Femtosecond optical synchronization systems for XFELs

A. Winter, F. Ö. Ilday, J. Chen, F. Kärtner,
H. Schlarb, F. Ludwig, P. Schmüser
DESY Hamburg, MIT

19.9.2005

LLRF Workshop, CERN Oct. 2005

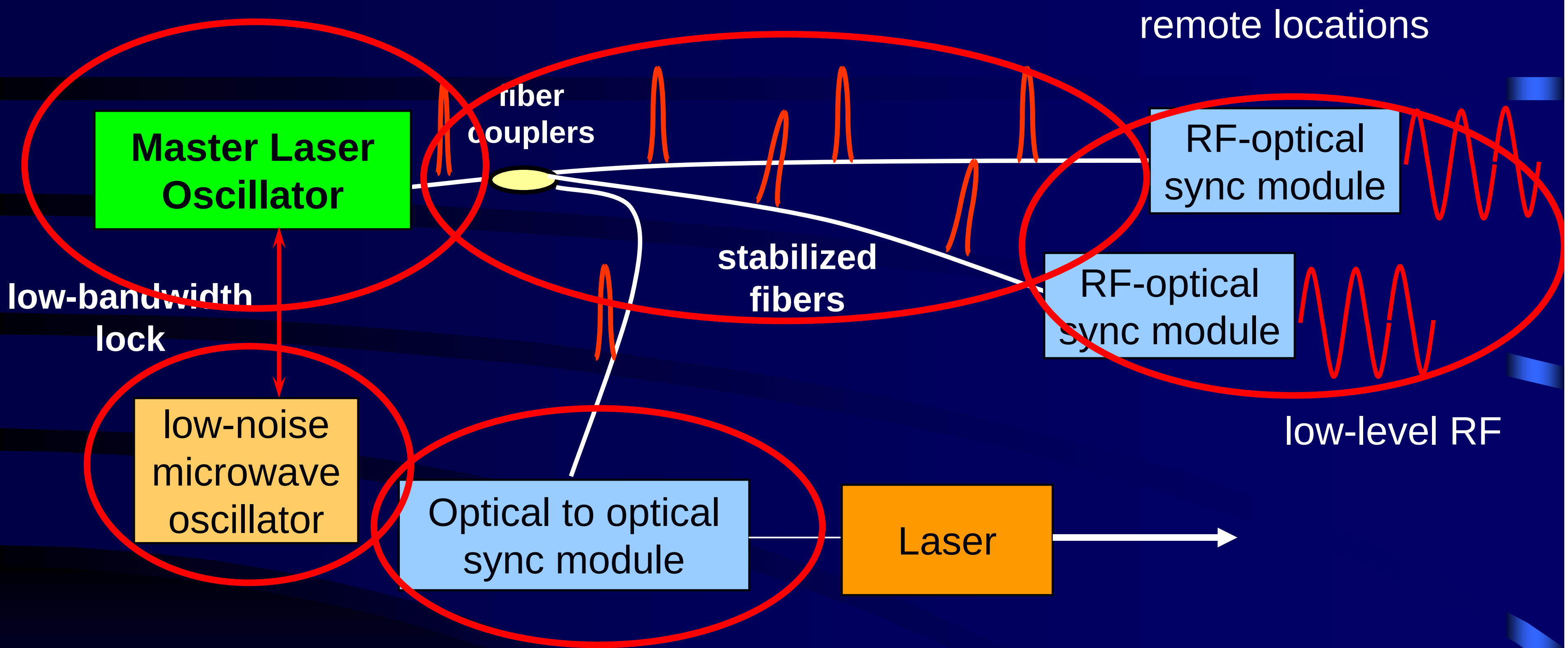
Overview

- Requirements
- Optical synchronization systems
  - •Optical master oscillator
  - •Optical timing distribution
  - •RF reconversion
  - •Synchronization of other laser systems
  - •Test in accelerator environment
- Conclusion and Outlook

Requirements

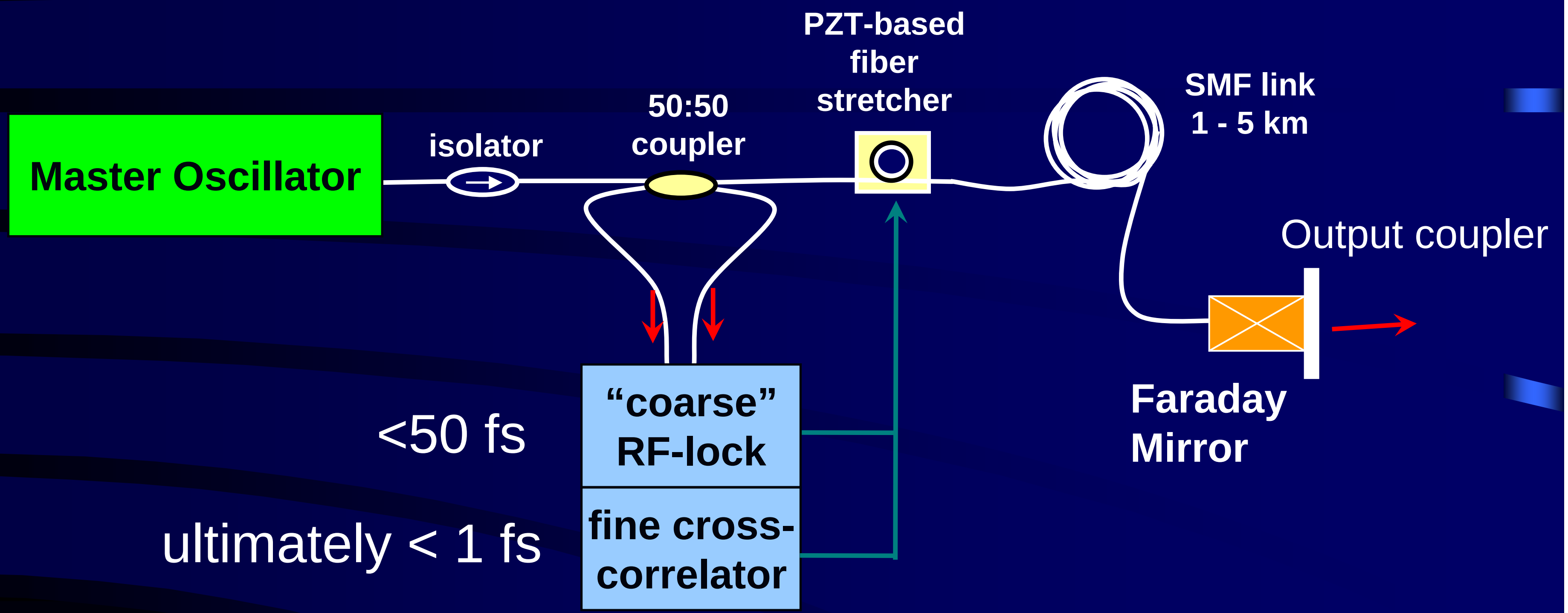
- Provide stability ~x-ray pulse width (down to ~10 fs)
  - Amplitude and phase stability in cavities (10^{-4}, 0.01deg) in most critical sections
  - Provide ultra-stable reference to select locations with femtosecond stability
  - Synchronize probe systems to reference with ~10 fs stability
- Precise 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

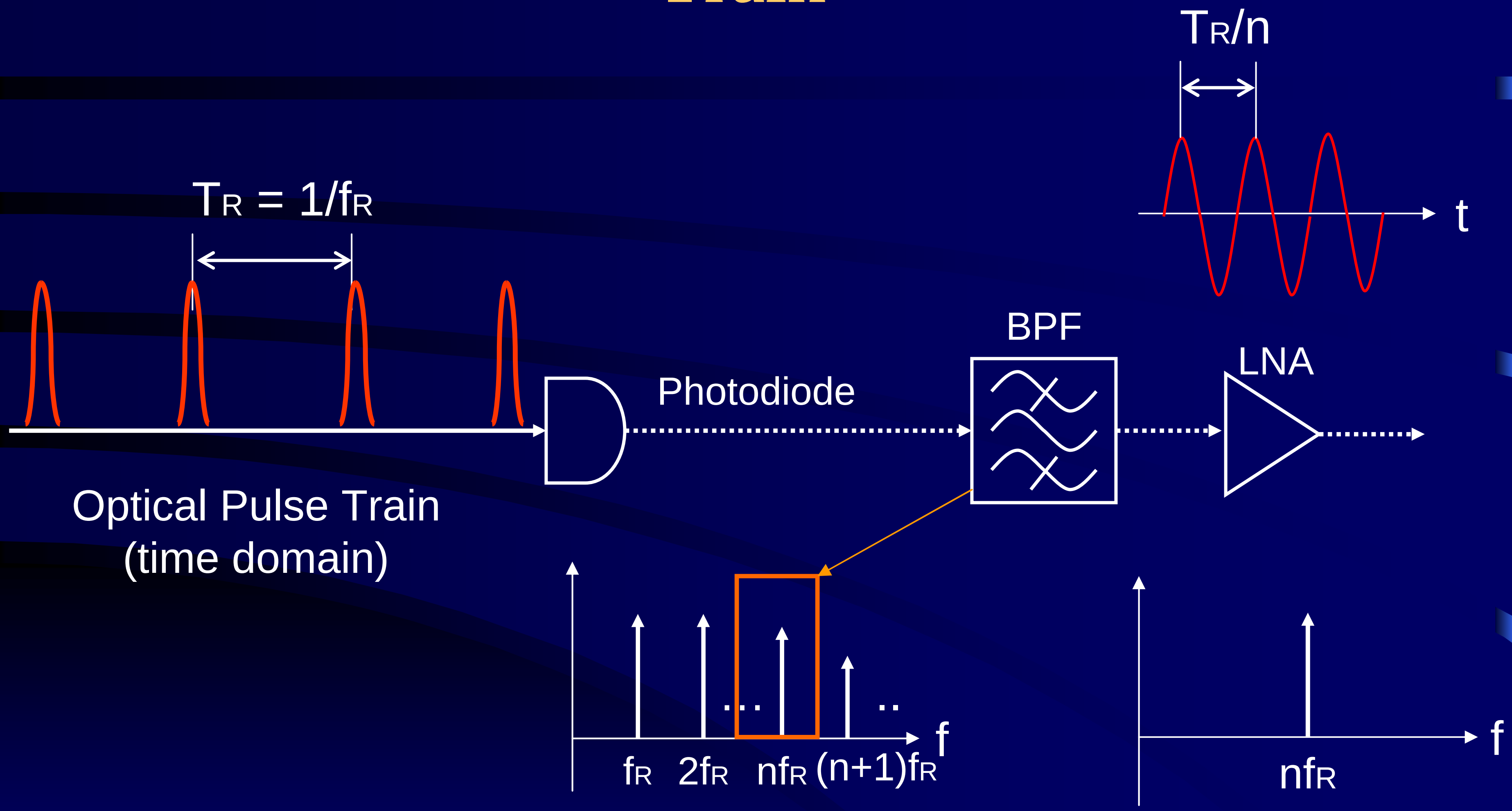
Timing stabilized fiber links



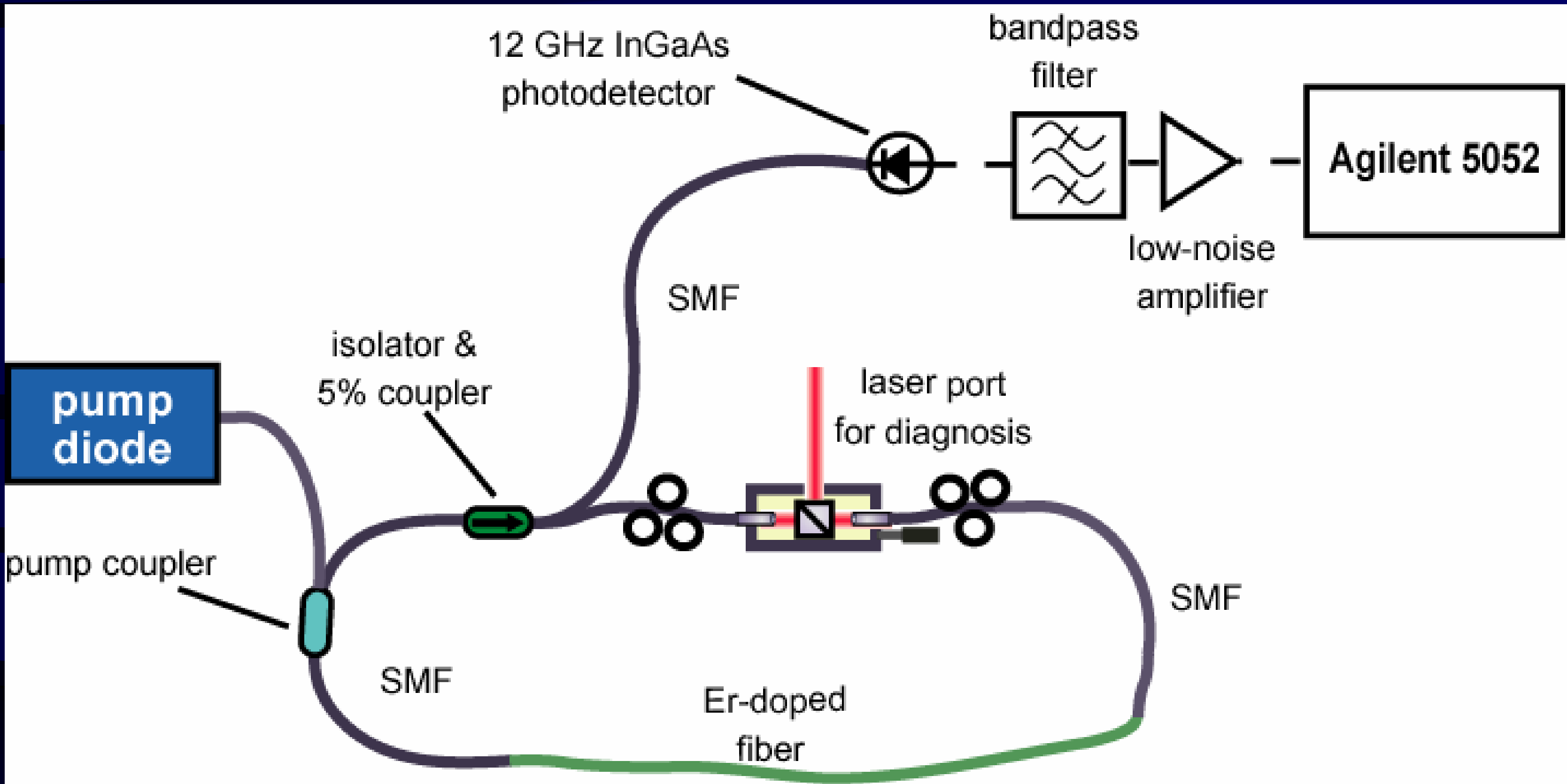
- transmit ~500 fs pulses via dispersion compensated fiber links
- assuming no fluctuations faster than T=2nL/c.

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

Direct Detection to Extract RF from the Pulse Train

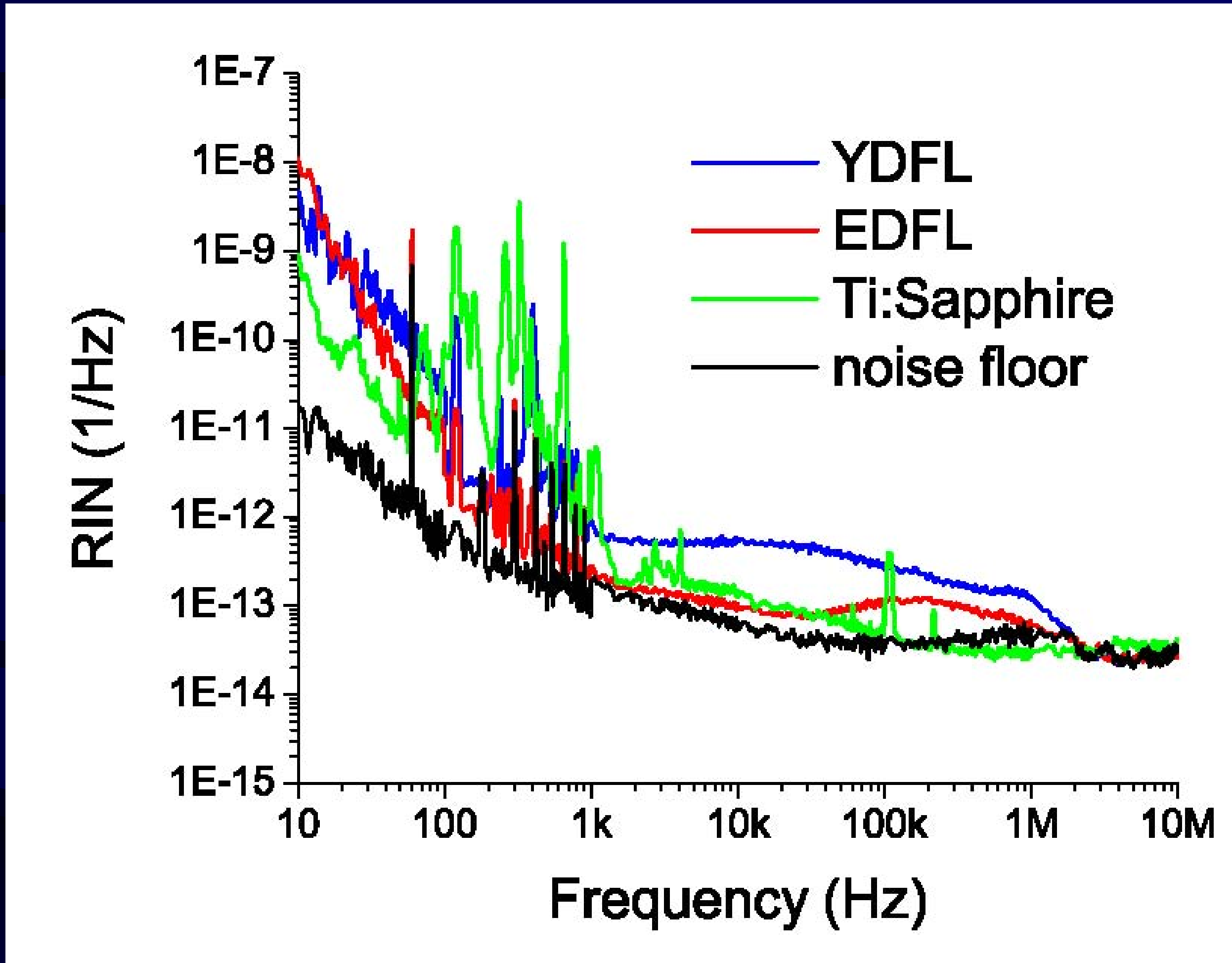


Timing jitter measurements



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

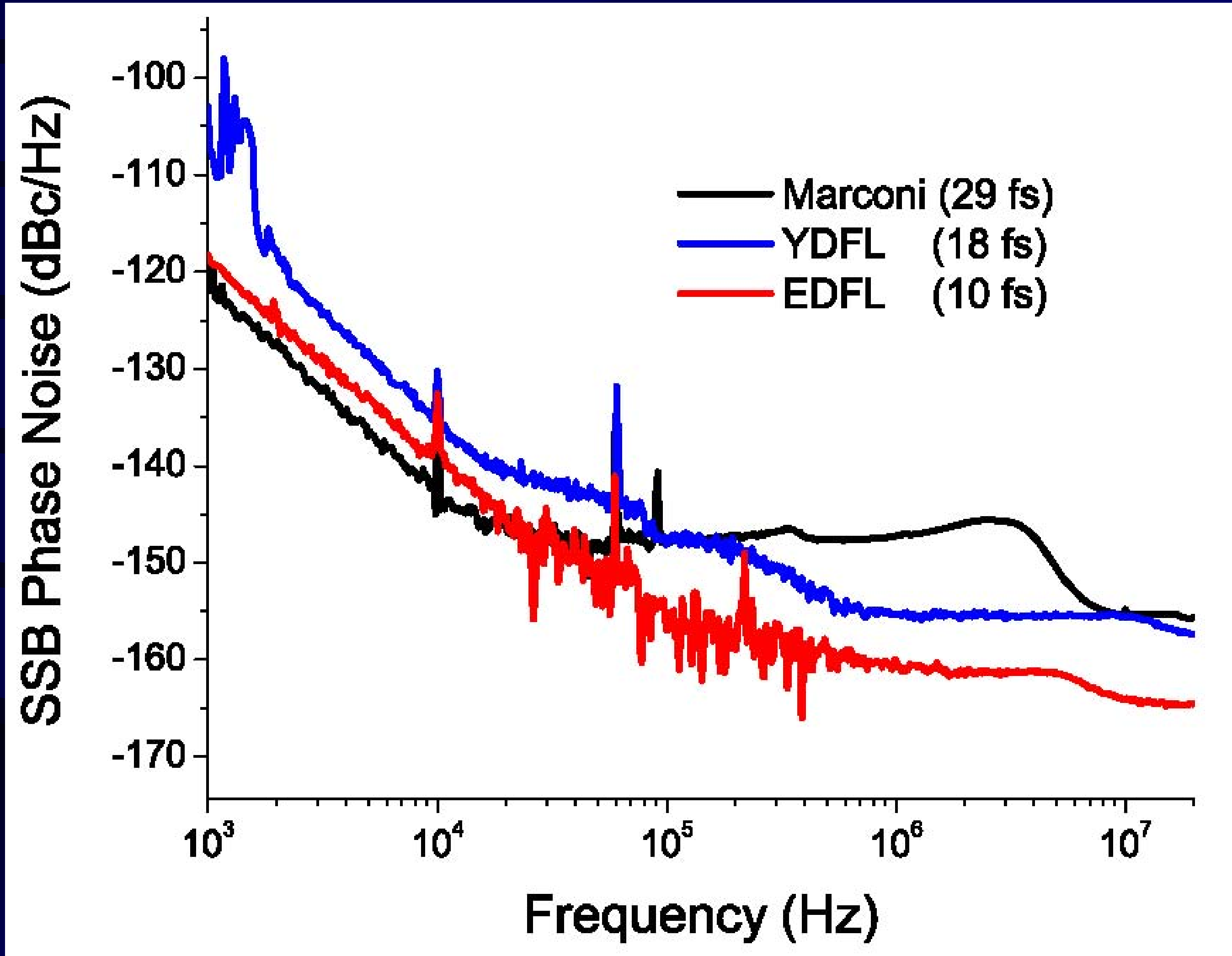
Amplitude noise of various fiber laser



0.03% rms for Er-doped fiber laser (EDFL)
0.04% rms for Yb-doped fiber laser (YDFL)
0.1% rms for Ti:Sapphire

Some of the quietest lasers around (3x-10x better than typical TiSa)

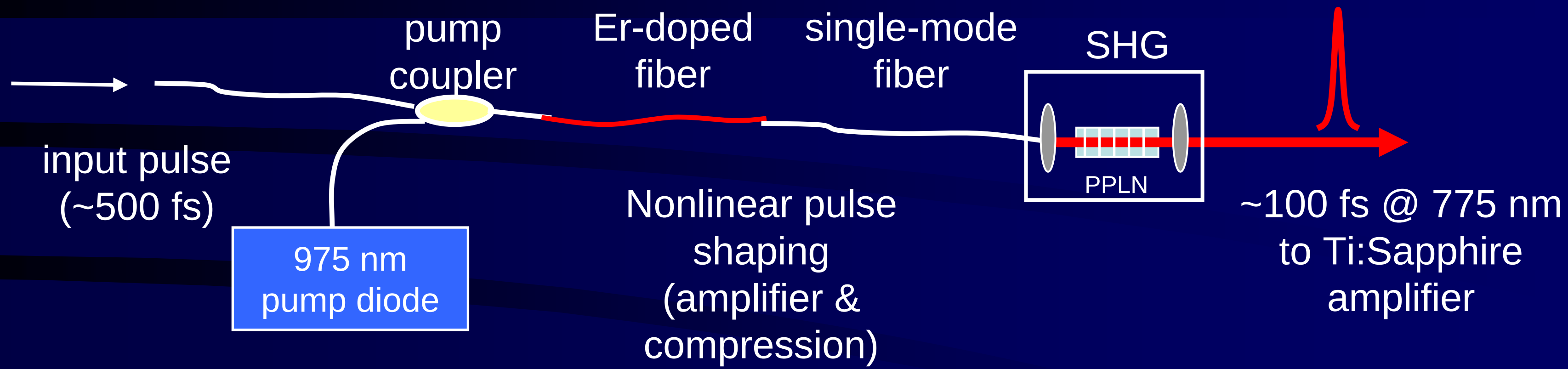
Timing Jitter of fiber lasers



- All measurements scaled to 1 GHz
- Noise floor limited by photodetection
- Theoretical noise limit ~1 fs

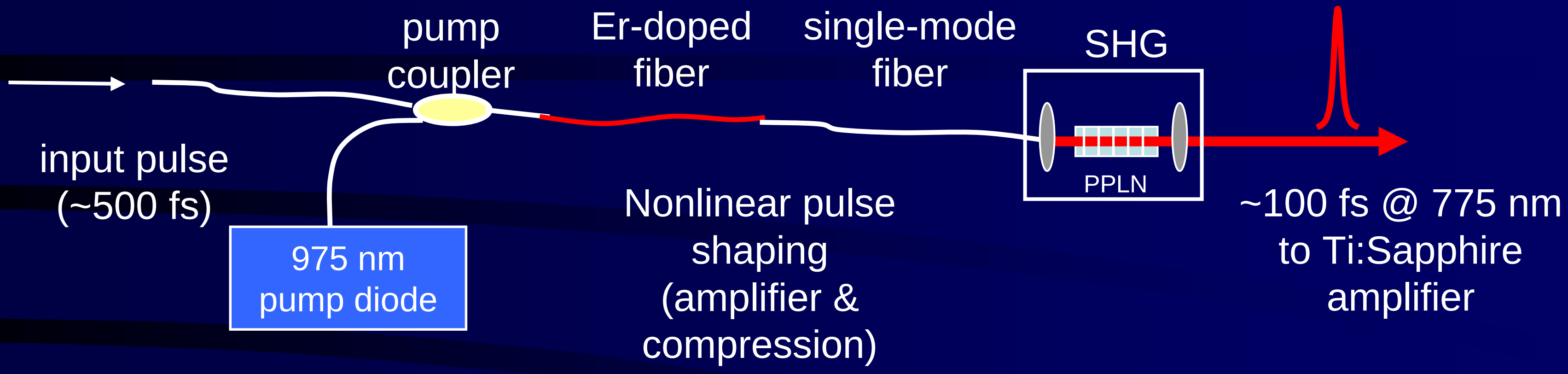
Direct seeding laser systems

Direct seeding a Ti:sapphire amplifier after pulse shaping with self-compression to ~100 fs (~1 nJ @ 1550 nm & ~0.3 nJ @ 775 nm)

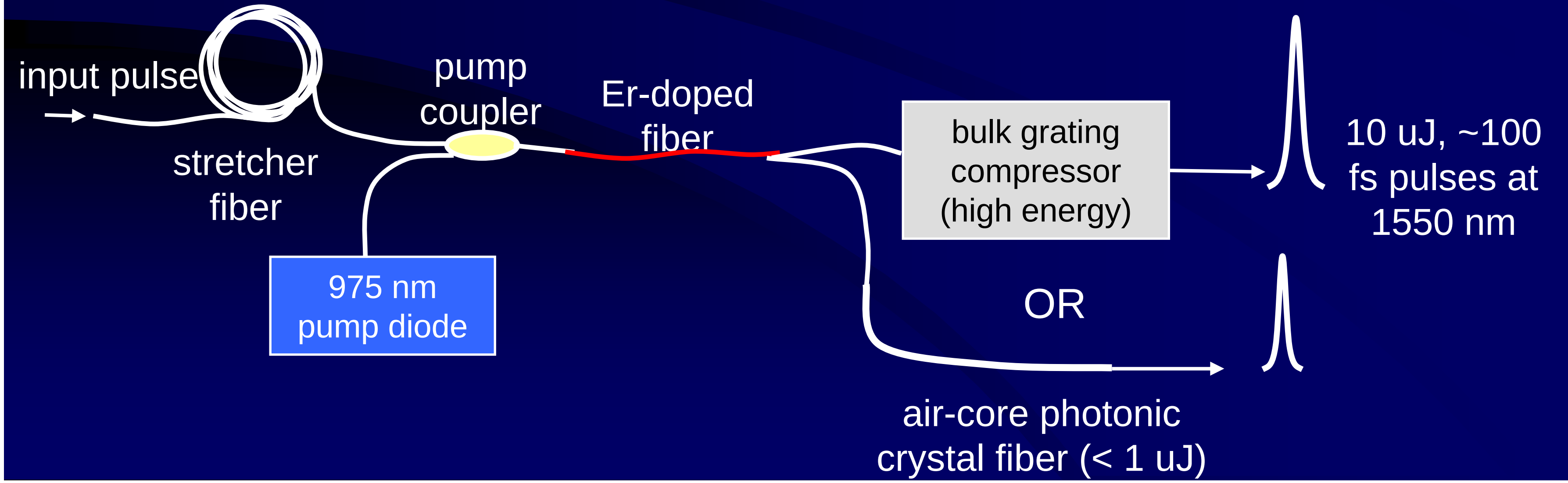


Direct seeding laser systems

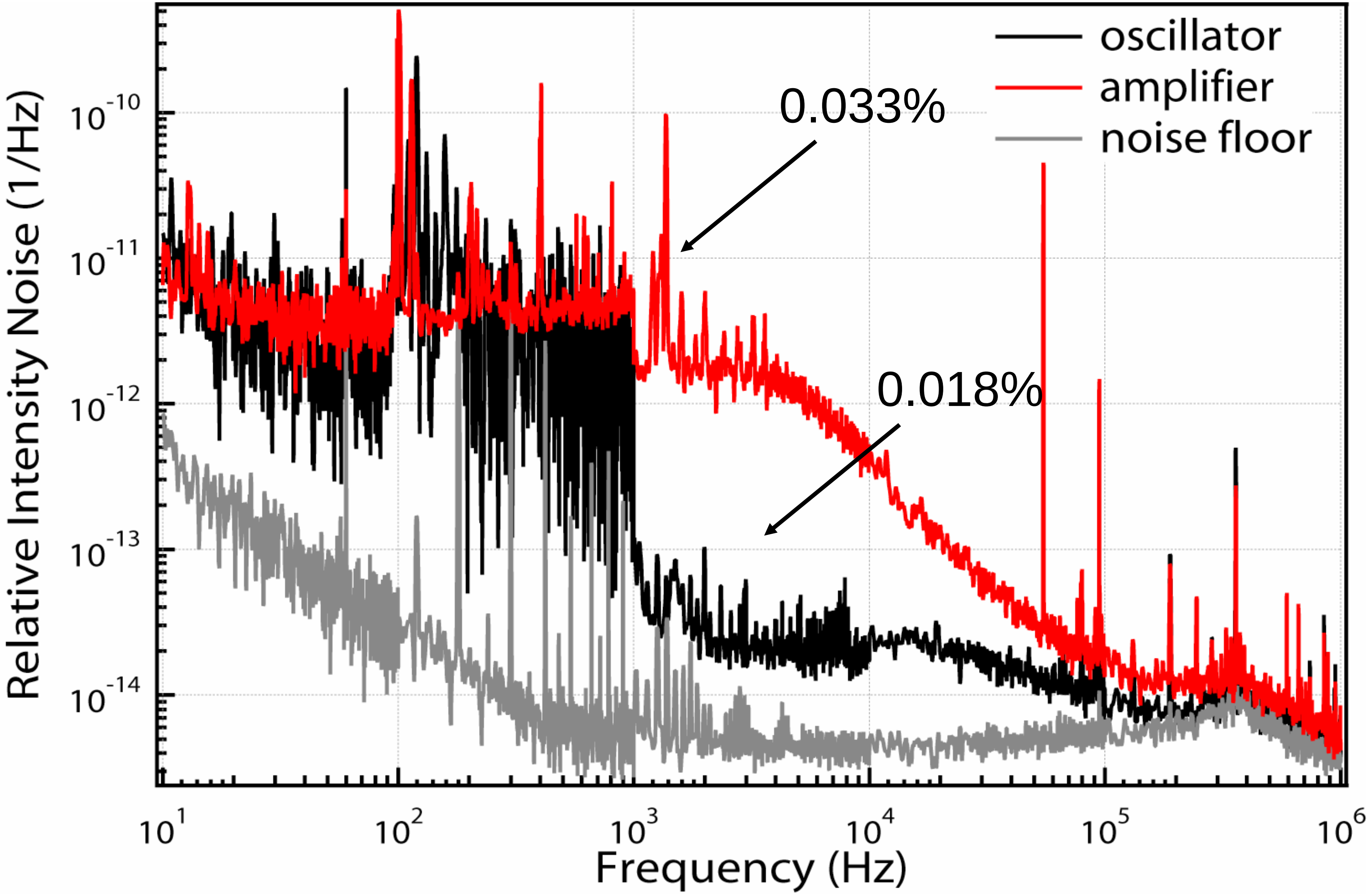
Direct seeding a Ti:sapphire amplifier after pulse shaping with self-compression to ~100 fs (~1 nJ @ 1550 nm & ~0.3 nJ @ 775 nm)



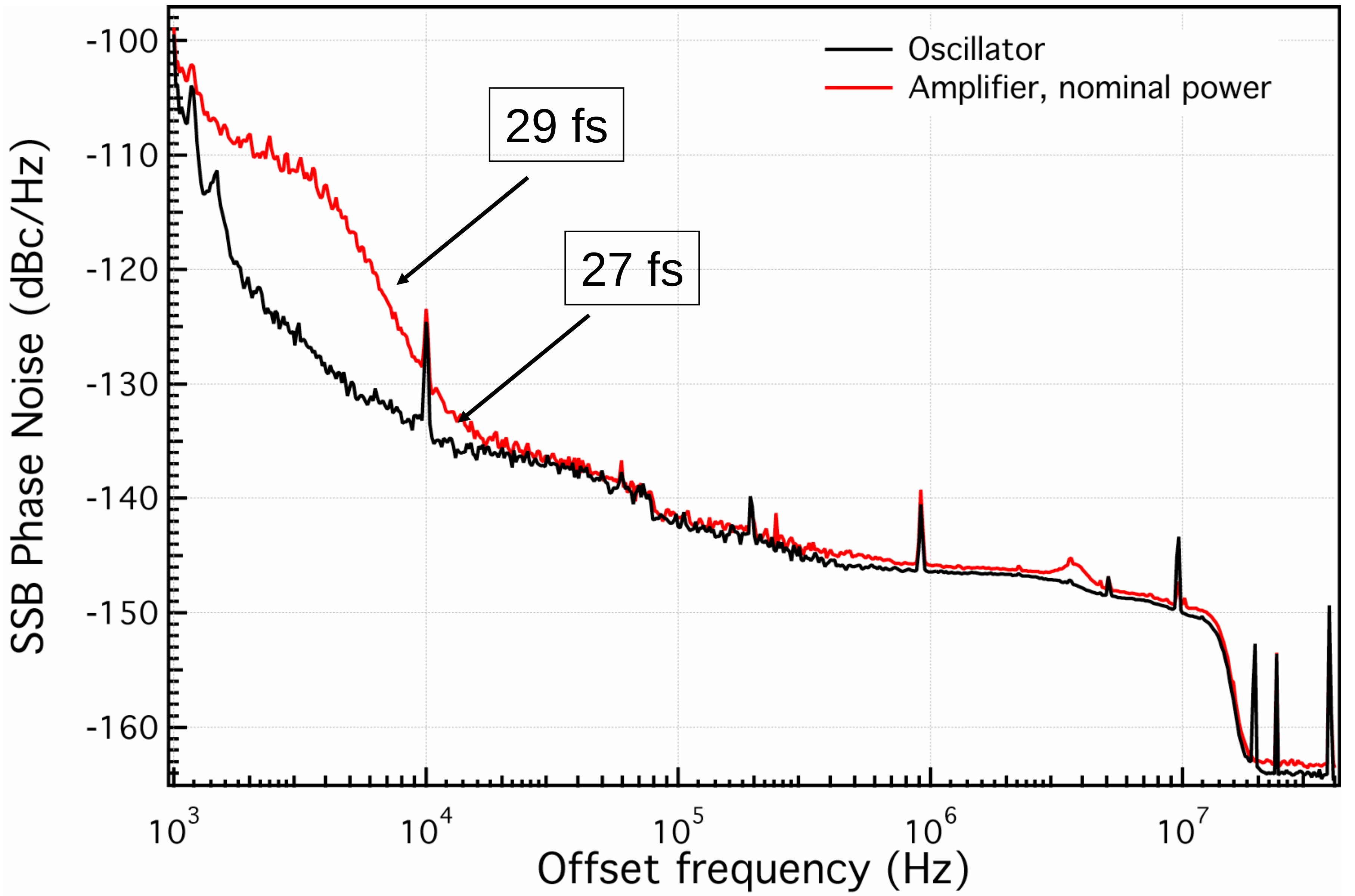
Amplification to high energy with nonlinear pulse shaping (~1 µJ @ 1550 nm, low repetition frequency)



Very little amplitude noise added



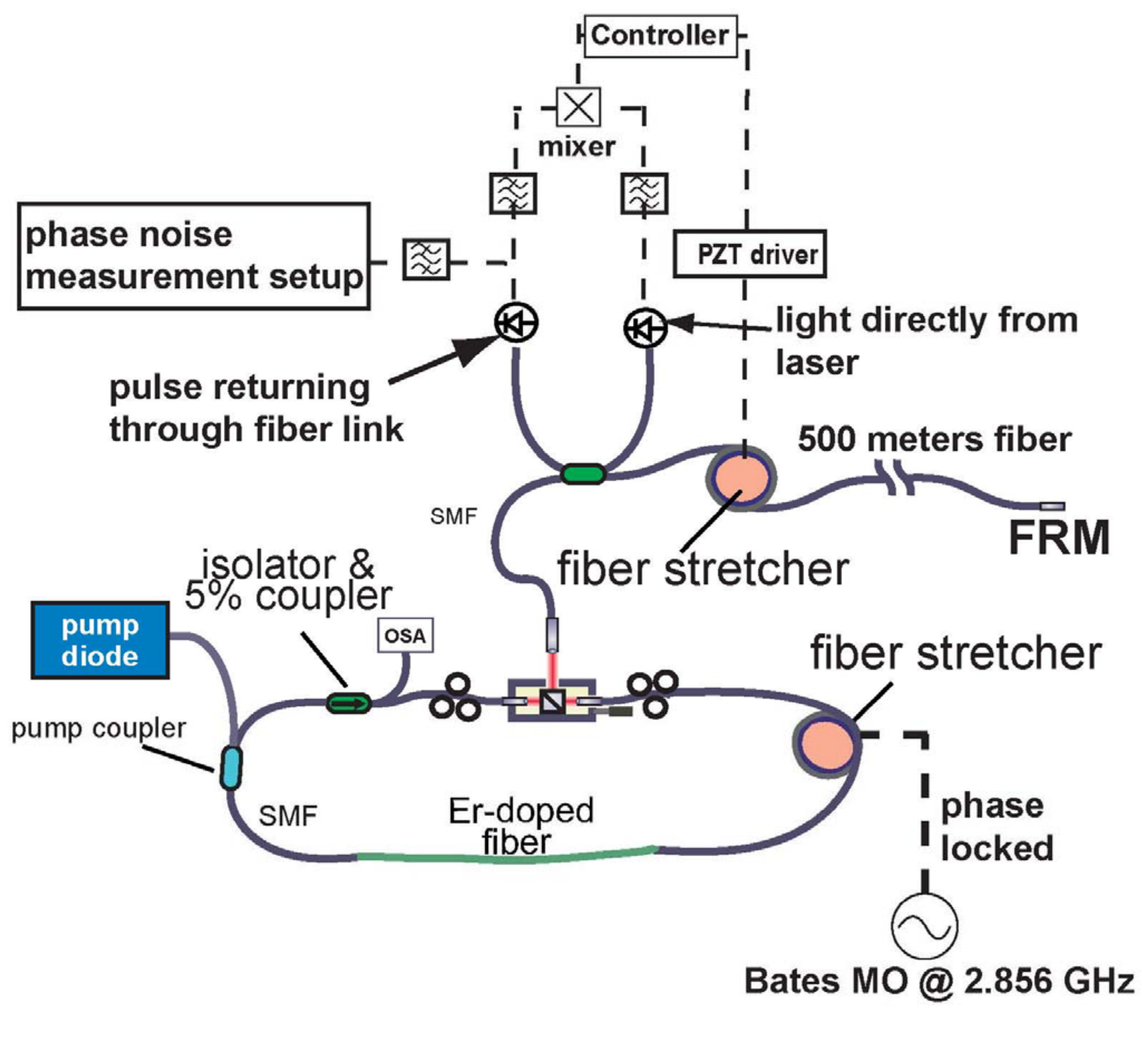
Very little phase noise added



System Test in Accelerator environment

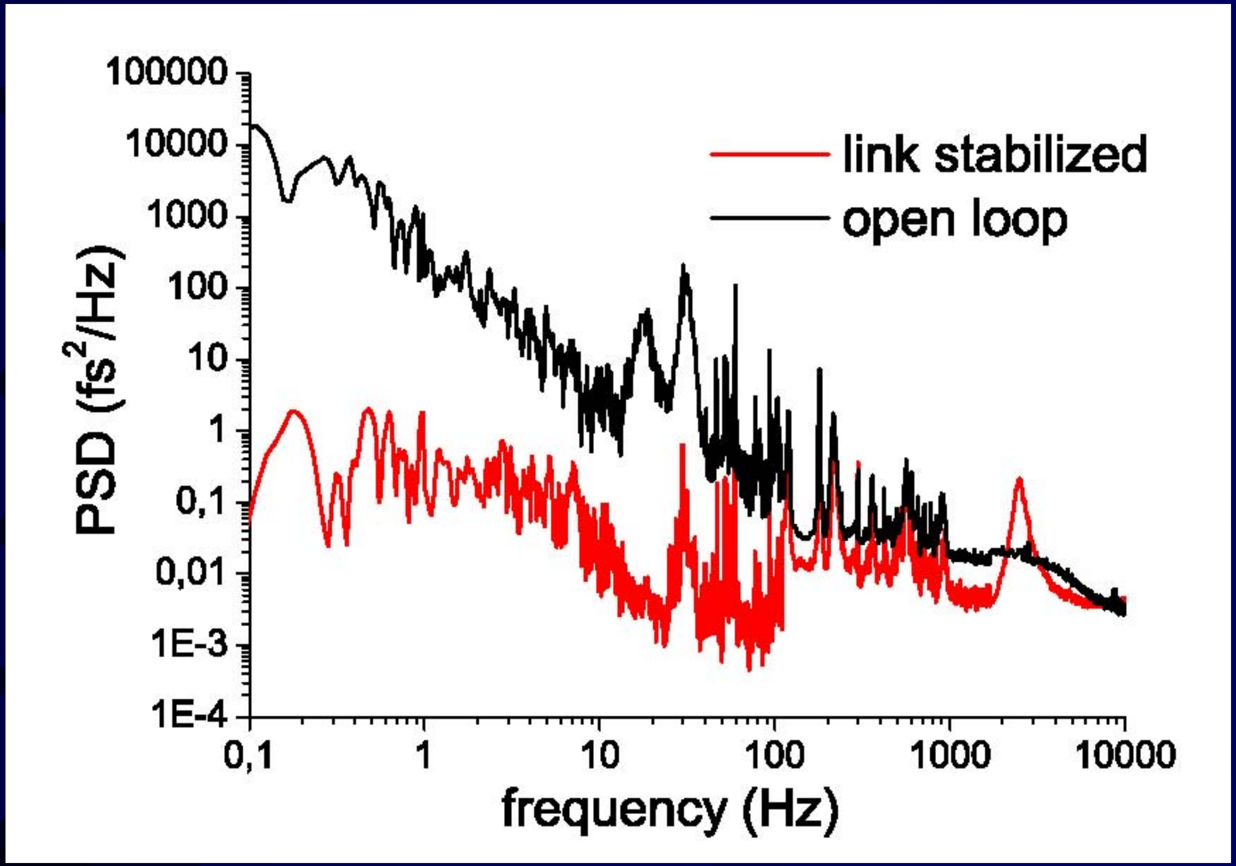
- Can lab results be transferred to real environment ?
- Test done at MIT Bates laboratory:
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 1km total of laid out fiber
  - Close loop on fiber length feedback

Setup



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

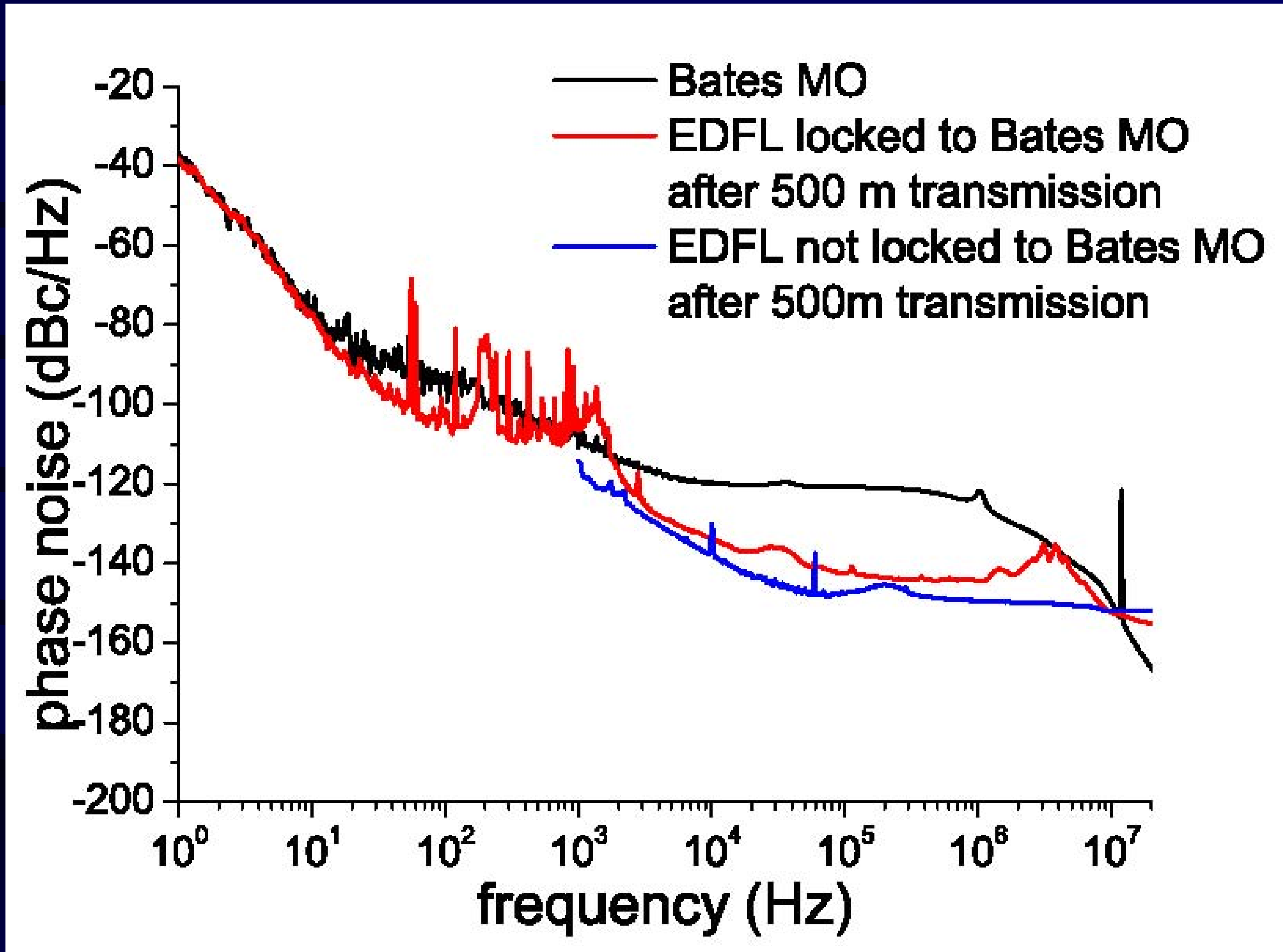
Results



- 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

- Can be stabilized to eventually sub-fs level using optical cross-correlation.

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 1 km 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 over weeks.
- Following a few years of development: < 10 fs