

# **Electro-optic Spectral Decoding Measurements at FLASH**

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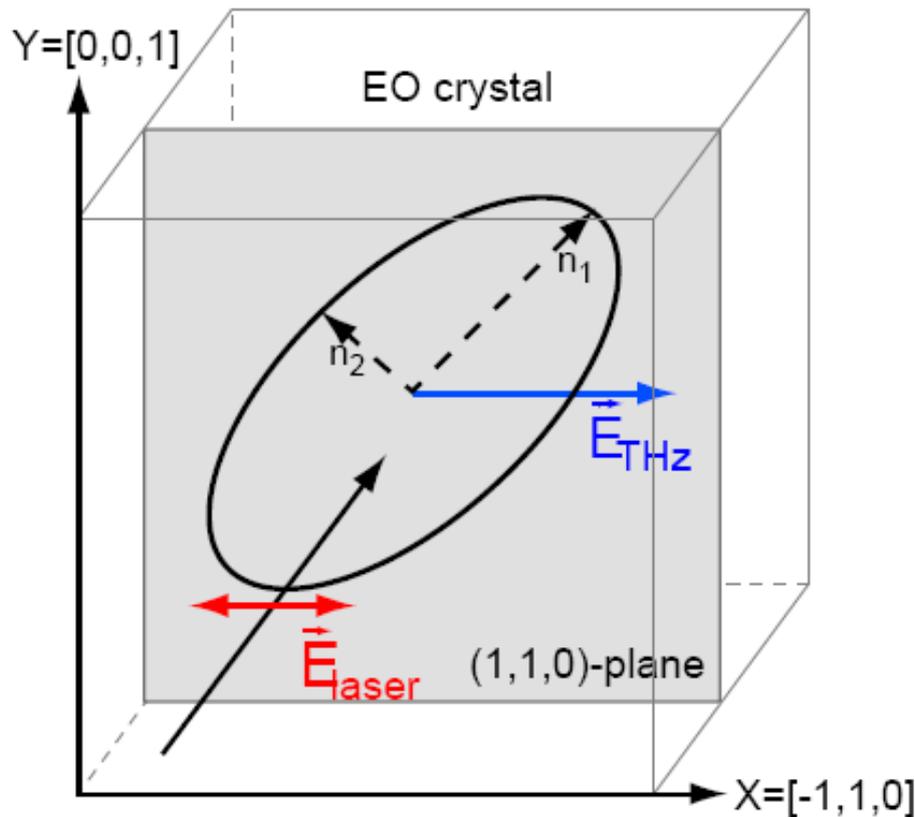


# Motivation

- Development of a robust online bunch length monitor for FLASH and XFEL
- Transition from a prototype to a user friendly system
  - Integration in the control system
  - Long term operation
  - High timing stability ( $< 10$  fs)
  - Compatibility with the optical synchronization system
  - High temporal resolution
  - Maintenance free

# Bunch length detection principle

linear electro-optic effect: induced birefringence by the THz field



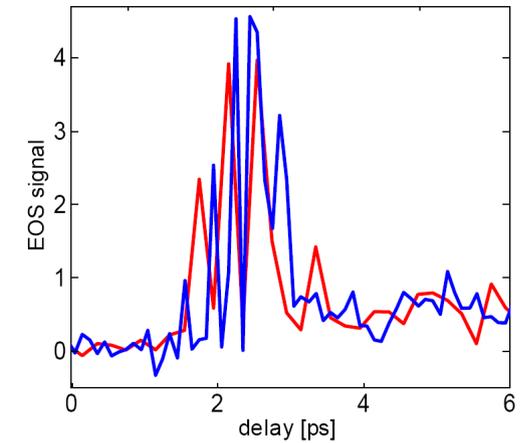
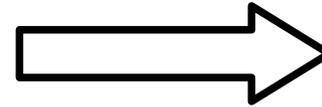
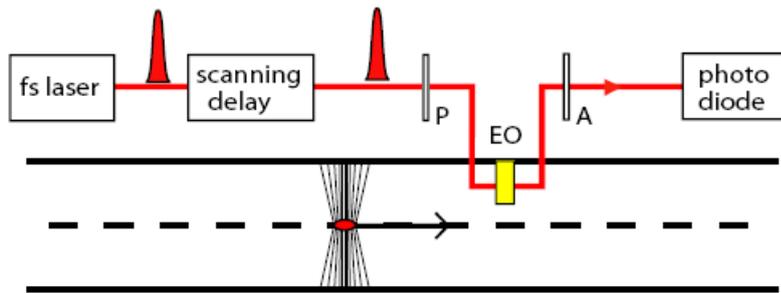
phase retardation for small signals:

$$\begin{aligned} \Gamma &= \frac{\omega d}{c} (n_1 - n_2) = \\ &= \frac{\omega d}{c} n_0^2 r_{41} E_{\text{Thz}} \end{aligned}$$

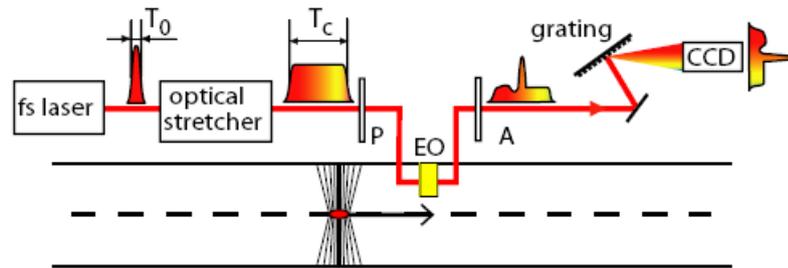
courtesy: B.Steffen

# Electro-optic techniques

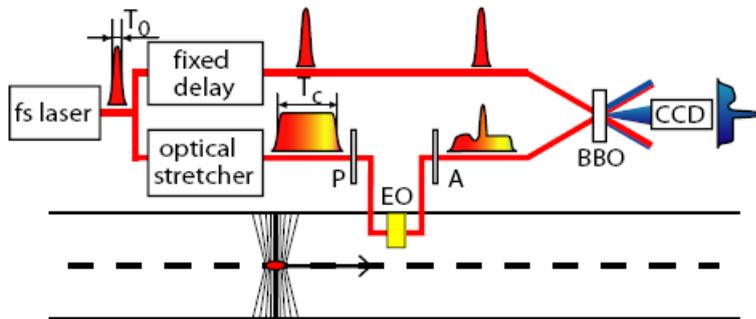
## 1) Electro-optic sampling



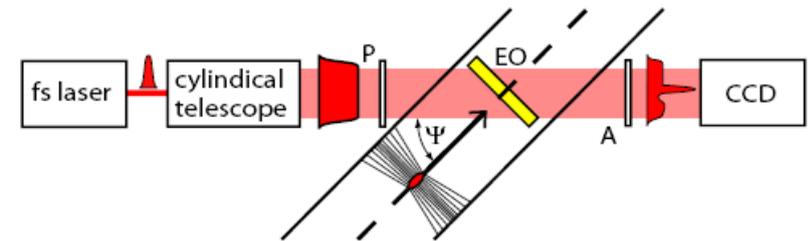
## 2) Electro-optic spectral decoding (EOSD)



## 3) Electro-optic temporal decoding (EOTD)

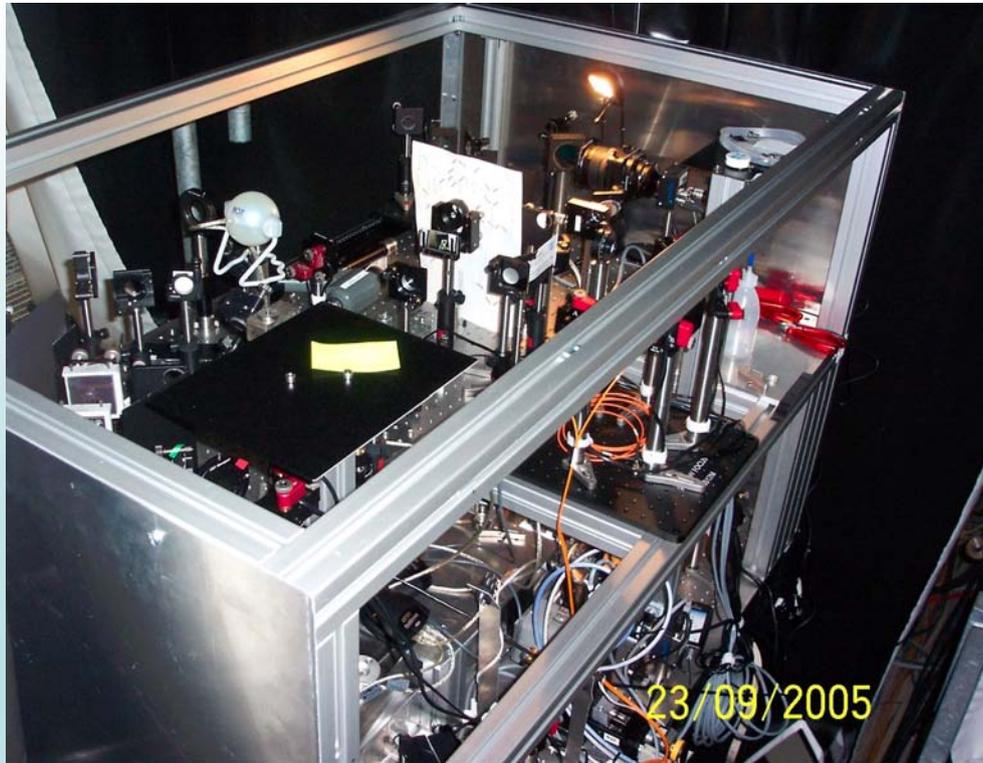


## 4) Spatially resolved EO (TEO)



courtesy: B.Steffen

# EO diagnostic setups @ 140 m before the shutdown 2007

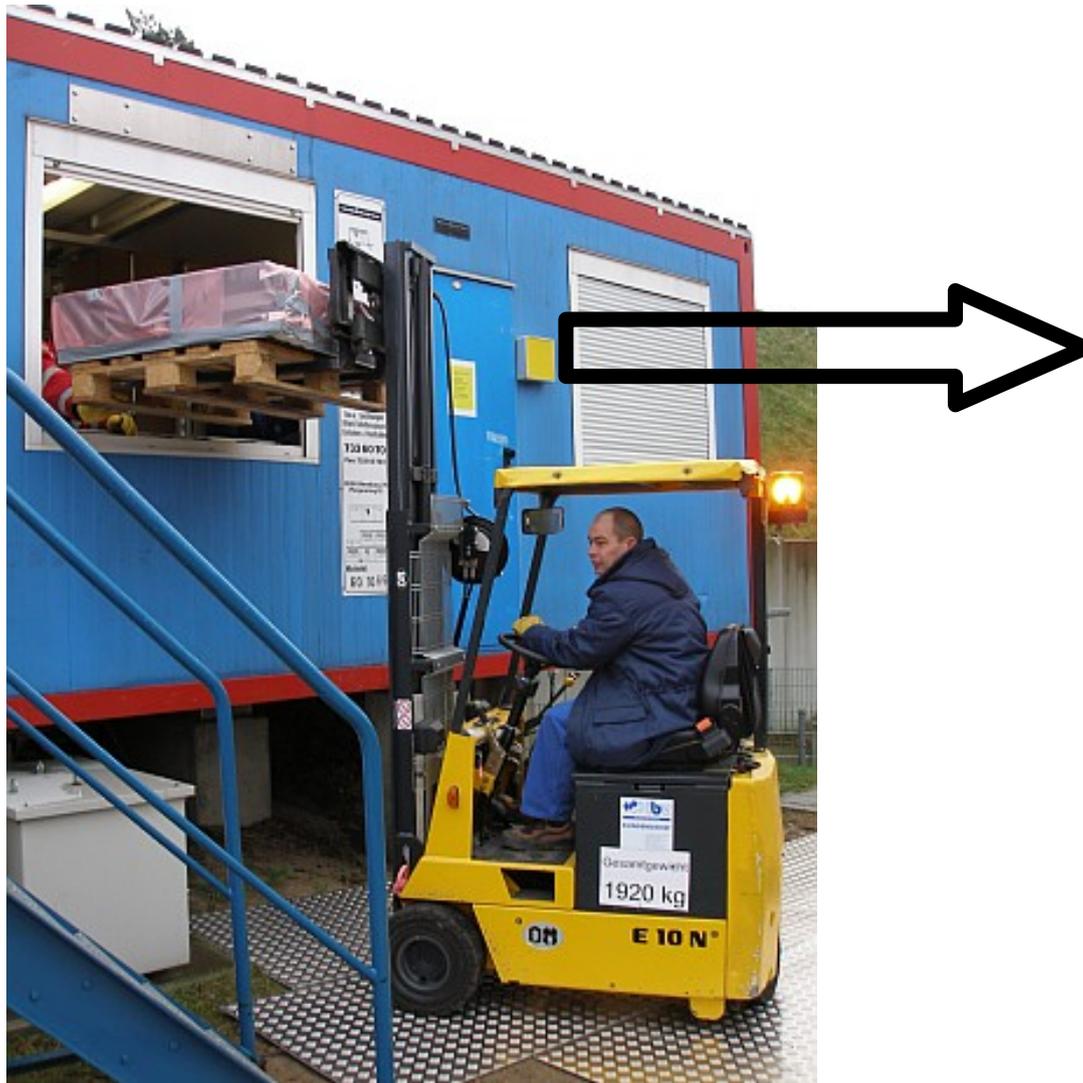


courtesy B.Steffen

## Benchmarking EO-experiments and simulations

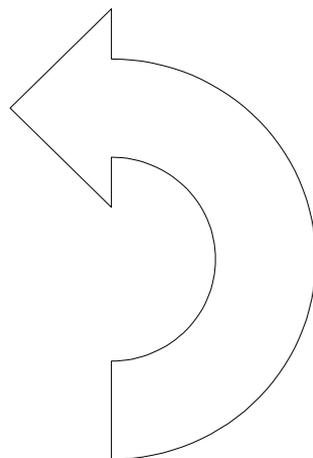
- G. Berden et. al., Phys. Rev. Lett. **99**, 164801 (2007)
- B. Steffen, PhD Thesis, DESY-THESIS-2007-020 (2007)
- S.Casalbuoni et. al., Phys. Rev. ST Accel. Beams **11**, 072802 (2008)

# Status of the EO setup, 30 January 2007

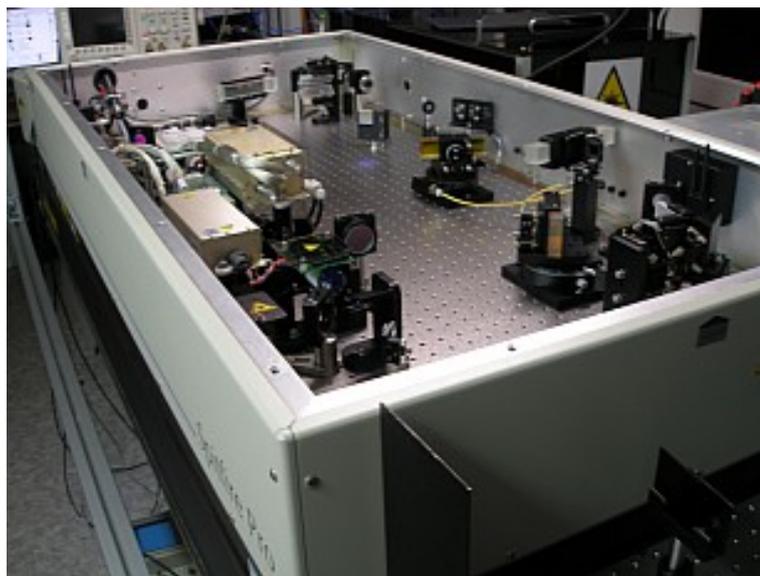
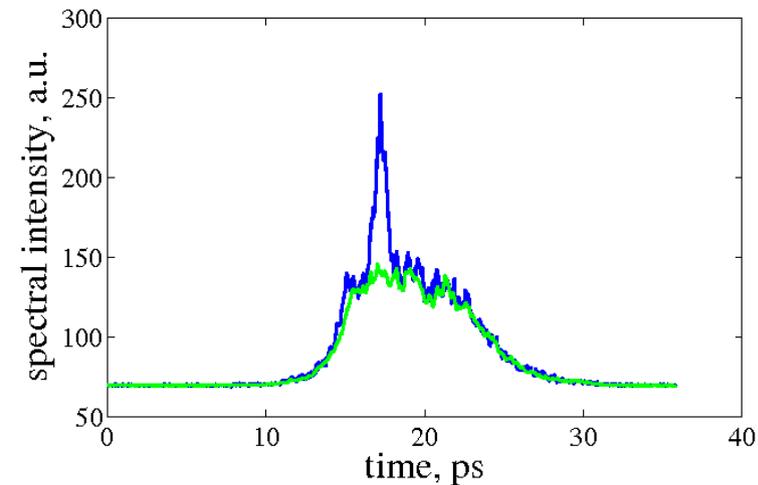


# Status of the EO setup, February-March 2007

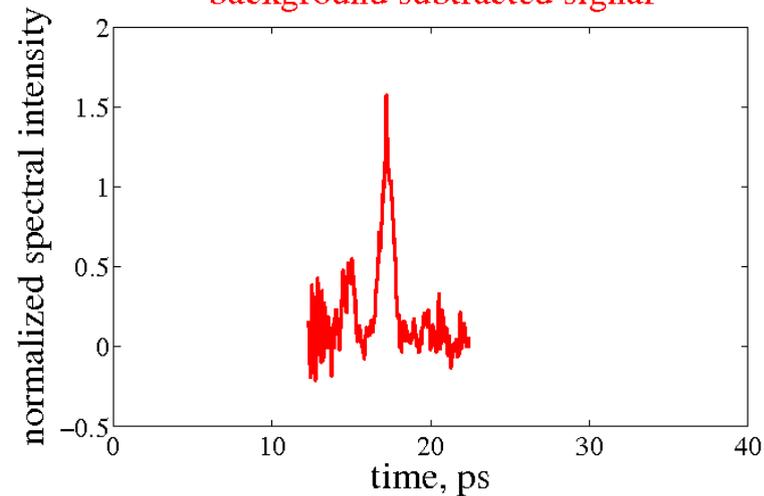
EOSD of CTR with 0.5 mm ZnTe in vacuum



with laser and CTR radiation  
without CTR radiation



background subtracted signal



typical FWHM ~ 400-900 fs  
-2° off-crossed polarizers

# April~September 2007



# Approaches for the EO diagnostic

Short term: Commercially available oscillators

Long term: Yb-fiber laser

# EO – setup reloaded

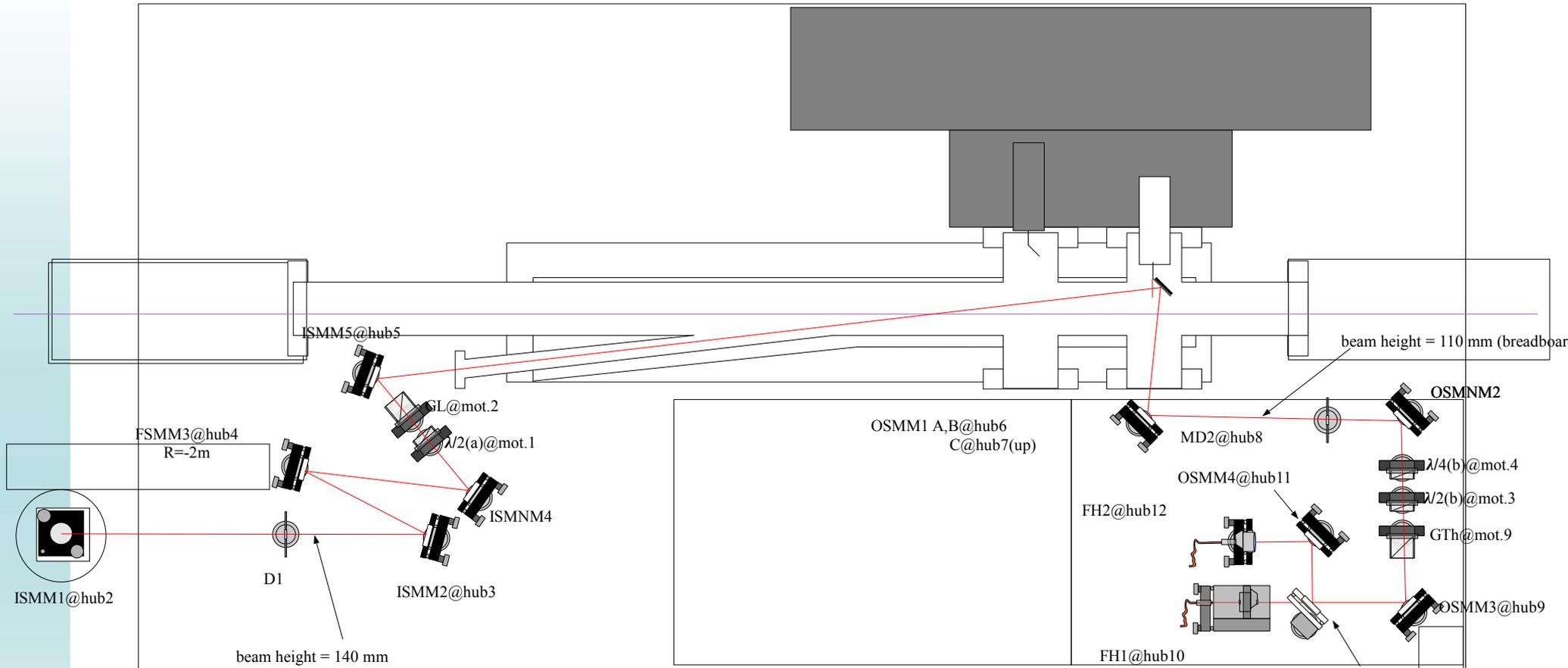
New:

1. Ti:Sapphire oscillator -Micra -5 (Coherent)
2. Synchronization electronic
  - phase detector
  - DSP control
  - piezo driver
  - stepper motor control
  - vector modulator
3. Optics for the tunnel
4. Camera server for remote control

retained:

1. Vacuum chamber and the motorized crystal holder
2. Pico motors control for the optomechanics

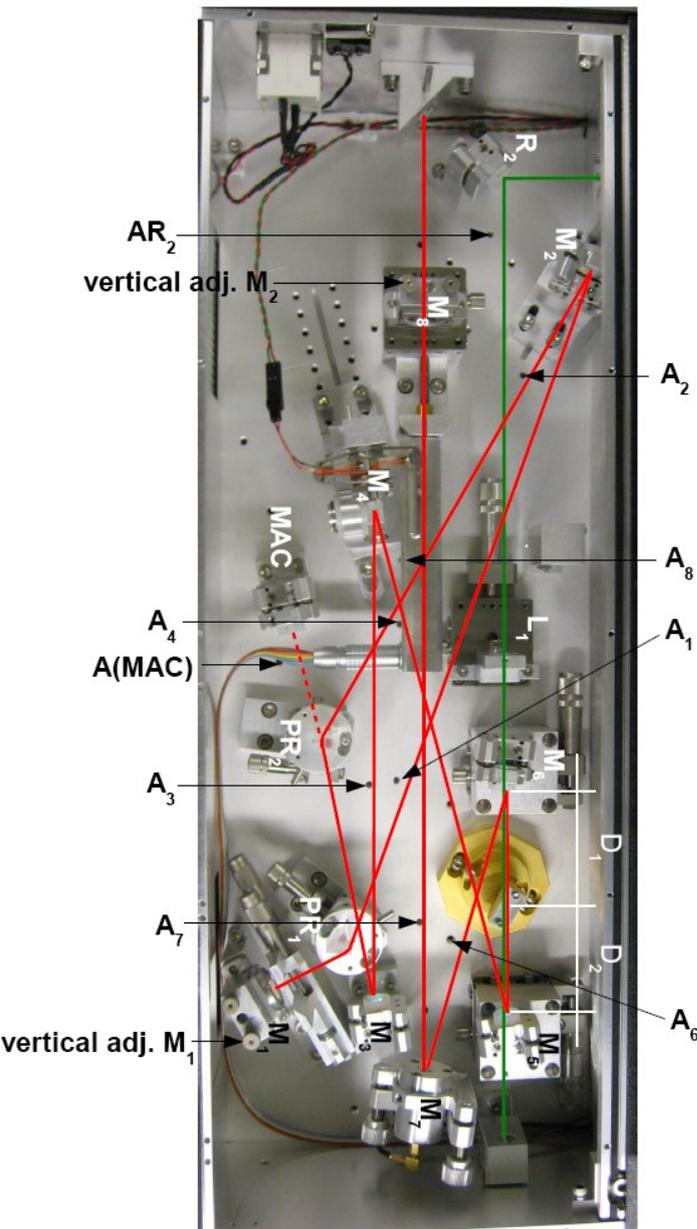
# EO – setup reloaded



FM1 (Doocs /or manual from the tunnel o



# Parameters of the EO-setup:



- Ti:Sa oscillator:

$$P_{ML} = 460 \text{ mW}, \lambda_0 = 800 \text{ nm}, \Delta\lambda_{FWHM} = 60 \text{ nm}$$

- EO crystal – 175  $\mu\text{m}$  GaP:

- Resolution limits:

TO resonances:  $\sim 200 \text{ fs}$  (FWHM)

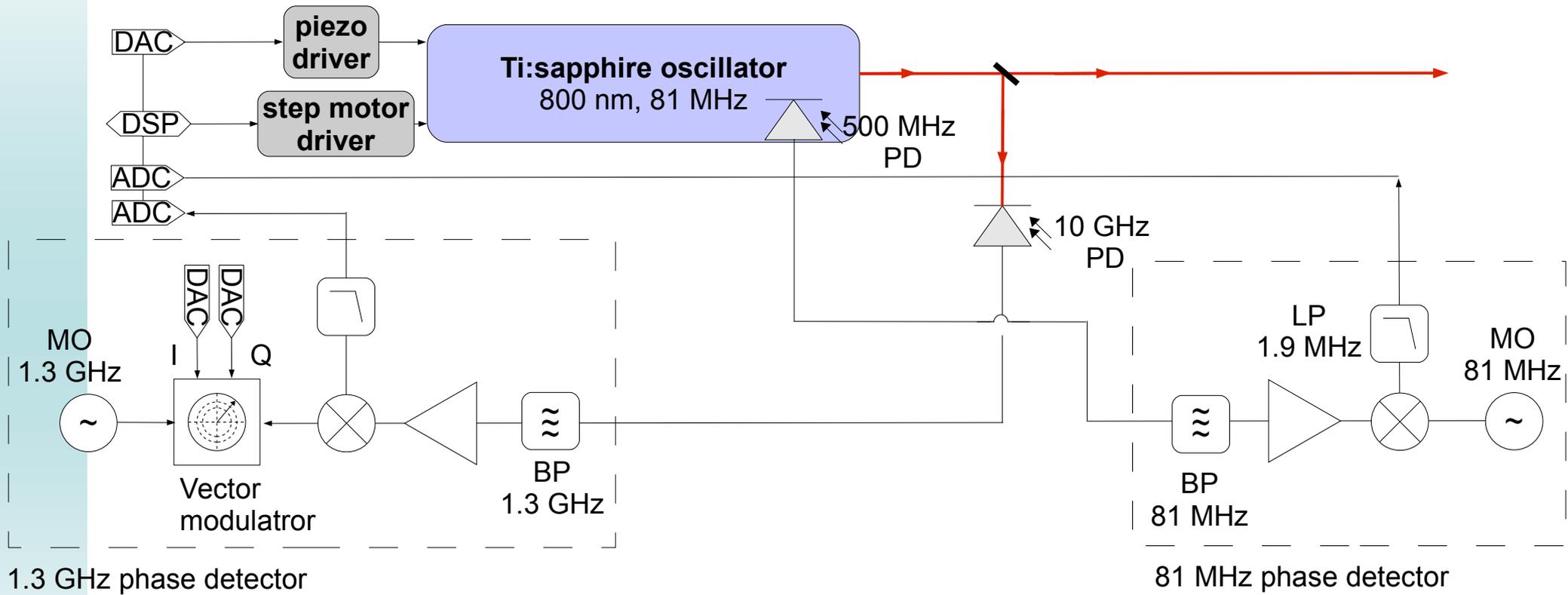
chirp (20 fs  $\rightarrow$  3 ps):  $\sim 250 \text{ fs}$  (FWHM),

overall resolution  $< 320 \text{ fs}$  (FWHM);

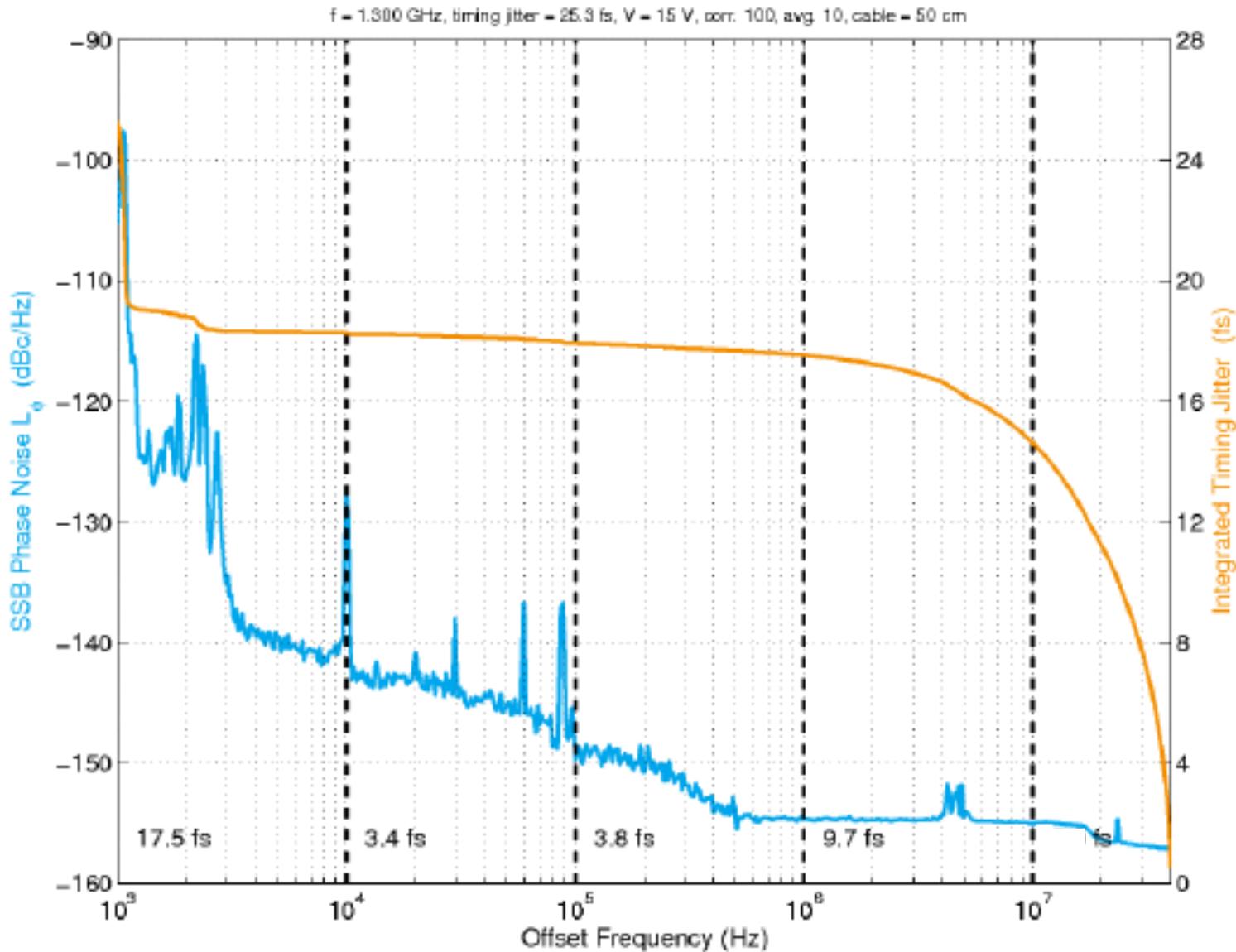
resolution of the spectrometer: 0.12 nm/pix

- Sensitivity to wavelength shift: 55 fs/nm

# Layout of the Ti:Sapphire RF synchronization



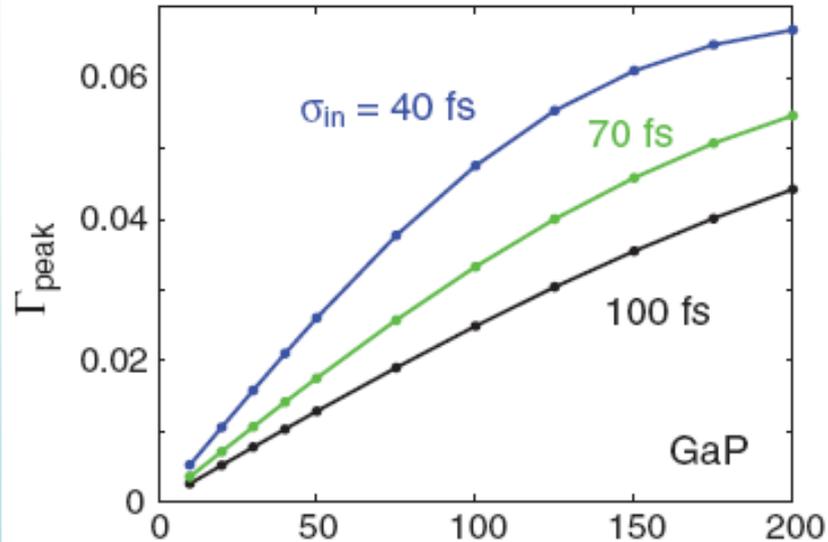
# Phase noise of the free-running Micra Ti:Sa oscillator



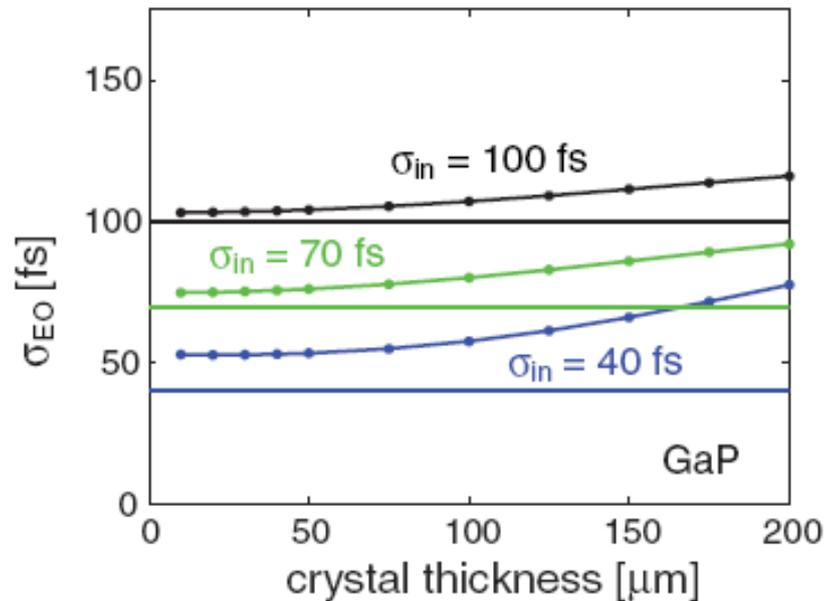
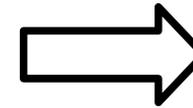
courtesy: S.Schulz

Integrated timing jitter in the range 50 kHz-40 MHz: 18 fs

# Limits of the crystal thickness



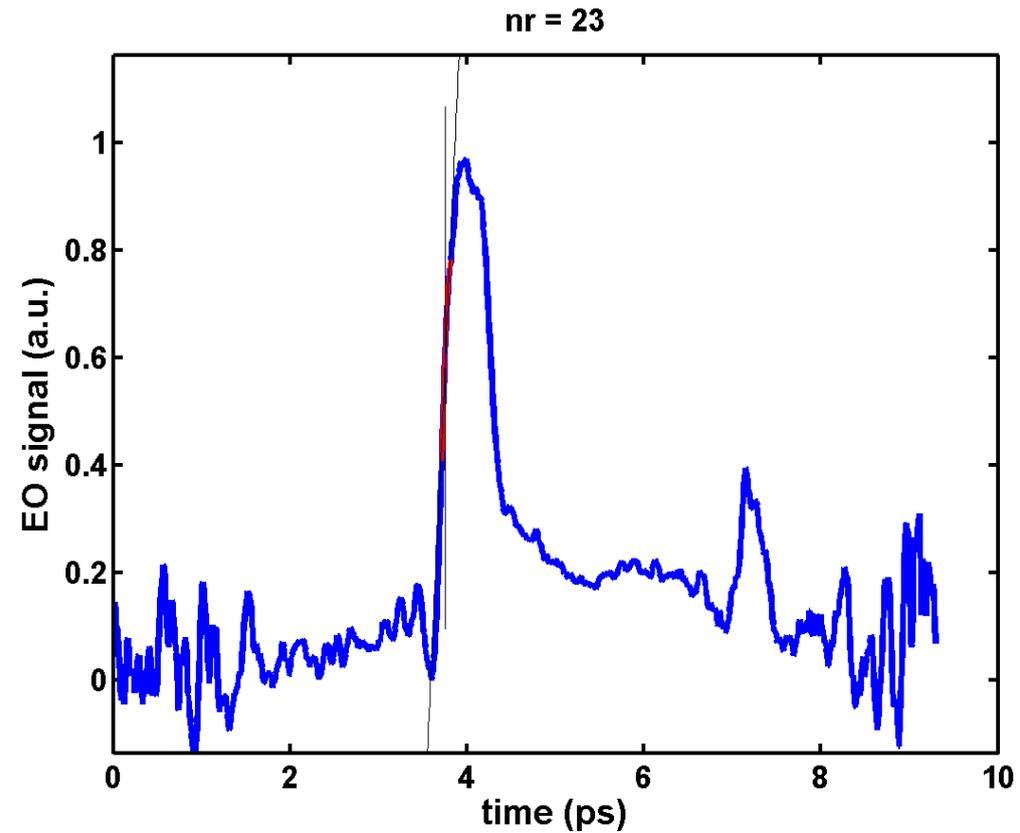
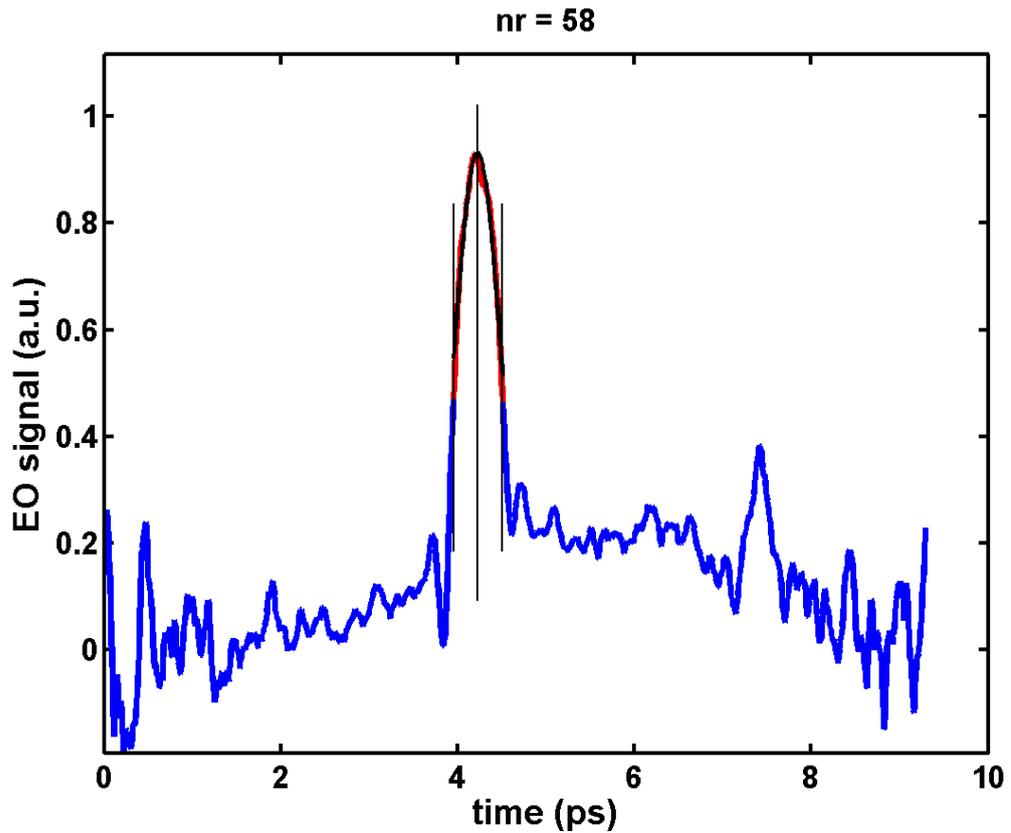
The present non-linear compression at FLASH prevents resolving structures below  $\sim 100$  fs rms with sufficiently high signal to noise ratio



The only useful application of EO at present is as a bunch arrival time reference

Casalbuoni et. al., Phys. Rev. ST  
Accel. Beams **11**, 072802 (2008)

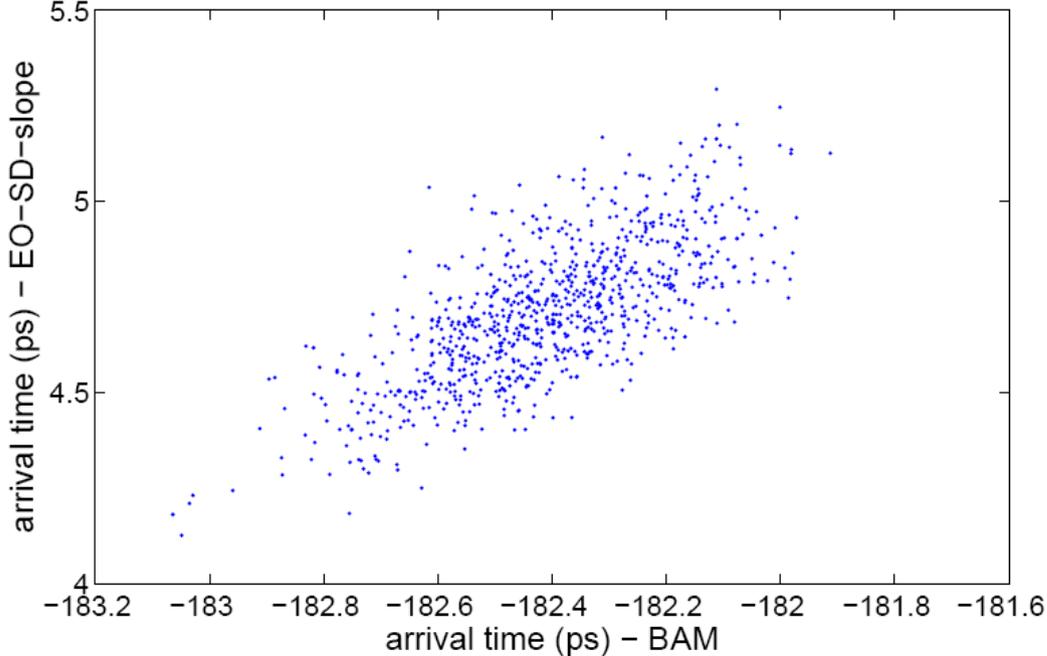
# Principle of arrival time detection



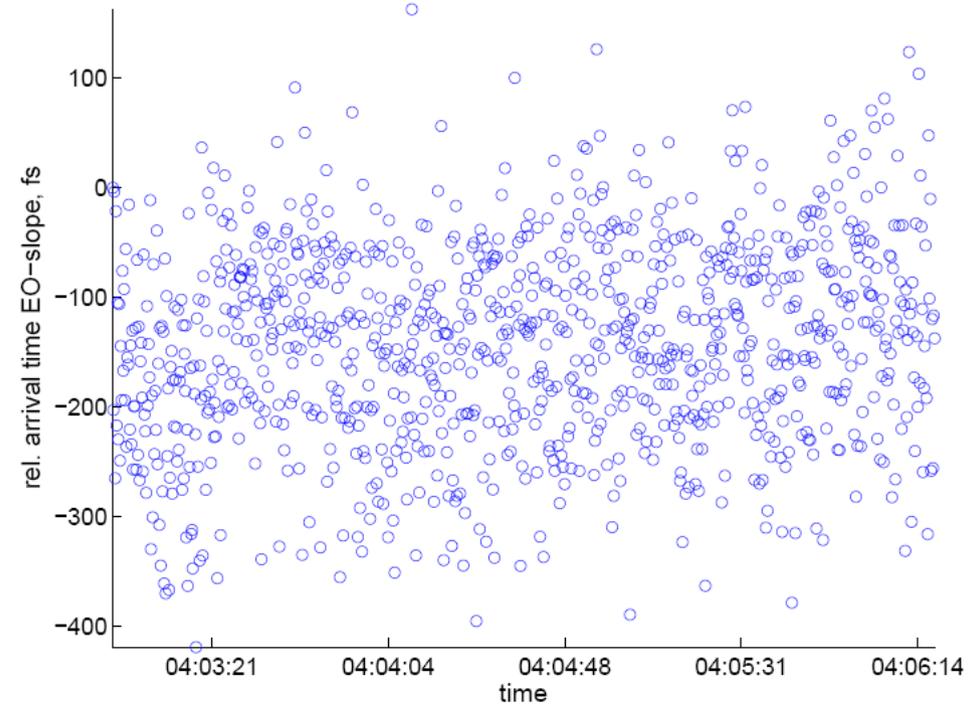
# Arrival time correlation between BAM and EO

- A typical measurement over 3 min (1000 bunches)
- RF lock, no arrival time feedback
- tendency: EO shows always somewhat smaller arrival time jitter
- dependence on the machine stability: shorter arrival have been observed

arrival time jitter (BAM) = 188.5fs  
arrival time jitter (EO-slope) = 182.8 fs  
arrival time jitter (BAM - EO-slope) = 138 fs

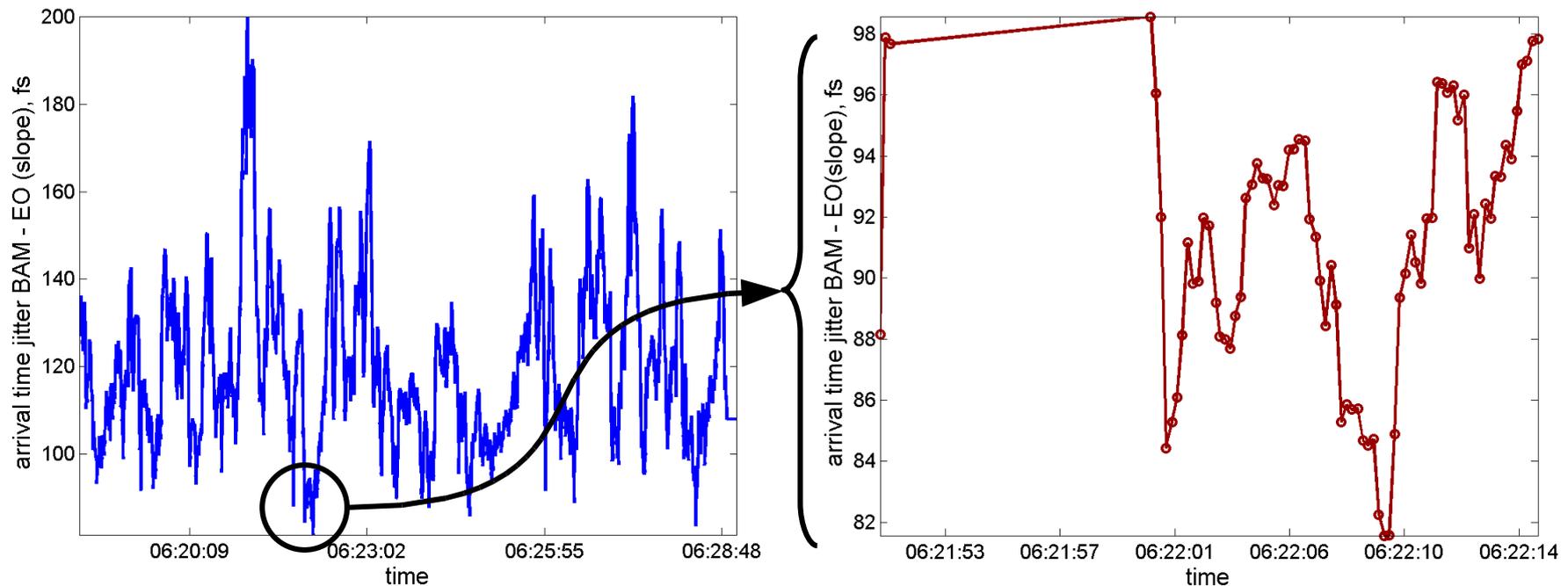


arrival time jitter EO-slope: 92.0 fs



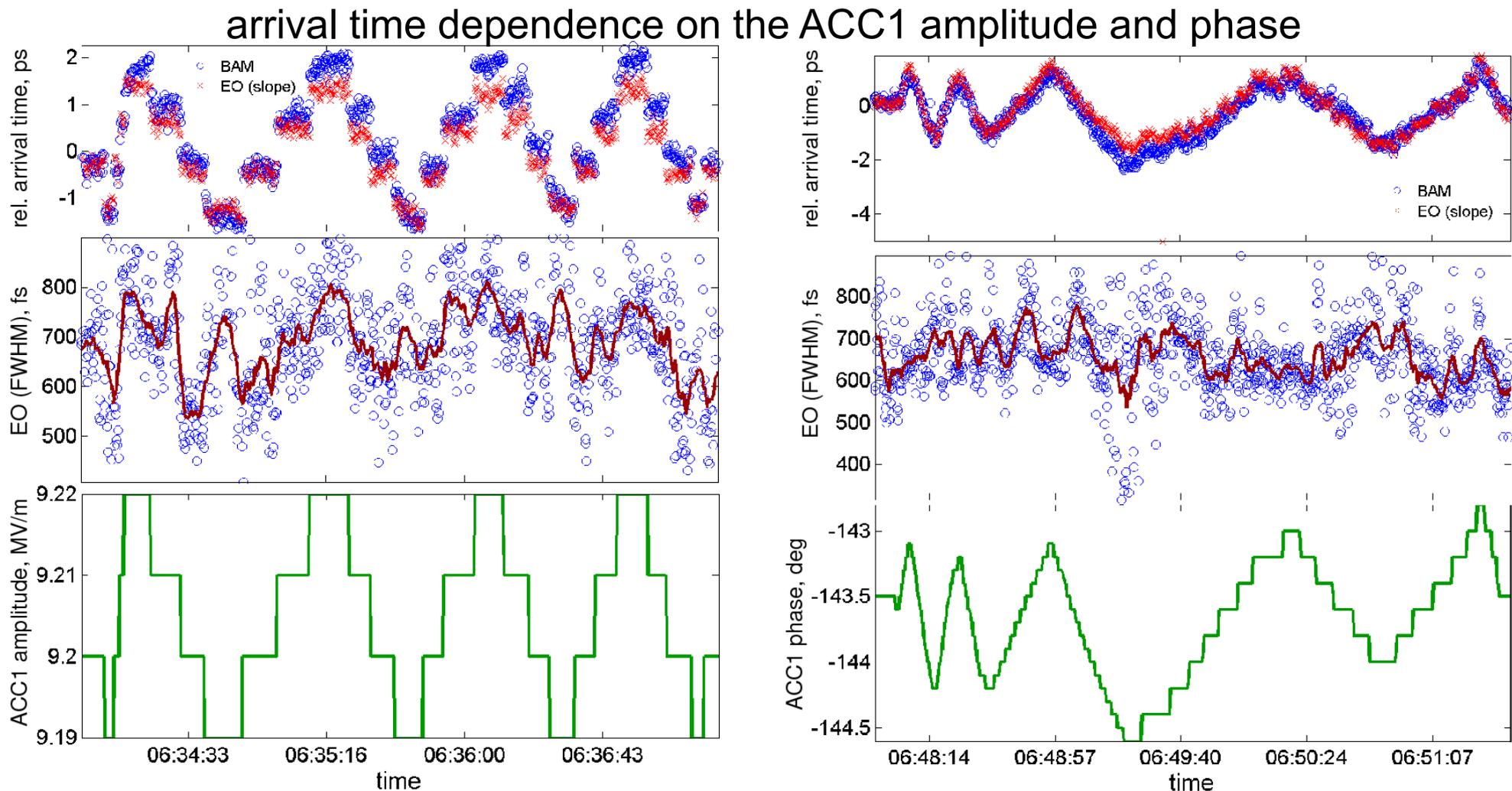
# Comparative BAM – EO measurements with RF synchronization

arrival time jitter in 10 s at fixed ACC 1 amplitude and phase

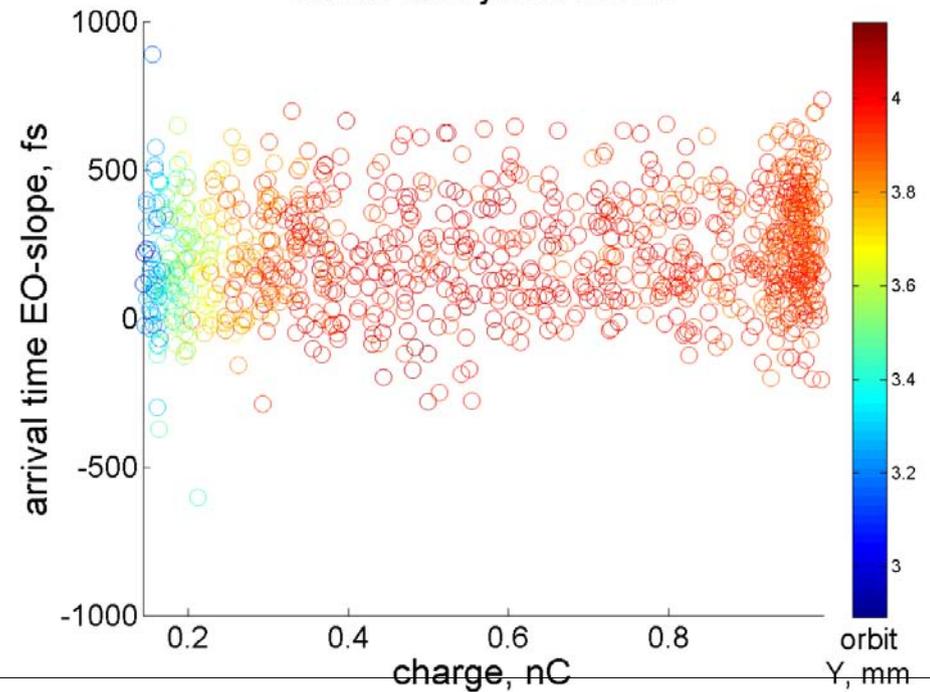
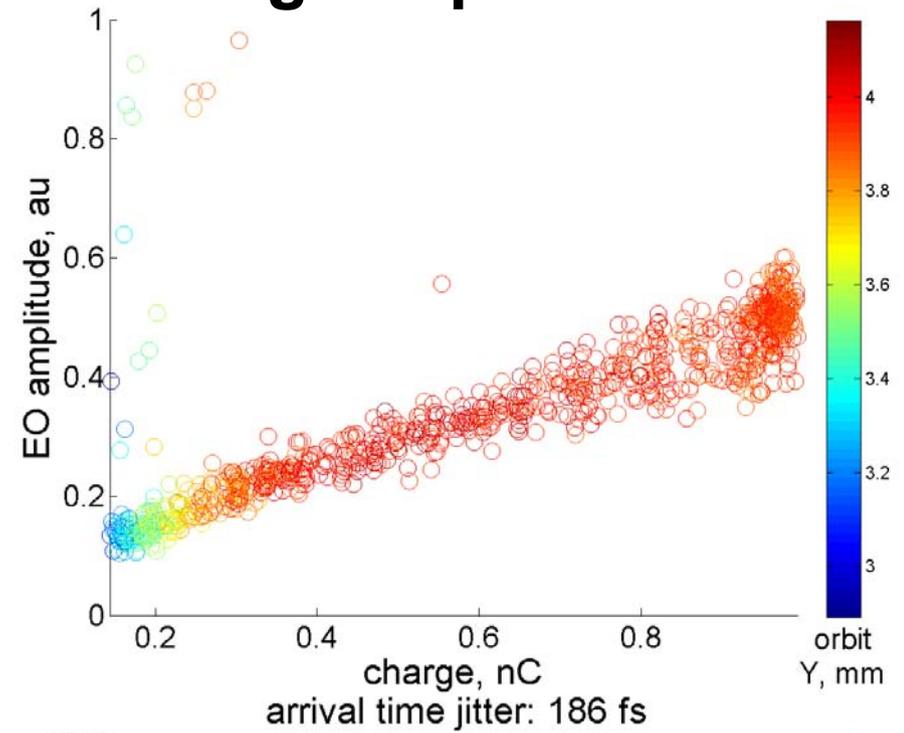
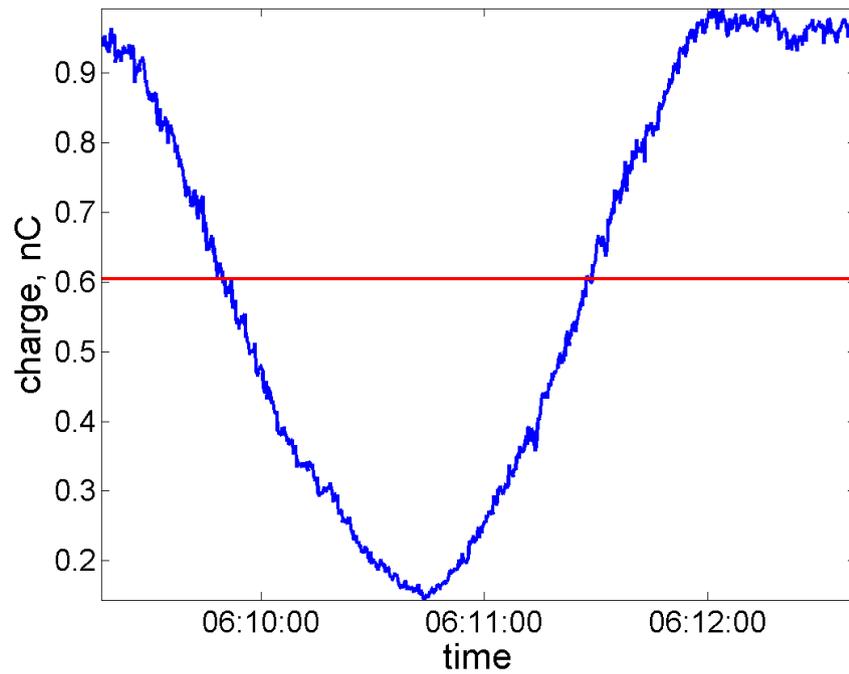


- The entire evolution contains ~3200 bunches (~11 min)
- each data point contains 50 arrival time events (10s)
- average arrival time jitter: 120 fs (rms),
- minimum arrival time jitter: 80 fs (rms) over 20 s.

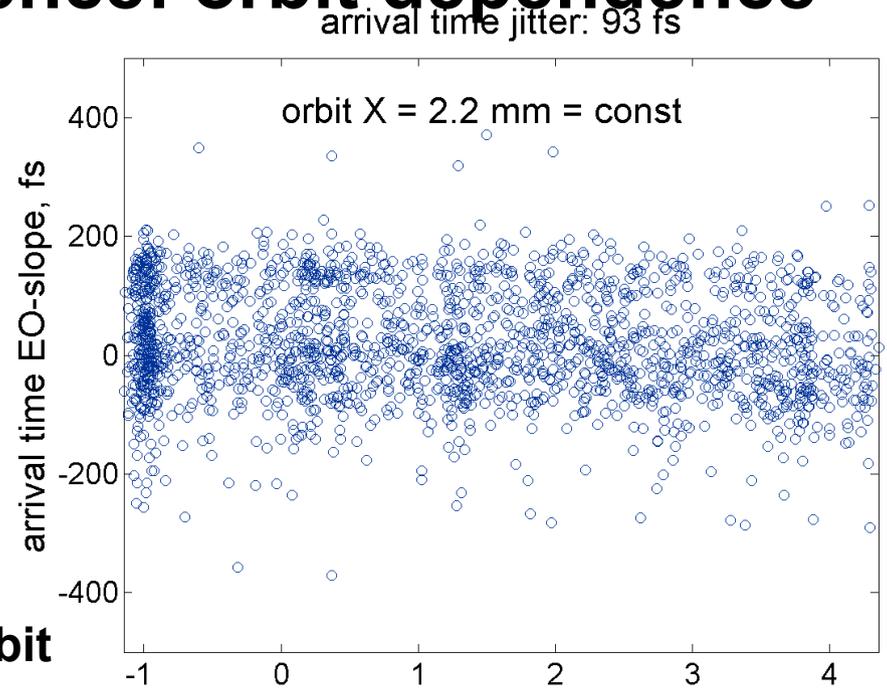
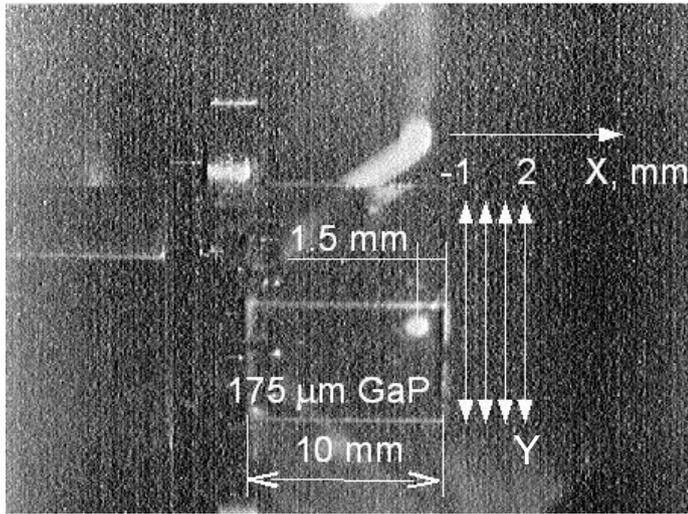
# Comparative BAM – EO measurements with RF synchronization



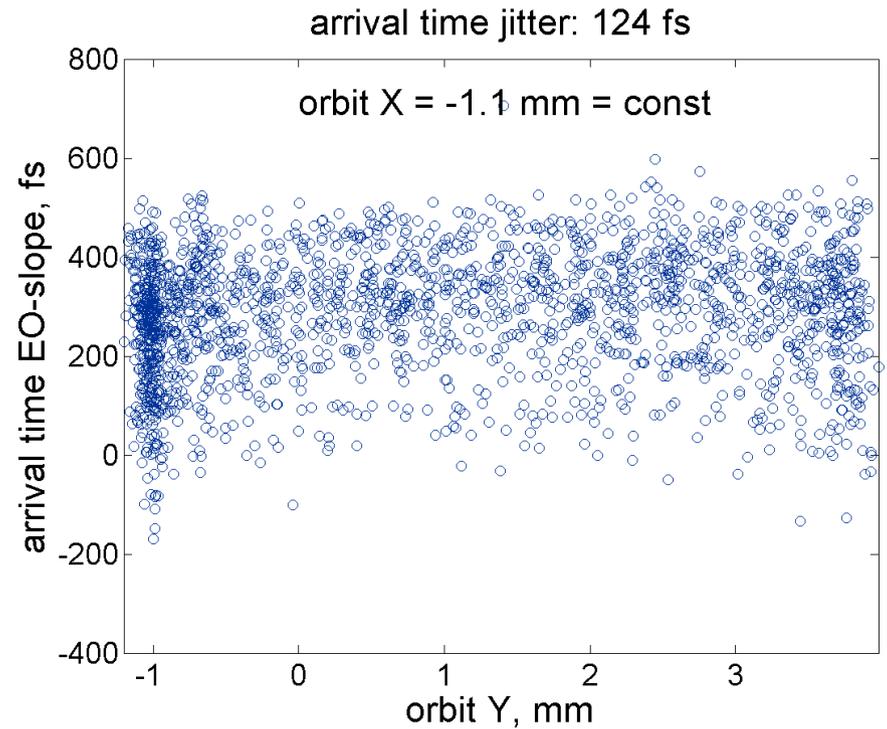
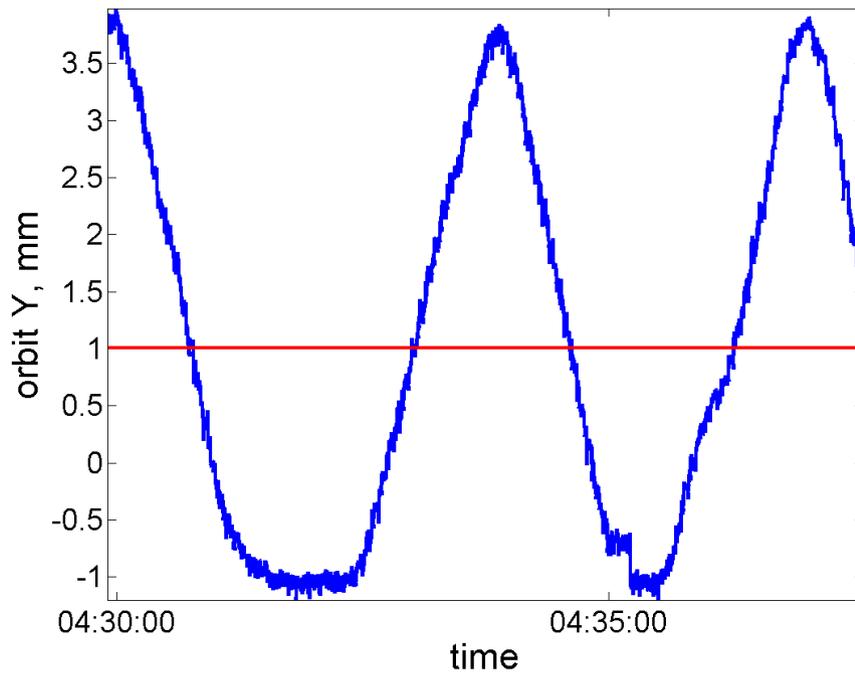
# EO as an arrival time reference: charge dependence



# EO as an arrival time reference: orbit dependence

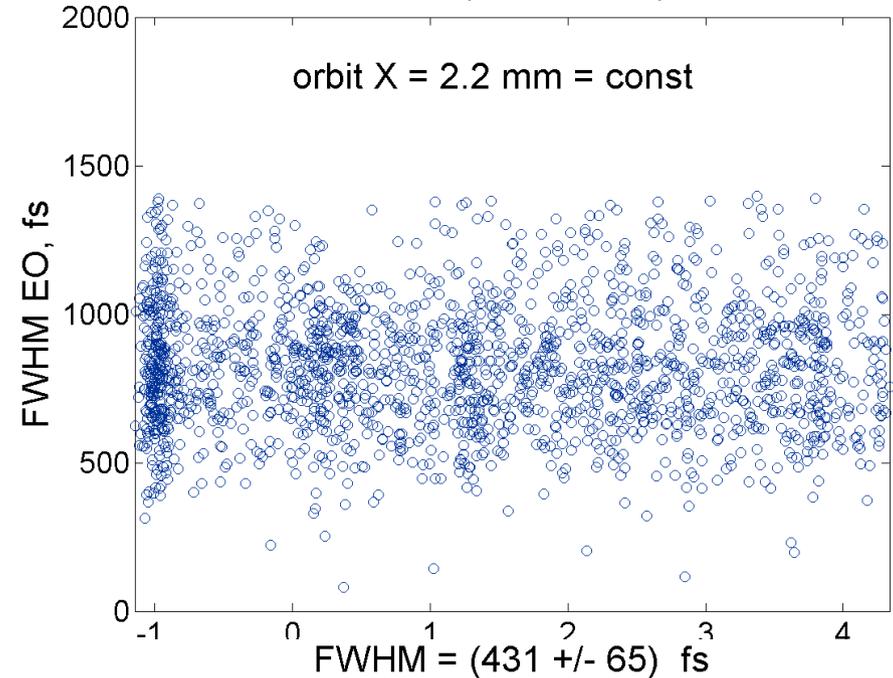
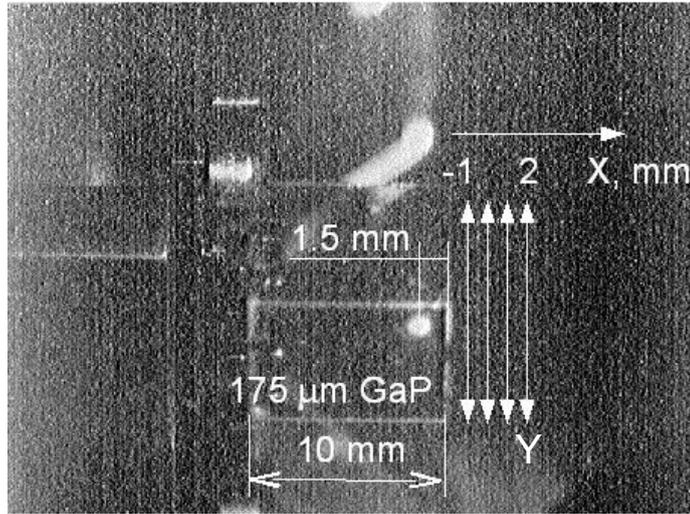


the arrival time is insensitive to changes in the orbit

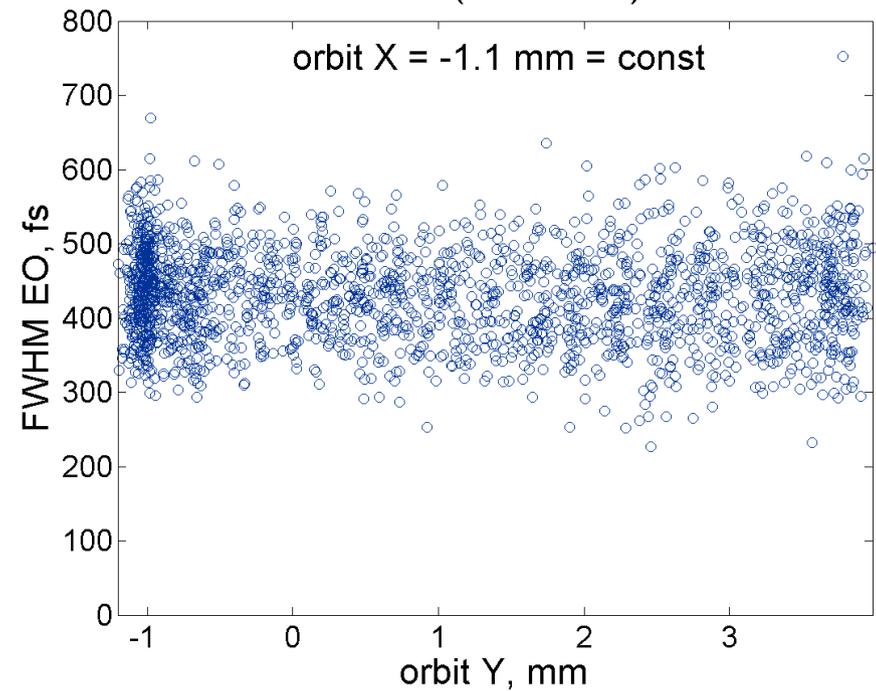
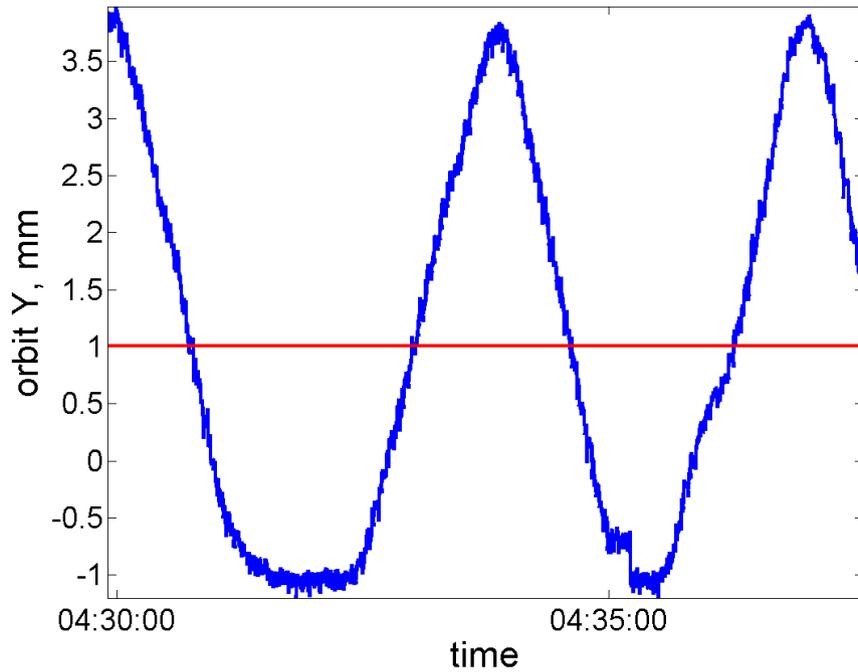


# EO as a bunch length monitor: orbit dependence

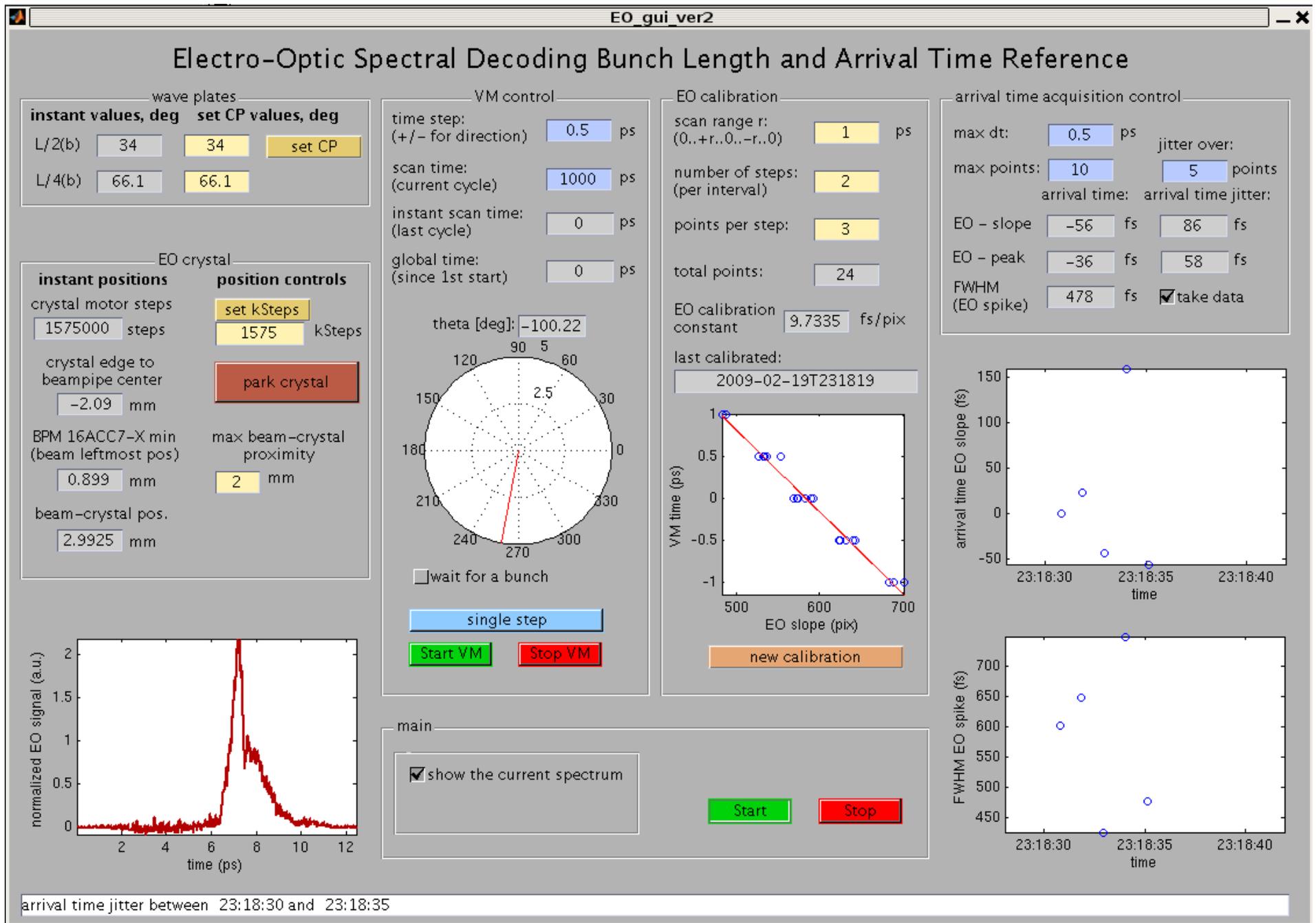
FWHM = (826 +/- 212) fs



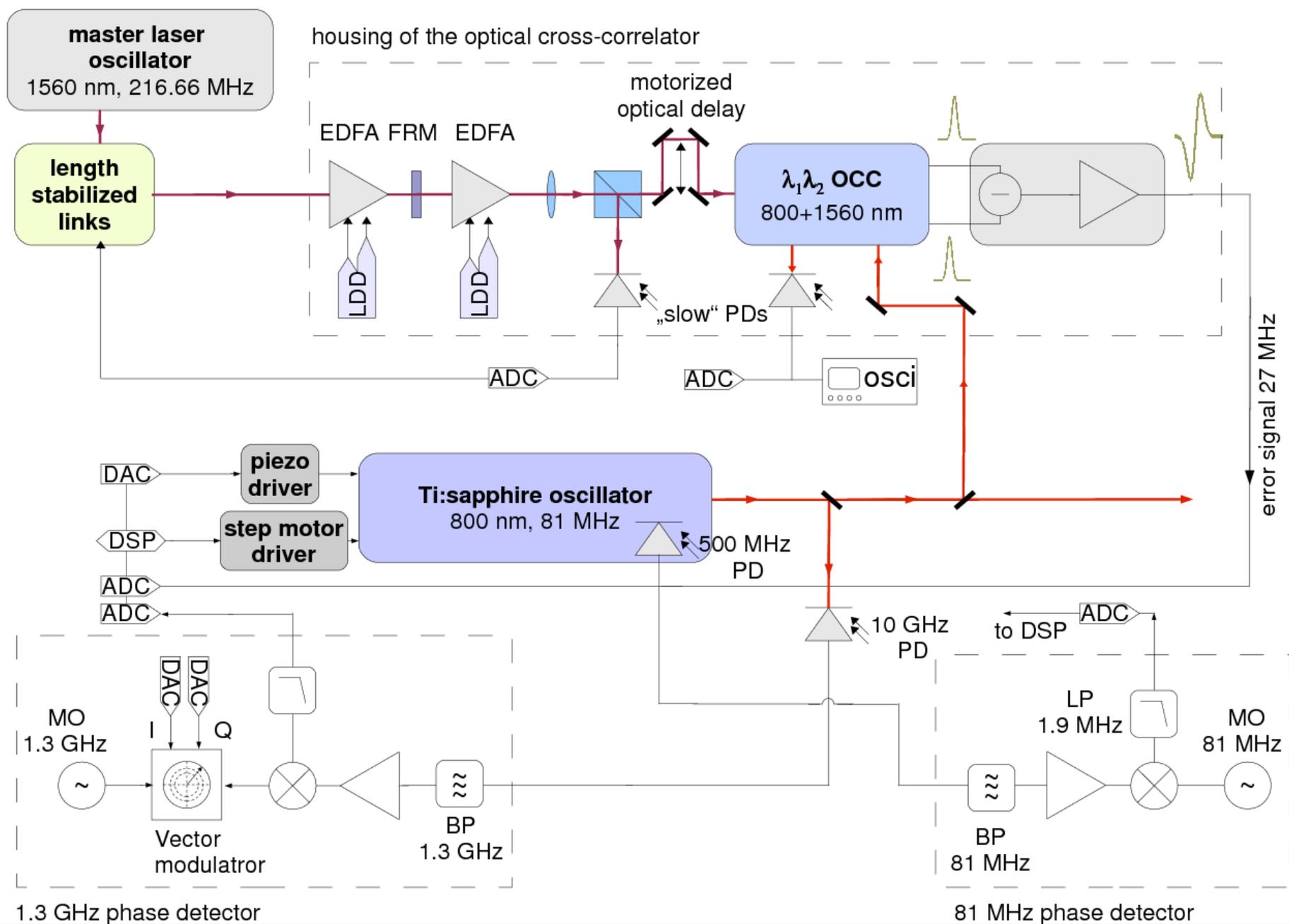
**FWHM is insensitive to changes in Y, but the analysis is more accurate for small X**



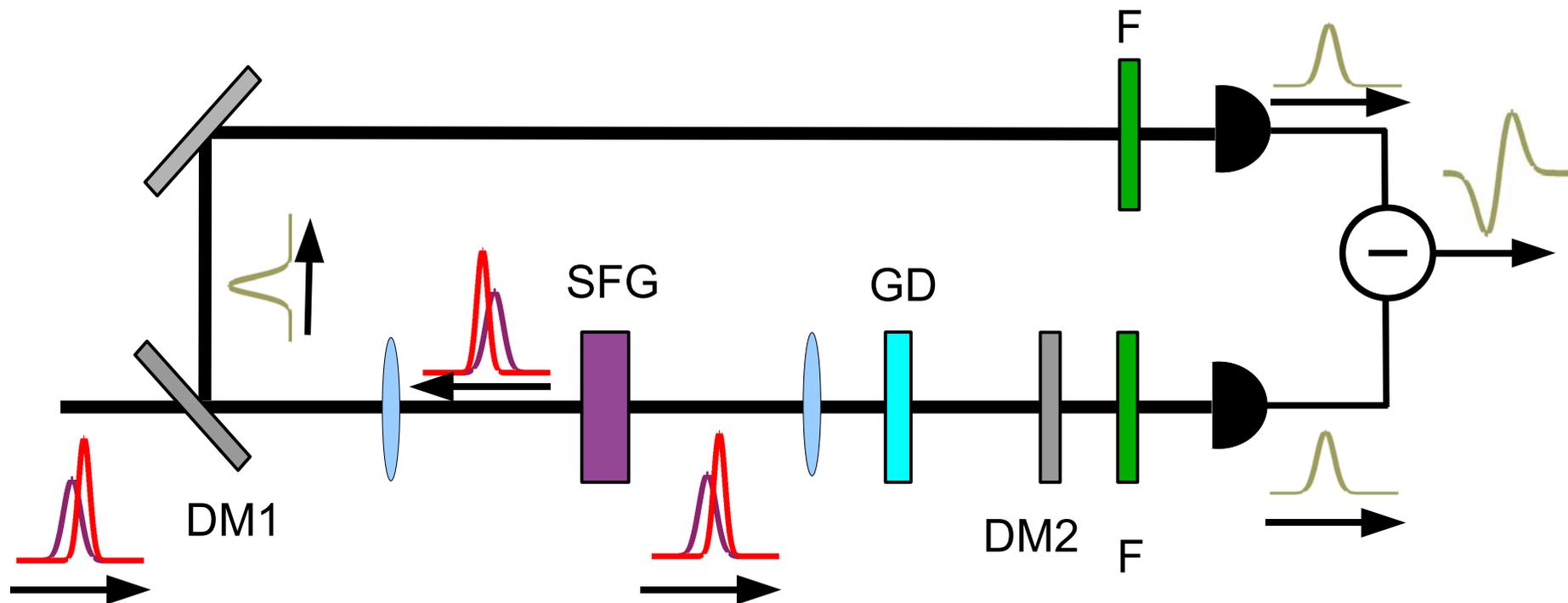
# A step towards automation of the EOSD acquisition



# Layout of the Ti:Sa RF and optical synchronization



# Design of the two wavelength optical cross-correlator



DM1 – dichroic mirror HT @  $\lambda_1$  and  $\lambda_2$ , HR @  $\lambda_{SF}$

DM2 – dichroic mirror HR @  $\lambda_1$  and  $\lambda_2$ , HT @  $\lambda_{SF}$

SFG – non-linear crystal, e.g. BBO

GD – group delay adjustment

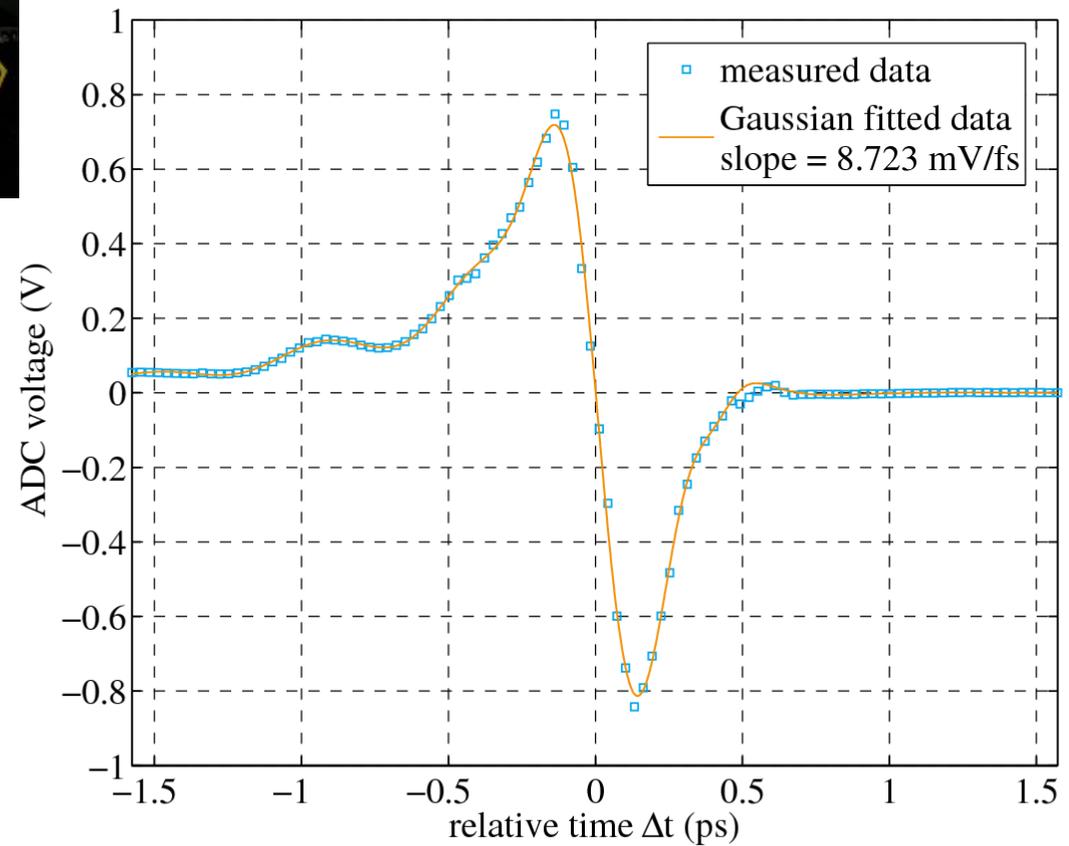
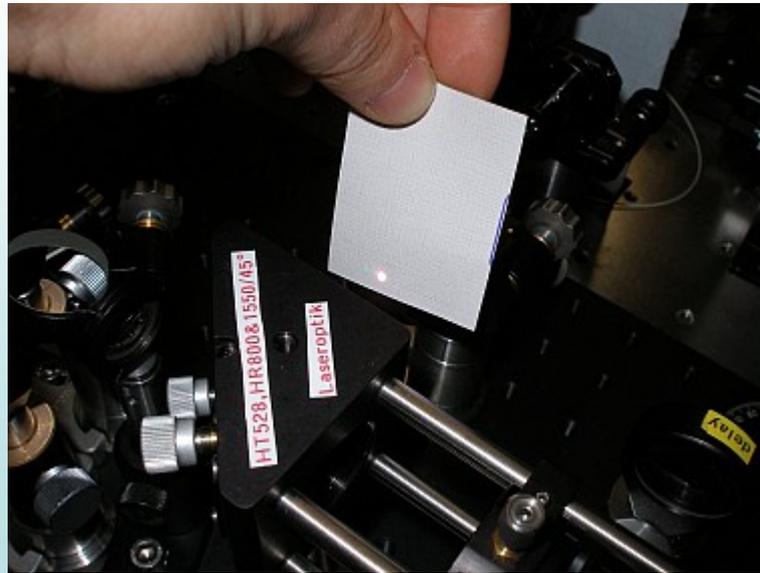
F – band pass filter, HT @  $\lambda_{SF}$

Consideration of:

- crystal properties
- group delay adjustment
- focusing

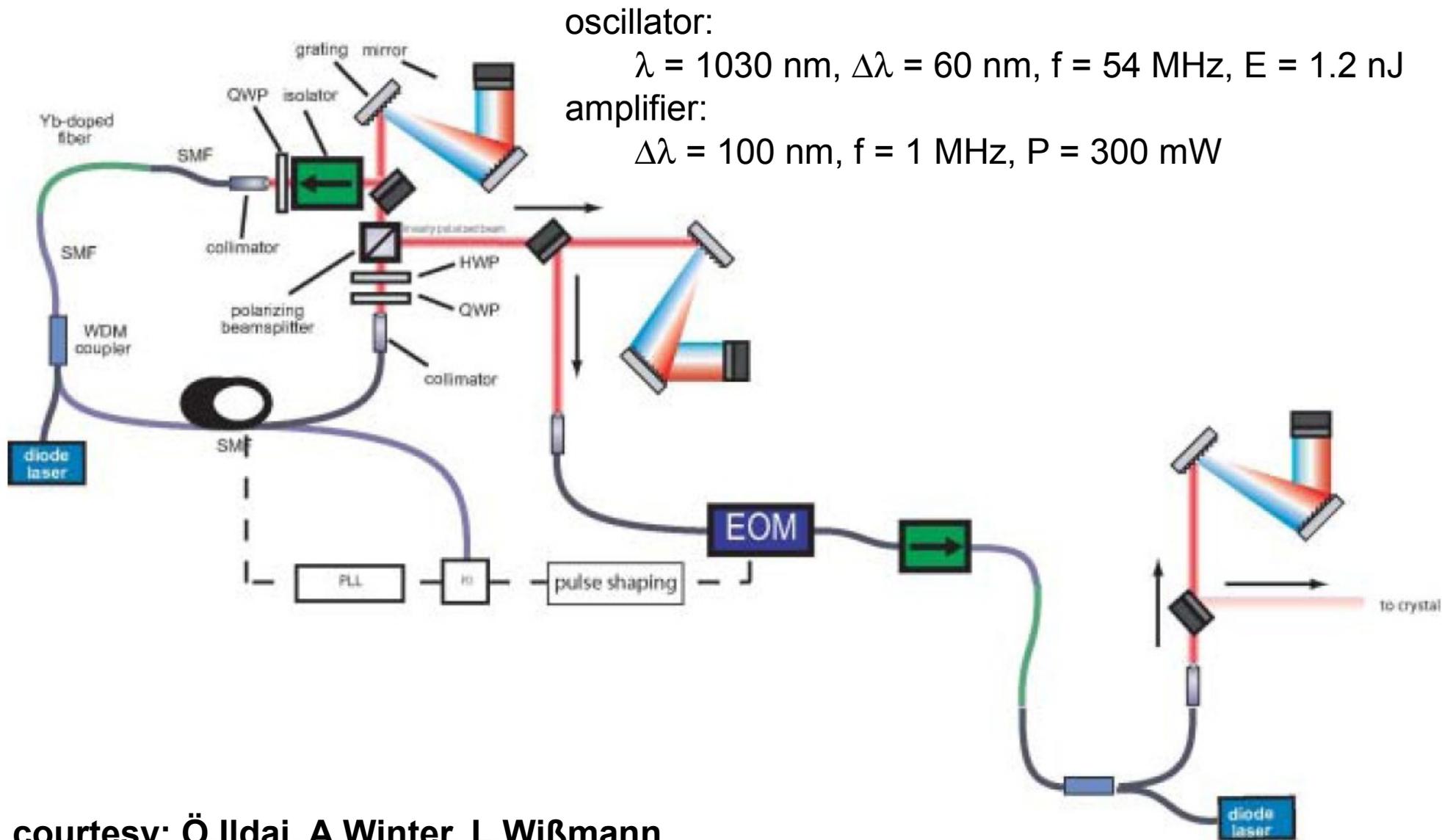
see e.g. FLA-Seminar, V.Arsov 15.06.2007

# First results from the optical cross-correlator



courtesy: S.Schulz

# Yb-fiber laser: main stream approach for bunch length diagnostics for FLASH and the European XFEL



courtesy: Ö.Ildai, A.Winter, L.Wißmann

# Yb-fiber laser

New:

- Synchronization electronic
  - phase detector
  - DSP control
  - piezo driver
  - stepper motor control
  - vector modulator
- Spectrometer
- Camera
  - IDUS diode array (Andor) – short term (100 KHz)
  - diode array (Hamamatsu) – long term (1 MHz)

retained:

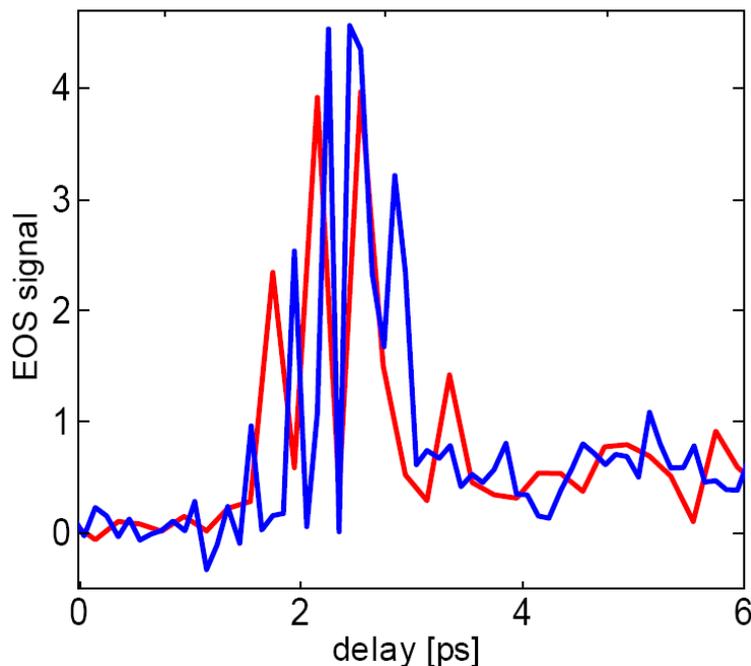
- all optics, optomechanics in the tunnel

Simultaneous acquisition with both Yb- and Ti:Sa is possible!

# Verification of the synchronization accuracy: back to the beginning - EO sampling, e.g. of CTR

Timing jitter:  
~ 200 fs, larger than  
the bunch length

only single-shot  
measurements were  
possible, due to electron  
beam arrival time jitter

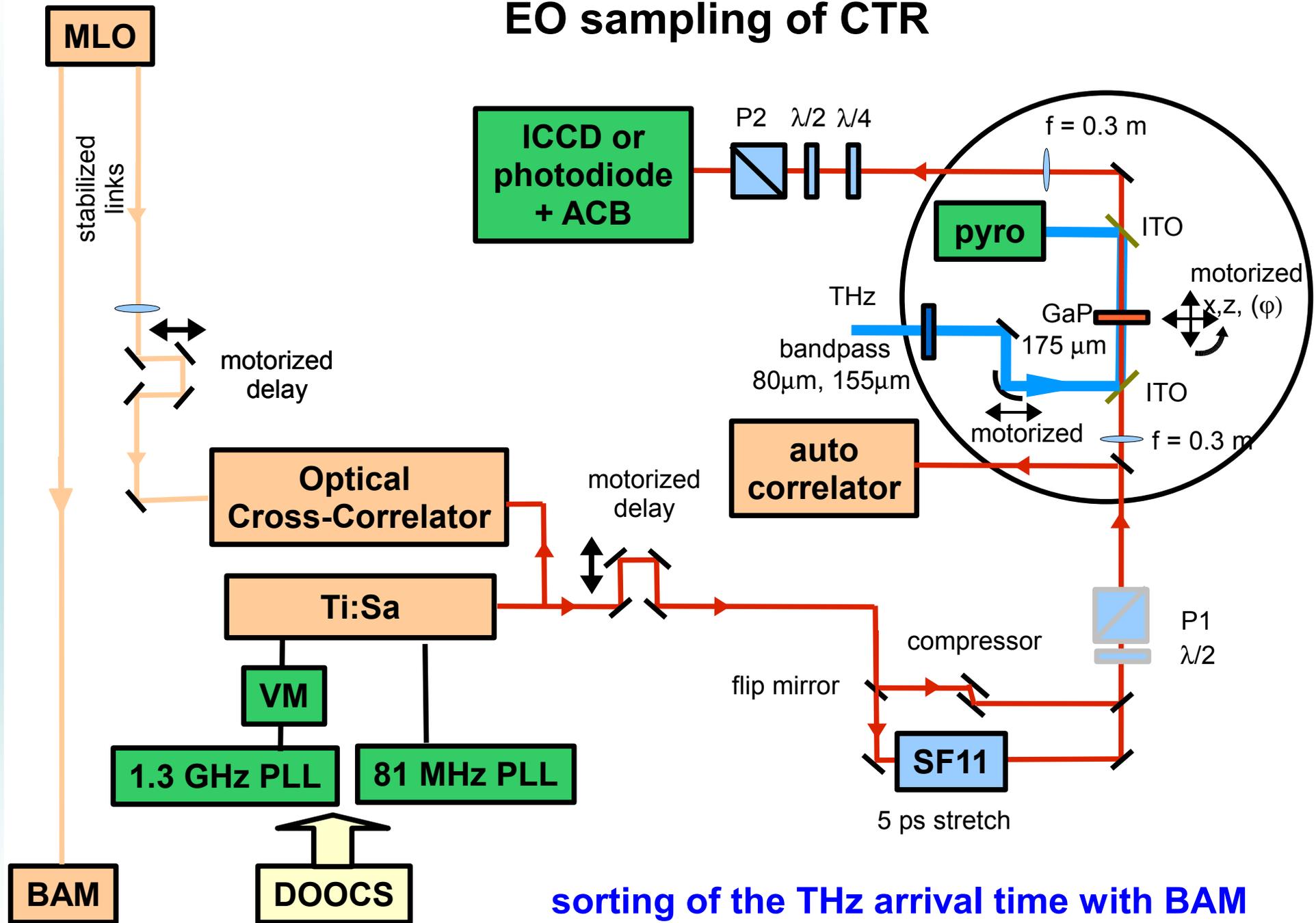


courtesy: B.Steffen

principle of the new experiment:

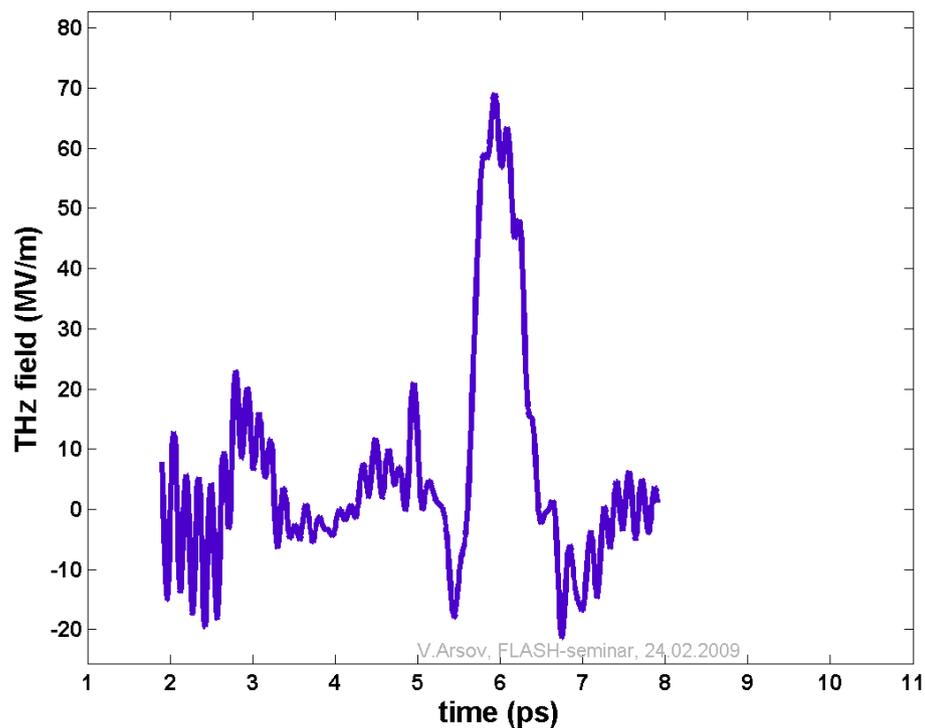
- to lock optically two diagnostic systems: the BAM and the EO laser
- one can not suppress the jitter, but...  
... one can obtain the timing information from the BAM and sort the EO signals accordingly
- a kind of a “pump-probe” experiment in which the “pump” is the electron beam itself

# Verification of the synchronization accuracy: EO sampling of CTR

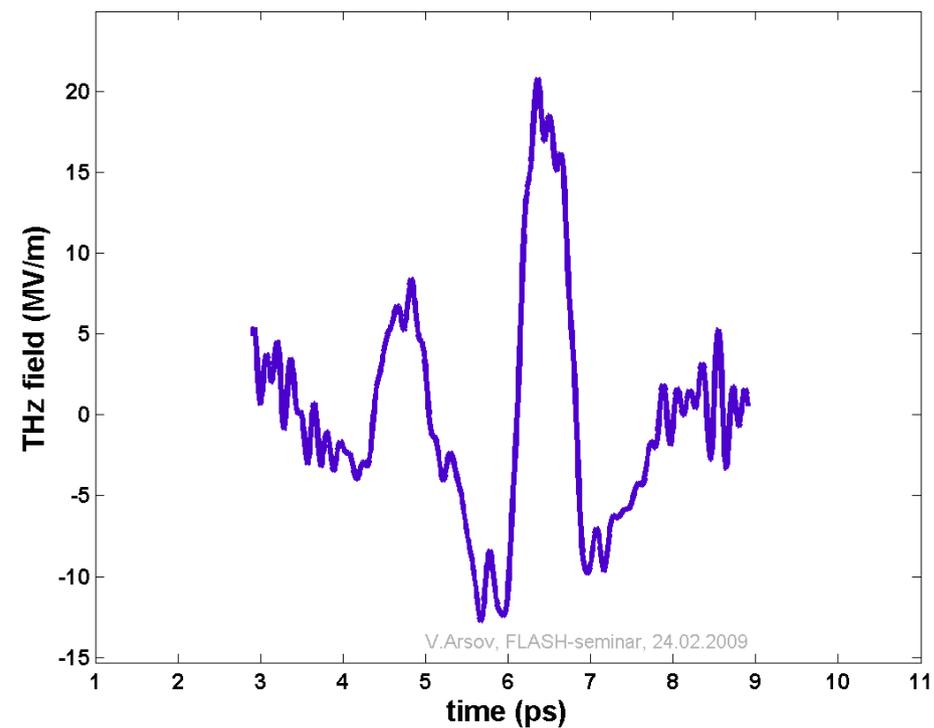


# CTR temporal profiles with EO-Spectral Decoding

measurements in vacuum,  $\Theta = -1^\circ$  off CP, no filter



GaP thickness: 130  $\mu\text{m}$



GaP thickness: 70  $\mu\text{m}$

# Summary

- There is a running EO diagnostic at 140 m of FLASH
- Continuous stable operation in RF-lock for more than 12 hours is possible
- Presently pulses shorter than  $\sim 200$  fs (FWHM) cannot be resolved
- Perfectly acceptable with the 3<sup>rd</sup> harmonic cavity installed
- Presently only one bunch per macropulse detectable
- First test with the optical synchronization are on the way
- First tests with the new Yb-fiber laser were made
- Steps towards detection of each bunch in the macropulse have been taken