Editor's Note: PDF version of slides from Beam Instrumentation Workshop 2010, Santa Fe, NM

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Felix Müller, Bernd Steffen, Volker Schlott, Pavel Chevtsov

Electro Optical Sampling of Coherent Synchrotron Radiation for Picosecond Electron Bunches with few-pC Charge

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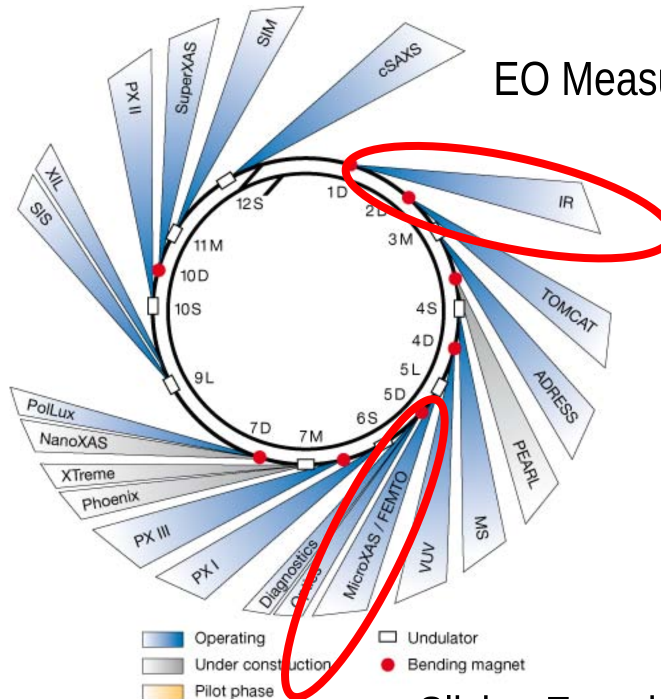
Introduction - Swiss Light Source - SLS



EO Measurement

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

Goal: Measurement of sliced particle distribution in time domain.

Method: EO offers the possibility to measure this low charge modulation single shot (turn by turn) with sub ps time resolution.

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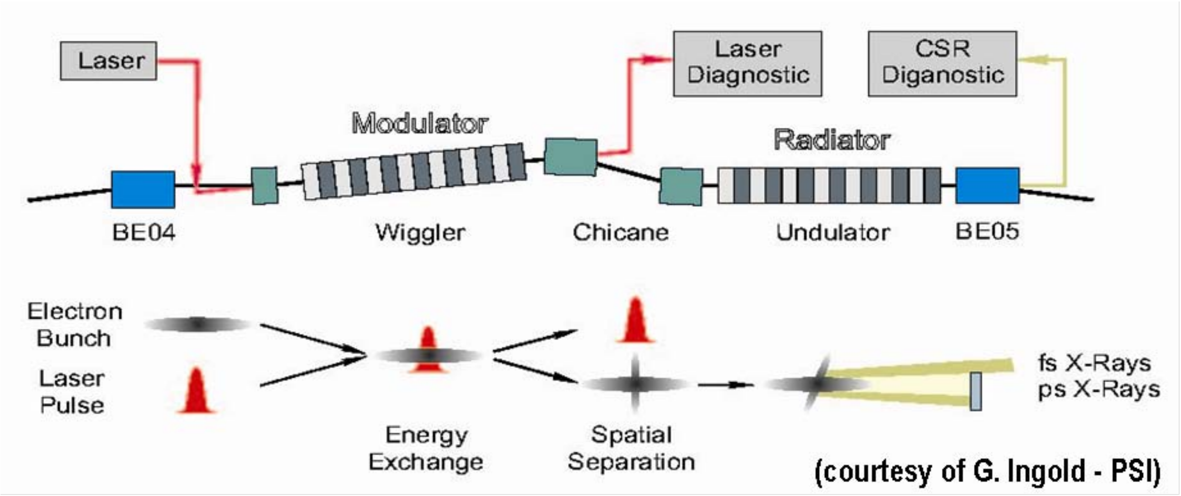
Outline

- SLS FEMTO Bunch Slicing
  - Layout and Principle
  - Efficiency
- Principle of Electro Optical Detection
  - Detection Schemes: Sampling and Spectral Decoding
- Results and Simulation
  - Sampling Measurements
  - Spectral Decoding Measurements
  - Comparison to Tracking Data

SLS FEMTO Bunch Slicing - Layout of FEMTO Bunch Slicing

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



Core Bunch/FEMTO slice separation
Angular Dispersion
(Chicane Magnets)

Sub-ps X-Rays
Radiator
(Undulator)
4.2-14 keV
$4*10^5$ ph/s/0.1%BW

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

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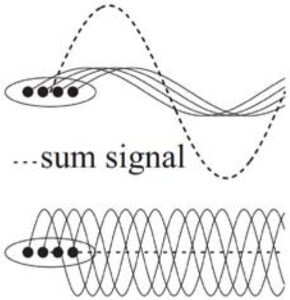
SLS FEMTO Bunch Slicing - Layout of FEMTO Bunch Slicing

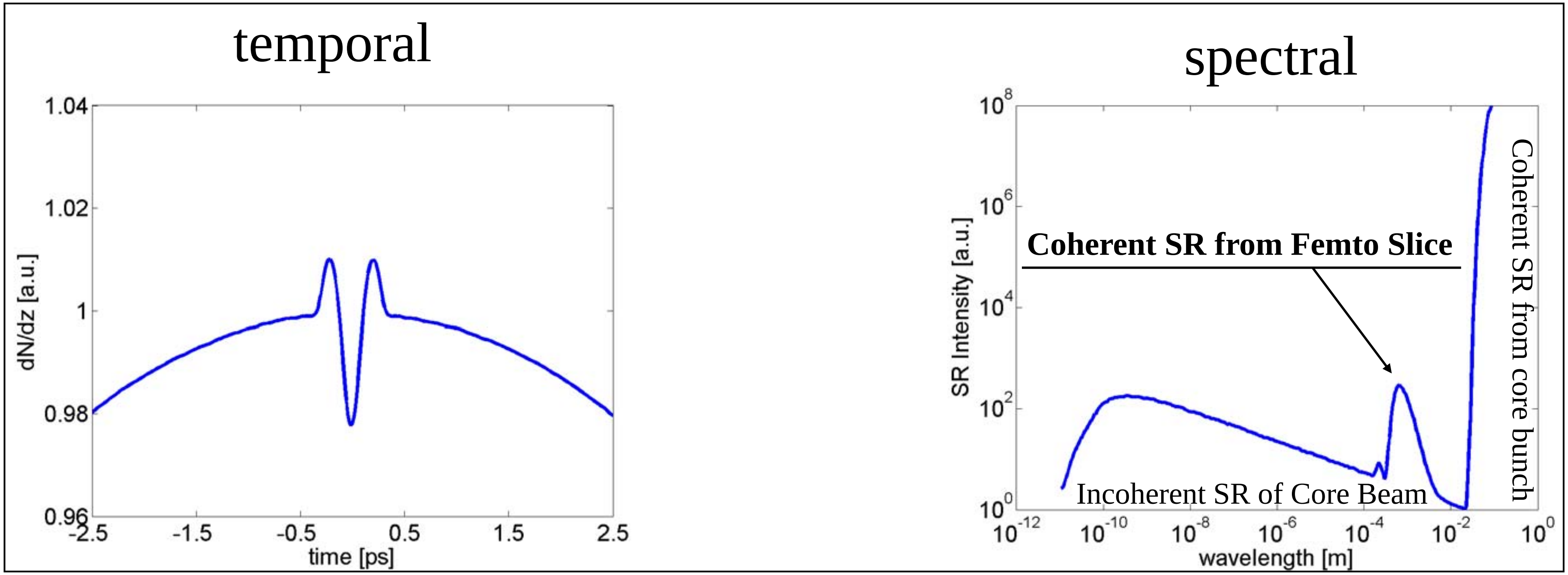
Electron Beam

- Bunchlength of sliced beam: σ =100 fs,
  core beam: σ = 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





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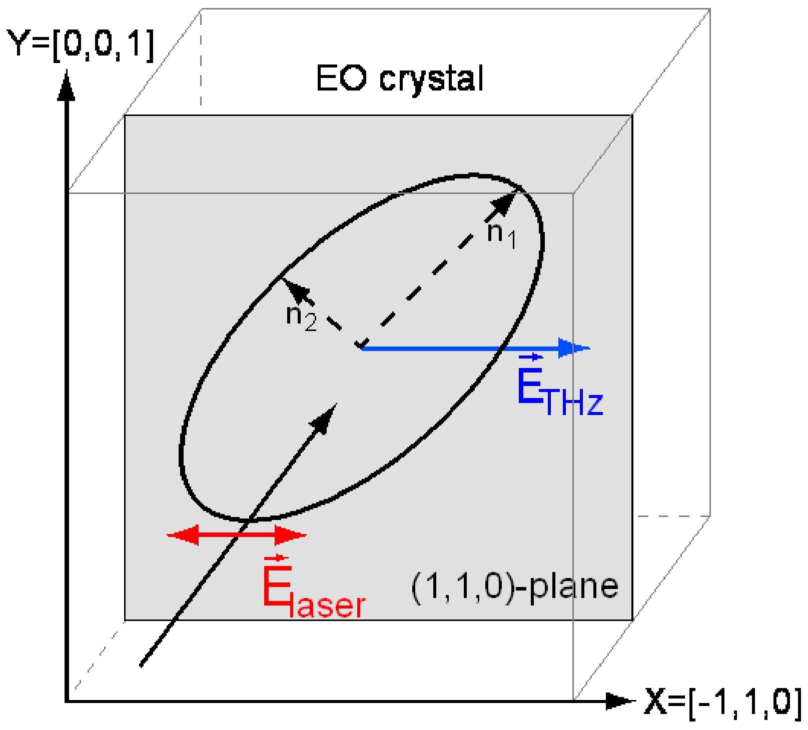
Principle of EO Detection - The Electro-Optic Effect: Field Ind. Birefringence



$$P = \varepsilon_0 \left(\chi_e^{(0)} E \right) + \chi_e^{(1)} E^2 + \chi_e^{(2)} E^3 + \ldots)$$

Pockels effect

Kerr effect

- The THz radiation E_{THz} passes the EO-crystal in the (1,1,0)-plane
- The two components of a linearly polarized probe laser pulse 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
- The phase retardation is proportional to the optical properties of the EO-crystal, the THz field strength and the crystal thickness..:

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

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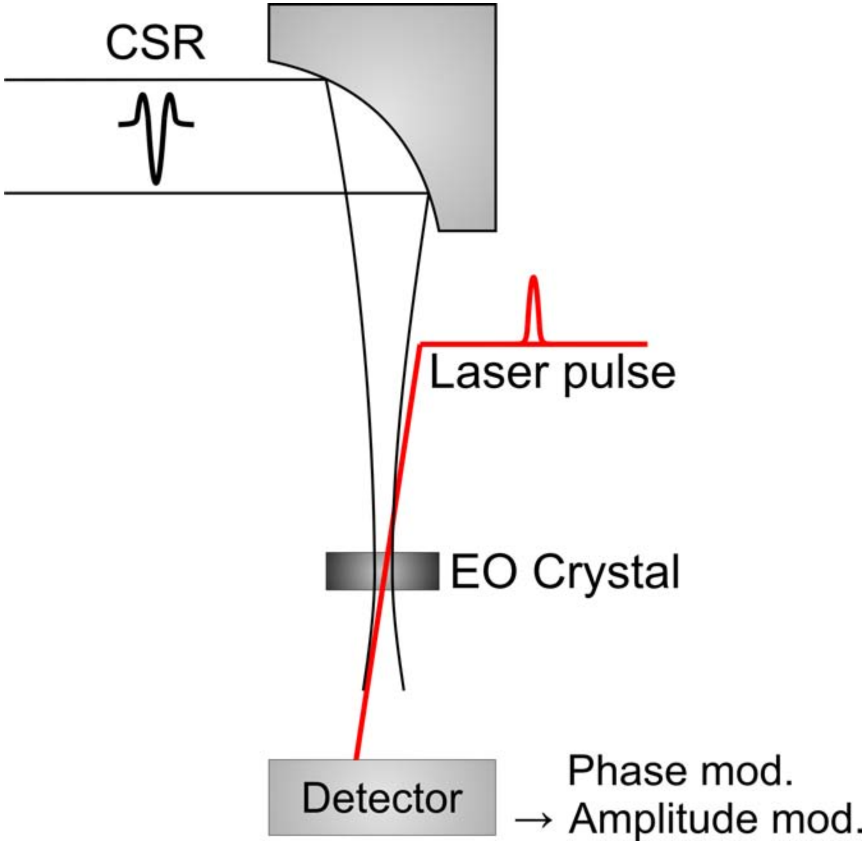
Principle of EO Detection - Phase Retardation to Ampl. Mod.

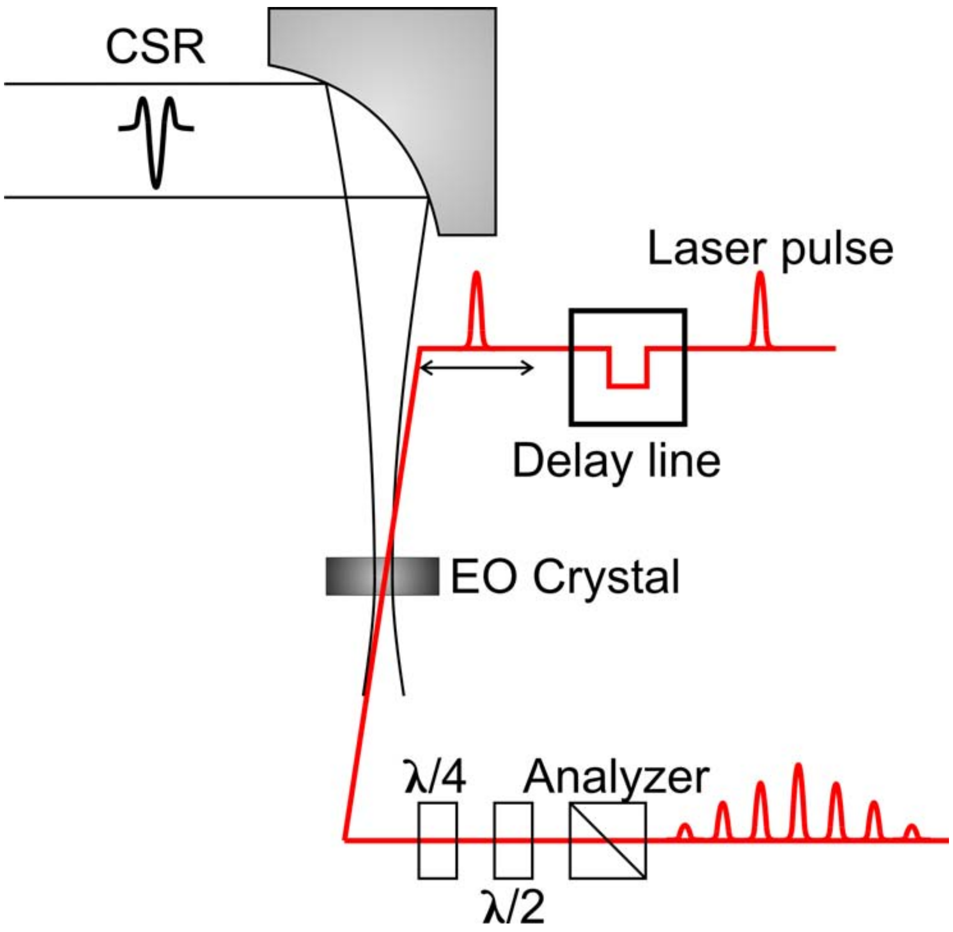


Synchronized Ytterbium fiber laser is modulated by Coherent Synchrotron Radiation (E_{THz}) in EO crystal (GaP, ZnTe)

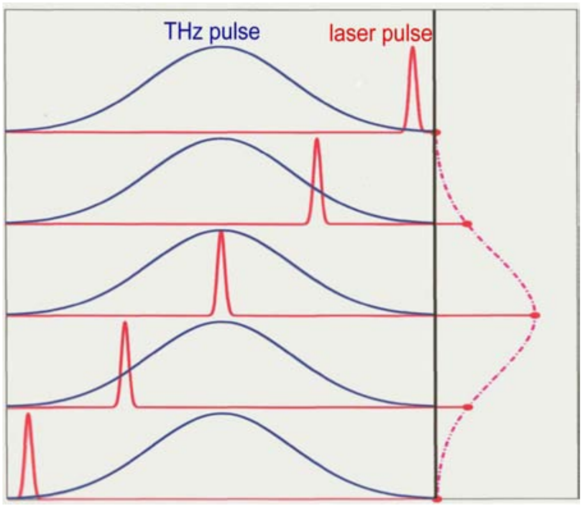
Detection Schemes:

- Sampling
- Spectral Decoding

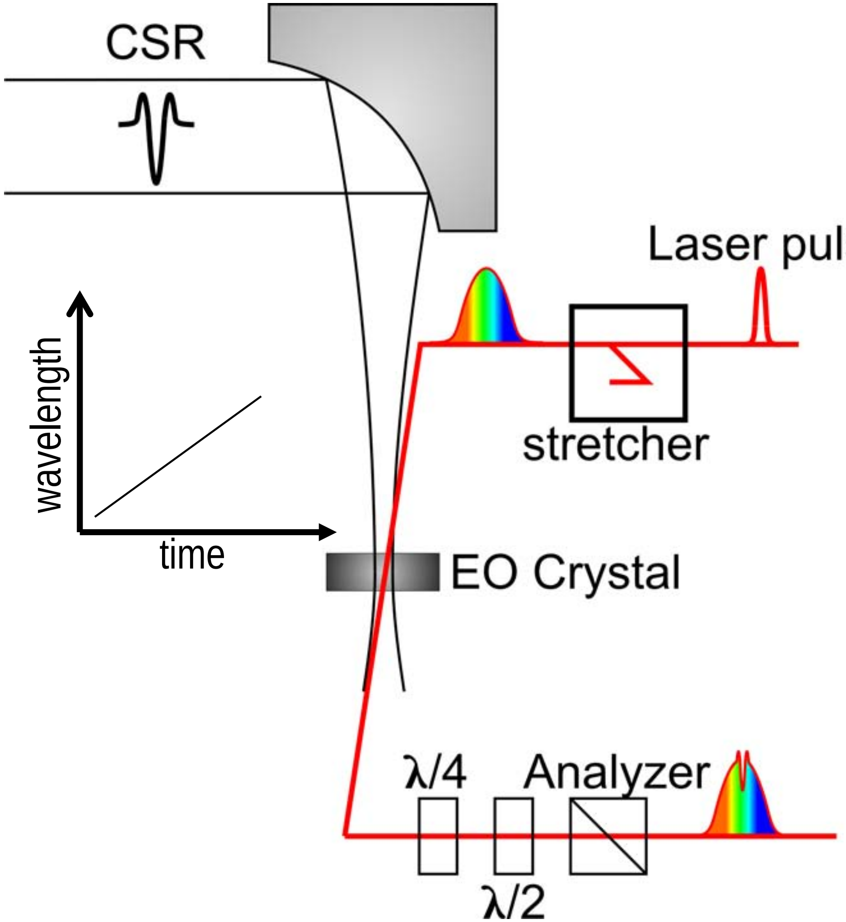
Principle of EO Detection - Differnent Schemes



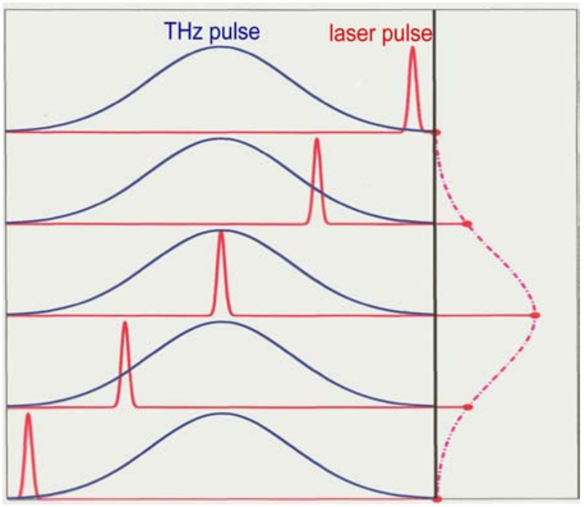
Sampling



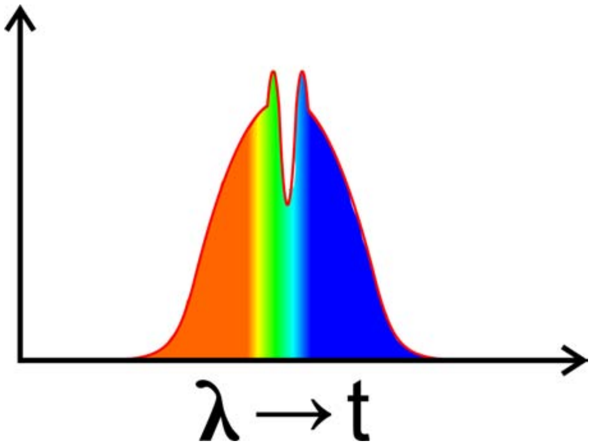
Principle of EO Detection - Diffenent Schemes



Sampling



Spectral Decoding



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Setup and Results - Sampling Measurements

- Delaystage with 100 fs stepwidth
- Averaged over 100 pulses
- Lab measurement:

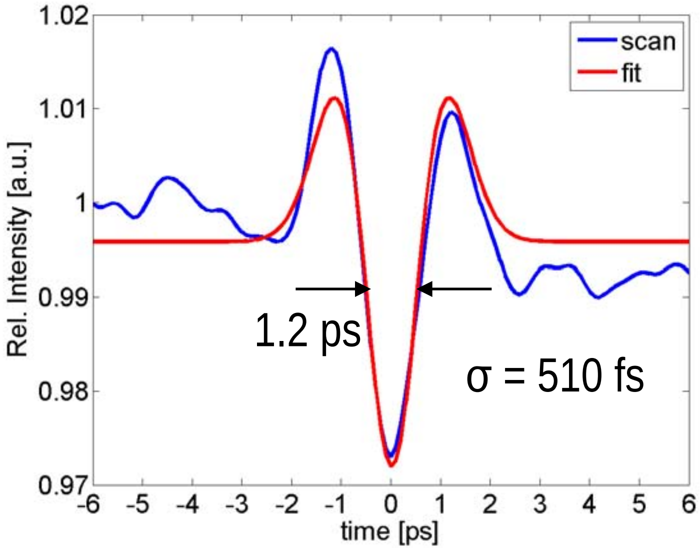
  FEMTO laser to EO laser jitter ~ 50 fs rms

  but...

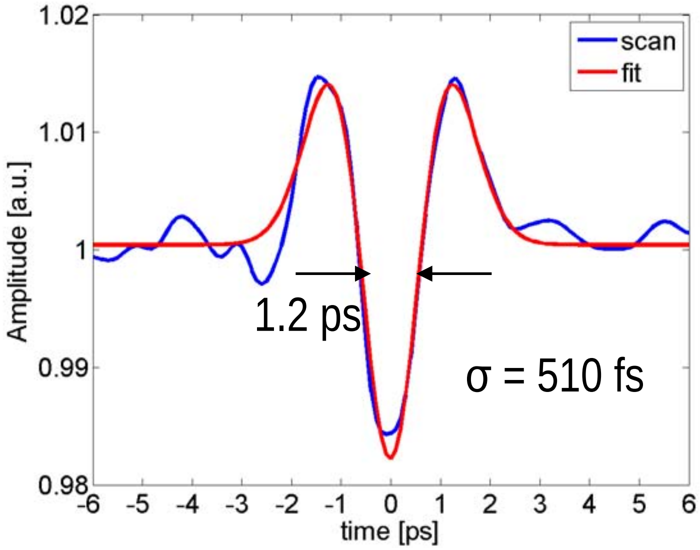
  additional arrival time jitter at IR beam line

- 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



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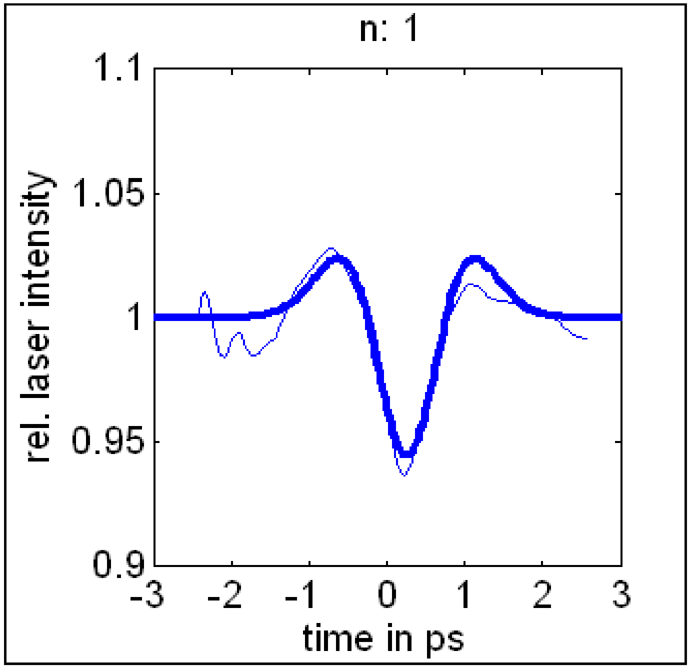
Setup and Results - Spectral Decoding; Single Shot Measurements

Spectral Decoding (5mm GaP crystal)

- Thin line: Measurement
- Thick line: Gaussfit

    → Fit parameters give

    - Pulse length
    - Arrival time



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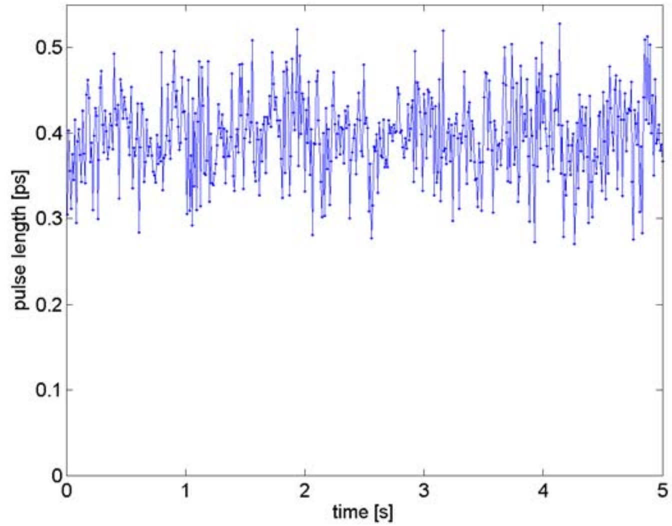
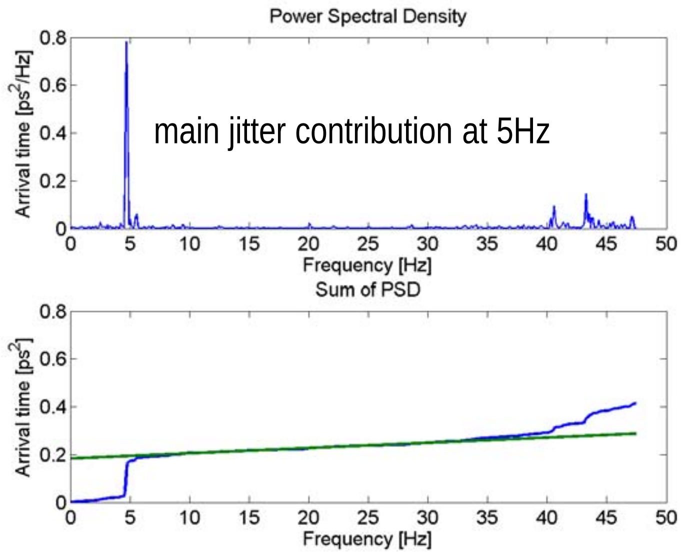
Pulse Length: (365 ± 50) fs rms



Spectrum of Autocorrelation



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

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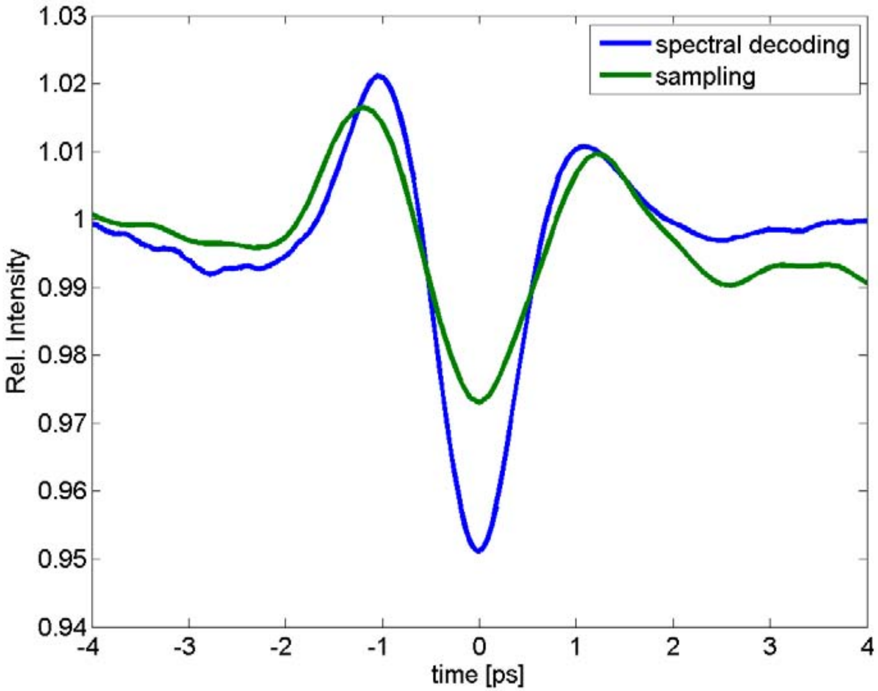
Setup and Results - Spectral Decoding; Average

Subtraction of arrival time jitter

→ averaged spectral decoding data doesn't suffer from jitter.

→ absolute THz field strength can be determined.

Comparison between spectral decoding and sampling measurements



Spectral decoding laser modulation: 7 %

→ $\Gamma \sim 0.55°$

→ $E_{THz} \sim 2*10^4$ V/m

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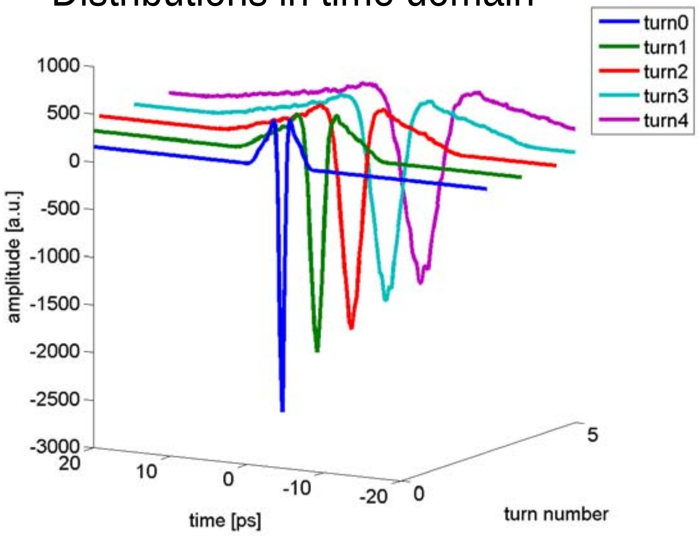
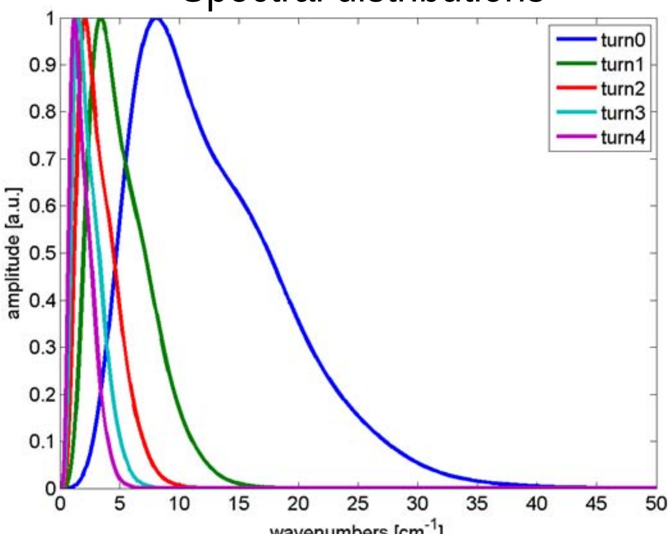
Setup and Results - Tracking Results

Distributions in time domain



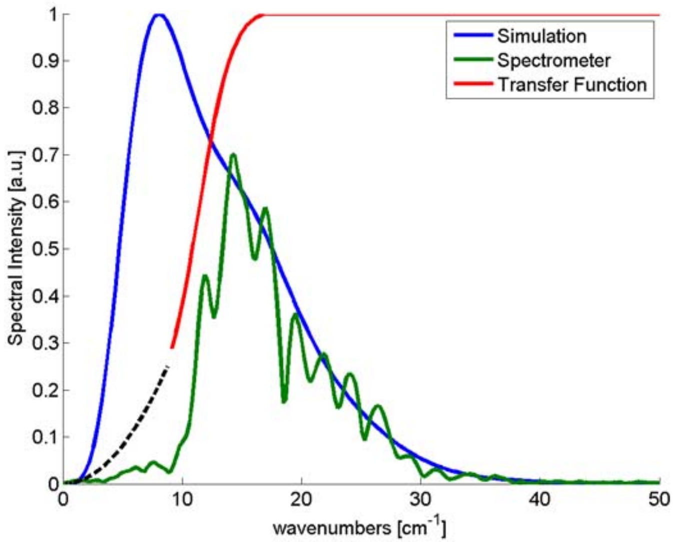
Spectral distributions



Particle tracking done by Andreas Streun

- Due to energy exchange, sliced electrons have about 10 times higher energy spread
  - → broadening of electron distribution ~ 4.8 ps / turn
  - → broadening of „hole“ ~ 520 fs / turn

IR beam line acts as a highpass filter



Measurement done by Hans Sigg

- Sliced electron distribution is supressed due to long wavelength cut-off of IR beam line

  → only the „hole“ is visible

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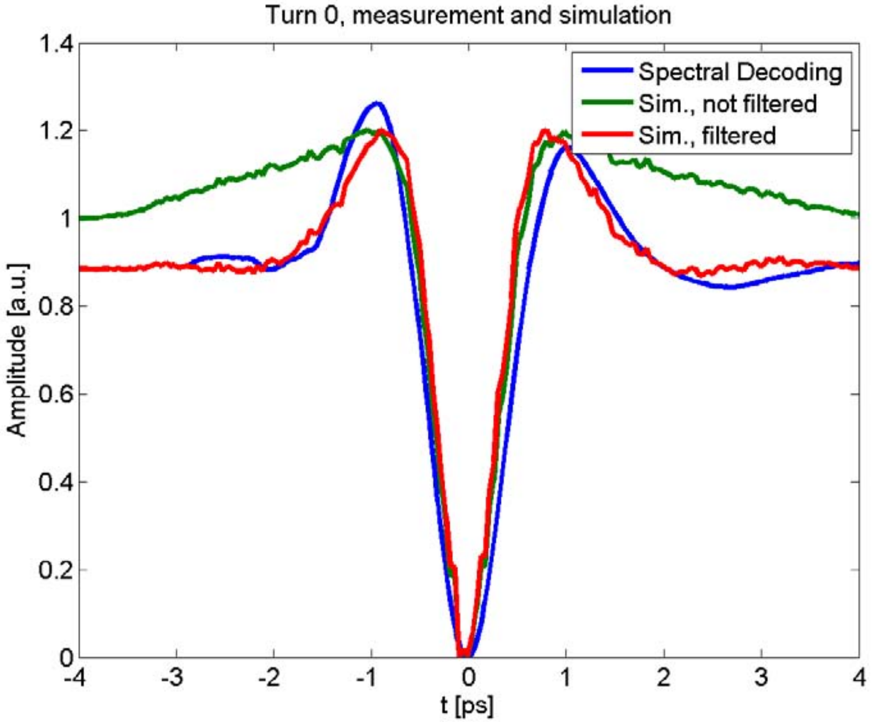
Setup and Results - Tracking results

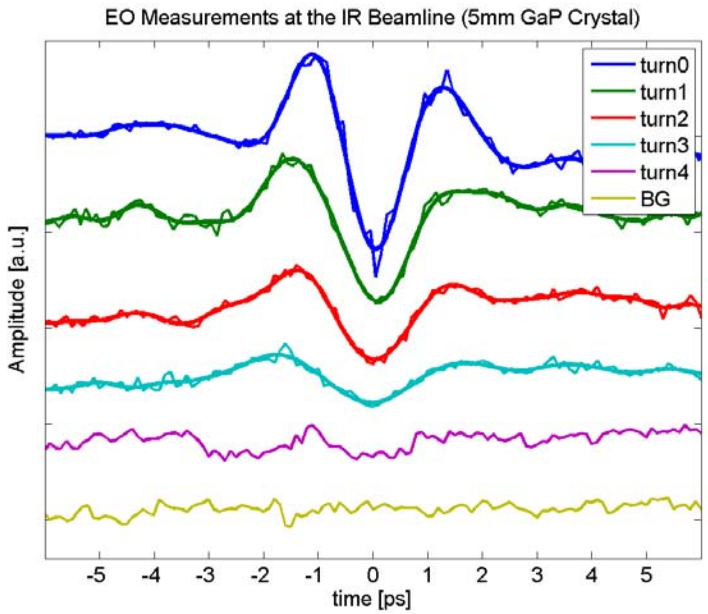
Averaged spectral decoding measurement of turn 0 is in good agreement with tracking results.



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

<u>Preliminary results:</u>
Sampling measurement system is sensitive enough to detect sliced particle distribution up to turn 3.

But: Tracking predicts much broader pulses
→ further analysis is required.



Felix Müller, Bernd Steffen

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Conclusion and Outlook

- It was possible to detect and characterize the low charge modulation produced by the FEMTO Slicing Experiment in time domain
  - with a scanning (EO sampling) technique
  - and in single shot (EO spectral decoding)
- Turn zero is in good agreement with the particle tracking

- Next steps:
  - Measurements directly after the FEMTO experiment
  - Freespace set-up is well suited for testing new crystals like DAST/DSTMS (much higher EO coefficient)
  - SwissFEL Injector will have 10 pC mode

    →EO measurement at the THz port after the first bunch compressor seems possible

My thanks go to:

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Infrared Beamline crew: Philippe Lerch, Hans Sigg and Luca Quaroni (PSI)

FEMTO Slicing team: Gerhard Ingold, Steven Johnson and Paul Beaud (PSI)

Thomas Feurer (Univ. Bern)

...and to the audience for the interest