Synchronization of THz and X-Rays (and Laser) for Pump-Probe Experiments

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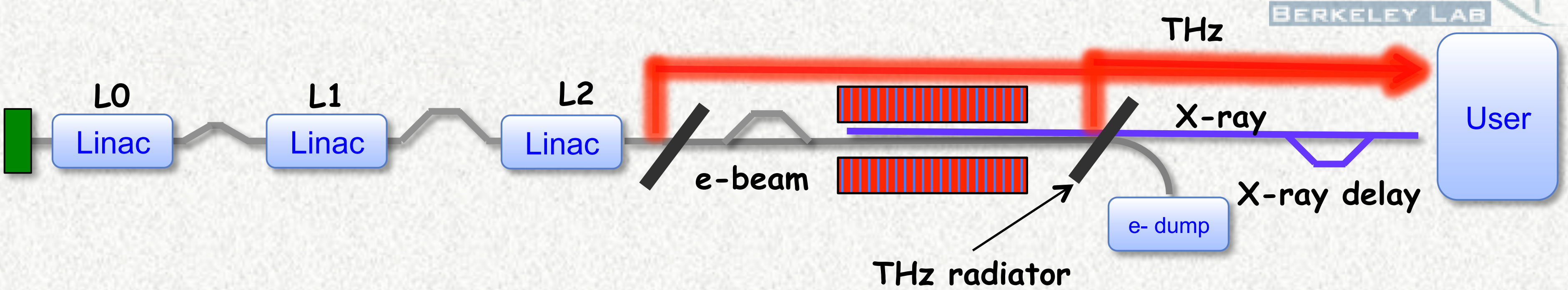
Summary

- Linac-driven FEL THz/x-ray Timing options
  - Primary electron THz source
  - Secondary electron THz source
  - Laser-based THz source
- High rep-rate sources
- Laser-laser synchronization
  - Stabilized fiber links
- Timing measurement
- Conclusions and outlook

THz pump/x-ray probe from pulsed linac-driven FEL



FEL e-beam (<100 fsec, 0.1-1 nC) is natural generator of coherent THz. However, science is the driver….

Specs:

- THz pump must arrive before x-ray probe (<1 nsec,0.3 m)
- X-ray/THz jitter below 10-50 fsec? (Please tell us…)

Options

- Delay x-ray pulse w.r.t. THz
  - X-ray delay is difficult, THz transport is long
- Delay e-beam following THz radiator
  - THz transport is very long, chicane makes beam dynamics problems

THz pump/x-ray probe from pulsed linac-driven FEL: 2-bunch

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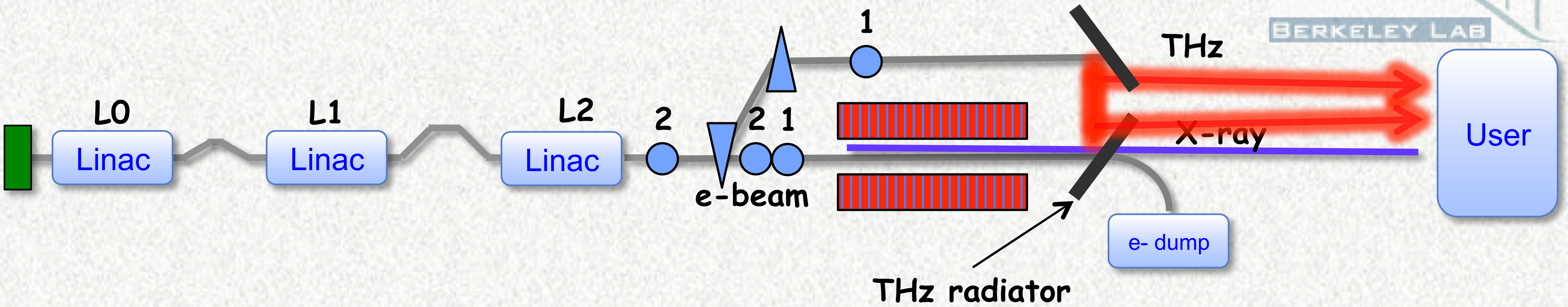
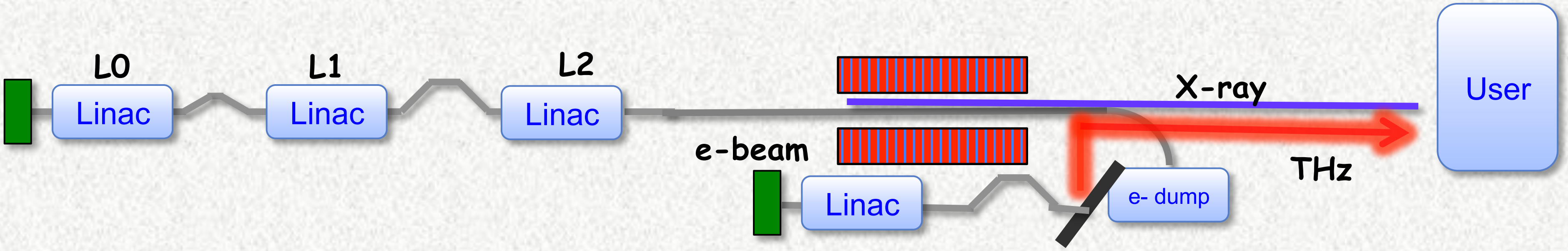


Use two bunches in the linac and use first as THz emitter. Note that $T_{S\text{-band}}$=330-350 psec

Options

- Spoil first bunch so it doesn't lase.
  - Spontaneous x-rays from first bunch
- Kick out first bunch before undulator
  - Fast kicker required.
- Two-bunch operation requires additional linac optimization
- Long THz transport required in all cases.

THz pump/x-ray probe from pulsed linac-driven FEL: secondary electron source



Use independent *synchronized* small electron linac as THz source

Options
- Fine synchronization of two linacs difficult (if not impossible)
  - Electron timing jitter via energy jitter from pulsed linac
- Rely on time-stamping each electron/x-ray/THz pulse and post-process binning
- High rep-rate e-source has interesting possibilities…
- Compact electron/THz "non-activated" source would be most convenient

THz pump/x-ray probe from pulsed linac-driven FEL: laser source

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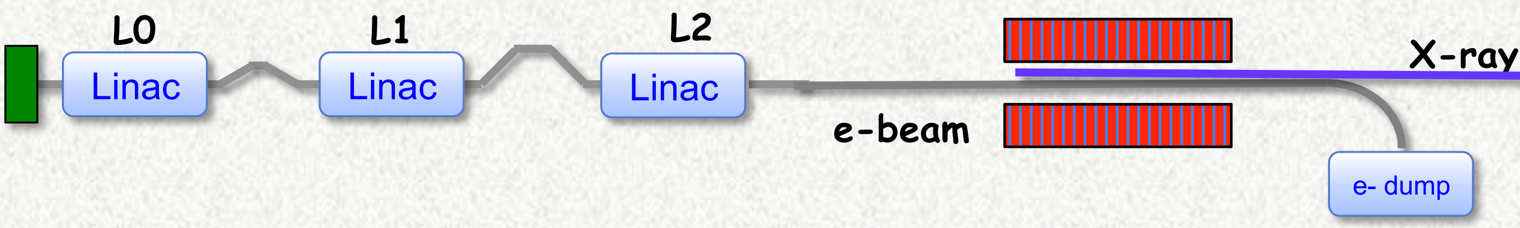

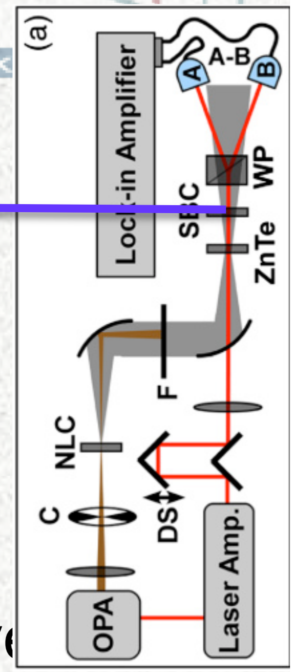

Use independent *synchronized* optical laser as THz source

Options

- Fine synchronization of optical laser and x-ray is active in FELs today. Several technology options with future improvements.
- THz laser can sit near end station.
- Modern laser sources limited to ~1 kHz. Good match to pulsed linac source.
- X-ray jitter will require time-stamping each electron/x-ray pulse with post-process binning.

High rep-rate sources: ERLs, SC FELs

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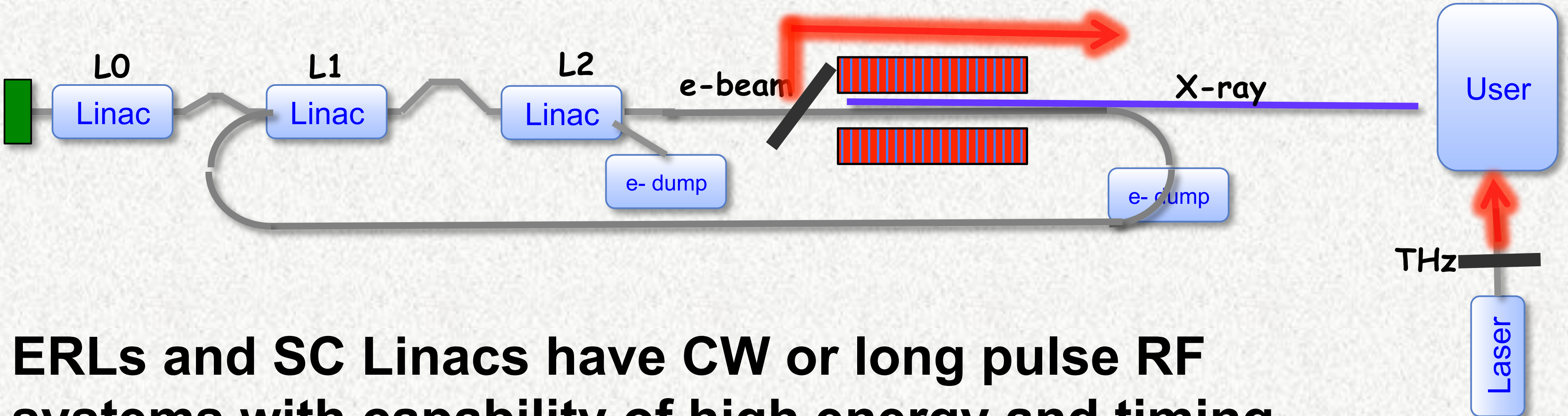

ERLs and SC Linacs have CW or long pulse RF systems with capability of high energy and timing stability.

- CW and long pulse electron beams have potentially much lower energy and timing jitter than pulsed linacs, significantly simplifying synchronization issues.
- High average power.
- Laser THz sources still limited to low rep rates.
- Depending on rep-rate THz pulse from previous bunch can be used as pump for next x-ray pulse.

High rep-rate sources: Rings

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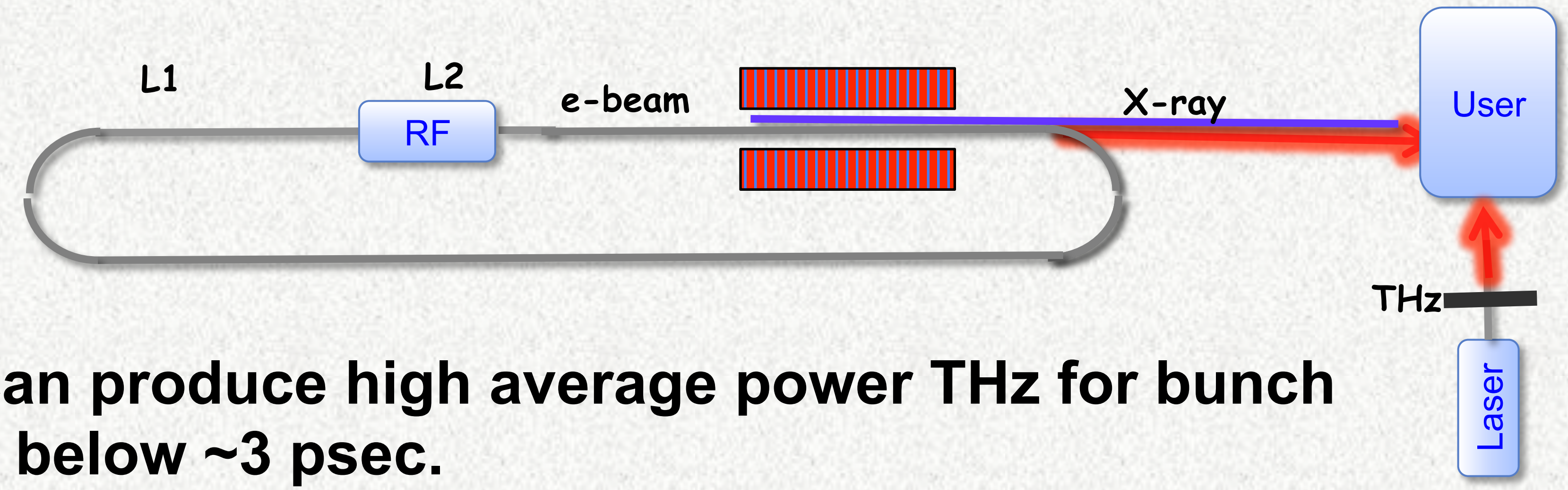

Rings can produce high average power THz for bunch lengths below ~3 psec.

- X-ray pulses have no longitudinal coherence, relatively low peak power. Pulse length given by the electron pulse length.
- Difficult to achieve THz pulses beyond few THz without laser modulation of electron bunch.
- Electron beam intensity reduces dramatically with electron bunch length.
- Electron beam jitter given by RF stability, collective effects.

High rep rate sources: Pulse stacking

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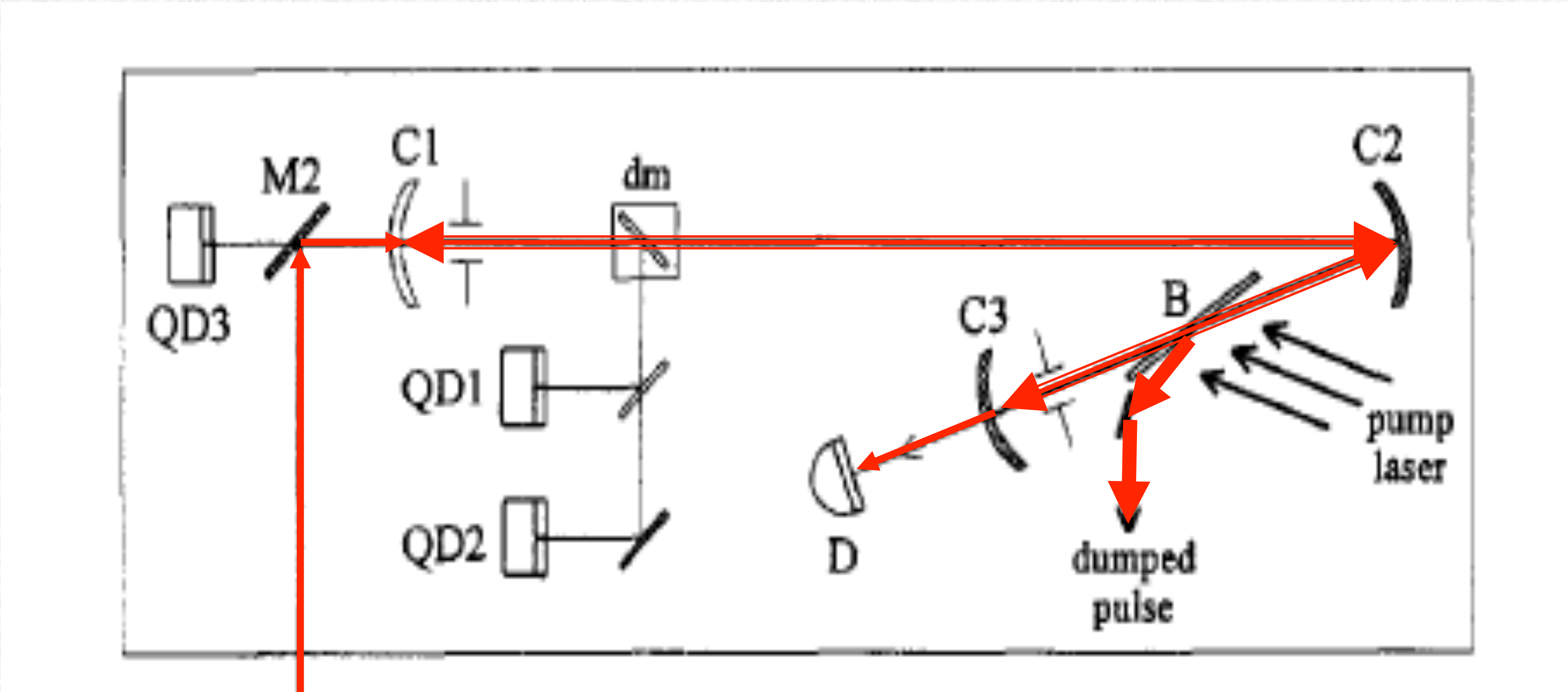
Because input pulses are coherent, it is possible to resonate the signals to gain high pulse power levels.



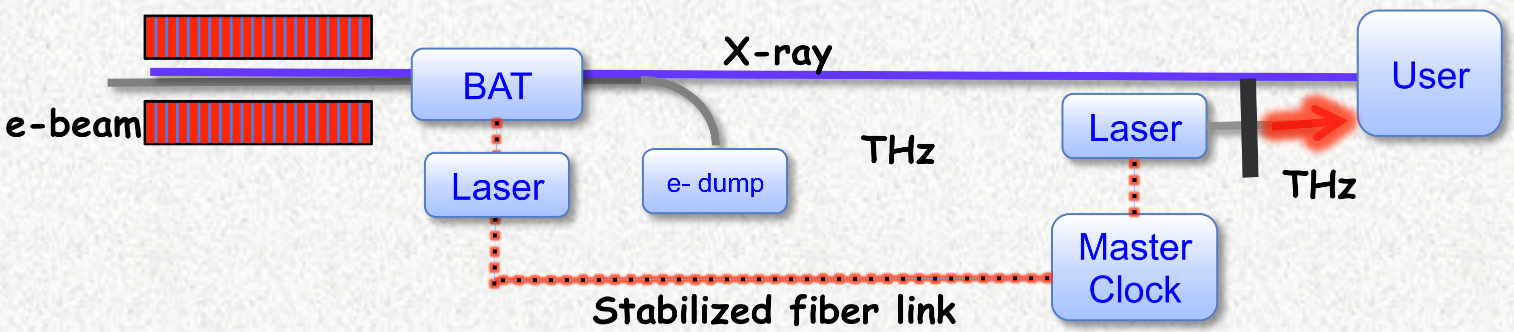
Peak power limited by cavity Q and phase stability of pulses

Input CSR pulses

T. Smith, et al., NIMA 393 (1997) 245-251.

It's all in the timing: e- time-stamping

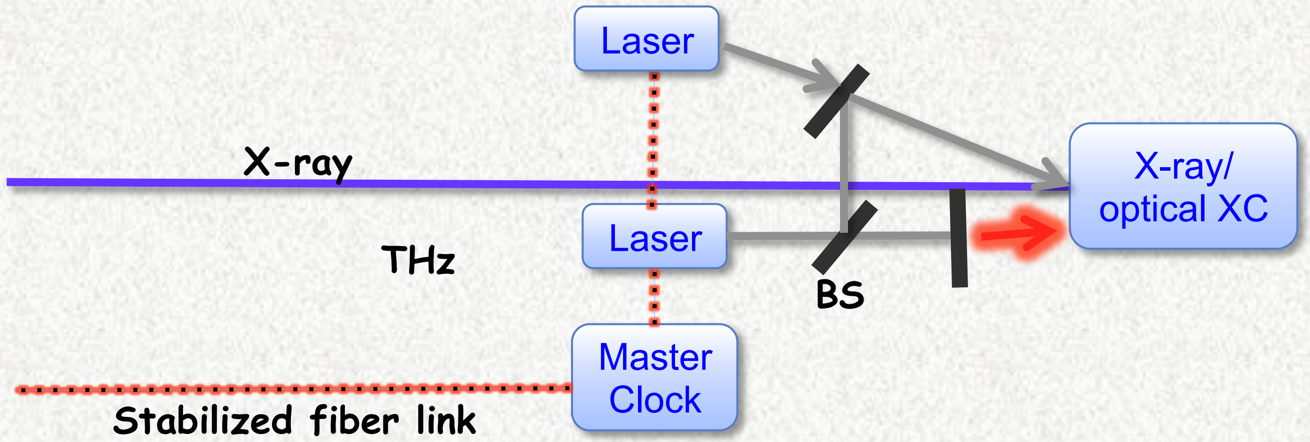
I assert that all THz/x-ray p-p timing issues amount to synchronizing one (or more) lasers with master clock



Example: Synchronized laser-based THz source

- X-ray timing jitter via electron timing jitter via energy jitter from pulsed linac
- Time-stamp each electron pulse using beam arrival time (BAT) monitor
- Synchronize BAT and THz laser to master clock via stabilized fiber links
- High-precision BAT uses a laser oscillator. Synchronize BAT laser with THz laser

It's all in the timing: x-ray time-stamping



Example: Synchronized laser-based THz source

- X-ray timing jitter from pulsed linac
- Time-stamp each x-ray pulse using X-ray/optical cross-correlator (XOXC) monitor
- Synchronize THz laser to master clock via stabilized fiber links
- Second laser could be used for XOXC.

Synching mode-locked lasers

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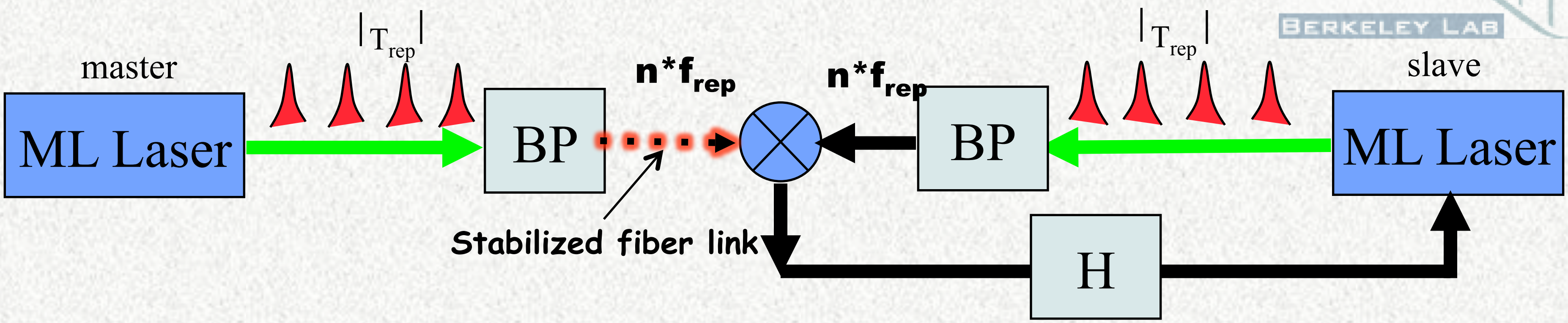
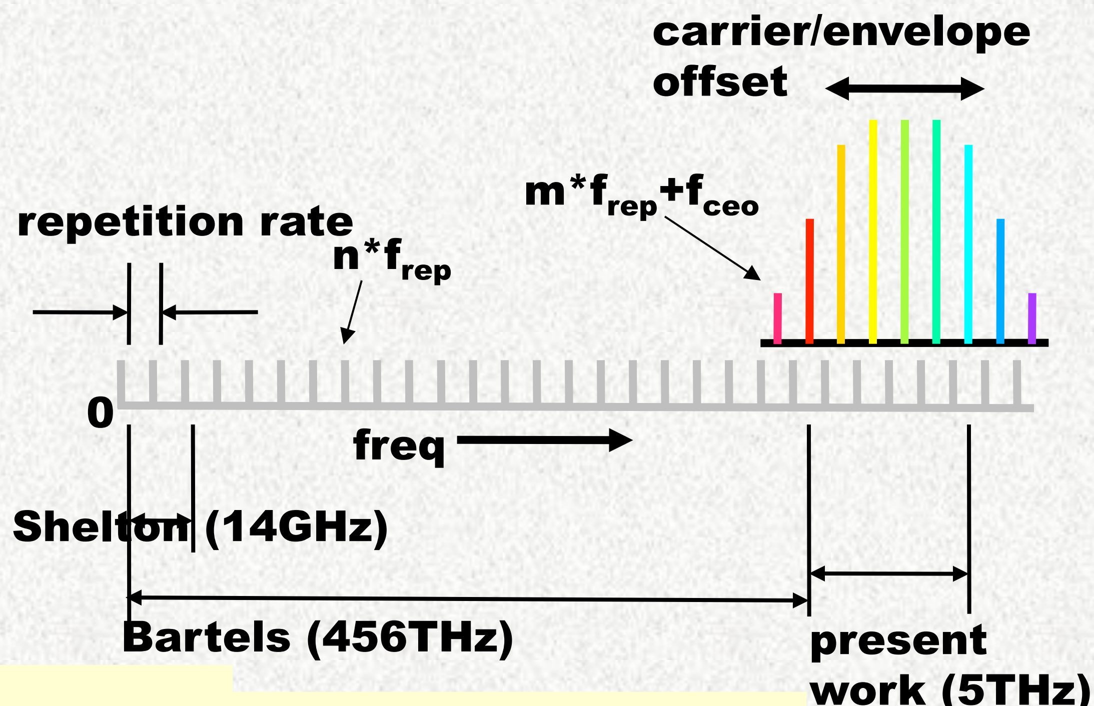


- Wide range of frequencies to transmit for locking
- Transmission must use SOFL
- Sensitivity for phase comparison proportional to frequency.



Shelton et al, O.L. 27, 312 (2002)
Bartels et al, O.L. 28, 663 (2003)

Time and Frequency Domain Stabilized Links

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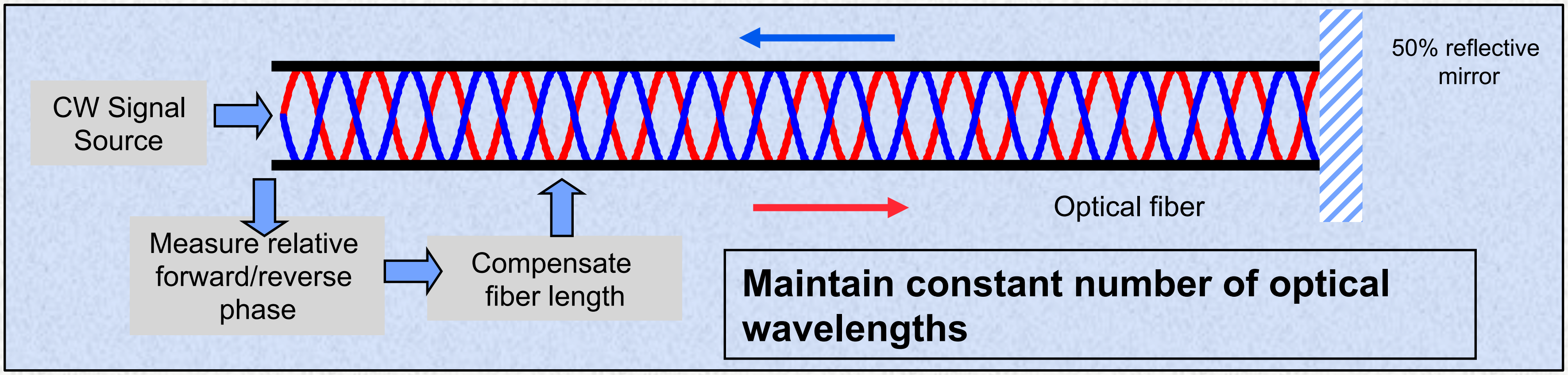
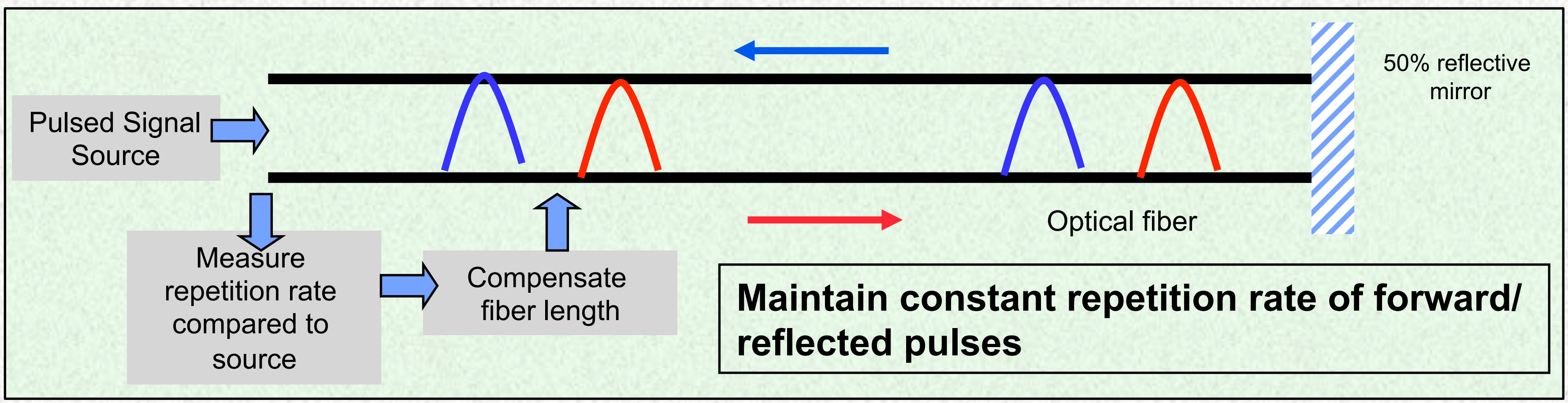
- Fiber links can be stabilized based on the revolution in metrology time and wavelength standards over the past decade.





Correction BW limited to R/T travel time on fiber (e.g. 1 km fiber gives 100 kHz)

Why optical fiber links?

- Problem: coaxial cables and optical fiber have a temperature dependence of propagation delay of about 50 psec/km/deg-C.
  - Completely unacceptable for next-gen light sources both for RF systems and lasers.
  - Temp. stabilized cables impractical for large installations.
- Solution: use optical interferometry over fiber links to measure length change and actively feedback to stabilize signal propagation delay.
  - Fiber provides THz bandwidth, low attenuation, electrical isolation. Acoustically sensitive.
  - Optical signal transmission allows very sensitive interferometry (time or frequency domain).
  - Commodity grade fiber technology relatively cheap.

RF Clock Distribution: Single Channel Link

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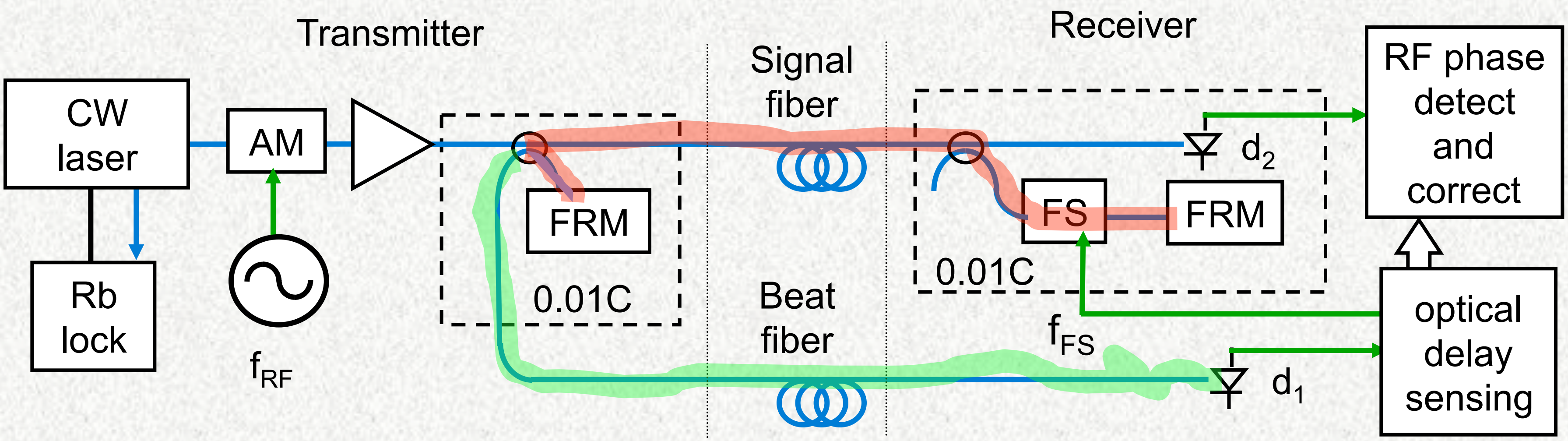
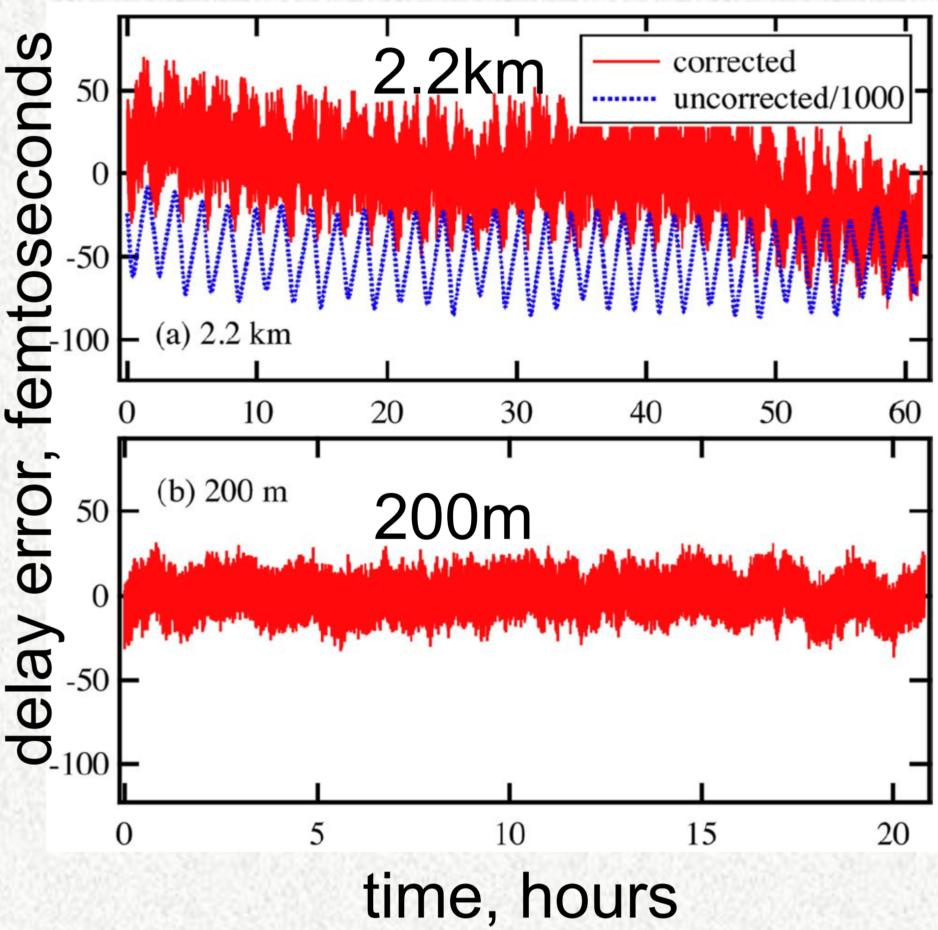
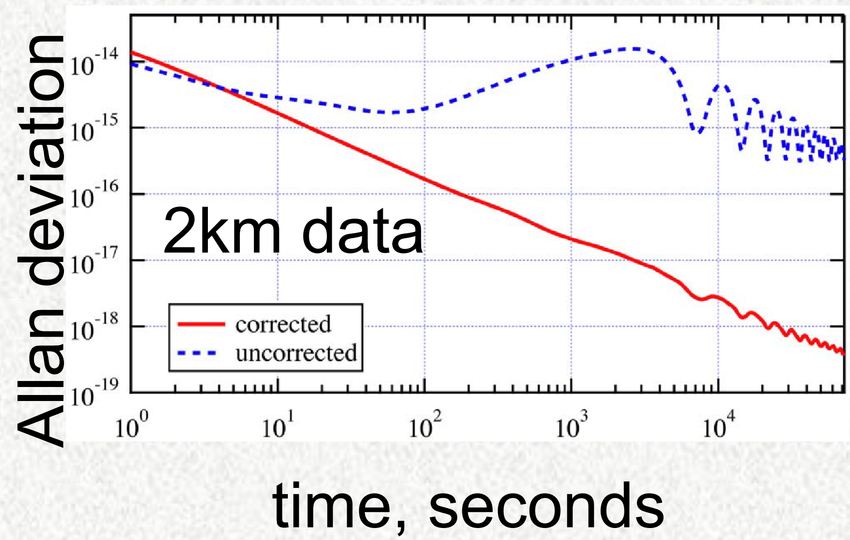


- FRM is Faraday rotator mirror (ends of the Michelson interferometer)
- FS is optical frequency shifter
- CW laser is absolutely stabilized
- Transmitted RF frequency is 2856 MHz
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

Detailed results

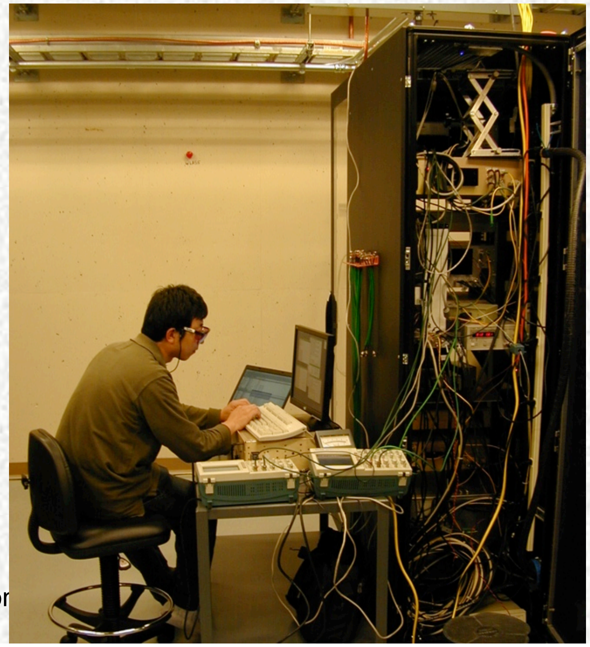


- 1 kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



LCLS System

- TX occupies half of standard rack.
- In operation since Sept. 2009.
- Fiber links are run in SMF28 in 12 fiber cables.



Laser dominates jitter

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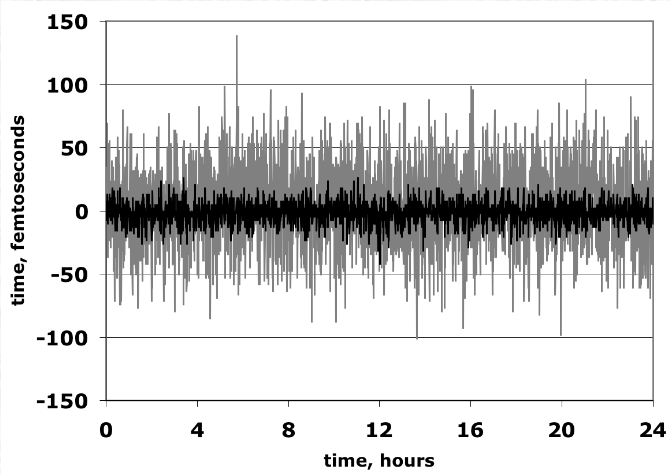
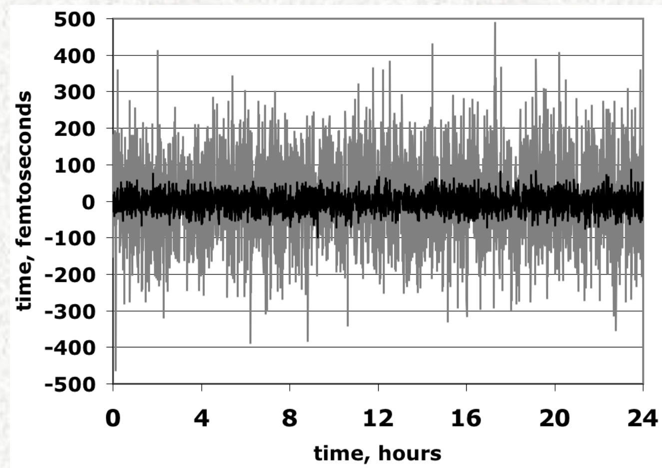
Phase shifter loop (reference)



125kHz BW (gray): 31fs RMS
1kHz BW (black): 8fs RMS

Laser loop (to experiment)



125kHz BW (gray): 120fs RMS
1kHz BW (black): 25fs RMS

- When controlling a nice RF phase shifter, performance is better than with lasers
- In-loop laser jitter a good indication of experimental jitter

Laser jitter studies at LCLS

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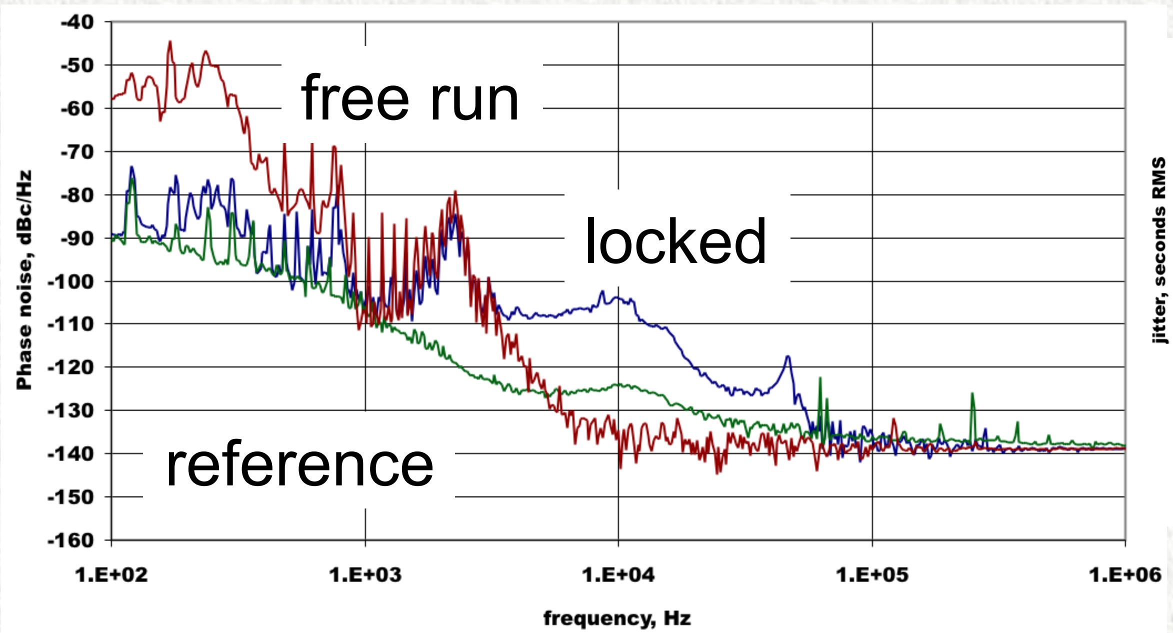

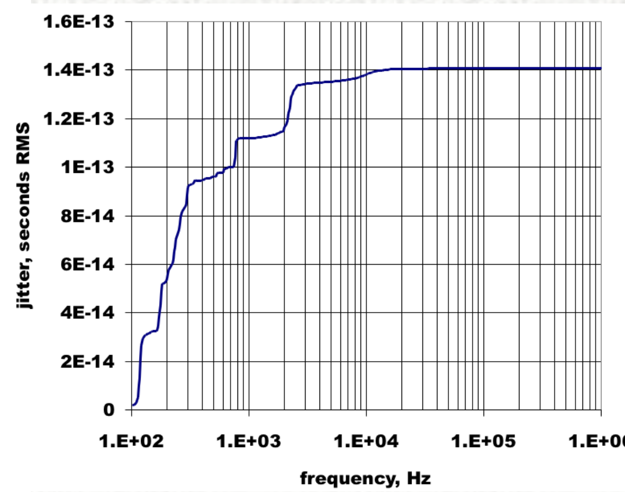

- Single side band phase noise measurement
- At the ~2kHz resonance, gain <1 to avoid oscillation
- This limits noise suppression at lower frequencies
  - Where most of the jitter comes from
- Look for mechanical resonances, acoustic noise

Optimize laser control

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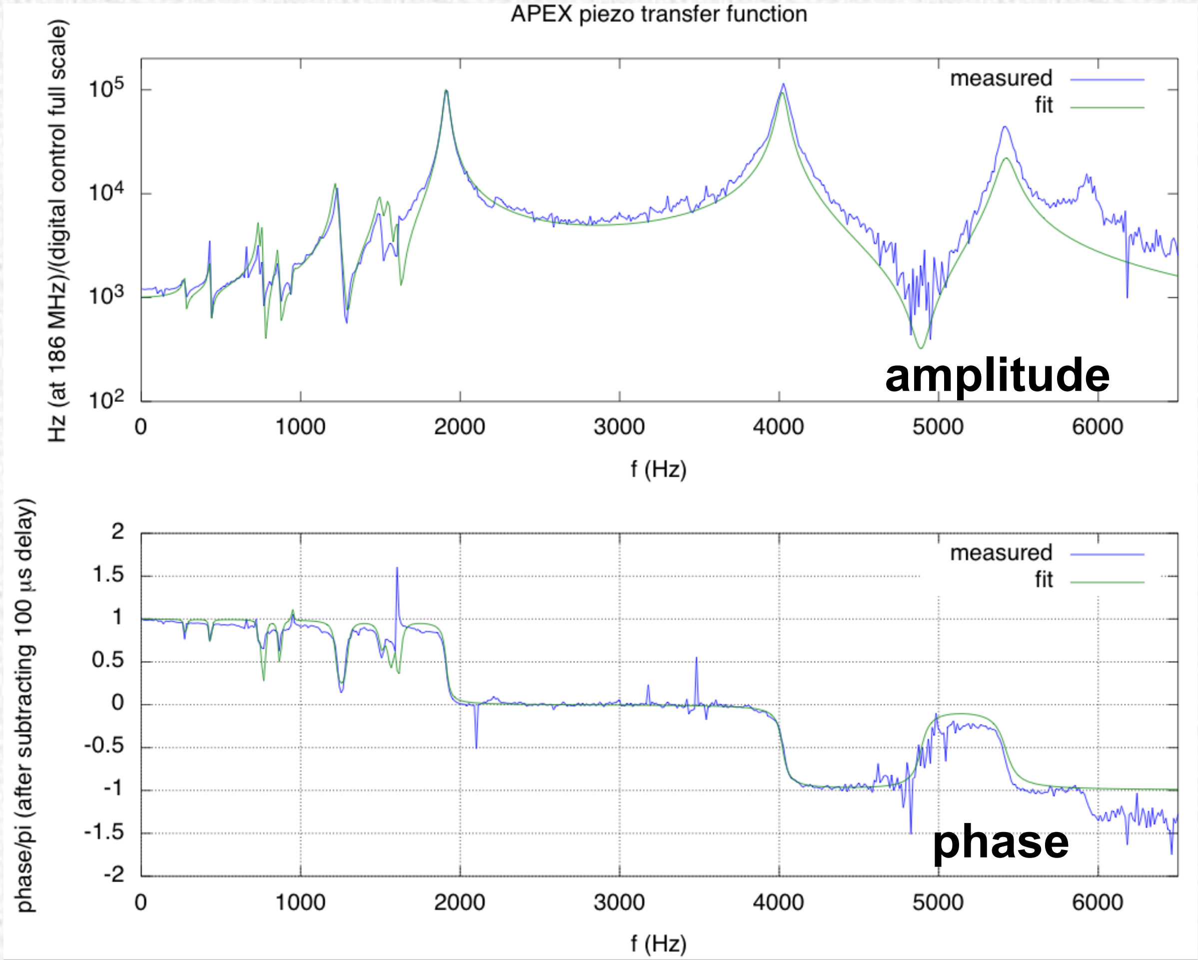
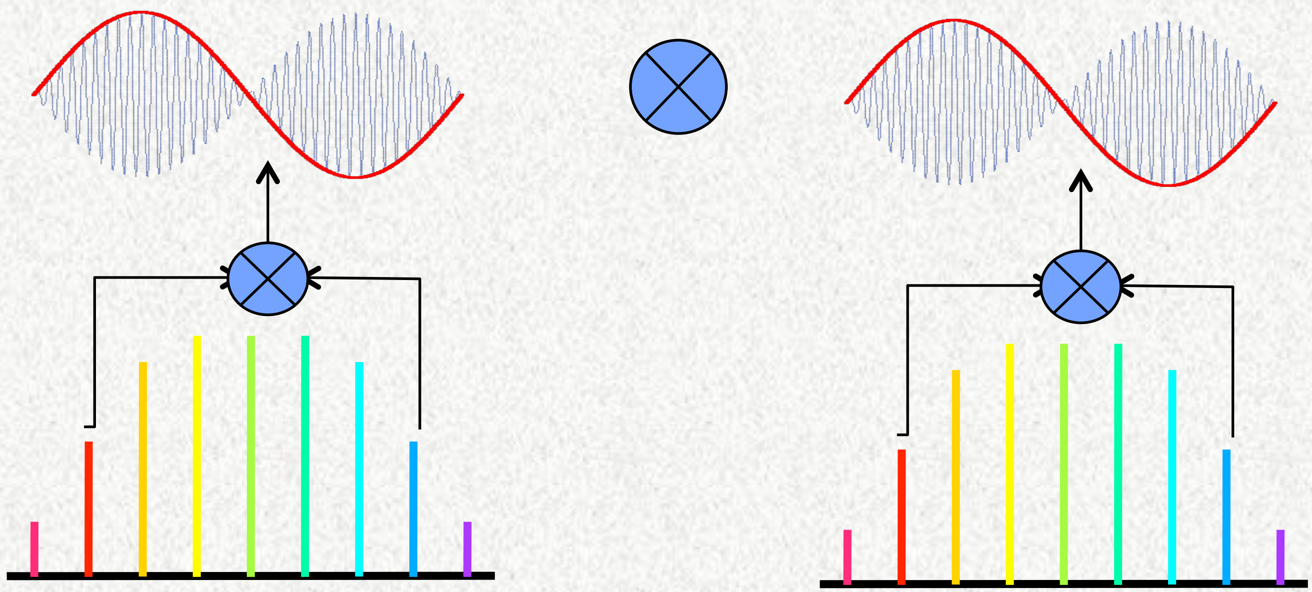
Measure dynamic response of laser to perturbations and optimize feedback loop

- Modelocked fiber laser tuned with piezo mirror
- Laser control loop pinged with step
- Transfer function analyzed
- Compensation added to loop gain
- This allows for higher gain, lower noise



All-optical lock schemes

- Synchronization of lasers with RF signals limited by resolution in phase(0.01 deg@3GHz=10 fsec)
- Go to optical frequencies…



- Create a beat wave generated from two mode-locked comb lines (up to a few THz)
- Lock the beat wave of one laser with a remote laser

Early results

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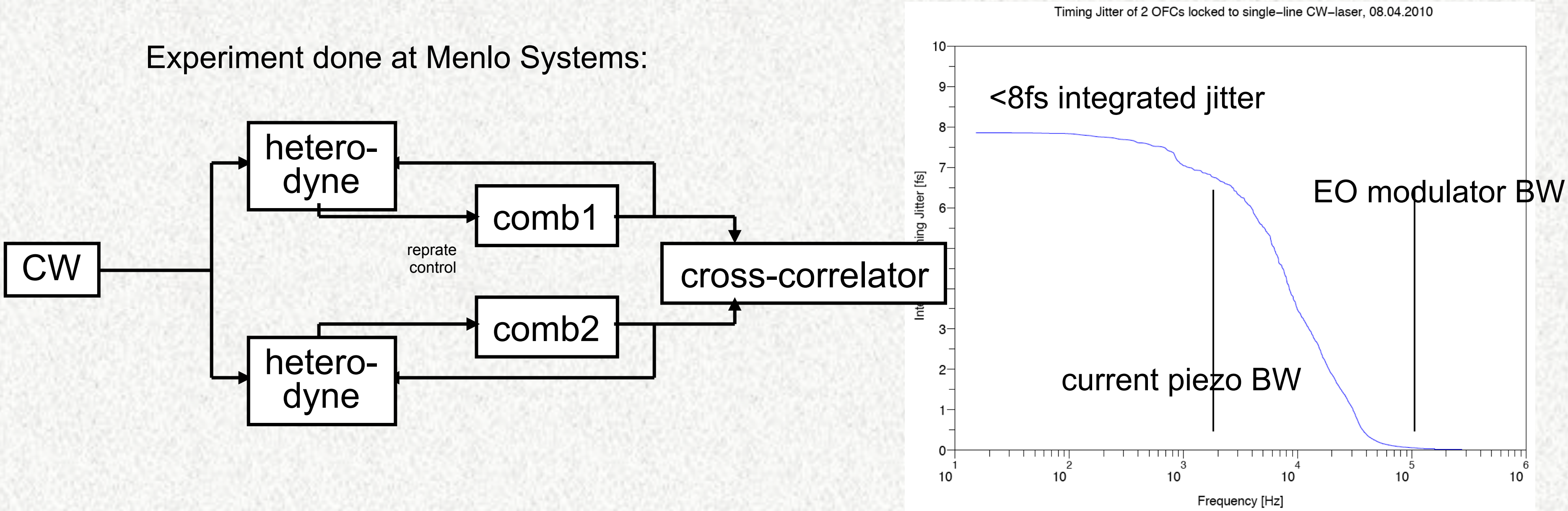
Experiment done at Menlo Systems:



- Erbium doped fiber laser used here
- By adding an EO phase modulator in the cavity, control BW can increase, cut jitter to ~1fs
- Previous experiments (e.g. Opt. Lett. 28, 663 (2003)) have shown ~1fs jitter with similar schemes, Ti/Sapphire laser used here

e- time-stamping

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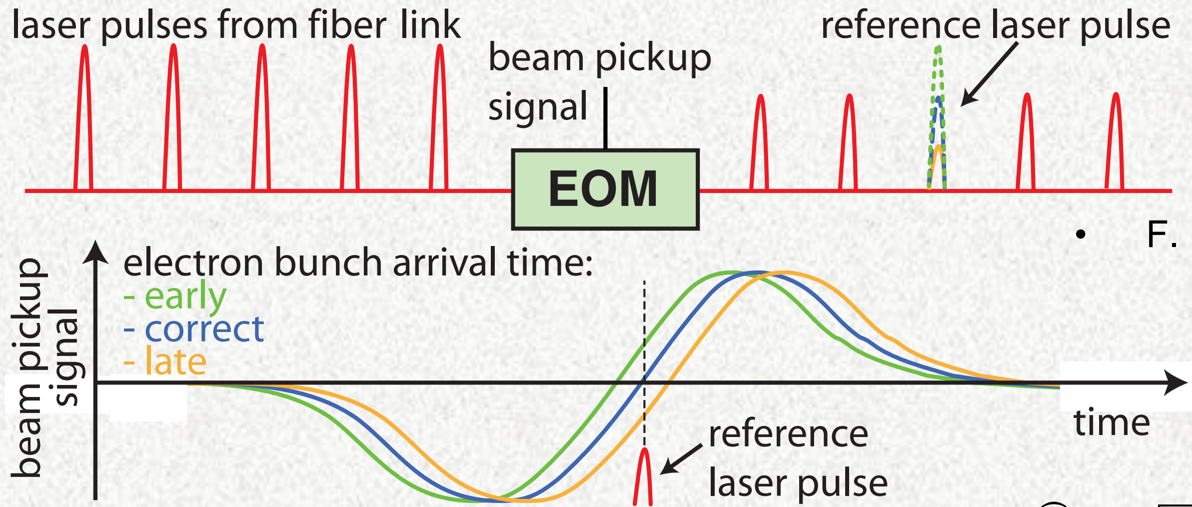
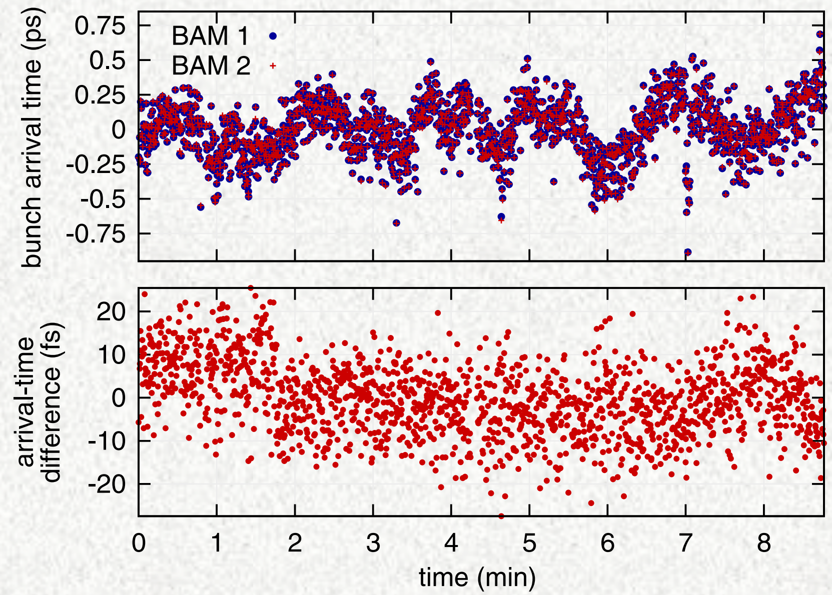
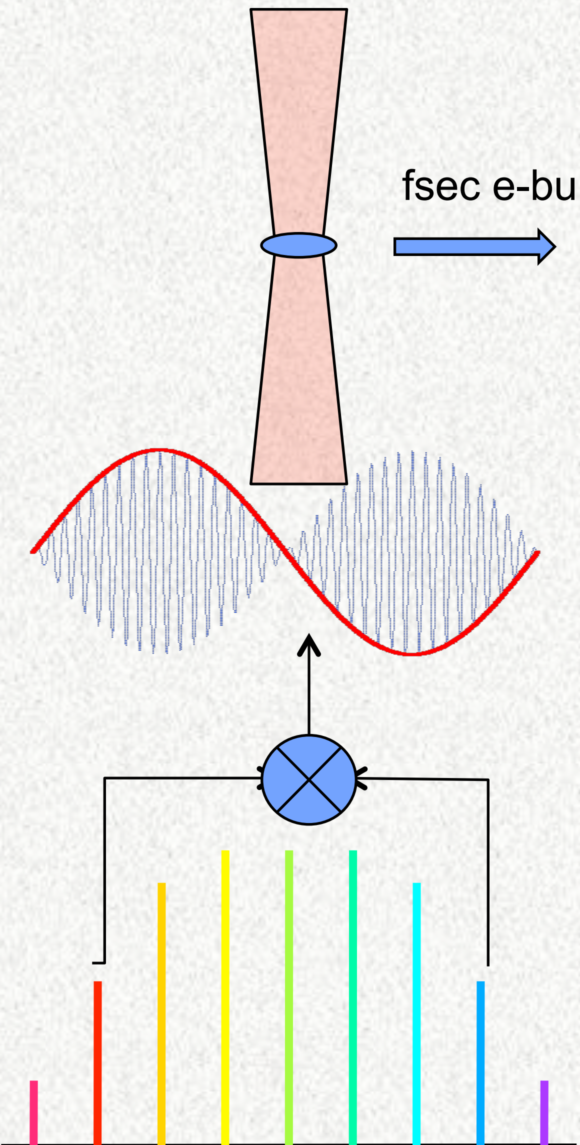


- F. Loehl, et al, PRL 104, 144801 (2010).

Modulate train of laser pulses using electron beam pickup. Converts relative time jitter into amplitude modulation of laser pulses. Sensitivity given by slope at zero crossing. Resolution of <10 fsec already achieved.

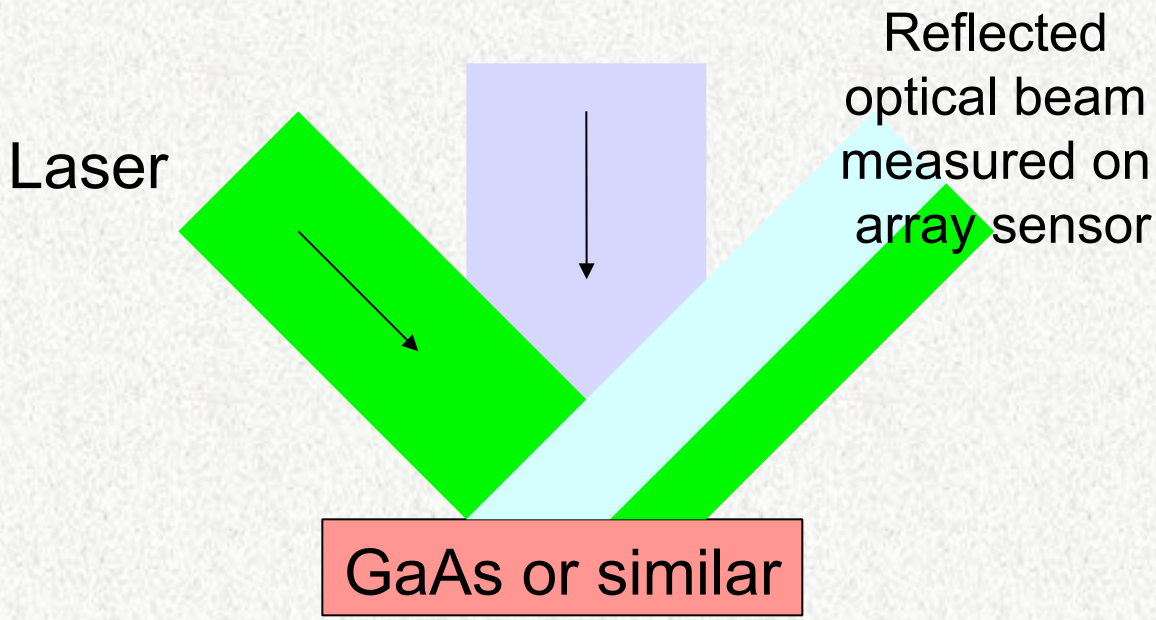


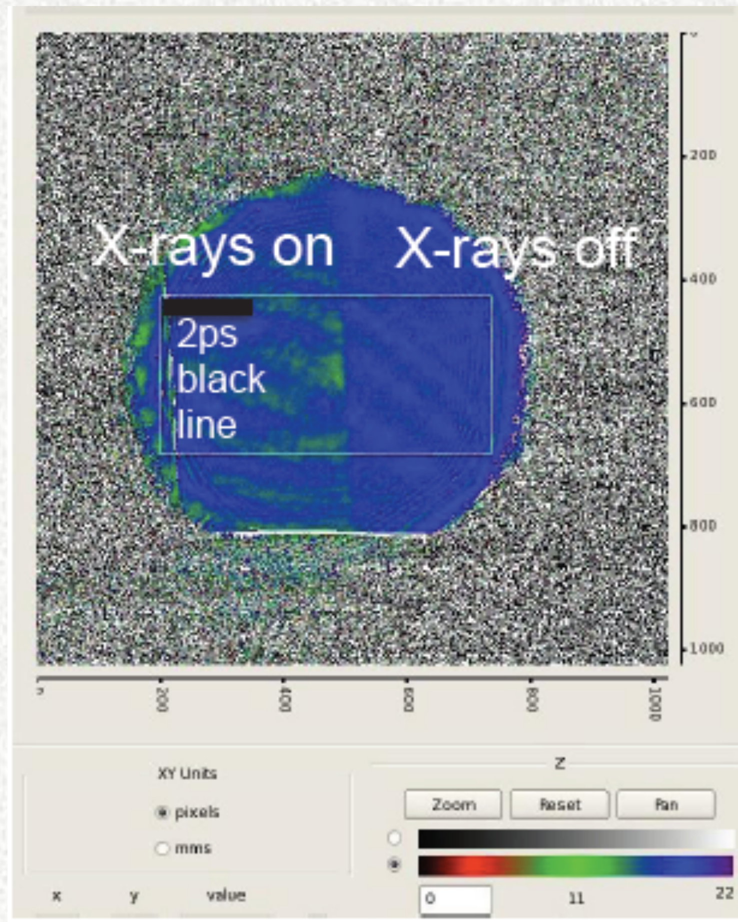
Sub-fsec arrival monitor



- Sensitivity of e-beam arrival monitors proportional to reference frequency.
- Use THz beat wave as a reference frequency.
- Electro-optically modulate beat wave with e-beam electric field.

X-ray/optical cross-correlator: Ex. 1





0 ps
143.3 mm on delay stage

- Use the x-ray induced change in reflectivity on GaAs as a cross correlator

X-ray induced reflectivity

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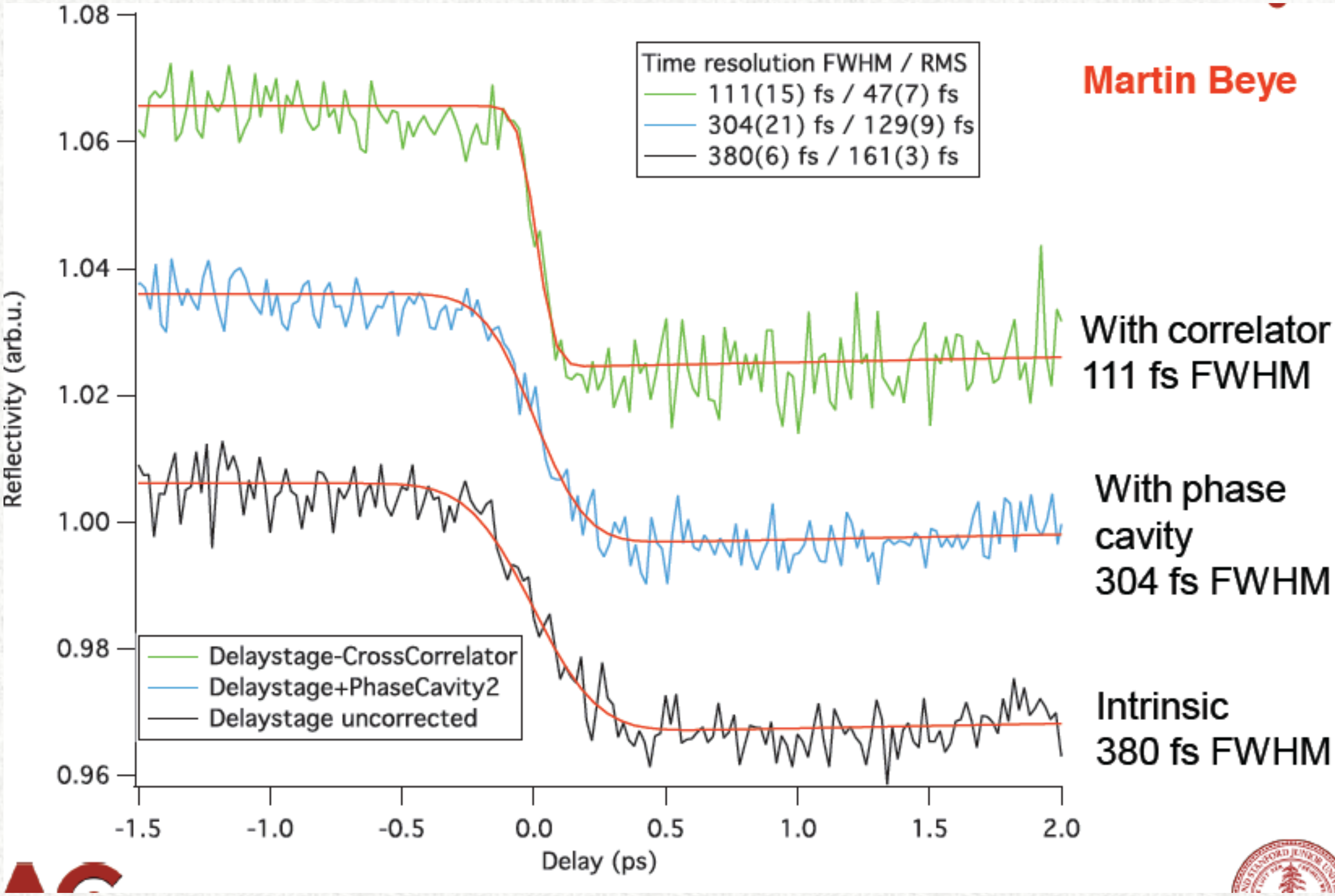

X-ray/optical cross-correlator: Ex. 2

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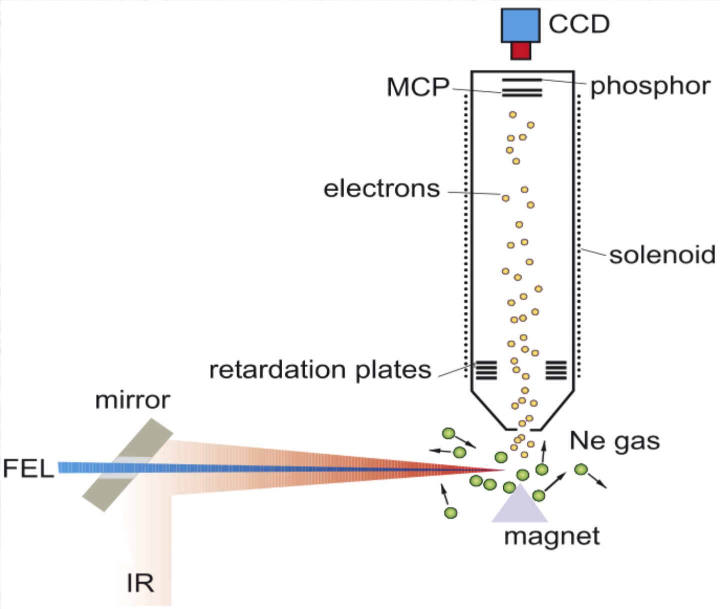

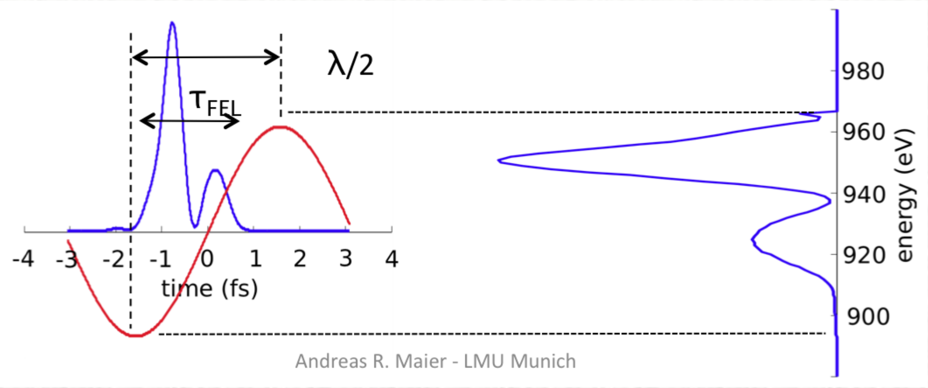

- Optically streaked photoelectron spectra
  - From A. R. Maier, FEL 2011
  - New J. Phys 13, 093024 (2011) (similar, longer pulse)
- Runs next to experiment, but with special laser

New machines can be very stable

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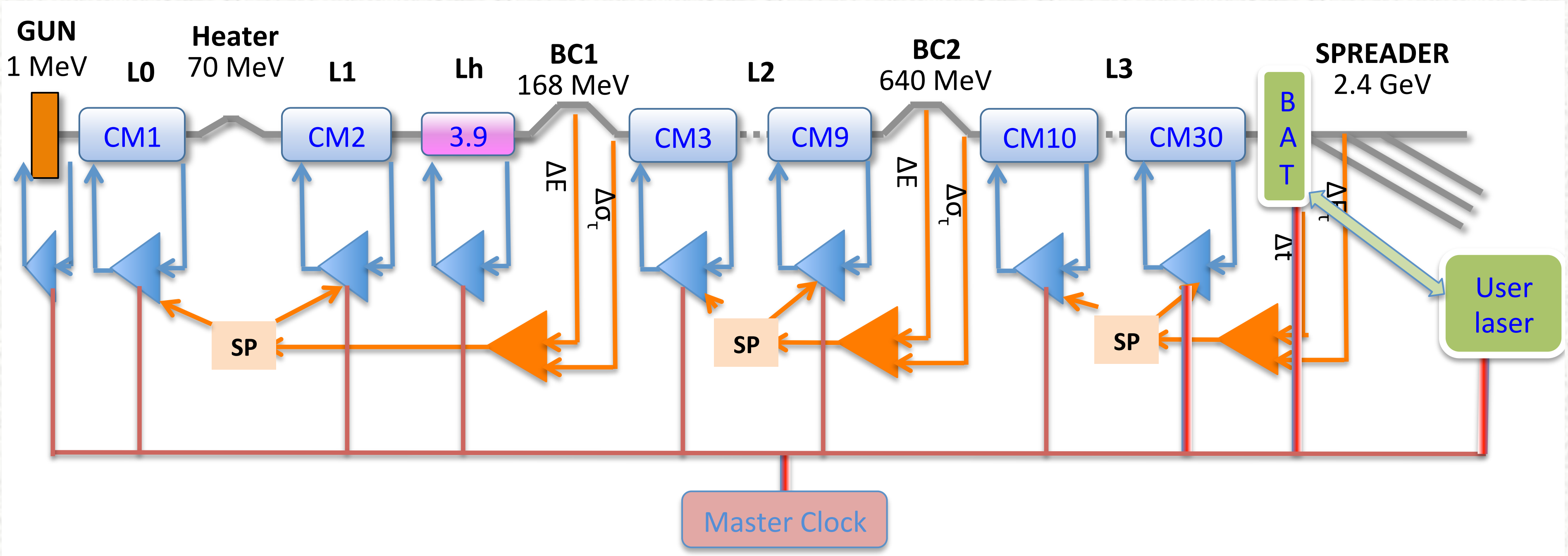

We are working on the design of a next generation light source where we plan to optimize the machine for stability.

Please let us know what you need to do the science!

Summary

John Byrd

- Synchronized THz/x-ray pump probe is real (already started at FLASH). Planned at several other facilities.
- Independent THz source seems to be the most flexible for pulsed linac.
  - Laser THz source matches pulsed linac FELs.
  - THz/x-ray synchronization at <10 fsec possible
- High rep-rate electron THz sources offer interesting possibilities (pulse stacking, etc.)
- Thanks to colleagues at Berkeley, SLAC, DESY, Trieste, and elsewhere for many ideas and contributions.