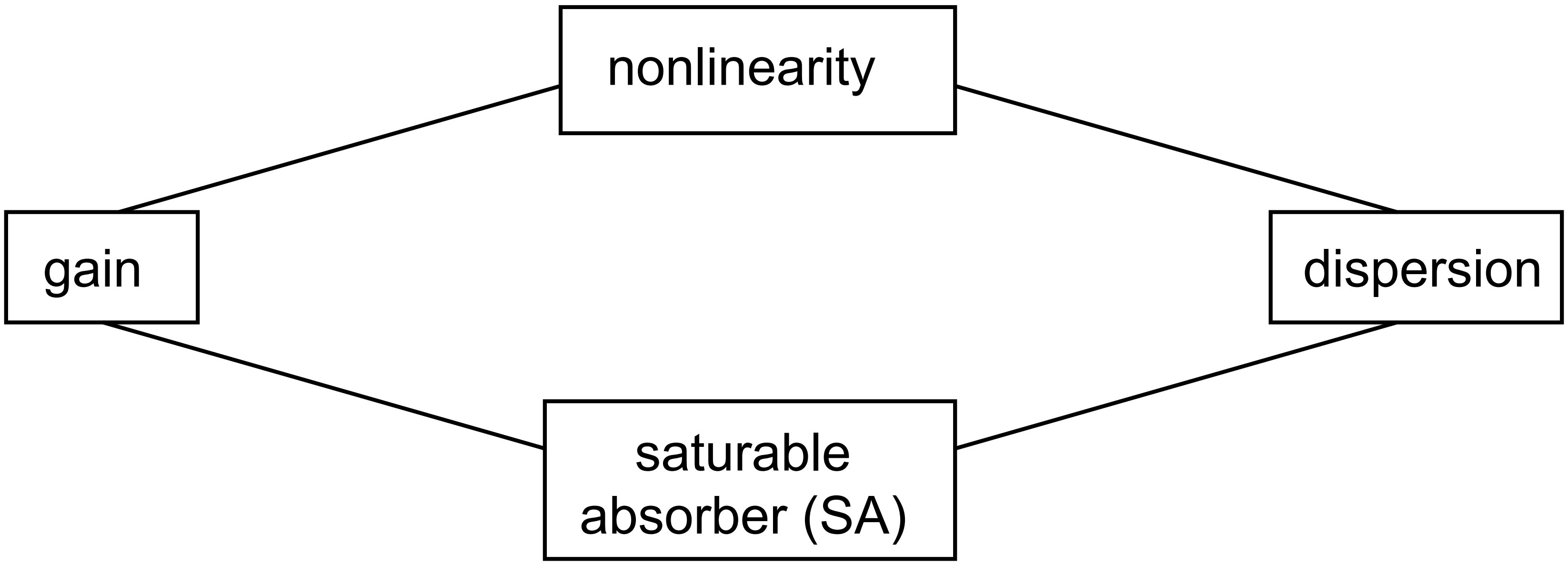
- A saturable absorber (SA) imposes lower loss to higher power
- A noise spike is shortened and grown roundtrip after roundtrip…




- Main principle:
  - let the pulse shape itself
  - create conditions *a priori* such that the laser dynamics naturally produce pulses

# Mini-tutorial on Mode-locking

- Extremely rich interplay of four effects:




- Various distinct types of mode-locking mechanisms exist:
  - Soliton-like
  - Stretched-pulse (dispersion-managed)
  - Self-similar (similariton)
  - All-normal dispersion
  - Soliton-similariton

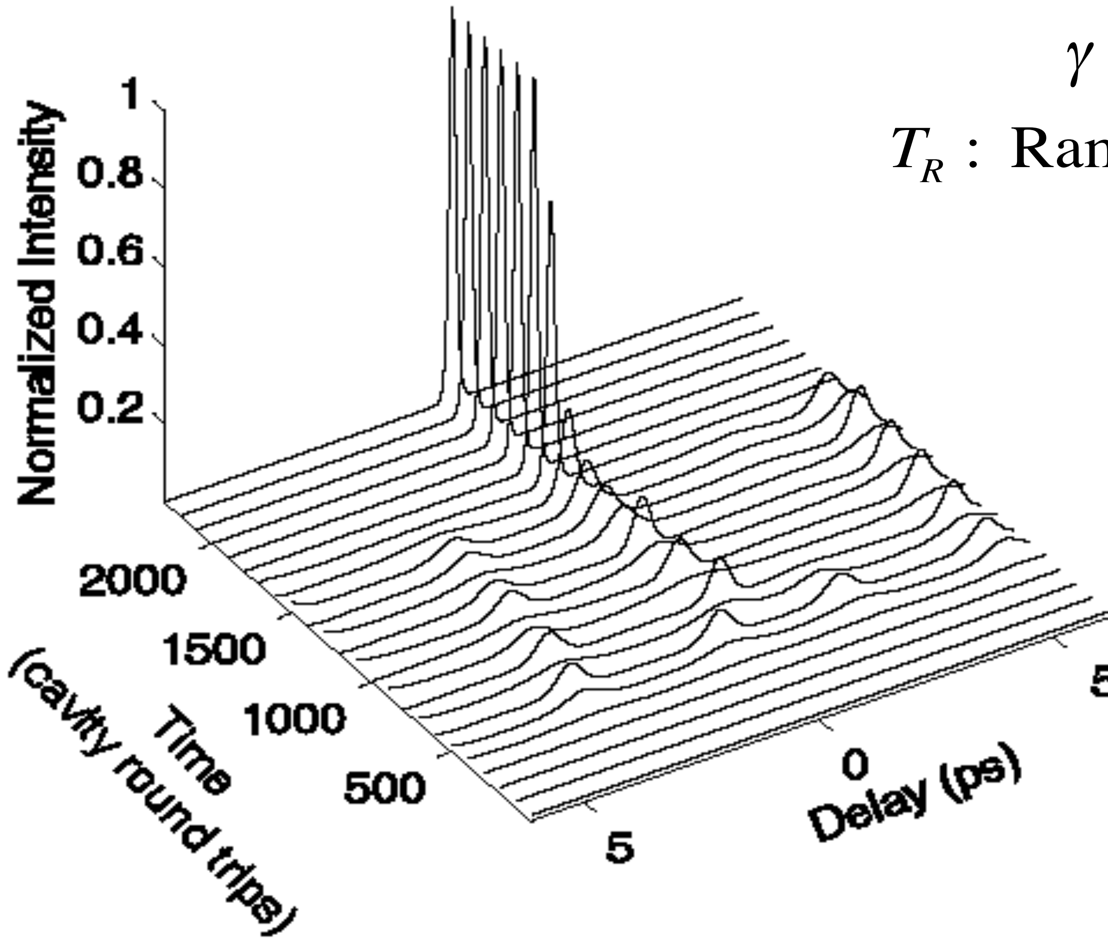
# Mini-tutorial on Mode-locking

- Propagation of pulses is modeled by nonlinear equations:

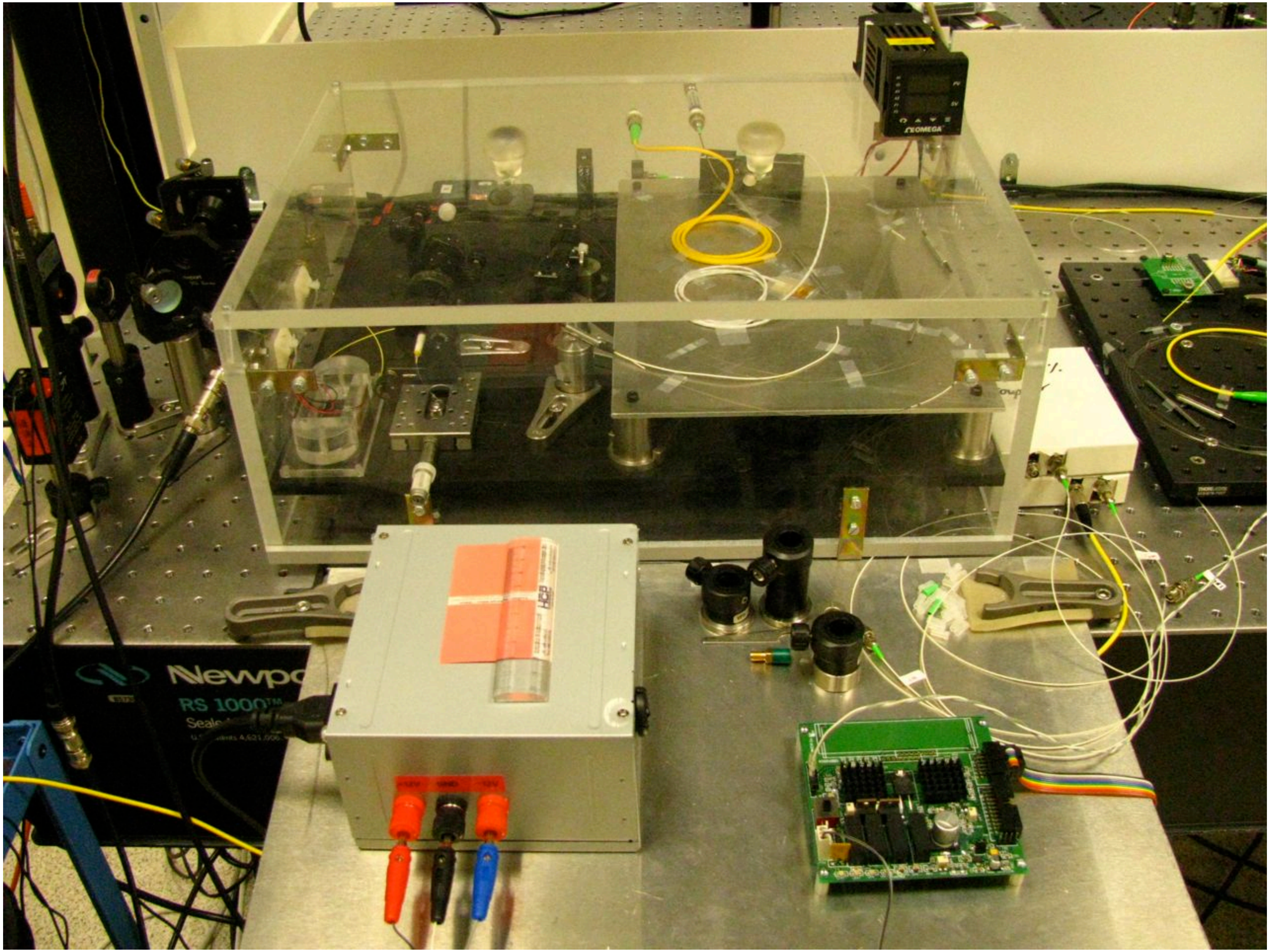
$$\frac{\partial A}{\partial z} + i\frac{\beta^{(2)}}{2}\frac{\partial^2 A}{\partial \tau^2} - \frac{\beta^{(3)}}{6}\frac{\partial^3 A}{\partial \tau^3} = \frac{g}{2}A + \delta\frac{\partial^2 A}{\partial \tau^2}A + i\gamma|A|^2 A + i\gamma T_R \frac{\partial |A|^2}{\partial \tau}A,$$

$$\gamma = n_2\omega_0 / cA_{eff}$$

$T_R$ : Raman response



# An Er-doped fiber laser (EDFL)



# Optical Synchronization Scheme:

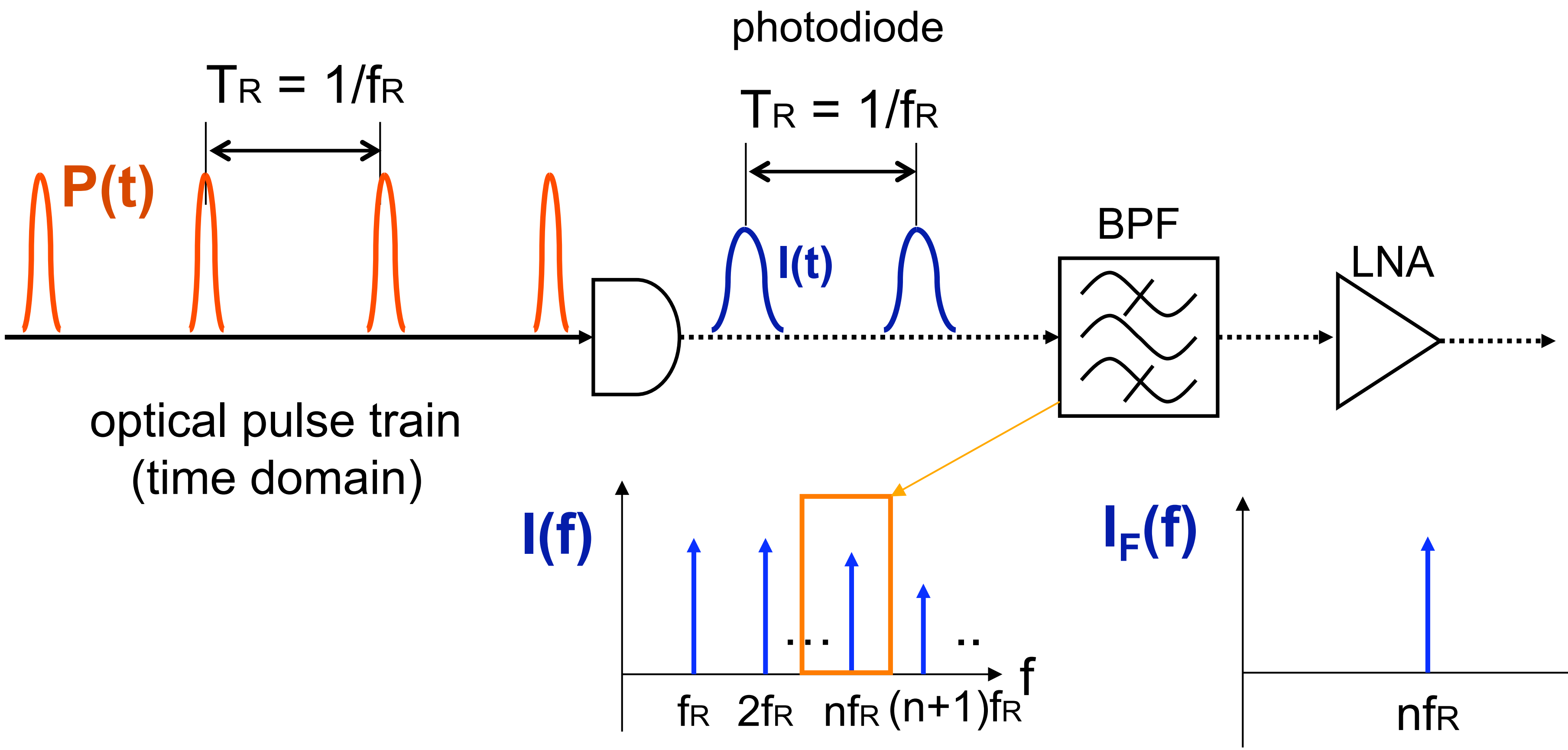
1 - Highly stable reference

2 - Optical master oscillator

3 - <u>Conversion to RF</u>

4 - Timing stabilized fiber links

# Direct detection to extract RF from pulse train




Amplitude-to-phase conversion introduces excess timing jitter.
Simple, low-cost, but limited to ≤ 10 fs in practice

***Advanced schemes for extracting the RF are available at increased complexity…***

## Optical Synchronization Scheme:

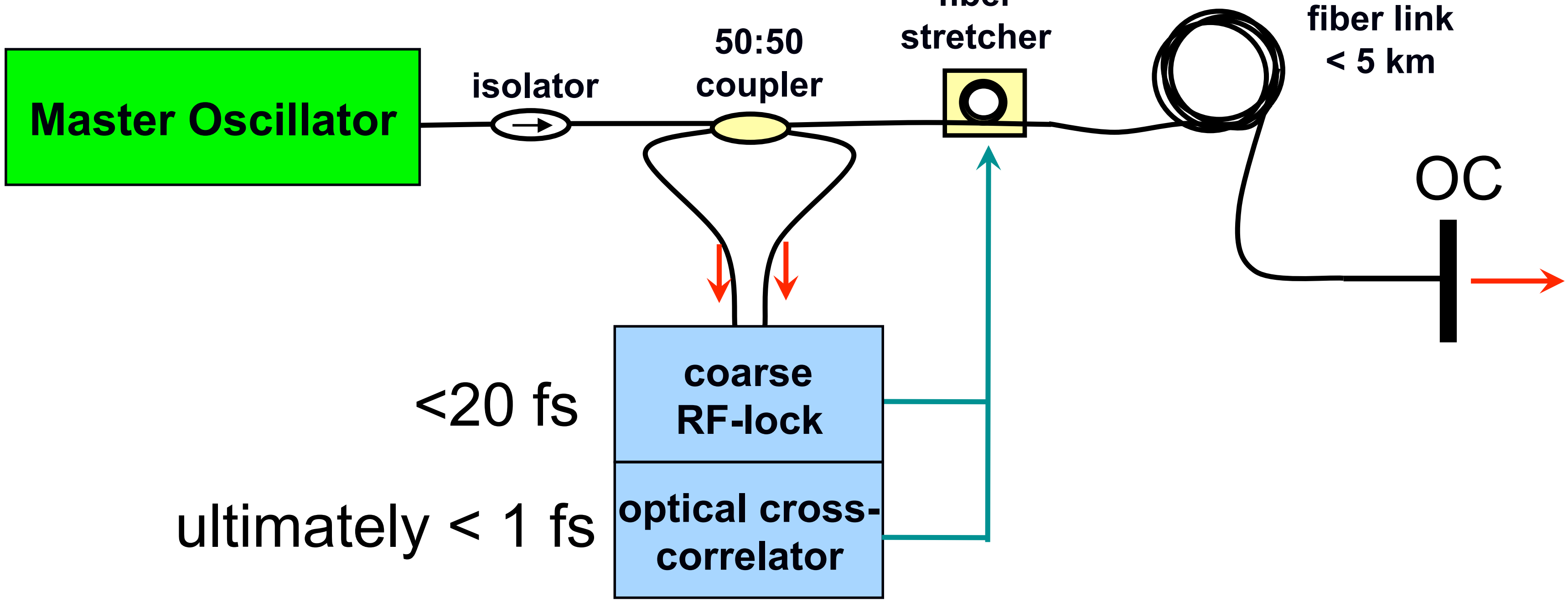
1 - Highly stable reference

2 - Optical master oscillator

3 - Conversion to RF

4 - Timing stabilized fiber links

# Timing-stabilized fiber links



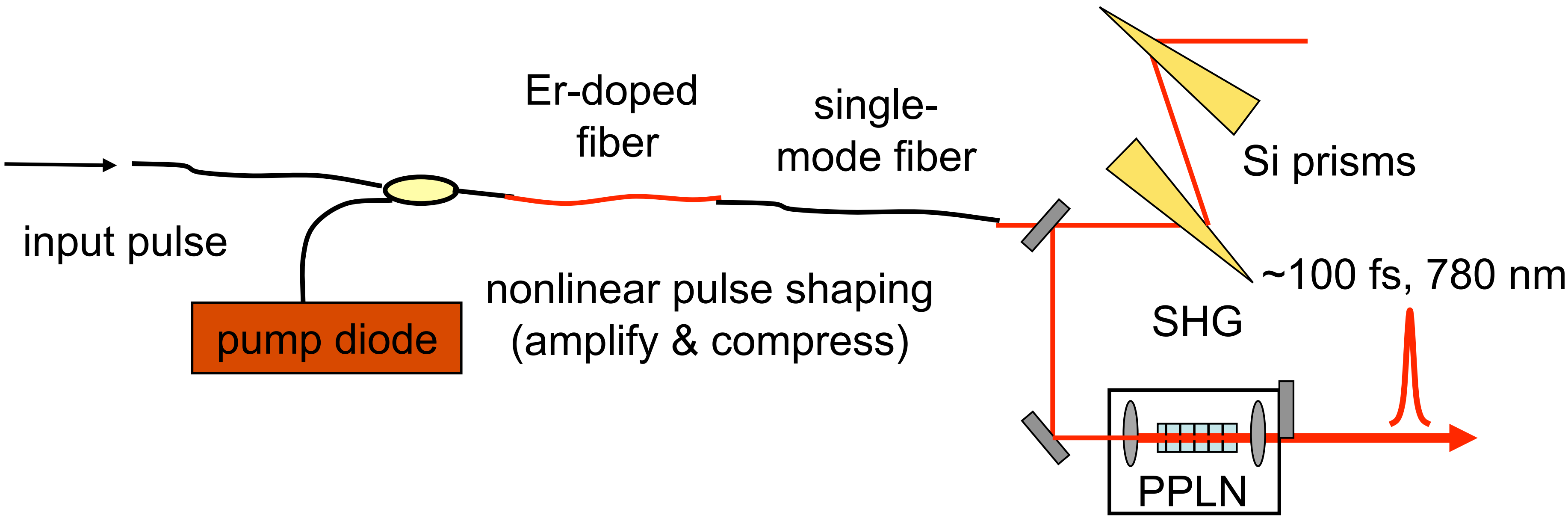

Assuming no fiber length fluctuations faster than $T = 2nL/c$.

for $L$ = 1 km, $n$ = 1.5 => $T$=10 μs, $f_{max}$ = 100 kHz

# Additional Applications of the Optical Synchronization System

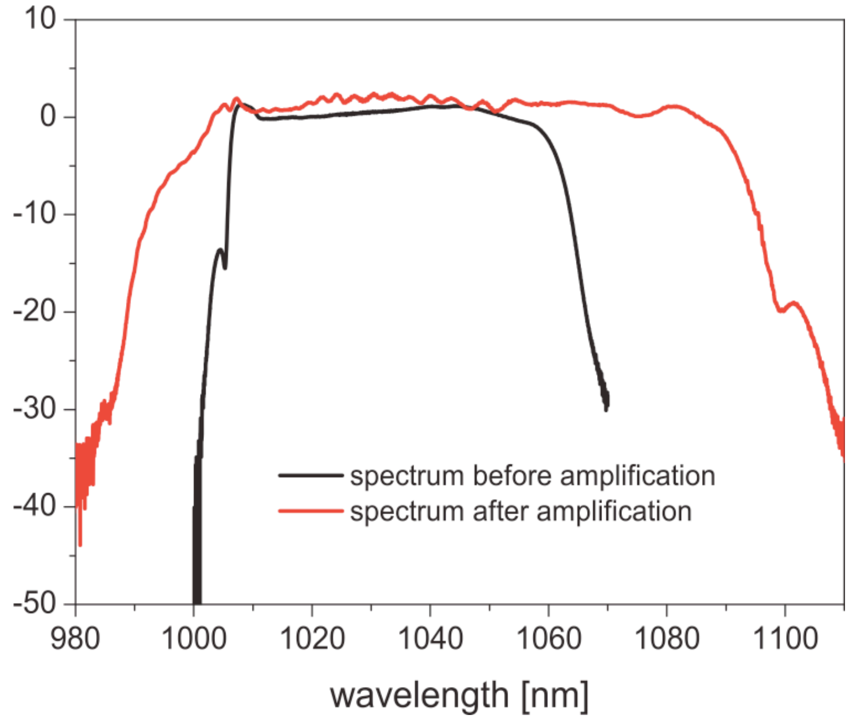
# Direct seeding of other laser systems

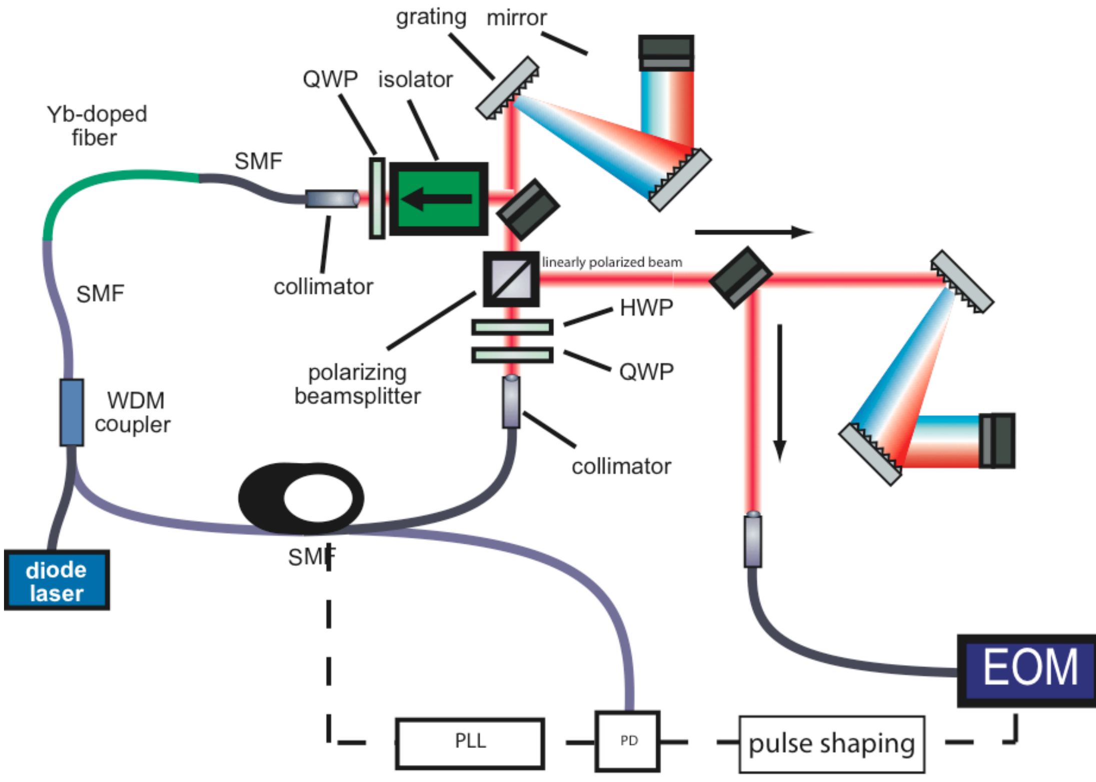
E.g., seed a Ti:sapphire amplifier after pulse shaping/amplification via second-harmonic generation from 1550 nm to 775 nm

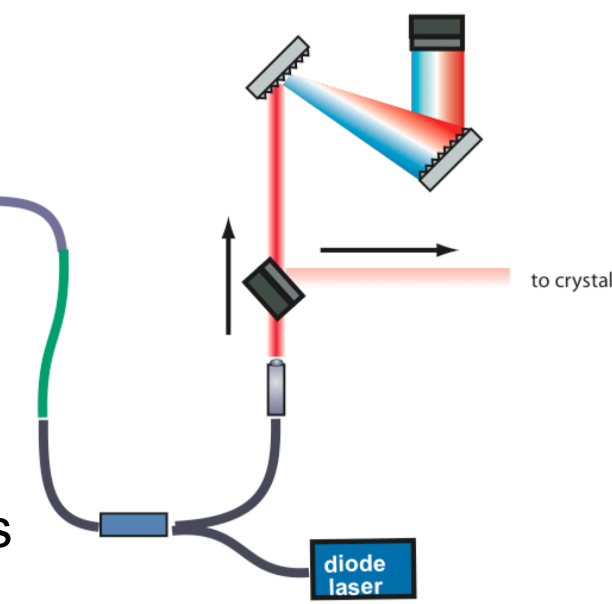


# Electron beam diagnostics

- Special fiber laser developed at Bilkent for electron beam diagnostics




- Currently explored at DESY
- Duplication at several other European accelerators

# Overview

- This approach has several basic advantages & side benefits.
- Distributing short pulses allows their direct use: beam diagnotics, seeding of powerful lasers, …
- Proof-of-principles have been made at DESY: the physics is sound
- With current approaches, 1-10 fs is achievable (over few km).

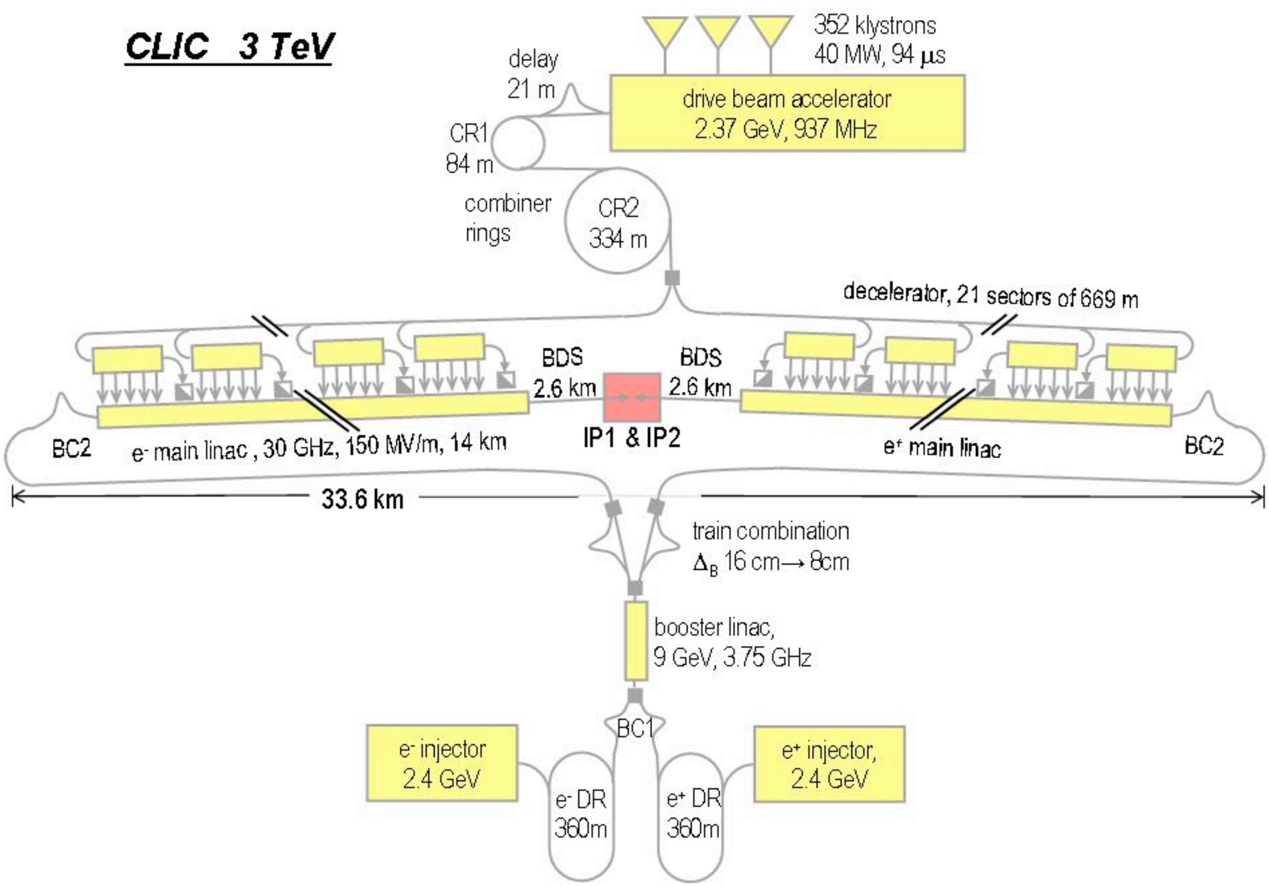
- Many engineering challenges exist…
- Full implementation corresponds to a complex system.

# Looking ahead for CLIC:

# What will be the new challenges?

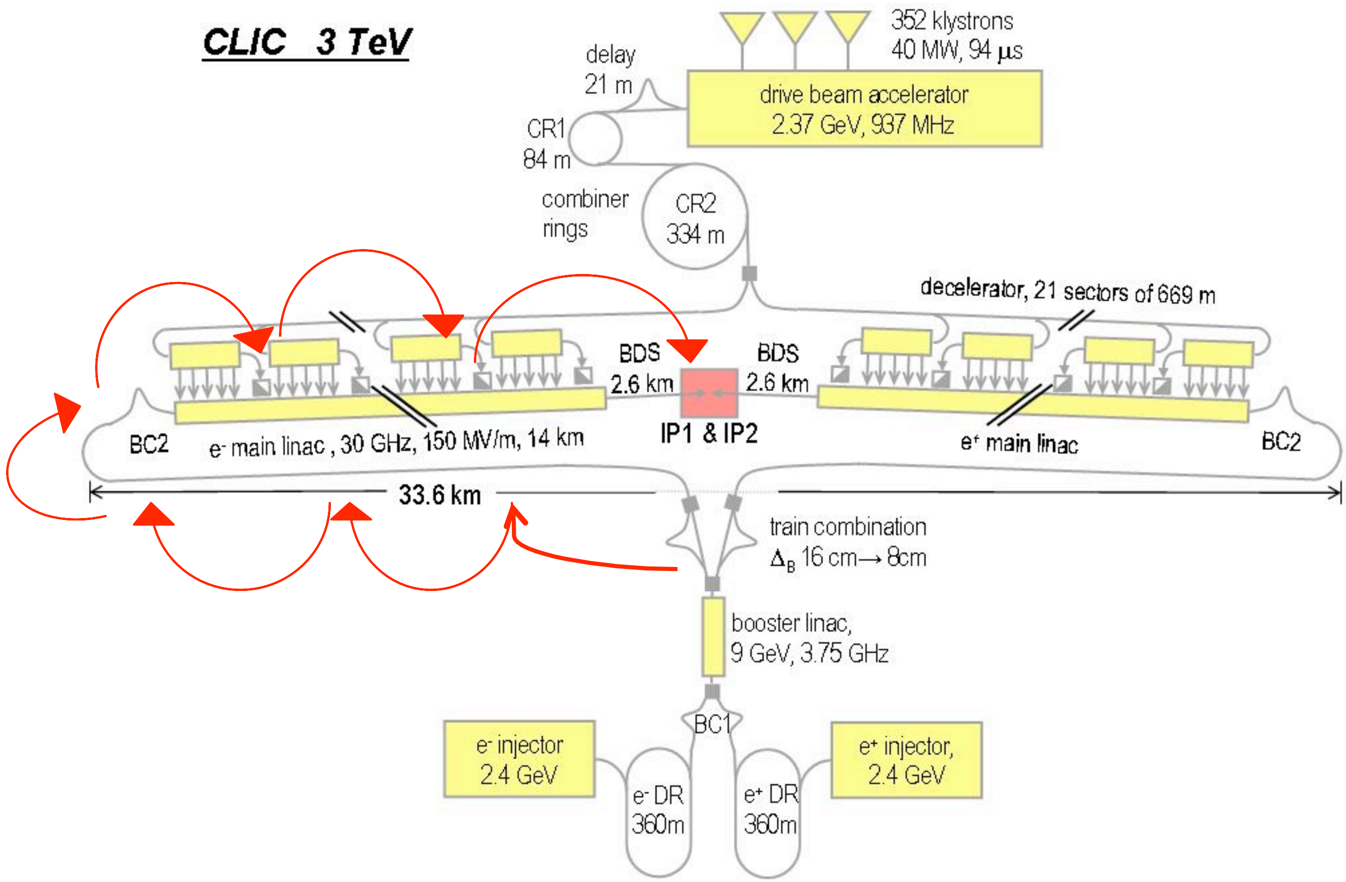
# A new challenge: vast distances & causality

- The primary difference is the much longer distances;
- CLIC may require sync over distances > 35 km; major difference!
- Signal roundtrip time is ~0.4 ms – no feedback can act faster (causality)
- New approaches will be necessary…



# A brute force solution: divide and conquer

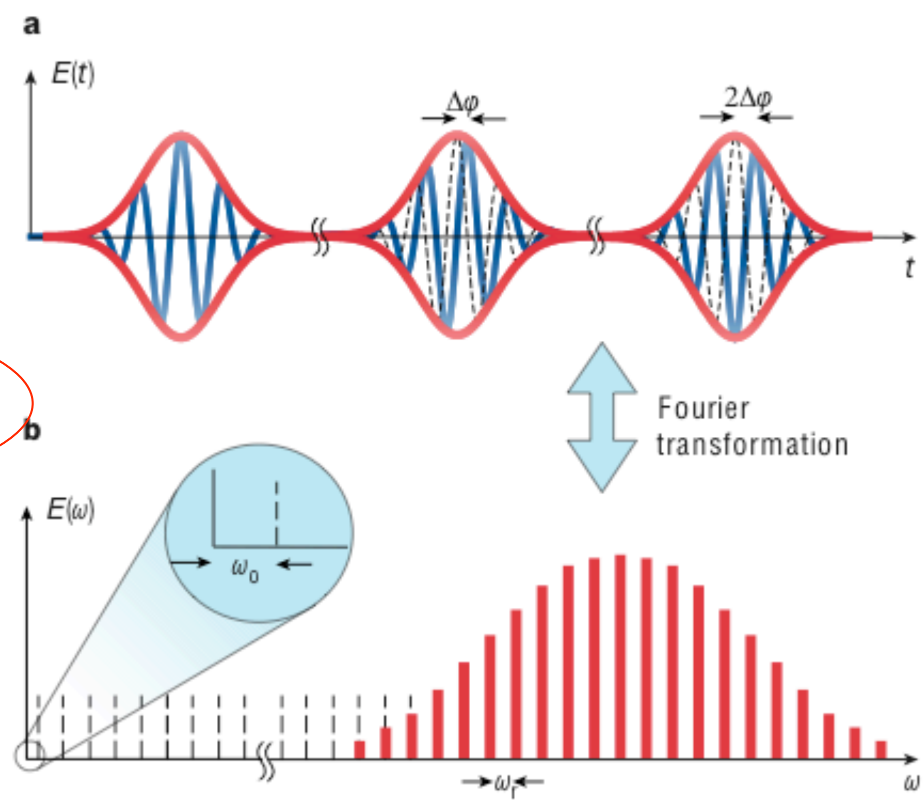
- Multiple stations with individual master oscillators and mutual links can form a chain, covering the full distance in several steps.
- However, errors add up and complexity increases further.



# Optical frequency combs and optical clocks

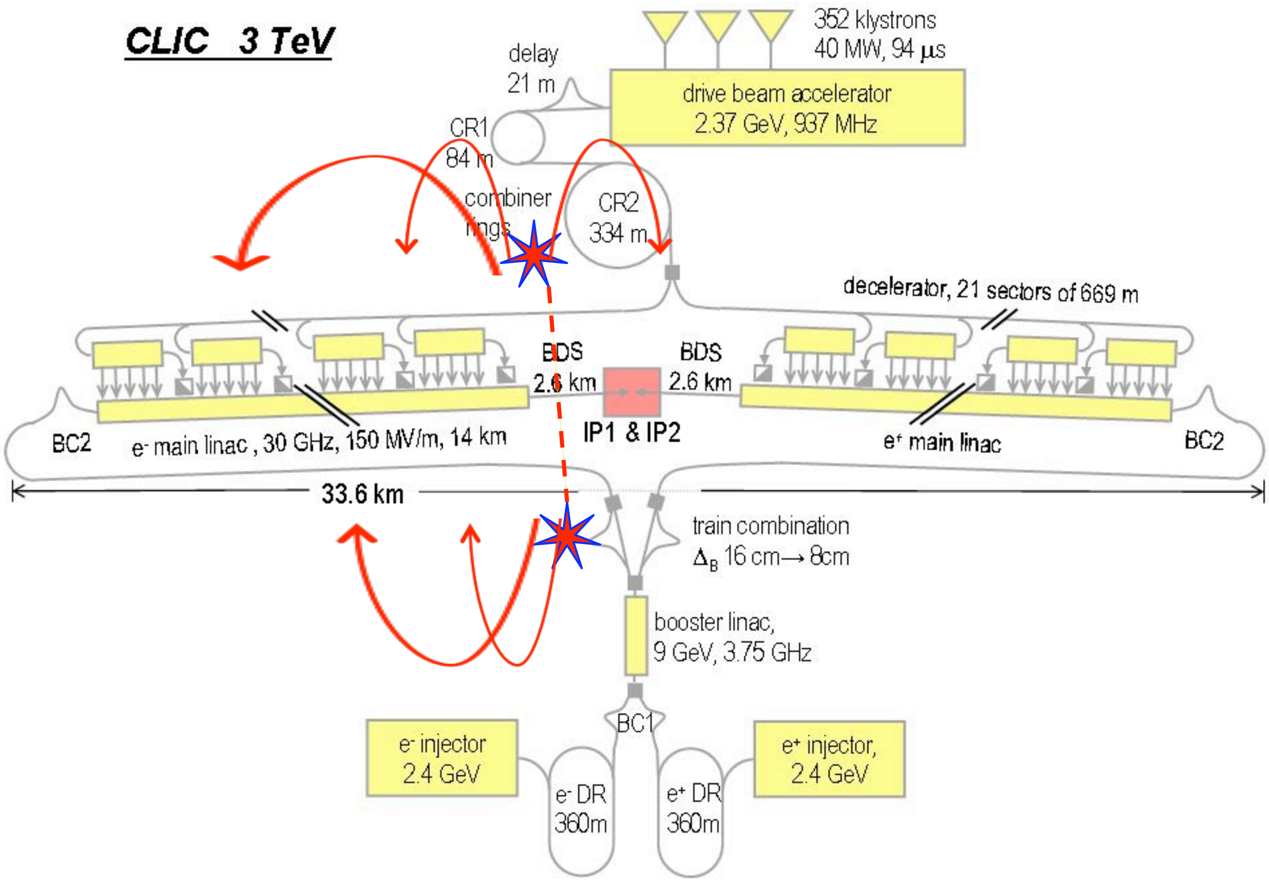
- The full frequency comb produced by a mode-locked laser has only two parameters: repetition rate and the offset frequency.
- Fixing the two ($f_R$ & $f_{offset}$) yields a completely stabilized frequency comb.
- *Nobel Prize in Physics 2005; explosive growth of the field since then.*

$$f_n = n.f_R + f_{offset}$$



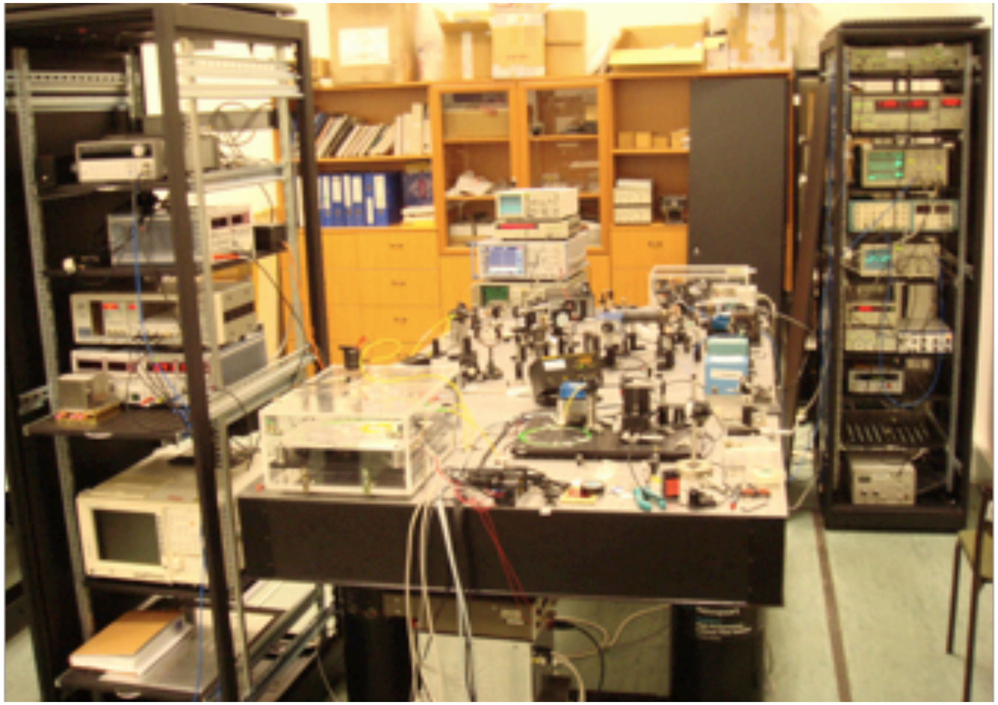
# How about using an optic-atomic clock?

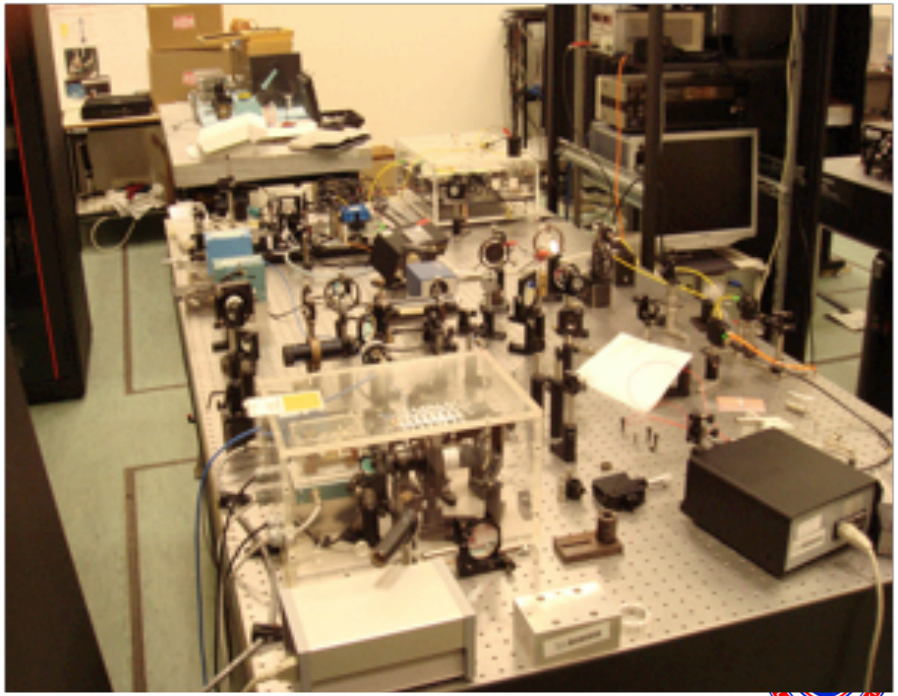
- Laser frequency combs locked to a precise quantum transition, can be absolutely stable
- Position one at each major point, distribute sync signal locally as before.
- Use long links to keep each clock locked to each other (slow corrections)
- Distribution of frequencies with $10^{-14}$ precision has been demonstrated.



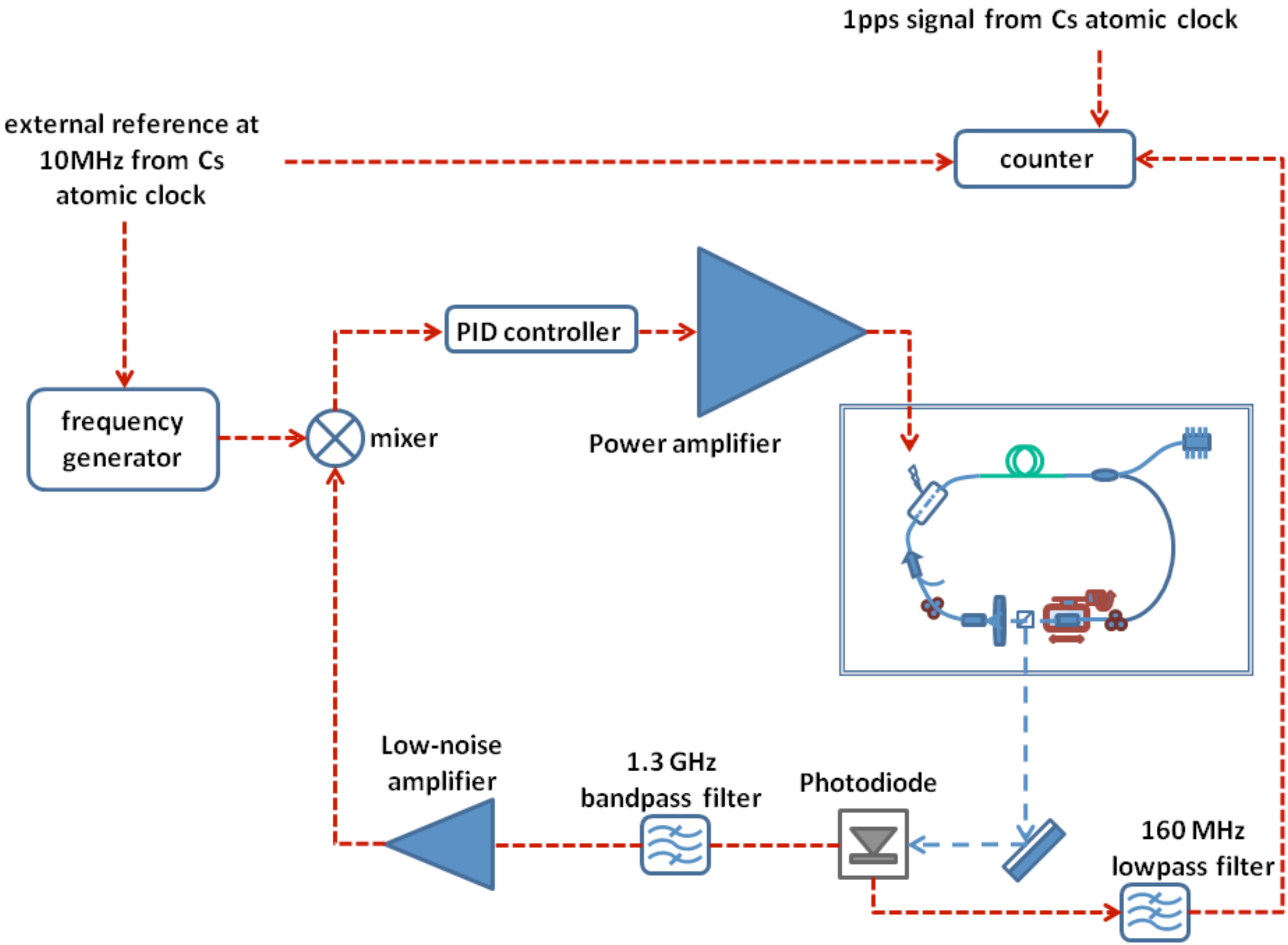
# Collaboration w/ Dr. Hamid @ National Metrology Institute

- To develop transportable and robust frequency standards based on fiber lasers locked to optical/atomic transitions
- Locking to Cs atomic clock accomplished with very robustness.
- Lab at UME where our laser was locked to the Cs atomic clock:

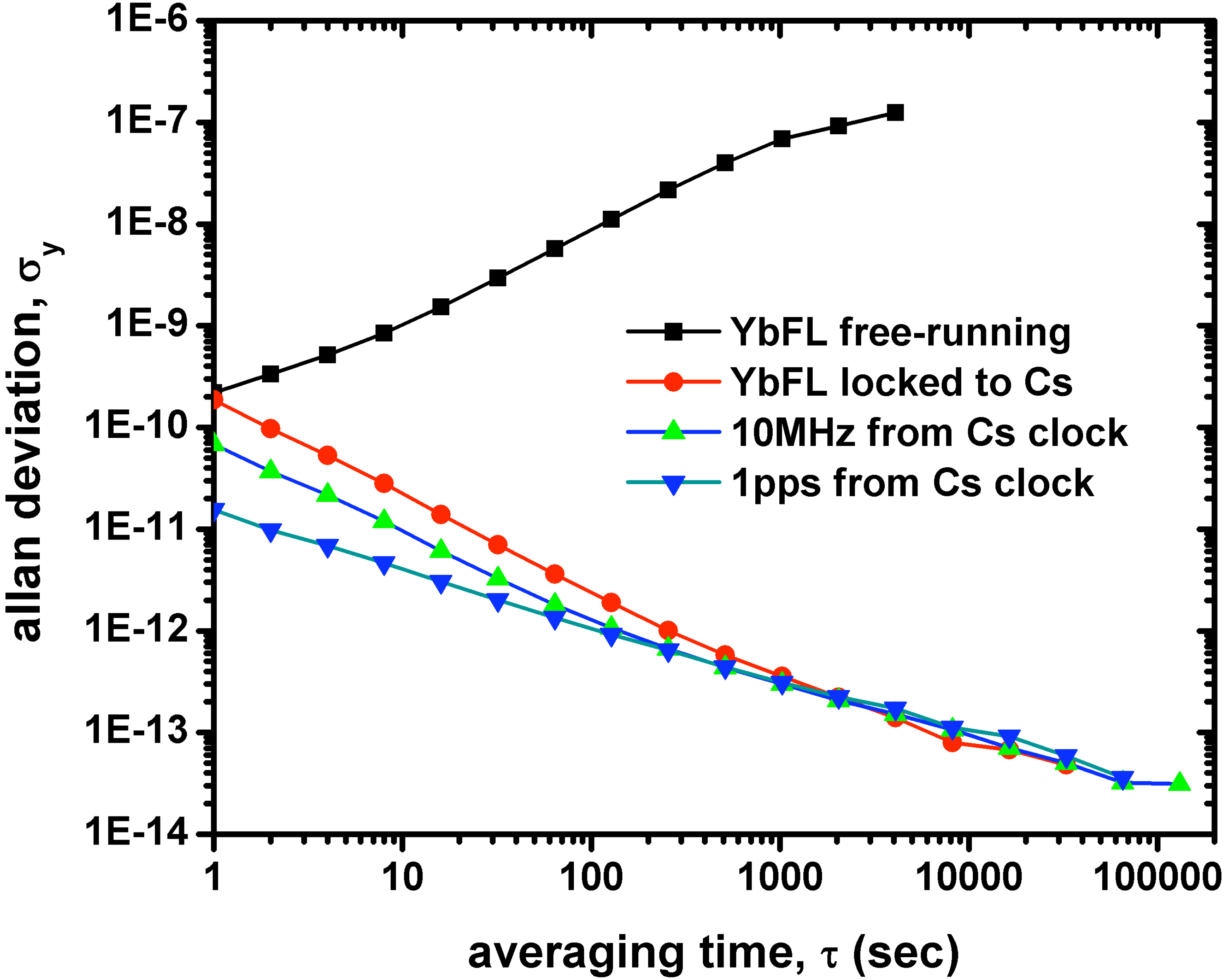


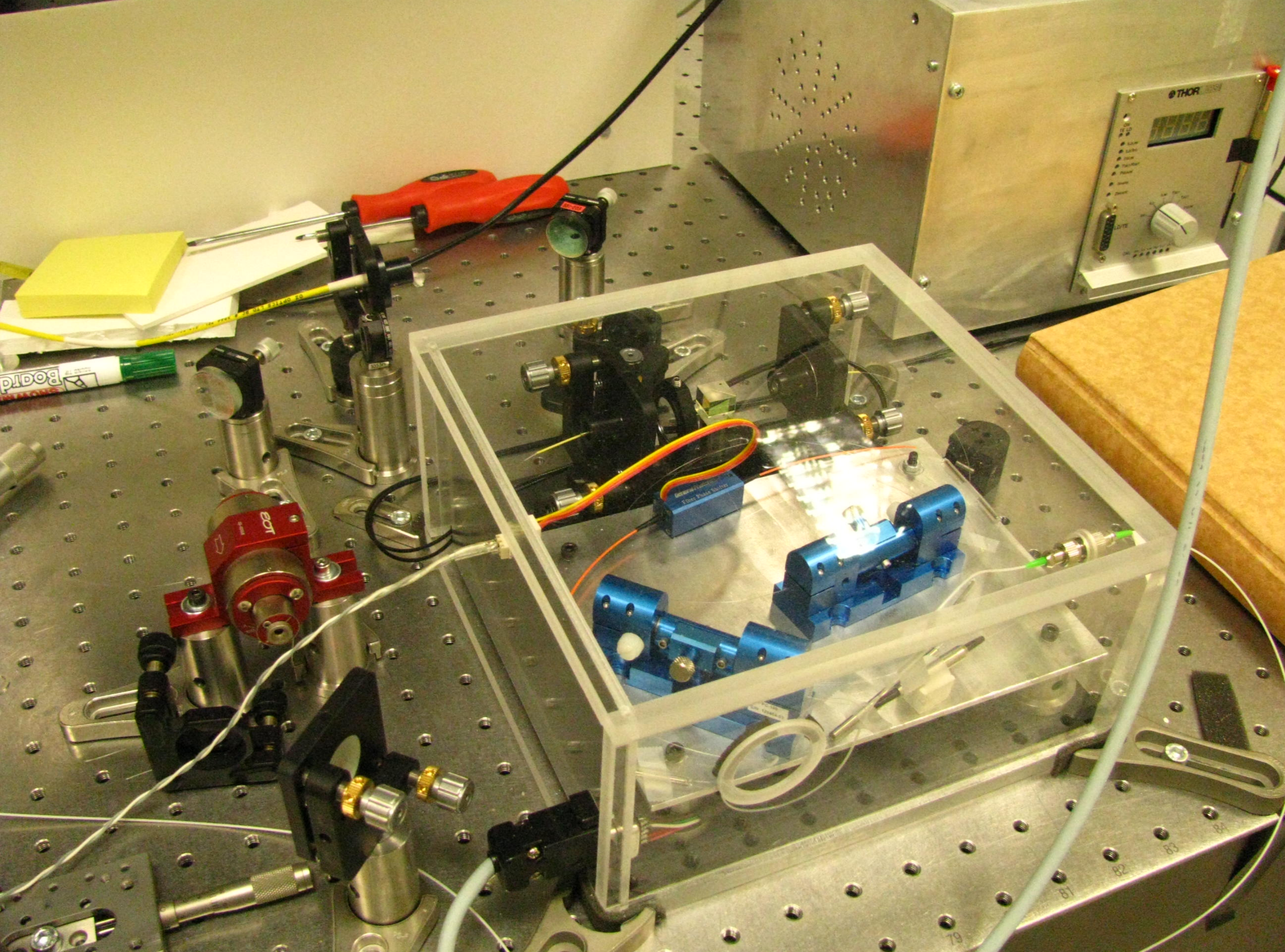


# Locking a Yb-fiber laser to the Cs atomic clock (rep rate only)



# Allan deviation characterization of the stability



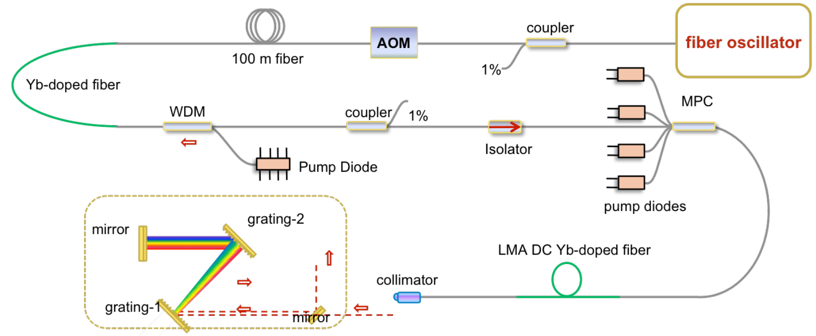

EOT

# Summary and outlook

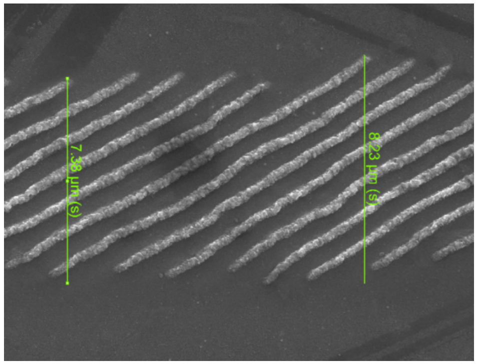
- Optical synchronization over ~1 km with fs resolution has been demonstrated at DESY.
- Various variations of the approach are possible. Basic idea: encode timing information into an optical signal and distribute via optical cables.
- This approach also allows to integrate various lasers systems (e.g., photoinjector laser)
- Application to very large distances as in CLIC pose new, exciting challenges.
- There is rapid progress in fiber laser-based optical frequency metrology
- So far, stabilized frequency combs and optical-atomic clocks have not been considered. New approaches suited to CLIC's challenges are possible.

# Fs fiber lasers are great tools, with many ongoing applications

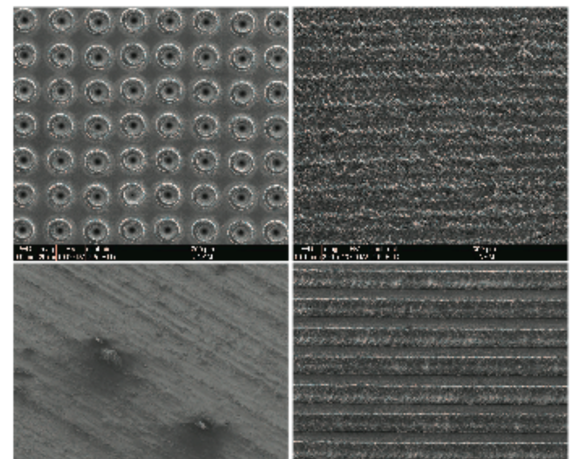
- High-energy, compact. all-fiber lasers:




- Nanoscale material processing



- Controlled surface texturing:



- Femtosecond nanosurgery:

- Femtosecond pulsed laser deposition: