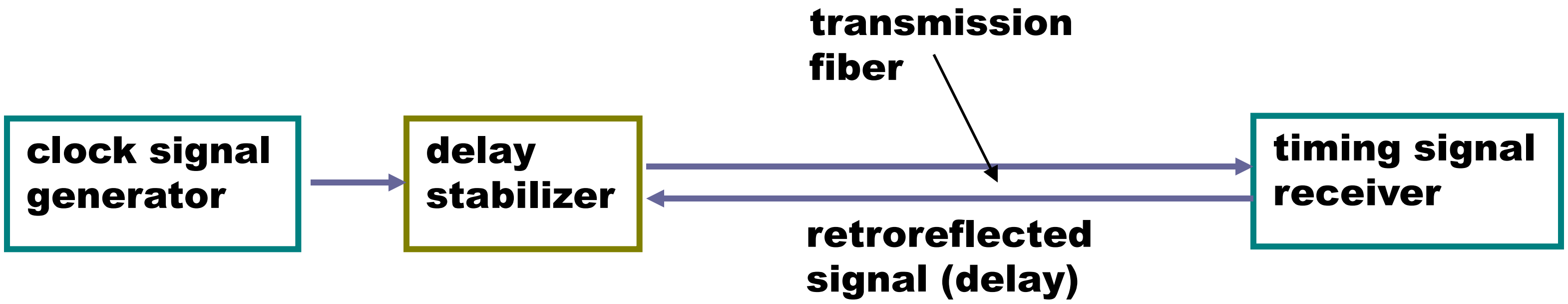
Part 1: Overview of applications and stability measurements

Generic synch link



transmission fiber

clock signal generator

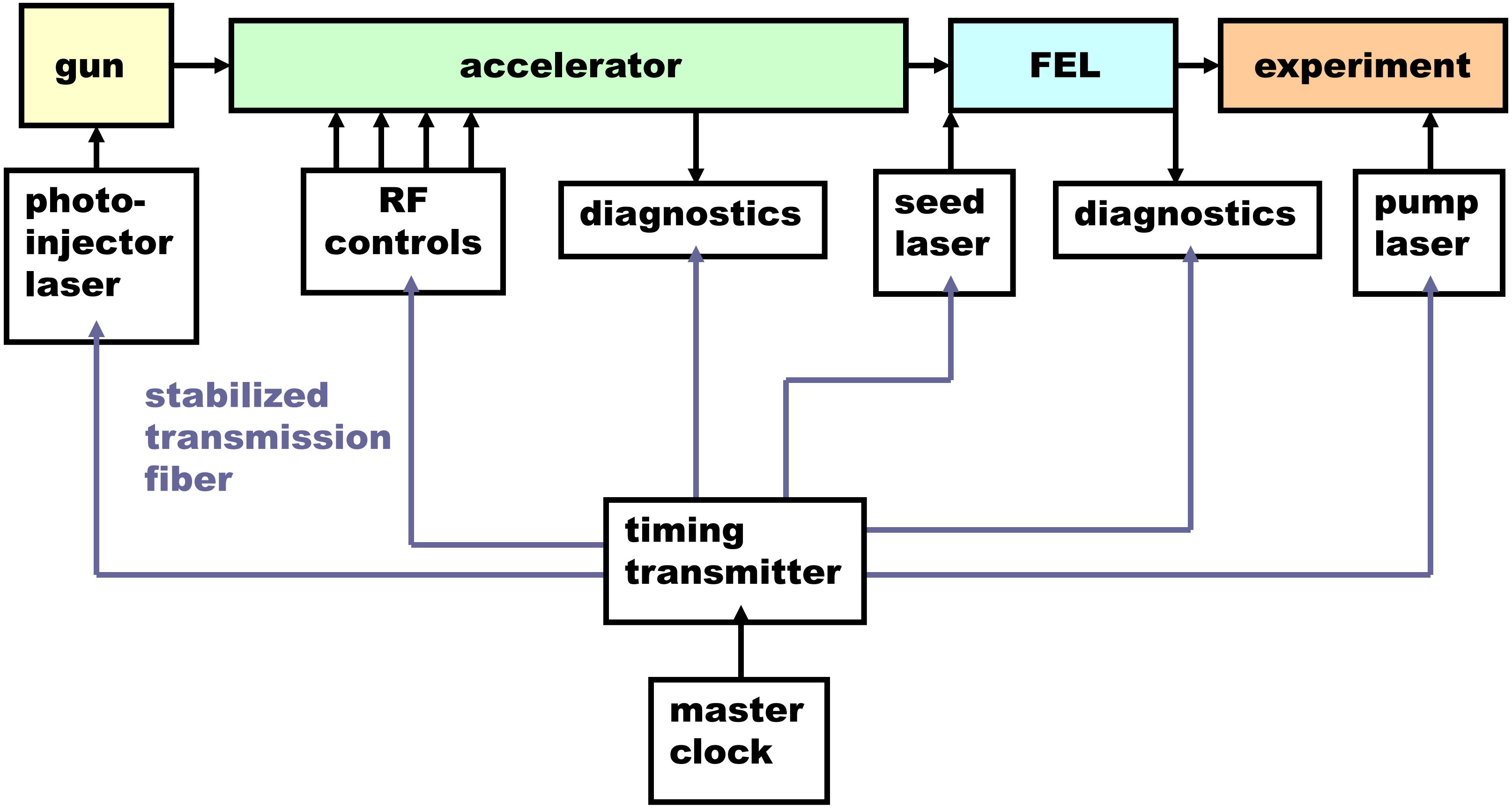
delay stabilizer

timing signal receiver

retroreflected signal (delay)

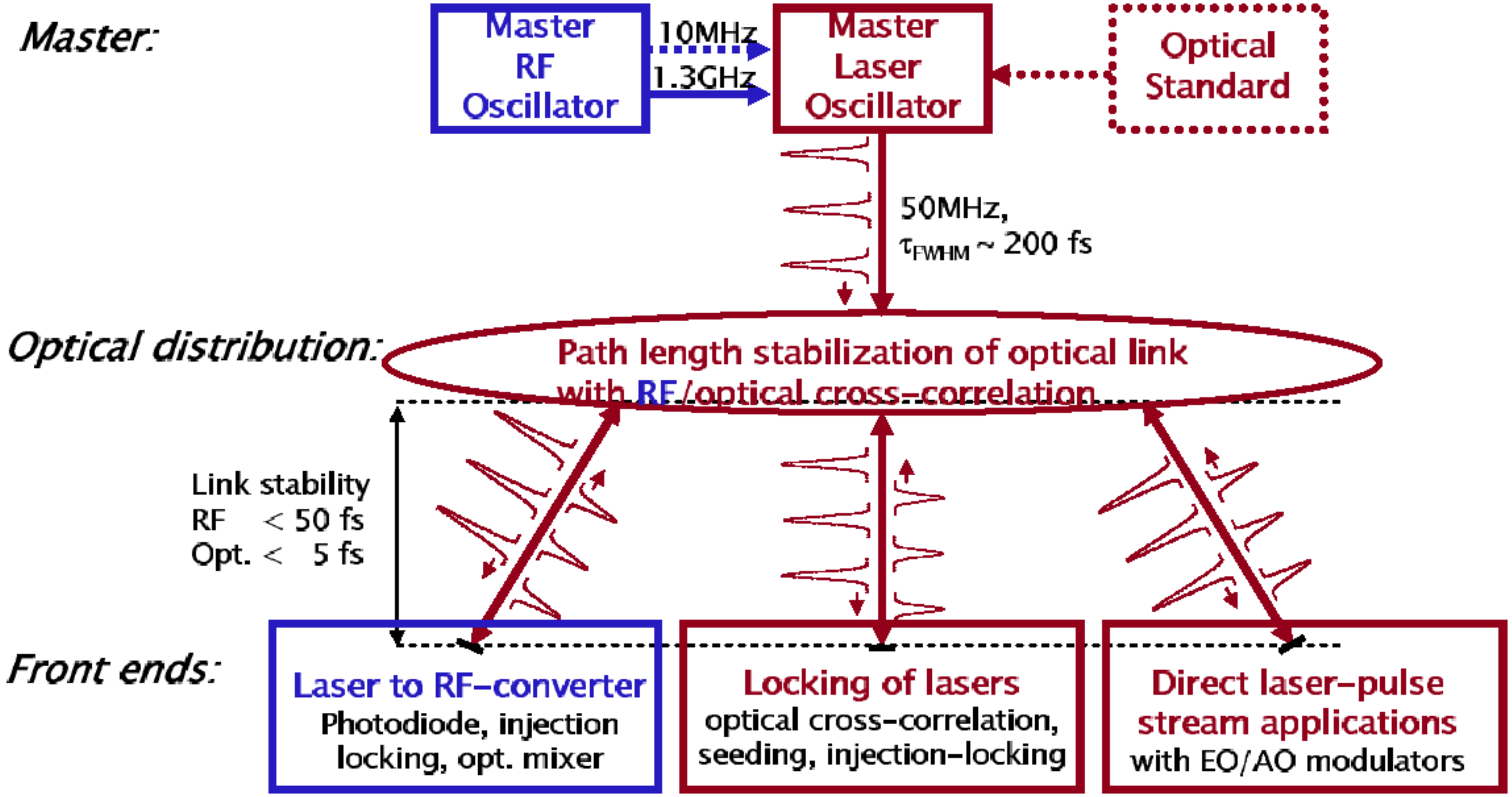
- A clock signal is sent to a remote location over optical fiber to a receiver
  - Various signal formats are possible
- The transmission delay is sensed and stabilized
  - Round trip delay is measured at the transmitter end
  - Various means of changing the delay or changing the signal are possible

What might one synch in an FEL?

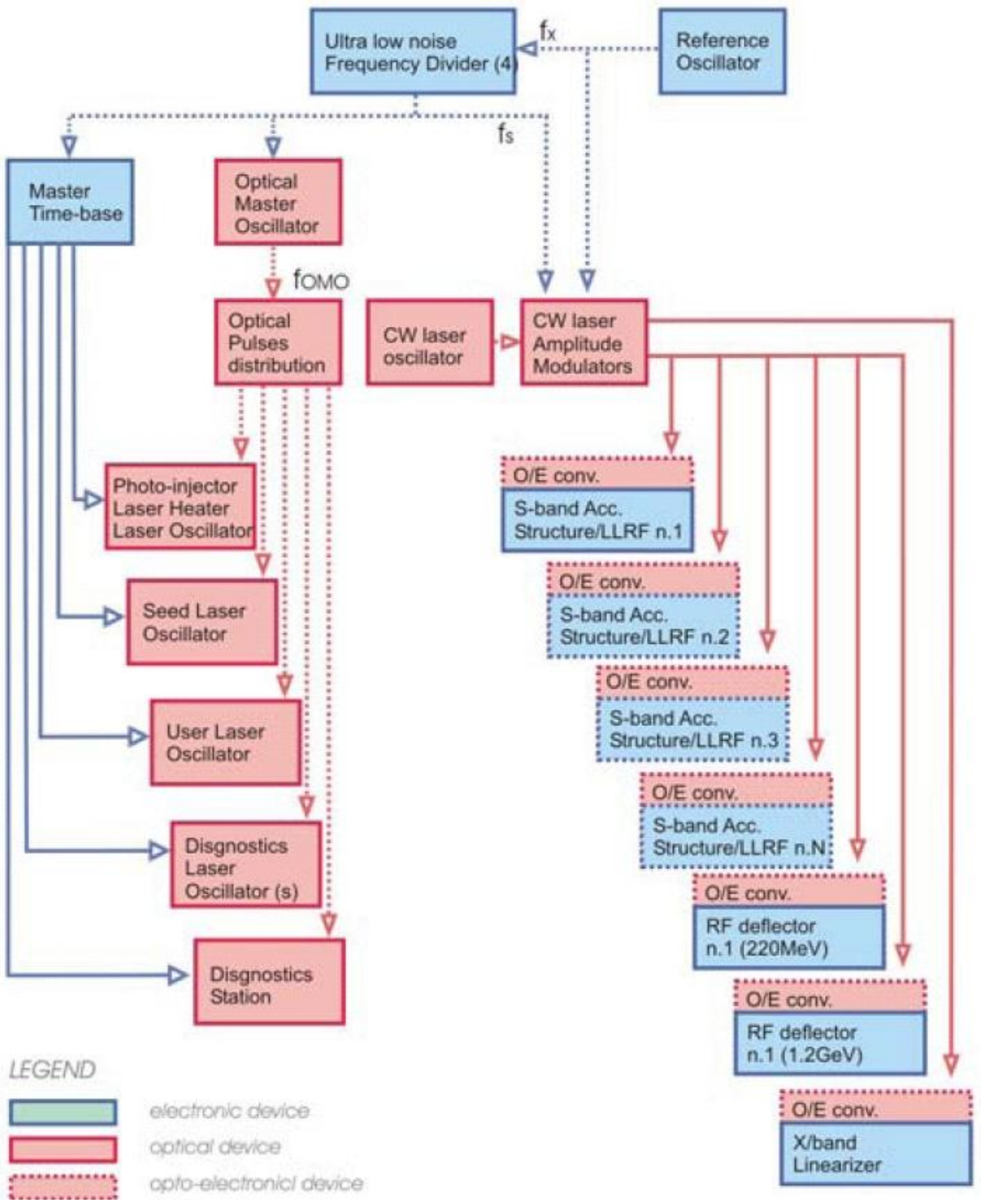


- Femtosecond FELs with ~100fs x-ray duration need10-100fs timing stability over 100m to km distance (10^{-9})
- Accelerators with short bunches also need synchronization

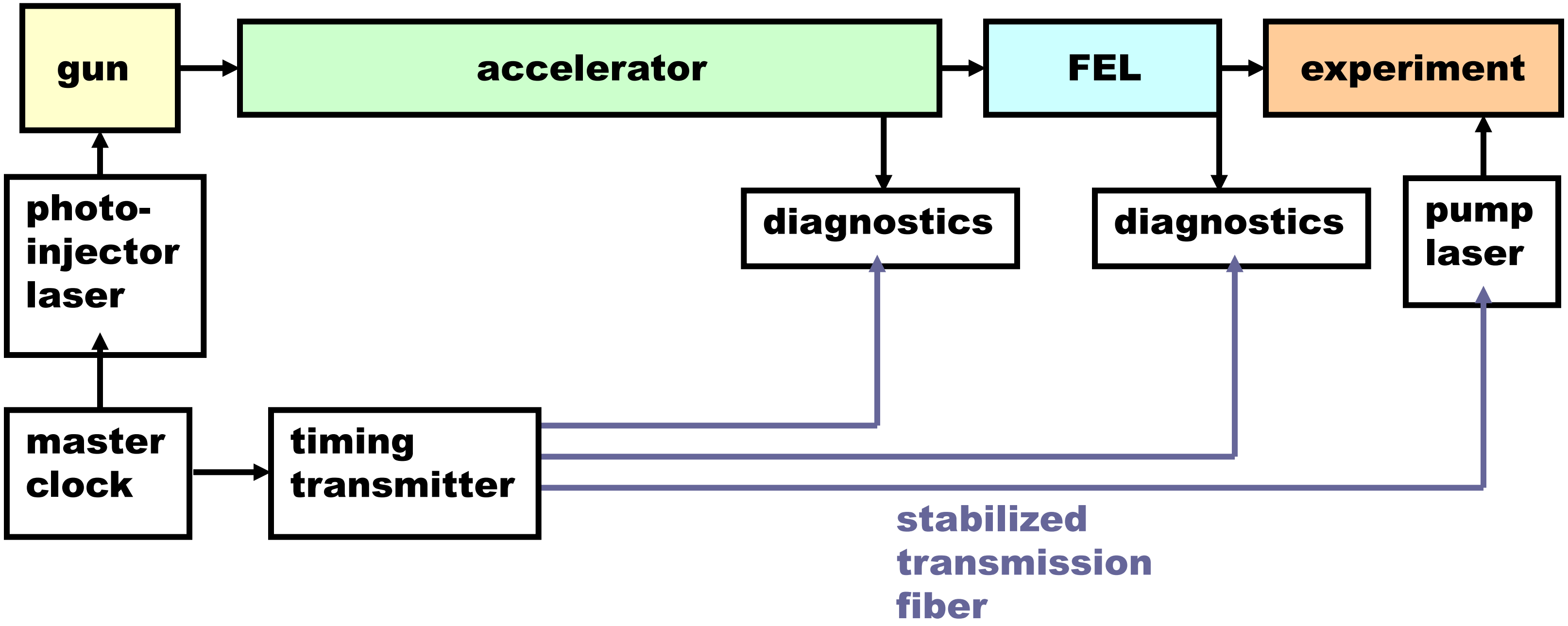
Proposed systems: FLASH



Proposed systems: FERMI



Proposed systems: LCLS



gun

accelerator

FEL

experiment

photo-injector laser

diagnostics

diagnostics

pump laser

master clock

timing transmitter

stabilized transmission fiber

Example requirements, FERMI

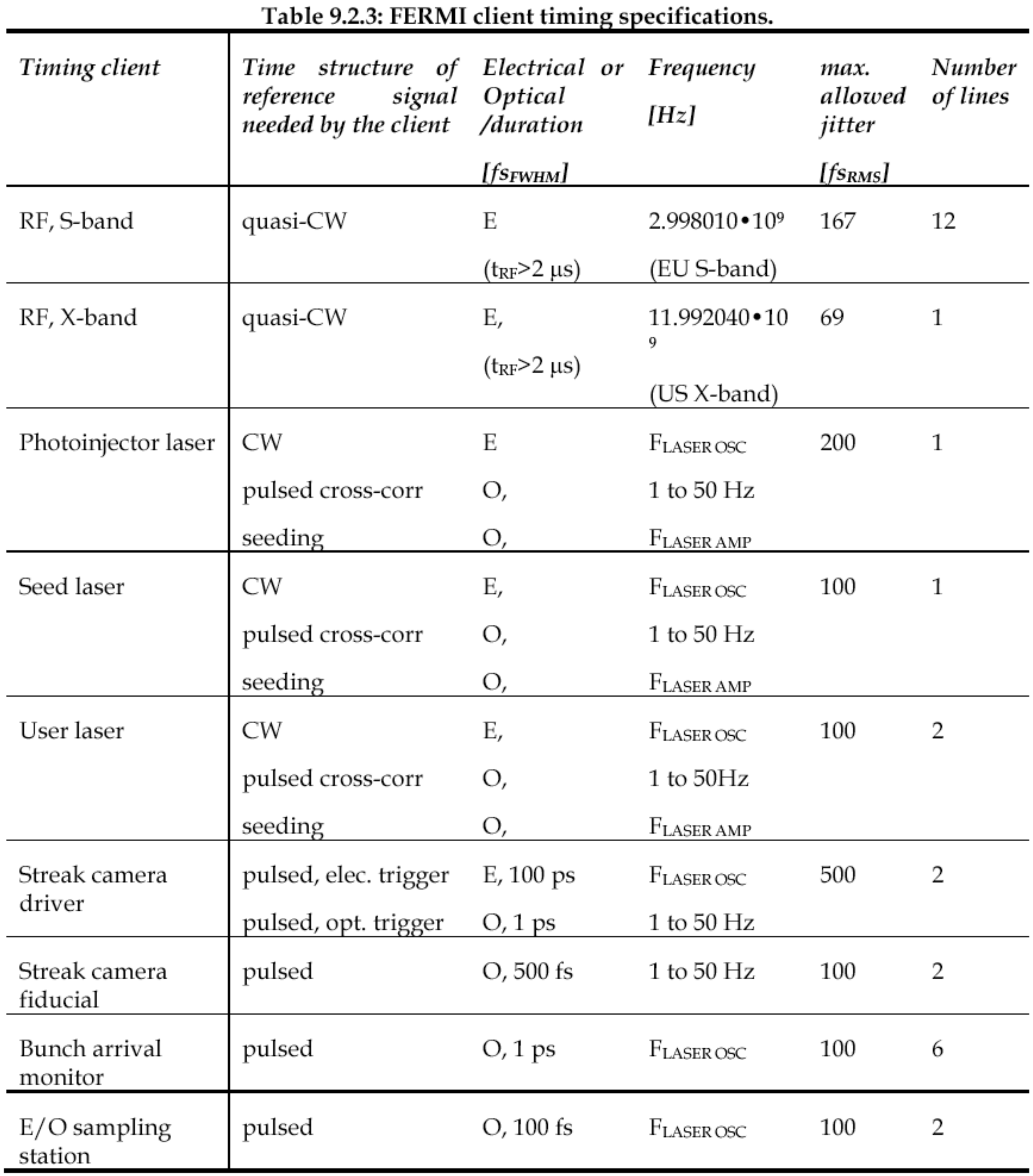


Table 9.2.3: FERMI client timing specifications.

Timing client	*Time structure of reference signal needed by the client*	*Electrical or Optical /duration* [fs_{FWHM}]	*Frequency* [Hz]	*max. allowed jitter* [fs_{RMS}]	*Number of lines*
RF, S-band	quasi-CW	E (t_{RF}>2 μs)	$2.998010 \bullet 10^9$ (EU S-band)	167	12
RF, X-band	quasi-CW	E, (t_{RF}>2 μs)	$11.992040 \bullet 10^9$ (US X-band)	69	1
Photoinjector laser	CW pulsed cross-corr seeding	E O, O,	$F_{LASER\ OSC}$ 1 to 50 Hz $F_{LASER\ AMP}$	200	1
Seed laser	CW pulsed cross-corr seeding	E, O, O,	$F_{LASER\ OSC}$ 1 to 50 Hz $F_{LASER\ AMP}$	100	1
User laser	CW pulsed cross-corr seeding	E, O, O,	$F_{LASER\ OSC}$ 1 to 50Hz $F_{LASER\ AMP}$	100	2
Streak camera driver	pulsed, elec. trigger pulsed, opt. trigger	E, 100 ps O, 1 ps	$F_{LASER\ OSC}$ 1 to 50 Hz	500	2
Streak camera fiducial	pulsed	O, 500 fs	1 to 50 Hz	100	2
Bunch arrival monitor	pulsed	O, 1 ps	$F_{LASER\ OSC}$	100	6
E/O sampling station	pulsed	O, 100 fs	$F_{LASER\ OSC}$	100	2

Magnitude of the problem

- Delay changes for 1m and 1 degree C

Material	Coefficient of delay	Δ delay for 1m, 1 ΛC
Steel	15 x 10^-6 / ΛC	50fs
Aluminum	22 x 10^-6 / ΛC	72fs
Fiber	8 x 10^-6 / ΛC	40fs
Coax, teflon	-85 x 10^-6 / ΛC	-425fs
Coax, air heliax	-10 x 10^-6 / ΛC	-50fs
Air (thermal)	-3 x 10^-6 / ΛC	-10fs
Air (pressure)	2 x 10^-6 / 10 millibars	7fs / 10mbar
Air (humidity)	4 x 10^-6 / 10%RH	13fs / 10%RH

- Clearly, several factors have to be controlled or compensated for
- A timing system solves some of the problem by providing stable clock signals and timing control points
- Overall problem will require other kinds of systems as well

Fractional frequency and time stability

- **Example: 10fs error budget over 1km distance**
  - **t = nl/c = 1.45*1000m/3e8m/s = 4.8us**
  - **10fs/4.8us = 2e-9**
- **Say 10Hz shot rate, and 24 hours experiment duration**
  - **2e-9 stability from 0.1s to 24 hours (~10^4 sec.)**

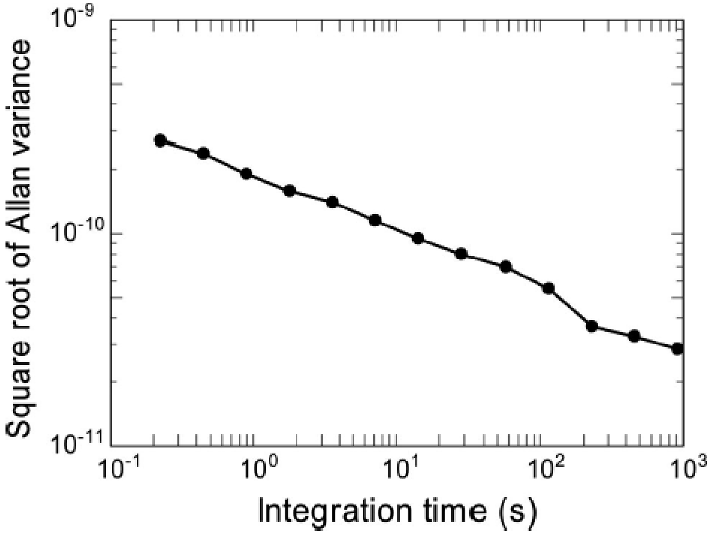
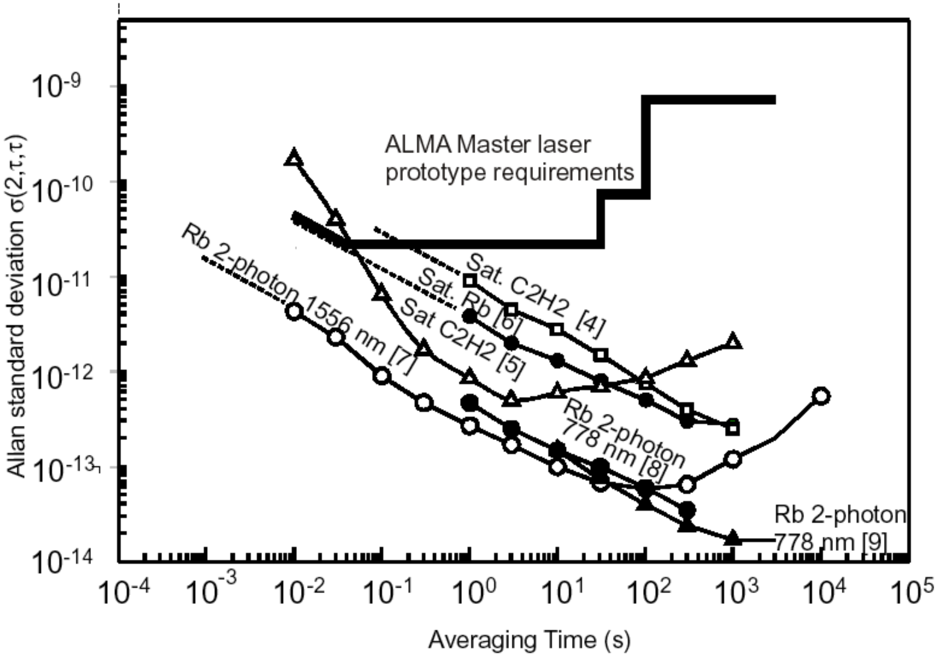
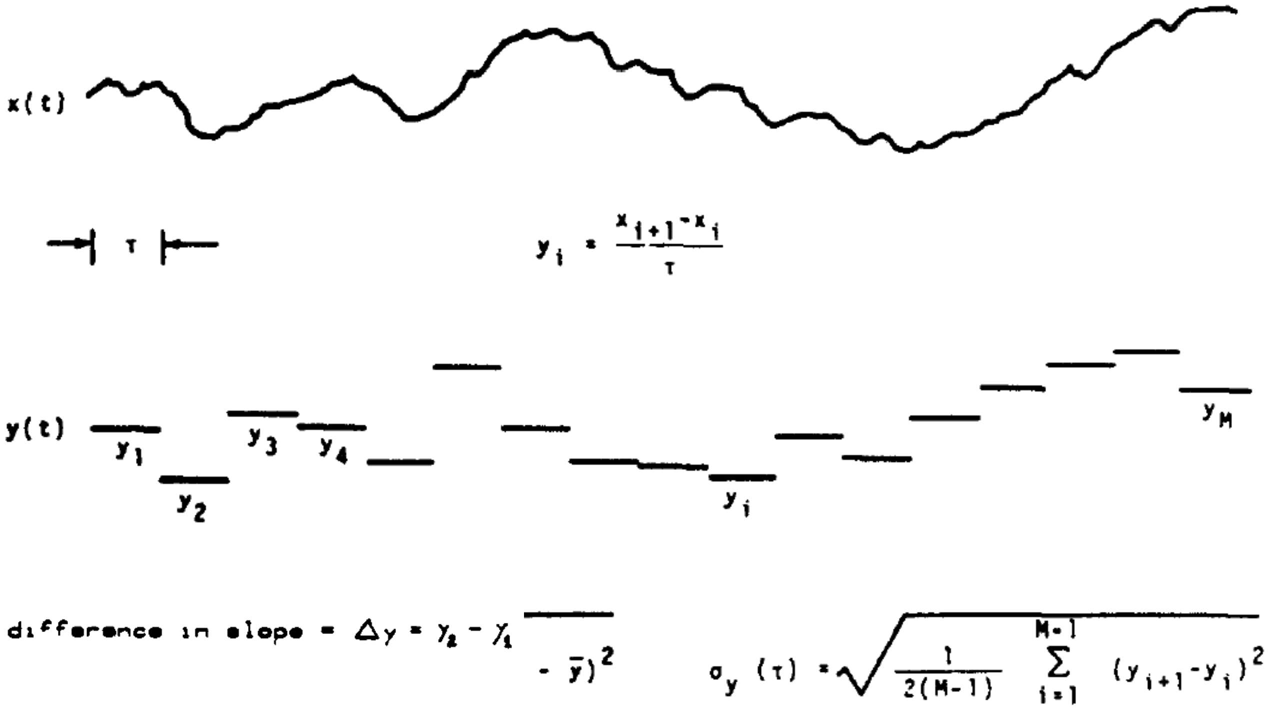


Fig. 4. Relative Allan standard deviation of beat signal generated from a pair of developed Rb-stabilized DFB diode lasers.



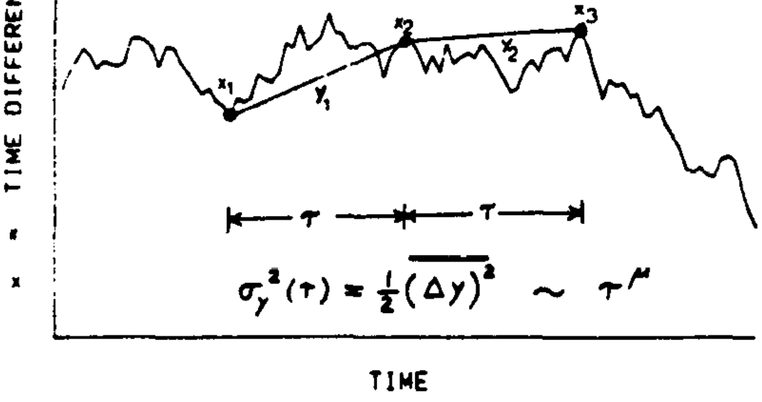
Measuring clocks: Allan variance



$$y_i = \frac{x_{i+1} - x_i}{\tau}$$

difference in slope $= \Delta y = y_2 - y_1$

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2}$$

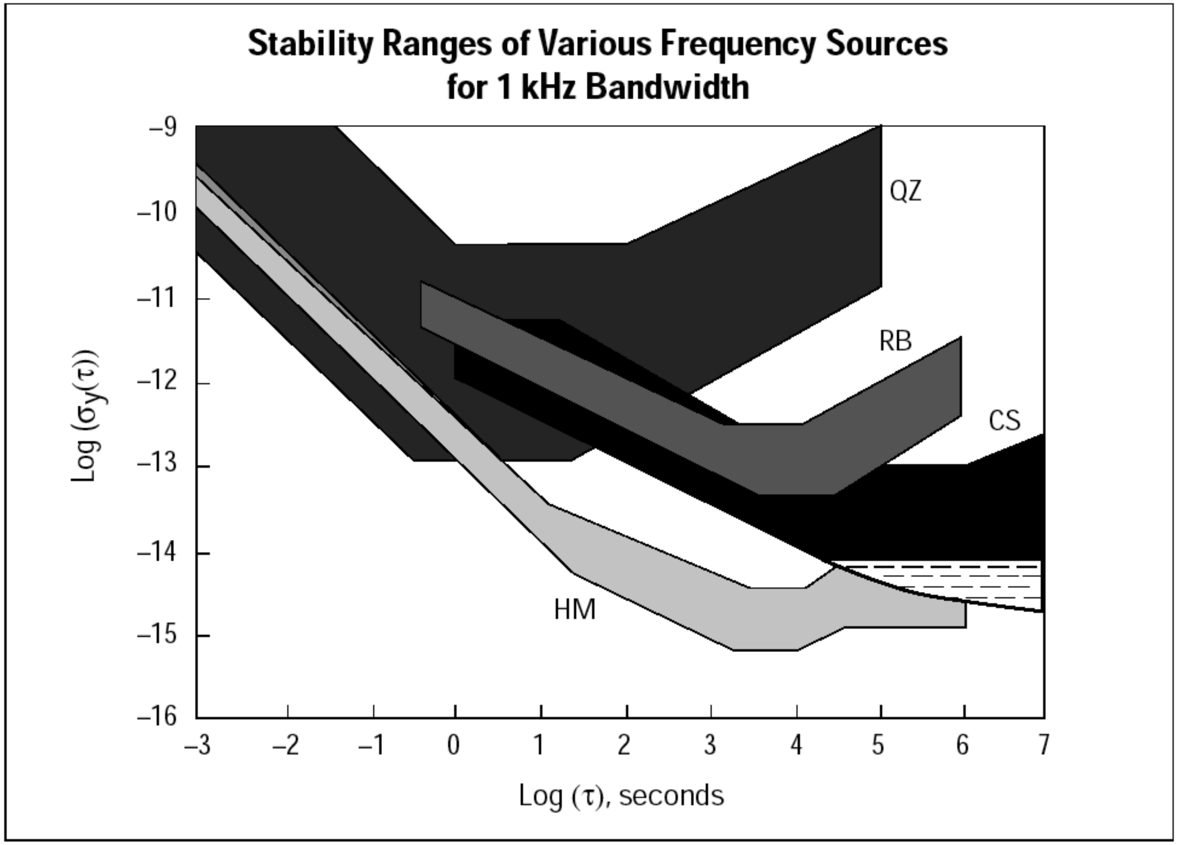


$$\sigma_y^2(\tau) = \frac{1}{2}\overline{(\Delta y)^2} \sim \tau^{\mu}$$

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2}\left\langle \left(\Delta^2 x\right)^2 \right\rangle = \frac{1}{2}\left\langle \left(\Delta y\right)^2 \right\rangle$$

$$x(t) = \int_0^t y(t')\, dt'$$

Allan variance of some high stability clocks



- D. W. Allan, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, UFFC-34, p647 (1987)
- Allan, Ashby and Hodge, HP Application Note 1289

Other types of Allan variance

- **Modified**
- **Time (telecom)**

$$\Delta^2 x_i = x_{i+2} - 2x_{i+1} + x_i$$

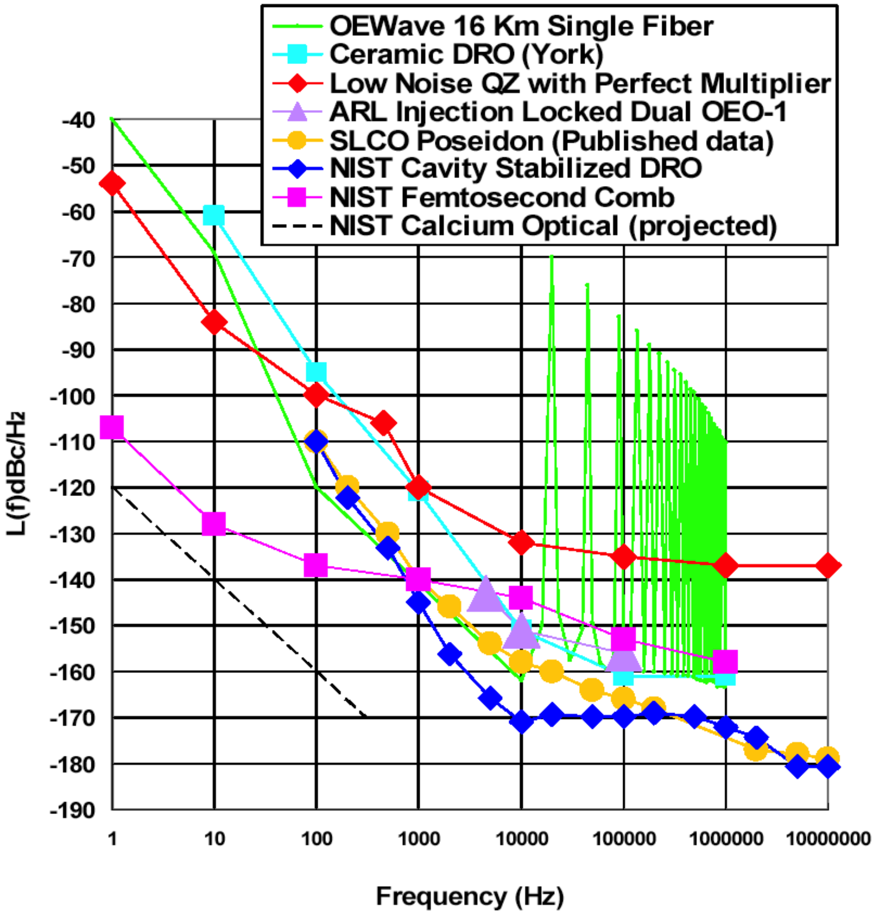
$$\mathrm{Mod.}\sigma_y^2(\tau) = \frac{1}{2\tau^2}\left\langle \left(\Delta^2 \overline{x}\right)^2 \right\rangle$$

$$\sigma_x^2(\tau) = \frac{\tau^2}{3}\mathrm{Mod.}\sigma_y^2(\tau)$$

$$= \frac{1}{6}\left\langle \left(\Delta^2 \overline{x}\right)^2 \right\rangle,$$

Phase spectral density plot

- **Power spectral density of the phase modulation sidebands, compared with the carrier, at an offset frequency f, and carrier frequency w_0**
- **Measured with a spectrum analyzer, or special but similar instrument**
- **Equivalent to the Allan deviation but used mostly for high frequency jitter rather than long term averaged measurements**



$$\Delta t_{rms} = \frac{1}{n\omega_0}\sqrt{2\int_{f_1}^{f_2} \mathcal{L}(f)\,df}$$

RMS time error from phase spectrum

$$L(f) = \frac{1}{2}S_\phi(f) = \frac{1}{2}\left(\frac{v_0^{2}}{f^{2}}S_y(f)\right)$$

phase spectrum from frequency spectrum

$$\sigma_y^{2}(\tau) = 2\int_0^{f_h} S_y(f)\,\frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}\,df$$

Allan variance from frequency spectrum

IEEE J. Selected Topics in QE, 7, p641 (2001)

RF oscillator and laser phase noise examples

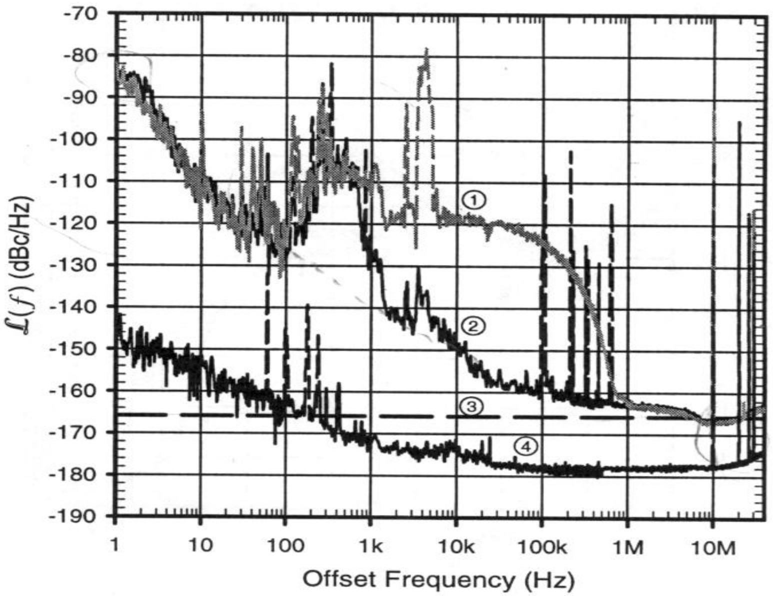
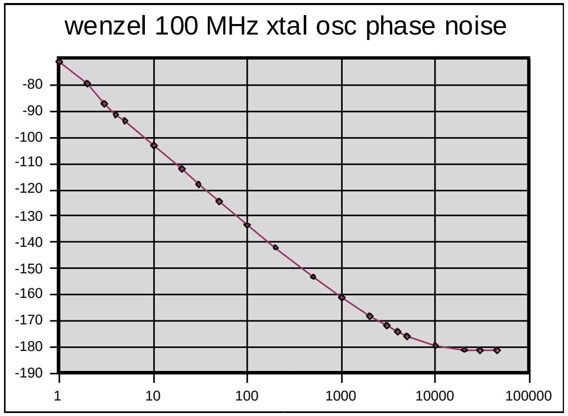


Fig. 14. Absolute SSB phase noise of phase-locked Ti : sapphire laser at 80 MHz with two different types of pump laser, $i_0 = 3$ mA. ① Argon-ion pump. ② DPSS pump. ③ Calculated shot-noise limit. ④ Worst case system phase-noise floor, +12 dBm at RF port and +15 dBm at LO port.

- **Knowing the whole spectrum is better than a single point!**
- **Integrated jitter number is useful, but need to know integration limits**



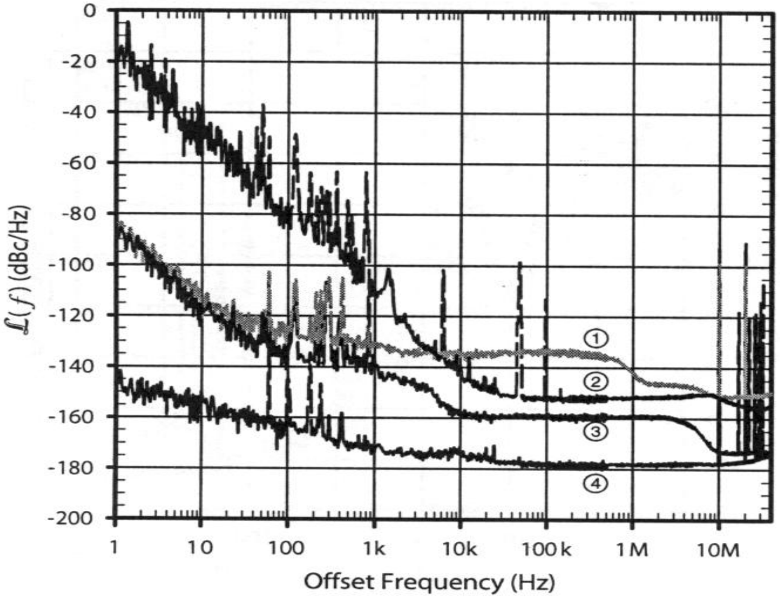


Fig. 13. Absolute SSB phase noise of various RF sources operating at 80 MHz. ① HP 8662A synthesized output. ② HP 8640B using DCFM. ③ HP 8662A's internal 10-MHz crystal oscillator and 8× multiplier chain versus similar 10-MHz crystal oscillator with 8× multiplier chain. ④ Worst case system phase noise floor, +12 dBm at RF port and +15 dBm at LO port.