High-precision Laser Master Oscillators for Optical Timing Distribution Systems in Future Light Sources

A. Winter[1], F. Ö. Ilday[2], J. Chen[2], F. Kärtner[2],
H. Schlarb[1], F. Ludwig[1], P. Schmueser[1]

DESY[1], MIT[2]

29.6.2005

EPAC 2006

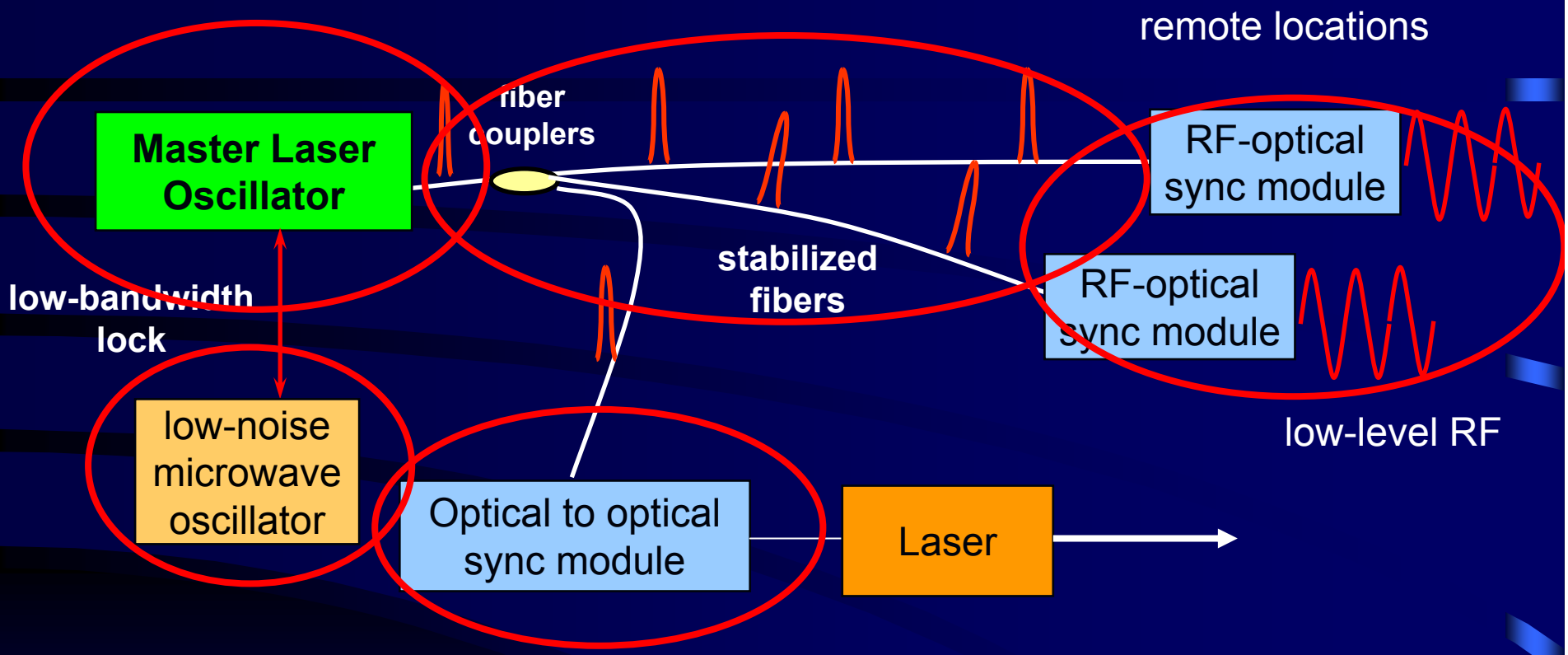
Overview

- Requirements for fs synchronization
- Optical synchronization systems
  - Optical master oscillator
  - Optical timing distribution and RF reconversion
  - Test in accelerator environment
- Conclusion and Outlook

Requirements

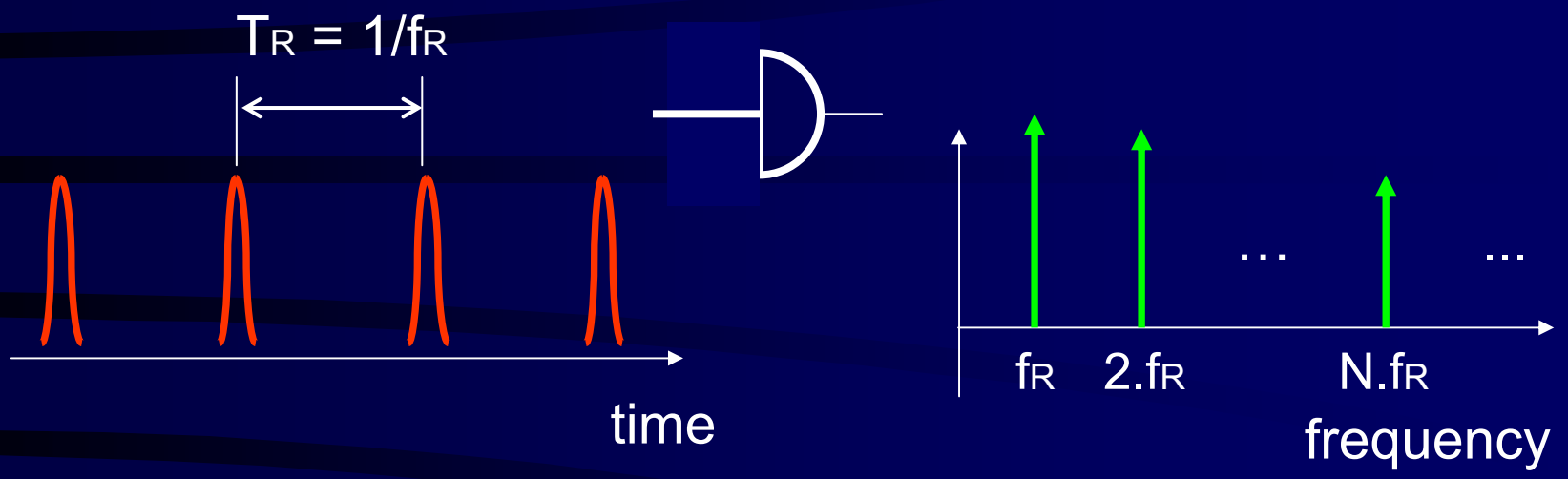
- Provide stability ~x-ray pulse width
  - Amplitude and phase stability in cavities (10^{-4}, 0.01deg) in most critical sections
  - Provide ultra-stable reference to select locations with 10 fs relative stability
  - Synchronize probe systems to reference with ~10 fs stability
- Precise reference frequency generation and distribution system required
  - "femtosecond" synchronization means systems follow reference with low added timing jitter and have intrinsic high-frequency timing jitter both, ~fs

Synchronization System Layout



- A master mode-locked laser producing a very stable pulse train
- The master laser is locked to a microwave oscillator for long-term stability
- length stabilized fiber links transport the pulses to remote locations
- other lasers can be linked or RF can be generated locally

Why Optical Pulses (Mode-locked Lasers)?



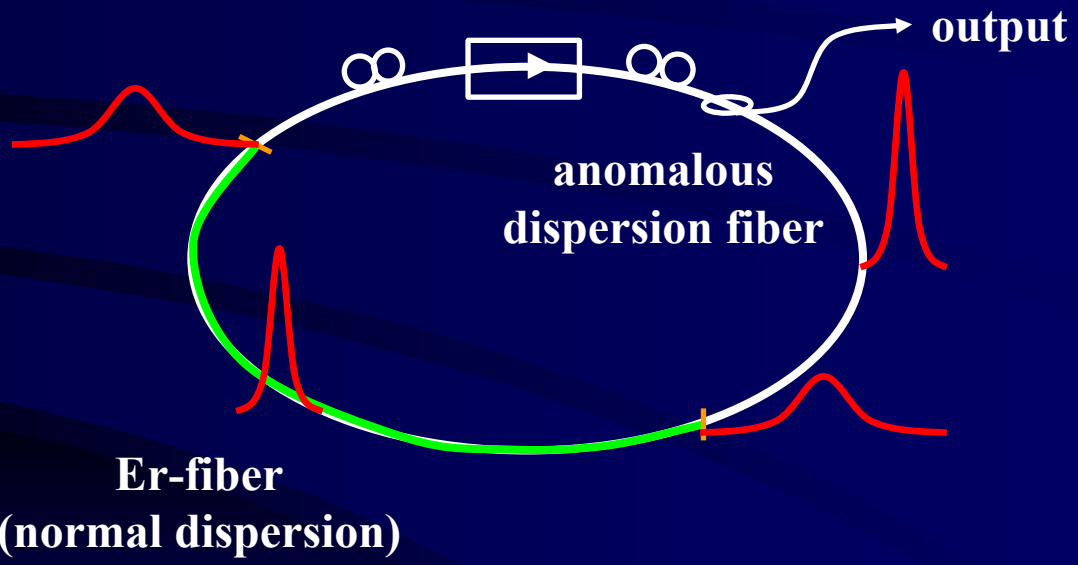
- RF is encoded in pulse repetition rate, any harmonic can be extracted at end stations.
- Pulses can directly seed laser amplifiers.
- Optical cross correlation can be used for link stabilization or for optical-to-optical synchronization
- Group delay is directly stabilized, not phase delay.

Low-Noise Laser Oscillator Development

- Passively mode-locked lasers offer superior high-frequency noise.
- Er-fiber lasers:
  - sub-100 fs to ps pulse duration
  - 1550 nm (telecom) wavelength for fiber-optic component availability
  - repetition rate 30-100 MHz
- Reliable, long-term operation without interruption:
  - weeks of uninterrupted operation, with minimal environmental protection (just a box around)
  - use multiple lasers for redundancy

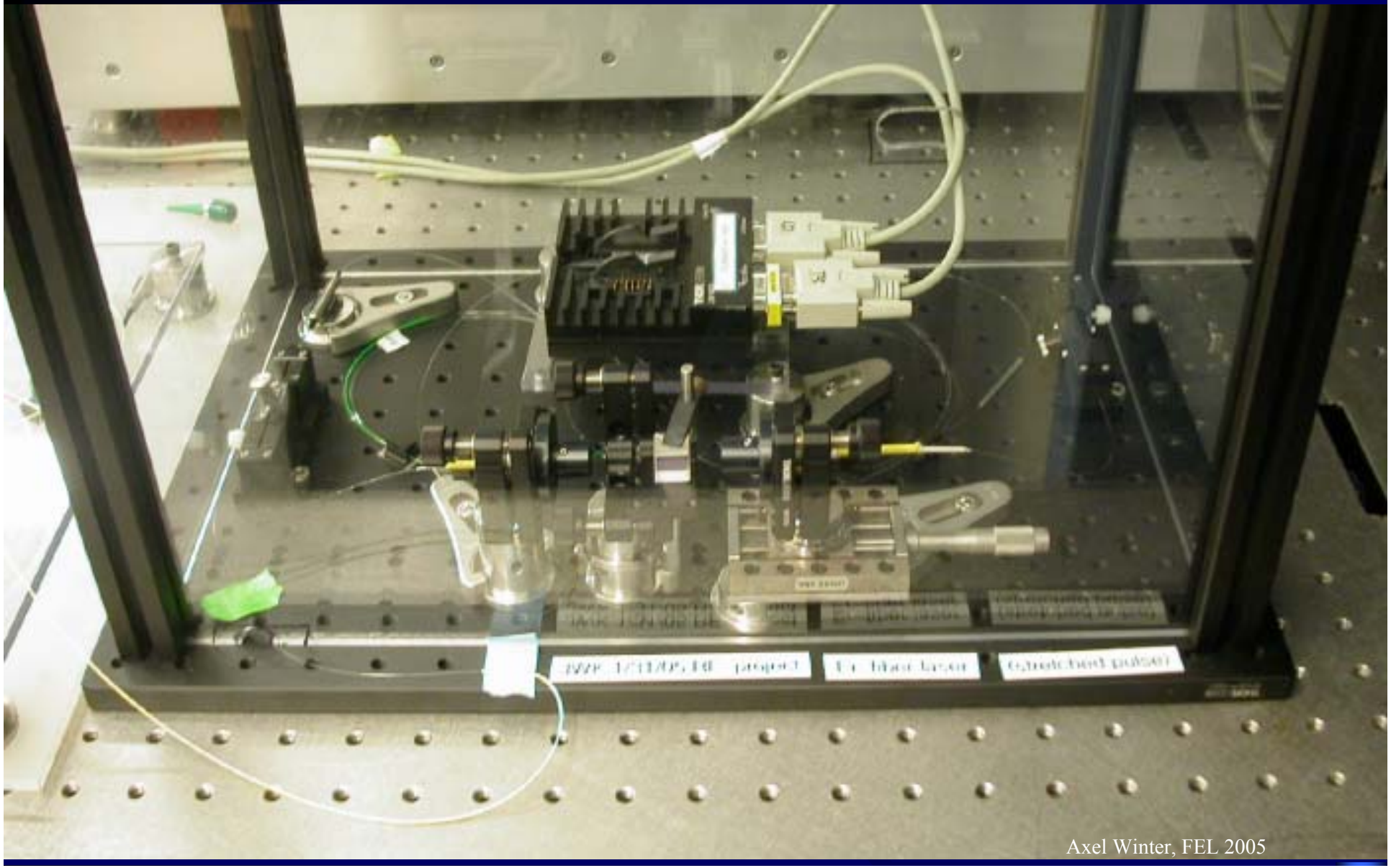
Passively Mode-locked Fiber Lasers

- Pulse builds up by itself from noise (ns-ps domain)
  - A saturable absorber ensures higher intensity <=> higher gain
  - Given constant intra-cavity energy, the stable solution is a localized solution (a single pulse).

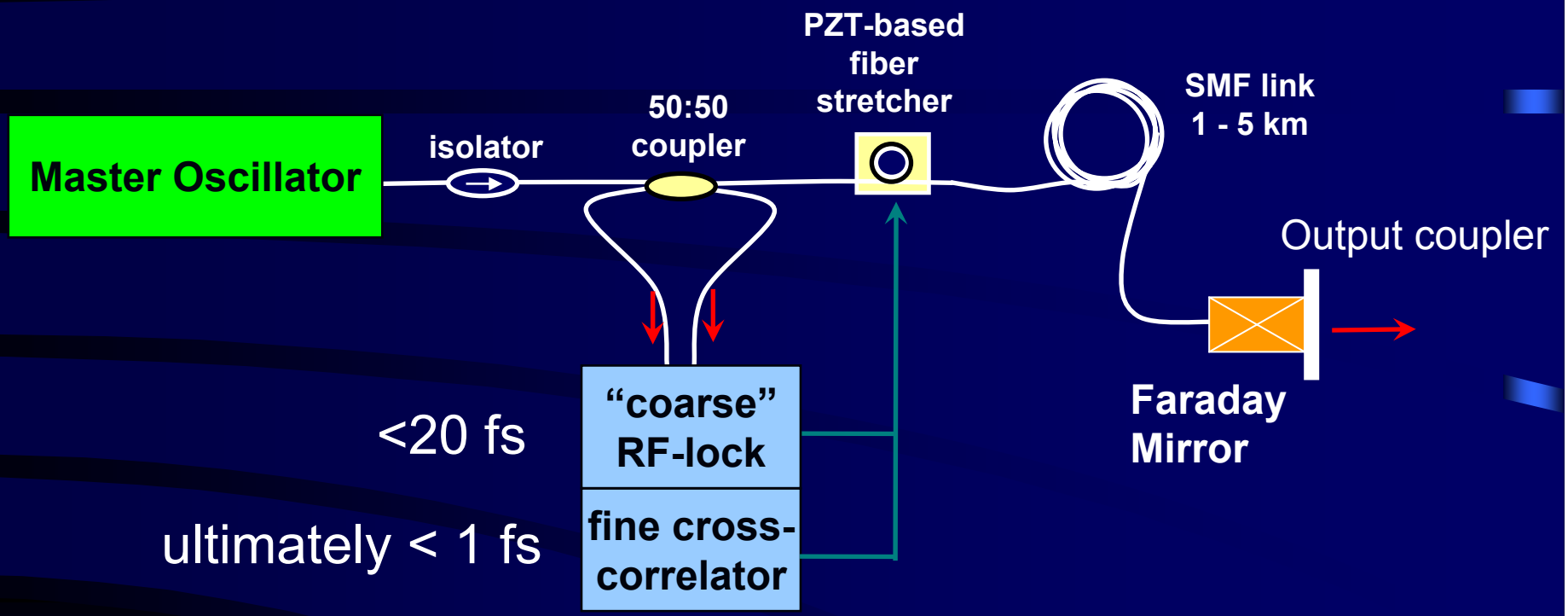


- Picture is different in the femtosecond domain:
  - Dispersion and Nonlinearity dominate pulse shaping.
  - Soliton-like pulses balance these effects => very short pulses

Erbium-doped fiber laser



Timing stabilized fiber links



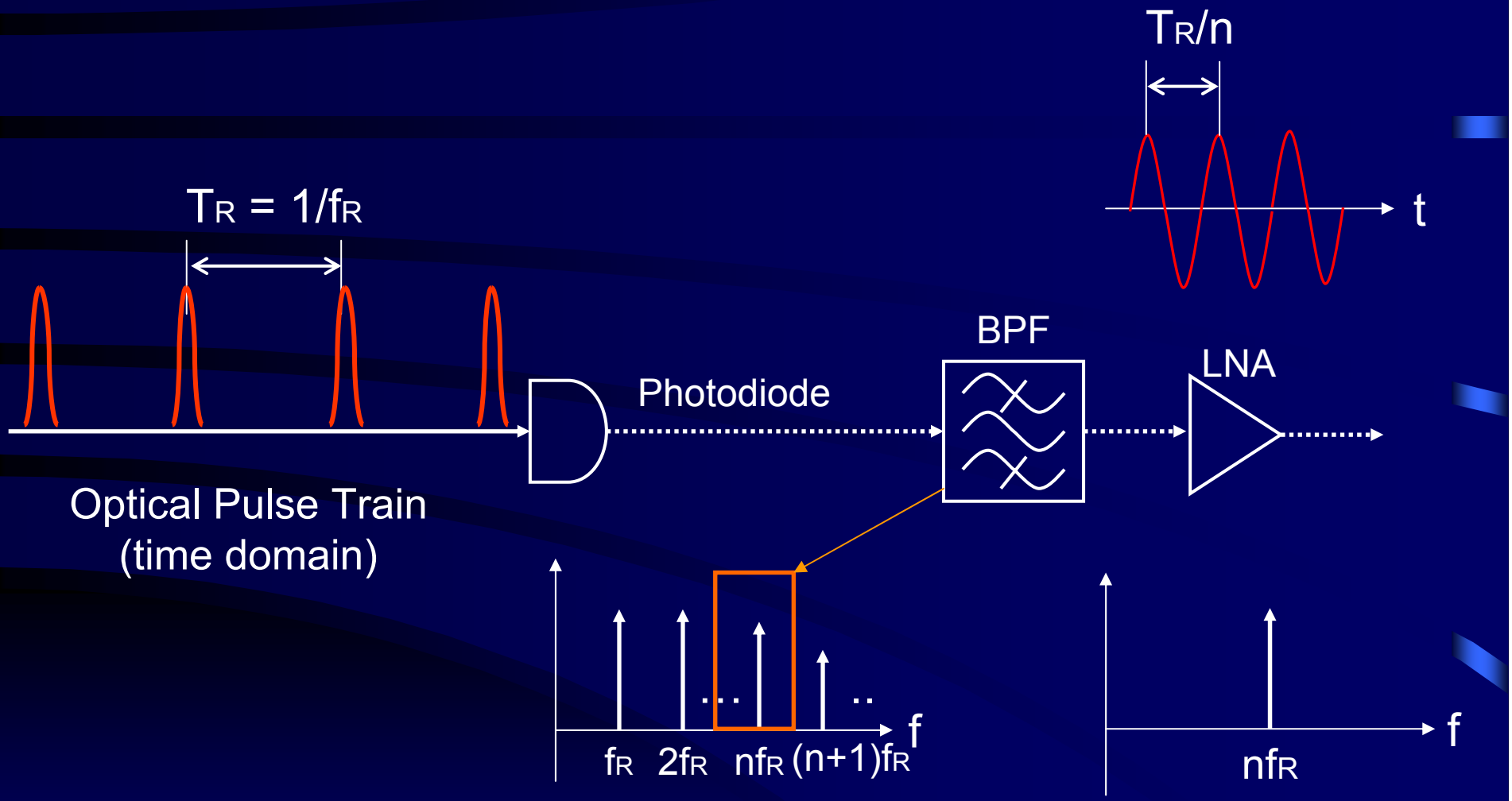
- transmit pulses in dispersion compensated fiber links
- no fluctuations faster than T=2nL/c (causality!)

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

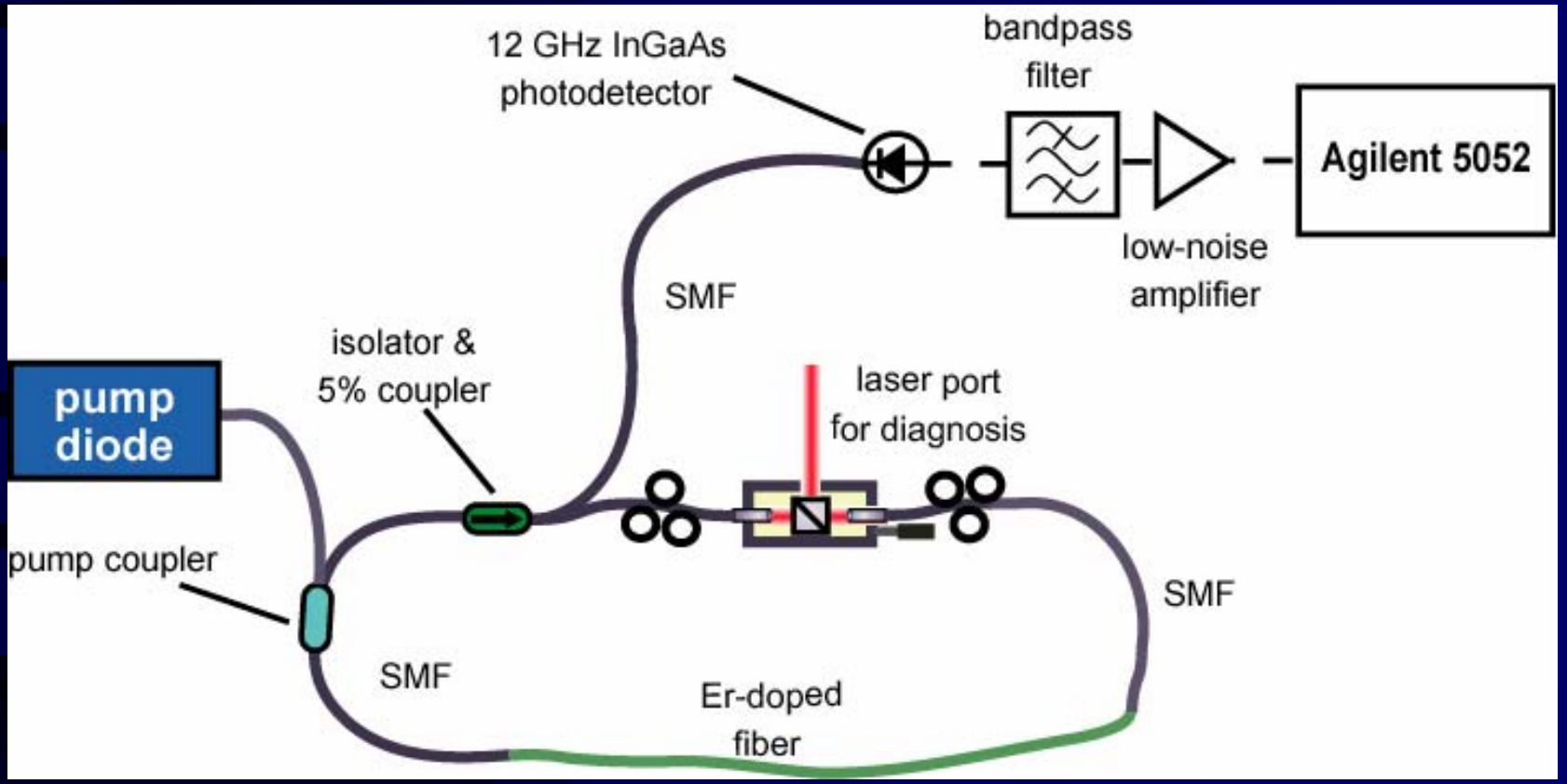
Lee et al. Opt. Lett. **14**, 1225-27

Fiber temperature coefficient: ~5x10^{-6} /m (1989)

Photodetection to extract RF from pulse train

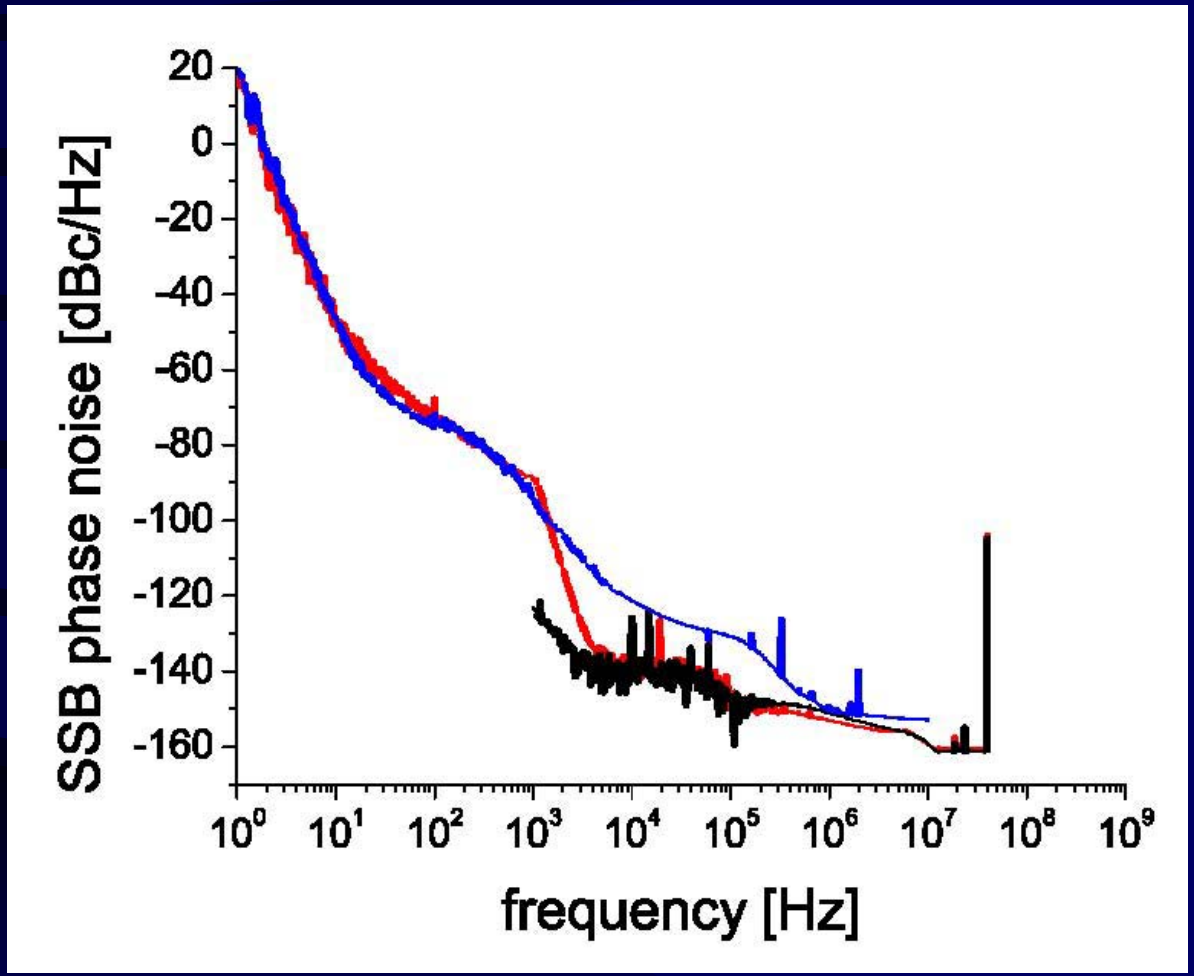


Timing jitter measurements



- signal converted to electronic domain by photodector
- harmonic (~1GHz) or repetition rate filtered
- phase noise measured with Signal Source Analyzer

Timing Jitter of fiber lasers



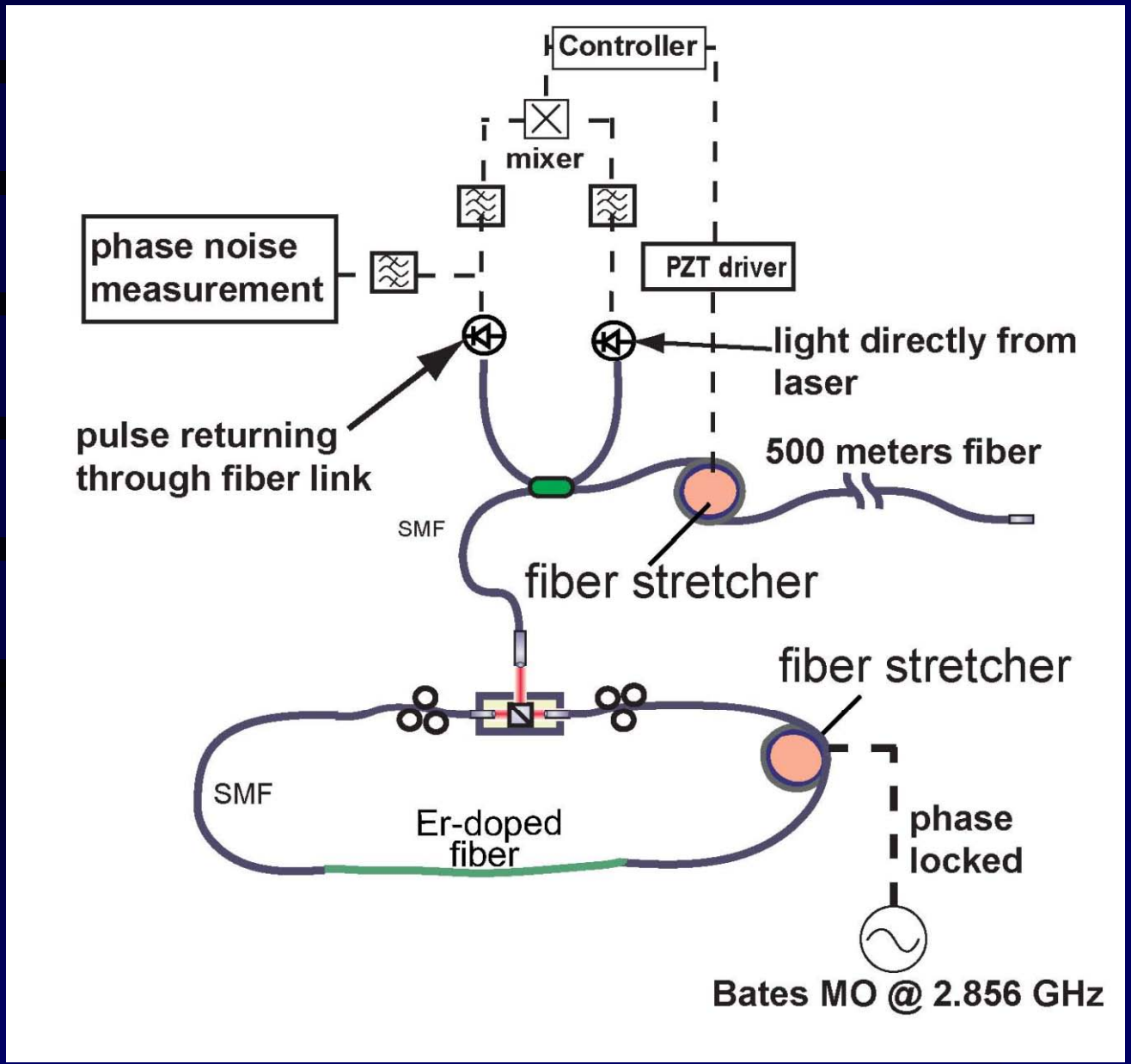
- All measurements at 1.3 GHz
- Noise floor limited by photodetection
- Theoretical noise floor ~1 fs

System Test in Accelerator environment

- Can lab results be transferred to real environment ?

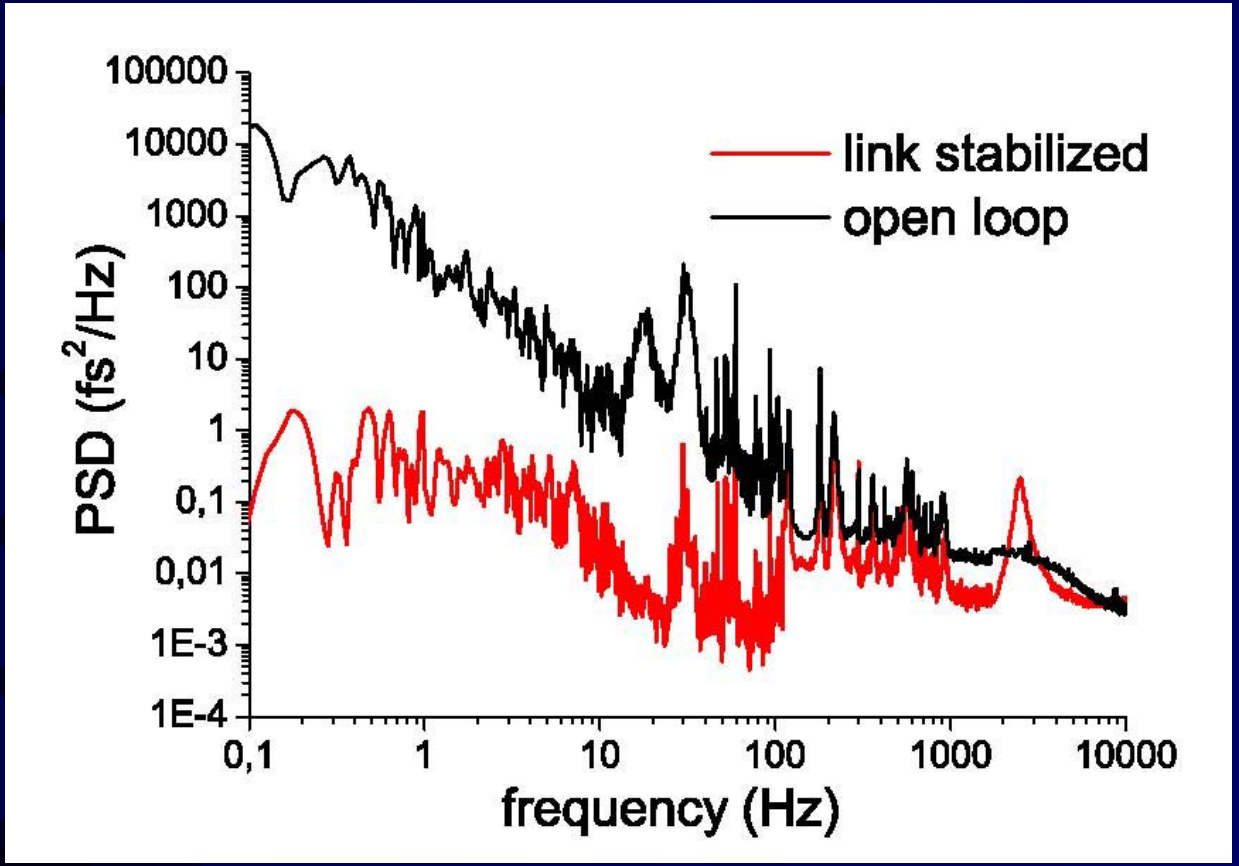
- Test done at MIT Bates laboratory:
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 1km total of laid out fiber
  - Close loop on fiber length feedback

Setup



- 1 km return of fiber
- Passive temperature stabilization of 500 m
- RF feedback for fiber link
- EDFL locked to 2.856 GHz Bates master oscillator

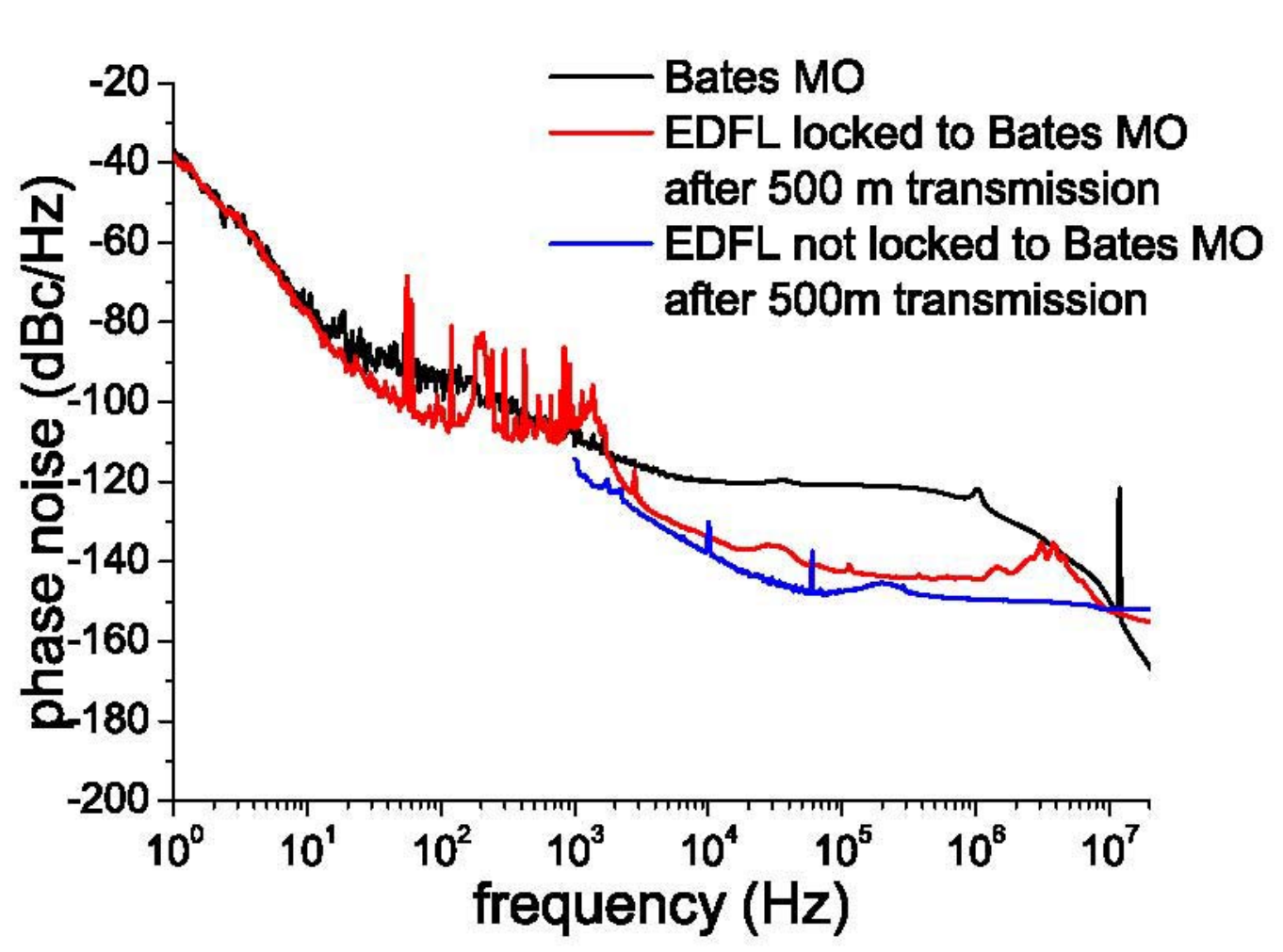
Results



- Fiber link extremely stable without closing loop (60 fs for 0.1 Hz…5 kHz)
- Closing feedback loop reduces noise (12 fs for 0.1 Hz .. 5kHz)
- No significant noise added at higher frequencies

- Sub-20 fs stability of fiber link with simple RF feedback
- Optical cross-correlation for sub-fs stability.

Transmitted frequency

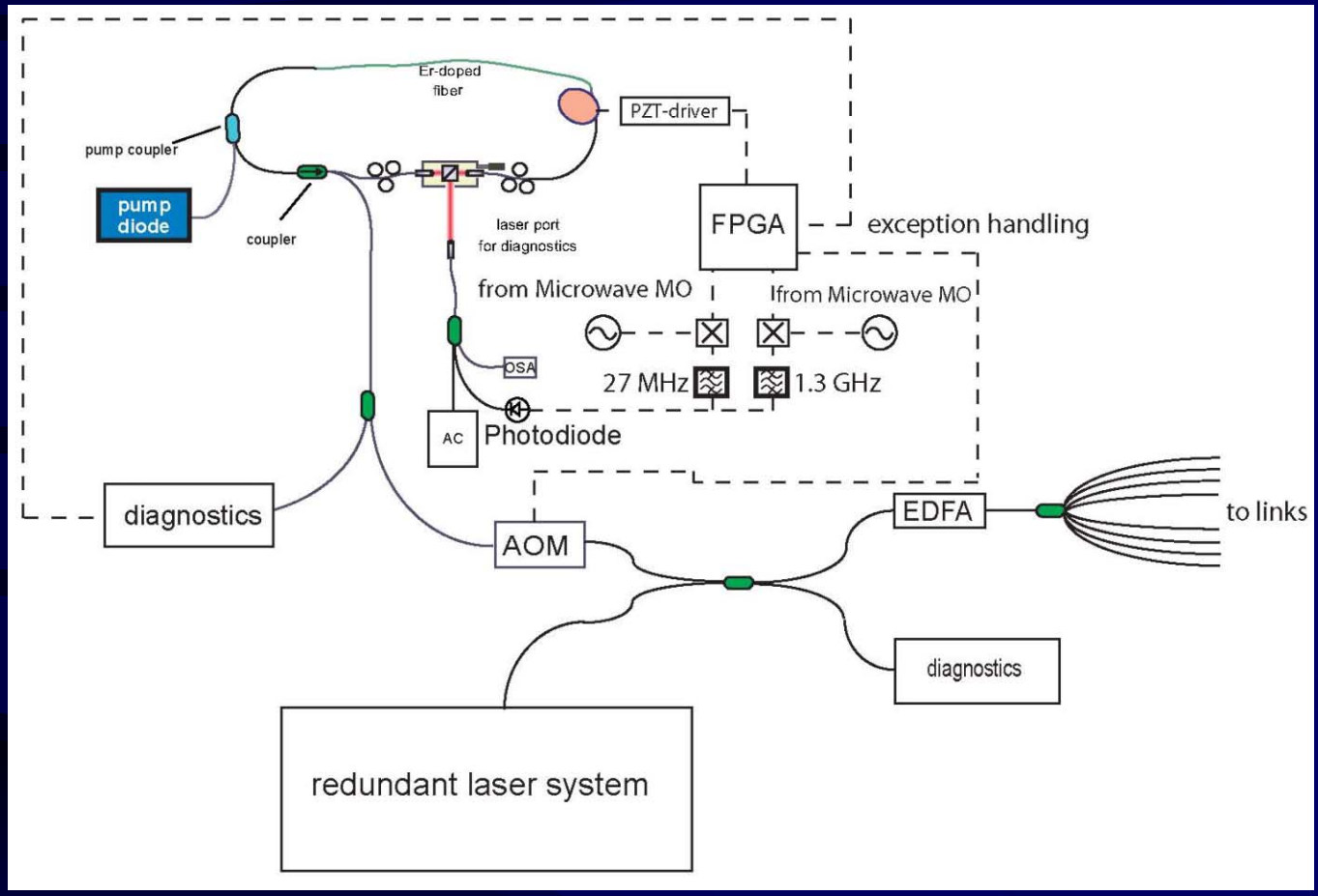


- Added jitter due to phase lock: ~30 fs (10 Hz..2 kHz)
- Total jitter added (link, phase lock, increase at high frequency) < 50 fs
- Overall improvement 272 fs vs. 178 fs (10Hz .. 20 MHz)
- Spurs are technical noise!

Conclusion and Outlook

- Successful demonstration of complete system in accelerator environment over 500 m fiber link
- sub-20 fs jitter added during transmission (0.1Hz .. 20MHz)
- 178 fs absolute phase noise limited by MO (10Hz .. 20 MHz)
- Most timing jitter is technical noise which can be eliminated.
- Stable, uninterrupted operation of the mode-locked fiber laser over weeks.
- Following a few years of development: < 10 fs

Design of the LMO for FLASH



- Two redundant lasers (54 MHz) with diagnostics
- FPGA will handle locking to RF (at 1.3 GHz and 27 MHz) and exception handling
- Switches between the two lasers in case one fails

Thank you for your attention !!