Progress in femtosecond timing distribution and synchronization for ultrafast light sources

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Overview

- New ideas at Berkeley
- Motivation: LCLS example
- Stabilized distribution links
- Synchronizing techniques
- Measuring synchronization

Acknowledgements

- *John Staples, LBNL*
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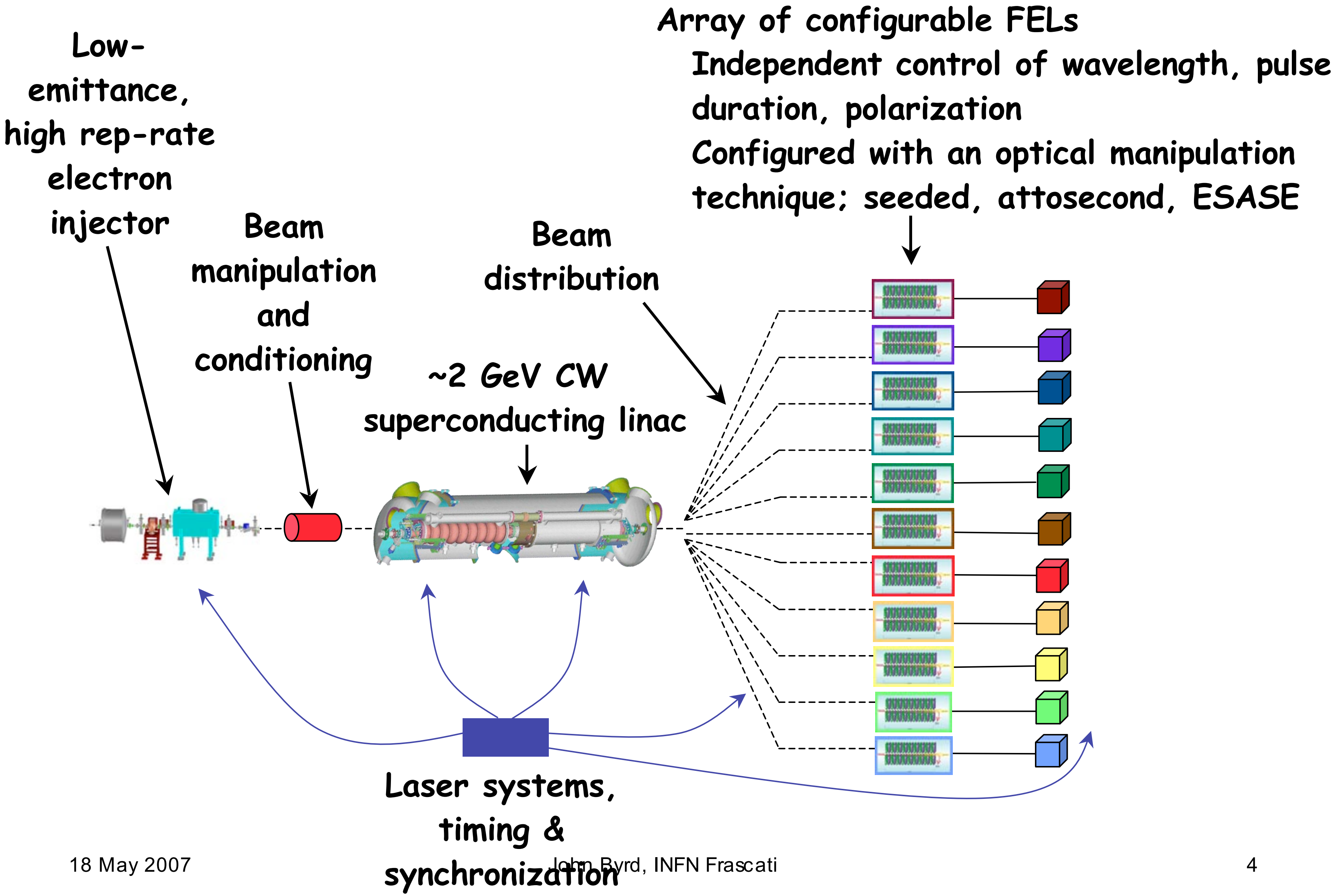
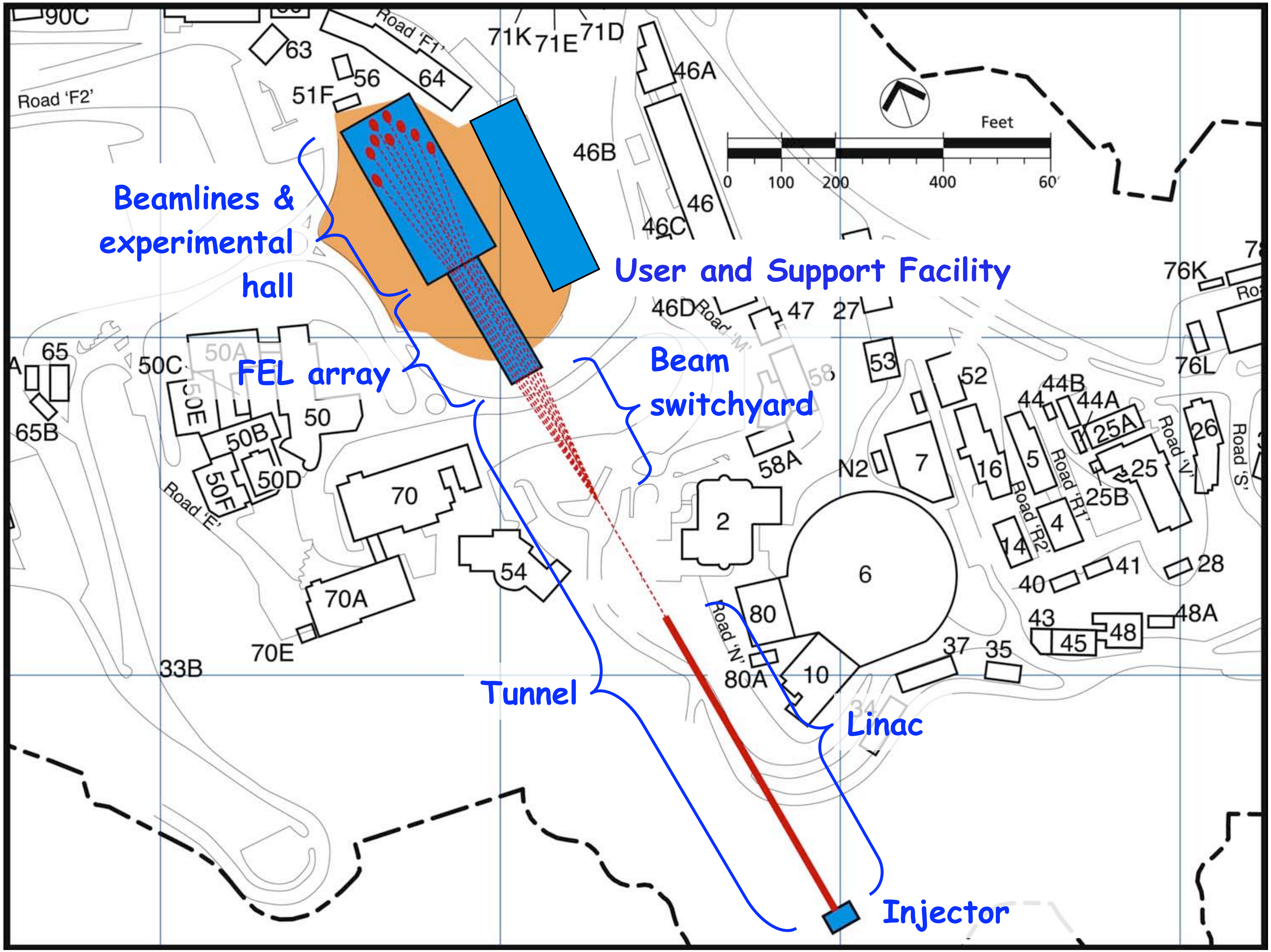
- *Bill White, SLAC*
- *Ron Akre, SLAC*
- *Patrick Krejcik, SLAC*

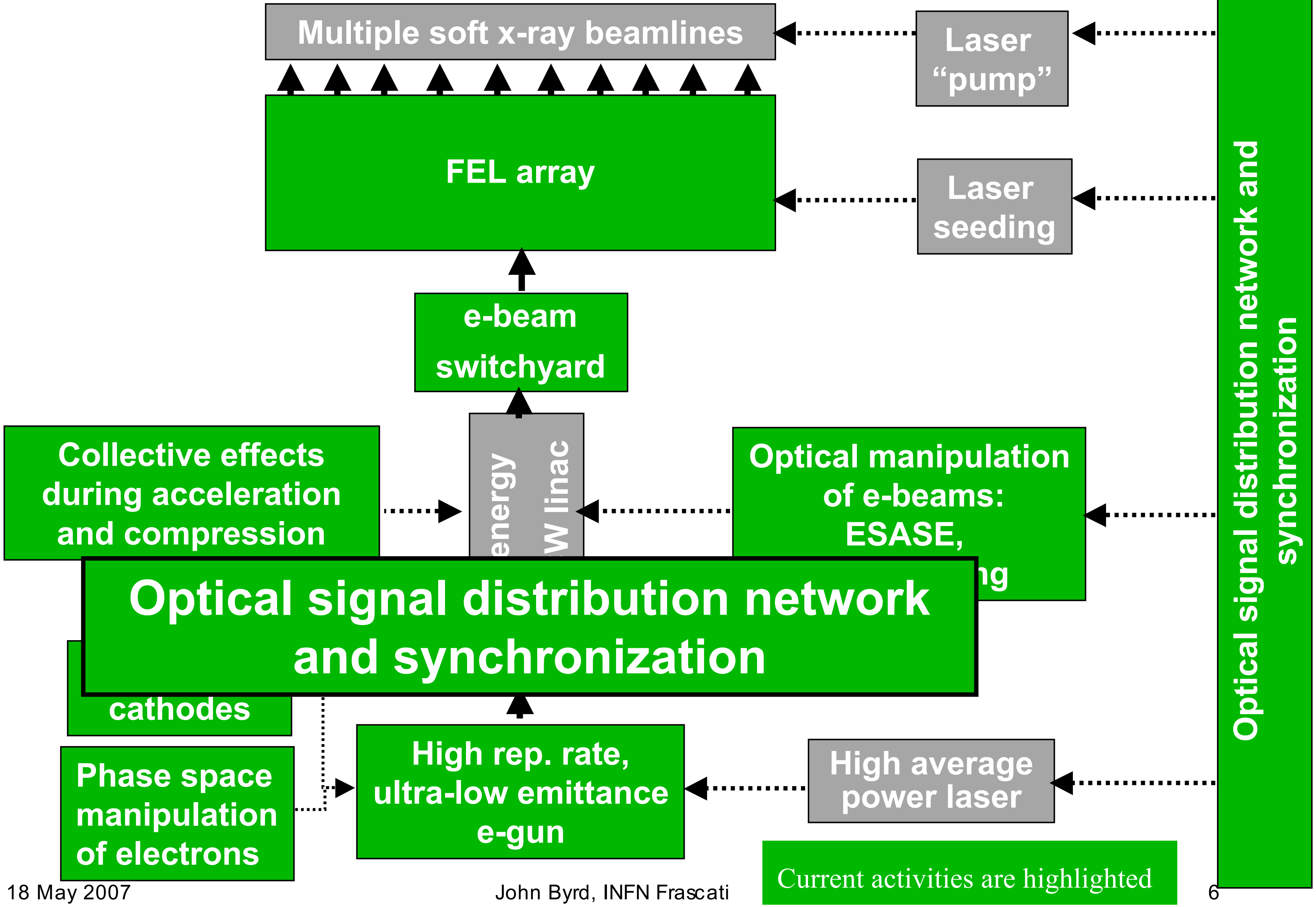
Vision for future light source at LBNL - a high rep-rate, seeded, FEL facility



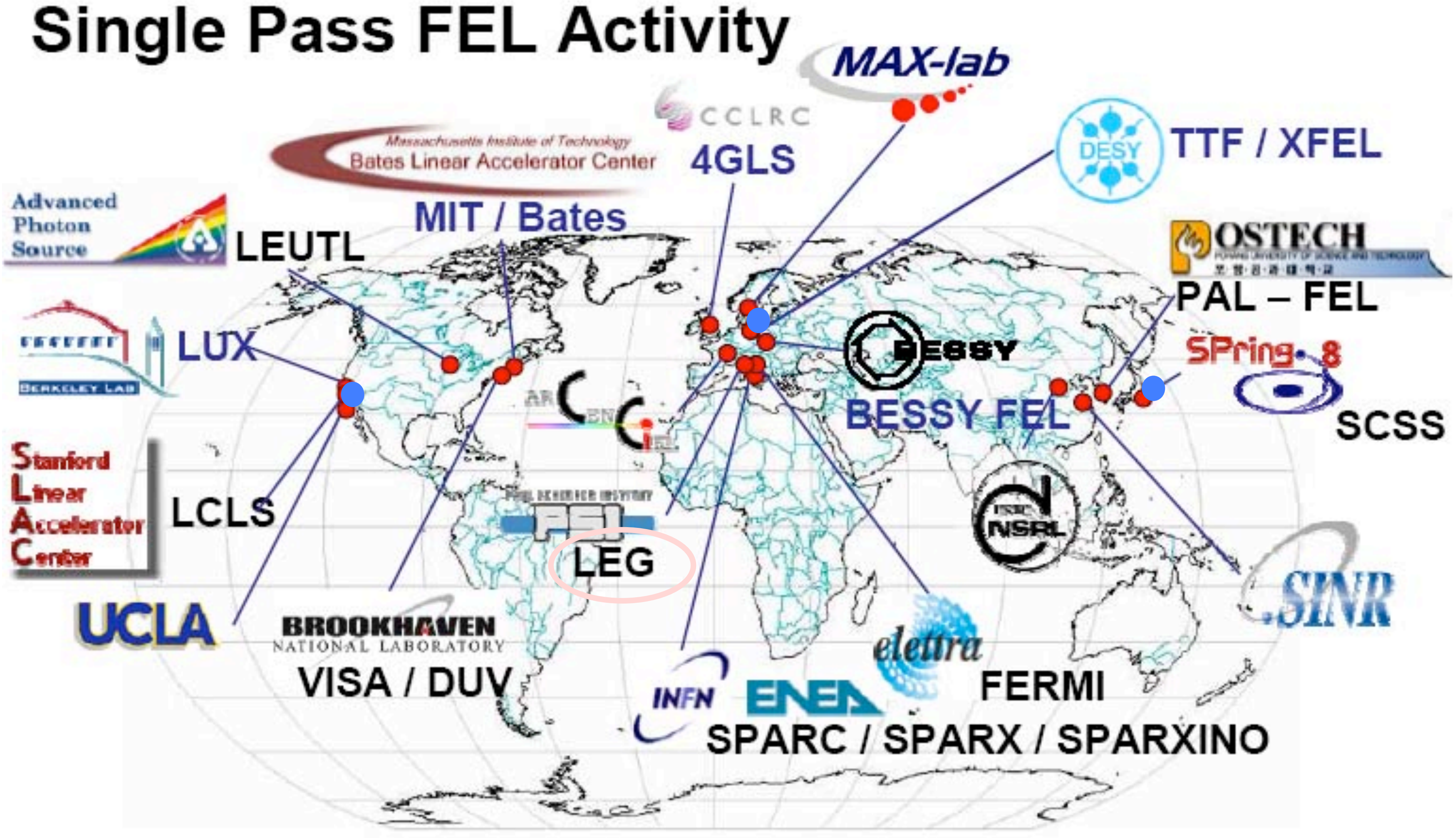


Beamlines & experimental hall
User and Support Facility
FEL array
Beam switchyard
Tunnel
Linac
Injector
Feet
0
100
200
400
Road 'F1'
Road 'F2'
Road 'E'
Road 'M'
Road 'N'
Road 'R1'
Road 'R2'
Road 'V'
Road 'S'

Berkeley FEL R&D



Lots of FEL activity



Motivation: LCLS

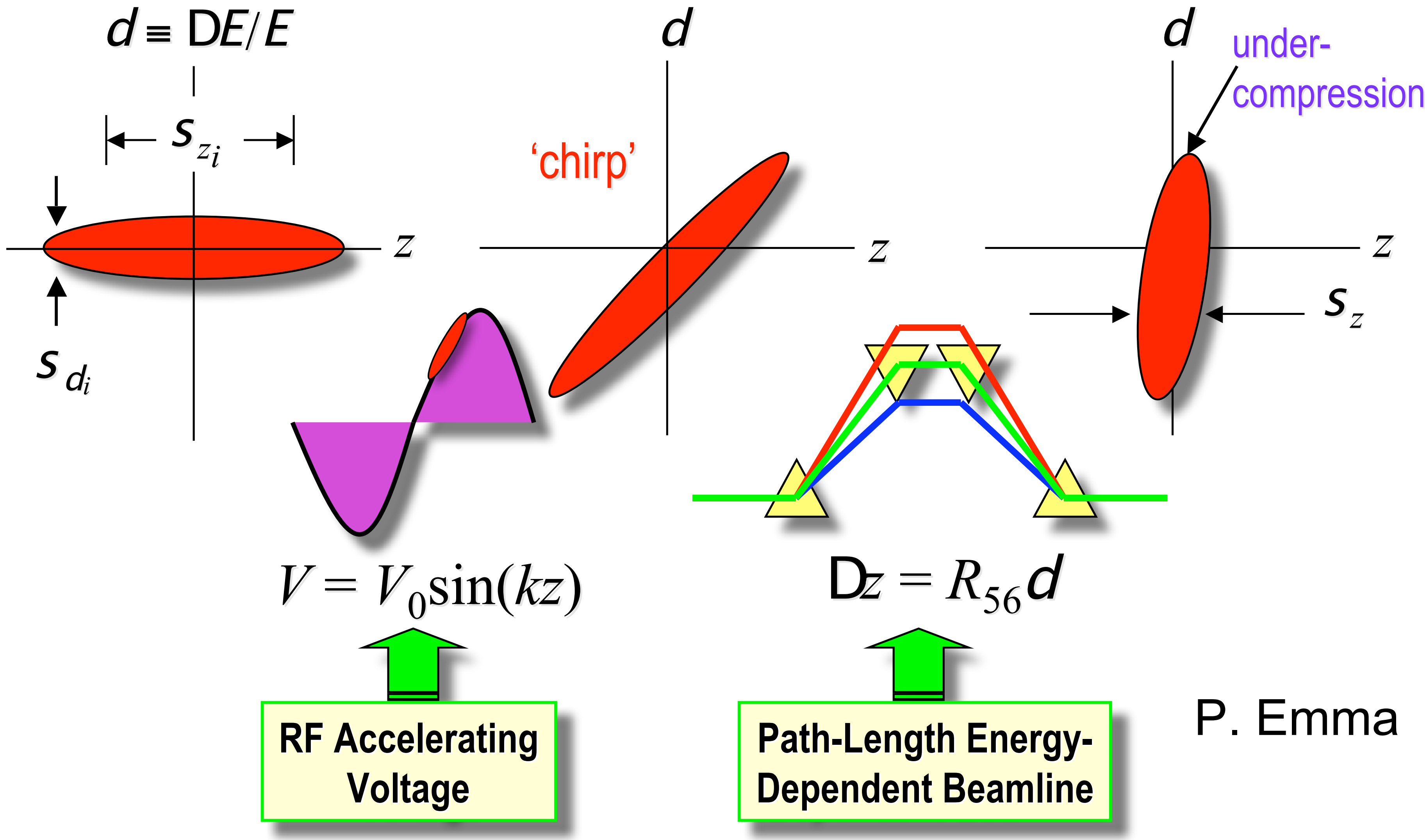
Critical *LCLS* Accelerator Parameters

- **Final energy 13.6 GeV (stable to <u>0.1%</u>)**
- **Final peak current 3.4 kA (stable to <u>12%</u>)**
- Transverse emittance 1.2 *m*m (stable to 5%)
- Final energy spread 10^{-4} (stable to 10%)
- Bunch arrival time (stable to 150 fs)

P. Emma

(stability specifications quoted as rms)

Electron Bunch Compression



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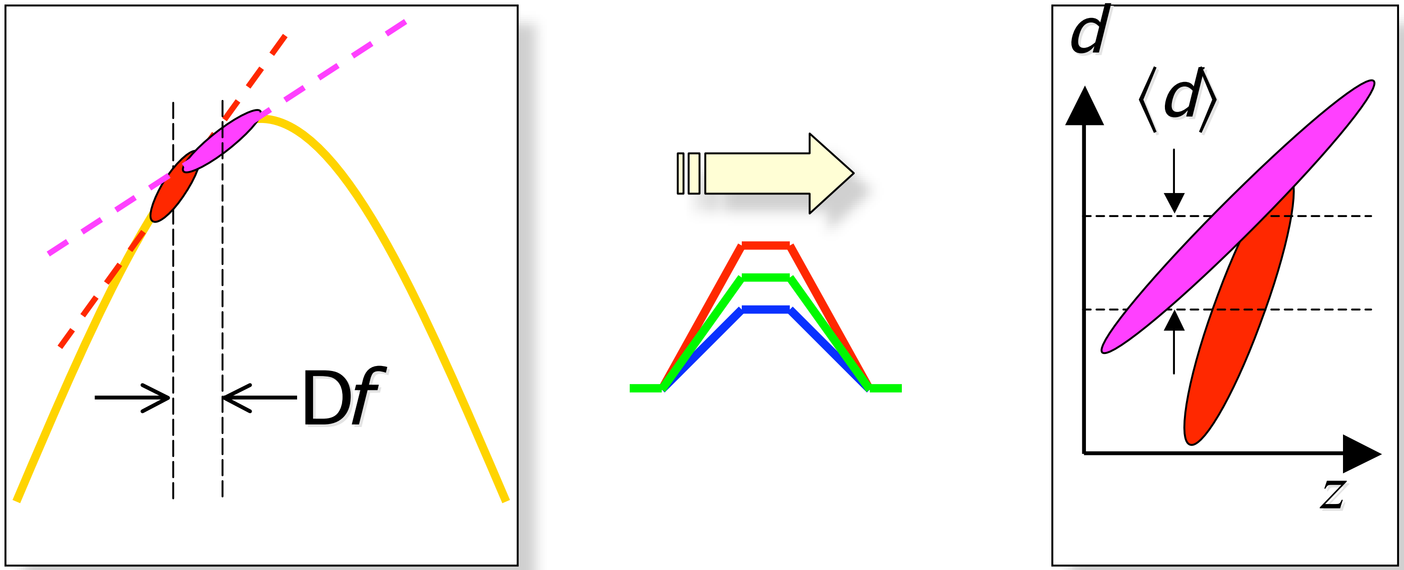
Compression Stability



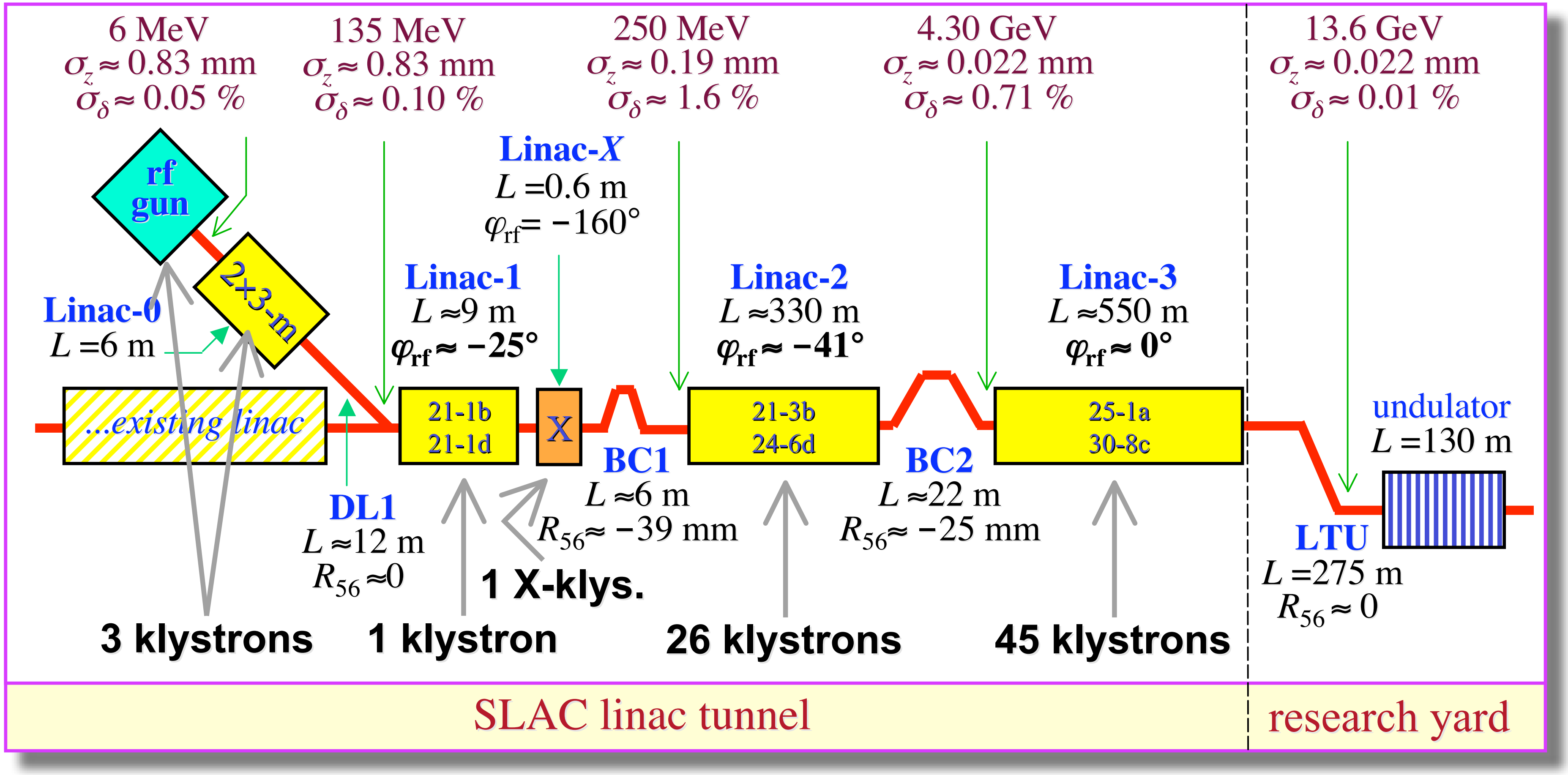
RF phase jitter becomes bunch length jitter…

Compression factor: $C \approx \frac{\sigma_{z_i}}{\sigma_z} > 1$

$$\boxed{\frac{\Delta\sigma_z}{\sigma_z} \approx -(C \mp 1)\left(\cot\phi - 3\frac{\lambda}{R_{56}}\right)\Delta\phi}$$

P. Emma

LCLS Machine Schematic



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Phase, Amplitude, and Charge Sensitivities

parameter	$\lvert DE/E_0 \rvert = 0.1\%$	$\lvert DI/I_0 \rvert = 12\%$	$\lvert Dt_f \rvert = 100$ fs	unit
Dt_i	1.6	4.4	1.5	psec
DQ/Q_0	46	5.2	24	%
Df_0	3.5	0.65	5.9	deg-S
DV_0/V_0	0.32	0.24	0.95	%
Df_1	0.32	0.17	1.0	deg-S
DV_1/V_1	0.29	0.25	0.78	%
Df_X	5.5	1.4	7.6	deg-X
DV_X/V_X	2.0	1.2	6.3	%
Df_2	0.54	0.21	0.084	deg-S
DV_2/V_2	1.1	1.0	0.13	%
D[illegible]	[illegible]	24.8	15	deg-S
D[illegible]	[illegible]	5.7	8.6	%

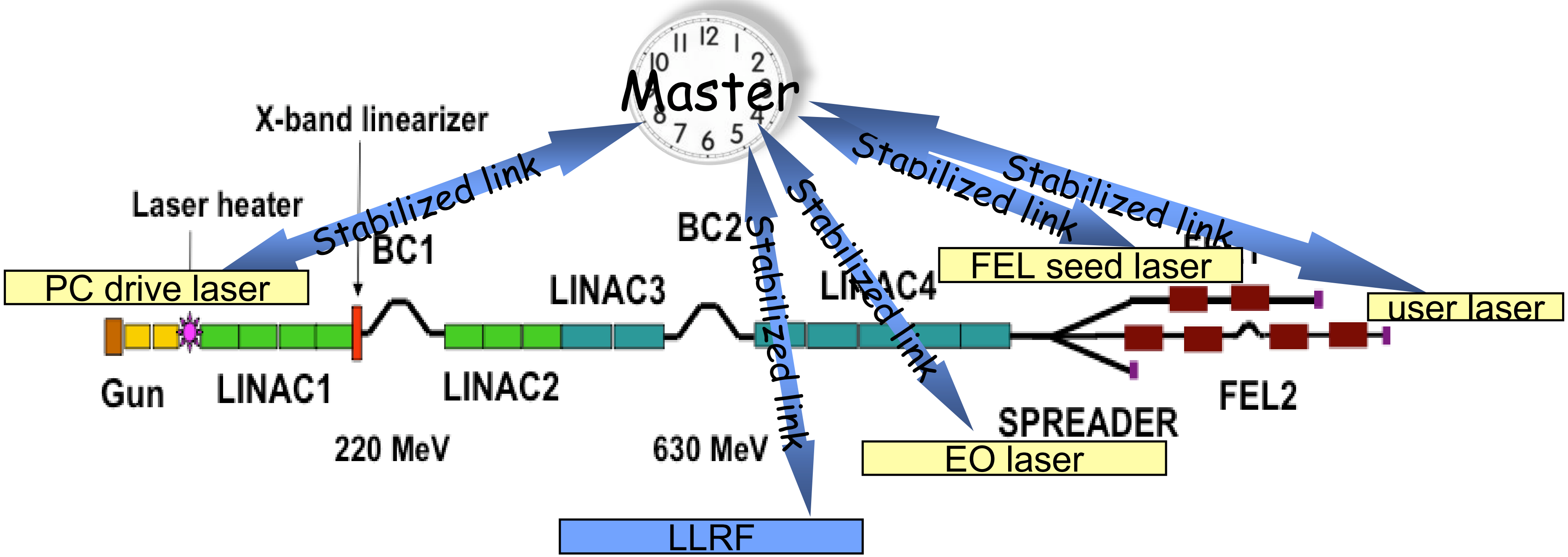
1 deg-S~1 psec

1 deg-X~0.25 psec

P. Emma

Synchronicity

- Next generation light sources require an unprecedented level of *remote* synchronization between x-rays, lasers, and RF accelerators to allow pump-probe experiments of fsec dynamics.
  - Photocathode laser to gun RF
  - FEL seed laser to user laser
  - Relative klystron phase
  - Electro-optic diagnostic laser to user laser



Optical metrology

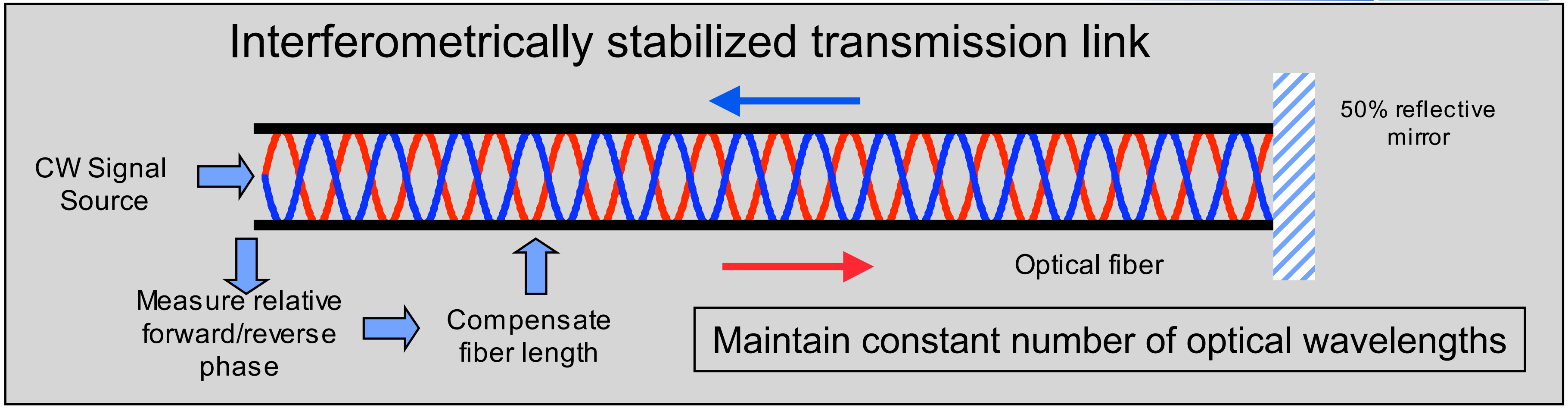
A revolution is going on in optical metrology due to several coincident factors:

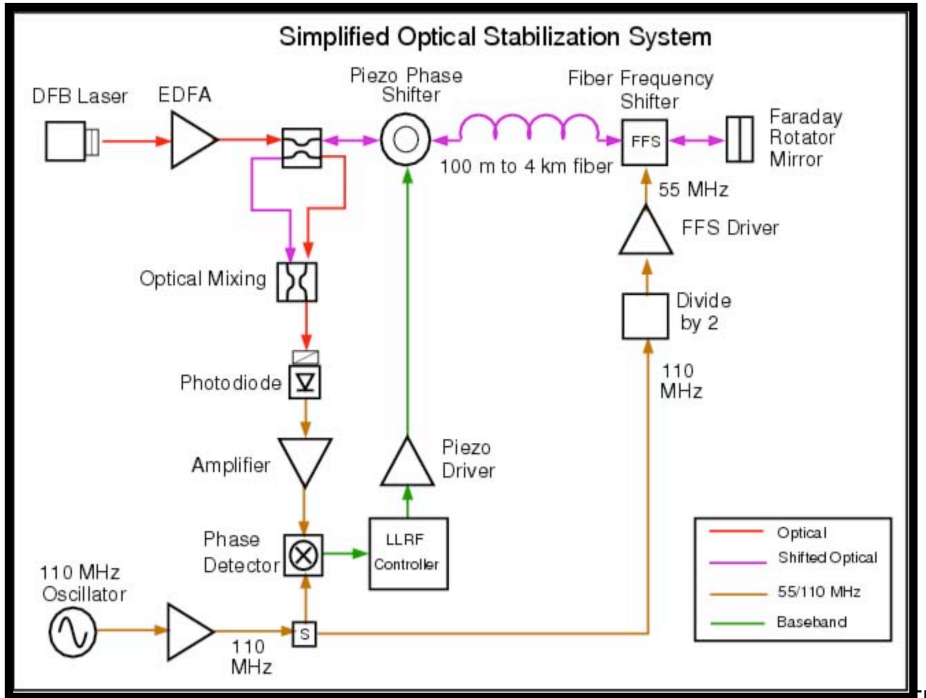
- development of femtosecond comb lasers
- breakthroughs in nonlinear optics
- wide availability of optical components

2005 Nobel Prize in Physics awarded to John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

This technology is *nearly* ready for applications in precision synchronization in accelerators

Stabilized fiber link



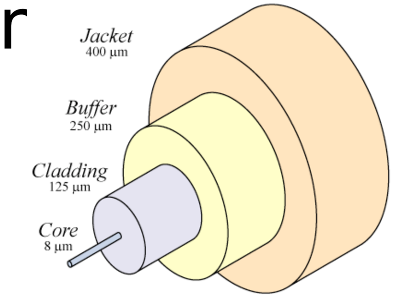


Our stabilized link uses several tricks to maximize stability:

- an offset carrier to make the phase comparison
  - high sensitivity
    1 deg RF=1 deg optical
    1 deg optical=0.014 fsec
  - avoids intermediate cable reflections
  - avoids DC phase measurement
- fast jitter compensated with piezo fiber stretcher
- timing signals transmitted as amplitude modulation of optical carrier

Why fiber transmission?

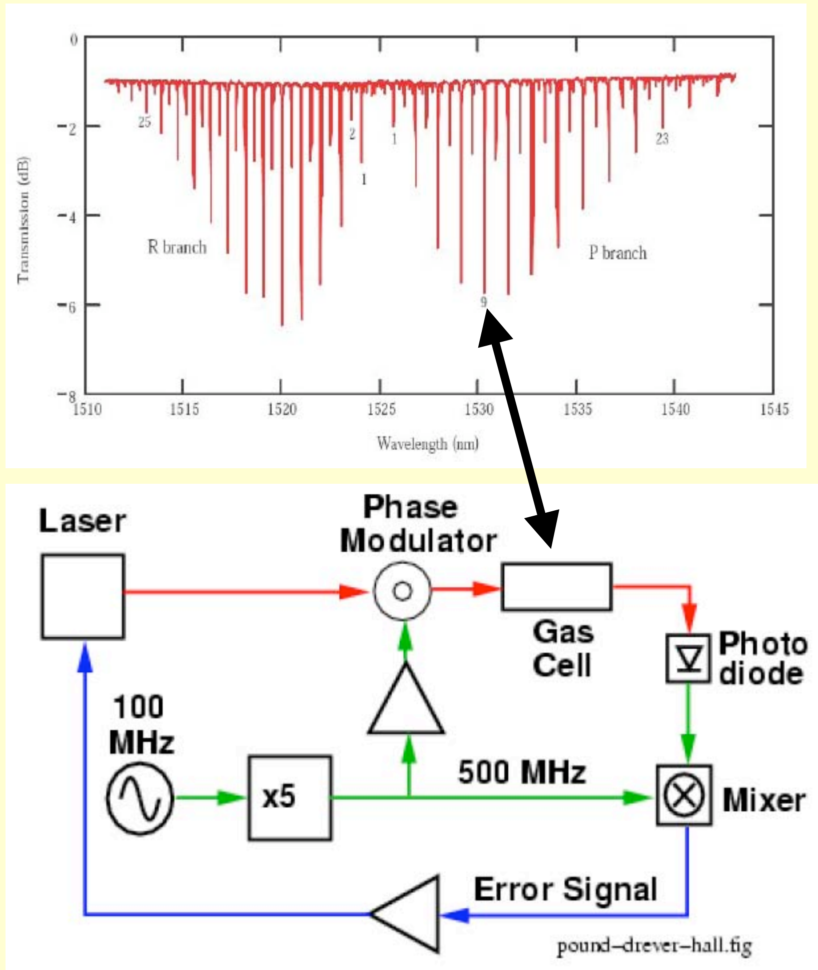
- Fiber offers THz bandwidth, immunity from electromagnetic interference, immunity from ground loops and very low attenuation
- However, the phase and group delay of single-mode glass fiber depend on its environment
  - temperature dependence
  - acoustical dependence
  - dependence on mechanical motion
  - dependence on polarization effects



- These are corrected by reflecting a signal from the far end of the fiber, compare to a reference, and correct fiber phase length.
- Two approaches: CW and pulsed

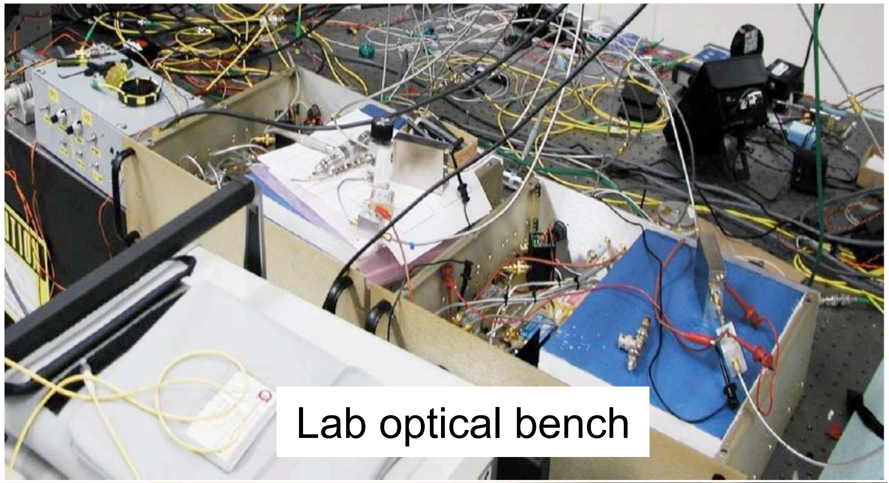
Laser Length Standard

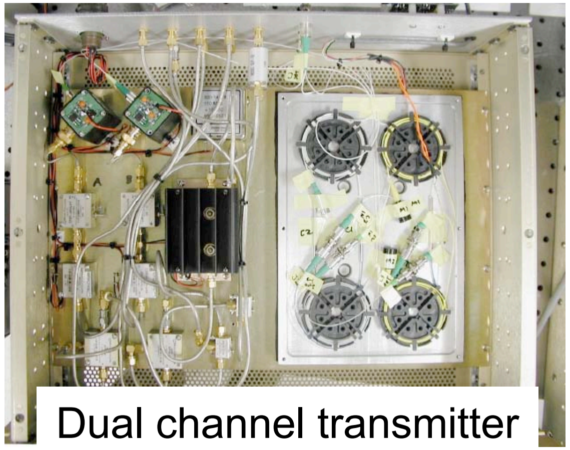
- Laser provides absolute standard for length of transmission line
  - Narrow-line (2 kHz) Koheras Laser (coherence length > 25 km)
  - For single fringe stabilization over 1 km, laser frequency must be stabilized to better than 1:10^9
  - Use frequency lock with acetylene cell in Pound-Drever-Hall configuration.
  - Techniques exist for greater improvement (I.e. lo
reference)

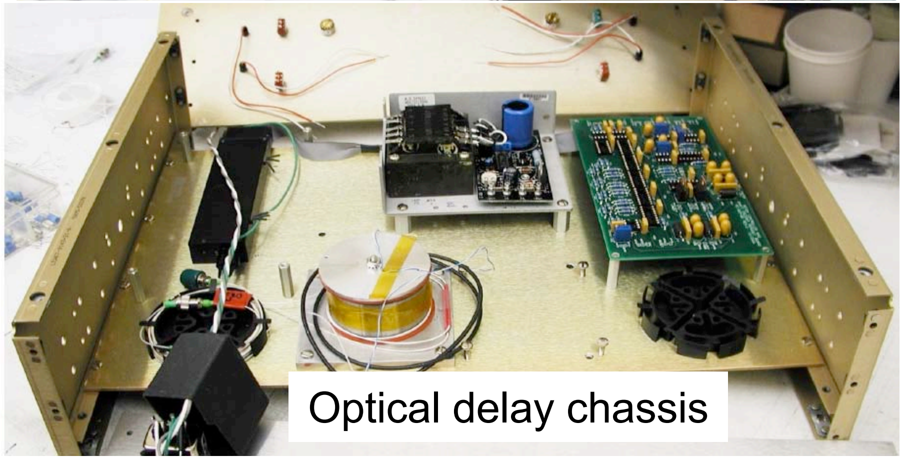


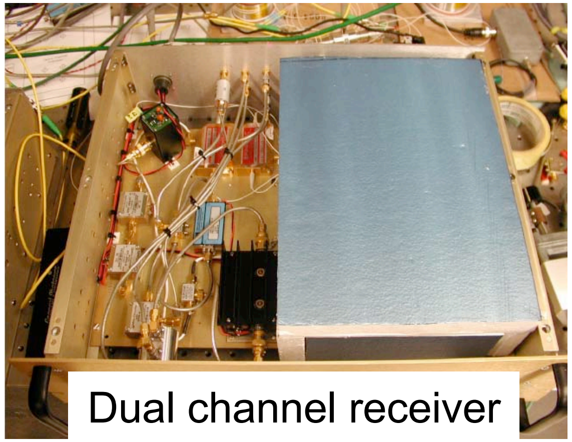
Frequency lock loop on acetylene (C_2H_2) 1530.3714 nm absorption line

Hardware setup





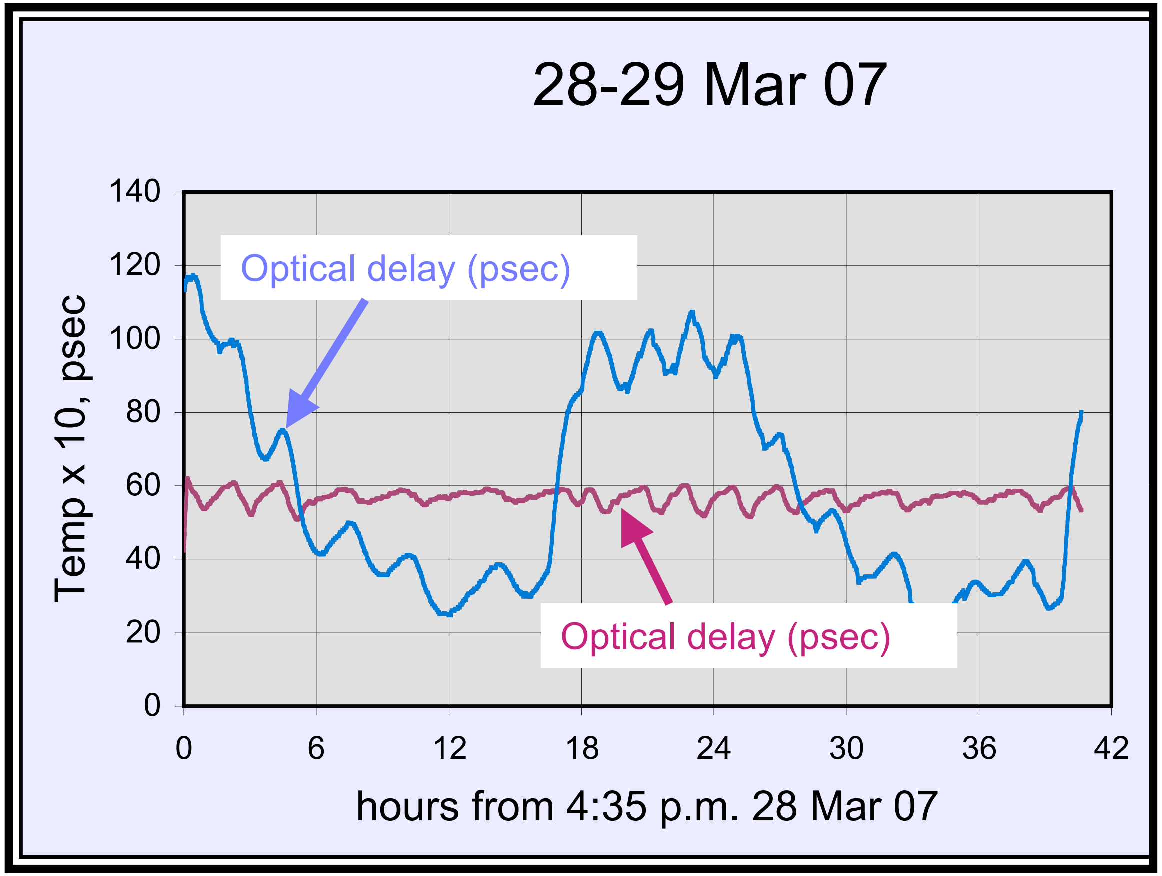




Long link stabilization

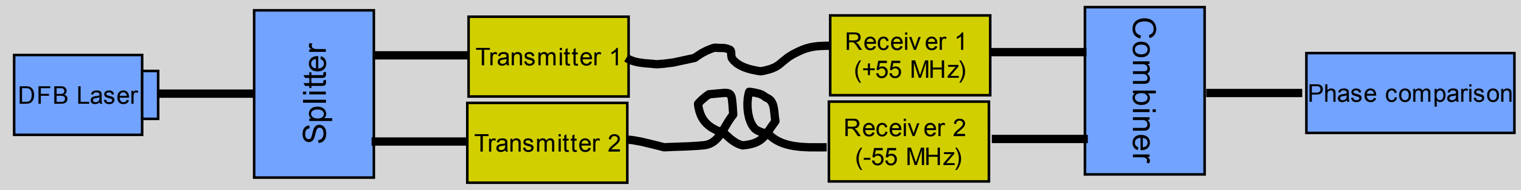
Goal: Test fiber stabilization on fiber outside of lab environment. Use part of lab's fiber optic communications network.

- Up to 4 km fiber has been stabilized with jitter of a few fsec. (2 km outside/2 km in lab).
- Feedback compensates for 100 psec (one way) of diurnal variation.
- Limit given by stability and linewidth of laser
- Gain/bandwidth of compensation feedback limited by roundtrip fiber delay.



Differential link phase stability

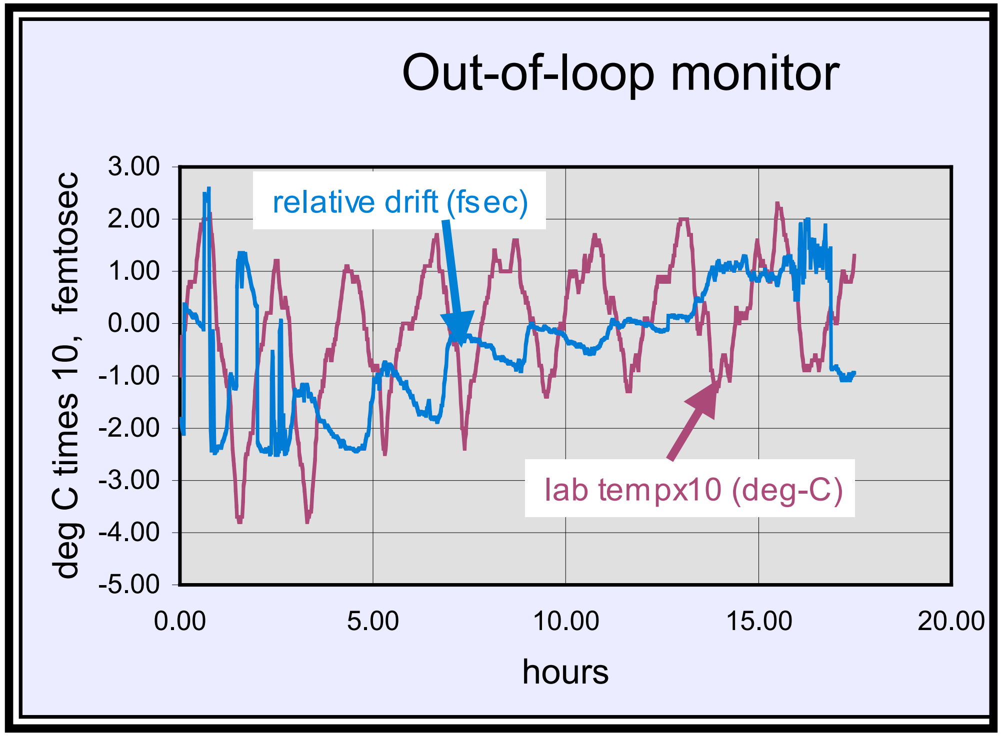
Goal: Compare relative length variation of two **independently** stabilized links



Use symmetric frequency shift at end of each link to bring relative optical phase information to 110 MHz beat frequency.

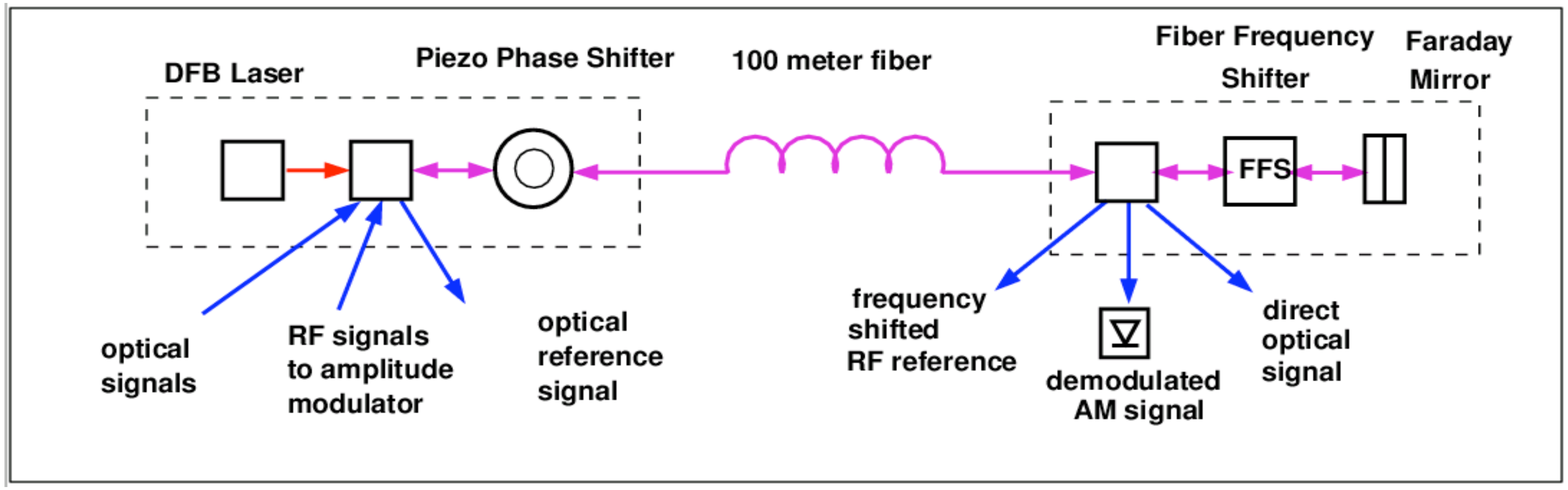
Results:

- 3 km long run/2 km external/1 km in lab, 2 m short run in lab
- 3 fsec drift over 3/4 day run!!!
- lab temp variation of ~0.5 deg-C
- external temperature variation ~20 deg-C



RF signal transmission

RF (S-band) may be modulated directly onto the optical carrier with a zero-chirp Mach-Zehnder modulator and recovered directly at the far end of the fiber. Any modulation pattern is acceptable.



Critical to minimize added phase noise at demodulation.

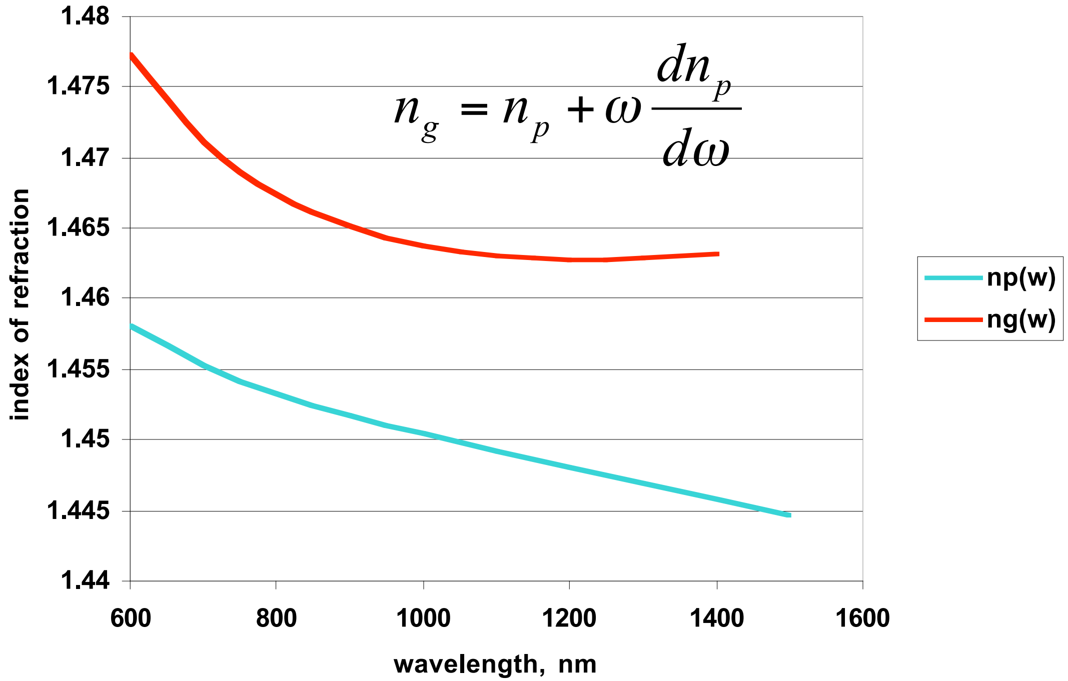
Modulation of CW carrier has signal S/N advantages over pulsed modulation.

Group and Phase Velocity Correction

Interferometric technique stabilizes phase delay at a single frequency . At a fixed T, simple a 1.6% correction for 1 km cable.

Possible fixes: measure group velocity from the differential phase velocity at two frequencies.

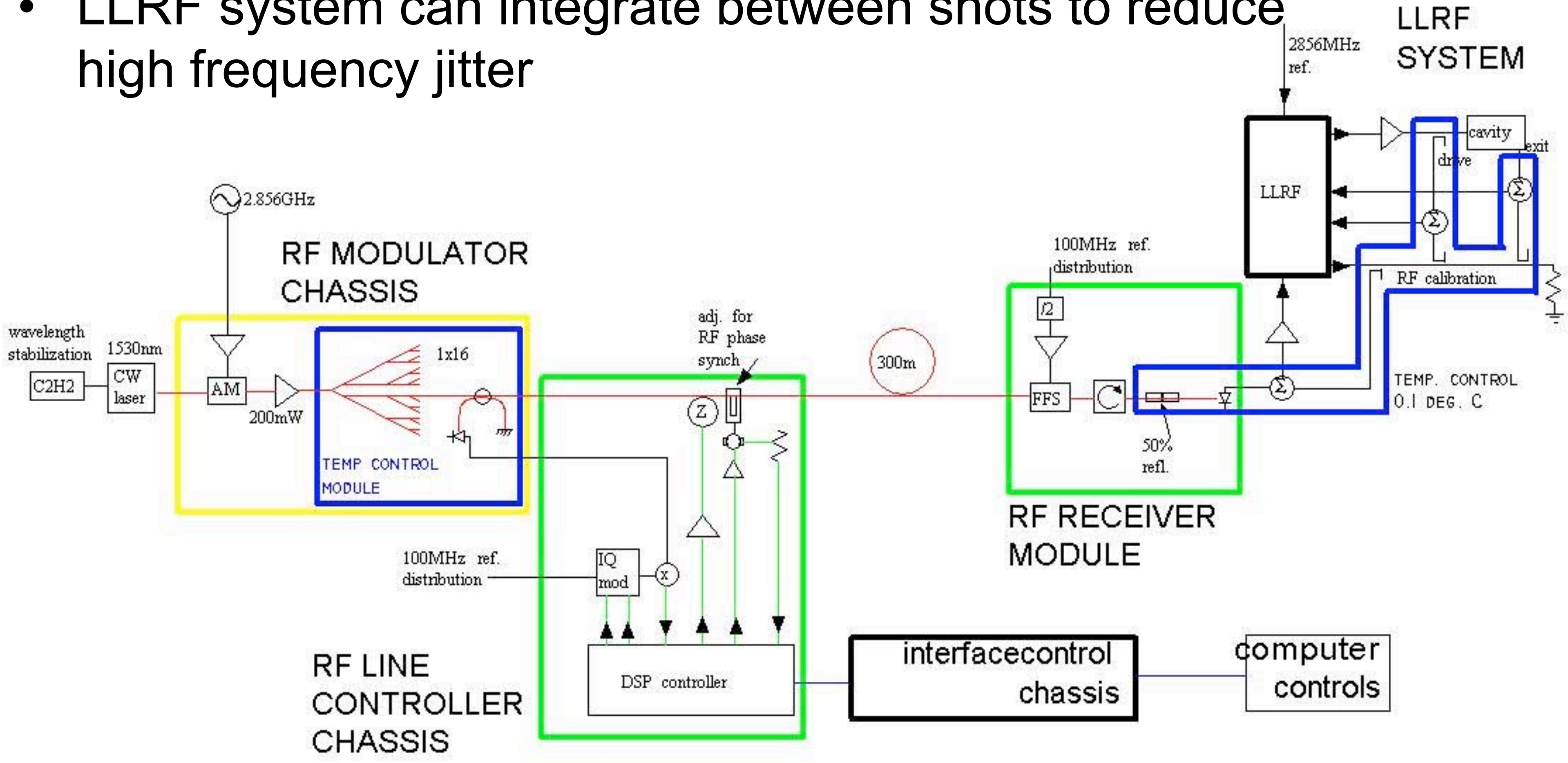
Correction can be applied dynamically or via a feedforward scheme.



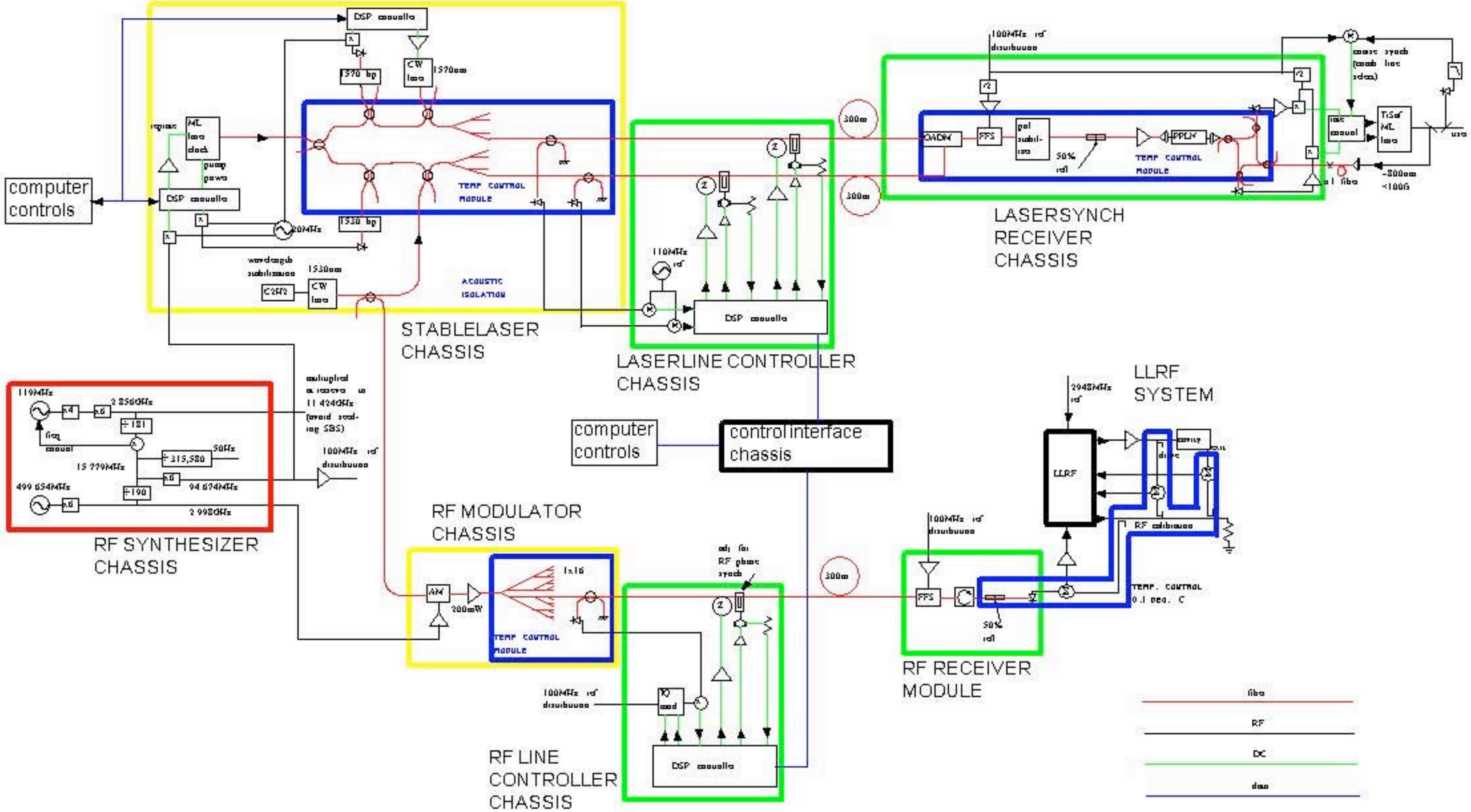
RF transmission design

John Byrd

- RF transmission has looser requirements on jitter
- LLRF system can integrate between shots to reduce high frequency jitter



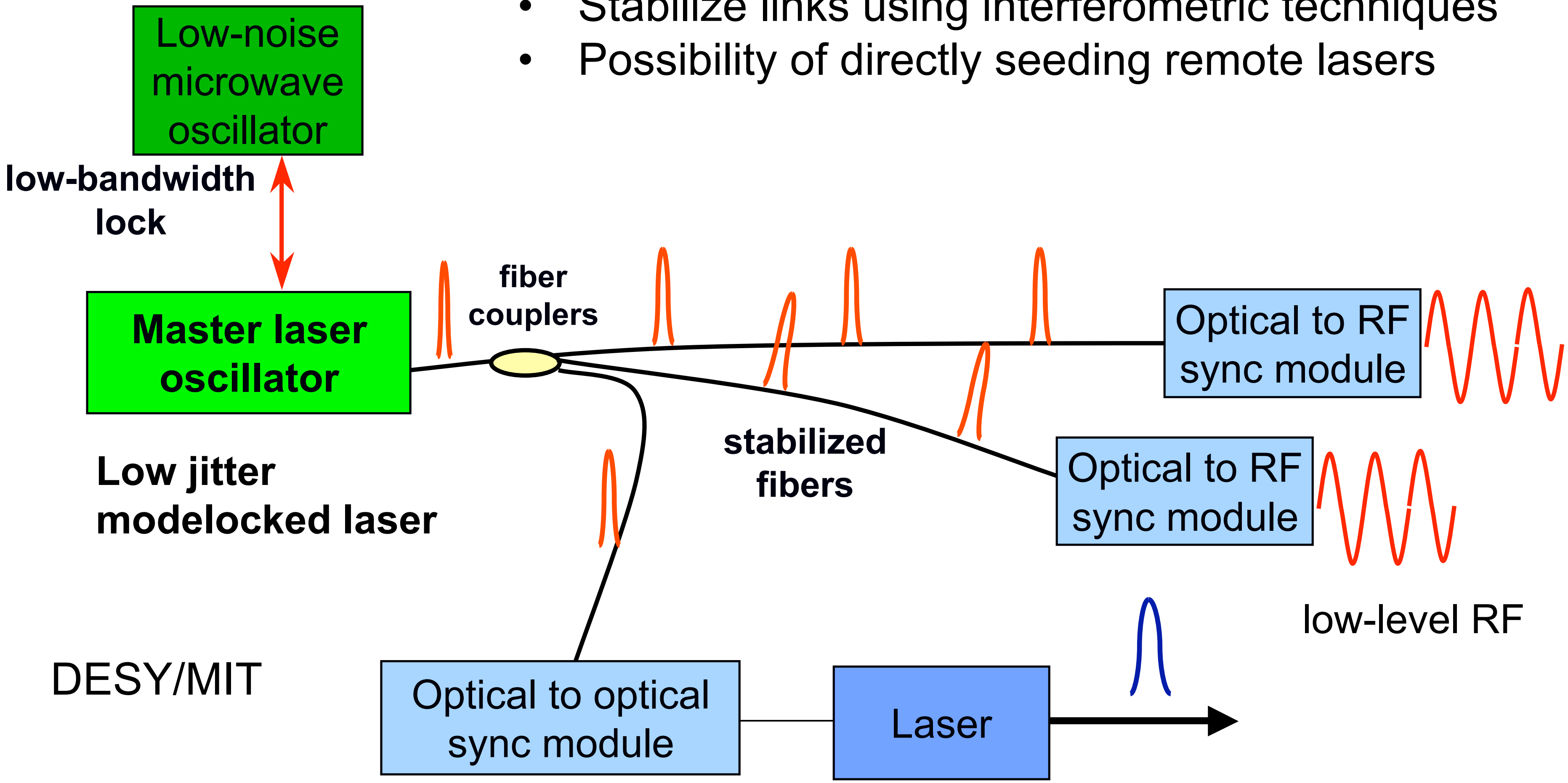
Conceptual system design



- Laser synch for any popular modelocked laser
- RF transmission via modulated CW, and interferometric line stabilization
- RF receiver is integrated with low level RF electronics design

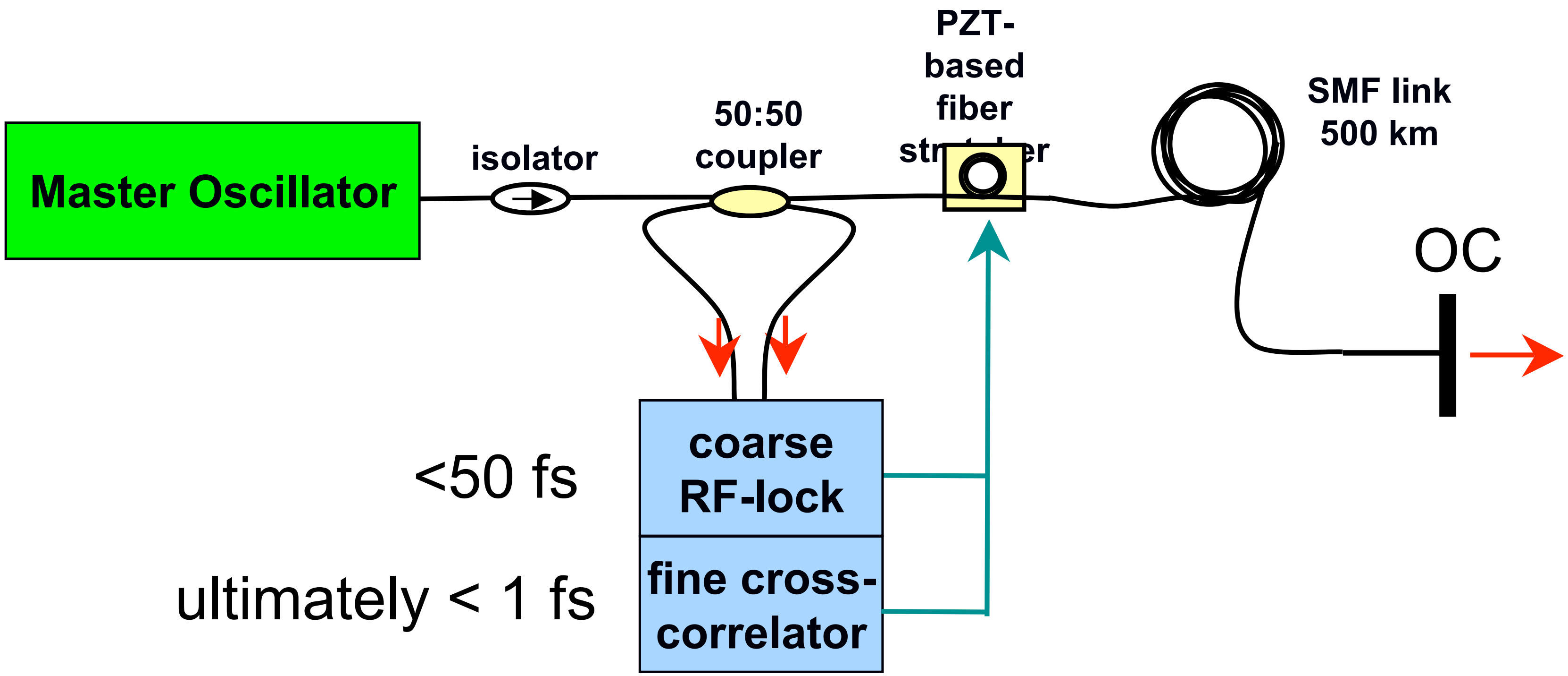
Pulsed distribution system

- Directly distribute laser oscillator pulses
- Extract RF frequency from harmonic of oscillator frequency
- Stabilize links using interferometric techniques
- Possibility of directly seeding remote lasers



DESY/MIT

Stabilized Fiber Links: pulsed



Optical cross correlator enables sub-femtosecond length stabilization,

if necessary

Stabilized fiber link summary

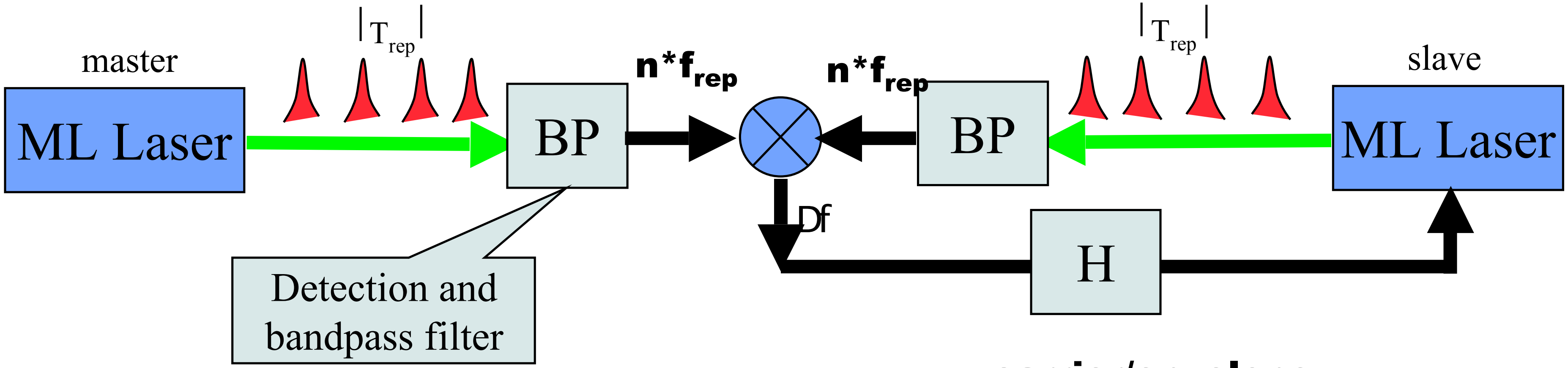
Results:

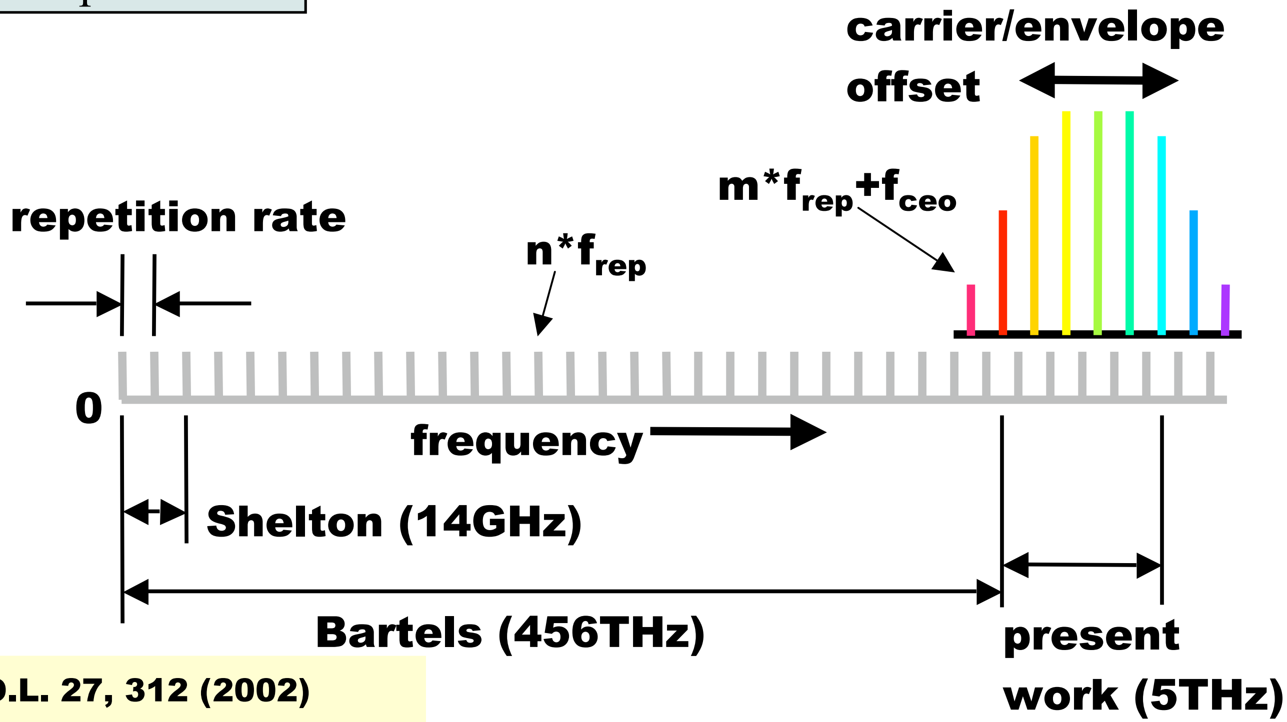
- A 4 km fiber link has been stabilized
  - Drift few fsec/hour (<50 microdeg @1.3 GHz) long-term
  - peak-to-peak jitter <1 fsec (55 MHz bandwidth).
- Effort has been funded by FEL development (LDRD, Fermi)
- A contract to supply LCLS with a timing system begins 15 May 2007.

In progress:

- Characterization
  - RF modulation on optical carrier over multiple links
  - temperature dependence of fiber dispersion
  - remote locking of mode-locked laser pair
- Test setup in accelerator environment (SLAC Linac tunnel)
- Integration with low-level RF modules

Synching mode-locked lasers





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

Idealized example

80 th harmonic

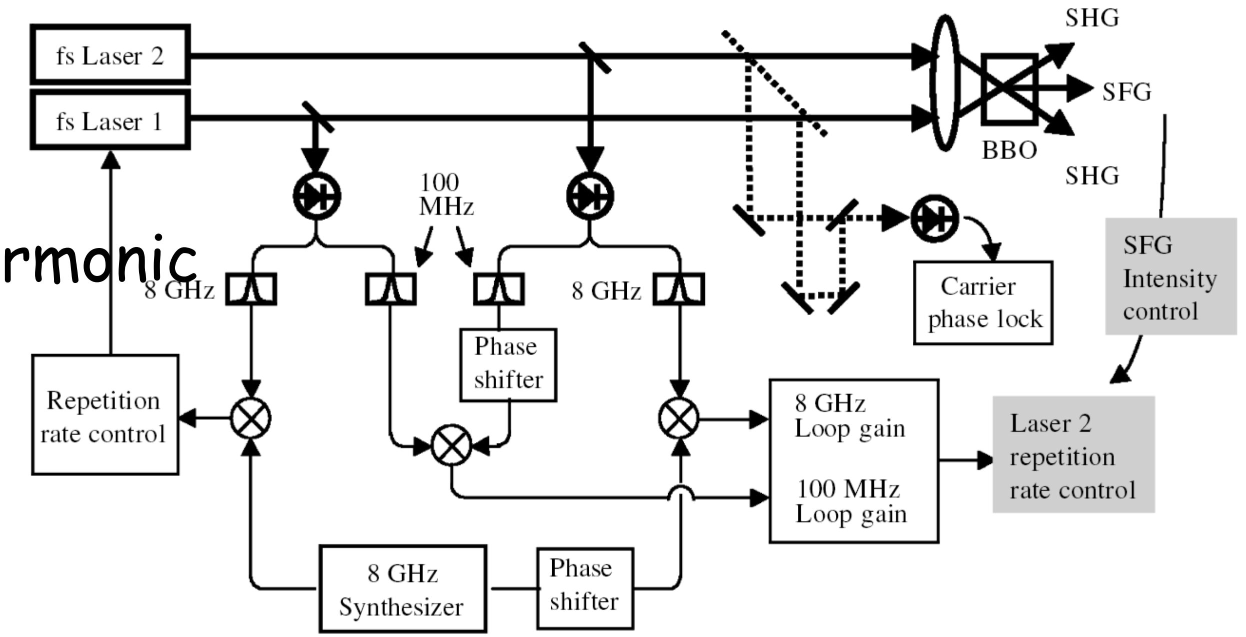


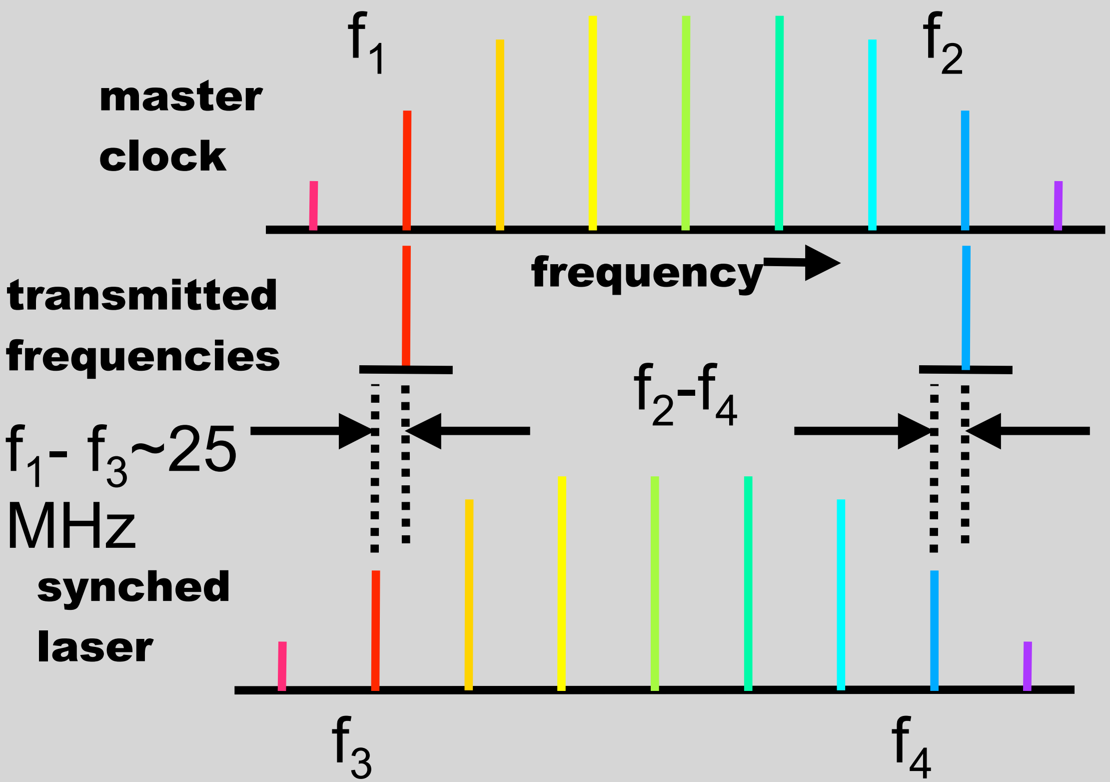
Figure 1. Experimental setup for timing synchronization of two fs lasers. The four phase-locked loops for synchronization are shown, along with the signal analysis scheme. Heterodyne detection of the carrier beat frequency between the two fs lasers is also shown.

R. K. Shelton et al.

JOURNAL OF MODERN OPTICS, 2002, VOL. 49, NO. 3/4, 401–409

Achieved 4.3 fsec jitter over 160 Hz BW for 10 seconds.

Four-frequency synch scheme

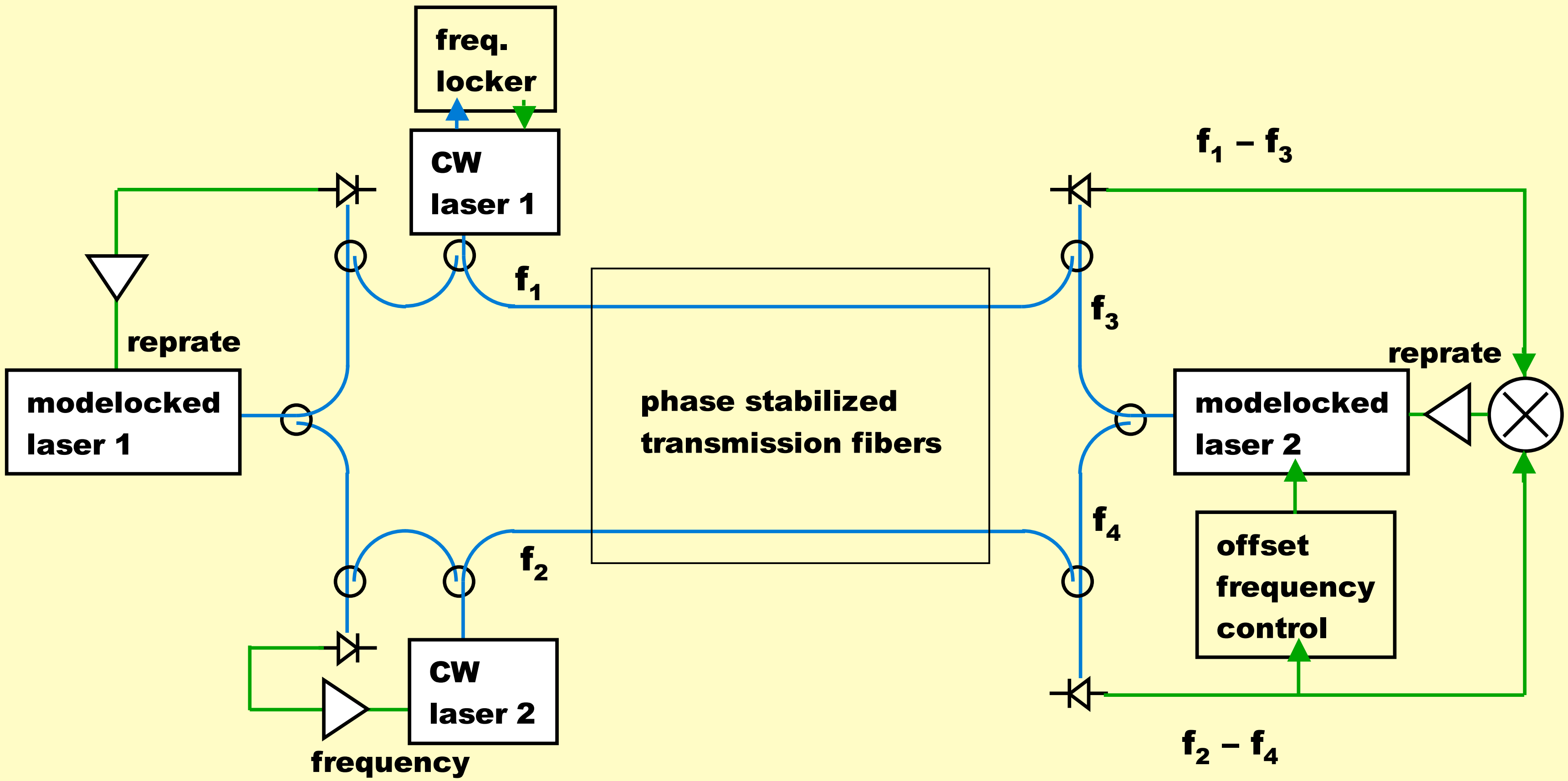


Lock two frequencies within the frequency comb separated by 5 THz.

For a 1 **degree** error in phase detection, temporal error is <0.6 fsec

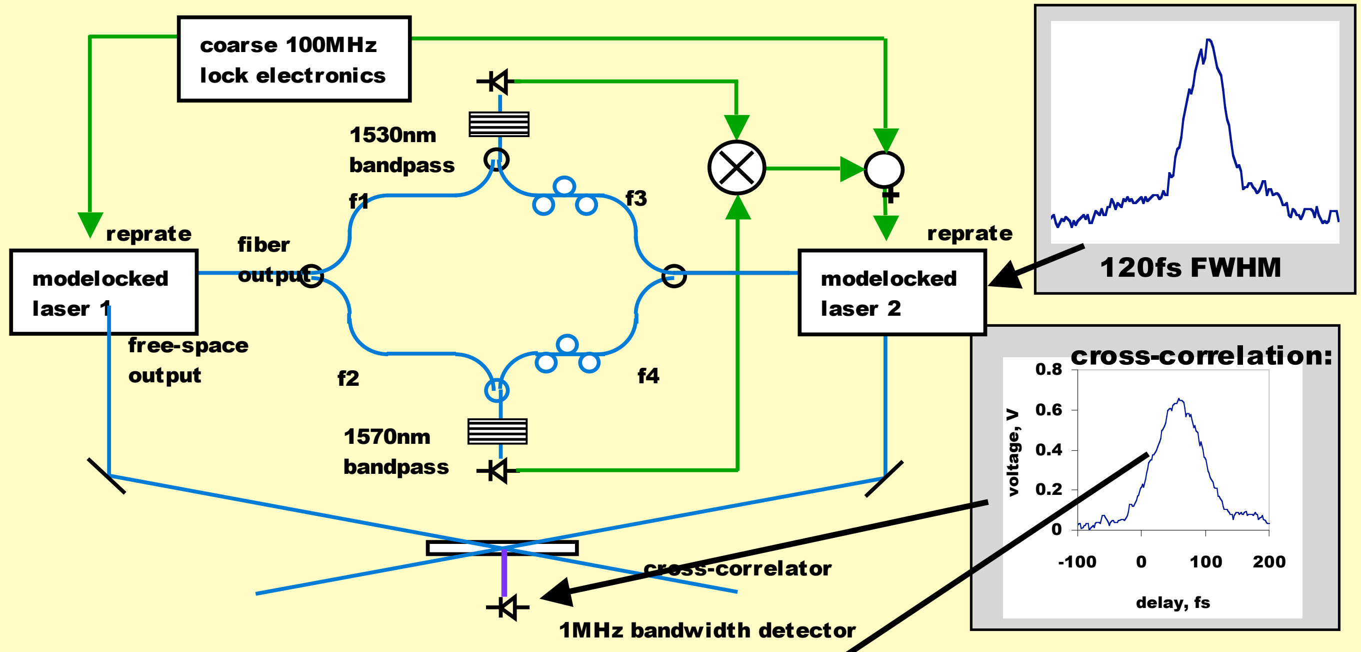
- **Novel approach for locking lasers**
- $(f_1 – f_3) – (f_2 – f_4)$ = error signal
- Yields relative phase of mode locked laser repetition rates
- Equivalent to difference of two THz signals
- Does not require carrier-envelope offset stabilized lasers

Conceptual schematic

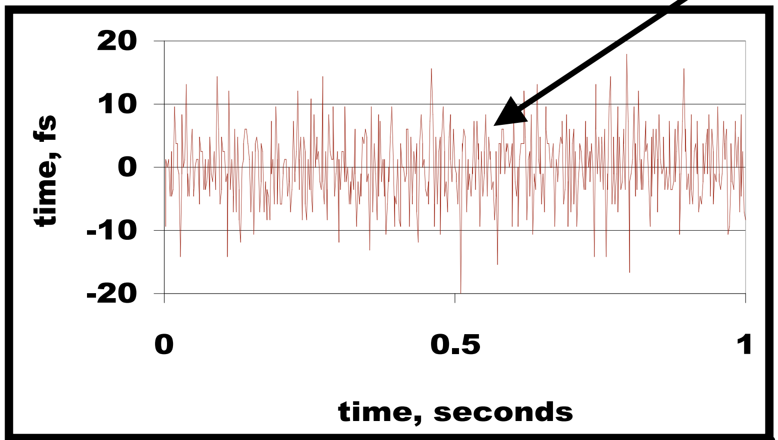


- Conceptual schematic
- Uses stabilized fibers transmission for inter-laser link
- Potential of tremendous gain over RF stabilized lasers

Initial results



- Simplified setup: lasers colocated on optical bench
- Cross-correlator delay set to partially overlap pulses
- Voltage versus time delay is close to linear
- Error signal sensitivity is 0.13mV/fs



5.7fs RMS from 1Hz to 100kHz

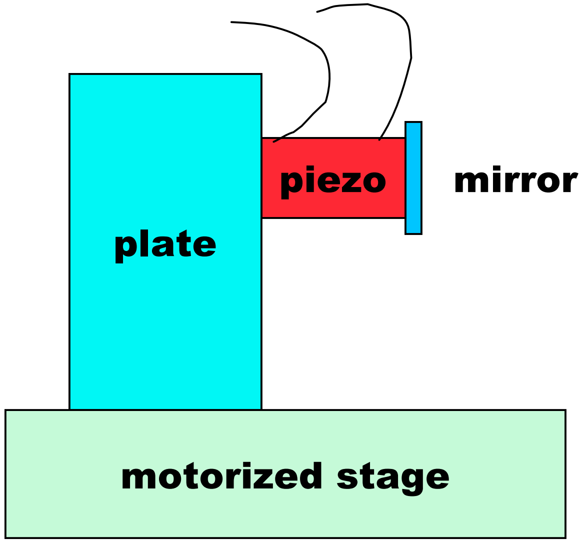
- **Inter-laser link not stabilized gives short stabilization time**
- **Currently no acoustic isolation**
- **Can improve loop gain by filtering**

Details, details…

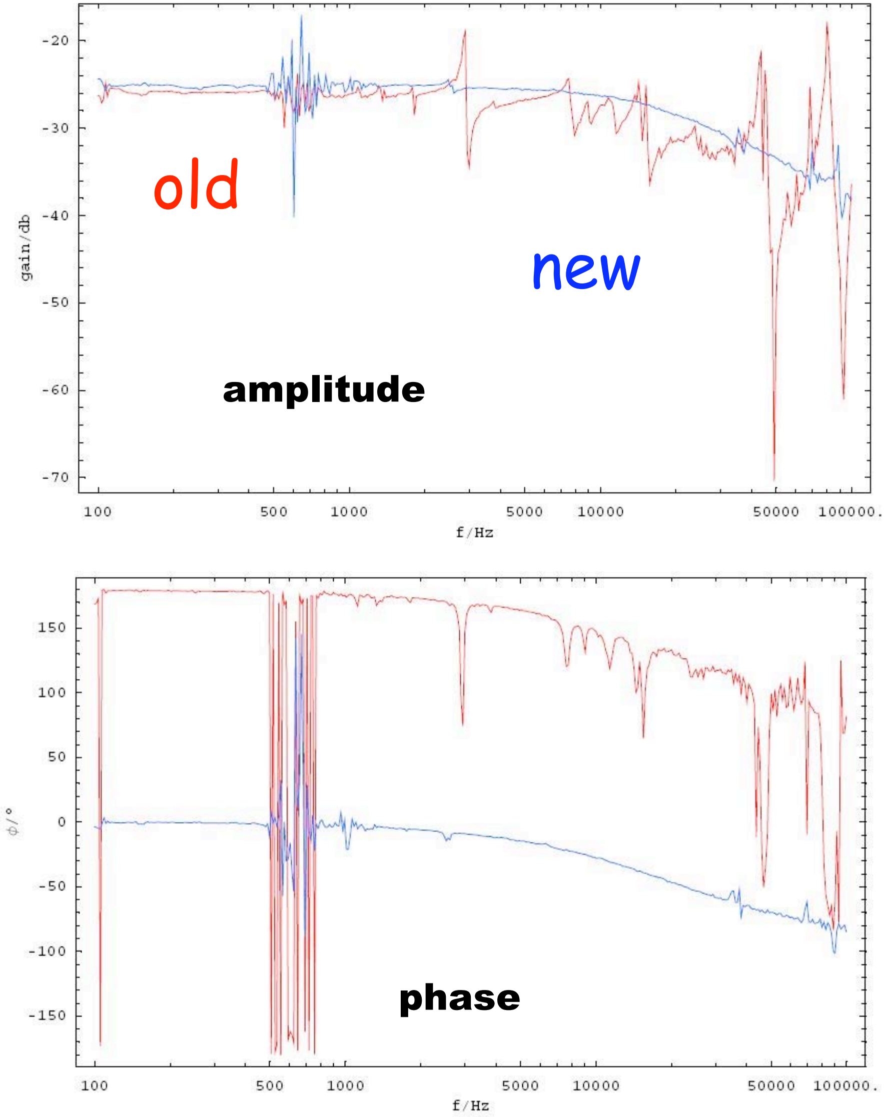
Actual performance depends on many technical details:

- thermal and acoustic environment of cable layout
- design of feedback loops
  - gain limited by system poles (i.e. resonances in the system)
  - multiple audio BW feedback loops suggests flexible digital platform
  - feedback must deal with drift and jitter (separate loops?)
- AM/PM conversion in photodiode downconversion

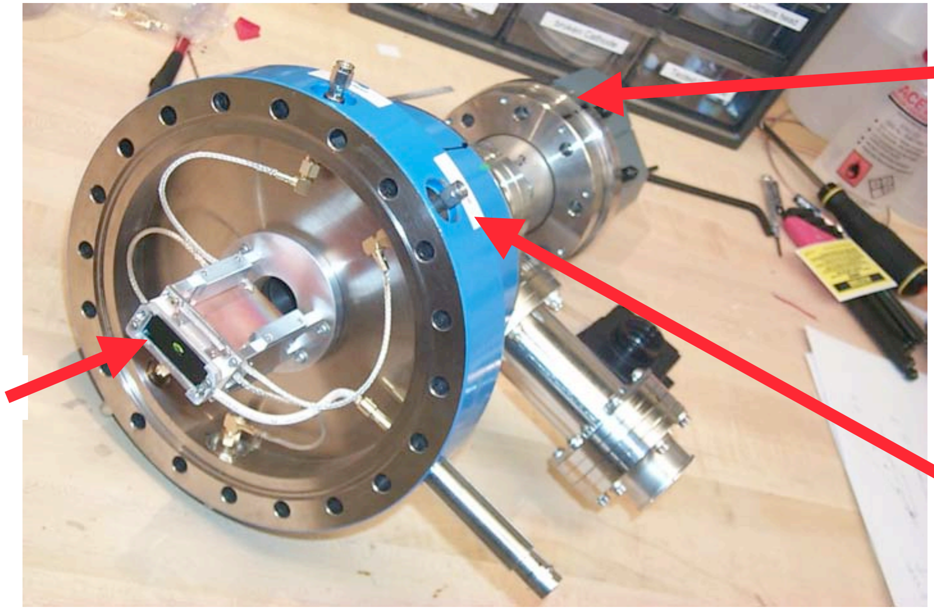
Example: Menlo EDFL



- Piezo driven cavity end mirror controls reprate
- Was a 10mm long piezo on a light Al plate
- Replaced with 2mm piezo on steel plate



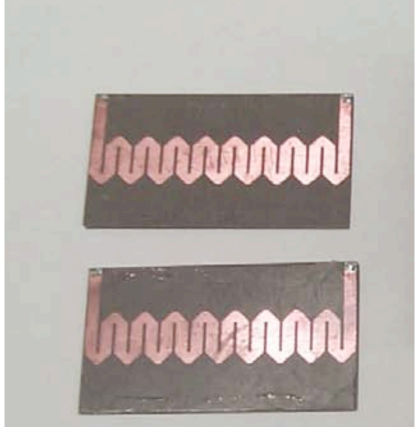
ALS x-ray streak camera



microchannel plates and imaging CCD

Photocathode / slit

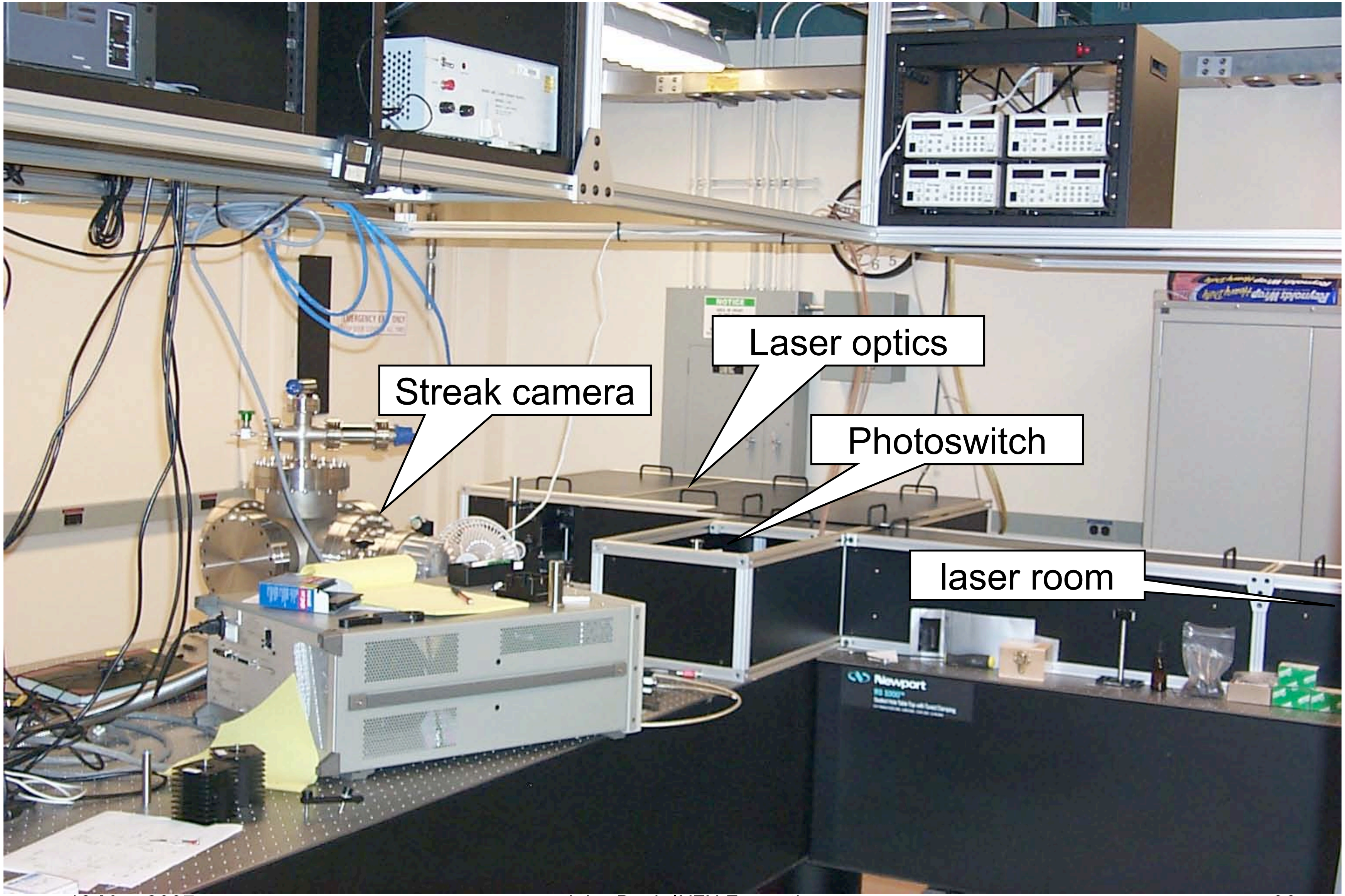
Solenoid magnet



Meander strip line

Photoconductive GaAs switch for triggering

ALS Streak camera R&D lab



Streak camera issues

- Fundamental time resolution limit set by ballistic expansion from energy spread at photocathode
  - reduced by higher voltage accelerating gaps
  - need an additional element to produce negative energy dependent time of flight (W. Wan)
- Jitter in triggering deflection requires each image to be fiducialized.
  - Use resonant deflector synchronized to periodic source (storage ring!)
- Space charge limits resolution for intense x-ray sources.
  - Develop start-end model to study effect.

Streak Camera Model

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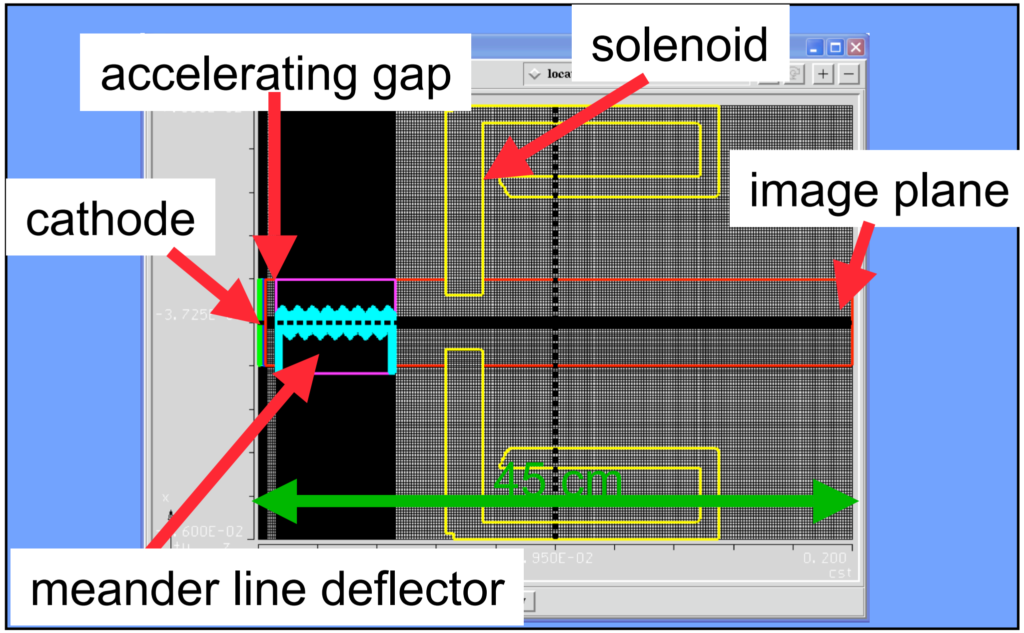
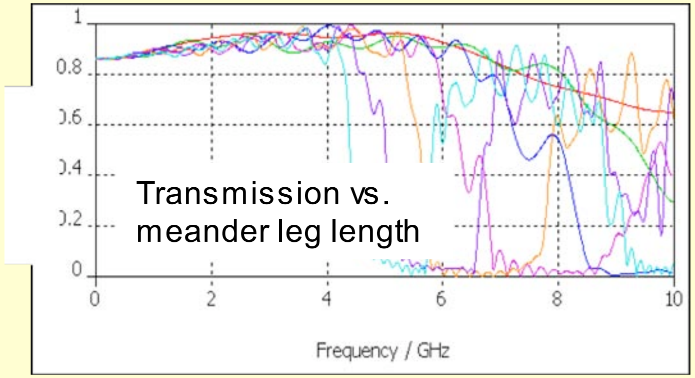
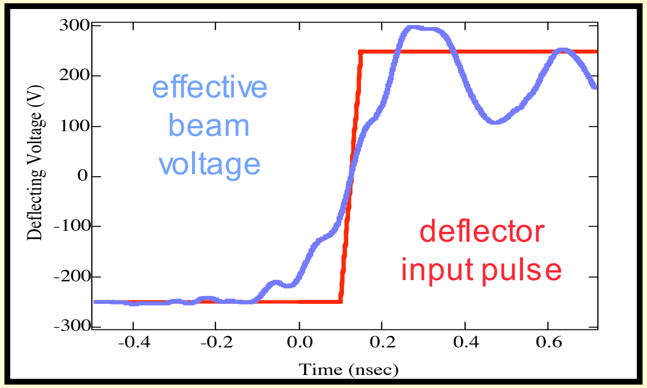


- Build 3-d model in environment that includes time domain beam dynamics and electromagnetism: MAFIA
- Initial electron energy spread assumed from model of secondary emission
- Use variable grid to account for important effects in anode-cathode and deflector.
- Space charge not yet included.
- **First start-to-end model of a streak camera.**

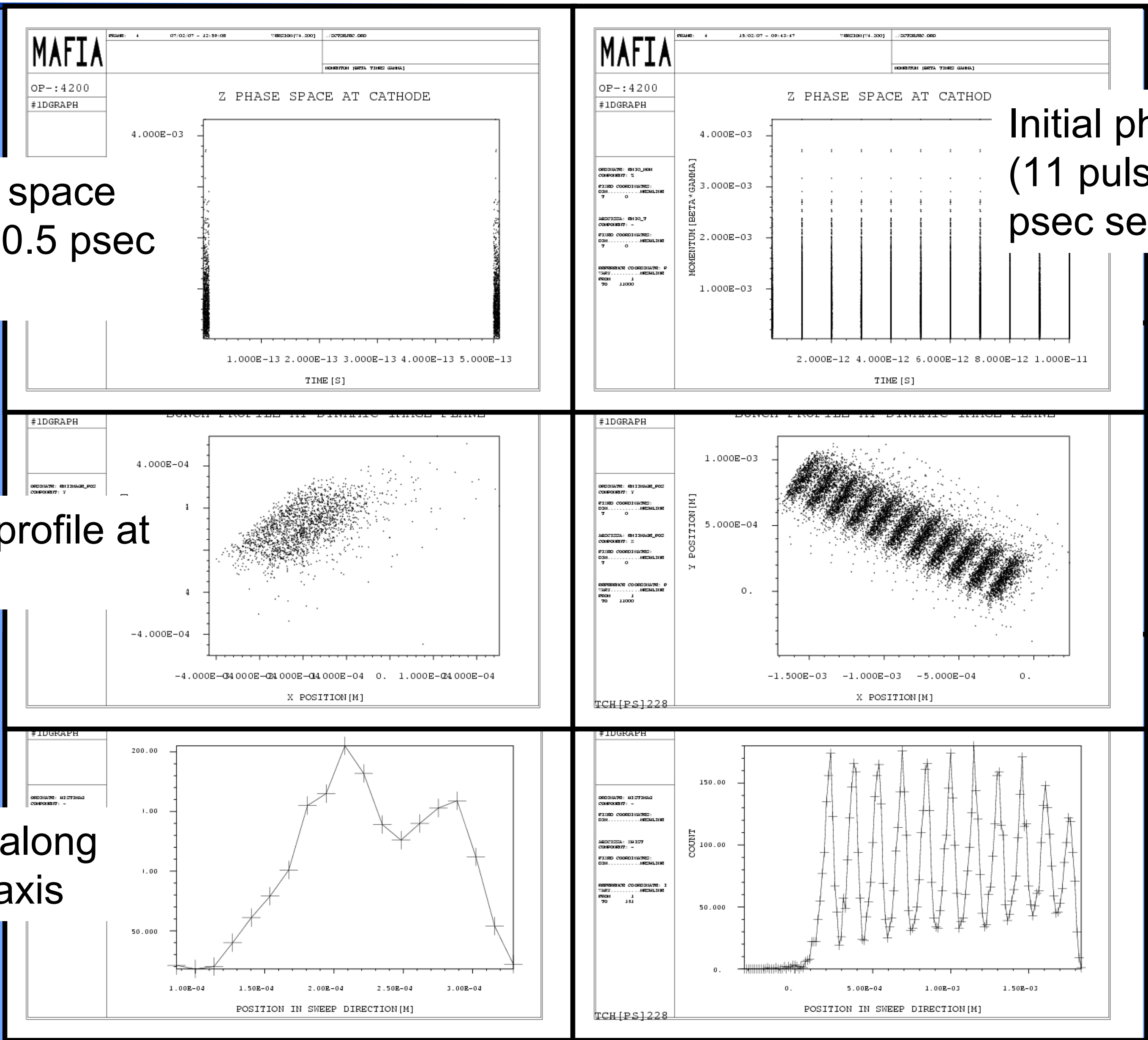
Meander Line Deflector Modeling

- geometry intended to match low beta beam
- structure forms lowpass filter, limiting pulse risetime
- careful design needed to match bandwidth of input pulse





Start-to-end SC Simulation



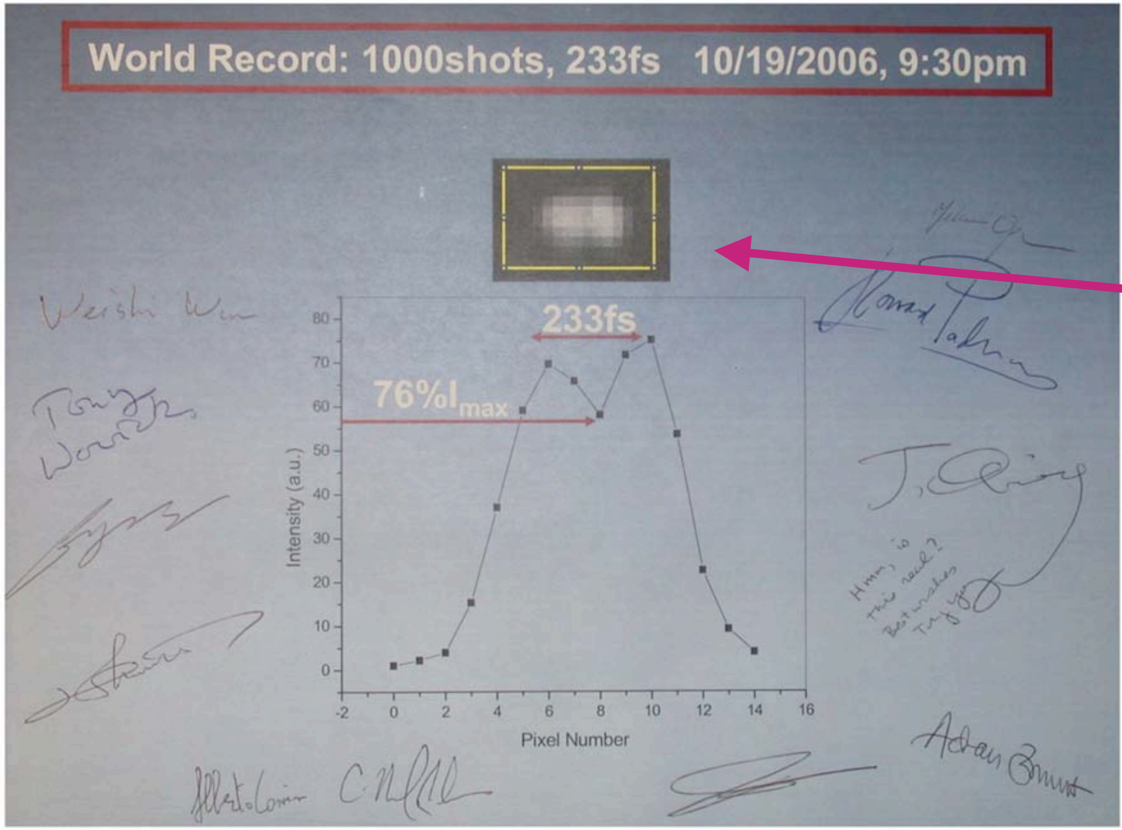
Initial phase space (2 pulses at 0.5 psec separation)

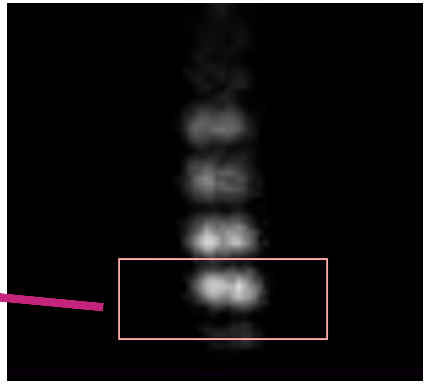
Initial phase space (11 pulses at 0.5 psec separation)

Transverse profile at image plane

Projection along deflection axis

Experimental Results





CCD Image with 1000 shots

Submitted to App. Phys. Lett.

World record resolution for SC.

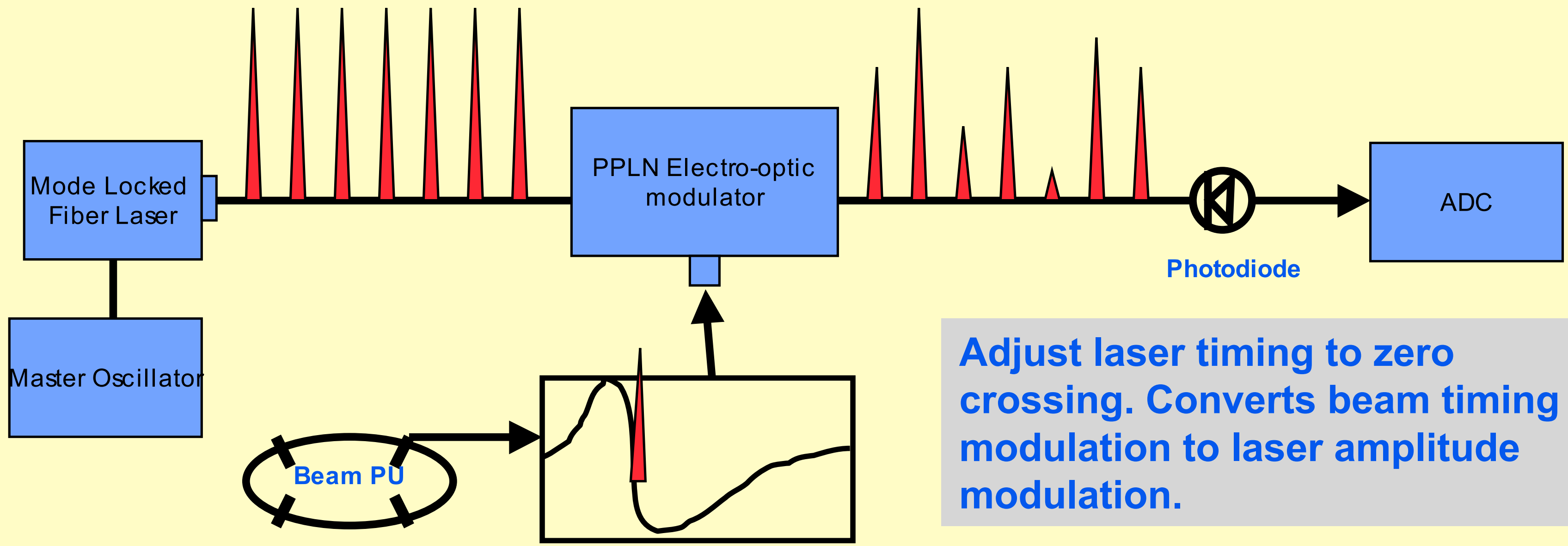
Low trigger jitter

SC model points the way to better results!

Beam Timing Monitor

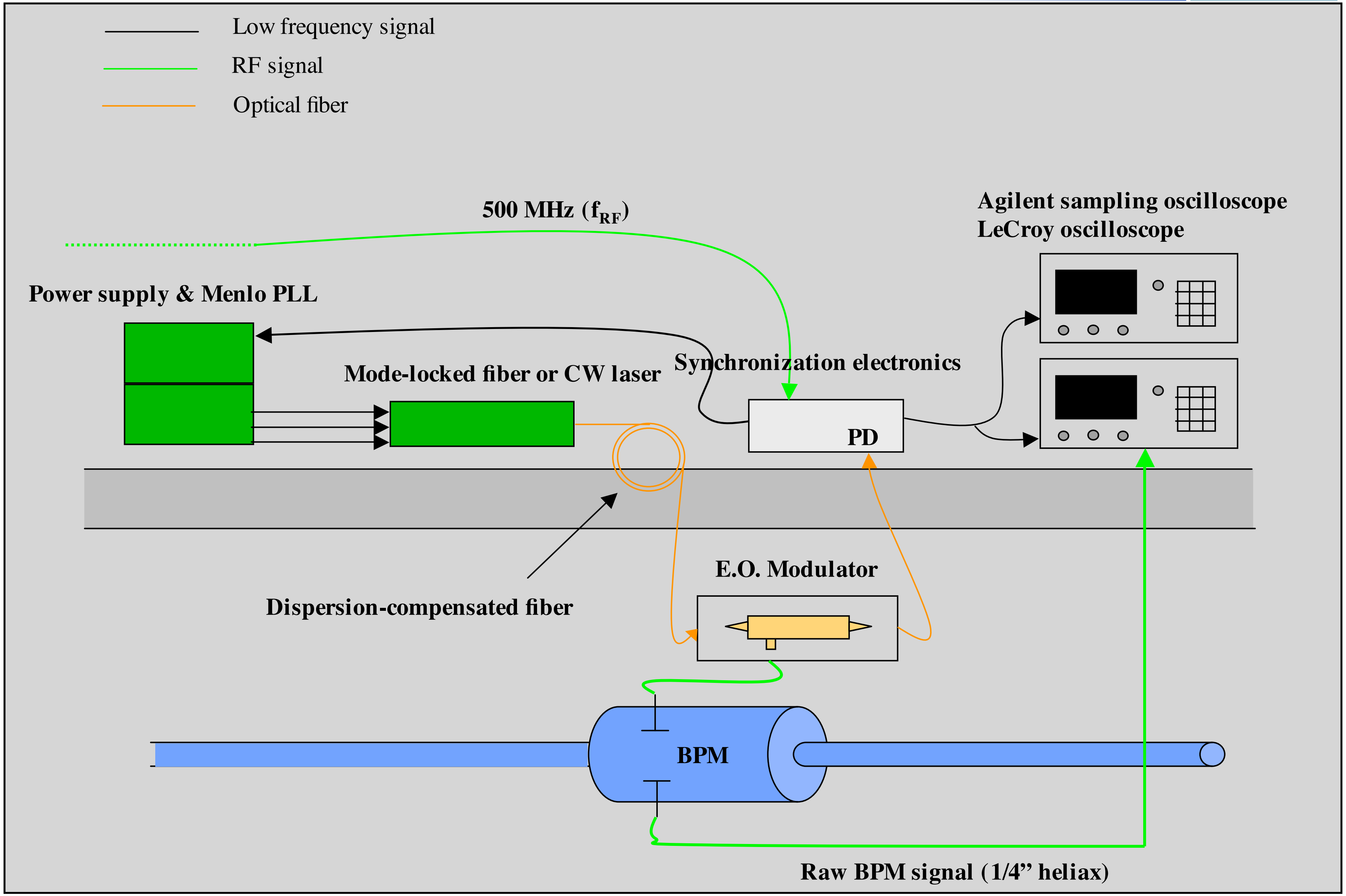
Beam timing relative to RF phase is critical for maintain overall beam quality:
- beam energy stability
- bunch compression
- beam energy via main linac phase

Our development of a stable timing reference opens the door for tremendous advances in measuring beam timing



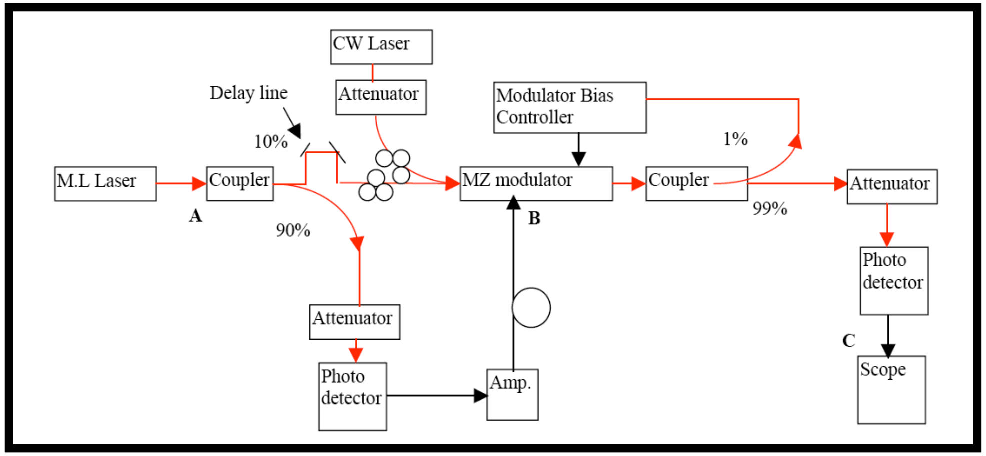
Adjust laser timing to zero crossing. Converts beam timing modulation to laser amplitude modulation.

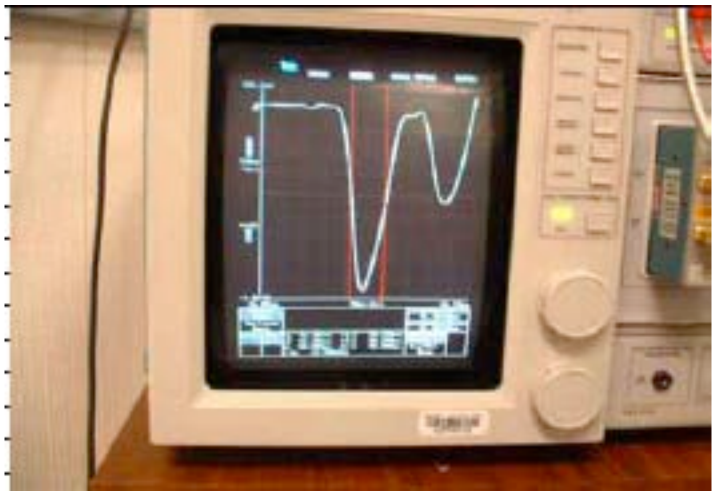
Experimental Setup

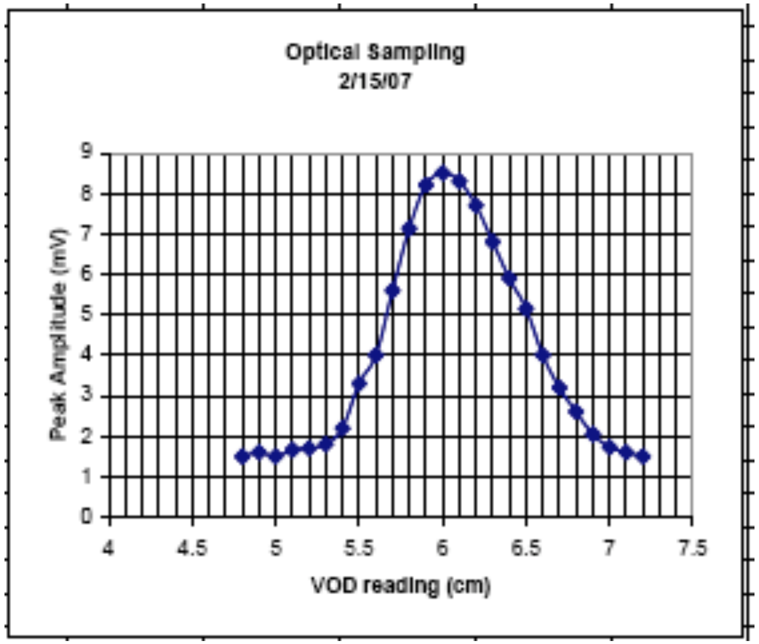


Initial lab results

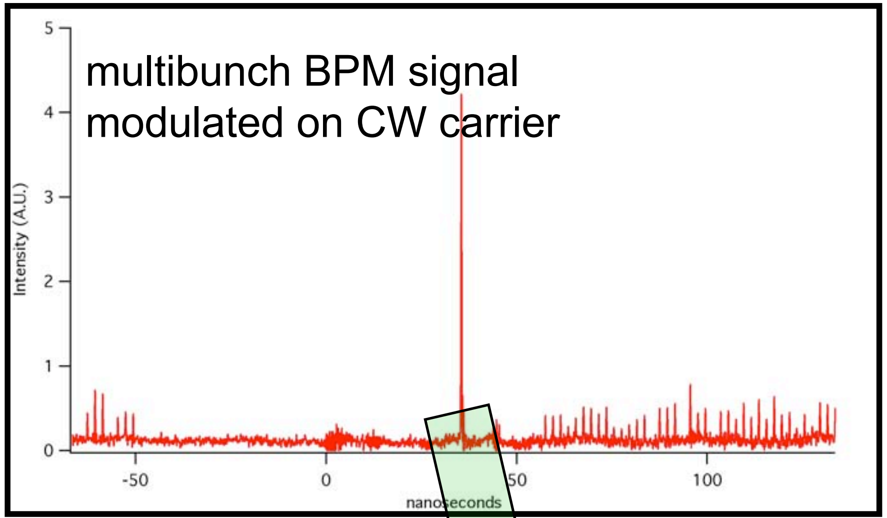
- MLLaser provide 100 fsec pulses at 100 MHz
- Fiber dispersion stretches to ~1 psec. Compensation should recover ~200 fsec.
- Tests using ALS BPM signals underway

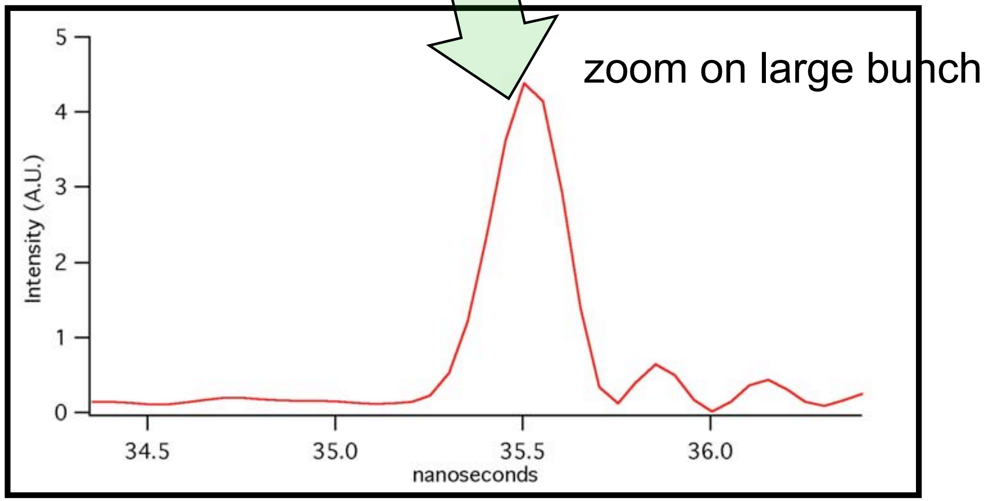






Initial beam results



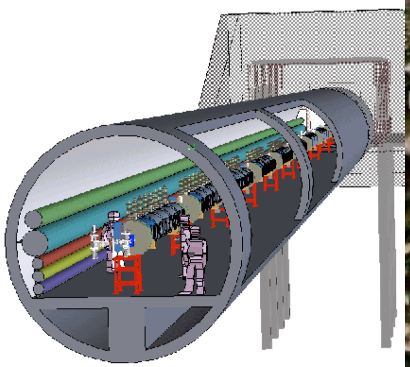


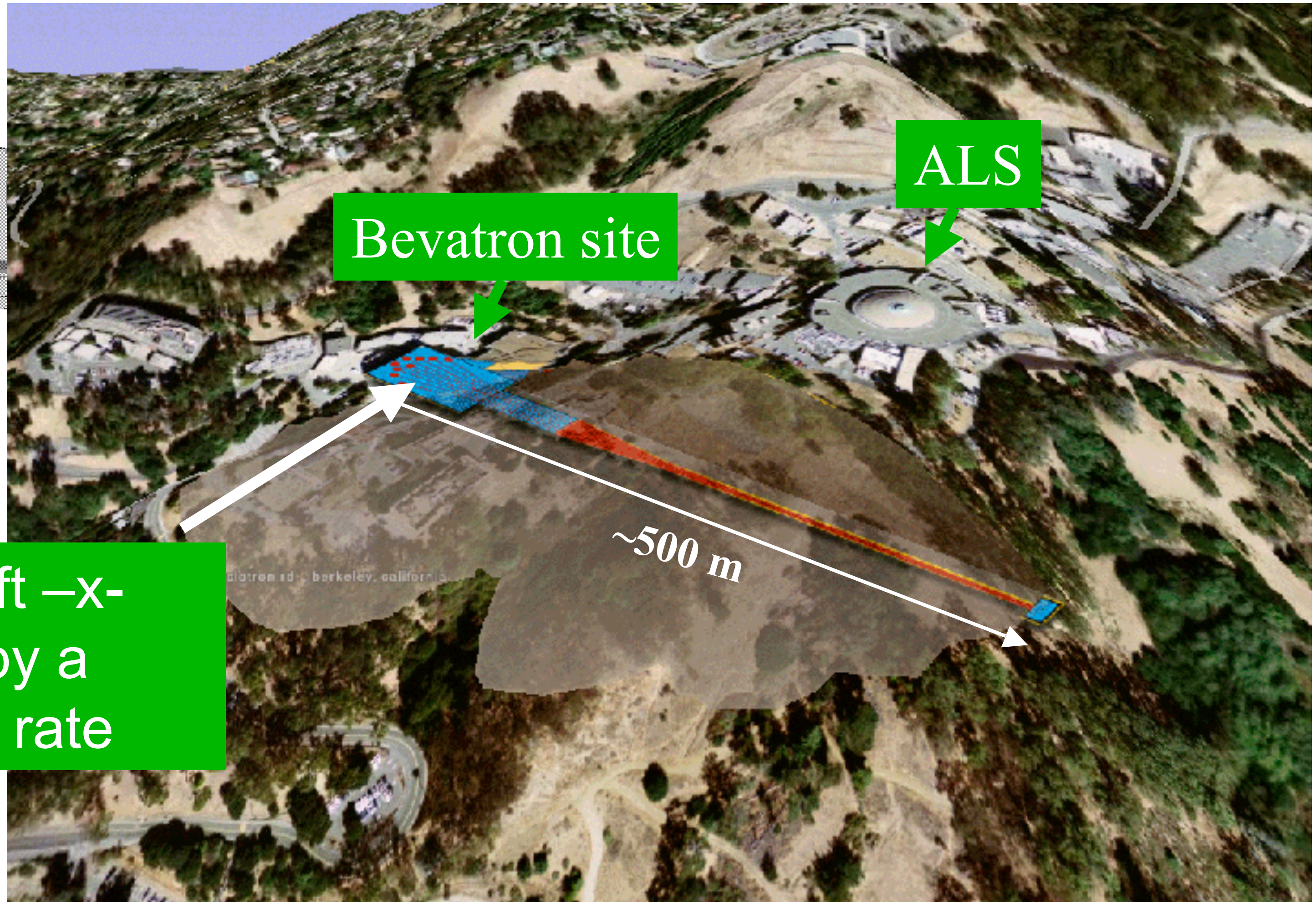
- Equipment assembled on ALS shielding
- ML laser locked to ALS RF
- Initial results observed with modulation of beam signal onto CW laser
- More results expected soon.

Summary

- Accelerators are ready to take advantage the revolution in optical metrology and telecomm technology
  - optical timing systems will be available for the next generation of light sources
    - LCLS, FLASH, XFEL, FERMI, SPARX (?)…
  - femtosecond lasers can be synchronized at the fsec level
  - distribution links can be (optically) stabilized to fsec level
  - results expected soon in synching remote mode-locked lasers
- Synchronization diagnostics have a bright future
  - streak cameras
  - electro-optic sampling techniques

Our future…





An array of soft –x-ray FELs fed by a high repetition rate

Aerial view of the Berkeley Laboratory