Fiber Laser Master Oscillators for Optical Synchronization Systems with Femtosecond Precision

Axel Winter

Overview

- Motivation
- Background on fiber lasers
- First prototype implementation in an accelerator environment
- Laser master oscillator for FLASH
- Outlook and conclusion

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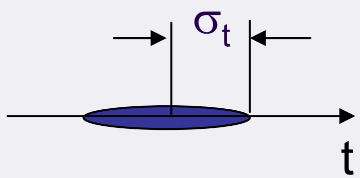
Decreasing Electron Bunch Length in Machines

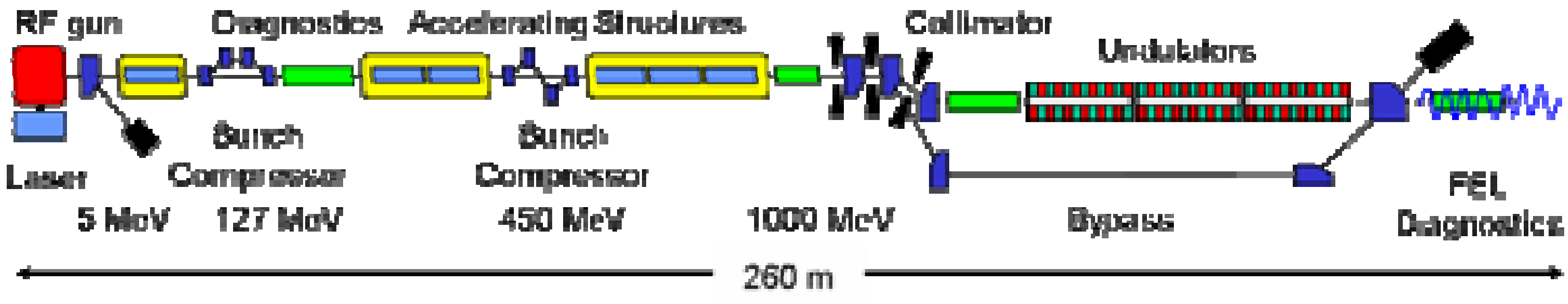
- Towards shorter electron pulse duration $1\ \text{ps} = 10^{-12}\ \text{s}$
  $= 1000\ \text{fs}$
  $= 300\mu\text{m}/c_0$



- Synchrotron light sources …BESSY, SLS $\sigma_z = 10\text{mm} \sim 20\ \text{ps}$

- Free Electron Lasers … XFEL $\sigma_z = 20\ \text{um} \sim 60\ \text{fs}$
  Short pulse operation @ FLASH: FEL pulses < 5 fs

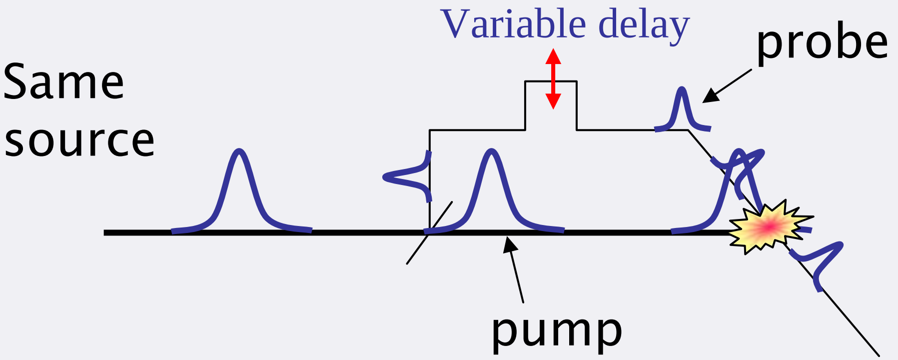
~ 10^{-3}

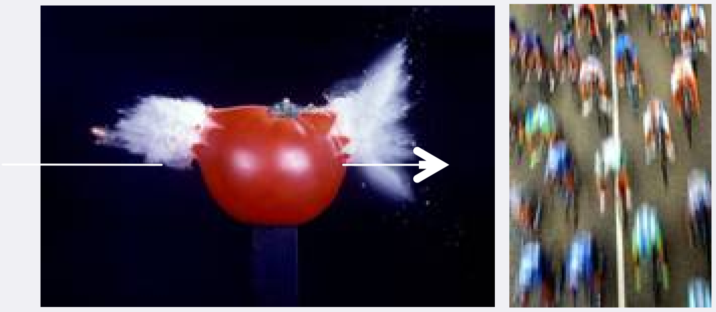


Courtesy: Holger Schlarb

Motivation: Pump-probe experiments

Classical setup:



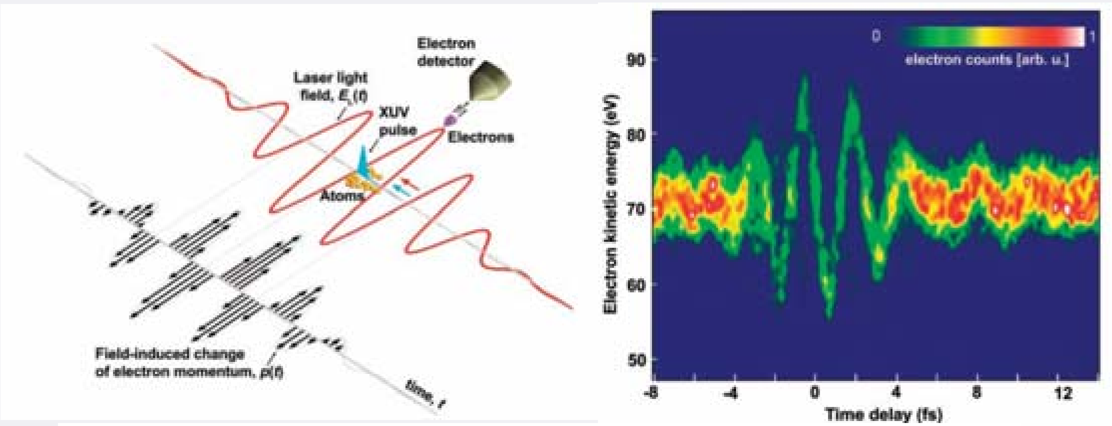


Shot pulses fs ⟸ ps

- Pump pulse initiate reaction, probe pulse records current state.
- Atomic / Molecular Physics/ Solid state dynamics

Example: Direct measurement of the electric field of 5 fs laser pulse

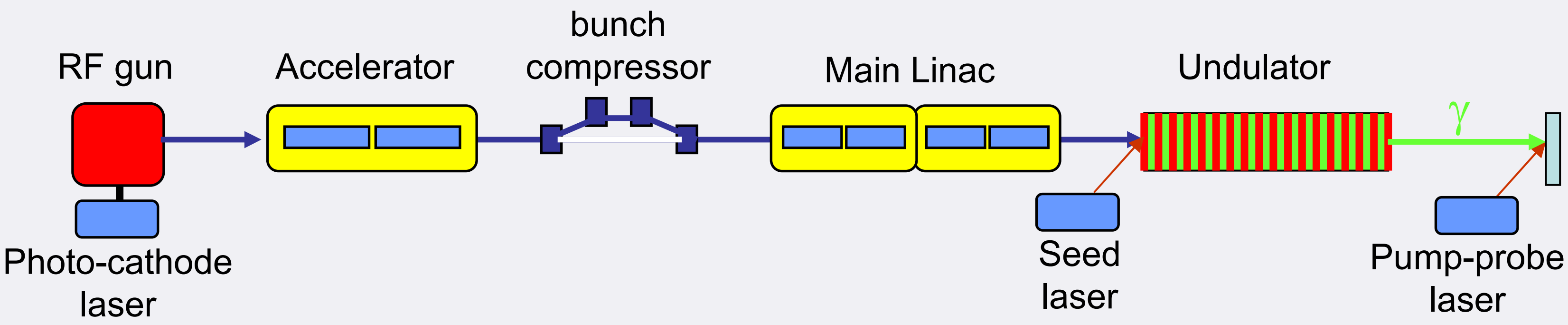
Knowledge of time delay is crucial!



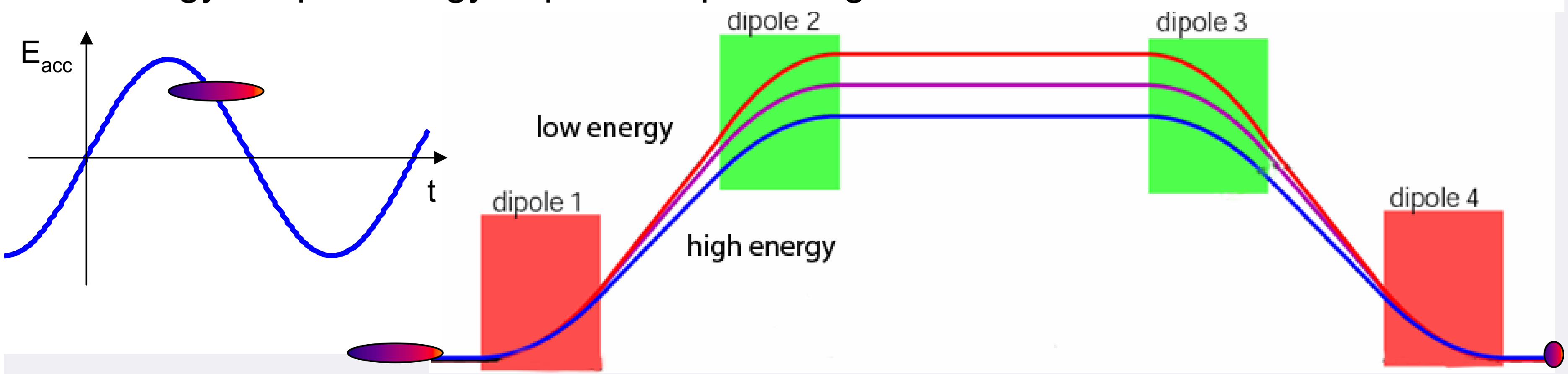
E. Goulielmakis, SCIENCE, VOL 305 27 AUGUST 2004

Sources of arrival timing jitter

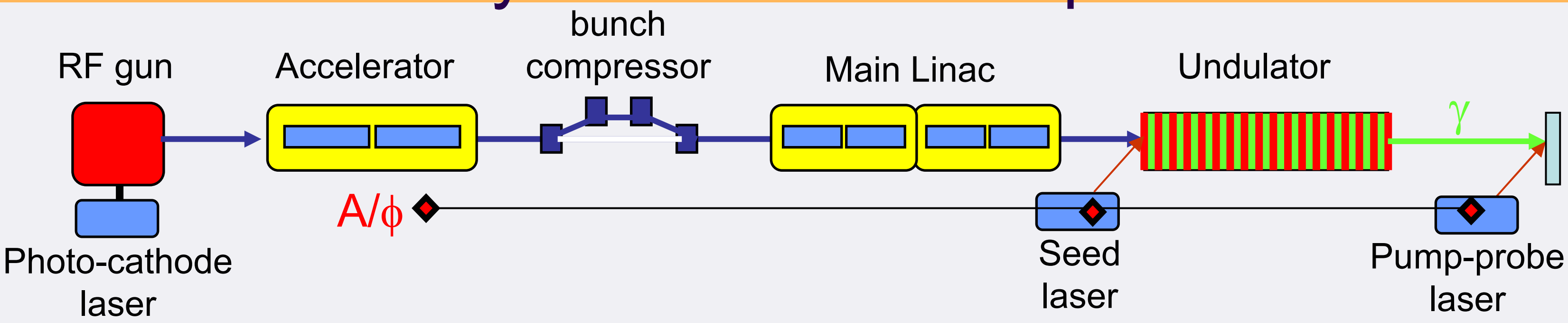
- arrival time jitter at entrance to undulator



Energy chirp + energy dependent path length



Main source of timing jitter
- Caused by RF acceleration prior to BC-



Gradient | Phase | Incoming

Timing jitter behind BC

$$\sigma_t^2 \approx \left(\frac{R_{56}}{c}\frac{\sigma_a}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2 \left(\frac{\sigma_\phi}{\omega_{RF}}\right)^2 + \left(\frac{1}{C}\right)^2 \sigma_{in,t}^2$$

XFEL: 3.3 ps/%
FLASH: 5.5ps/%

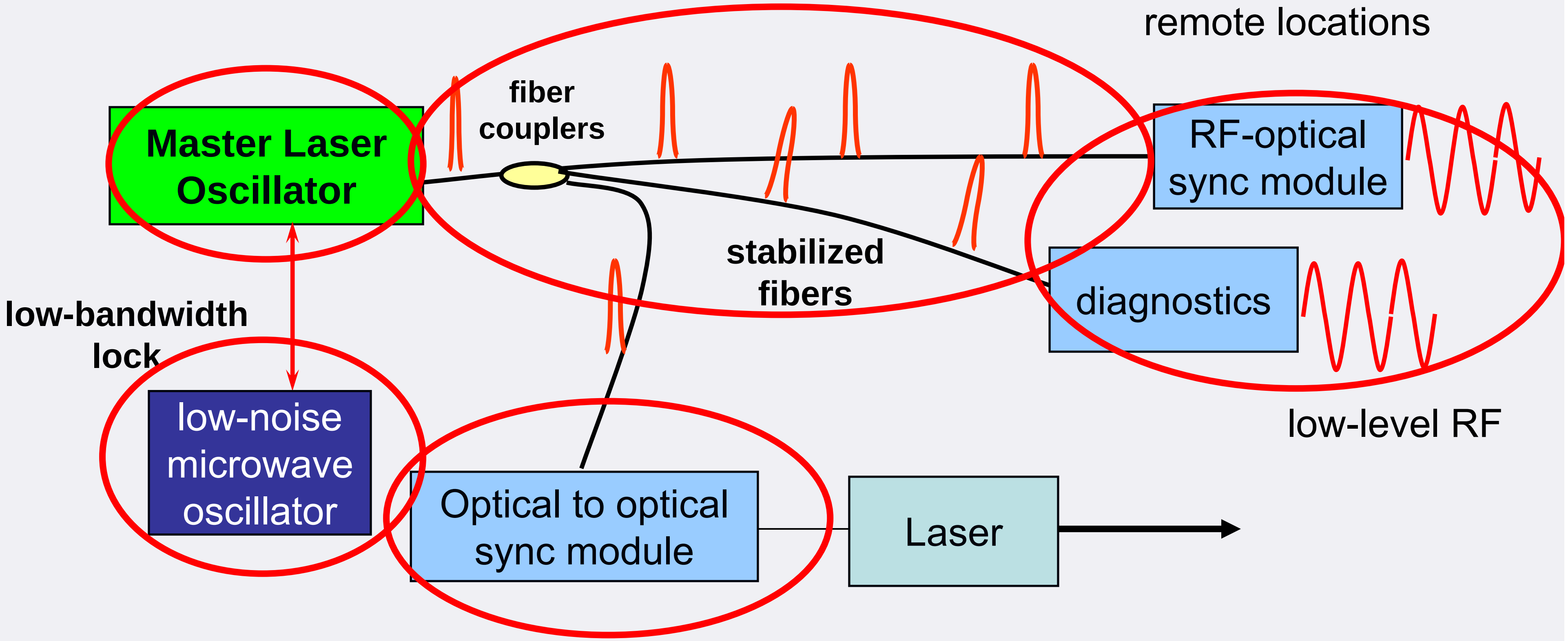
2 ps/deg

0.05 ps/ps

C compression factor (20-100)
R_{56} ~ 100 mm XFEL /180 mm FLASH
ω_{RF}: RF frequency

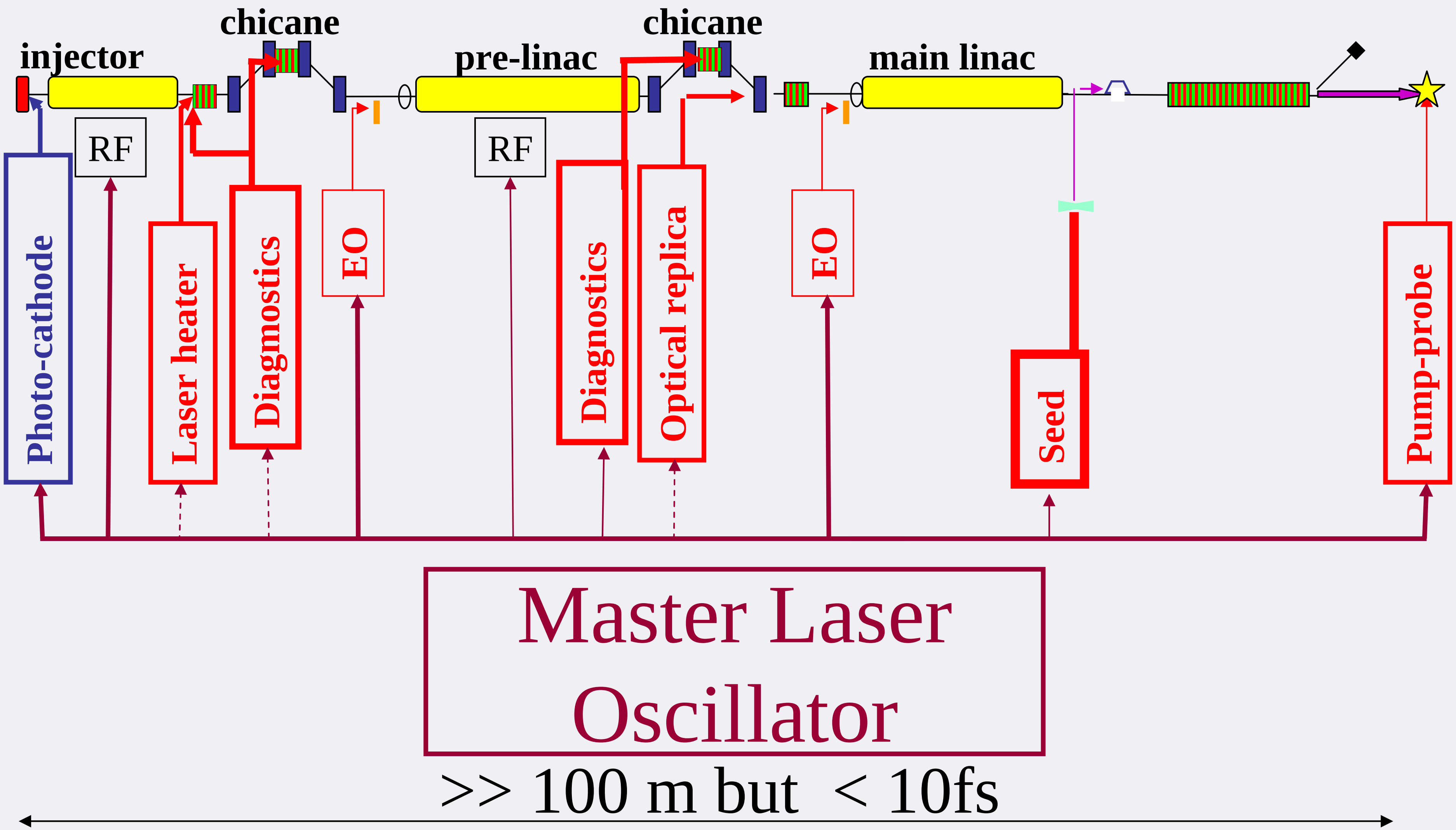
10 fs stability → 0.01° phase stability
10^{-4} amplitude stability

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

Optical Lasers in FEL-facilities



Why Fiber Lasers? – Requirements for frequency source

- 100 fs pulse duration
- Operation at telecom wavelength (1550 nm)
- Repetition rate ~ 50 MHz (later 200 MHz)
- Reliable, long-term operation without interruption
- Ultra-low time jitter at high offset frequencies (= on fast time scales)
  - Only relative jitter of systems important up to ~ 1 kHz
  - Some systems follow faster – absolute phase noise important

Erbium-doped fiber lasers are the only type of laser that fulfill all above requirements

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Light propagation in optical fibers

- Propagation in optical fibers is governed by the nonlinear Schrödinger Equation:

$$i\frac{\partial a}{\partial z} = +\frac{\beta_2}{2}\frac{\partial^2 a}{\partial t^2} - i\frac{\alpha}{2}a - \gamma|a|^2 a$$

Dispersion Losses Nonlinearity

- a – slowly varying complex pulse ampltiude,
  z – direction of propagation,
  β_2 – dispersion parameter,
  γ – nonlinearity parameter

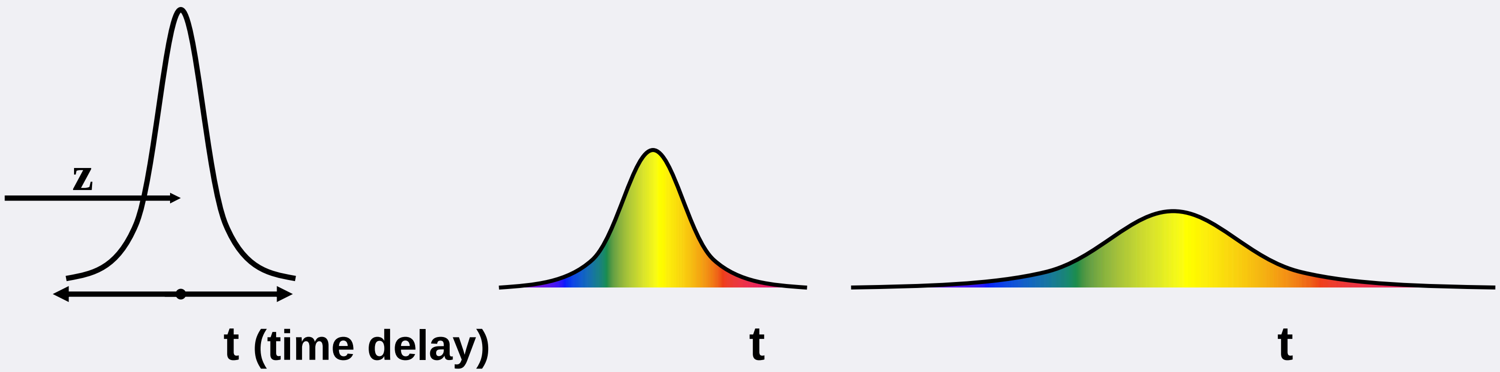
- t is time measured in frame of reference moving with the pulse at group velocity

Linear Dispersion

$$i\frac{\partial a}{\partial z} = +\frac{\beta_2}{2}\frac{\partial^2 a}{\partial t^2} - i\frac{\alpha}{2}a - \gamma|a|^2 a$$

dispersive medium:

index of refraction depends on frequency $n = n(\nu)$



Pulse spreads due to (group-velocity) dispersion (GVD)

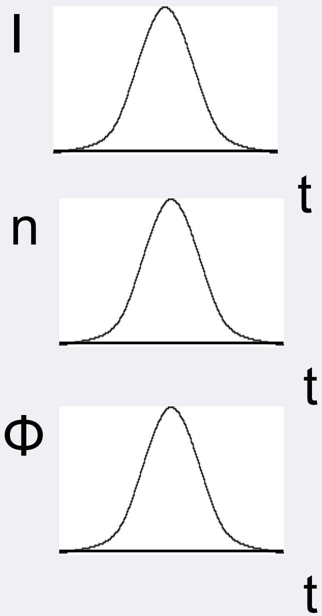
Nonlinear propagation ($\chi(3)$)

$$i\frac{\partial a}{\partial z} = +\frac{\beta_2}{2}\frac{\partial^2 a}{\partial t^2} - i\frac{\alpha}{2}a - \gamma|a|^2 a$$

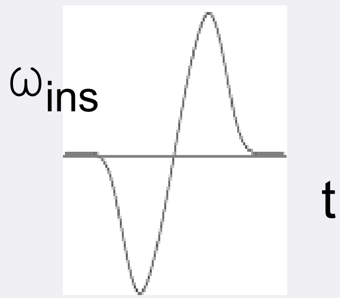
nonlinear medium:

$n = n_0 + n_2 I$

index of refraction depends on intensity

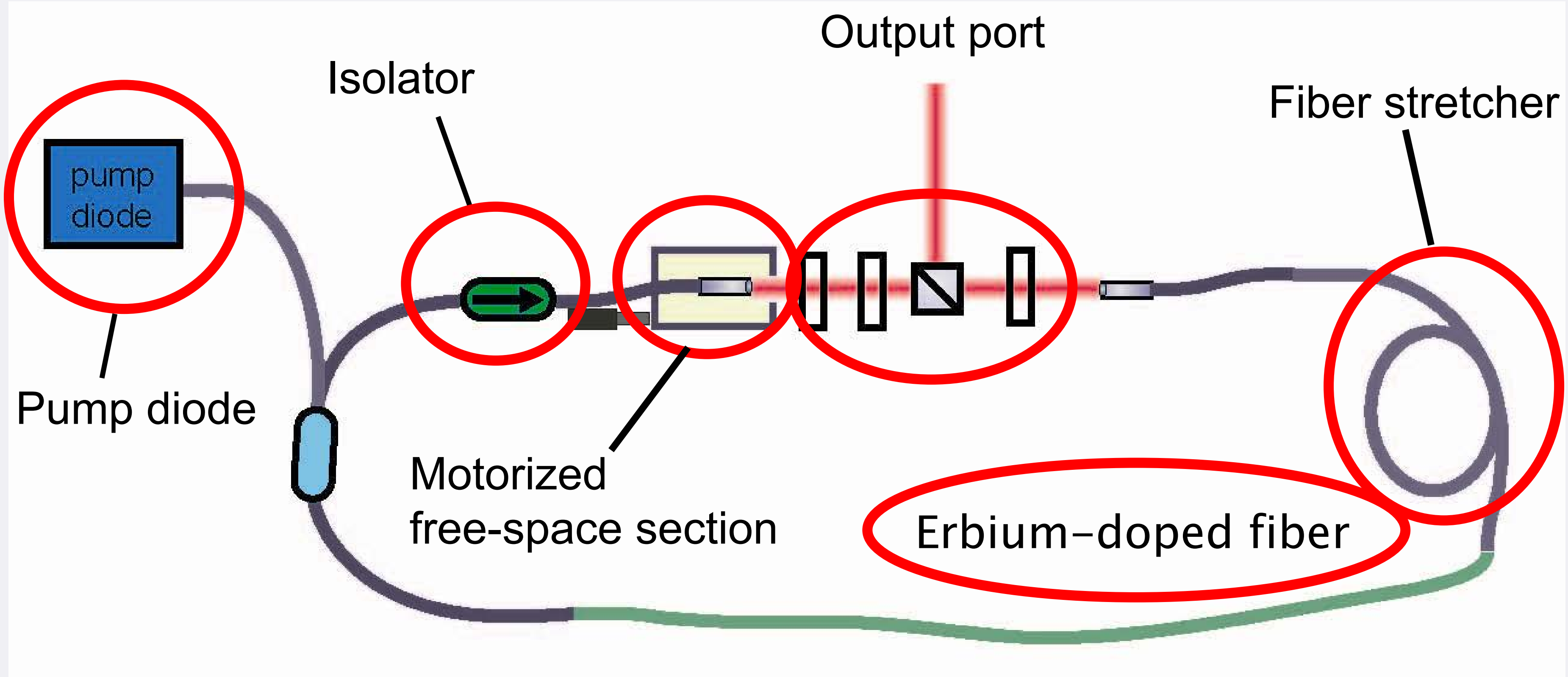


$$\omega_{ins} = \frac{\partial \phi}{\partial t}$$



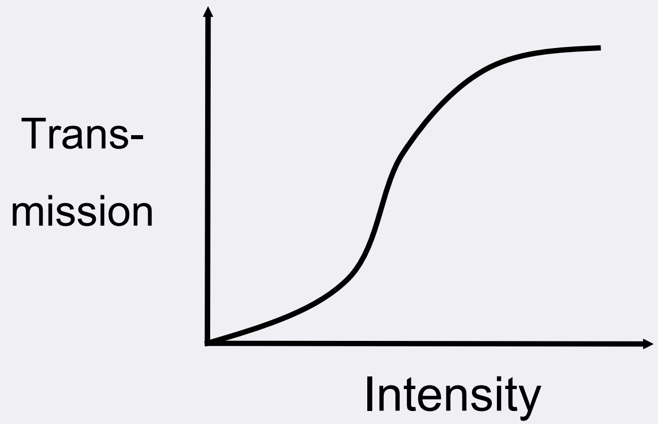
New frequency components are created

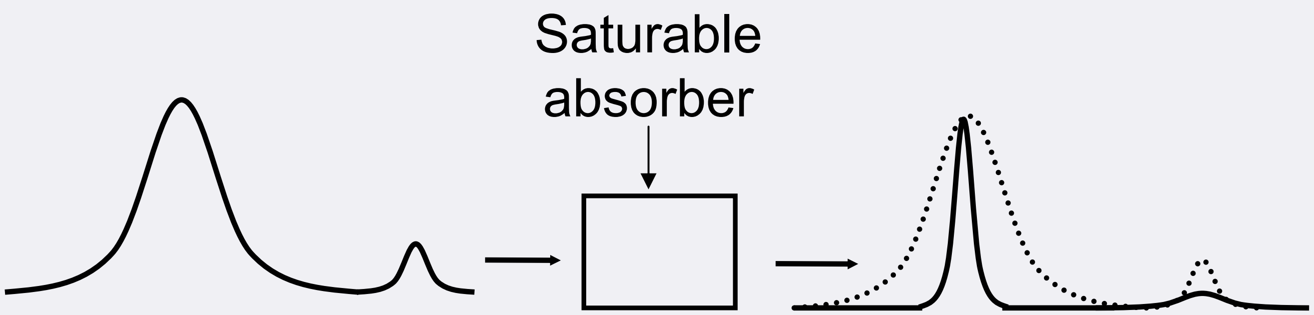
Erbium-doped fiber lasers



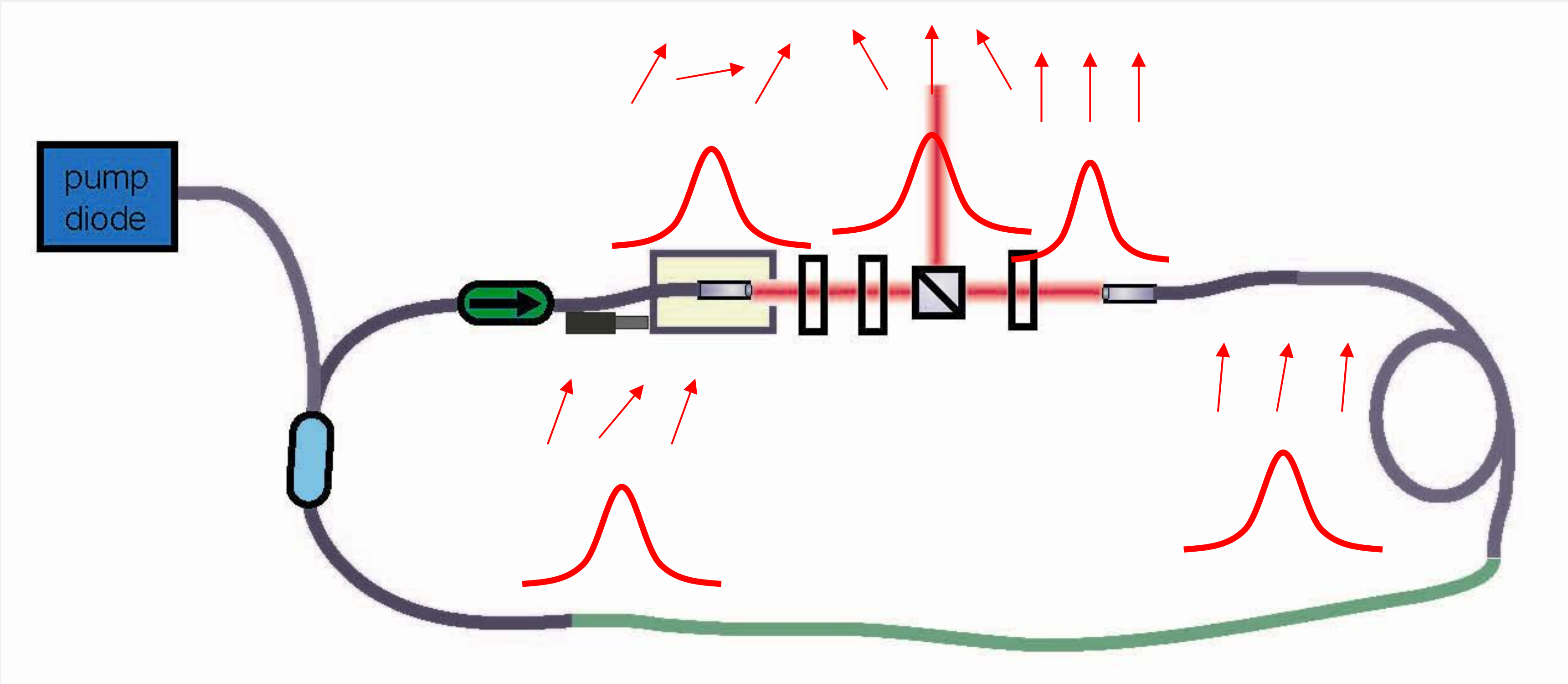
Passively Mode-locked Fiber Lasers

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



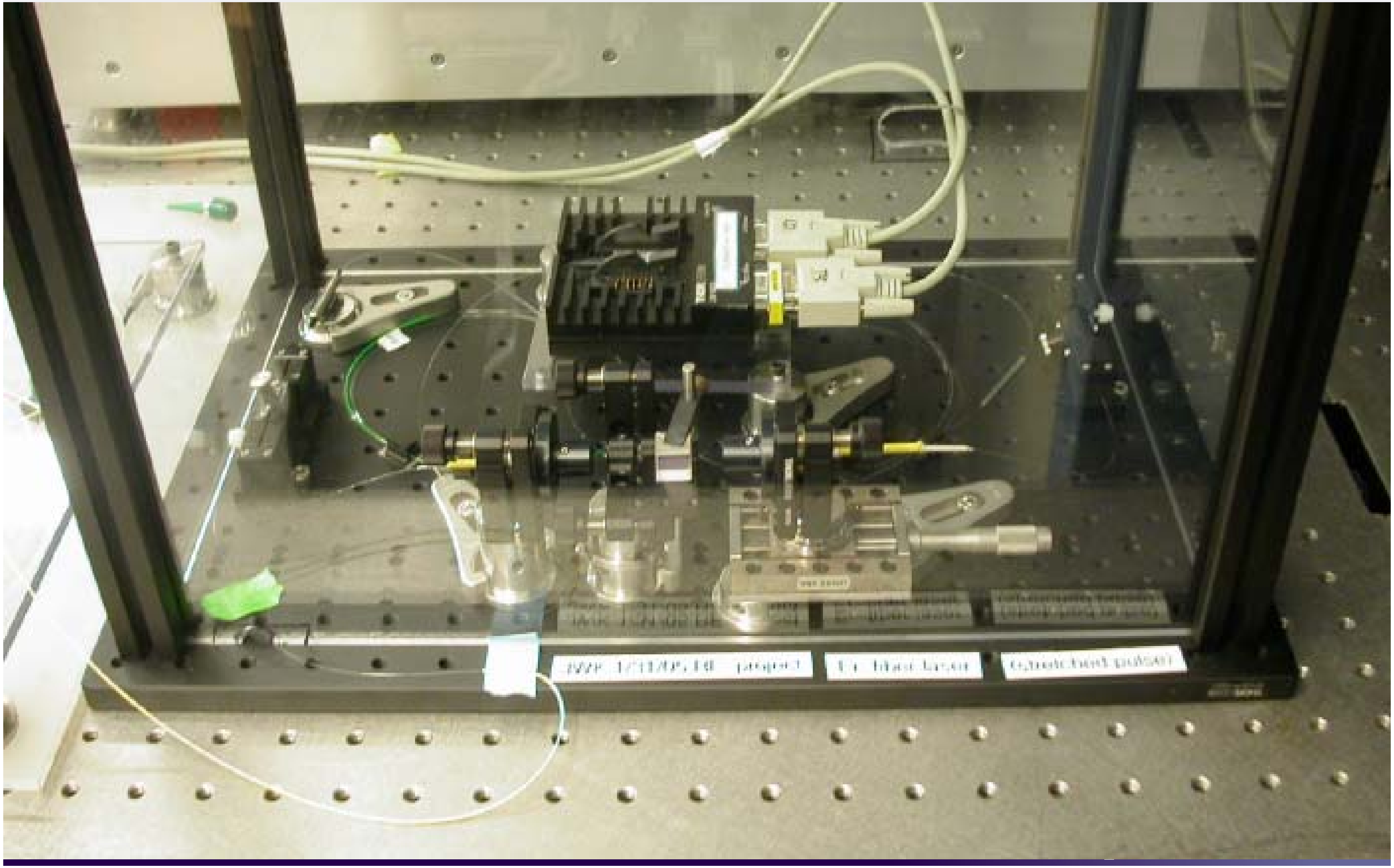


Mode-locking: Nonlinear polarisation evolution

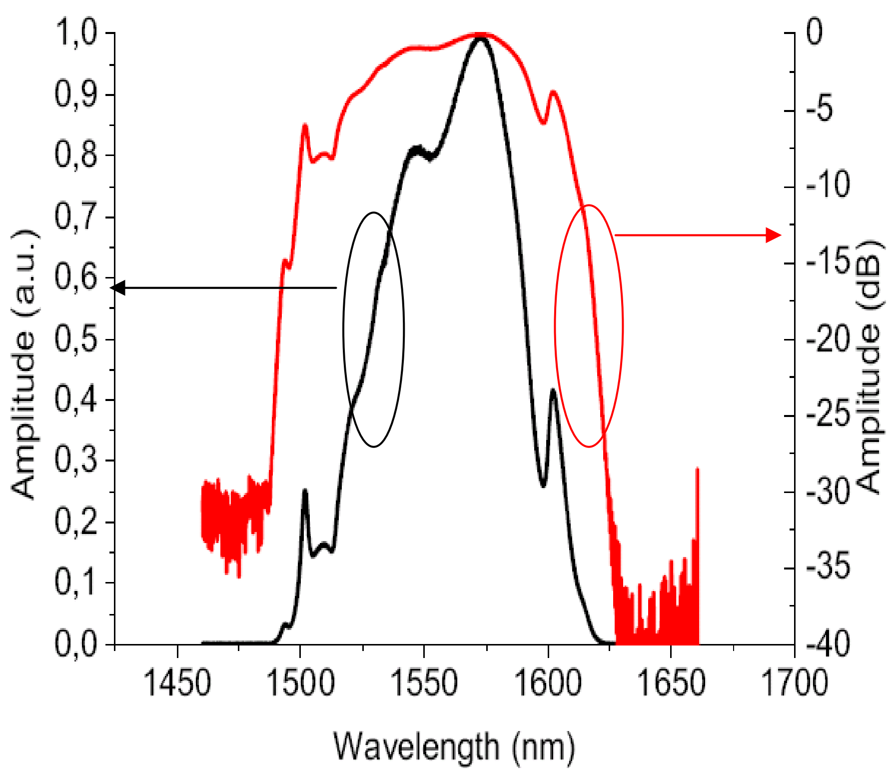


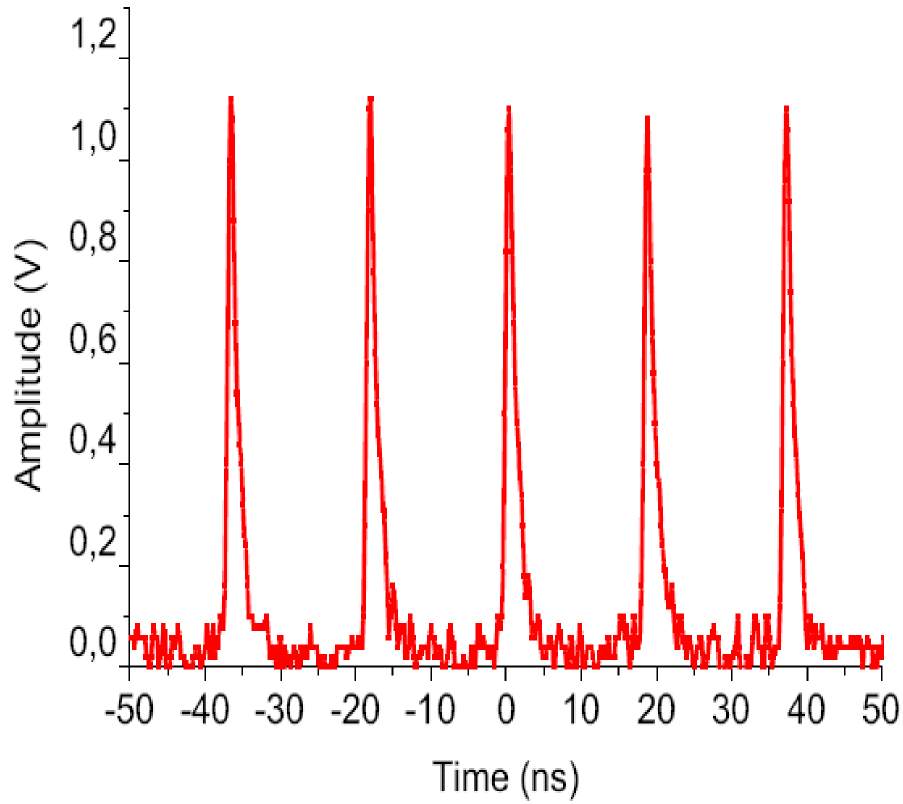
- Linear polarized pulse behind polariser
- Kerr-Effect in optical fiber $n(I) = n_0 + n_2(I)$
- Center of pulse is rotated more than wings and rejected at polarizer

Erbium-doped fiber laser



Optical properties

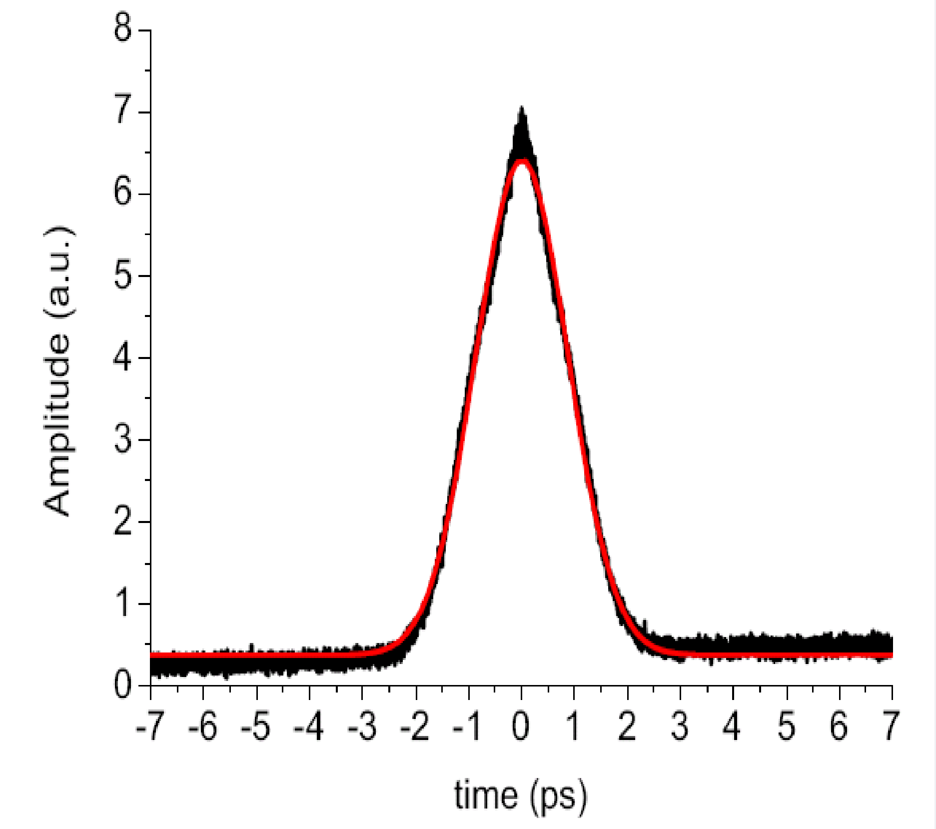


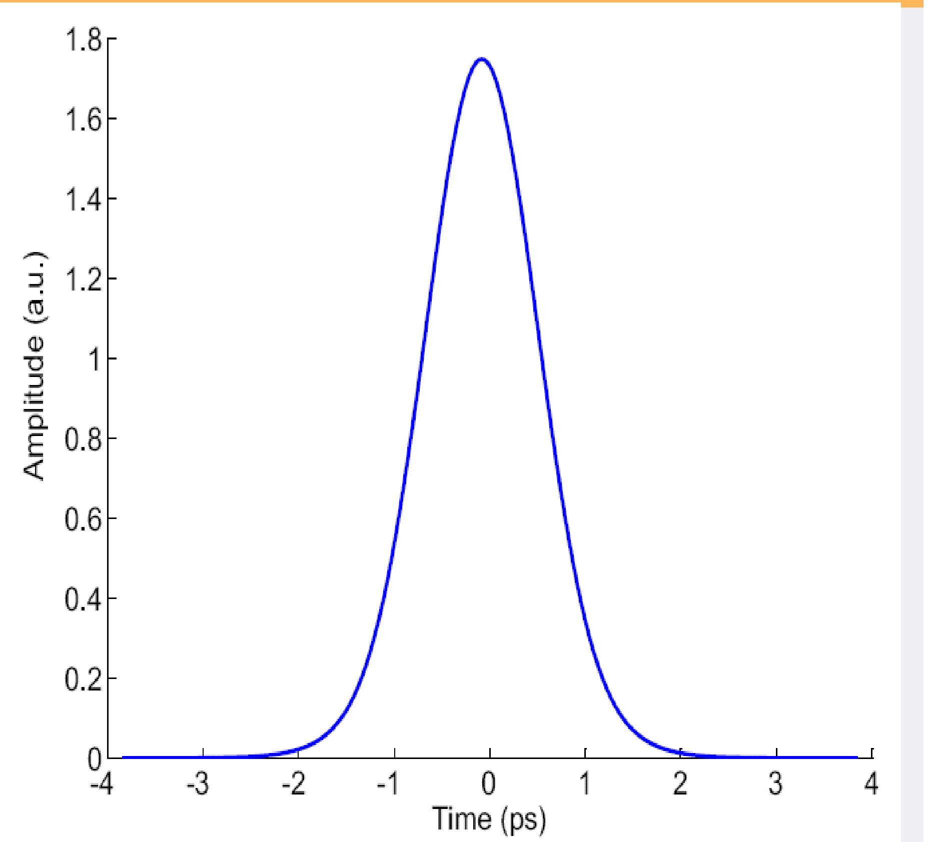


•Typical optical spectrum and oscilloscope trace (after photodetection) of a 54 MHz fiber laser

•Duration of electrical pulses given by photodiode bandwidth (<< optical pulse duration)

Pulse duration

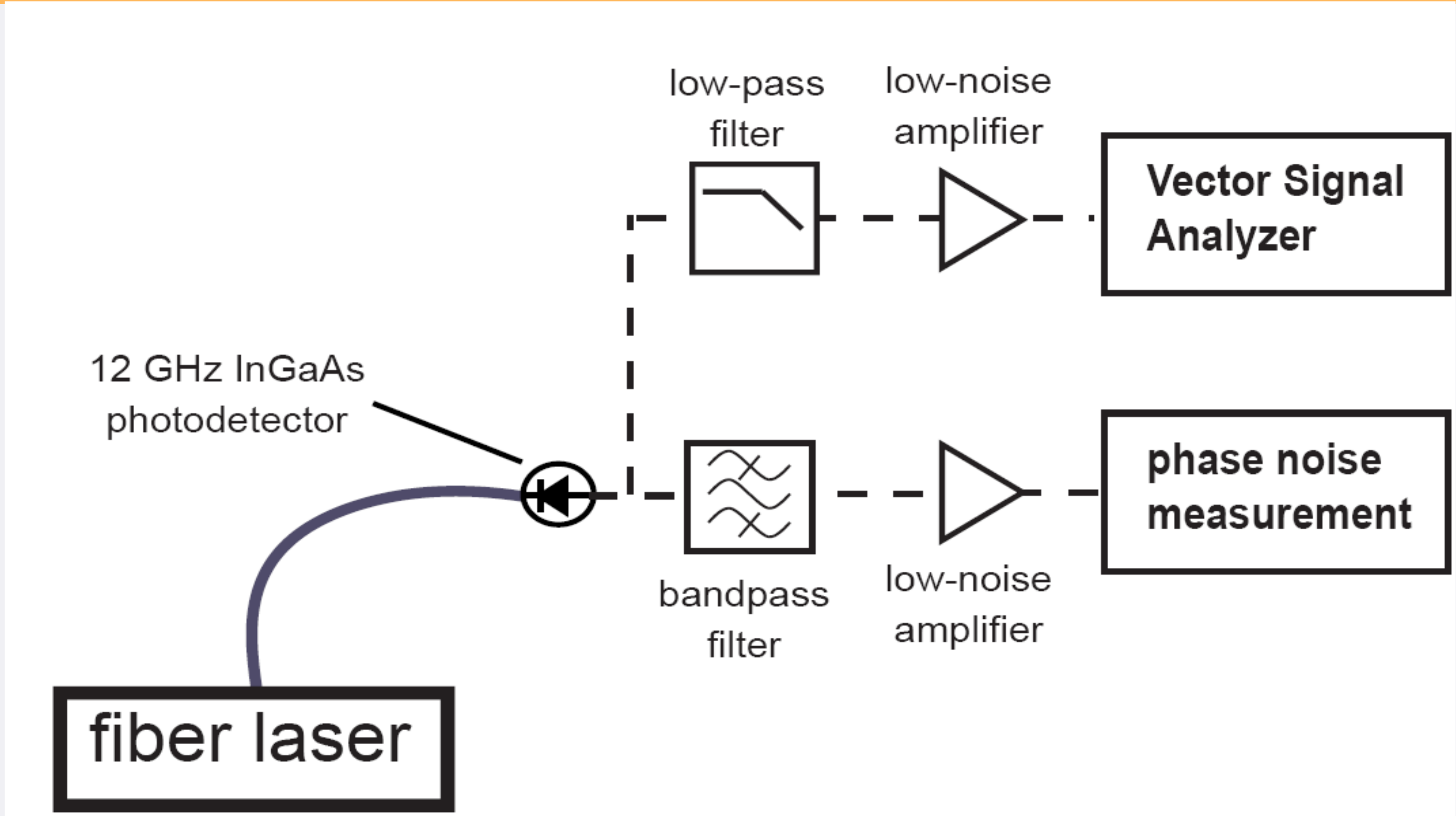




•Pulse duration 1.45 ps FWHM (from autocorrelation assuming Gaussian shape)

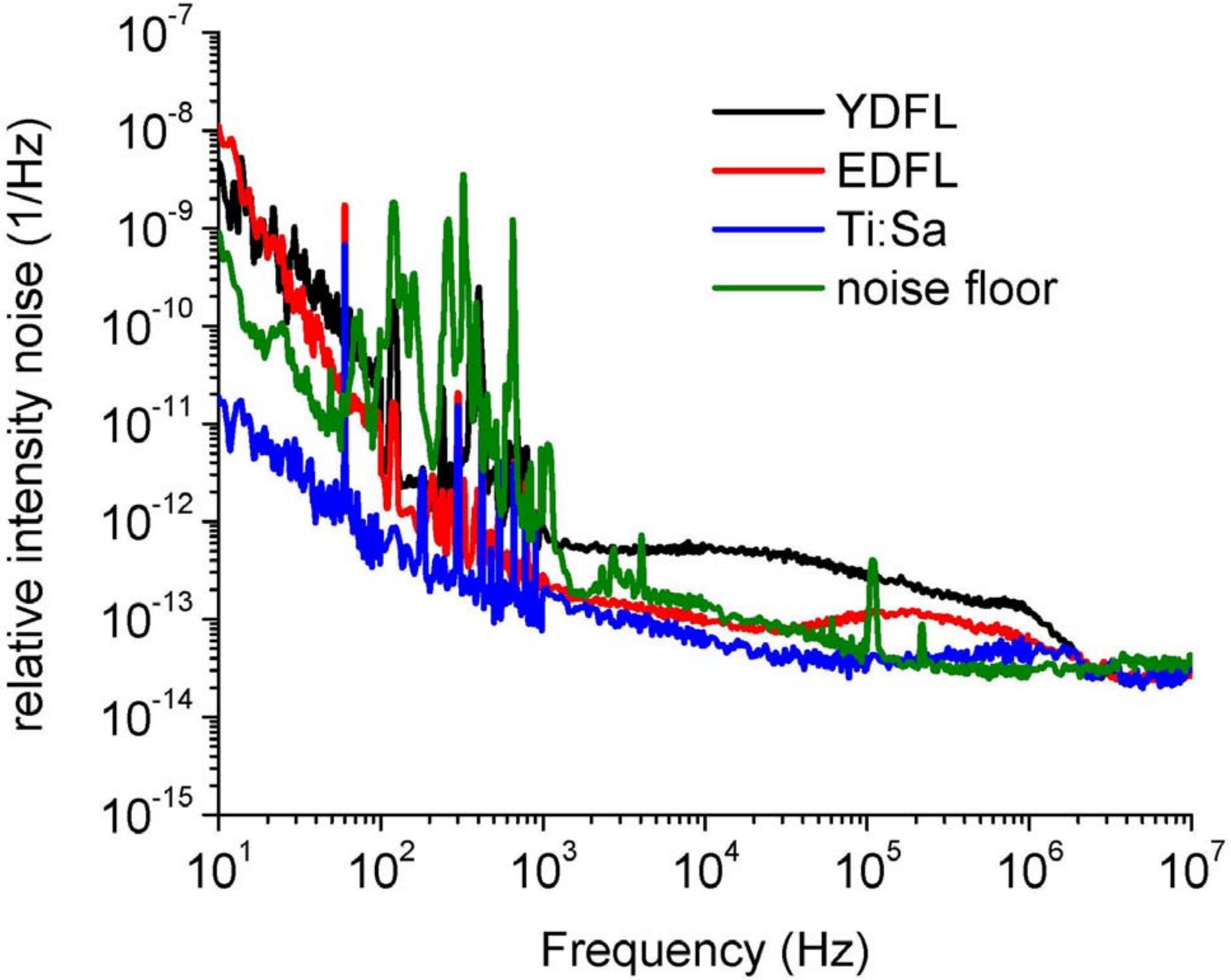
• Good agreement with simulations (1.4 ps FWHM)

Measurement of amplitude and phase noise



- Amplitude noise measured at DC with high resolution spectrum analyzer
- Phase noise measured at high frequency (1.3 GHz) by comparison to reference

Amplitude Noise Results

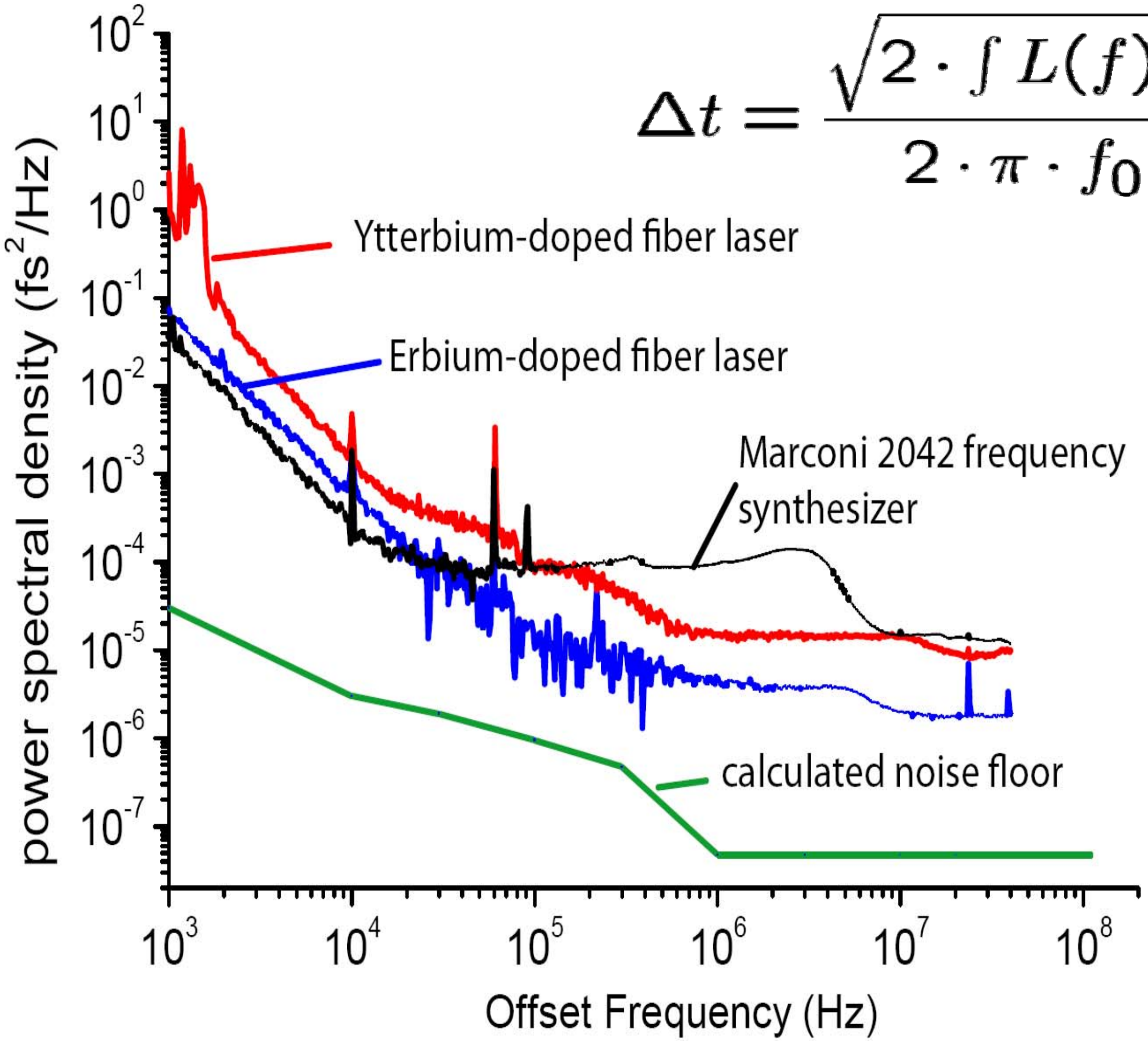


- EDFL (0.03 % rms)
- YDFL (0.04 % rms)
- Ti:Sa laser (0.17 % rms)

Performance crucial for diagnostics

Cannot be stabilized by PLL

Phase Noise Results



$$\Delta t = \frac{\sqrt{2 \cdot \int L(f)df}}{2 \cdot \pi \cdot f_0}$$

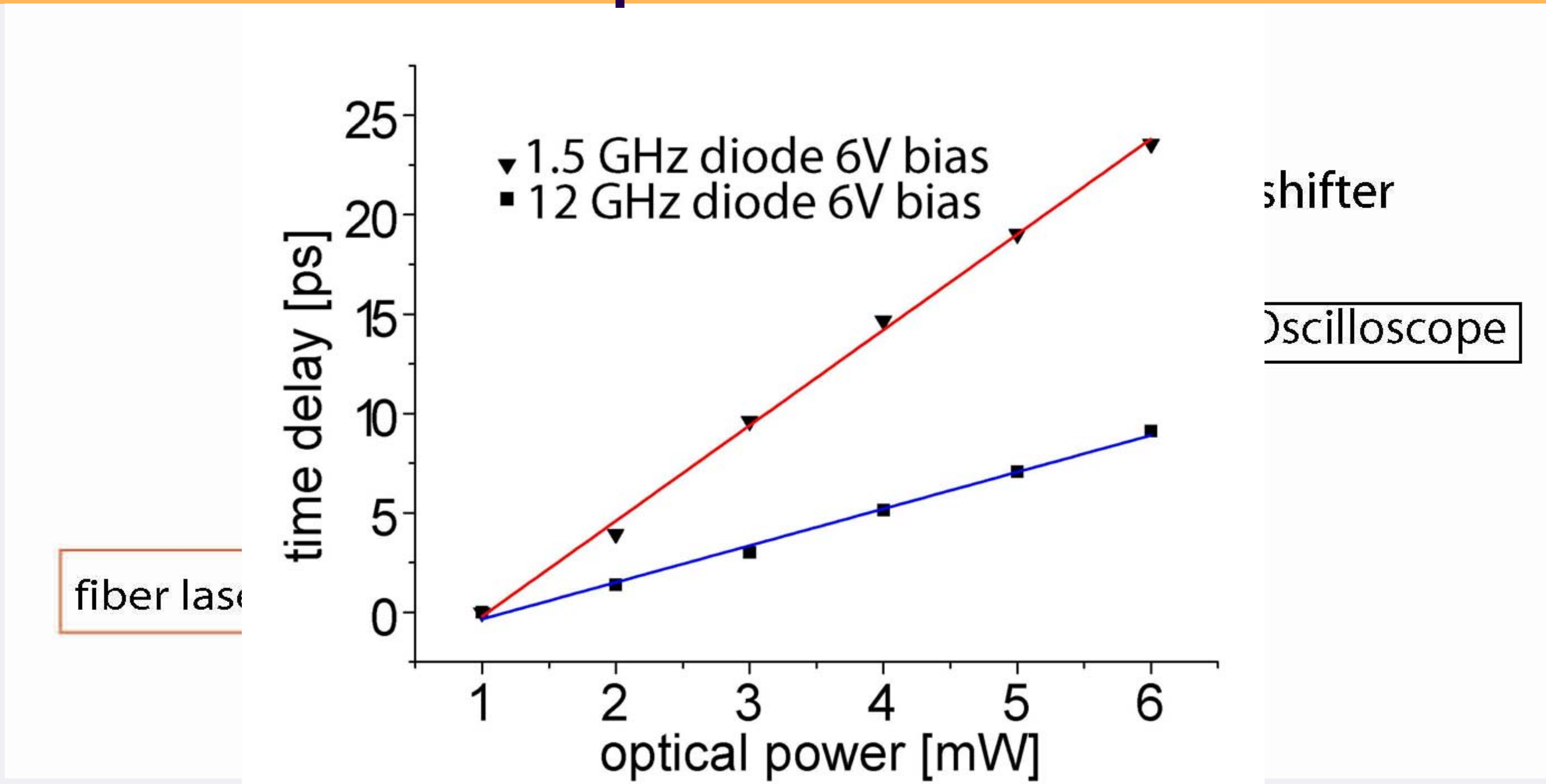
•EDFL → 10 fs rms (1 kHz.. 27 MHz)

•YDFL → 18 fs rms (1 kHz..27 MHz)

•Marconi →28 fs rms (1 kHz.. 27 MHz)

• noise is low enough to enable fs synchronization

Amplitude dependence of Photodiode output phase



- split laser pulse and feed to two photodiodes, compare the phase with variable input
- Significant variation (1-5 ps/mW) depending on diode type and operating condition

For 10^{-4} amplitude stability → 2.5 fs added jitter

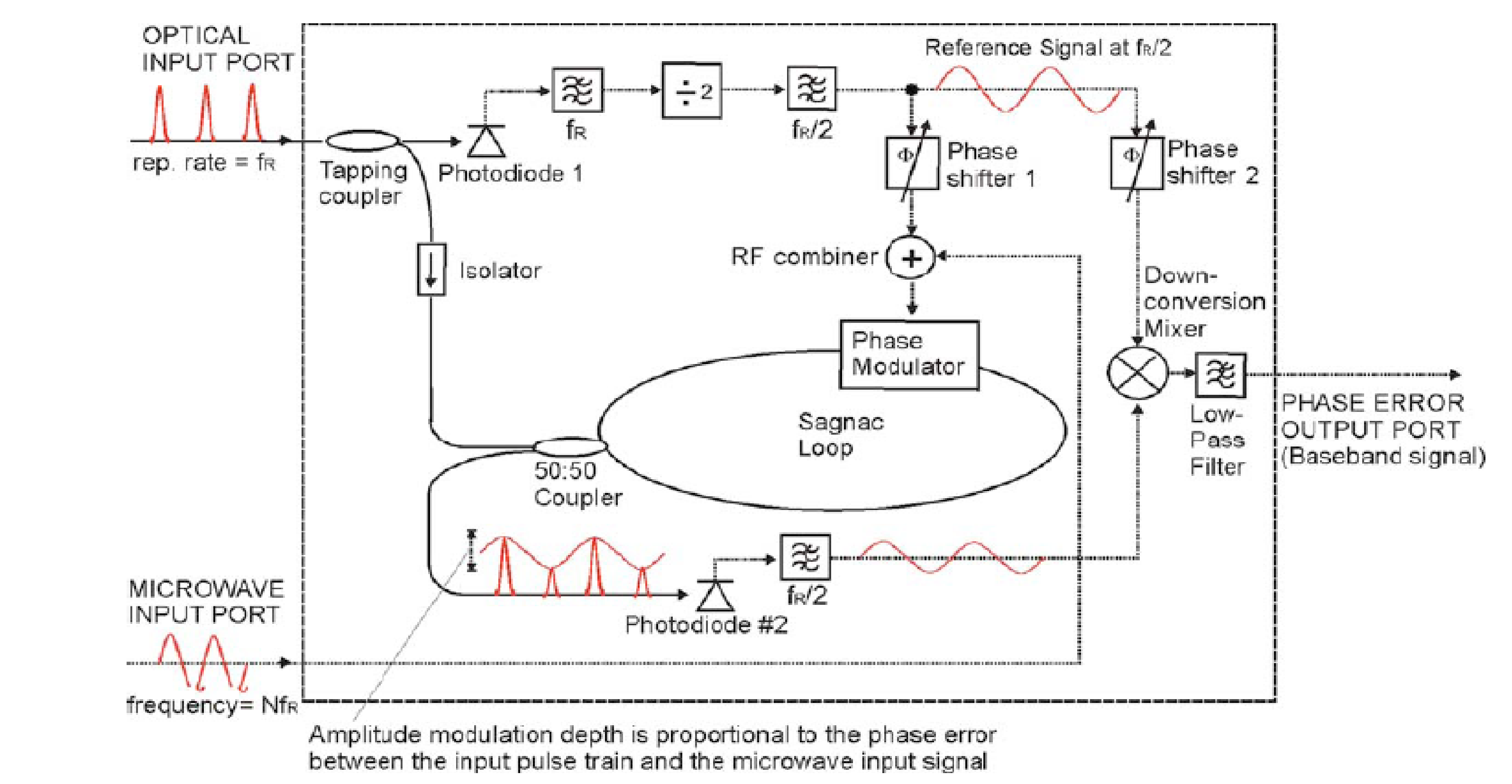
Limitations due to Photodetectors

- Amplitude to phase noise conversion is problematic
- Phase noise floor dominated by output power of photodiode
- Temperature dependence of phase (~300 fs/°C) makes stable long-term operation difficult to achieve

- However: applicable for measurements of phase noise on short timescales and for less drift critical applications (3x 10^{-4} amplitude stability of <--> 2.5 fs additional fitter)

Solution: Sagnac-type Interferometer

Solution: Balanced detection by Sagnac-loop



- balanced optical-microwave phase detector (Sagnac Interferometer)
- enables fs synchronization of external oscillator over hours/days

J-W Kim, F. Ludwig, M. Felber, B. Lorbeer

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System Test in Accelerator environment

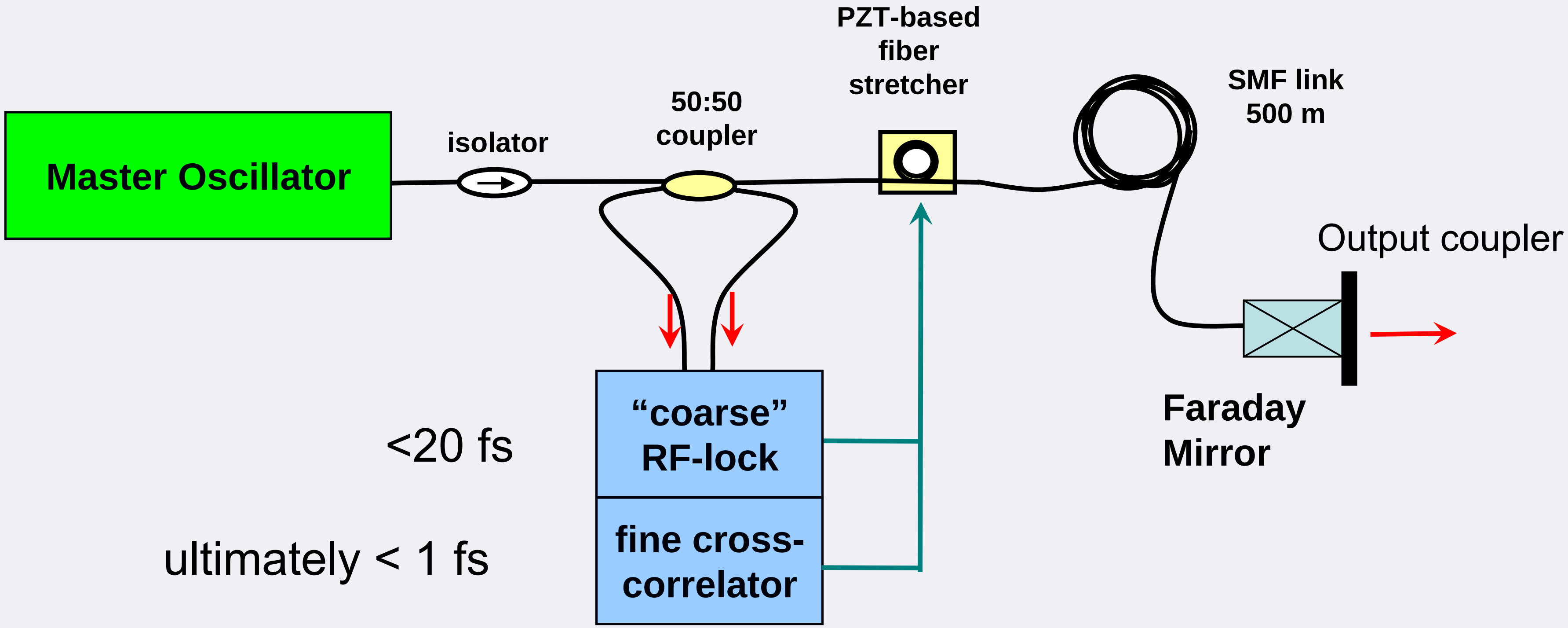
- Can lab results be transferred to real environment ?

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

•Short-term stability of fiber laser
•Stable transfer of pulse train through real machine

Timing stabilized fiber links



<20 fs

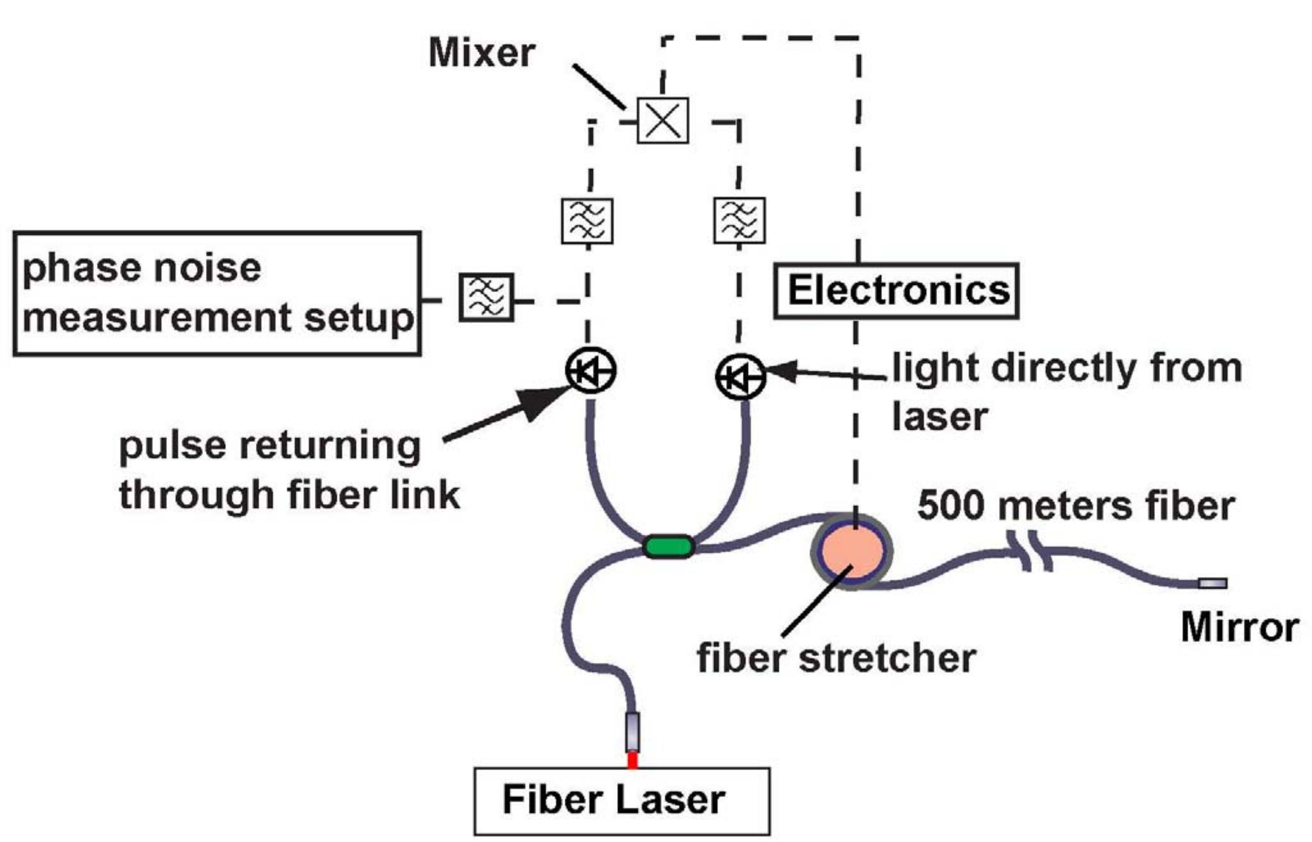
ultimately < 1 fs

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

L = 0.5 km, n = 1.5 => T=5 μs, f_{max} = 200 kHz

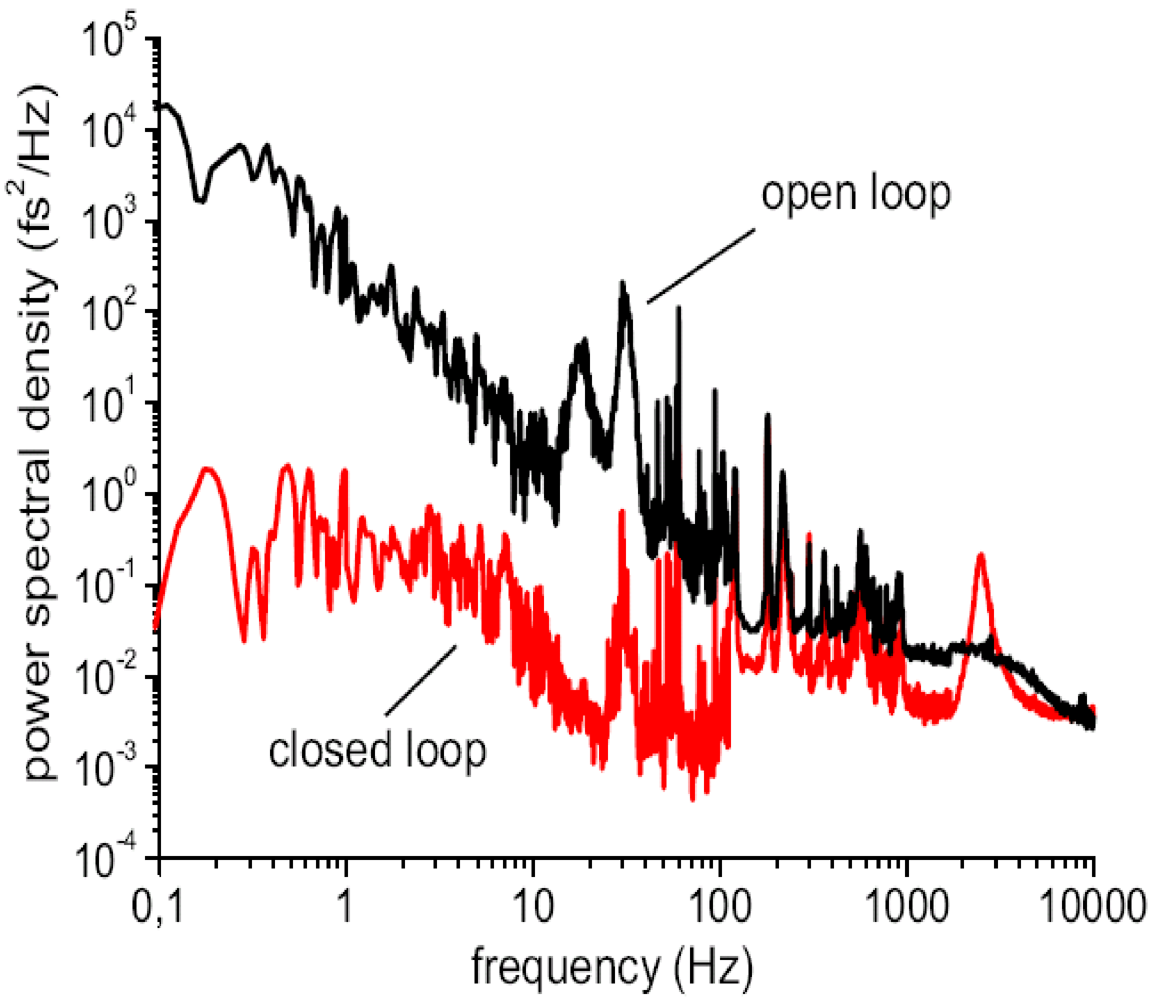
Fiber temperature coefficient: ~1-5x10^{-6} /°C   Lee et al. Opt. Lett. **14**, 1225-27 (1989)

Fiber Length Stabilization



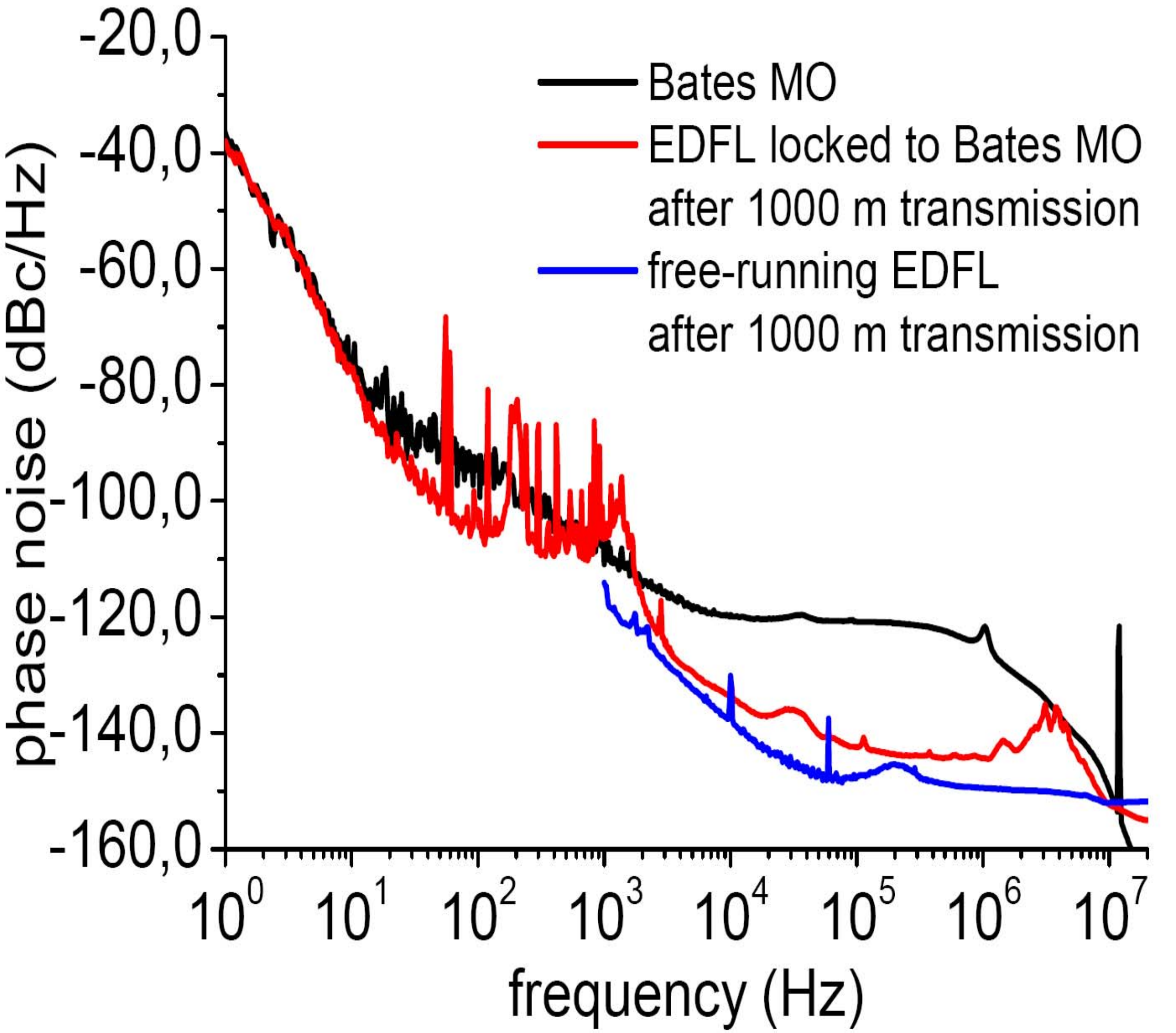
- Passive temperature stabilization of half the total fiber length
- RF feedback for fiber link
- EDFL locked to 2.856 GHz Bates master oscillator

Results



- Open loop stability: 60 fs (0.1 Hz…5 kHz)
- Closed loop stability: 12 fs (0.1 Hz .. 5kHz)
- No significant noise added at higher frequencies
- 12 fs stability over seconds of fiber link with simple RF feedback

Frequency Transmission



- 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 due to power supply ripple (60 Hz and multiple)

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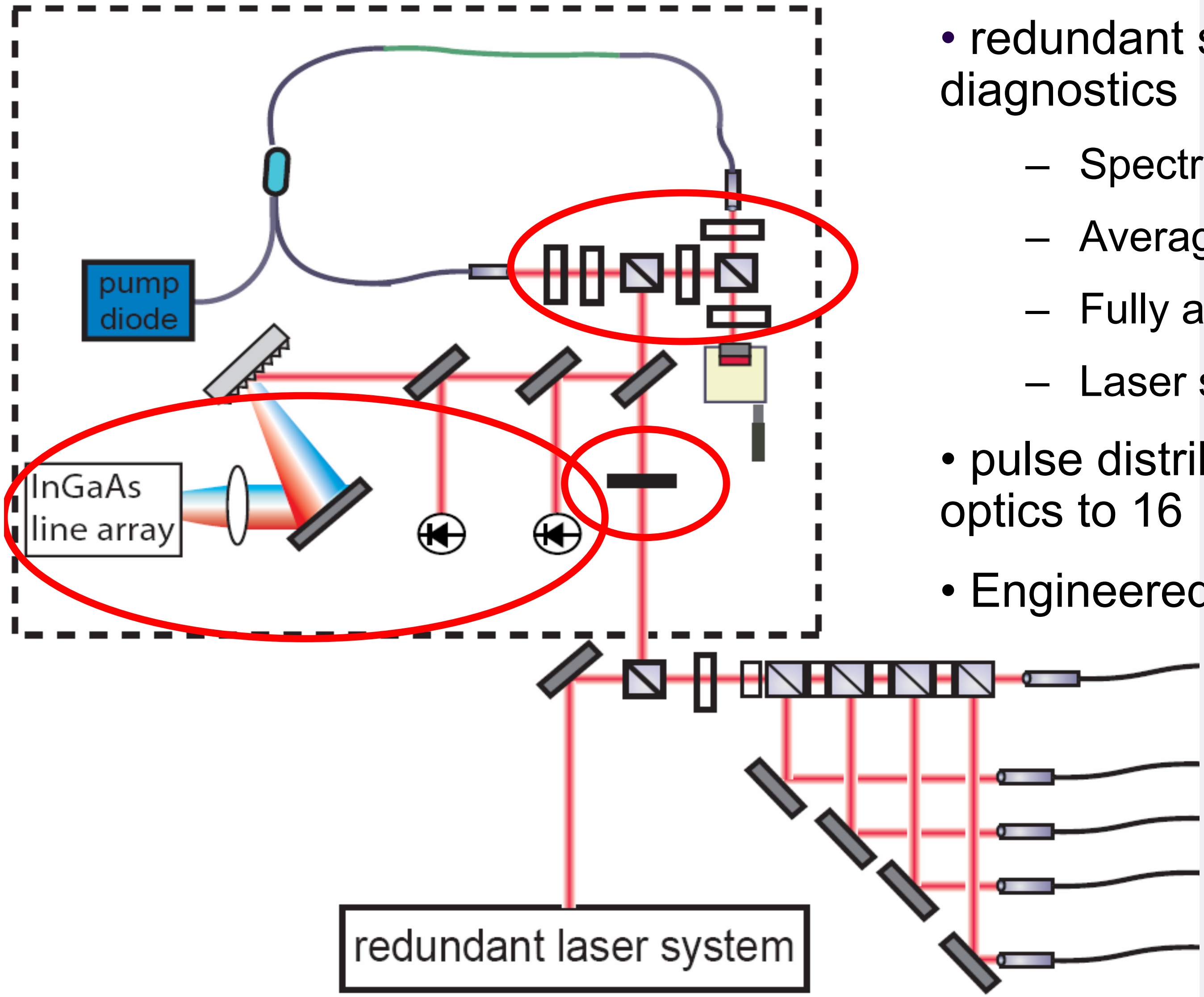
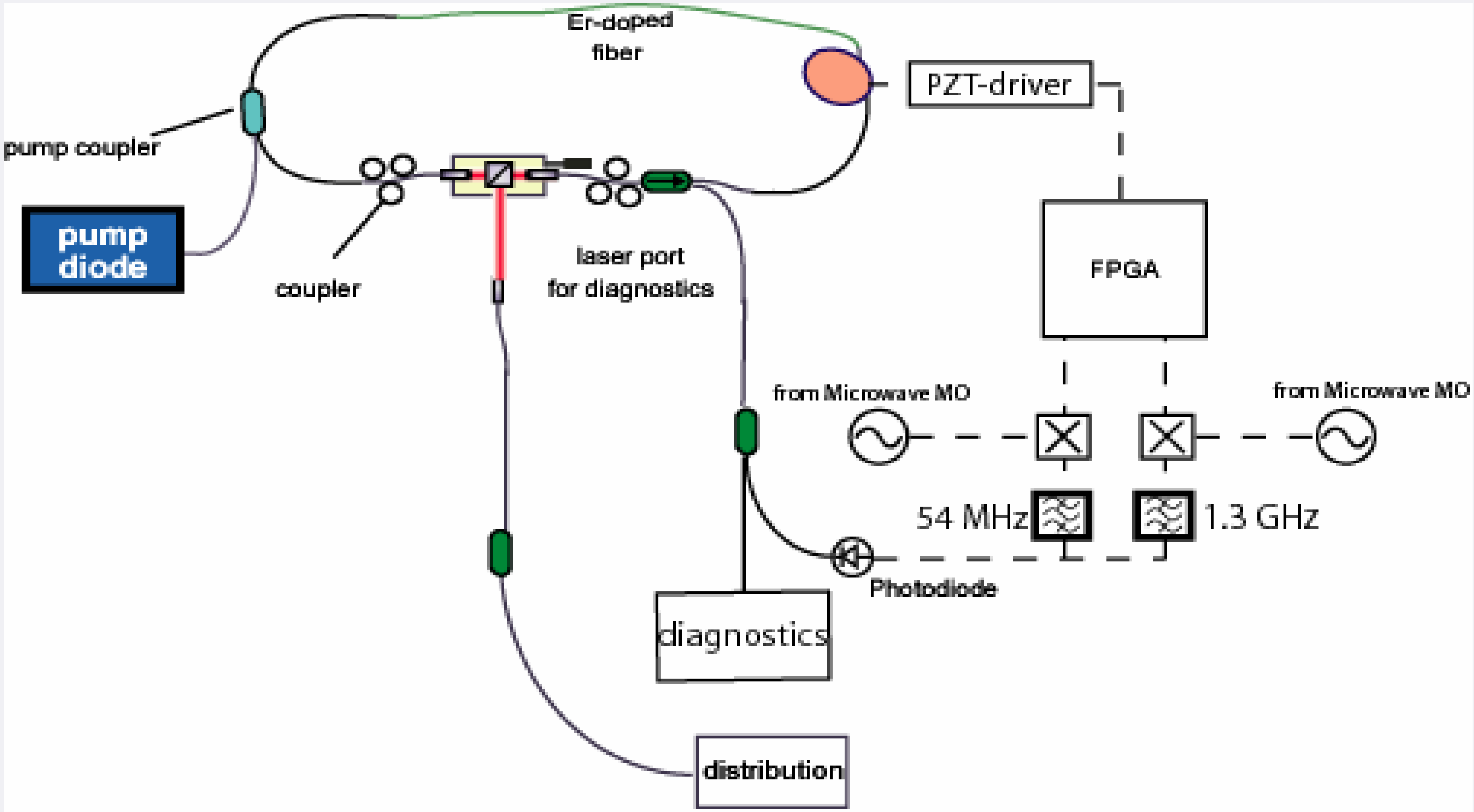
Layout of the Laser Master Oscillator System for FLASH



- redundant system with embedded diagnostics
  - Spectrometer
  - Average & peak power detection
  - Fully automated
  - Laser switching via shutter
- pulse distribution via free-space optics to 16 links
- Engineered versions in production

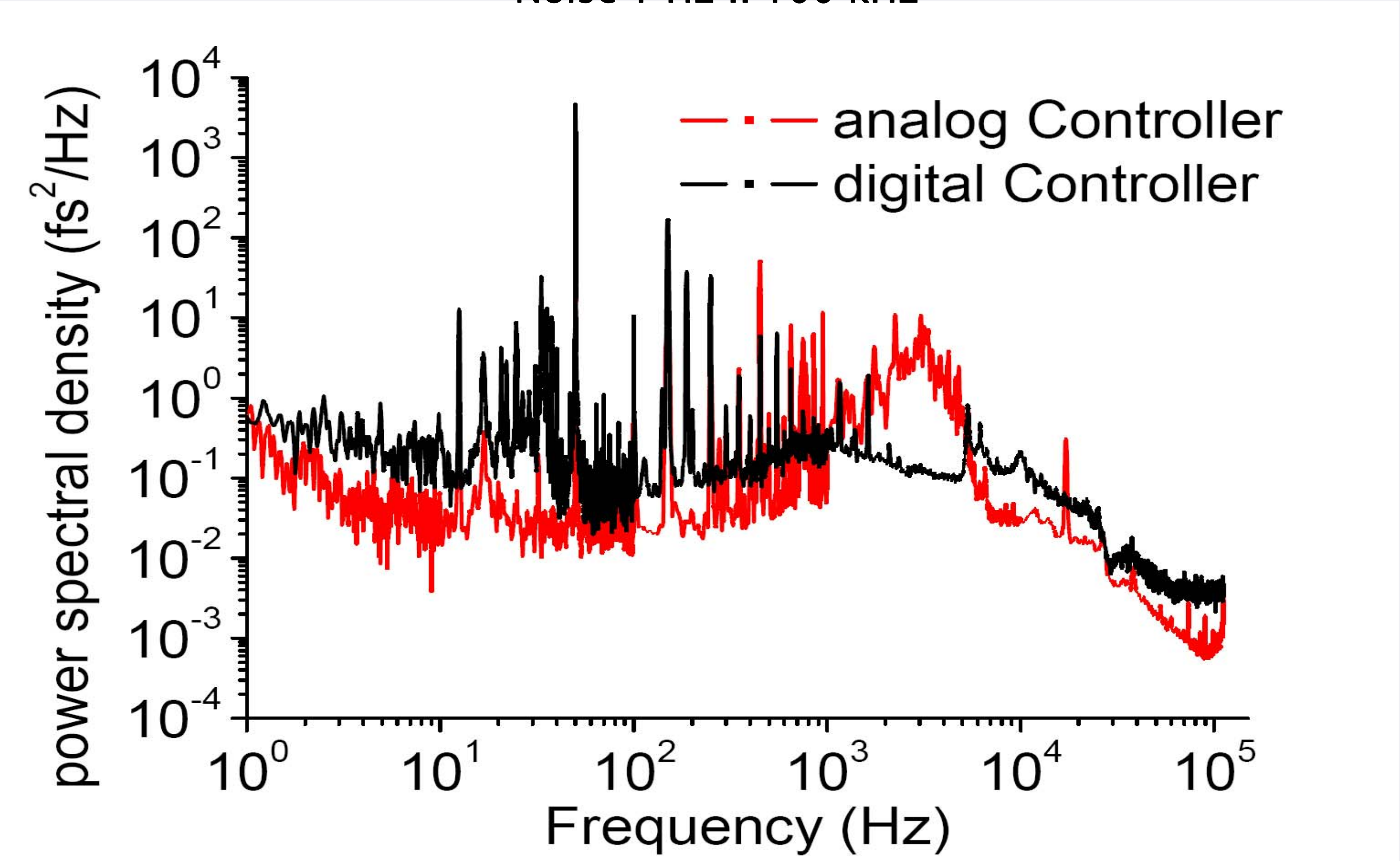
Locking to the Accelerator RF



- For stability – phase-lock to high frequency preferred (1.3 GHz)
- For phase information – phase lock at repetition rate needed

Comparison of analog and digital controllers

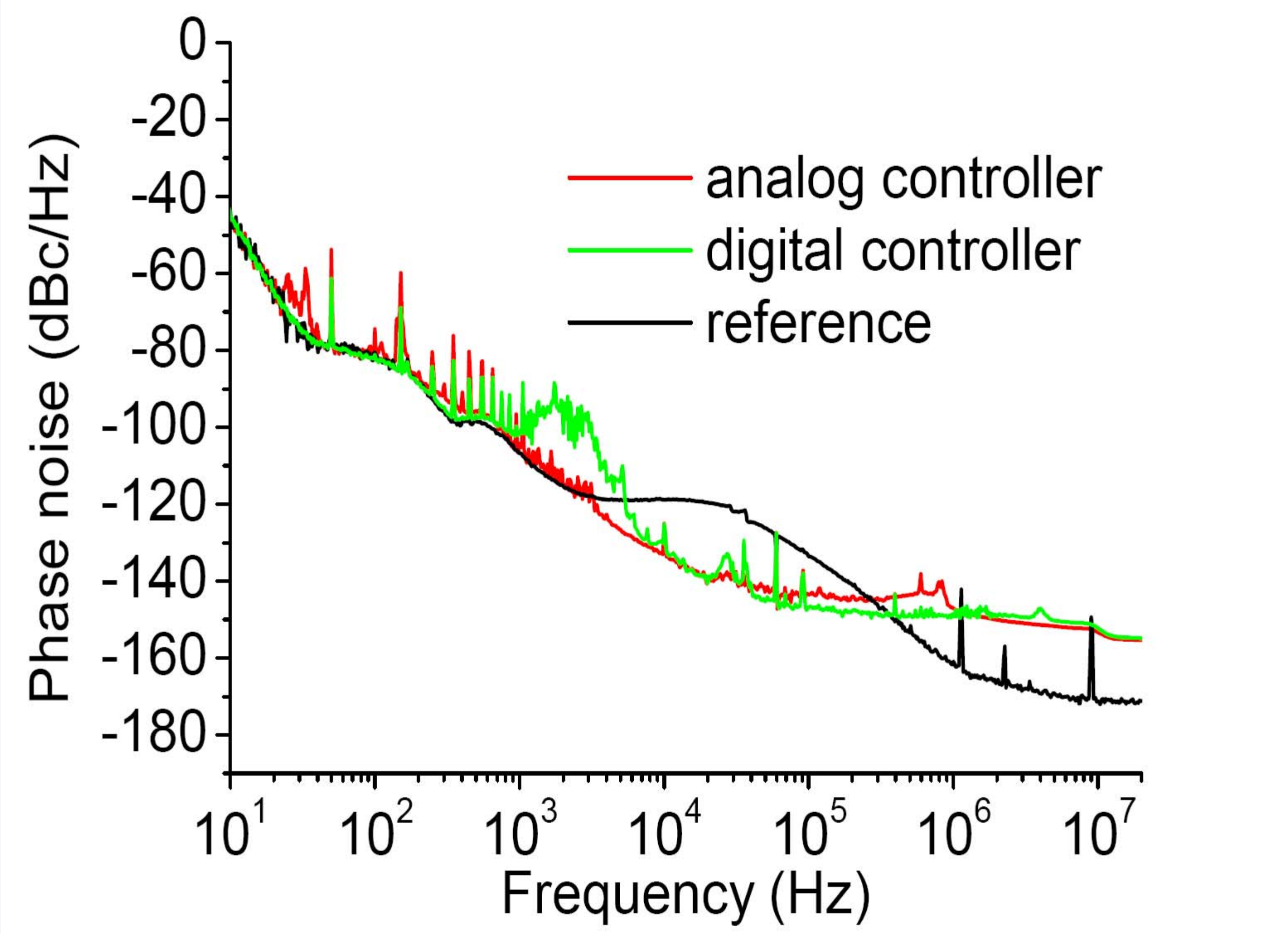
Noise 1 Hz .. 100 kHz



- residual noise of analog and digital PLL comparable (~50-70 fs)

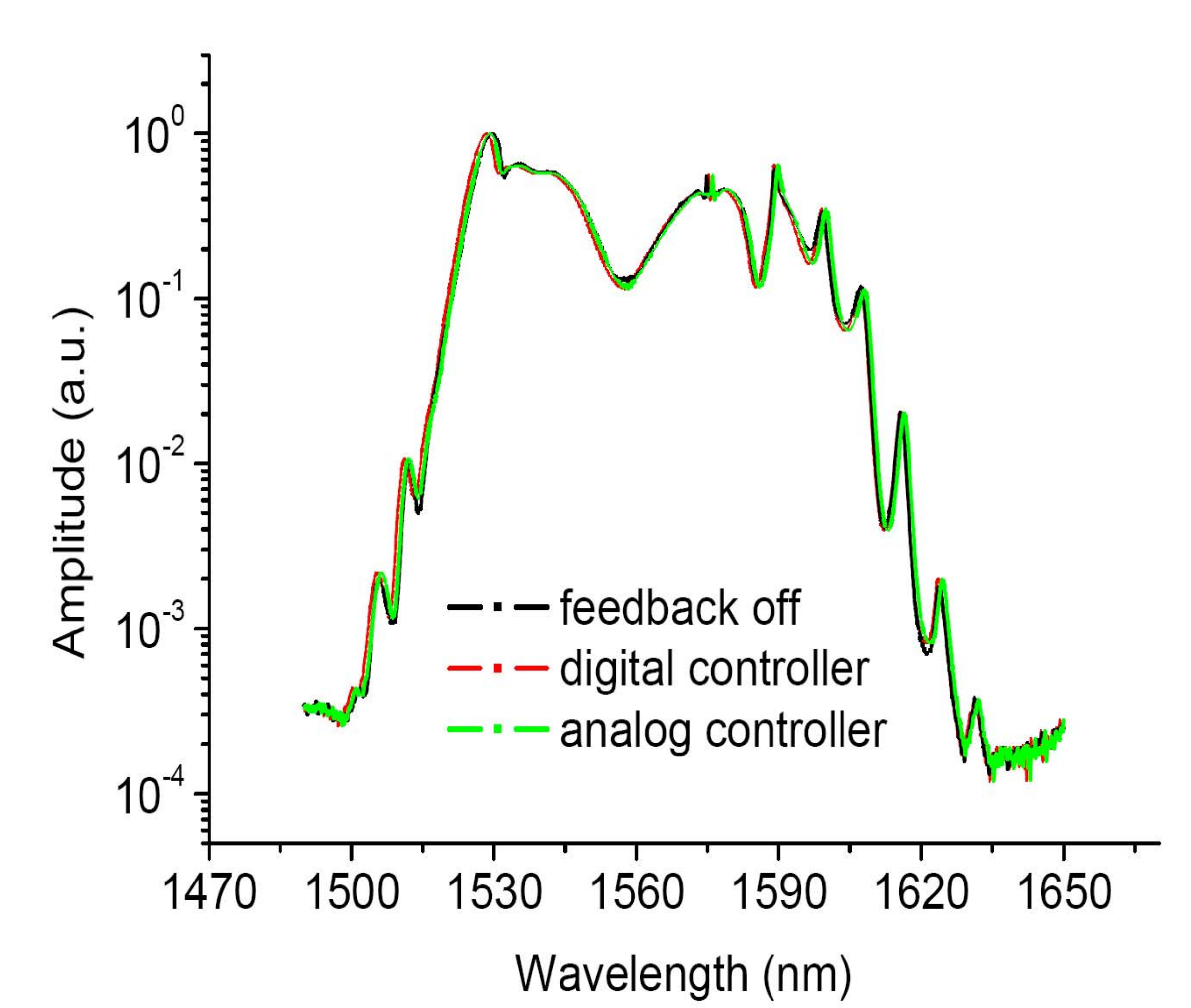
Comparison of analog and digital controllers

Noise 1 kHz .. 20 MHz



- No additional high frequency noise observed

Comparison of analog and digital controllers



•No change in optical spectrum observed

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Conclusion

- Designed, constructed and characterized the mode-locked fiber laser which will be used as laser master oscillator
- First test of a complete system in an accelerator environment
- Infrastructure setup for FLASH system

Outlook

- Optical cross-correlators can stabilize fiber links to few fs level over hours
- Beam diagnostics based on synchronization system pulses have been developed -- ~15 fs arrival time resolution within bunch train
- Transition of FLASH system from prototype to engineered version expected during summer/autumn
- Experience gained during operation is vital for XFEL synchronization system design

Vielen Dank!

Ömer Ilday, Jeff Chen, Franz Kärtner, Jung-Won Kim, Defa Wang, Dan Cheever, Burkhardt Sparr, Frank Ludwig, Johan Zemella, Sebastian Schulz, Karl-Heinz Matthiesen, Matthias Felber, Bibiane Wendland, Wojtek Jalmuzna, Albert Schleiermacher, Bernd Beyer, Bernhard Schmidt, Ernst-Axel Knabbe, Florian Löhl, Gerhard Grygiel, Holger Schlarb, Ingrid Nikodem, Jens Hansen, Jörg Rossbach, Jörg Thomas, Kai Ludwig, Kay Rehlich, Manfred Tonutti, Matthias Böttcher, Matthias Hoffmann, Olaf Hensler, Otto Peters, Peter Schmüser, Stefan Simrock, Thomas Bruns, Uschi Djuanda, Vladimir Arsov, Wolfgang Reinsch, u.v.m.

Last but not least...

Thank you

for your attention