Femto-Second Stable
Timing and Synchronization Systems

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- **Motivation –** Future XFELs and Time Resolved Experiments on fs-Level
- **Architecture of Optical Synchronization Systems**
  - Fiber Lasers
  - Optical Master Oscillator
  - Optical Timing Distribution
- **First Experimental Results**

Motivation – Future XFELs and Time Resolved Experiments on fs-Level

- **Stability of RF and RF Distribution**
  - arrival time jitter of electron beam in undulator ≤ bunch length (~ 30 - 50 fs)
    - ⇨ RF amplitude stability ~ 10^{-4}
    - ⇨ RF phase stability ~ 0.01 ° (21 fs @ 1.3 GHz)

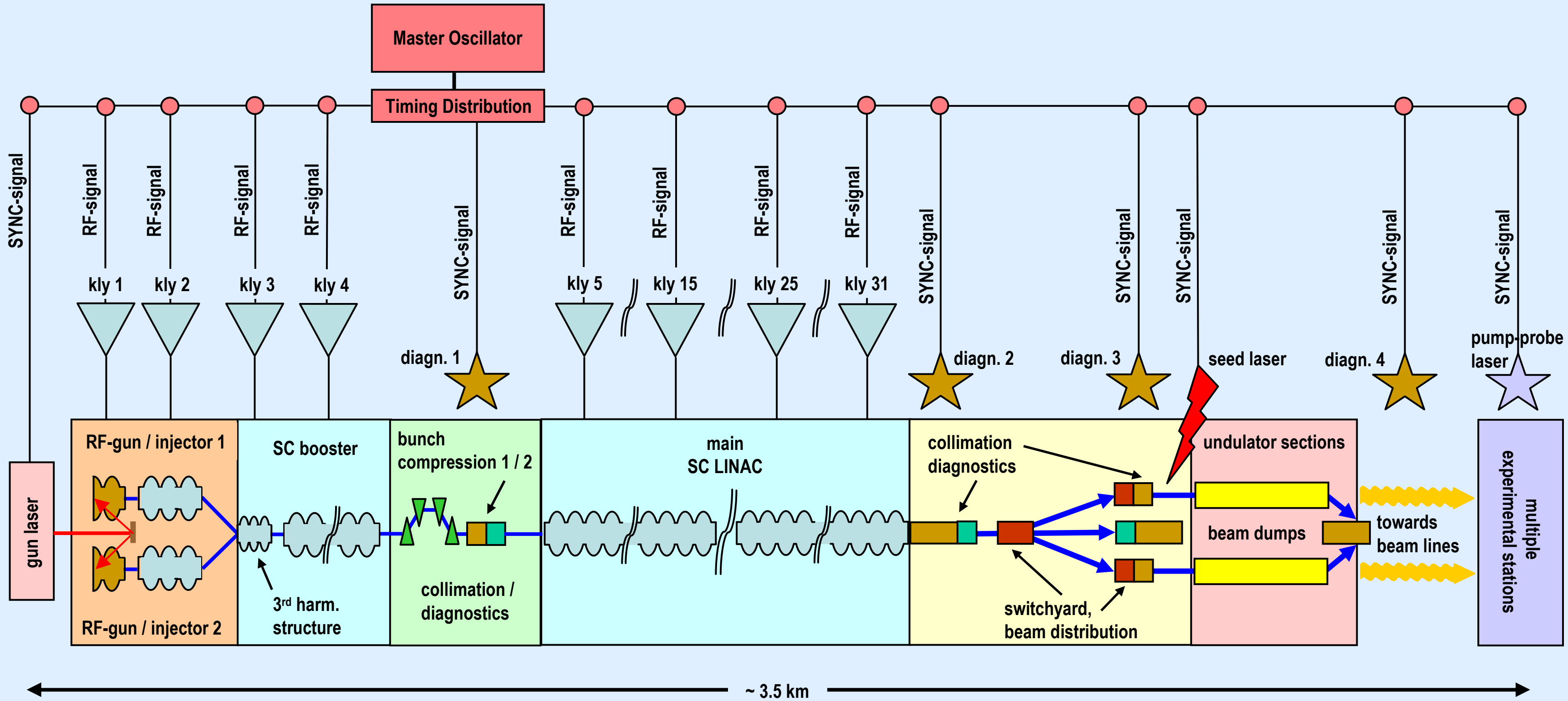
    } in injector, booster and bunch compressor

- **Single Bunch Beam Diagnostics along Accelerator**
  - single bunch and "sliced" beam parameters are relevant for SASE process (not rms!)
  - measurement locations are spread over kilometers along LINAC
    - ⇨ highly stable timing / sync distribution on fs-level

- **Laser-Electron Beam and Laser-Photon Beam Interaction on a fs-Level**
  - stable reference for seeding and HGHG generation
  - time-resolved ("pump-probe") experiments at user end stations
  - synchronization for today's "femto-second slicing sources" in storage rings
    - ⇨ highly stable timing / sync distribution on fs-level

but: inherent arrival time jitter of photon pulses due to stochastic SASE process!

Motivation – Schematic Layout of Timing Distribution in Future XFEL Facilities



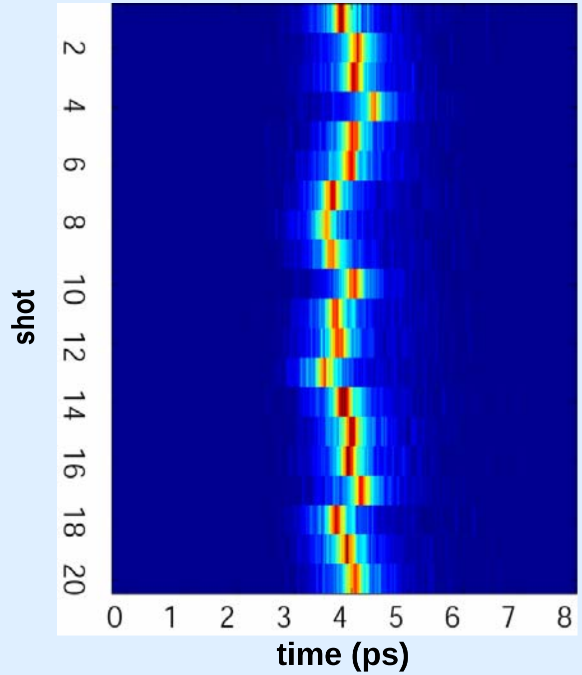
Requirements for future 4th generation light sources:

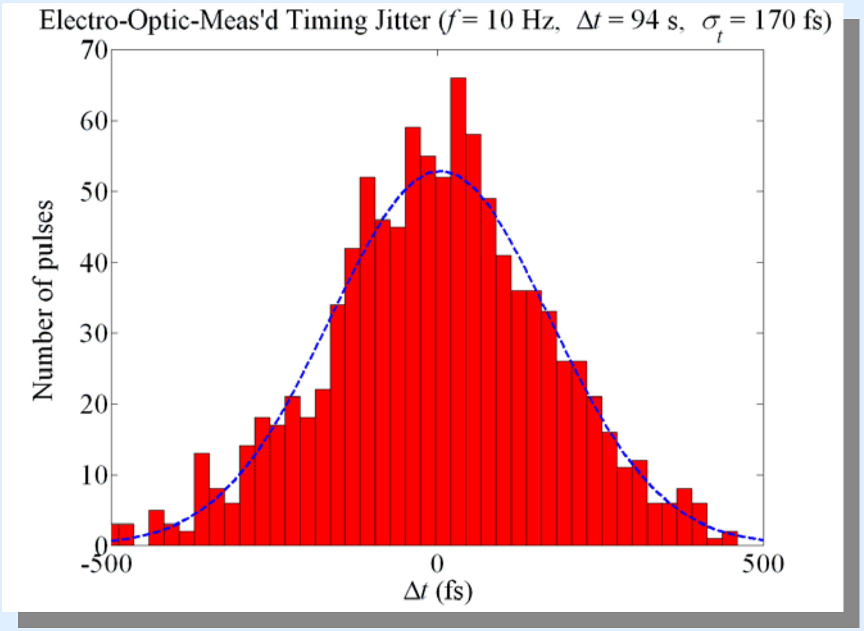
- provision of highly stable reference with fs-stability ⇨ master oscillator
- highly stable distribution of timing and SYNC signals with jitter < 10 fs over km-length

Motivation: electron beam – laser arrival time jitter measurements

EO cross-correlation-measurements performed by A.L.Cavalieri et al. @ SPPS, SLAC

Timing Jitter Data (20 successive shots)





courtesy of A.L.Cavalieri

Stabilized Optical Synchronization Systems – Proposed Schemes

Optical Heterodyne Technique - proposed by J. Staples and R. Wilcox, LBNL

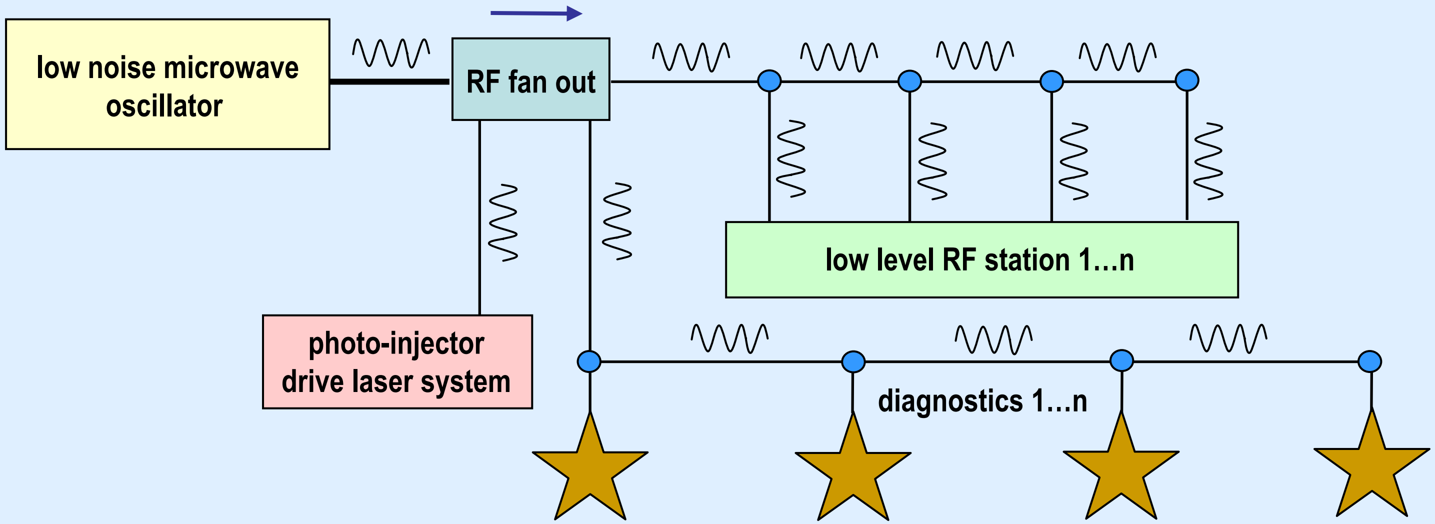
- **single frequency Er-doped cw fiber laser as optical carrier (2 kHz LW ~ 25 km coherence length)**
- **transmission of RF signals** ⇨ amplitude modulation of cw optical carrier (wide band zero-chirp MZI)
- **synchronization of mode-locked lasers** ⇨ phase-locking of two optical frequencies
- **stabilization** ⇨ down-conversion of optical phase shifts to RF (acousto-optical frequency shifter)
  ⇨ applying simple, inexpensive heterodyne technique at 110 MHz
- **first results achieved in lab:** stabilizing 100 m of optical fiber to 20 fs !

Short pulse fiber lasers - proposed by A. Winter et al. (DESY), F. Kärtner et al. (MIT)

- **femto-second Er-doped fiber laser locked to microwave master oscillator**
- **transmission of RF signals** ⇨ photo-detection of n^{th} harmonics of laser rep.-rate
- **direct synchronization of mode-locked lasers**
- **stabilization** ⇨ optical cross-correlation technique
- **first results achieved at MIT Bates accelerator:** stabilizing 500 m of optical fiber to 12 fs!

in general: high precision at optical frequencies and immunity of photons to noise

Schematic Layout of Classical Synchronization System



Classical Synchronization Layout based on:

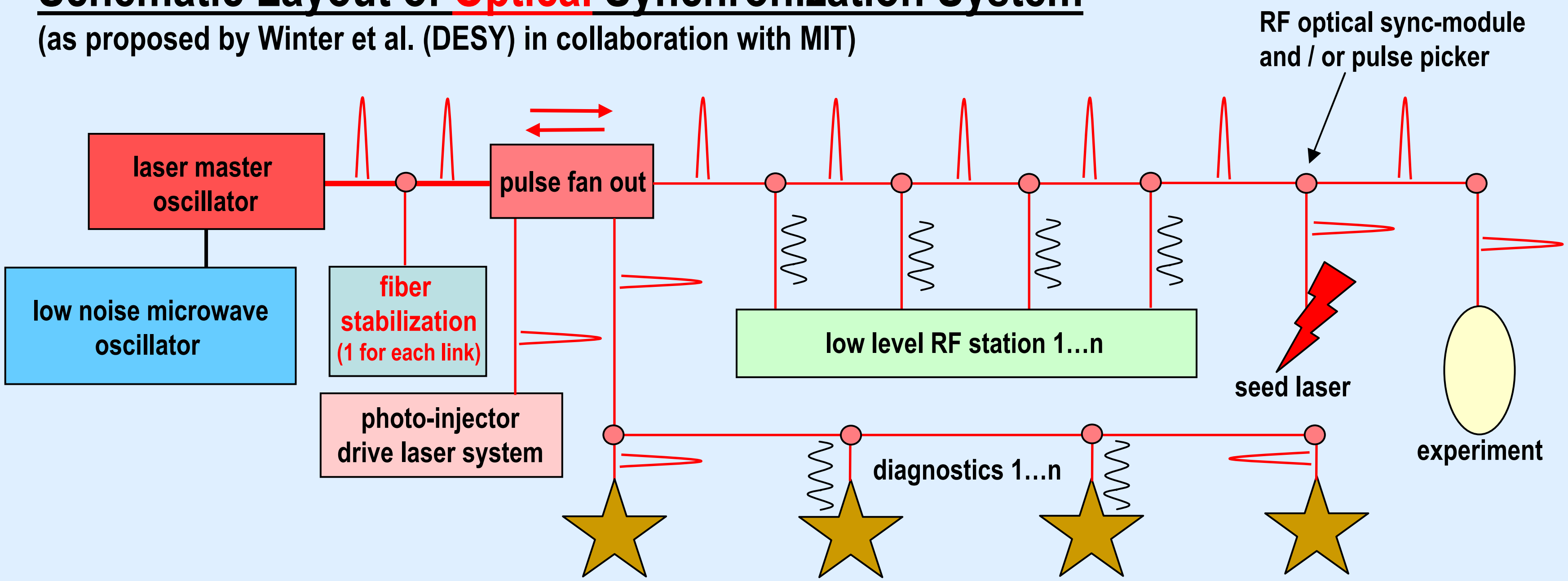
- low noise microwave master oscillator
- usually (non-) stabilized RF coaxial cable distribution

⇨ RF amplitude and phase stability in the order of 10^{-3} to 10^{-4} (JLAB - sc cw-RF, DESY VUV-FEL)

⇨ stability of timing / synchronization distribution typically in the order of pico-second(s)

Schematic Layout of Optical Synchronization System

(as proposed by Winter et al. (DESY) in collaboration with MIT)



Optical Synchronization Layout based on:

- low noise microwave master oscillator as stable low frequency reference (DC to < 10 kHz)
- mode-locked Er-doped fiber lasers as "new" optical master oscillator
- RF can be re-generated locally by photo-detection (n^{th} harmonic of laser rep.-rate)
- other lasers (for gun, diagnostics, seeding and experiments) can be linked directly

- optical fiber distribution: length stabilization over kilometers achieved with fiber stretchers

Passively Mode-Locked Fiber Lasers

Noise characteristics:

< 10 kHz ⇨ worse than microwave oscillators due to thermal and vibrational disturbances

> 10 kHz ⇨ low-pass characteristic of pump source due to long (ms) upper state lifetime of Er

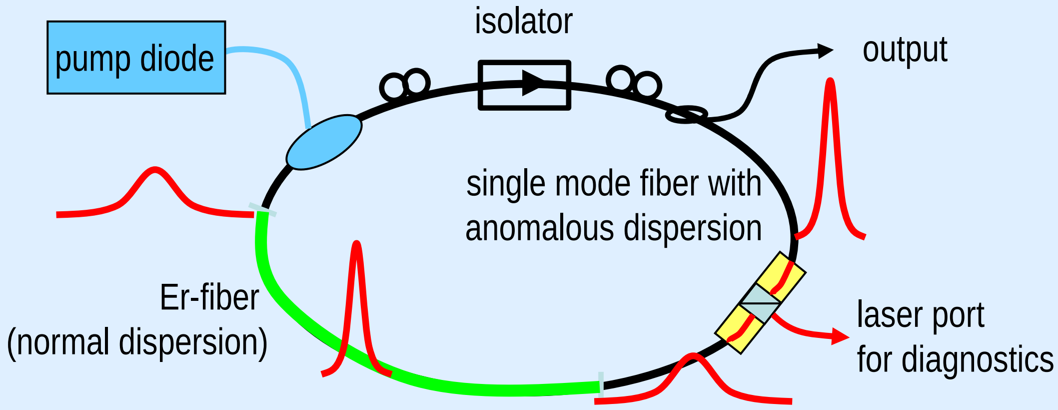
Er-fiber lasers

⇨ sub 100 femto-second to pico-second pulse durations

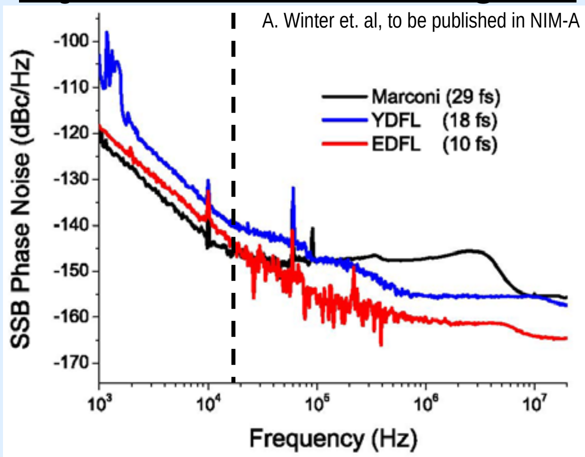
⇨ high availability of fiber-optic components @ 1550 nm (telecom)

⇨ 30 – 100 MHz repetitions rates (lockable to accelerator RF)

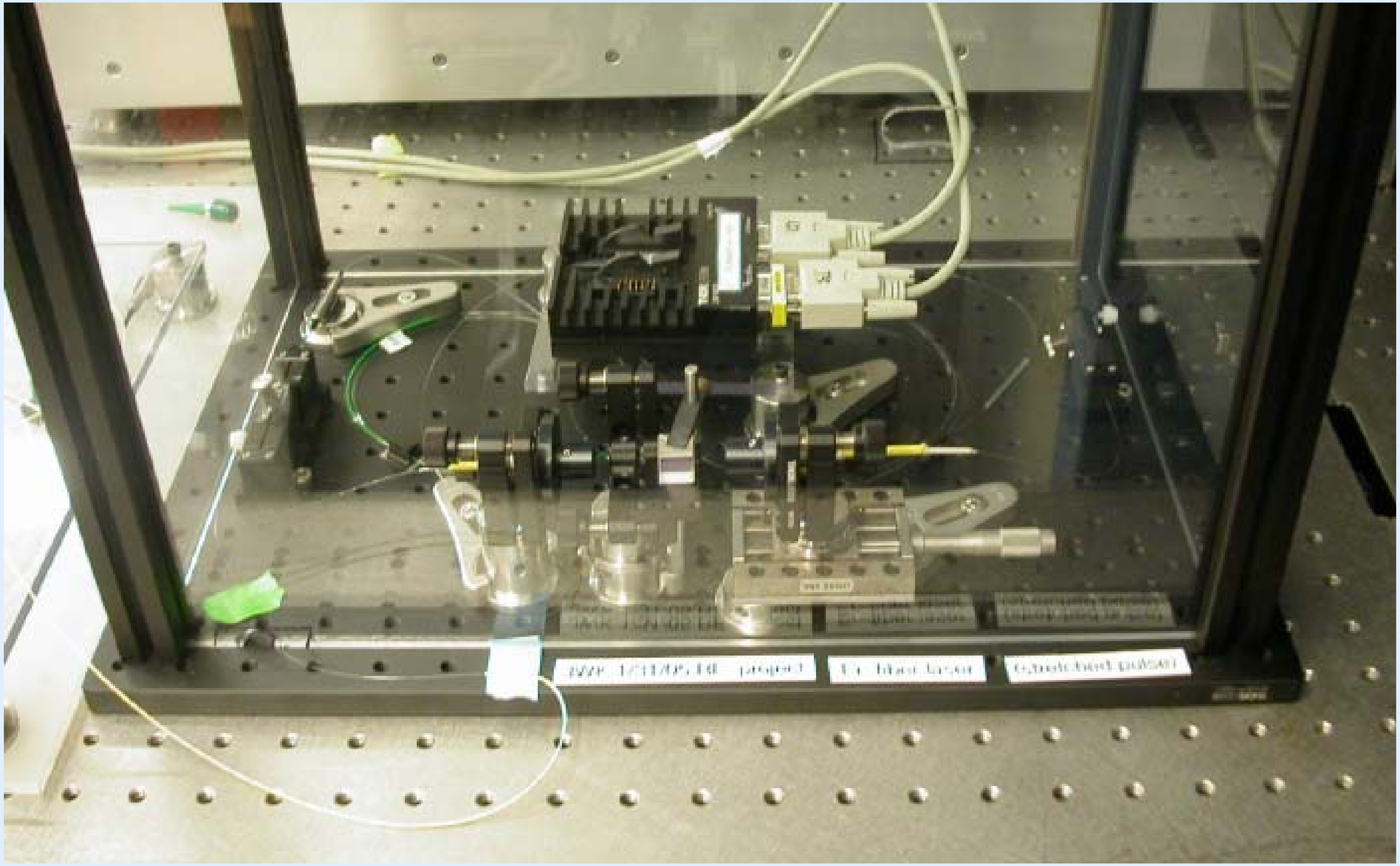
⇨ high reliability and long term stability (commercial systems available)



single sideband noise for harmonic @ 1 GHz

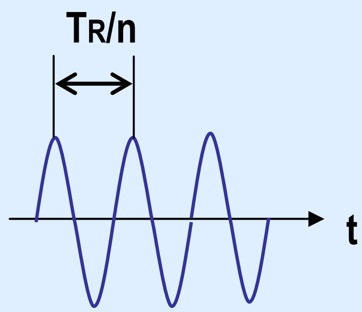


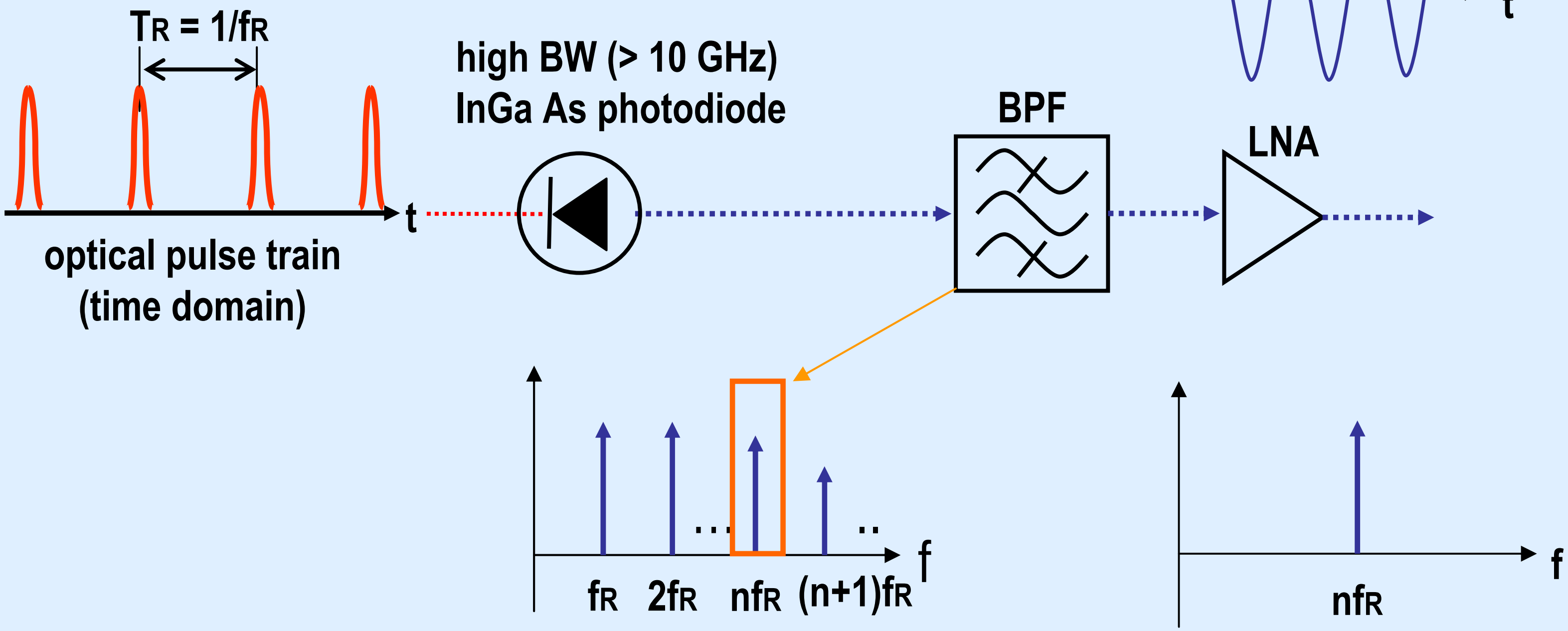
Er-doped Fiber Laser (non-commercial set-up by Axel Winter)



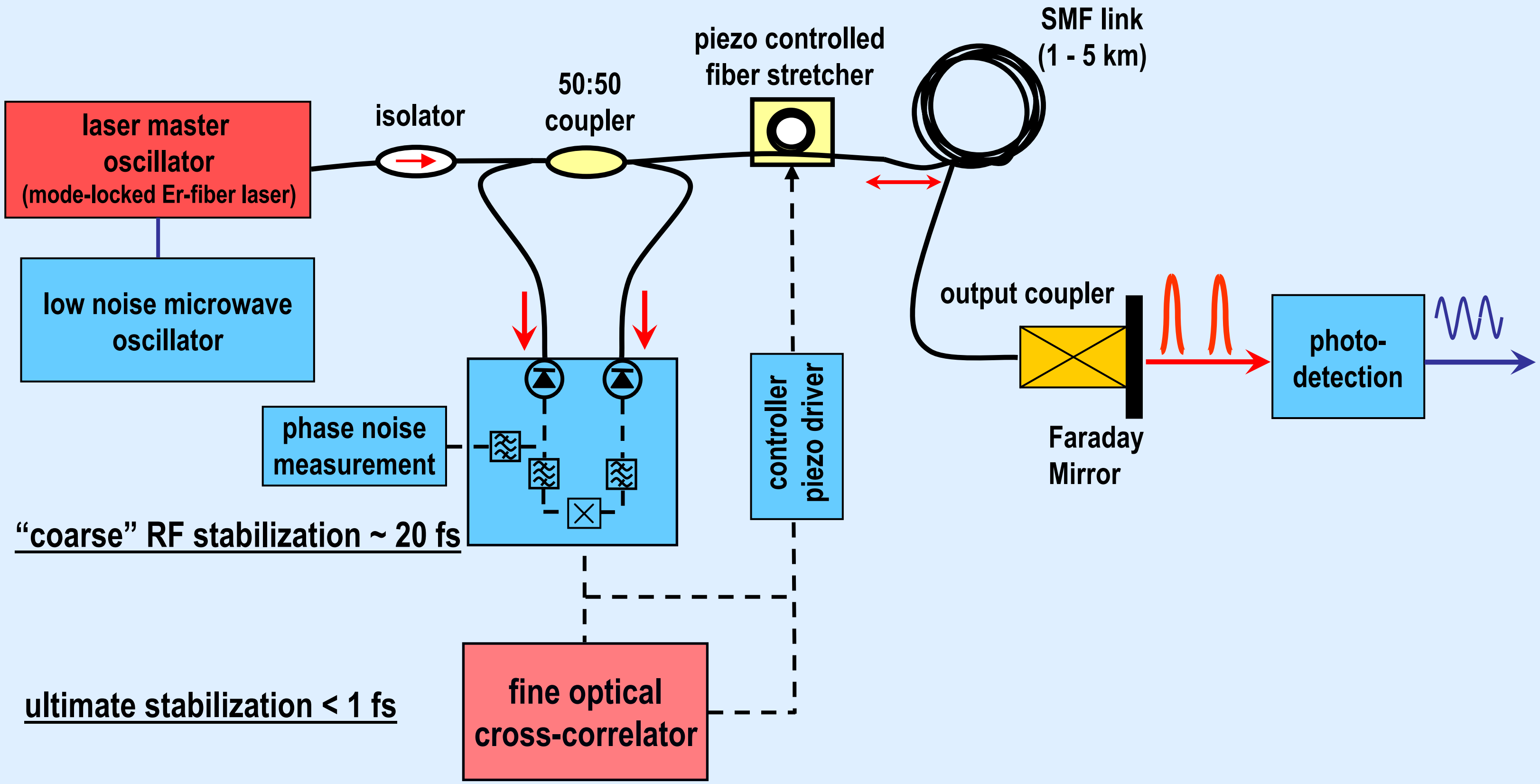
RF Distribution – Photo-Detection to Extract RF from Laser Pulse Train

- RF is encoded in laser pulse repetition rate
- signal converted to electronic domain by photo-detector
- any suitable harmonics (nfR) can be extracted





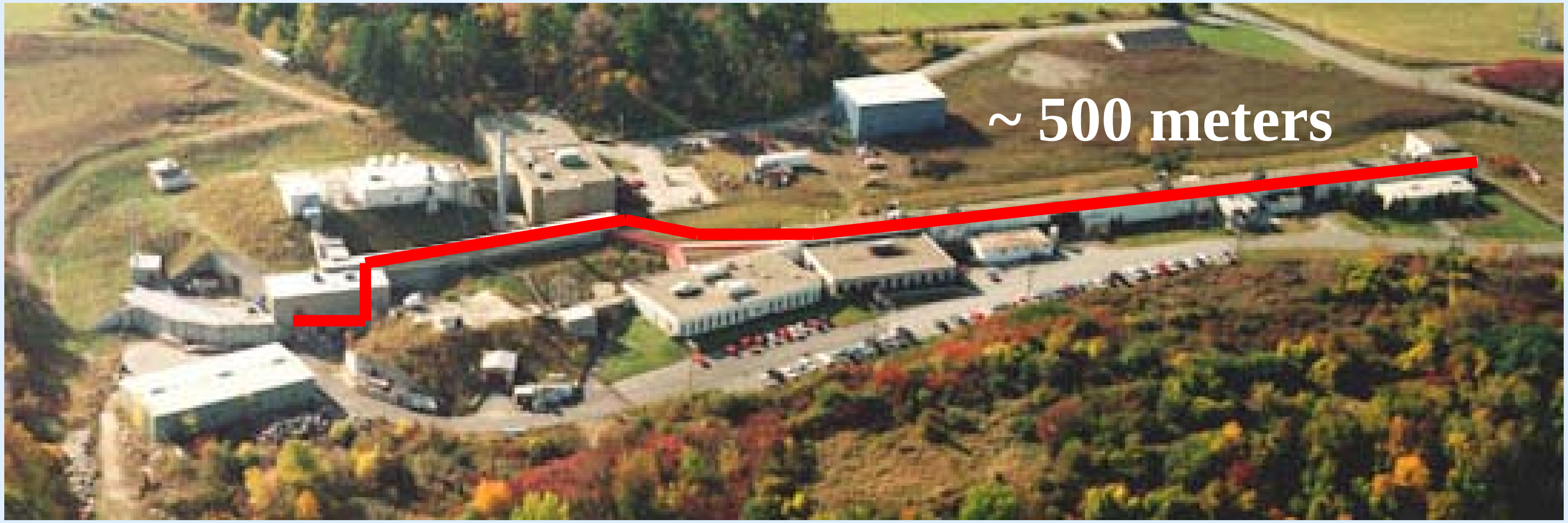
Optical Fiber Stabilization Scheme (as proposed by Winter et al. (DESY) in collaboration with MIT)



- direct stabilization of group velocity in fiber
- temperature effects and vibrations are compensated (fiber temp. coefficient ~ $5 \times 10^{-6}\ m^{-1}$)

First Experimental Results by Winter (DESY) and MIT co-workers

- tests in real accelerator environment @ MIT Bates laboratory
- Er-doped fiber laser locked to Bates master oscillator
- laser pulses transmitted through a total fiber length of 1 km
- "passive" temperature stabilization of fiber link
- stabilization of fiber length by RF feedback



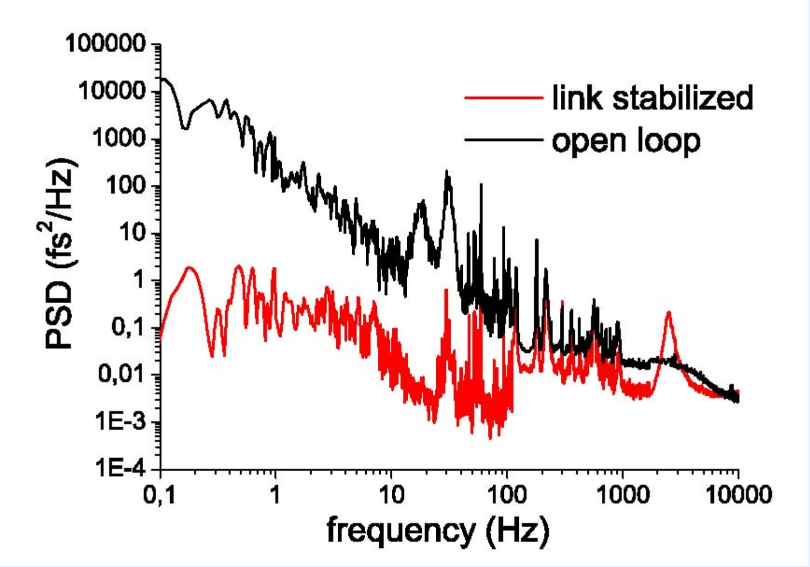
First Experimental Results by Winter (DESY) and MIT co-workers

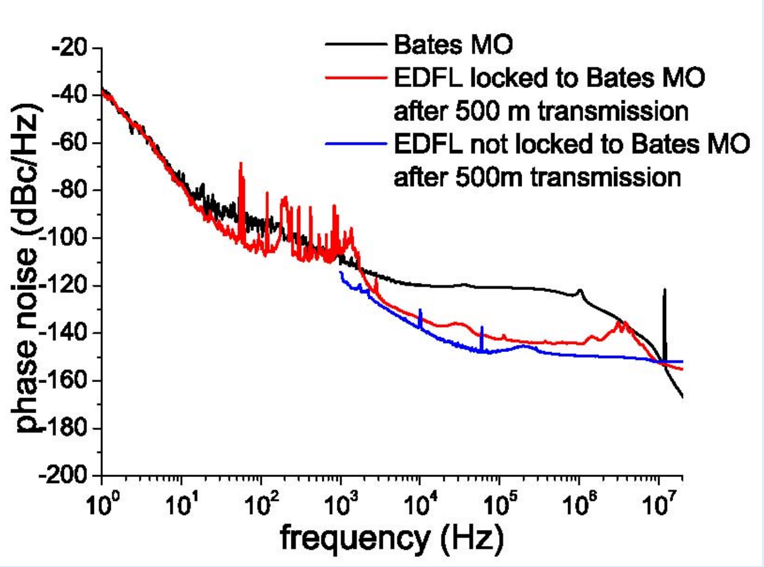
open / closed loop performance

- open loop stability ⇨ 60 fs (0.1 Hz – 5 kHz)
- closed loop stability ⇨ 12 fs (0.1 Hz – 5 kHz)
- stability achieved with "simple" RF feedback
- no significant noise added at high frequencies

transmited RF-signal (2.856 GHz)

- phase lock jitter ⇨ 30 fs (10 Hz – 2 kHz)
- total jitter added ⇨ 50 fs
- overall improvement 272 fs vs. 178 fs (up to 20 MHz)
- spurs are technical noise (pump diode PS)





Summary

• future XFELs (and today's fs-slicing sources at storage rings) need fs stable RF and timing distribution

• mode-locked Er-doped fiber lasers are candidates for *optical master oscillators*

⇨ excellent noise performance at high frequencies

⇨ lockable to microwave oscillators to suppress low frequency noise

⇨ high reliability and availability of pump sources and optical components (@ 1550 nm)

• stabilization of fiber optical RF and timing distribution of kilometers is possible

⇨ applying RF feedback schemes… < 20 fs

⇨ applying optical cross correlation… < 1 fs

⇨ applying optical heterodyne techniques… < 1 fs

• stabilization of RF distribution (@ 1 GHz) demonstrated in real accelerator environment @ MIT Bates to… < 50 fs jitter (0.1 Hz – 20 MHz)

Acknowledgements

many thanks again to Axel Winter (DESY) for many instructive and inspiring discussions…!