Strategies for achieving sub-10fs timing in large-scale FELs

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MENLO SYSTEMS

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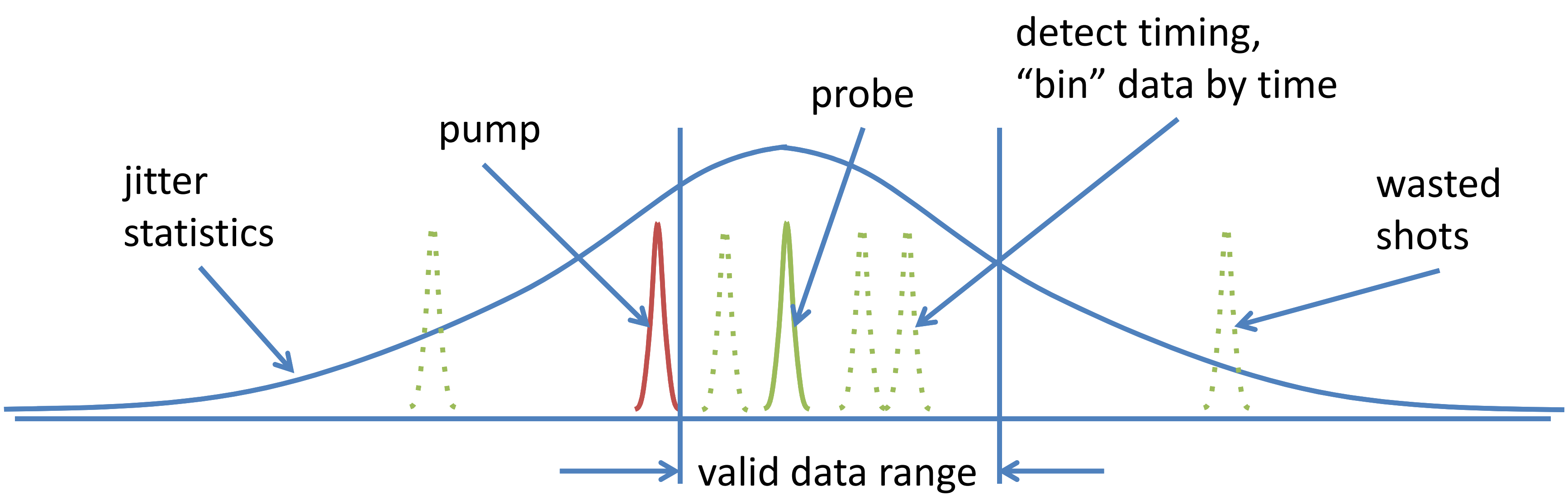
Outline

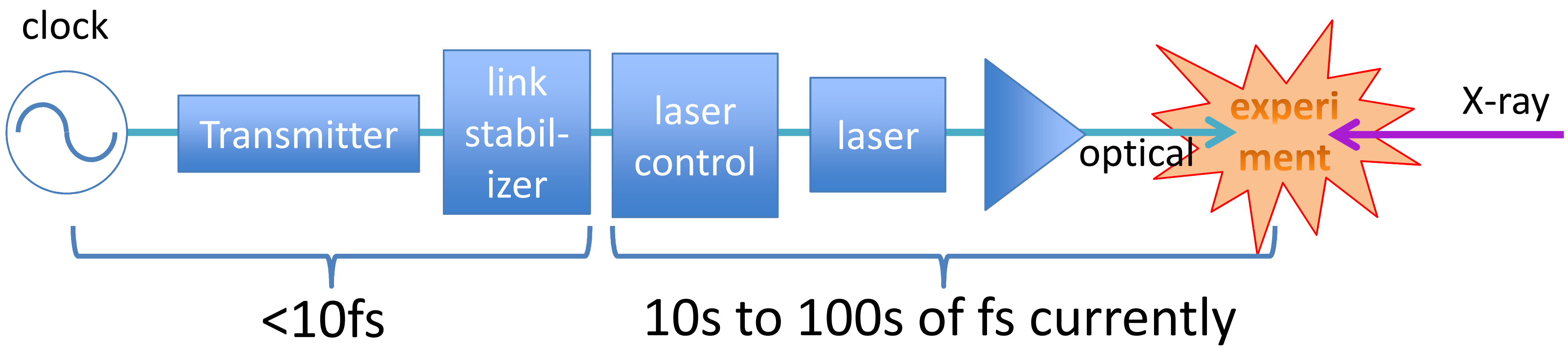
- Overall system design approach for <10fs
- Subsystems
  - Clock requirements
  - Stabilized link
  - Laser oscillator timing control
  - Downstream monitors and feedback
- Conclusions

<10fs pump/probe experiments drive timing requirements

- ≤10fs photon pulses from LCLS, SACLA, FLASH…
- Want timing uncertainty ≤ pulse width, otherwise…
  - Pulse is statistically widened
  - Timing range is statistically sampled (then “binned” if measured)
  - Shots are wasted, reducing effective reprate

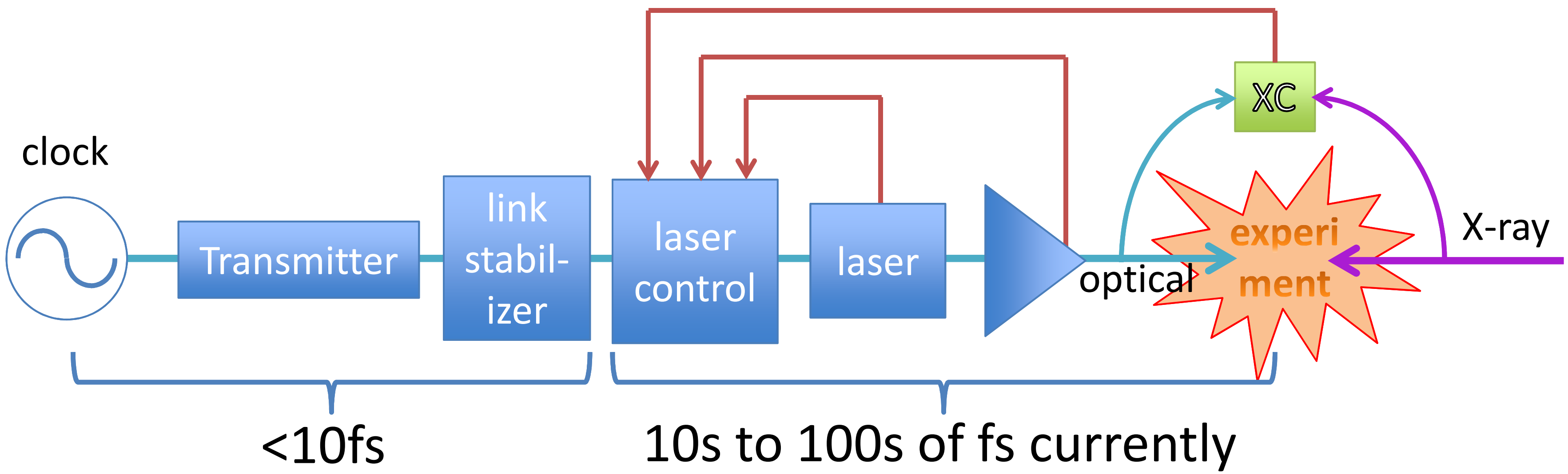


Laser synchronization path



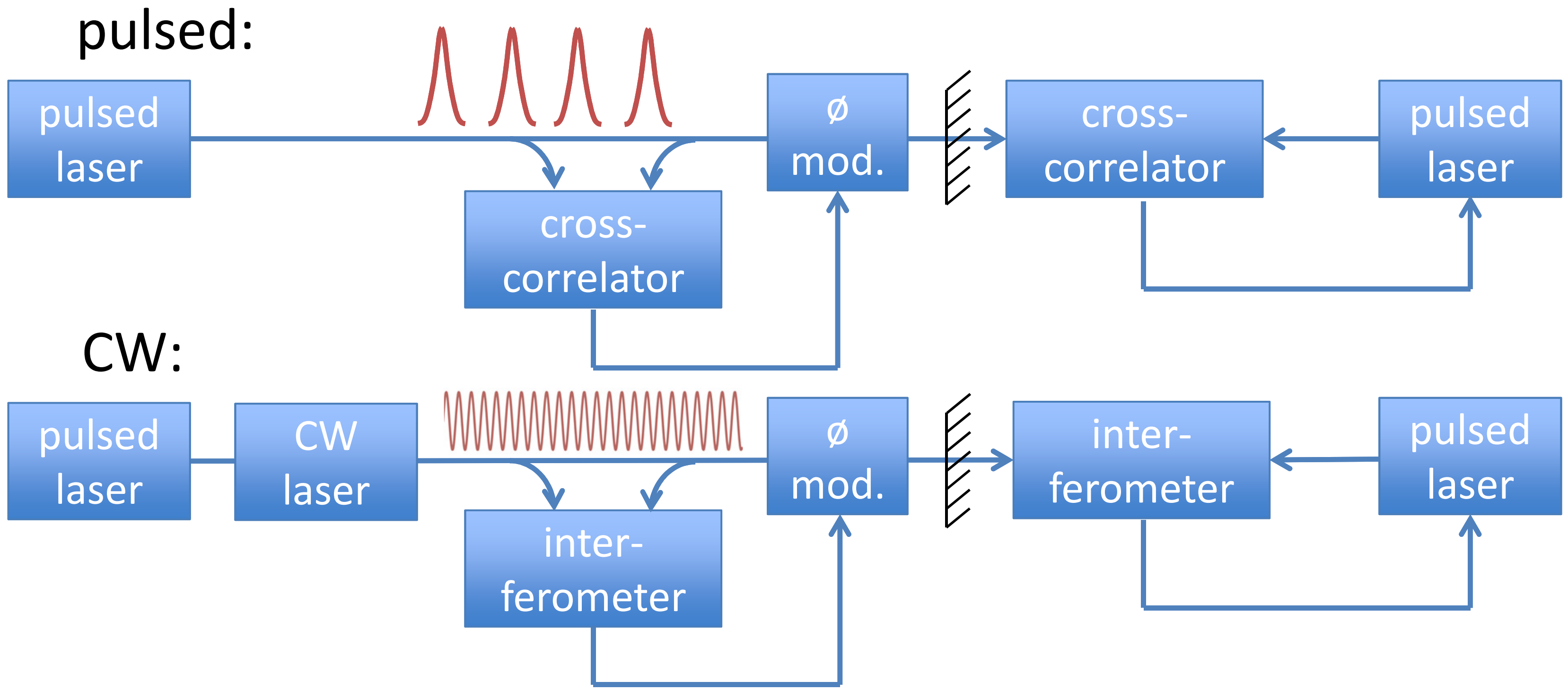
- Carry stability of clock down stream
  - Minimize jitter added by subsystems

Laser synchronization path



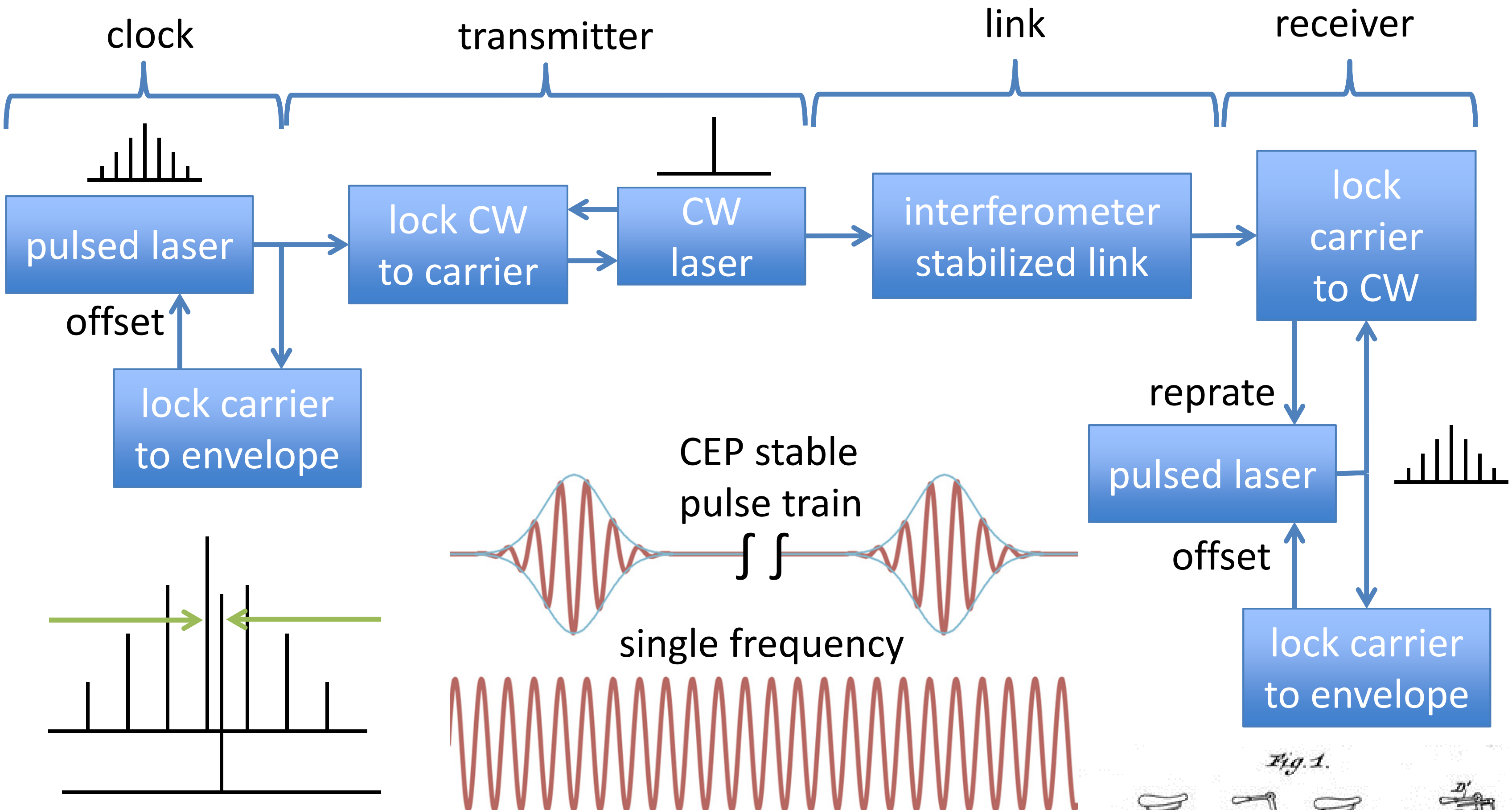
- Carry stability of clock down stream
  - Minimize jitter added by subsystems
  - Feedback at maximum bandwidth for each stage
- X-ray jitter assumed to be low (Byrd et al, TUPD29)

Clock distribution methods

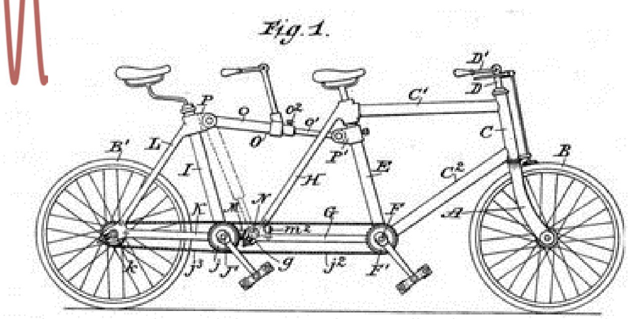


- CW carrier : continuous signal (fringe counting), no fiber nonlinearity
  – Analogous to RF clock, but 10^6 higher frequency
  – $\Delta t = \Delta\phi/2\pi f = 1\text{rad}/(2\pi*200\text{THz}) = 0.8\text{fs}$

Linking CW and pulsed lasers



- Timing always transferred via optical phase detection

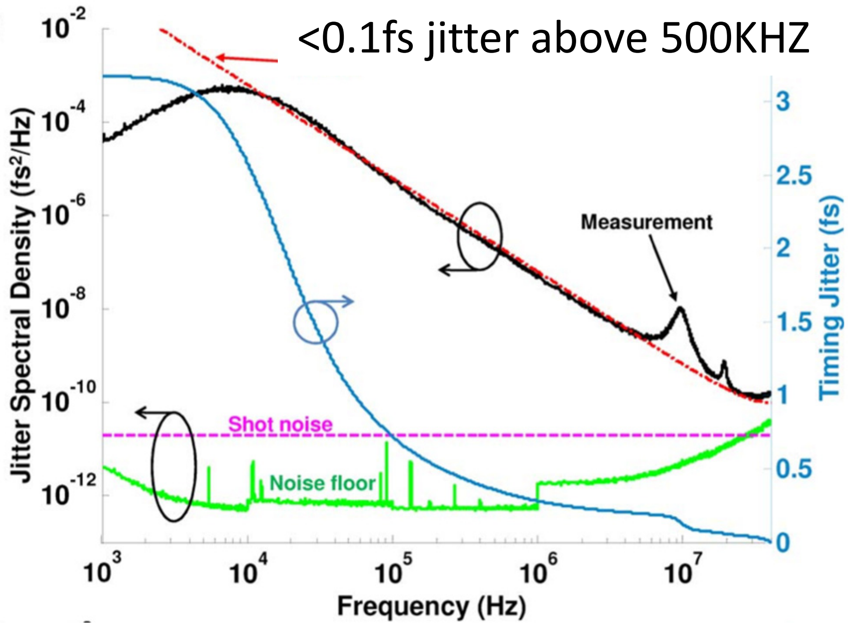


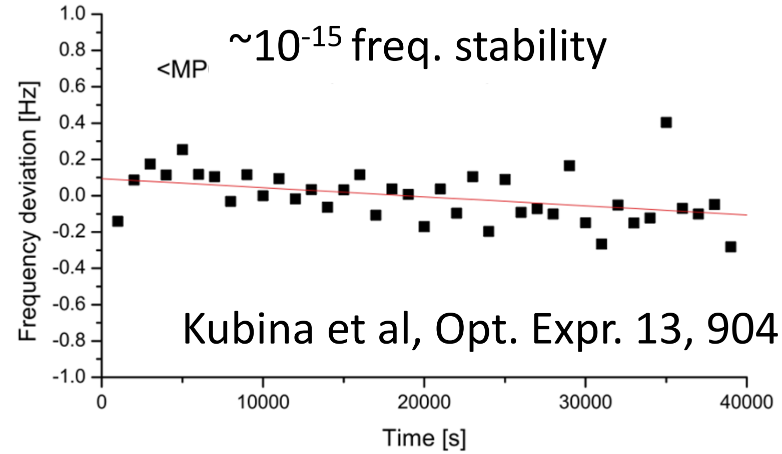
Clock and distribution via links

How good does the clock have to be?

- Determined by delay difference $t_D = t_A - t_B$
- High frequency: differential noise with period $<2t_D$
- Low frequency: phase delay change $\Delta t = t_D \frac{\Delta f}{f}$
- Example: 200m fiber
  - t_D is 1μS
  - High frequency noise above 500kHz < 1fs
  - Long term frequency drift < 10^{-9}

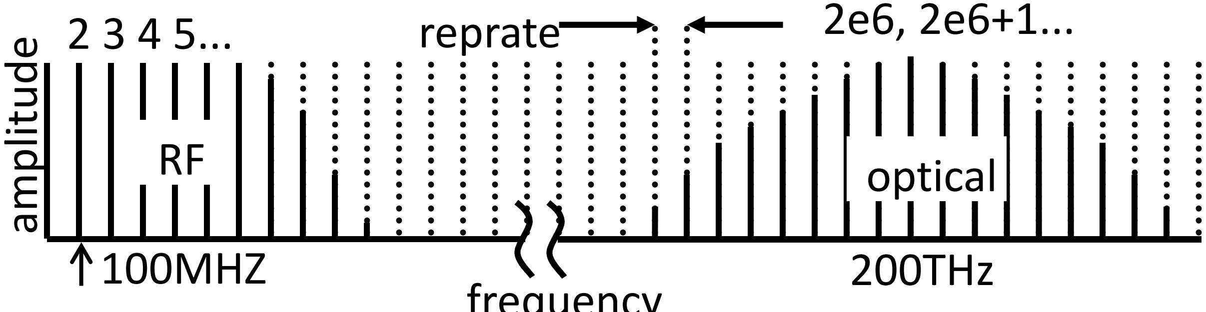
Optical clocks are good enough





J. A. Cox et al, Opt. Lett. 35, 3522 (2010)

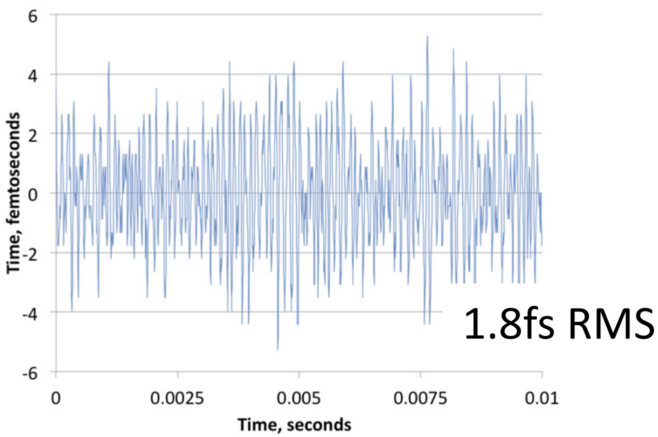
- RF and optical frequencies, at exact integer multiples

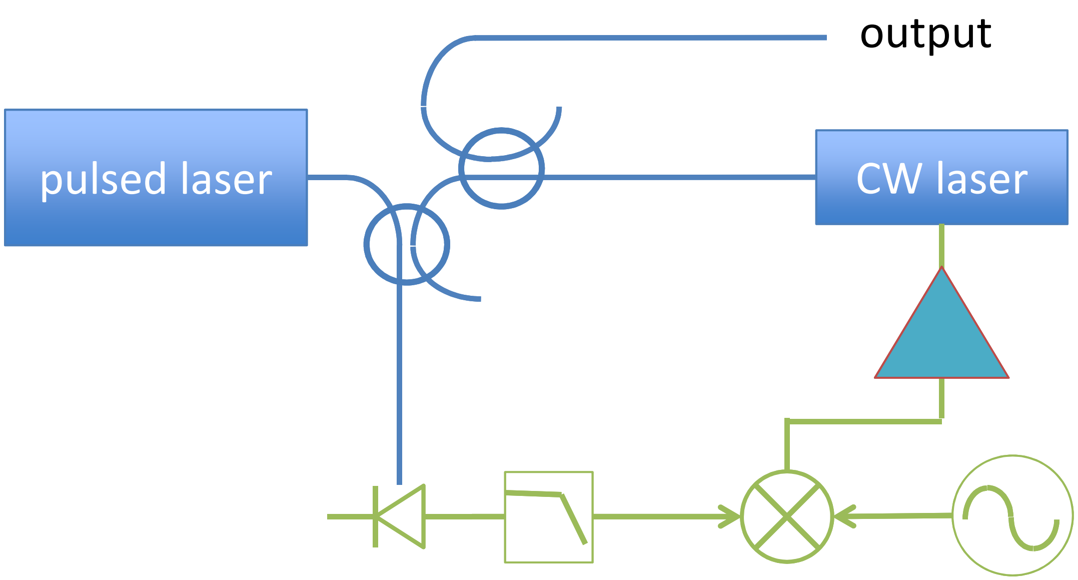


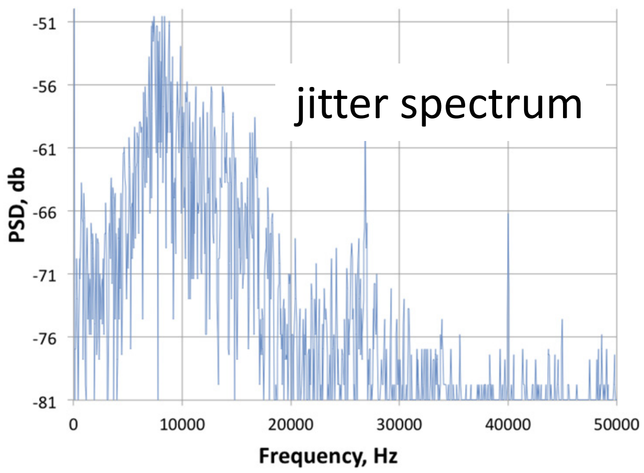
Menlo Systems

Lock CW to clock

- Optical phase-locked loop
  - Beat CW with nearest comb line
- 8kHz bandwidth piezo tuner
  - 1.8fs RMS jitter

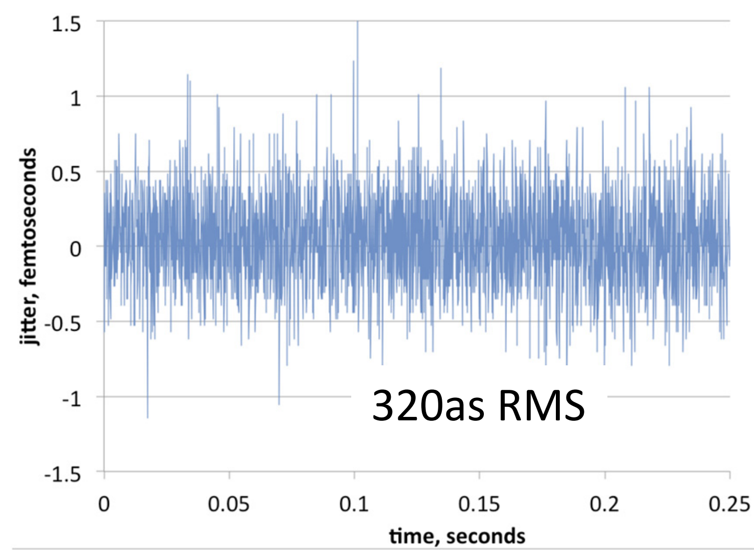


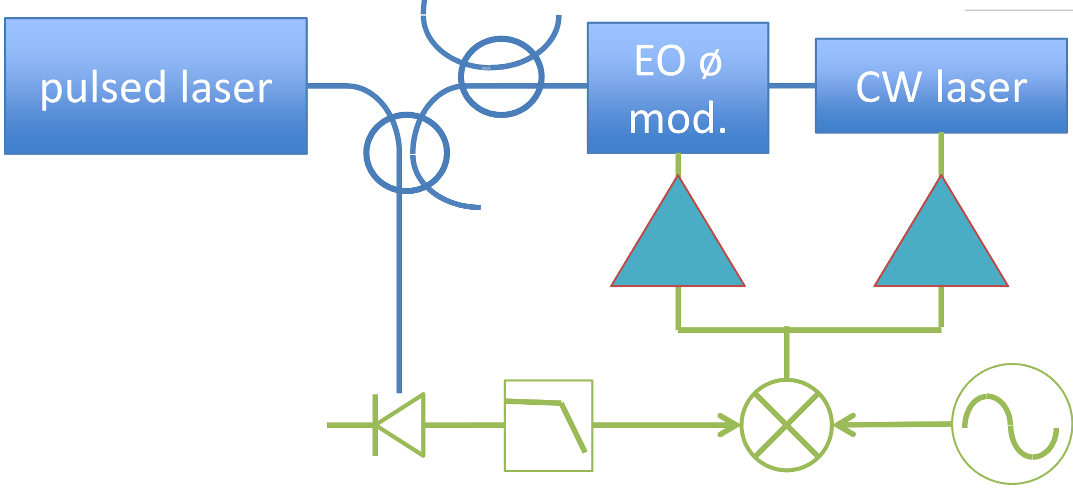




Lock CW to clock

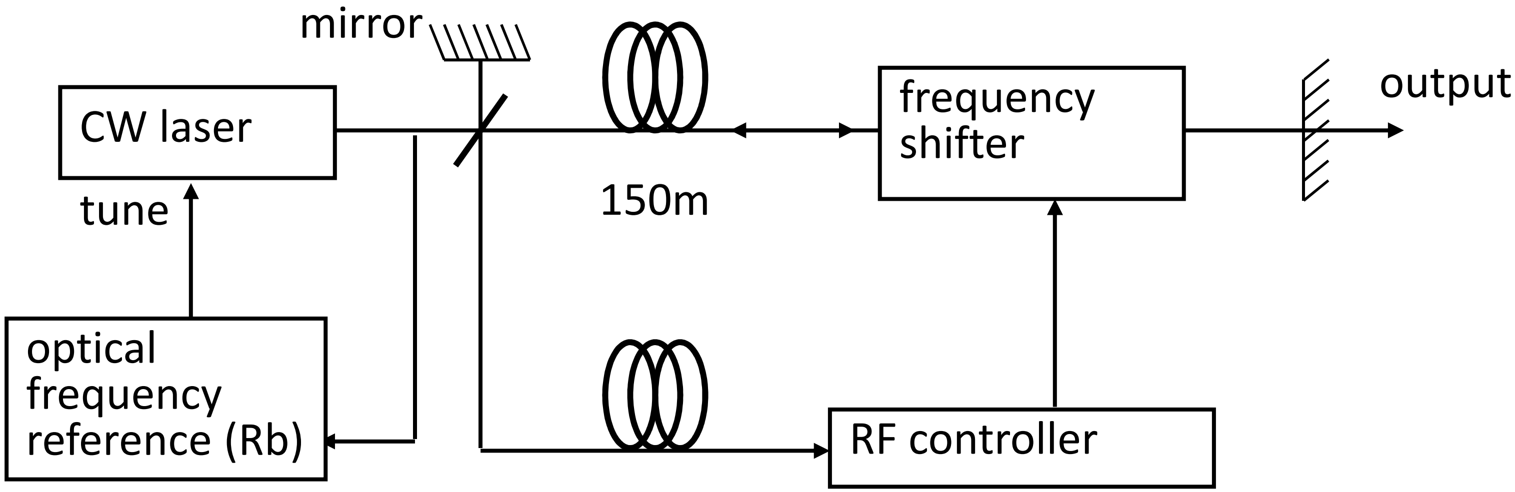
- Optical phase-locked loop
  - Beat CW with nearest comb line
- 8kHz bandwidth piezo tuner
  - 1.8fs RMS jitter
- >1MHz EO phase modulator
  - 320as RMS jitter



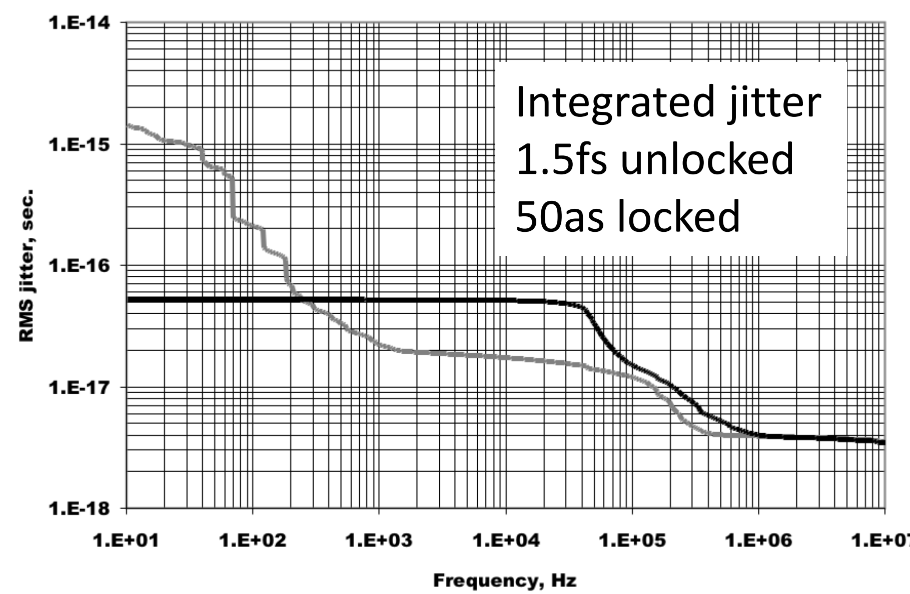


- *Fast extracavity control becomes possible when jitter is <10fs*

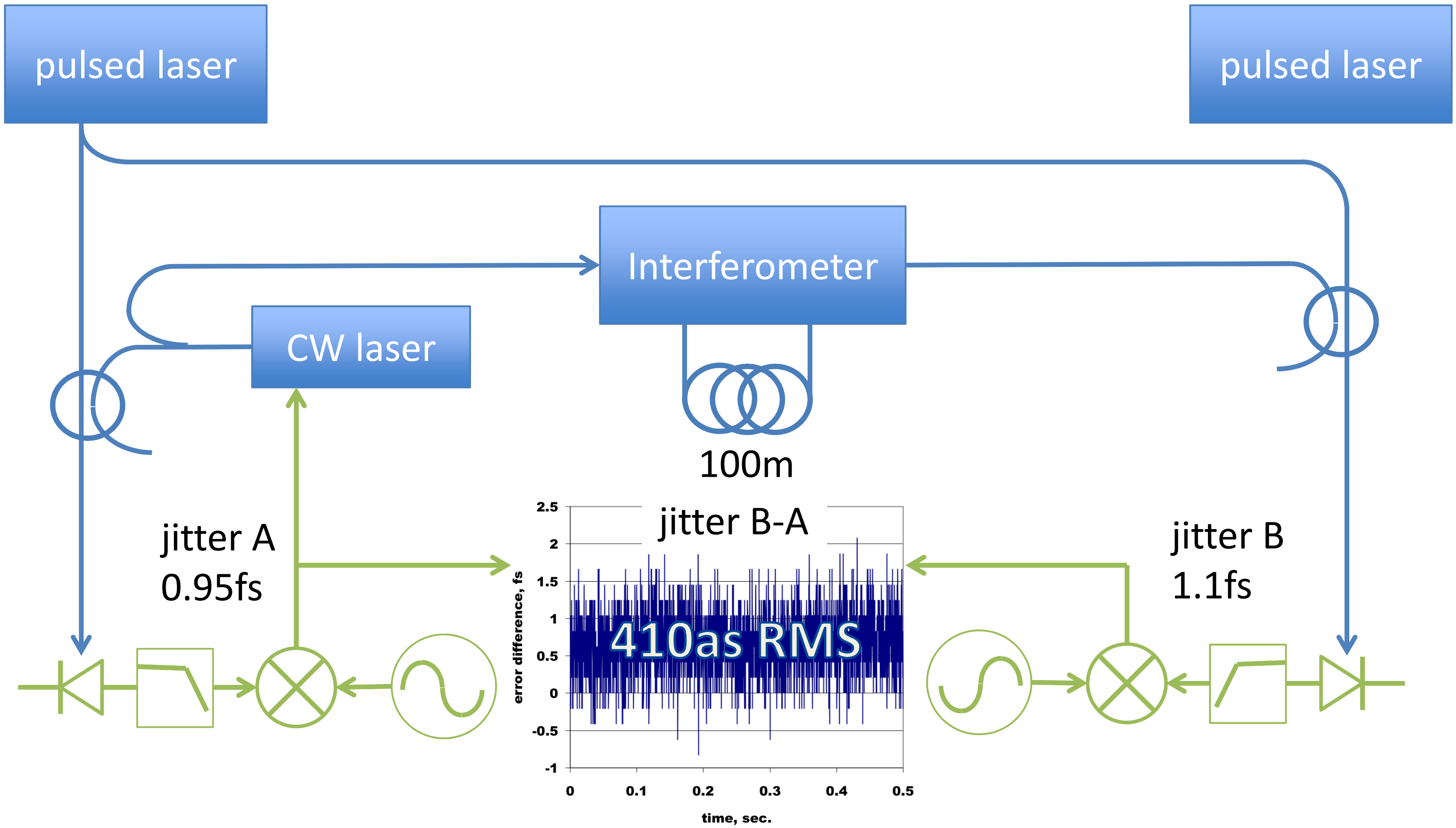
Interferometric link stabilizer



- No moving parts
- Similar device demonstrated over 500km fiber (Science 336, 441 (2012))
- Tracks phase continuously
  - Nanosecond error range
  - Sub-fs precision



Link transmission jitter

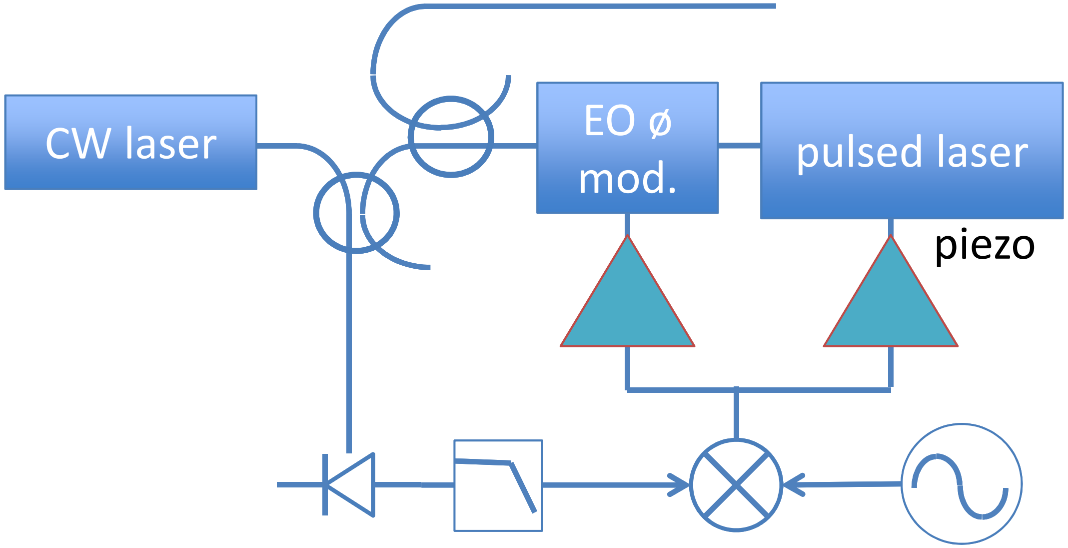


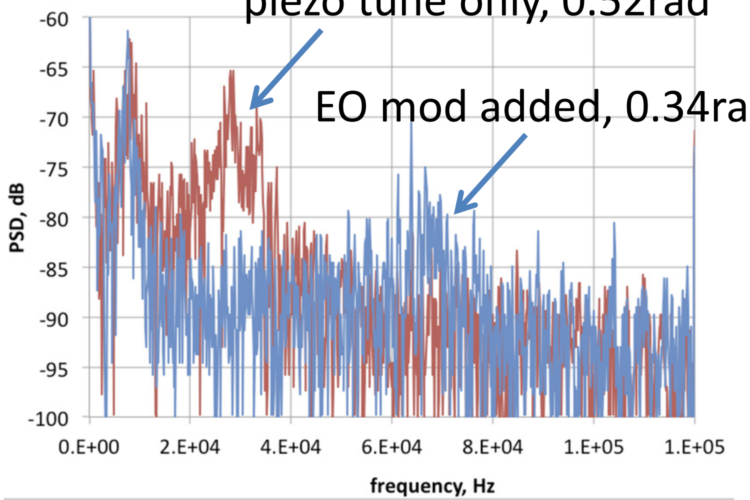
- Transmission over 100m fiber adds ~400as to optical jitter

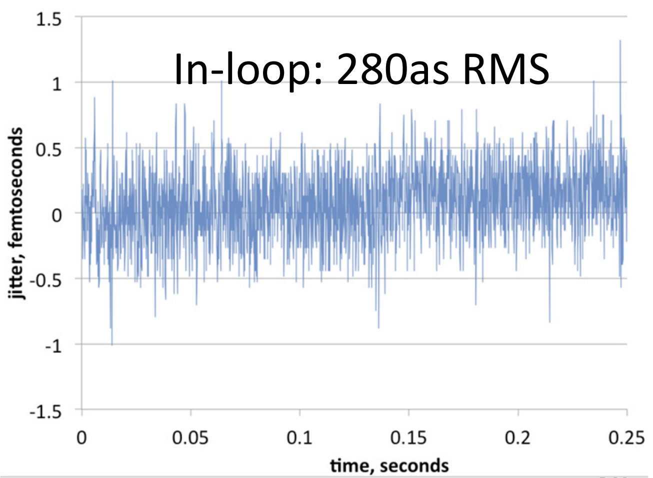
NGLS next generation light source

Control of laser timing

Lock pulsed laser to CW

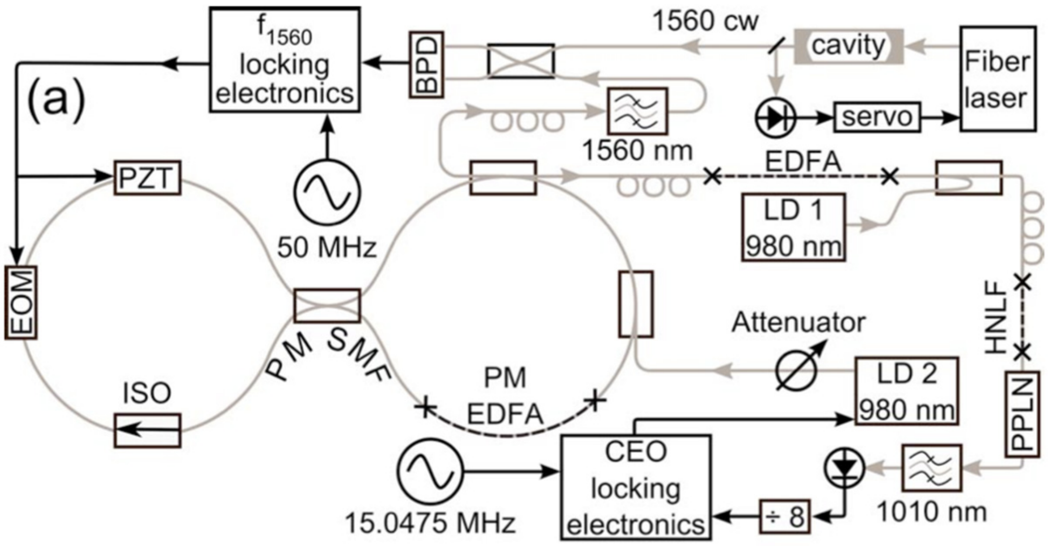






- Control reprate based on CW laser phase
- Increase control BW with EO
- Pulsed laser not CEP stable

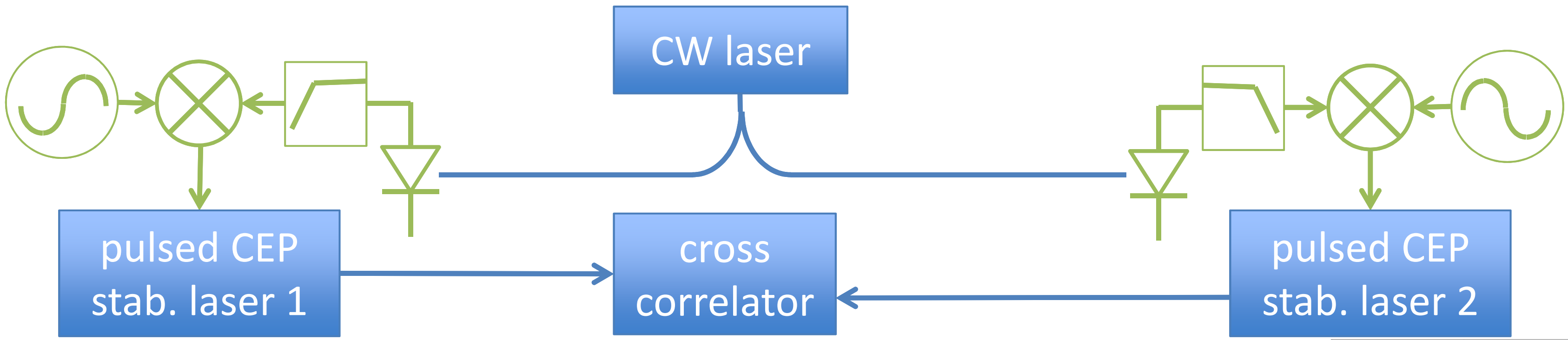
CEP-stabilized fiber laser locked to CW



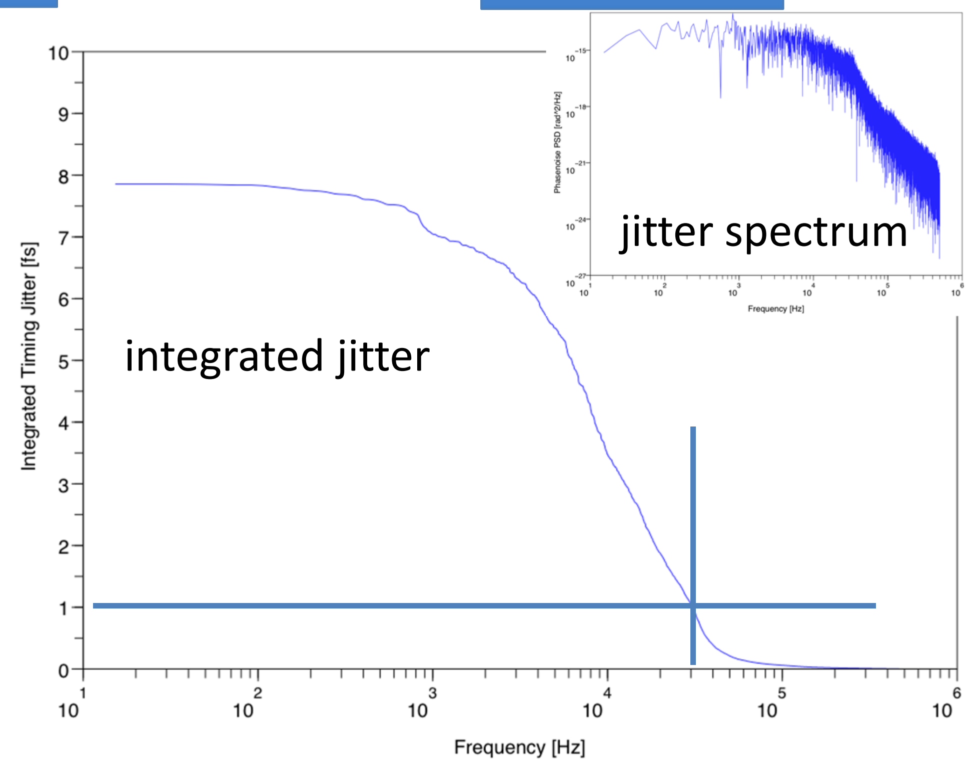
Baumann et al
Opt. Lett. 34, 638 (2009)

- 0.138 radian envelope-to-CW phase (113as at 1550nm)
  - With intracavity electro-optic modulator
    - Envelope synced to CW phase with 113as RMS jitter

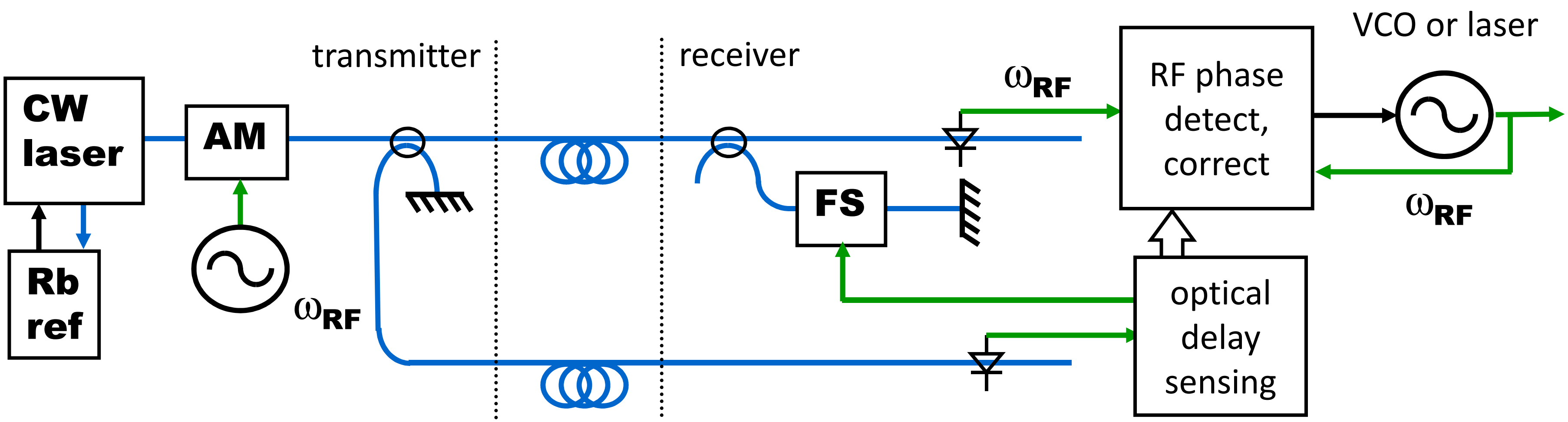
Cross-correlation of locked lasers



- <8fs RMS difference, 10Hz to 1MHz
- 8fs/√2 = 5.6fs
- Most noise below 100kHz
- Limited control bandwidth
  - Increase BW to 1MHz with EO crystal in cavity

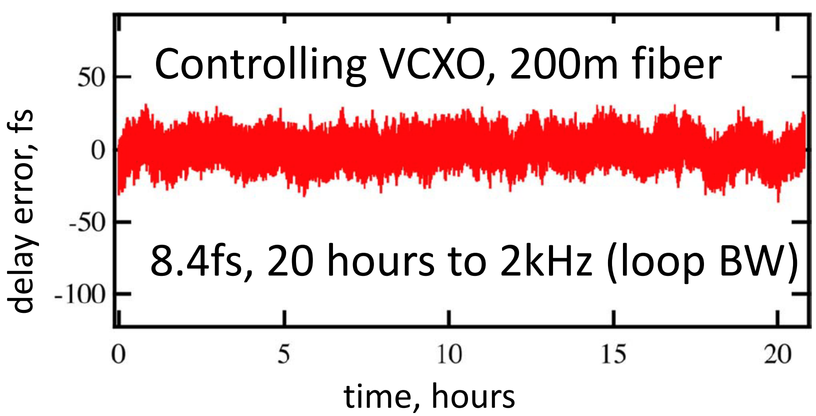


Need to first “coarse” lock at 10s of fs



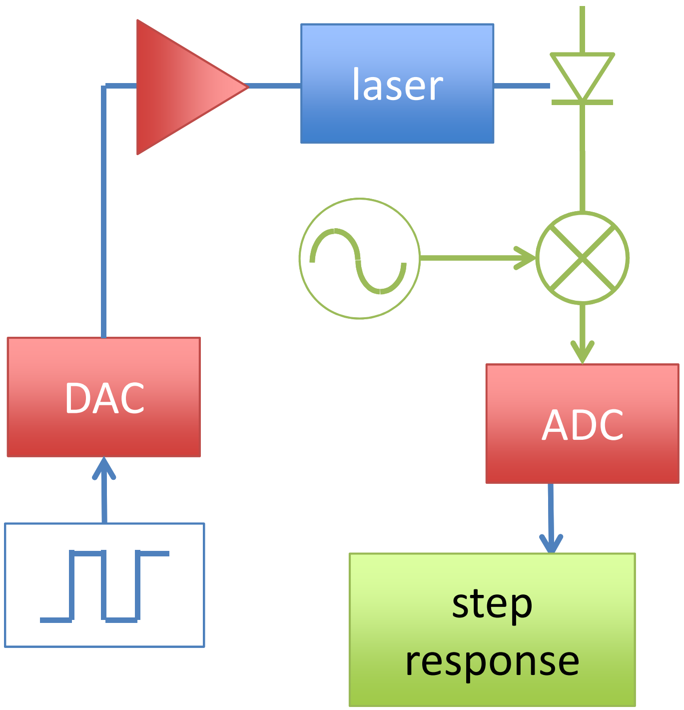
- RF clock controls remote oscillator
- ~10fs is the limit
  - 0.01 degree phase error
  - 10fs at 3GHz
- Currently used in LCLS and Fermi@Elettra

Out-of-loop resuts:

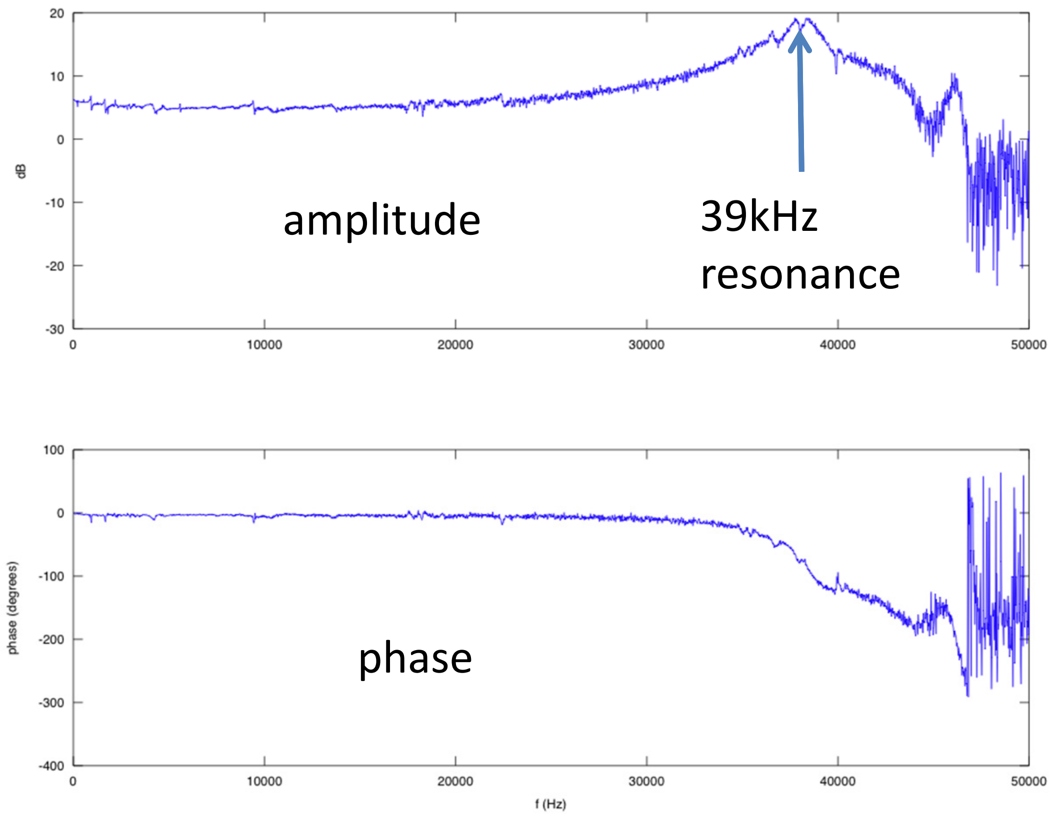


Optimizing RF lock for ti:sapphire laser

- Determine open loop transfer function
- Add filter to prevent oscillation with high gain (30kHz LPF)



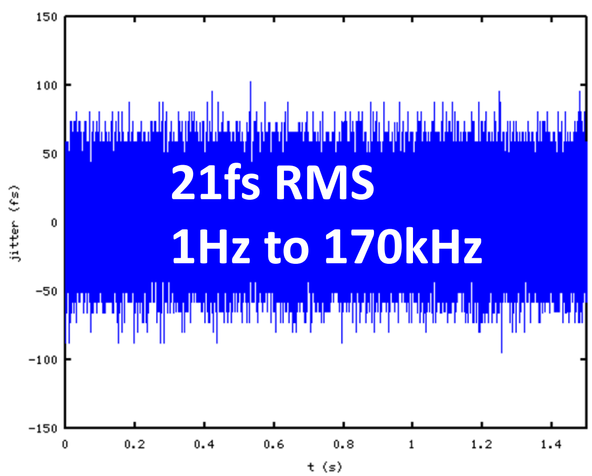
Transfer function:

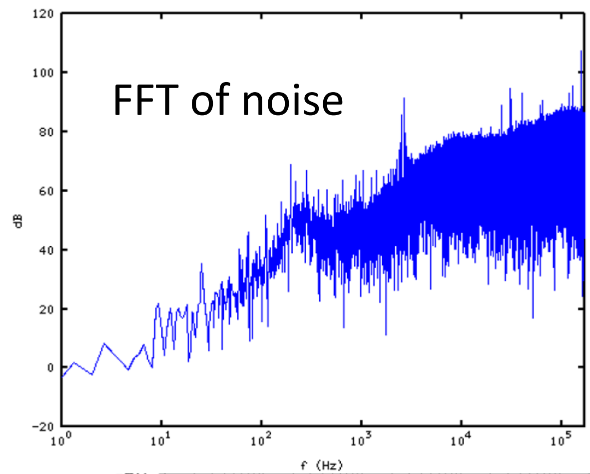


RF locking results with tisaf

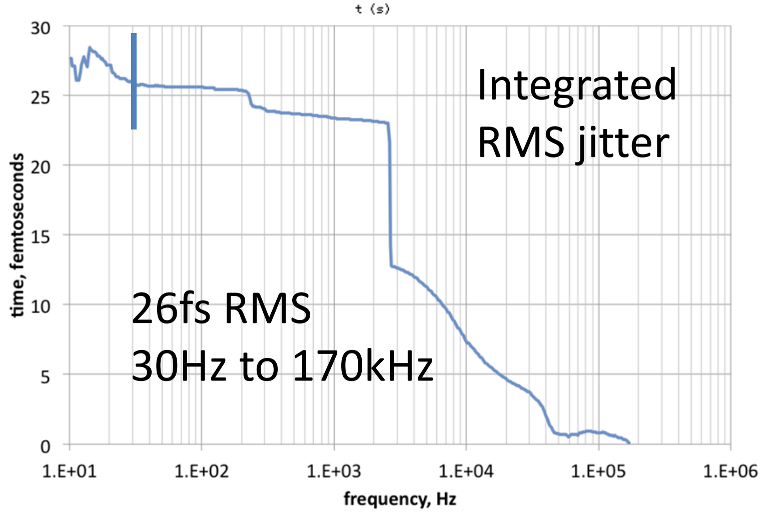
- In-loop measurement compared with difference between two externally referenced measuements

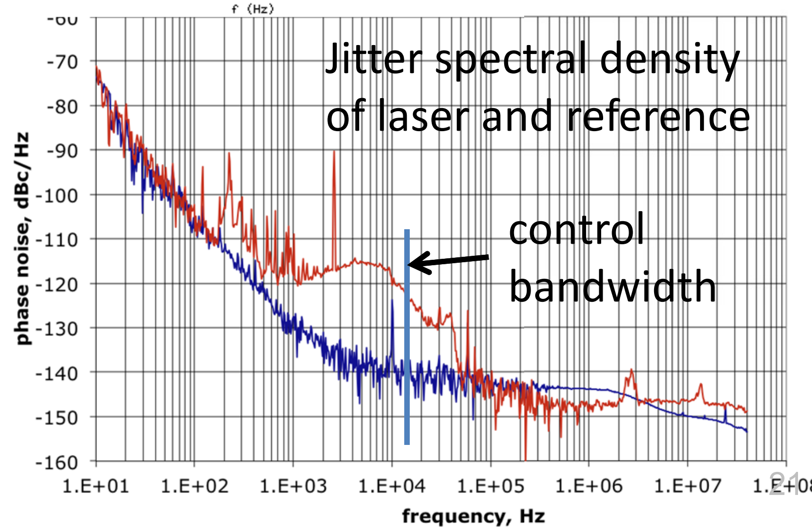
In-loop:





Out-of-loop:

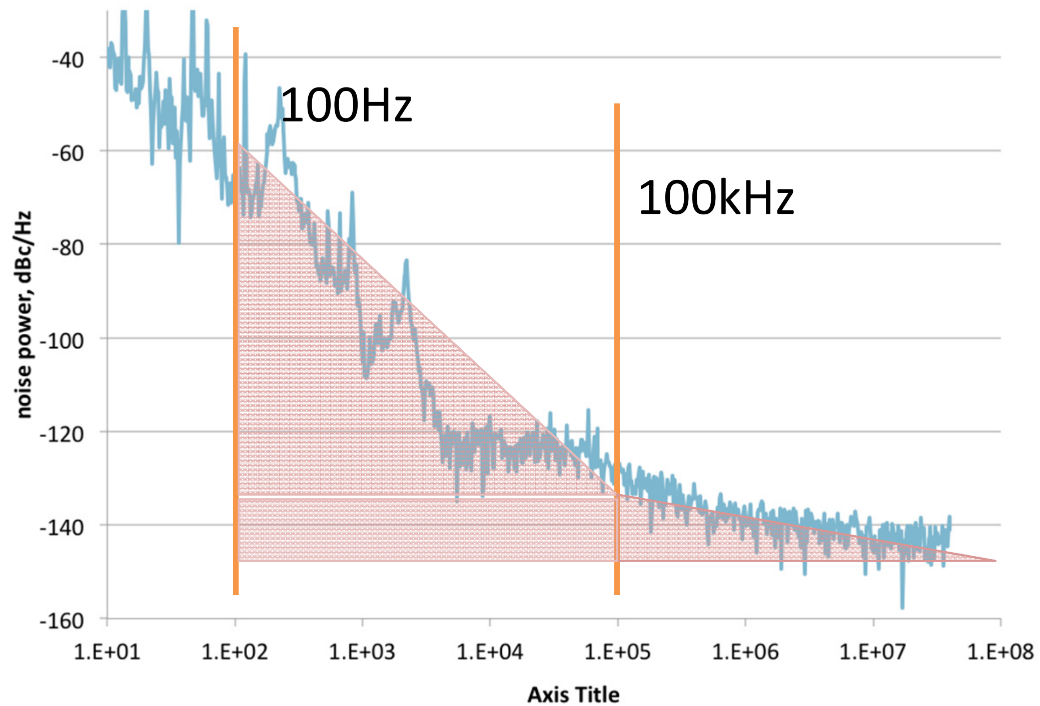




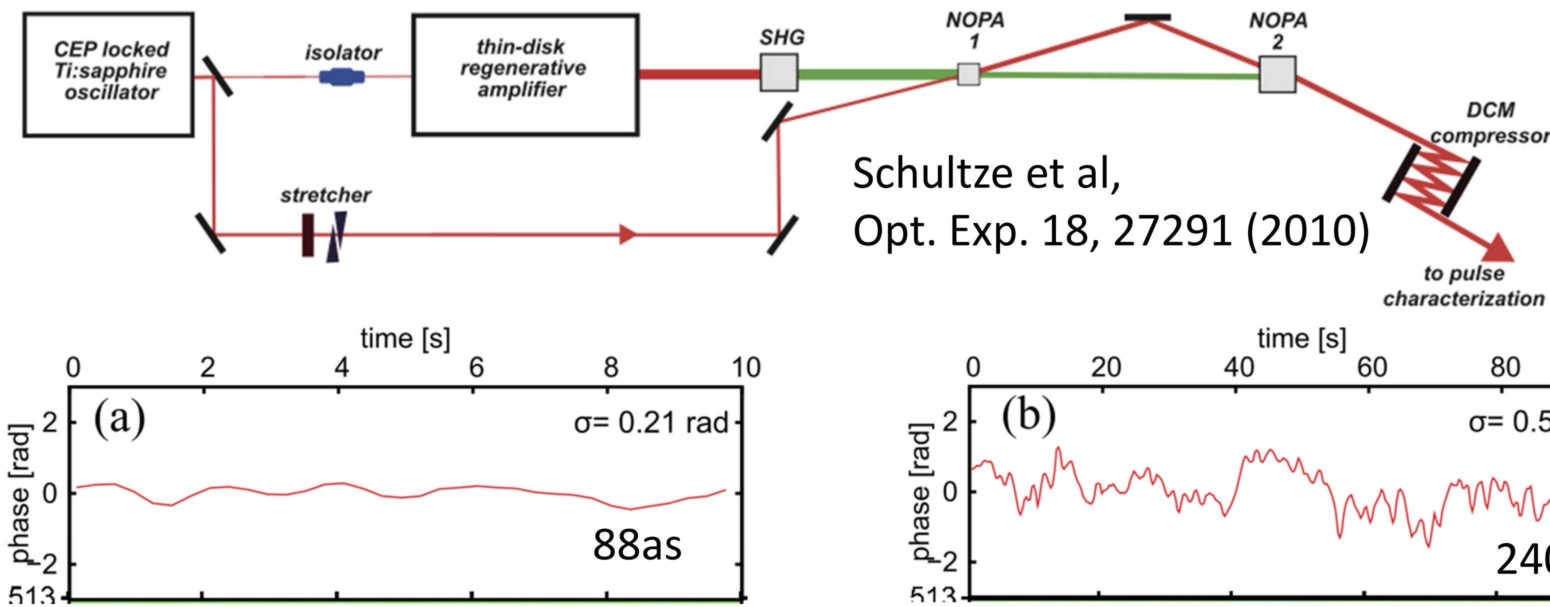
Downstream monitors and feedback

Noise measurement and control depends on repetition (sample) rate

- High reprate enables high bandwidth feedback
  - Control BW ≈ sample rate/10
- Integrated jitter above sample rate is “shot to shot”



Effect of amplifiers on CEP



Schultze et al,
Opt. Exp. 18, 27291 (2010)

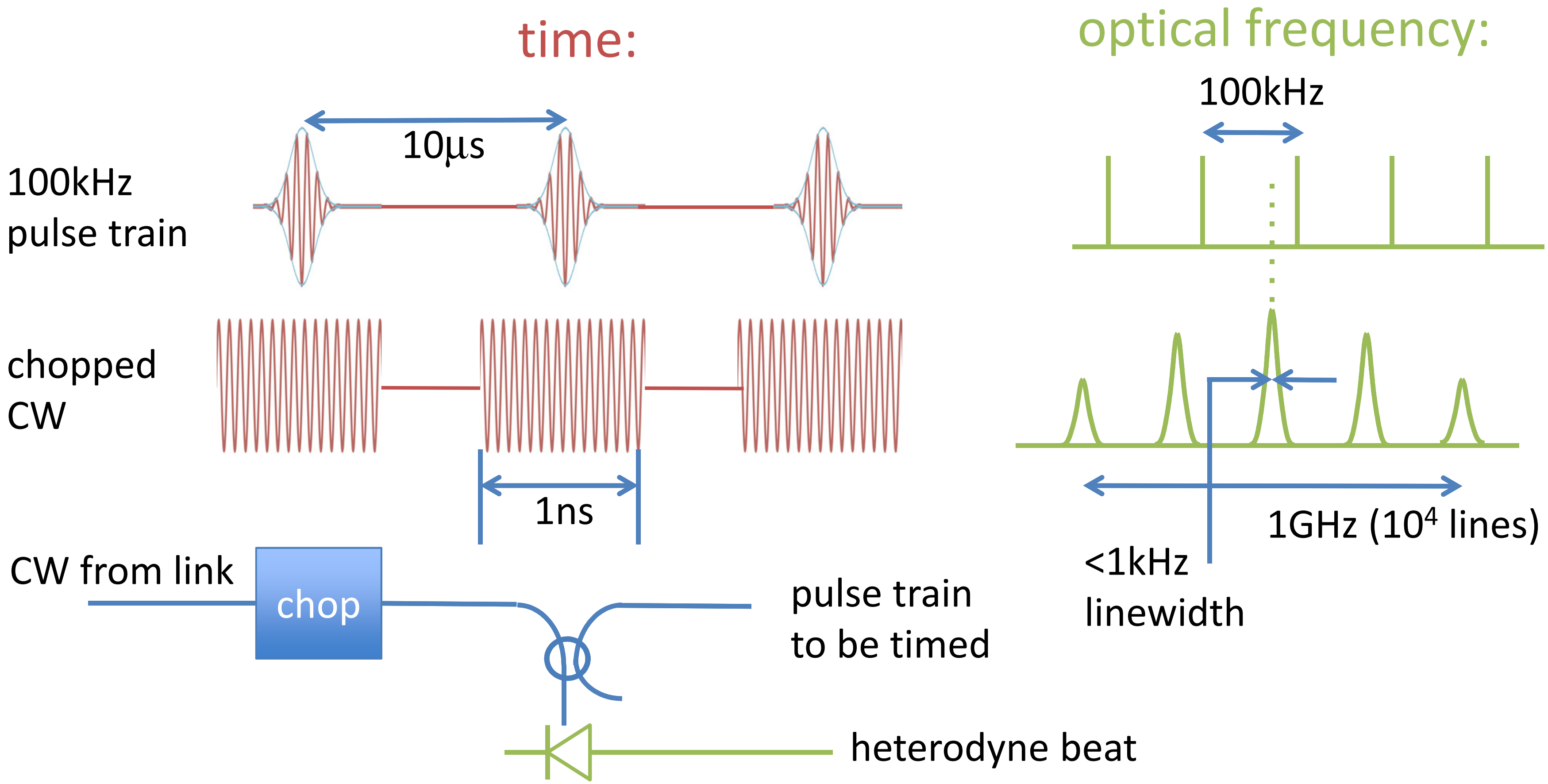
3μJ
6fs
100kHz

88as

240as

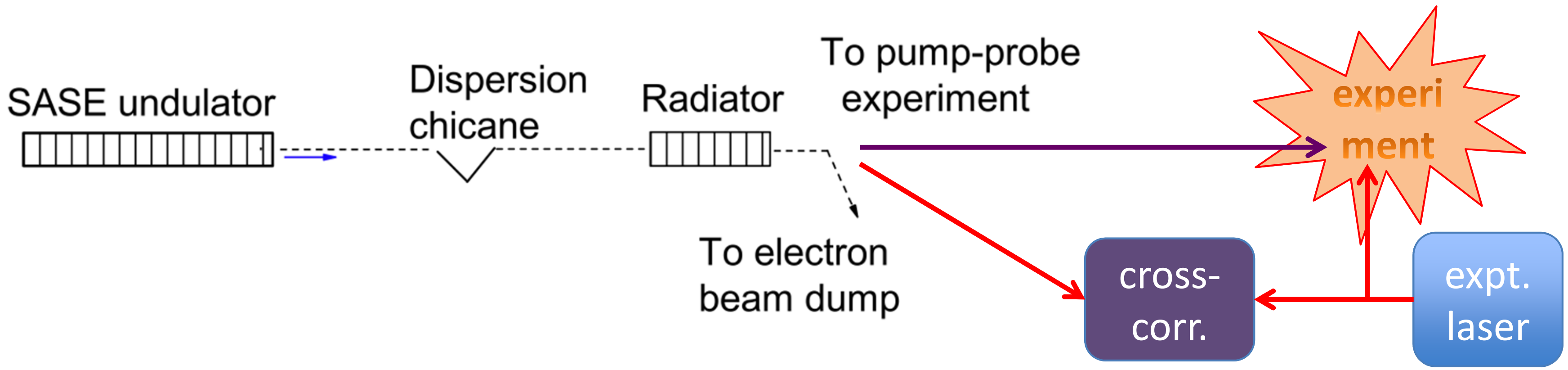
- CEP thru example optical parametric amp, 240as long term
  - Measured with a nonlinear interferometer after the amp
  - Variations due to air turbulence in compressor?

Optical pulse timing detector



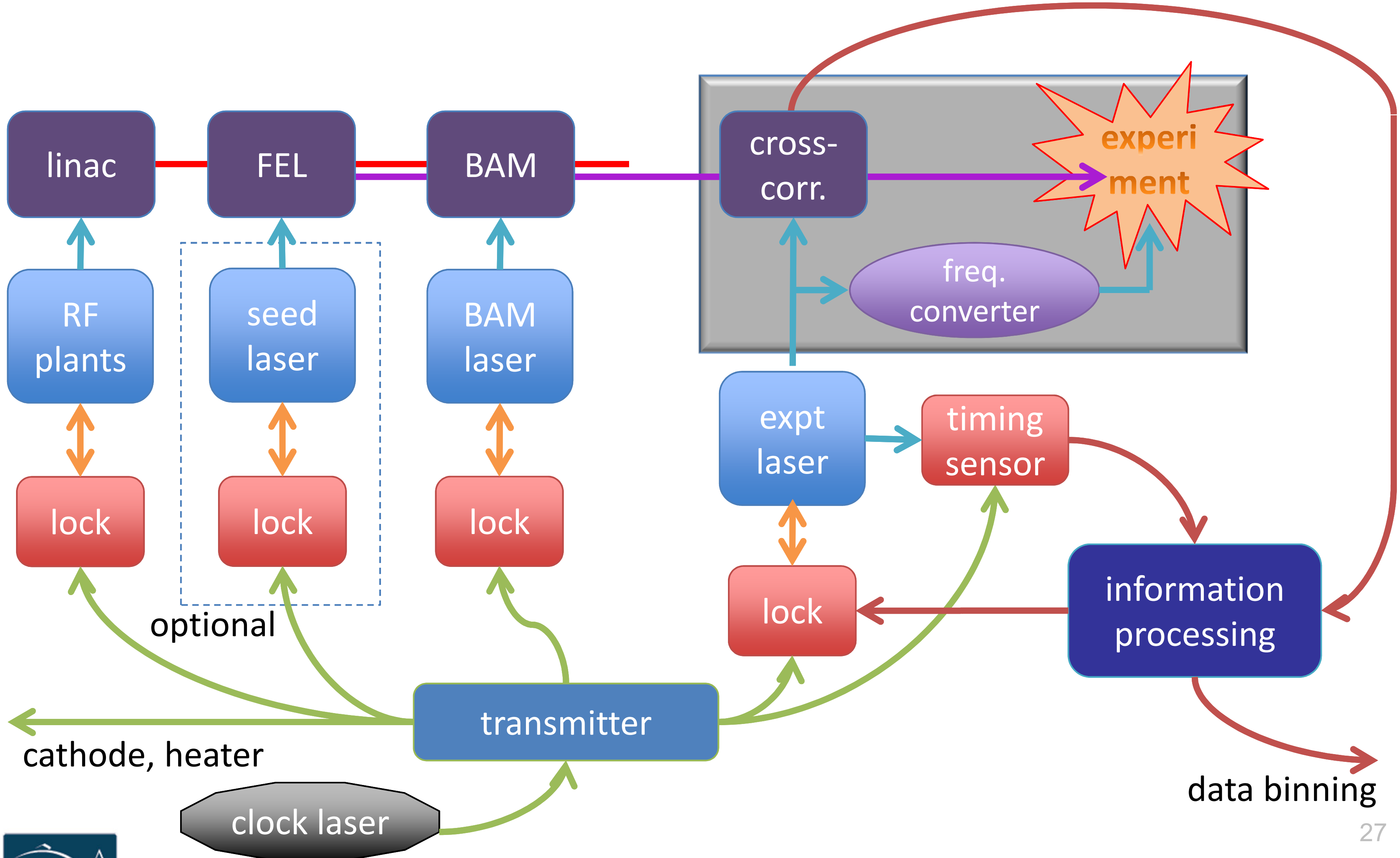
- Same heterodyne scheme at low reprate
- Beat frequency is down at ~20kHz
  - More noise, narrow bandwidth

Cross correlating with optical radiation



- 2-color or "optical afterburner" concept
  - Saldin et al, PRST AB 13, 030701 (2010)
  - Optical synced with X-ray to 30as (10^-4 energy jitter)
  - Cross correlate with experiment laser, sub-fs uncertainty
- X-ray/optical cross-correlators 5-10fs currently
- Use to correct long term drift
  - No need for passive thermal stability in other subsystems

Timing system block diagram



Conclusion: robust <10fs sync is likely

- All subsystems capable of ≤1fs short term jitter
  - Optical phase lock provides fine timing sensitivity
  - Well developed technology for optical metrology
- Slow drift corrected based on cross-correlation at experiment
- Experiments to further demonstrate capabilities are ongoing