
Wir schaffen Wissen – heute für morgen

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Electro Optical Sampling of Coherent Synchrotron Radiation for ps Electron Bunches with pC Charge

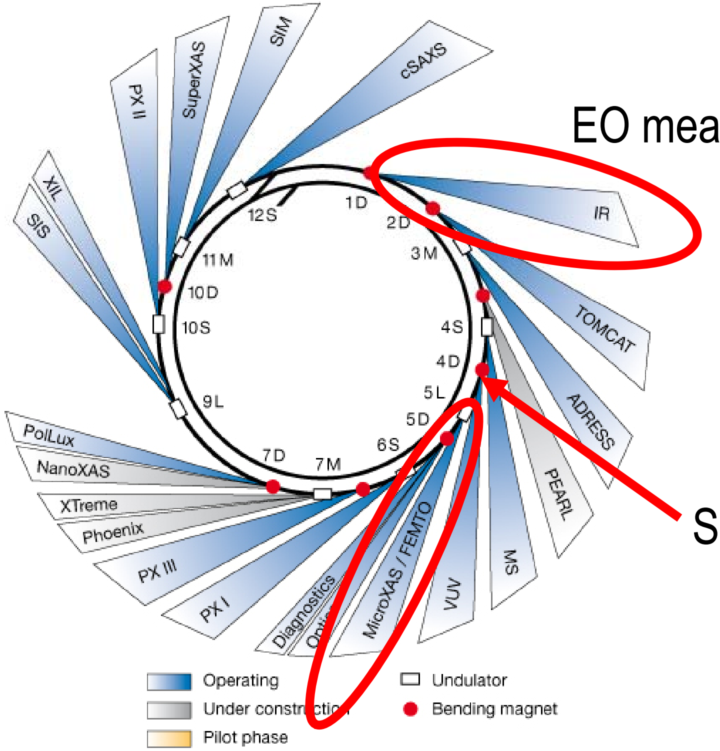
Contents

Motivation

Goal:	Measurement of particle distribution in time domain
Requirements:	Non-destructive bunch length measurement Measurement of small charge modulations of the electron bunch (few pC) High temporal resolution (< 1ps) Jitter insensitive → single shot
Method:	EO offers the possibility to measure electron bunches and low charge modulation single shot (turn by turn) with sub ps time resolution

	FEMTO @ SLS	Injector	Injector BC	SwissFEL
Energy [MeV]	2400	250	250	2100
Charge [pC]	1-10	10-200	10-200	10-200
timescale [ps]	0.2-10	10	0.2	0.01-0.03
(sub-)structure	modulation	bunch	bunch	bunch
Method	CSR	Coulomb field	Coulomb field / CSR	Coulomb field / CSR
Crystal	GaP/ZnTe/DAST	GaP	GaP	GaP/DAST

Swiss Light Source - SLS



EO measurement

Storage ring

Slicing Experiment

Key data:

• Beam energy	2.4 GeV
• Circumference	288 m
• Emittances	
horizontal	5 - 6.8 nm rad
vertical	3 - 10 pm rad
• Energy spread	0.09 %
• Beam current	400 mA (top-up)
• Life time	~ 8 h
• Nominal pulse length	35 ps (rms)

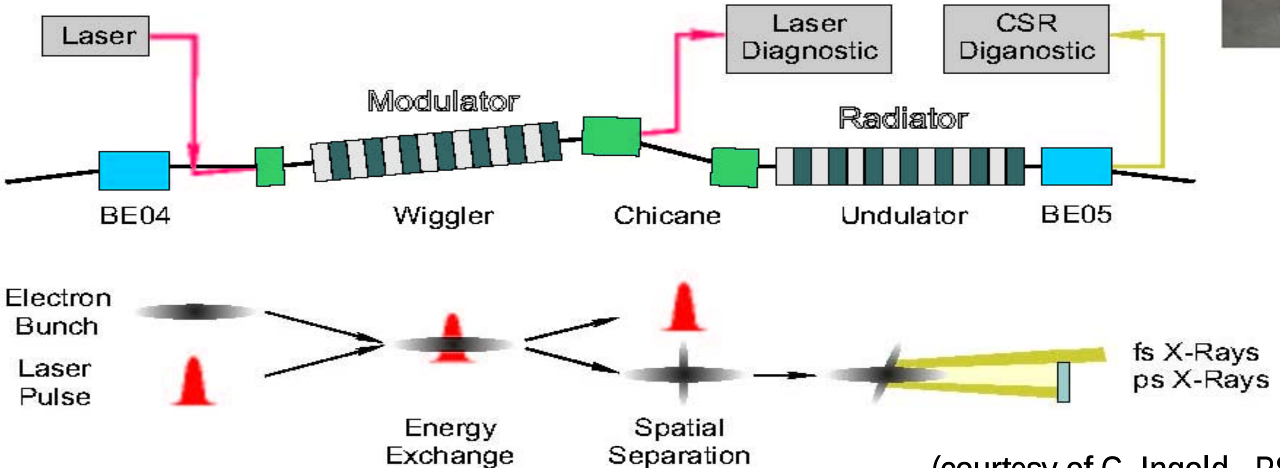
SLS FEMTO slicing project:
Tunable sub-ps X-ray source

FEMTO Bunch Slicing – Layout and Principle

Electron/Laser Interaction
Modulator (Wiggler)
→periodic transverse component of momentum

Sub-ps X-Rays
Radiator (Undulator)
4.2-14 keV
4*105 ph/s/0.1%BW

Ti:Sa Laser
Two stage amplification
5 mJ/pulse
2 kHz rep. rate
30 fs (rms)



(courtesy of G. Ingold - PSI)

Chicane
Laser – electron separation
Angular dispersion
Electron energy modulation
→ longitudinal electron density modulation

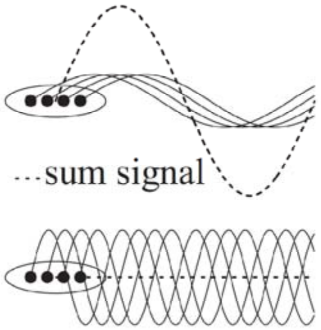
FEMTO Slicing – Coherent Synchrotron Radiation (CSR)

Electron Beam

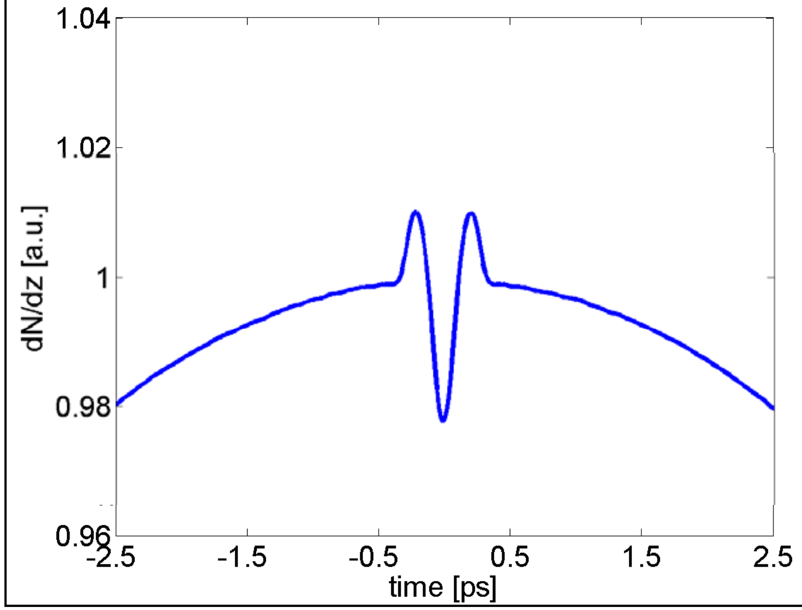
- Bunch length of sliced beam: s =100 fs,
  core beam: s = 35 ps
- Slicing leads to longitudinal density modulation of core bunch, which will be lengthened through passage of storage ring proportional to the linear Momentum Compaction Factor.
- Slicing efficiency per bunch: ~10^{-4}
  Bunch Charge: 5 nC
  →modulated bunch: few pC

Synchrotron Radiation

- Coherent (~ N^2) enhancement of SR up to a factor of 100 compared to incoherent SR for wavelengths from ~ 0.1 mm up to 1 mm

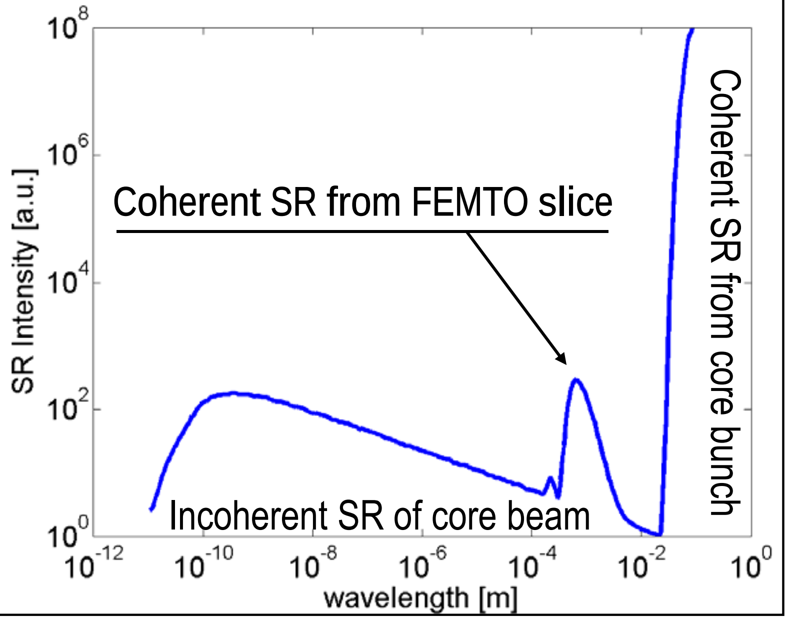


temporal



$$\left|\int e^{i\omega z/c} S(z)\,dz\right|^2$$

spectral



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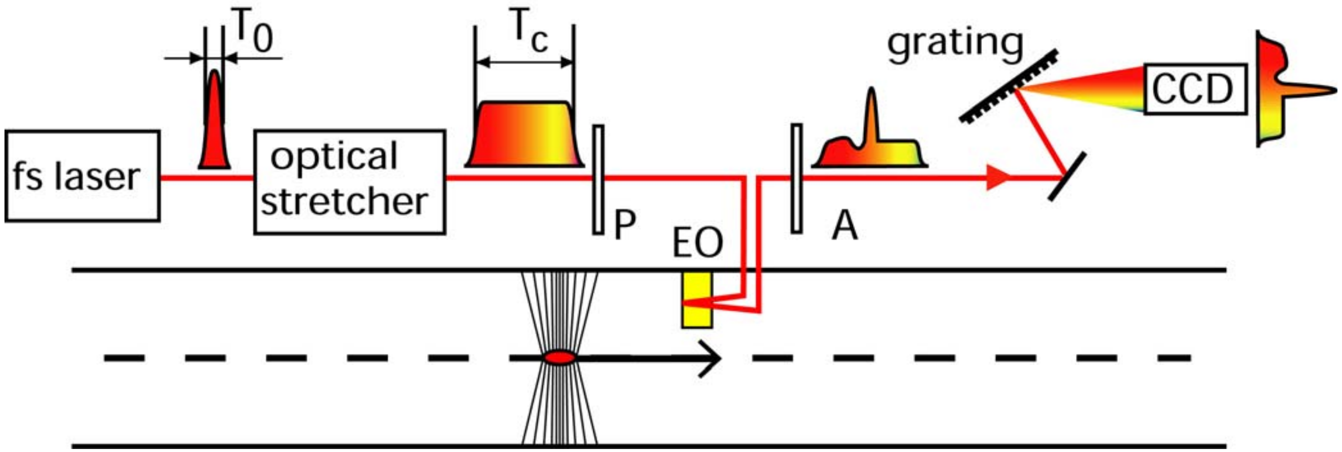
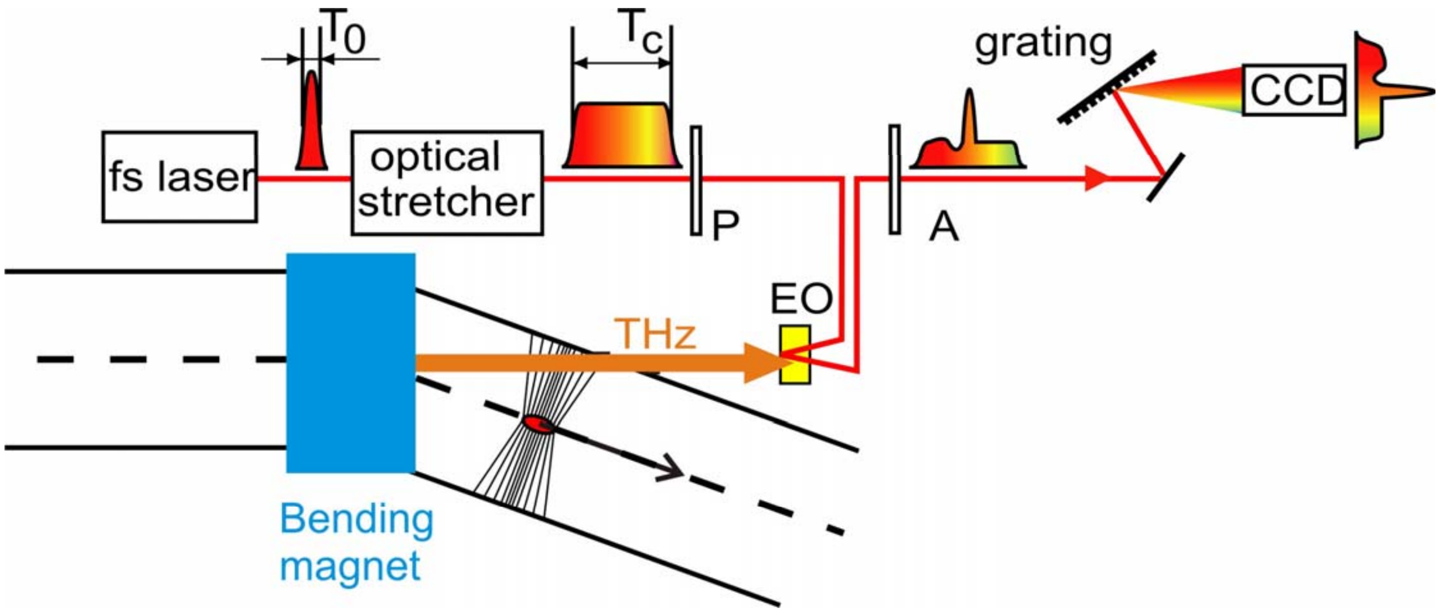
CSR ←→ Coulomb Field

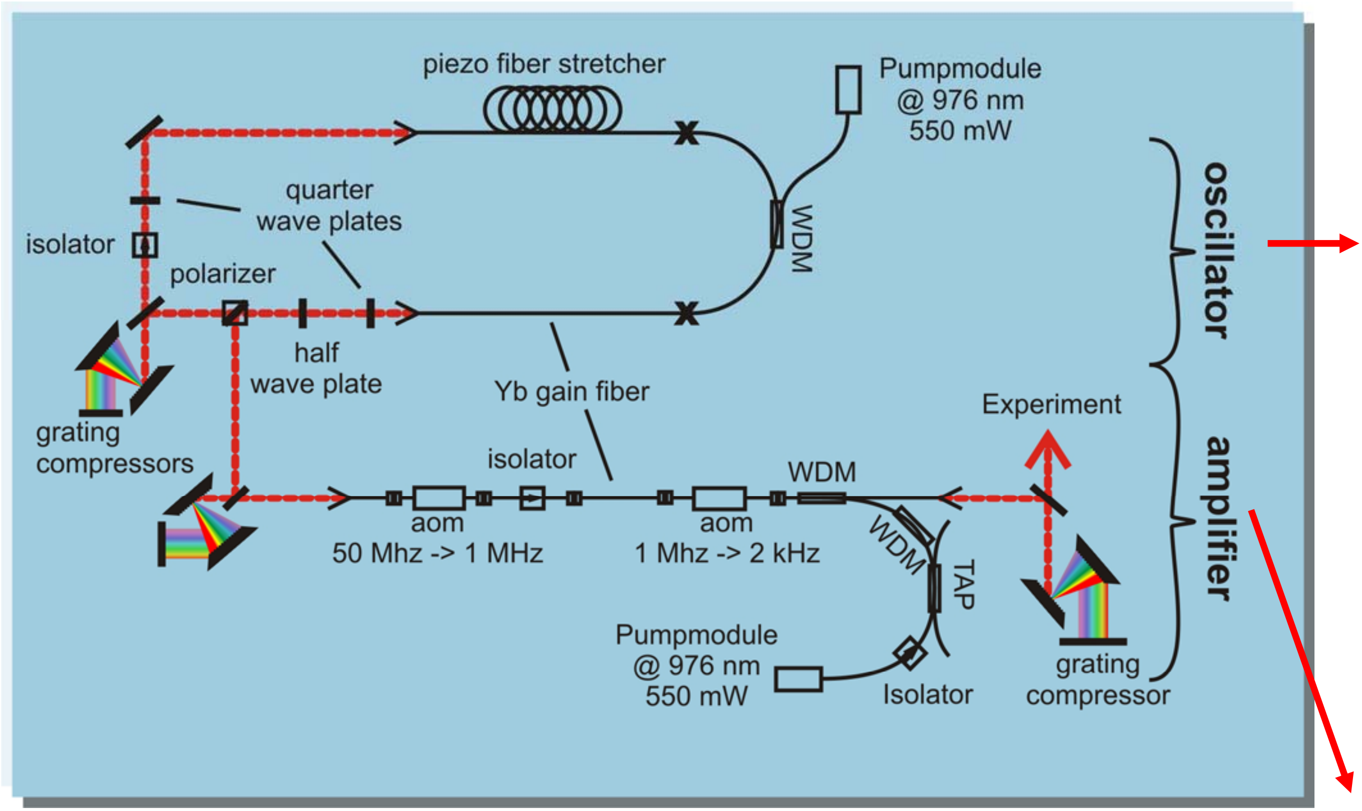
Coulomb field

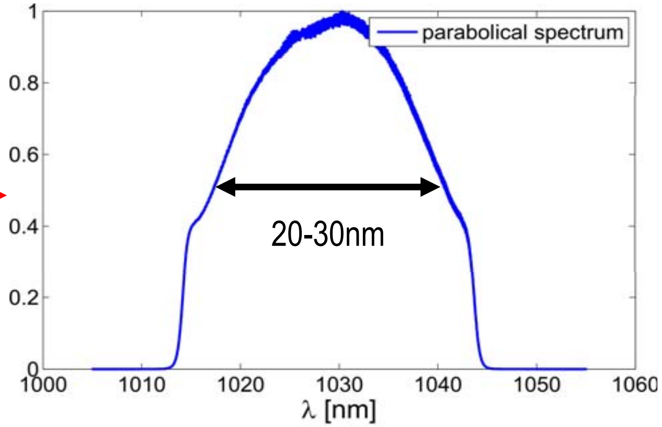


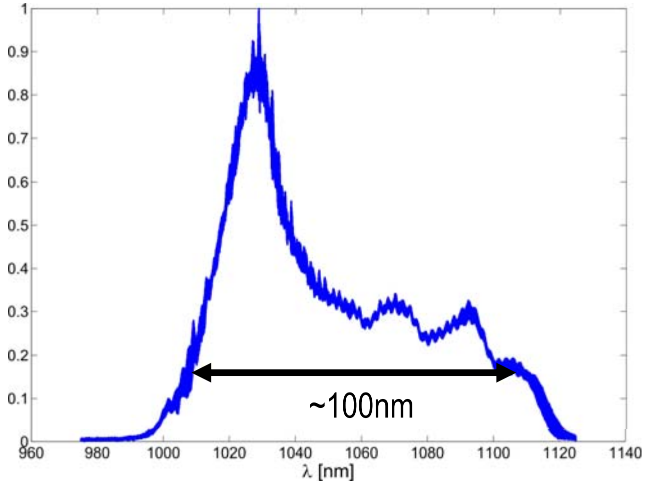
Coherent Synchrotron Radiation



Yb-Fiber Laser – Layout and Performance







Oscillator:

P = 50 – 100 mW

E_{Pulse} = 1 – 2 nJ

Δt = 50 fs

f_{rep} = 50 MHz

Amplifier:

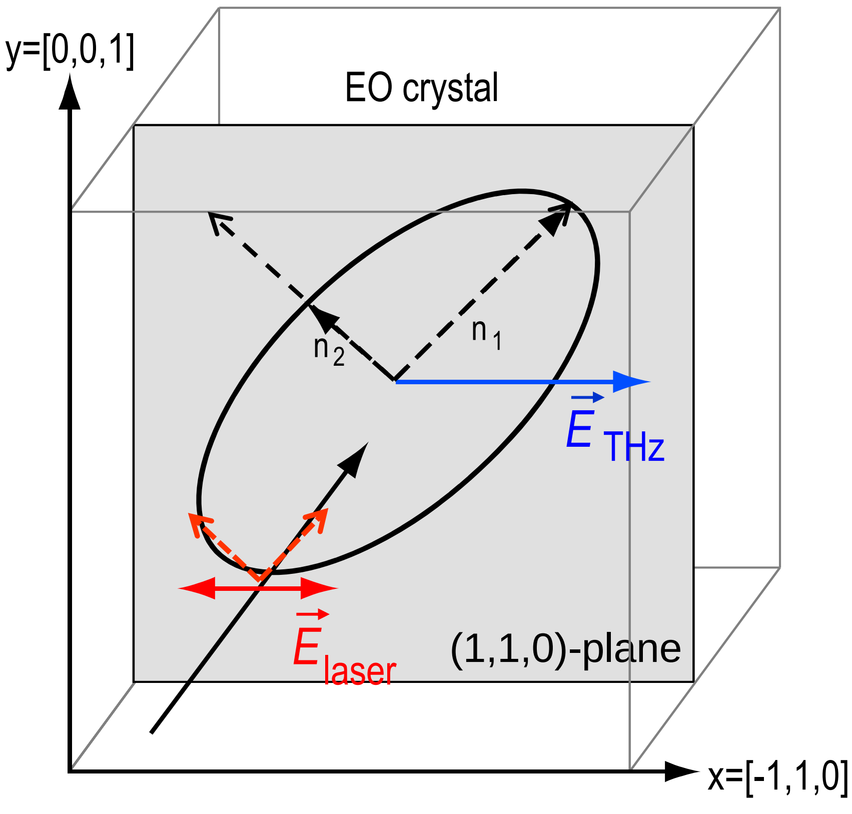
P = 10 – 20 mW

E_{Pulse} = 10 – 20 nJ

Δt = 35 fs

f_{rep} = 1 MHz

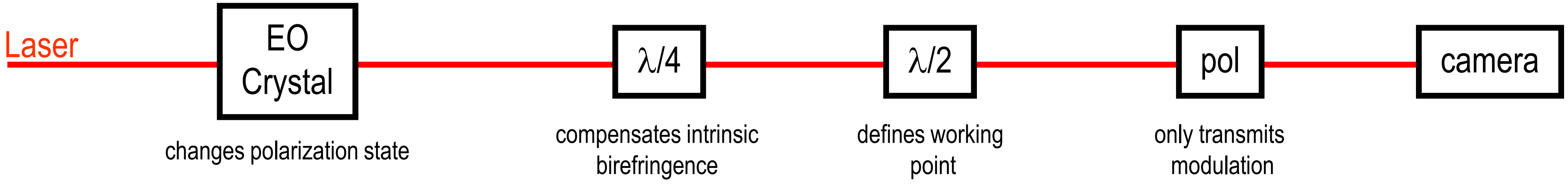
The Electro Optic Effect



$$P = \varepsilon_0\left(\underbrace{\chi_e^{(0)}E}_{\text{Pockels effect}} + \underbrace{\chi_e^{(1)}E^2}_{\text{Kerr effect}} + \chi_e^{(2)}E^3 + \ldots\right)$$

- $\vec{E}_{THz}$ passes the EO-crystal in the (1,1,0)-plane
- The two components of a linearly polarized probe laser pulse $\vec{E}_{laser}$ will see different refractive indices n_1 and n_2 in the crystal leading to a phase retardation and a subsequent polarization change (from linear to elliptical) of the laser pulse

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



Laser

EO Crystal

changes polarization state

λ/4

compensates intrinsic birefringence

λ/2

defines working point

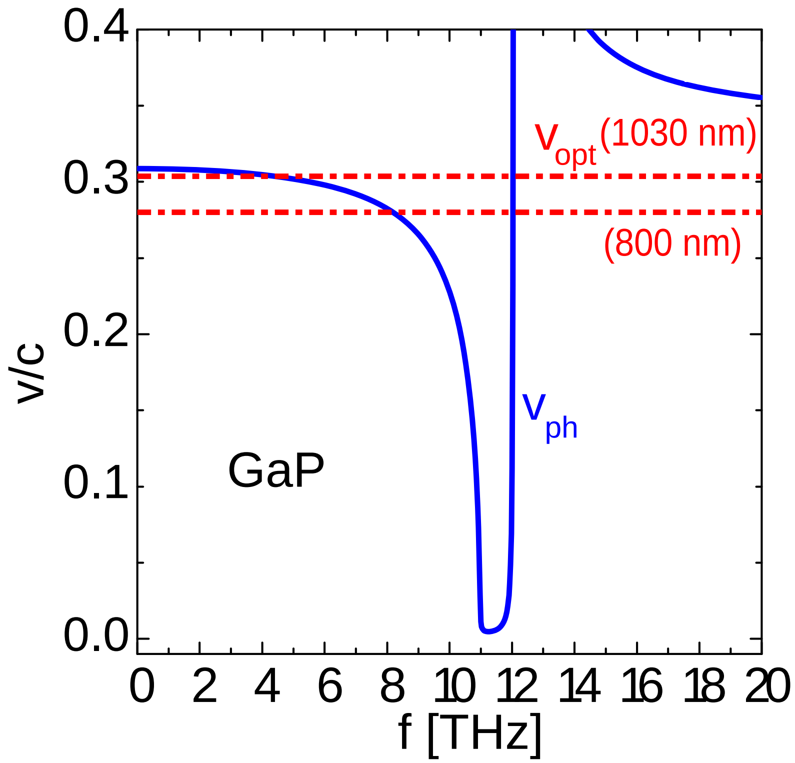
pol

only transmits modulation

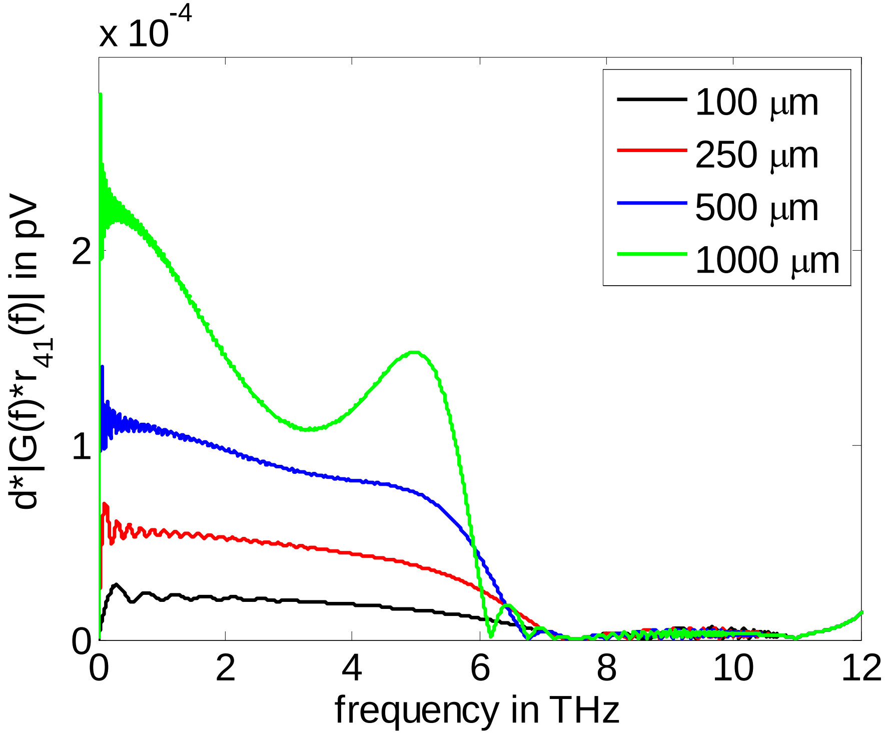
camera

EO Crystal – Gallium Phosphide (GaP)

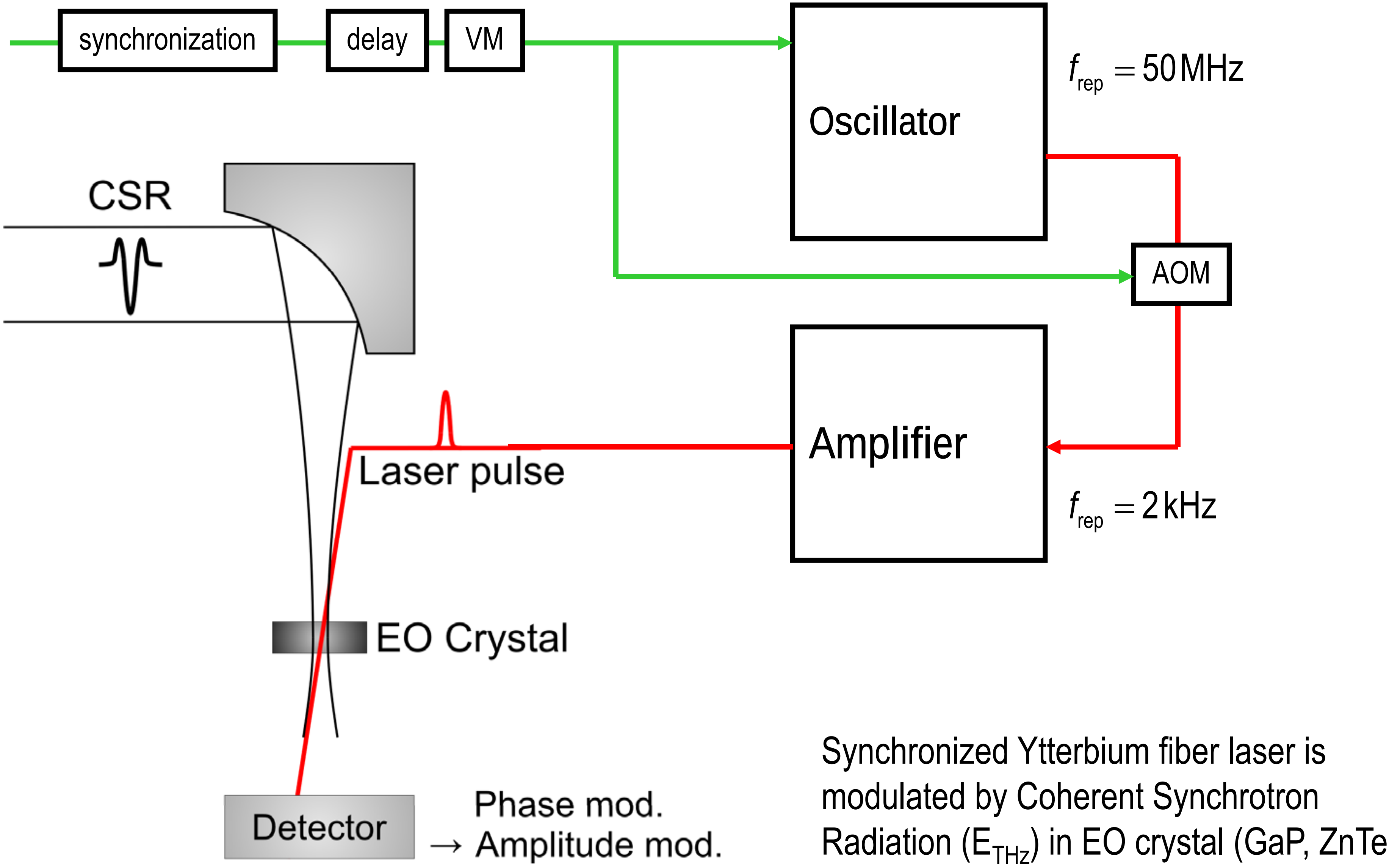
Dispersion plot: phase velocity vs. frequency



Response of GaP of a certain thickness

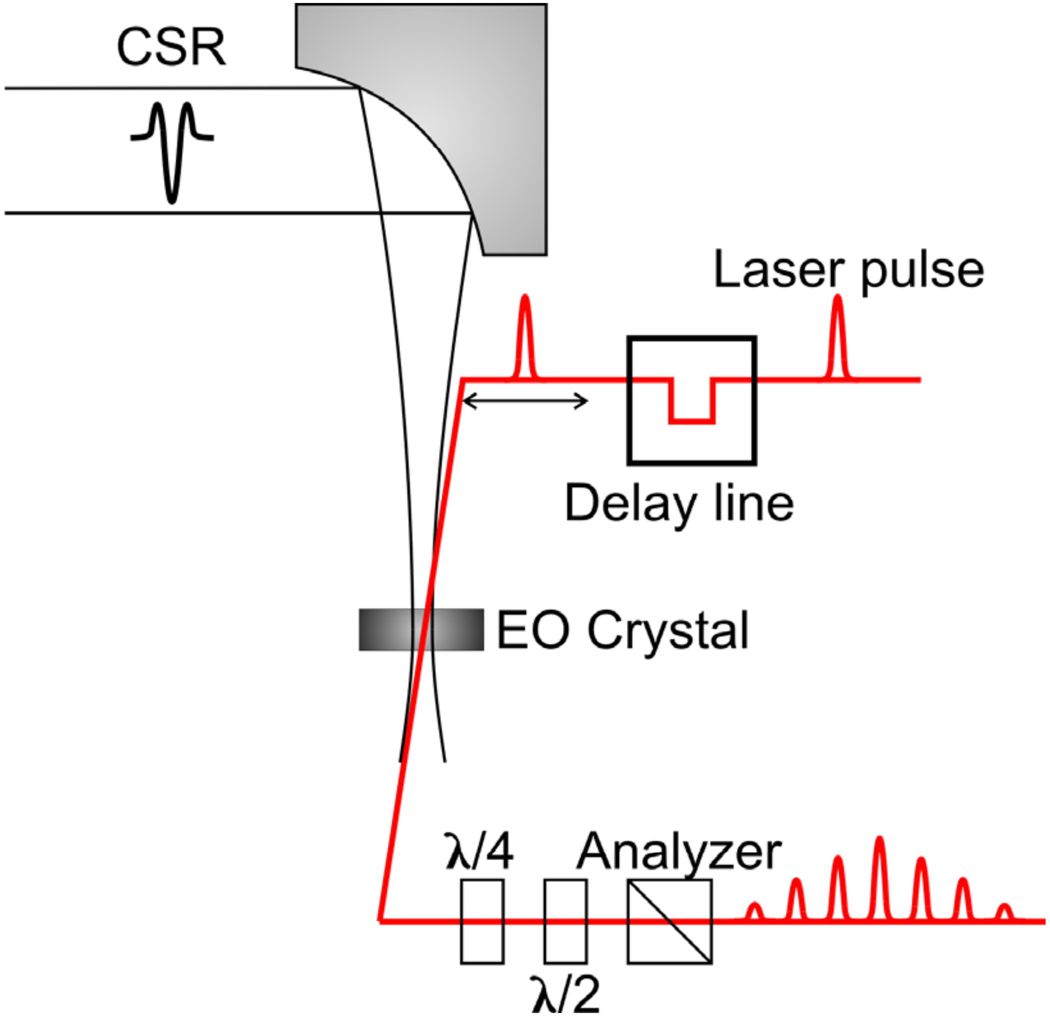


Principle of EO Detection

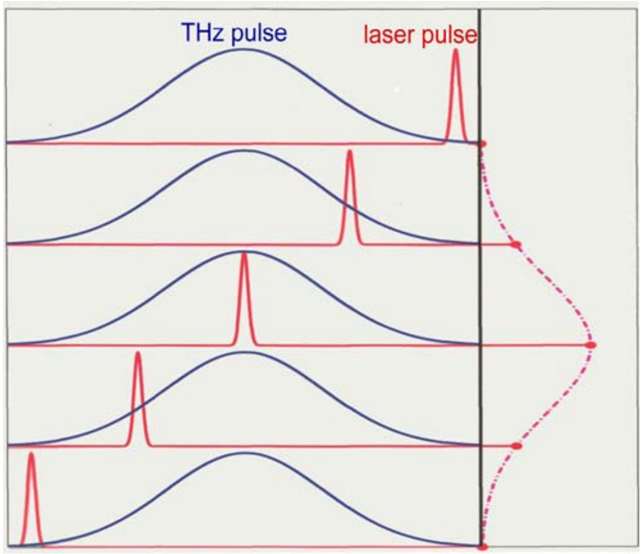


Synchronized Ytterbium fiber laser is modulated by Coherent Synchrotron Radiation (E_{THz}) in EO crystal (GaP, ZnTe)

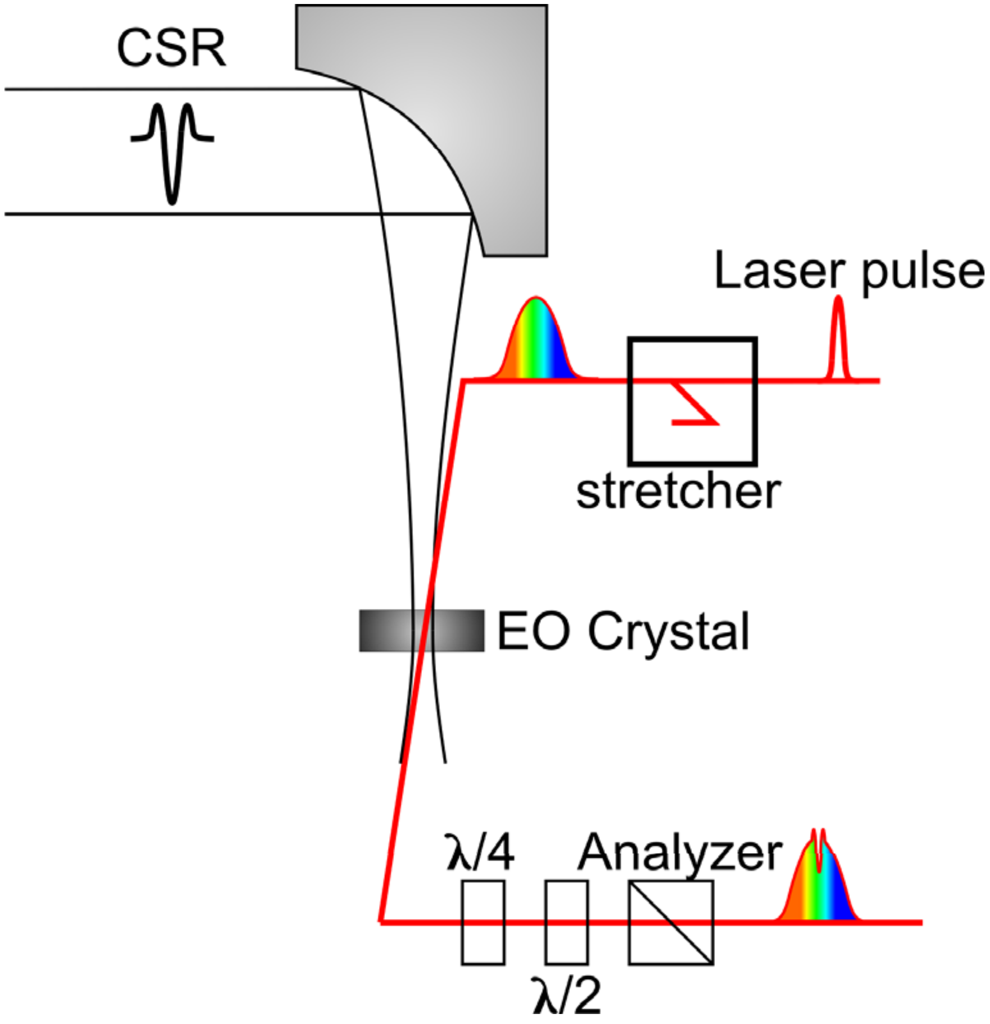
Principle of EO Detection - Sampling



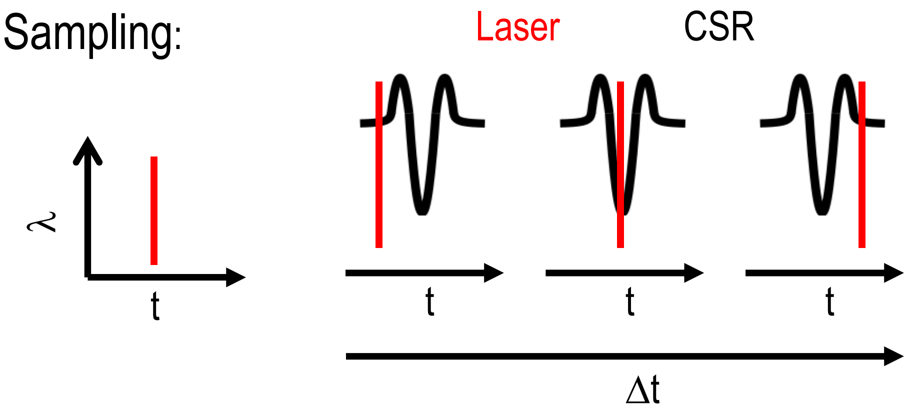
Sampling



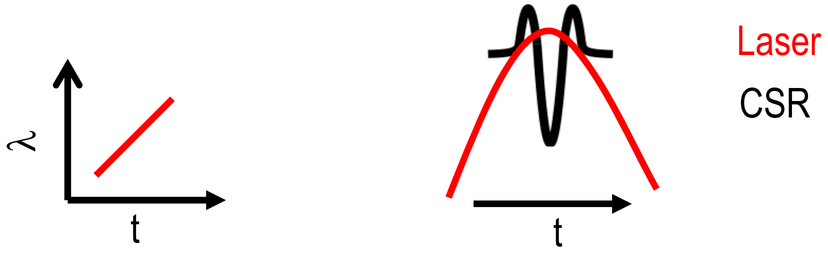
Principle of EO Detection – Spectral Decoding

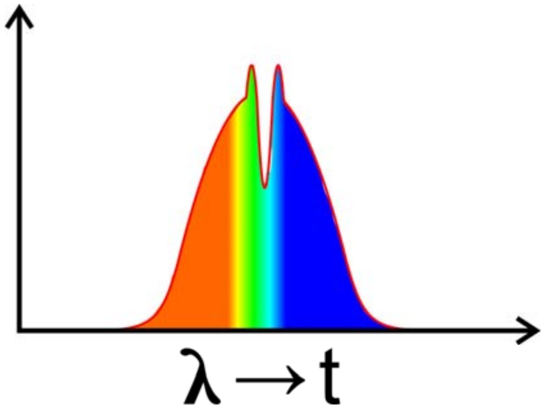


Sampling:



Spectral decoding:





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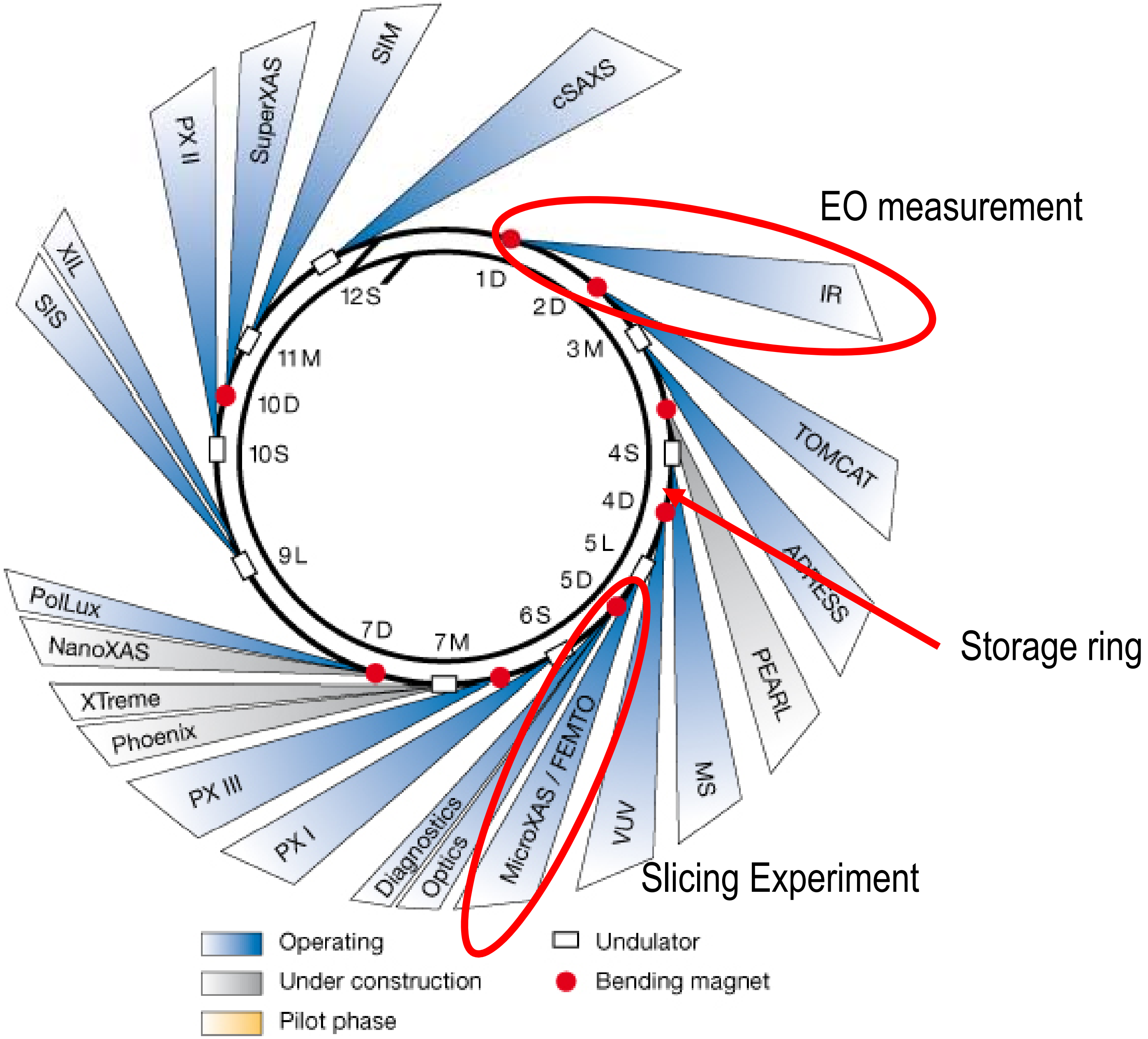
SLS Measurements



EO measurement

Storage ring

Slicing Experiment

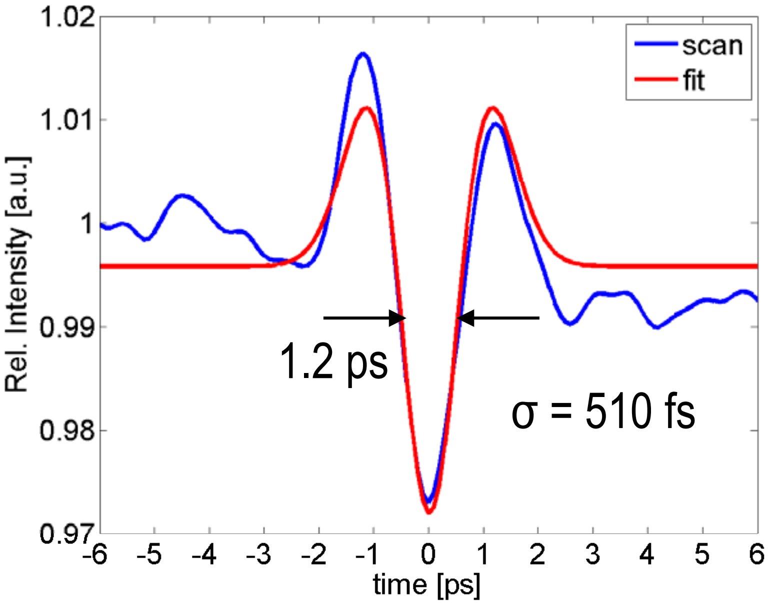
Setup and Results - Sampling Measurements @ IR Beamline

- Delaystage with 100fs stepwidth
- Averaged over 100 pulses
- FEMTO laser to EO laser Jitter ~ 50 fs rms

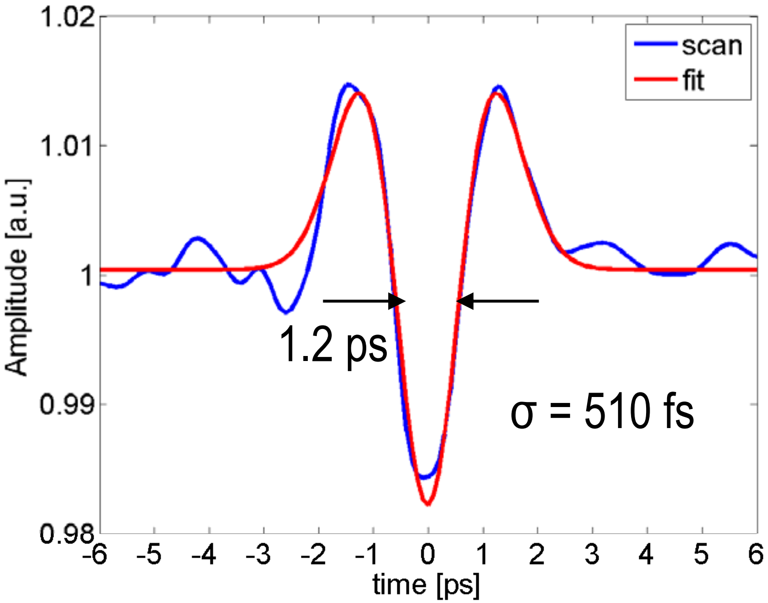
- Additional arrival time Jitter
  → pulse broadening

- Good phasematching and low frequencies allow thick crystals
- ZnTe has a higher r_{41} but worse optical quality

5mm thick GaP crystal



1mm thick ZnTe crystal

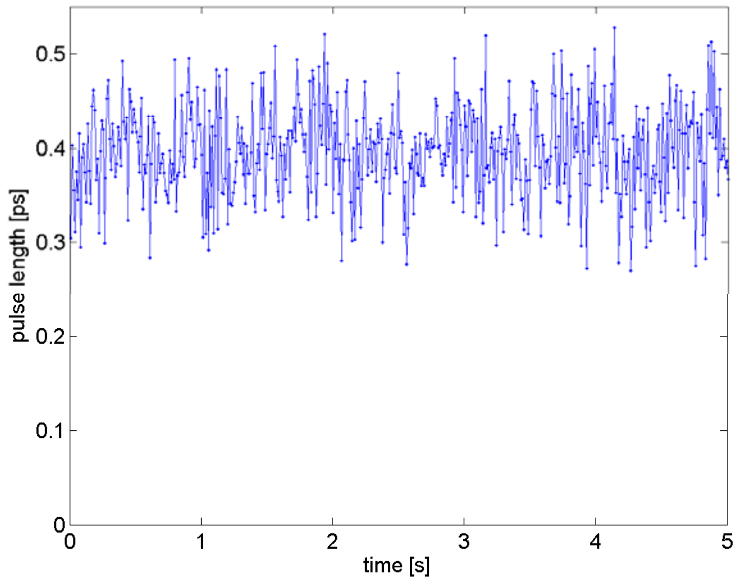


Setup and Results - Spectral Decoding; Single Shot

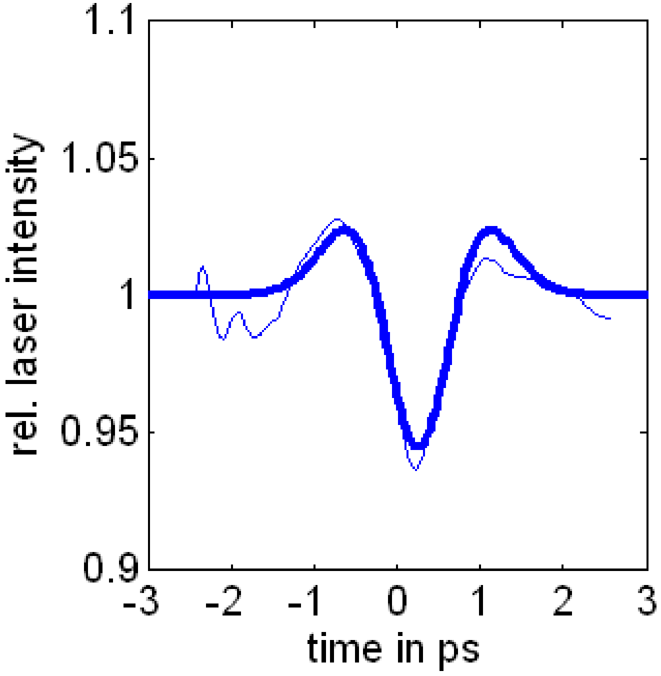
Spectral Decoding (5mm GaP crystal)
- Thin line: Measurement
- Thick line: Gaussfit
  → Fit parameters give
    - Arrival time
    - Pulse length

Pulse Length: (365 ± 50) fs rms

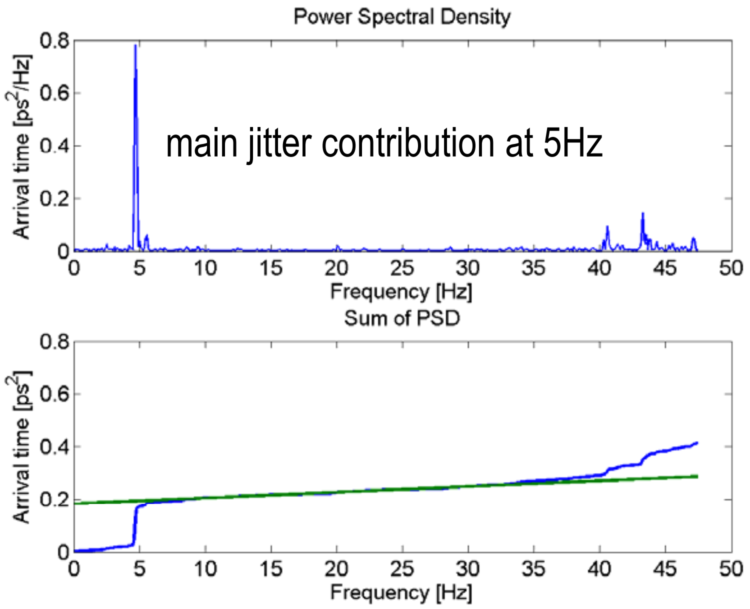
Arrival Time: ([illegible]) fs (rms)



n: 1



Spectrum of Autocorrelation



Estimation of EO arrival time resolution: σ= 330 fs (limited by signal strength)

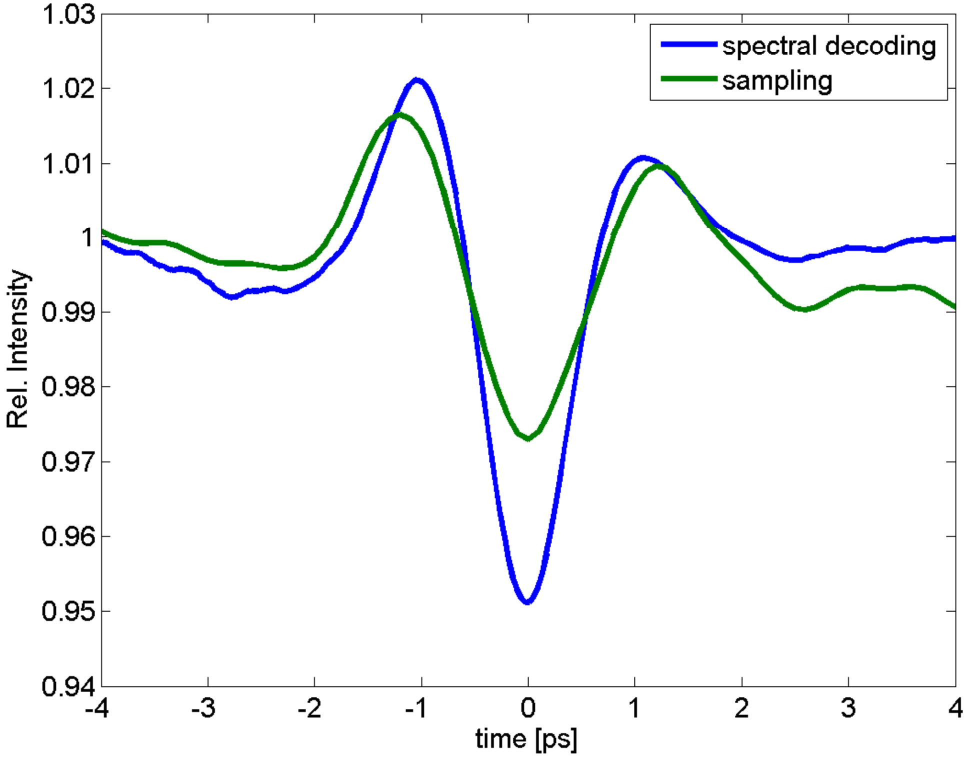
Setup and Results - Spectral Decoding; Average

Arrival time can be subtracted

→Averaged signal doesn't suffer from Jitter.

→Absolute THz field strength can be determined.

Comparison between spectral decoding and sampling measurements

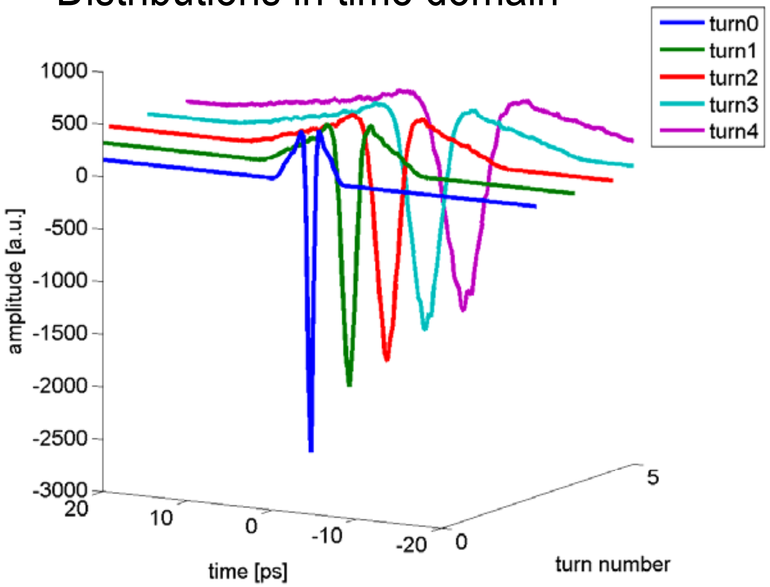


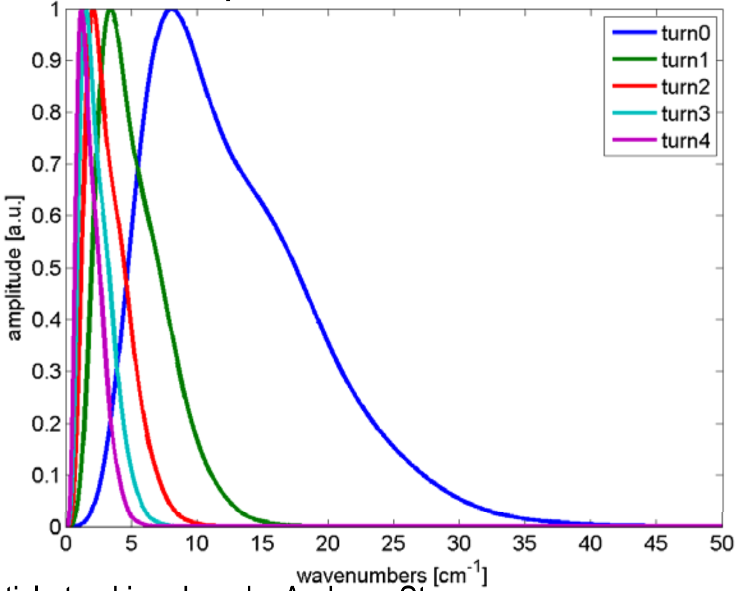
SD Laser modulation: 7 %

→ Γ ~ 0.55°

→ E_{THz} ~ 2*10^4 V/m

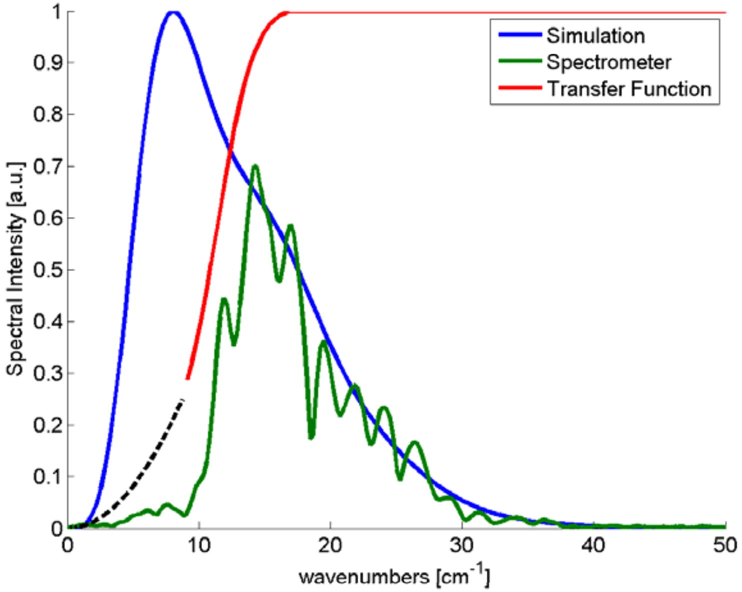
Setup and Results - Tracking Results


Distributions in time domain


Spectral distributions

Particle tracking done by Andreas Streun

- Due to energy modulation, electrons have about 10 times higher energy spread
  - →broadening of electron distribution ~ 4.8 ps/turn
  - →broadening of the dip ~ 520 fs/turn


Beamline acts as a highpass Filter

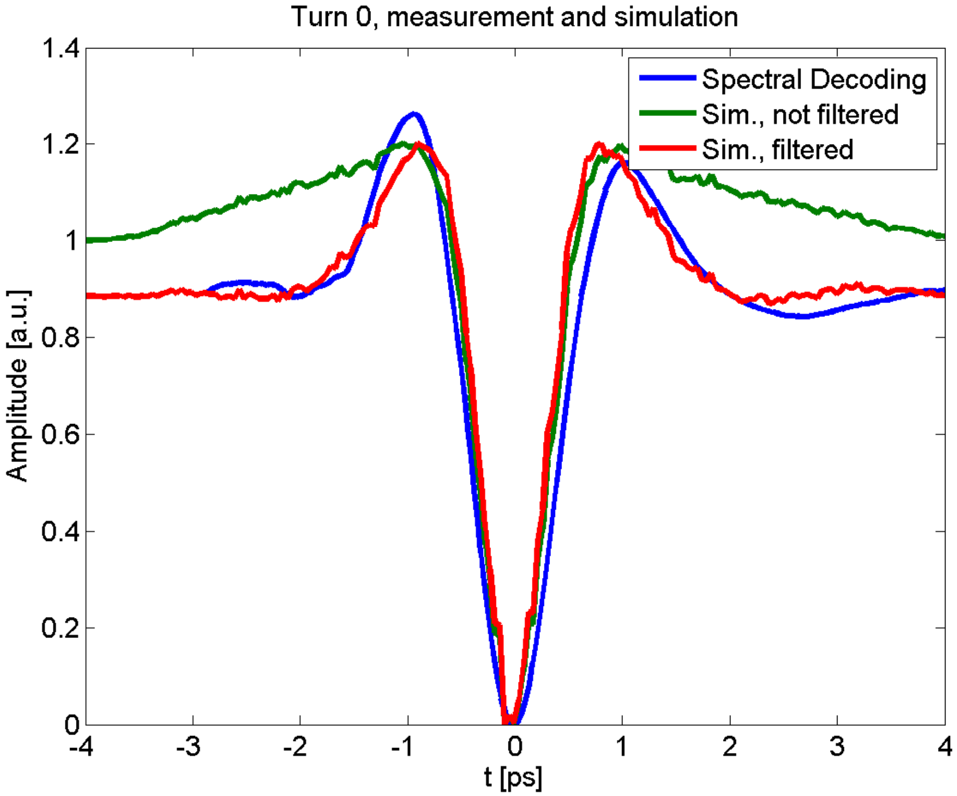
Measurement done by Hans Sigg

- Energy modulated electron distribution is suppressed due to long wavelength cut-off at the IR Beamline

→only the „hole“ is visible

Setup and Results - Tracking results

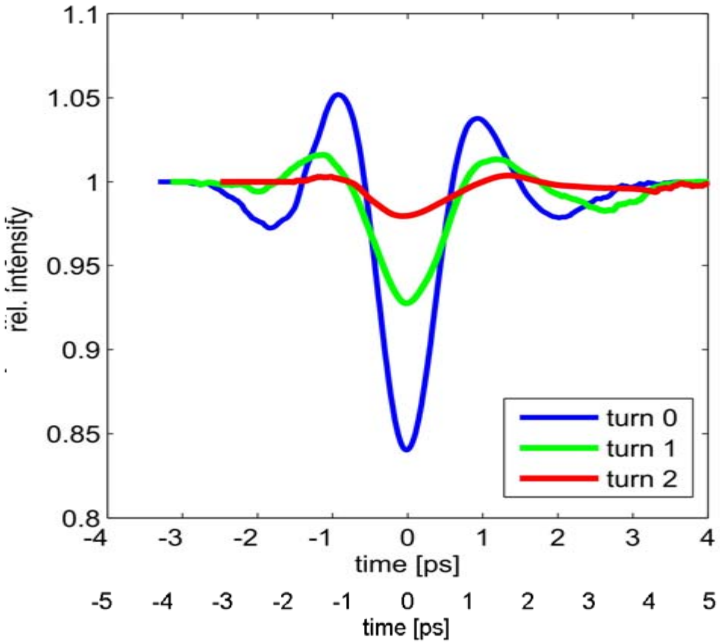
Averaged Spectral Decoding measurement of turn 0 is in good agreement with theory.



Comparison of pulse length
Simulation: 286 fs
Measurement: (365 ± 50) fs

Preliminary Results:

- Sampling measurement system is sensitive enough to detect sliced particle distribution up to turn 3.
- Spectral decoding can be used up to turn 2
- But: Tracking predicts much broader pulses →further analysis is required.



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- Principle of Electro Optical Detection and Bunch Length Measurement
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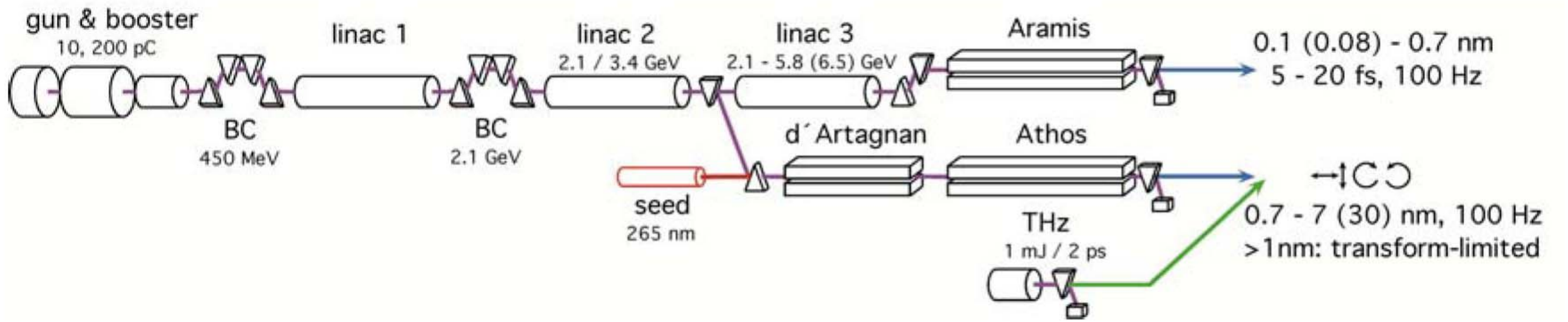
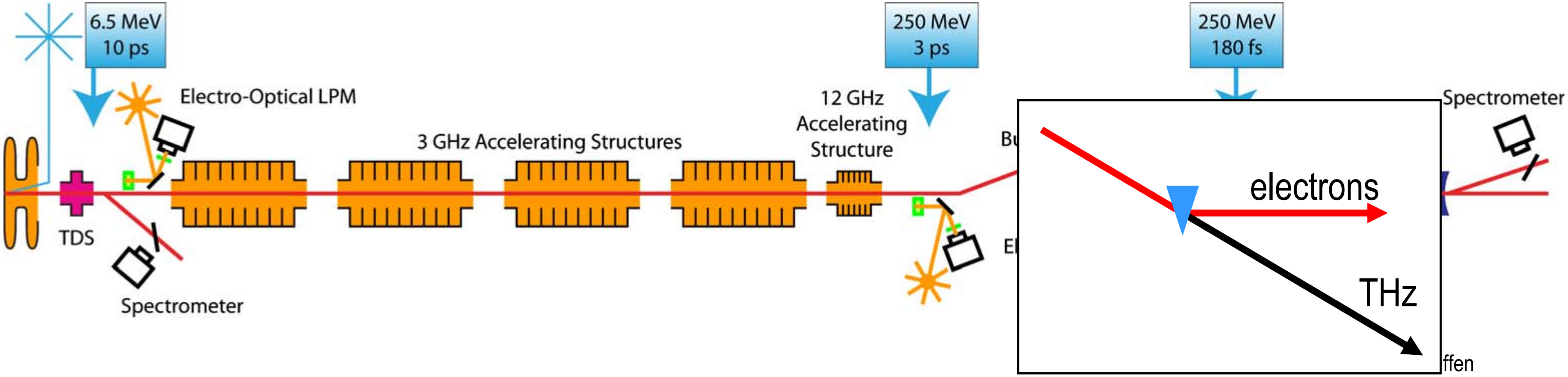
- Conclusion

SwissFEL

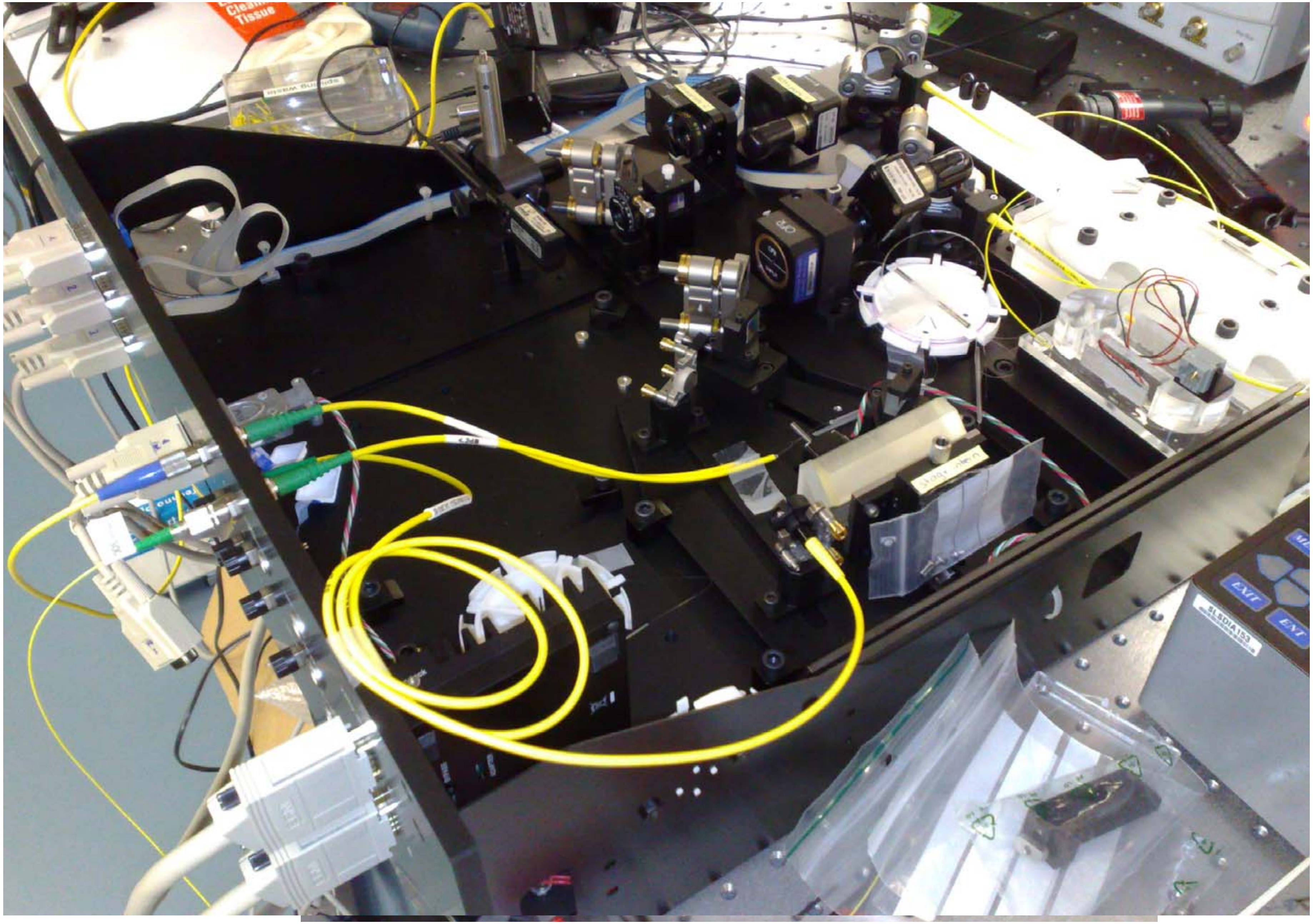
- SwissFEL – start of operation 2016



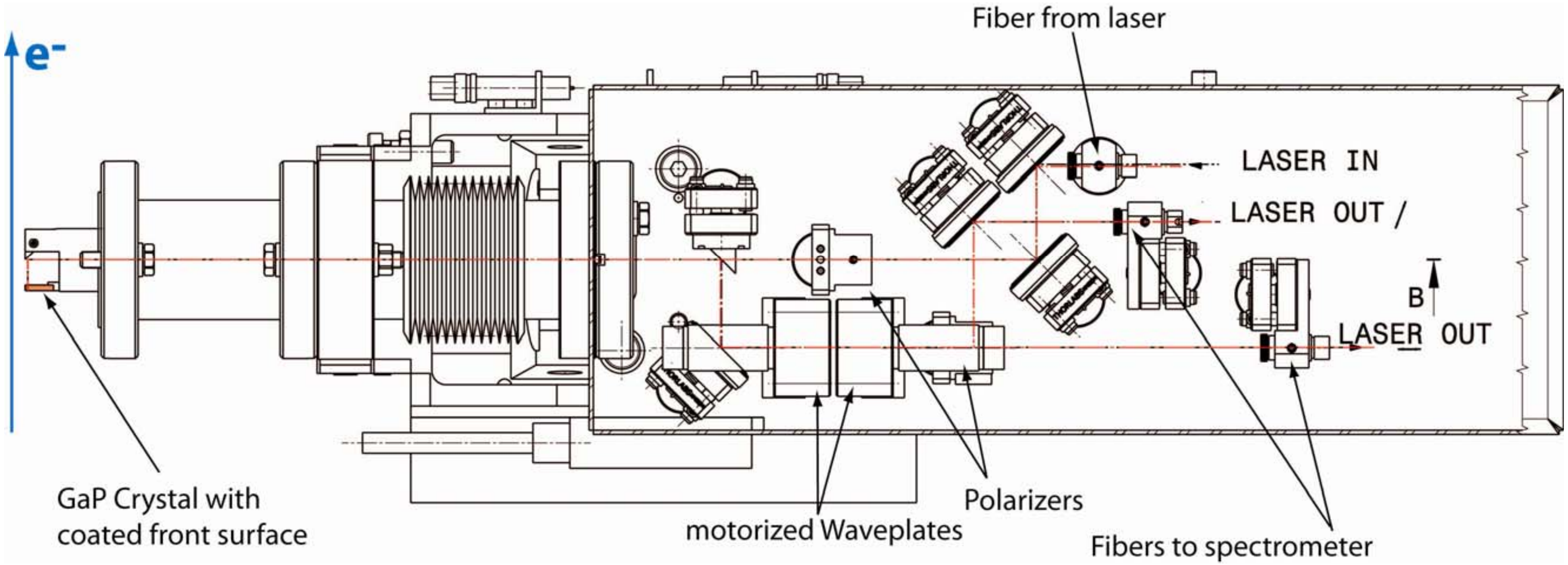
- 250MeV injector test facility – start of operation 2010/2011

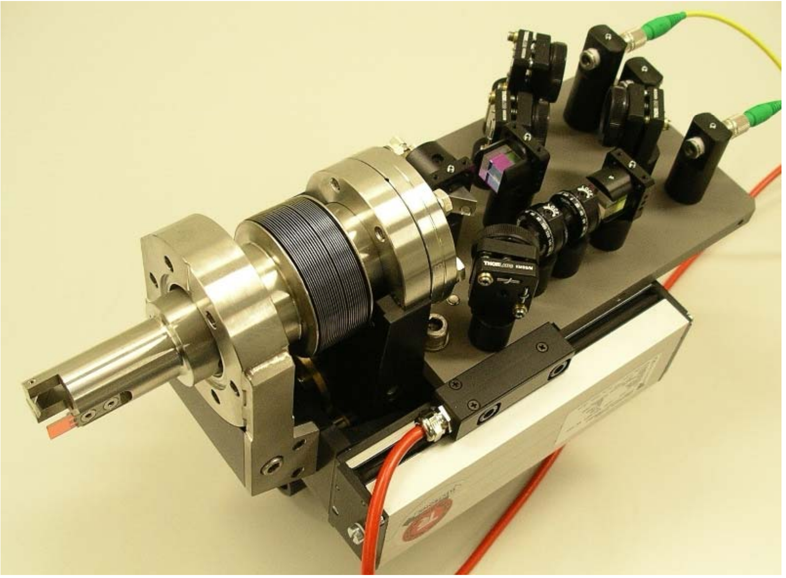


EO Monitors for SwissFEL Injector - Laser



EO Monitors for SwissFEL Injector - Monitor





Conclusion & Acknowledgments

- Activities at PSI
- FEMTO: Slicing experiment at Swiss Light Source
  - longitudinal density modulation of core bunch
  - Coherent Synchrotron Radiation in the THz region
- Electro optical method to measure longitudinal bunch structure
  - Sampling technique
  - Spectral decoding
- Experimental results compared to simulation
  - Signal form → temporal structure
  - Jitter → arrival time
- Presentation of a packaged laser and a compact EO monitor for SwissFEL 250MeV injector

- Thanks
  - Simulations: Andreas Streun (PSI)
  - Infrared Beamline crew: Philippe Lerch, Hans Sigg and Luca Quaroni (PSI)
  - FEMTO Slicing team: Gerhard Ingold, Steven Johnson and Paul Beaud (PSI)