First Electro-Optical bunch length measurements at the E-XFEL.

Bernd Steffen
7th IBIC, Shanghai, September 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Overview

1 The European XFEL

2 Why Electro-Optical bunch length detection?

3 EOD measurement principle

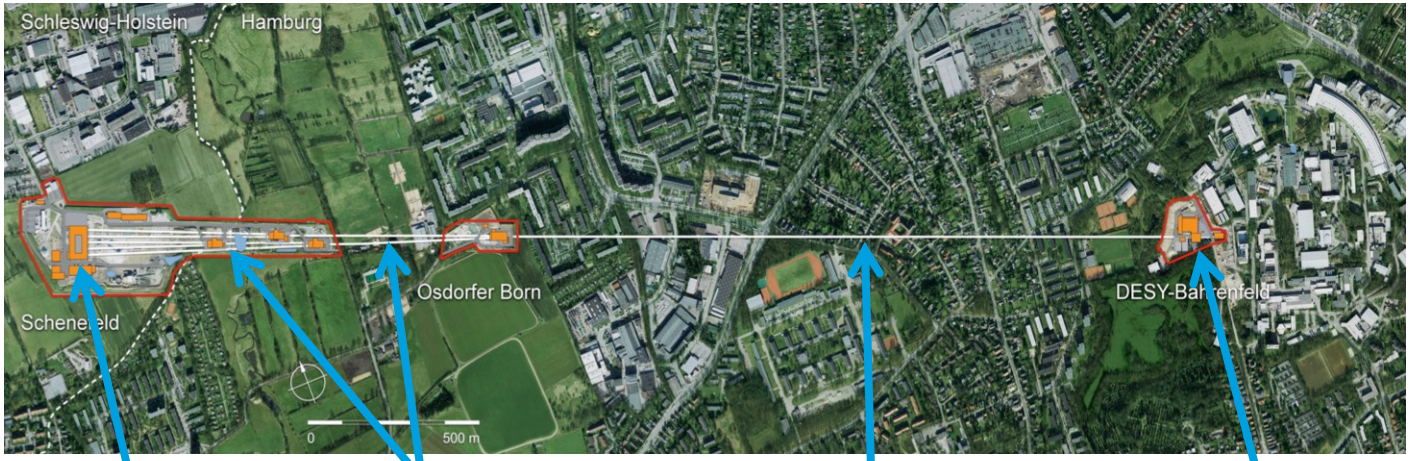
4 EOD hardware

5 First measurements

6 Summary

The European XFEL

Aerial view of the European XFEL



Super conducting accelerator
Three undulator beamlines
in two
6 experiments
4 for hard X-rays
2 for soft X-rays

Parameters:
Electron beam energy 17.5 GeV
Repetition Rate 1 - 10 Hz
RF Pulse (flat top) 600 µs
Bunches up to 27000/s
Bunch Charge 0.02 - 1 nC
Final bunch length 5 - 100 fs

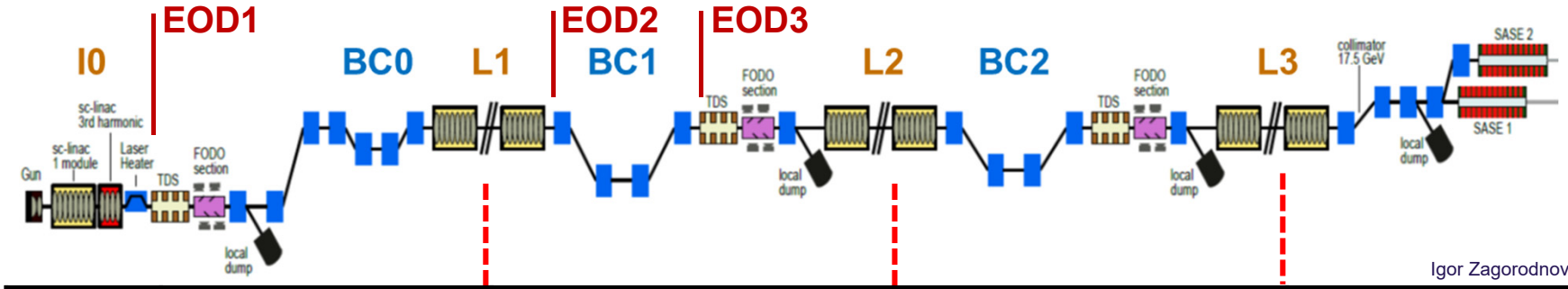
Why Electro-Optical Detection?

Why the Electro-Optical Spectral Decoding technique?

+ Non destructive
+ Capable of full bunch trains at 1.13MHz
+ (Fairly) simple

- Lower bunch length limit ~200fs (rms)

➢ No EOD after BC2

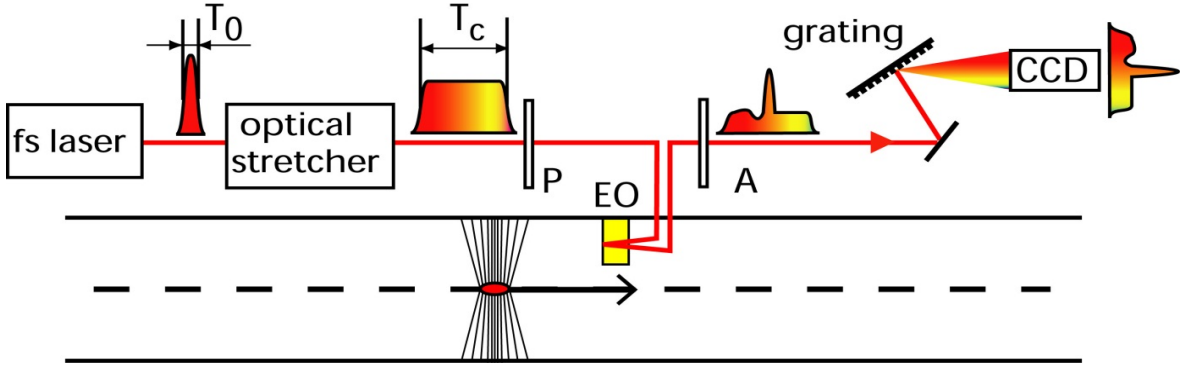


Igor Zagorodnov, 2011

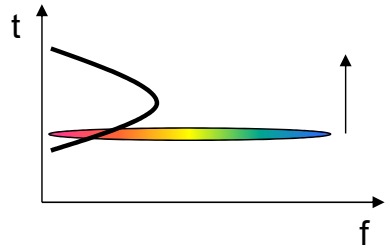
Energy	130MeV	600MeV	2.5GeV	17.5GeV
20pC	4.53ps	1.46ps	185fs	5.23fs
100pC	4.80ps	1.55ps	197fs	11.6fs
250pC	5.27ps	1.70ps	223fs	25.4fs
500pC	6.00ps	1.96ps	259fs	43.0fs
1000pC	6.77ps	2.23ps	303fs	84.0fs

Electro-Optical bunch Detection

Electro-Optical Spectral Decoding principle

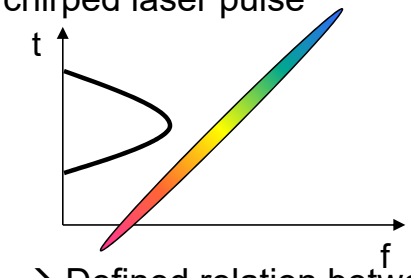


Electro-Optical Sampling:
sampling with laser pulse



→ Sample electron bunch with many laser delayed pulses

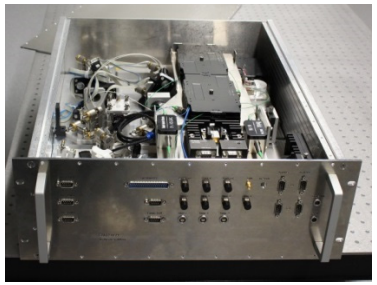
Electro-Optical Spectral Detection:
chirped laser pulse

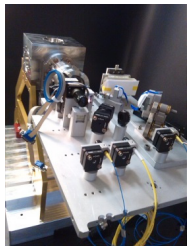


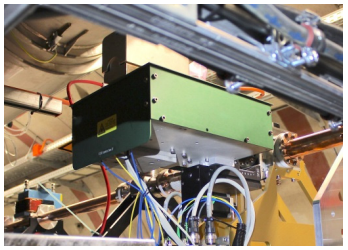
→ Defined relation between time and frequency gives timing

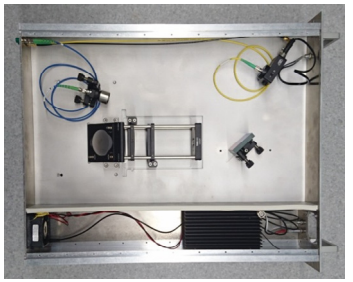
EOD hardware

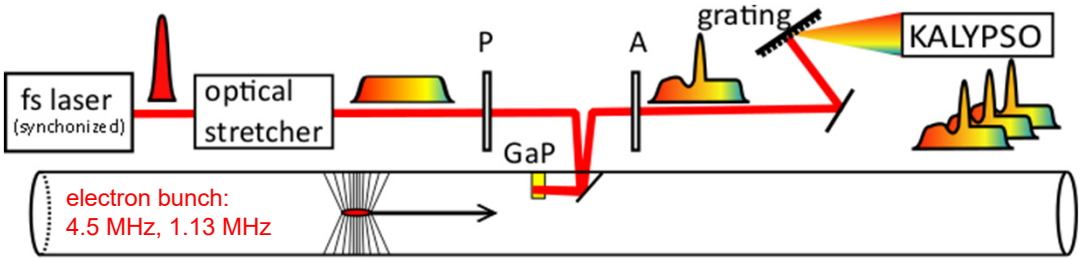
Main components

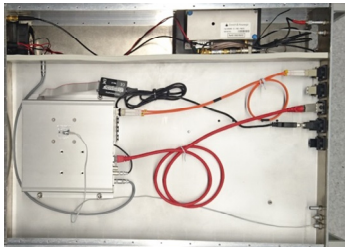




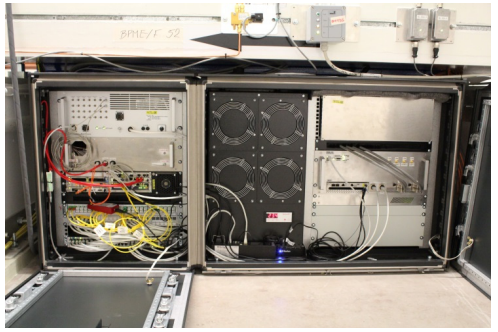






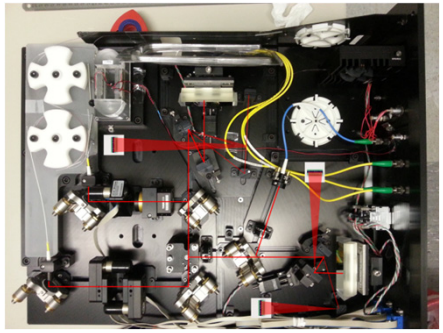


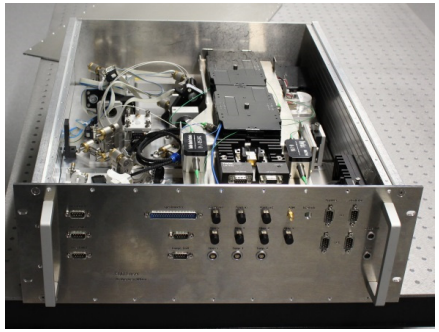
- **Ytterbium fiber laser** and amplifier,
- **Optics set-up** at the beam line vacuum chamber incl. the **GaP crystal**
- **Spectrometer** with the KALYPSO **MHz line detector**,
- **MicroTCA.4 crate** with the analogue and digital boards or laser synchronization and data readout,
- **Laser to RF synchronization** unit with other supporting electronics,
- **Full system** (including laser, detector, MTCA crate, synchronization electronics, motor drivers, power supply, ect.) now **only 25 HU in 19" rack**

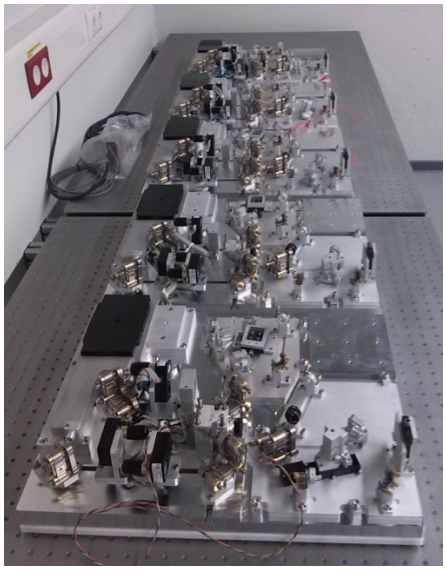


Yb fiber laser

- The **laser** was originally designed at PSI for EOD to be **compact and rack mounted**
- Further development at DESY (amplifier integrated into the laser box, synchronization, other electronics)
- Now **in operation at European X-FEL (DESY), ANKA (KIT), DELTA (Univ. Dortmund)**







Yb fiber laser parameters	
wavelength	1030 nm
bandwidth (osc.)	25nm – 50nm (up to 100nm with ampl.)
chirped laser pulse length	~5ps (compressible to <100fs)
pulse energy (osc.)	1 nJ – 2 nJ (up to 100 nJ with ampl. at 1 MHz)
repetition rate	54 MHz

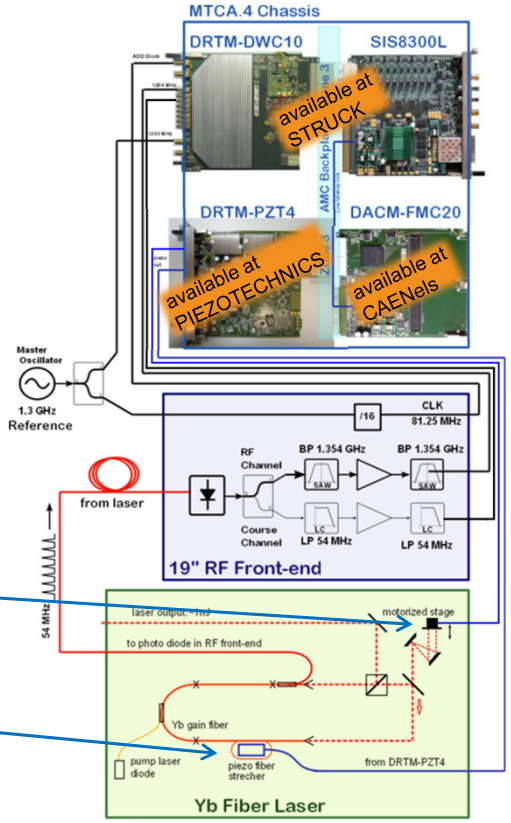
MTCA.4 based synchronization for the EOD laser

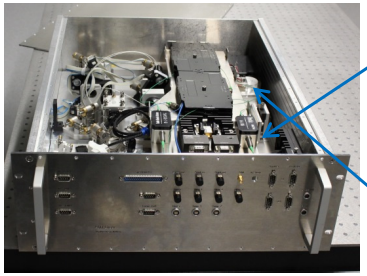
System now fully integrated MTCA.4 system:

- Detection and controls: Struck ADC + downconverter RTM
- Piezo driver: MTCA-RTM PZT4 for fiber stretcher and linear piezo stage

\+ RF-front-end: temperature stabilized in Special Diagnostics Module chassis (SDM, together with LDDs and laser temperature control)

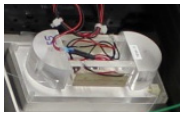
\+ Yb fiber laser and amplifier





SmarAct SLC-1730 piezo stepper for coarse tuning

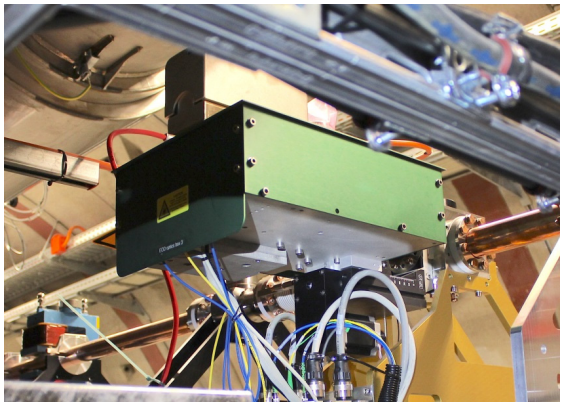
Evanescent Optics fiber stretcher 915B for fast synchronization

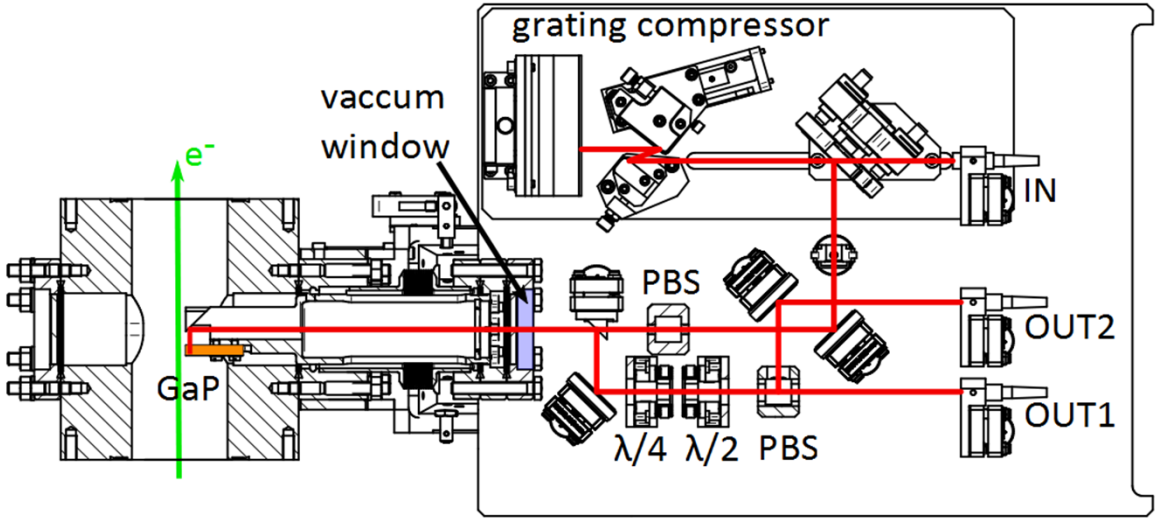


Optics set-up

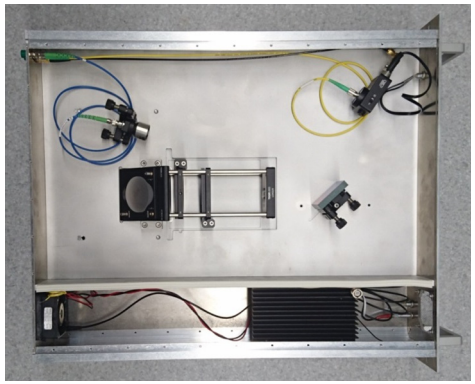
at the electron beam line

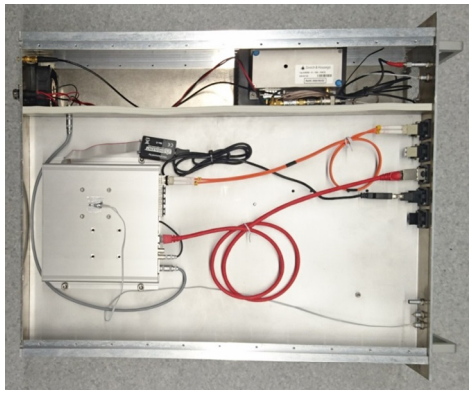
- All optics and GaP crystal on a fixed on a rigid vacuum feed-trough to avoid misalignment
- Grating compressor to adjust chirp of the laser pulses
- Design adopted from PSI with compressor added



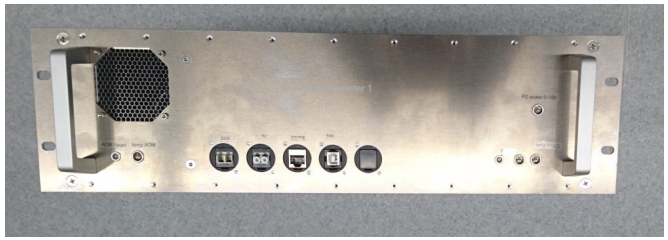


Spectrometer with KALYPSO detector





- **Self build fiber coupled grating spectrometer**
  - 19”, 3HU
  - Approx. 120nm range (adjustable)
  - <1nm resolution
- **KALYPSO/HOLD detector**
  - 256 pixel linear InGaAs PDA (900nm - 2.5µm) or Si (300nm-1050nm)
  - Up to 2.7 MHz continuous line rate
  - 2% noise (prototype)
  - Sensitivity: few pJ laser pulse energy for a good single-shot spectrum



The KALYSO / HOLD detector

Designed in a collaboration of KIT, DMCS, DESY

KALYSO
KArlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy

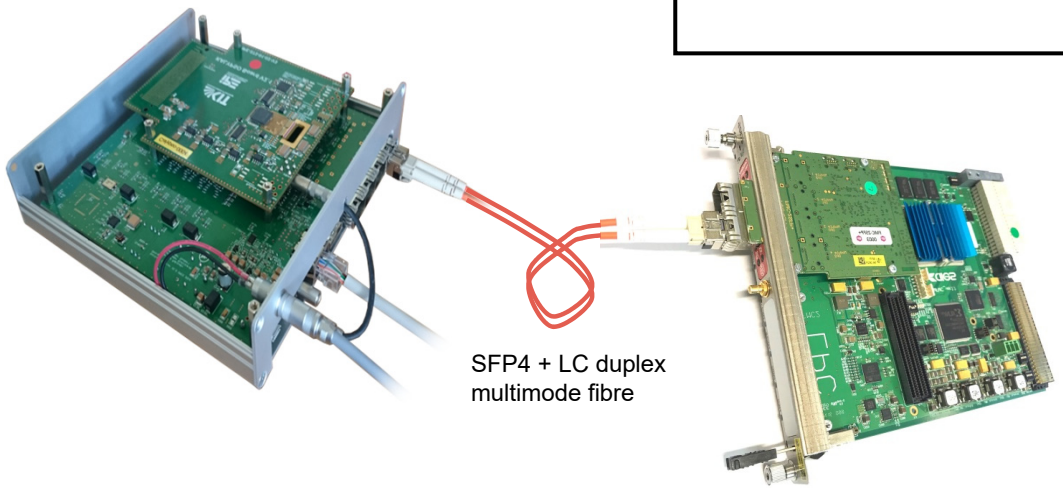
Karlsruher Institut für Technologie
Karlsruhe, Germany

HOLD
High-speed Optical Line Detector

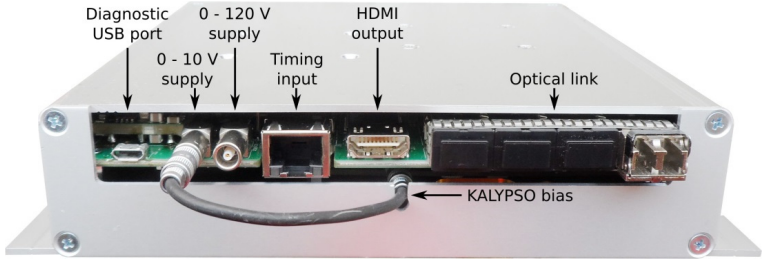
(KALYPSO detector + carrier + optical readout via MicroTCA.4)

DMCS
Univ. Lodz, Poland

- Parameters for first version 2.1
  - 256 pixels, 50 µm pitch
  - 14 bit ADC (low noise)
  - 2.7 Mfps
- New version 2.5 in preparation
  - 12 Mfps
  - 512/1024/2048 pixels
- cw capability (for storage rings or cw FELs)
  - Single bunch/pulse resolution
  - Continuous data stream out
- Fast feedback capability
  - Low latency
  - Local pre-processing (FPGA)
- First applications
  - ANKA/KLARA: 2.7 Mfps
  - E-XFEL: 1.13 Mfps / 2.26 Mfps

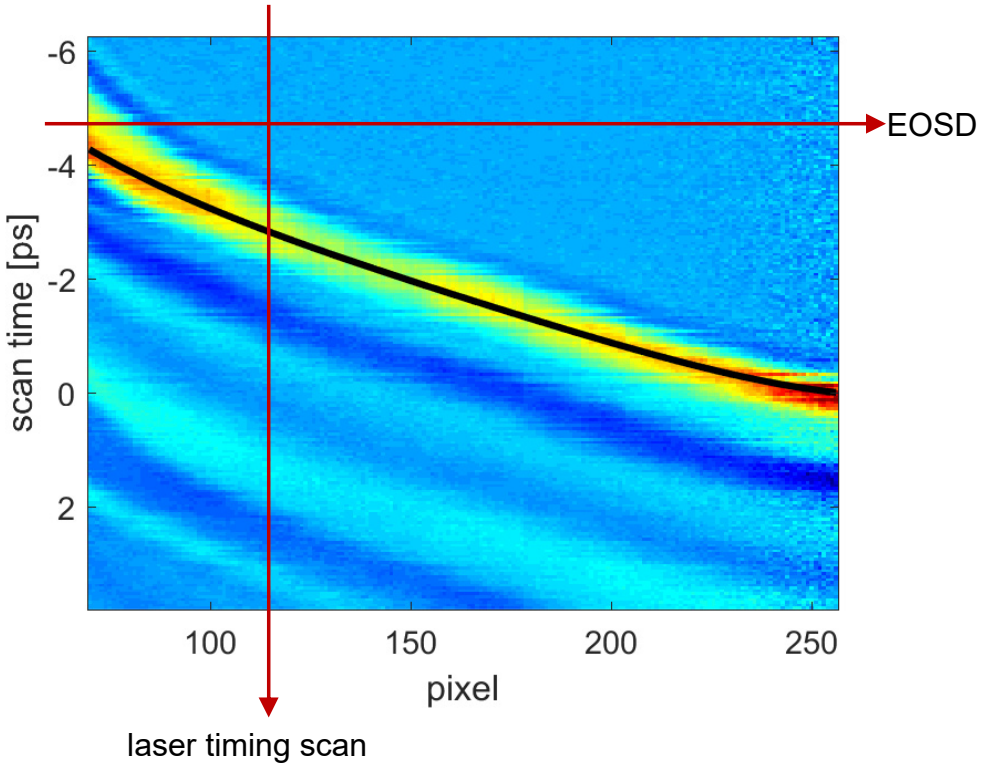


SFP4 + LC duplex multimode fibre

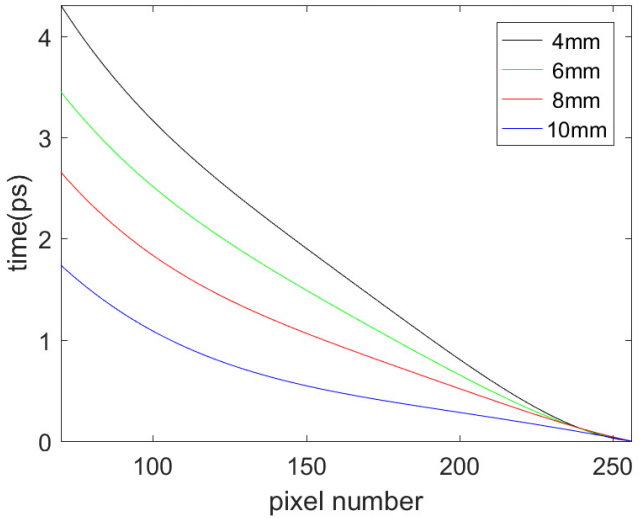


For more informantion:
L. Rota *et al.*, “KALYPSO: A Mfps linear array detector for visible to NIR radiation,” in *Proc. IBIC 2016*, Barcelona, Spain, 2016.
A. Mielczarek *et al.*, “Real-time Data Acquisition and Processing System for MHz Repetition Rate Image Sensors,” *IEEE Transactions on Nuclear Science*, vol. in print, 2018

Time calibration

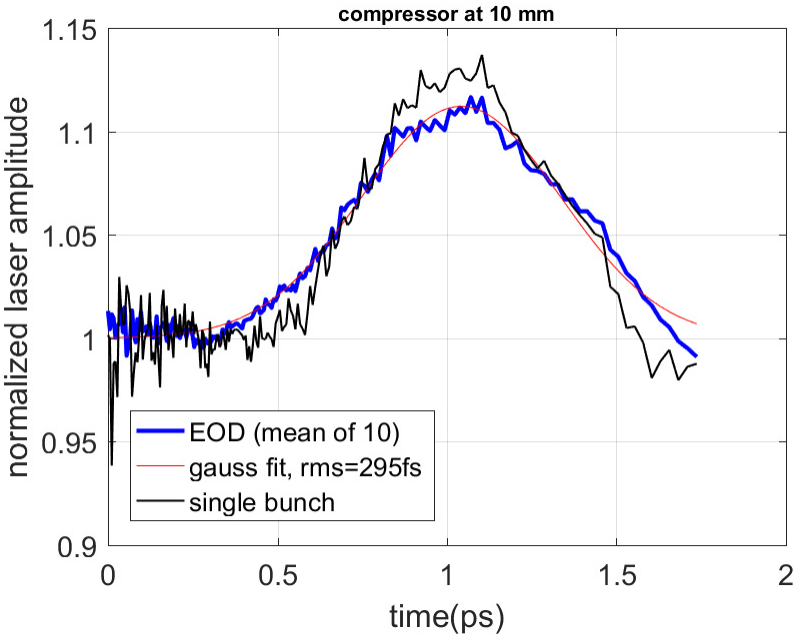


- **Scanning the laser delay** will move the electron bunch signal through the laser spectrum
- A fit to the signal maxima will give a **calibration function** for **time vs. pixel number**
- The calibration function and useful time window change for different compressor settings

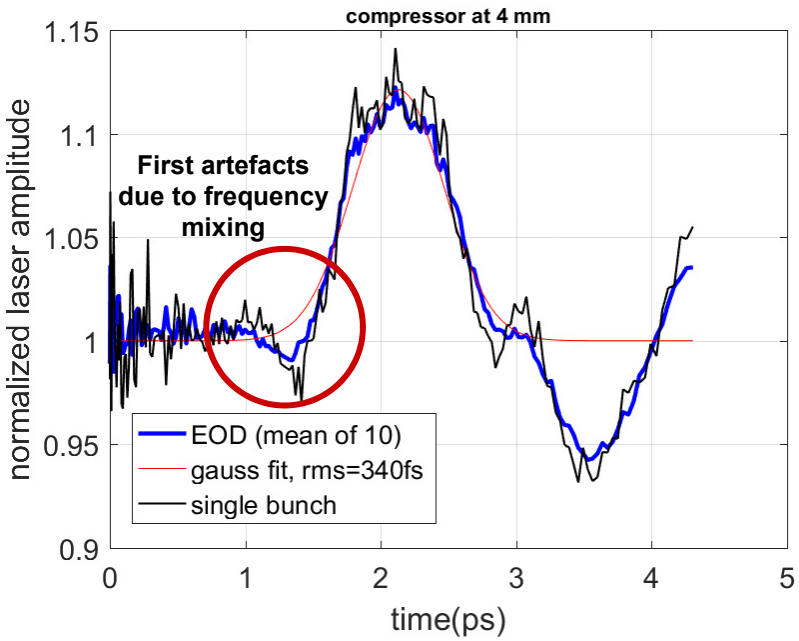


Measurements at different compressor settings

Measurements at different compressor settings

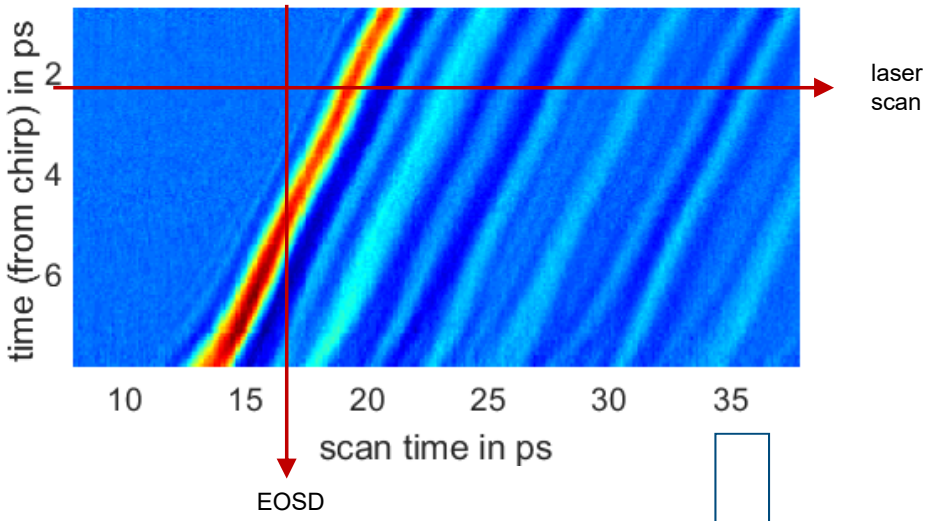


- For large chirp, the laser bandwidth is too low to fully resolve the short pulses:



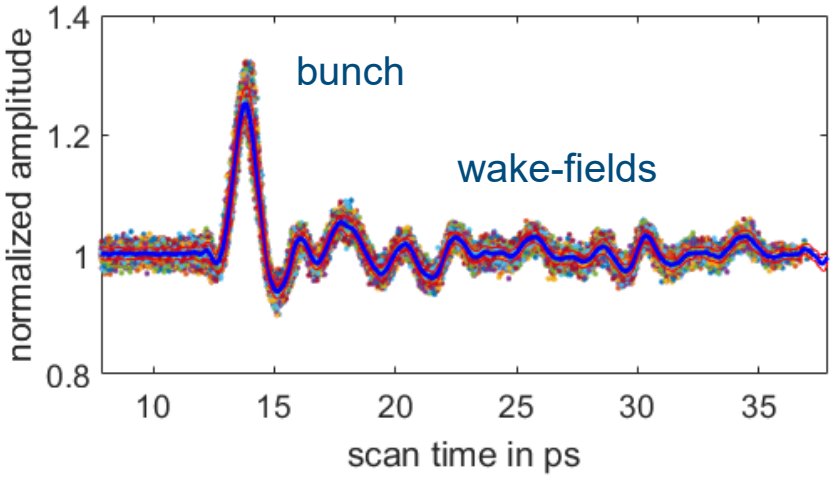
Measurements downstream BC1

Laser time scans



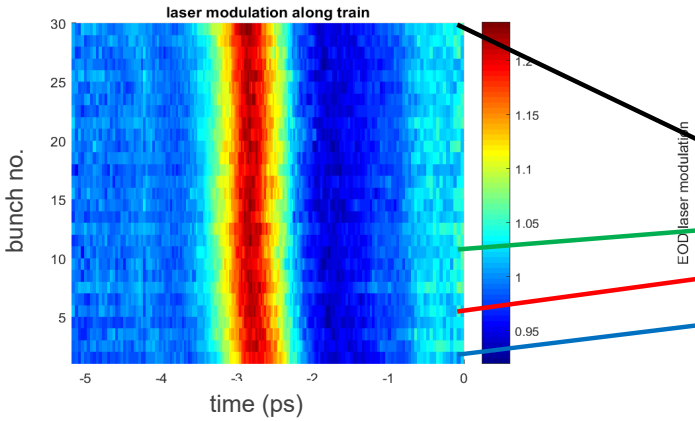
Raw signal from 5 bunches each line averaged and corrected with laser chirp

Stacked data

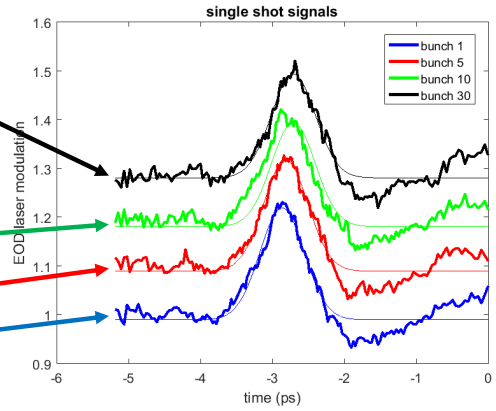


Measurements downstream BC1

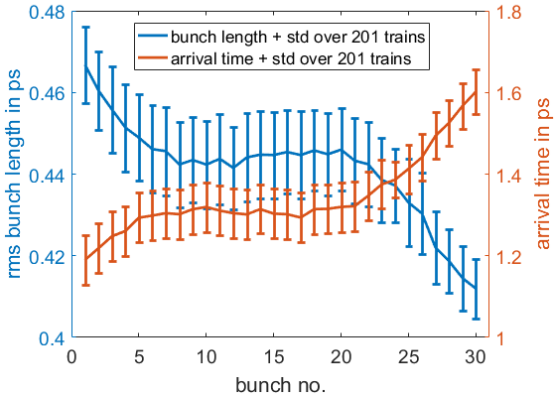
Single shot measurements of full bunch trains



EOD traces of all 30 bunches of a bunch train with 1.13 MHz repetition rate



Single shot EOD traces and fitted Gaussians from the same bunch train

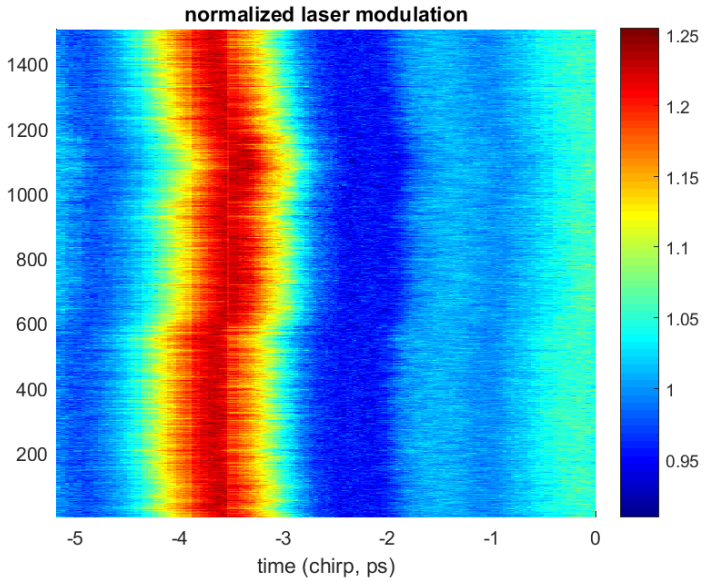


Arrival time and bunch length (rms) along the bunch train

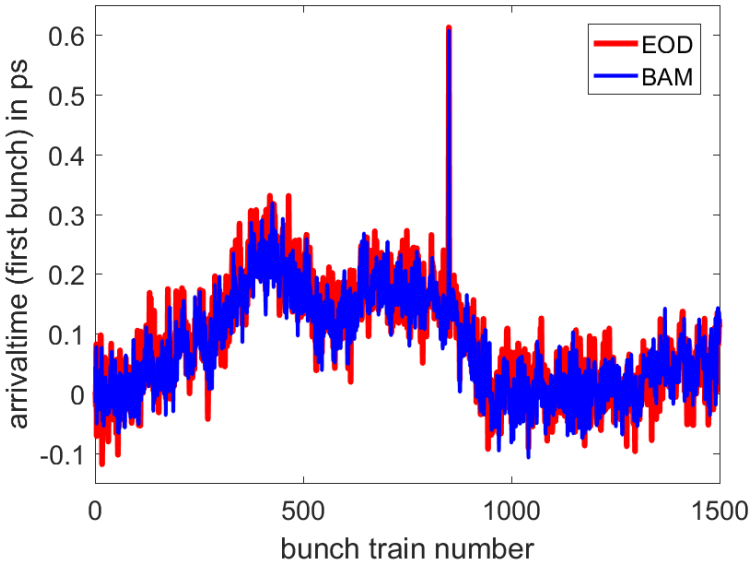
Measurements downstream BC1

Arrival time from EOD compared to BAM

BAM: Bunch Arrival-time Monitor
Optical Sampling of a picked-up RF voltage signal with 40GHz bandwidth with a fiber coupled electro-optical modulator



EOD signal from 1500 consecutive bunches (2.5 minutes, 1st of each train) taken during SASE tuning

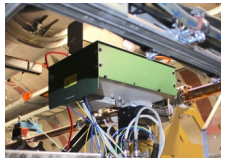


…and their arrival time measured with EOD and BAM

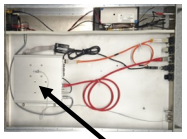
Summary

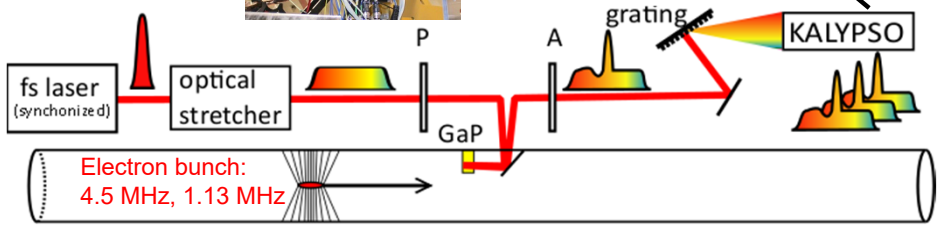
Electro-Optical Diagnostics for bunch length monitoring

Laser:
2.26 MHz, 1.13 MHz

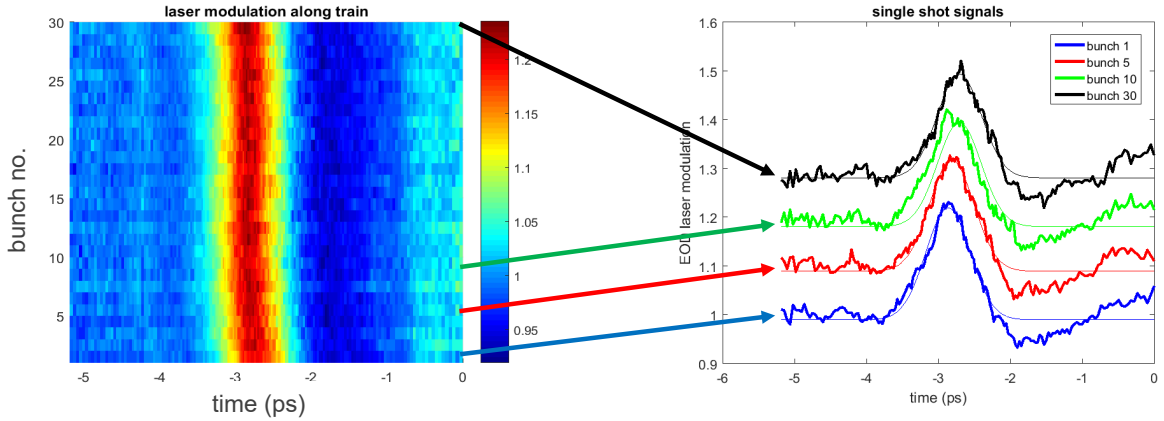


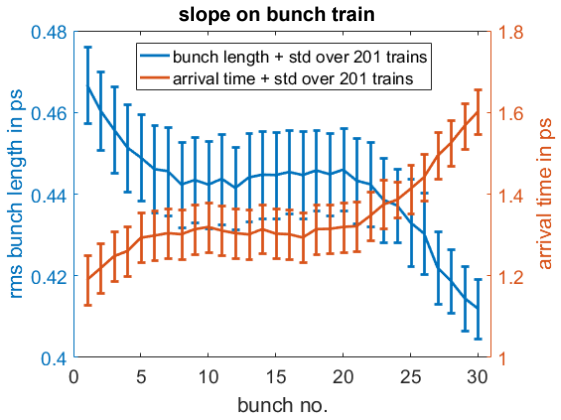
Line detector:
2.26 MHz, 1.13 MHz





- 3 EOD systems installed at E-XFEL
- Full system installed in racks below beamline (fully remotely controlled)
- All sub-systems in 19" crate standard with a compact design (25 HU total)
- Bunch arrival times measured are in good agreement with BAM measurements
- Bunch length measured are in agreement with beam dynamics simulations for given RF settings





Thank you for your attention!

Contact

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Outlook

KALYPSO User Needs

Outcome: *Workshop on Longitudinal Diagnostics for FELs,* 25-27/6/2018, DESY

	KALYPSO v2.1 *current*	KALYPSO v2.5 *NEW*	KARA/ DELTA	EOD@XFEL	Photon Diagnostics	TELBE	SLS	SOLEIL (EO)
No. of pixels	256	512/1024/2048	≥ 256	(256-)512	512-1024	1024	1024	1024
pixel width	50 µm	25 µm / 50 µm	25 / 50 µm	25 / 50 µm	25 µm	25 µm	25 µm	25 µm
pixel height	Si:10 mm, InGaAs:500 µm	3 mm	> 500 µm					
total width	12.8 mm	12.8 / 25.6 / 51.2 mm	--	< 26 mm		51 mm	51 mm	26 mm
Line rate	> 2.7 Mfps	**> 12 Mfps**	2.7 Mfps	>1.1 Mfps	>1.1 Mfps	13 Mfps	> 1 Mfps	< 1 Mfps
clock rate	Adjustable by on-board PLL	**Adjustable by on-board PLL**	--					
wavelength	Si: 300nm-1µm, InGaAs: 900nm-1.7µm	Si: NIR, VIS & NUV ARC process	NUV NIR VIS	1050 nm	VIS (or X-ray)	VIS	NUV	NIR and VIS
S/N	600 e^-	**Improved**						
Dynamic range	66 dB	**Improved**						
Adjustable gain	Three gains	**Three gains**						
Bit resolution	14 bit (ADCs)	**14 / 12 bits (ADCs)**						