Synchronization Part II

S. Simrock
DESY, Hamburg, Germany

Lecture Schedule (March 2008)

- LLRF Part I (Requirements and Design)
  - March 6, 13:30
- LLRF Part 2 (Maschine Studies at FLASH)
  - March 7: 10:00
- LLRF Part 3 (LLRF for the XFEL)
  - March 11 at 13:30
- Timing and Sync. Part I (Concepts)
  - March 14 at 10:00
- <u>**Timing and Sync. Part II (Design)**</u>
  - <u>**March 17 at 10:00**</u>
- European XFEL (Project Overview)
  - March 26 at 13:30

Outline Synchronization Part II

- Summary of synchronization part I
  - Including remarks to timing
- Beam diagnostics
  - Overview
  - EOS/TEO
  - BAM (Beam arrival time)
- Design and Performance
  - FLASH/XFEL
  - LBNL
  - MIT

Summary Part I

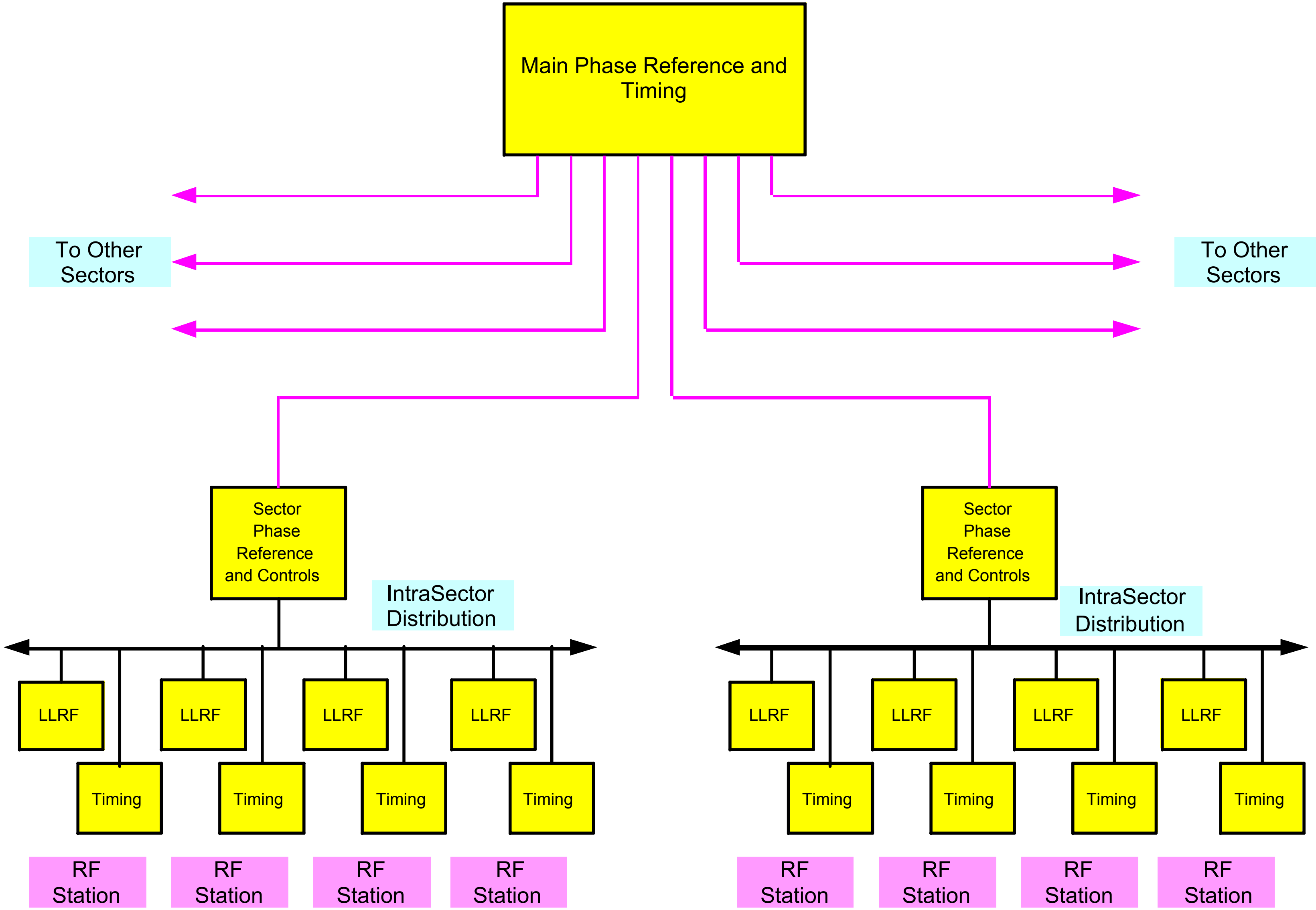
Motivation

- Timing System
  - **Generation and distribution of event triggers to subsystems**
    … Includes time stamps, pulse IDs and data
  - **Generation and distribution of stable clocks signals**
  - **Subsystems include lasers, rf systems, beam diagnostics, and experiments**
  - **Typical stability of the order of ps (clocks) to ns (trigger)**
- Synchronization
  - **Generation and distribution of frequency references**
  - **Generation and distribution of ultrastable phase references**
    … as zero crossings of sine wave or as short pulses
  - **Subsystems include lasers, rf systems, beam diagnostics, and experiments**
  - **Typical stability of the order of fs (phase) to ps (frequency)**

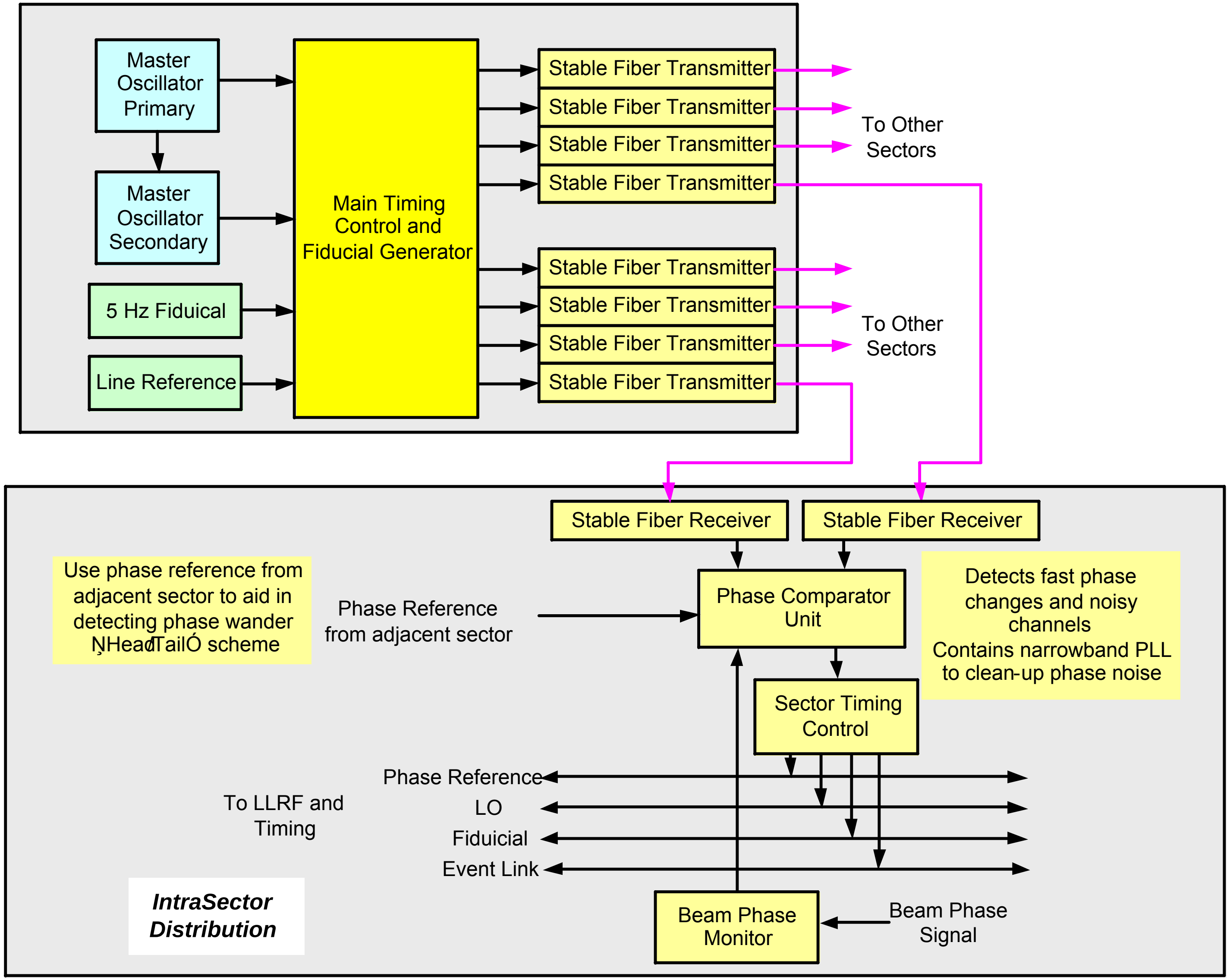
Timing and Synchronization Needs

		accelerator sub-systems						
		LL RF	mag. & PS	undul.	diags.	timing	lasers	ctrl
accelerator sections	inj	x	x		x	x	x	x
	low en linac	x	x		x	x		x
	bunch compr.		x		x	x		x
	linac	x	x		x	x		x
	spread		x		x			x
	hν gen		x	x	x	x	x	x
	beam lines				x	x	x	x

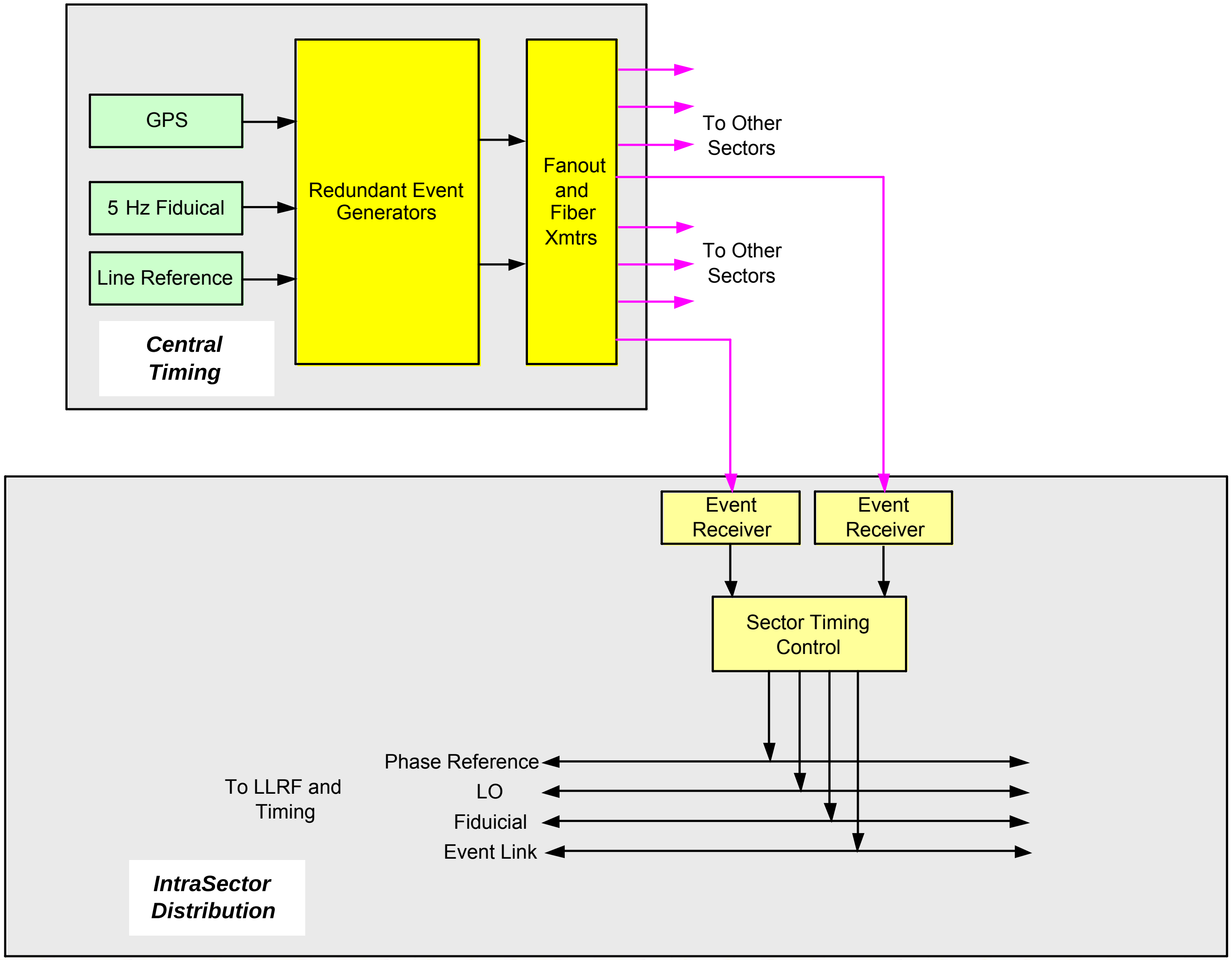
Timing system overview



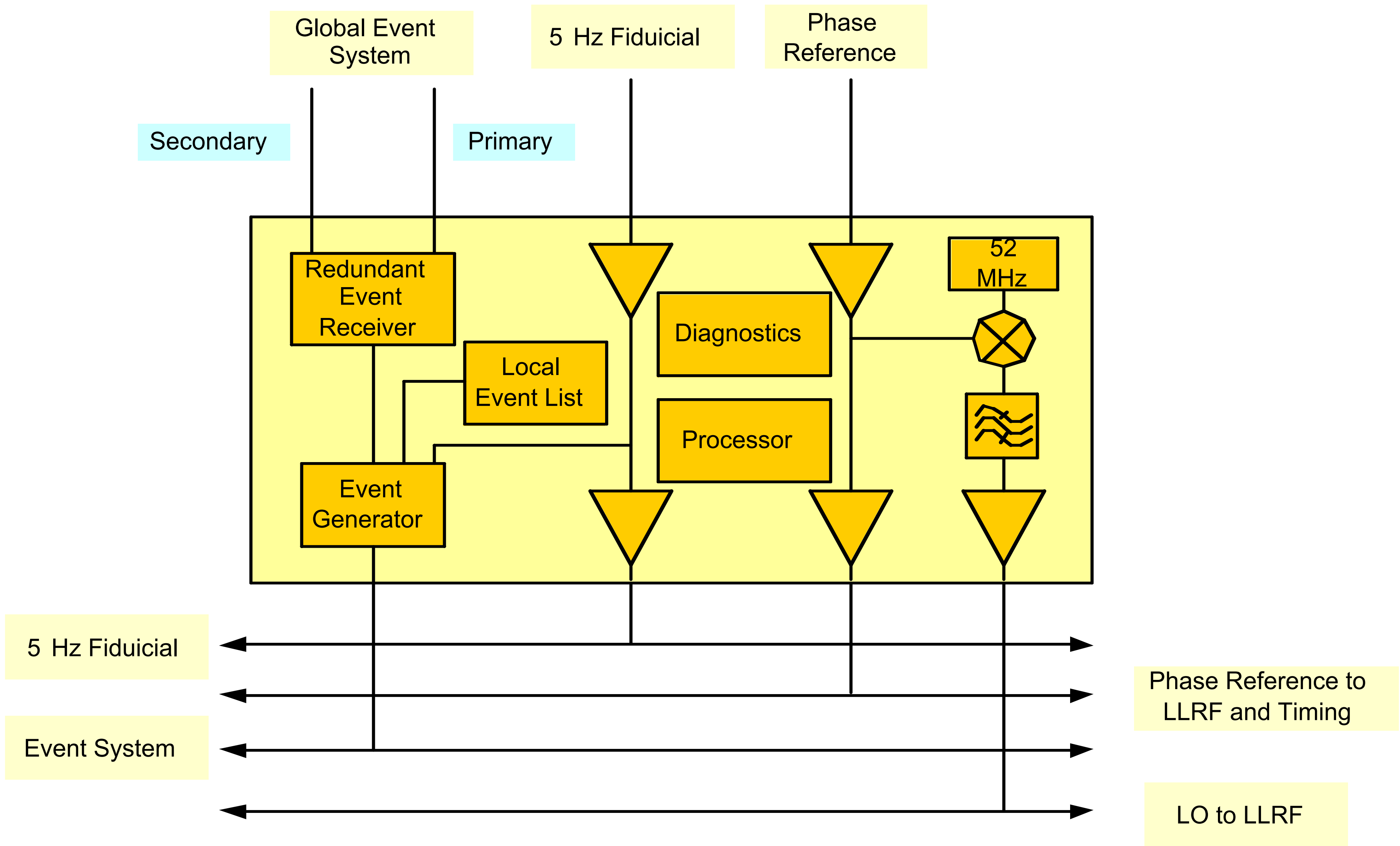
Redundant reference transmission with failover



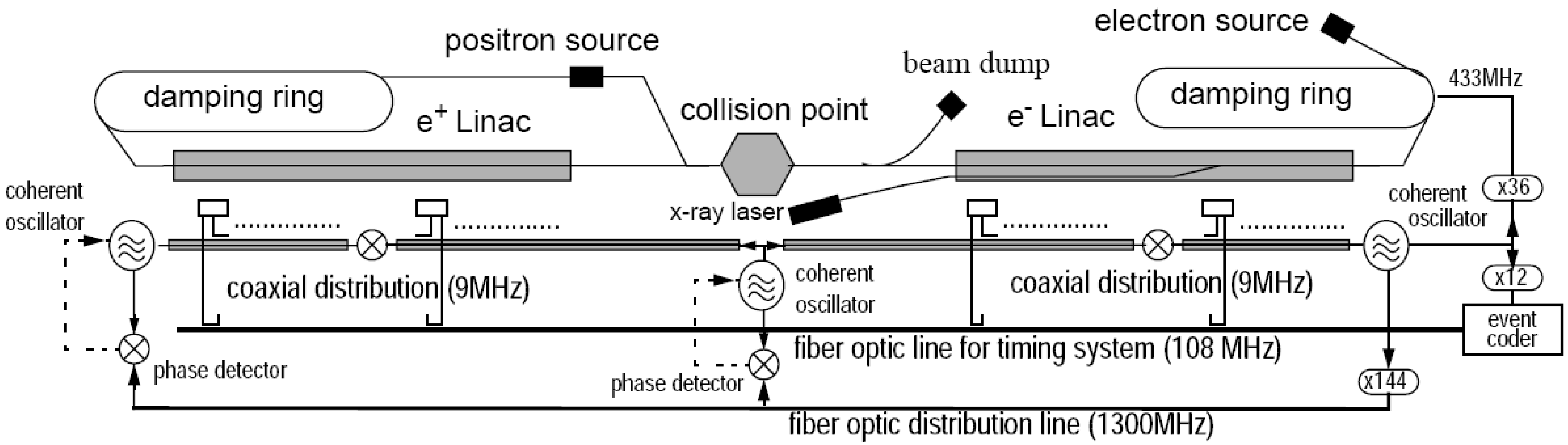
Redundant event system distribution

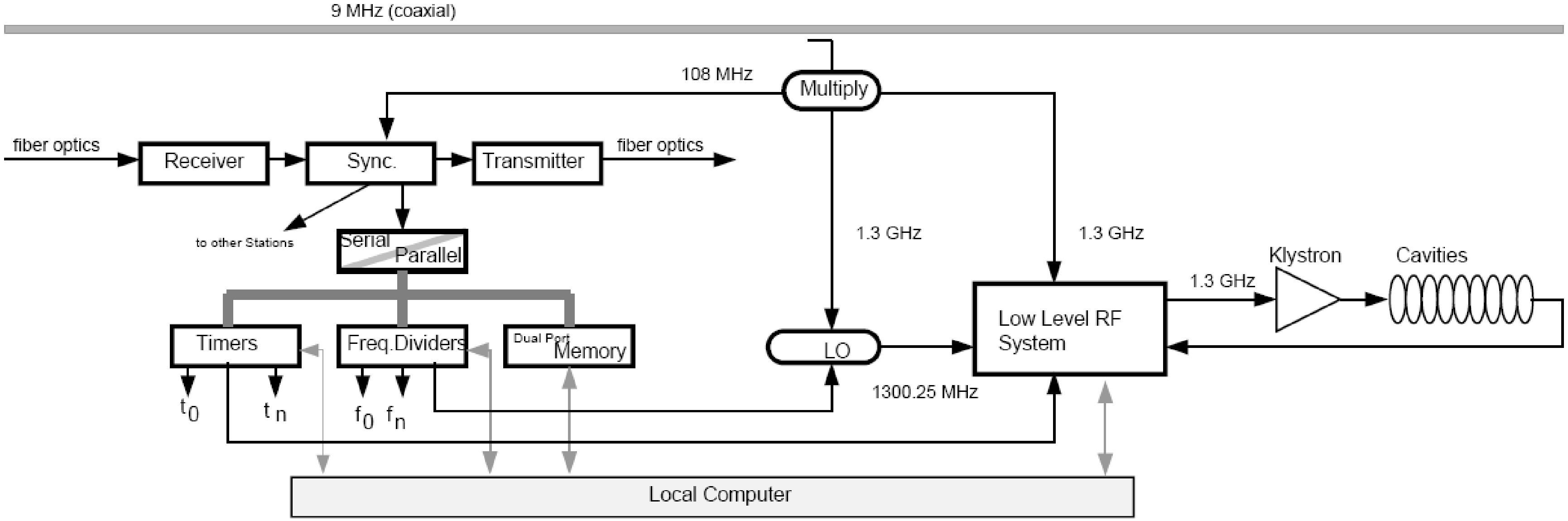


Sector timing controller



Synchronization Concept TESLA (1996)



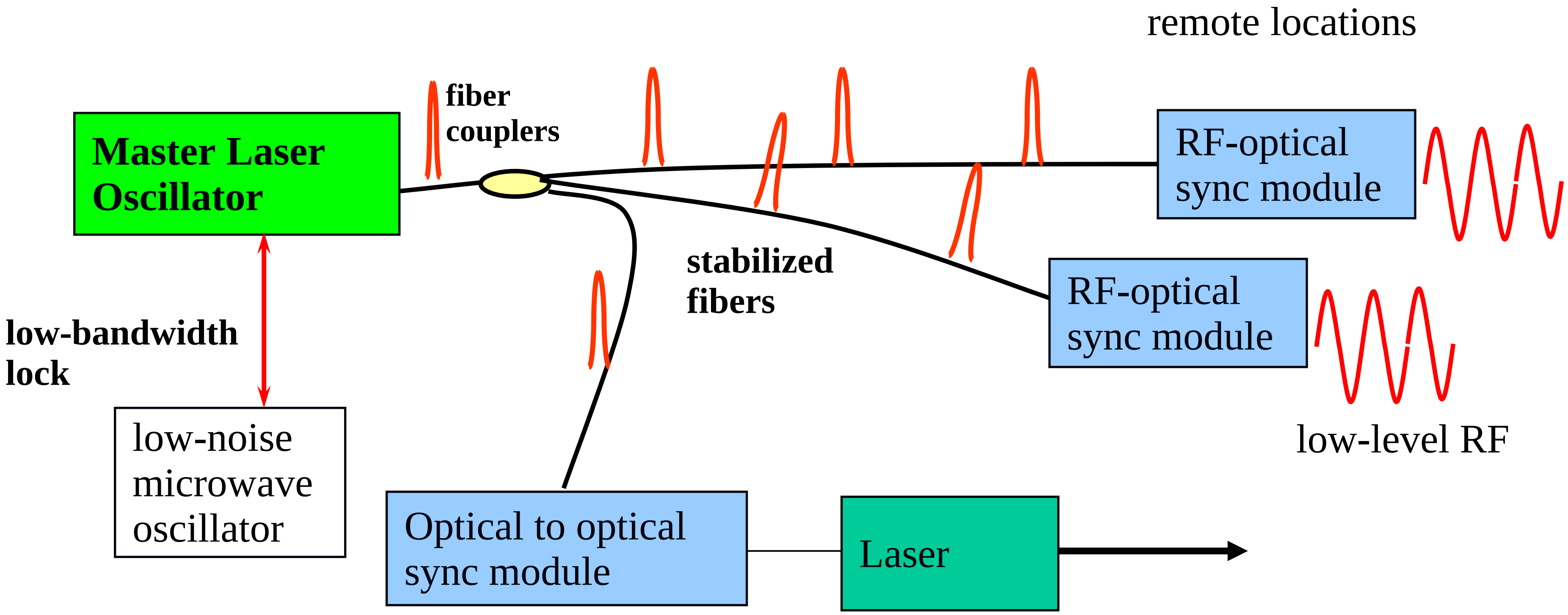


Why optical ?

- **Advantages:**
  - **Optical generation and transmission with better jitter and drift performance.**
  - **Not susceptible to EMI**
  - **Ground loop avoidance**
  - **Free benefit: Some diagnostics are only possible with optical references**

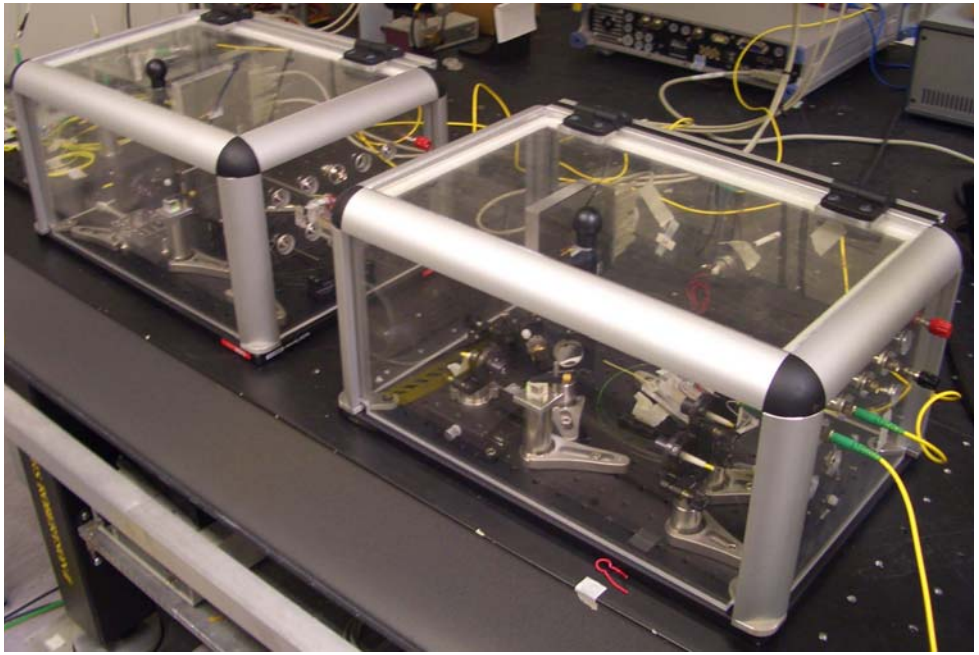
- **Disadvantages:**
  - **Only point to point links**
  - **More complex**
  - **Conversion to rf required**

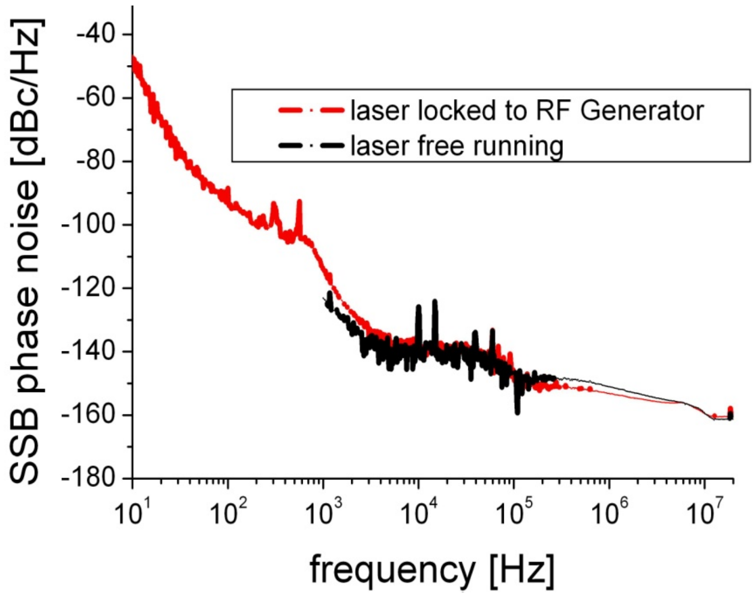
Synchronization System Layout



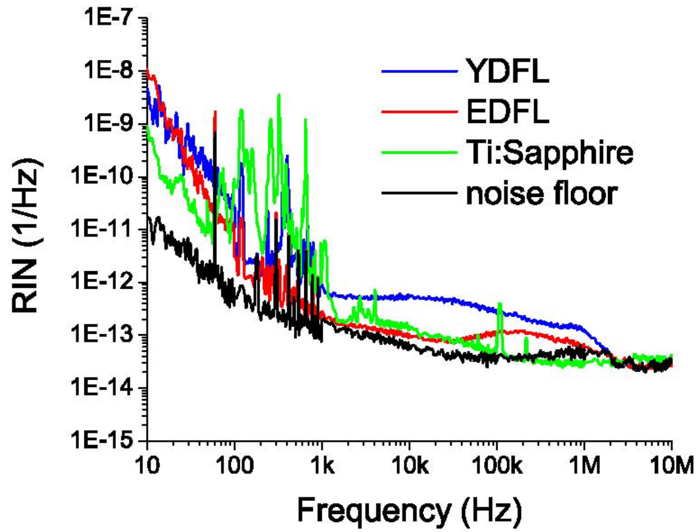
- A master mode-locked laser producing a very stable pulse train
- The master laser is locked to a microwave oscillator for long-term stability
- length stabilized fiber links transport the pulses to remote locations
- other lasers can be linked or RF can be generated locally

Laser Oscillator synchronized to MO

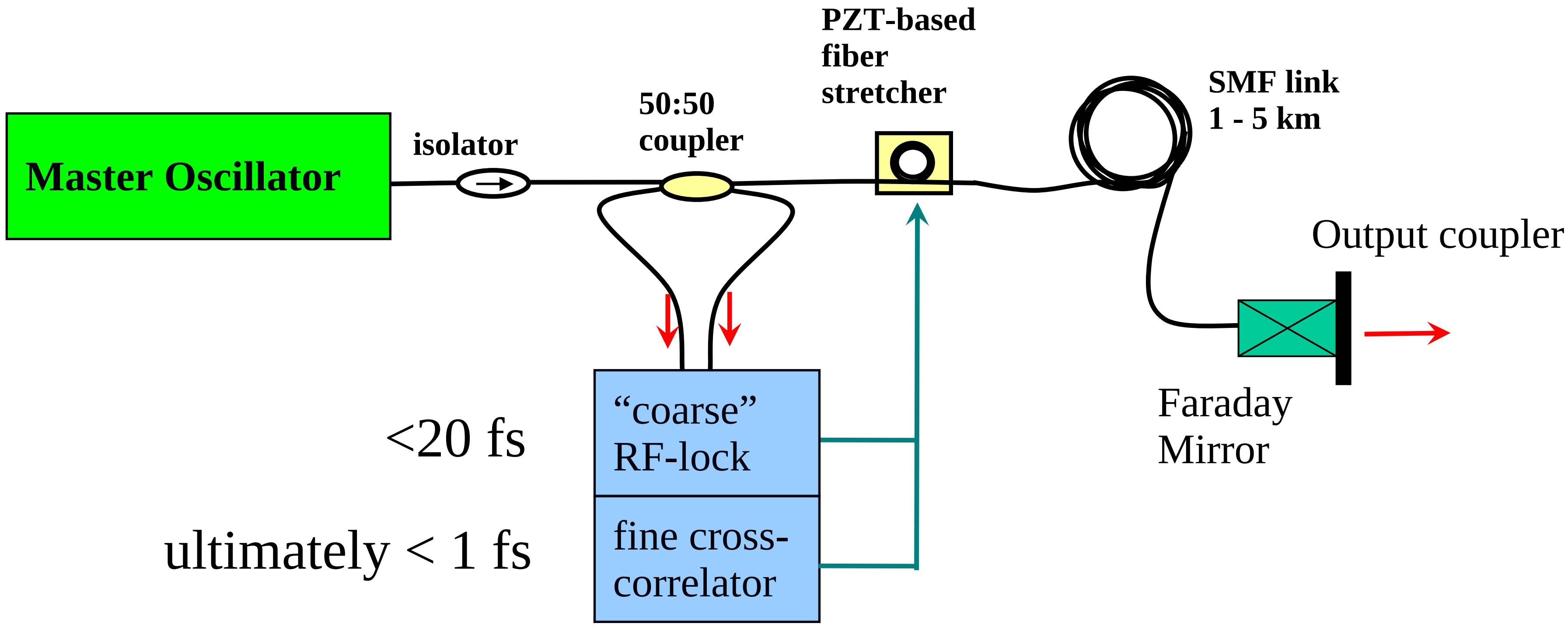




- Mode locked laser emits femtosecond laser pulses
- High pulse energy (~ 1 nJ)
- Pulse duration: ~ 100 fs FWHM
- Repetition rate: 30 -100 MHz
- Integrated timing jitter (1 kHz – 20 MHz) ~ 10 fs
- Integrated amplitude noise (10 Hz – 1 MHz): 0.03 %

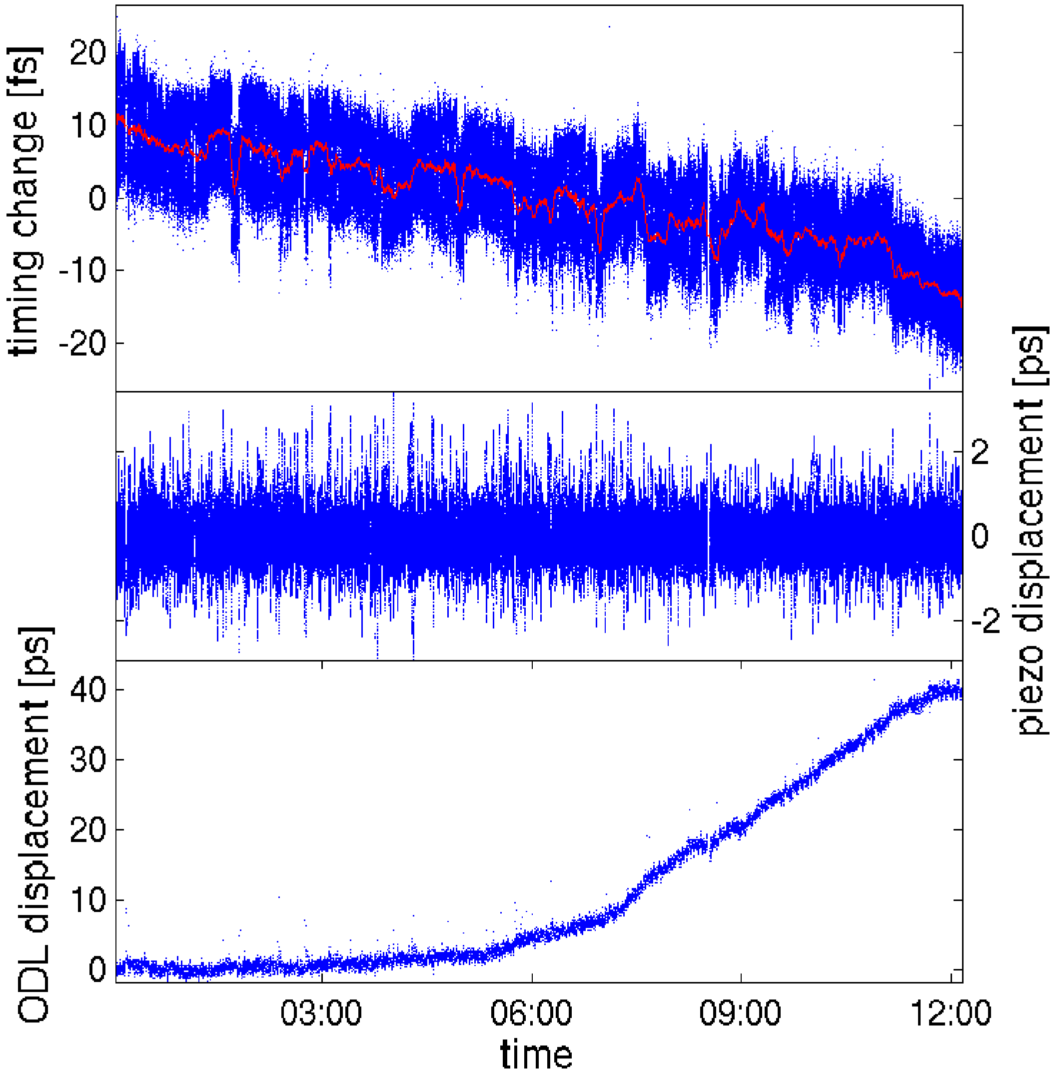


Timing stabilized fiber links



- Transmit pulses in dispersion compensated fiber links
- No fluctuations faster than T=2nL/c (causality!)
- L = 1 km, n = 1.5 => T=10 µs, f_{max} = 100 kHz
- Fiber temperature coefficient: $\sim 5\times10^{-6}$ /m   Lee et al. Opt. Lett. **14**, 1225-27 (1989)

Fiber link stabilization



Courtesy F. Loehl, DESY

- 400 meter stabilized test link in Hall 1 at DESY
- Jitter 7.5 fs rms during 12 hours
- Additional 25 fs rms drift during that time

Demonstrated timing stability

item	dev. at	value [fs_{RMS}]	bandwidth	notes
μ-wave ref. osc.	off-the-shelf	<10	100-10MHz	f_C=10GHz
Optical Master Clock	MIT/ DESY	10 <20	1kHz-Nyq. 1kHz-Nyq.	Er Fiber laser Er/Yb glass laser
Fiber Optic stabilized link	MIT field test at MIT-BATES	12	0.1Hz-10kHz	group delay stabilization
	LBNL	<2/°C 0.1/h	L=200m long term drift	phase delay stabilization
RF over FO trans-mission	MIT	8.8±2.6	1Hz-1MHz	Optical to RF conversion
	LBNL	15	1kHz-40MHz	11fs noise of the RF source

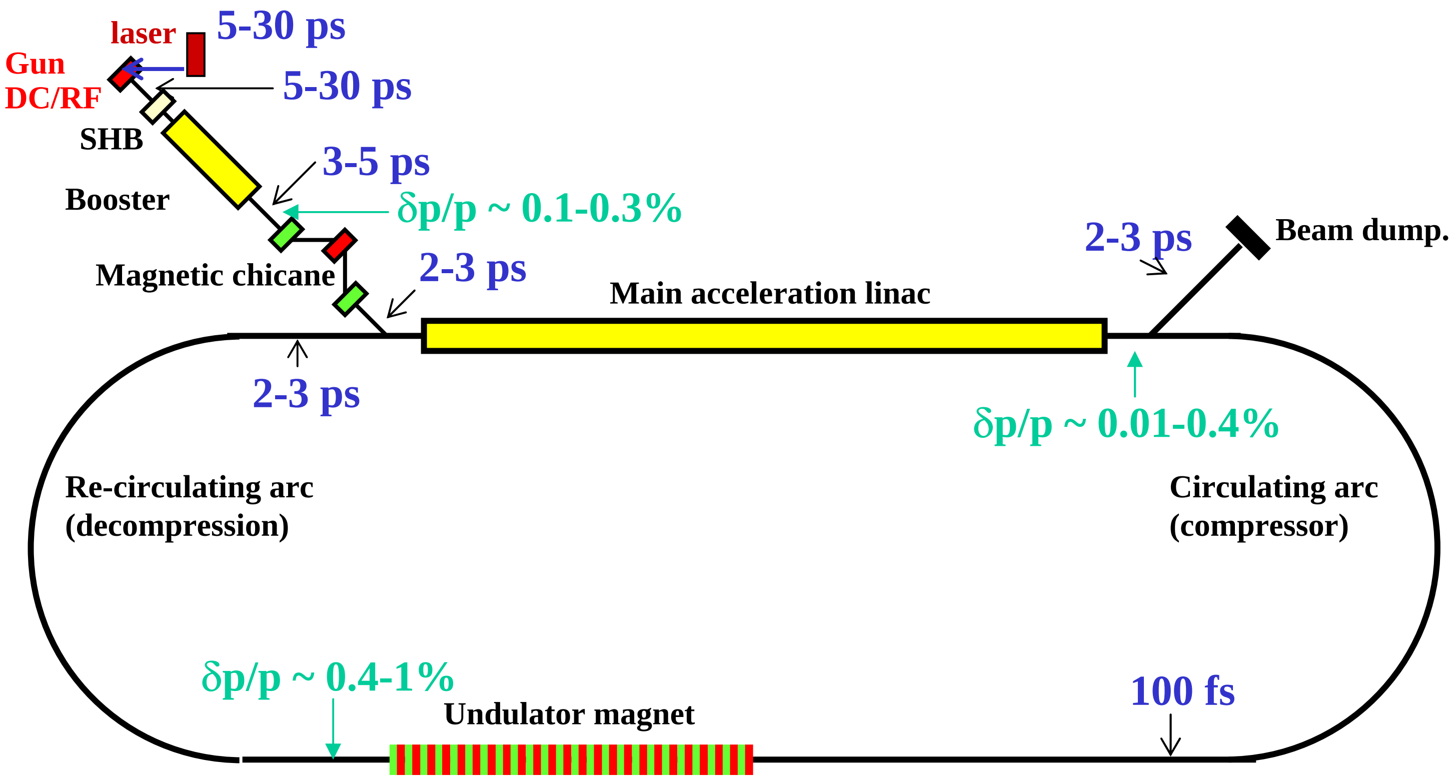
Beam Diagnostics

Overview on the longitudinal diagnostics for ERLs

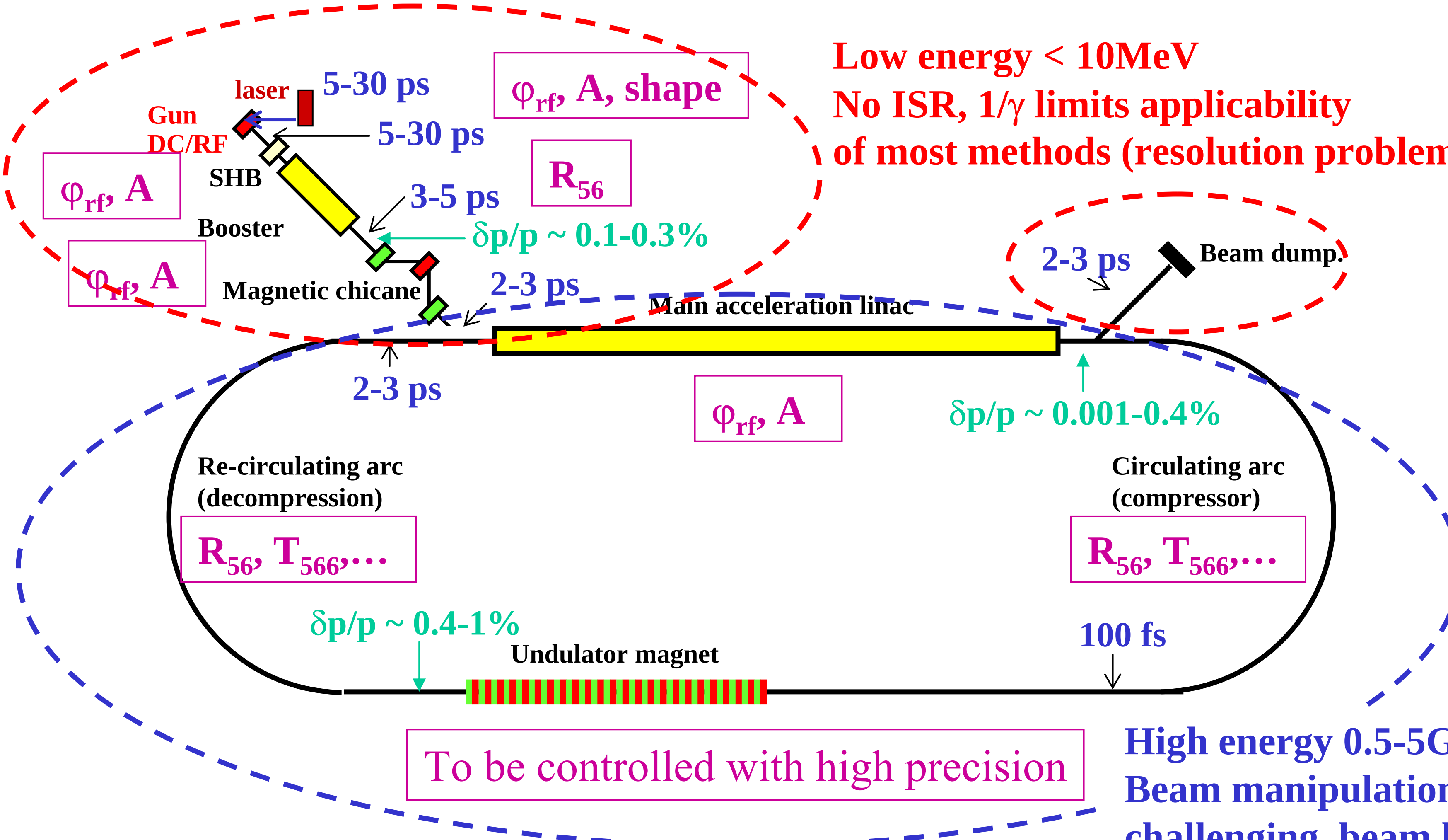
Holger Schlarb
DESY
22607 Hamburg

- introduction
- injector & energy spread
- coherent radiation diagnostics and feedback
- ultra-short pulse diagnostics

Prototype Layout for ERL



Prototype Layout for ERL



Low energy < 10MeV
No ISR, 1/γ limits applicability of most methods (resolution problems)

High energy 0.5-5GeV
Beam manipulation more challenging, beam highly destructive,
10fs resolution desired!

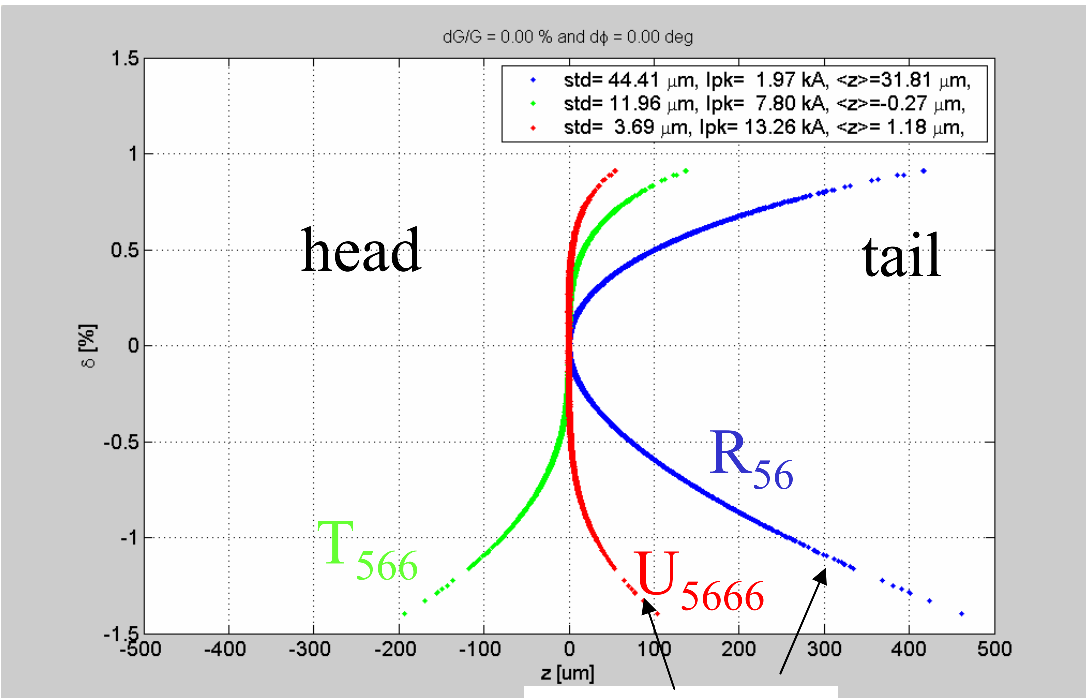
Bunch compression

Low energy spread can cause trouble …

I spike $\rightarrow$Min(σ_z) $\propto$ σ_{E0}/E, CSR: dE/E $\propto$ min(σ_z)$^{-4/3}$/E $\propto$ E$^{1/3}$

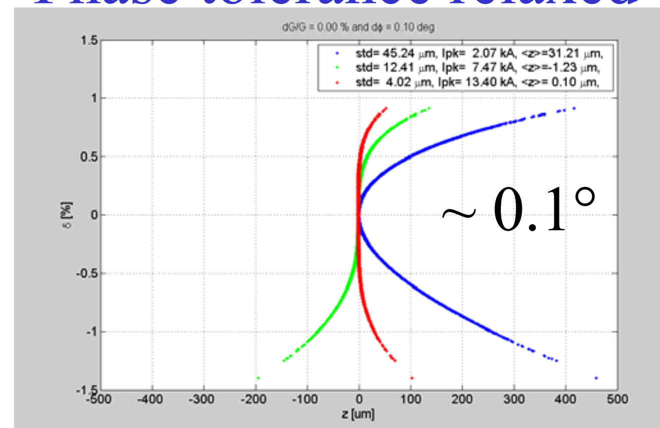
$\Rightarrow$Effect increase with energy

Example: CHESS, E=5.3GeV, σ_{E0}=10keV, 77pC

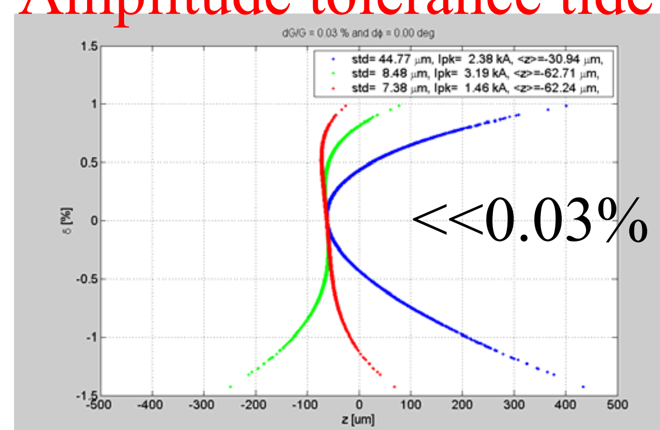


Cross over

Phase tolerance relaxed



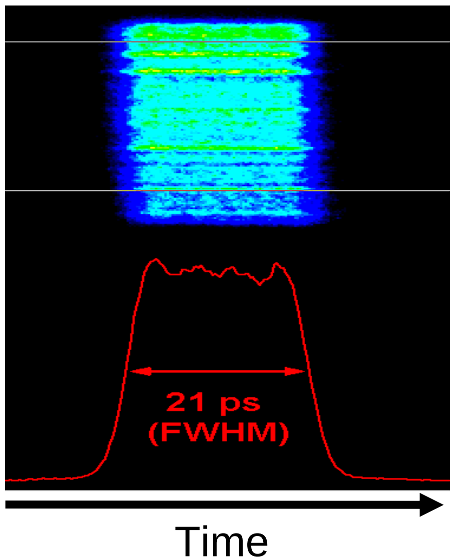
Amplitude tolerance tide

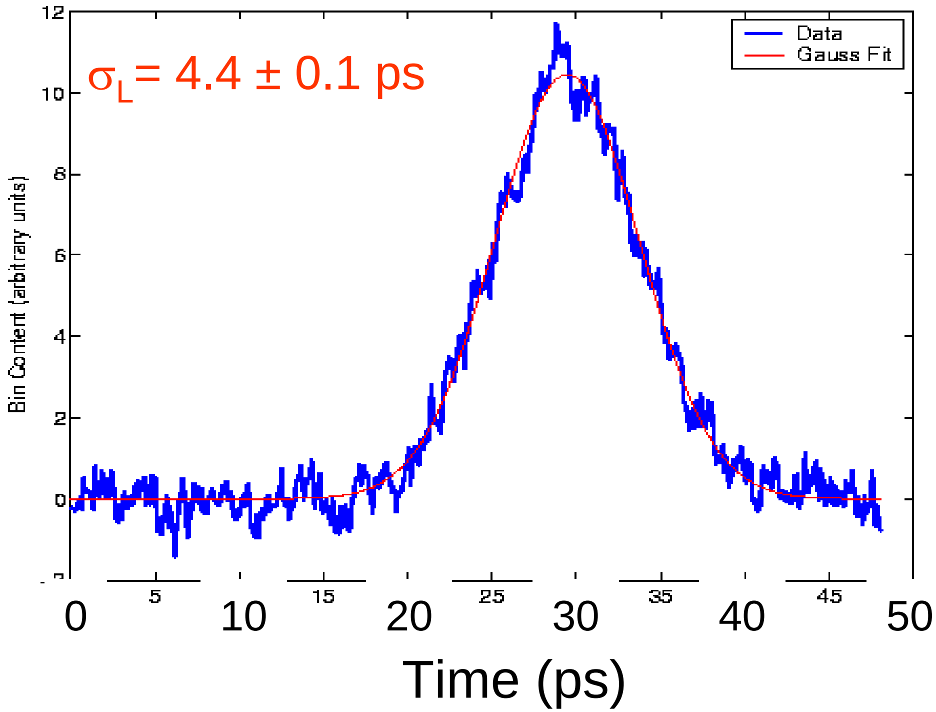


Longitudinal laser profile

Streak camera:

- UV single laser pulse, measured with a streak camera (FESCA 200)
- Average over 50 measurements gives $\sigma_L = 4.4 \pm 0.1$ ps (as expected)
- Longitudinal shape is Gaussian
- Or flat hat profile …





Optical techniques:

- if laser pulses shorter than 1 ps

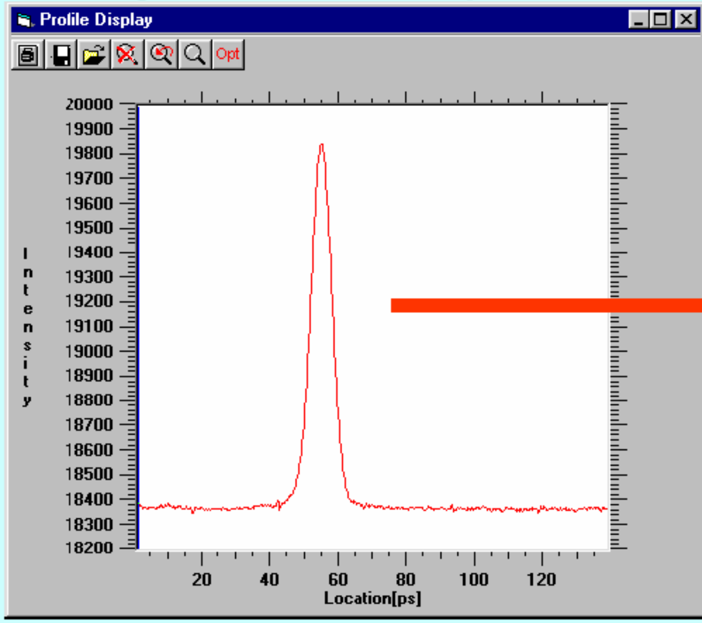
⇒ SHG auto-correlation

⇒ FROG

to achieve higher resolution.

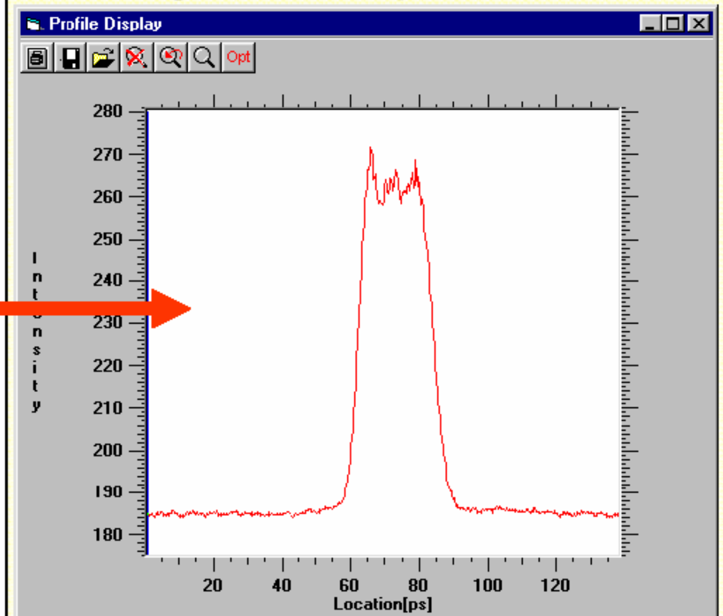
Longitudinal laser profile

Until 23.06.2003 - Gaussian longitudinal laser shape:



FWHM = 7 ± 1ps

On 23.06.2003 longitudinal shape changed to flat top



FWHM ≈ 18-23 ps
rise and fall time about 5-8 ps

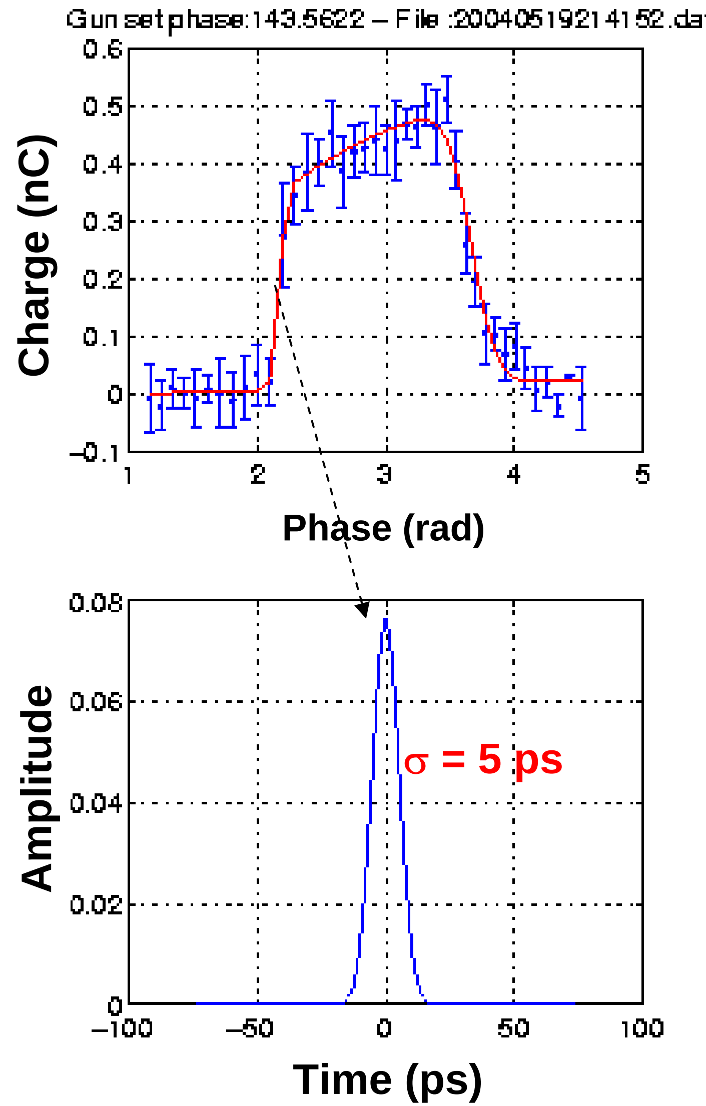
Minimum measured emittance

≥ 3 mm mrad

1.6 mm mrad

Phasing of RF gun

- Measure charge output of the gun as a function of phase laser/gun RF
- Important and fast method to
  - → determine the phase of the laser in respect to the gun RF
  - → to detect longitudinal problems of the laser (satellites, phase jitter etc.)
- We use a fit to the expected shape to chose the right phase:
  - → reproducibility = ± 1.3° (rms)
- It gives an estimate of the laser pulse length from the derivative of the rising edge
- Invasive ⇒ relevant commissioning



Energy spread measurements

- Screen in dispersive section + tight focusing
- Spectrometer dipole with 60° bend
- Dispersion at OTR screen D = -1.367m
- Diagnostics: BPMs and toroids
- Quadrupole triplet used to focus the beam

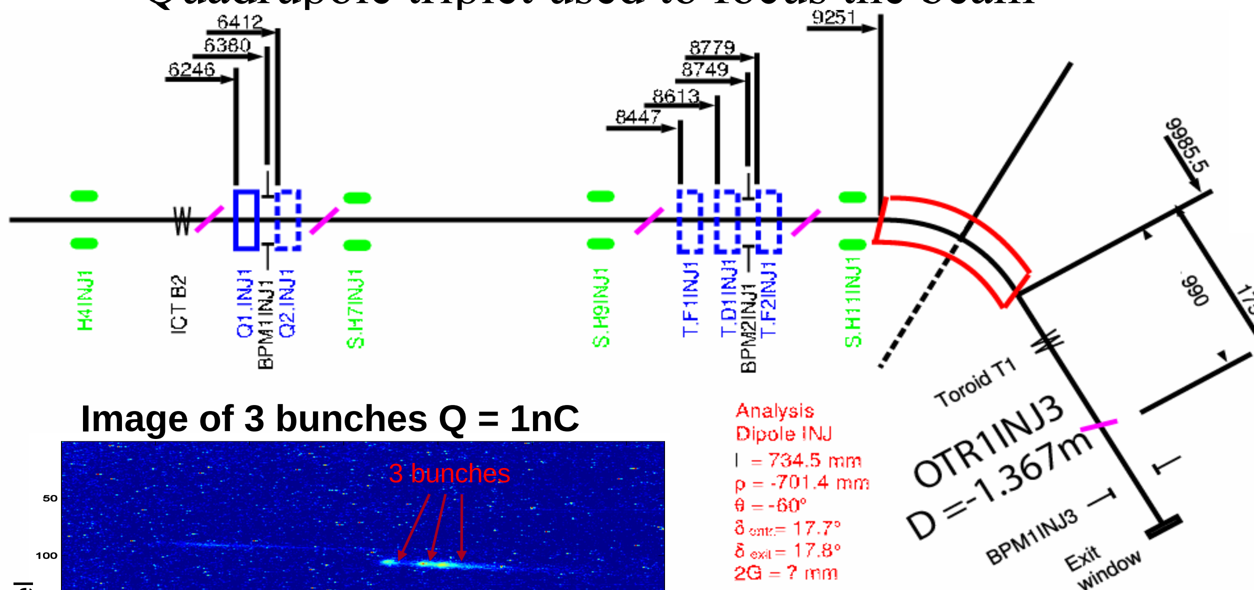
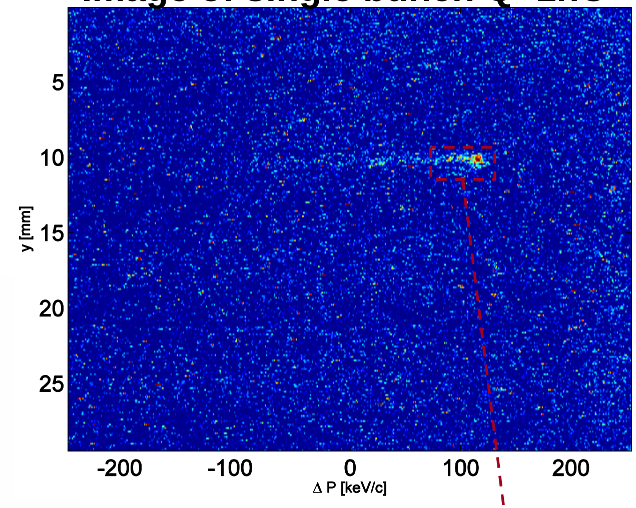


Image of single bunch Q=1nC



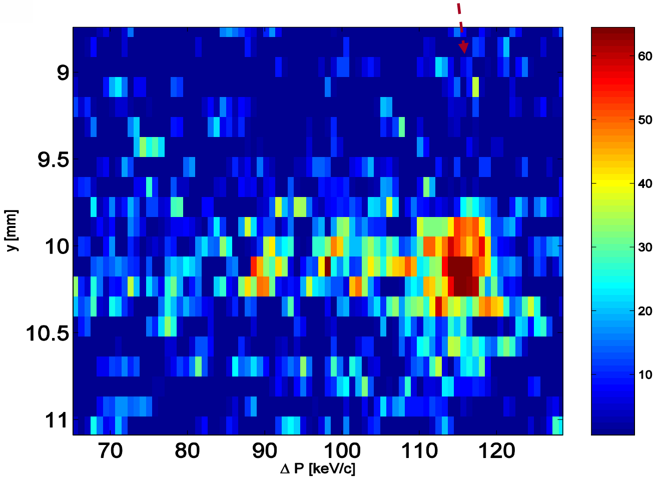
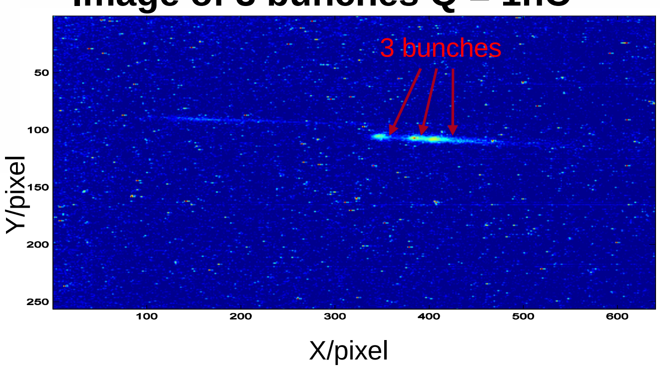


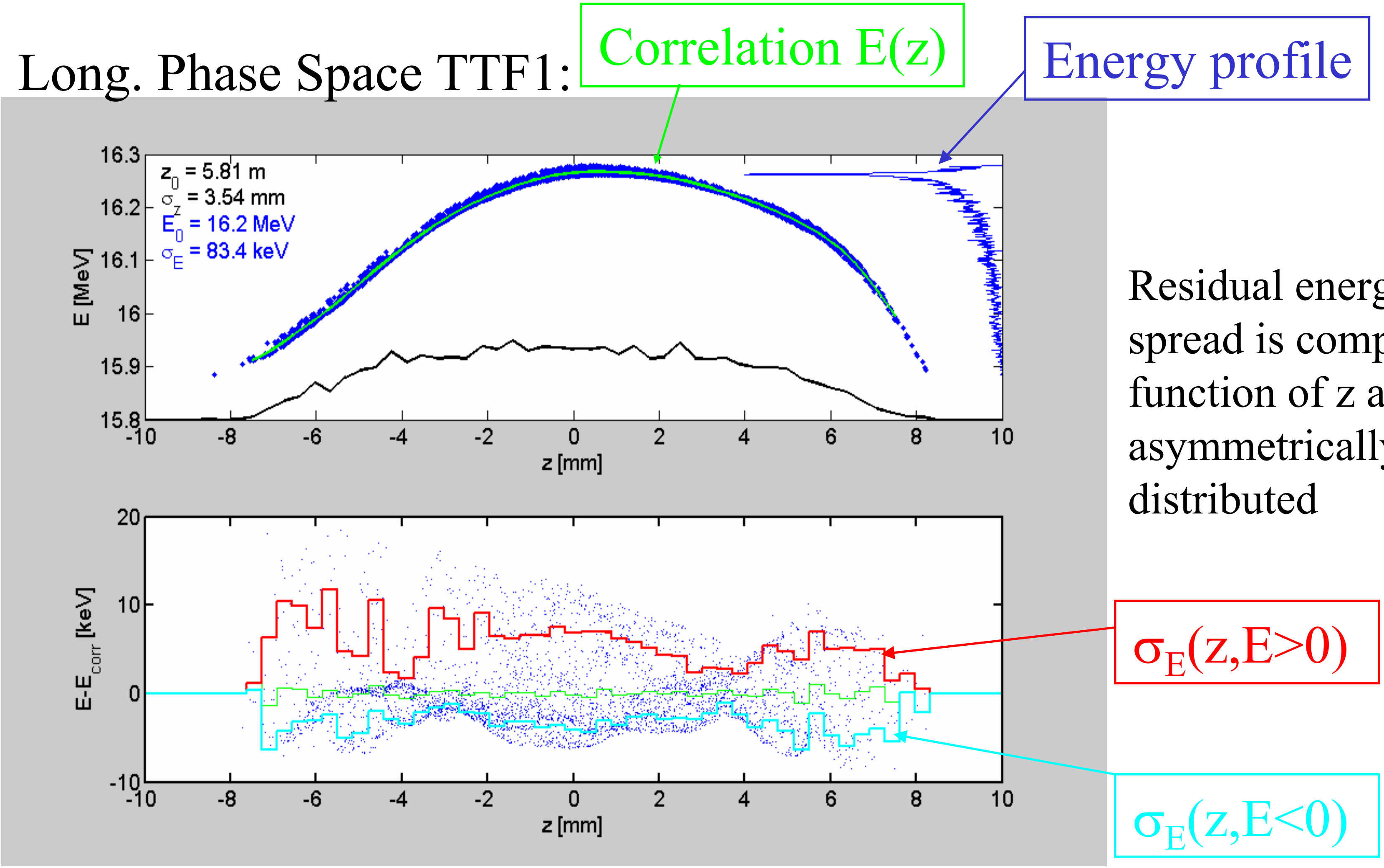
Image of 3 bunches Q = 1nC



Large low energy tail of about 100 keV but very small residual energy spread 2-4 keV (rms)

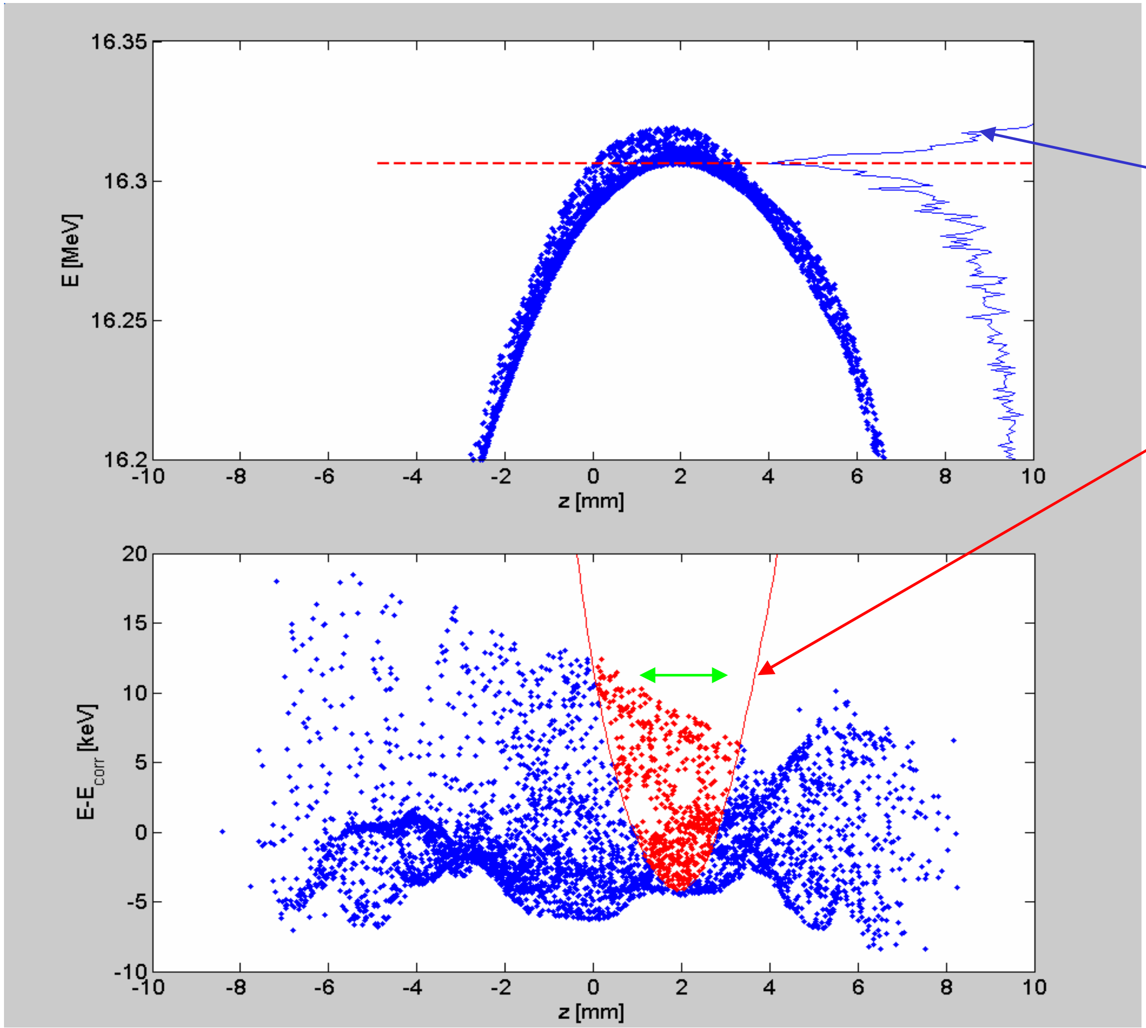
Energy spread measurement - correlated & residual -

Long. Phase Space TTF1:



Residual energy spread is complex function of z and asymmetrically distributed

Energy spread measurement - residual -



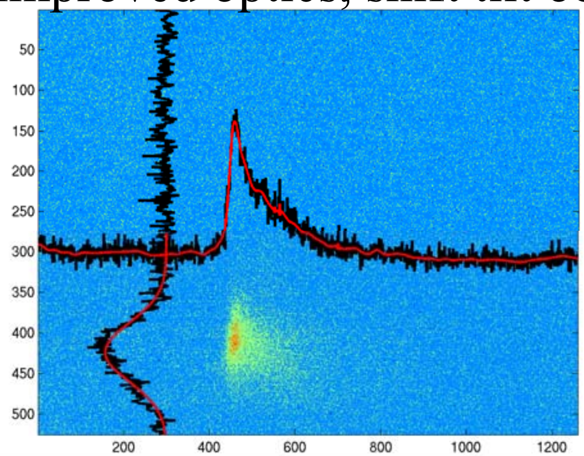
Rising of energy profile is determined by the residual energy spread of particles surround by parabola

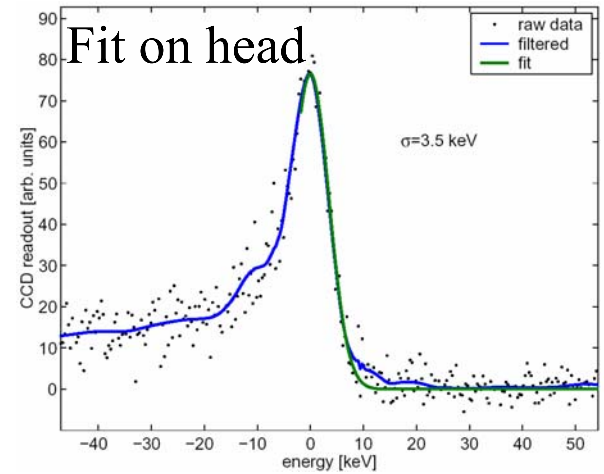
Rms width of surround particles amounts to $\sigma_{z,para} = 0.68$ mm

$\Rightarrow$ slice of $0.2^* \sigma_z$

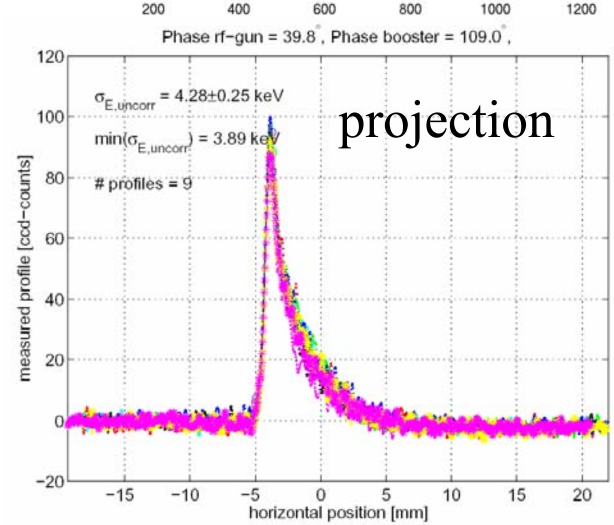
Energy spread measurements - residual -

Improved optics, shift tilt obj.

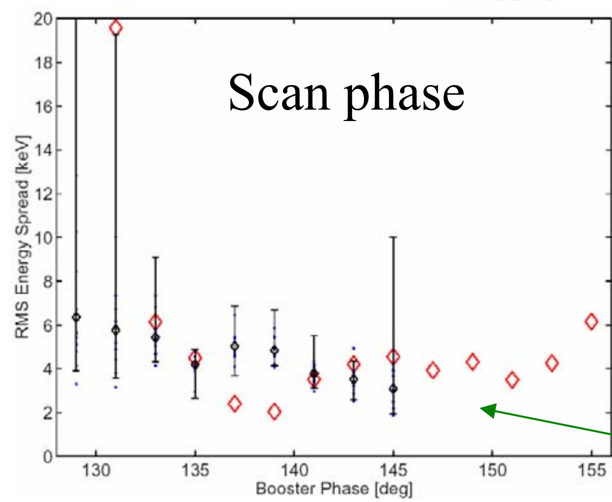




projection



Scan phase

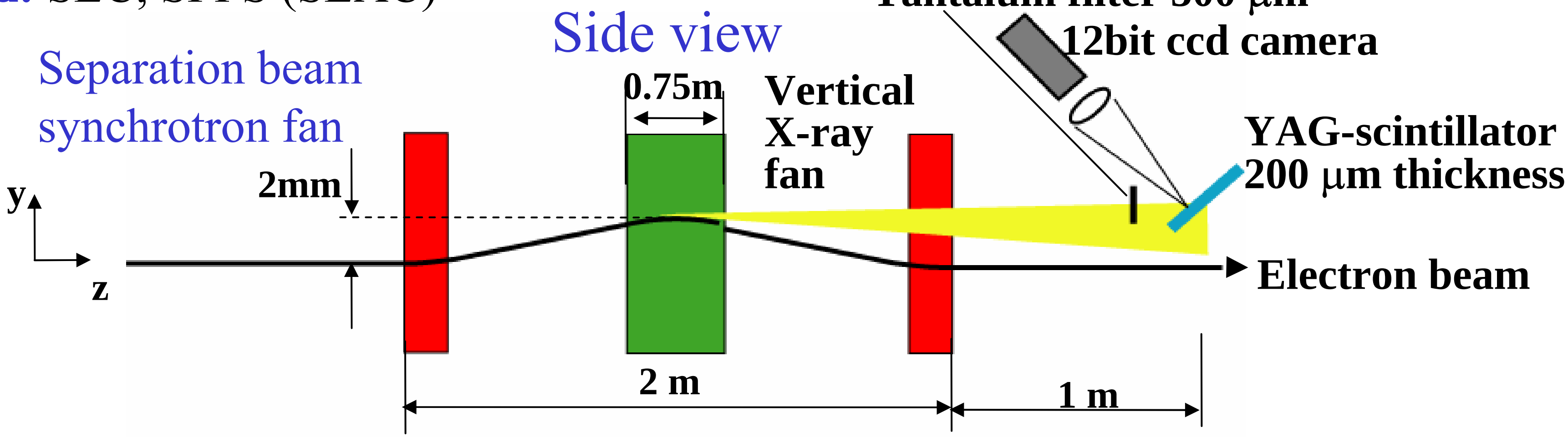


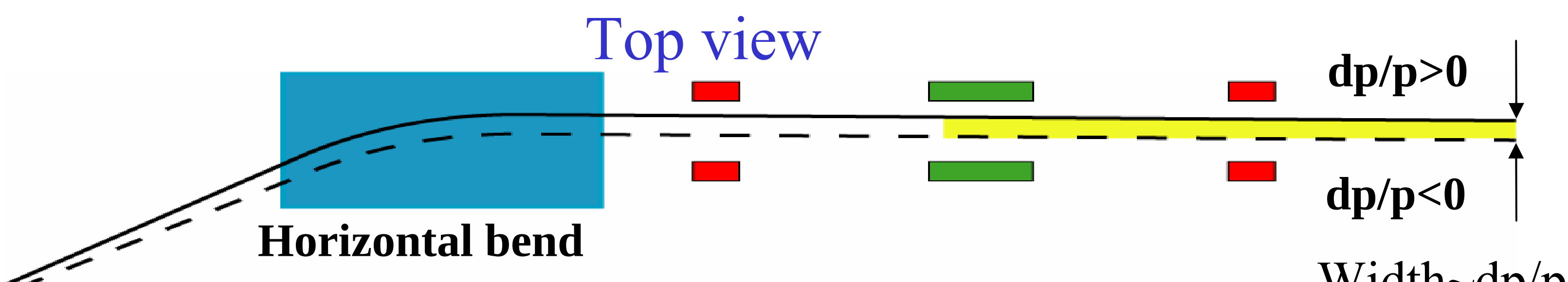
Conditions:
E = 16.3 MeV
Q = 3 nC
20 ps FWHM

2-5 keV

Energy spread measurement
-online using vertical chicane -

- **Goal:** online, non-interceptive beam energy spread measurement
- **Basic idee**: ISR produced in vertical chicane located in section with large horizontal dispersion
- **Tested:** SLC, SPPS (SLAC)

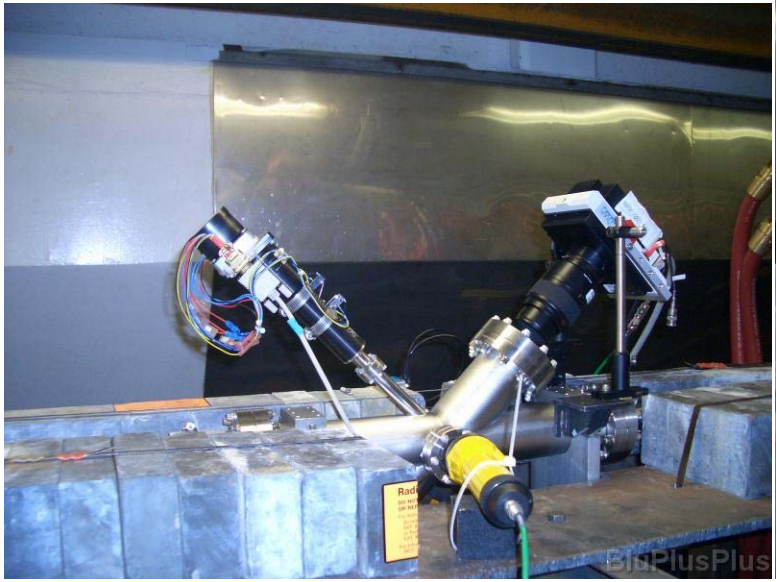




Experiment prepared by E164 group SLAC, C. Barns

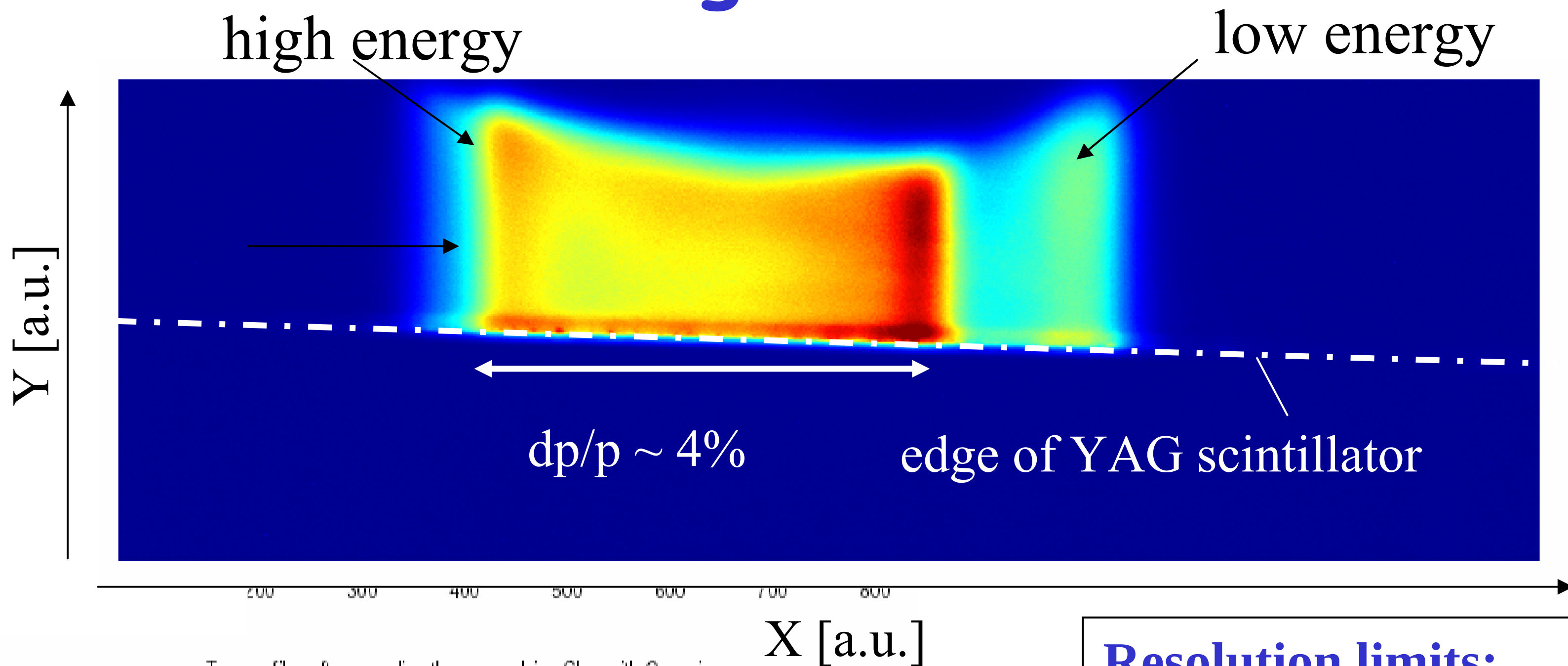
Energy spread measurement
-online using vertical chicane -

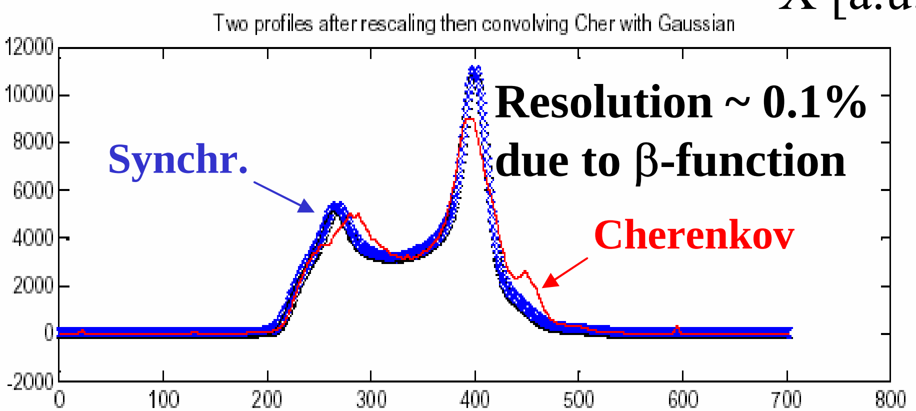
- installation in FFTB tunnel
- old wiggle used
- high resolution camera
- movable scintillator
- E = 28.5 GeV



Experiment prepared by E164 group SLAC, C. Barns

Energy spread measurement
-online using vertical chicane -





Resolution limits:

Beam size: $dp/p \sim \sigma_x/D_x$

Energy: $dp/p \sim \Delta z/\gamma$

(or x-ray imaging)

Blooming in YAG: ~ thickness

$dp/p < 10^{-4}$ possible

$dp/p \sim 10^{-5}$ challenging

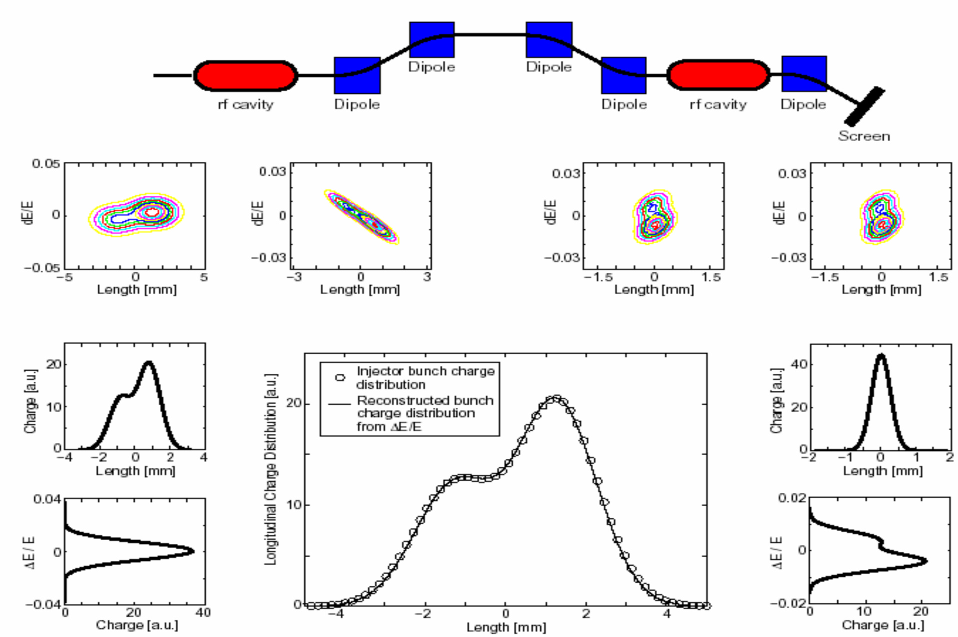
Experiment prepared by E164 group SLAC, C. Barns

Longitudinal tomography

Principle: 'rotation' of z-p phase space + imaging
reconstruction of long. phase space from profiles

Requires: complete picture only possible with $R_{56} \neq 0$

Ideal world:



Real world:

- compress change properties of z-p phase space (CSR, …)
- restricted to one accel. section
- limitation on acceptance of the beam line reduce projection to smaller angle (±60° is much)
- non-linear mapping

Longitudinal tomography

- Radon transformation: standard "Filtered back-projection algorithm"

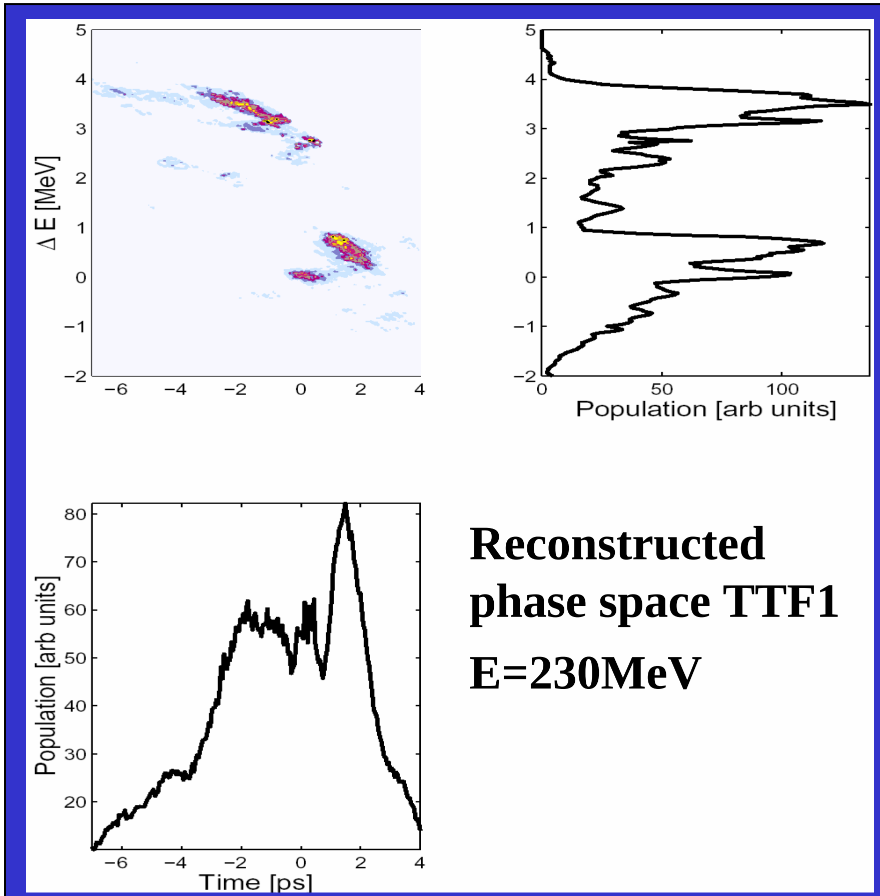
Better suited:

- ART: algebraic reconstruction technique, here
  MENT: Maximum Entropy Algorithm

(See i.e. J. Scheins, TESLA-Report 2004-08)

- Even complex structures can be can be reconstructed

- Disadvantage: multi-shot method, destructive

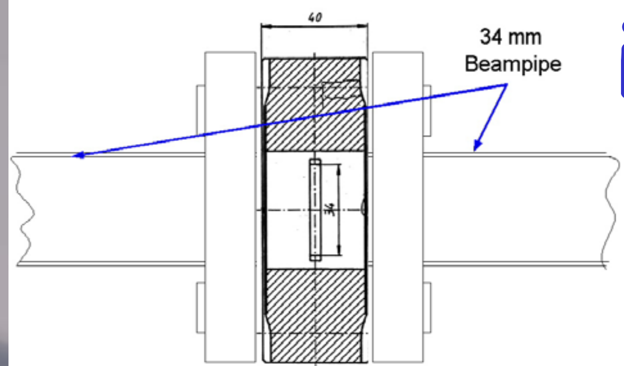


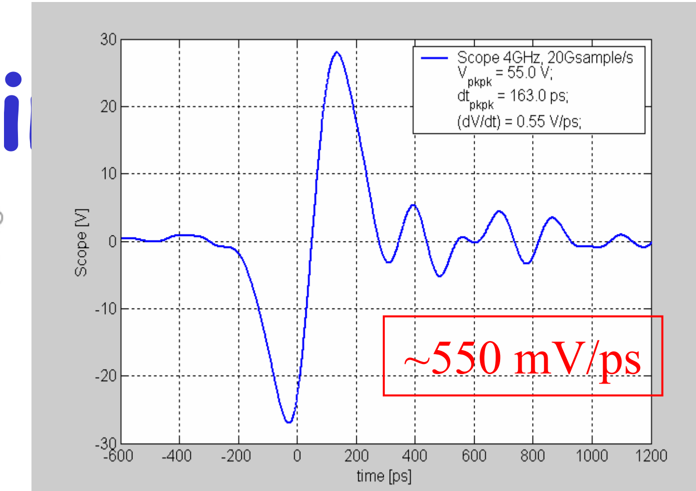
Reconstructed phase space TTF1

E=230MeV

PhD-Thesis, M.Hüning, 2002, Uni. HH

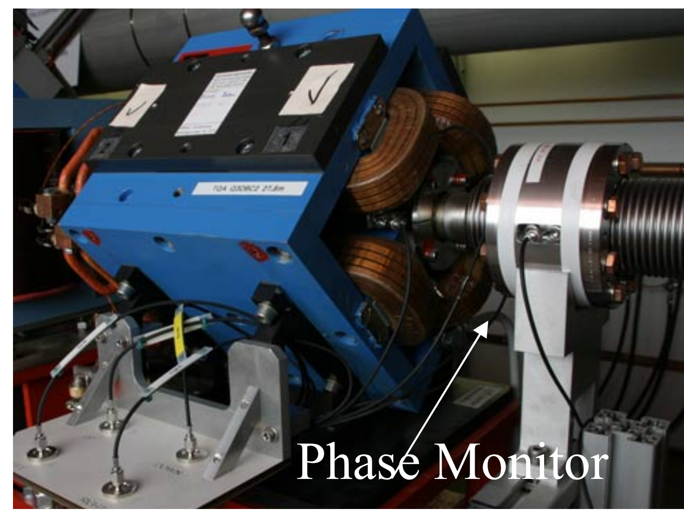
Phase monitor



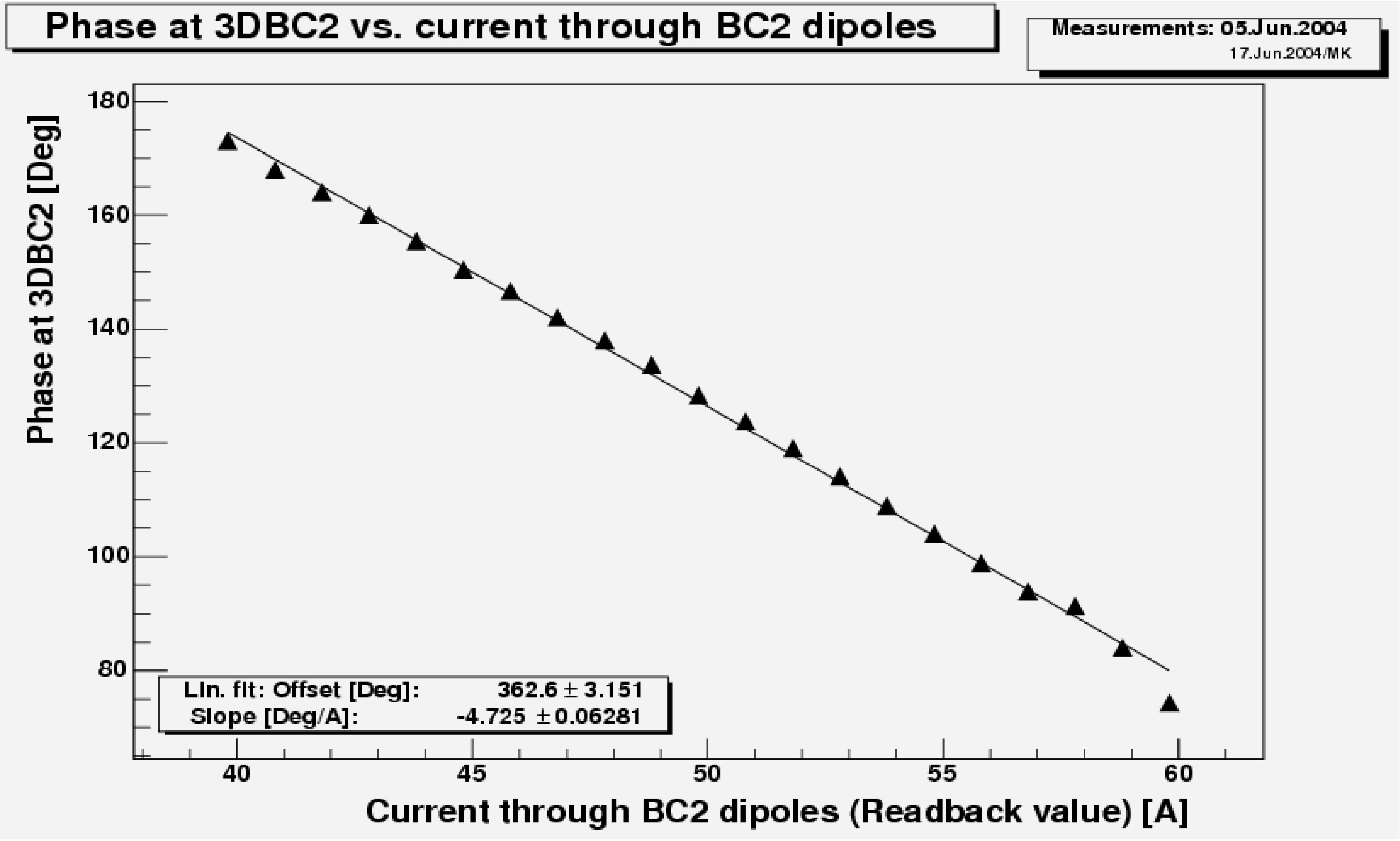


Principle:

- Isolated impedance-matched Ring Electrode installed in a „thick Flange“
- Broadband, Position independent Signal
- One installed after the Gun, each magnetic Chicane (both BCs, the Collimator + before Undulator)
- BC´s: Energy Fluctuations -> Phase Fluctuations TOF Measurement: Resolution ≈ 0.2° or 0.4 ps
- Fast timing signals with sub ps resolution



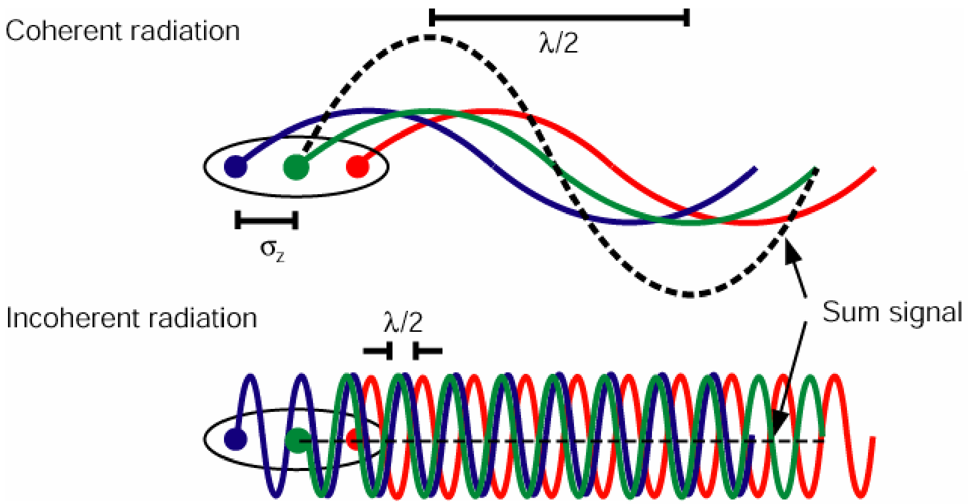
Phase monitor



Coherent radiation

Sources:

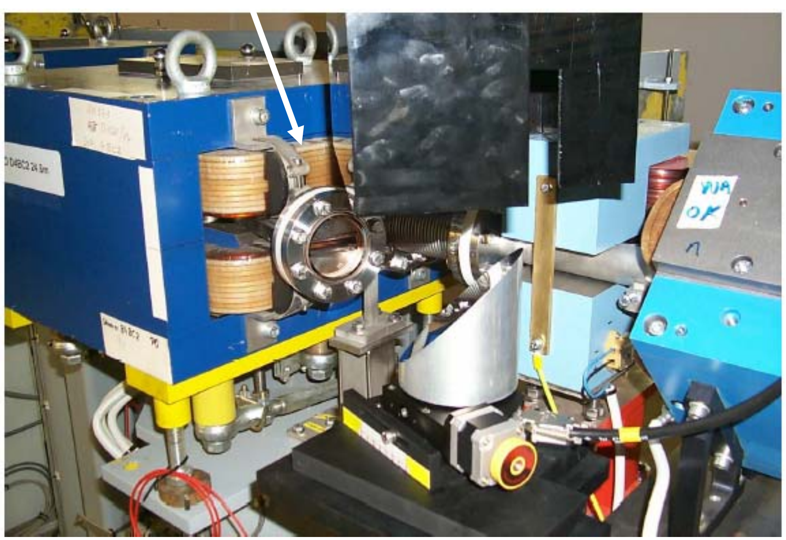
- coh. transition radiation
- coh. diffraction radiation
- coh. synchrotron
- FIR-undulator
- Smith-Purcel rad.
- edge radiation

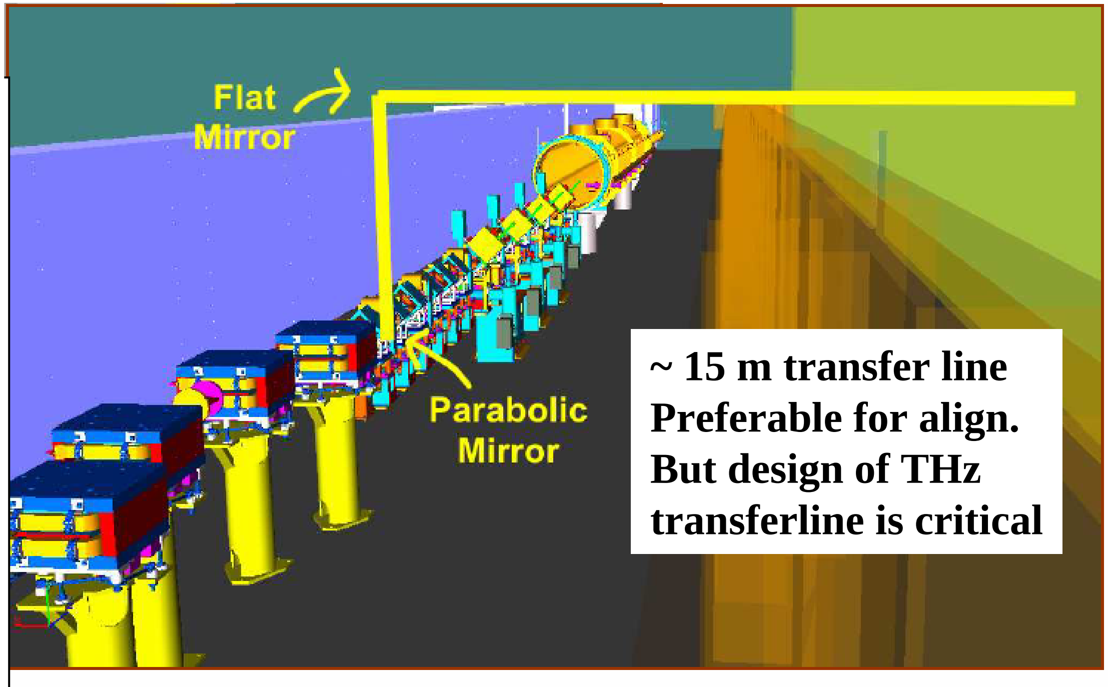


Purpose:

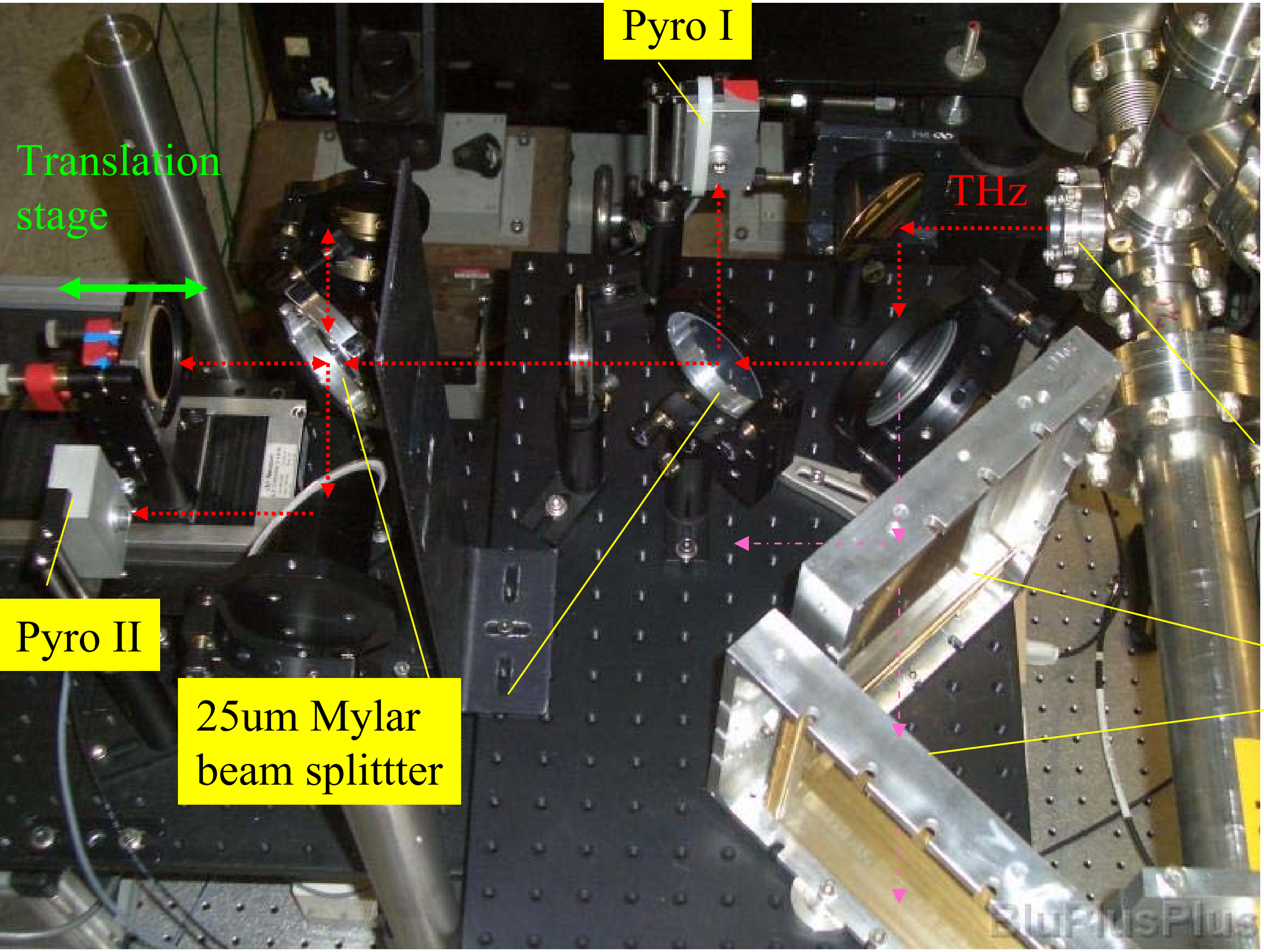
- longitudinal profiling
- compression monitor $P \sim 1/\sigma_z$

Z-cut quartz window/diamond/mylar

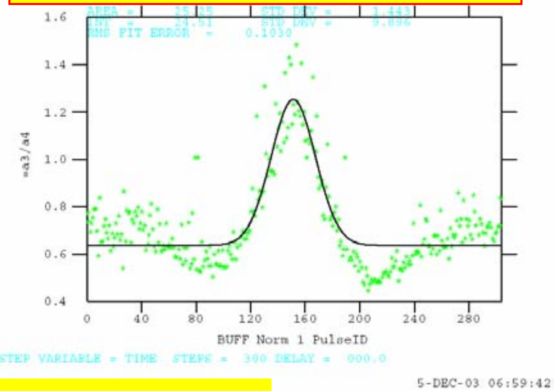




Bunch Length Diagnostics - Michelson Interferemeter-



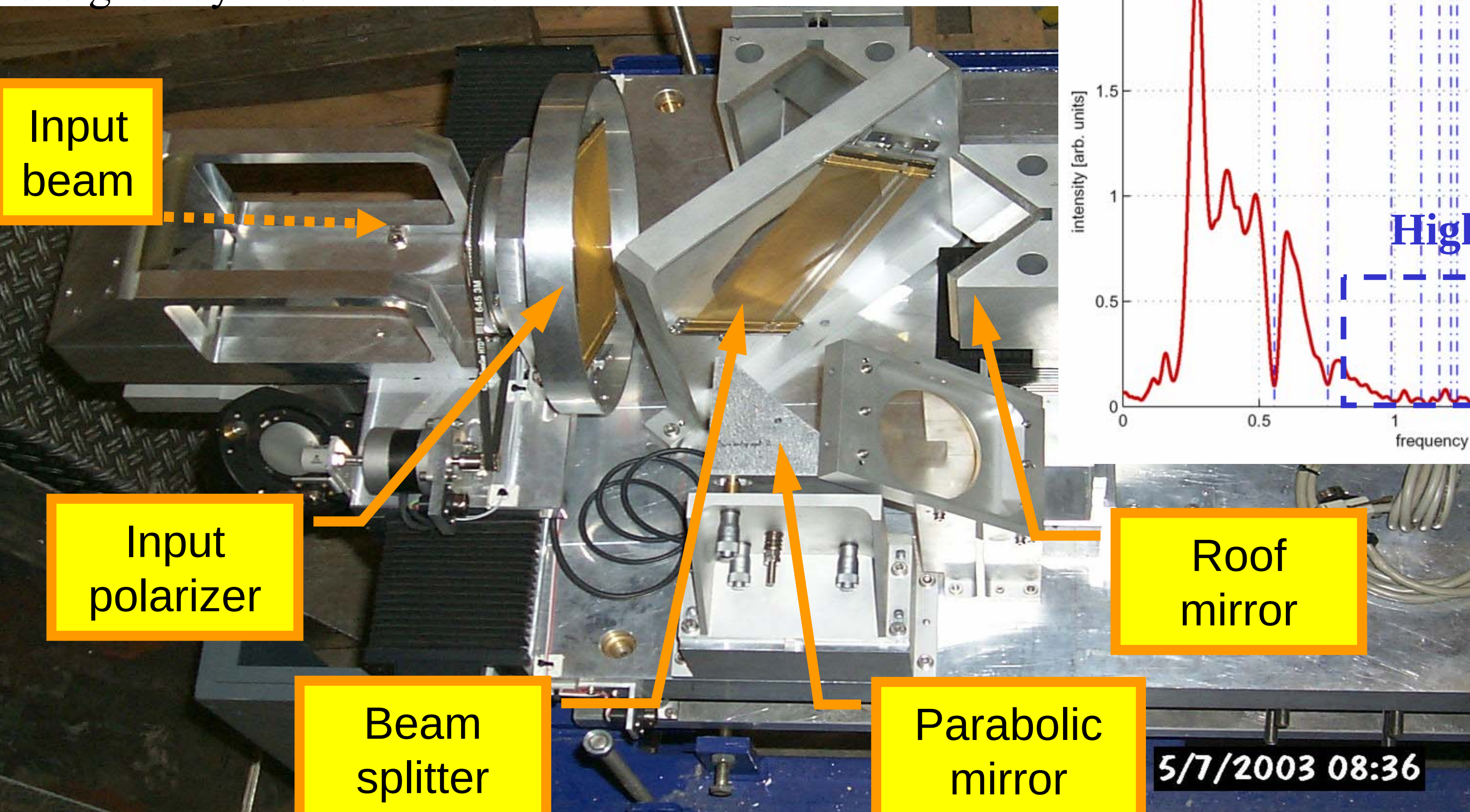
Rms = 32.7 um
⇒ σ_z ~ 23.1 um



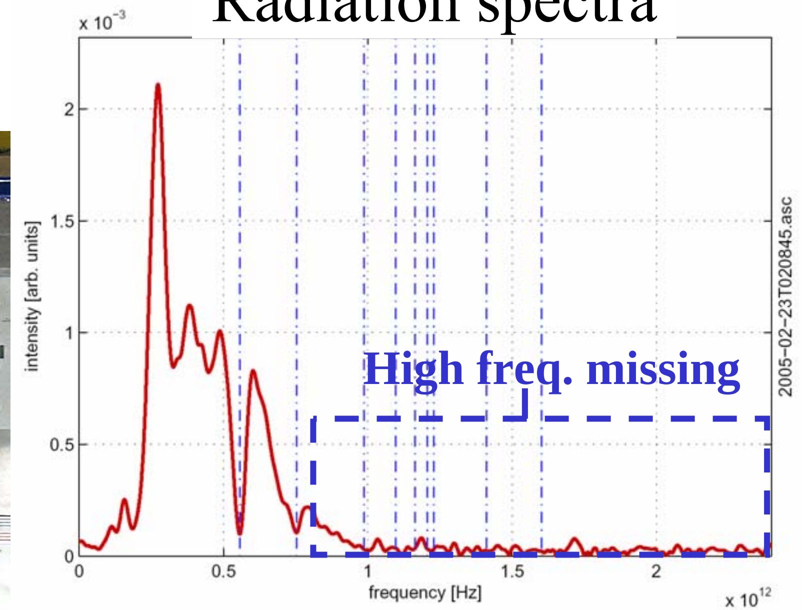
P. Muggli (E164 exp. SLAC)

Bunch Length Diagnostics
- Martin-Puplett Interferometer-

Martin-Puplett Far Infrared Interferometer:
designed by RWTH Aachen



Radiation spectra

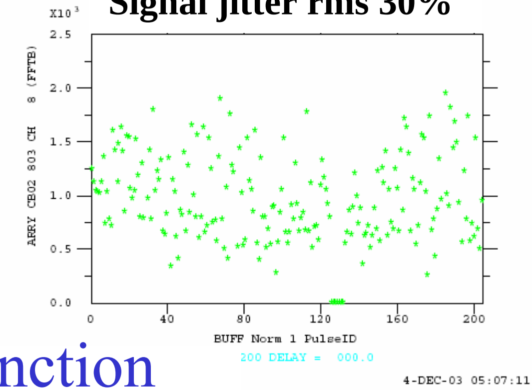


Courtesies
O. Grimm &
L. Fröhlich

Detectors removed, types used DTGS, Pyro, Golay

Interferometers

Challenges related to interferometer setup



Signal jitter rms 30%

- multi-shot measurement
- phase information is missing

⇒ reconstruction via Kramer Kronig disp. relation

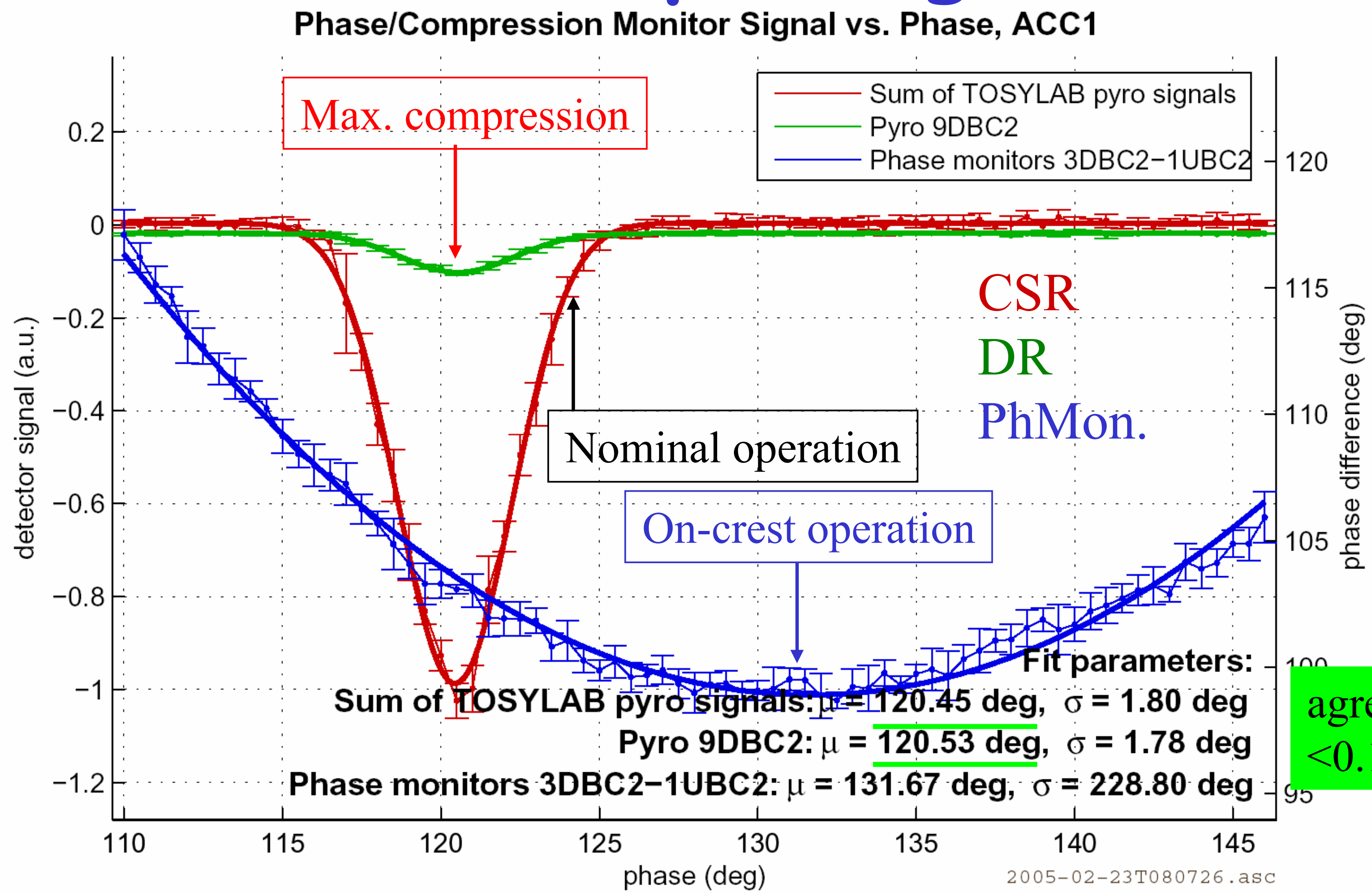
- significant and complicate frequency response function

– effects of finite foil
– diffraction at apertures and diffraction limited transport
– beam splitters and window (lower cutoff)
– near field and far field transitions
– detector response function
– absorption in air

⇒ extraction of “rms” bunch length is feasible, but an accurate measurement of the longitudinal bunch profile is very difficult!

- Future: ideas for single shot FIR bunch length measurements (FIR spectrometer, not yet demonstrated)
- Growing interest: easier for shorter bunches, micro-bunch instability

Beam Compression Monitor
- acc. phasing -



agreement <0.1°

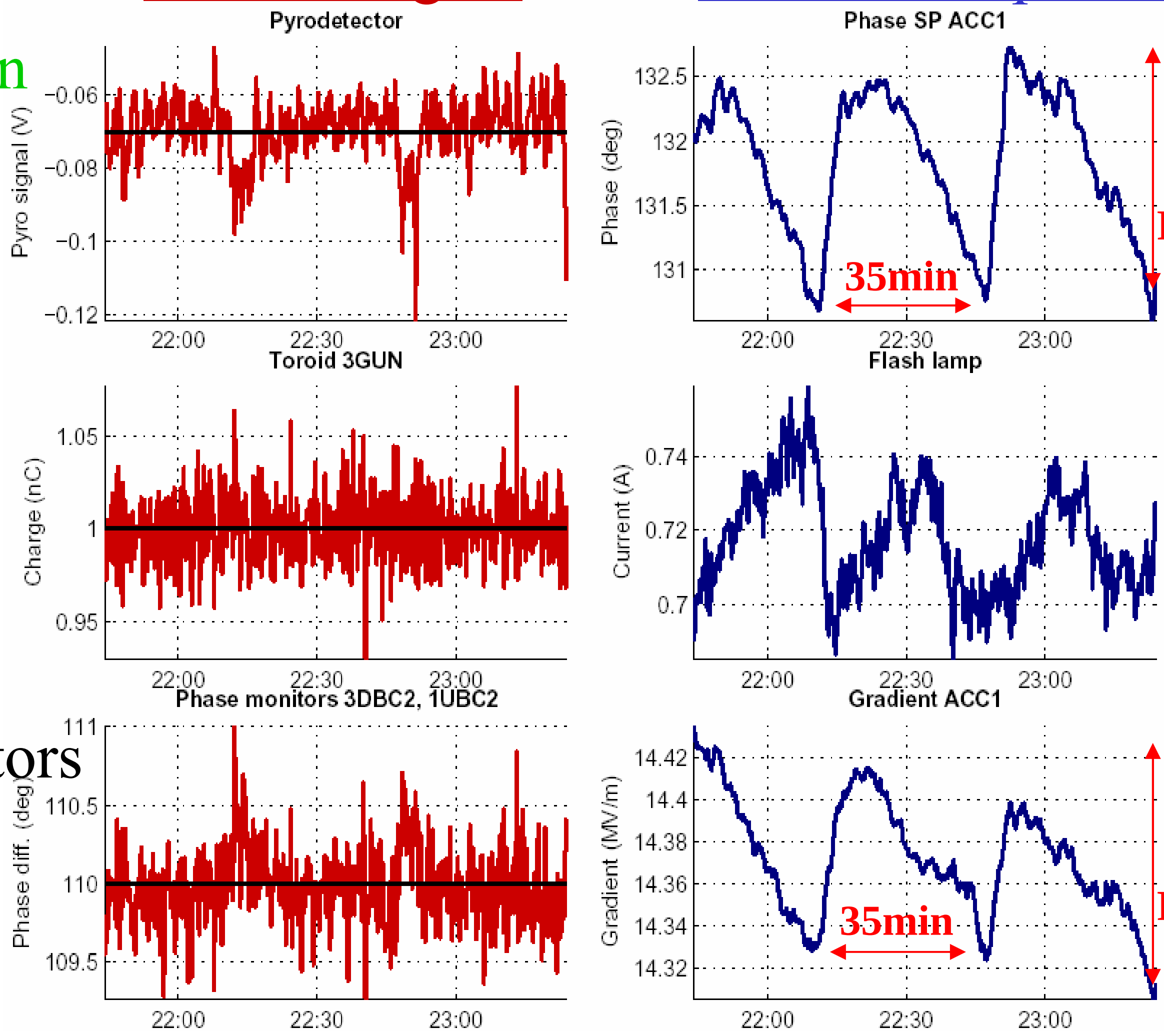
Slow feedback for acc. phase

Monitor signal | Actuator responds

Compression monitor | Acceleration phase

Charge | Laser power

Phase monitors (Energy) | Acceleration gradient



PkPk = 2°

Large phase drifts observed!!!

PkPk = 1%

Large ampl. drifts observed!!!

Example: TTF2

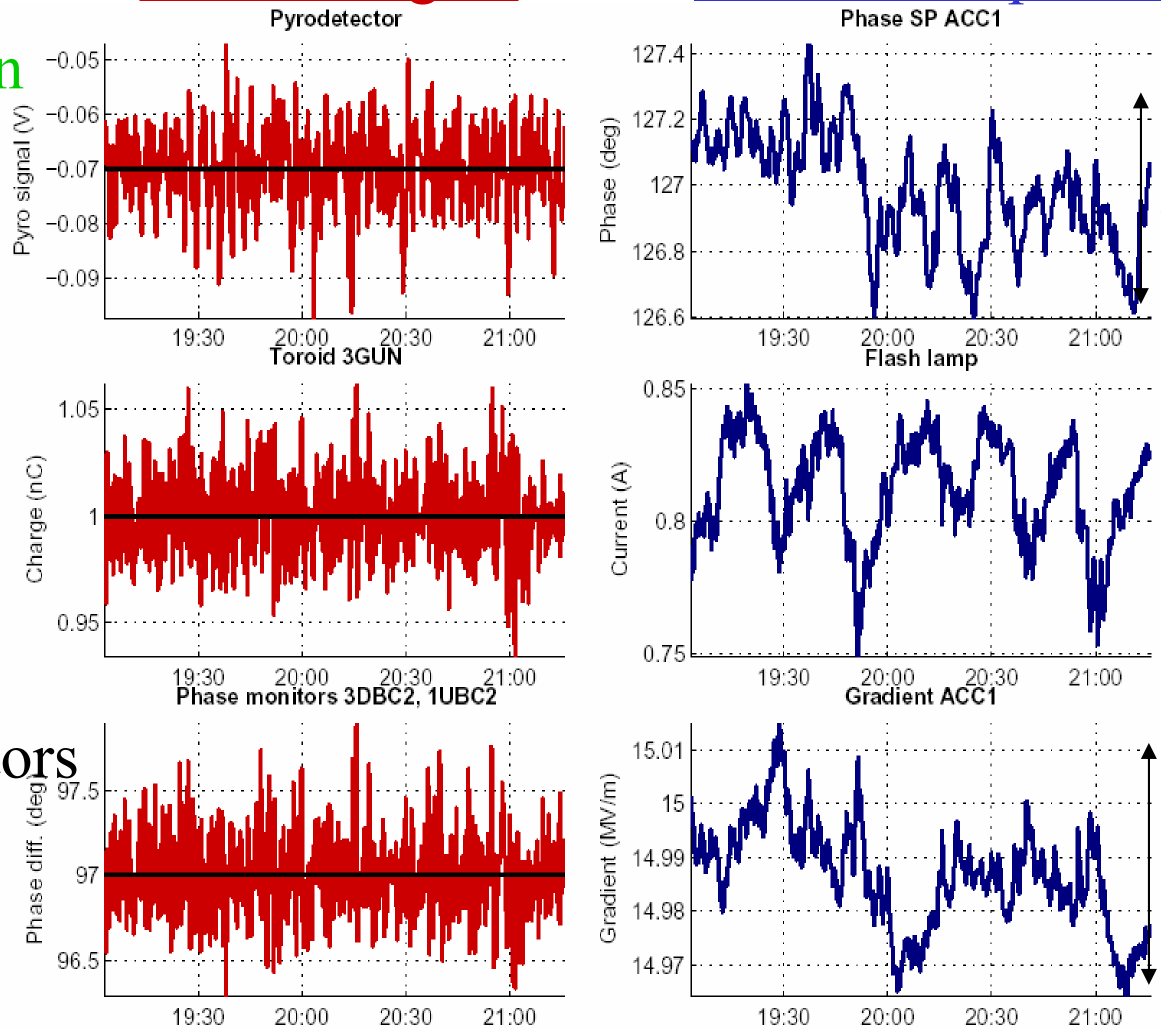
Slow feedback for acc. phase

Monitor signal | Actuator responds

Compression monitor — Acceleration phase

Charge — Laser power

Phase monitors (Energy) — Acceleration gradient



PkPk = 0.7°

Reasonable phase drift (~0.1° rms)

PkPk = 0.4 %

Reasonable ampl. drift (~ 0.1% rms)

Example: TTF2

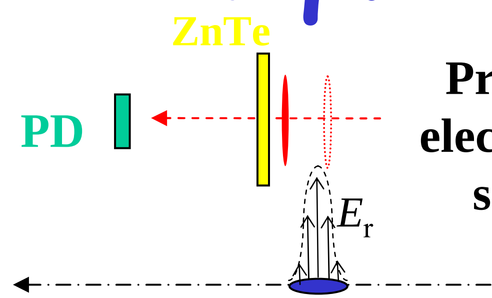
Electro-optical techniques

1. Sampling:
- scan delay to move laser over the bunch
- good synchronization required
- multi-shot method
- arbitrary time window possible

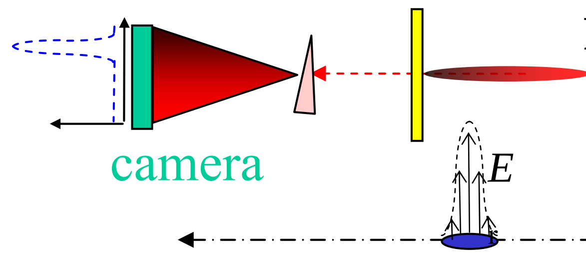
2. Chirp laser method:
- single shot method
- some more effort for laser and laser diagnostics required
- time window ~ 1-20ps
- limit by laser diagnostics ~ 400fs

3. Spatial method:
- single shot method
- imaging optics is critical
- time window ~ 1-20ps

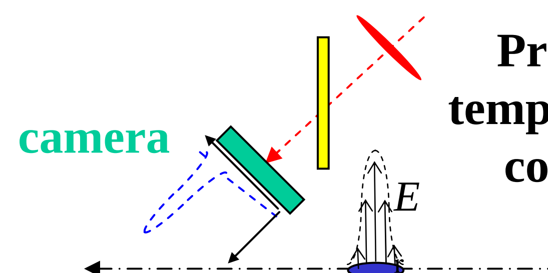
4. Temporal decoding:
- uses single shot auto-correlator
- optical resolution limit 30fs
- requires laser amplifier (~1-10kHz)



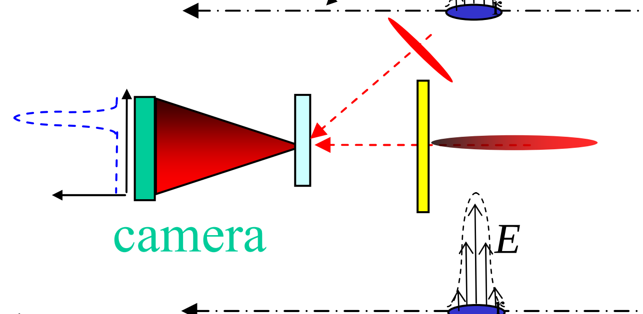
Principal of electro-optical sampling



Principal of temporal-wavelength correlation



Principal of temporal-spatial correlation



Principal of temporal-decoding

Electro-optical techniques

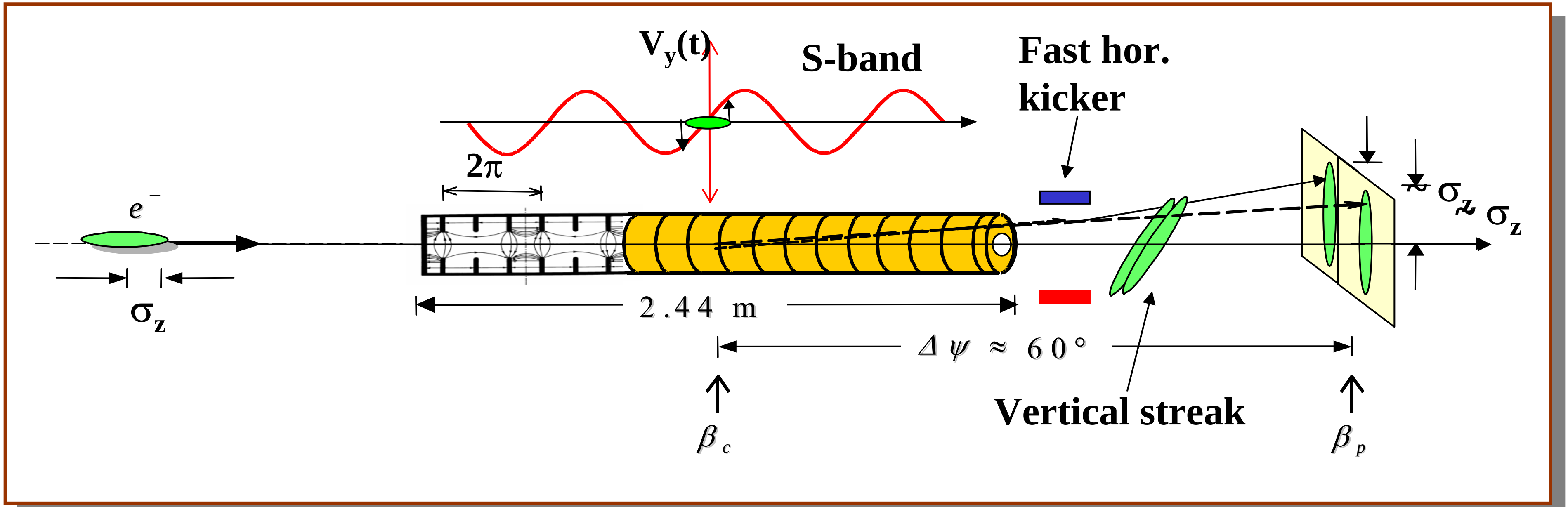
- All techniques have been successfully tested ☺
- Parasitic operation and non-invasive ~ 100mA possible
- High readout rate up to ~ MHz (method 2&3)
- If laser is properly synchronized
  ⇒ high accuracy beam arrival time monitor ~10-30 fs
- Spatial method and temporal decoding overcome the optical resolution limits
- but any technique has presently the limitations given by the electro-optical process

ZnTe	~	200 fs FWHM
GaP	~	100 fs FWHM
?	<	30 fs FWHM

- limited dynamic range (2 ps, 1 nC ok, but 20 ps, 100pC diff.)
- all together TECHNICAL CHALLENGING

Transverse deflecting structure

- vertical deflecting RF structure (2.856 GHz) operated at zero crossing
- vertical size of beam at imaging screen ⇒ depends on bunch length
- used structures sofar: “LOLA” at exit of SLAC linac, and TTF2 linac
- 25 MW klystron power to “streak” the 28.5 GeV for SPPS, (0.5GeV)
- ‘Parasitical’ measurement using hor. kicker and off-axis screens
- Resolution: SPPS ~ 60 µm, TTF2 ~ 5 µm (expected)



SPPS: P. Krejcik et. al.,TTF2: M. Ross et.al. + MIN DESY

Transverse deflecting structure

Beam size RF off

Bunch Length

Beta fn at cavity & screen

Cavity voltage and beam energy

Phase adv cavity to screen

Beam size on screen

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin \Delta\psi \cos\varphi \right)^2}$$

RF phase

Net deflection

SLAC cavity shunt impedance

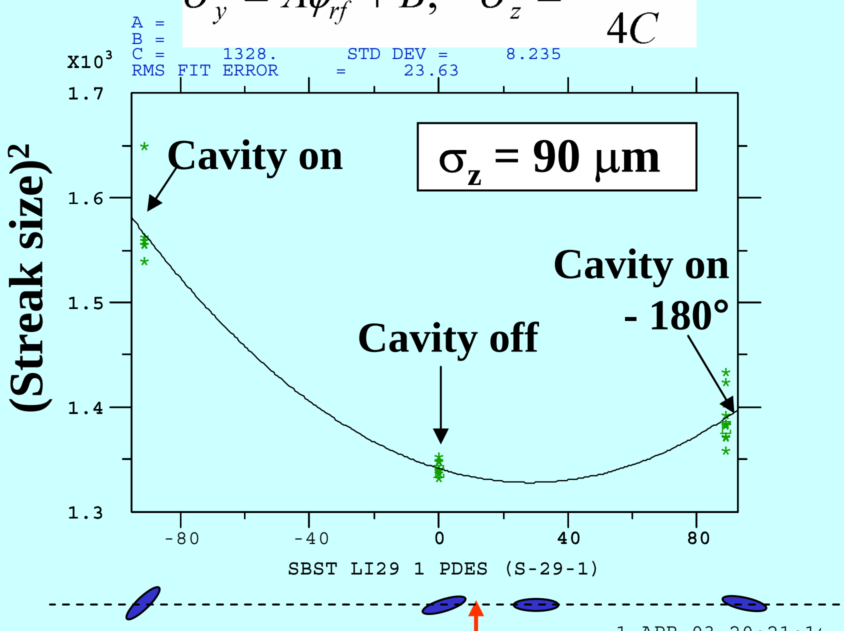
$$\langle \Delta y \rangle = \frac{eV}{E_0} \sqrt{\beta_c \beta_p} \sin \Delta\psi \sin\varphi \,, \qquad V_0 \approx \left(1.6 \text{ MV/m/MW}^{1/2} \right) L \sqrt{P_0}$$

Transverse deflecting structure

Little streak $\sigma_y > \sigma_{y,0}$(SPPS):

rms bunch length reconstruction by measure streak at 3 different phases

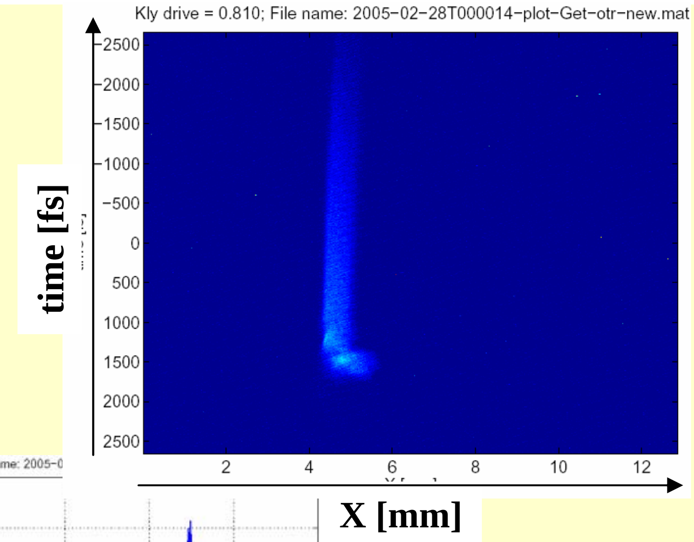
$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$

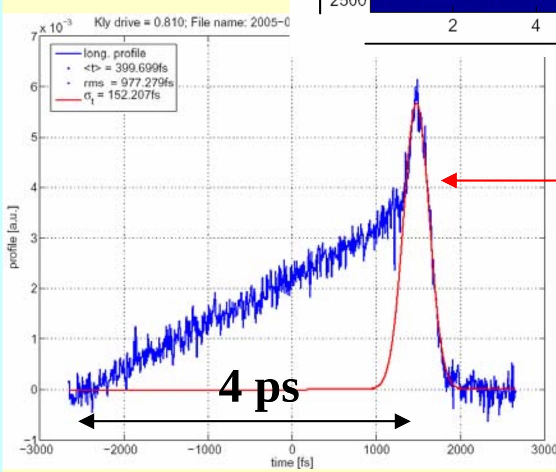


Asymmetric parabola indicates incoming tilt to beam

Strong streak $\sigma_y >> \sigma_{y,0}$(TTF2):

Profile reconstruction





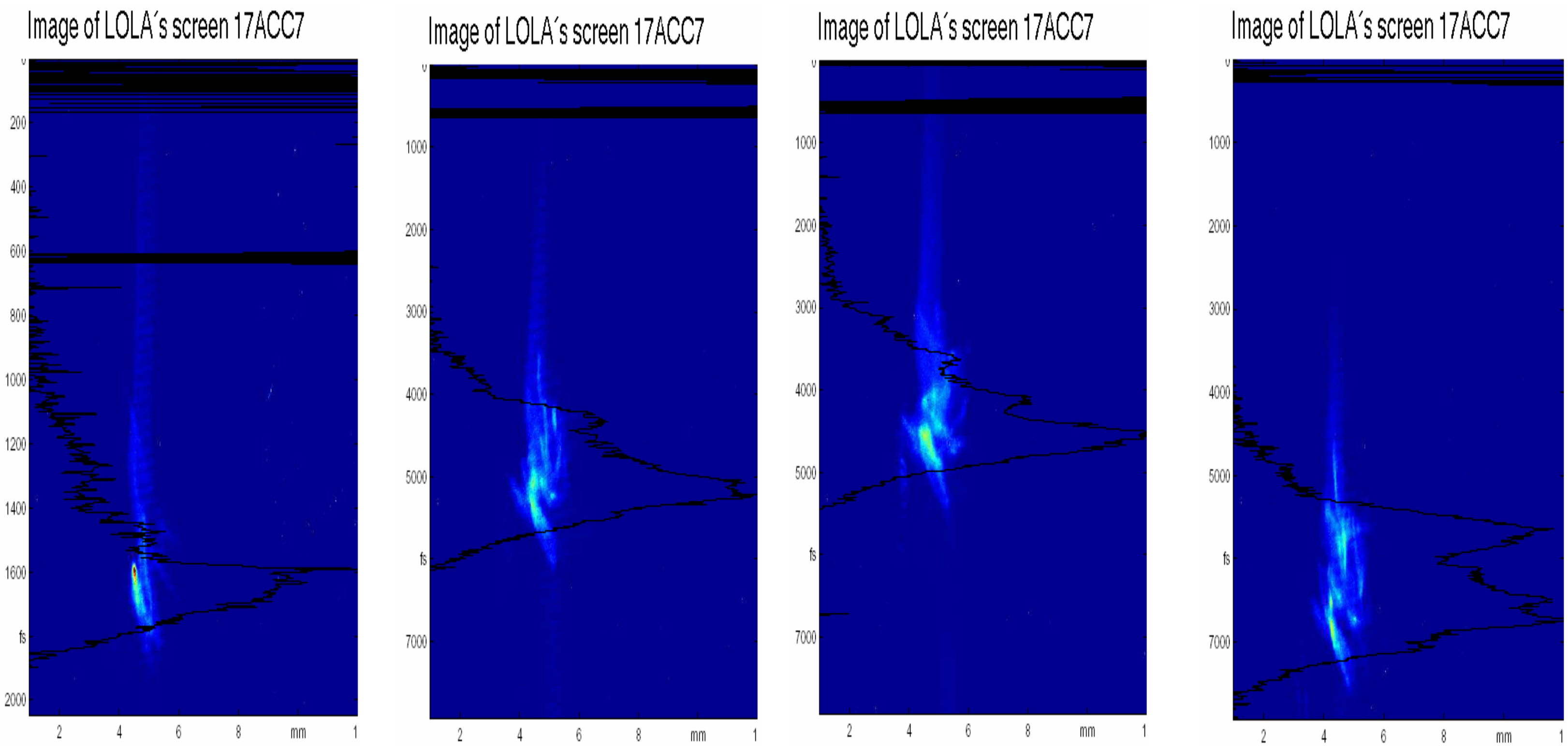
σ_z = 45 µm

Moderate compr. (+5 from max.)
Not fully streak
Not optimized

Transverse deflecting structure

Phase from maximum pyro-electrical signal …

+3° +2° +1° +0°

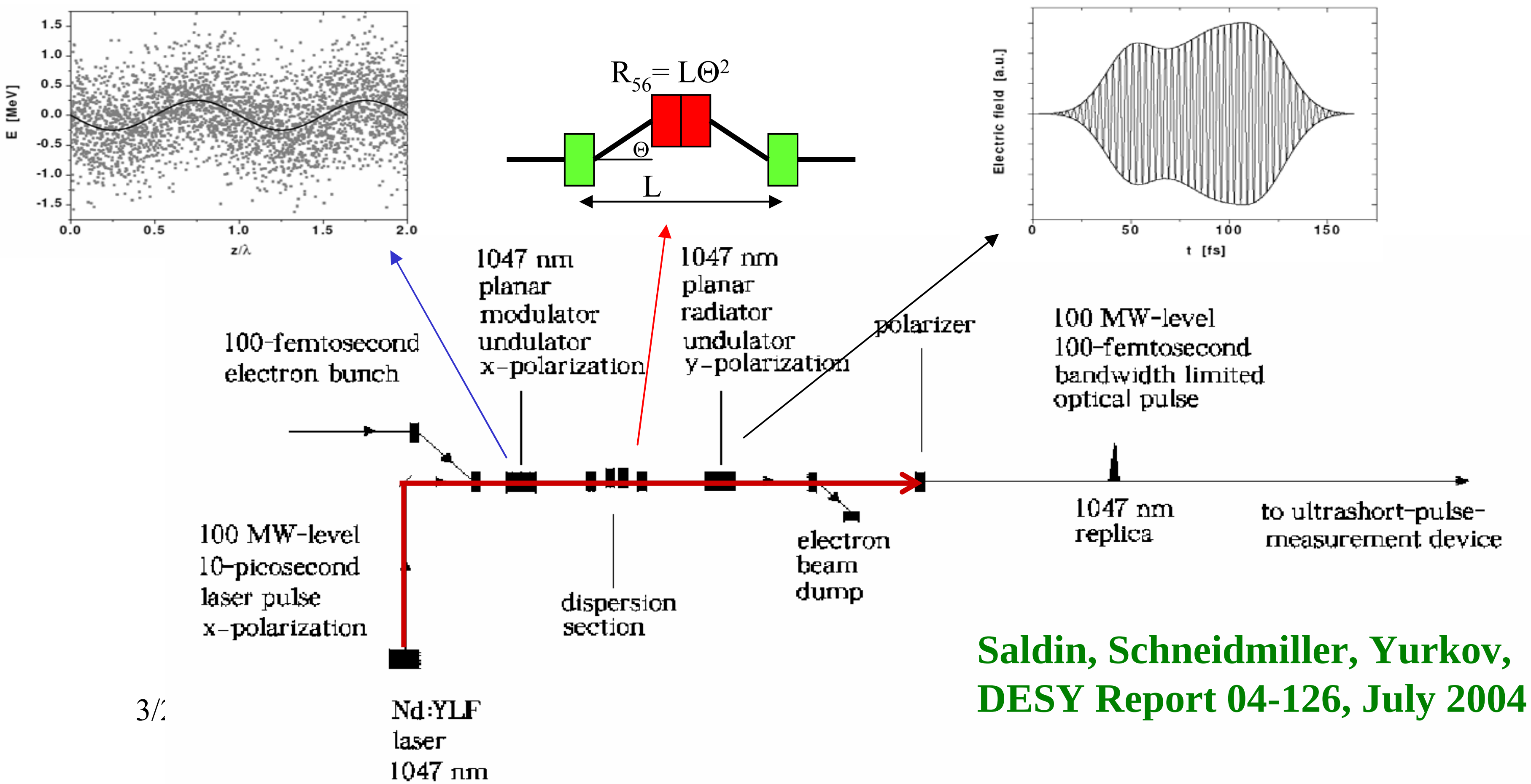


Fragmentation of beam in longitudinal and x direction (csr+space charge)

⇒ Ideal suited for slice emittance measurements

Optical pulse replica

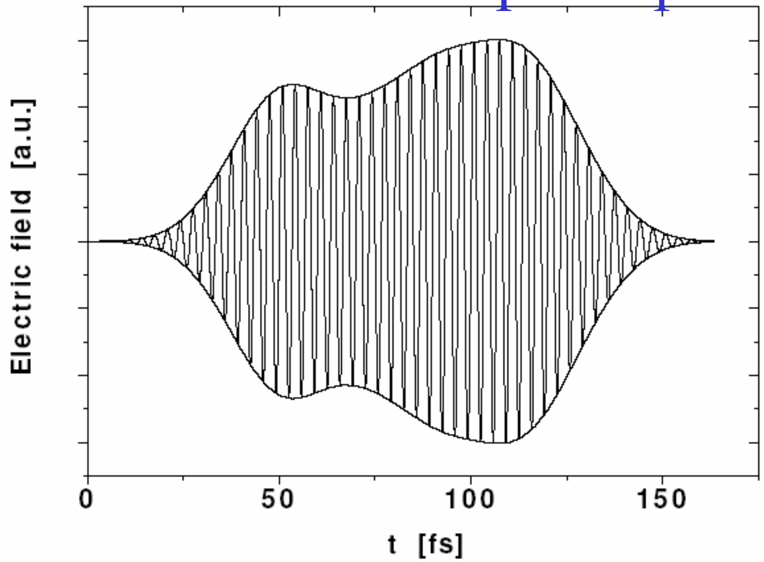
1. energy modulation with external laser in planar undulator
2. conversion to density modulation
3. coherent radiation in output undulator
4. optical pulse measurement (FROG, auto-correlation)



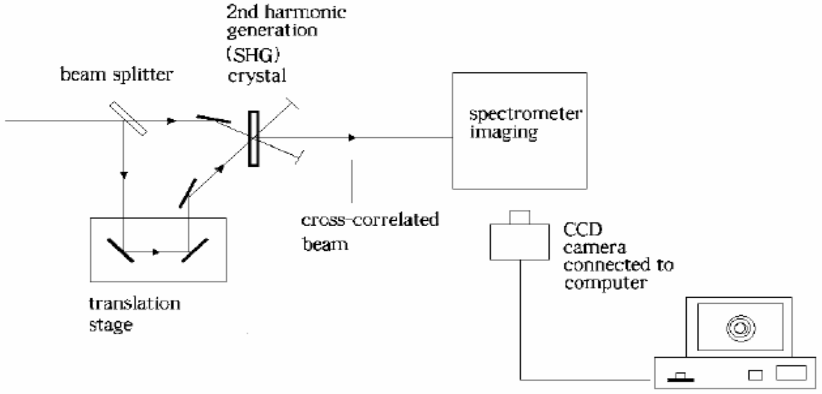
Saldin, Schneidmiller, Yurkov, DESY Report 04-126, July 2004

Optical pulse replica

Fourier limited optical pulse



Scheme of SHG-FROG



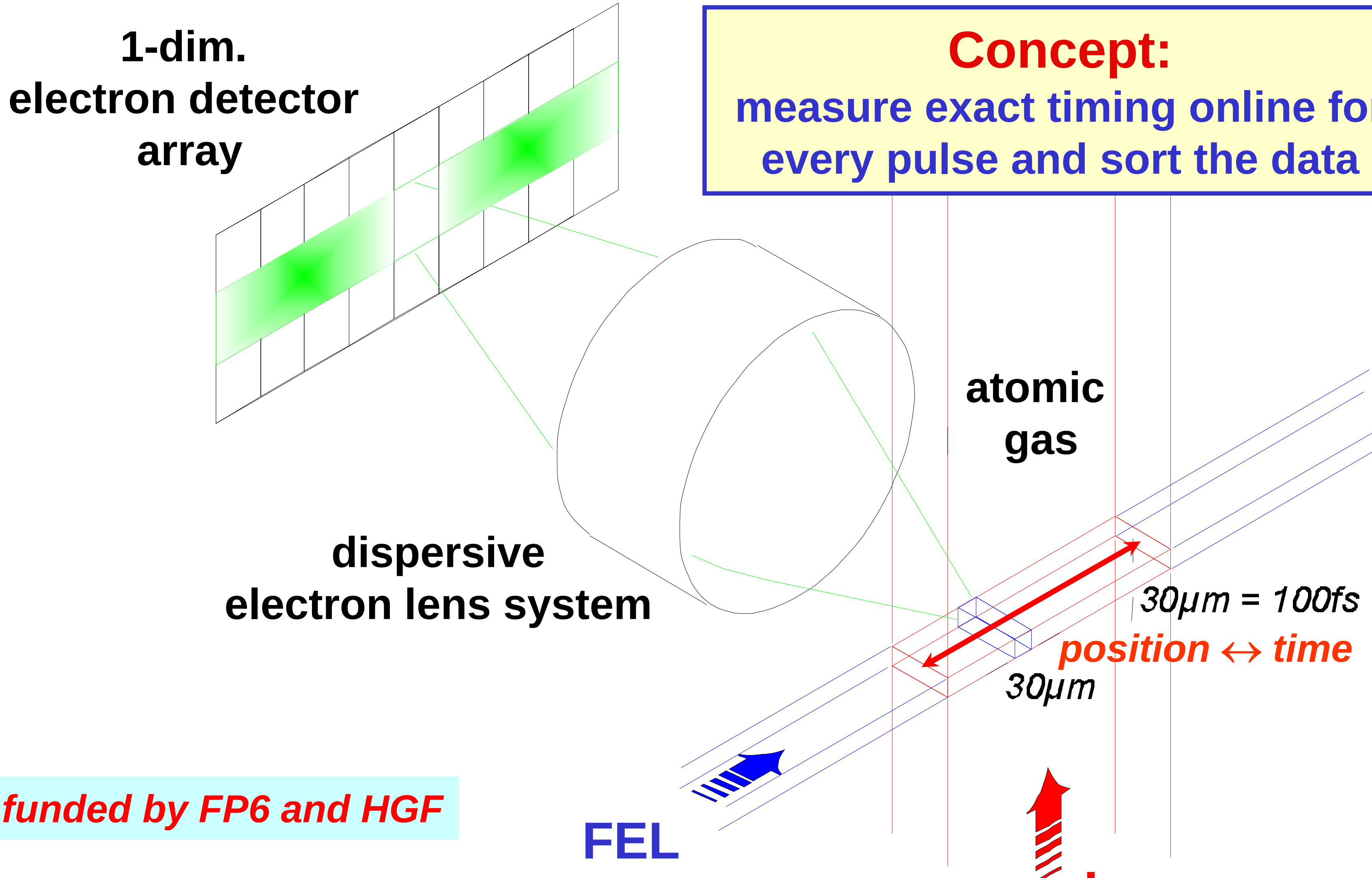
$\Rightarrow$ Combination of auto-correlation and spectrum provides exact intensity profile

+ High resolution $\delta z \sim N_w \cdot \lambda \approx 5\mu m$ (limited by slippage only)
+ Allows to extract slice energy spread
+ provides high power synchronized optical pulse (timing)
+ quasi parasitically, online

- low rep. rate (100Hz-1kHz)
- limited dynamic range (pulses <<1ps)
- requires high power seed laser
- challenging if large residual energy spread across the bunch

Single-shot cross correlator

Concept:
measure exact timing online for every pulse and sort the data



funded by FP6 and HGF

M.Drescher, University Bielefeld/Hamburg

Other methods …

- ISR in optical regime in combination with ultra-short pulse lasers (SHG)
- CR in combination with EO (outside tunnel, other EO-materials)
- General for quasi-non destructive methods:

  Ultra fast kickers (<20ns) + …
- Compton back scattering for arrival timing

and hopefully some more new ideas in the near future …

Electro-Optical Sampling (EOS)

Electro-Optic Longitudinal Bunch Profile Measurements at FLASH

Bernd Steffen, DESY
for the EO@FLASH team
(Daresbury, DESY, Dundee, FELIX)

FLASH
Free-Electron Laser
in Hamburg

DESY

Bernd.Steffen@desy.de

Overview

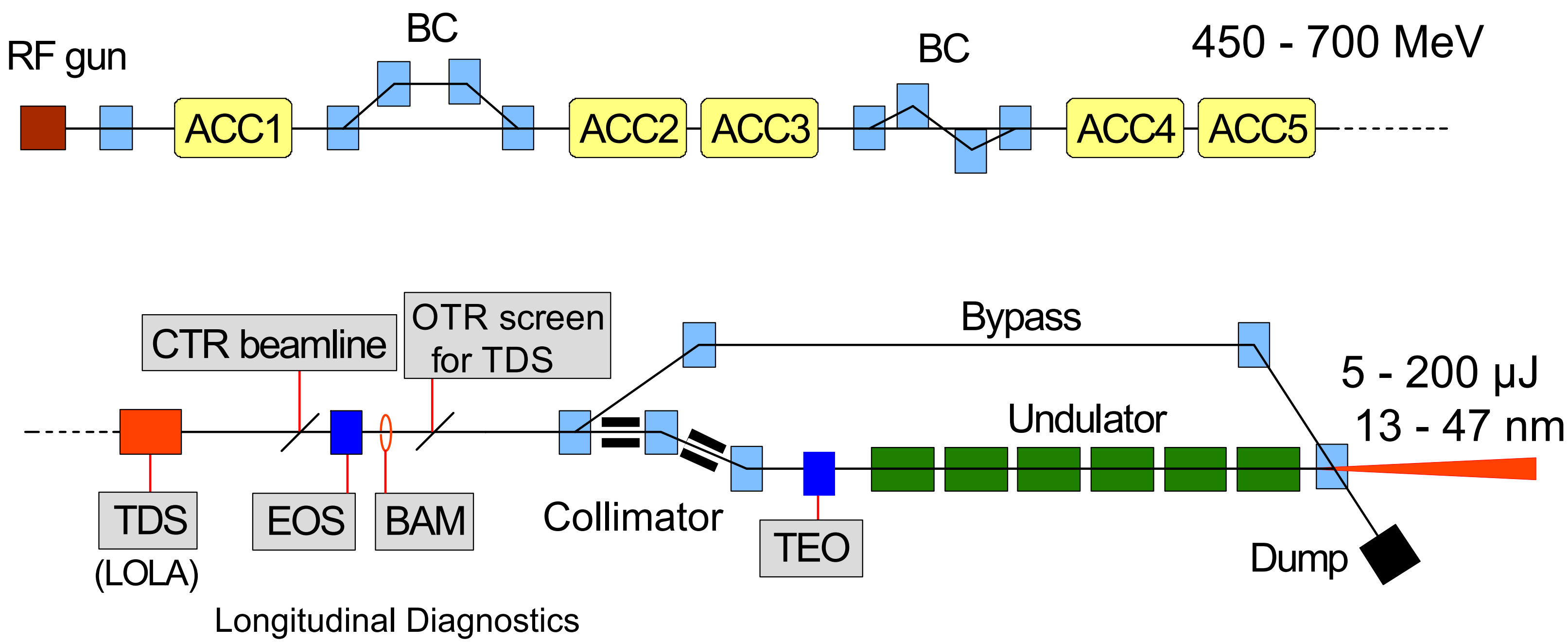
- Motivation
- Basics
  - Electro-optic effect
  - EO measurement principle
  - Detection schemes
- Measurement schemes and results
  - Electro-optic sampling using a variable delay
  - Spectrally resolved detection
  - Temporally resolved detection
- Applications
- Conclusion

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

FLASH
Free-Electron Laser in Hamburg

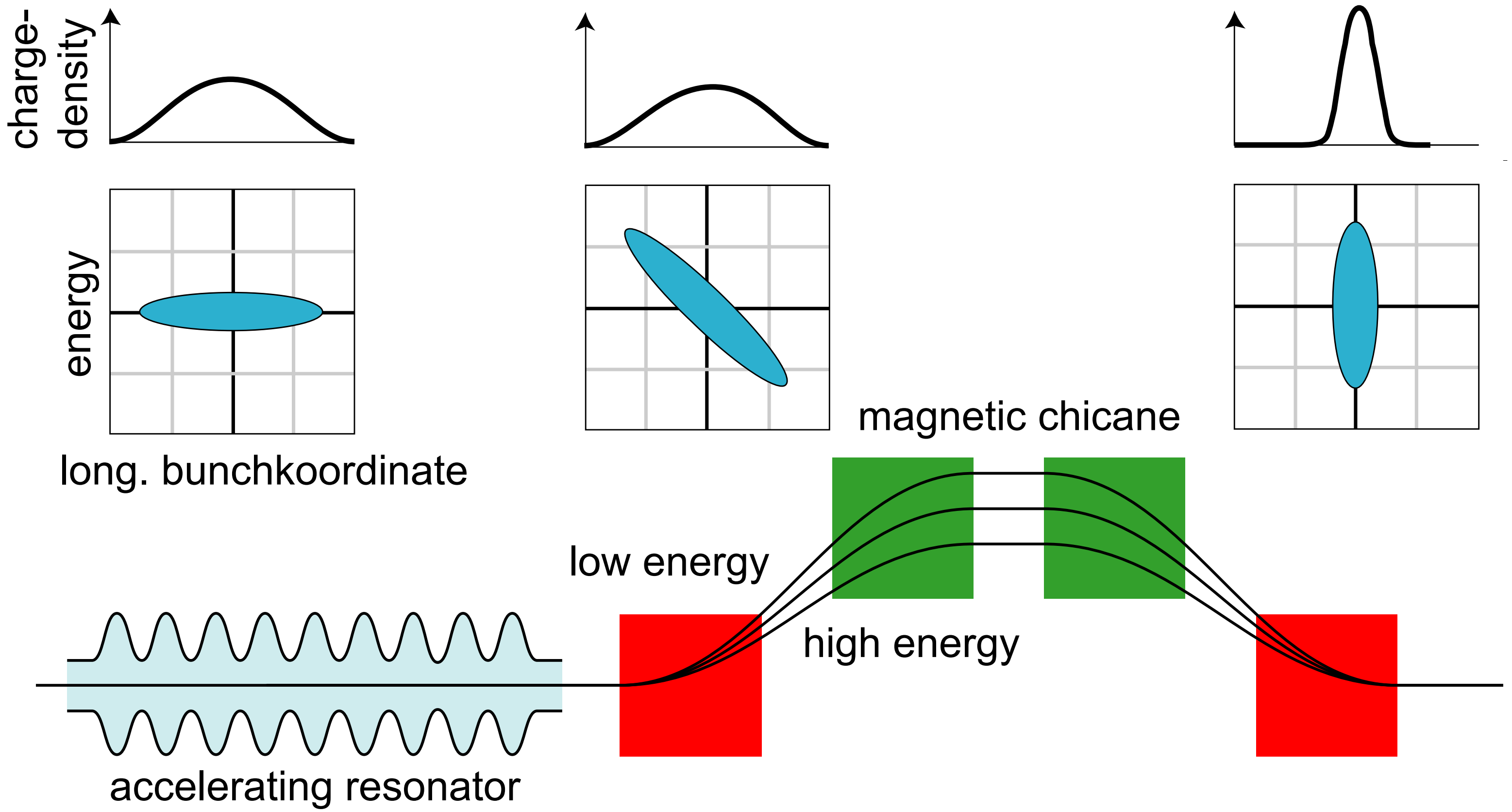


Electron bunches:
- ≈ 30 fs duration
- ≈ 700 MeV electron energy
- ≈ 0.5 nC charge
- ≈ 1 kA peak current

All pulse length: **σ of a fitted Gaussian**

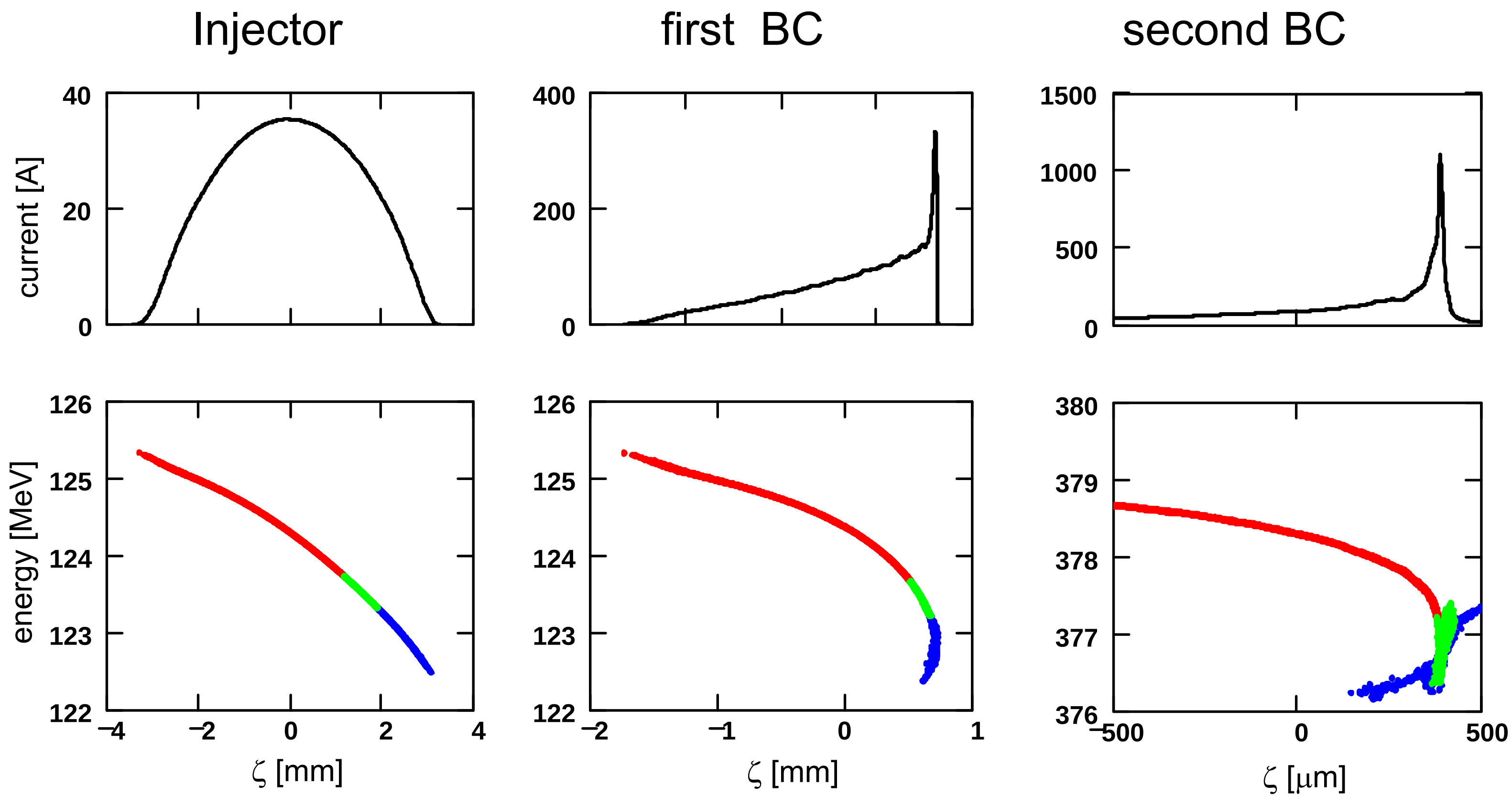
FLASH Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

Bunch compression



FLASH
Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

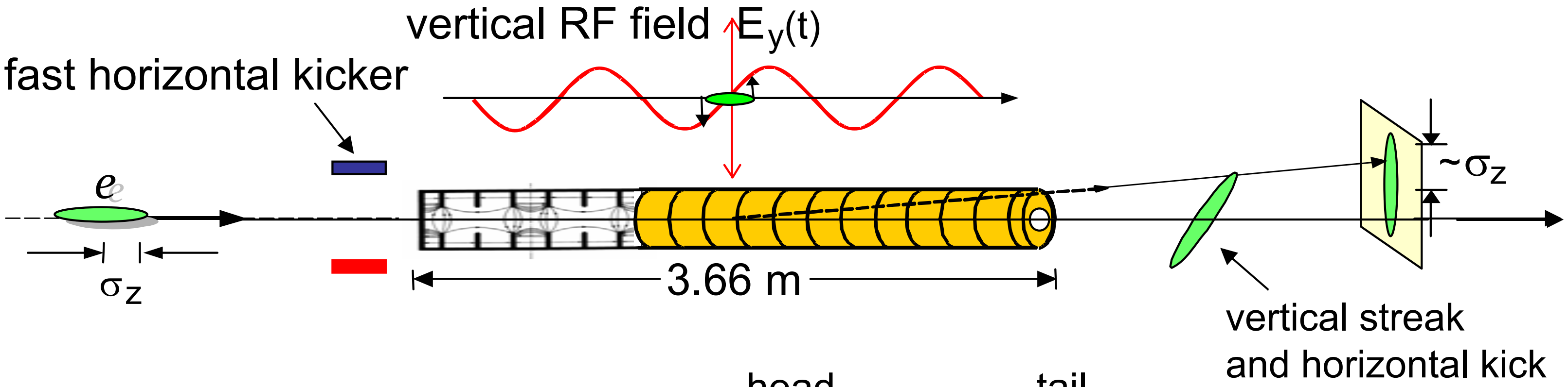
Bunch compression

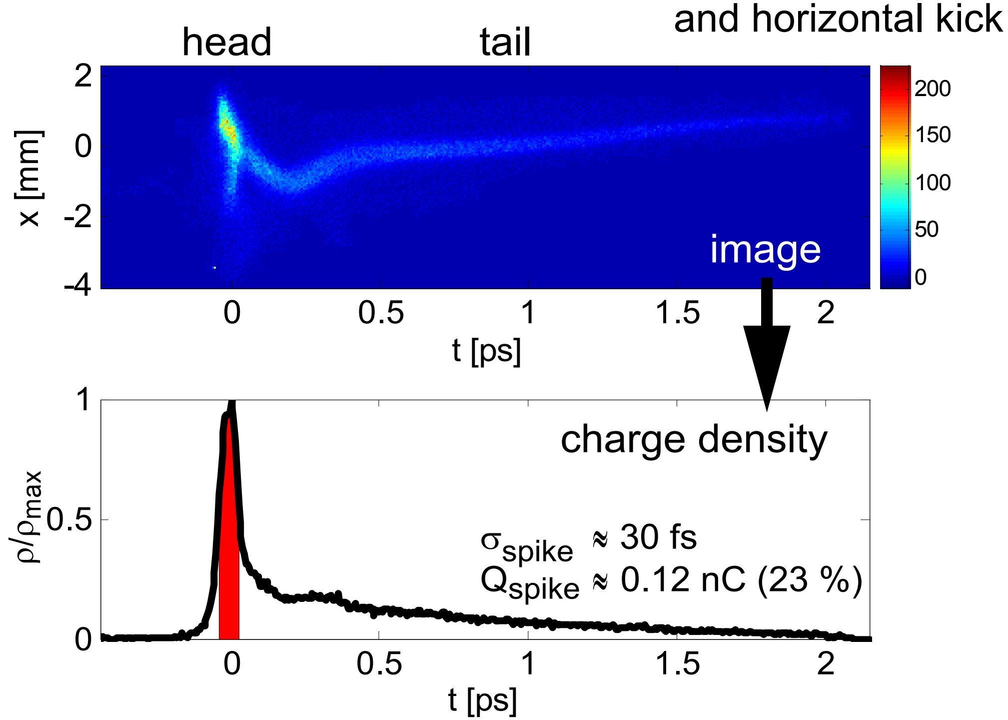


Courtesy of Martin Dohlus

Bernd.Steffen@desy.de

Bunch length measurements using the transverse deflecting structure (TDS)





Resolution:
approx. 20 fs
at a time window of 2 ps

FLASH
Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

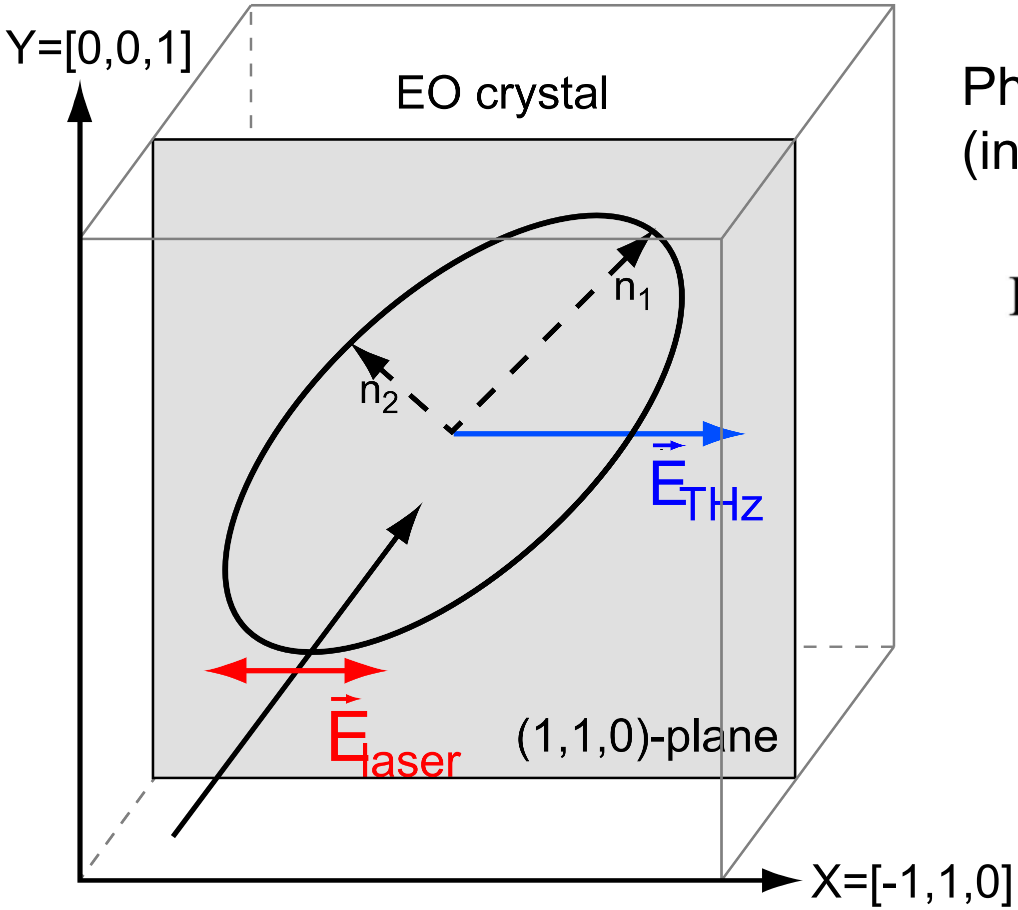
Overview

- Motivation
- Basics
  - Electro-optic effect
  - EO measurement principle
  - Detection schemes
- Measurement schemes and results
  - Electro-optic sampling using a variable delay
  - Spectrally resolved detection
  - Temporally resolved detection
- Applications
- Conclusion

FLASH
Free-Electron Laser in Hamburg

Bernd.Steffen@desy.de

The Electro-Optic Effect: THz-field induced Birefringence

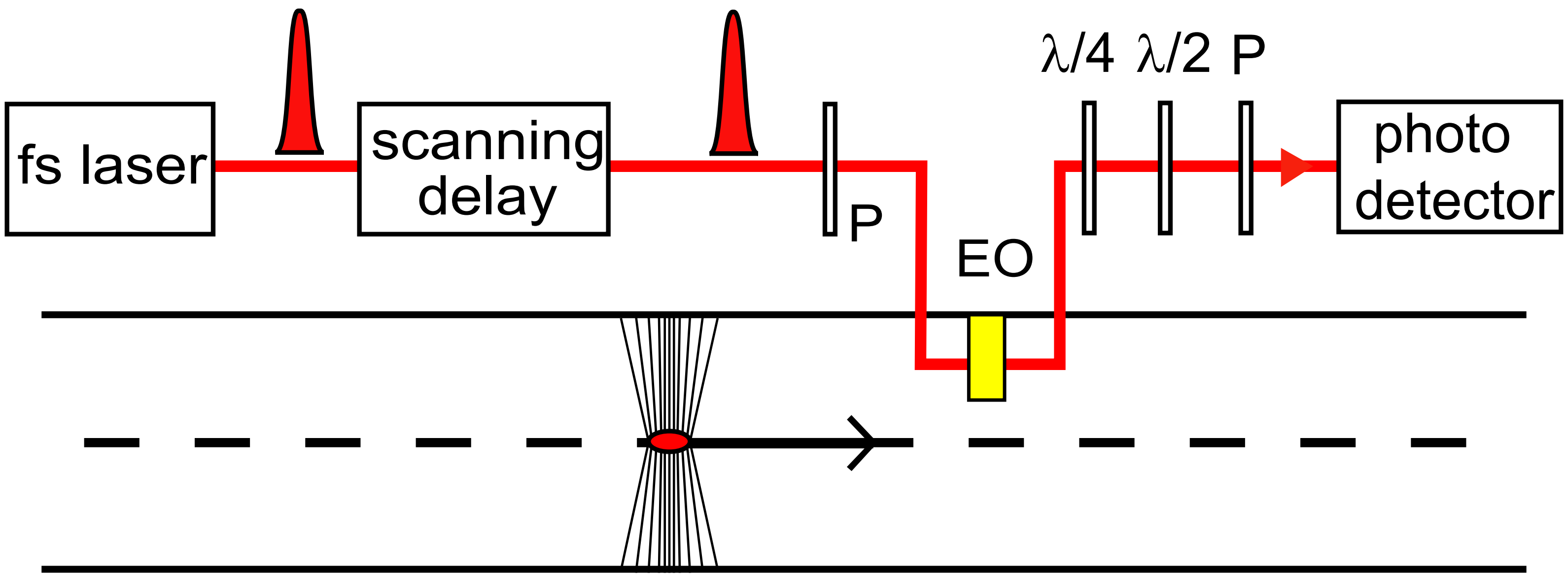


Phase retardation
(in the small signal limit):

$$\Gamma = \frac{\omega d}{c}(n_1 - n_2) = \frac{\omega d}{c} n_0^3 r_{41} E_{\mathrm{THz}}$$

FLASH
Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

Electro-Optic Sampling



- Coulomb field of electron bunch induces birefringence in EO-crystal.

- birefringence is sampled by Ti:Sa laser pulse.

Bernd.Steffen@desy.de

Effect of the wave plates

$$E_{\mathrm{det}}(\theta,\phi,\Gamma) = \begin{pmatrix} 0 & 1 \end{pmatrix} \cdot \boldsymbol{H}(\theta) \cdot \boldsymbol{Q}(\phi) \cdot \boldsymbol{EO} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot E_{\mathrm{laser}}$$

$$\boldsymbol{EO} = \boldsymbol{R}(-\pi/4) \cdot \begin{pmatrix} \exp(-i\Gamma/2) & 0 \\ 0 & \exp(+i\Gamma/2) \end{pmatrix} \cdot \boldsymbol{R}(\pi/4)$$

$\boldsymbol{Q}(\phi)$: Quarter wave plate, rotated by ϕ

$\boldsymbol{H}(\theta)$: Half wave plate, rotated by θ

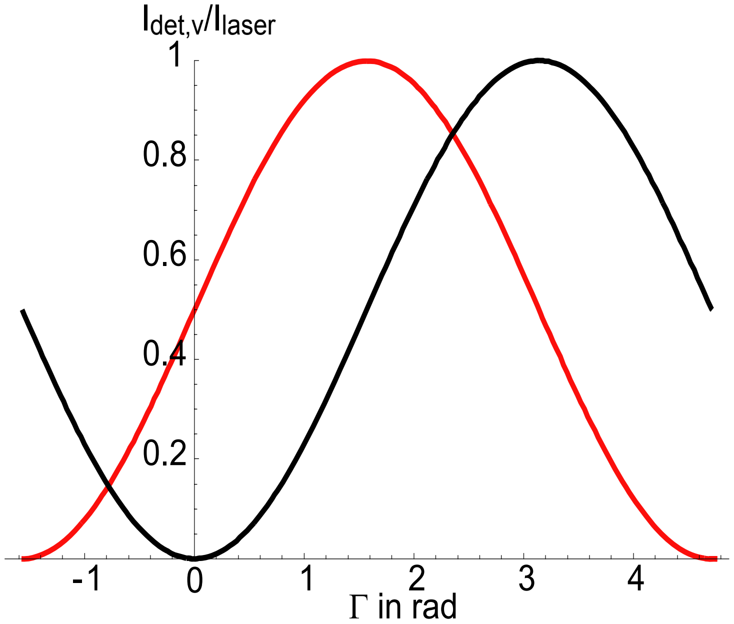
$$I_{\mathrm{det}}(\theta,0,\Gamma) = \frac{I_{\mathrm{laser}}}{2}\left[1-\cos(\Gamma+4\theta)\right]$$

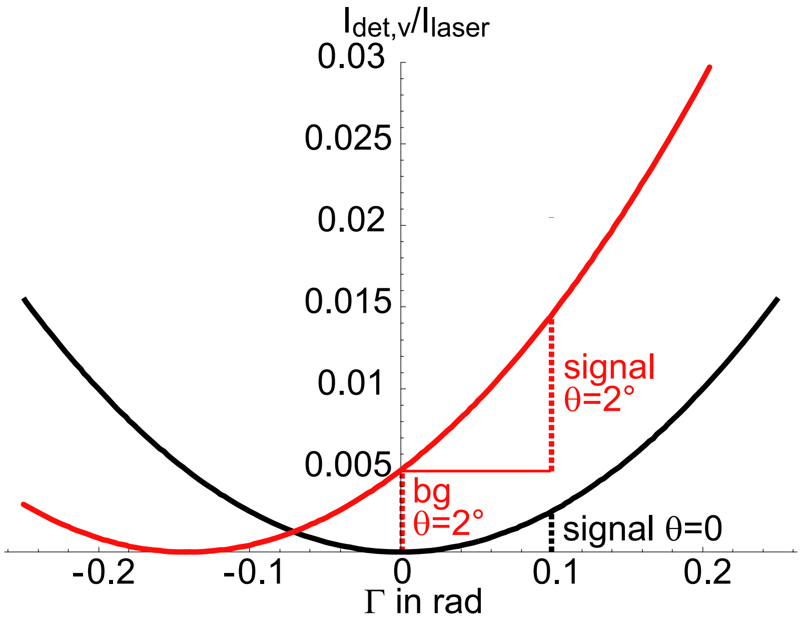
FLASH
Free-Electron Laser
in Hamburg

DESY

Bernd.Steffen@desy.de

Effect of half wave plate





θ=0 4θ=π/2

θ=0° θ=2°

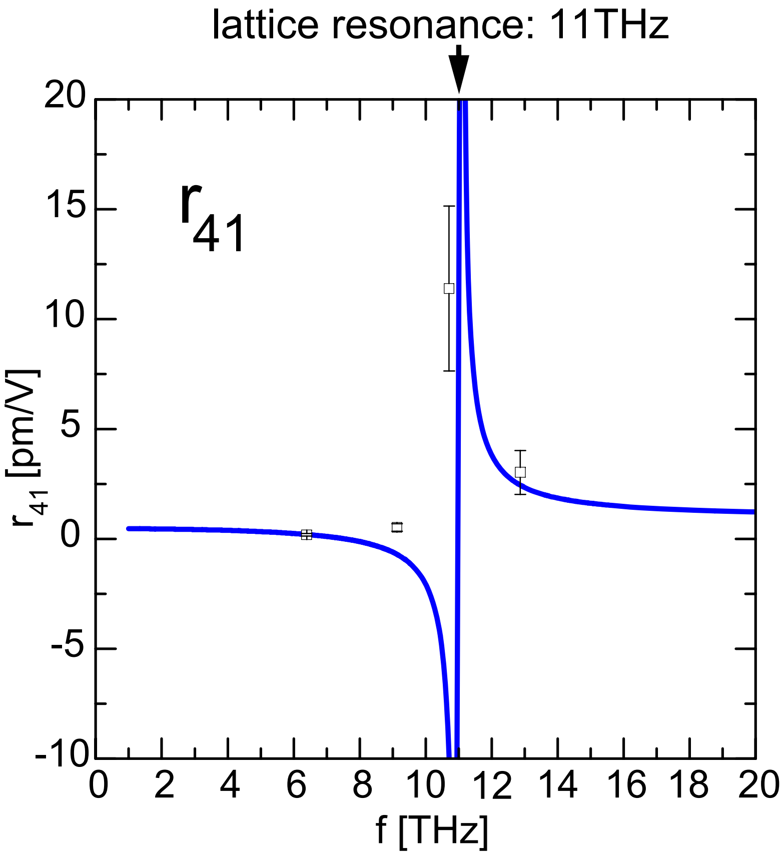
$$I_{\mathrm{det}}(\theta, 0, \Gamma) = \frac{I_{\mathrm{laser}}}{2}\left[1 - \cos(\Gamma + 4\theta)\right]$$

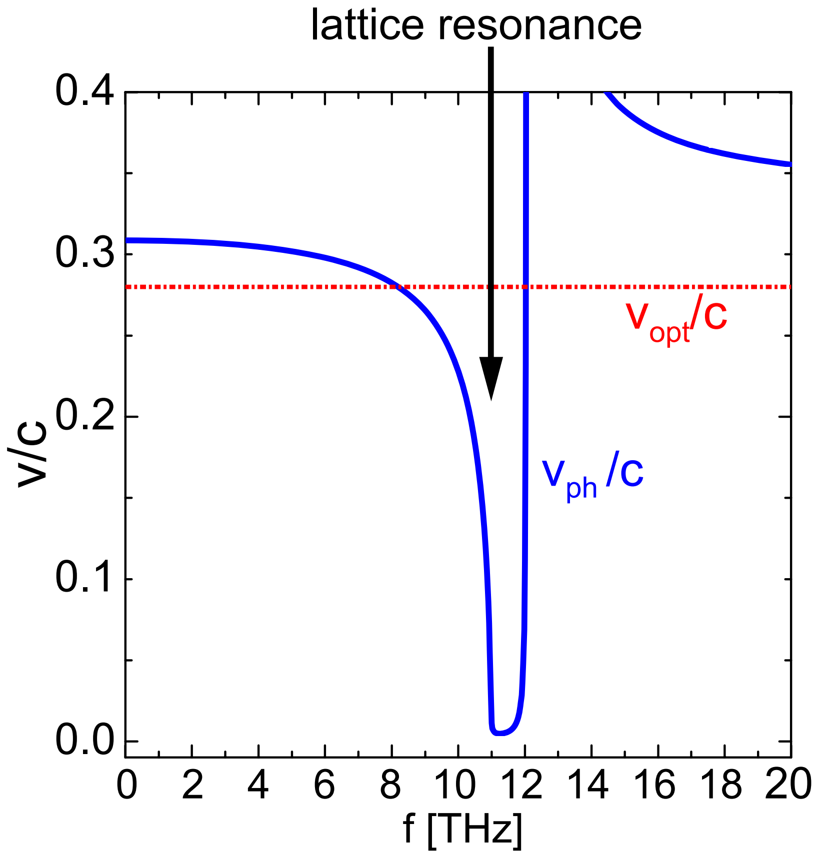
FLASH Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

EO coefficient r_{41}(f) and THz phase velocity in GaP

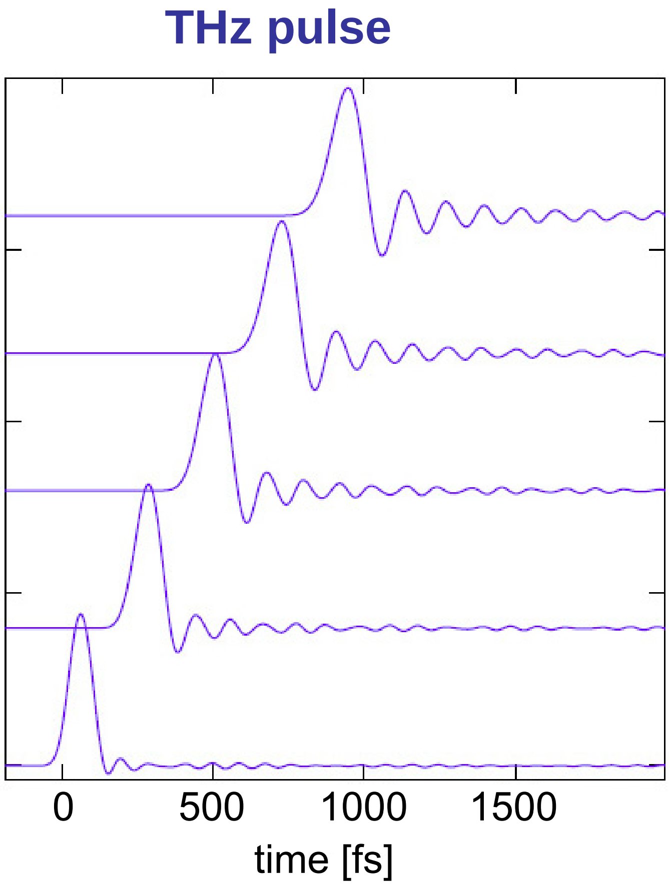


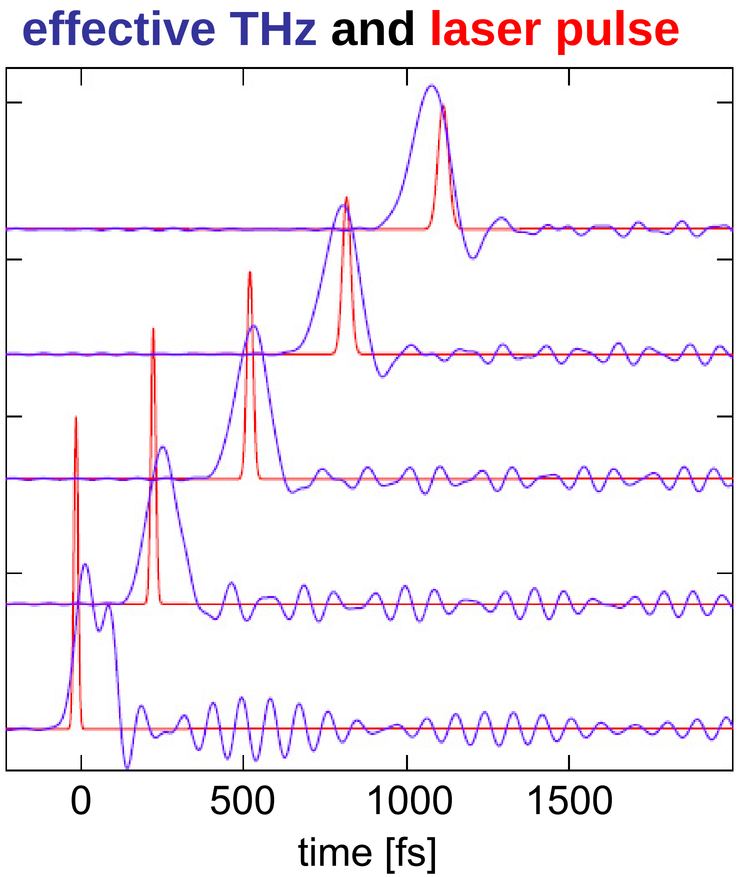


Faust, Henry. PRL 1966
Nelson, Turner. J. Appl. P. 1968

FLASH
Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

Propagation of the pulses in 100 µm GaP: EO-Sampling





EO-Signal: Product of the effective THz-field and laser integrated over the thickness of the crystal

Bernd.Steffen@desy.de

The simulation program

- Effective THz pulse calculated from electron bunch and EO response function
- Phase retardation Γ from effective THz pulse
- Complex electric field of the modulated chirped laser pulse calculated according to:

$$
\begin{aligned}
E_{\text{det}}(\theta,\phi,\Gamma) &= \begin{pmatrix} 0 & 1 \end{pmatrix} \cdot \boldsymbol{H}(\theta) \cdot \boldsymbol{Q}(\phi) \cdot \boldsymbol{EO} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot \; E_{\text{laser}} \\
&= \frac{E_{\text{laser}}}{\sqrt{2}} \left[\cos(2\theta)\sin(\Gamma/2) - \sin(2\phi - 2\theta)\cos(\Gamma/2)\right. \\
&\qquad \left. -i\left(\sin(2\theta)\cos(\Gamma/2) + \cos(2\phi - 2\theta)\sin(\Gamma/2)\right)\right]
\end{aligned}
$$

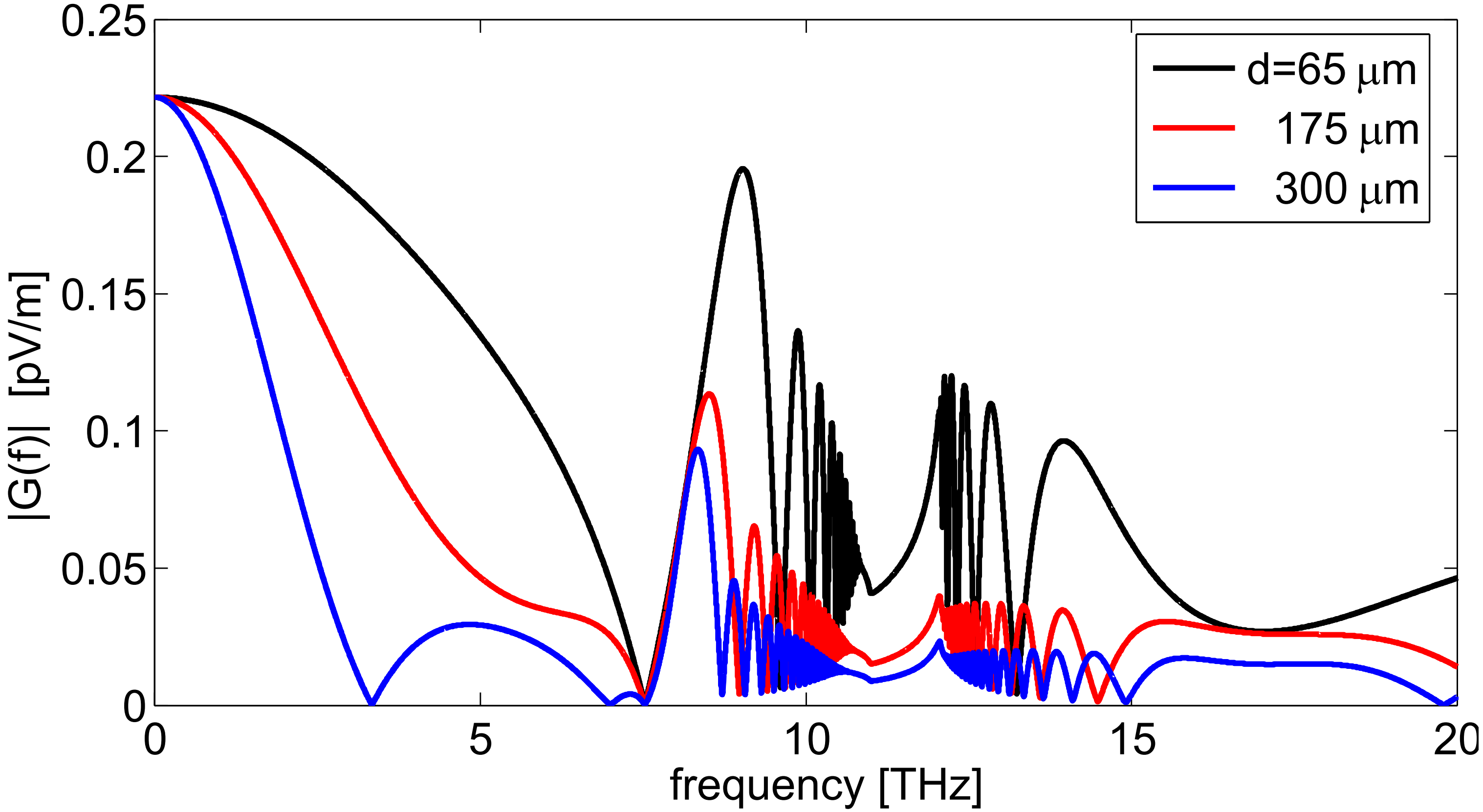
- Temporal and spectral intensity in both polarisations can be calculated.

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Response function of the EO crystal



$$G(f,d) \;=\; r_{41}(f)\frac{2}{1+n(f)+i\kappa(f)}\,\frac{1}{d}\int_0^d \exp\left[i\,2\pi f\,z\left(\frac{1}{v_{\mathrm{ph}}(f)}-\frac{1}{v_{\mathrm{g}}}\right)\right]\mathrm{d}z$$

EO coeff., transmission, velocity matching

Signal distortion esp. for thick crystals !

FLASH
Free-Electron Laser in Hamburg

DESY

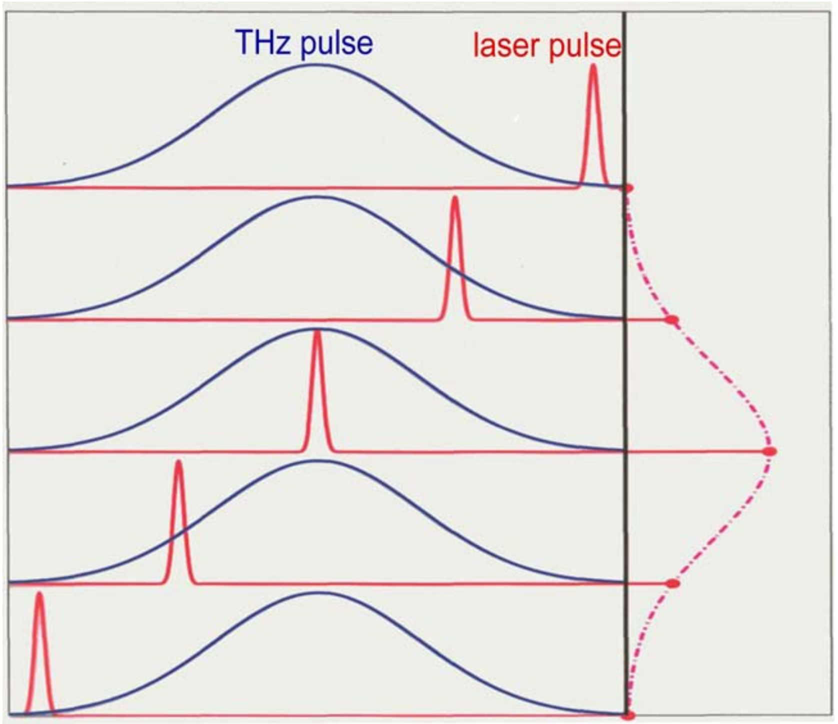
Bernd.Steffen@desy.de

Overview

FLASH
Free-Electron Laser in Hamburg

Bernd.Steffen@desy.de

Electro-Optic Sampling using a variable Delay



EOS:
Electro-Optic Sampling

- frequently used for THz-spectroscopy
- technically simple, high resolution

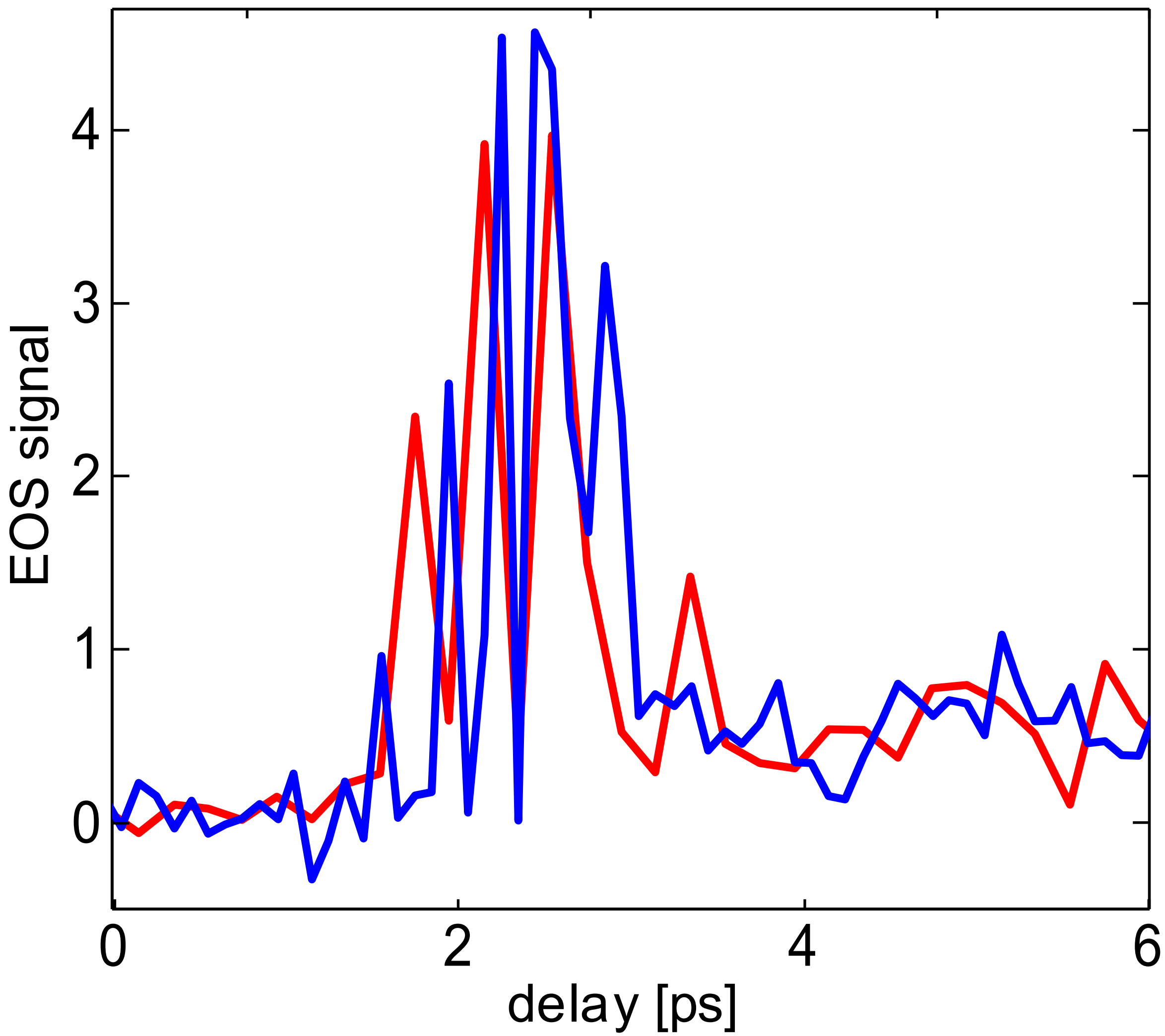
Problem: - averages over many bunches
- sensitive to time jitter

FLASH
Free-Electron Laser in Hamburg
DESY
Bernd.Steffen@desy.de

Electro-Optic Sampling using a variable delay

Time jitter: approx. 200 fs, larger than bunch length

Single shot measurements necessary!

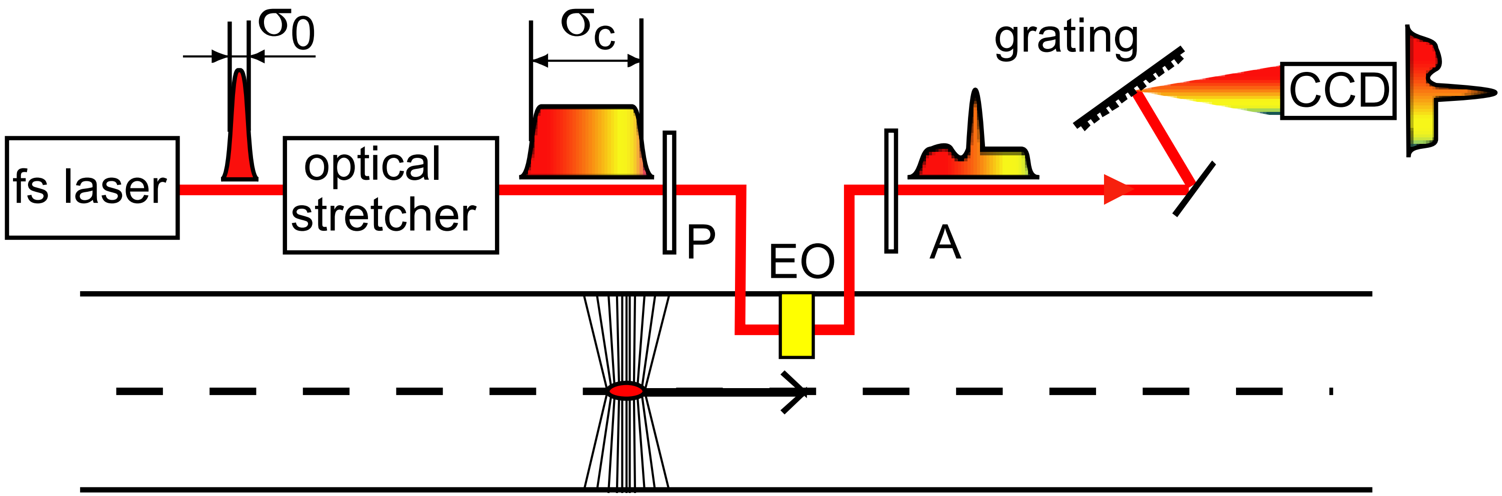


FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

EO Spectral Detection



- Linear relationship between wavelength and long. position in laser pulse (“linear chirp“)
- Bunch profile is transferred to spectral profile of the laser pulse
  - Problem: Frequency mixing with THz pulse creates new frequency components:

    $\Rightarrow$ Distortions at large chirp $\alpha \approx 1/\sqrt{\sigma_0\,\sigma_c}$

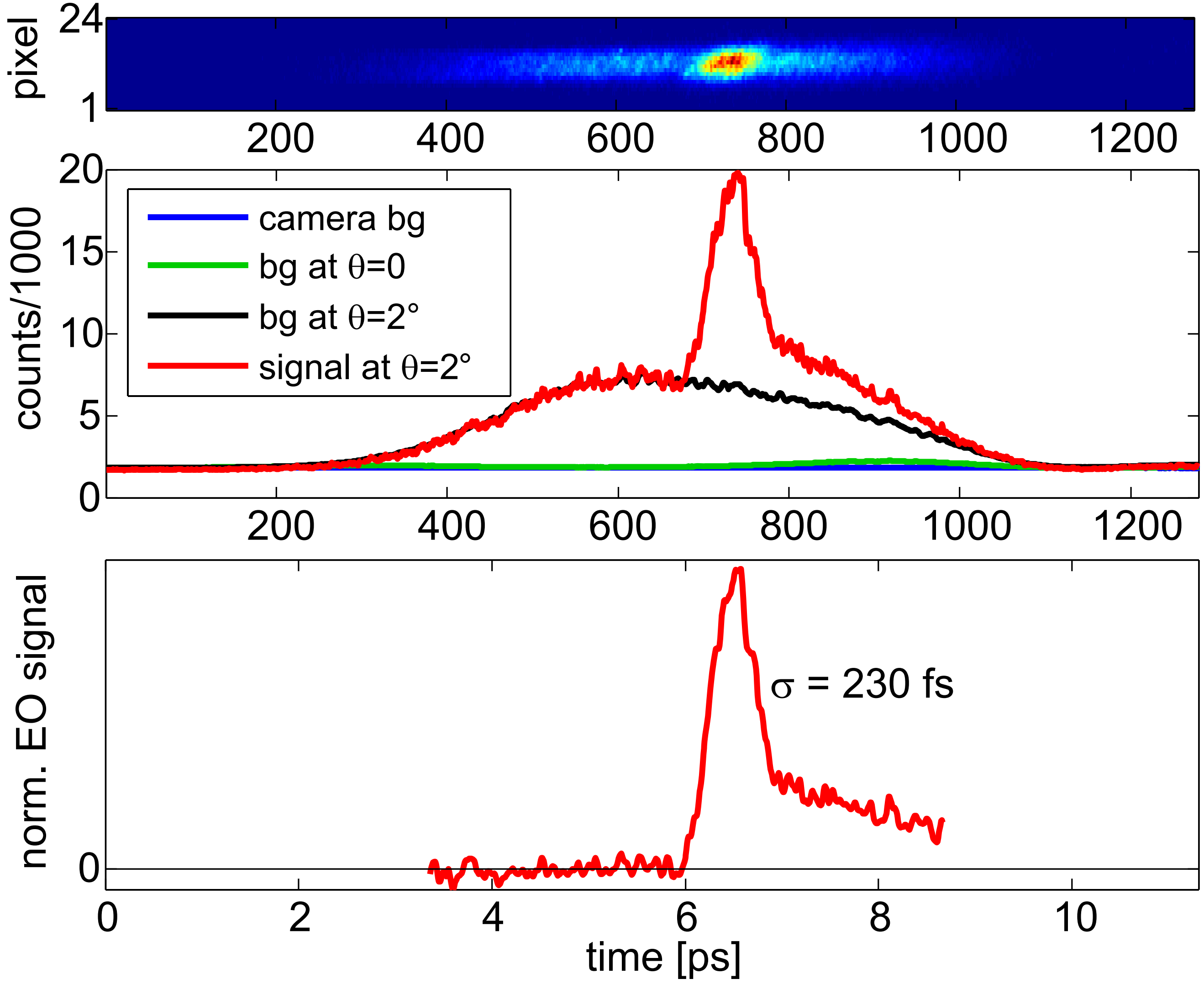
$$\sigma_{\min} \approx 2.6\sqrt{\sigma_0\,\sigma_c} \approx 200\ \mathrm{fs}$$ (for Gaussian pulses!)

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

EO Spectral Detection



GaP 175 µm, σ_0=7 fs, σ_c=1.5 ps

Bernd Steffen, 18.10.2007

FLASH
Free-Electron Laser in Hamburg

DESY

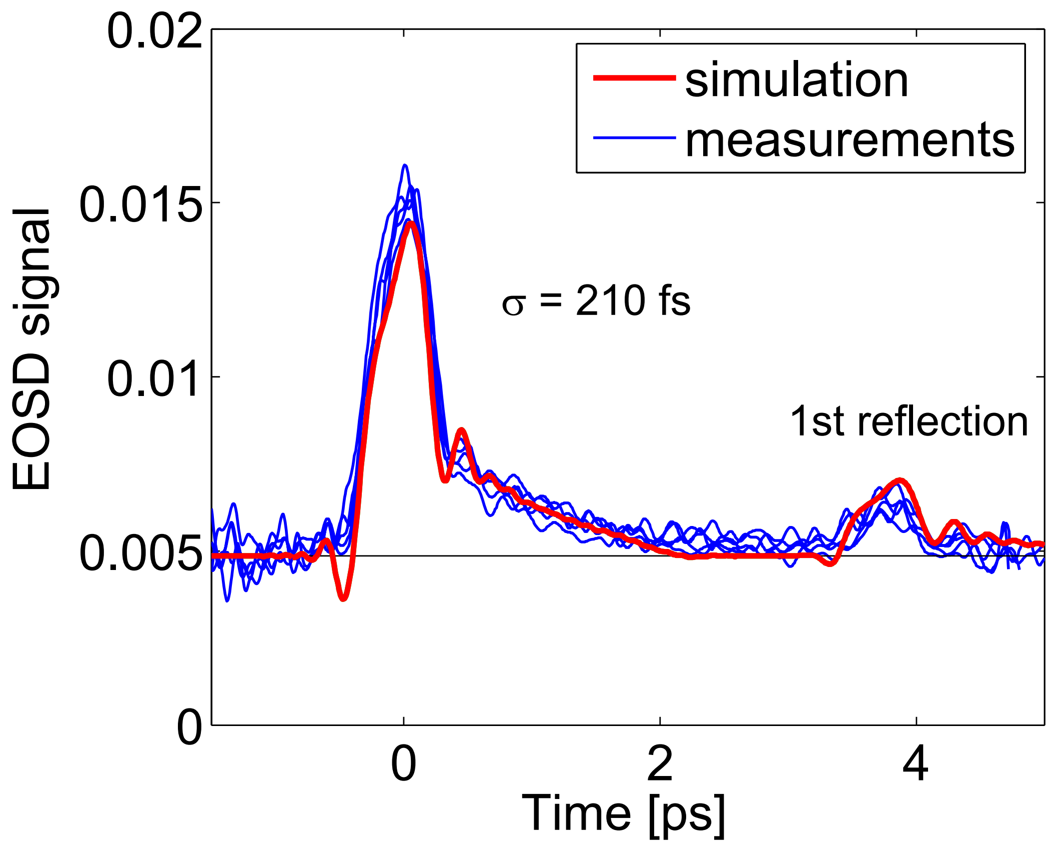
Bernd.Steffen@desy.de

Spectrally resolved detection: Comparison of measured to simulated signals

5 consecutive bunches, corrected for different arrival times

Simulation:
EOSD signal of a bunch measured with TDS

GaP 175 µm
θ=2°
σ_0=7 fs
σ_c=1.5ps



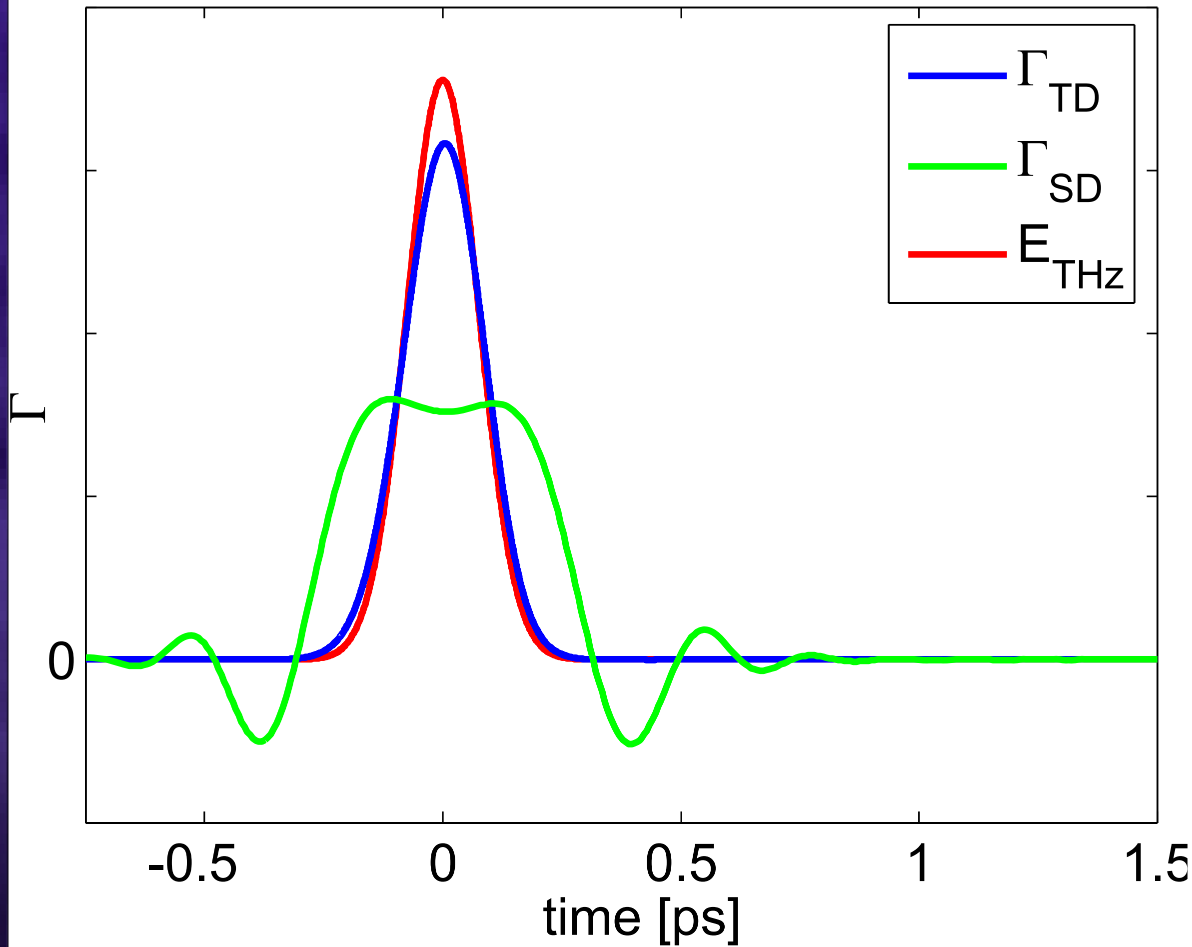
Excellent agreement with simulation in shape and amplitude, but much wider than electron bunch due to response function and frequency mixing

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

EOSD: Distortions due to frequency mixing for thin crystal and large chirp



GaP 100μm thick

σ_{THz}= 75 fs

Laser σ_0=6 fs
chirped to: σ_c=1.5 ps

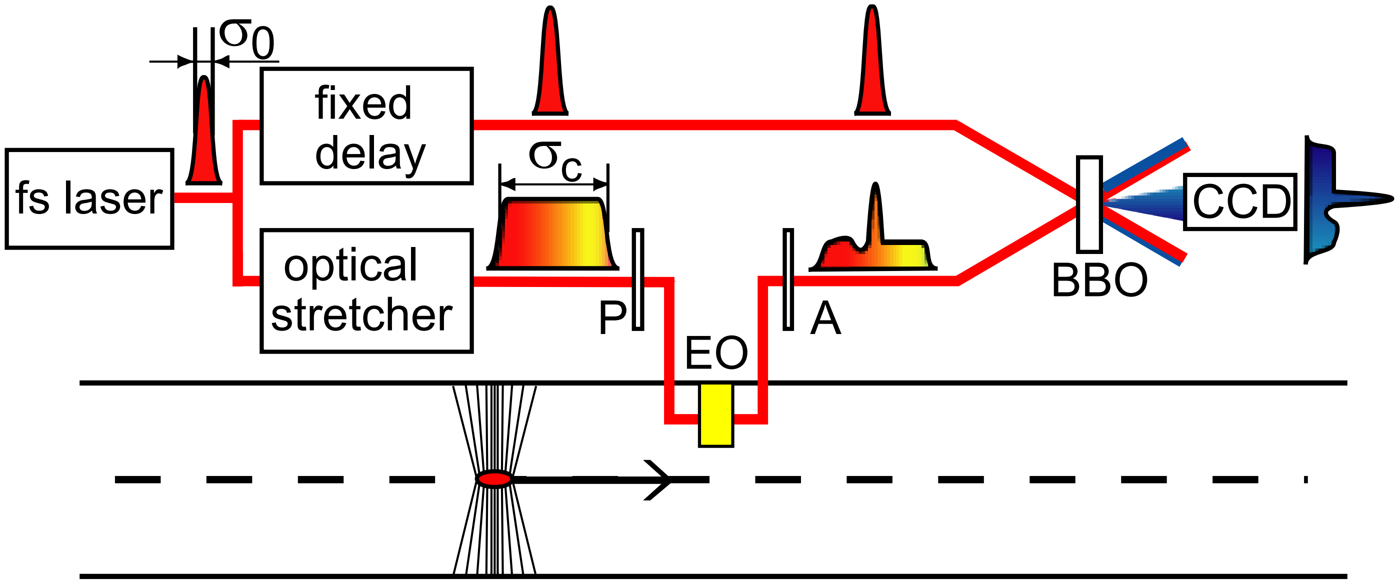
θ=45°

FLASH
Free-Electron Laser in Hamburg

DESY

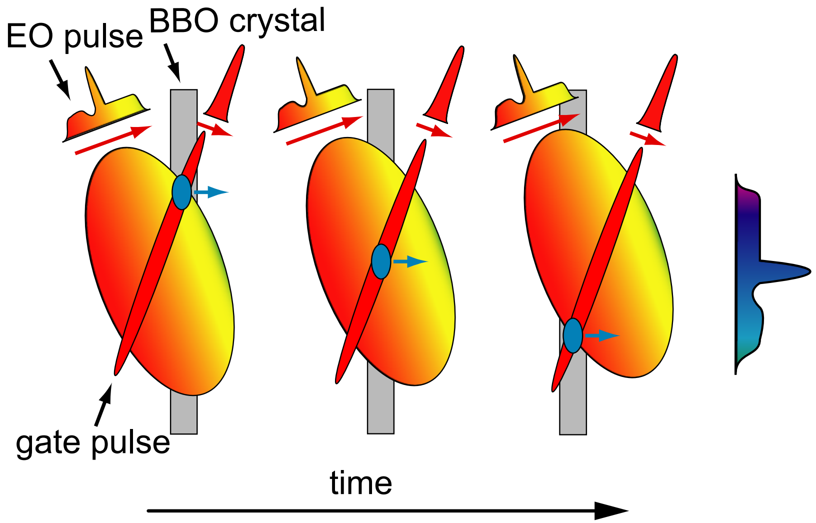
Bernd.Steffen@desy.de

EO Temporal Detection



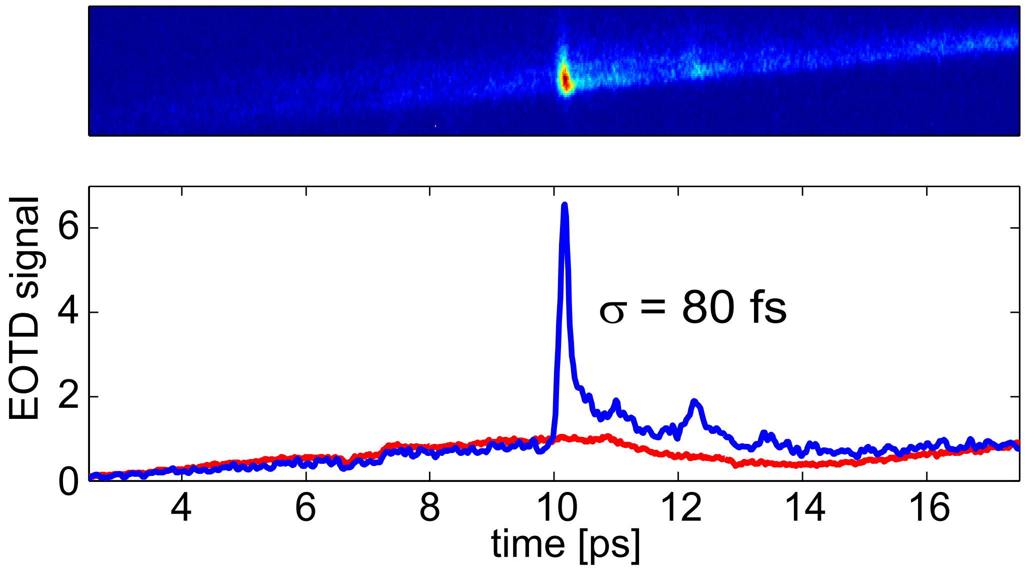
- Cross-correlation with fs pulse in a frequency doubling crystal (BBO)

- approx. 100 μJ pulse energy necessary for 10 ps time window



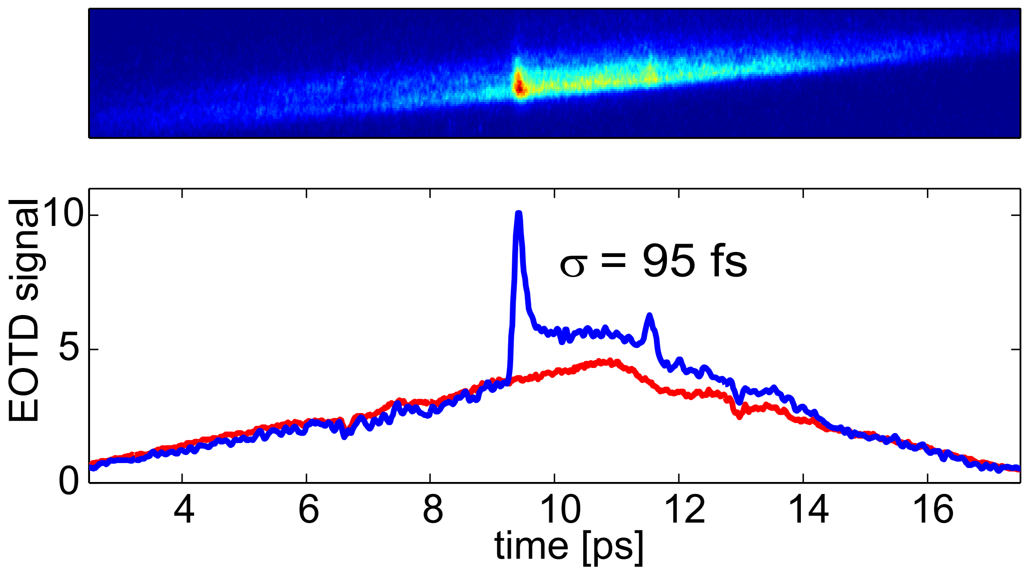
FLASH
Free-Electron Laser
in Hamburg
DESY
Bernd.Steffen@desy.de

EO Temporal Detection



$\theta = 0$

EO signal $\propto$ E_{THz}^2



$\theta = 1°$

EO signal $\propto$ E_{THz}

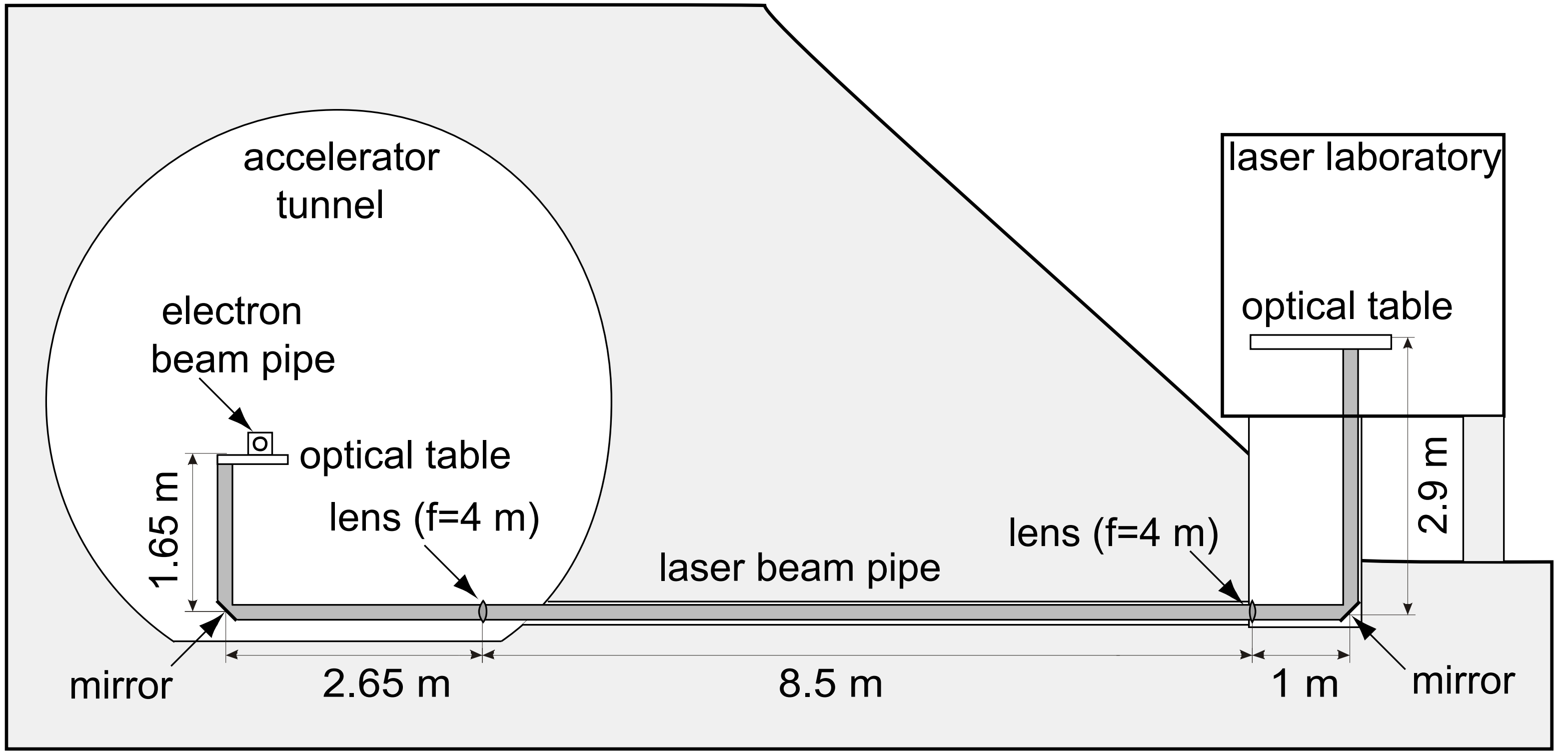
Bernd Steffen, 18.10.2007

FLASH
Free-Electron Laser
in Hamburg

DESY

Bernd.Steffen@desy.de

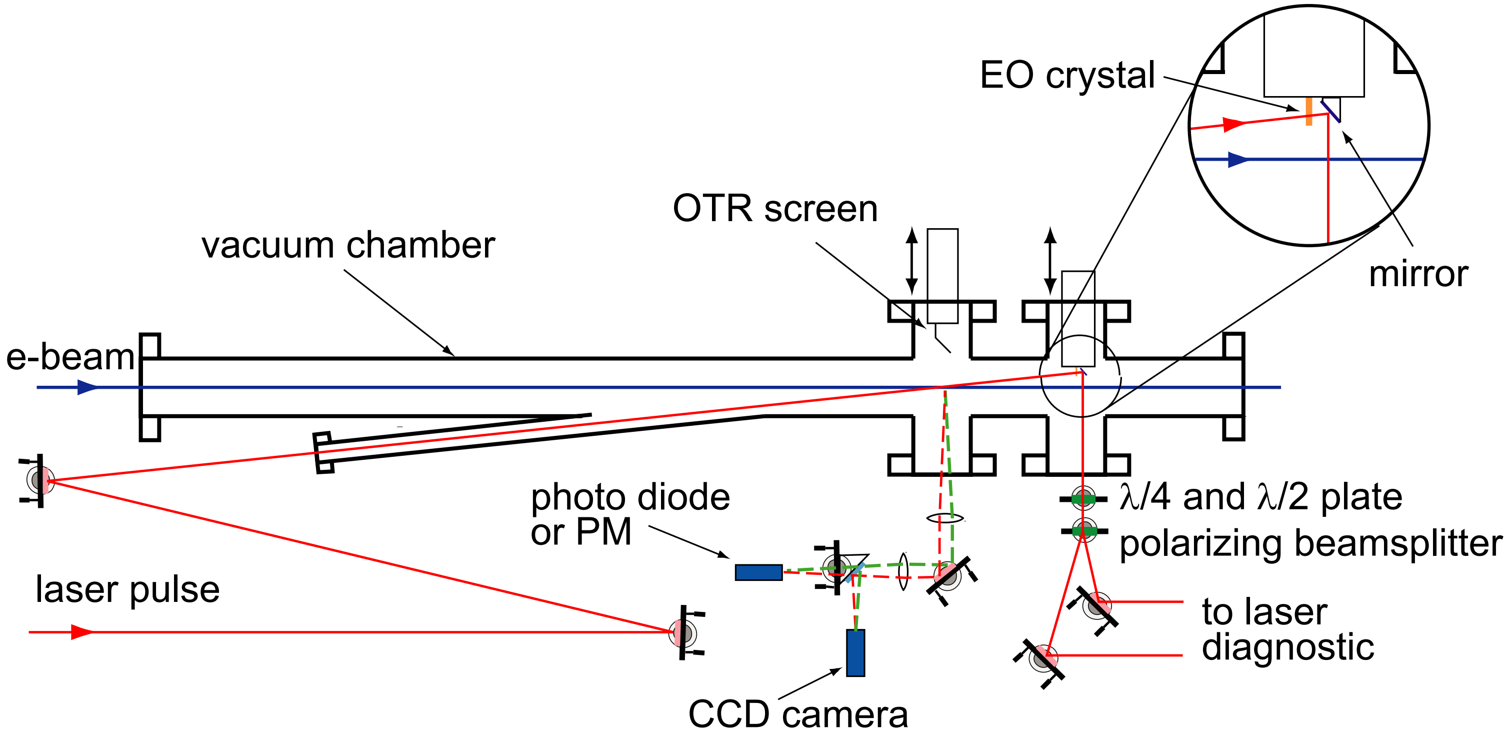
EO setup at FLASH



- Laser systems in lab outside the accelerator:
    - 4 nJ, 7 fs Ti:Sa Oscillator
    - 1 mJ, 15 fs Ti:Sa amplifier
- 20 m evacuated transfer pipe to the tunnel

Bernd.Steffen@desy.de

EO vacuum chamber in the beam pipe



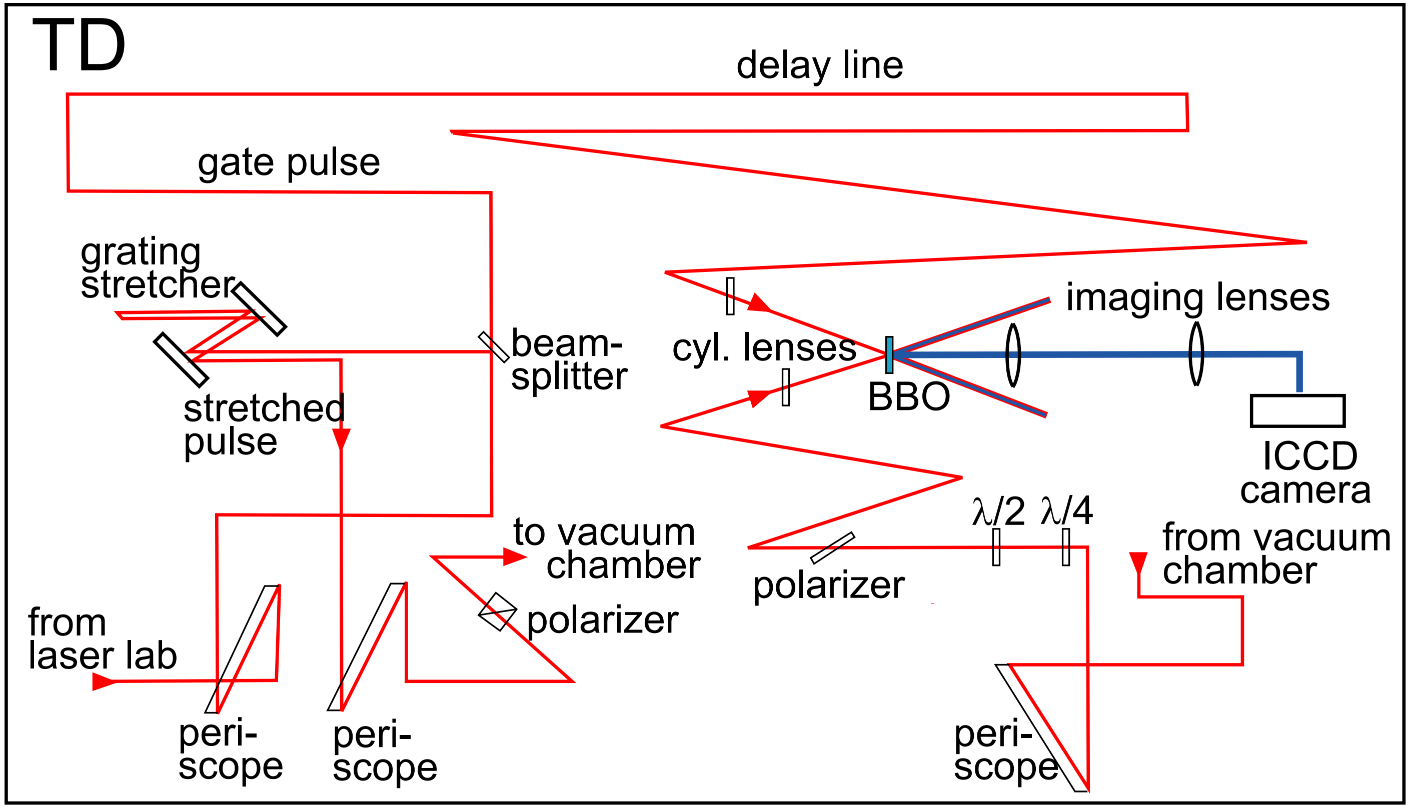
- plane (175 µm) and wedged (30-200 µm) GaP crystal in the beam pipe

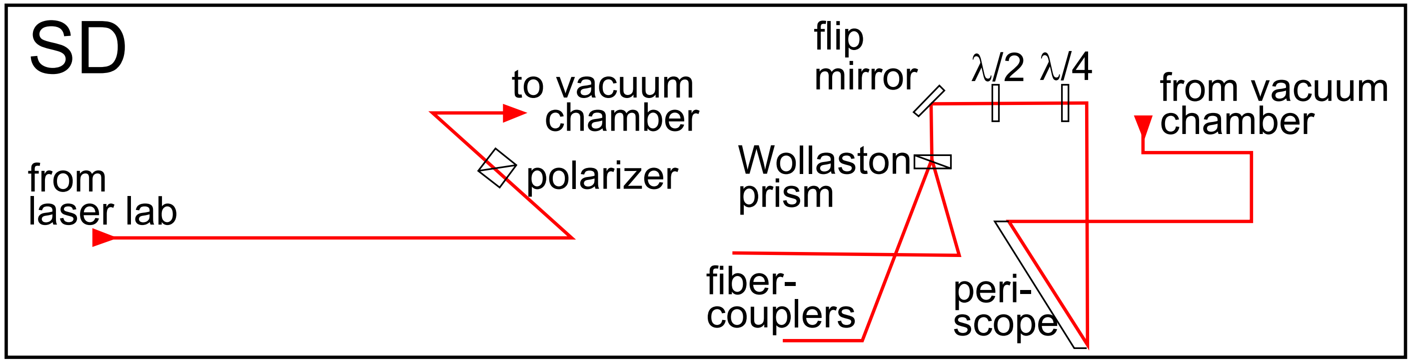
- allows spectrally and temporally decoded measurements

FLASH
Free-Electron Laser
in Hamburg
DESY
Bernd.Steffen@desy.de


Newport

EO setup in the accelerator tunnel

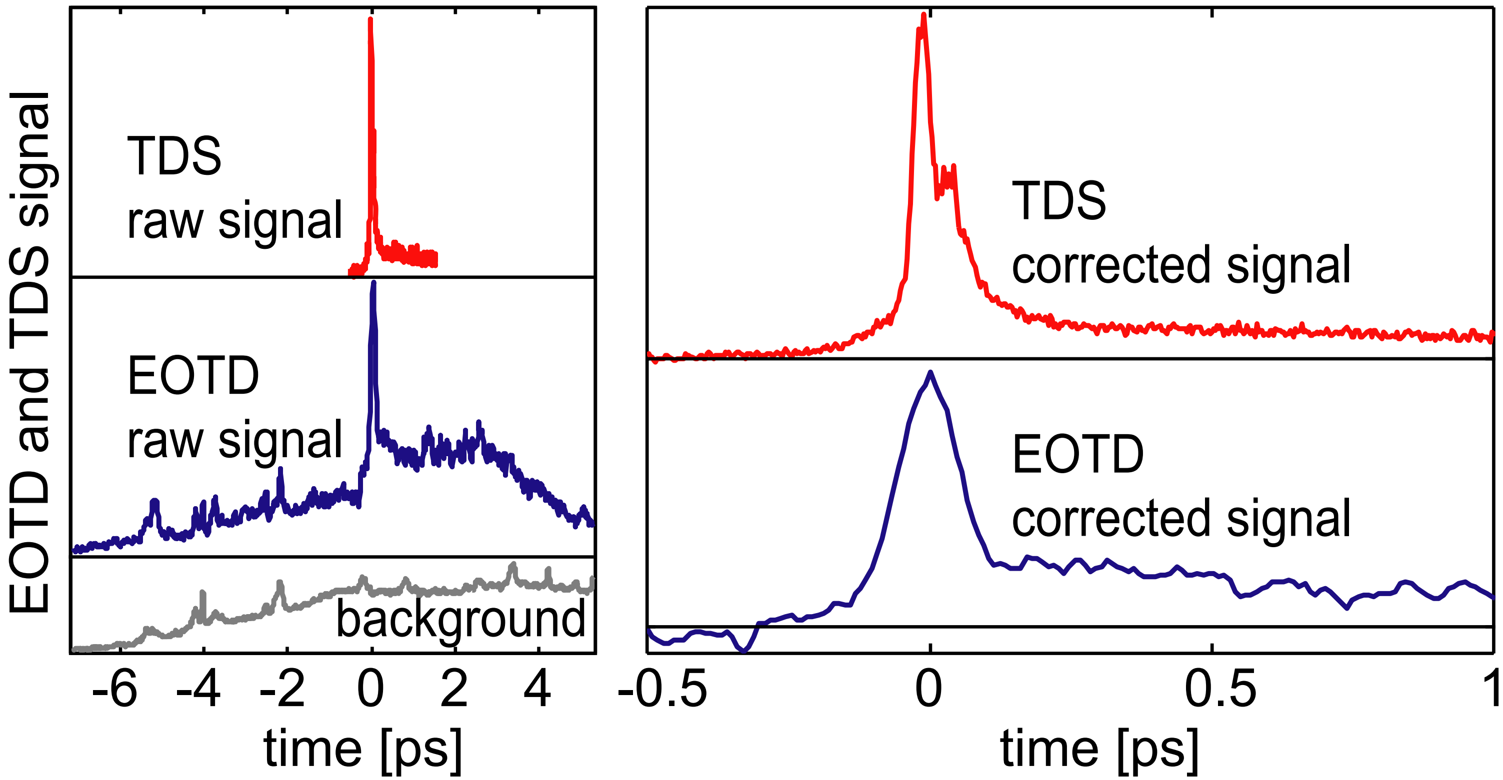




FLASH
Free-Electron Laser in Hamburg

Bernd.Steffen@desy.de

Comparison of EOTD vs. TDS measurements



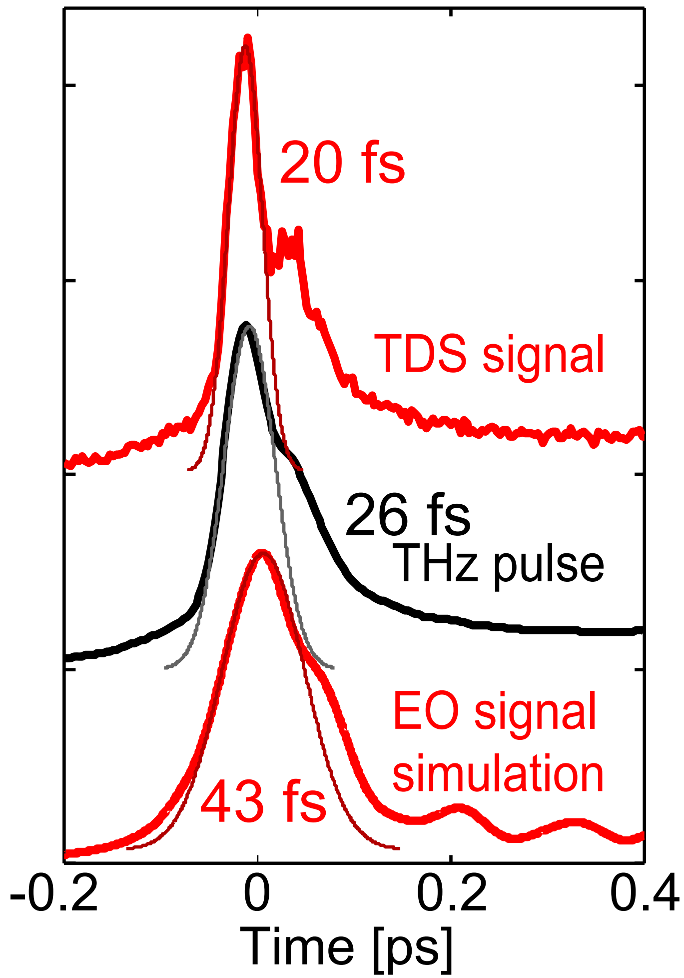
- 10th bunch in bunch train: electro-optic detection
- 11th bunch: TDS

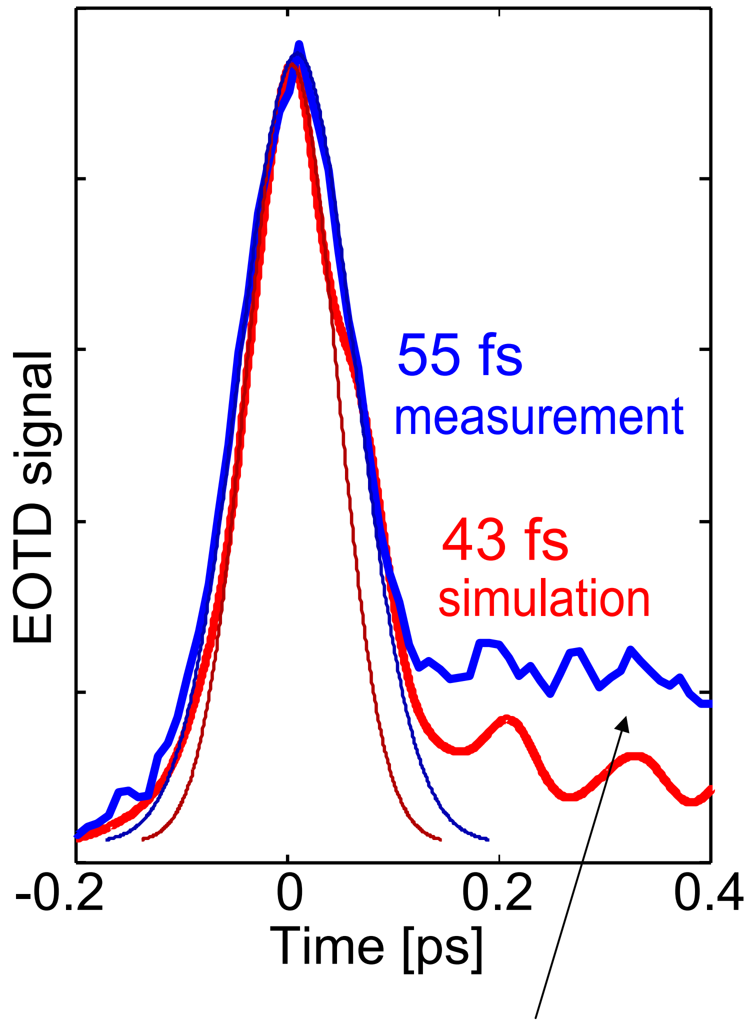
Bernd.Steffen@desy.de

FLASH Free-Electron Laser in Hamburg

DESY

Comparison of EOTD vs. TDS measurements





Signal due to wake fields?

- Good agreement between measurement and simulation

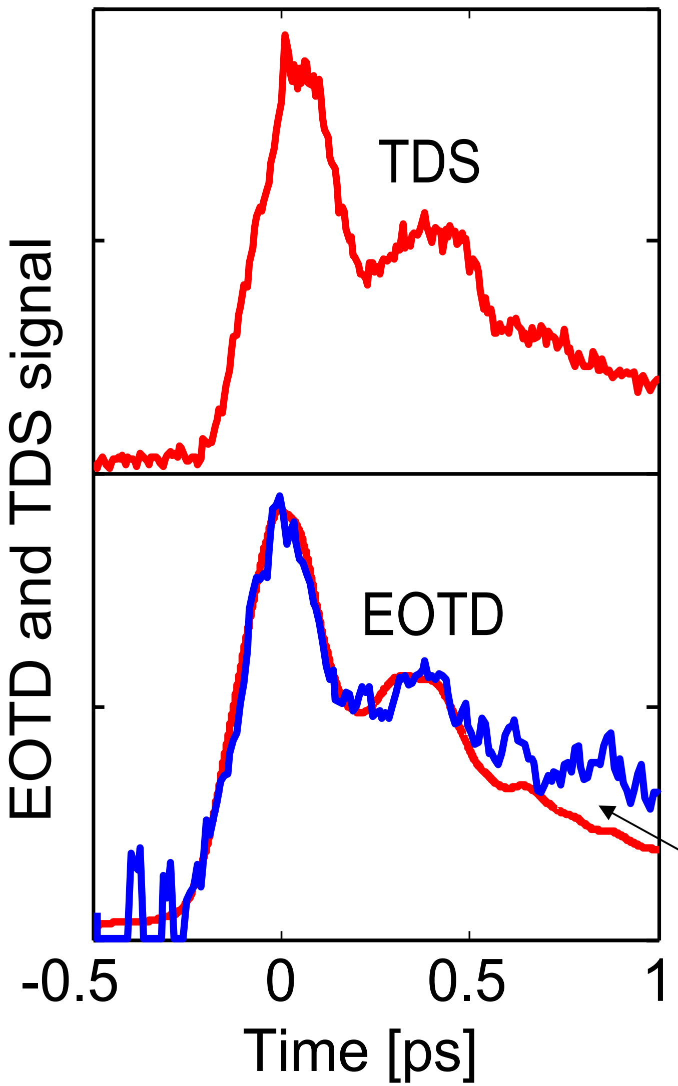
- close to the resolution limit of GaP

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

TDS and EOTD measurement of overcompressed bunches



In good agreement with the electron bunch shape

Signal due to wake fields?

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Overview

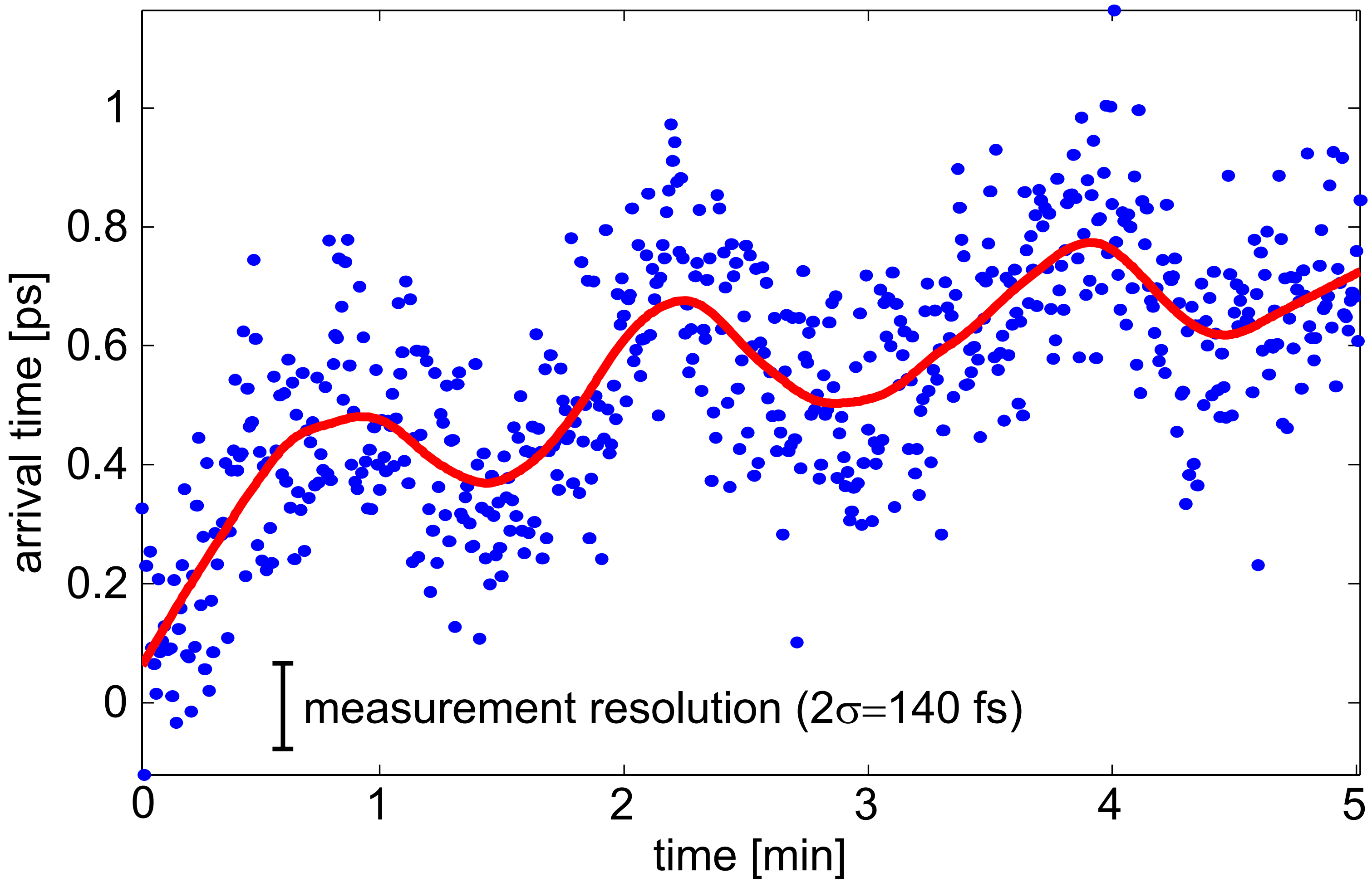
- Motivation
- Basics
  - Electro-optic effect
  - EO measurement principle
  - Detection schemes
- Measurement schemes and results
  - Electro-optic sampling using a variable delay
  - Spectrally resolved detection
  - Temporally resolved detection
- **Applications**
- Conclusion

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Time jitter, measured with EOSD



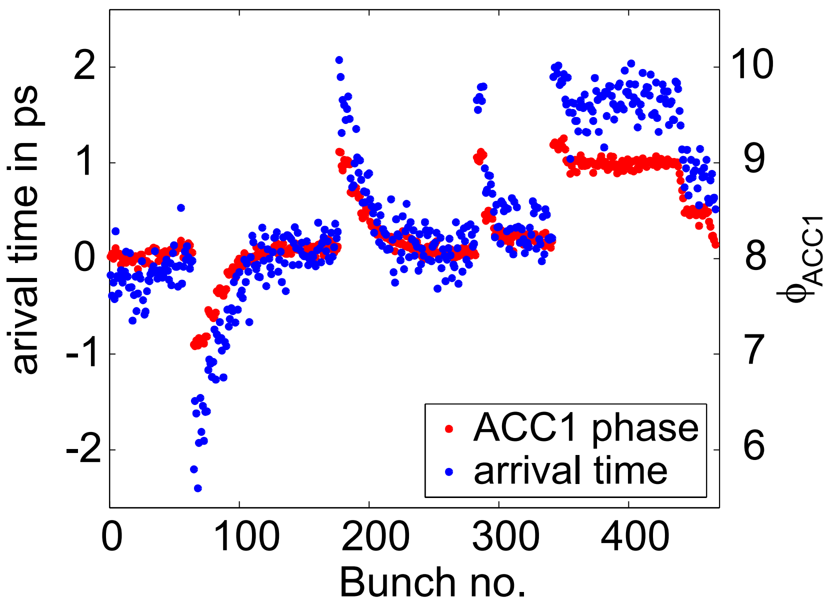
- Time jitter: 200 fs (rms) incl. slow drift
- Slow drift removed: **130 fs (rms)**

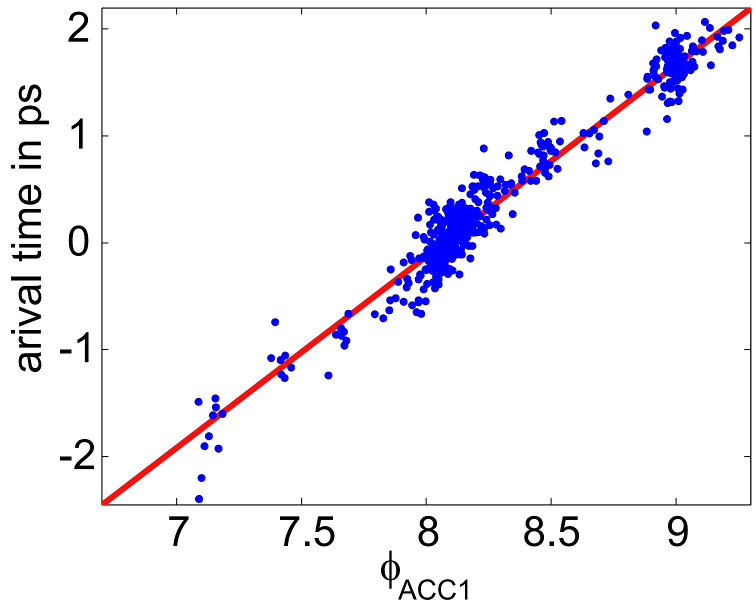
Bernd Steffen, 18.10.2007

FLASH
Free-Electron Laser in Hamburg
DESY

Bernd.Steffen@desy.de

Bunch arrival time dependence on the ACC1 phase

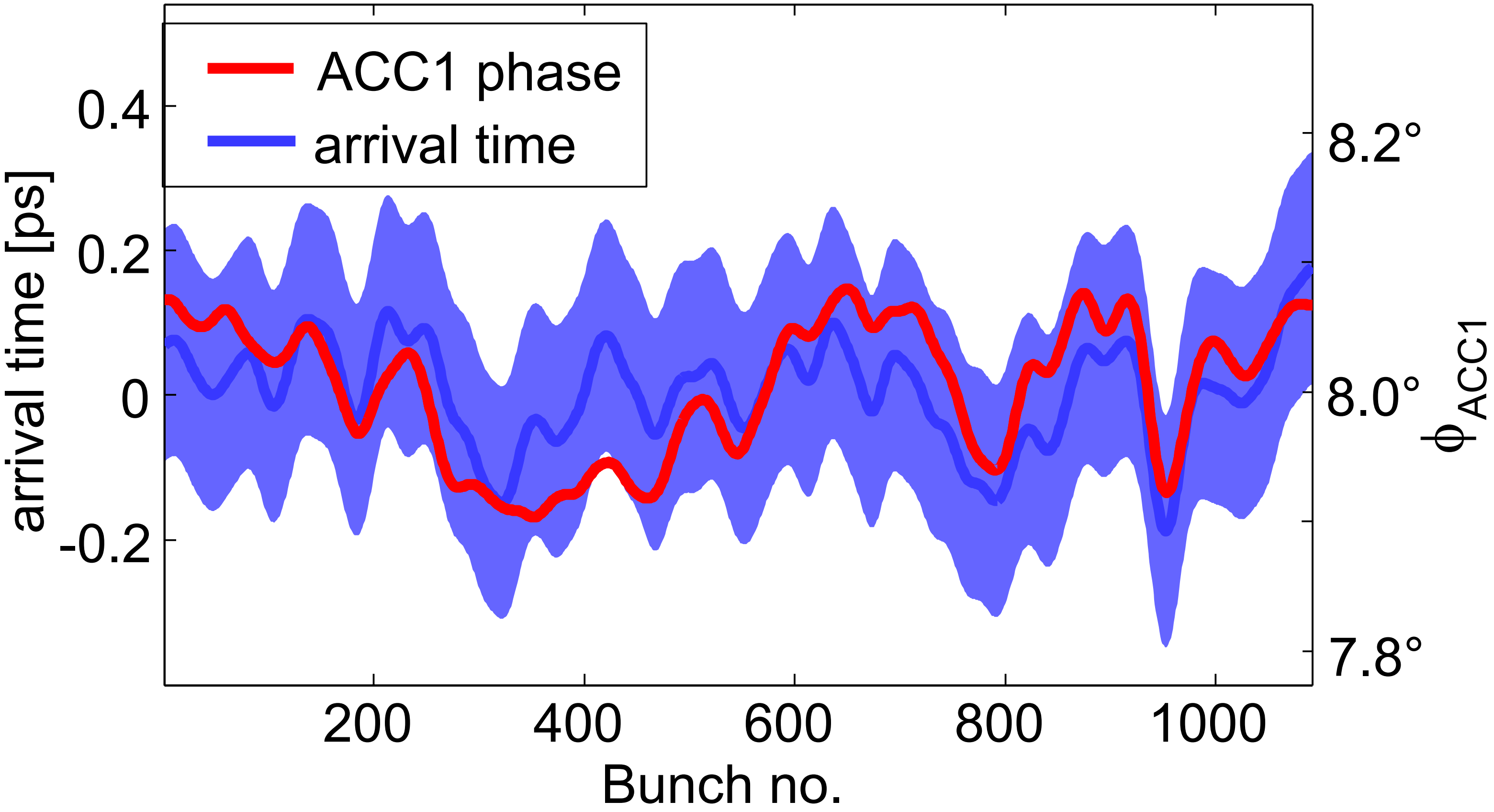




Arrival time change: 1.79 ps/Grad

Bernd.Steffen@desy.de

Correlation between arrival time and ACC1 phase



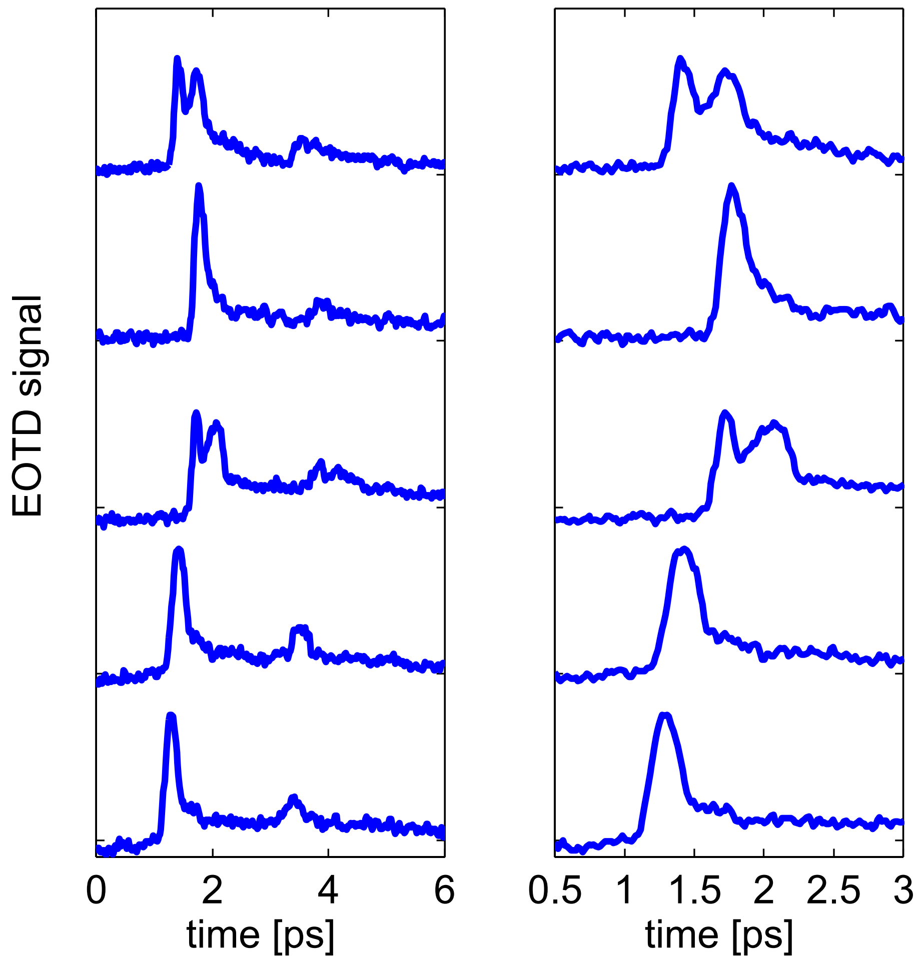
⇒ correlated time jitter due to phase jitter: 103 fs
⇒ uncorrelated time jitter due to other sources: 135 fs
⇒ uncertainty in the phase measurement: 0.04° or 73 fs

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Bunch shape without at maximum compression (without feedback)



occasionally double pulses

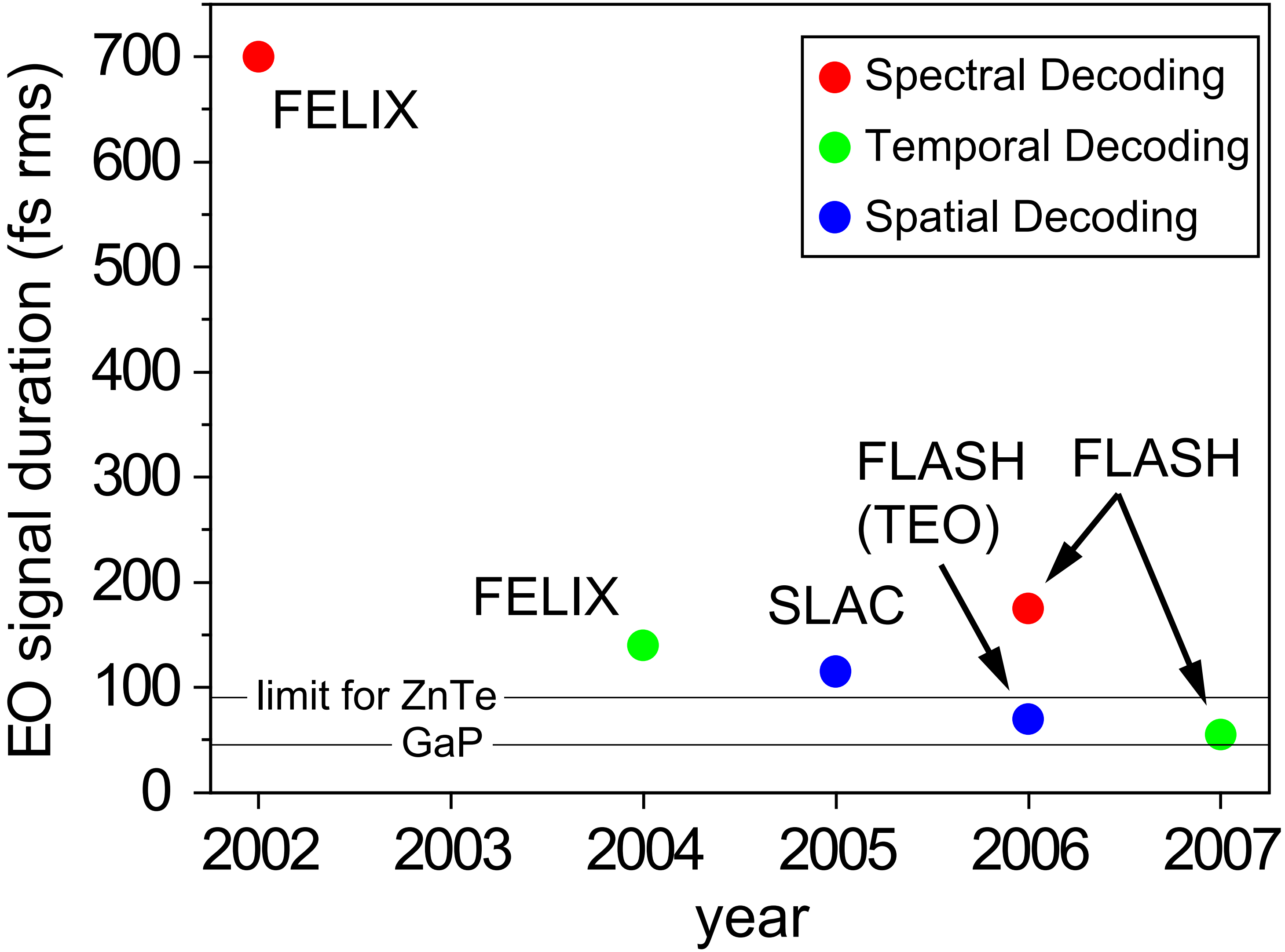
Down to a separation of approx. 130 fs double pulses can be separated

Bernd.Steffen@desy.de

FLASH
Free-Electron Laser in Hamburg

DESY

Comparison to other EO experiments



FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Conclusions

- Benchmarked EO detection against TDS
- Simulations based on published material data consistent in shape and amplitude with measured signals for GaP
- EO signals measured with of 55 fs (rms) length (linear in field and without deconvolution!) are close to the resolution limit of GaP

FLASH
Free-Electron Laser in Hamburg

DESY

Bernd.Steffen@desy.de

Thanks to

- G. Berden, A.F.G. van der Meer (FELIX)
- S. Jamison (ASTeC, Daresbury Laboratory)
- P.J. Phillips, W.A. Gillespie (University of Dundee)
- A.M. MacLeod (School of Computing and Advanced Technologies, University of Abertay, Dundee)
- V. Arsov, E.-A. Knabbe, H. Schlarb, B. Schmidt, P. Schmüser (DESY)

“Progress of the TEO experiment at FLASH”

VUV-FEL at DESY

-

Armin Azima

S. Duesterer, J. Feldhaus, H. Schlarb, H. Redlin, B. Steffen, **DESY Hamburg**

K. Sengstock, **Uni Hamburg**

Adrian Cavalieri, David Fritz, David Reis, **Michigan University Ann Arbor, Michigan**

Motivation

FLASH

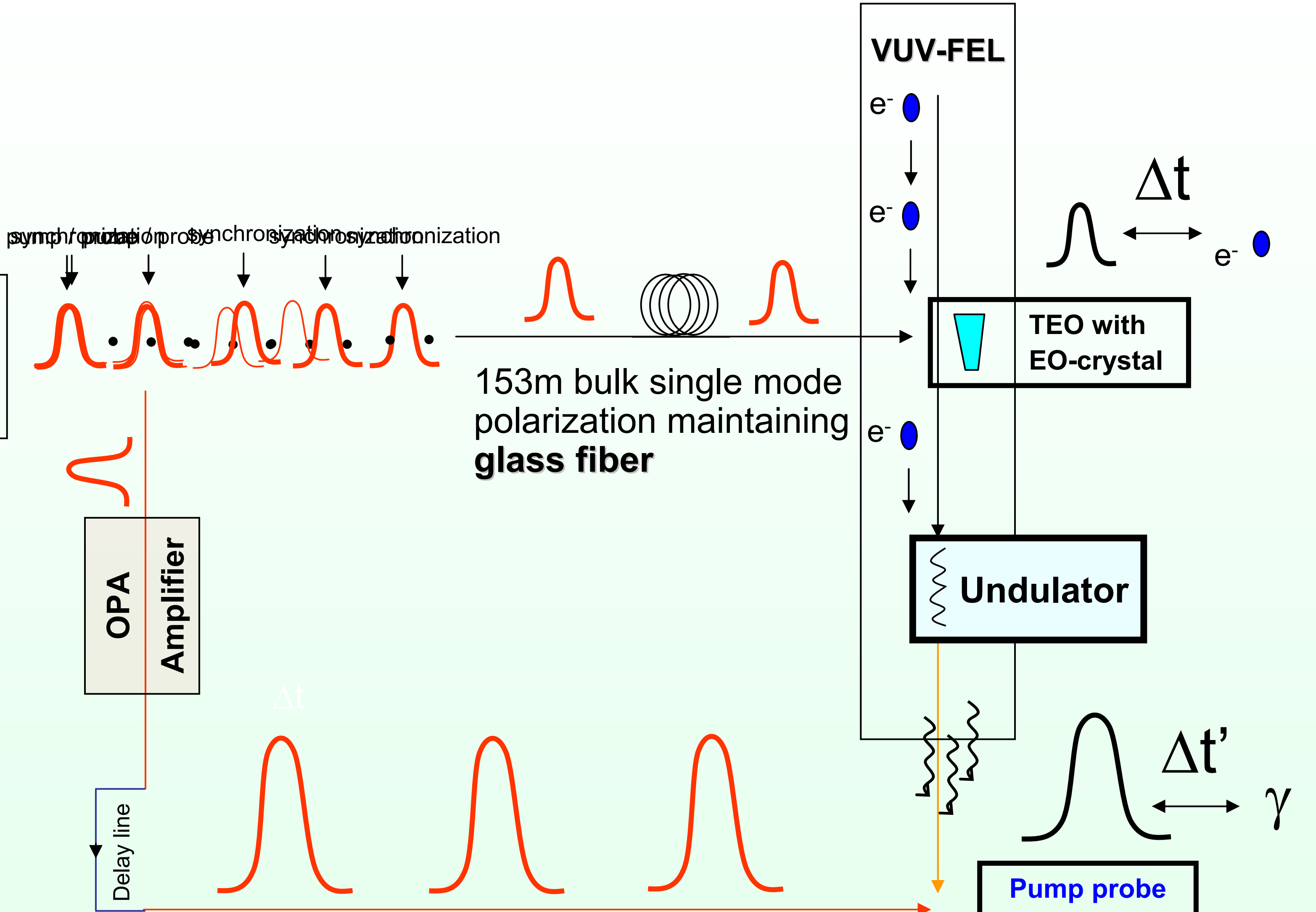
- TEO: “Timing by Electro Optical sampling”
  - correlation between an optical laser pulse and the electric field of an electron bunch
  - based upon Pockel’s effect

- Purpose:
  - jitter measurement for pump probe experiments
  - electron bunch analyzing

Timing of TEO experiment - principle

FLASH

TiSa - Laser oscillator

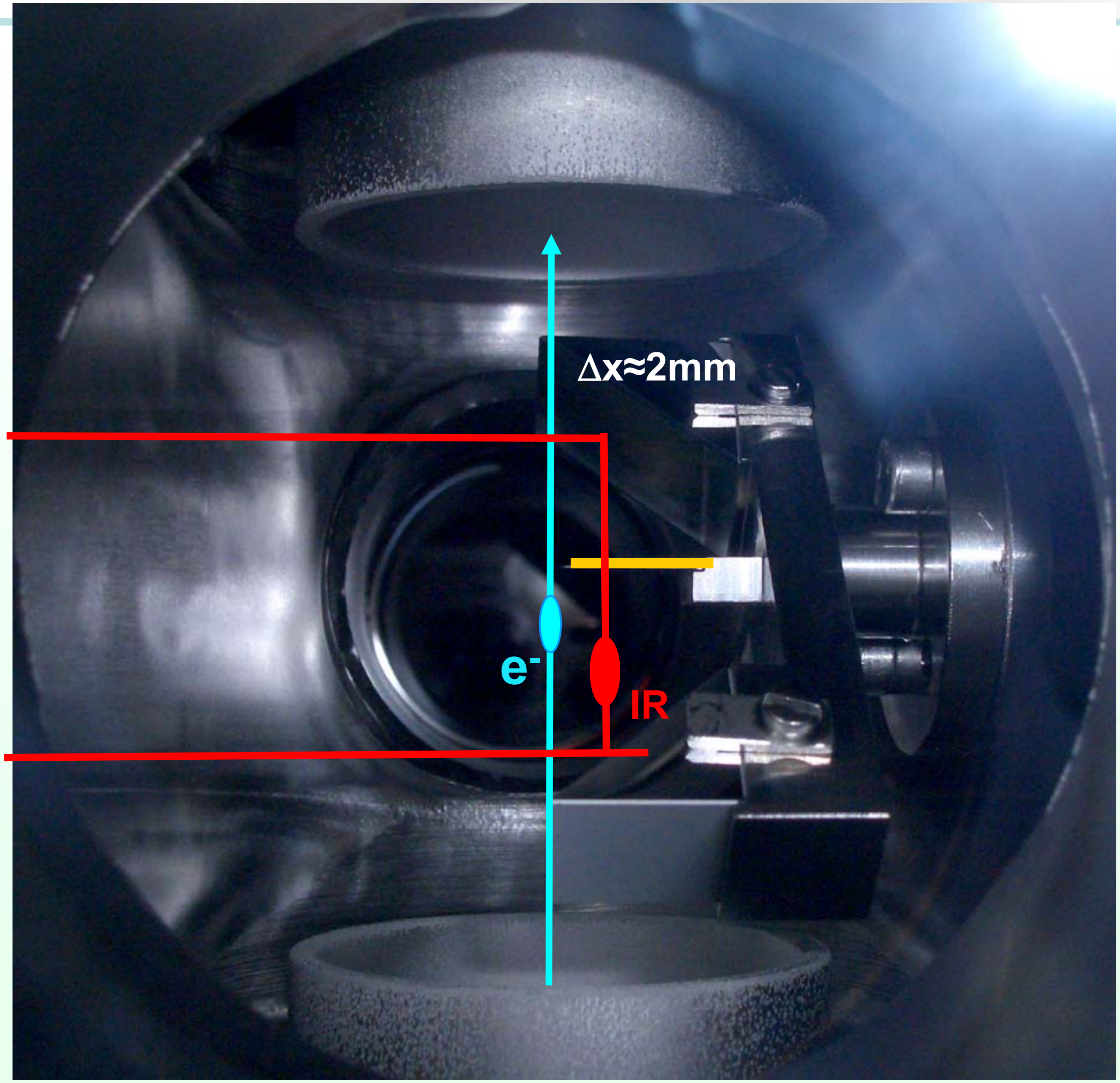


- *Laser puls FWHM Δt_{FWHM} = 60fs*
- *Phase-loop-locked to FEL master oscillator*

Goal: Δt - Δt' < 50fs RMS

TEO detection area - top view

FLASH



EO-crystal material

started with:
ZnTe 50-500μm, wedged

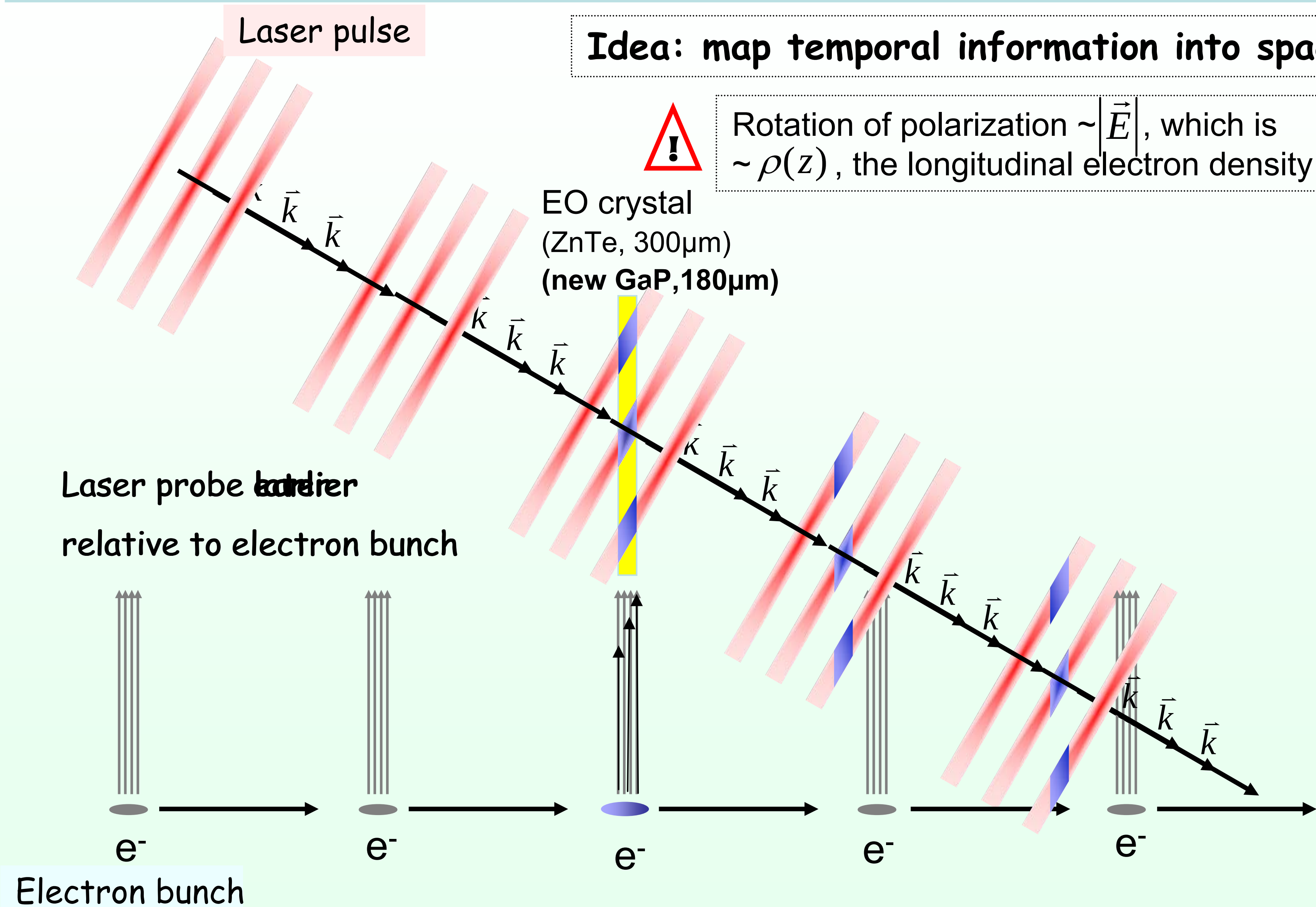
today, resolution optimized:
GaP 180μm

TEO signal detection – side view

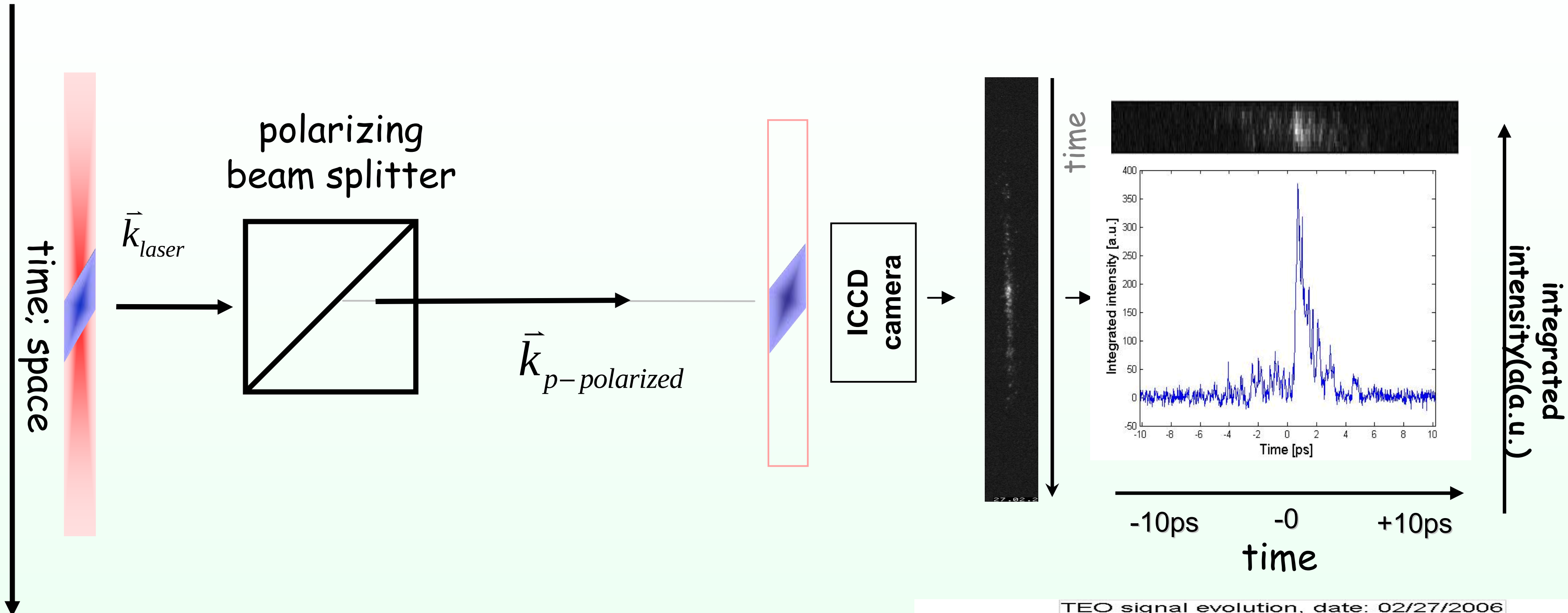
FLASH

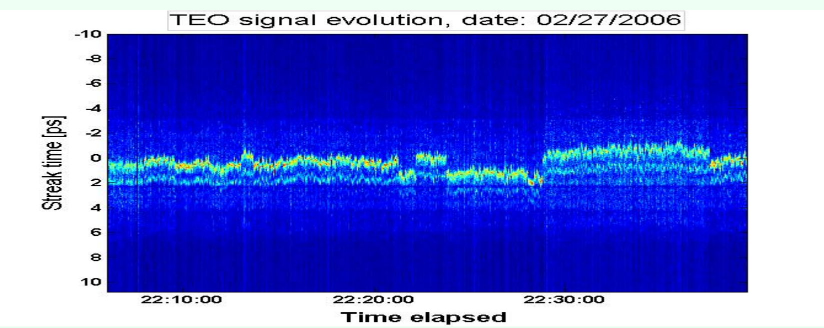
Idea: map temporal information into space

Rotation of polarization ~$|\vec{E}|$, which is ~$\rho(z)$, the longitudinal electron density



TEO signal detection



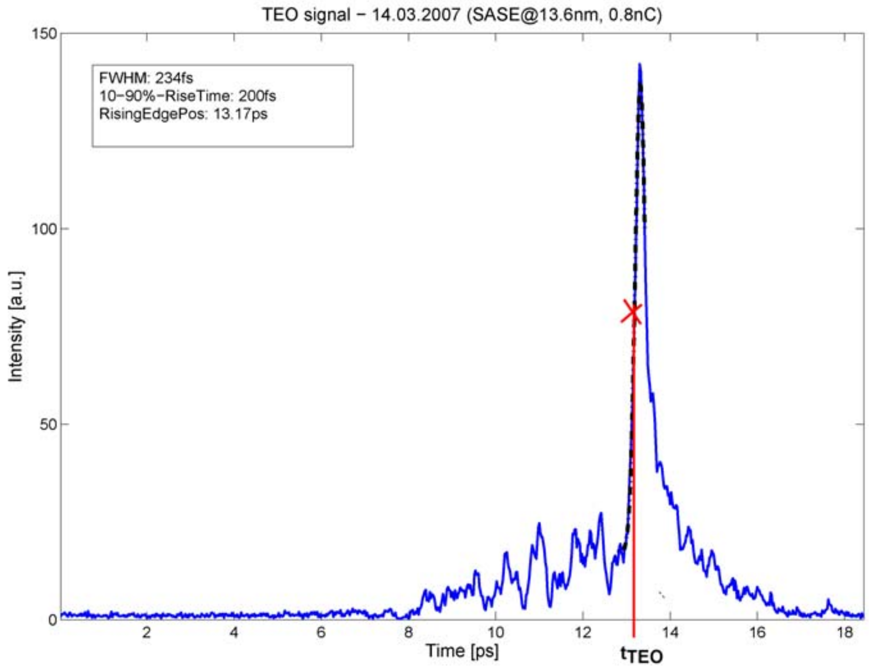


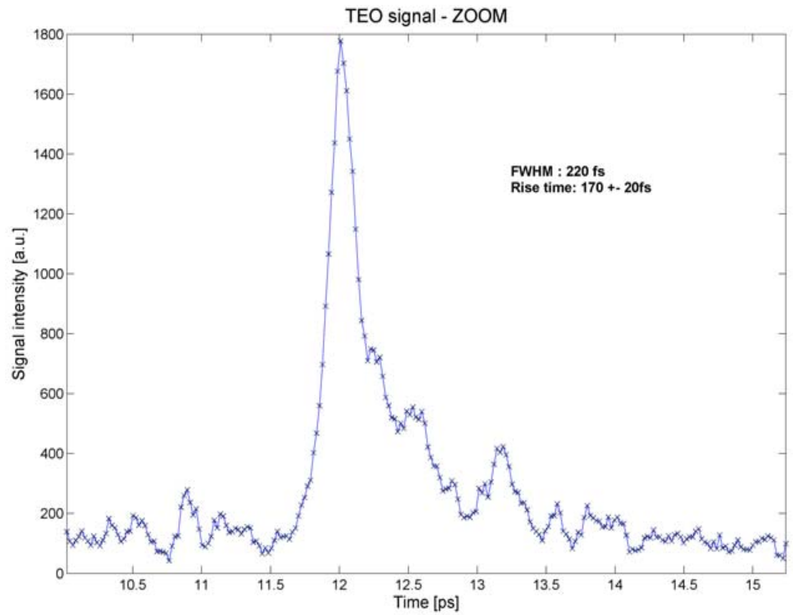
- ***Arrival time* and *duration of bunch* is encoded on profile of laser**

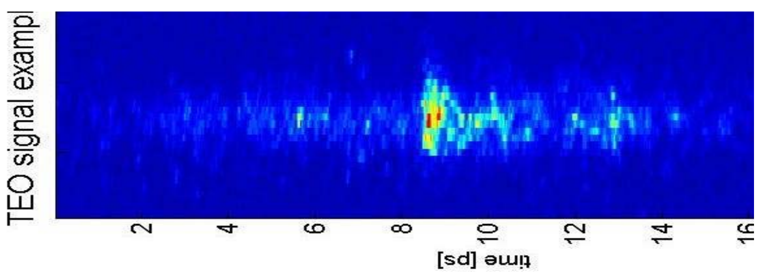
Temporal resolution of Pump-Probe exp. is given by the precision of the jitter measurement, actually 90 fs RMS.

TEO signal examples

FLASH







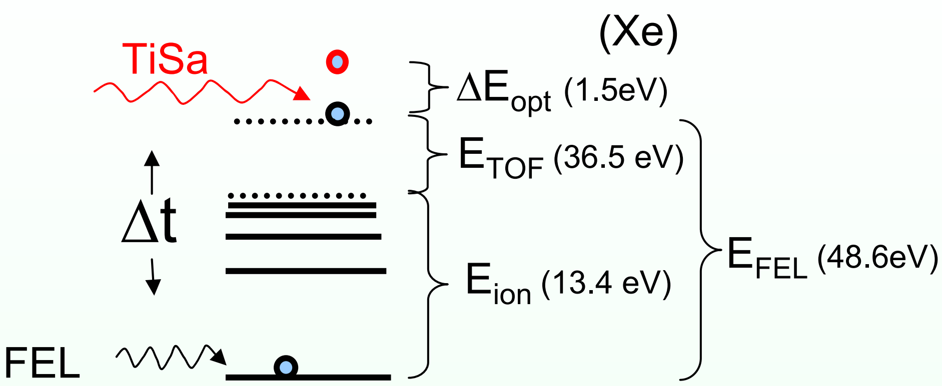
<u>minimal width measured:</u>
220fs FWHM **(95 fs RMS)**

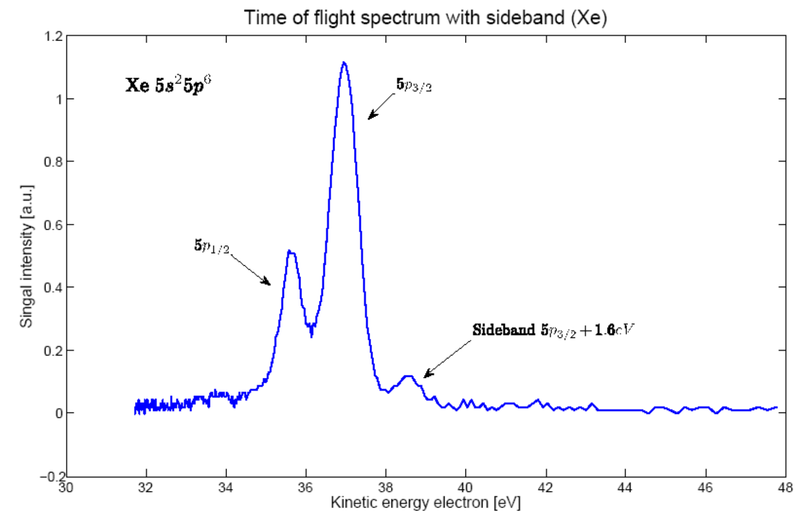
⇔

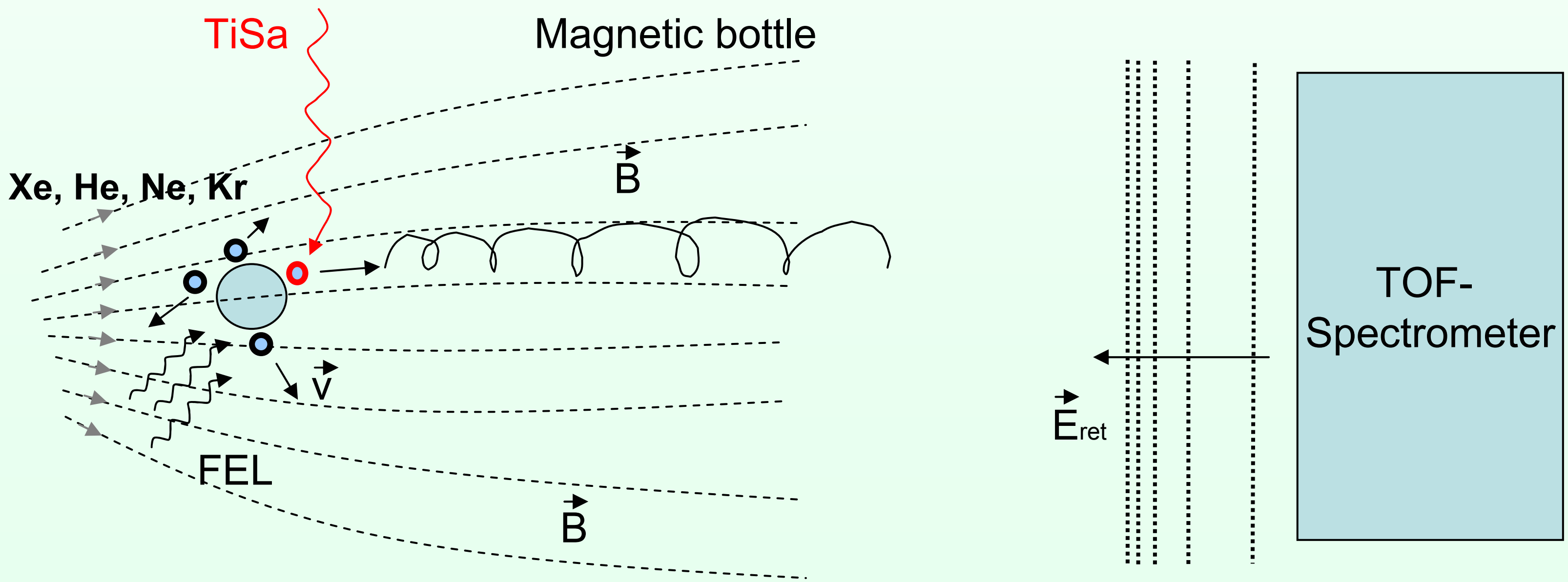
temporal resolution of TEO

Having a peak of 220fs FWHM and 170fs rise time one expects to determine the temporal location of the peak approximately with at least 50fs FWHM (≈20fs RMS) precision.

Pump-Probe experiment in gaseous phase

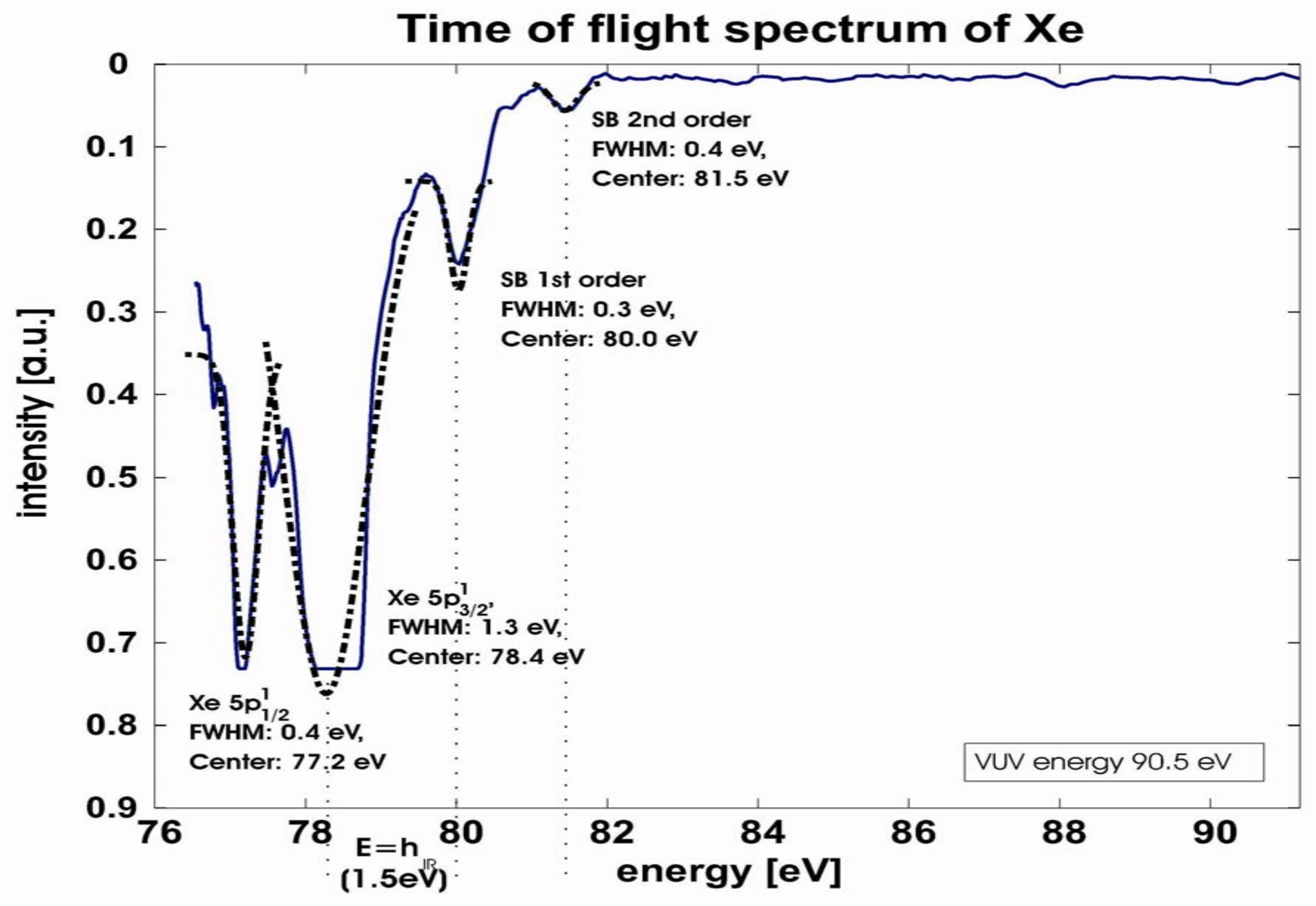






Time of flight spectrum at temporal pulse overlap

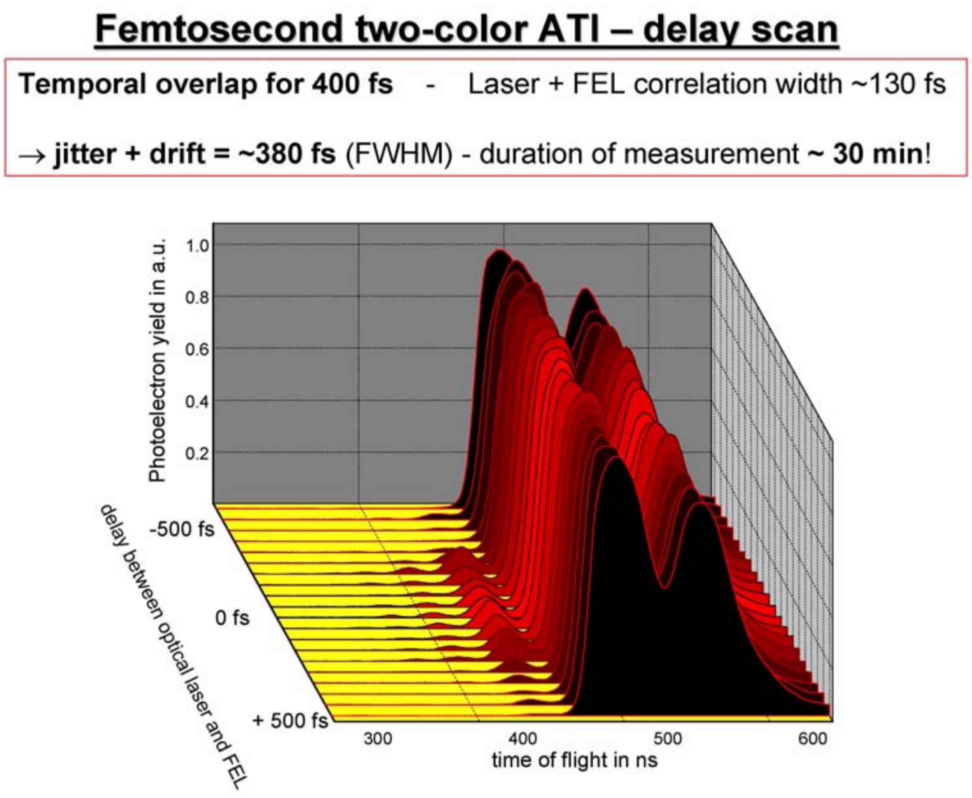
FLASH



Time of flight spectrum of one pump-probe event in Xenon at FLASH

Pump-probe delay scan measurement

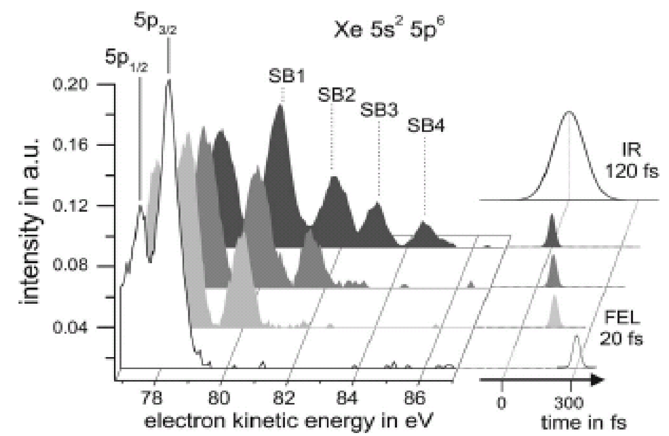
FLASH



Each spectrum shows an average over 200 time-of-flight spectra per delay stage position.

Delay scan measurement of a Two-Colour Pump-Probe experiment in gaseous phase to generate sidebands of the main photo-emission lines of the spin-orbit split states $5p_{1/2}$ and $5p_{3/2}$ of Xenon.

The sideband amplitude is proportional to the degree of pulse overlap.



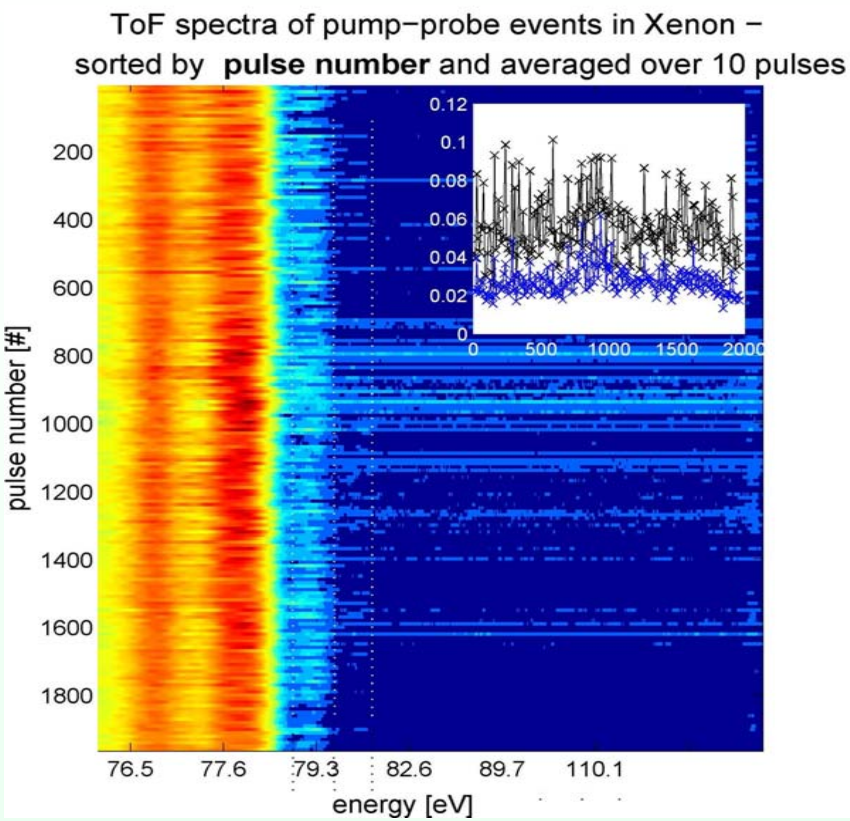
published in
P. Radcliffe, S. Düsterer, M. Meyer,
Applied Physics Letters 90, (2007)

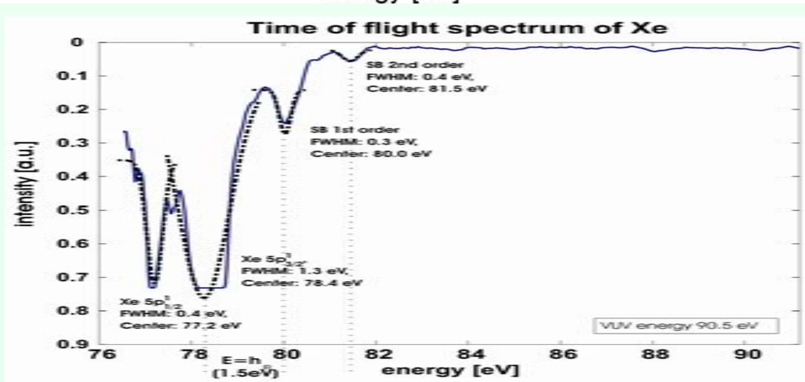
courtesy: S.Duesterer

Pump-probe experiment with fixed delay stage

FLASH

Pulse number [#]





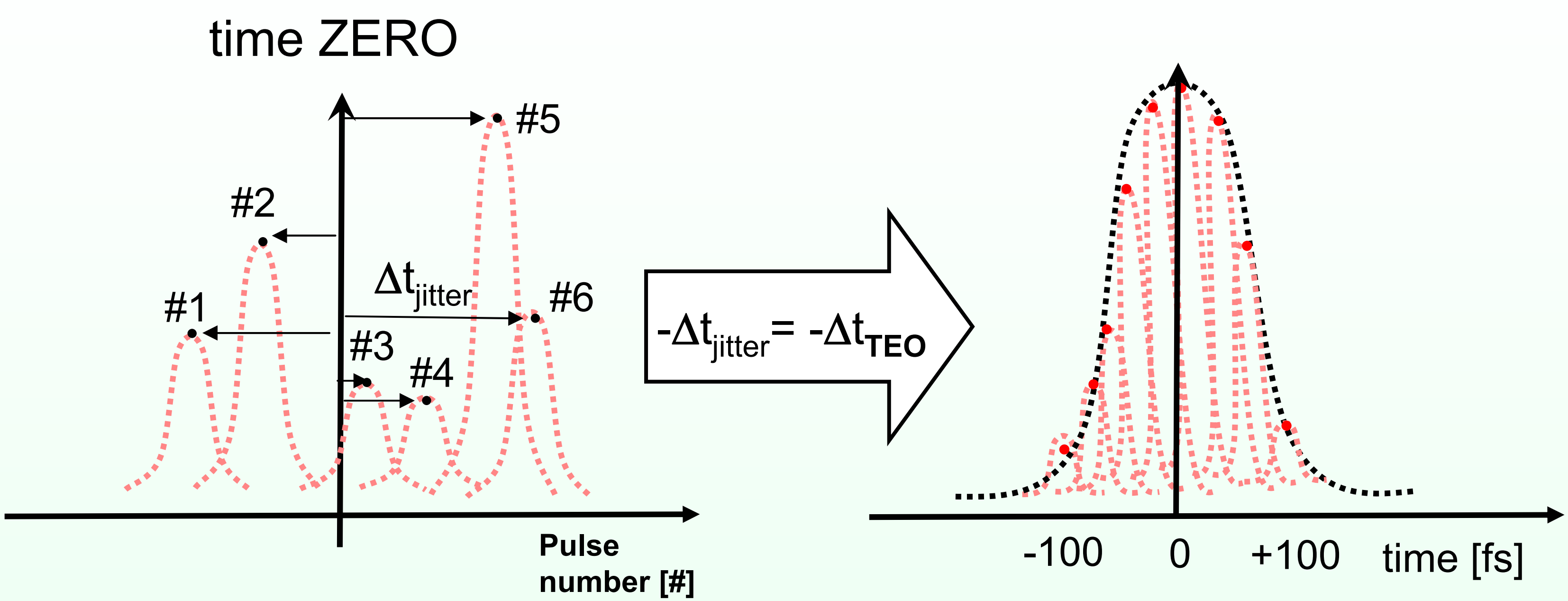
Single shot measurement of the previous pump-probe system, now with a fixed delay stage.

The ToF spectra are plotted in rows, while the spectral amplitude is colour-encoded

In this case the temporal “scan” is performed by the temporal jitter itself !!

Sideband amplitude at fixed delay time -TEO sorting

FLASH

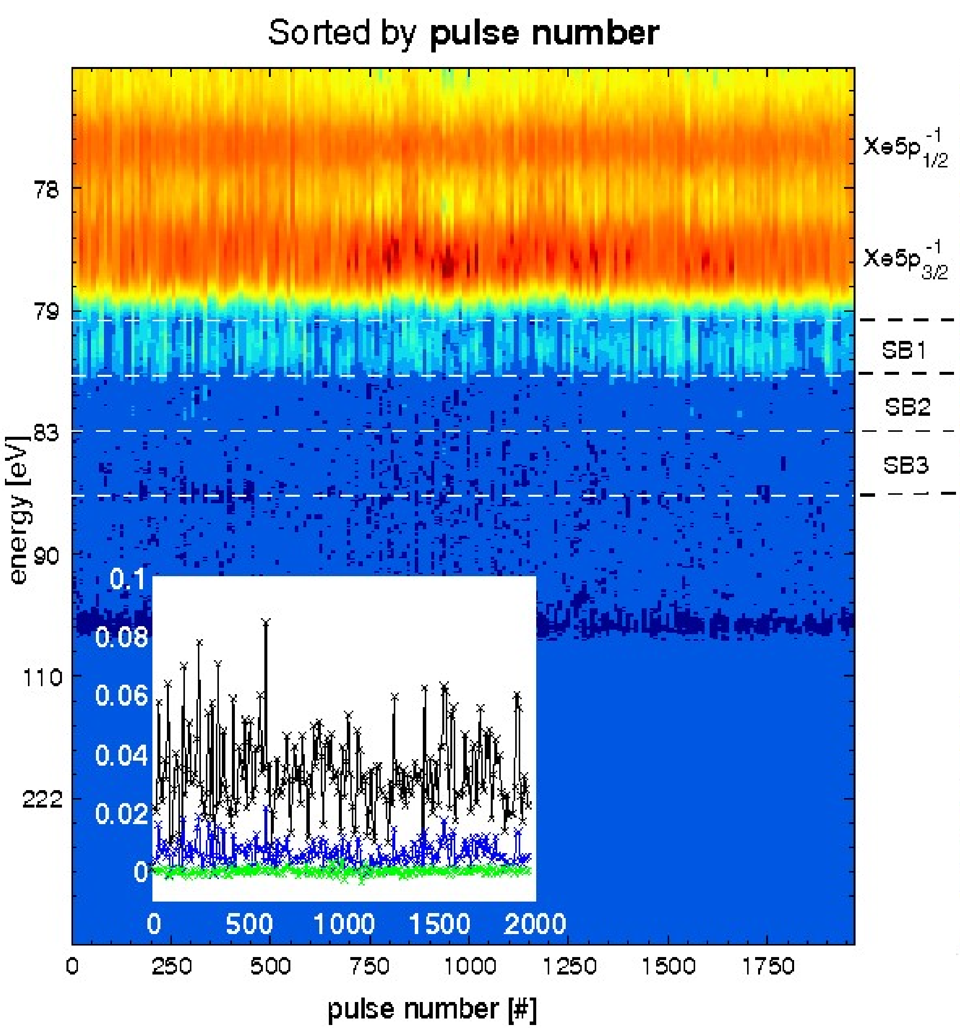


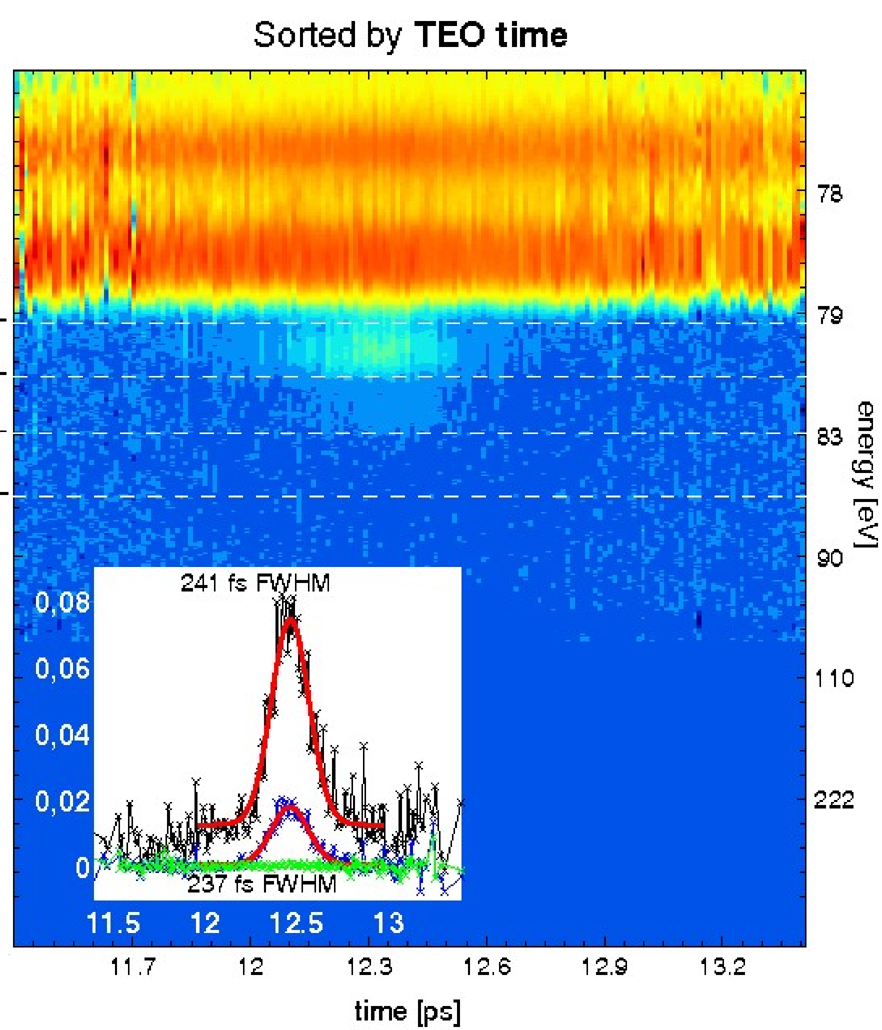
Temporal jitter determines degree of temporal overlap and sideband amplitude.

With the information of the temporal jitter measured by TEO the temporal pump-probe signal trace can be reconstructed.

Temporal resolution is only limited by the detection error of TEO.

FLASH



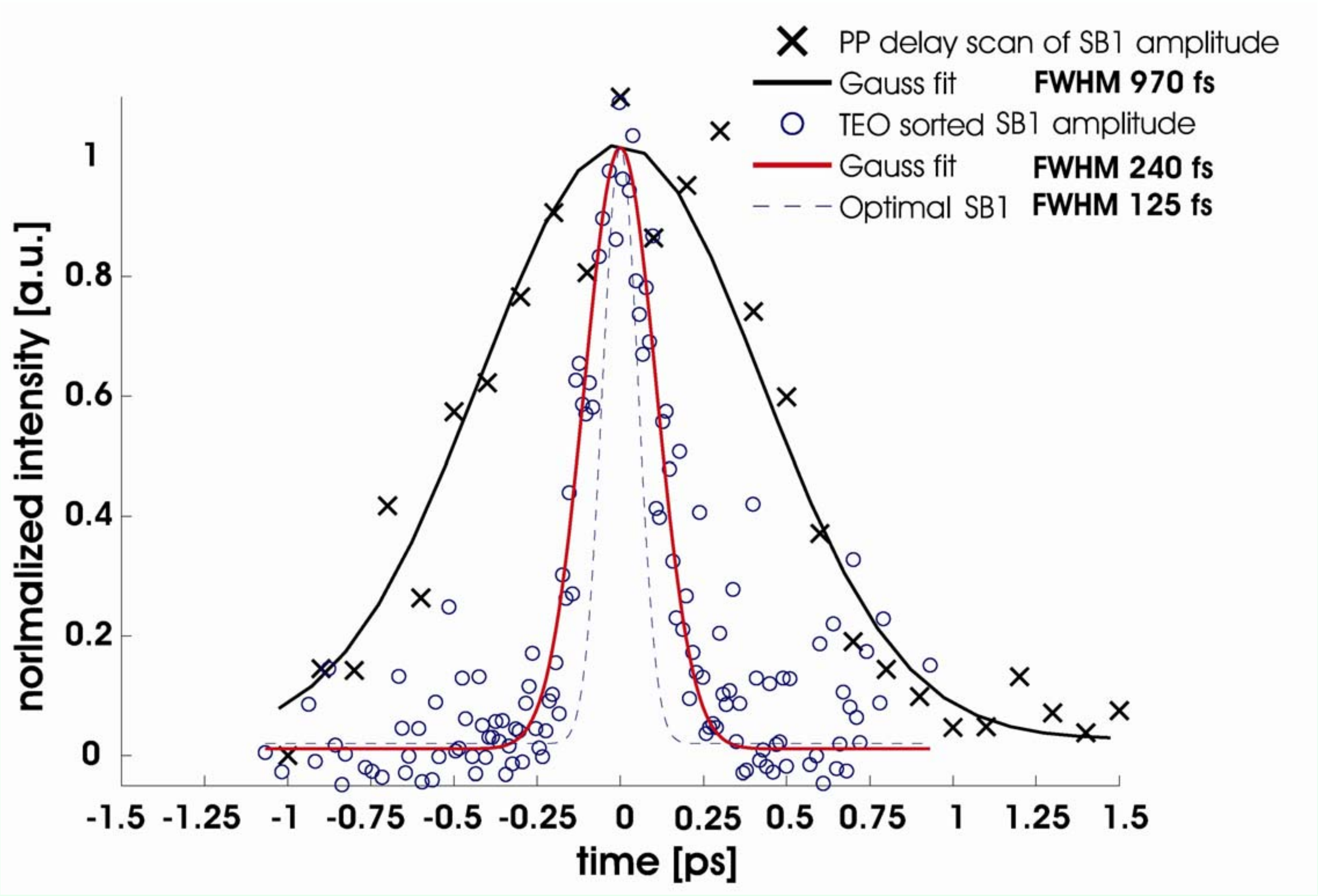


ToF data sorted by pulse number

ToF data sorted by TEO time

TEO benchmark

FLASH

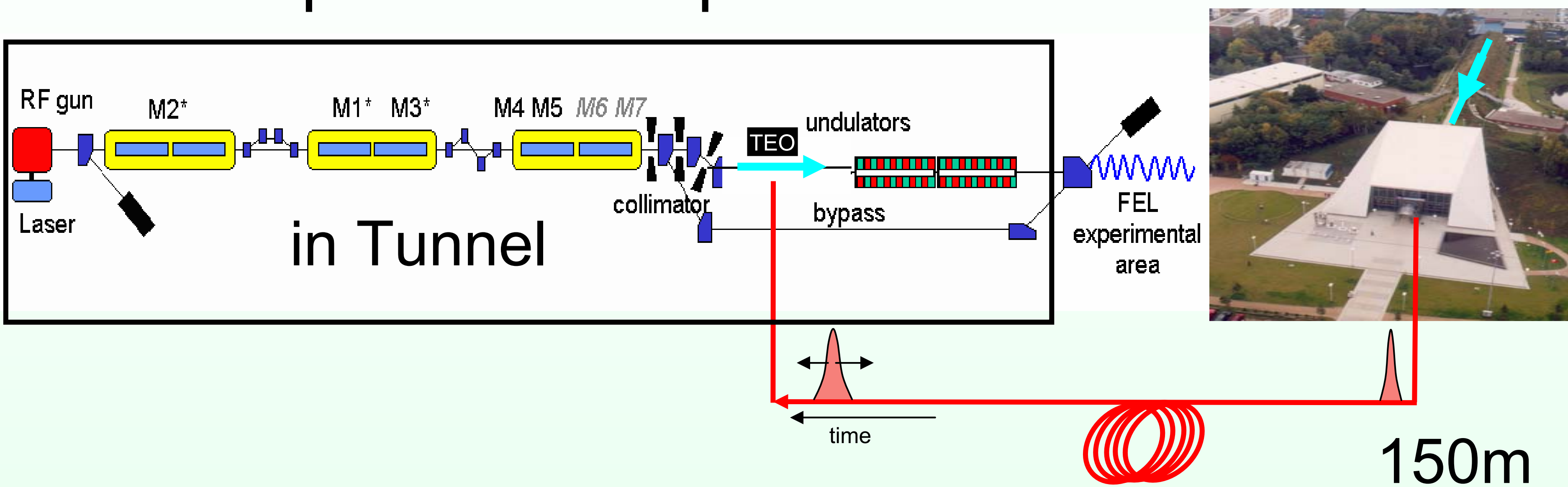


$$\Delta t_{TEO} = \sqrt{(\Delta t_{sorted})^2 - (\Delta t_{optimal})^2}$$ = 204 fs FWHM (**87 fs RMS**)

Dispersion during pulse transport

FLASH

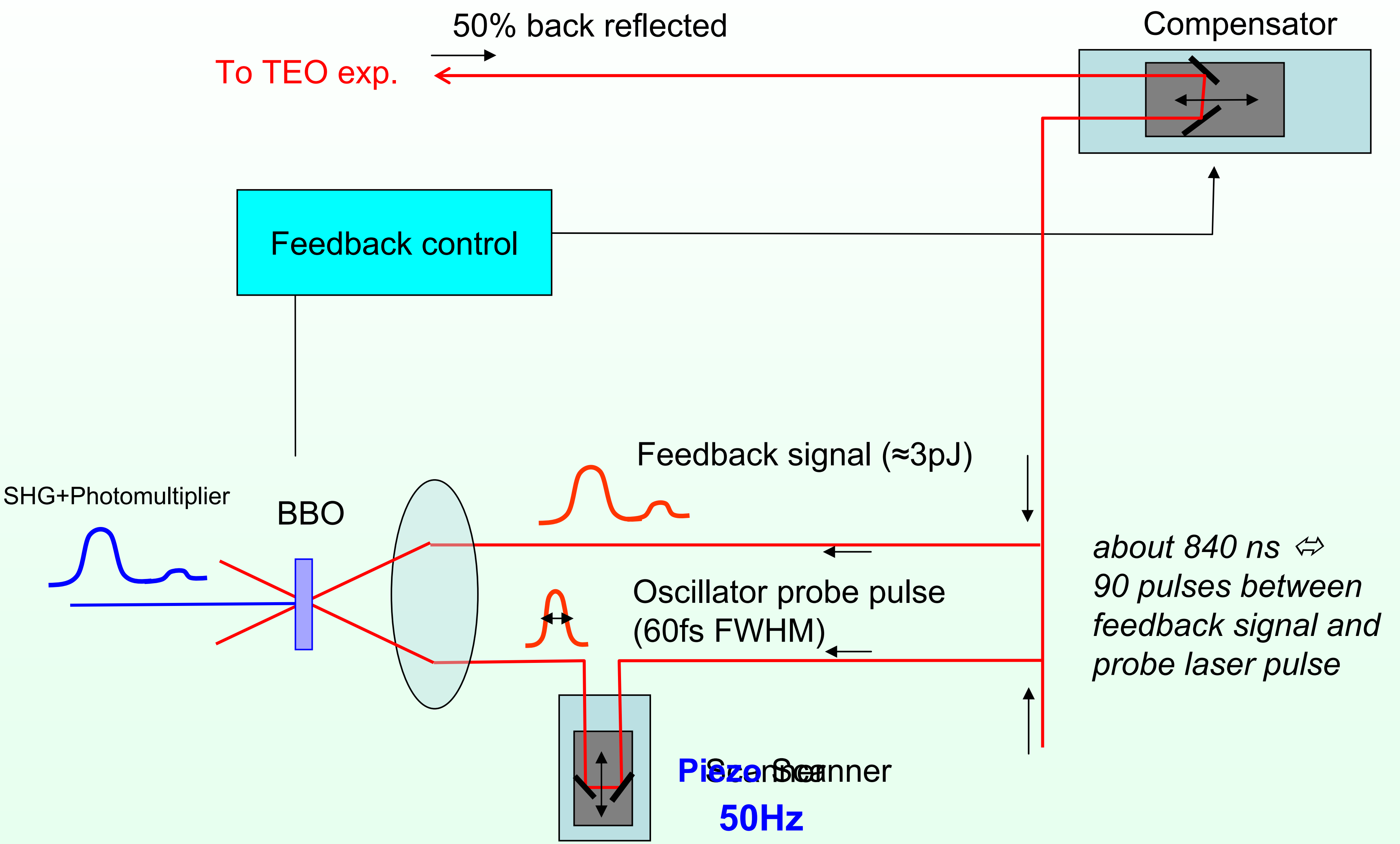
- Transport of laser pulse



- Temperature change and micro-phonics in fiber changes the optical path length through the fiber and delays/accelerates the pulse for each event.

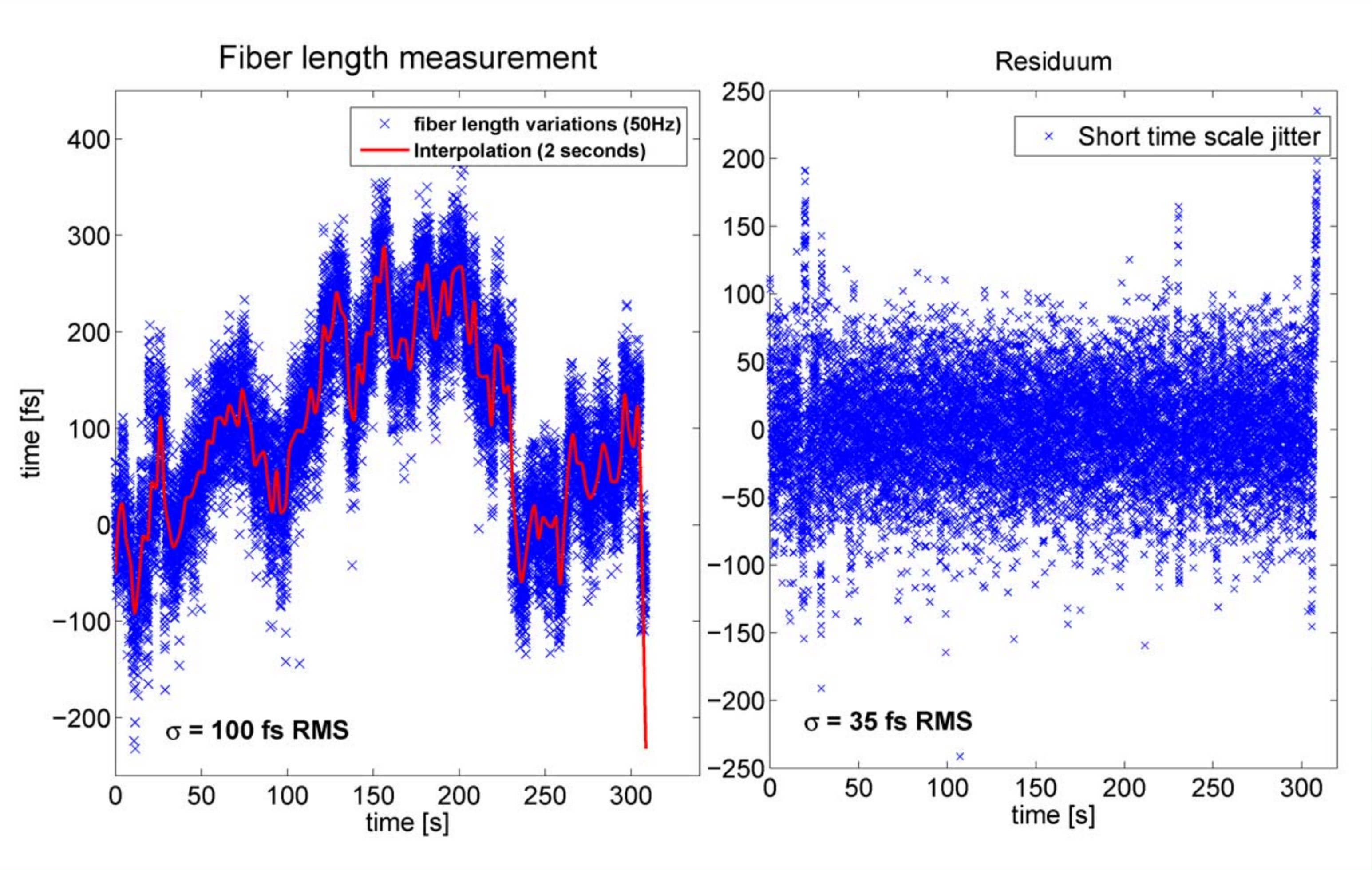
  This path length change is an error source for the arrival time measurement of TEO and must be compensated.

Feedback signal measurement



Possible reason of TEO uncertainty

FLASH



Conclusion

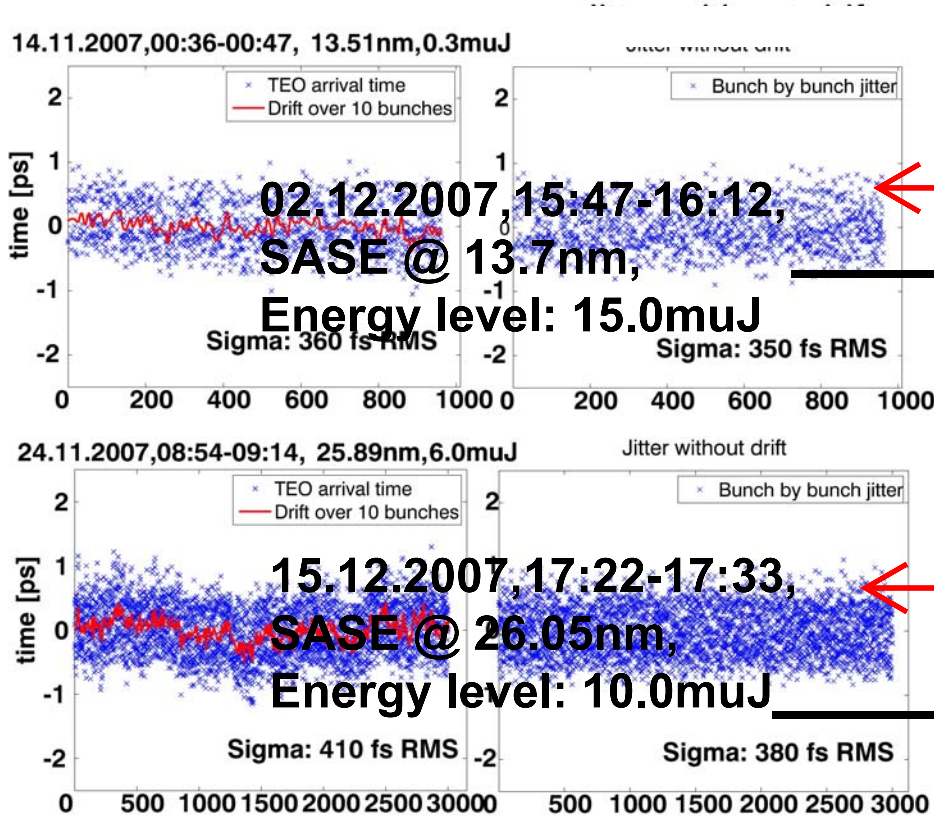
1. TEO is able to measure (indirectly) the relative arrival time between the NIR laser pulse used in a Pump-Probe experiment with the XUV pulse of FLASH. Presently the detection error for the XUV pulse arrival time is approx. **90 fs RMS**, which has been demonstrated in a pump-probe experiment.

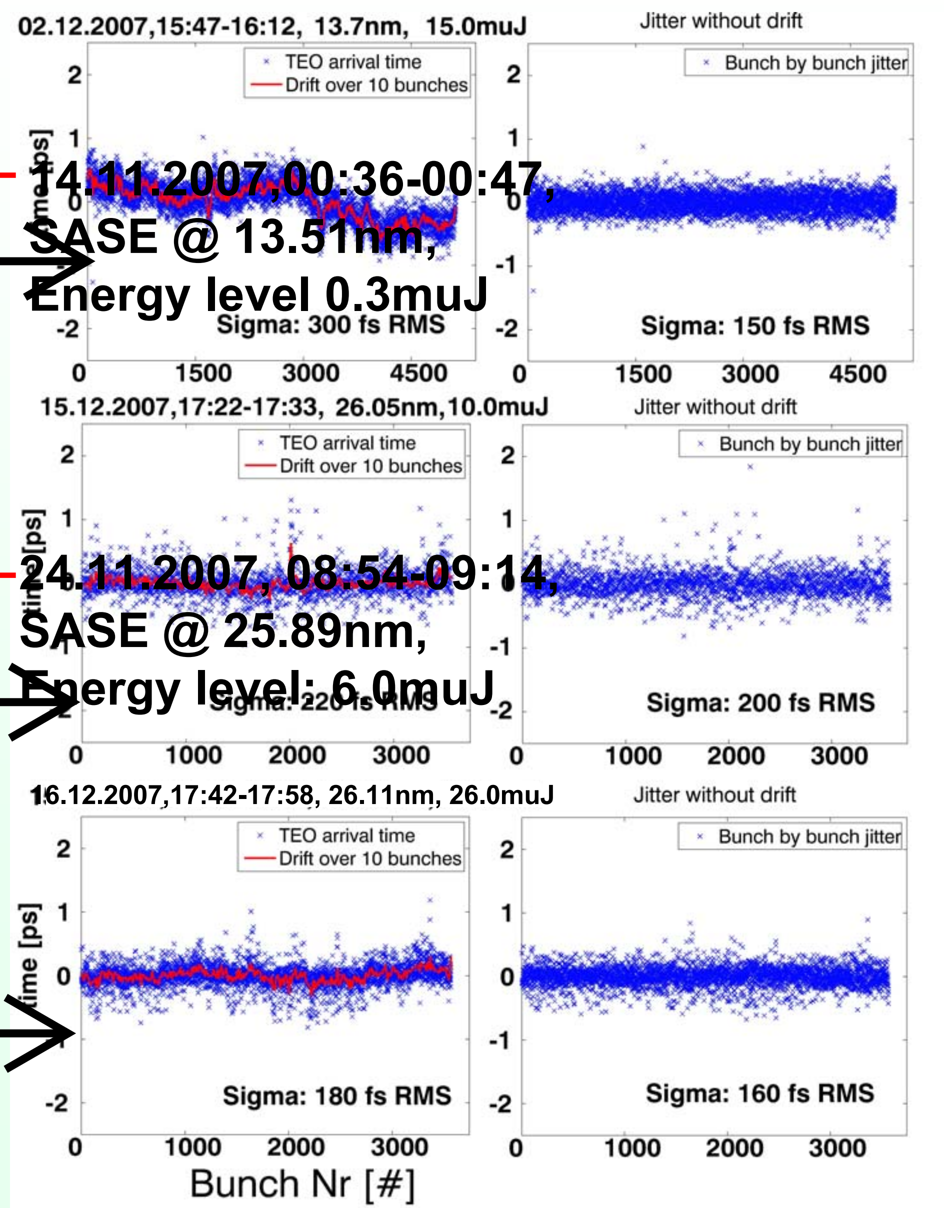
2. ➔ From this one can conclude, that TEO is also able to detect the electron bunch arrival of FLASH with a precision of at least **90 fs RMS**.

3. A possible error source, which limits the timing detection of TEO has been identified. The fibre length varies statistically with 10Hz – 100Hz by about 50-100 fs RMS.

Temporal jitter studies of FLASH during the first beam period after shutdown (Nov.,Dez. 2007)

FLASH





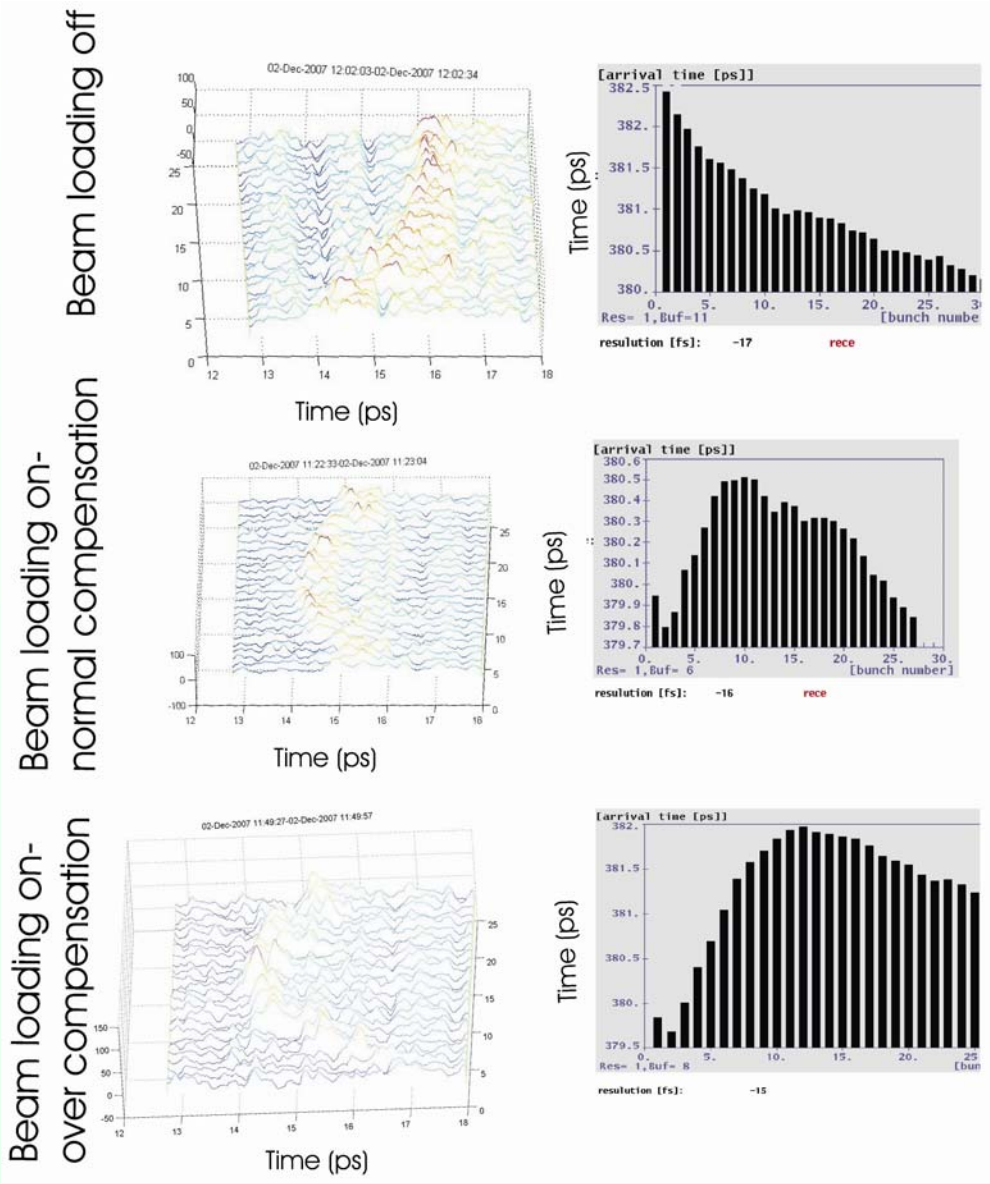
16.12.2007,17:42-17:58,
SASE @ 26.11nm,
Energy level: 26.0muJ

During time period from 24.11. to 02.12. the machine jitter stabilized independently from the set wavelength.

Reason unknown.

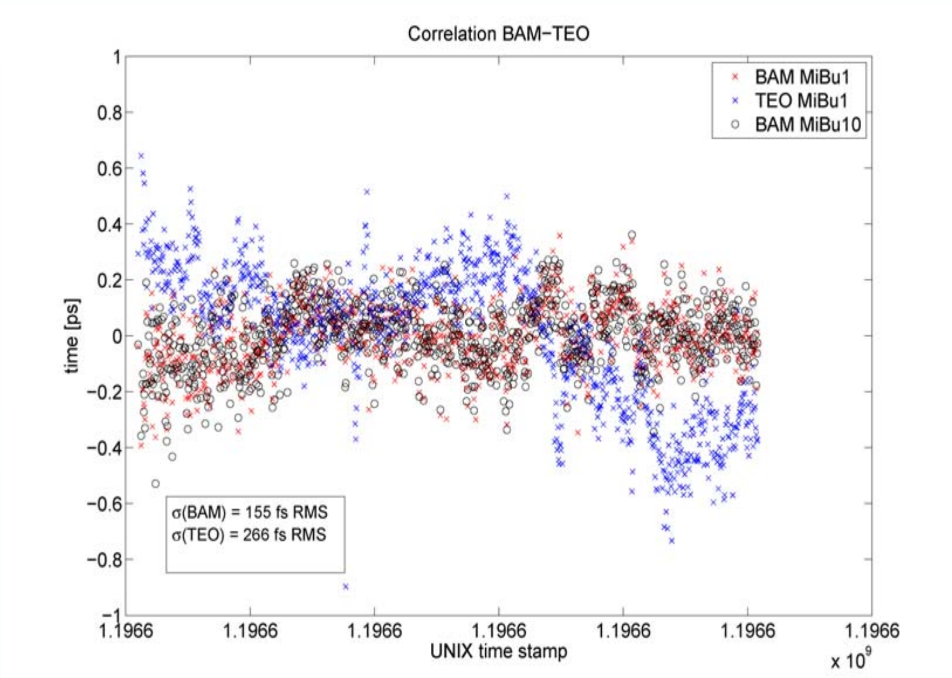
Micro Bunch correlations TEO-BAM

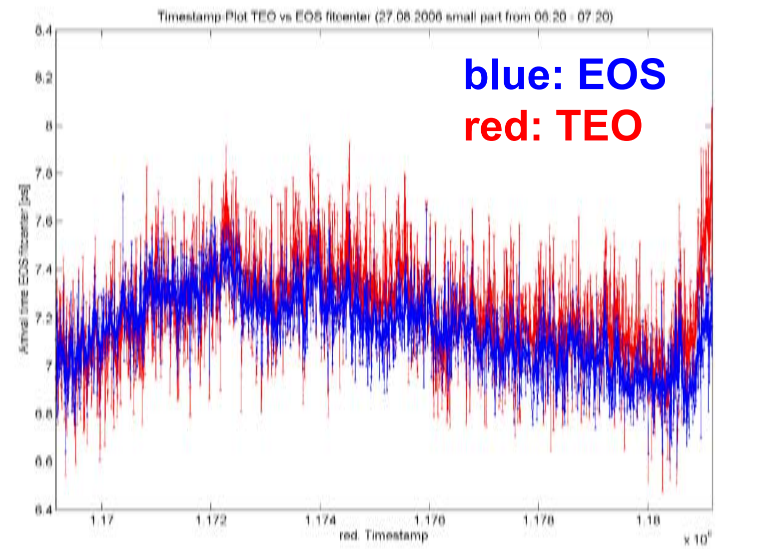
FLASH



Correlation BAM-TEO, EOS-TEO

FLASH





Nov. 2007
TEO fibre stabilization off

Okt. 2006
TEO fibre stabilization on
(every 30sec)

Outlook

FLASH

Still to do:

- Fast fiber stabilization system will be installed.
- TEO times shall be easier to achieve and online available.

New responsible scientist for TEO

Nikola Stojanovic, 4504

Acknowledgements:

Photon diagnostic:

Stefan Duesterer, Harald Redlin, Paul Radcliffe, Josef Feldhaus

Accelerator group:

FLA: ***Holger Schlarb, Bernd Steffen, Florian Loehl, Peter Schmueser***

MSC4: ***Vladimir Rybnikov, Boris Fominykh, Vitali Kocharyan, Olaf Hensler, Gerhard Grygiel***

FLASH

END

Beam arrival time monitor (BAM)

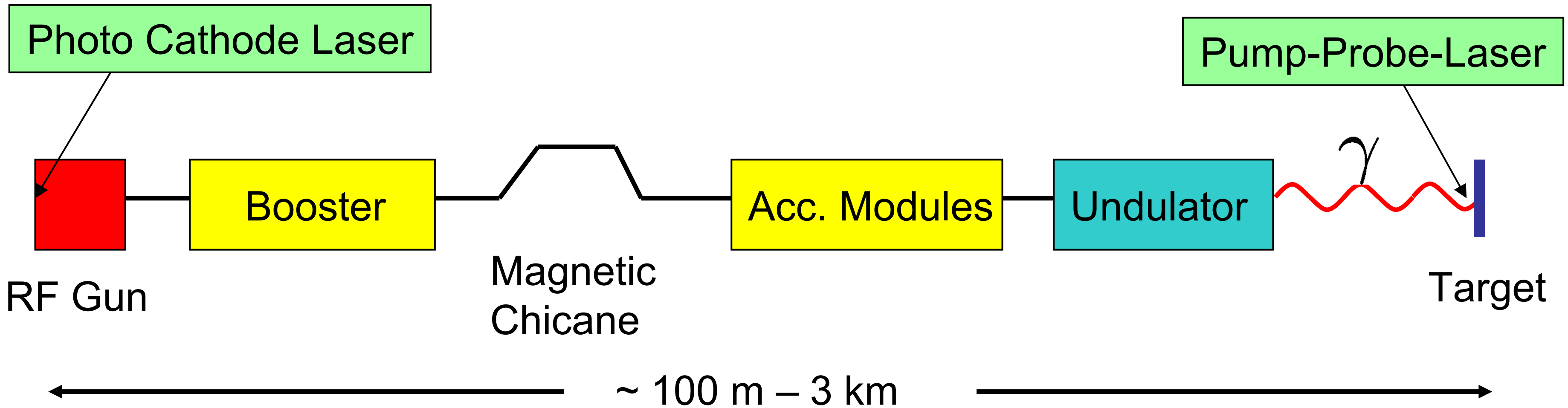
A sub-100 fs electron bunch arrival-time monitor system for FLASH

K. Hacker[1], F. Löhl[1], F. Ludwig[1], H. Schlarb[1], B. Schmidt[1], A. Winter[2]

DESY[1], Hamburg University[2]

June 29th, EPAC 2006

Main Sources of Timing Jitters in FEL Facilities



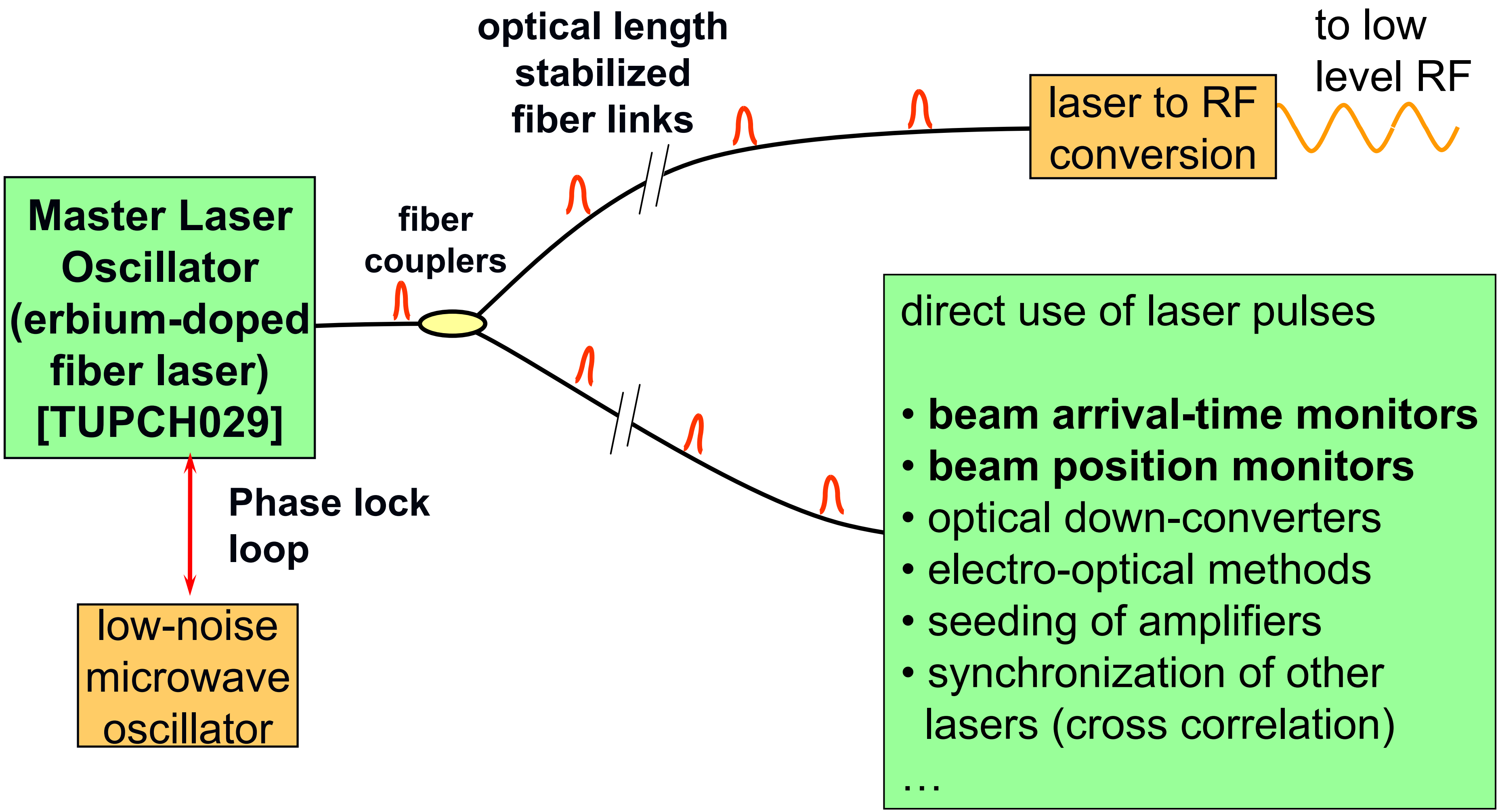
Main sources of γ-ray arrival-time changes

- Arrival-time of photo cathode laser pulses
- Phase of RF gun
- Amplitude and phase of Booster module
- Arrival-time of pump-probe laser

First Goals

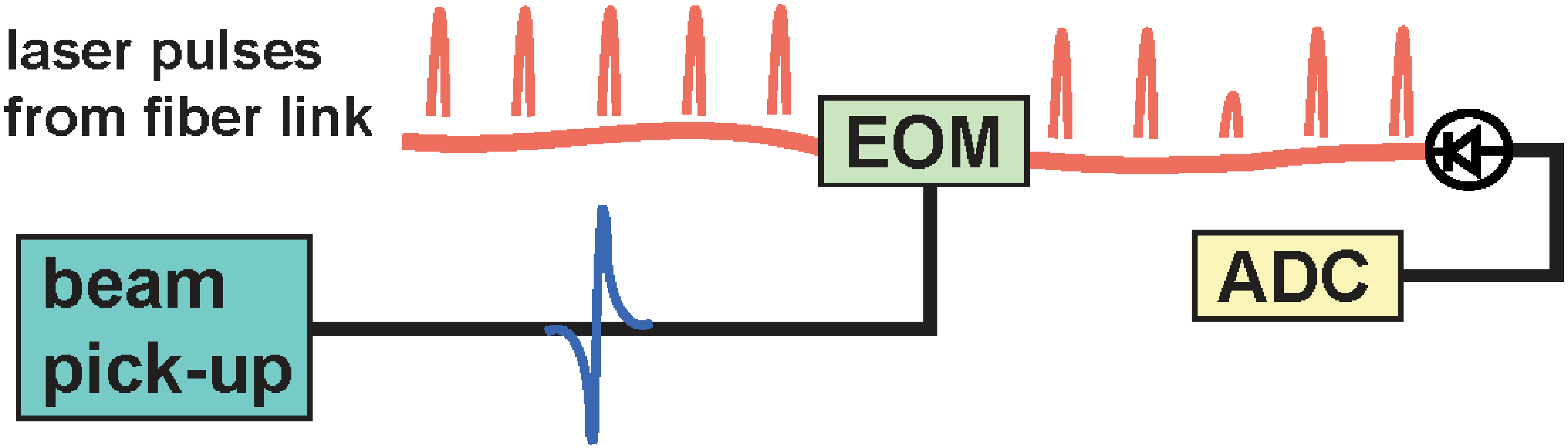
1) Improve timing stability of machine by a new, optical timing system
2) Measure electron bunch arrival-time to post-order data sets
3) Identify and reduce major sources of arrival-time jitter

Optical Timing System



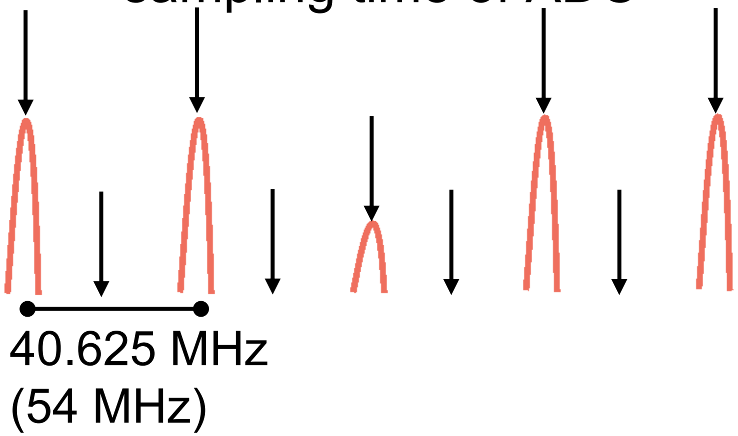
See [TUPCH028], [THOPA03]

Principle of the Arrival Time Detection

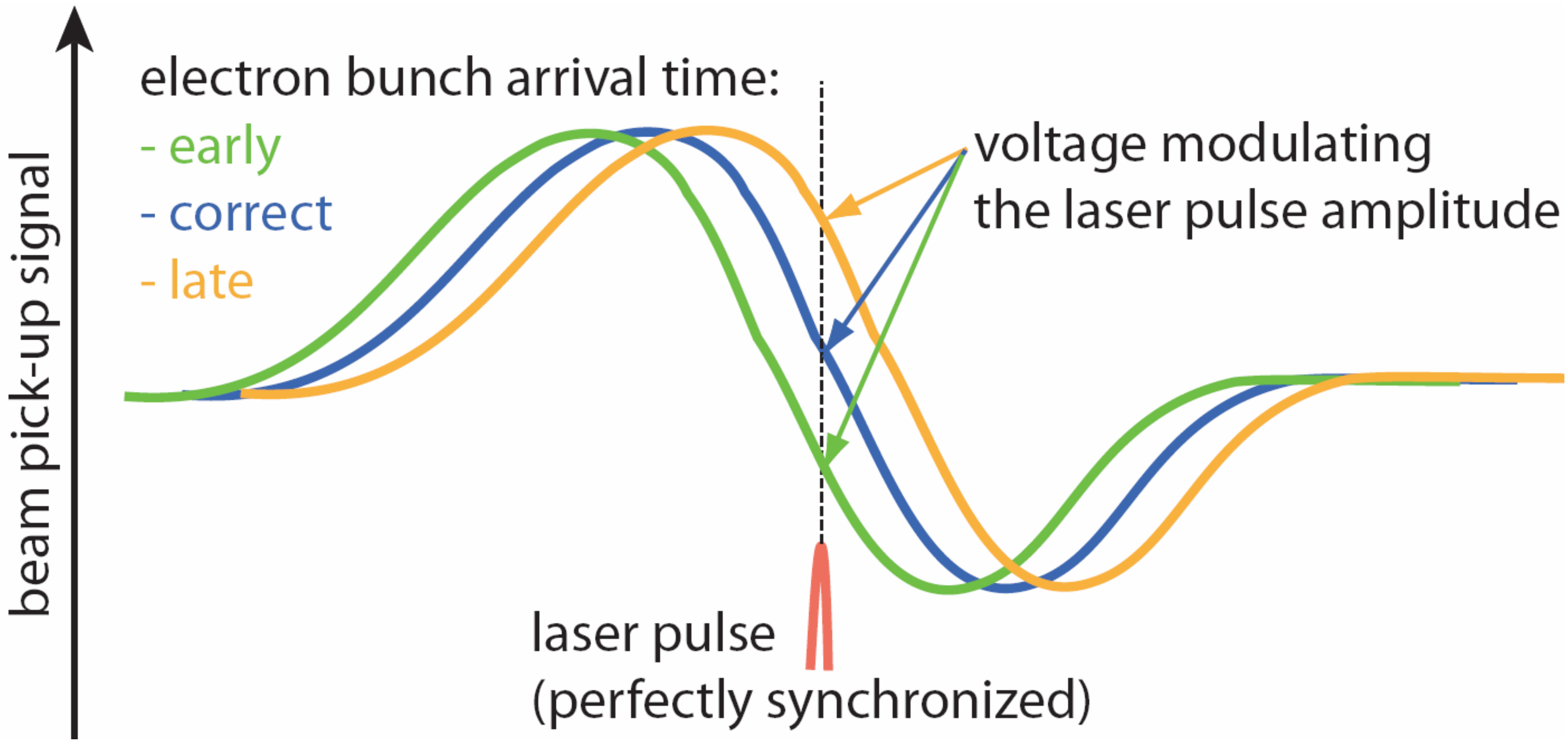


The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

sampling time of ADC



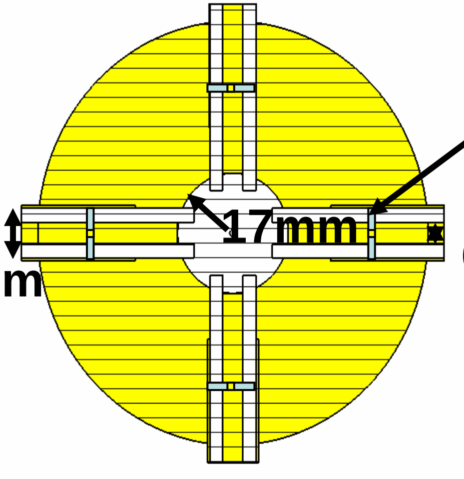
Principle of the arrival time detection



Comparison of new and old pick-up

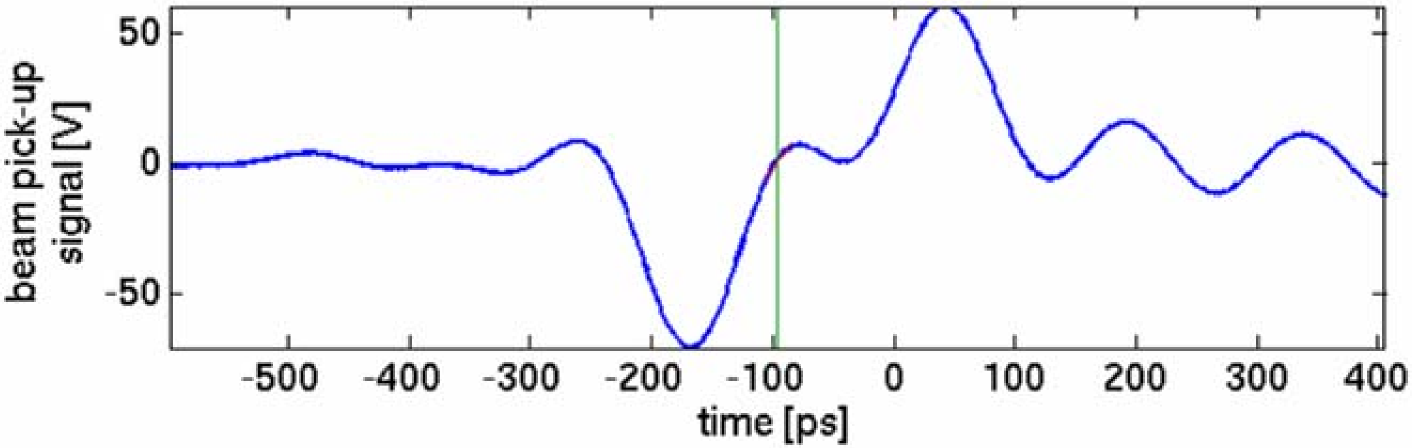
old design:

new design:
(by K. Hacker)

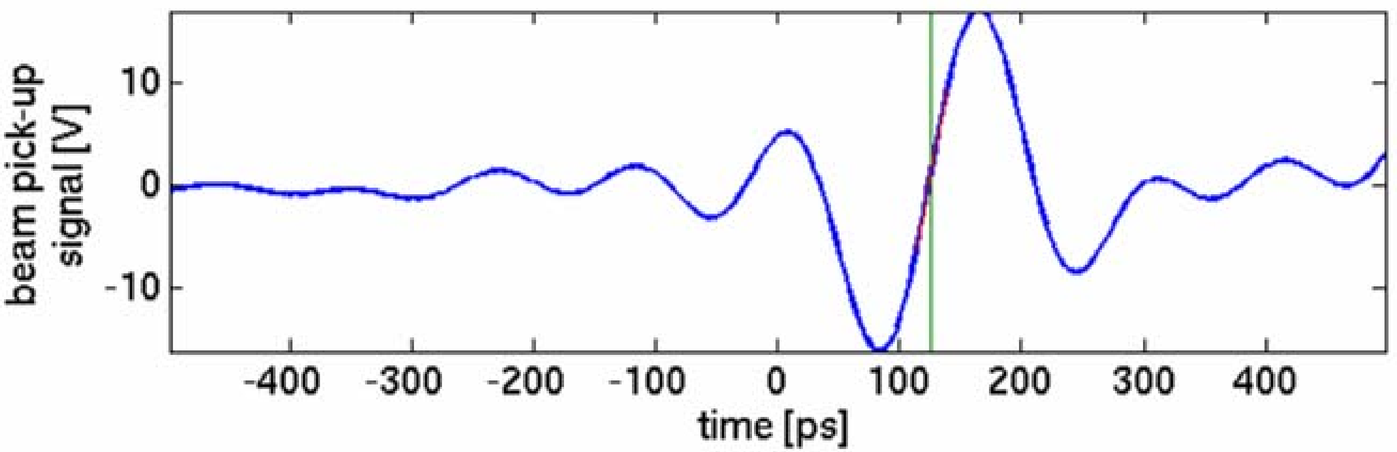


Comparison of pick-up signals

old pick-up
(“bump” is strongly orbit dependent)

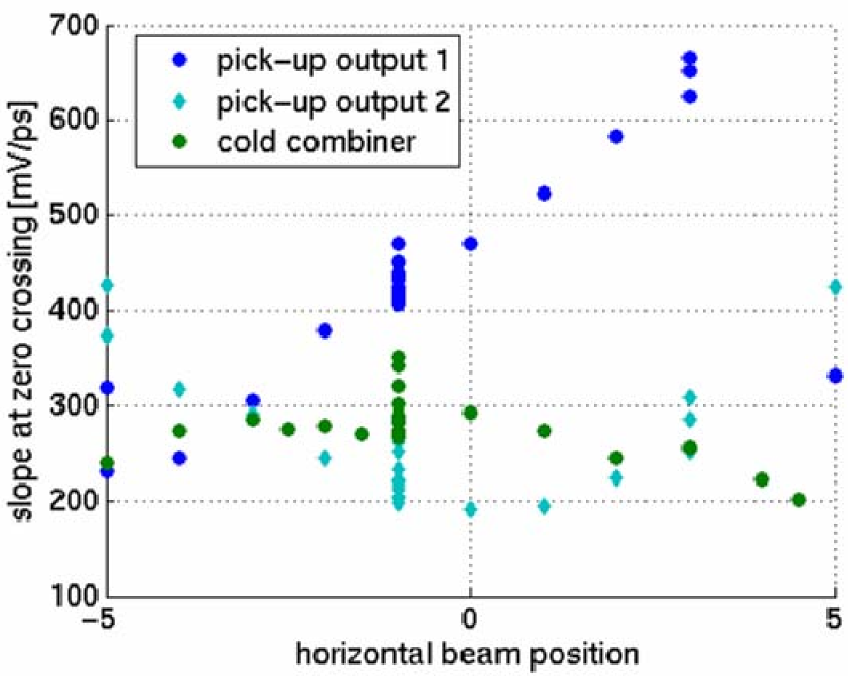


new pick-up

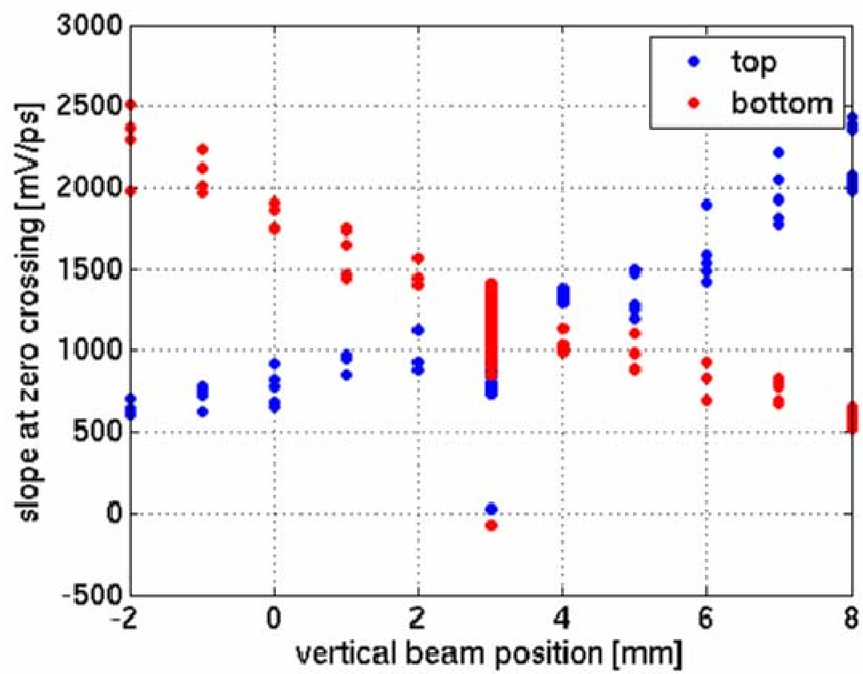


Slope of pick-up signals

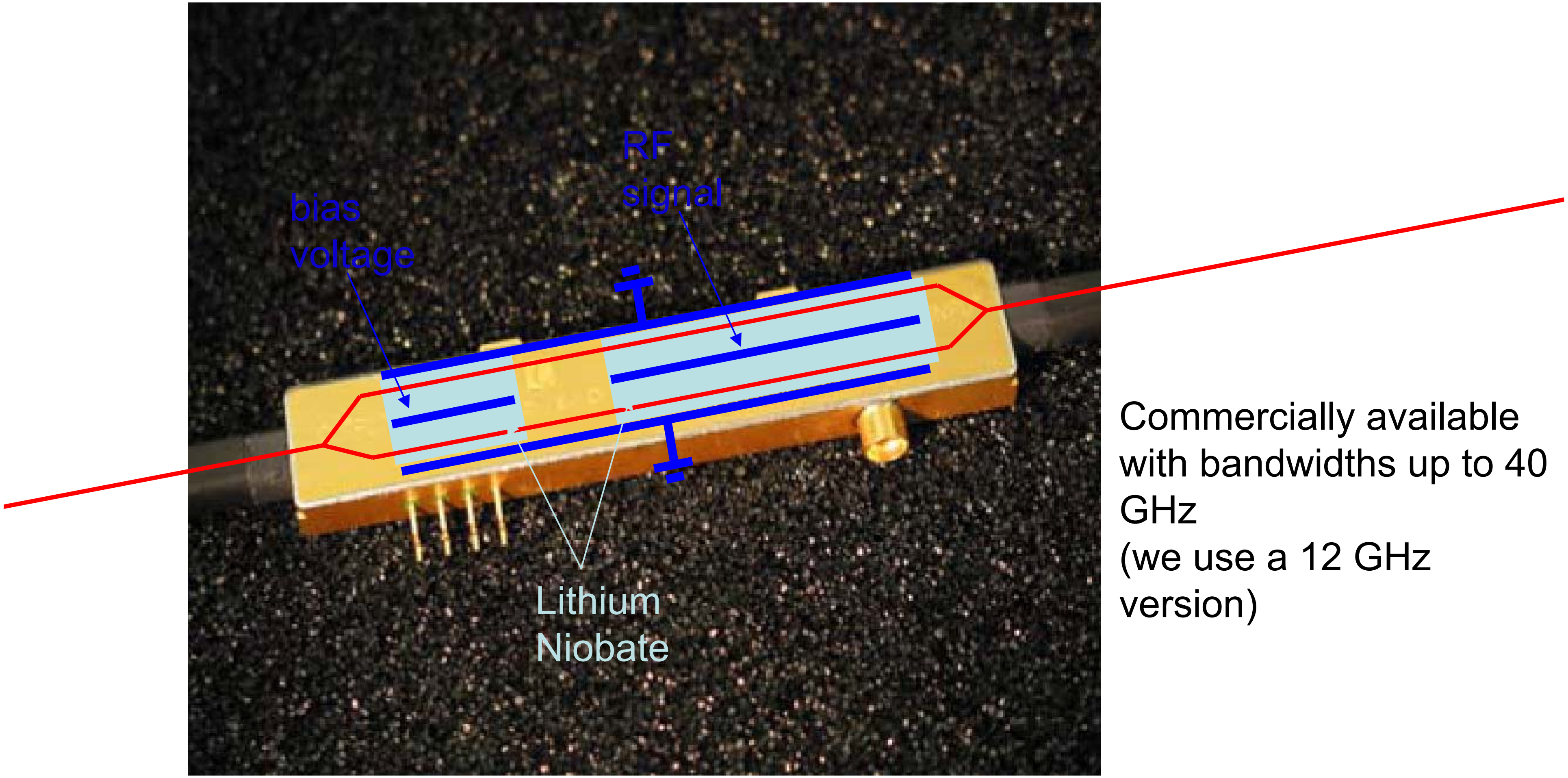
old pick-up



new pick-up

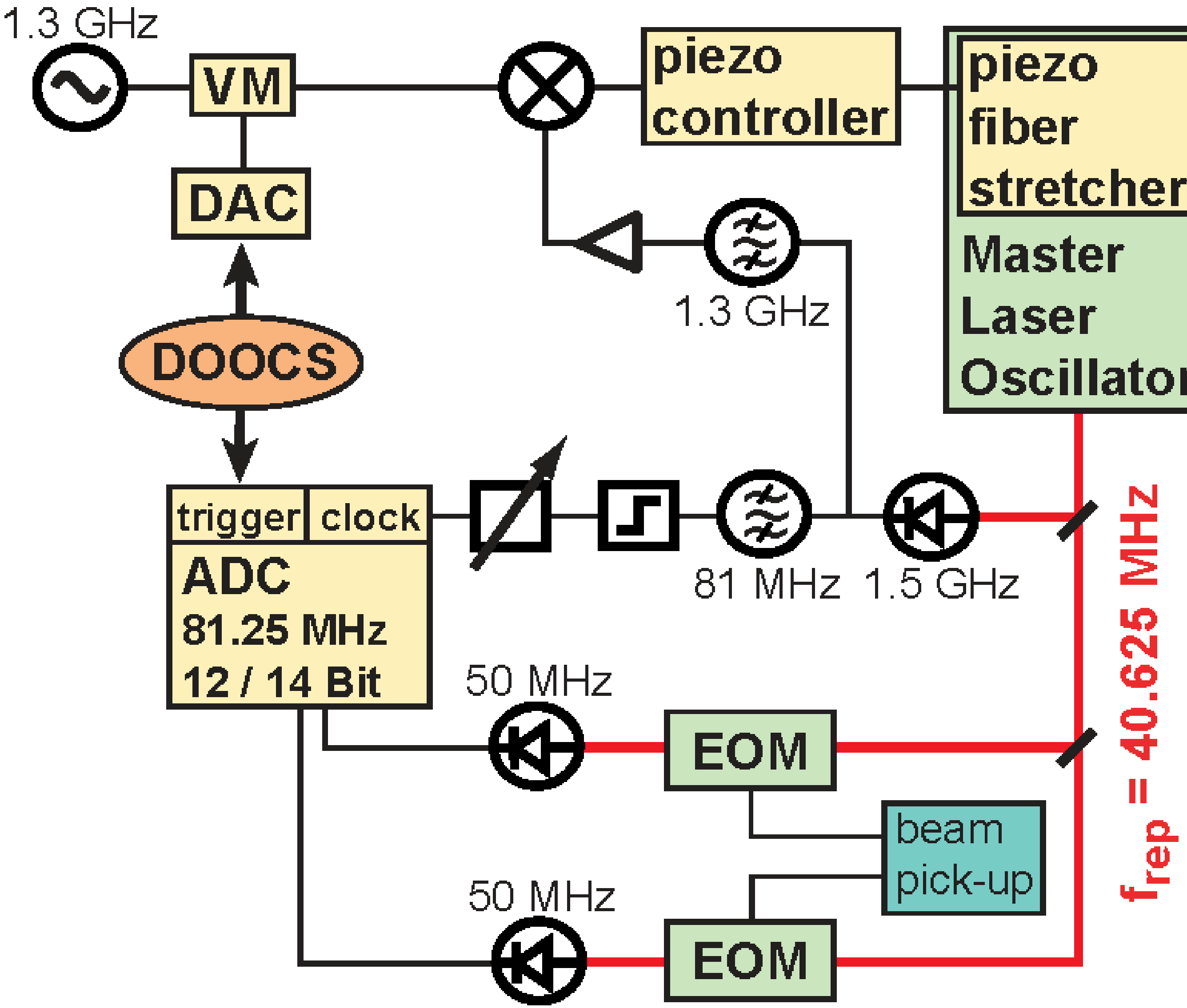


Electro-Optical-Modulator (EOM)

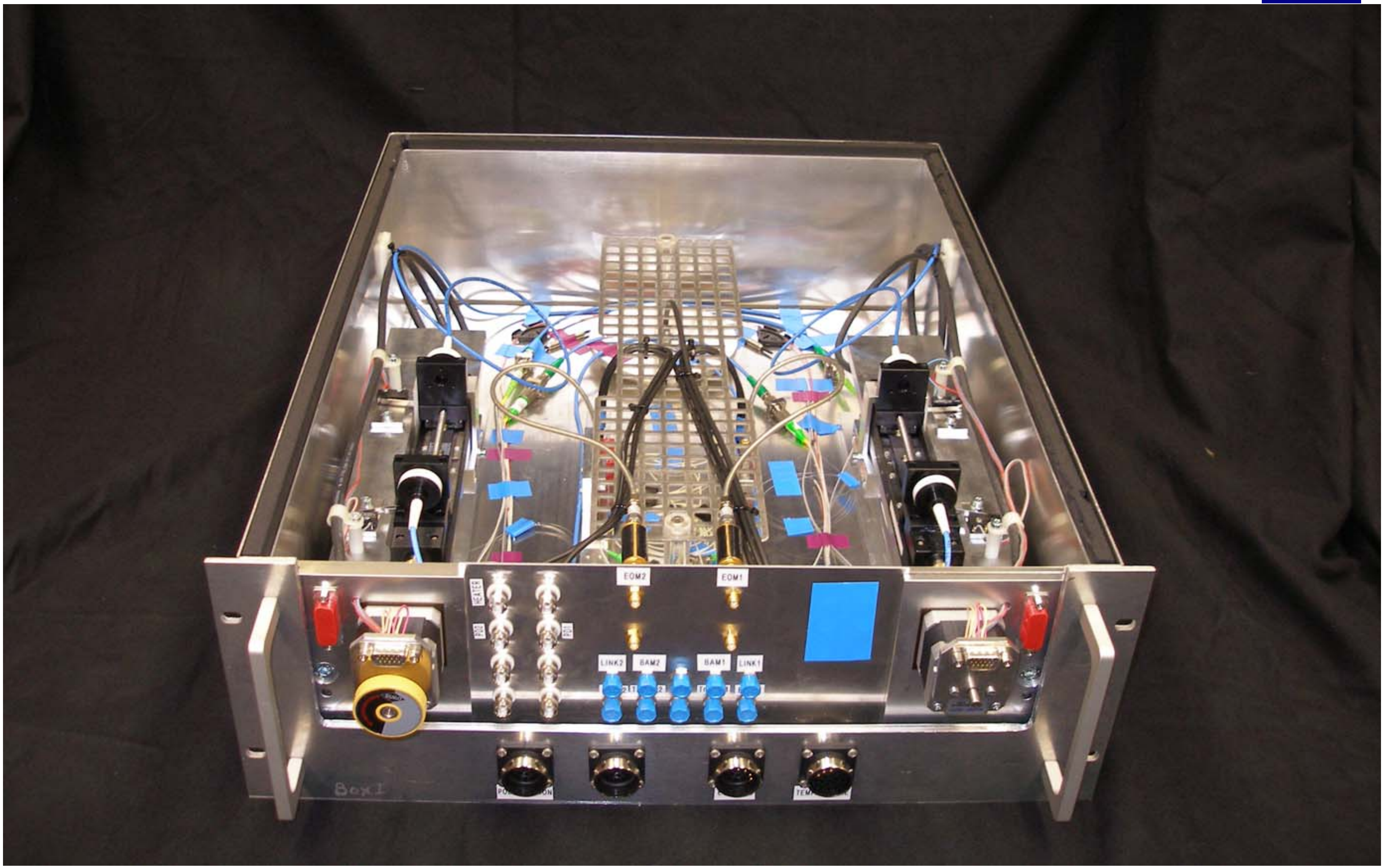


Commercially available with bandwidths up to 40 GHz
(we use a 12 GHz version)

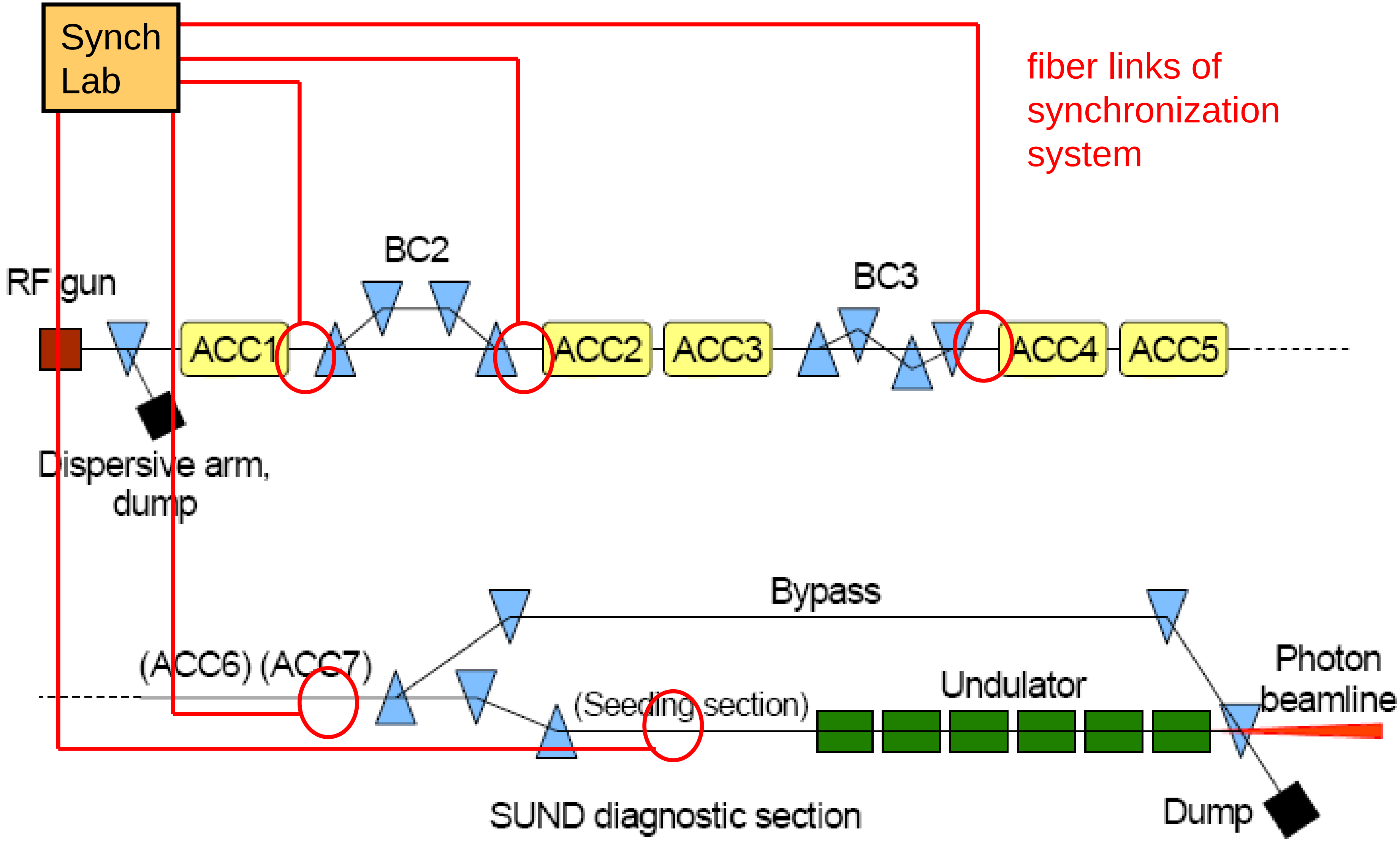
Test Bench for the Arrival-time Monitor System



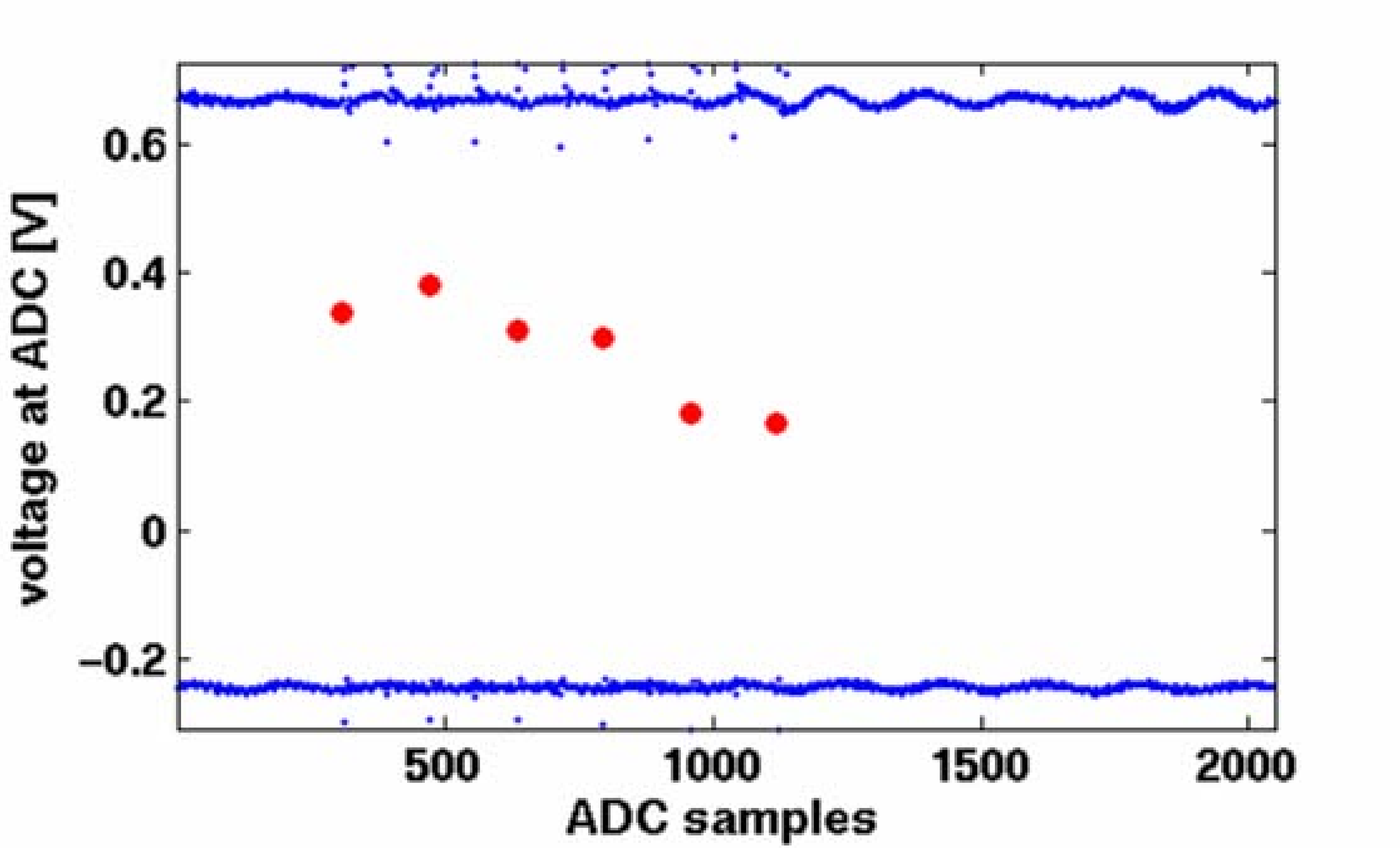
Installation of electro-optical frontends



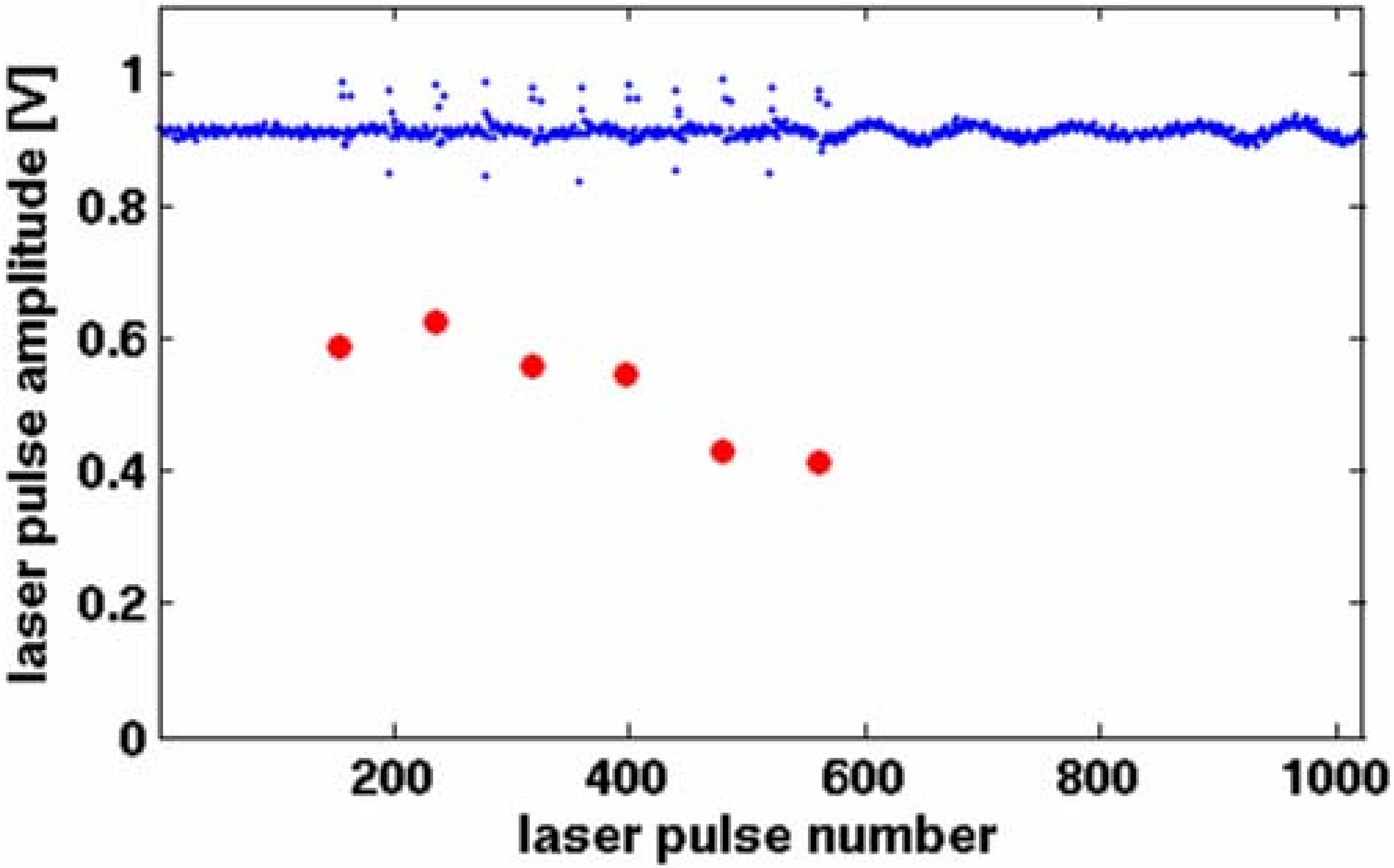
Positions of BAMs in the FLASH linac



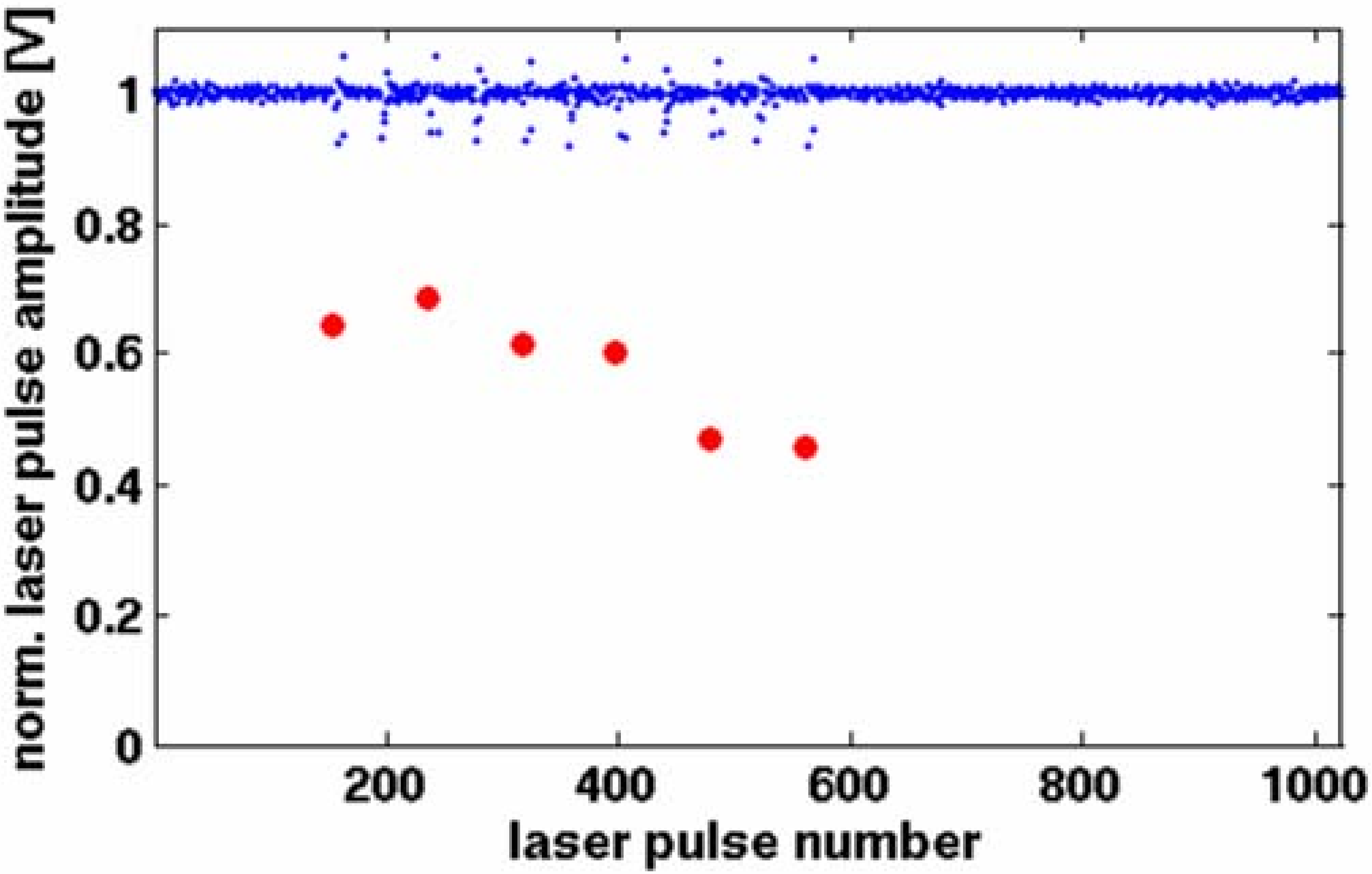
Raw Data of EOM Detector Signal



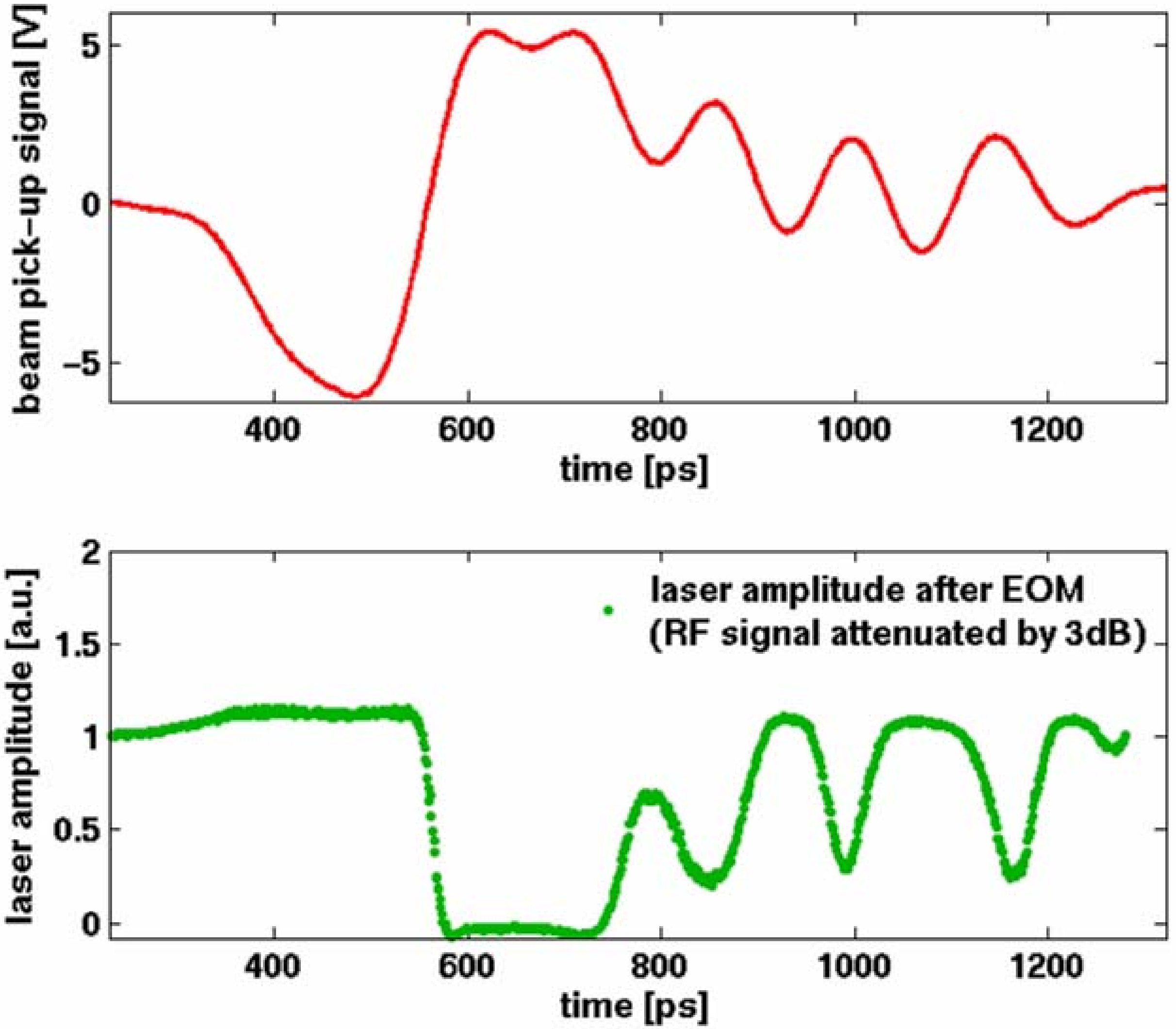
Amplitude of Laser Pulses



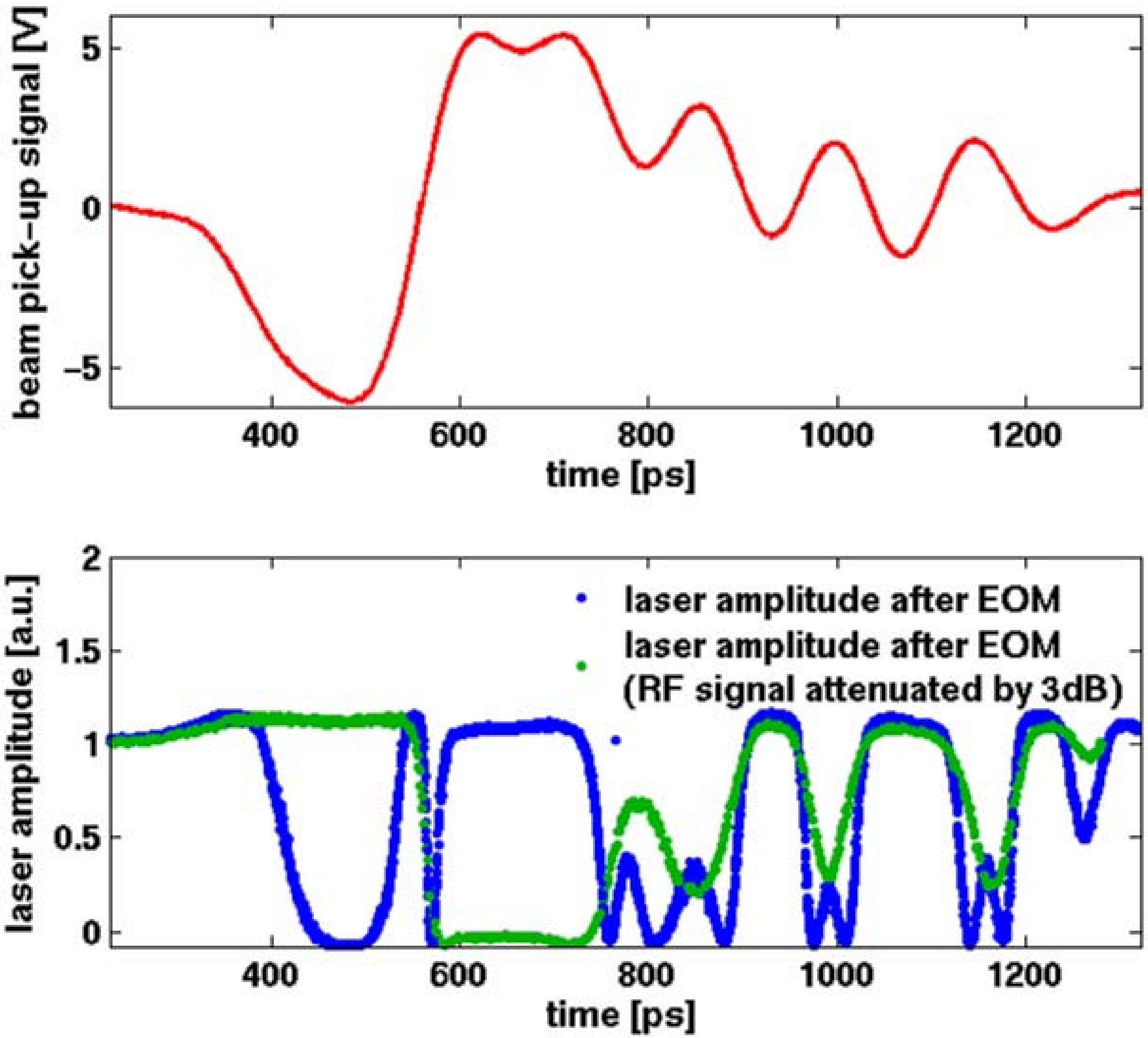
Amplitude of Laser Pulses (normalized)



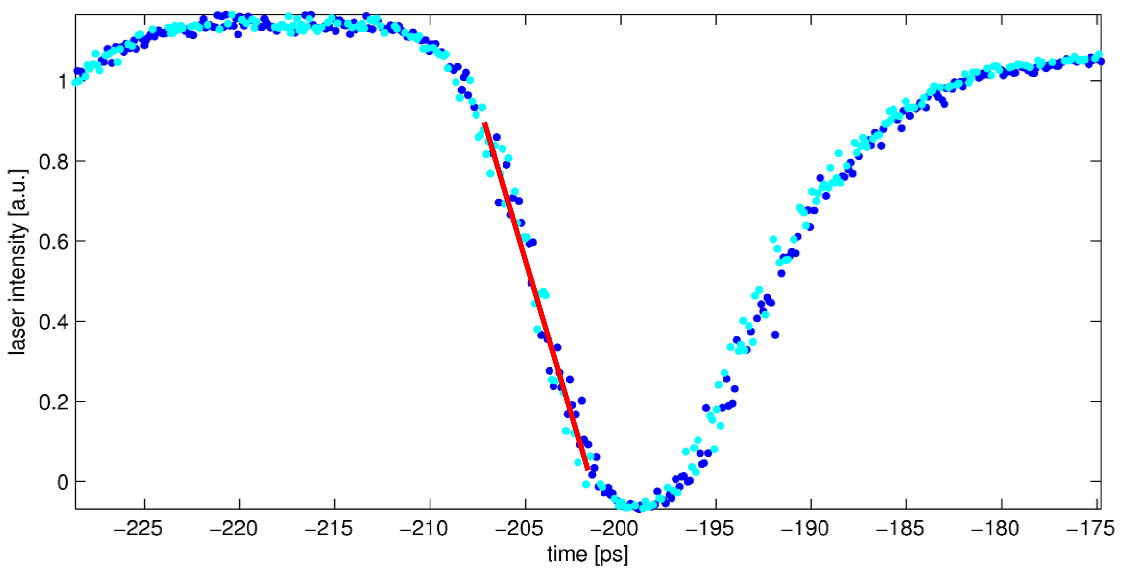
Scan of Laser Pulse over Beam Pick-up Signal



Scan of Laser Pulse over Beam Pick-up Signal



Calibration and Resolution of the EOM Detectors



The resolution can be estimated from the slope of the phase monitor signal and the amplitude noise on the not modulated laser pulses:

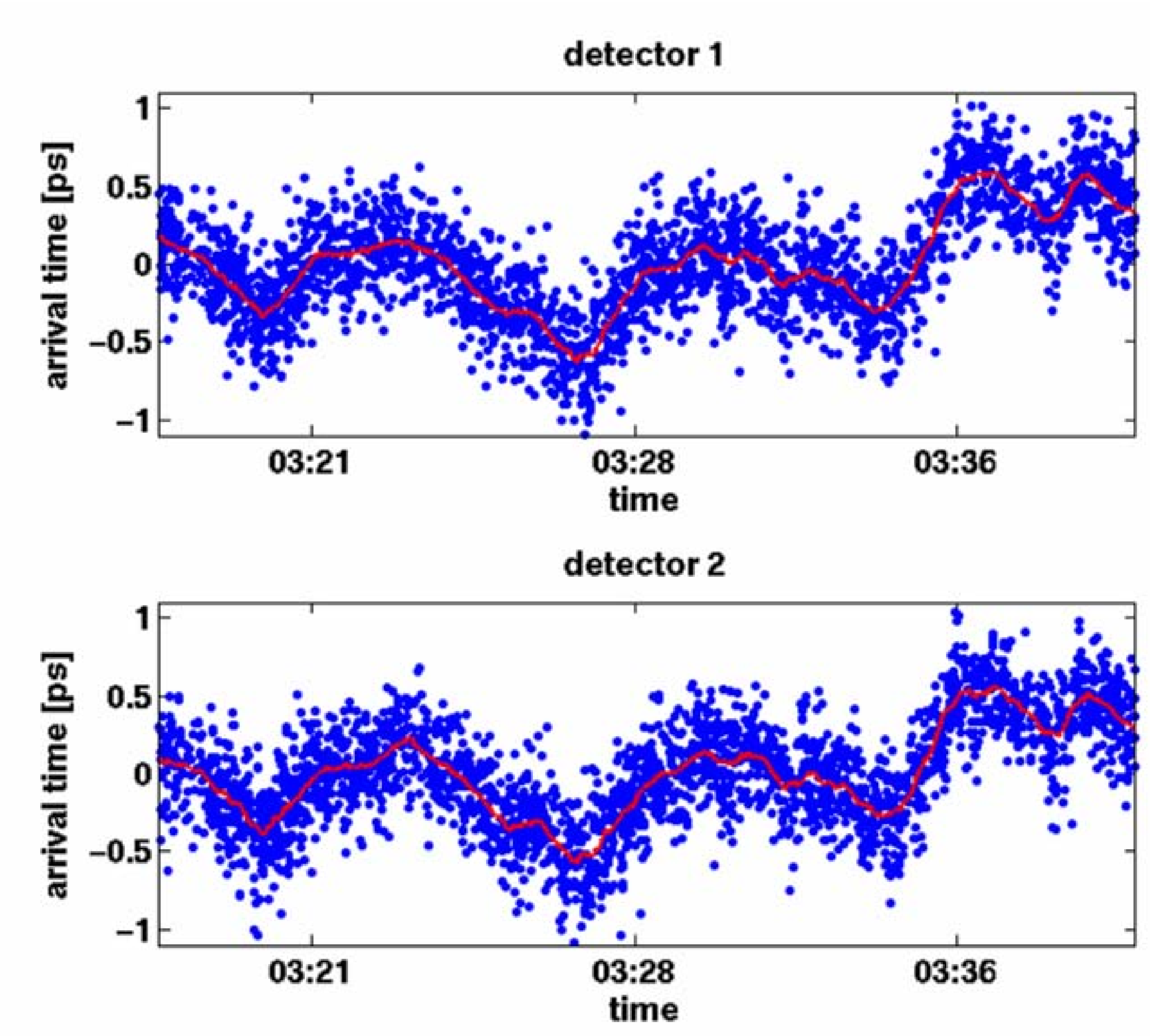
Typical values are:

Slope:
~ 60 - 100 fs / (% modulation)

Laser amplitude detection:
rms ~ 0.2 – 0.3 %

➢ Resolution of EOM detectors:
~ 20 - 50 fs

Comparison Measurement between two Arrival-time Detectors

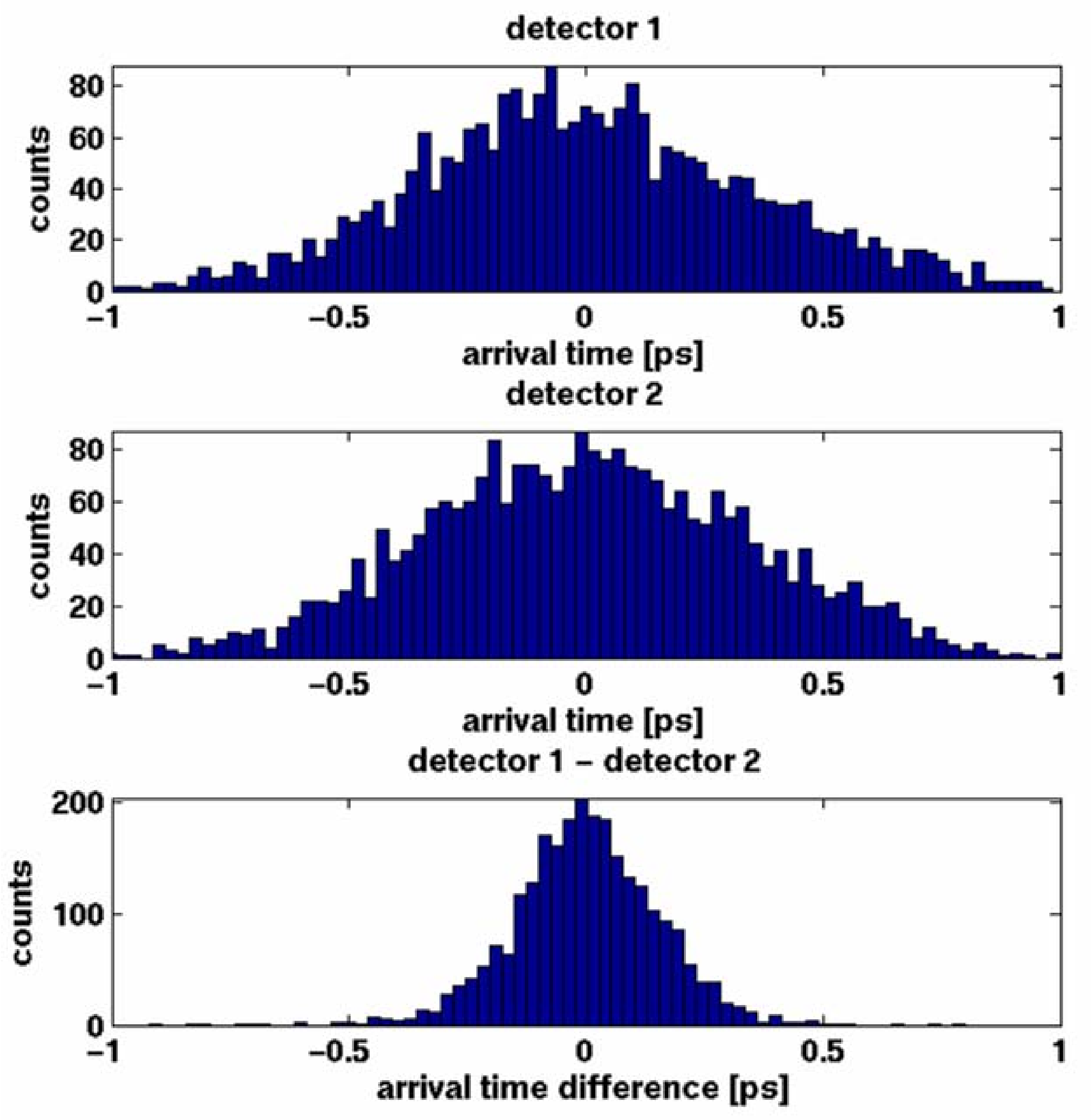


The signal of the beam pick-up was split and connected to the two EOM detectors.

The rms-resolution of the detectors was estimated from the laser amplitude noise and the slope from the calibration:

Detector 1:	**99 fs**
Detector 2:	**114 fs**

Comparison Measurement between two Arrival-time Detectors



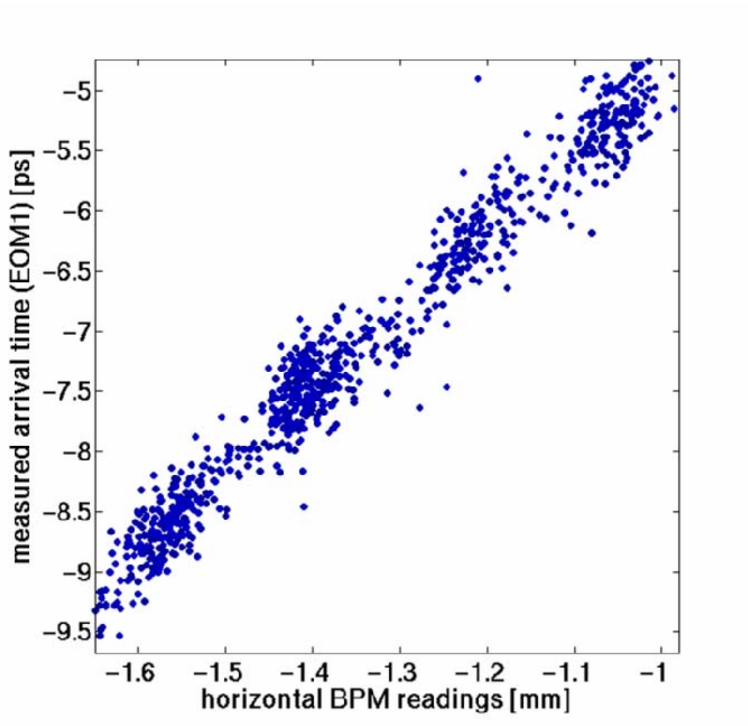
	rms jitter
Detector 1	**357 fs**
Detector 2	**342 fs**
Det. 1 – Det. 2	**139 fs**

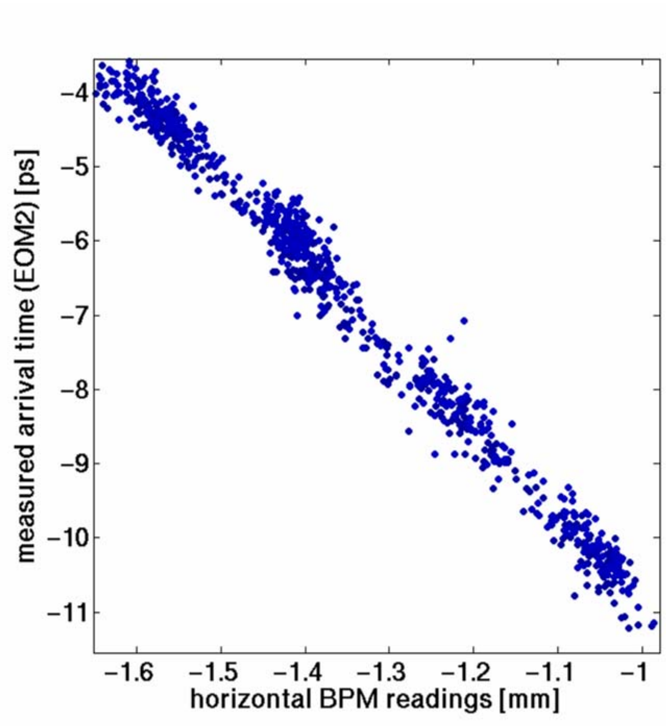
Position Dependence of the Beam Pick-up Signal

Using the two different output ports of the beam pick-up as input for the EOM detectors gives rms resolutions of about 30 fs for both detectors.

But: the measured rms jitter of the difference signal is around 1.5 ps.

➢ Orbit dependence of beam pick-up signal!





Position Dependence of the Beam Pickup Signal

The beam arrival time depends linearly on the beam position in x and y:

$$t_{\text{arrival}} = t_{\text{meas},1} + a_{x,1}x + a_{y,1}y$$
$$t_{\text{arrival}} = t_{\text{meas},2} + a_{x,2}x + a_{y,2}y$$

The constants a_i were determined by changing the orbit at the pick-up with corrector coils:

$$a_{x,1} = (-6.94 \pm 0.05)\frac{\text{fs}}{\mu\text{m}} \qquad a_{x,2} = (10.7 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$
$$a_{y,1} = (-0.16 \pm 0.07)\frac{\text{fs}}{\mu\text{m}} \qquad a_{y,2} = (0.29 \pm 0.02)\frac{\text{fs}}{\mu\text{m}}$$

When using the BPM system (~ 20 µm resolution) to correct for the orbit dependence the remaining rms jitter of the difference signal is still 300 fs (dominated by the BPM system).

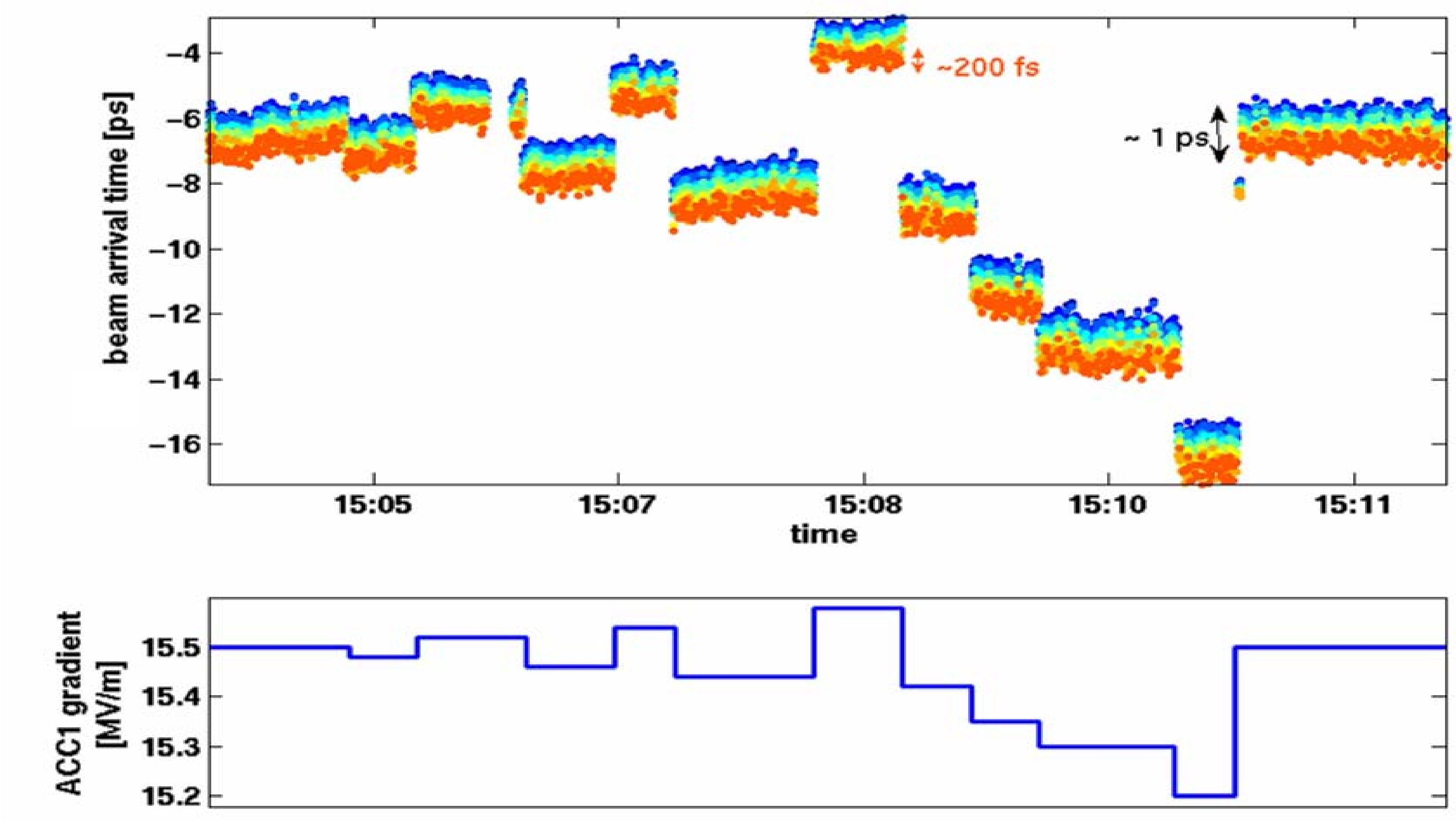
However, we can use the EOM detectors to measure the horizontal beam position:

$$x = \frac{t_1 - t_2 + (a_{2,y} - a_{2,x})y}{a_{1,x} - a_{2,x}}$$

An rms resolution of 33 fs for the EOM detectors and 20 µm for the vertical beam position yields a resolution for the horizontal beam position of 3 µm (rms).

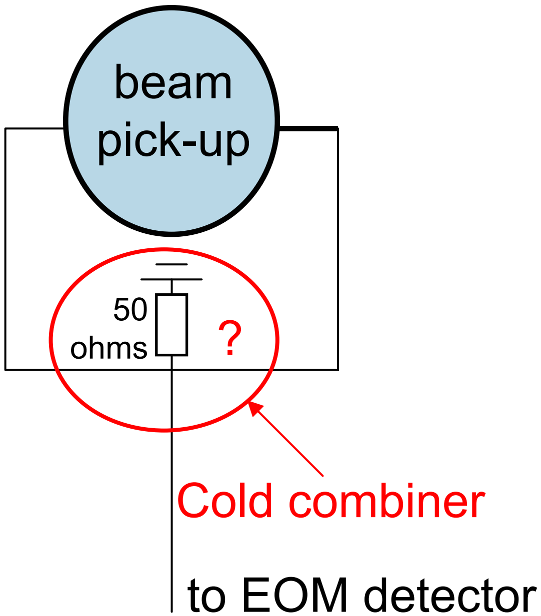
This precise beam position we can use to reduce the error in the arrival time from ~ 300 fs to below 30 fs (rms).

Bunch Arrival-time Measurement

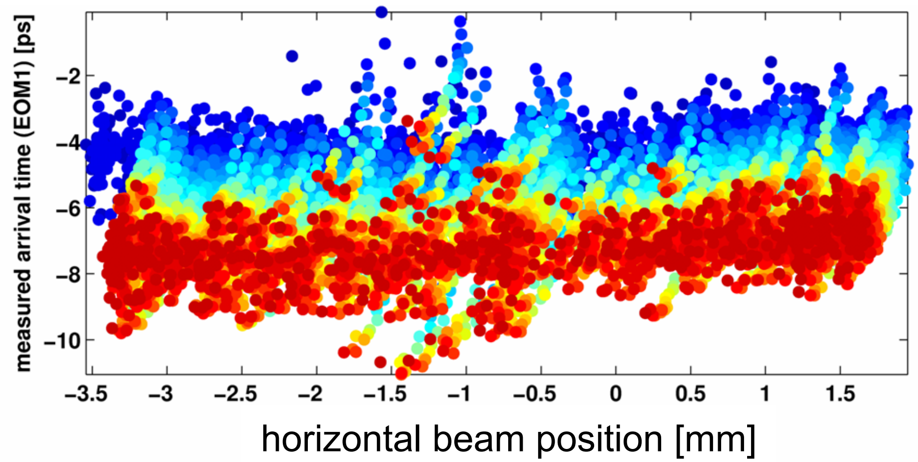


Time change seen by arrival time monitor: ~ 5 ps / (% ACC1 gradient change)
Time change seen by TCAV: ~ 5.8 ps / (% ACC1 gradient change)
Intra-bunch train jitter between two adjacent bunches: ~ 40 – 60 fs

Reduction of orbit dependence with "cold-combiner"



To minimize the orbit dependence the two output signals of the beam pick-up were combined with a so-called "cold combiner".

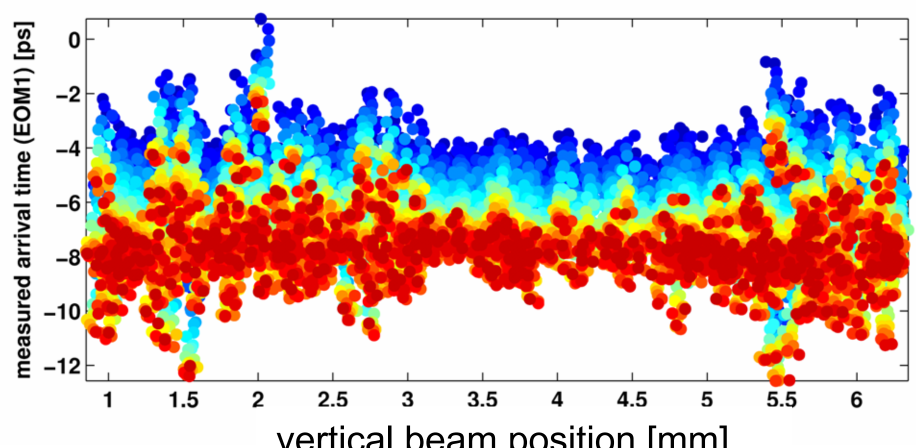


measured orbit dependence:

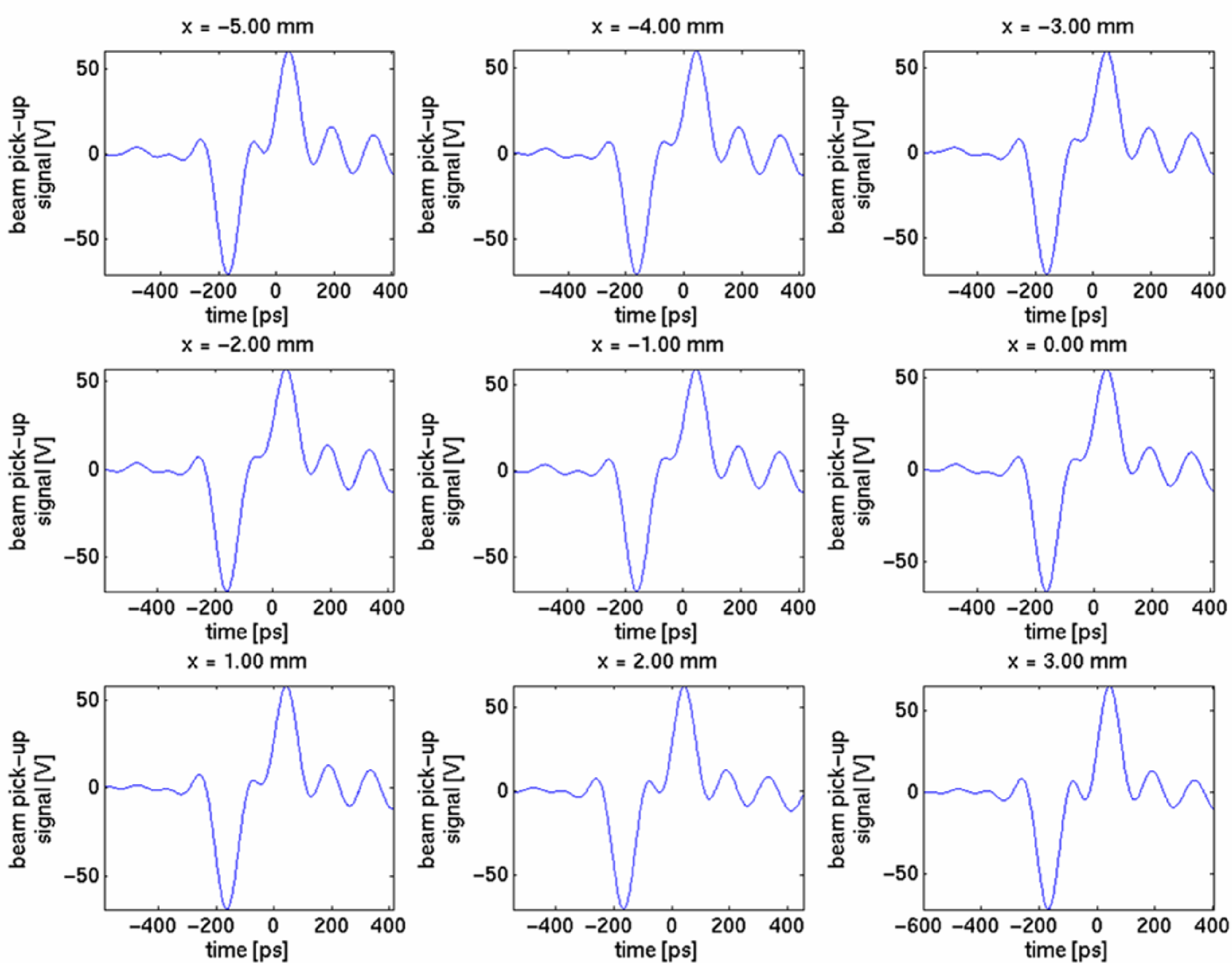
ax = (-0.190 +- 0.022) ps / mm
ax = (-0.191 +- 0.026) ps / mm

ay = (0.060 +- 0.032) ps / mm
ay = (0.064 +- 0.046) ps / mm

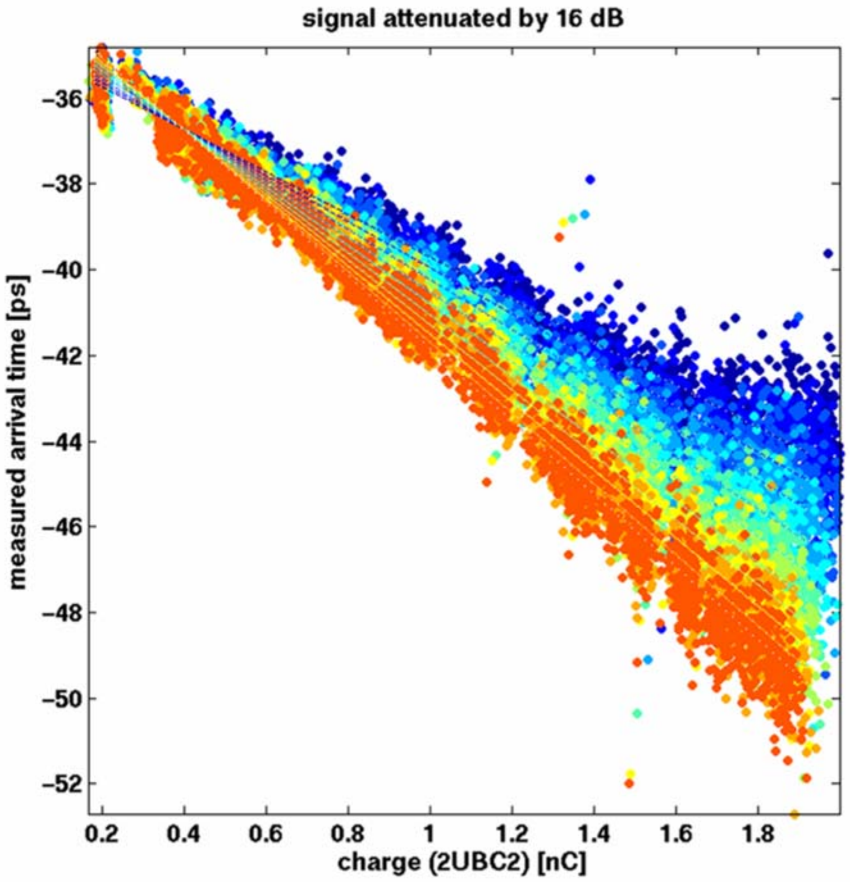
Reduction of the horizontal orbit dependence by a factor of 30-50!

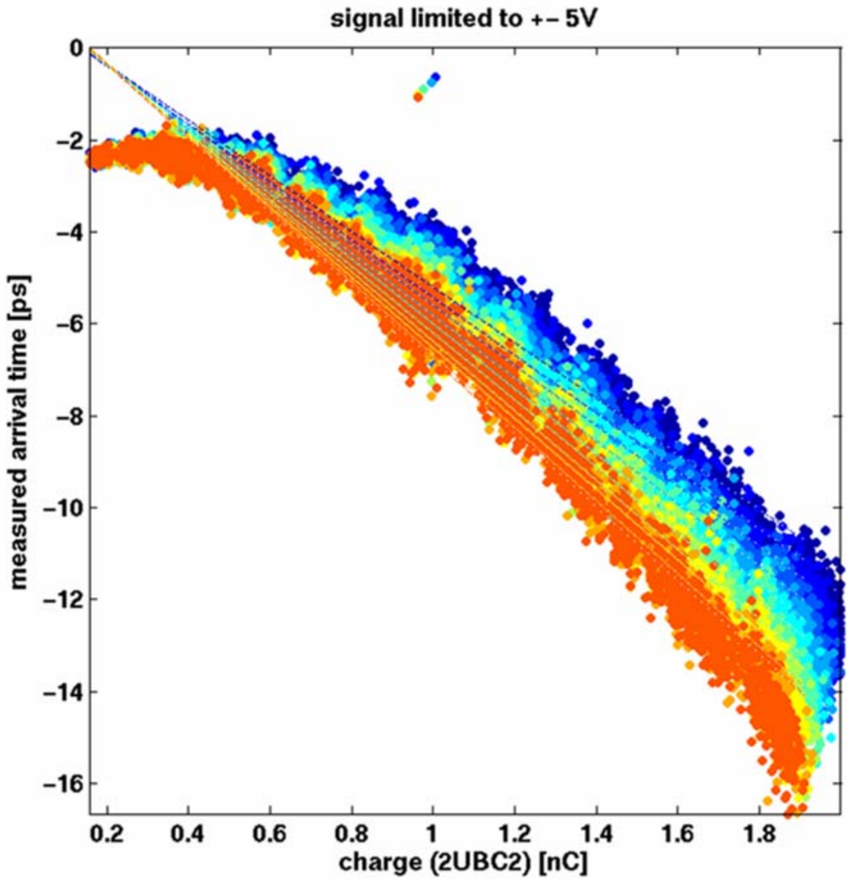


Measurement of pick-up signal in the tunnel



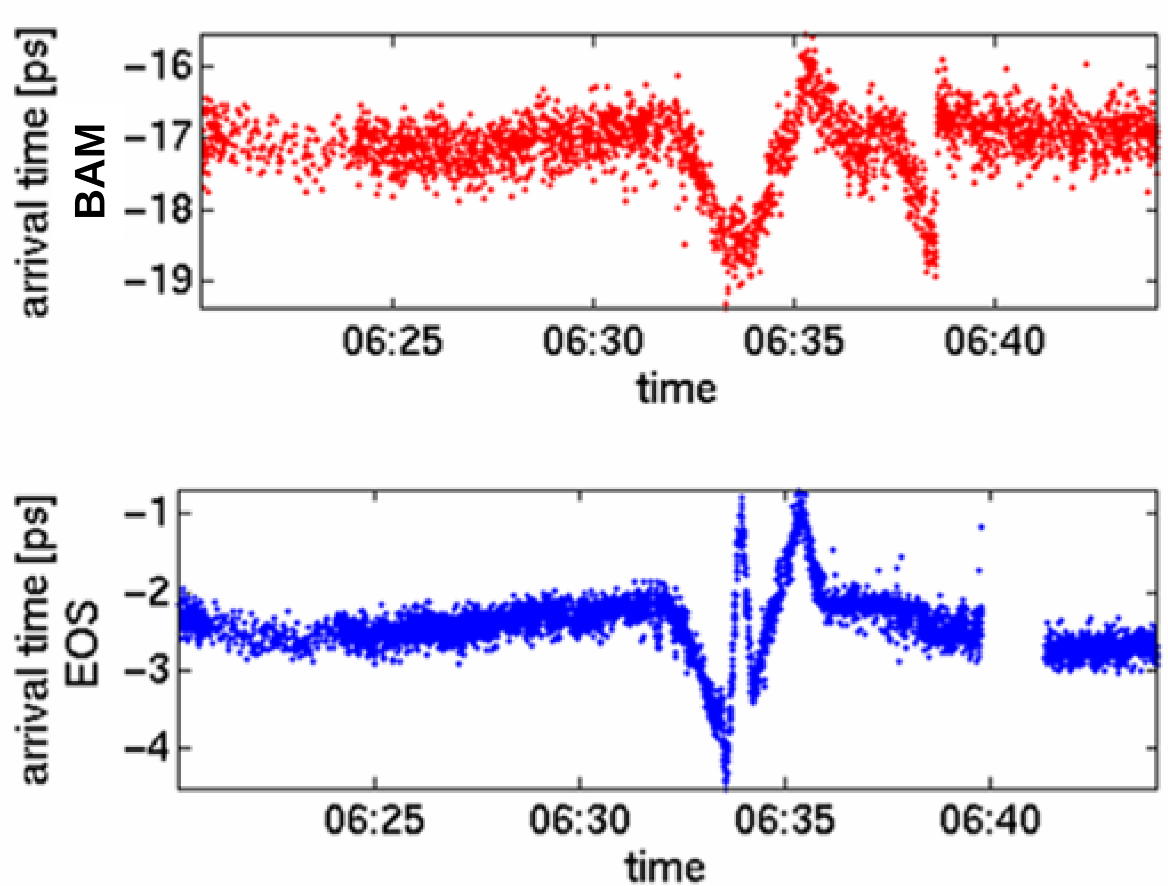
Charge dependence of BAM measurement with and without limiter





Limiter transfers amplitude modulations of the beam pick-up signal to phase changes! The data has to be analyzed in detail, the nonlinearity might be easy to correct…

Comparison measurement with EOS experiment

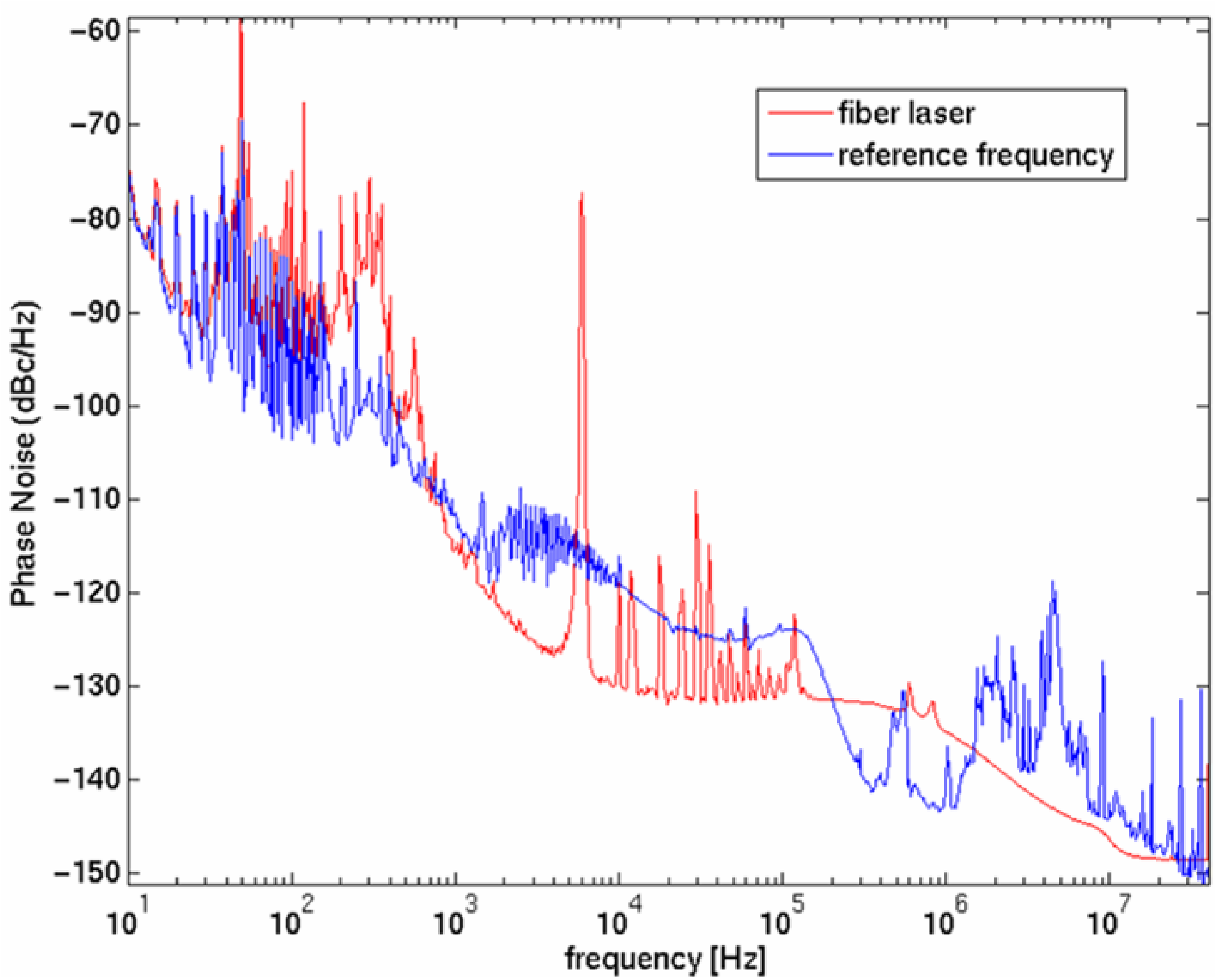


Arrival time jitter between EOS and BAM is about 300 fs!

EOS has clearly the higher resolution. A measurement with the TCAV confirms that this is not due to the difference that EOS detects the high density spike of the electron bunch while the BAM is only sensitive to the center.

Source for bad correlation: laser synchronization

Phase noise measurement of BAM fiber laser



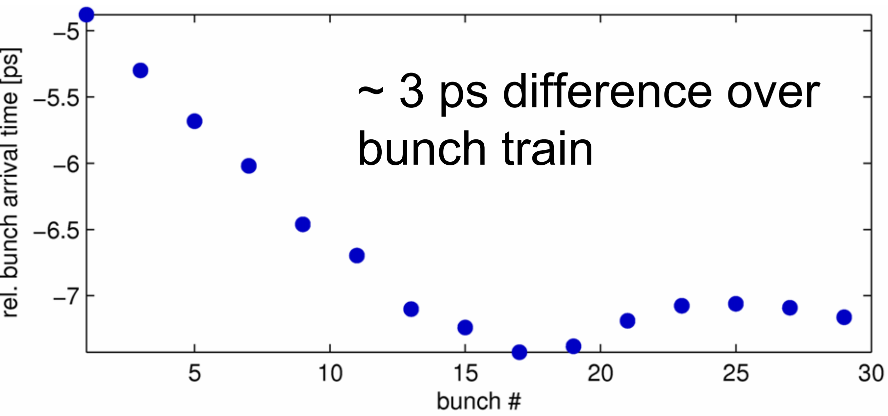
Integrated jitter of reference frequency (10 Hz – 100 kHz): ~ 120 fs

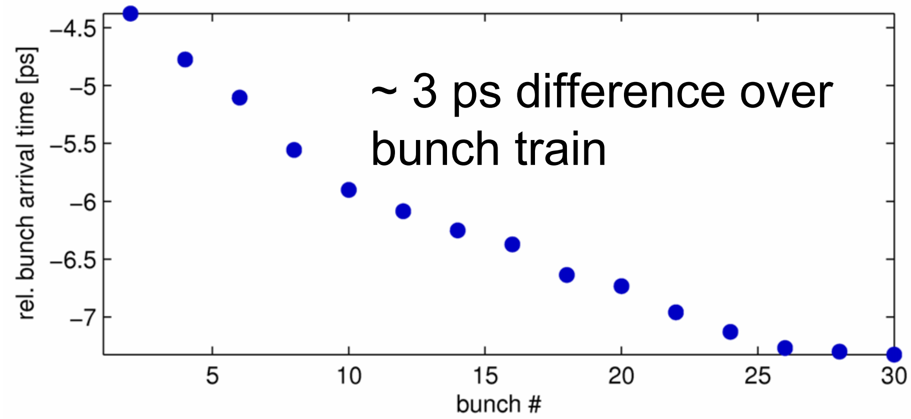
Integrated jitter of Fiber laser (10 Hz – 100 kHz): ~300 – 500 fs (depending on settings)

The synchronization has been improved meanwhile to about 150 fs jitter with respect to the reference.

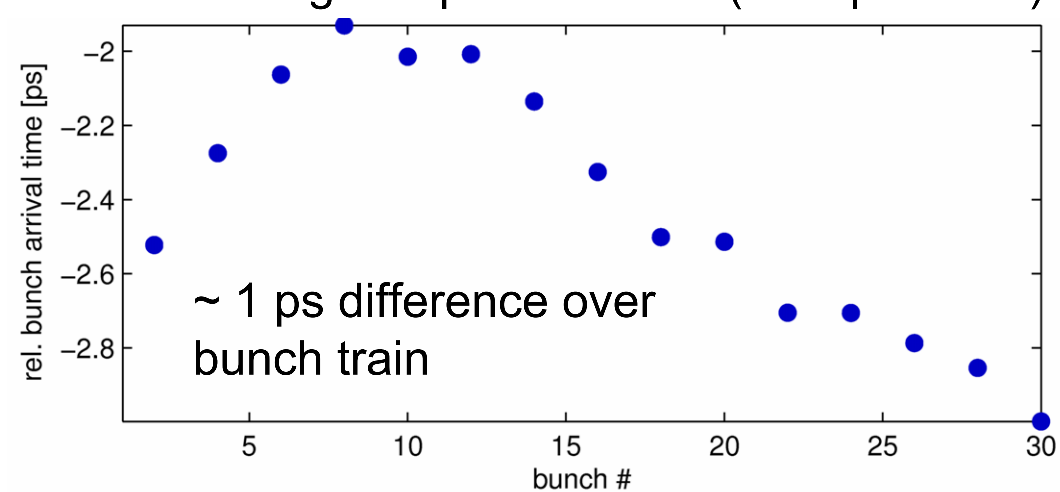
Measurement of the bunch arrival time over the bunch train

Beam loading compensation off

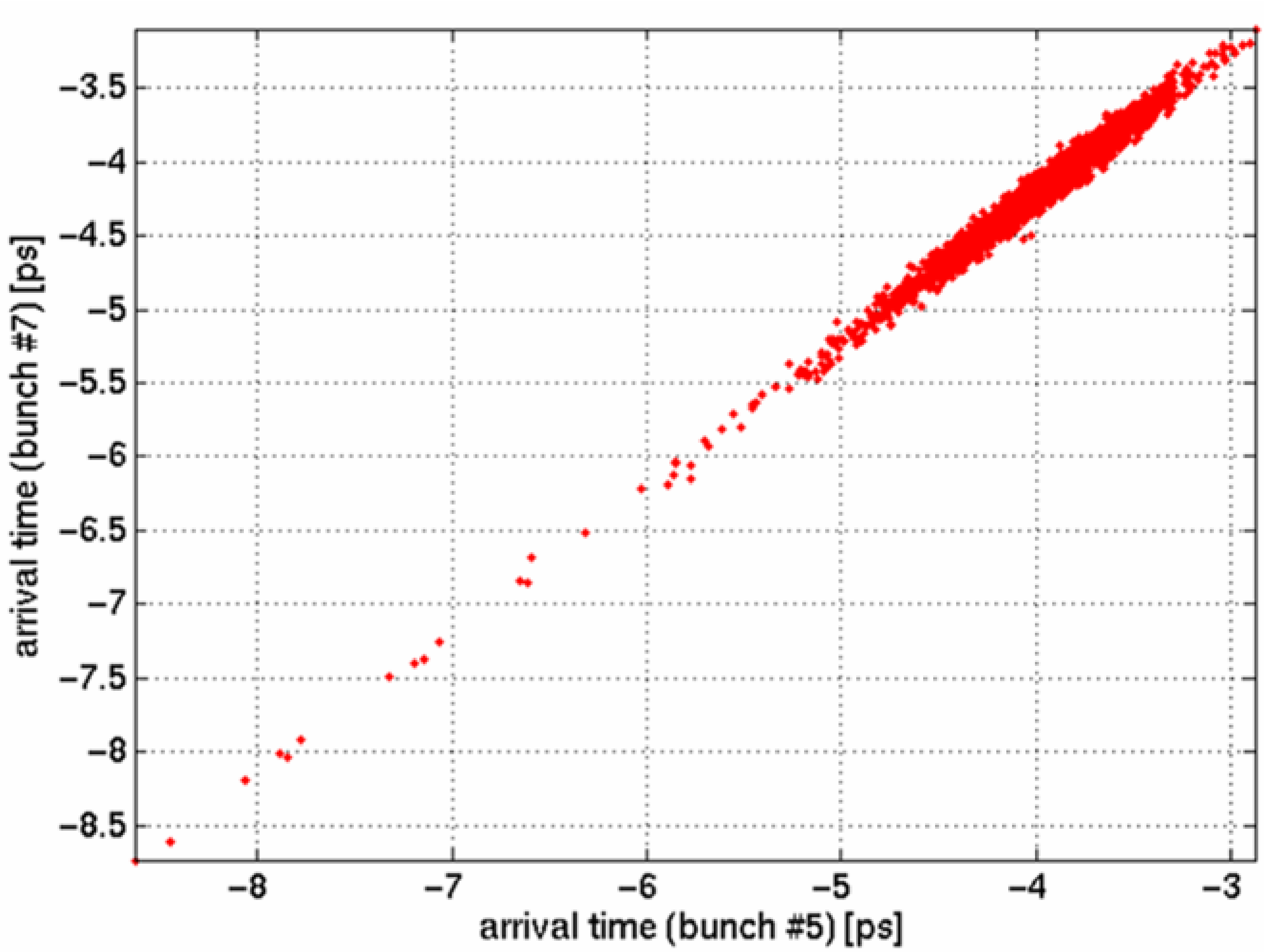




Beam loading compensation on (not optimized)



Confirmation of high BAM resolution in spite of synchronization problem

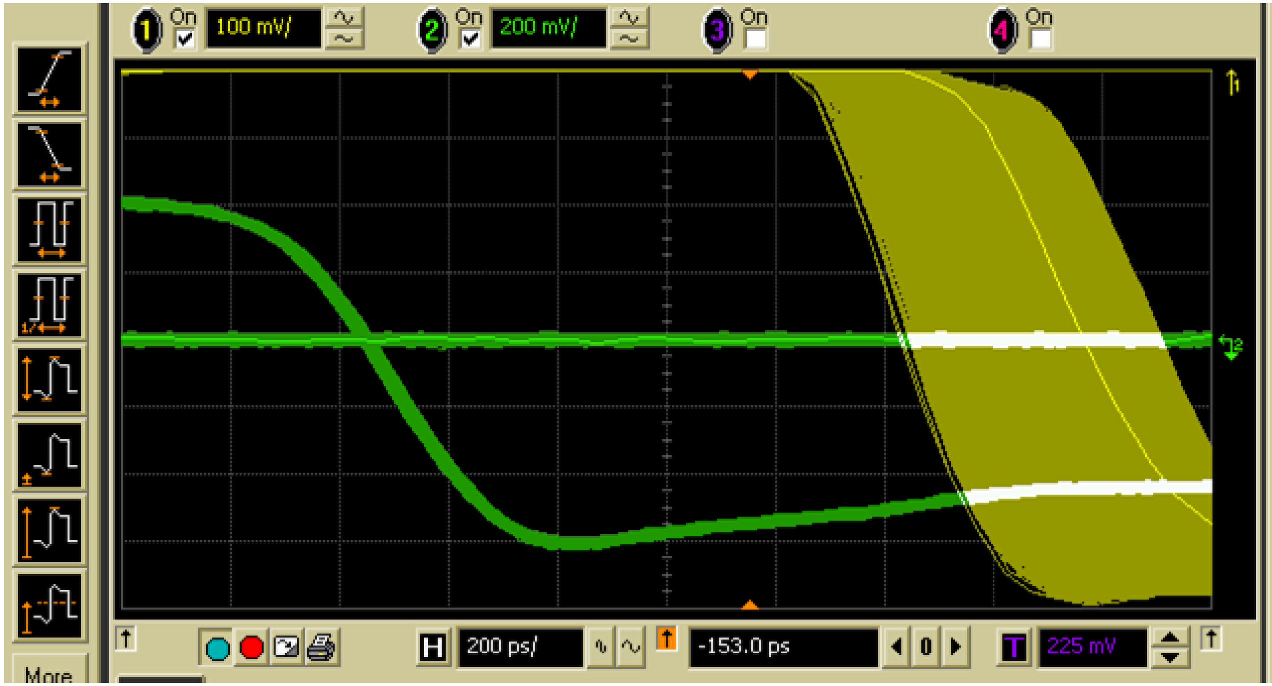


Jitter between two adjacent bunches: ~ **50 fs**

Laser amplitude measurement: clock jitter of ADC board

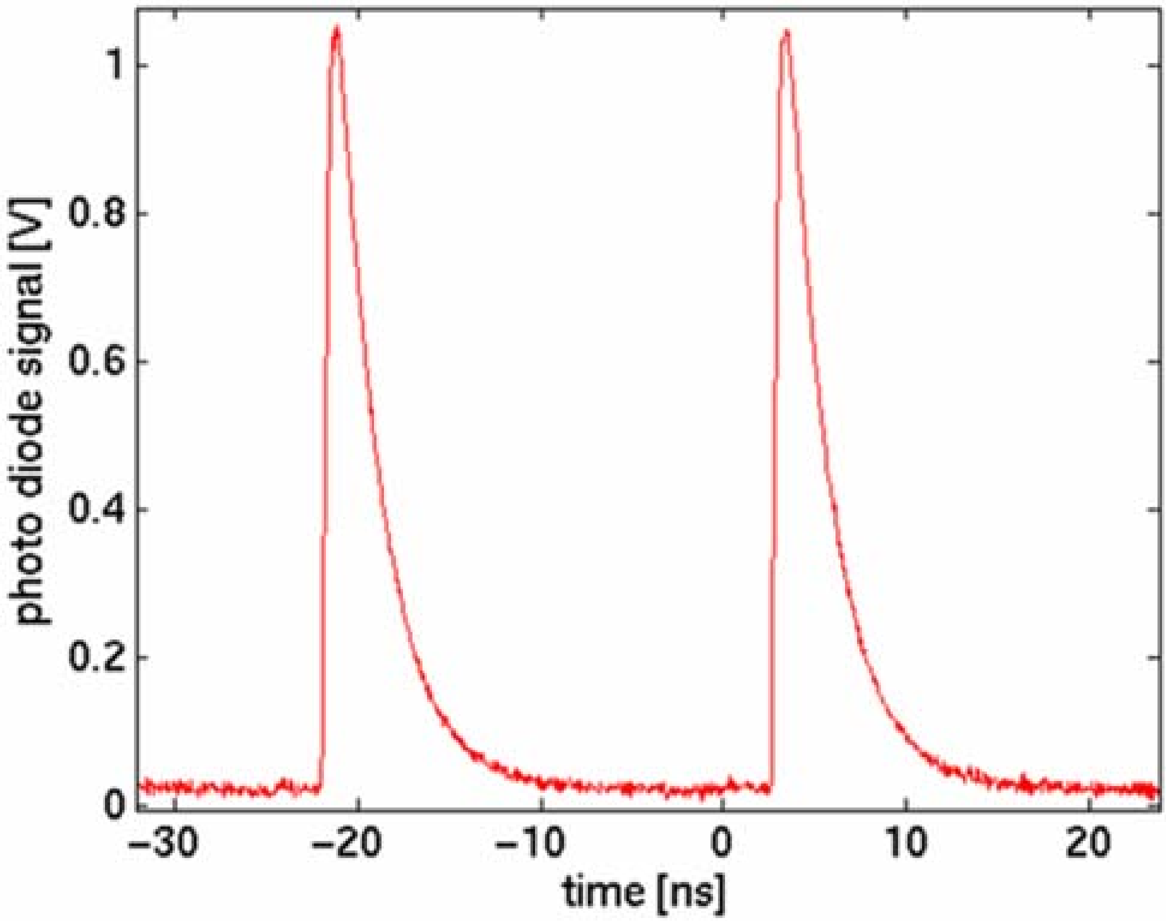
With the SIS ADC board which is currently used to detect the amplitude of the laser pulses the resolution is limited to about 0.2 % (best results was ~ 0.12 %).

Reason: Clock jitter of ADC board (~ 500 – 600 ps peak-peak)



Laser Amplitude Measurement: Clock Jitter of ADC Board

Why does this clock jitter disturb our measurement?

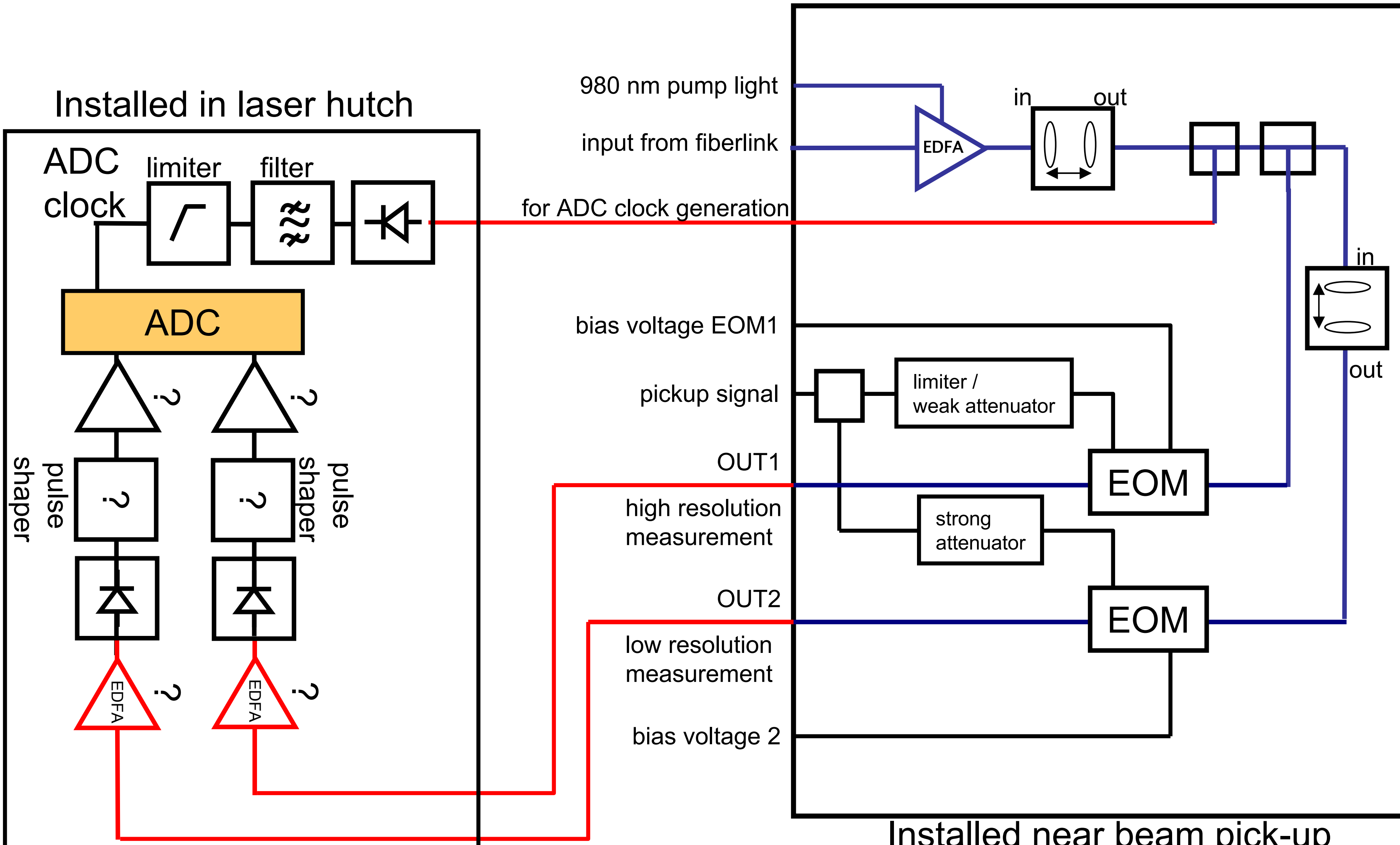


ADC samples different positions of the photo diode signal

- We need a small ADC clock jitter
- We have to stretch the pulse

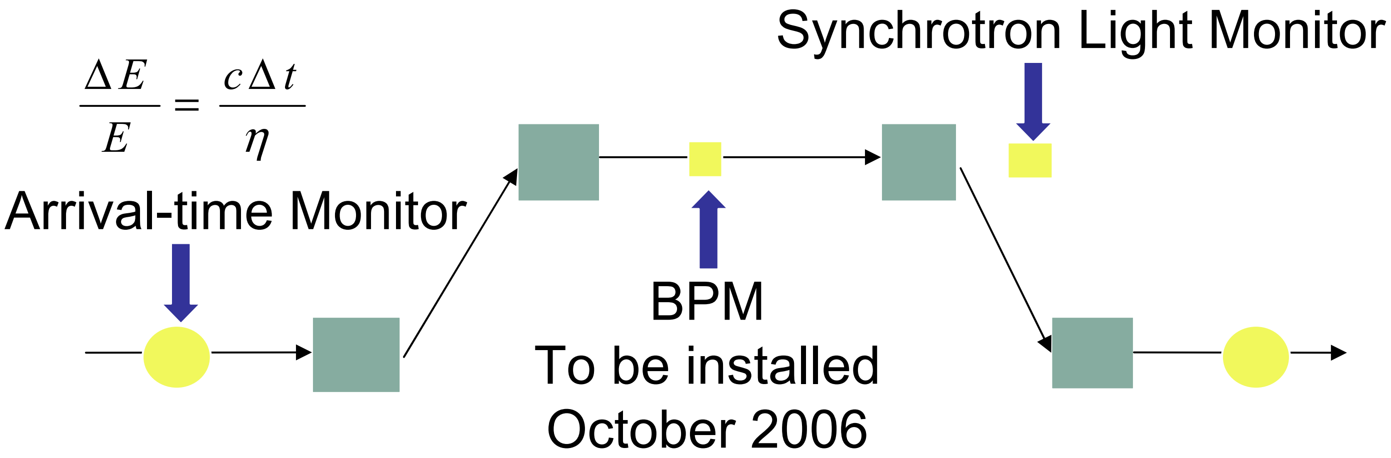
With a better ADC (Linear Technology Eval board) the resolution of the readout recently could be improved to ~ 0.08 % (~62 dB). This could still be limited by noise on the PD supply voltage.

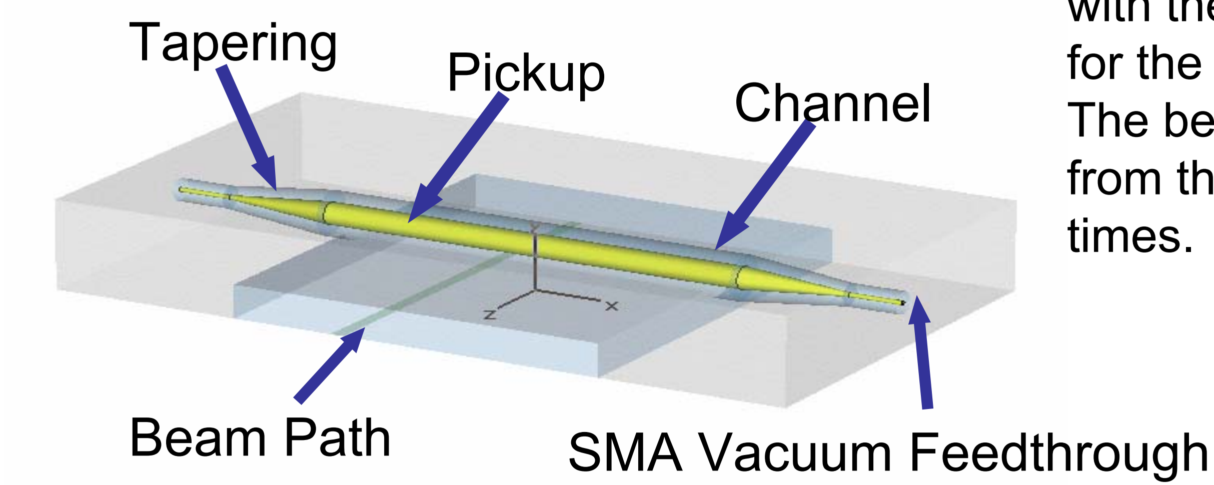
Frontends for the BAM



BPM with Large Horizontal Aperture for Magnetic Chicanes

$$\frac{\Delta E}{E} = \frac{c\Delta t}{\eta}$$

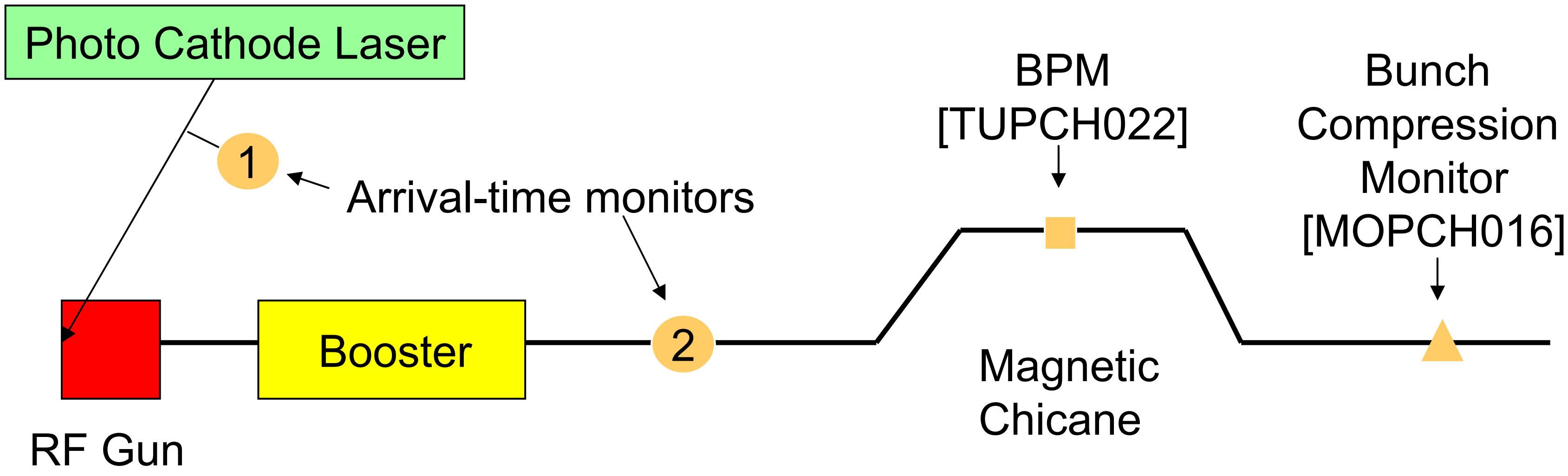




The arrival time of the pickup signals at both ends is measured with the same technique as used for the beam arrival time monitor. The beam position is determined from the difference of both arrival times.

Courtesy of
K. Hacker (DESY)

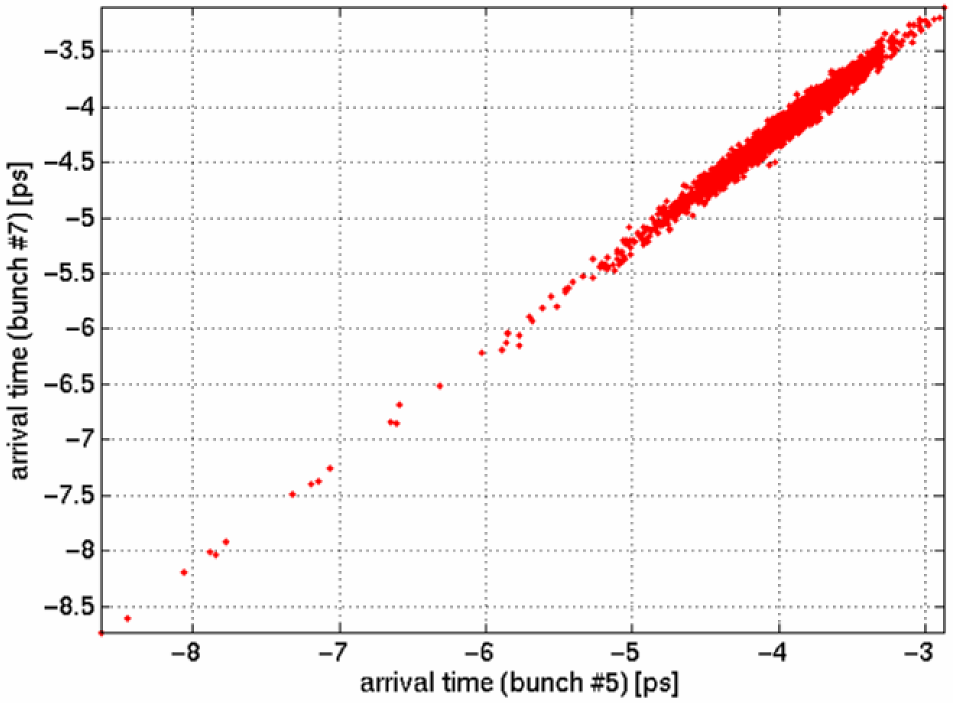
Identification of Sources for Arrival-time Changes

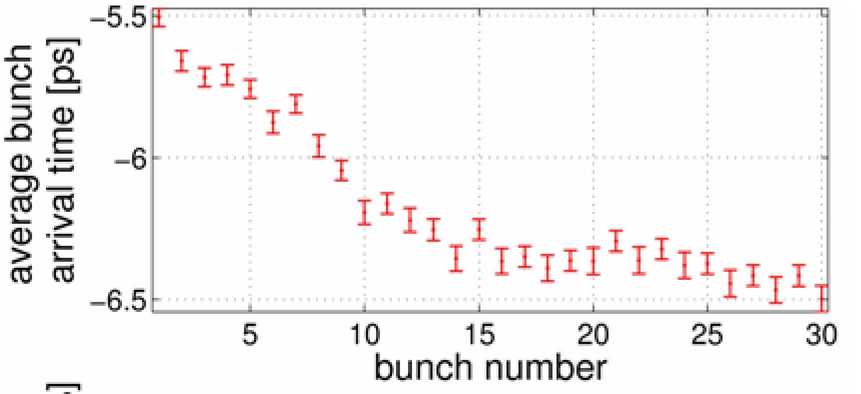


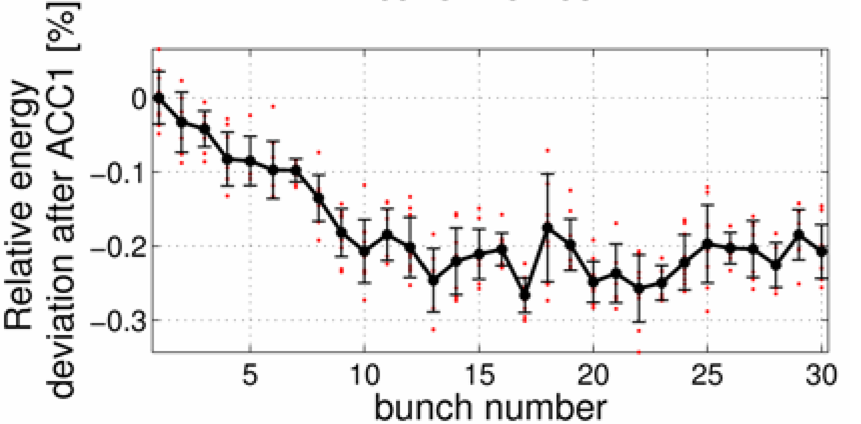
Detection of main arrival-time jitter sources

- Arrival time of photo cathode laser pulses **(1st arrival time monitor)**
- Phase of RF gun **(difference between 1st and 2nd arrival time monitor)**
- Amplitude of Booster module **(BPM in magnetic chicane)**
- Phase of Booster module **(Bunch Compression Monitor)**
- Arrival time of pump-probe laser **(cross-correlation with timing system)**

Recent results







Jitter between two adjacent bunches: **~ 40-50 fs**

→ Timing resolution with respect to reference laser: **< 30 fs**

Arrival time measurement for all bunches in the bunch train possible!

→ Plan to implement this into feedback system of LLRF group

Development at DESY

Overview

- Why sub-ps Synchronization
  - Where does jitter in an FEL-based machine come from?
  - How do we measure it?
  - How and to what level can we get rid of it?
- Present day concepts and state of development of optical synchronization systems
  - Time domain vs. frequency domain techniques
- (optical) Measurement techniques based on optical synchronization systems
  - EO techniques, optical replica synthesizer, beam arrival time monitor

Overview

- Why sub-ps Synchronization
  - Where does jitter in an FEL-based machine come from?
  - How do we measure it?
  - How and to what level can we get rid of it?
- Present day concepts and state of development of optical synchronization systems
  - Time domain vs. frequency domain techniques
- (optical) Measurement techniques based on optical synchronization systems
  - EO techniques, optical replica synthesizer, beam arrival time monitor

Timing jitter

What's important at the end of the day?

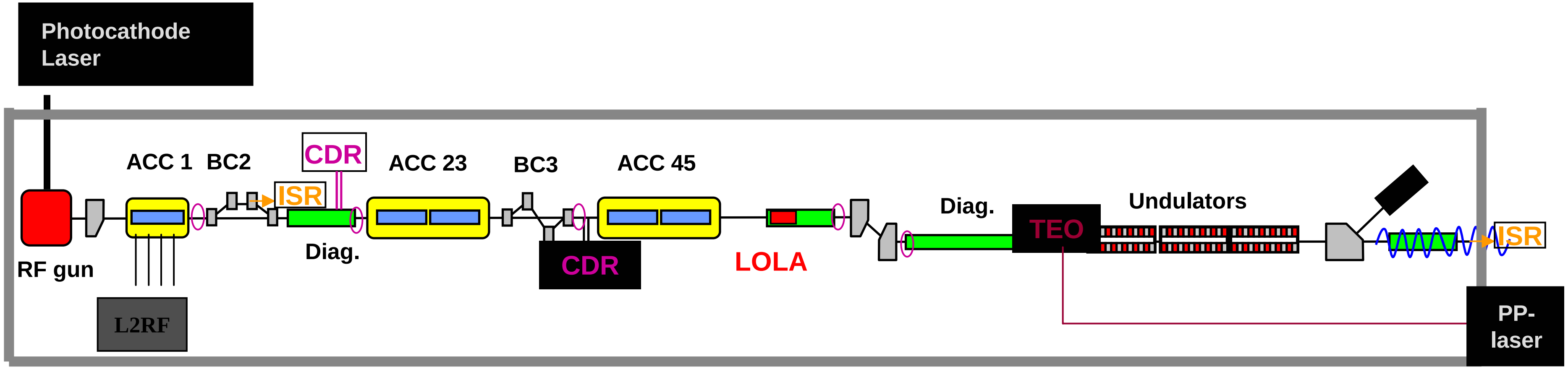
fluctuations between experimental laser of user and FEL pulse!

so not only stability of reference at given points in the machine…

Sources of Jitter/Drift

- Jitter from RF gun laser
- Energy jitter added through RF fluctuations in cavities, transformed into timing jitter in bunch compressor
- Jitter of diagnostics (via beam-based feedback loops)
- Jitter of user laser locked to RF/optical reference
- Jitter of seed lasers vs. user lasers (for seeded operation)

Example: linac-driven FEL



- Laser-driven RF gun
- Booster section with bunch compression system at beam energy of ~150 MeV
- Compression factor around 30-100
- Undulator/seed laser section
- Pump/probe laser system for users

Courtesy H. Schlarb, DESY

Source of timing jitter
- Caused by RF acceleration prior to BC-

Timing jitter behind BC **Gradient** **Phase** **Incoming Timing jitter**

$$\boxed{\Sigma_t^2 \approx \underbrace{\left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2}_{} + \underbrace{\left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{c_0 k_{rf}}\right)^2}_{} + \underbrace{\left(\frac{1}{C}\right)^2}_{}\Sigma_{i,t}^2}$$

XFEL: 3.3 ps/% **2 ps/deg** **0.05 ps/ps**

FLASH: 5.5ps/%

C – compression factor (20)

R_{56} ~ 100 mm XFEL /180 mm FLASH

k_{rf}: wavenumber RF acceleration (27.2/m)

Vector sum regulation => 1 deg == 1.8% (statistic 32/8 cav. helps)

But! Phase changes can be correlated due to local oscillator changes

Courtesy H. Schlarb, DESY

Intermediate Conclusion

Injector is most critical area in terms of stability/jitter/drift issues

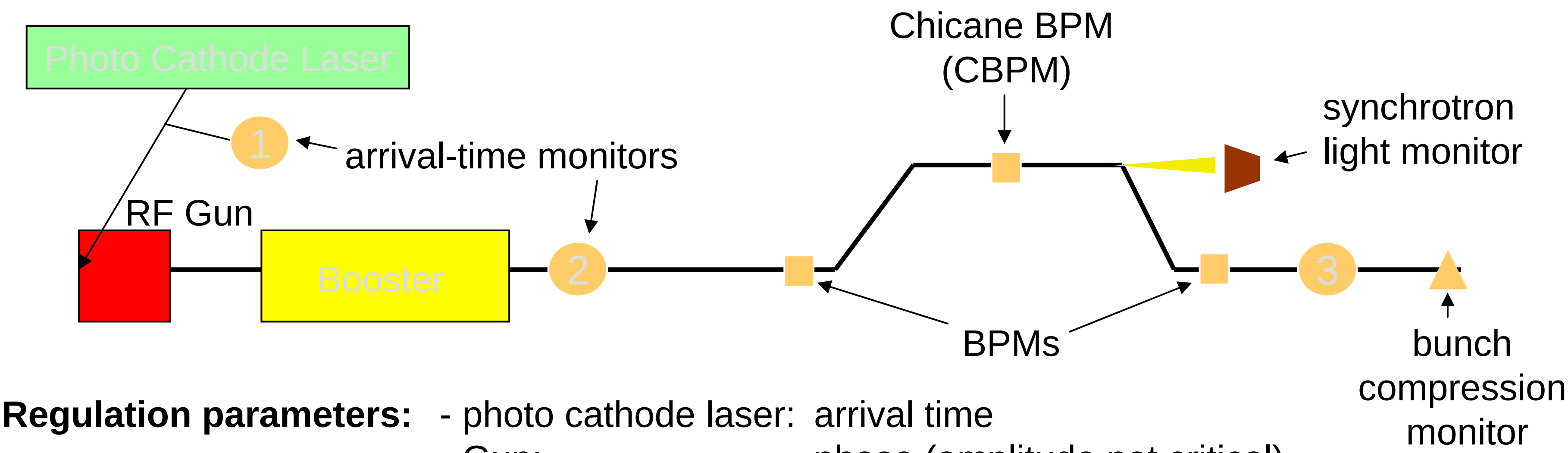
Present day LLRF can do (s.c. pulsed structures) 0.03 deg phase stability (0.02 % rms amplitude stability) limited by noise in downconverters.

If LLRF downconversion and regulation is not good enough, even the best local oscillator will not help

Overview

- Why sub-ps Synchronization
  - Where does jitter in an FEL-based machine come from?
  - How do we measure it?
  - How and to what level can we get rid of it?
- Present day concepts and state of development of optical synchronization systems
  - Time domain vs. frequency domain techniques
- (optical) Measurement techniques based on optical synchronization systems
  - EO techniques, optical replica synthesizer, beam arrival time monitor

Regulation of injector using beam based measurements



Regulation parameters: - photo cathode laser: arrival time
- Gun: phase (amplitude not critical)
- Booster: phase, amplitude

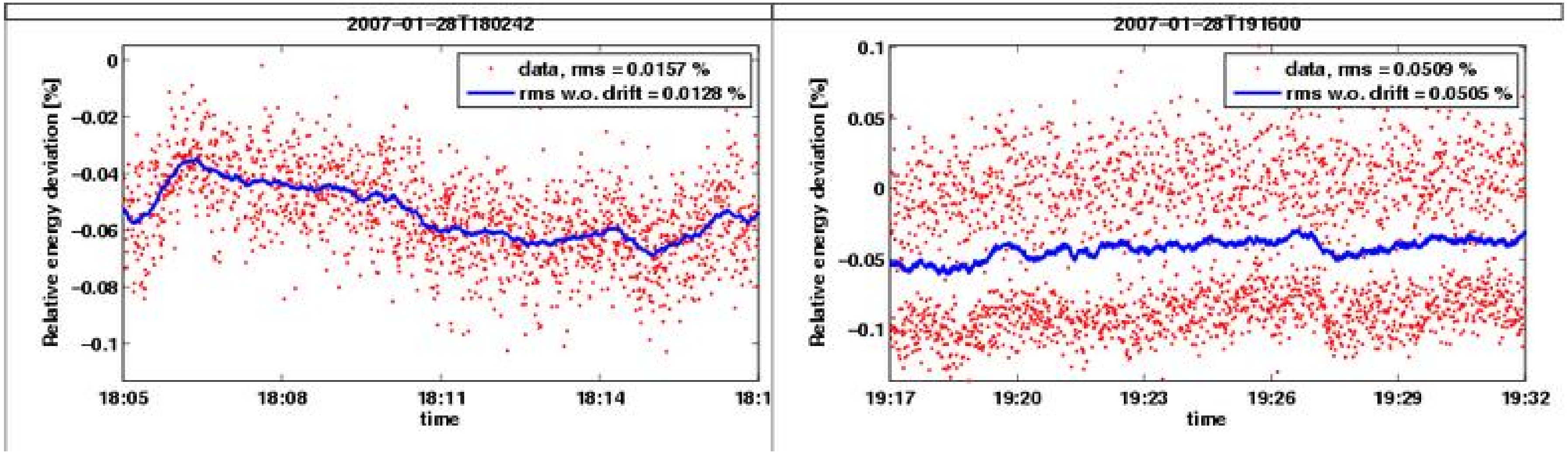
Goal: stable bunch compression **and** arrival time

→ Many different monitor systems and complex regulation algorithms needed!

•Arrival time of photo cathode laser pulses **(1st arrival time monitor)**
•Phase of RF gun **(difference between 1st and 2nd arrival time monitor)**
•Amplitude of booster module **(CBPM + BPMs)**
(synchrotron light monitor + BPMs)
(difference between 3rd and 2nd arrival time monitor)
•Phase of booster module **(bunch compression monitor)**
(fiber laser + EO)

Courtesy H. Schlarb, DESY

dE/E stability results from FLASH



- **Measured by fitting to images of OTR screens**
- **Best up to now: 1.6 10^{-4} incl. drift and 1.3 10^{-4} w/o drift**

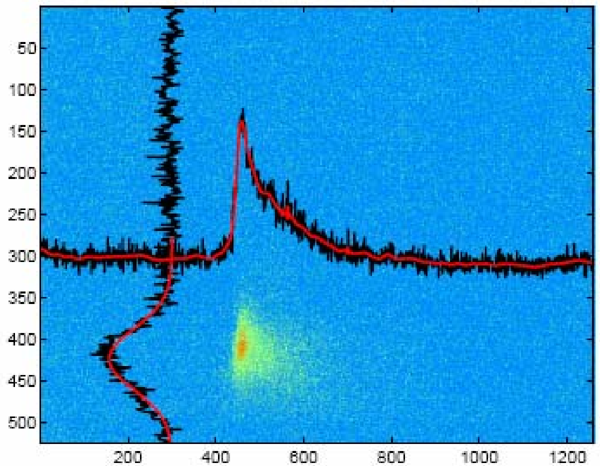
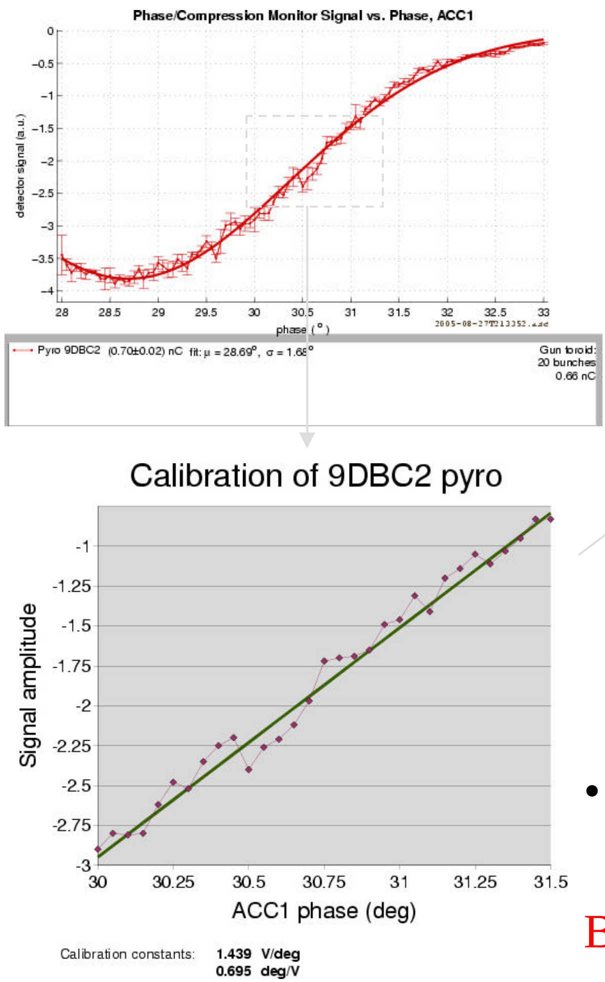


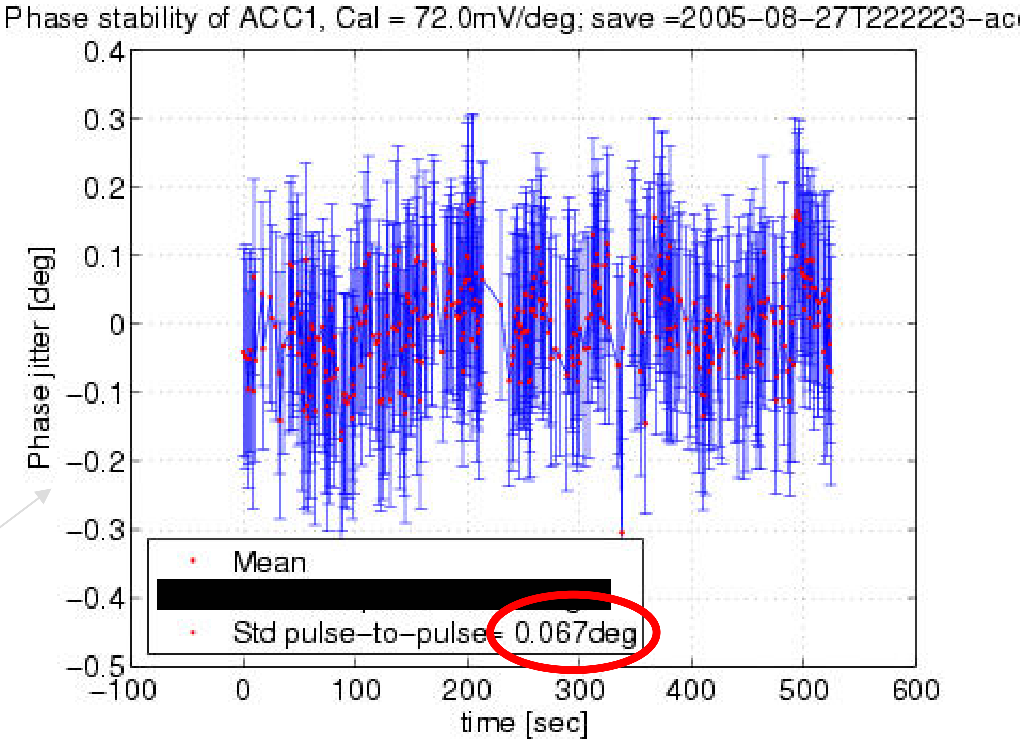
Figure 2: Image of bunch at OTR6.

(a)

Courtesy H. Schlarb, DESY

Phase stability ACC1 with feedback from 'BeamCompressionMonitor'





• Pyro-electric detector monitors FIR power emitted by diffraction radiator

But! This is the phase stability of beam arrival into the acceleration module relative to the RF phase

Courtesy H. Schlarb, DESY

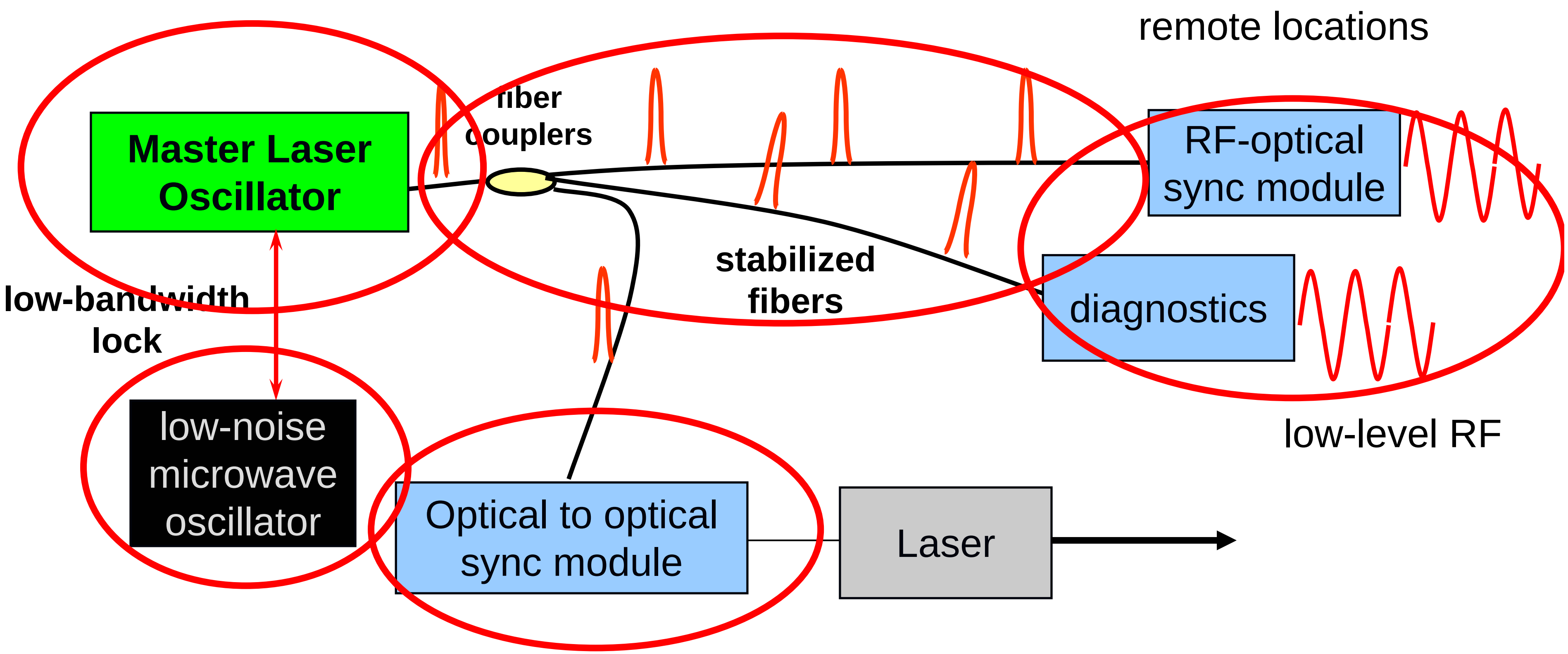
Overview

- Why sub-ps Synchronization
  - Where does jitter in an FEL-based machine come from?
  - How do we measure it?
  - How and to what level can we get rid of it?
- Present day concepts and state of development of optical synchronization systems
  - Time domain vs. frequency domain techniques
- (optical) Measurement techniques based on optical synchronization systems
  - EO techniques, optical replica synthesizer, beam arrival time monitor

Why optical ?

- RF transmission with sub-100 fs level jitter and drift over long distances cumbersome
- Optical methods promise drift free (or extremely low drift) and low-jitter signal transmission and recovery
- Free benefit: locking different lasers to reference possible with fs jitter

Synchronization System Layout



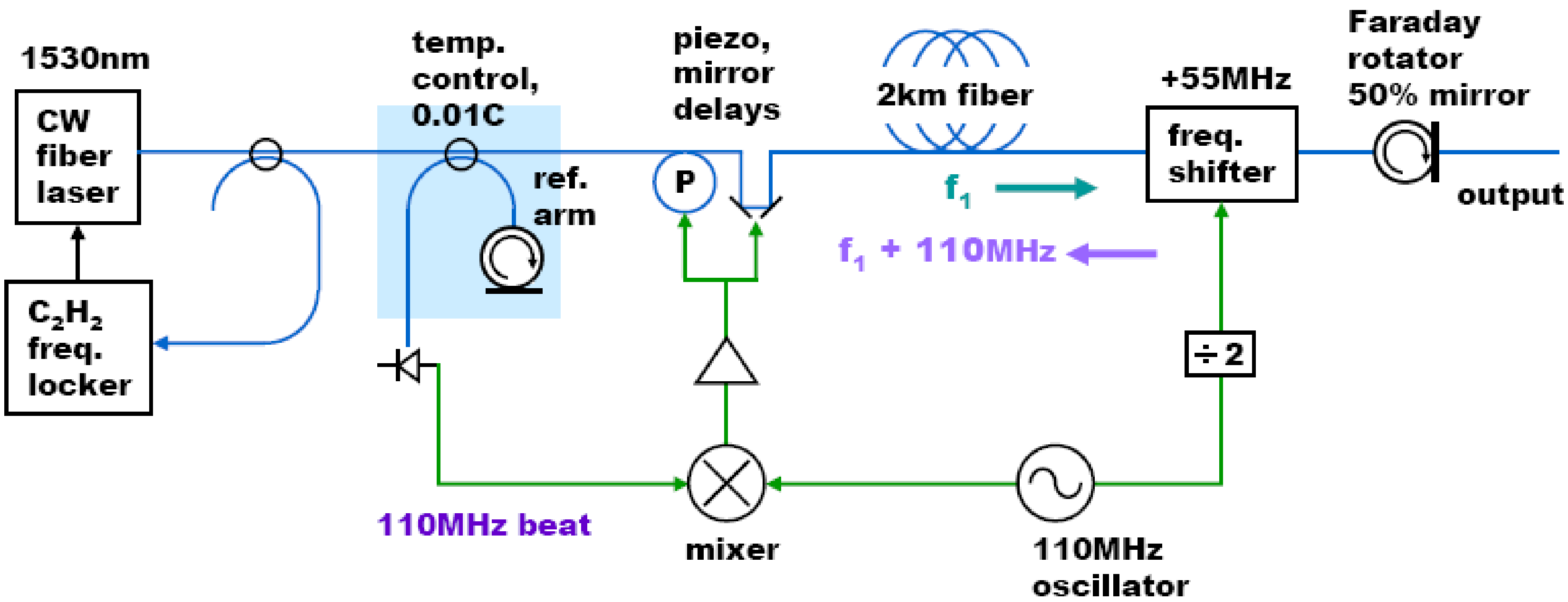
- A master mode-locked laser producing a very stable pulse train
- The master laser is locked to a microwave oscillator for long-term stability
- length stabilized fiber links transport the pulses to remote locations
- other lasers can be linked or RF can be generated locally

Two different approaches

- Frequency domain:
  - Uses stabilized cw fiber laser
  - Stabilization by heterodyne beat of cw signal
  - Signal transmission using amplitude modulation
- Time domain:
  - Uses mode-locked fiber laser
  - Stabilization by optical cross-correlation of transmitted pulses
  - Signal transmission through frequency components of laser pulses

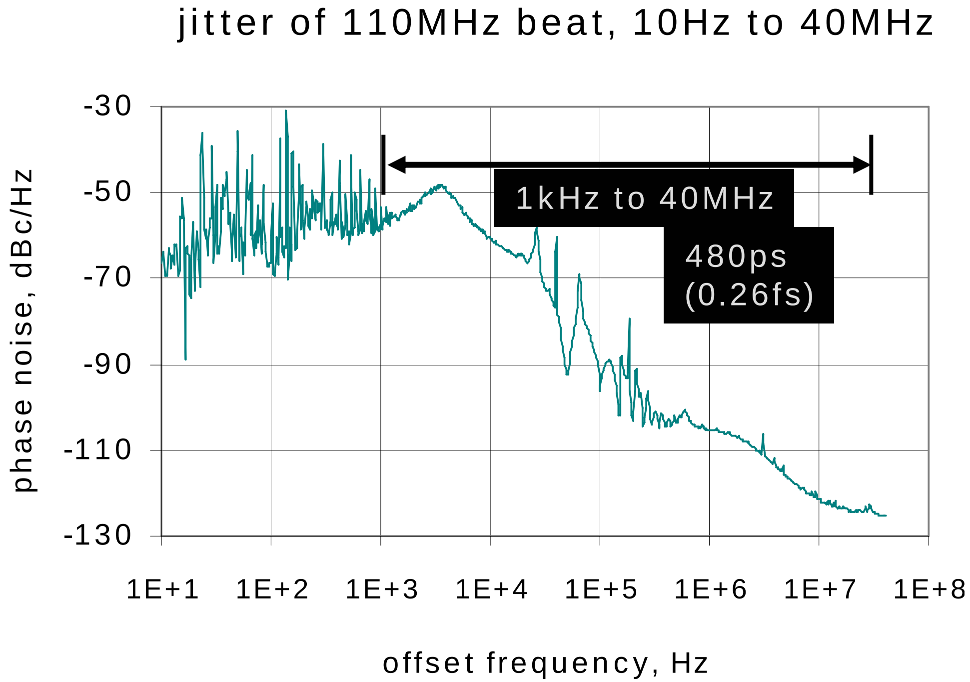
Interferometric phase delay controller

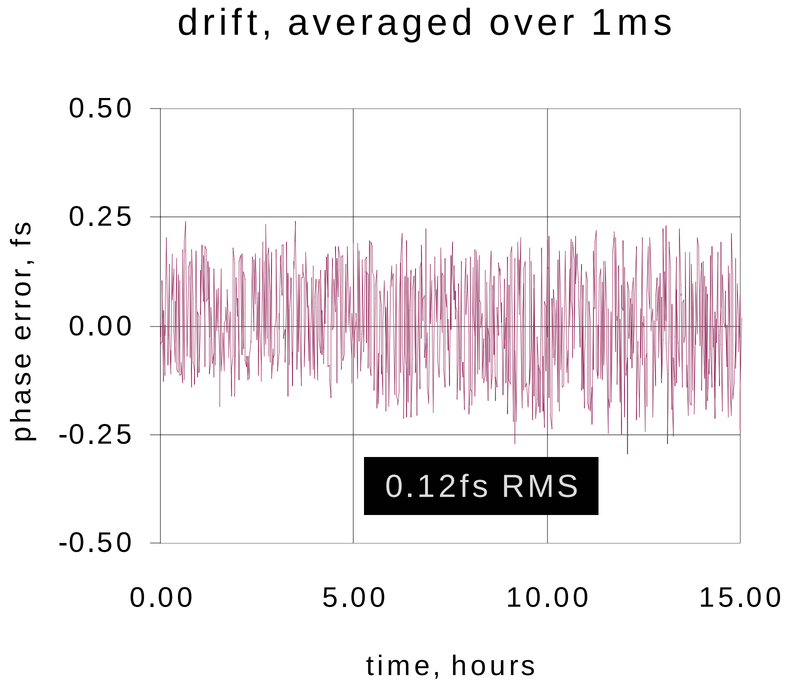
- Measure delay with frequency shifting interferometer
  - RF phase = optical phase
- Laser frequency stability = allowable error / total delay
  - Required stability is 10^{-9} for 10fs, 2km → stabilize cw laser to e.g. acetylene resonance



Cortesy R. Willcox, LBNL

In-loop jitter and drift measurements



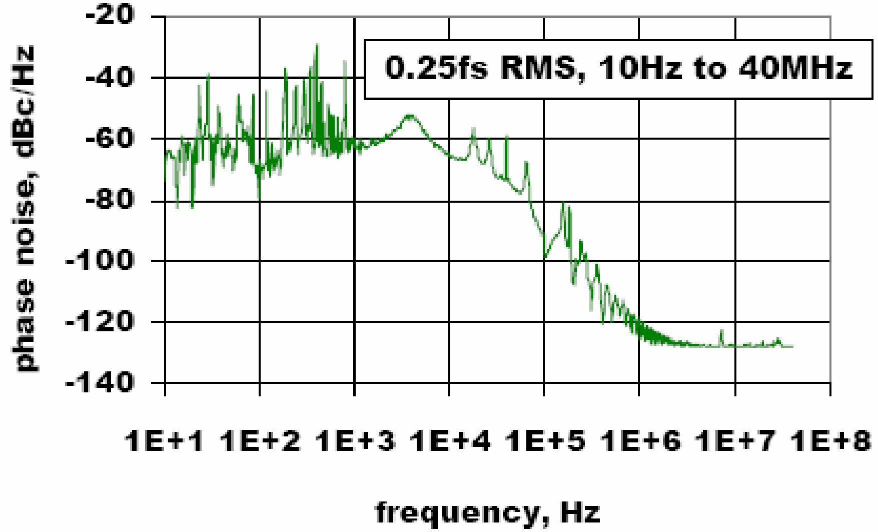


- Phase jitter of 110 MHz = phase jitter of 200 THz
- Time jitter is divided by frequency ratio
  - 480ps rms at 110 MHz = 0.26fs rms at optical frequencies
  - Loop gain = 1 at ~1kHz
- Uncontrolled high frequency jitter of reference 55 MHz oscillator contributes little to total jitter

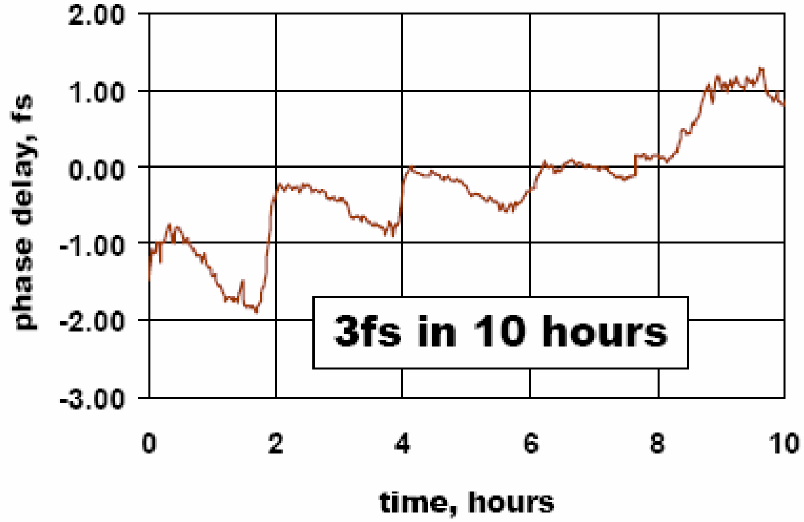
Courtesy R. Willcox, LBNL

Results of two-arm experiment

Jitter versus frequency:



Phase delay in fs versus time:

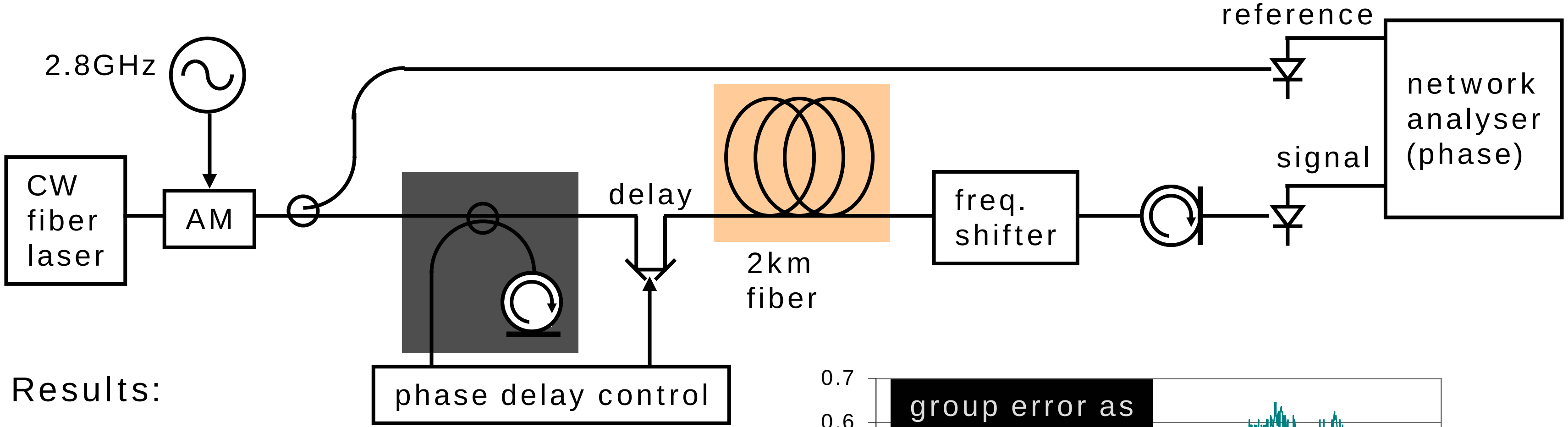


- One arm two km vs 1 meter → compare relative phase, out of loop measurement
- Total correction is ~100 ps per day
- Frequency domain techniques stabilize phase velocity in fiber
- Transmission of signals (AM) requires constant group velocity
- Different temperature behavior on order of percent
- Most likely ok for ~100 fs stability, but for lower drift and jitter values additional correction needed

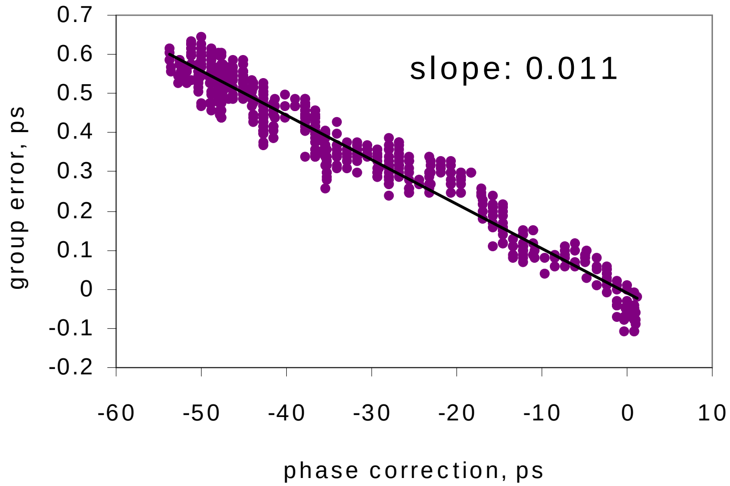
Courtesy R. Willcox, LBNL

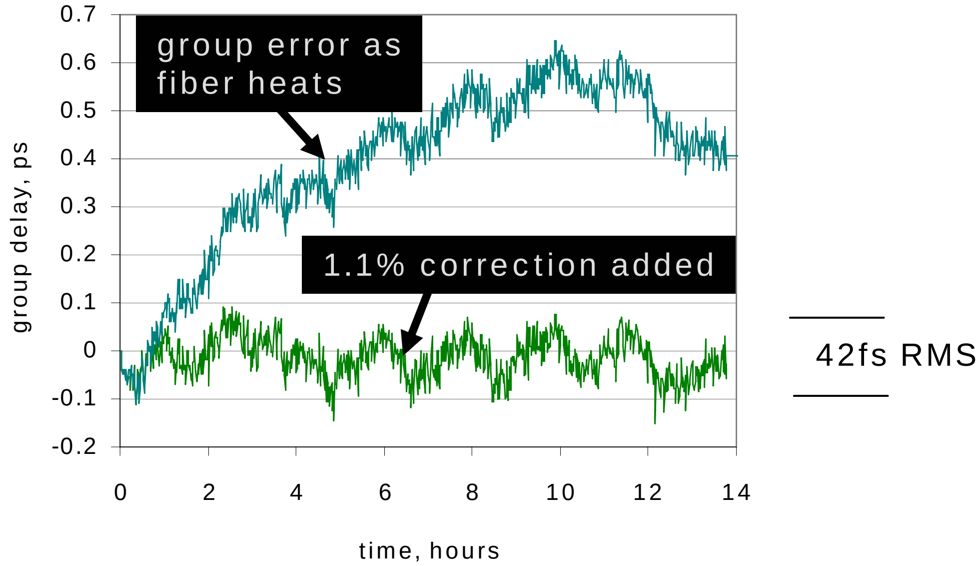
Transmitting signals

Experiment: optical and RF interferometers share an arm



Results:



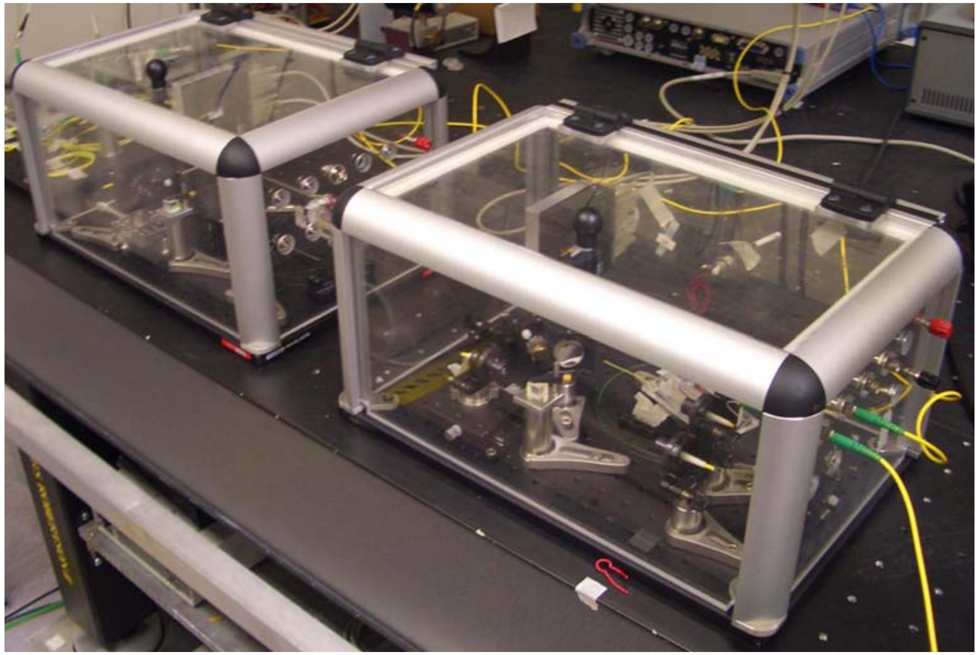


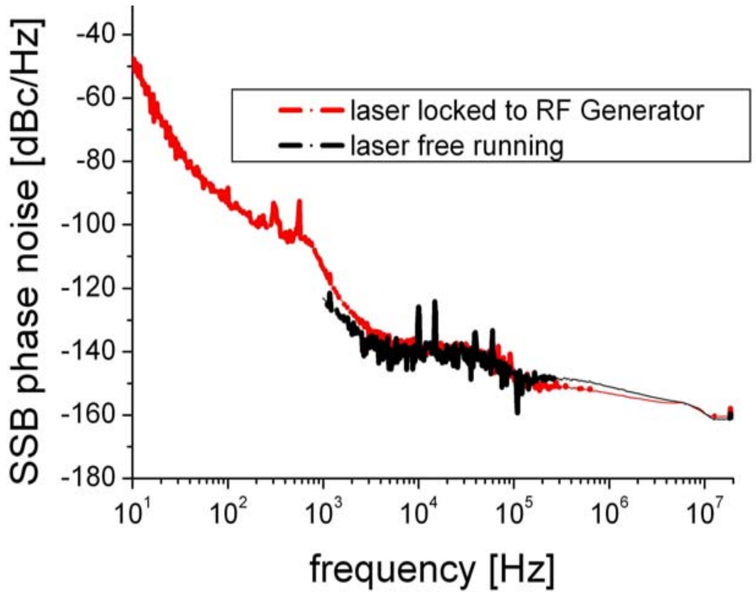
- Ongoing work, effort needed for 10 fs signal stability over long timescales

Some interpretation of jitter and drift

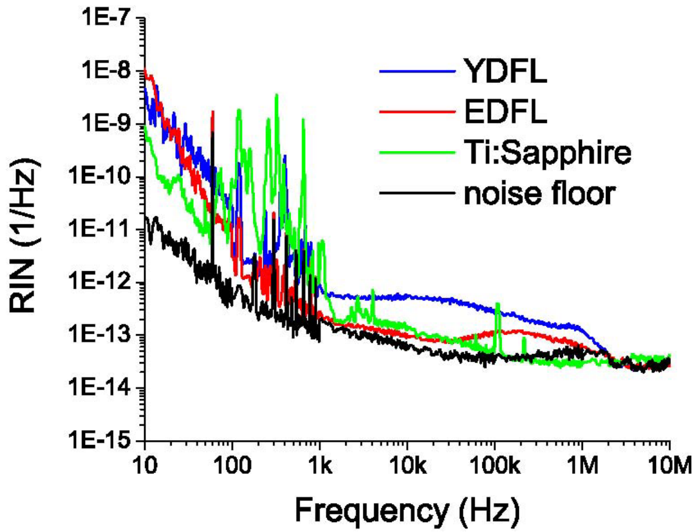
- All parts of machine need to be synchronized to common reference.
- Usually done through PLL with corner frequency ~ kHz
- Hence: fluctuations up to kHz level is common to all subsystems and only relative fluctuations matter, absolute magnitude of phase noise irrelevant
- Fast fluctuations cannot be compensated. Here absolute phase noise is important!

MLO I (stretched-pulse EDFL)

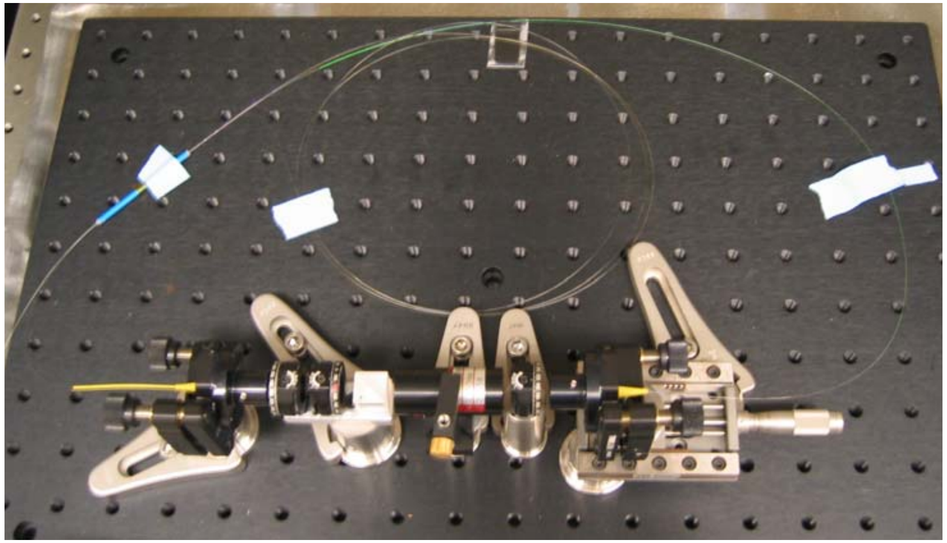




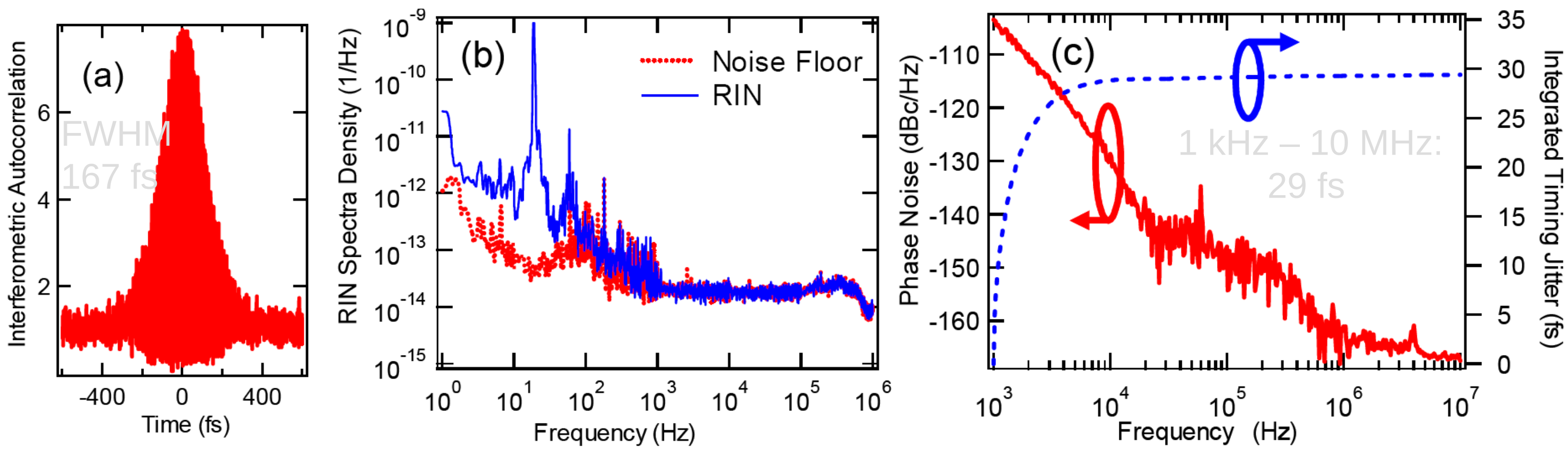
- Dispersion managed stretched pulse fiber-laser
- Gain medium erbium (center at 1550 nm)
- High pulse energy (~ 1 nJ)
- Pulse duration: ~ 100 fs FWHM
- Repetition rate: 30 -100 MHz
- Integrated timing jitter (1 kHz – 20 MHz) ~ 10 fs
- Integrated amplitude noise (10 Hz – 1 MHz): 0.03 %



MLO II (soliton EDFL)

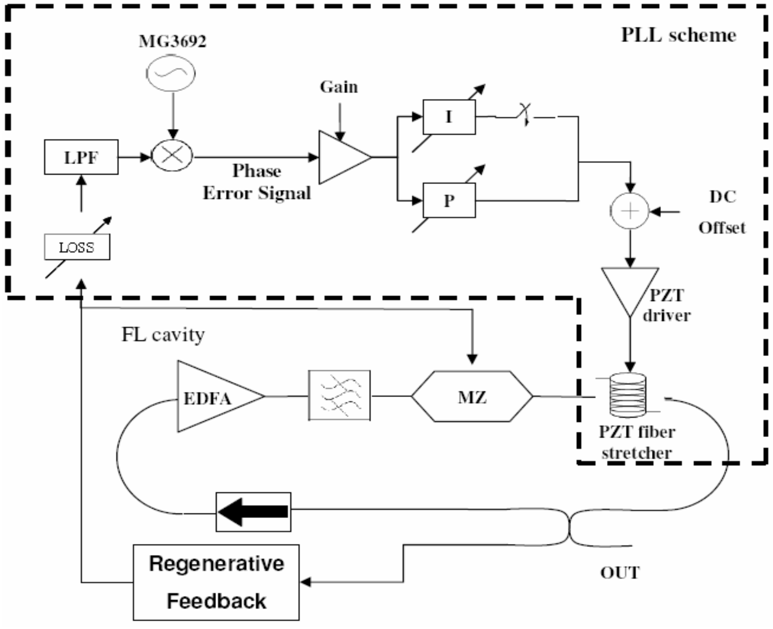


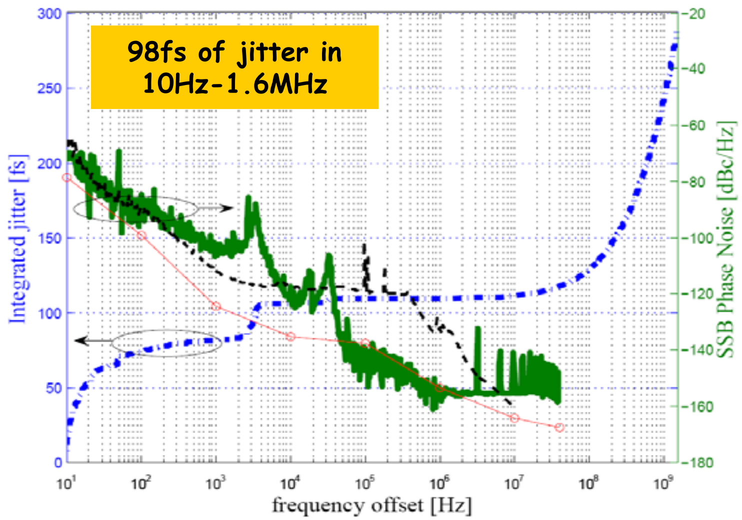
- **All negative dispersion cavity**
- **Higher repetition rates possible due to shorter fiber length required**
- **Pulse duration: ~150-200 fs**
- **Phase noise similar to stretched-pulse**
- **Good amplitude noise**



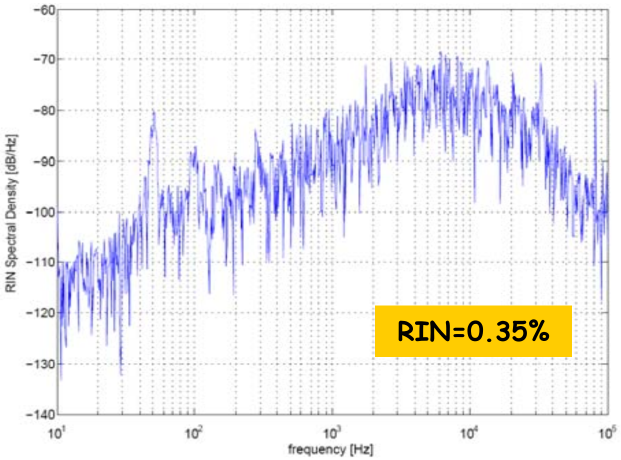
Cortesy of Jeff Chen, MIT

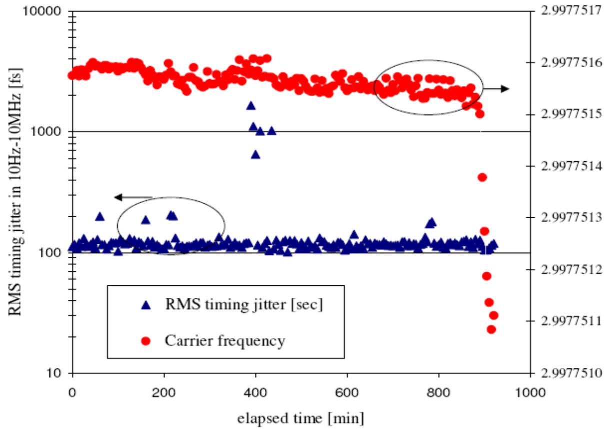
Harmonically mode-locked fiber lasers





Left axes: integrated RMS timing jitter up to 1.5GHz (blue). Right axes: SSB phase noise of the HML laser (green) and the reference MO (black). Interpolated SSA phase noise floor (red).



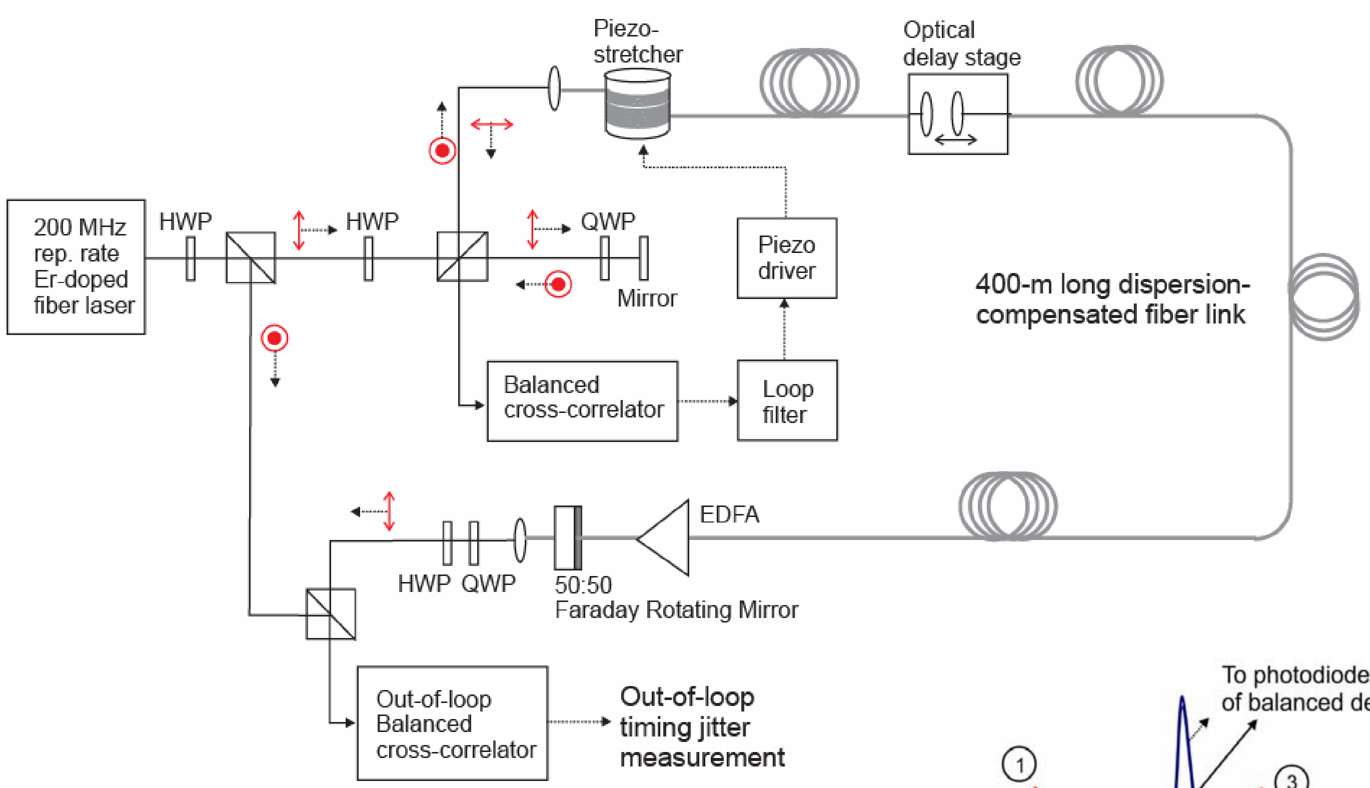


- **GHz repetition rate through regenerative mode-locking**
- **Phase noise ~ 200 fs 1 kHz..1.5 GHz**
- **RIN: 0.35 % 1 Hz..100 kHz**

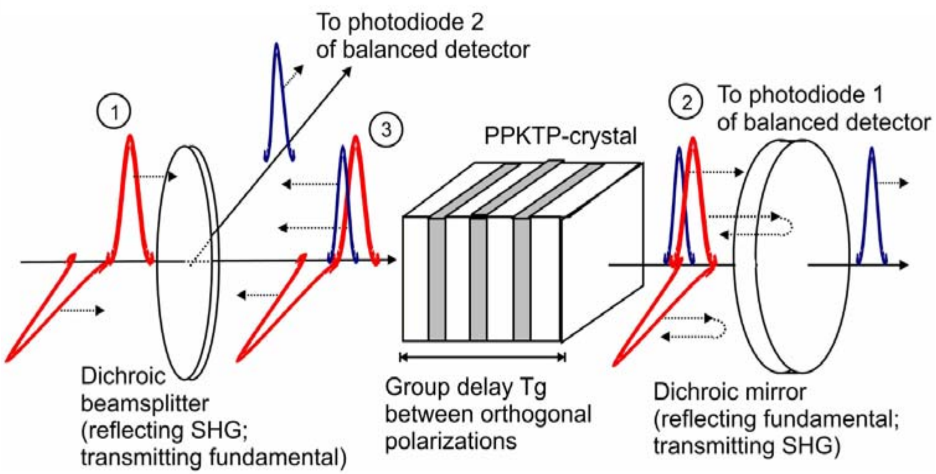
See WEPC22

Courtesy L. Banchi, Elettra

Fiber link stabilization

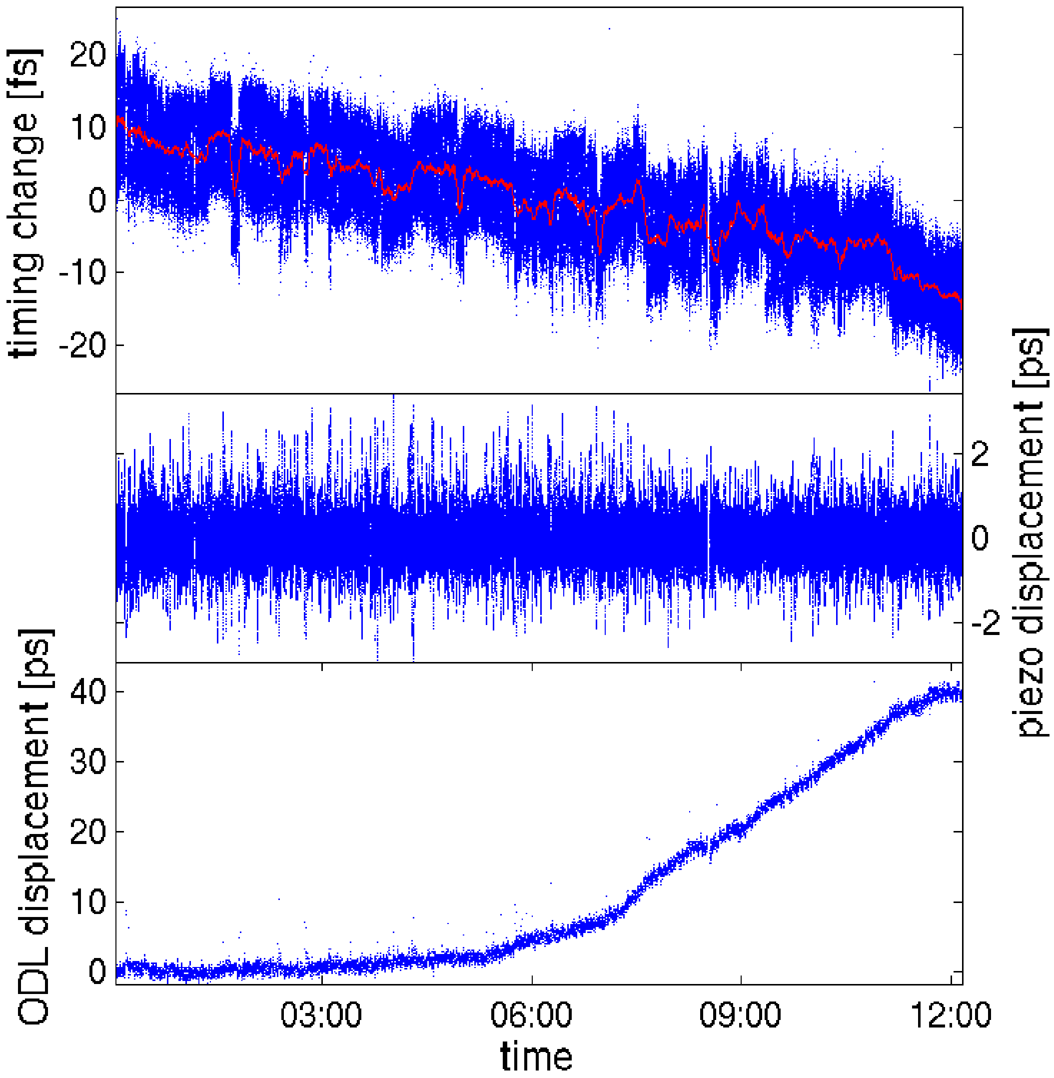


- Type II sum frequency generation makes scheme background free
- Balanced detectors dramatically reduce drift susceptibility



Courtesy F. Loehl, DESY

Fiber link stabilization

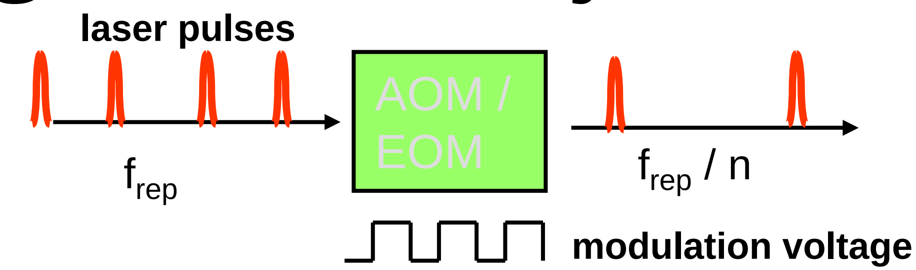


Courtesy F. Loehl, DESY

- **400 meter stabilized test link in Hall 1 at DESY**
- **Jitter 7.5 fs rms during 12 hours**
- **Additional 25 fs rms drift during that time**

Signal recovery

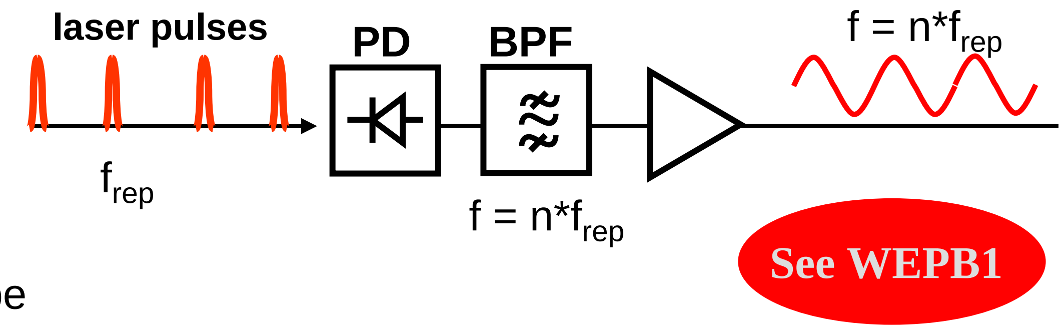
Optical division of distributed frequency



- Essentially arbitrary gating possible
- but: speed and extinction ratio of modulators is limited
- GHz repetition rate lasers are very difficult to gate optically

Direct conversion with PD

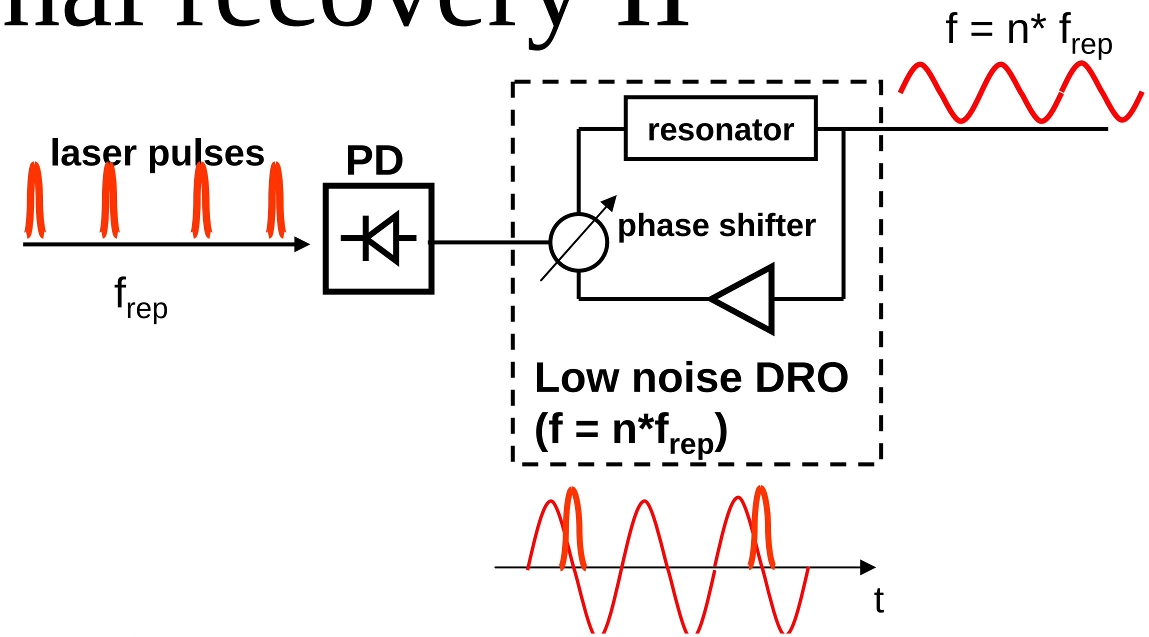
– temperature drifts
– AM to PM conversion*
– noise limitation due to low power in spectral line of PD output
– still 10 fs high frequency jitter can be obtained



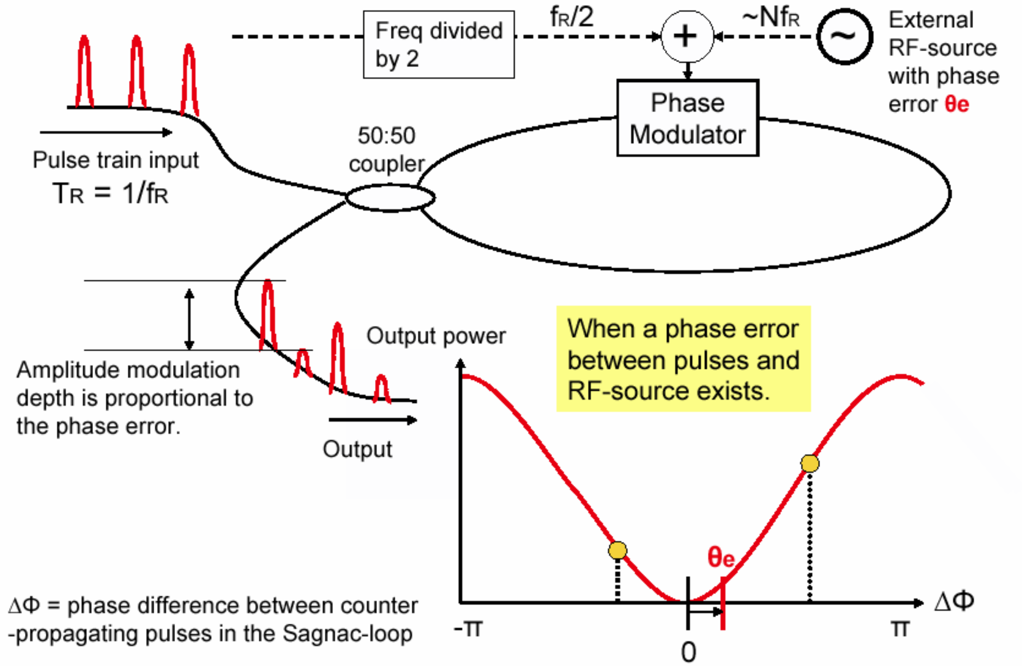
(*) typical AM to PM conversion: 1-10ps/mW

Signal recovery II

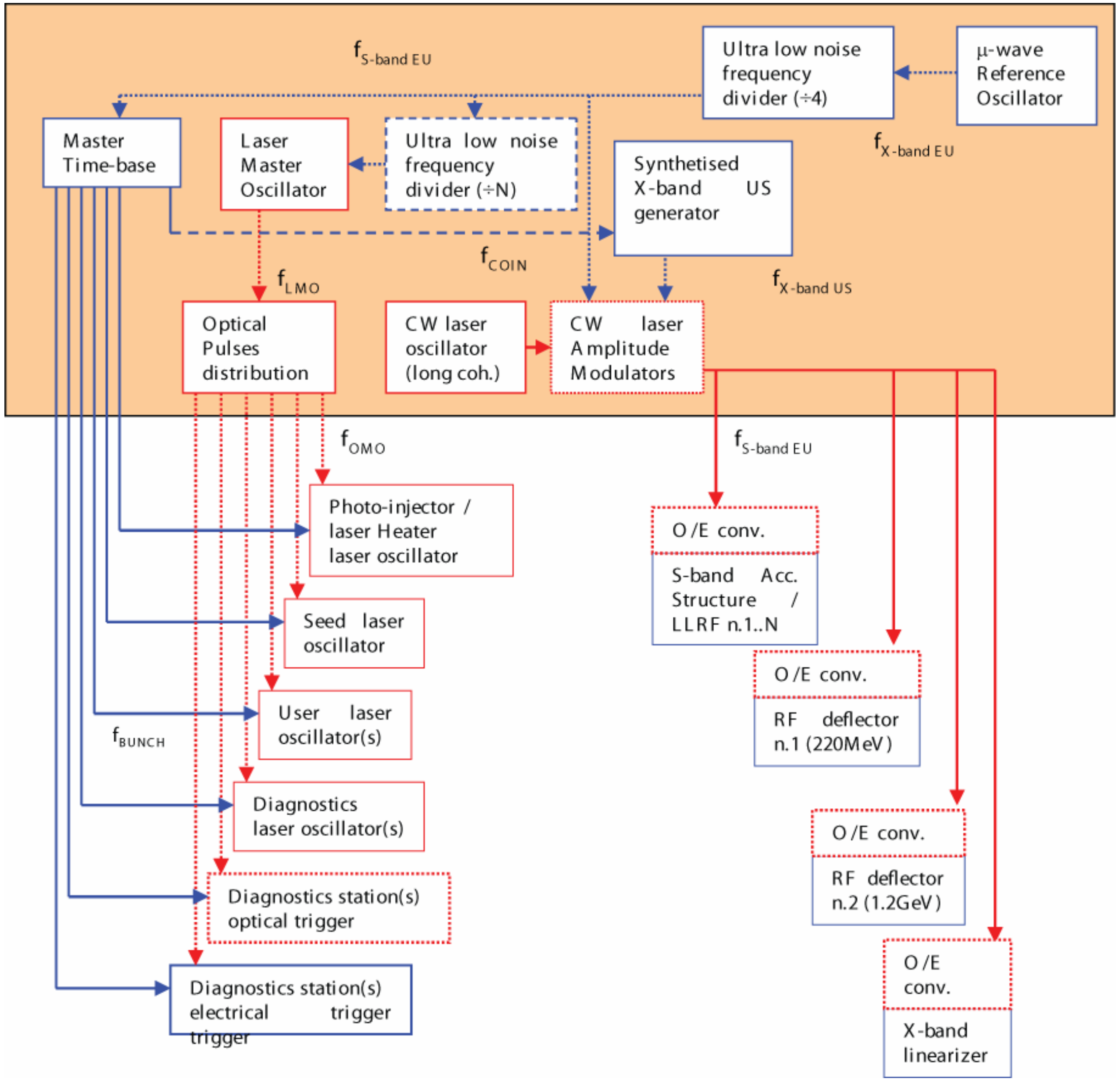
Injection Locking
– temperature drifts of PD
– AM to PM conversion of PD*
+ DRO determines high frequency noise
+ entire photo detector signal used



Sagnac loop
– complex system
– expensive
+ virtually drift free
+ balanced detection, so AM/PM no issue



Concept for FERMI Hybrid System



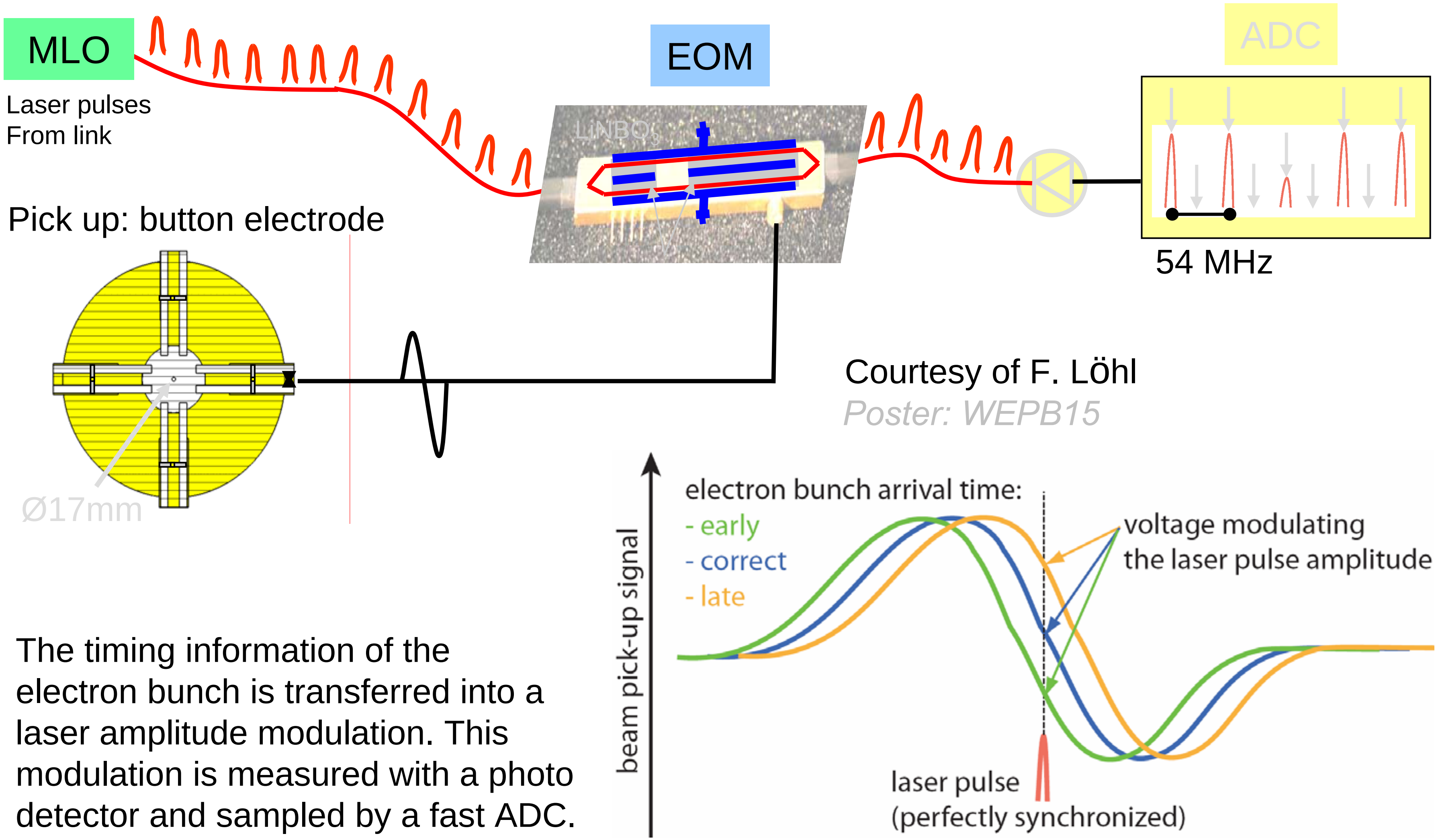
- **frequency domain stabilization and cw signal transmission for RF stations**
- **time domain stabilization and distribution of optical pulses for locking lasers, diagnostics etc.**
- **Allowable timing line jitter 50-120 fs for RF cavities**
- **Seed and experimental laser ~70 fs**
- **Diagnostics ~70 fs**

Courtesy M.. Ferianis, Trieste

Overview

- Why sub-ps Synchronization
  - Where does jitter in an FEL-based machine come from?
  - How do we measure it?
  - How and to what level can we get rid of it?
- Present day concepts and state of development of optical synchronization systems
  - Time domain vs. frequency domain techniques
- Measurement techniques based on optical synchronization systems
  - EO techniques, optical replica synthesizer, beam arrival time monitor

Bunch Arrival Time Monitor (BAM)

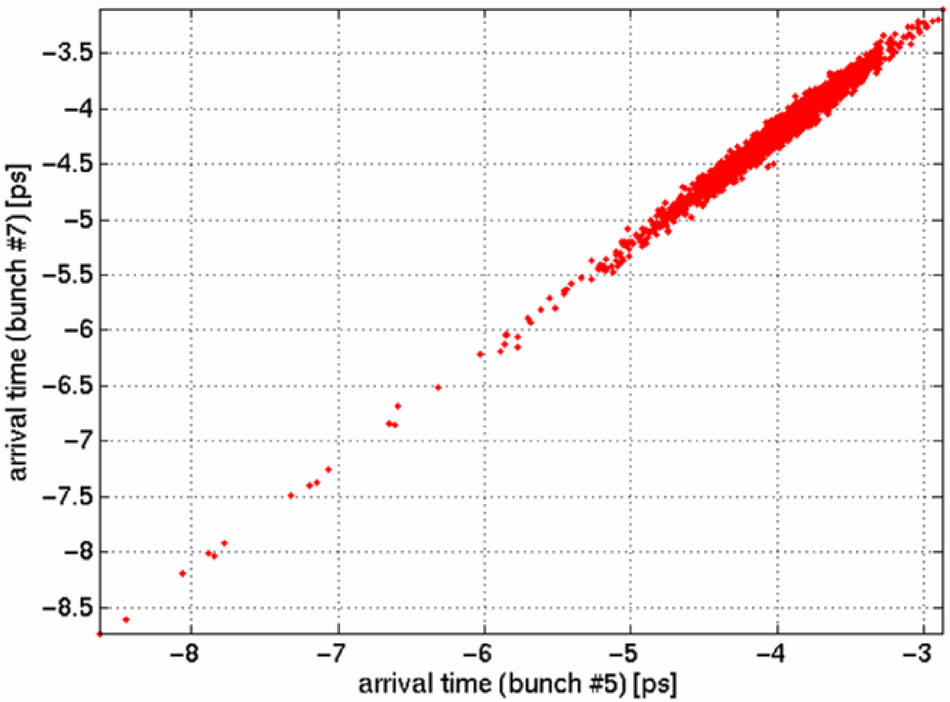


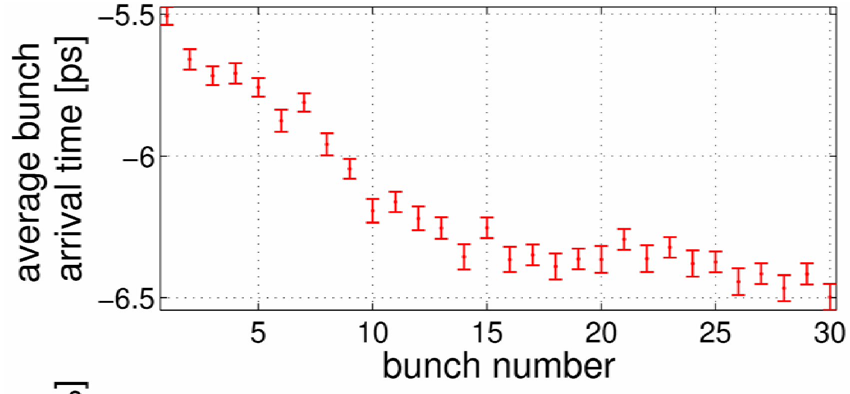
Courtesy of F. Löhl

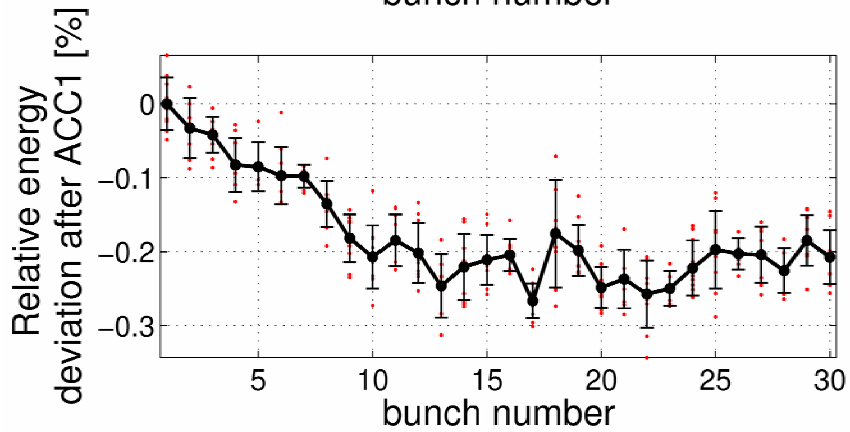
Poster: WEPB15

The timing information of the electron bunch is transferred into a laser amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

Bunch arrival time monitor (BAM)







Jitter between two adjacent bunches: ~ **40-50 fs**

→ Timing resolution with respect to reference laser: **< 30 fs**

•Arrival time measurement for all bunches in the bunch train possible!

• Prime candidate for implementation into feedback system

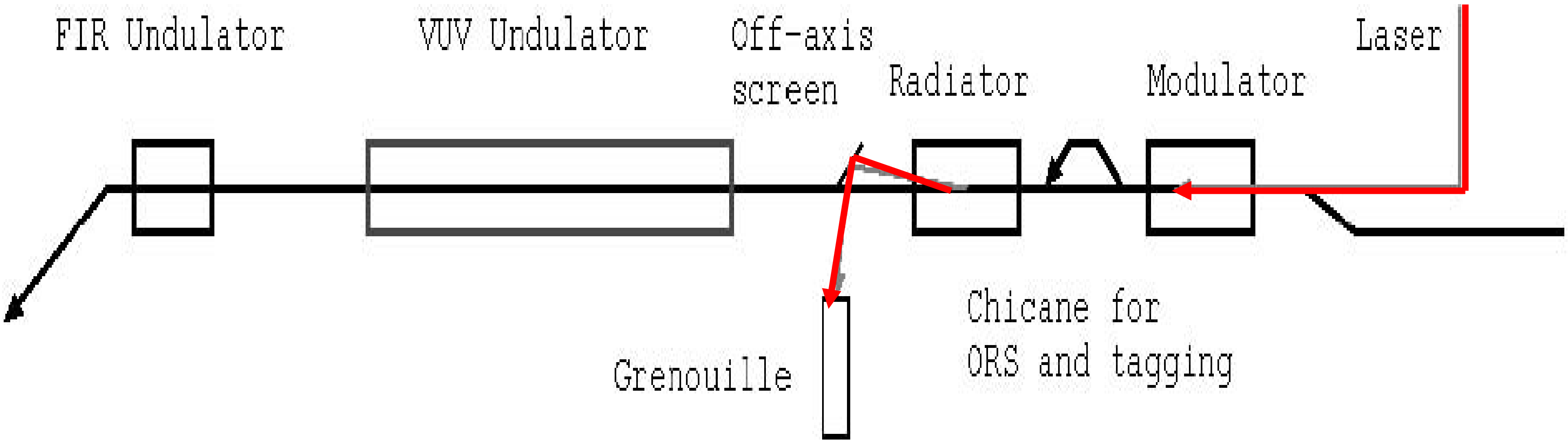
See WEPB15

Courtesy F. Loehl, DESY

Electro-optical measurements

- Various possibilities, all based on induced polarization change of short laser pulse in an electro-optic crystal by electric field of electron bunch
- All systems require ultra-short pulse laser source tightly locked to machine reference → optical locking techniques extremely beneficial
- Resolution down to ~120 fs has been shown with temporal decoding technique
- No plots and sketches → see talk by Phillips later today.
- Amplified Ti:Sa lasers may be seeded directly with frequency doubled timing system laser pulses

Optical Replica Synthesizer



- Measure the longitudinal bunch profile of the femtosecond long electron bunches (*Saldin, Schneidmiller, Yurkov: NIM A 539 (2005) 499*)
- Energy modulation via ps-long amplified Ti:Sa pulse
- Longitudinal density modulation in chicane
- Coherent emission of light pulse in radiator that mimics the longitudinal shape of the electron bunch (optical replica).

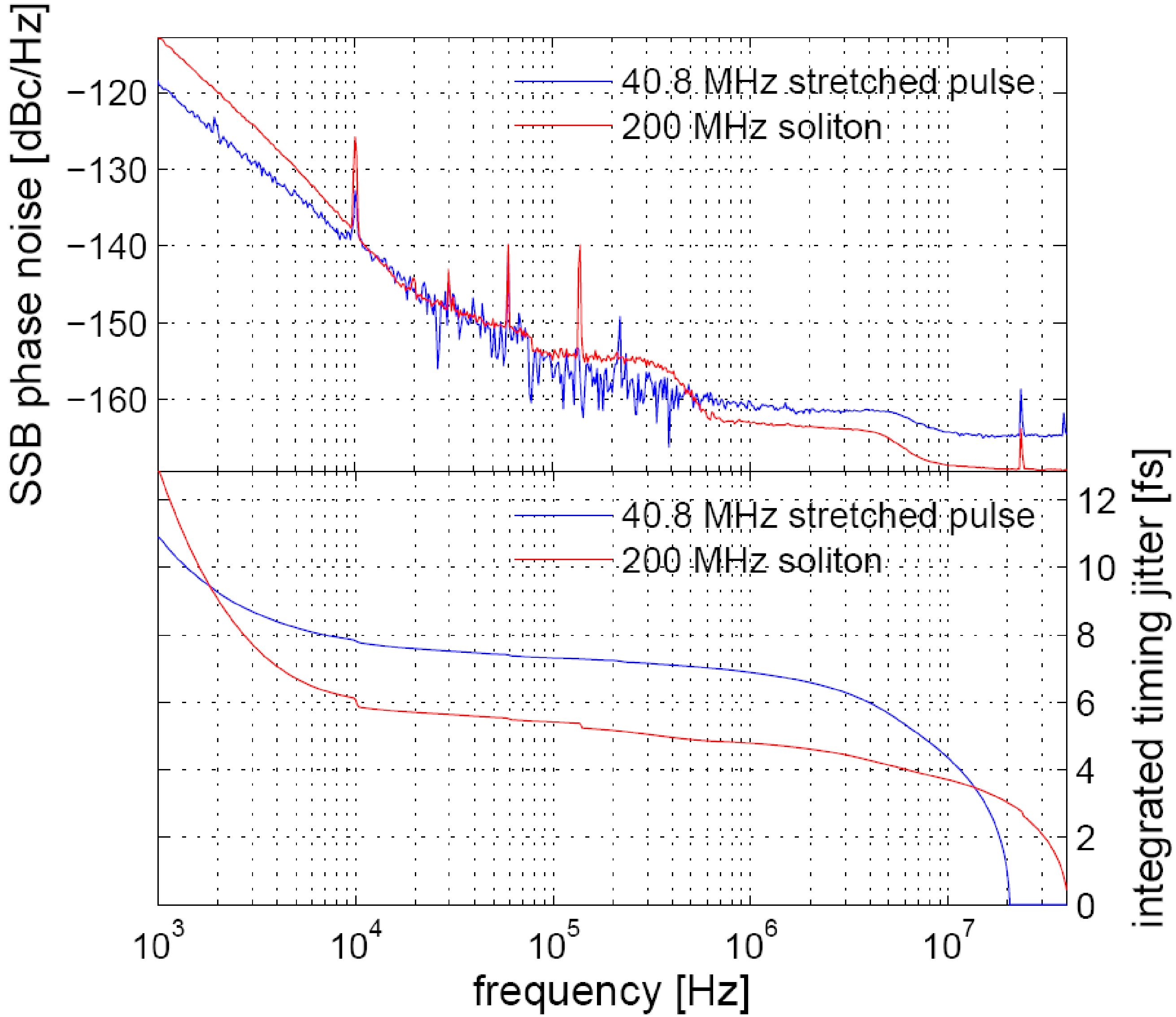
•Seed of Amplifier is frequency doubled EDFL → can be seeded directly from pulsed synchronization system

Courtesy G. Angelova, DESY

Conclusion and outlook

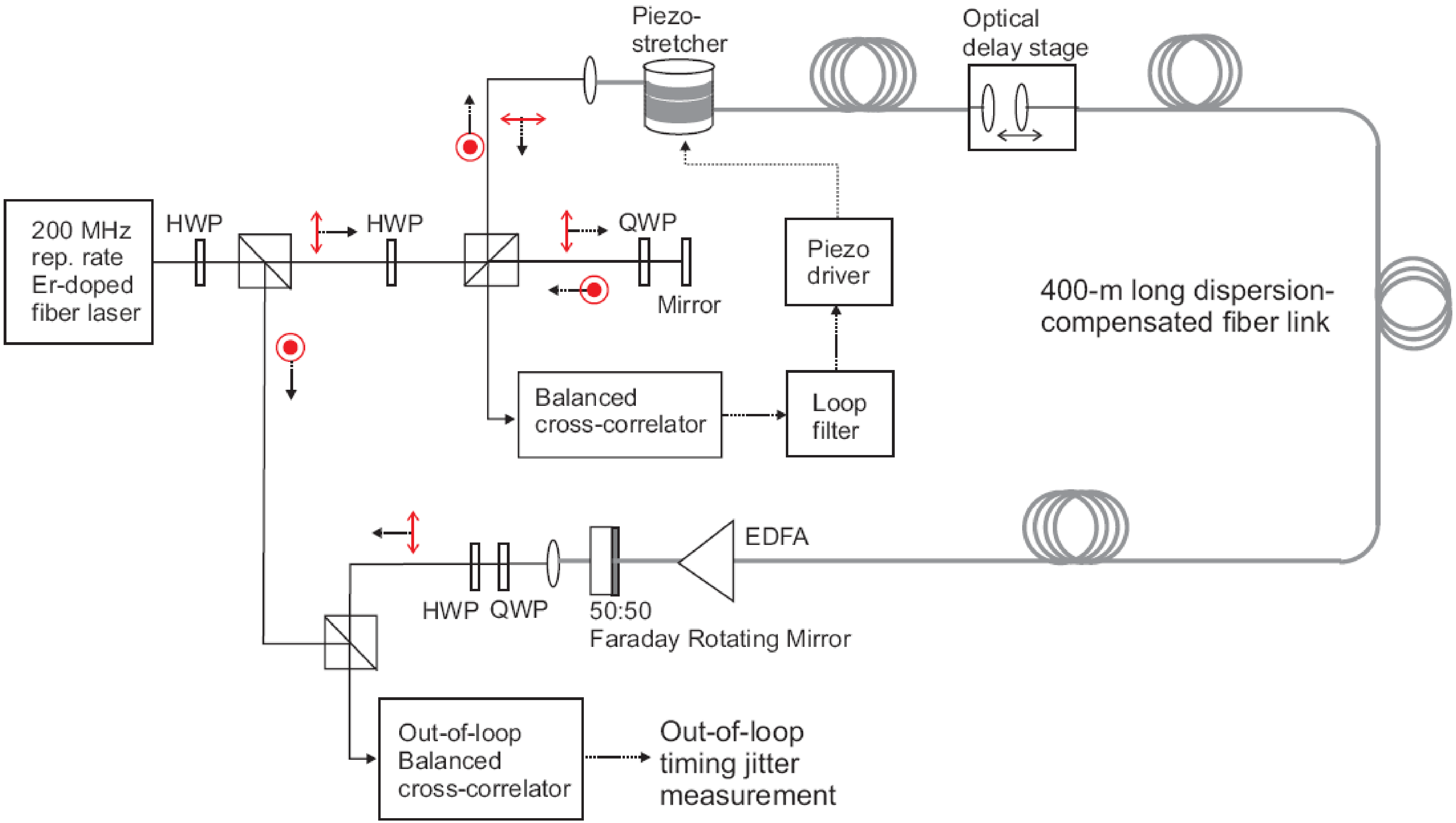
- Increased demands on machine stability require new ways of providing stable timing information
- Together with improved LLRF, road to sub-100 fs electron bunch stability open
- At FLASH 0.03 deg phase stability achieved → XFEL specs almost met
- Optical synchronization systems can deliver required stability of references, both time domain and frequency domain techniques have demonstrated their capabilities
- First systems to be commissioned 2007/2008 (FLASH), 2009 (FERMI)
- Direct arrival time measurements possible using timing system laser pulses with sub-50 fs resolution

Phase noise comparison

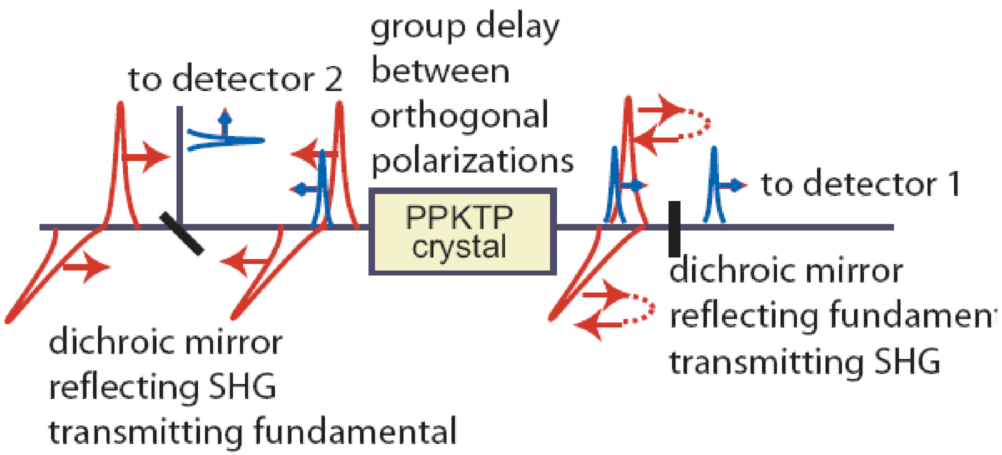


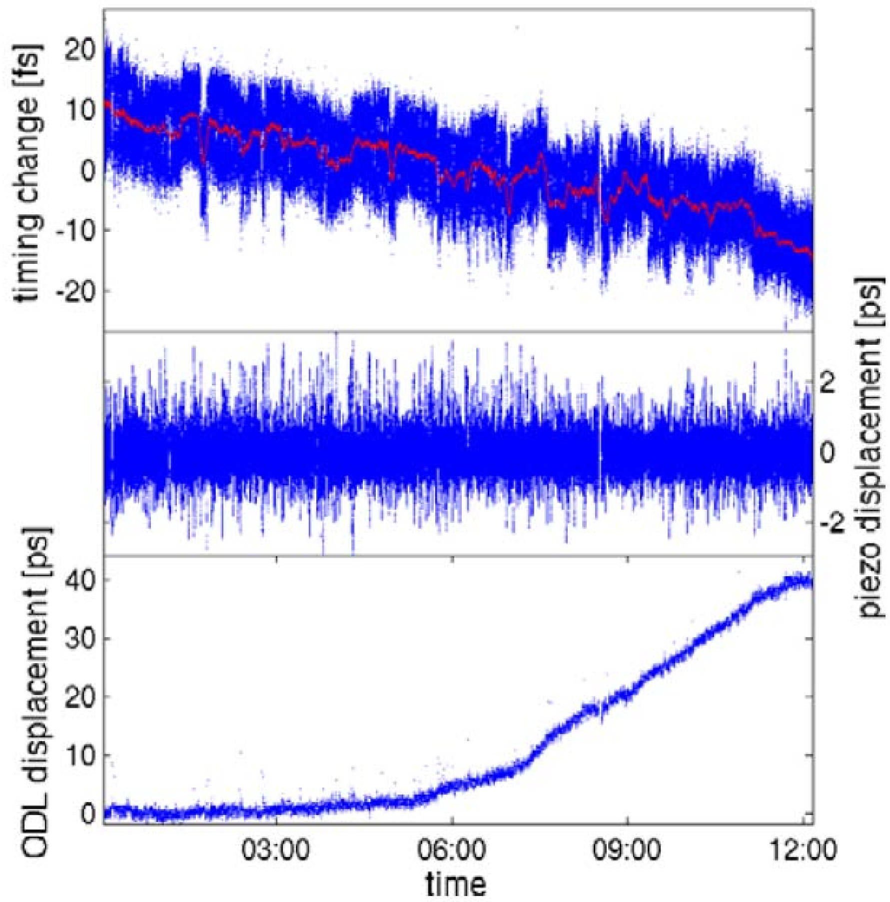
Phase noise comparision between a 40.8MHz stretched-pulse laser and a 200MHz soliton laser.
Top:
single-sideband phase noise measured at the harmonics at 980 MHz (stretched-pulse) and 1.2 GHz (soliton), respectively.
Bottom:
integrated timing jitter starting integration at 20.4MHz (stretched-pulse) and 40MHz (soliton).

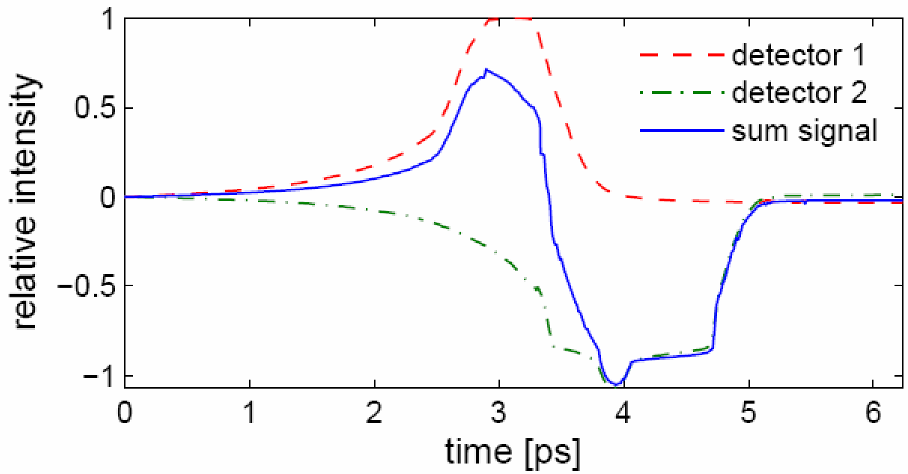
Experimental setup of fiber link



Optical cross correlator and measurment







Development at LBNL

Progress in High Precision Timing and Synchronization at LBNL

Steve Lidia
Center for Beam Physics
Lawrence Berkeley National Laboratory

Acknowledgements

- *John Staples, LBNL*
- *Russell Wilcox, LBNL*
- *Larry Doolittle, LBNL*
- *Alex Ratti, LBNL*
- *Franz Kaertner, MIT*
- *Omar Illday, MIT*
- *Axel Winter, DESY*
- *Paul Emma, SLAC*
- *John Corlett, LBNL*
- *Mario Ferianis, ST*
- *Jun Ye, JILA*
- *David Jones, U of B.C.*
- *Joe Frisch, SLAC*
- *Bill White, SLAC*
- *Ron Akre, SLAC*
- *Patrick Krejcik, SLAC*

Outline

- Motivation
- Stabilized transmission over fibers
  - RF transmission

  Results!
- Synchronizing mode-locked lasers

  Results!

Recent References

- "Synchronizing Lasers Over Fiber by Transmitting Continuous Waves", R.B. Wilcox and J.W. Staples, Proceedings CLEO 2007

- "TIMING DISTRIBUTION IN ACCELERATORS VIA STABILIZED OPTICAL FIBER LINKS", J. Byrd, et. al., Proceedings of LINAC 2006.

- "GENERATION AND DISTRIBUTION OF STABLE TIMING SIGNALS TO SYNCHRONIZE RF AND LASERS AT THE FERMI FEL FACILITY", M. Ferianis, et. al., Proceedings of the 27th International Free Electron Laser Conference.

- "FIBER TRANSMISSION STABILIZATION BY OPTICAL HETERODYNING TECHNIQUES AND SYNCHRONIZATION OF MODE-LOCKED LASERS USING TWO SPECTRAL LINES", J. Staples and R. Wilcox, Proceedings of the 27th International Free Electron Laser Conference.

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 μm (stable to 5%)
- Final energy spread 10^{-4} (stable to 10%)
- Bunch arrival time (stable to 150 fs)

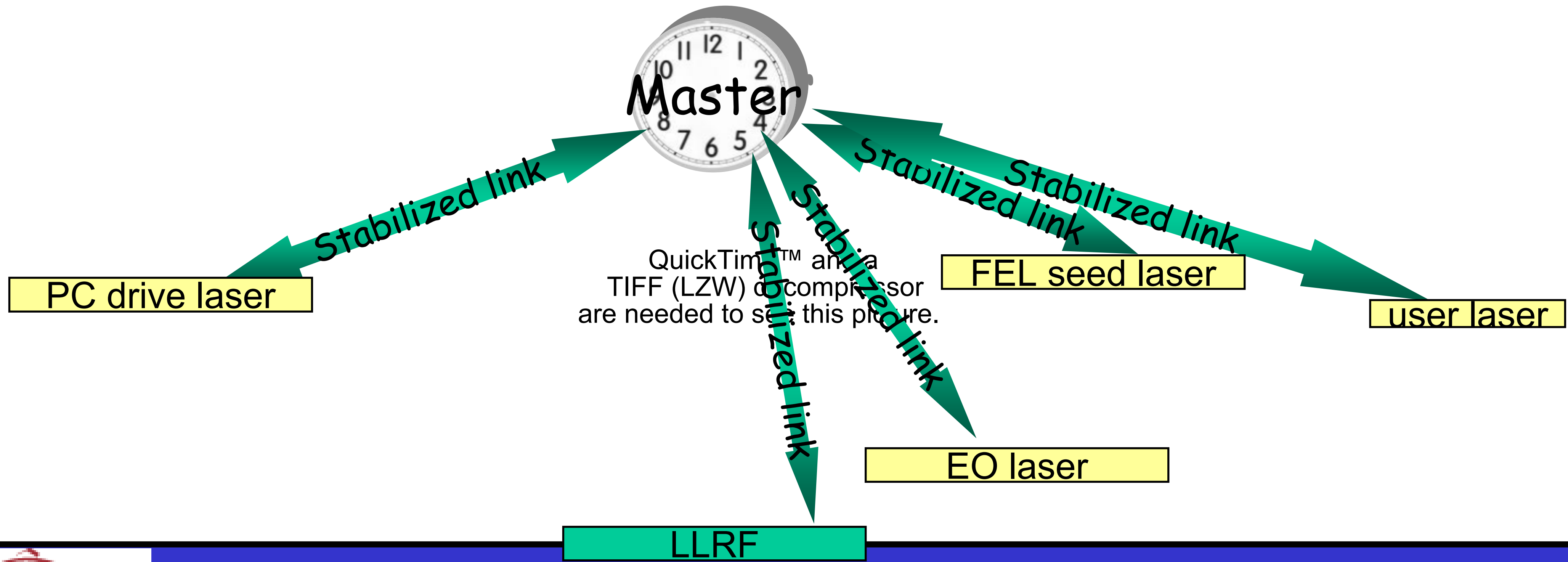
P. Emma

(stability specifications quoted as rms)

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:

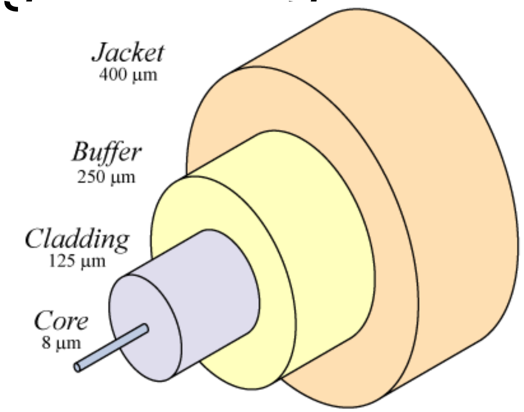
- development of femtosecond comb lasers
- breakthroughs in nonlinear optics
- wide availability of optical components

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

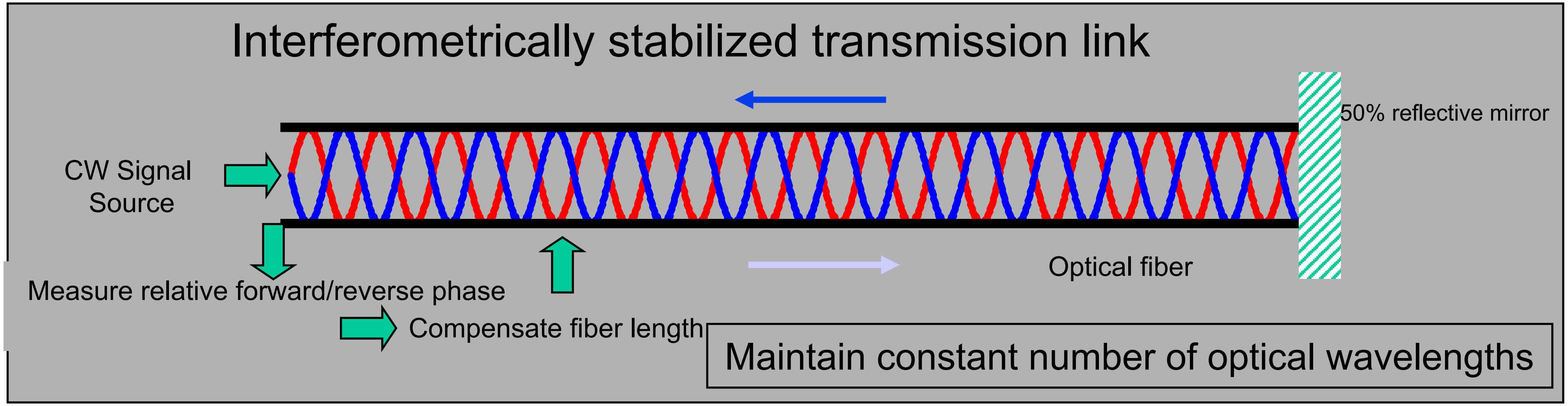
Why fiber transmission?

- 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

Stabilized fiber link



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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

Fiber Stabilizer – Principle of Operation

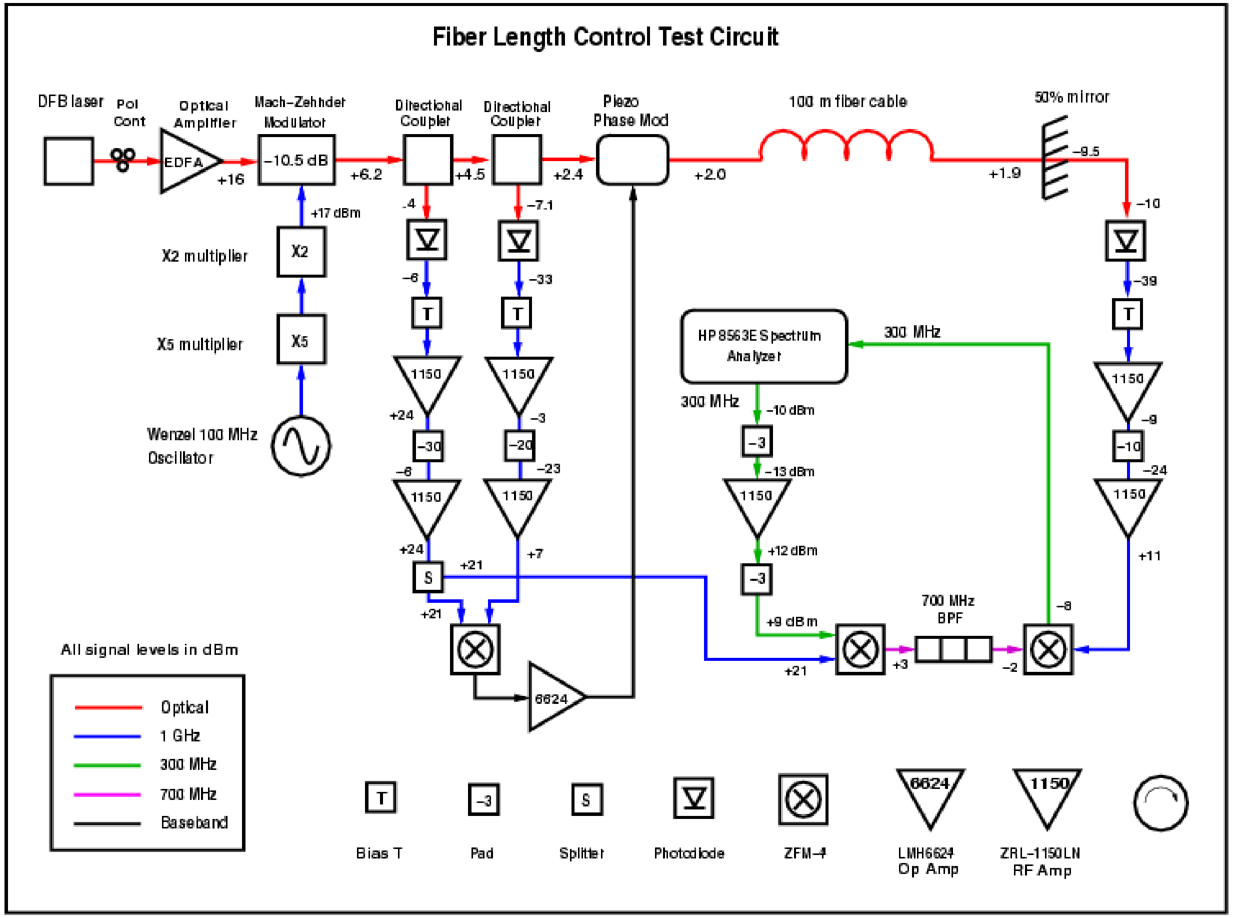
Original, abandoned configuration

A 500 MHz signal is modulated on the CW laser output and reflected from the far end of the fiber with a mirror. The phase of the reflected modulated laser signal is recovered by detecting the return signal with a photodiode and comparing with the 500 MHz modulation drive.

Issues

Phase detector operates at 500 MHz. Small DC offsets are significant at the femtosecond scale.

Intermediate reflections along the fiber interfere with the signal reflected from the far end and produce a phase error.



fiber_length_controller.fig

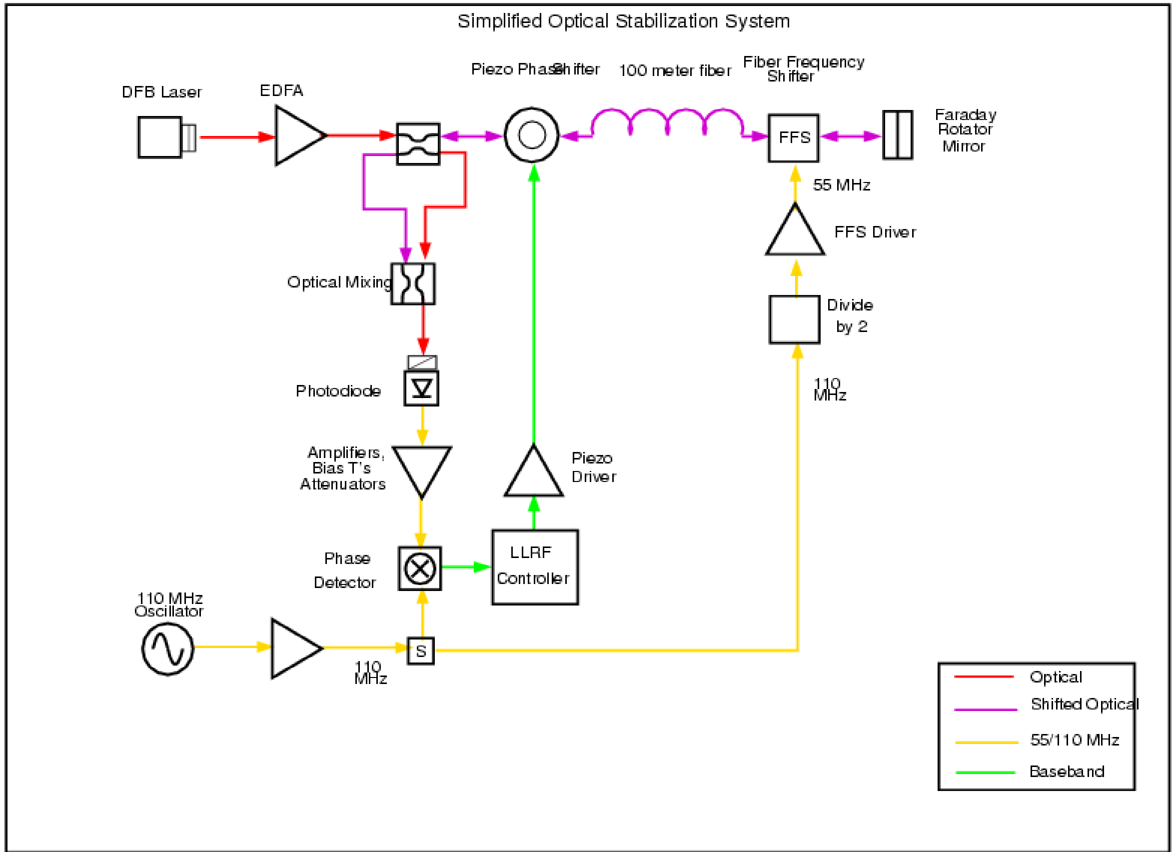
Offset-Carrier Configuration

Send an optical carrier to the far end of the fiber, offset the 200 THz optical carrier phase-coherently by 55+55 MHz (two passes through the AOM) and phase compare the 110 MHz optical carrier with a sample of the unshifted carrier. The system is linear, and the optical beatnote is detected in a photodiode. A piezo phase modulator corrects the fiber length.

Intermediate reflections do not generate a 110 MHz component to the mixing product.

Heterodyning from optical to the RF domain preserves optical phase relationship in the Michelson configuration. *Leverage of $2x10^6$ in the phase detector*.

One degree phase error at 110 MHz is equivalent to 0.018 fsec at optical frequency.

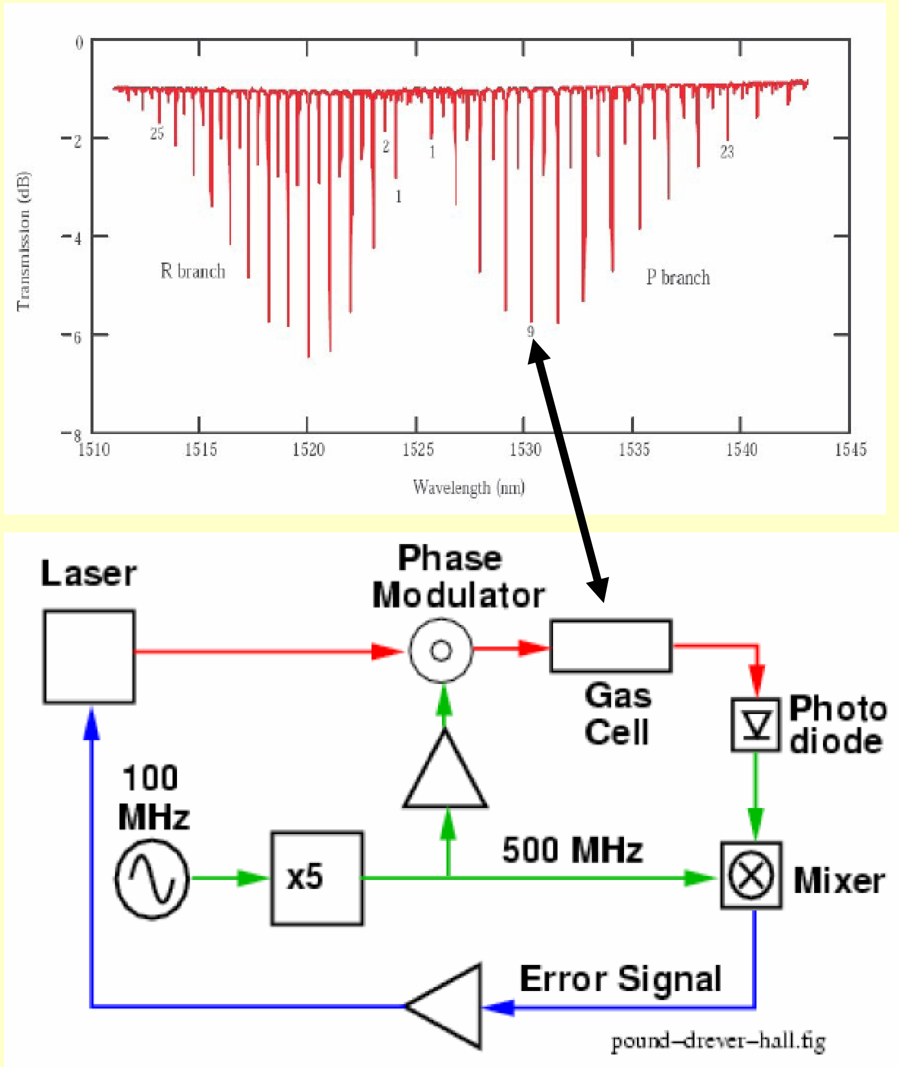


optical_simple.fig

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. lock to atomic reference)



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

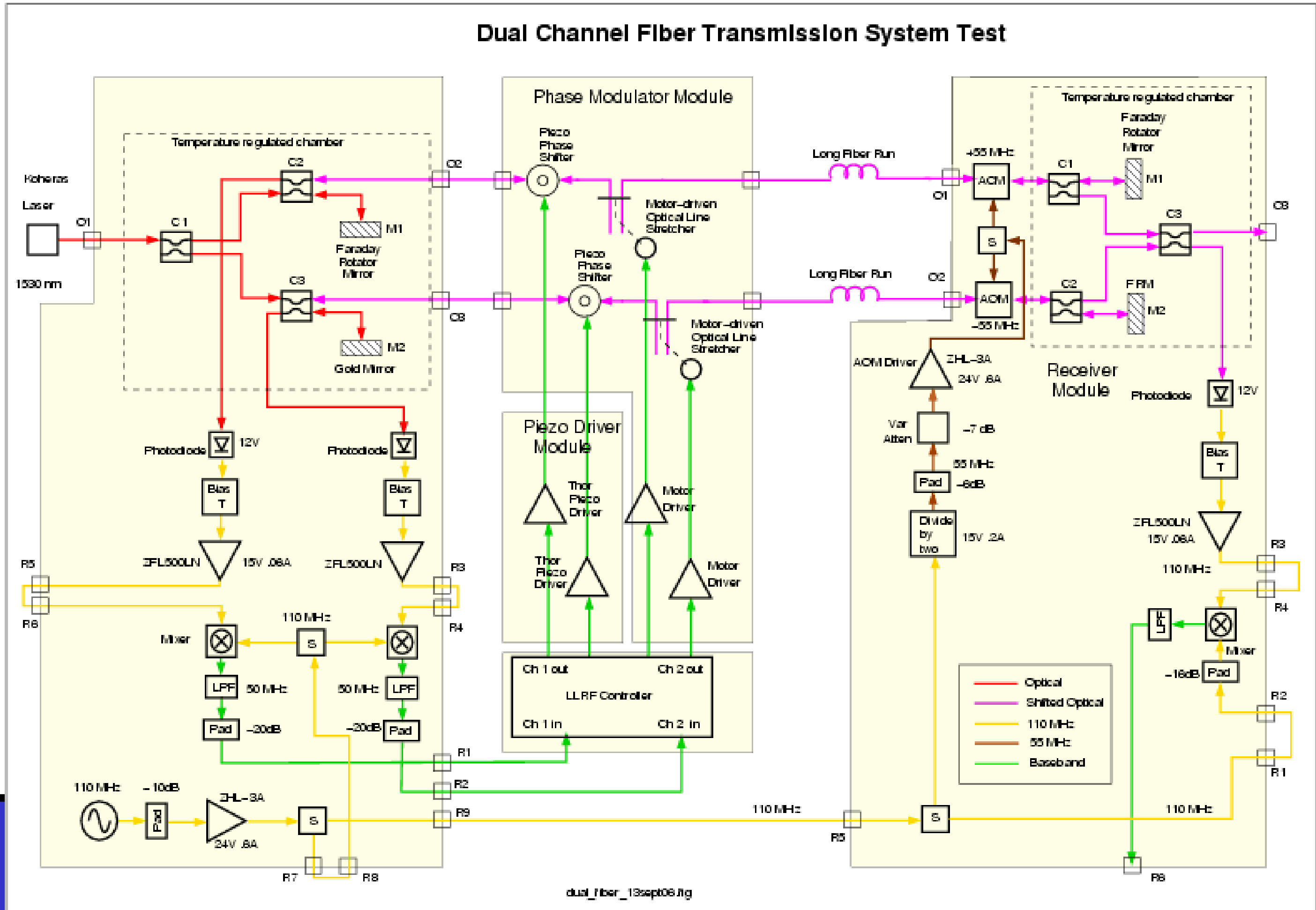
Verifying the Stabilization Scheme

The offset-carrier technique generates an error signal fed back to the piezo phase shifter (and a motor-driven optical delay) to correct changes in fiber phase length. An independent check of the stabilization adds an out-of-loop monitor channel.

As two or more widely-spaced devices are to be synchronized, the demonstration includes two independently stabilized fibers and an out-of-loop monitor, using one molecular absorption line stabilized CW laser.

At the far end, one AOM raises and the other lowers the laser frequency by 55 MHz. The 110 MHz beat note between these carries the phase information of the differential-mode error.

The unequal-length arms in the Michelson configuration also validate the stabilization of the laser wavelength.



New Wide-Band Phase Detector

The stabilization system bandwidth is about 3 kHz, limited by the strong 19 kHz resonance of the piezo phase shifter. The low-frequency gain is over 70 dB (voltage gain of 3000), which is verified by closed-loop perturbation tests.

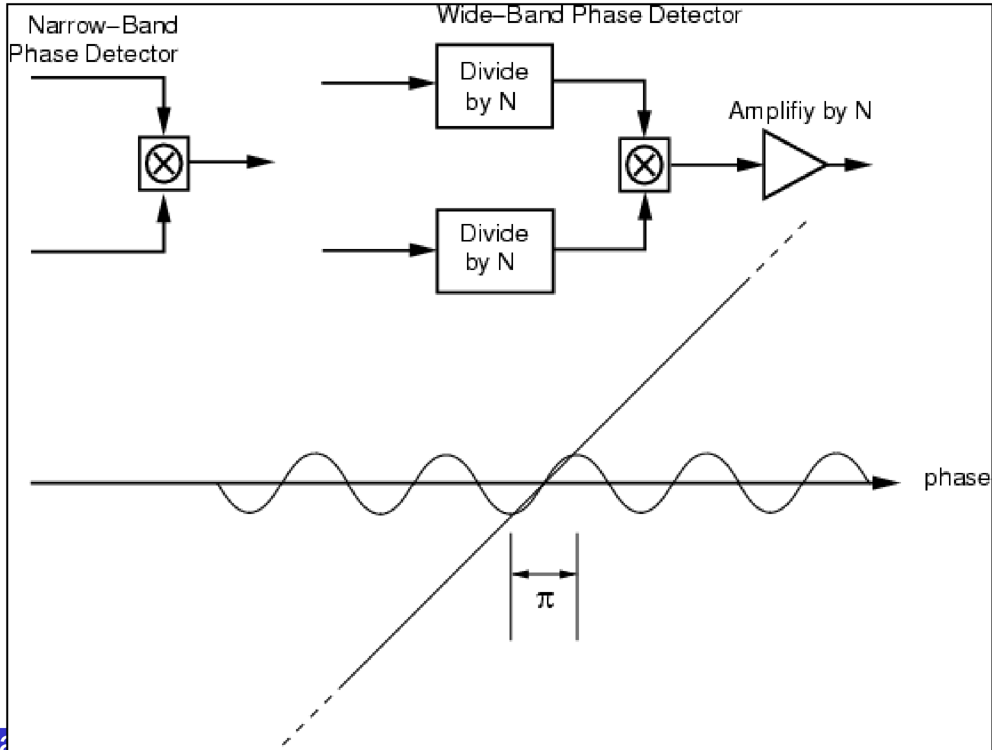
If a phase perturbation occurs faster than 2 fsec in 1 millisecond, it is possible to jump a fringe in the interferometer. Acoustical perturbations are possible, especially if the fiber is in an acoustically noisy environment, such as a klystron gallery.

A significant improvement to the system involved replacing the analog phase detector, which operates between $-\pi/2$ and $\pi/2$, with a digitally enhances one that operates between -32π and 32π.

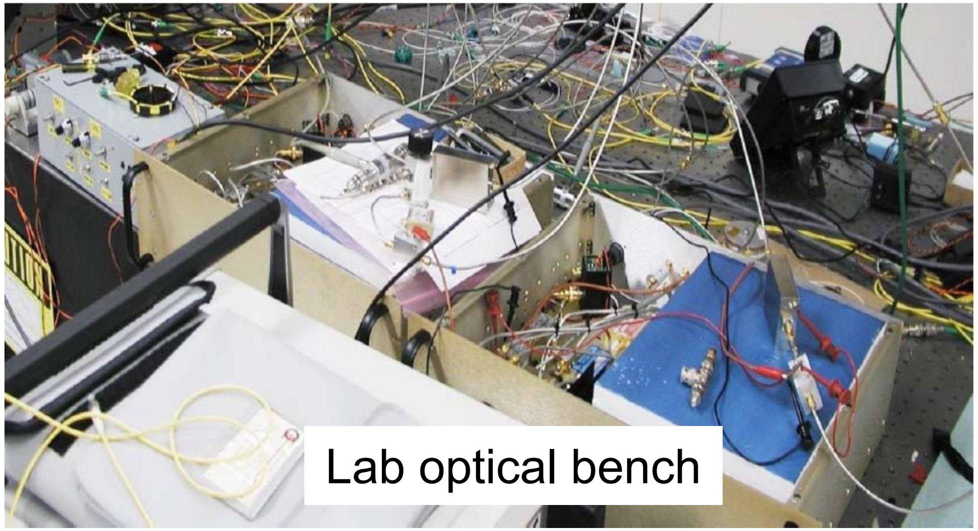
As a bonus, the inputs to the mixer are square waves, which linearizes the mixer output to $-N\pi/2$ to $+N\pi/2$.

This phase detector is simpler than the up-down counter-XOR type typically used and has no DC bias offset and does not jump from max positive to max negative at the end of its range.

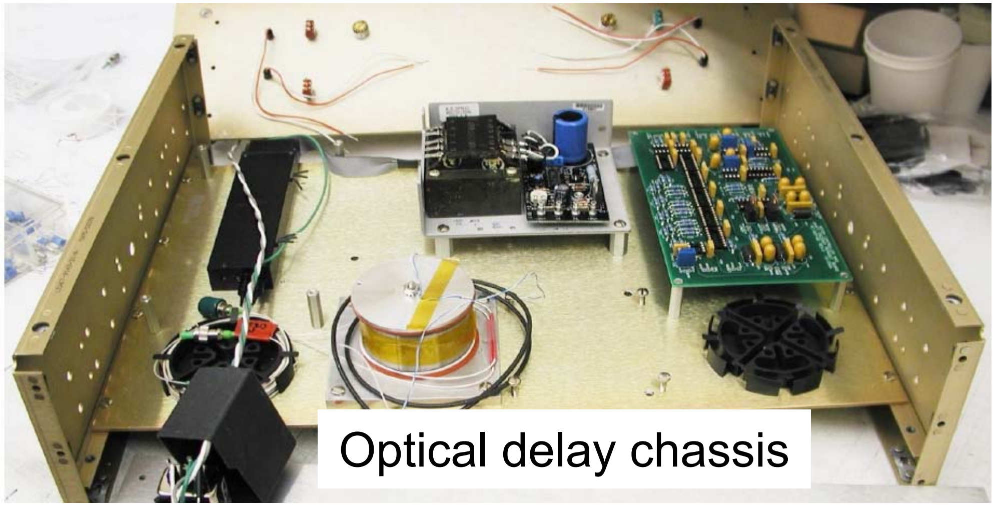
This change has resulted in a system with very robust rejection of acoustic perturbations.



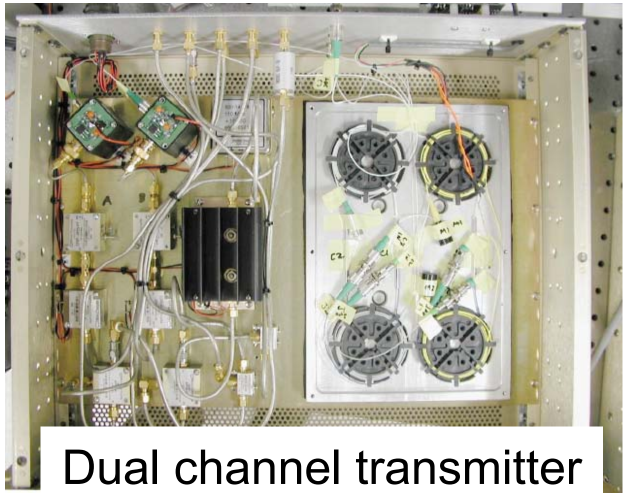
Hardware setup



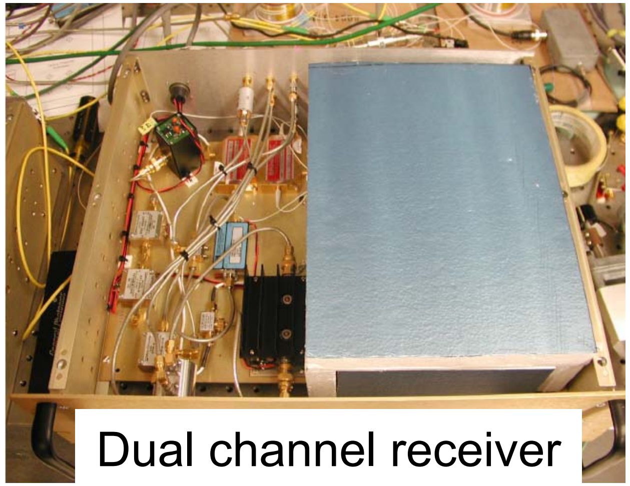
Lab optical bench



Optical delay chassis



Dual channel transmitter

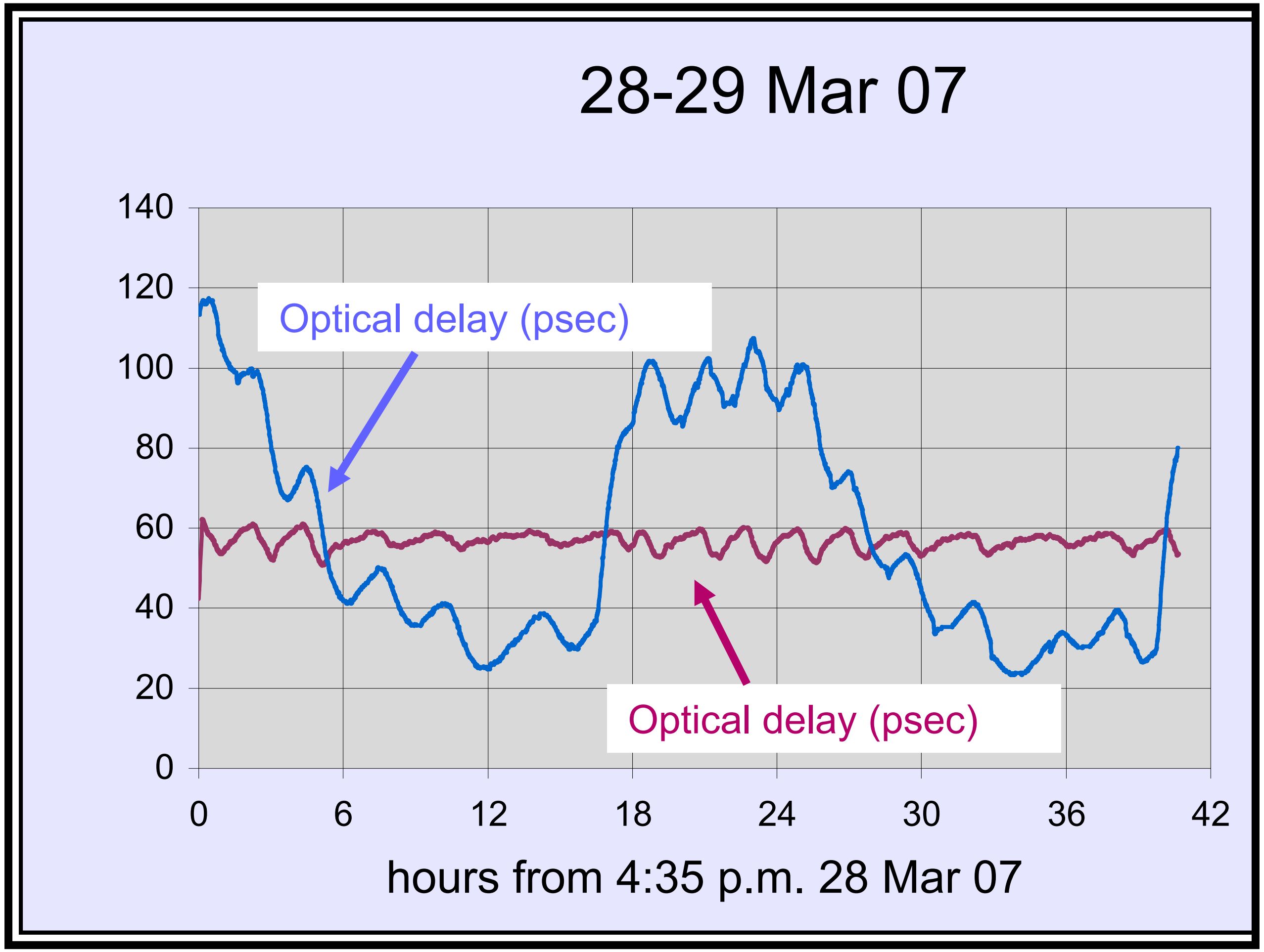


Dual channel receiver

Long link stabilization

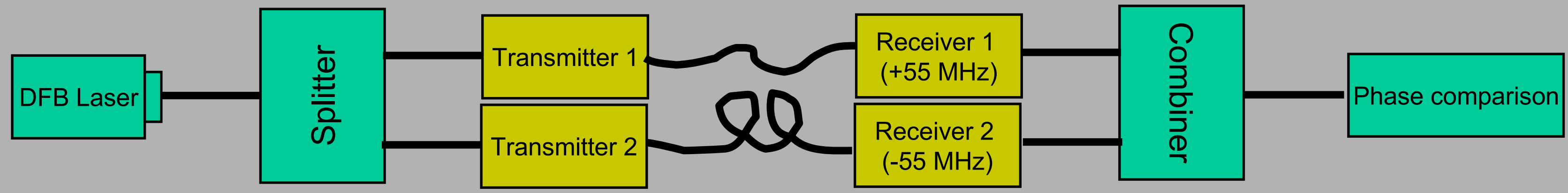
Goal: Test fiber stabilization on fiber outside of lab environment.
Use part of lab's fiber optic communications network.

- •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.

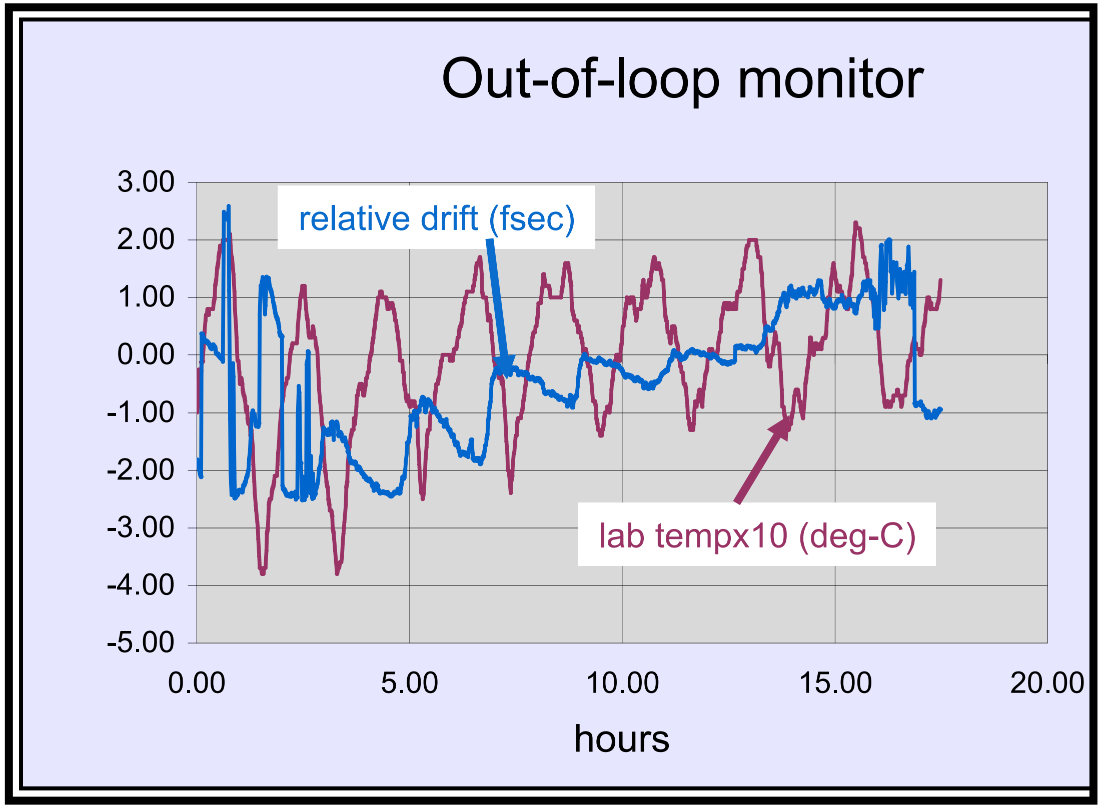
Results:

•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!!!

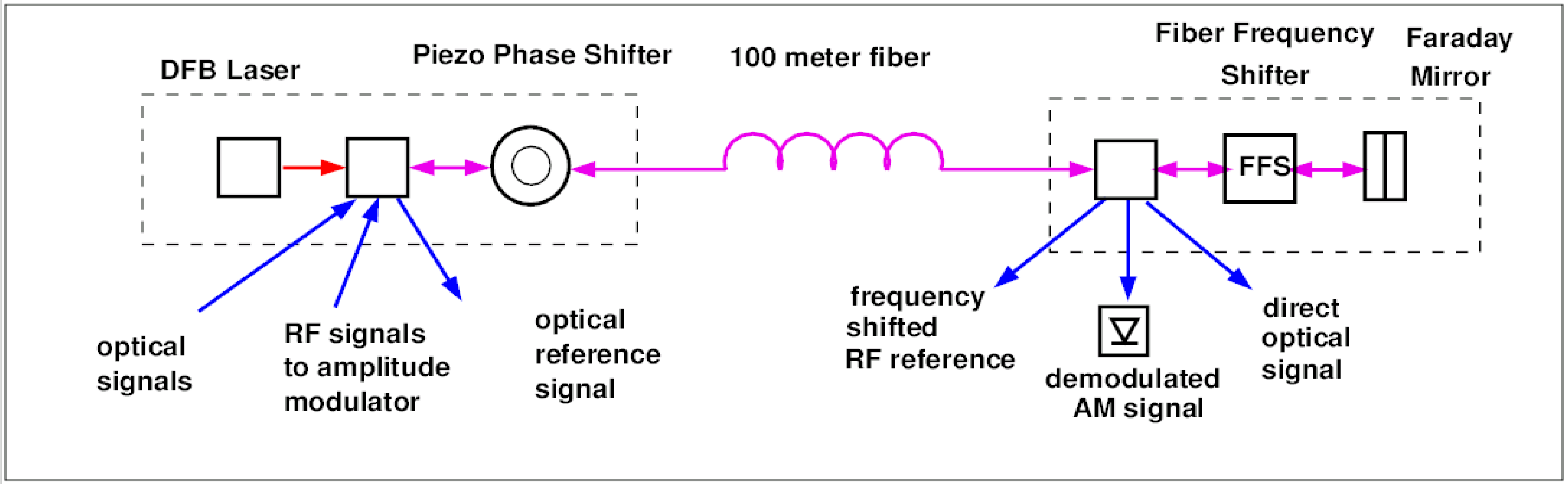
•lab temp variation of ~0.5 deg-C

•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.

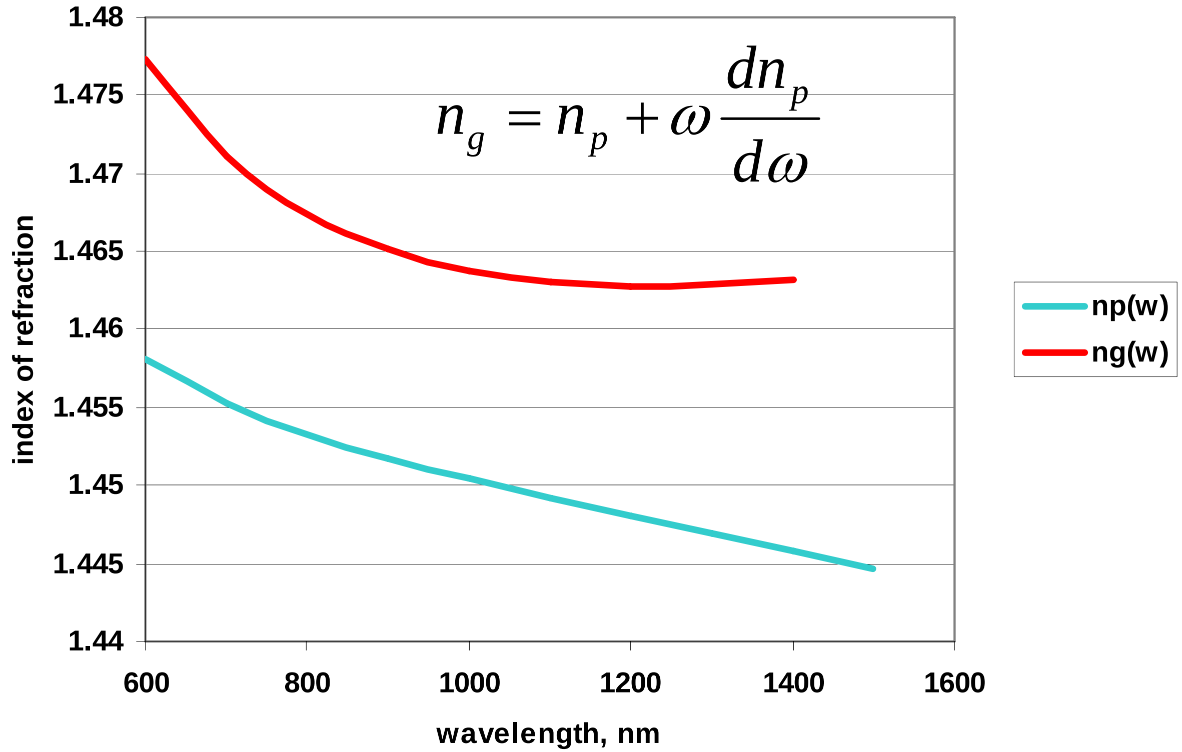
Modulation of CW carrier has signal S/N advantages over pulsed modulation.

Group and Phase Velocity Correction

Interferometric technique stabilizes phase delay at a single frequency . At a fixed T, simply 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.



Phase-Group Velocity Experiment

The stabilization system maintains a constant number of optical wavelengths in the fiber at the fixed frequency of the 1530 nm CW laser.

When transmitting wideband signals, the temperature-dependent optical dispersion will promote changes in group velocity.   We will measure this effect with a two-color measurement using 1530 nm and 1570 nm stabilized lasers.

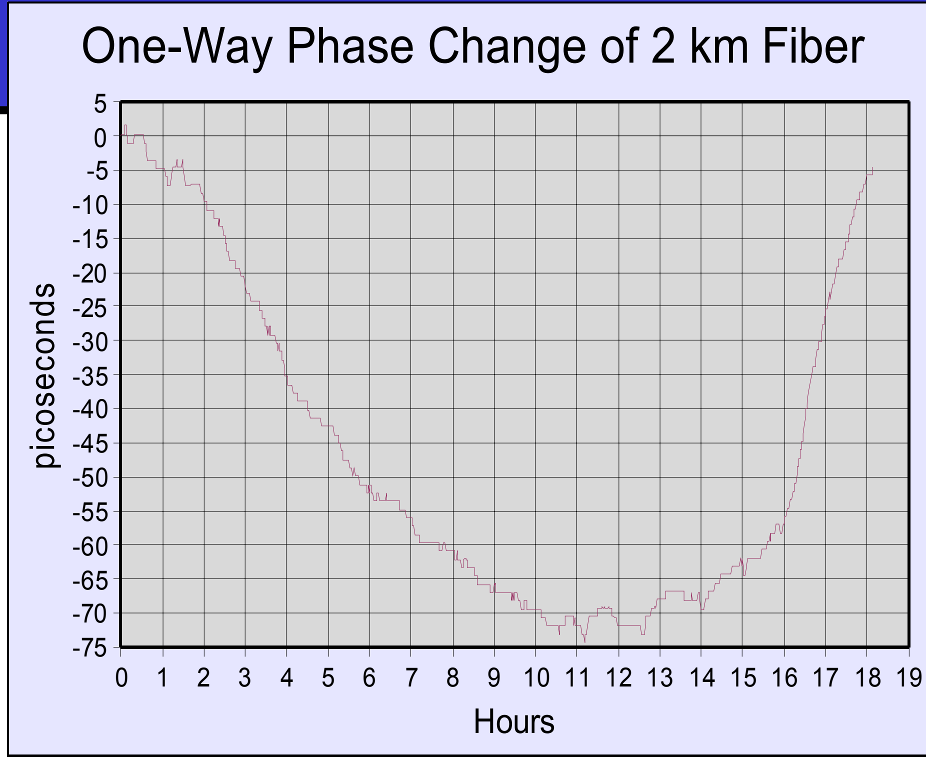
The temperature-controlled fiber will be phase-stabilized at 1530 nm and the phase shift at 1570 nm as a function of temperature will be measured. The first-order temperature effect on the dispersion will then be applied as a correction to the group velocity of signals transmitted by the fiber.

The long-term stabilization of the fiber is excellent, with drift rates less than 1 fsec per hour. The fiber should provide an excellent backbone to carry wideband synchronization and reference signals over kilometer distances.

Other experiments, such as the contribution of the fiber to phase noise of RF signals modulated on the stabilized fiber will be described at a later date.

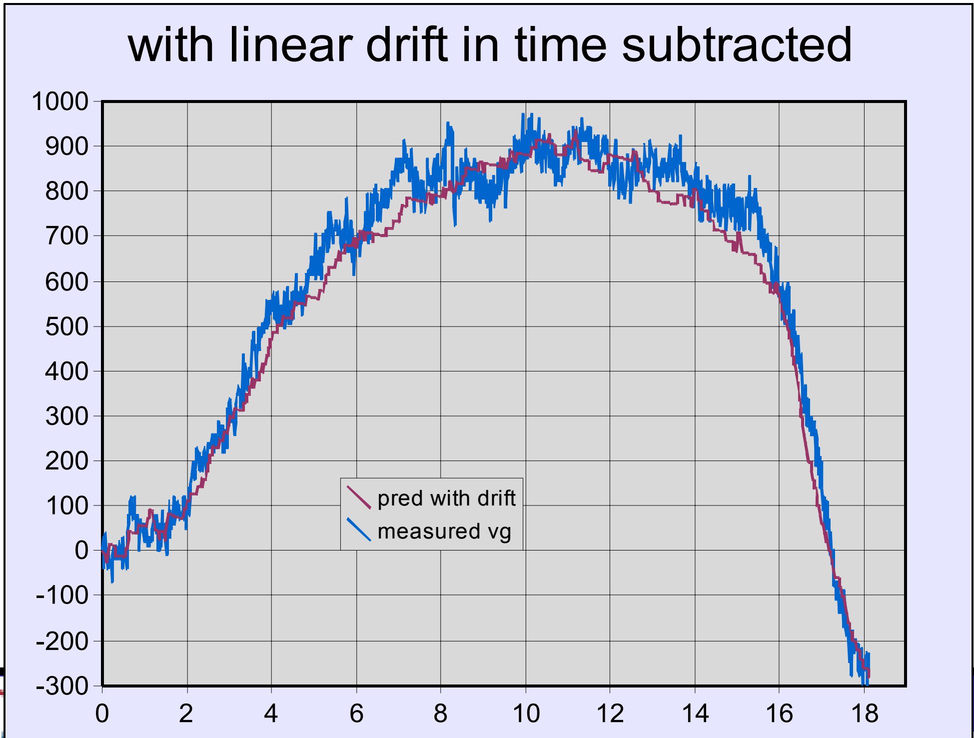
Experiments show that there is no significant contribution (femtosecond-level) from the fiber itself, but the modulation and demodulation process contributes jitter in the low ten's of femtosecond range.

Very Preliminary Results of v_g Experiment



The 2 km fiber run outside the lab is subject to diurnal temperature variation. The phase length is recorded (right plot) and corrected. The 1-way change over an 18 hour interval is 75 psec.

A 2.8 GHz RF carrier is modulated onto the fiber and the group velocity difference is measured. The additional delay that is

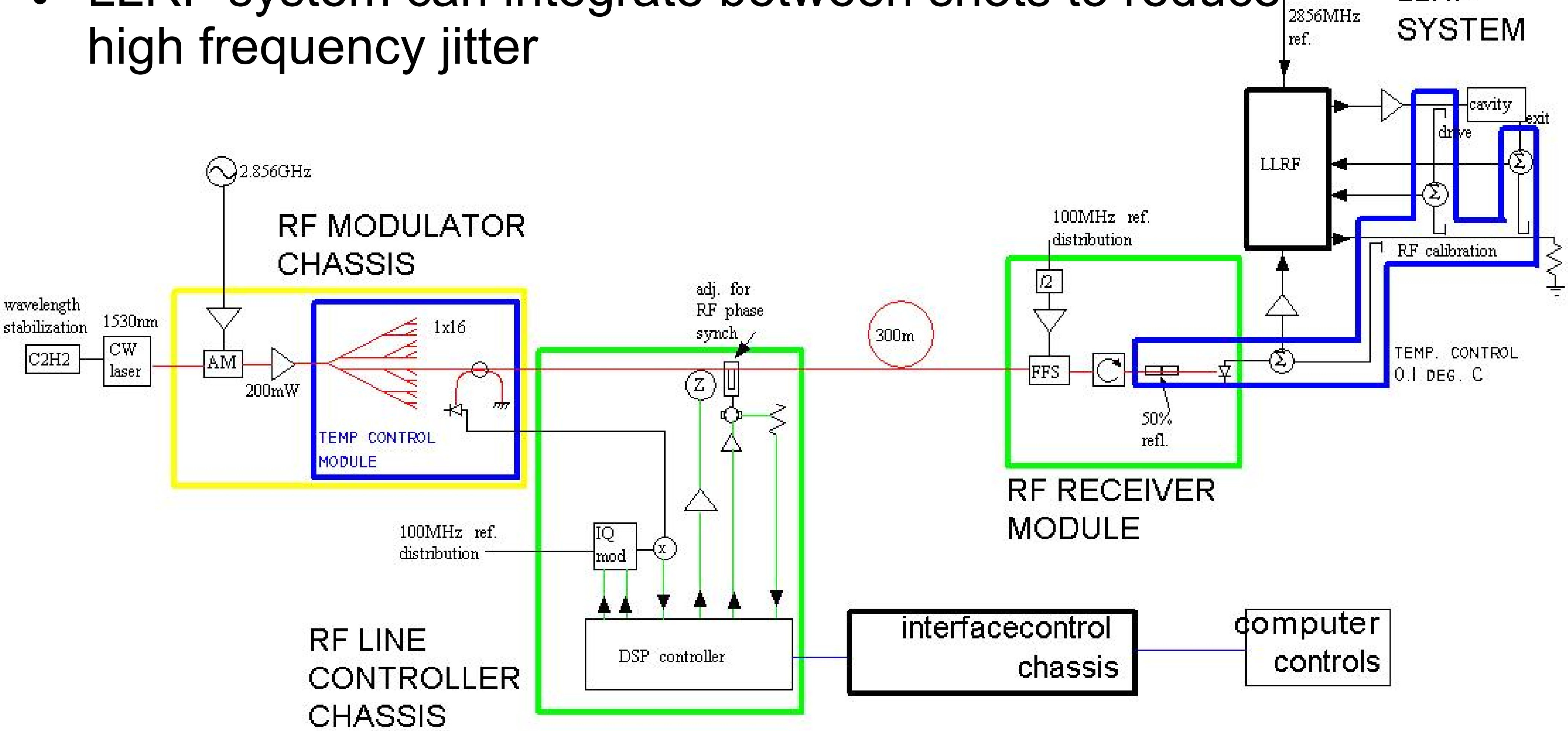


imposed for group velocity correction is 1.55% more than the phase velocity correction. The blue trace is the measured group velocity change with temperature, and the red is the predicted change, based on the phase velocity measurement, in fsec.

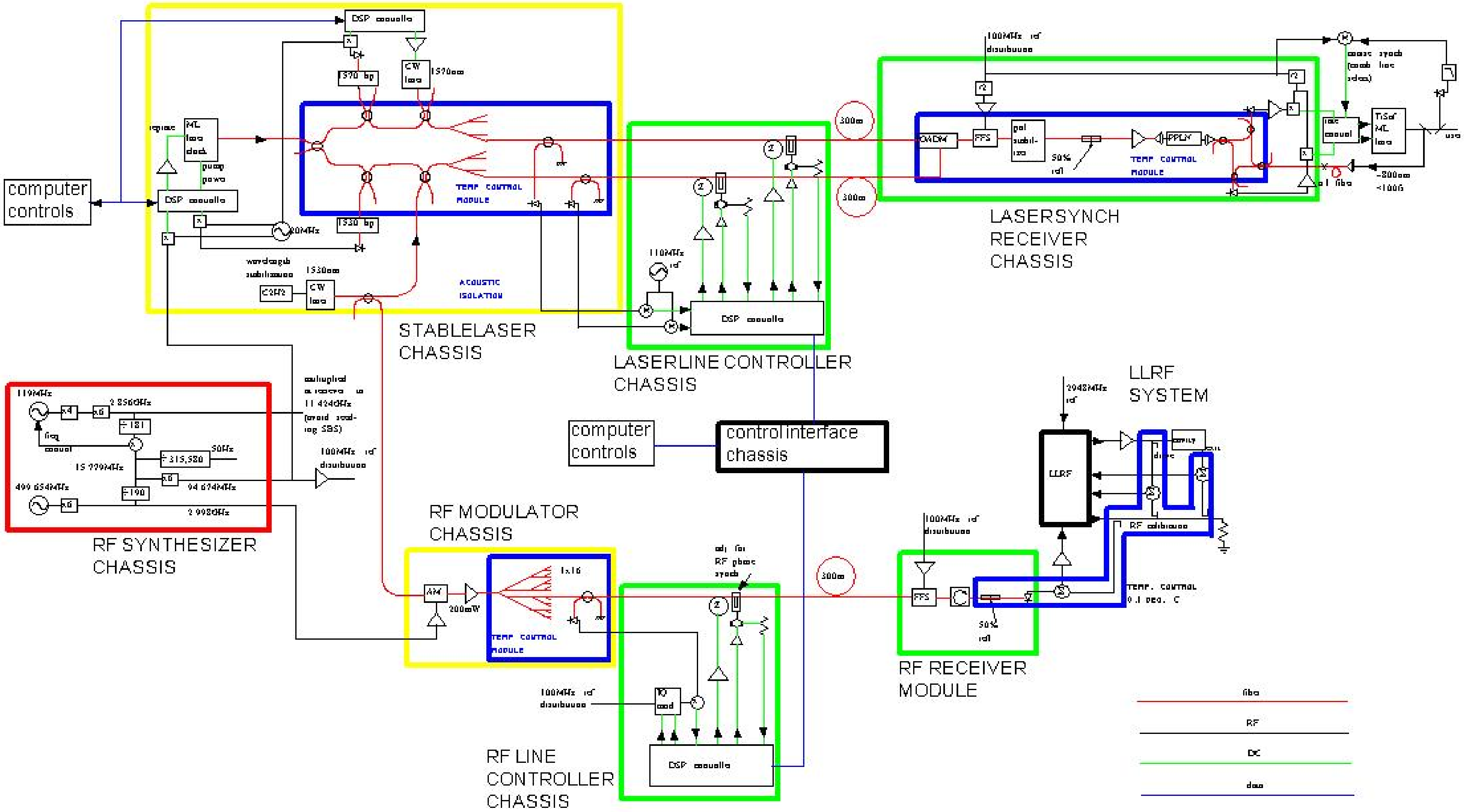
Note that these are the temperature-dependent phase and group delay values. The phase change measures the integrated temperature variation over the entire 2 km fiber link.

RF transmission design

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



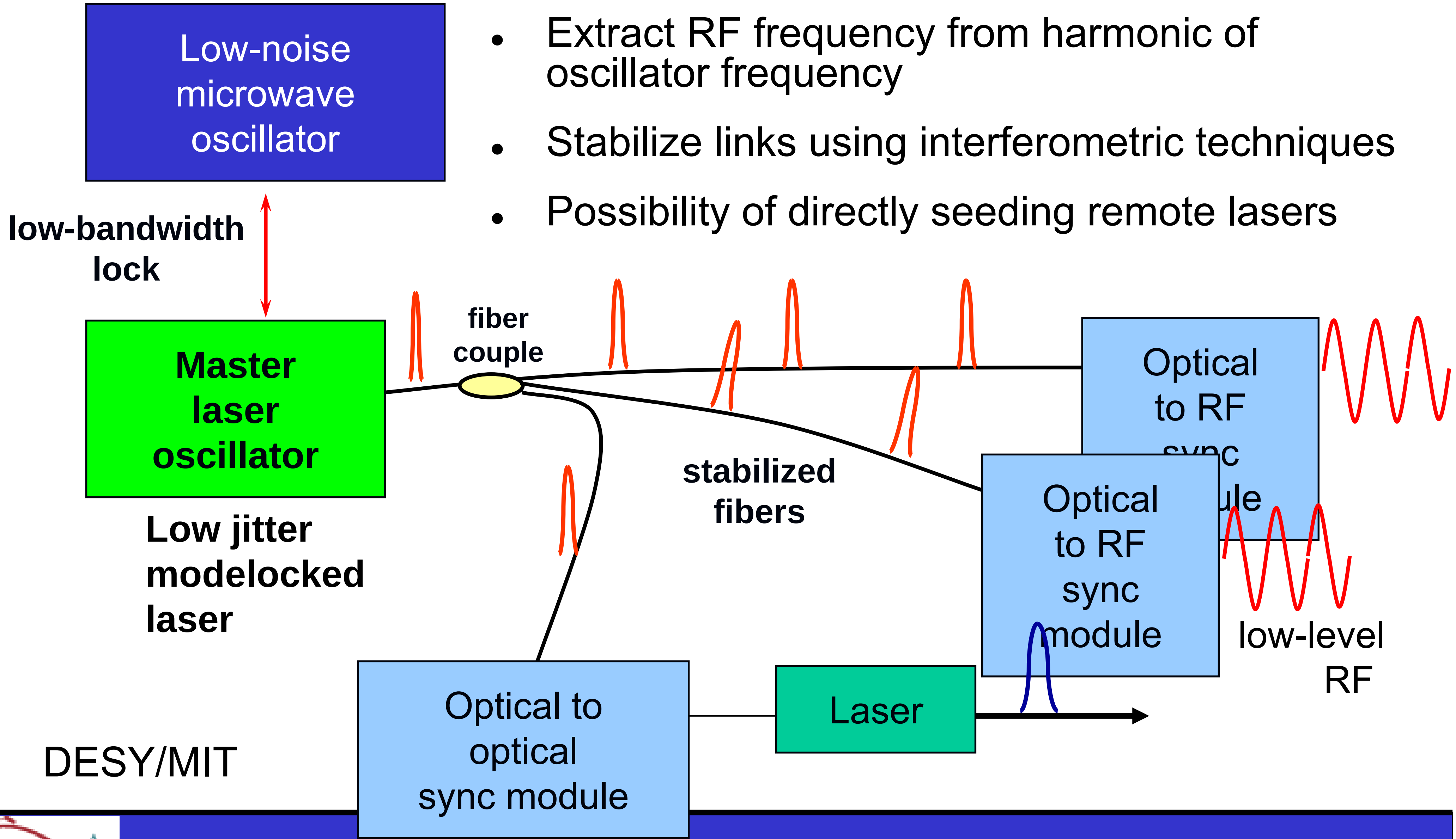
Conceptual system design



- 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

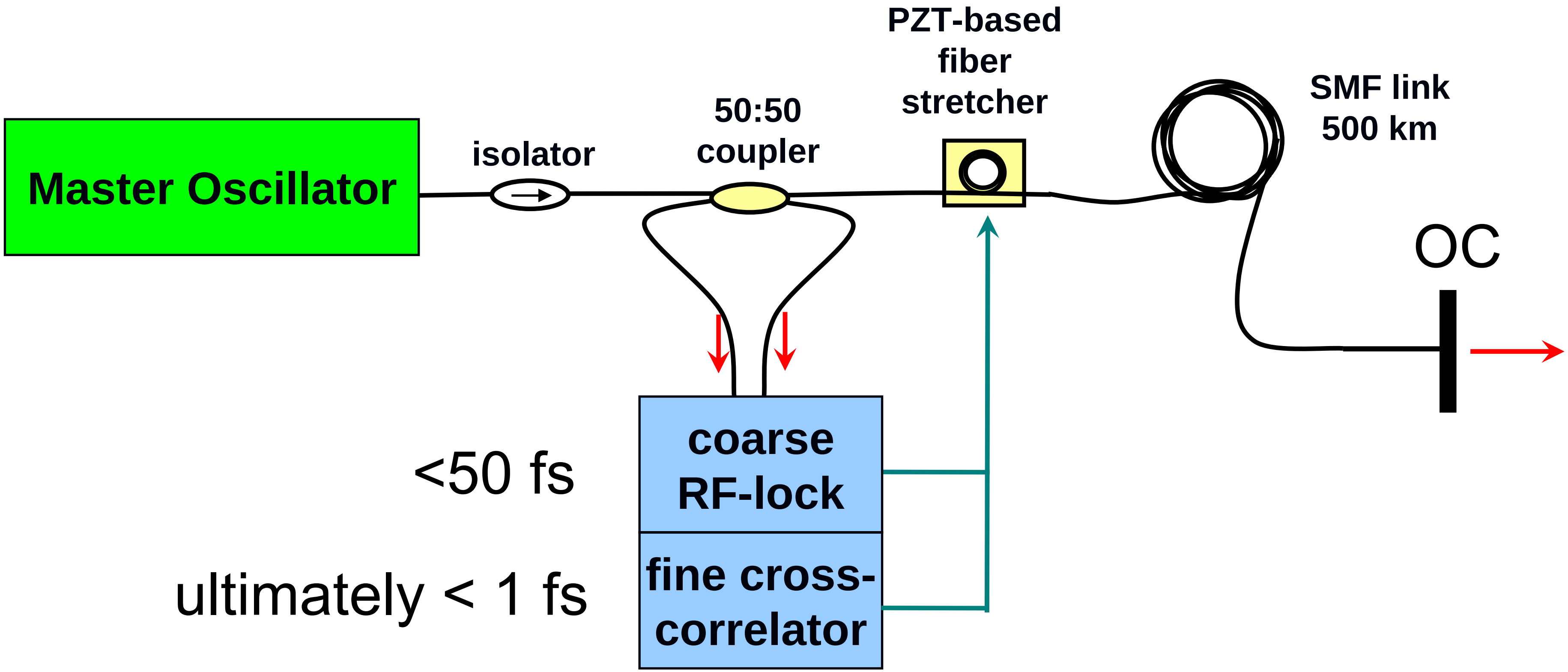
Pulsed distribution system

- 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

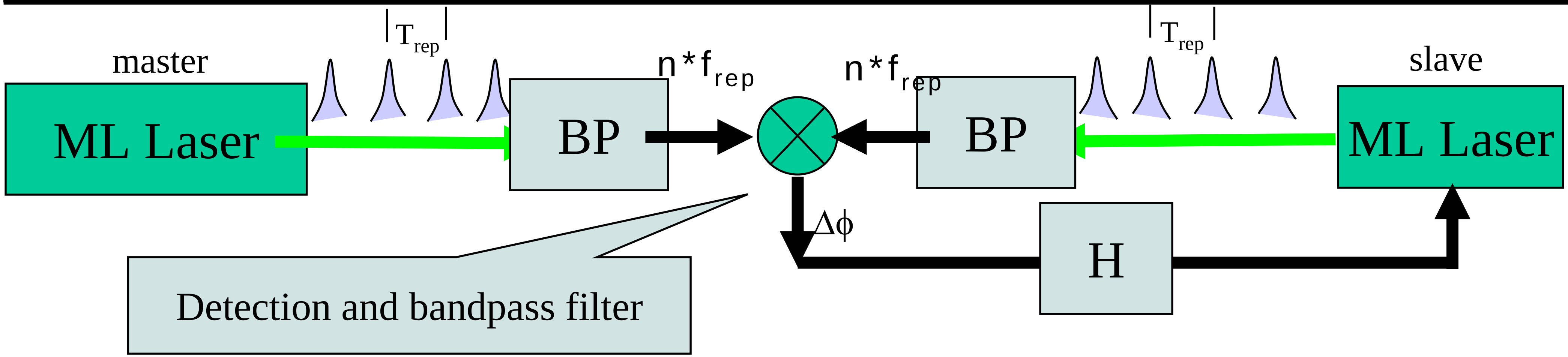
Results:

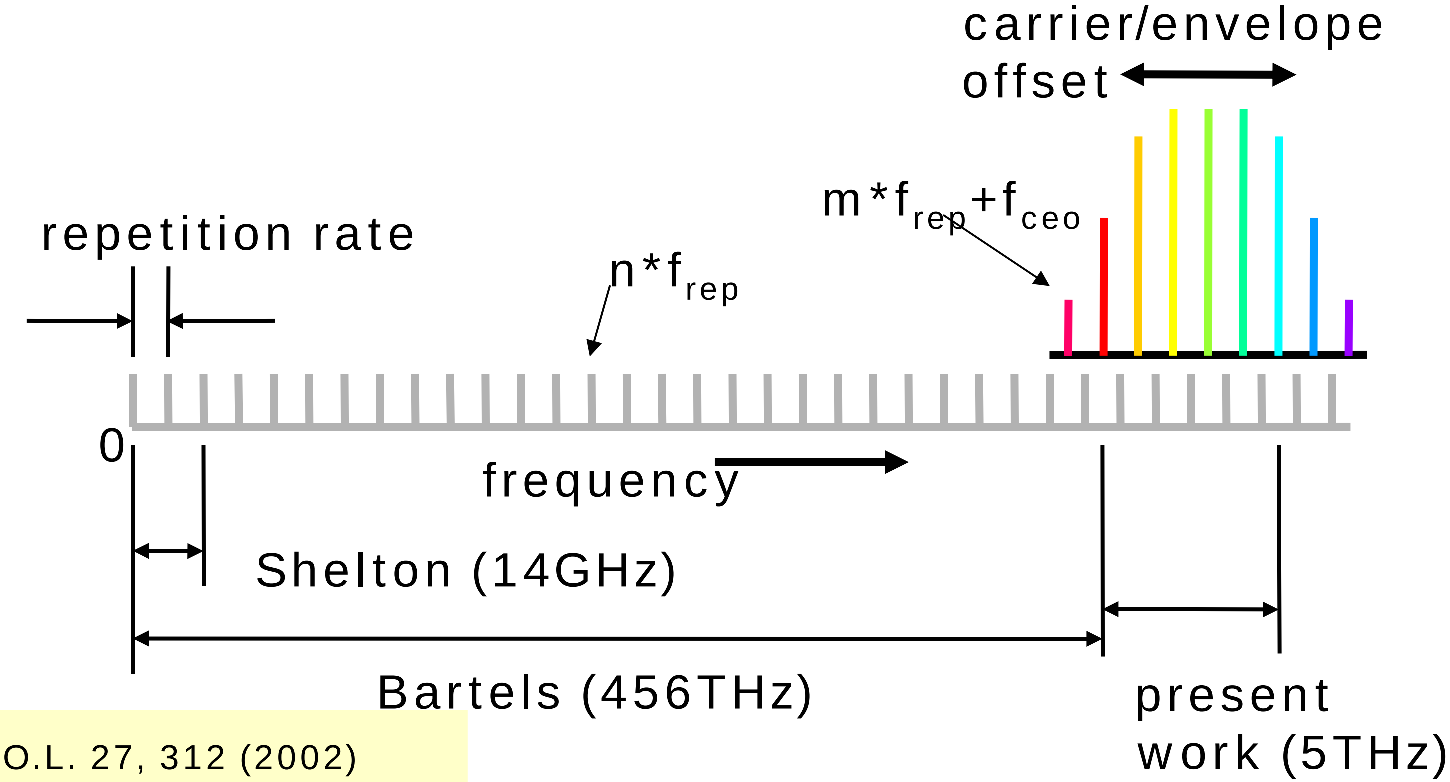
- A 4 km fiber link has been stabilized
  - Drift few fsec/hour (<50 microdeg @1.3 GHz) long-term
  - Peak-to-peak jitter <1 fsec (55 MHz bandwidth).
- Effort has been funded by FEL development (LDRD, Fermi)
- A contract to supply LCLS with a timing system begins 15 May 2007.

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

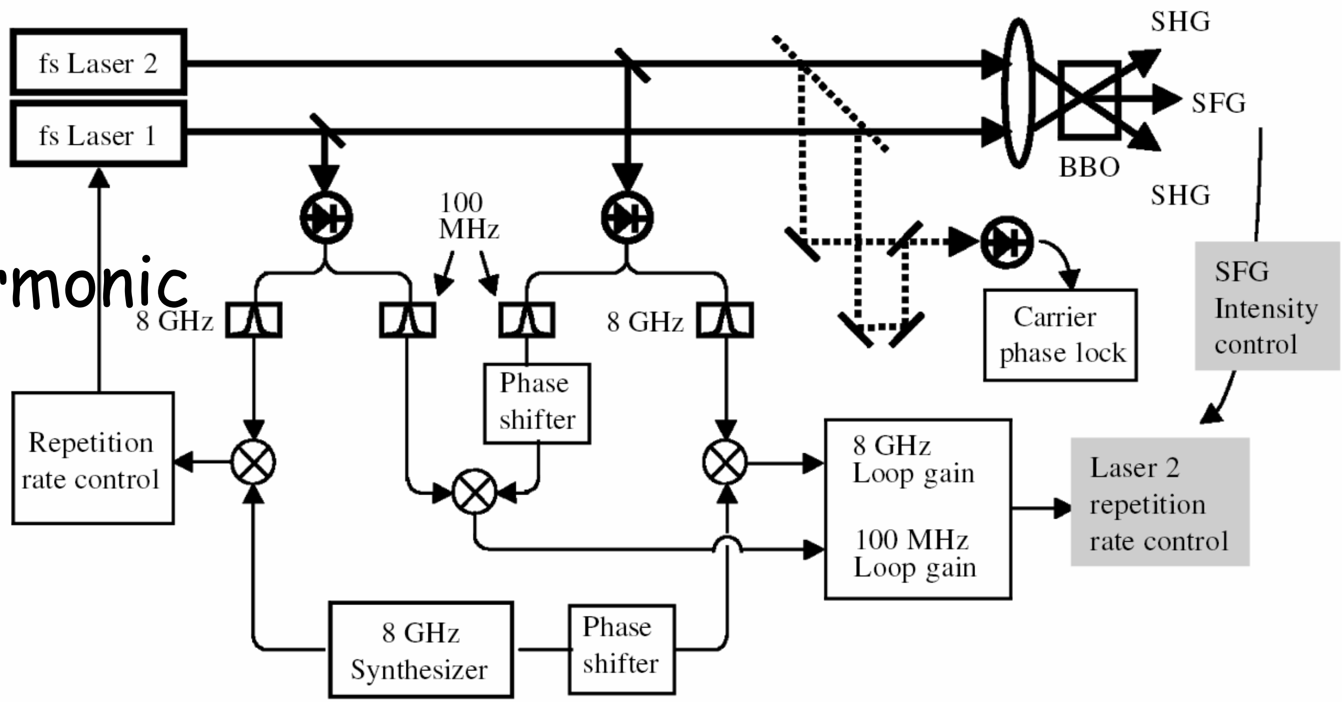


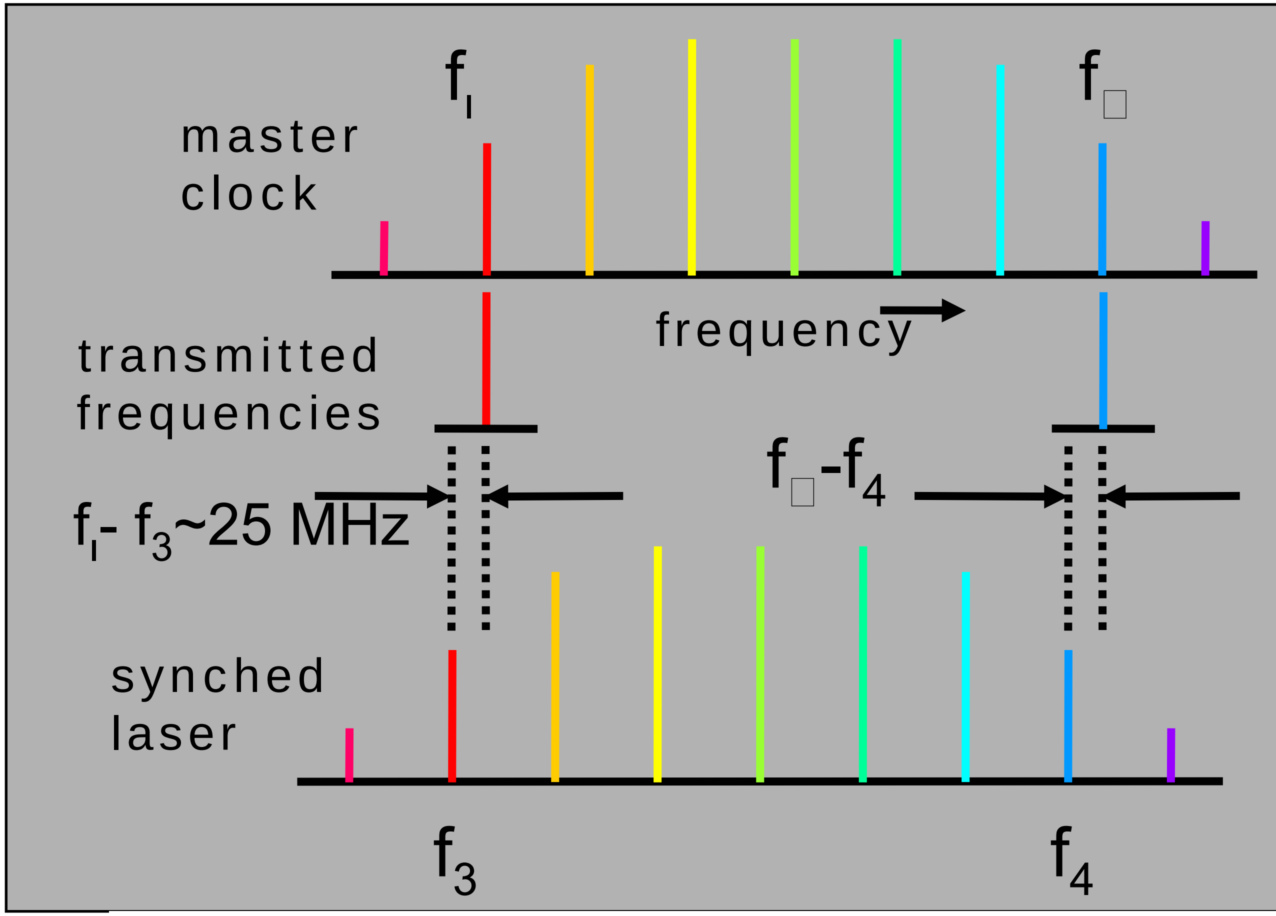
Figure 1. Experimental setup for timing synchronization of two fs lasers. The four phase-locked loops for synchronization are shown, along with the signal analysis scheme. Heterodyne detection of the carrier beat frequency between the two fs lasers is also shown.

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

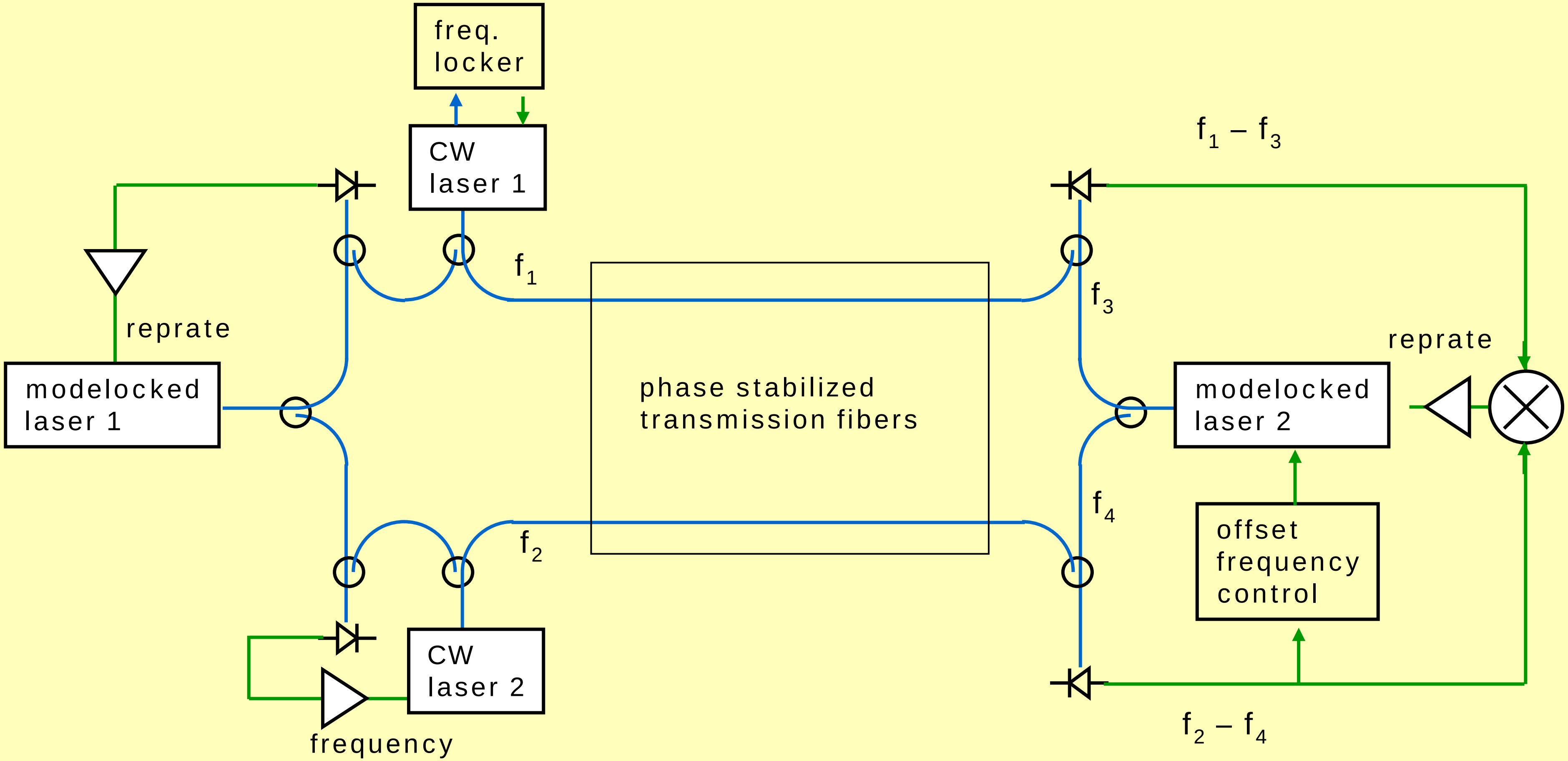


Lock two frequencies within the frequency comb separated by 5 THz.

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

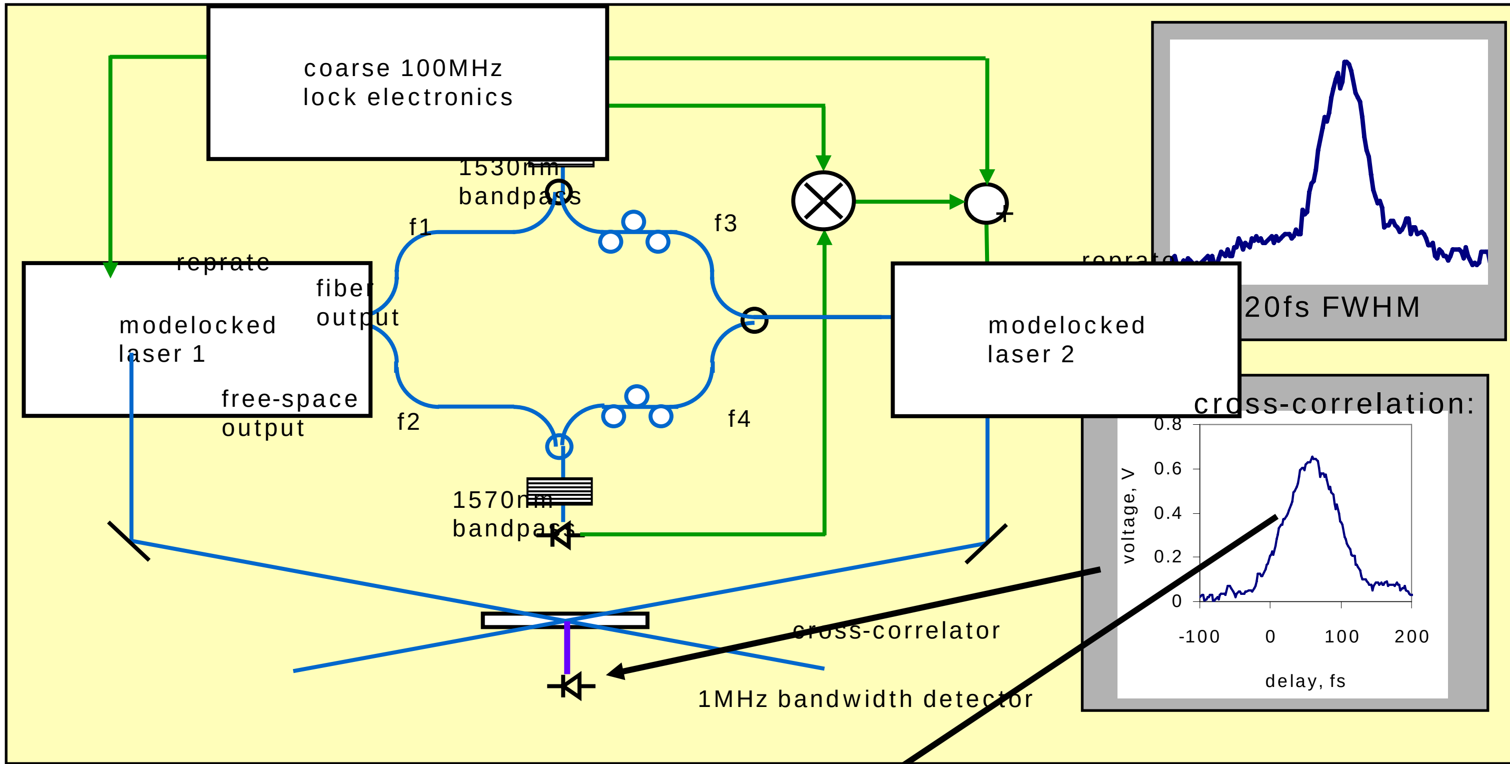
- **Novel approach for locking lasers**
- $(f_1 - f_3) - (f_2 - f_4)$ = error signal
- Yields relative phase of mode locked laser repetition rates
- Equivalent to difference of two THz signals
- Does not require carrier-envelope offset stabilized lasers

Conceptual schematic

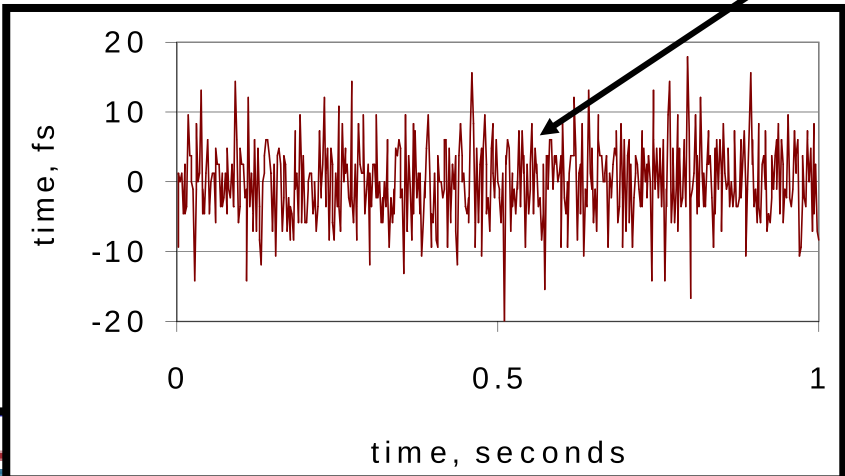


- **Conceptual schematic**
- **Uses stabilized fibers transmission for inter-laser link**
- **Potential of tremendous gain over RF stabilized lasers**

Initial results



- **Simplified setup: lasers co-located 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 down-conversion

Conclusions and Systems Integration

Future facilities require synchronization of pump and probe beams, RF stations, photoinjector laser and diagnostic elements. Each has different jitter requirements and clock waveforms (RF, pulses, or optical).

Group and phase stabilized fiber will satisfy all these requirements, offering immunity from electrical noise and very wide bandwidths.

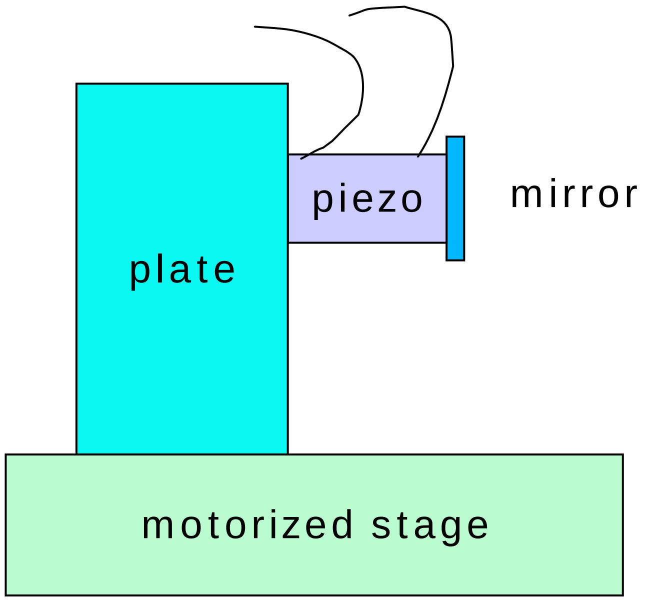
Wide-band transmission over fiber by modulating a CW laser signal with a Mach-Zehnder from a stripline pickup and sending the result over stabilized fiber provides stable, wide-band monitoring of the electron pulse in the linac itself.

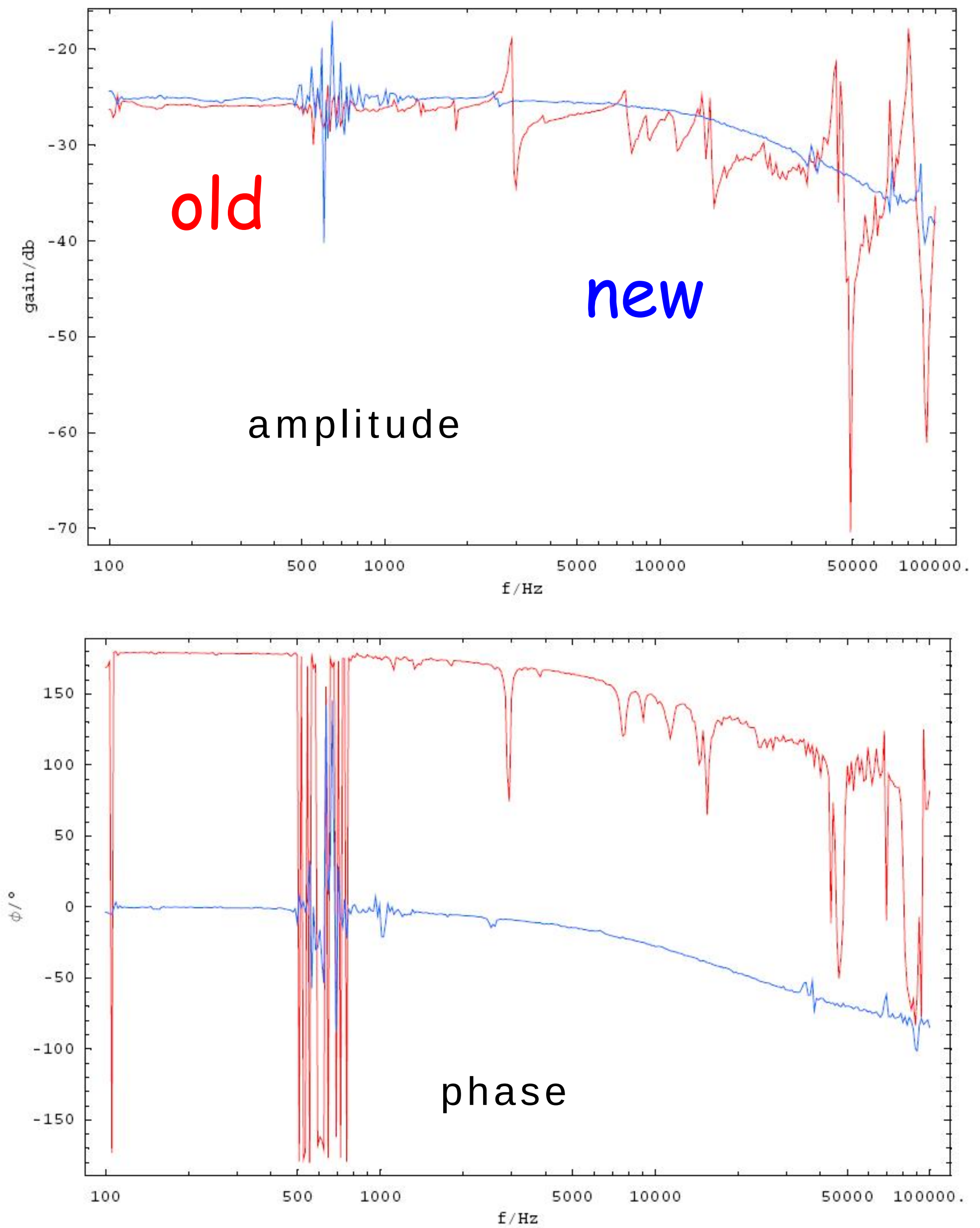
Synchronization of a mode-locked pump laser at a pump-probe experiment with a FEL seed laser will provide femtosecond level stability and resolution.

We have analyzed system requirements for new projects and designed an overall system that satisfies the timing and synchronization requirements for all the subsystems in a unified manner.

-fin-

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

Introduction

The fiber forms the backbone of a phase stable transport of wideband signals.

It must be reliable and work in a “real world” environment

Various signals are transported to phase lock RF systems (klystrons) and to synchronize mode-locked lasers at the photoinjector and experimental systems, as well as provide a time reference for diagnostic systems.

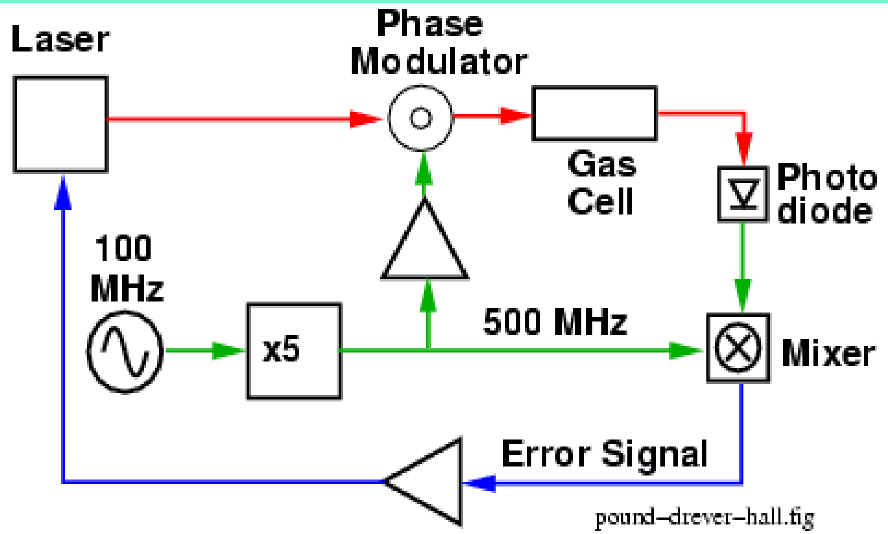
Fiber provides a bandwidth of TeraHertz, is immune to electrical noise and provides electrical common-mode isolation.

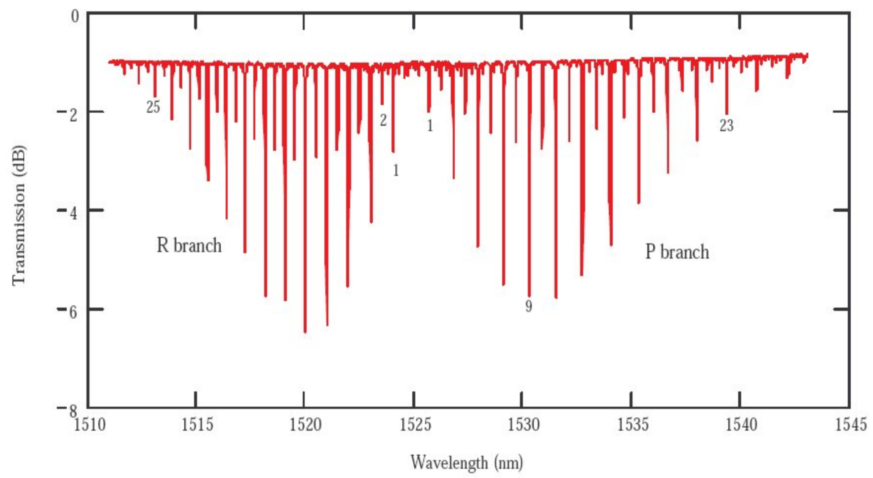
However, signal propagation velocity in fiber has about the same temperature coefficient as copper (0.1 ps/meter/C) and is acoustically sensitive.

Fiber components (lasers, isolators, directional couplers, etc) have strong analogies to RF components. Cheap devices have been developed in the telecomm industry.

Stabilizing the Laser Wavelength

As the number of fringes in the fiber is held constant (phase stabilization, not group velocity stabilization as in the first scheme) the laser wavelength is the physical reference and must be stabilized. We use an atomic absorption line in acetylene (C_2H_2) at 1530 nm in a Pound-Drever-Hall configuration.





The laser line is swept across the 1530 nm absorption band at 500 MHz. The amplitude-modulated resultant is phase compared to the phase (frequency) modulation driver and the error signal is filtered and applied to a frequency-determining piezo driver in the CW laser.

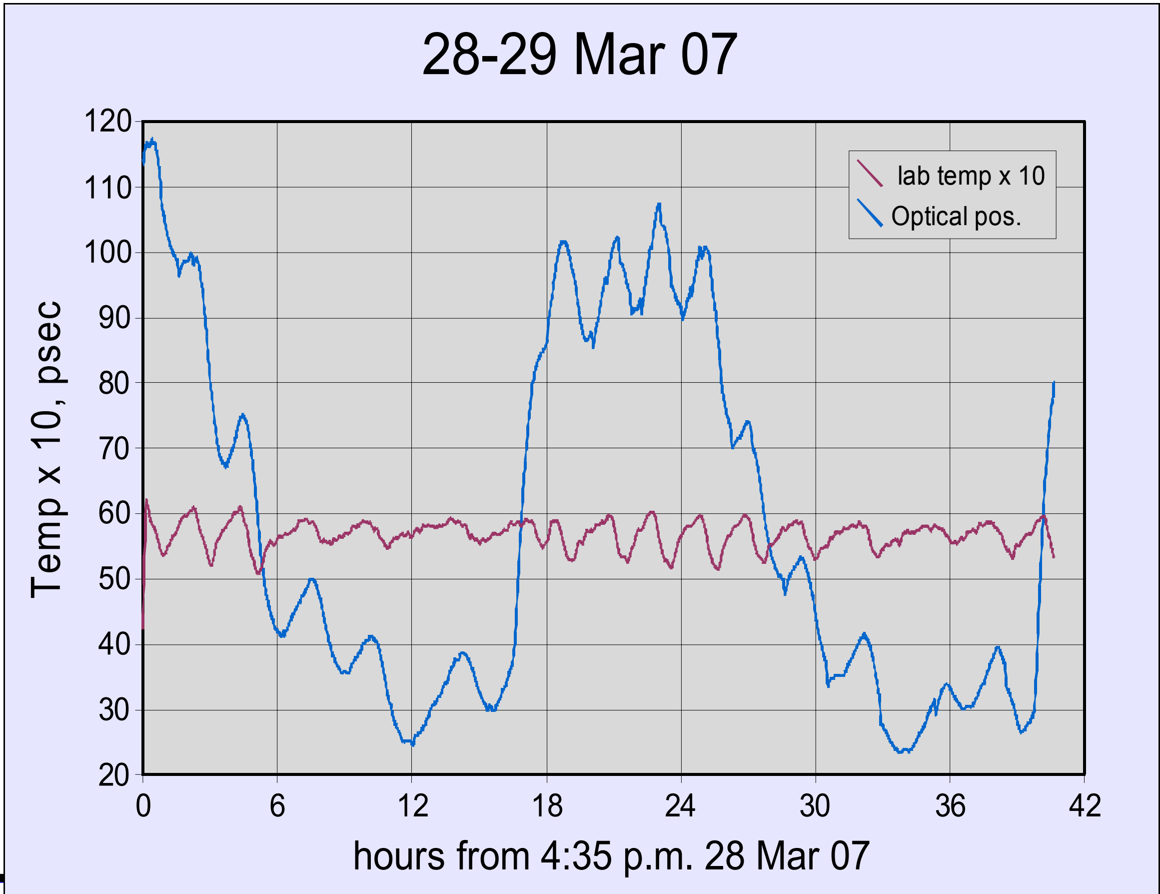
Note that the laser itself is not dithered: the laser produces an unmodulated signal.

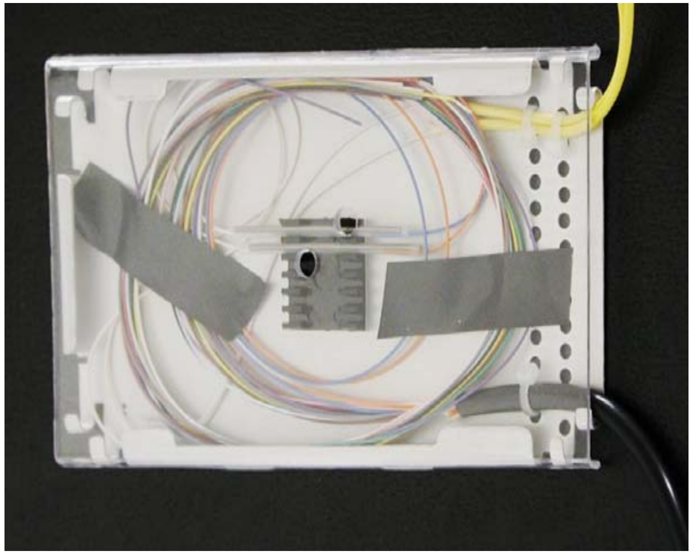
The natural laser line width is 1 kHz (spec) and the frequency stability is estimated to be in the 1 MHz regime. The 1570 nm laser is stabilized with a CO absorption line.

Using the LBNL Fiber Network to Simulate Real-World Environment

The Lab data network uses 1550 nm single-mode fiber in multi-bundled cables. We included a 2 km loop of Lab fiber in one arm of the stabilizer.

A 4 km loop stabilizes easily, and the 150 psec variation is due mainly to outdoor temperature variation.





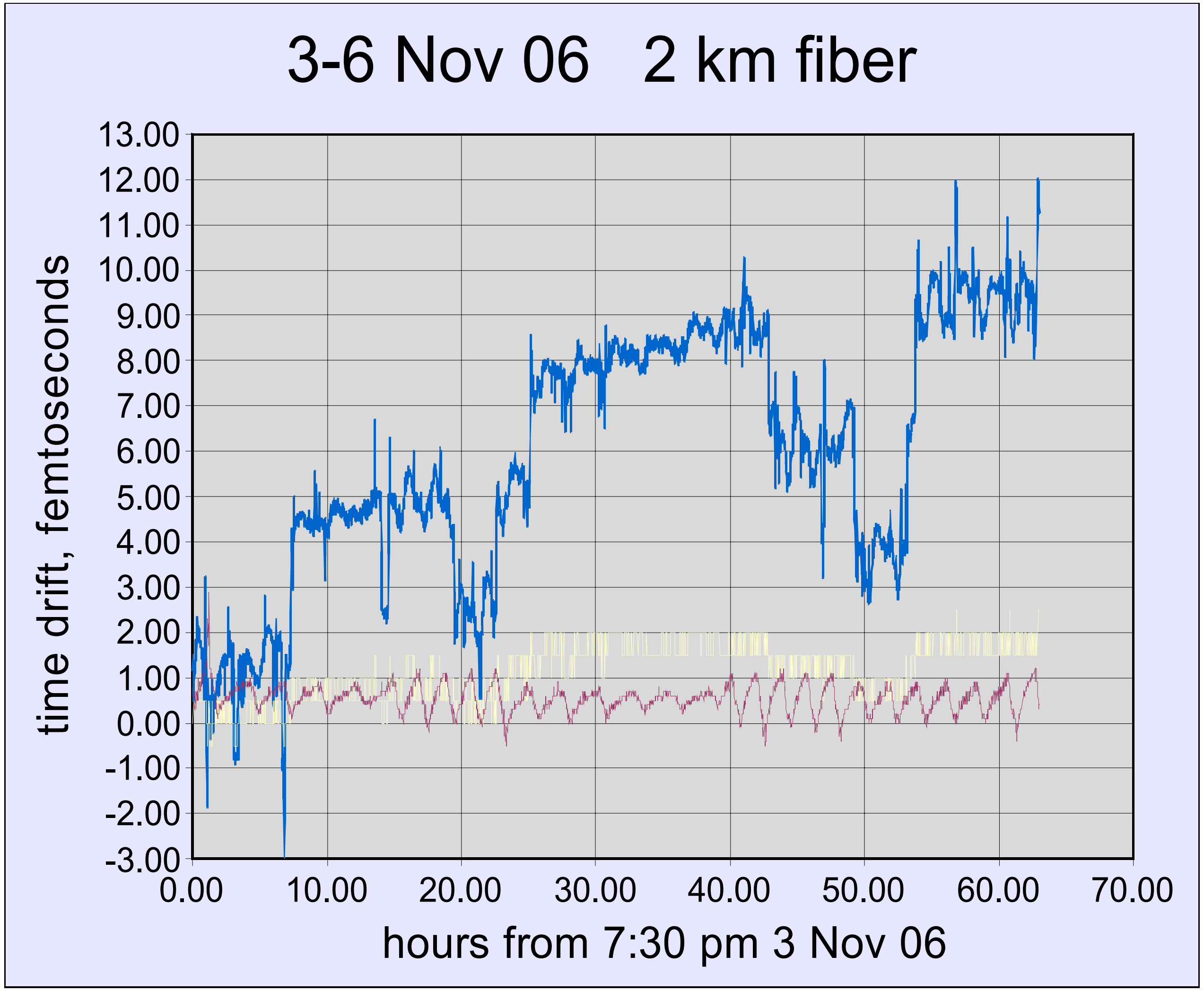
The loop comprises **2 km fiber external to the lab**, running under roads to Building 10 and back. **Another 2 km fiber is spooled in the lab**, which has an hourly 0.5C temperature variation, responsible for the faster oscillations on the plot. These two fiber segments are connected in series for a total of 4 km. Note that the round-trip distance of the corrector is 8 km, as the light goes to the far end and is reflected.

Preliminary Results from November 2006

2 km fiber in one leg of the two-fiber experiment, a short fiber in the other leg of the unequal-arm Michelson configuration.

The monitor signal is the differential phase difference, expressed in time, between the two independently-stabilized fibers. The 1530 nm laser frequency is stabilized.

Over a 63 hour run, the drift was about 9 fsec (blue), and the lab temperature variation about 1C (dark red).

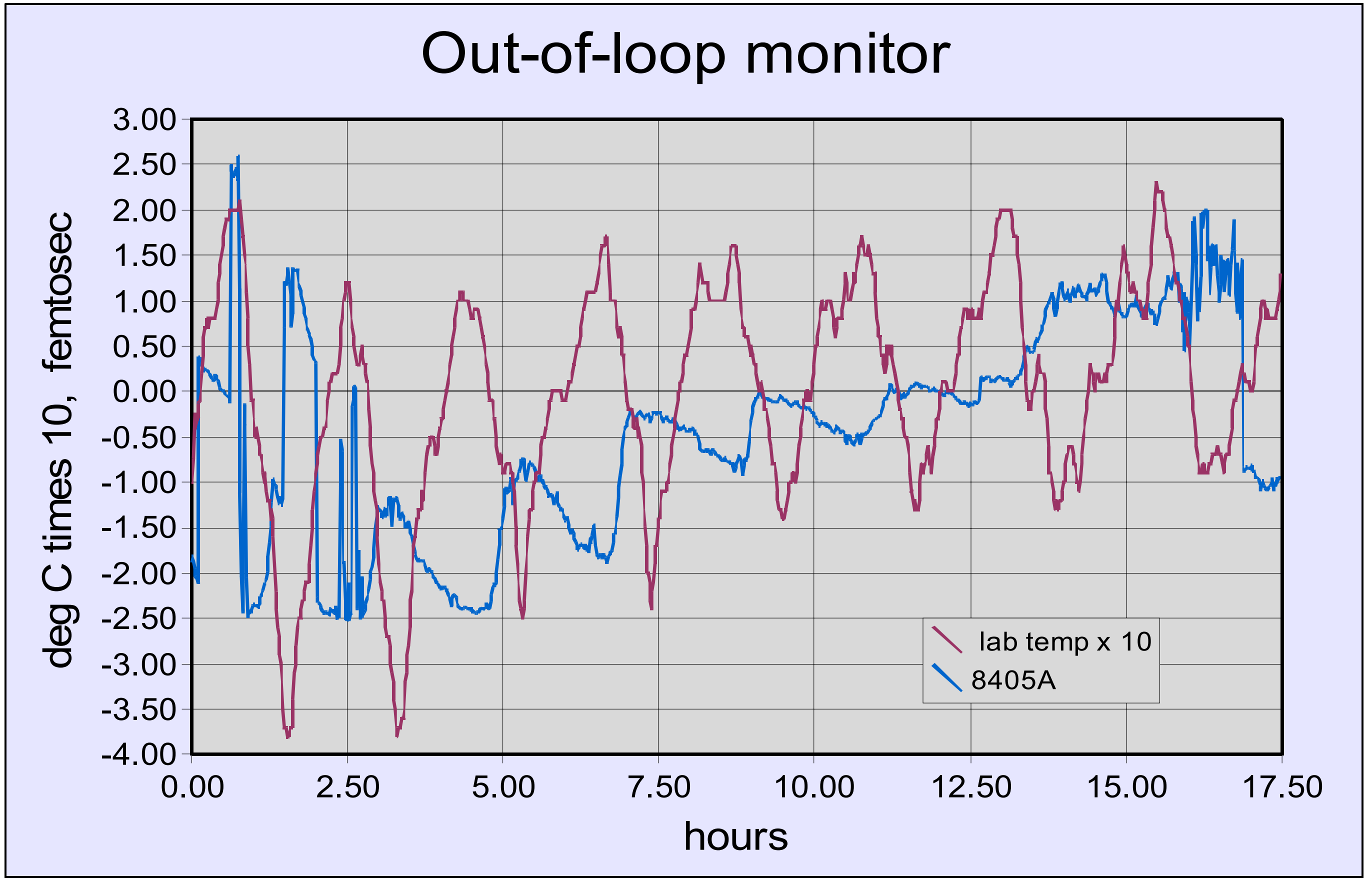


Out-of-Loop Monitor Results

The true measure of the performance is from the out-of-loop monitor. The error signal of the in-loop monitor controls the line stretcher, and an independent monitor measures the differential phase difference over time between the end of the stabilzed fiber and another, independently stabilized fiber. To simulate worst-case conditions, the second fiber is short, 2 meters, (a second 4 km fiber would not reflect changes in the clock of other common mode elements).

The blue trace shows that the phase of the two independent fibers (4 km and 2 m) stays within 4 femtoseconds over the 17.5 hour run. This data is typical.

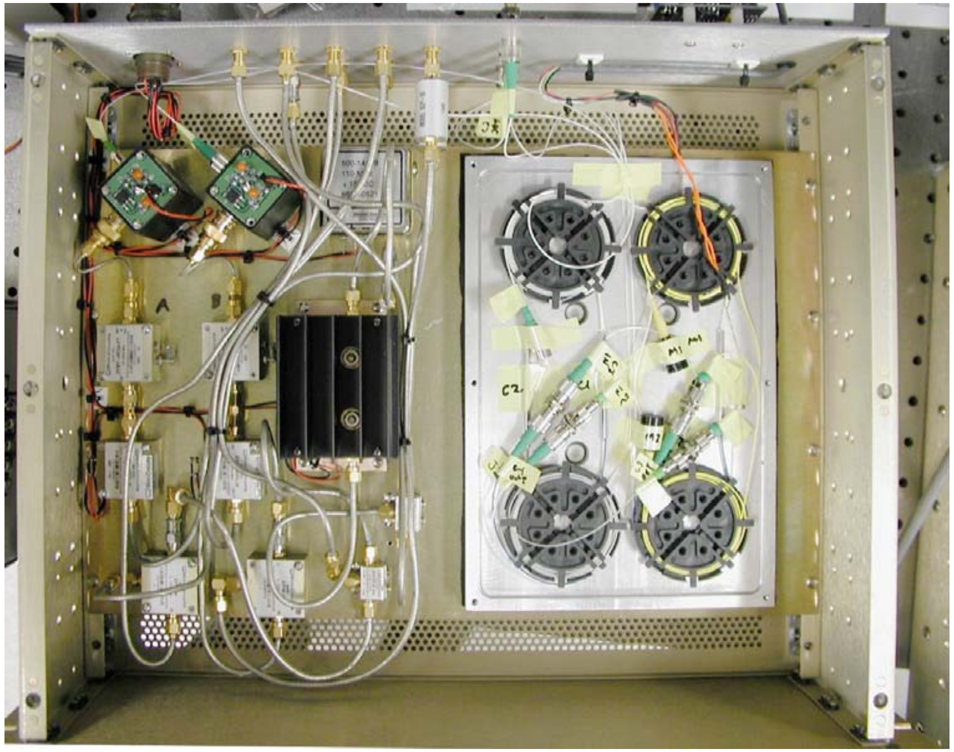
The red trace is the variation of lab temperature x 10C.



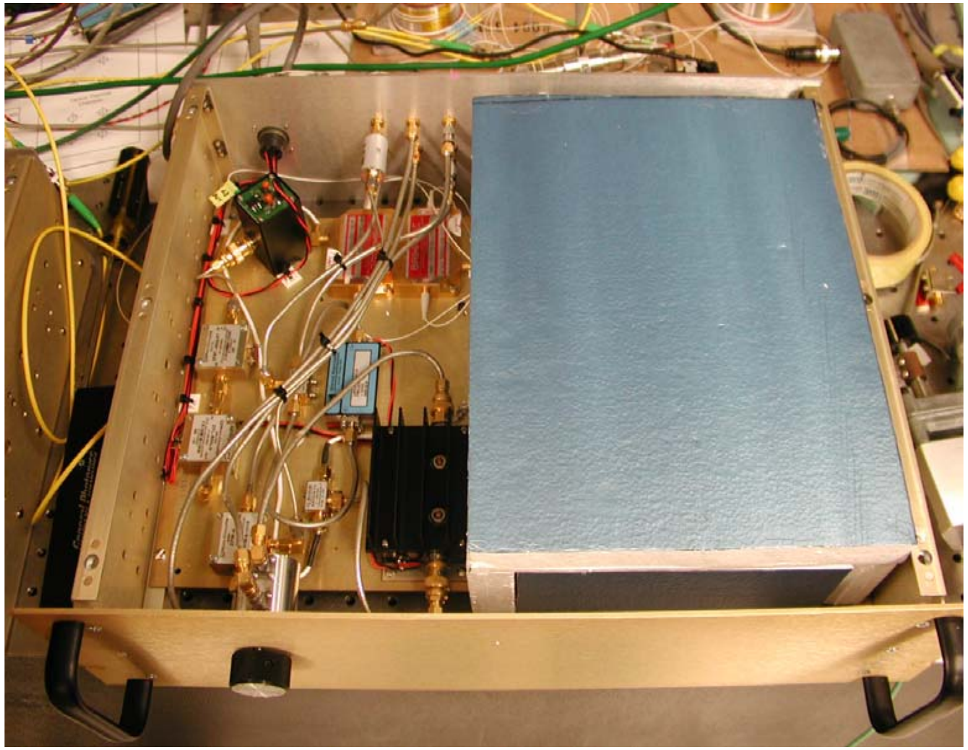
Packaging

The frequency-offset method is very sensitive, as optical phase differences are heterodyned down into the RF domain. Mixer offsets are now negligible, with each degree of phase error at 110 MHz equivalent to 0.018 asec.

The only critical parts are the optical splitters and Faraday rotator mirrors, which are contained in environments controlled to 0.01C by Peltier thermoelectric devices.

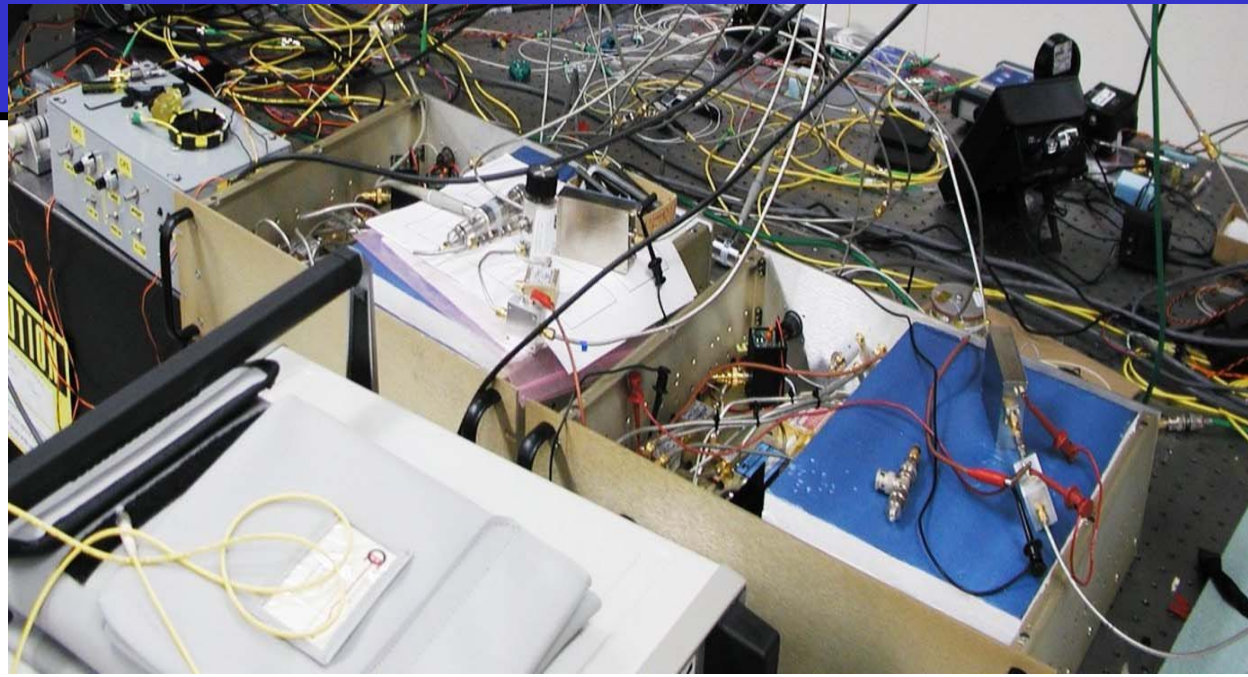


Dual-channel transmitter



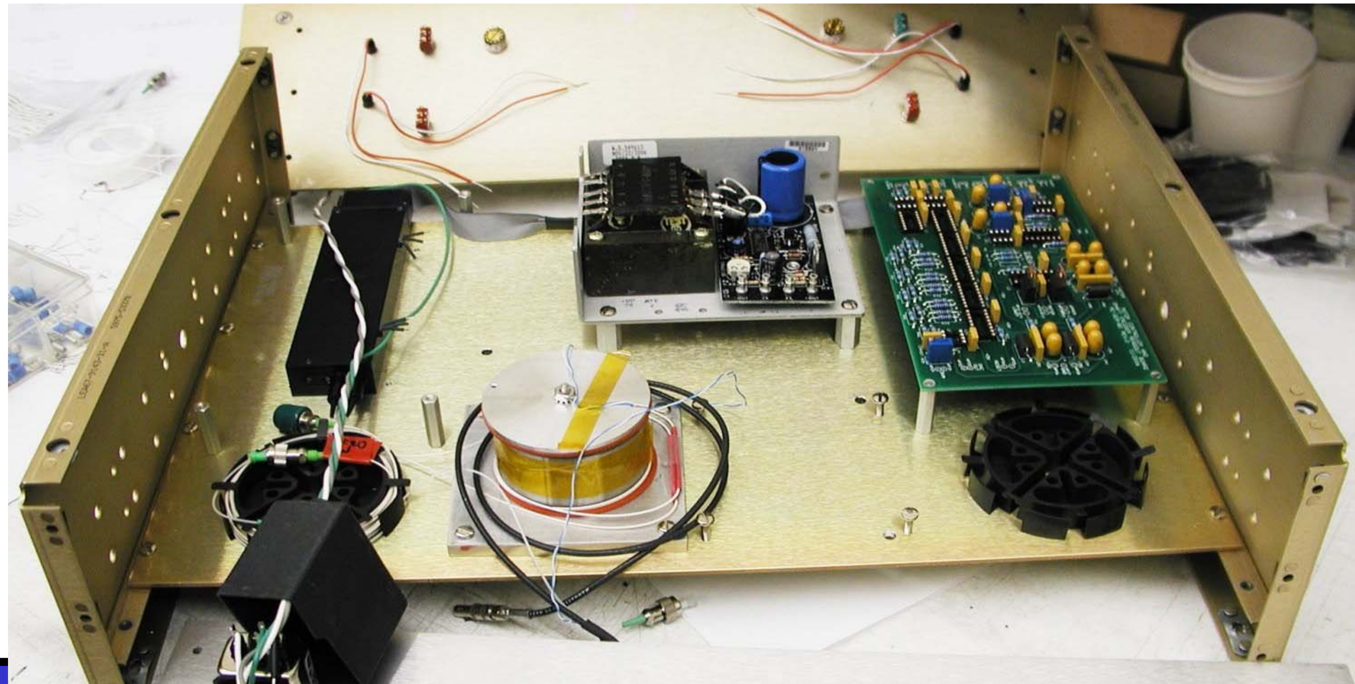
Dual-channel receiver

More Packaging



There are still some components loose on the laser table.

We will conducts test with fiber strung in accelerator tunnels, with the ALS and SLAC as primary candidates.



The rest of the components are being packaged and mounted in a single relay rack for transport to sites where we will gather data under actual operating conditions.

Conclusions

To produce an ultra-stable timing and synchronization system with jitter reduced to the few femtosecond level, we have developed a laser-based scheme with optical signals distributed over a stabilized optical fiber [22].

Transmitting precise frequency and timing signals over distances of hundreds of meters, stabilized to a few femtoseconds (a few parts in 10^8), is accomplished by measuring the phase delay in an optical fiber and actively compensating for differences with a piezoelectric modulator. In our scheme, illustrated in Figure 3, phase differences at optical frequency are down-converted to 110 MHz. Because phase information is preserved during the heterodyning process, phase differences at optical frequency can be detected at radio frequencies, using conventional RF electronics. The radiofrequency reference signal need not be provided with femtosecond accuracy at the far end of the fiber, because one degree of error at 110 MHz is equivalent to only one degree at the optical frequency, or 0.014 fs.

The system is linear, and signals modulated onto the CW laser carrier at the fiber entrance do not intermodulate with each other. Moreover, the optical power level is significantly below any nonlinear threshold in the fiber. The laser frequency itself must be stabilized, so the laser is locked to an absorption line in an acetylene cell.

At present, a 4 km fiber link has been stabilized to the femtosecond level. 2 km of fiber in this link passes under several roads and through several buildings at LBNL, demonstrating that the fiber stabilization system is robust under real-world conditions. This technique will soon be used as a backbone to demonstrate synchronization of mode-locked lasers. Further developments will include integration with controls and low-level RF systems, and high-resolution diagnostics of photon and electron beams, to provide enhanced feedback control of the integrated laser/accelerator systems. We are planning to develop and implement similar systems at the LCLS, and FERMI@Elettra.

Development at MIT

Femtosecond Technologies for Optical clocks, Timing Distribution and RF Synchronization

J.-W. Kim, F. Ö. Ilday, T. Schibli, F. G. Grawert, J. Chen, O. D. Muecke, M. H. Perrot, and F. X. Kaertner

Department of Electrical Engineering and Computer Science
and Research Laboratory of Electronics

W. Graves, D. Moncton
Bates Linear Accelerator Center
Massachusetts Institute of Technology

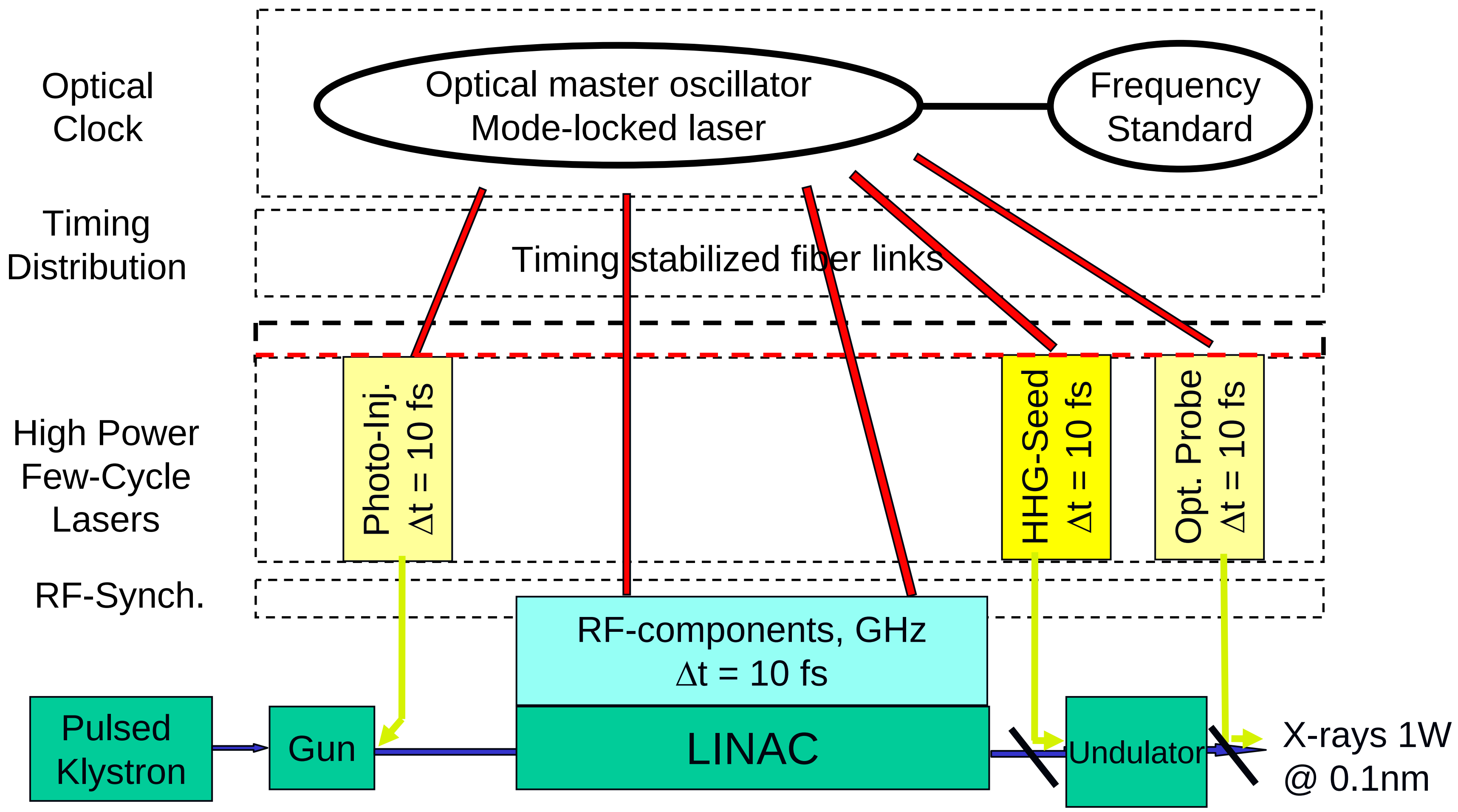
Femtosecond Timing Distribution & Synchronization

- Synchronization of multiple events at multiple locations in a FEL facility with femtosecond precision is required.

- We envision that:
  - A master microwave oscillator that “keeps the time”,
  - A master mode-locked laser locked to this oscillator,
  - Stabilized fiber links that transport the clock signal in the form of a pulse train to multiple locations,
  - A scheme that locks other lasers to this signal and/or generates an RF signal

  form a complete scheme with eventually few fs precision.

MIT X-Ray Laser Project



Less than 10 fs timing jitter between lasers is required.

Master microwave oscillator

Locking and sync:
- laser to laser optically (< 1 fs)
- laser to RF (< 100 fs)

Timing-distribution *via* fiber-links

Low jitter modelocked lasers

Master Microwave Oscillator

- Extremely good microwave oscillators are commercially available.
- Jitter < 6 fs from 10 Hz to 10 MHz.
- *Development effort not necessary at this stage.*

Master microwave oscillator

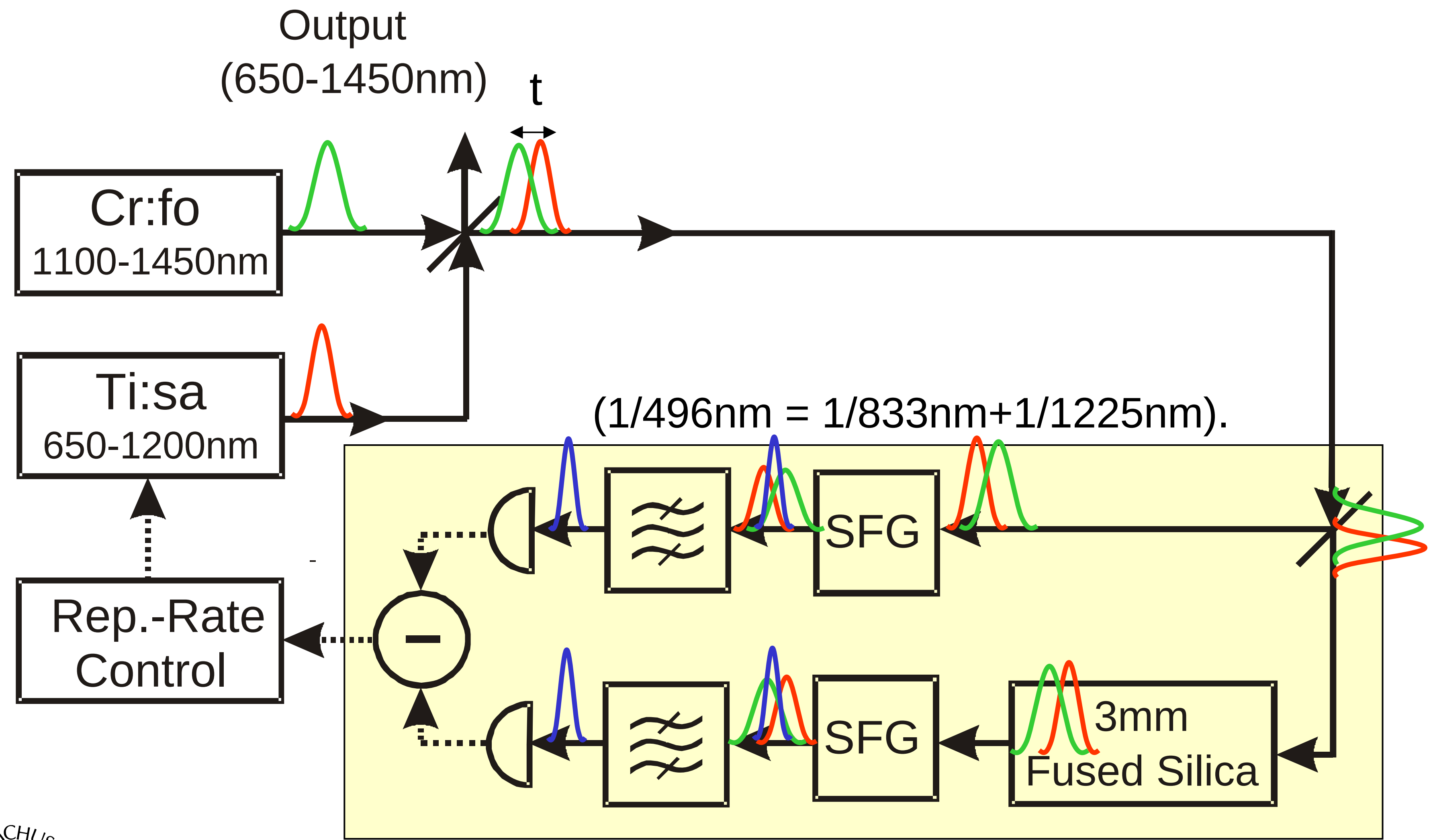
Locking and sync:

- laser to laser optically (< 1 fs)
- laser to RF (< 100 fs)

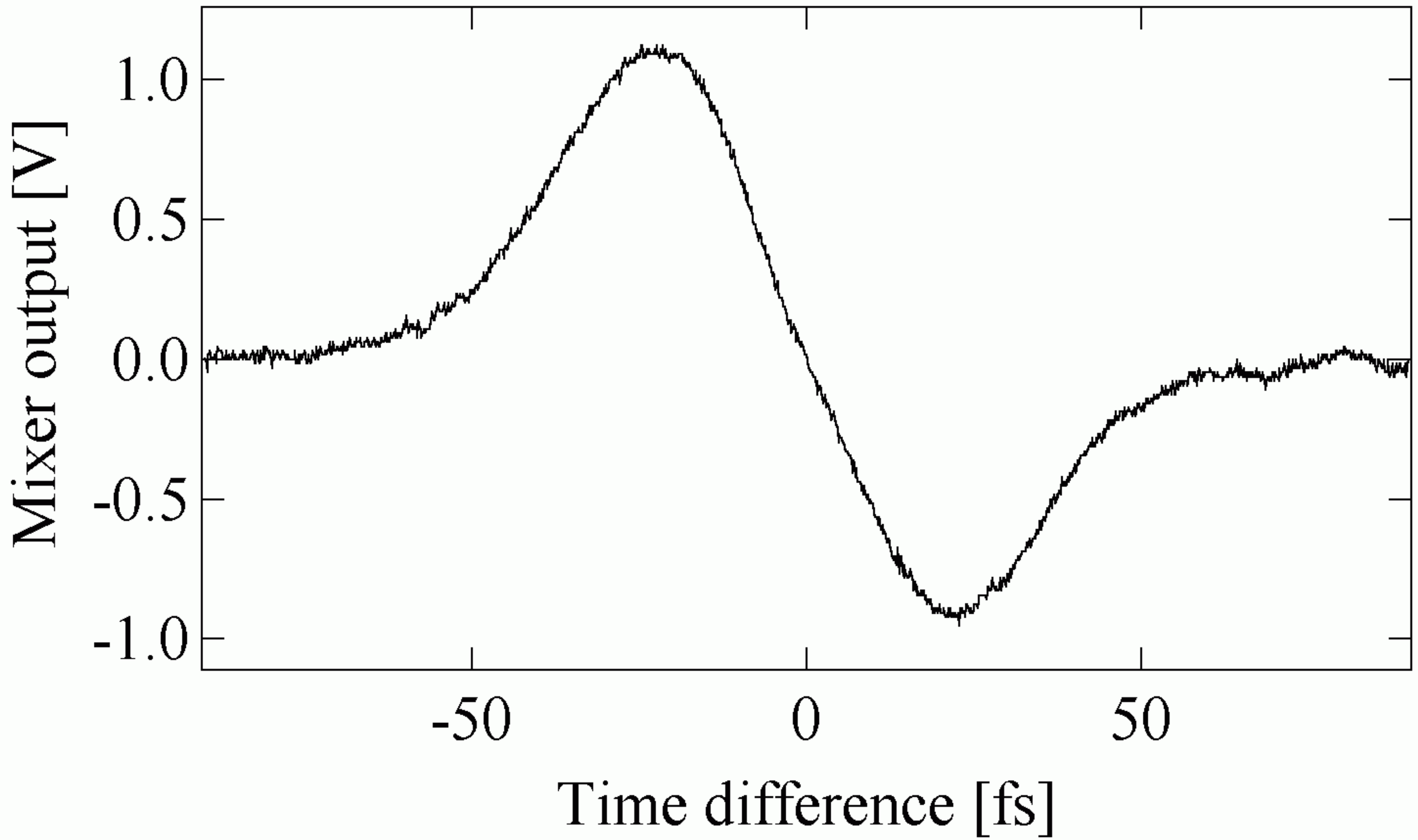
Timing-distribution *via* fiber-links

Low jitter modelocked lasers

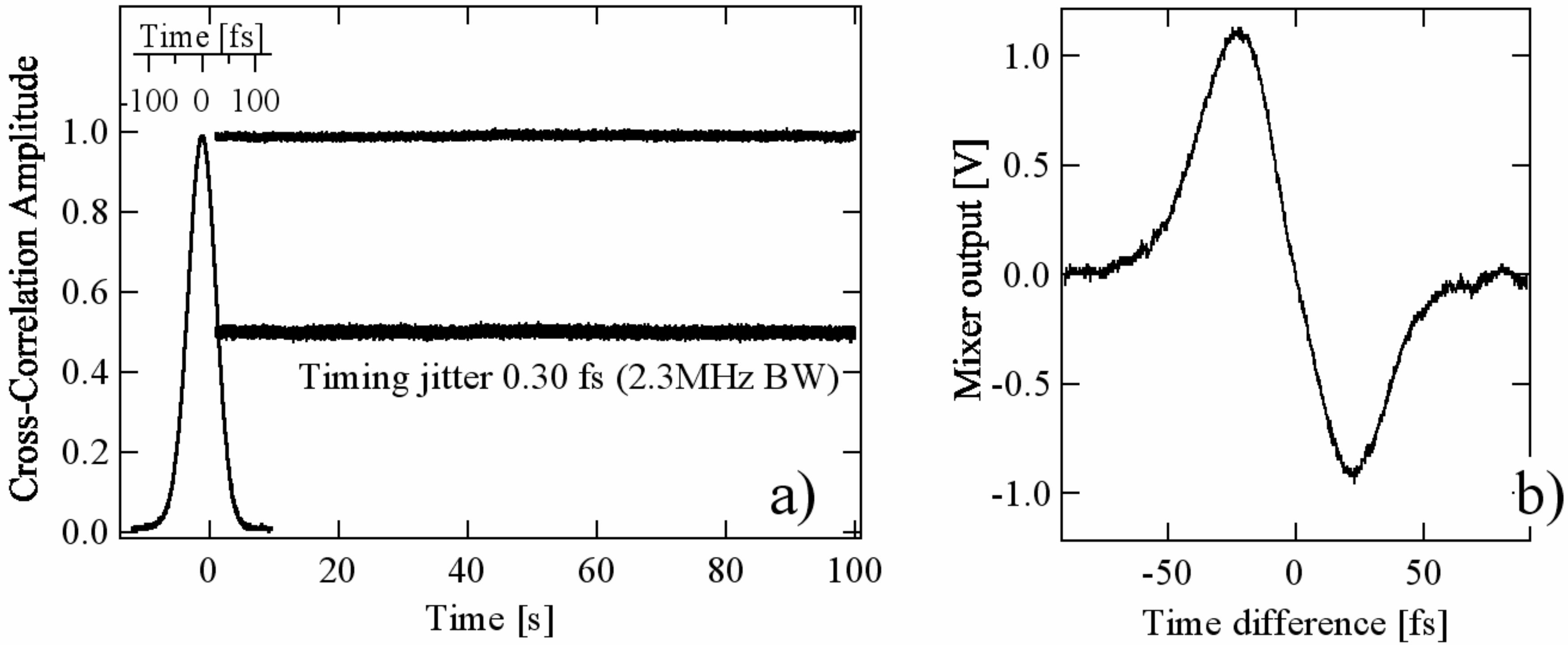
Balanced Cross-Correlator



Balanced Detector Output



Residual Timing Jitter



The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 300 as (a tenth of an optical cycle)

T.R. Schibli *et al.*, Opt. Lett. **28**, 947 (2003)

Master microwave oscillator

Locking and sync:

- laser to laser optically (< 1 fs)
- RF to laser (< 100 fs)

Timing-distribution *via* fiber-links

Low jitter modelocked lasers

Laser and RF Synchronization

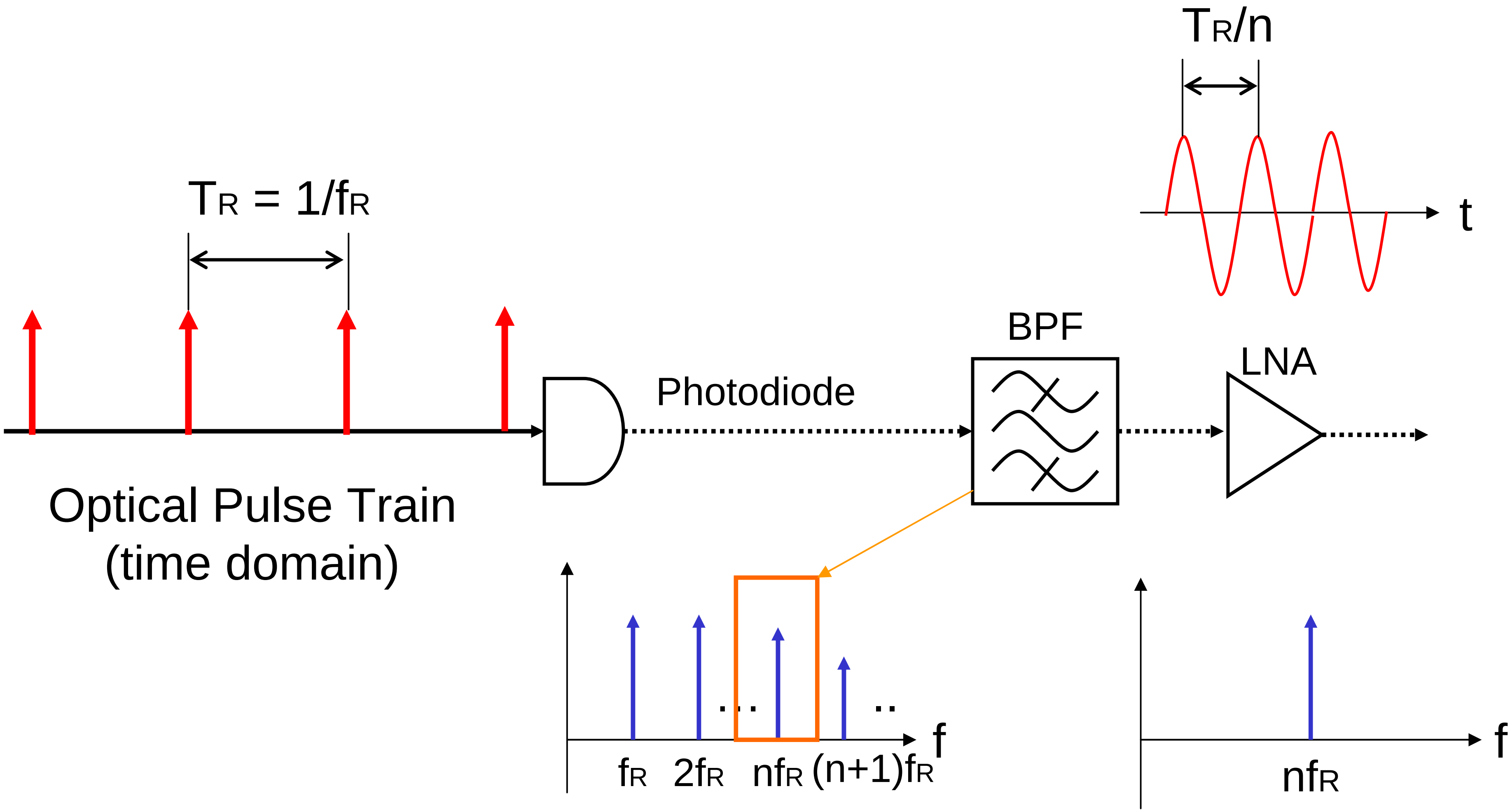
Requirements:

- Modular building block for laser-RF and laser-laser synchronizations.

- Low timing jitter (< 10 fs)

- Long-term drift-free

Direct Detection to Extract RF from Pulse Train



Potential Limitations of Direct Detection

- Excess phase noise in photo-detection process
  - Amplitude-to-phase conversion in photo-detection
  - Pulse distortions due to photo-detector nonlinearities

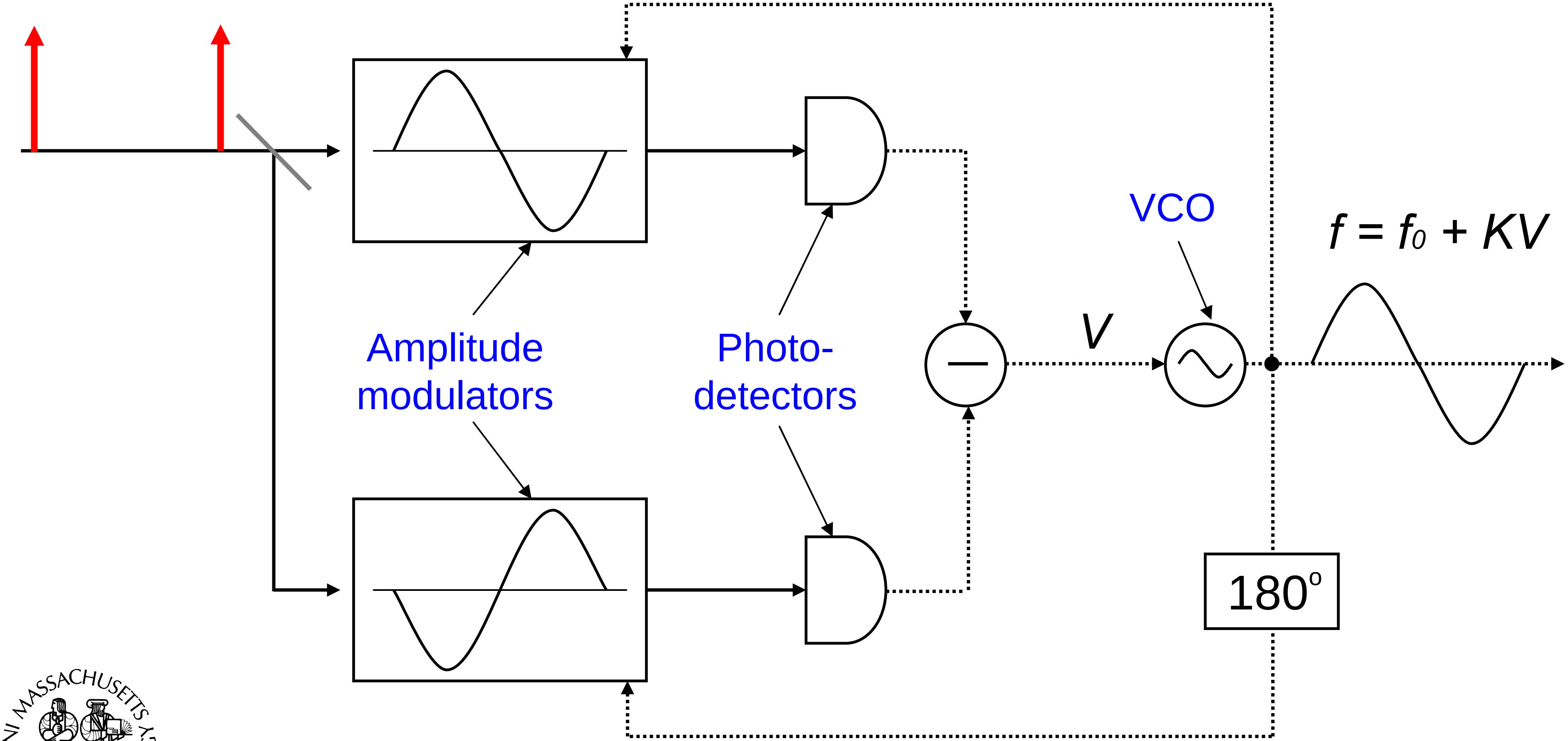
E.N. Ivanov et al., IEEE JSTQE **9**, 1059 (2003)

- Long-term stability issue
  Thermal drift in photodiode (semiconductor device)

→ A new synchronization scheme for both lower timing jitter and long-term stability is highly desirable.

Locking the RF to the Pulse Train

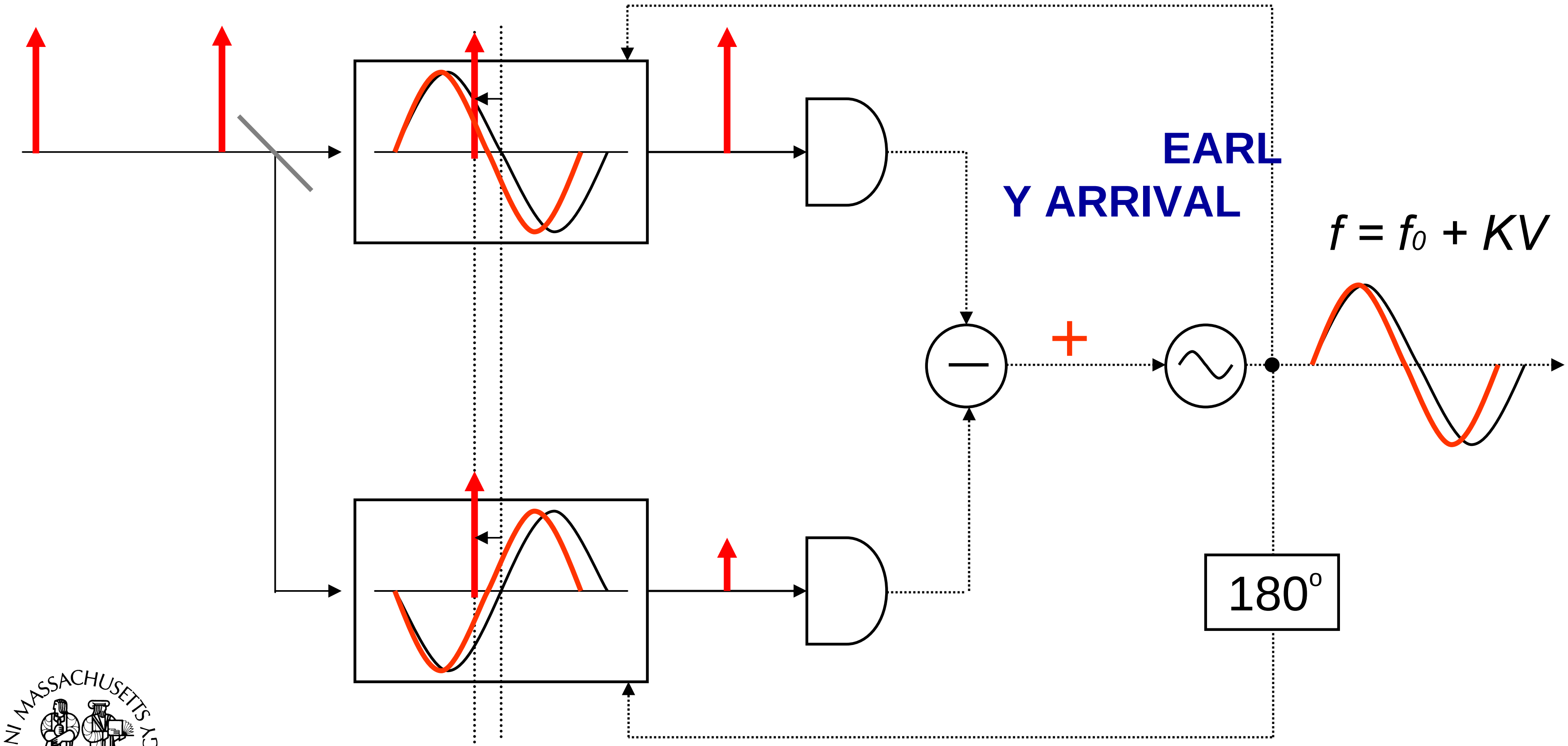
Convert timing info to intensity imbalance



Locking the RF to the Pulse Train

Convert timing info to intensity imbalance

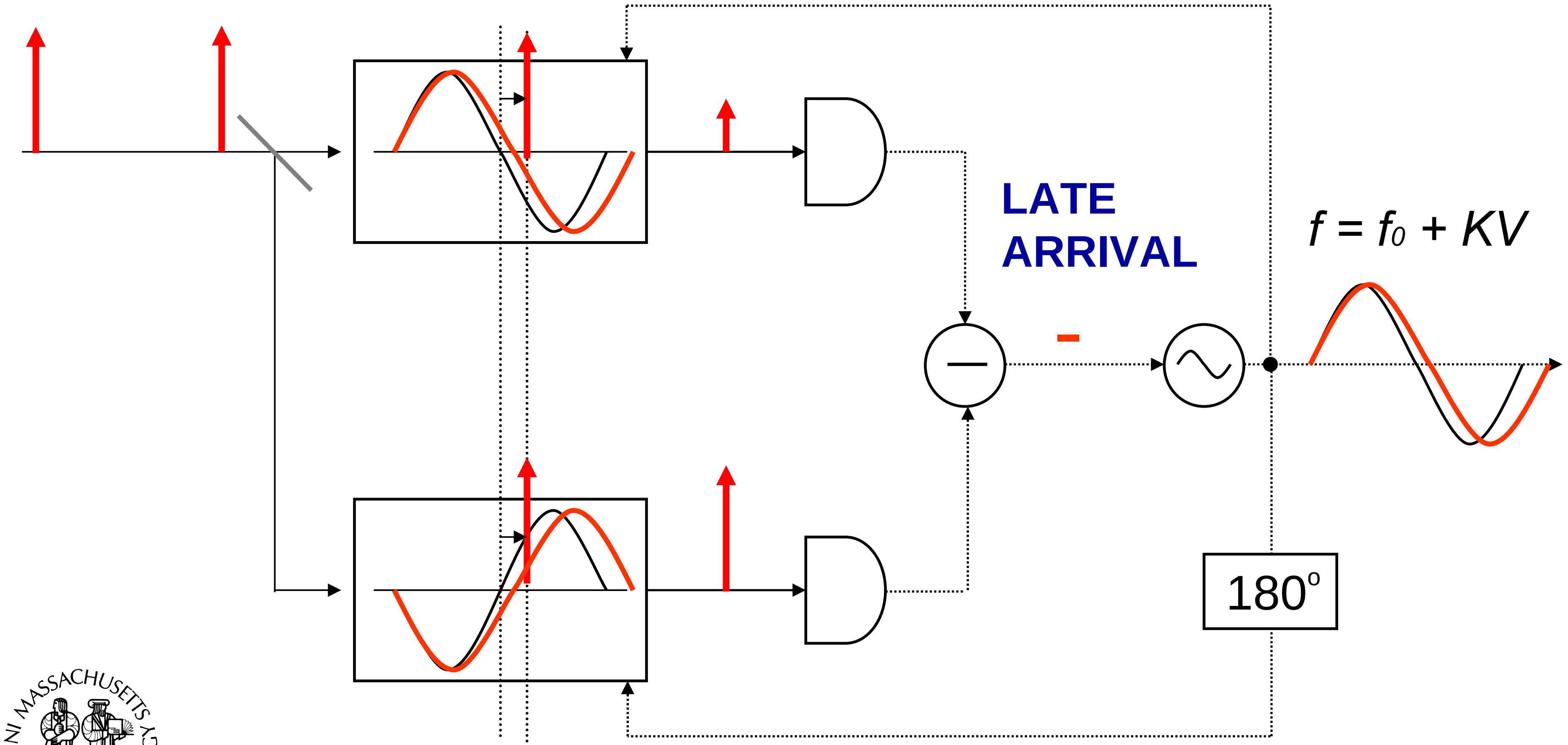
- **Amplitude modulators take "derivative" of the signal intensity**
- **Differentiation eliminates effect of detector problems**



Locking the RF to the Pulse Train

Convert timing info to intensity imbalance

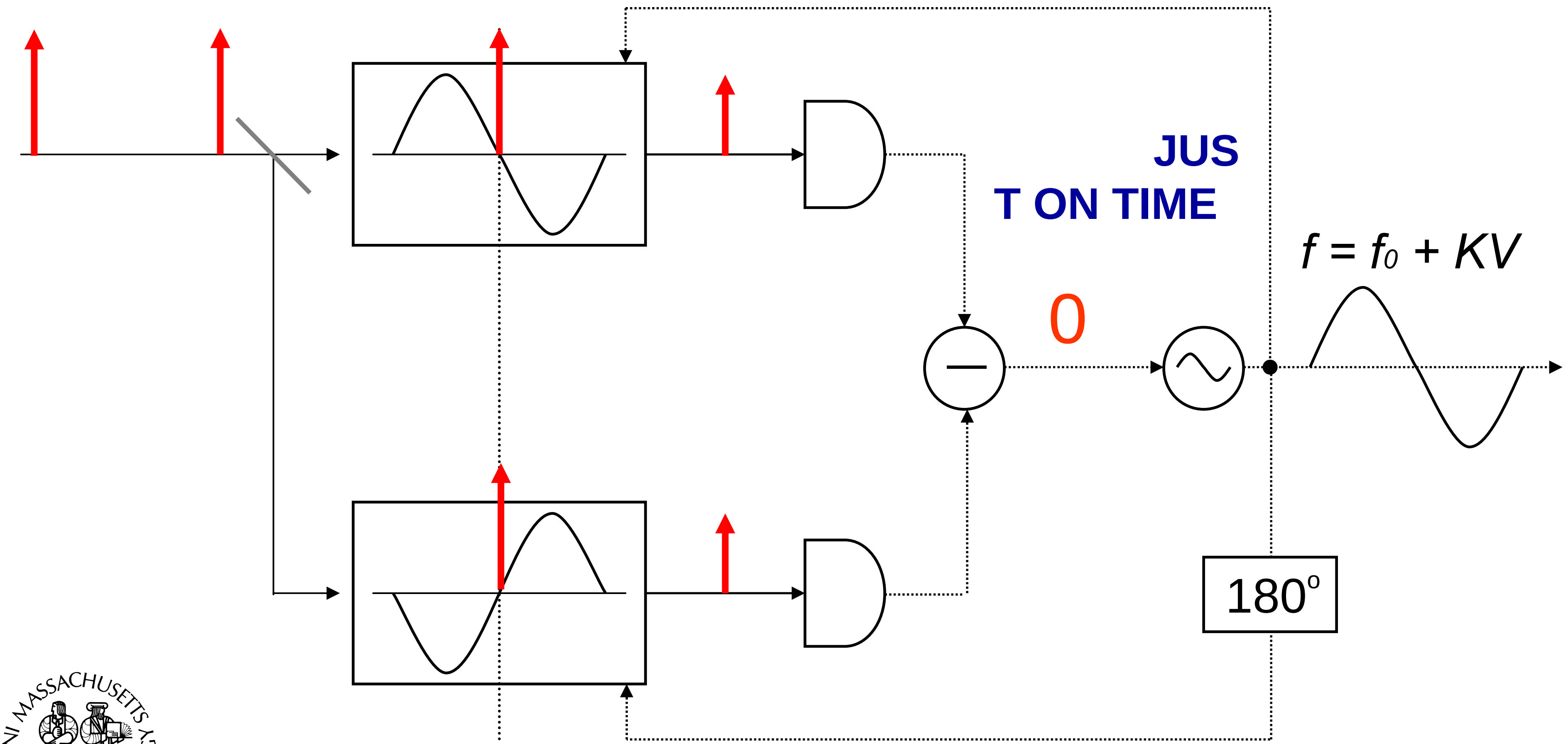
- **Amplitude modulators take "derivative" of the signal intensity**
- **Differentiation eliminates effect of detector problems**



Locking the RF to the Pulse Train

Convert timing info to intensity imbalance

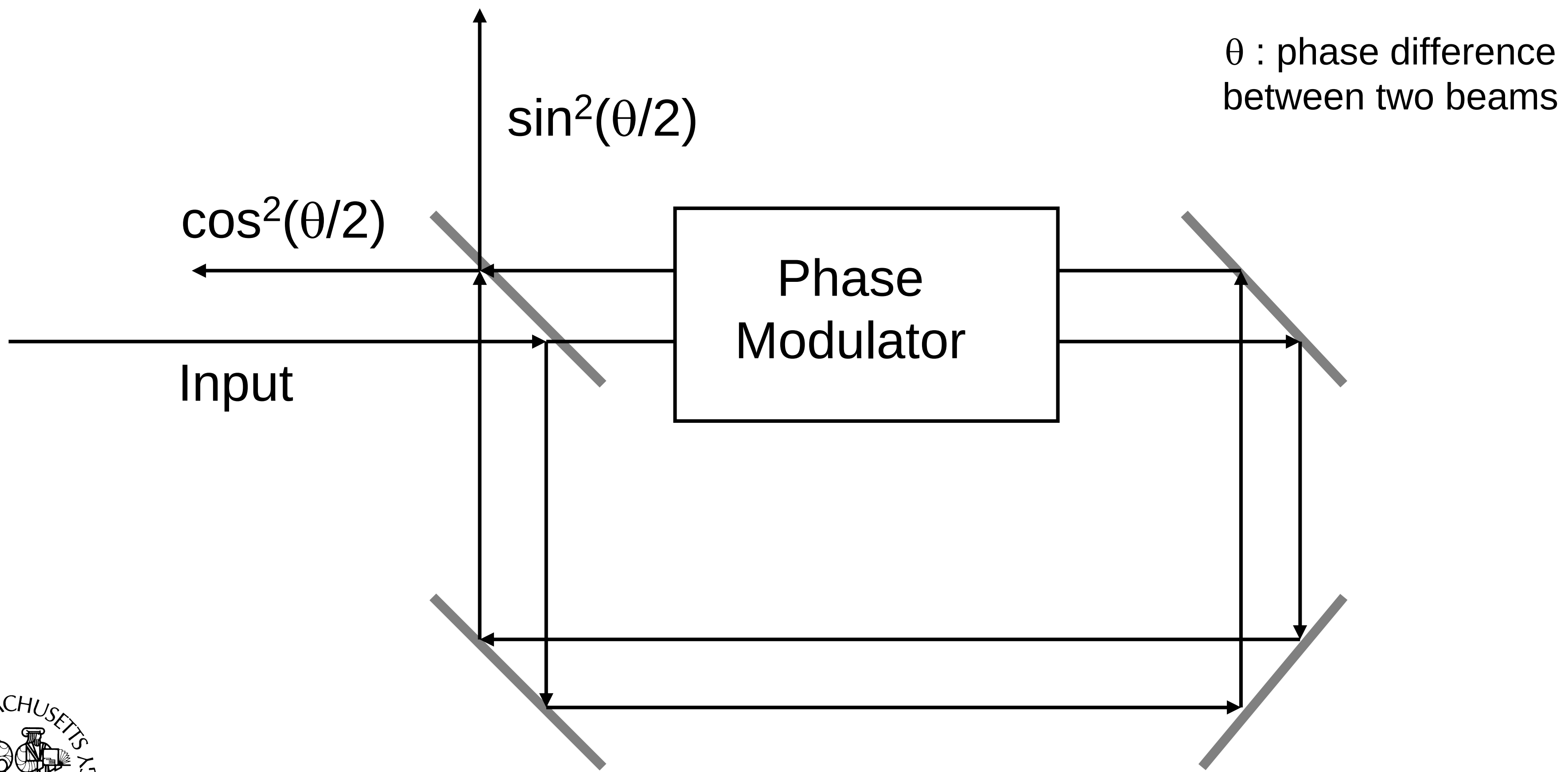
PLL locks the VCO to the pulse train



Implementation

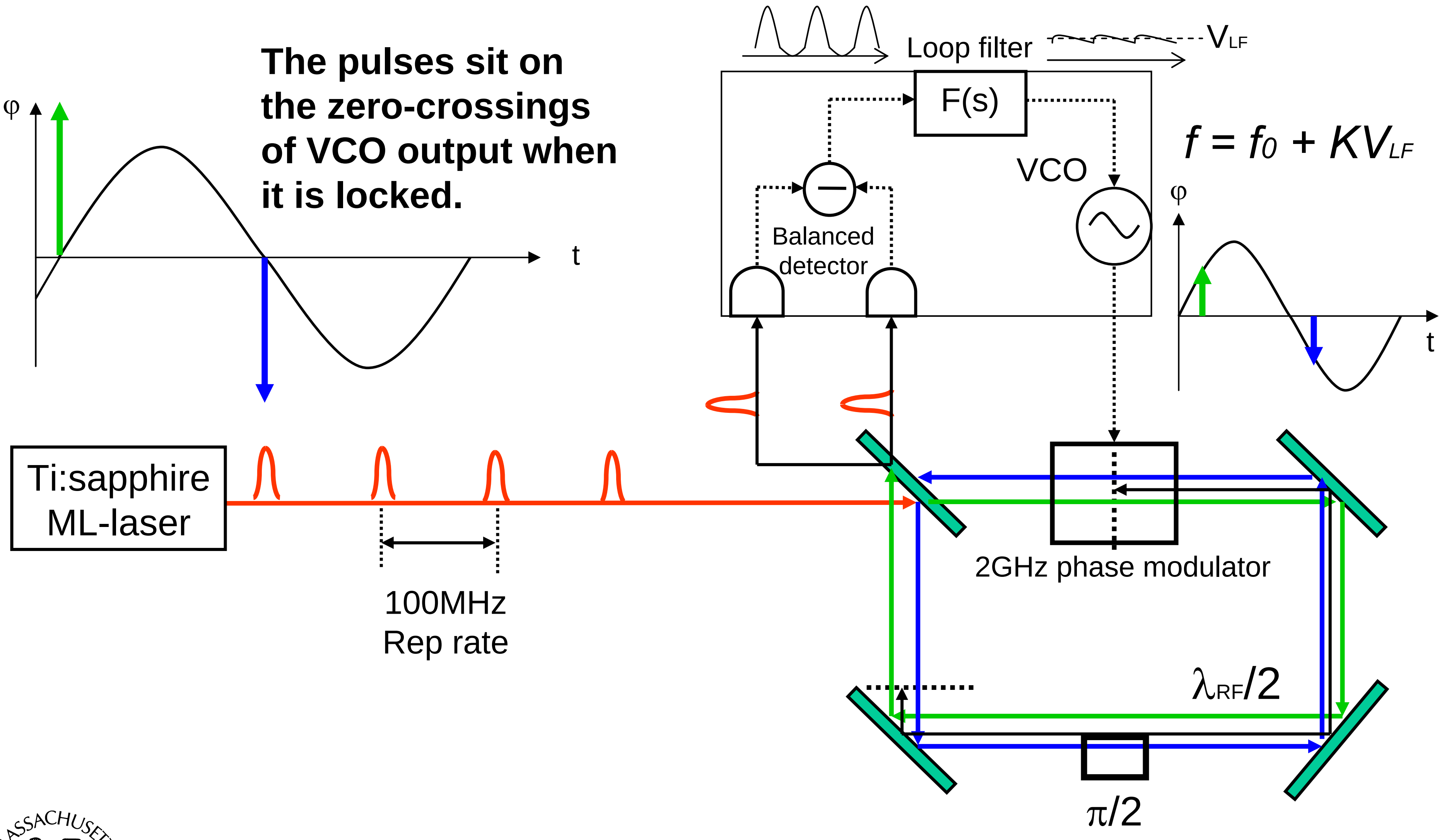
Use a Sagnac-loop interferometer for interferometric stability

Eventually use a fiber loop



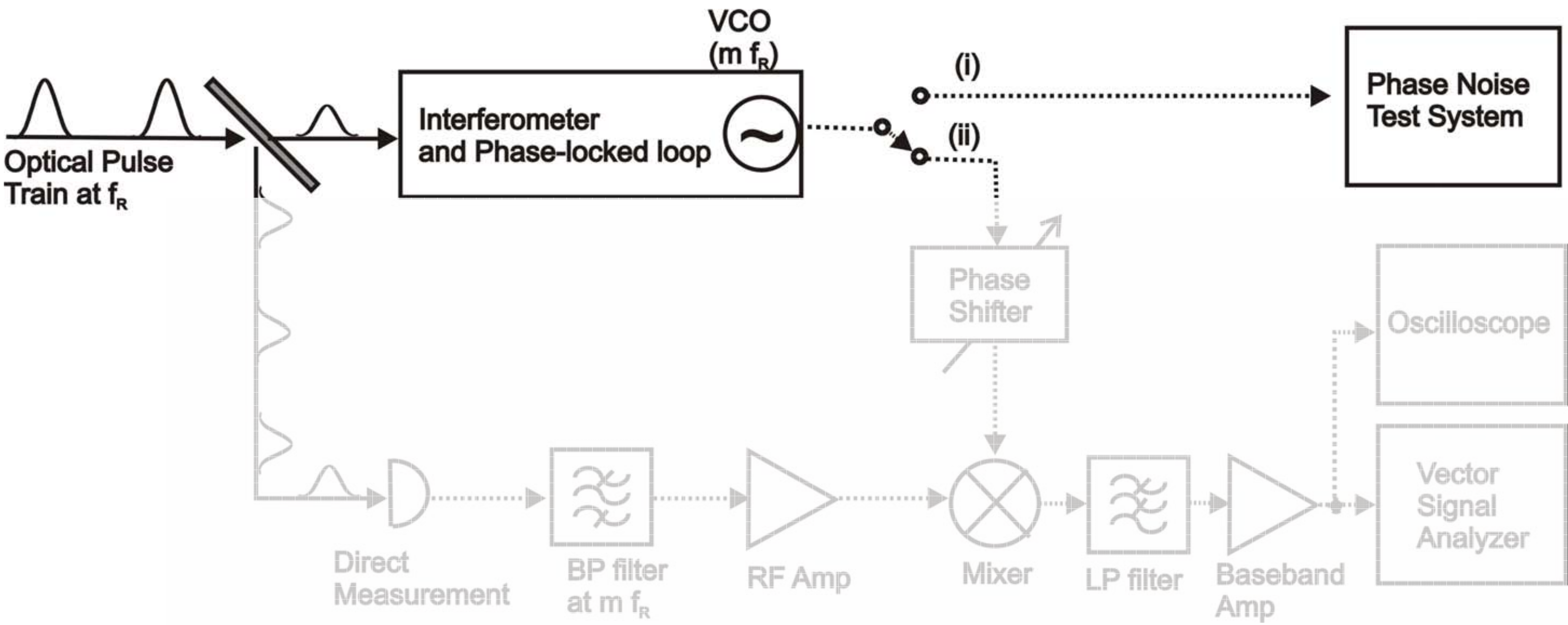
Implementation

The pulses sit on the zero-crossings of VCO output when it is locked.

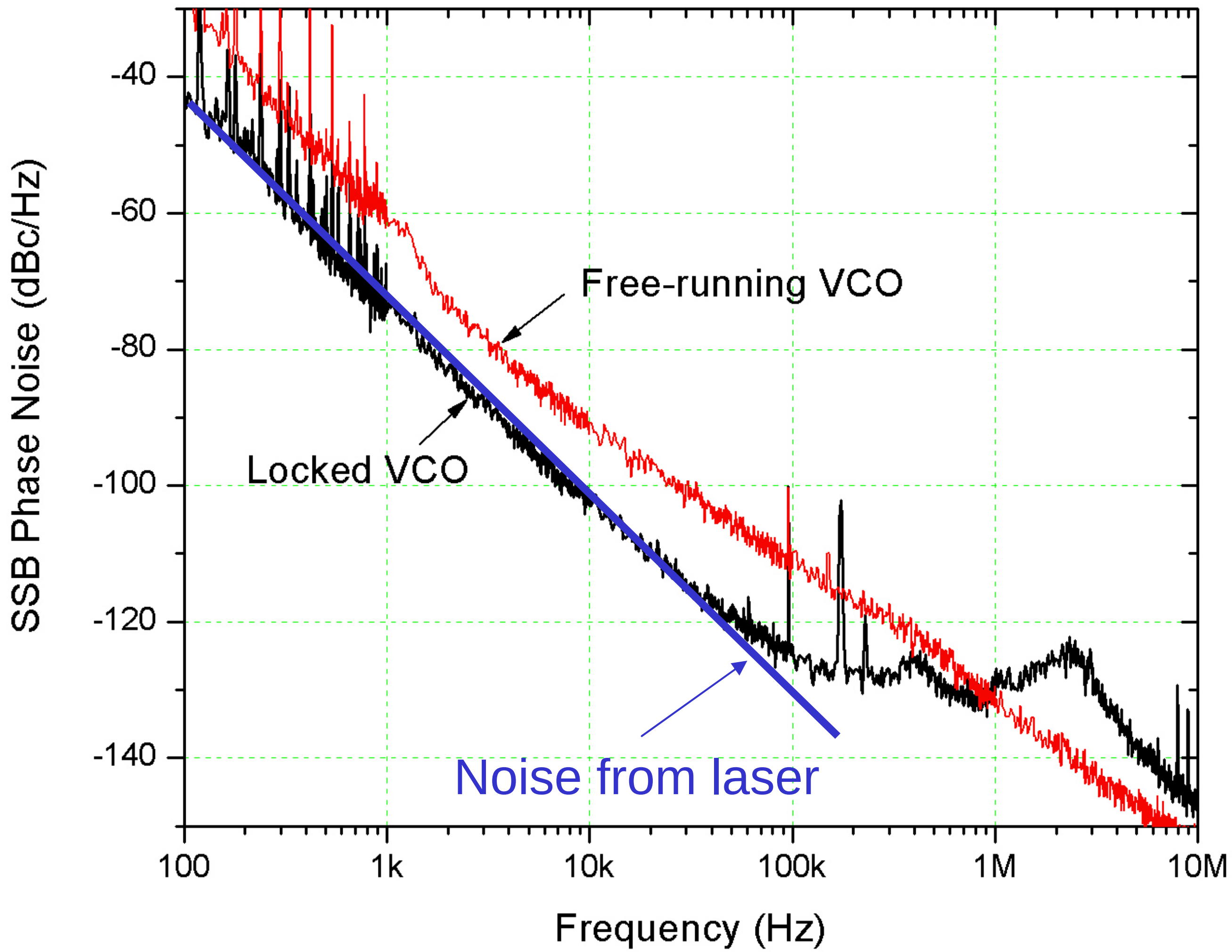


Testing the Scheme

1 - Phase Noise of the System
(laser noise present)

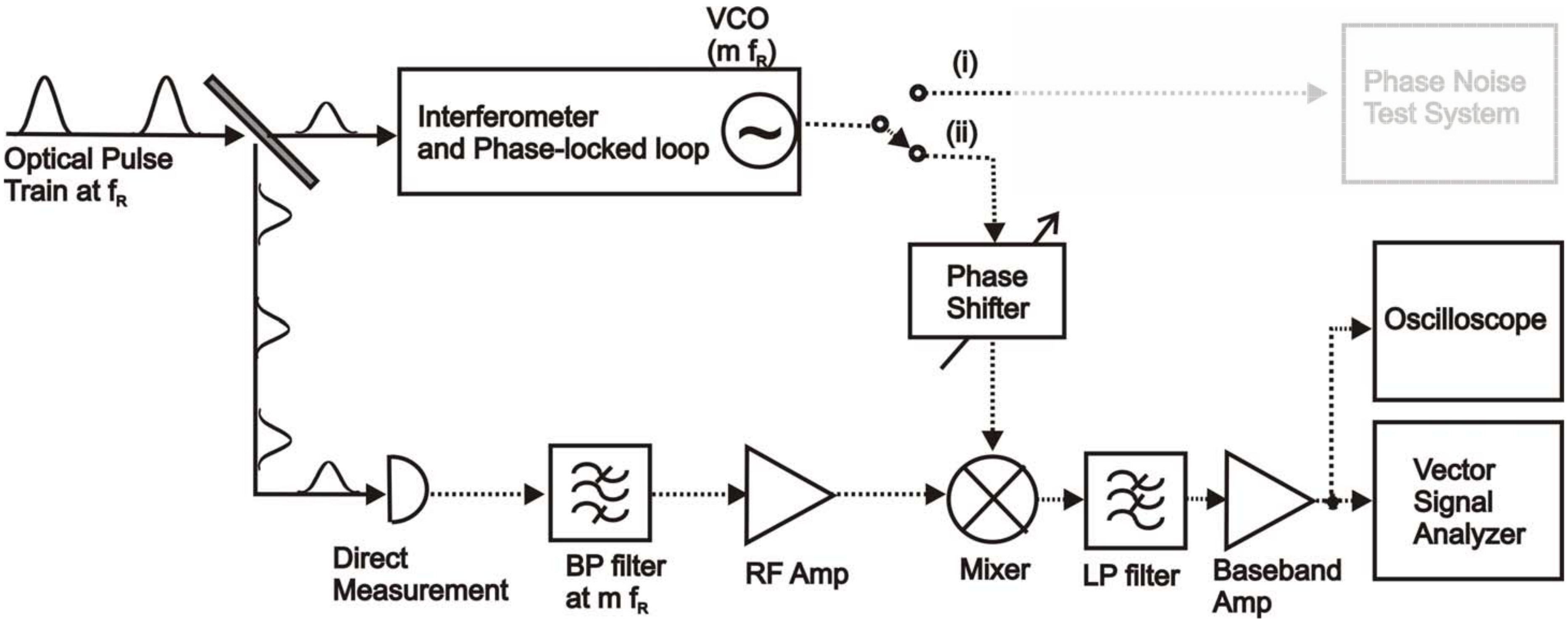


Measured Phase Noise

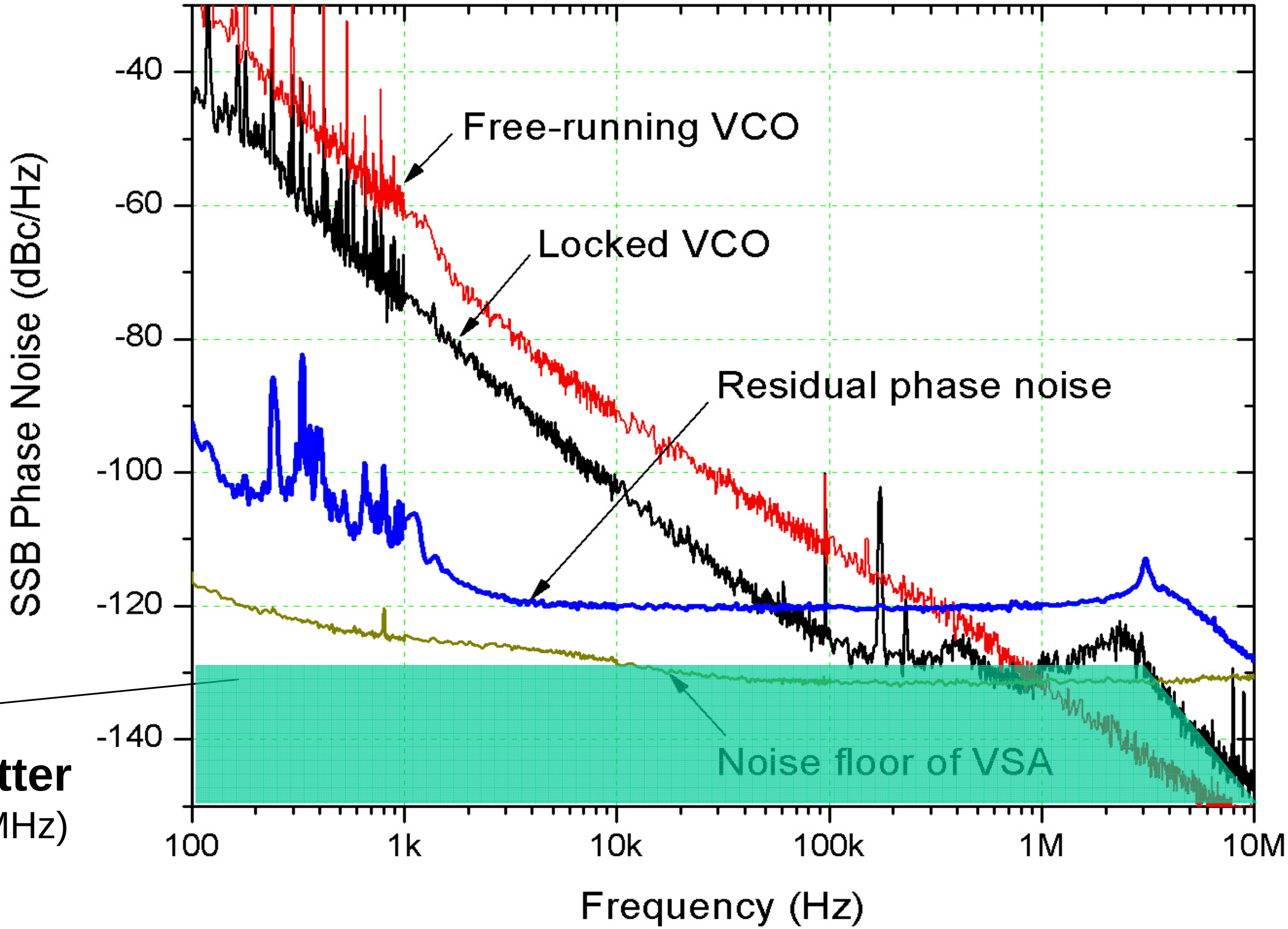


Testing the Scheme

2 - Residual phase noise (laser noise subtracted)



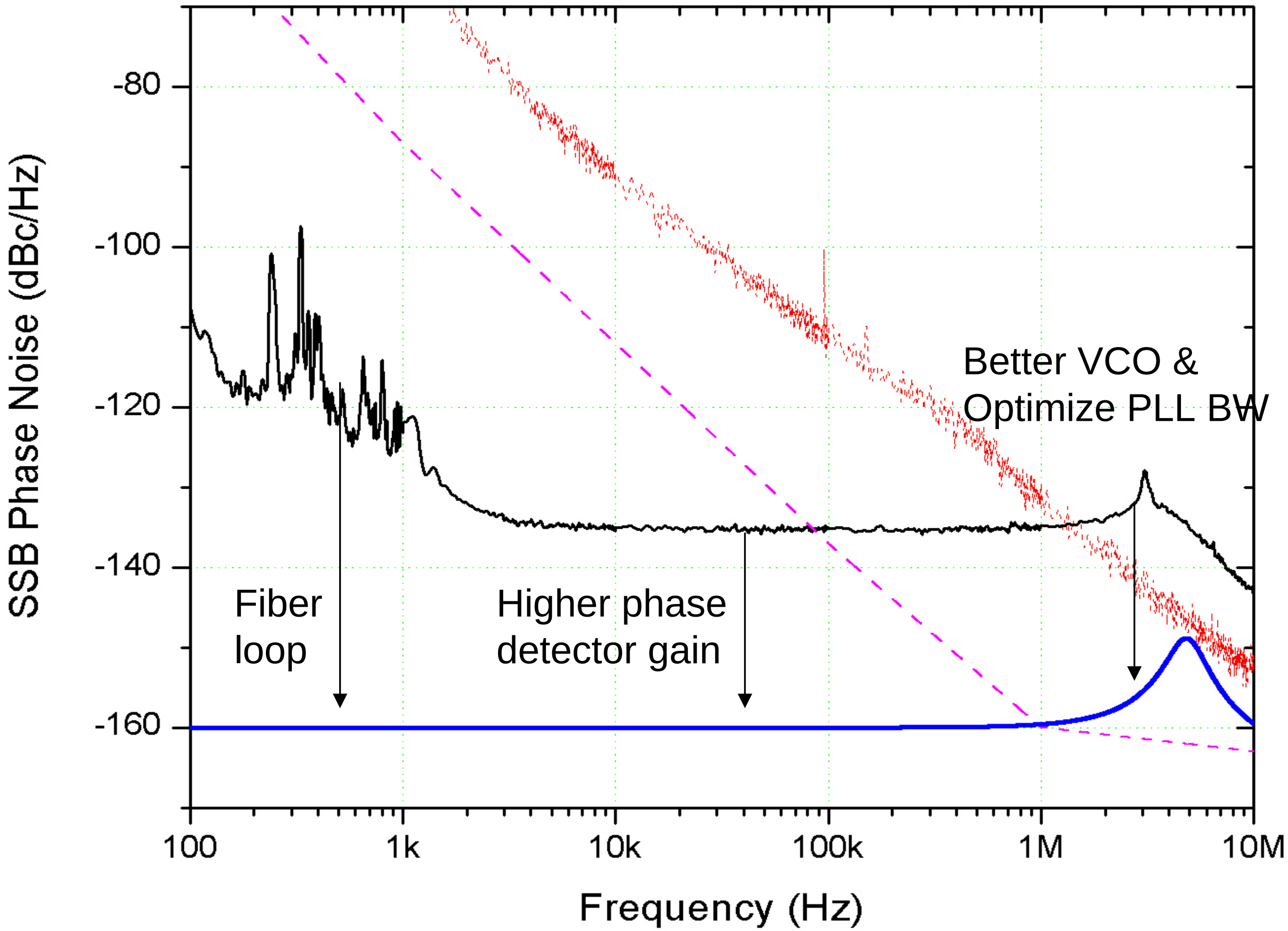
Measured Phase Noise



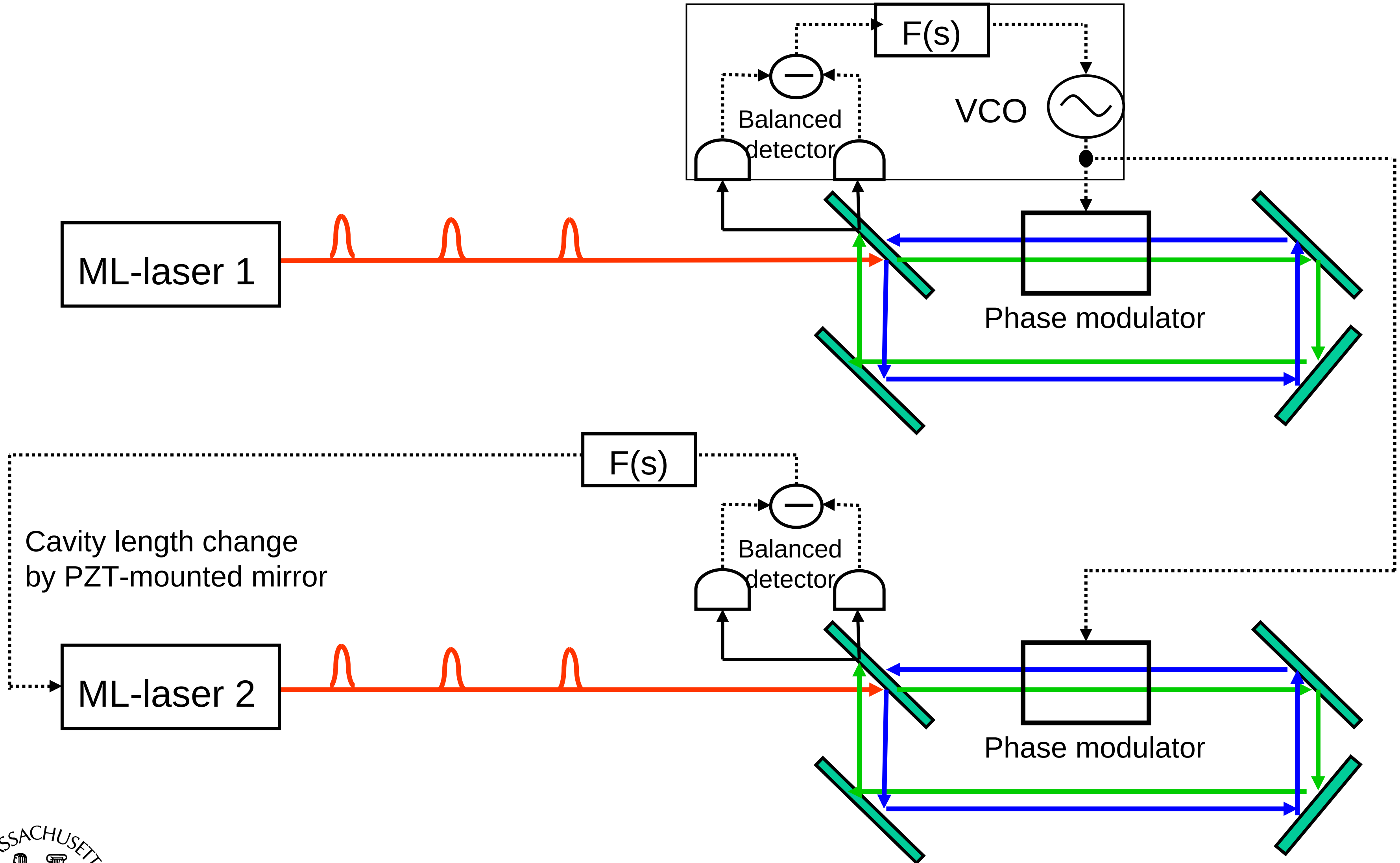
<60 fs
Timing jitter
(100Hz-10MHz)

J. Kim et al., Opt. Lett., in press (2004)

Toward sub-fs Timing Jitter



Modularity: Sync 2 lasers with common VCO



Master microwave oscillator

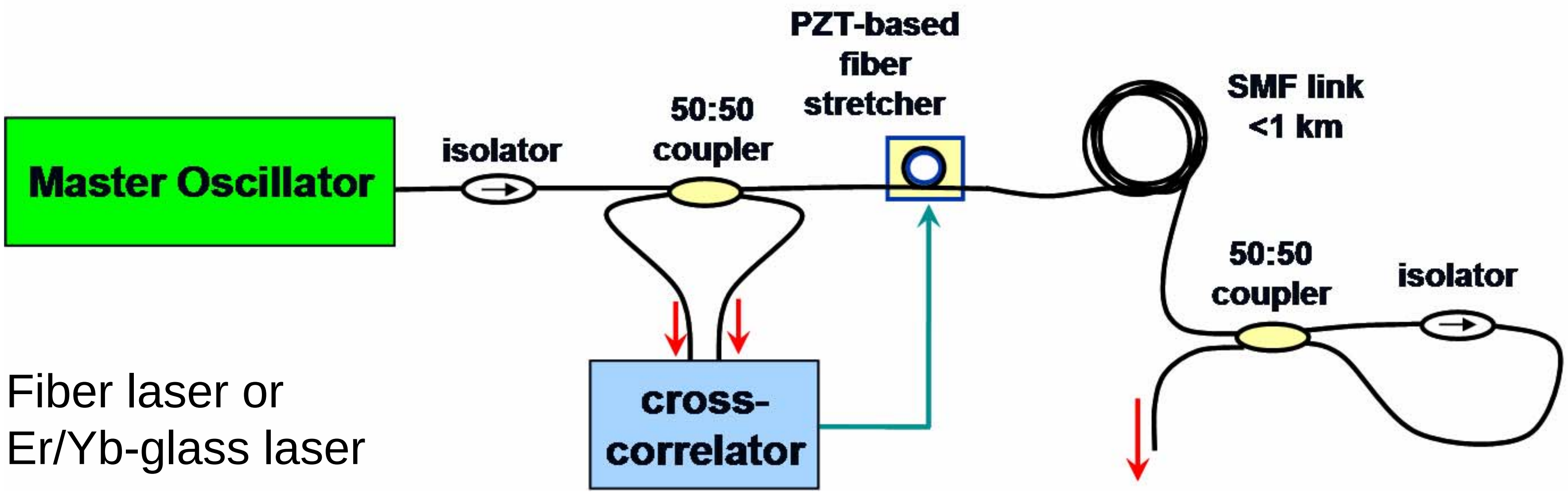
Locking and sync:

- laser to laser optically (< 1 fs)
- laser to RF (< 100 fs)

Timing-distribution *via* fiber-links

Low jitter modelocked lasers

Timing Stabilized Fiber Links (~1 km)



Fiber laser or
Er/Yb-glass laser

Assuming no fiber length fluctuations faster than 2L/c (~100 kHz)

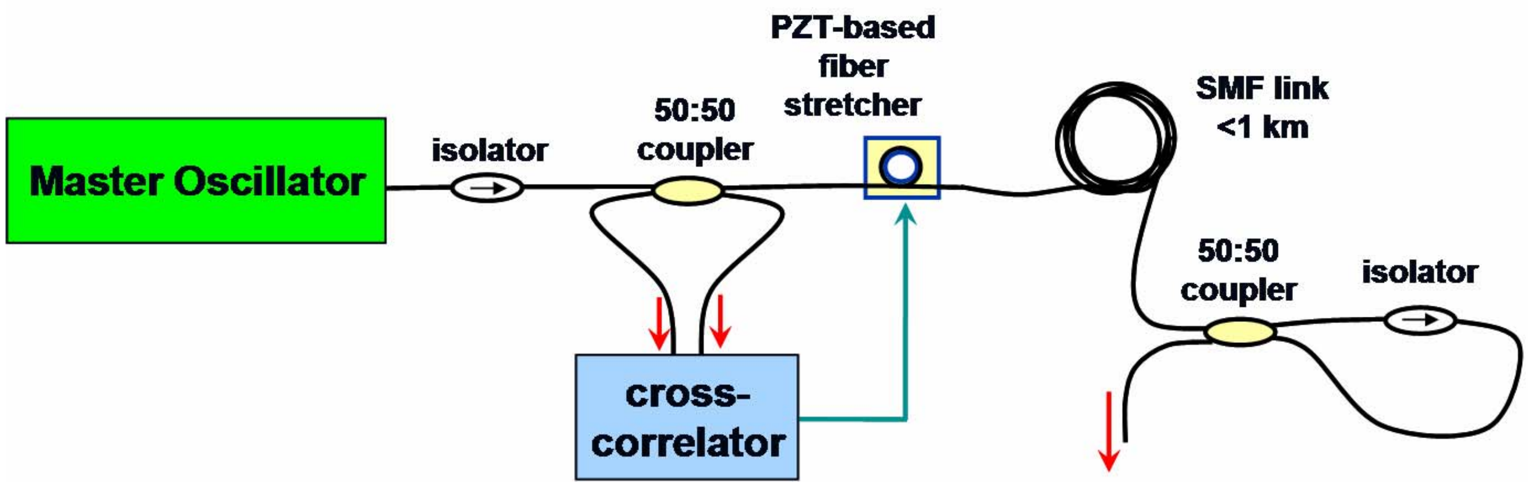
Thermal fluctuations: ~ 20 μm (~ 100 fs) over 1 km for 0.1°C

Timing Stabilized Fiber Links (~1 km)

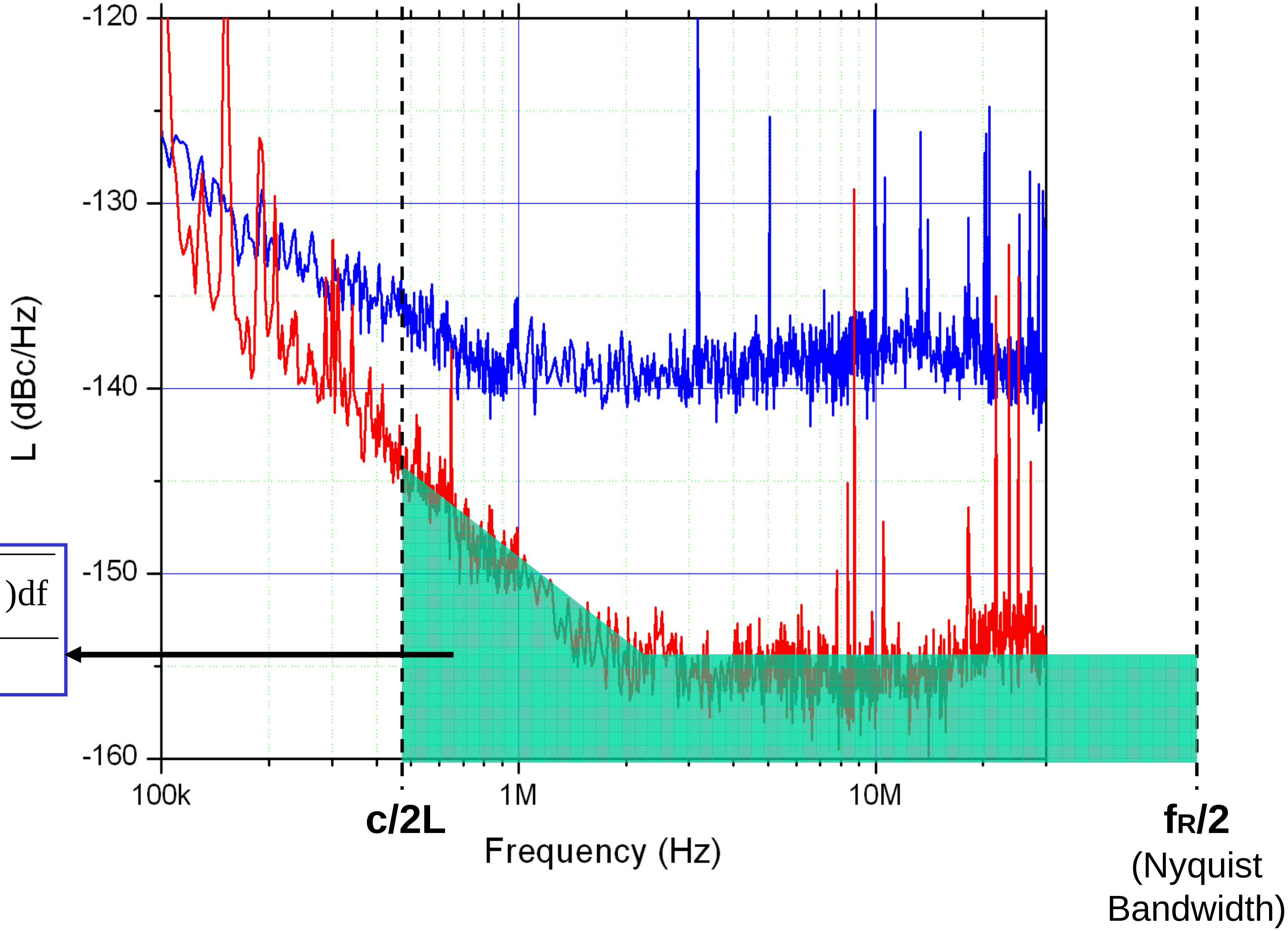
1. Build two copies and cross-correlate the outputs

2. Demonstrate few fs jitter operation stable over days

3. Test in accelerator-like environment



Phase Noise of a Free-running Laser



$$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)\,df}}{2\pi f_0}$$

Master microwave oscillator

Locking and sync:

- laser to laser optically (< 1 fs)
- laser to RF (< 100 fs)

Timing-distribution *via* fiber-links

Low jitter modelocked lasers

Development of Low Jitter, Robust Lasers

- Very low jitter (< 10 fs) mode-locked lasers needed.
- Reliable, long-term operation without interruption.
- No satisfactory source has been demonstrated yet.
- Which laser is ideal? Work at MIT is on:
  - Er-fiber lasers
  - Yb-fiber lasers (similariton or stretched-pulse?)
  - Er/Yb-glass lasers
- Optimal laser parameters need to be identified:
  - Pulse duration
  - Repetition rate
  - Central wavelength

Stretched-pulse Er-fiber Lasers (1550 nm)

- Long gain relaxation time => low jitter

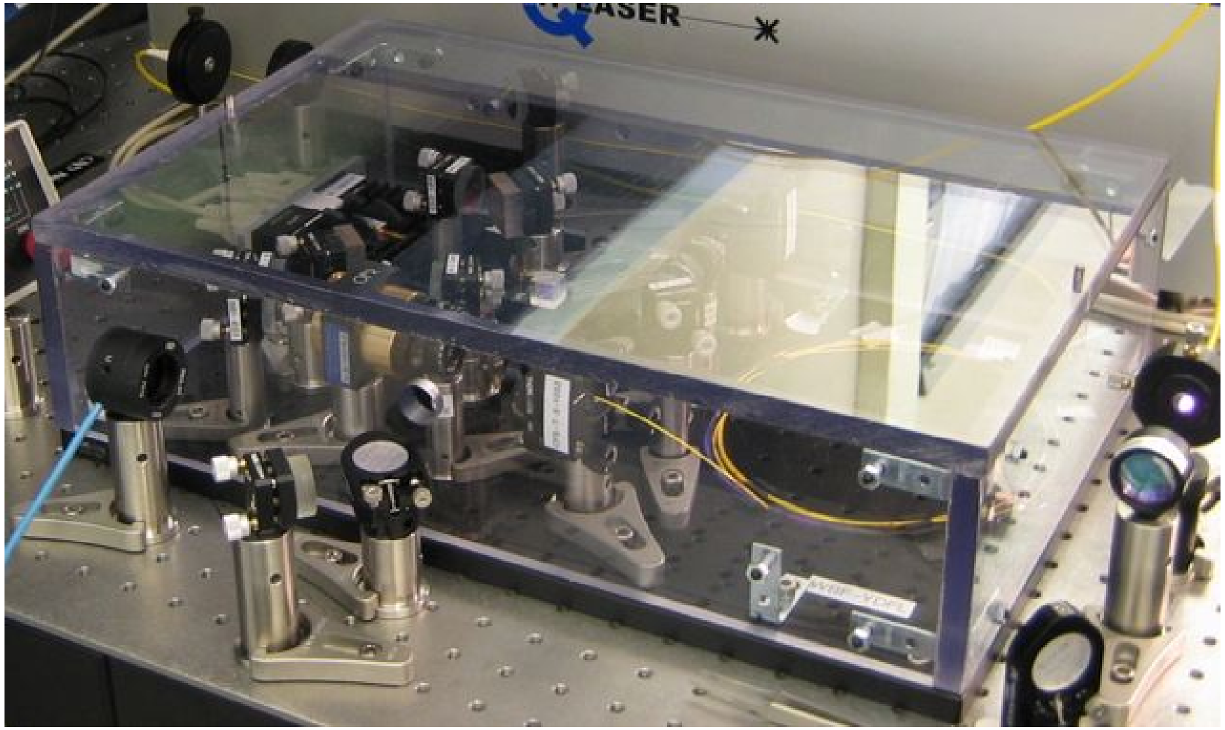
(Ippen, *et al.*, *circa* 1994)

- 100 fs pulses, excellent long-term stability (for weeks), very low cost

- Can operate at zero dispersion -- to minimize (Gordon-Haus) jitter

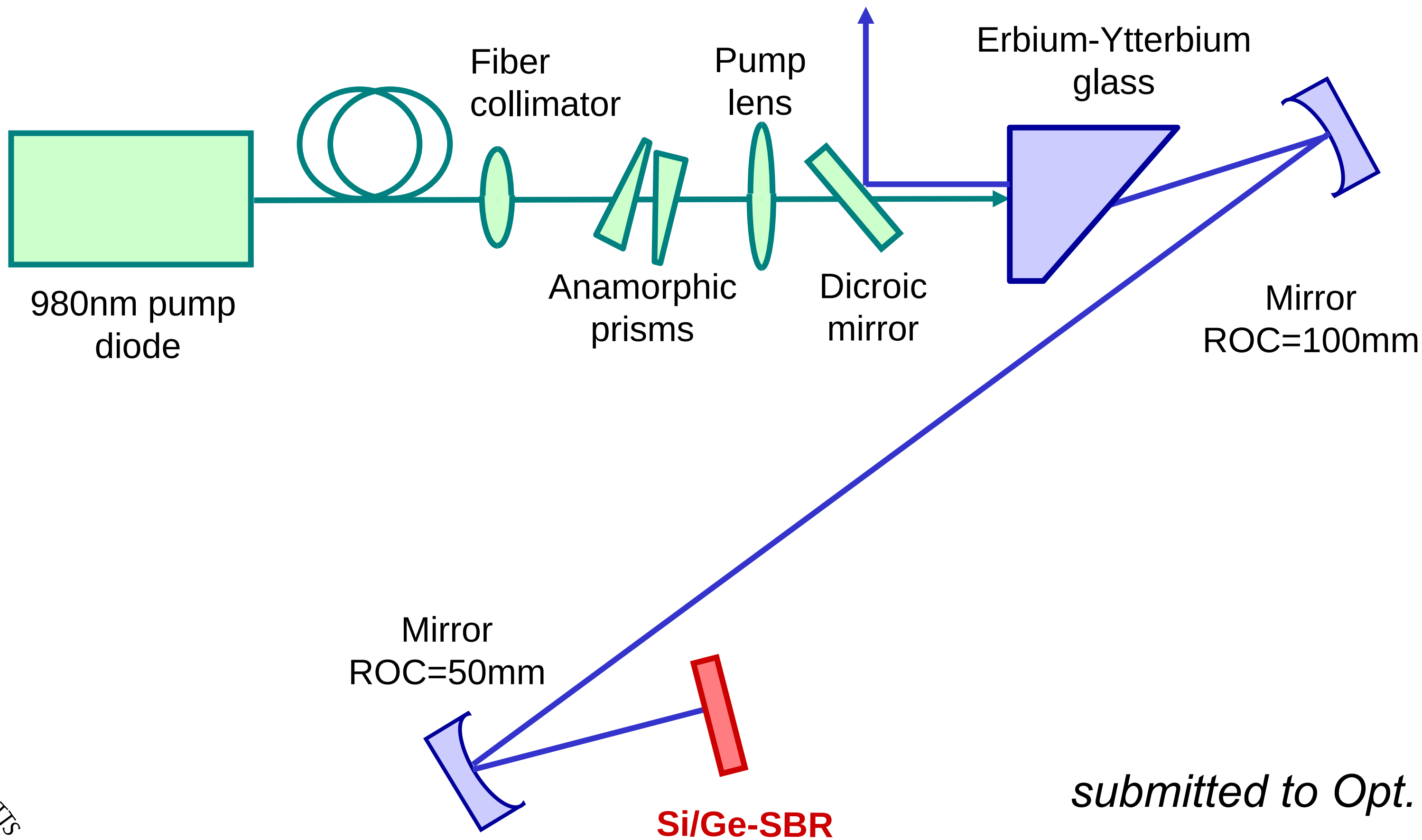
Yb-fiber Lasers (1040 nm)

- Long lifetime as well, even better stability.
- Zero dispersion (stretched-pulse) or large dispersion (similariton)
- Similaritons are robust against nonlinearity   (Ilday, Wise, PRL, 2004)



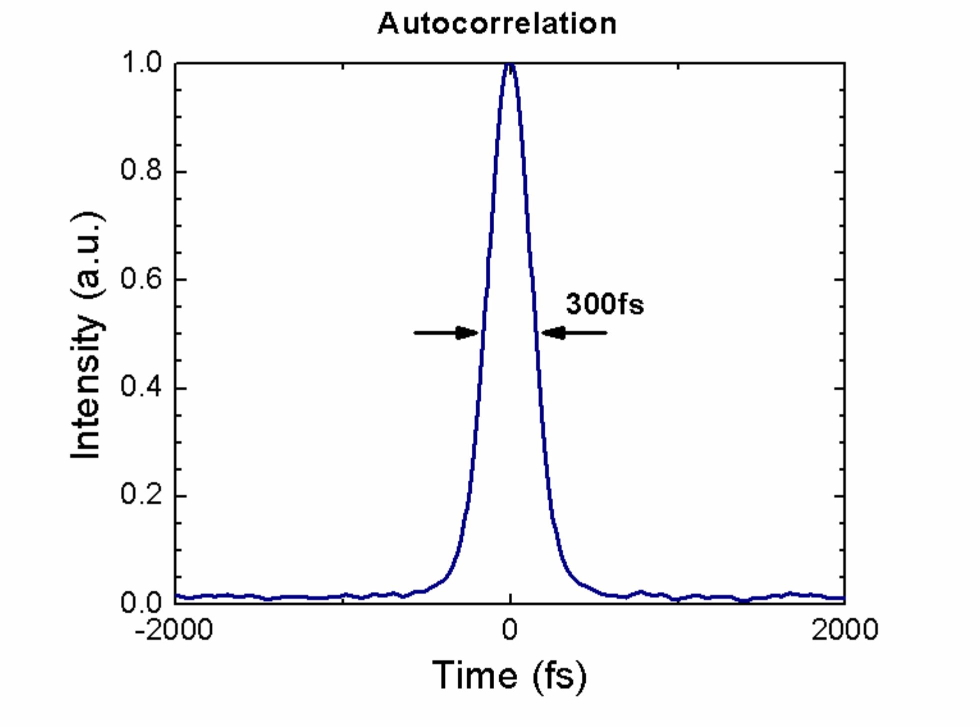
Er/Yb:glass Laser (1550 nm)

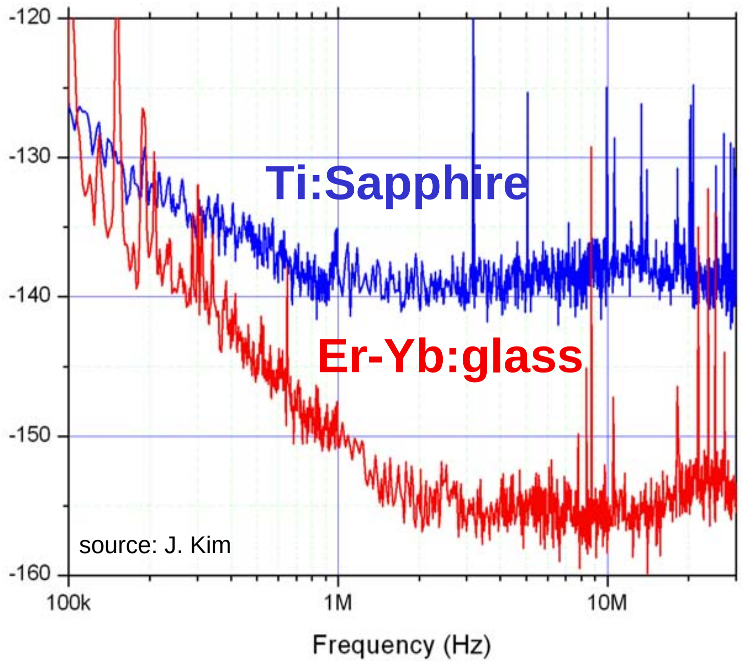
- Long gain relaxation time (> ms) reduces jitter



submitted to Opt. Lett.

Er/Yb:glass Laser (1550 nm)





220 fs pulses, self-starting operation

Low timing jitter (preliminary result)

Assessment and "To-do" List

- ✓ Master microwave oscillators commercially available
- ✓ Sub-fs optical sync between lasers demonstrated
- ✓ Sub-100 fs sync between RF-signal and pulse train achieved, to be improved to ~ 1 fs precision
- Timing-stabilized (< 10 fs) fiber links under development
- Developing fiber and solid-state lasers for ultra-low jitter, reliable operation

Acknowledgment

ONR
AFOSR
NSF
MIT Bates Linear Accelerator Center