Investigating longitudinal bunch structure - developments at FLASH

Bernhard Schmidt, DESY-FLA

fingerprints of longitudinal structure

direct	charge distribution	$\rho(z)$	time domain
↓	coulomb field	$E_r(z)$	
indirect	coherent radiation	$P(\lambda)$	wavelength domain

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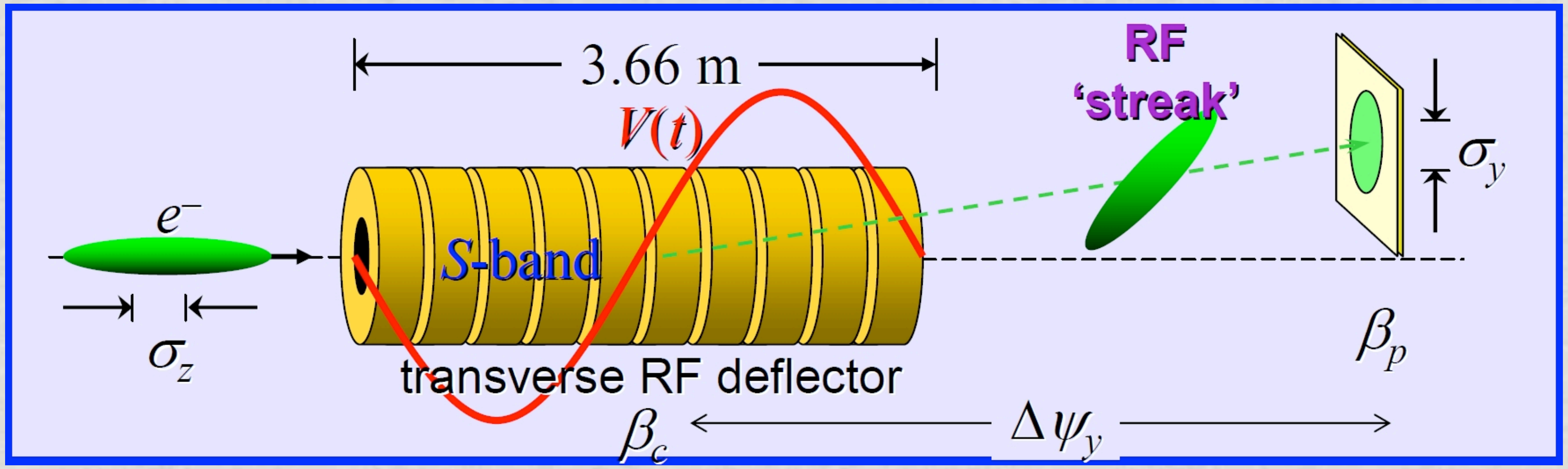
indirect	coherent radiation	$P(\lambda)$		wavelength domain

fluctuations from shot to shot

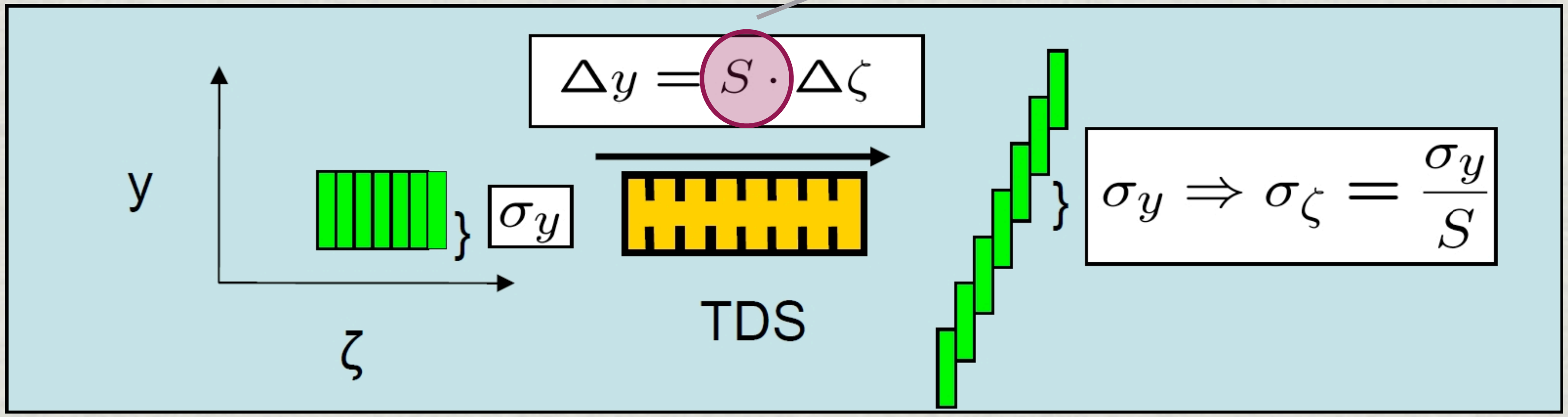
➡ single shot methods preferential

charge distribution:
transverse deflecting structures (TDS)

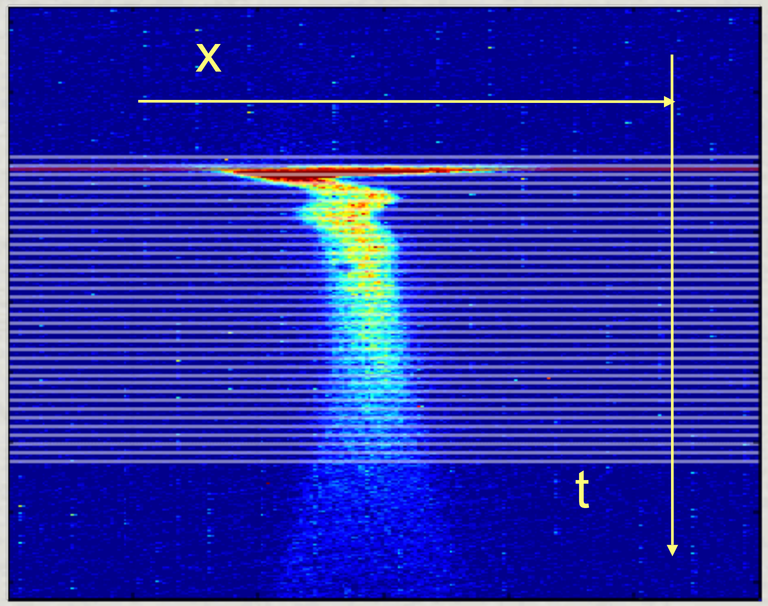
principle of operation



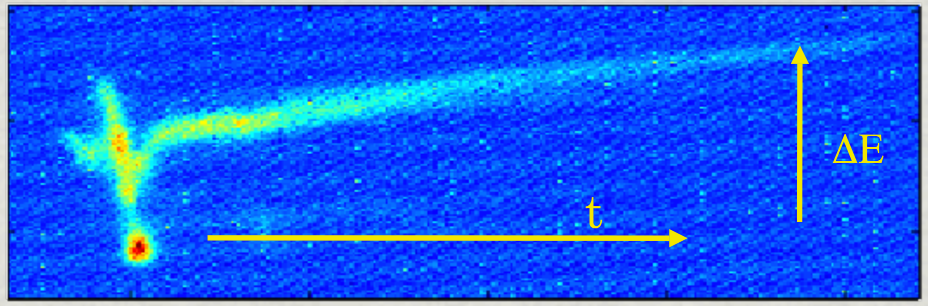
shear parameter

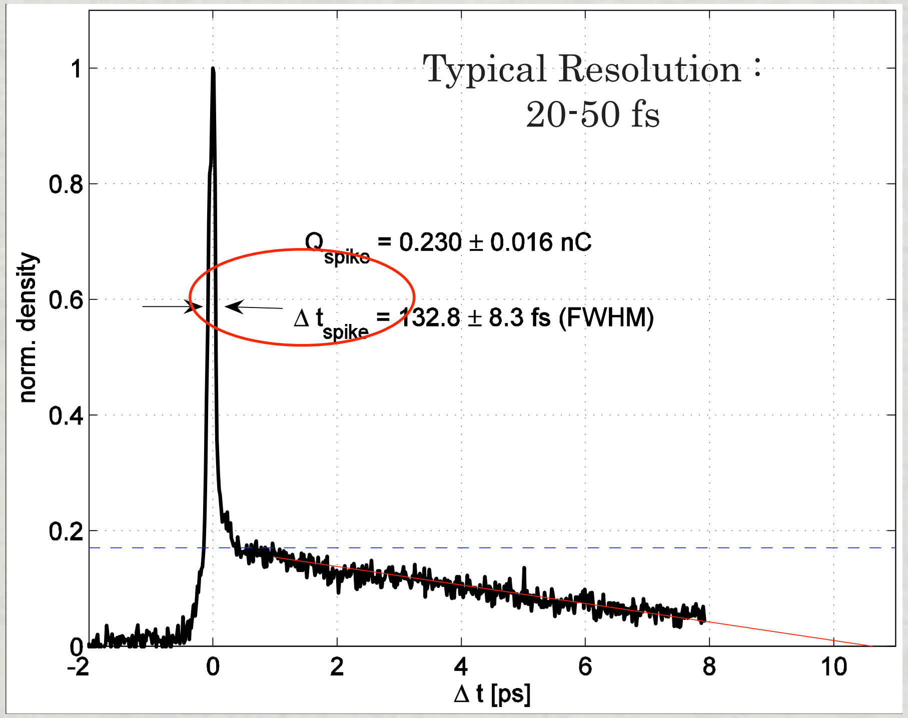


some FLASH results, E~800 MeV



+ dipol magnet : long. phase space





all data courtesy M. Röhrs

TDS : formulas

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

$$\langle S_y \rangle = \frac{eV_0}{E_0} \sqrt{\beta_c \beta_p} \sin \Delta\psi_y \sin\varphi \,, \qquad V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

~ 10 m

≤ 1

☠

beam energy

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☠ beam energy

~ 10 m

≤ 1

to resolve σ_ζ :

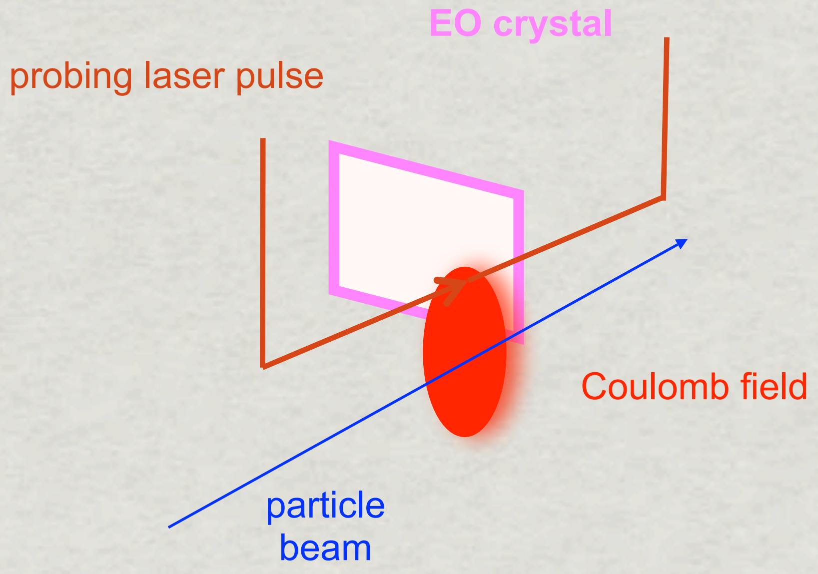
$$S_y(s_1) \cdot \sigma_\zeta > \sqrt{\epsilon_y \cdot \beta_y(s_1)}$$

σ_ζ ~1mm

$$L\sqrt{P_0} > 1000 \text{ m}\sqrt{MW}$$

not usable at 450 GeV/ c !

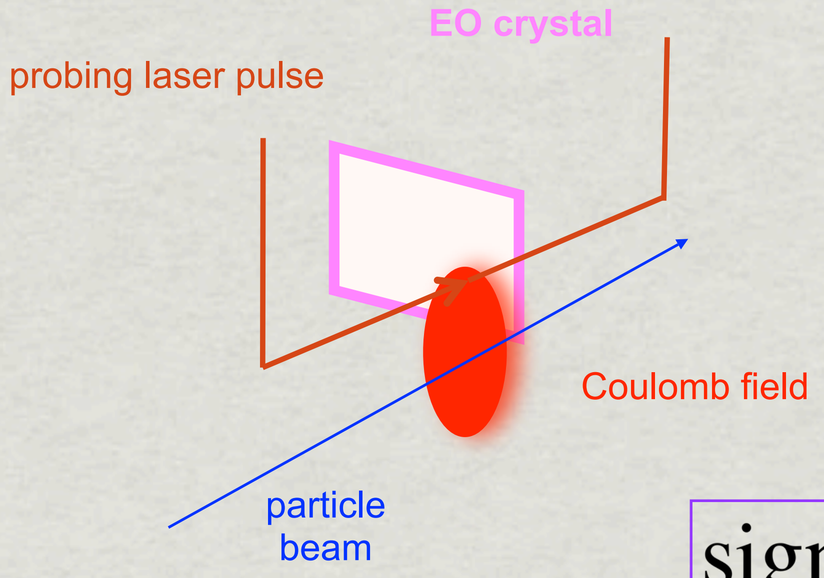
Coulomb field: electro-optic modulation



Intra-beamline measurement of the bunch Coulomb field

- Field induced refractive index change
- Polarization-modulation of probing laser
- Temporal structure of Coulomb field ➔ impressed to ellipticity of optical pulse

Coulomb field: electro-optic modulation



Intra-beamline measurement of the bunch Coulomb field

- Field induced refractive index change
- Polarization-modulation of probing laser
- Temporal structure of Coulomb field ➔ impressed to ellipticity of optical pulse

$$\text{signal} \sim E_r(t)$$

$$\text{for } \gamma >> 1$$

$$E_r(t) = \frac{\lambda(t)}{2\pi b \varepsilon_0} = \frac{I(t)}{2\pi b \varepsilon_0 c}$$

independent of γ !

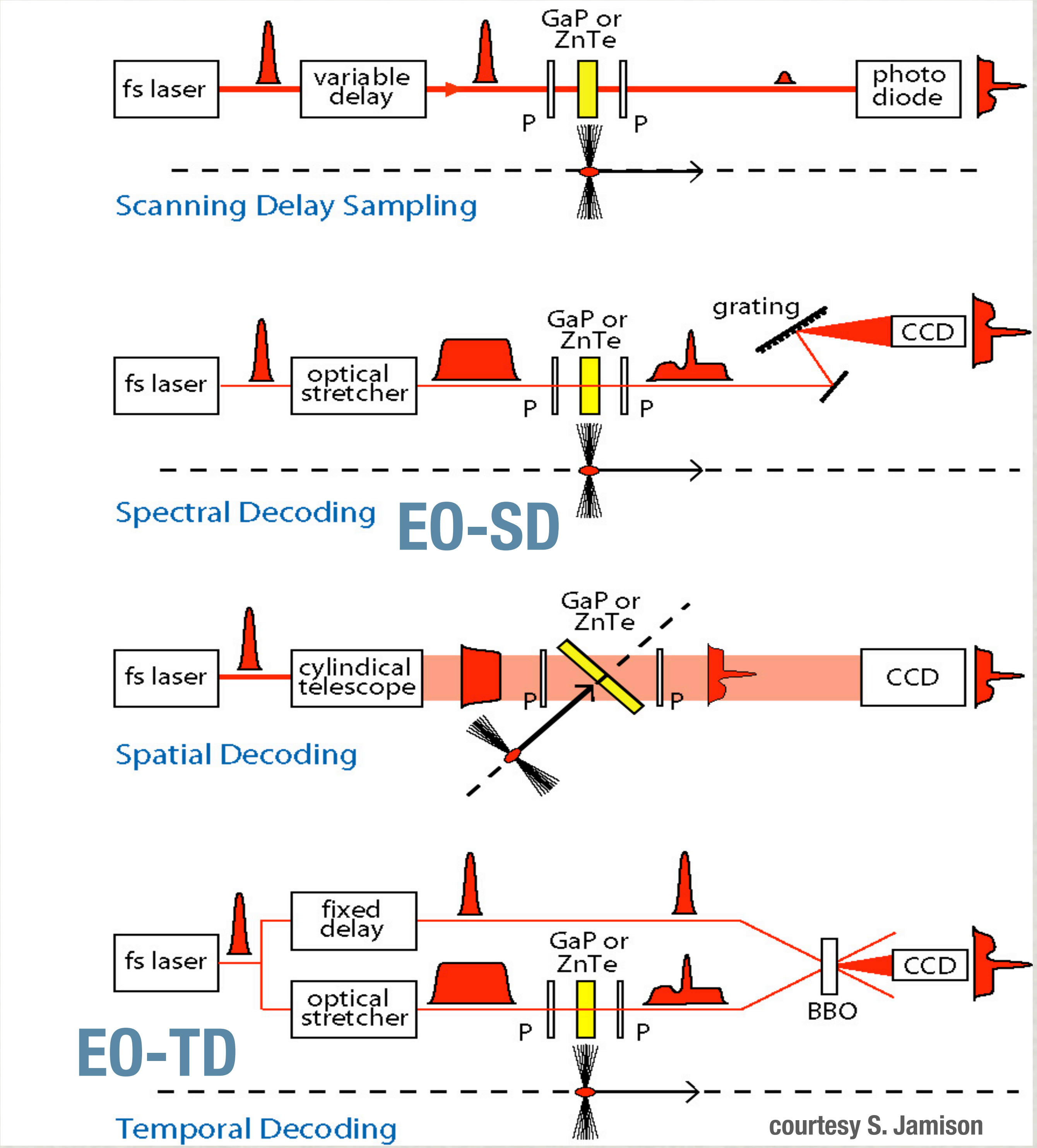
$\lambda(t)$ linecharge

$I(t)$ current

EO : detection methods

not single shot

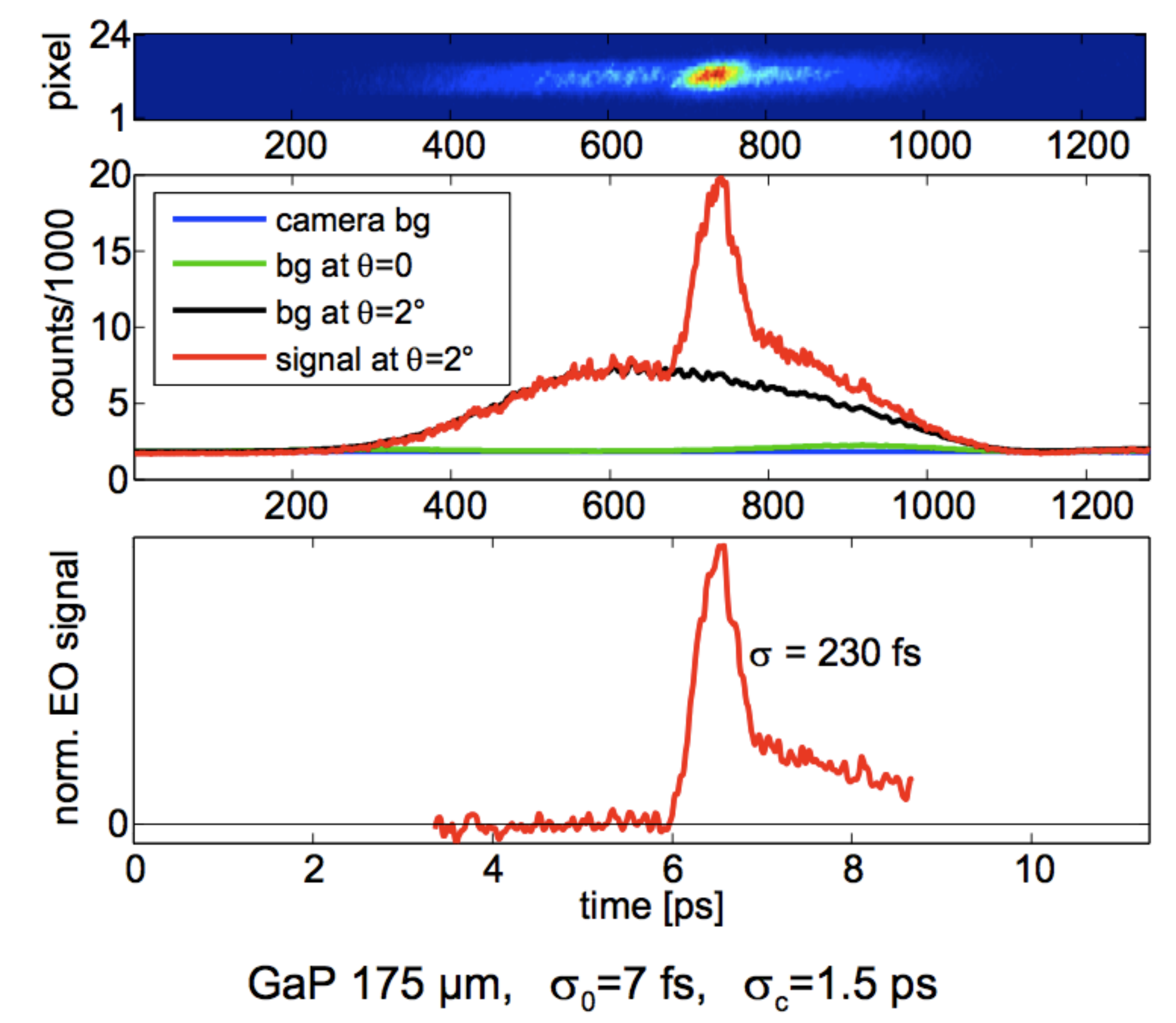
single shot



less complex
limited resolution

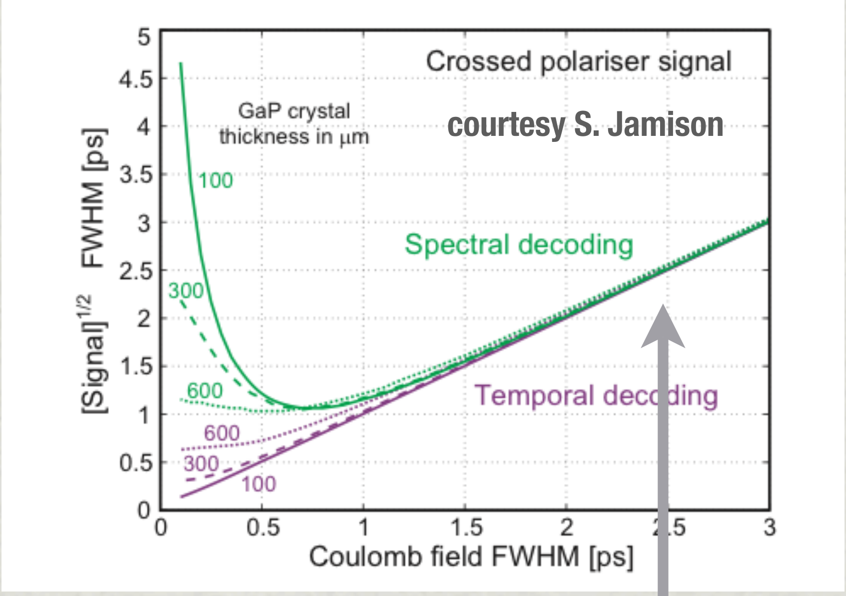
quite complex
ultimate resolution

EO spectral decoding : sample results

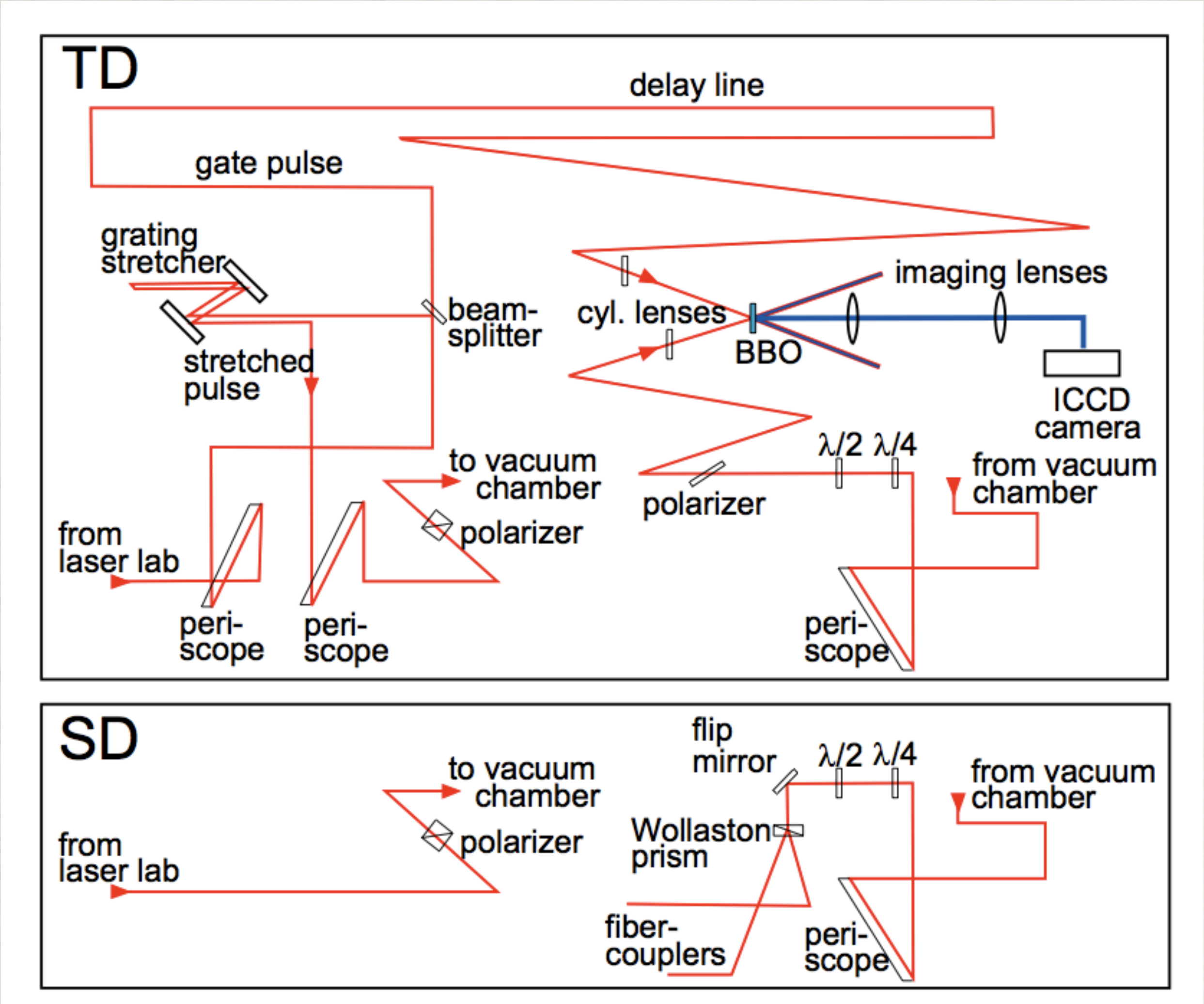


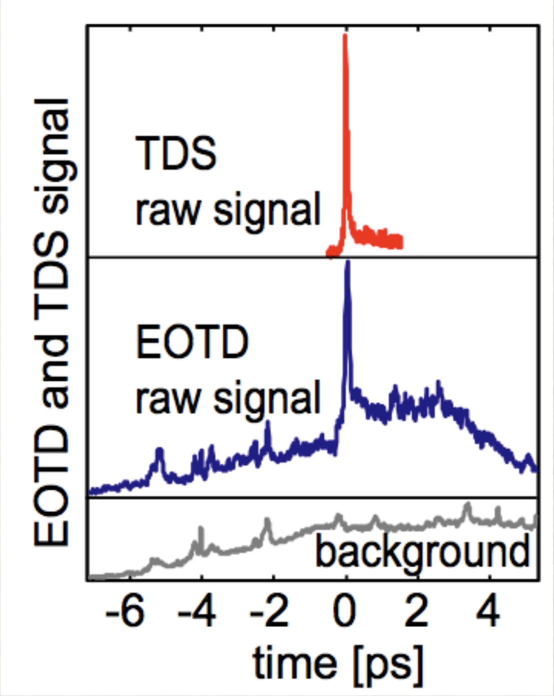
all data courtesy B. Steffen

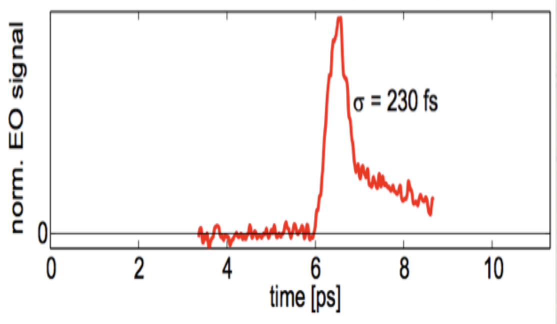
EO techniques, compared



expected regime



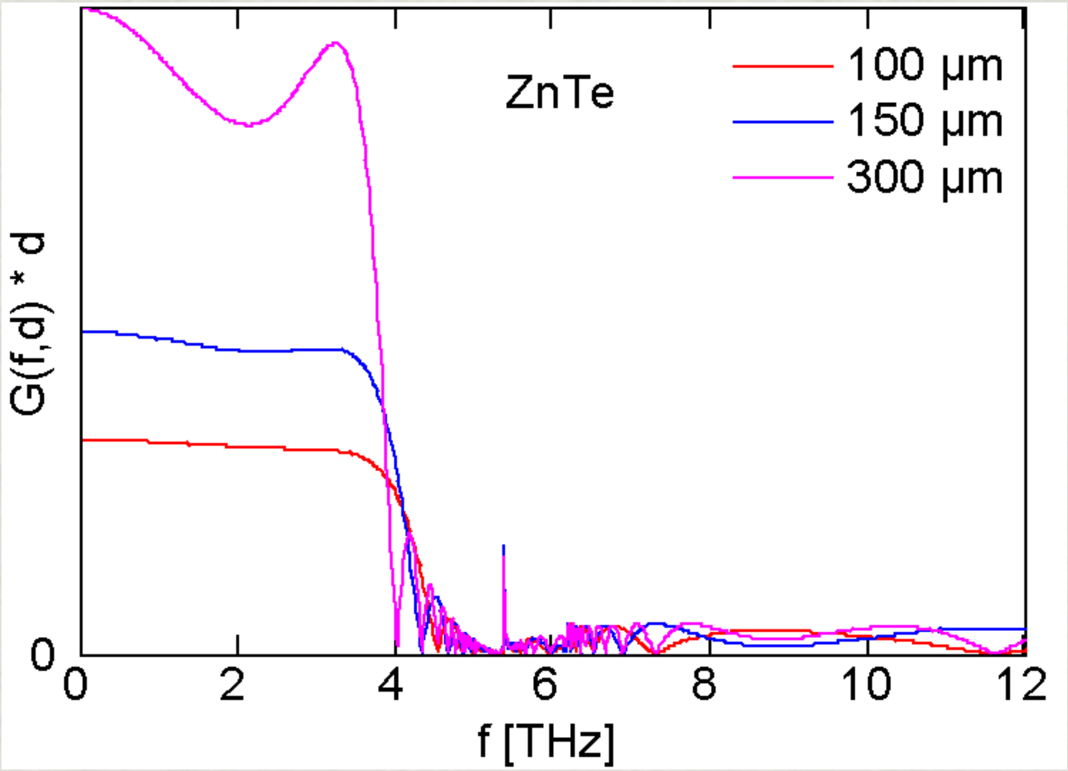


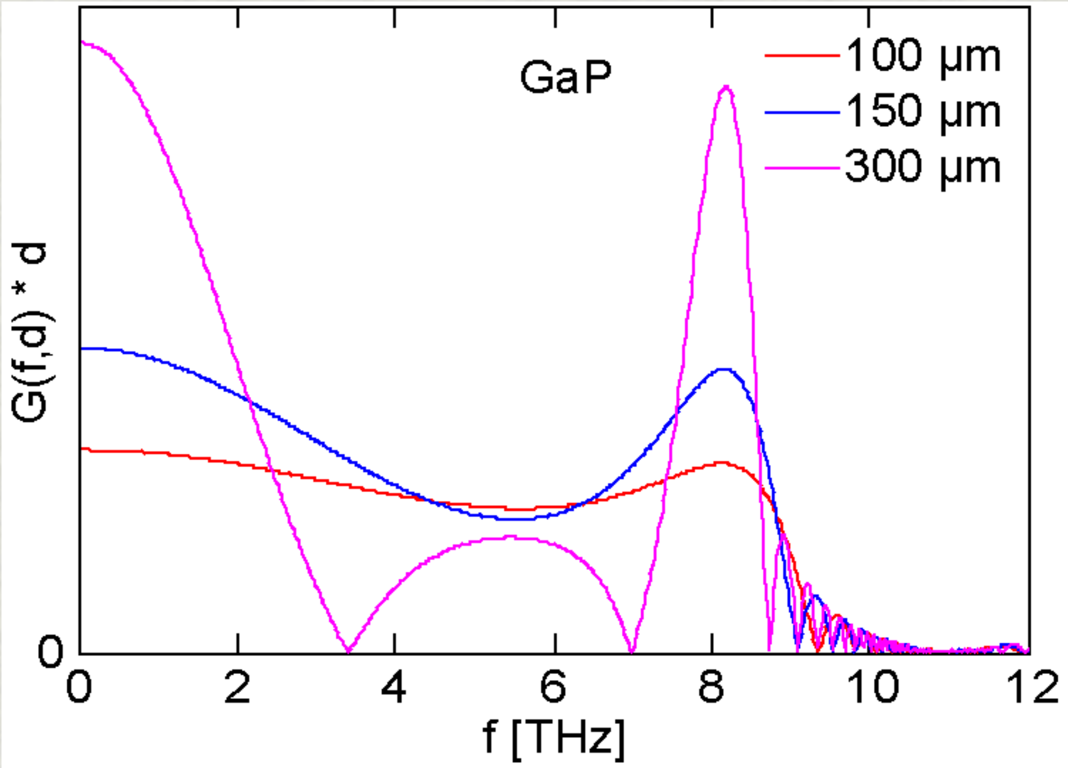


all data courtesy B. Steffen

EO: limits of temporal resolution

crystal response functions





for λ_p = 1 mm (f = 0.3 THz) : both crystals are fine, thick crystals preferential

ZnTe : smaller EO coefficient, pure quality

GaP : smaller EO coefficient, good quality

EO: spectral decoding

$$\sigma_t \approx 1.1\sqrt{T_0 T_c}$$

T_0 compressed length

T_c chirped length

λ_p	T_{per}	T_c	T_0	σ/λ_p
1mm	3 ps	6 ps	15 fs	0,11
1mm	3 ps	6 ps	35 fs	0,17
1mm	3 ps	15 ps	35 fs	0,26

← **tough !**

- **only few periods can be covered with reasonable resolution**
- **measure „modulation distribution“ along bunch**
- **stable synchronization (< 1 ps) required**

more rigorous simulation

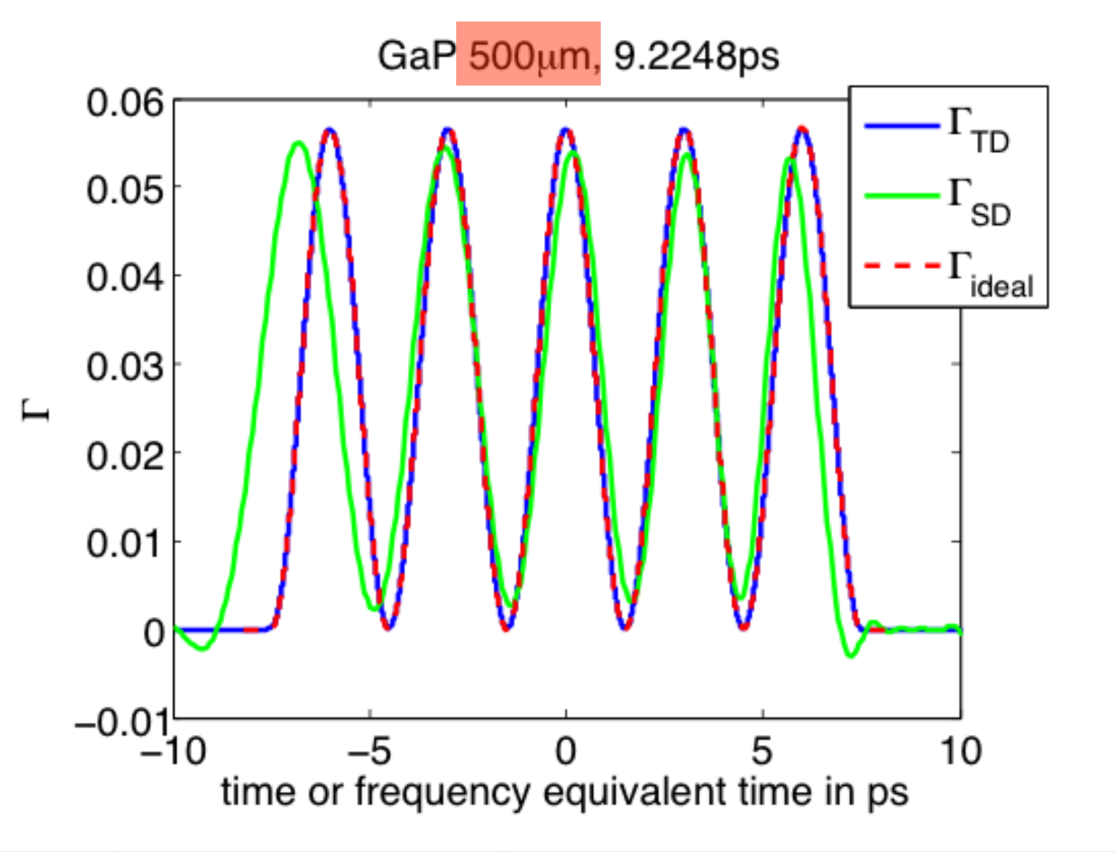
- realistic chirp
- crystal effects
- detection

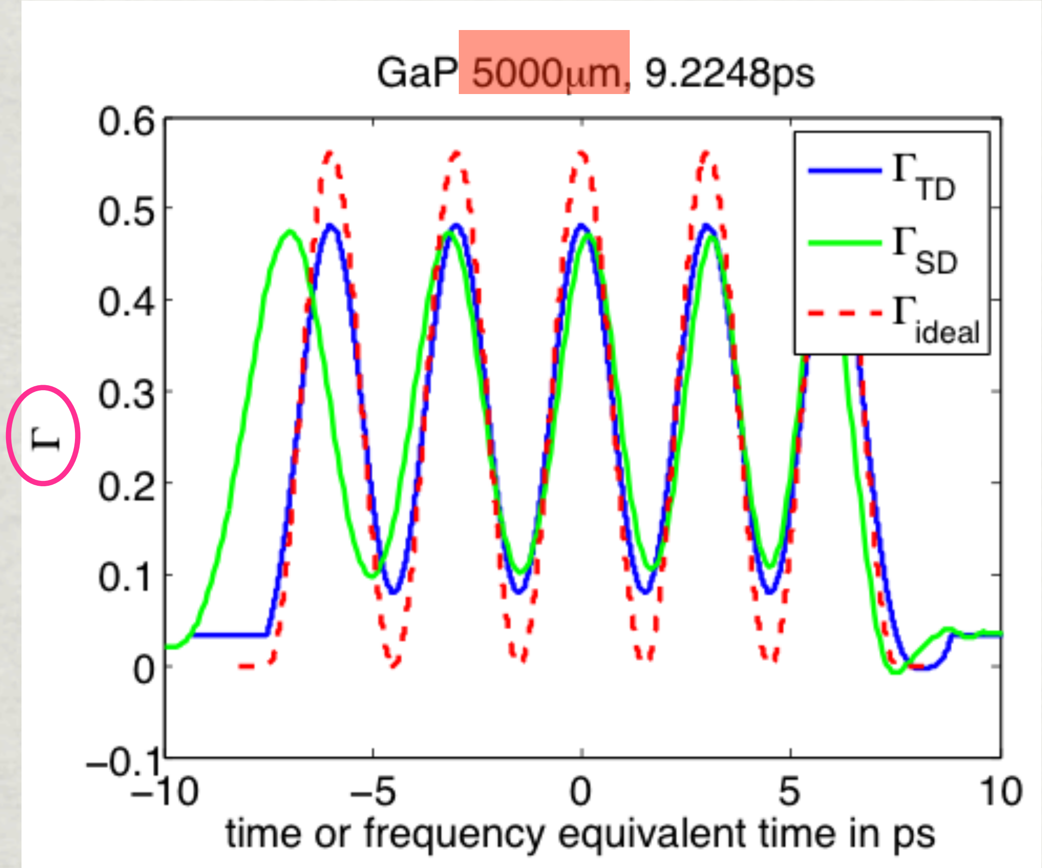
16 nC with 400 ps σ_t

T_0 = 60 fs, λ=1030 nm

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

courtesy L. Wißmann





- no need for thin crystals (resolution)
- thick crystals allow to detect partial modulation

EO-SD set up : what is needed ?

- EO crystal in movable mount, close to beam
- short pulse laser, $T_0 < 50$ fs
- laser synchronization to beam
- pulse stretcher, conventional optics, polarizers etc.
- commercial spectrometer
- gated read-out system (ICCD or optical gating)

typical laser system :
TiSa oscillator, 800 nm

new developments (DESY, PSI ..) :
Yb fibre laser, 1030 nm

other EO methods ?
more resolution (not needed) but MUCH more complex

coherent radiation:
spectrum reveals form factor

N number of particles   source characteristics

$$\frac{dU}{d\omega} = C\ N^2 \left|F_{long}(\omega)\right|^2 T(\omega,\gamma,r_b,\theta,source)$$

F **longitudinal** form factor

$$F_{long}(\omega) = \int_{-\infty}^{\infty} \tilde{\rho}(t)\exp(-i\omega t)\,dt$$

integral and indirect information on charge density

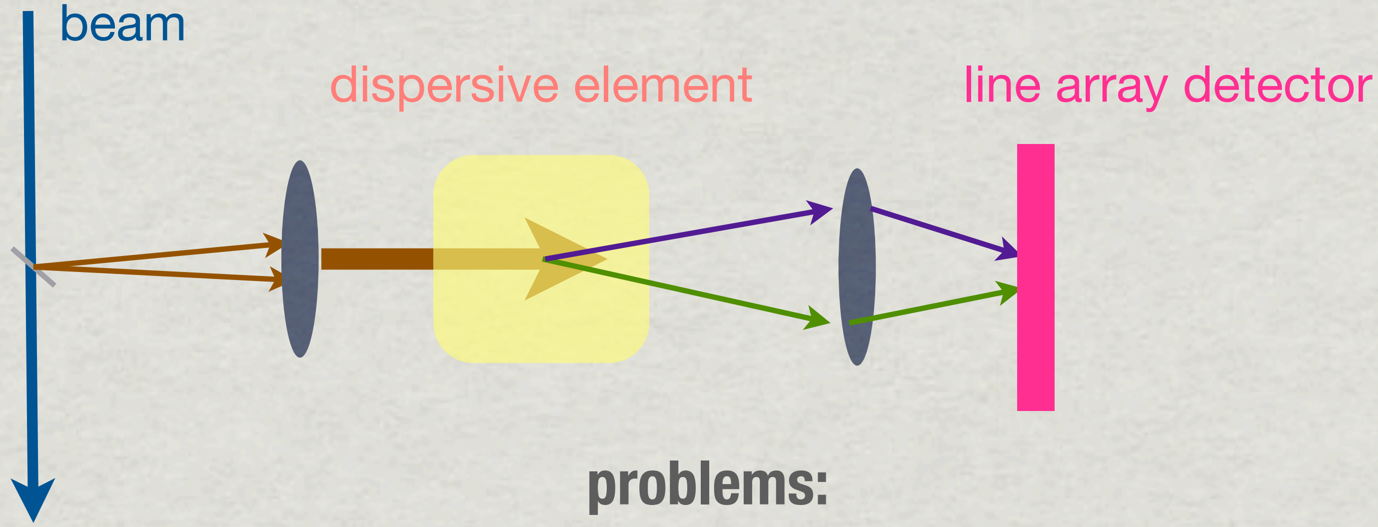
unstructured bunch with ~nsec length : no coherent radiation (f > GHz)

detection of „**integral intensity**“ in THz regime : **substructure**, no further information (spike, periodic modulation, non-statistic ripples..)

spectrally resolved measurement : type of structure, but still integral

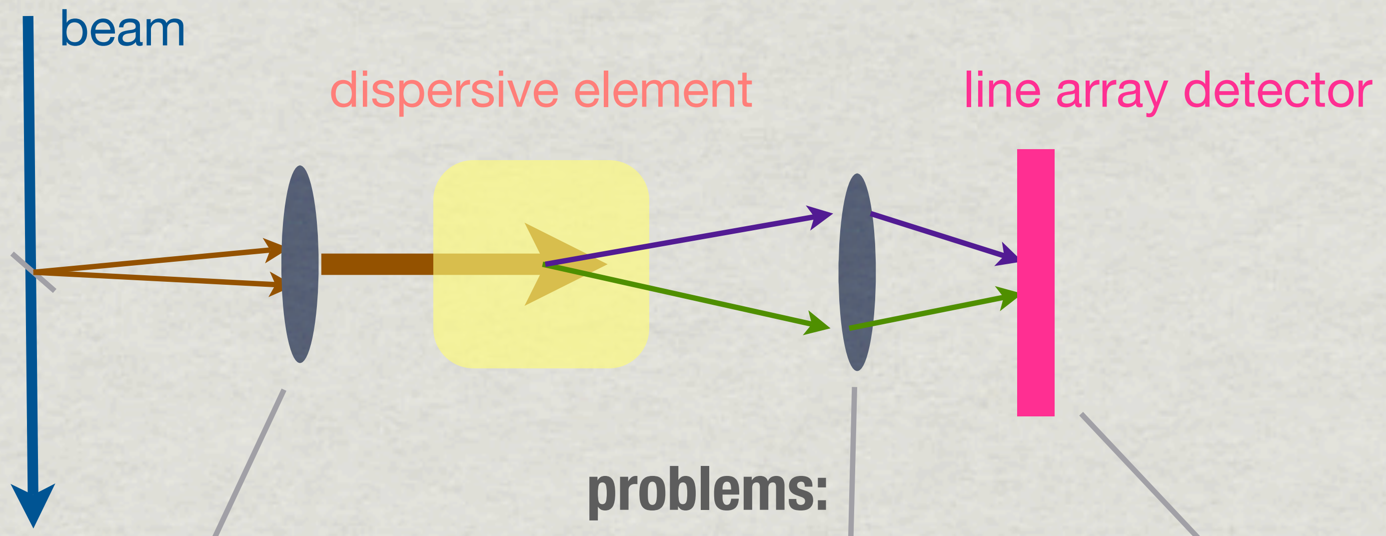
if wavelength unknown, broadband or variable :
need broadband single shot spectrometer

coherent transition radiation



problems:
-long wavelength, diffraction limited
-needs „large“ optics and detectors
-dispersive elements (gratings) cover small Δλ

coherent transition radiation



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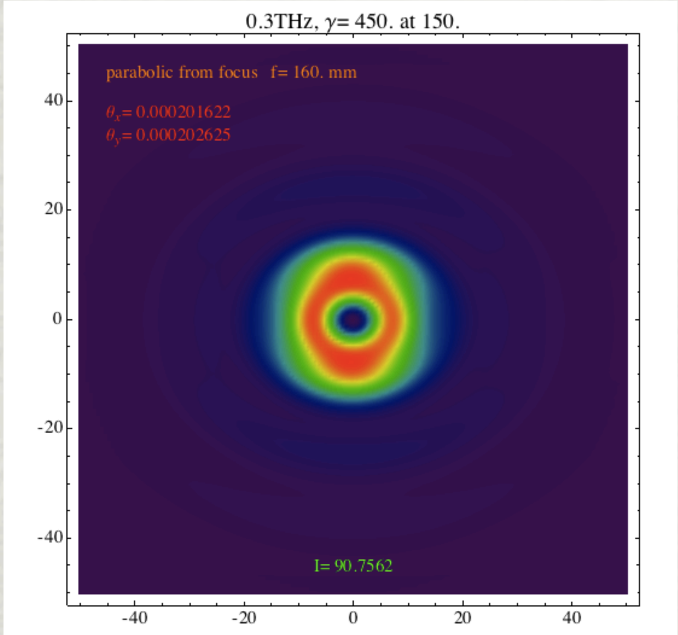
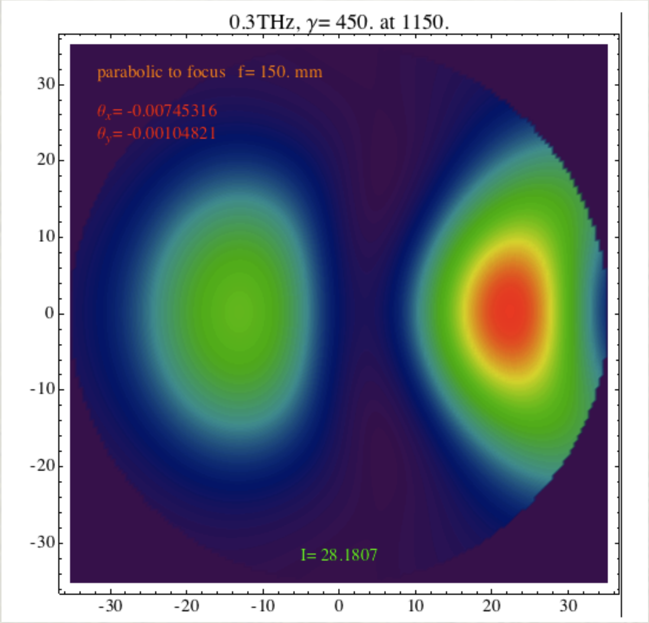
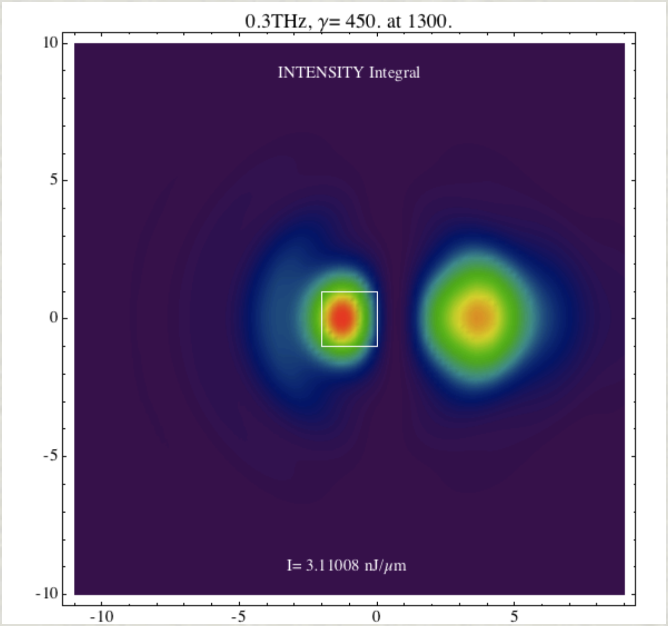
λ= 1mm



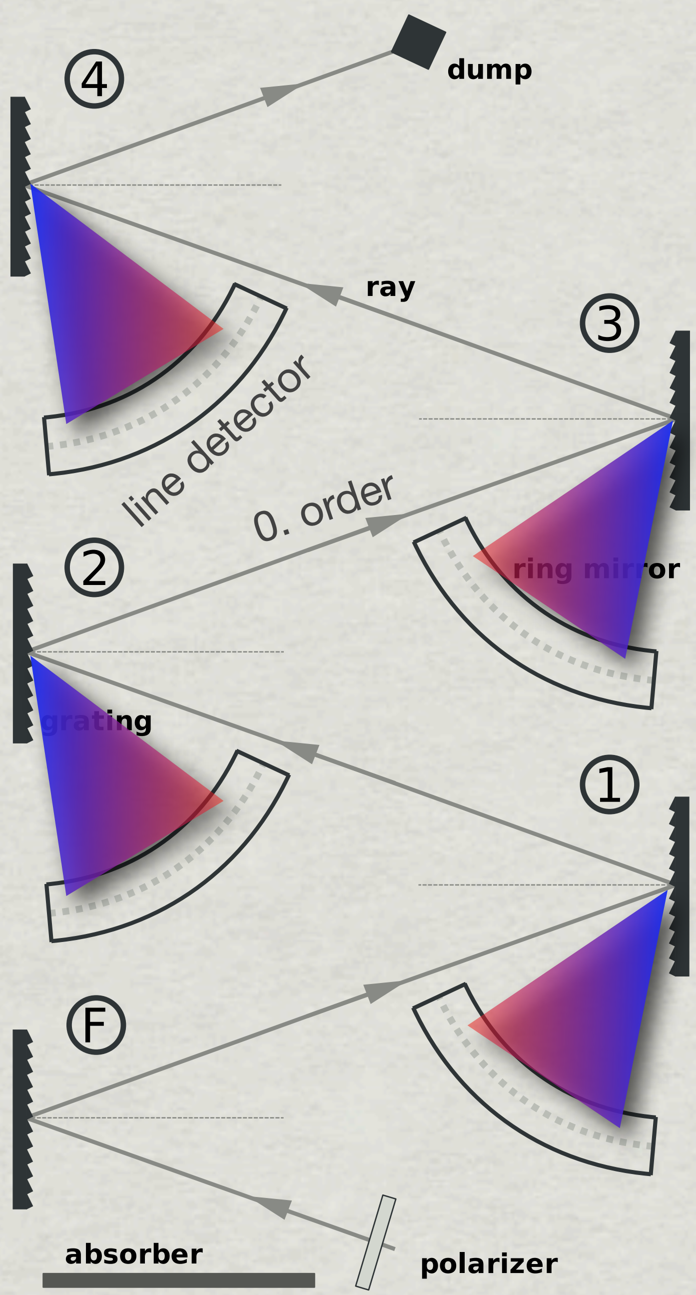


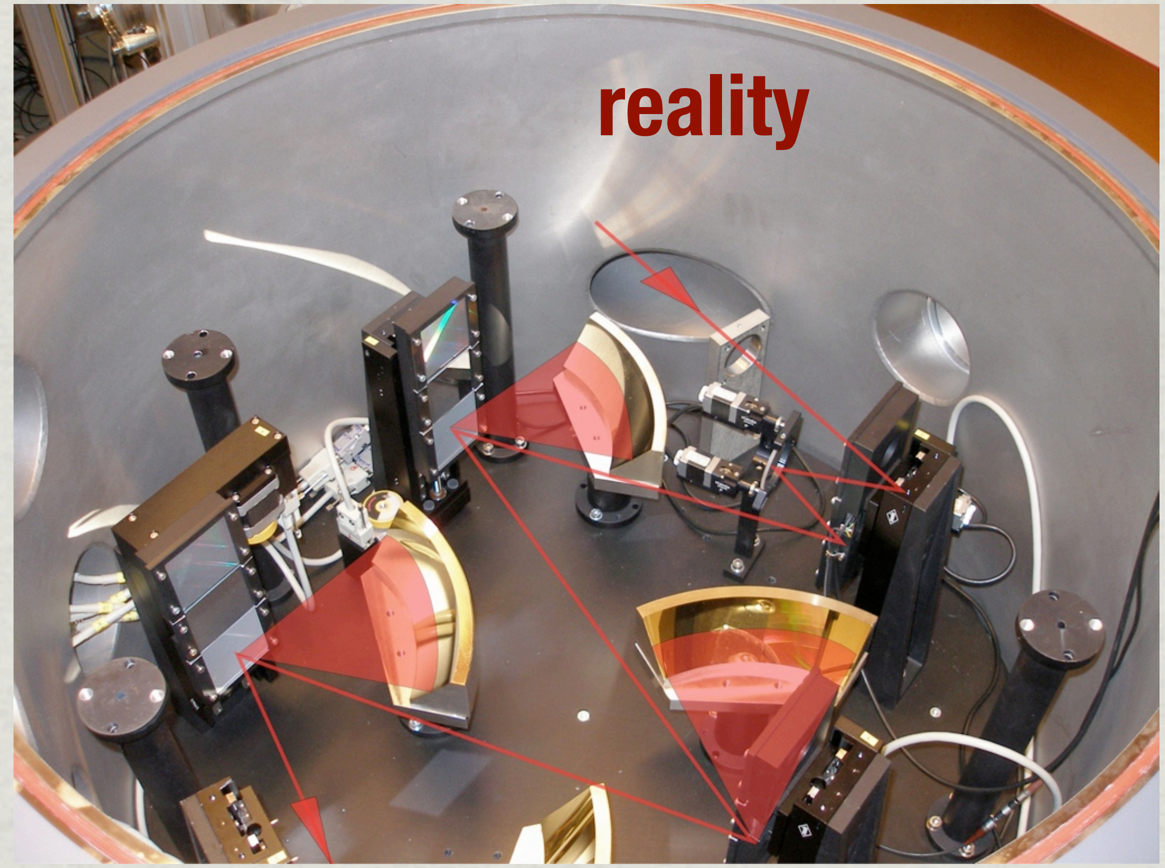


DESY staged grating spectrometer

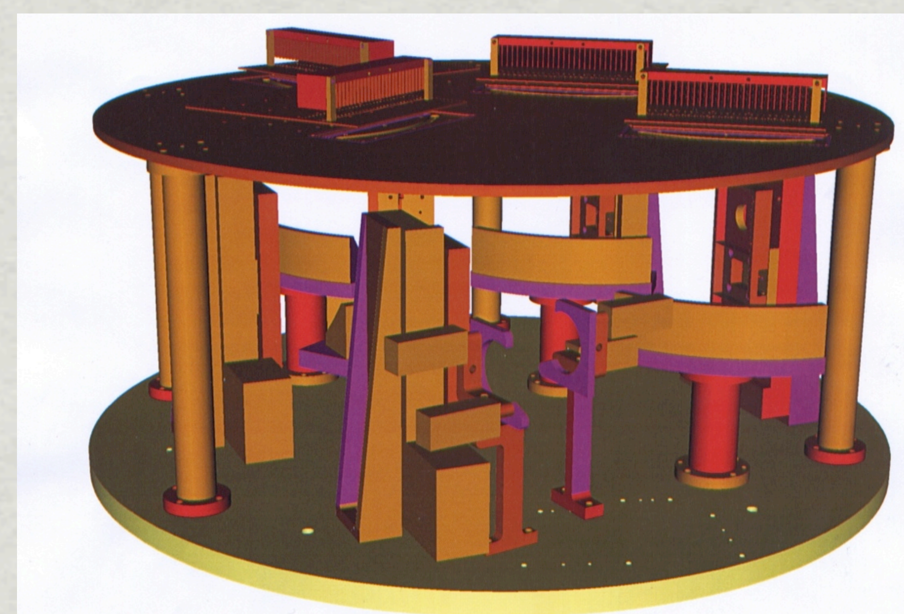
5 µm < λ < 450 µm

principle

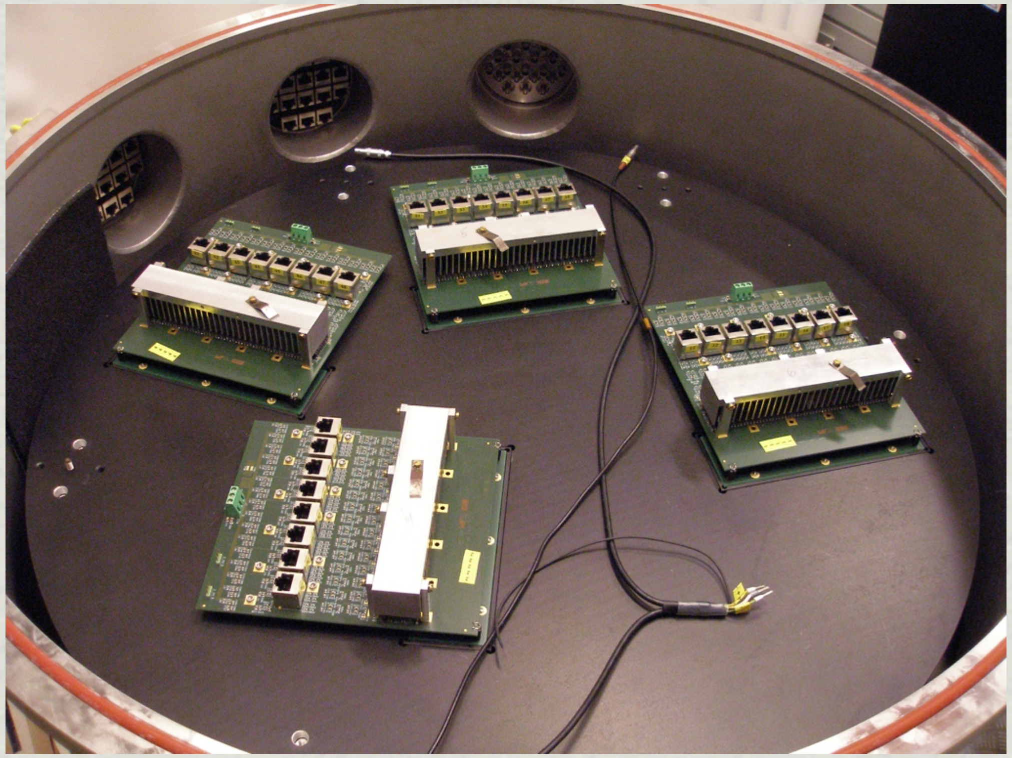


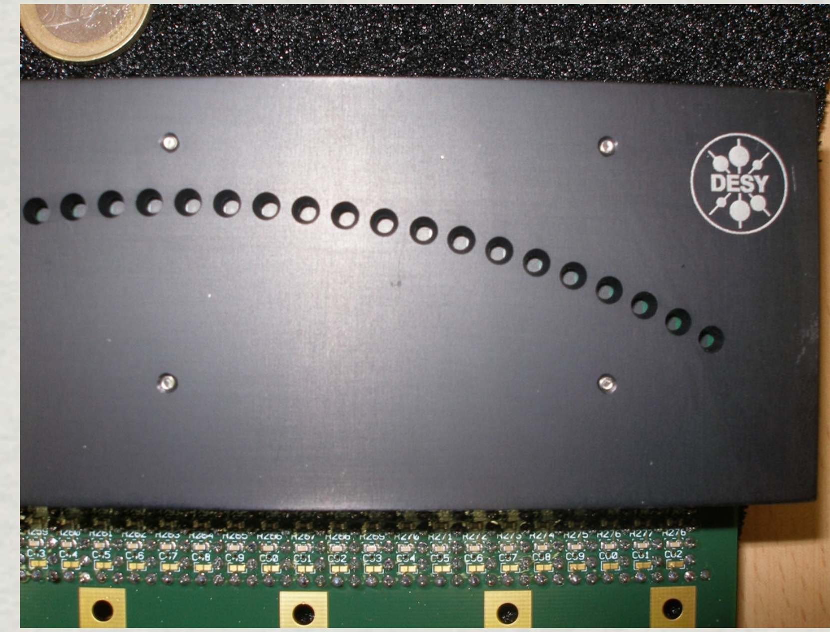


engineering



DESY staged grating spectrometer - detectors





electronics

Pyroelektrischer Detektor

Sensorzeile zur THz- und mm-Wellenlängen-Detektion

In Zusammenarbeit mit dem Institut „**D**eutsches **E**lektronen-**Sy**nchrotron DESY" hat InfraTec eine 30-elementige pyroelektrische Zeile (LIM-107) entwickelt, welche Synchrotron-Strahlung im Terahertz- und Millimeterwellenbereich in einem Spektrometer detektiert.

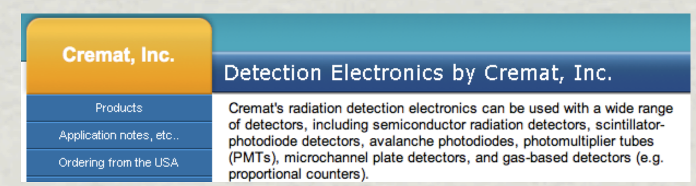
Die Eckdaten des Detektors LIM-107 sind wie folgt:

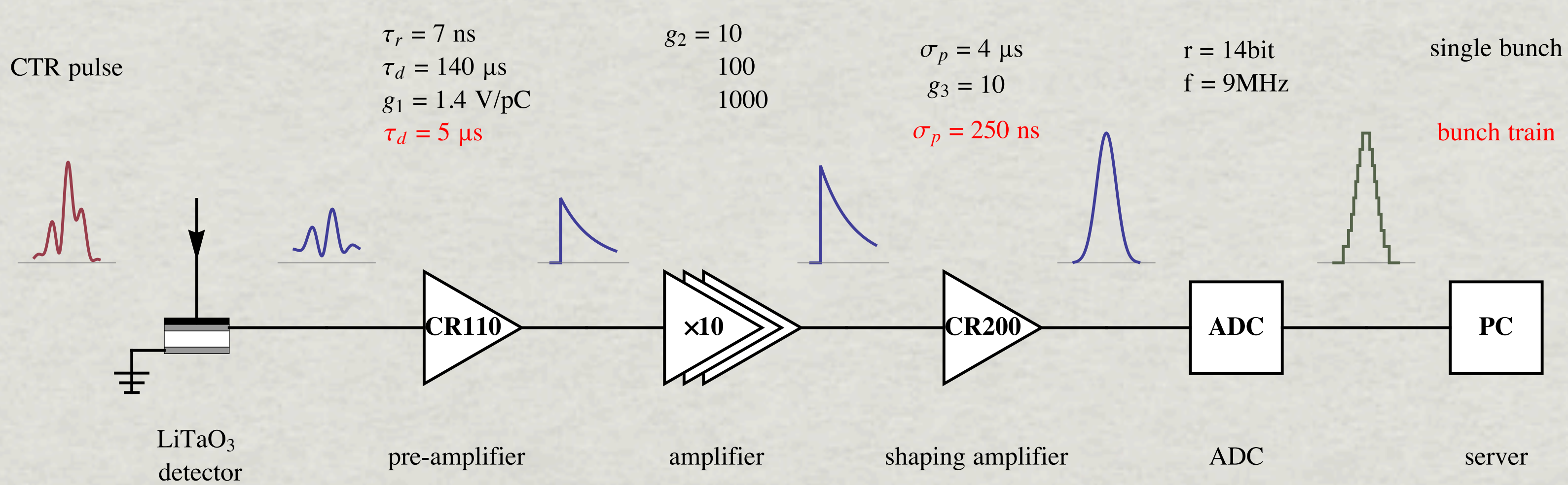
- 30 Elemente 2 x 2 mm² angeordnet auf einem Kreisbogen R = 150 mm im Abstand 5 mm
- 3 alternative Elektrodenbeschichtungen möglich für die Wellenlängenbereiche um 100 µm (3 THz), 300 µm (1 THz) und 1 mm (0,33 THz)
- Kein Fenster
- Betrieb im Vakuum möglich
- Außenabmessung ca. 170 x 55 x 5 mm³

Eine angepasste schnelle Vorverstärkerelektronik ist bei Bedarf verfügbar.

Joe Kunsch: 08142 2864-28
Datenblattservice - Webcode 033

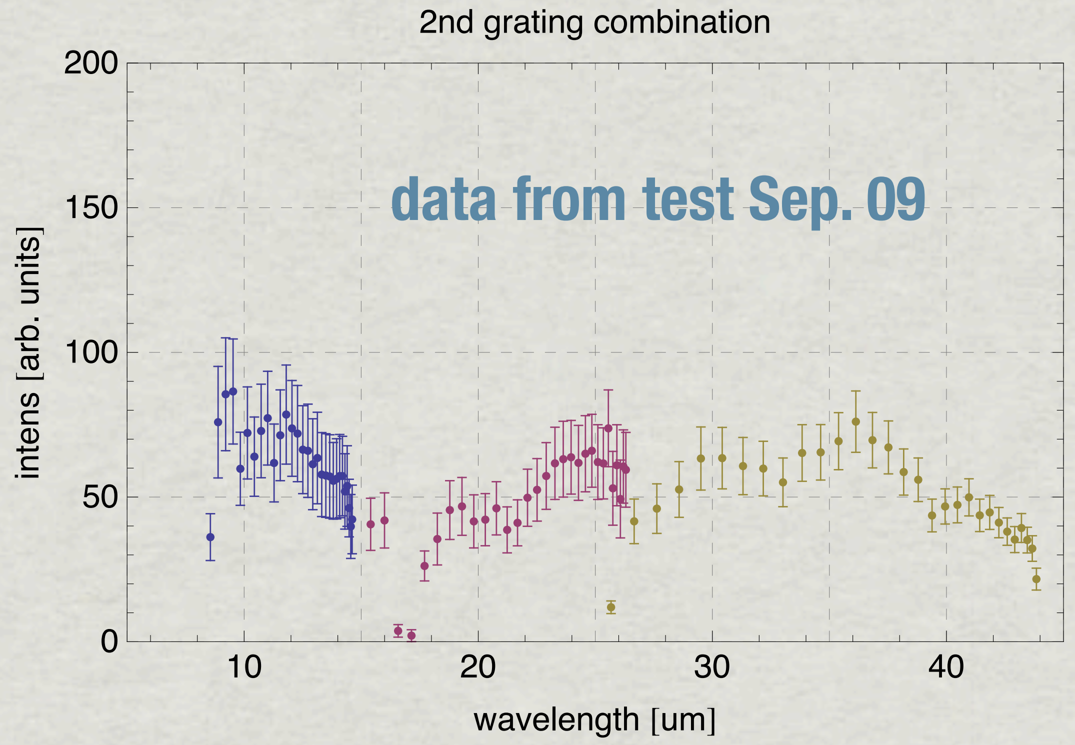
commercial hybrids by





DESY staged grating spectrometer - status

- extensive experience with two stage prototype
- two four stage devices set up
- few test runs with one device, summer 2009
- two will be operational after FLASH shut-down



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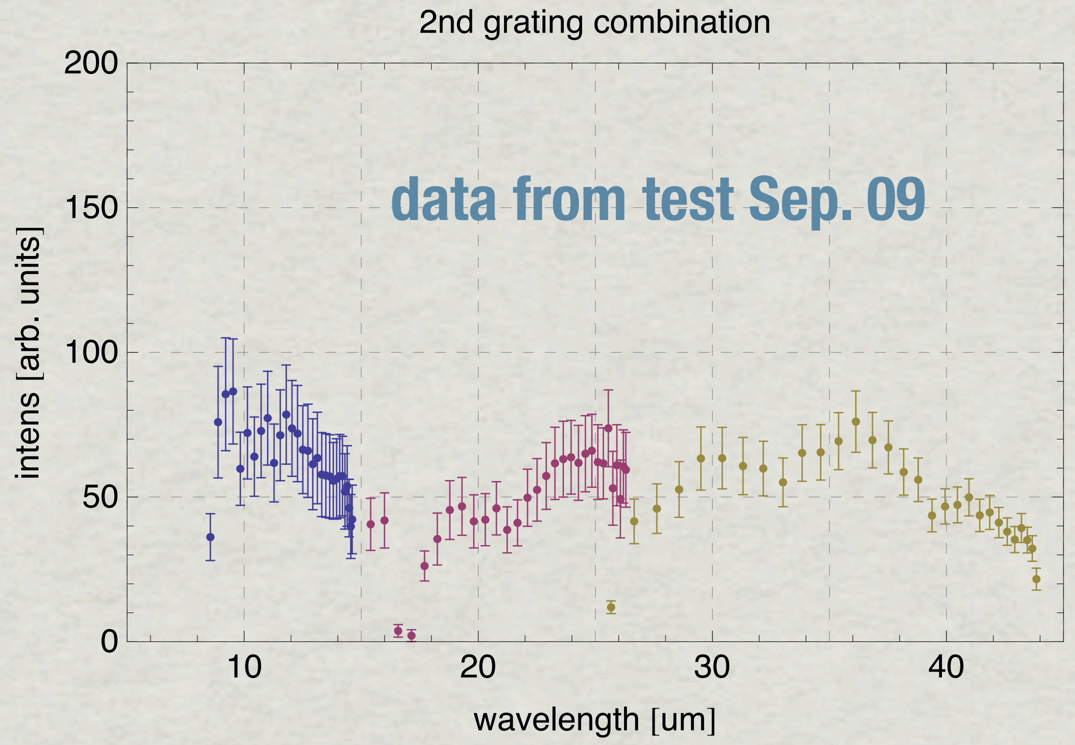

exisiting spectrometer optimized for λ<400 µm
change gratings, but „tight“ for λ~mm
? use „old“ prototype version with 1 - 2 stages ? (2x larger)

form factor modulated bunch

sensitivity of pyroelectric sensors **: ~3 mV/nJ**
noise level : < 1 mV (depending on integration time)
detectable : < 1 nJ (with 4 μs shaping)

form factor modulated bunch

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model bunch :
long sequence of *m* Gaussian bunches, width σ_b , separation t_p

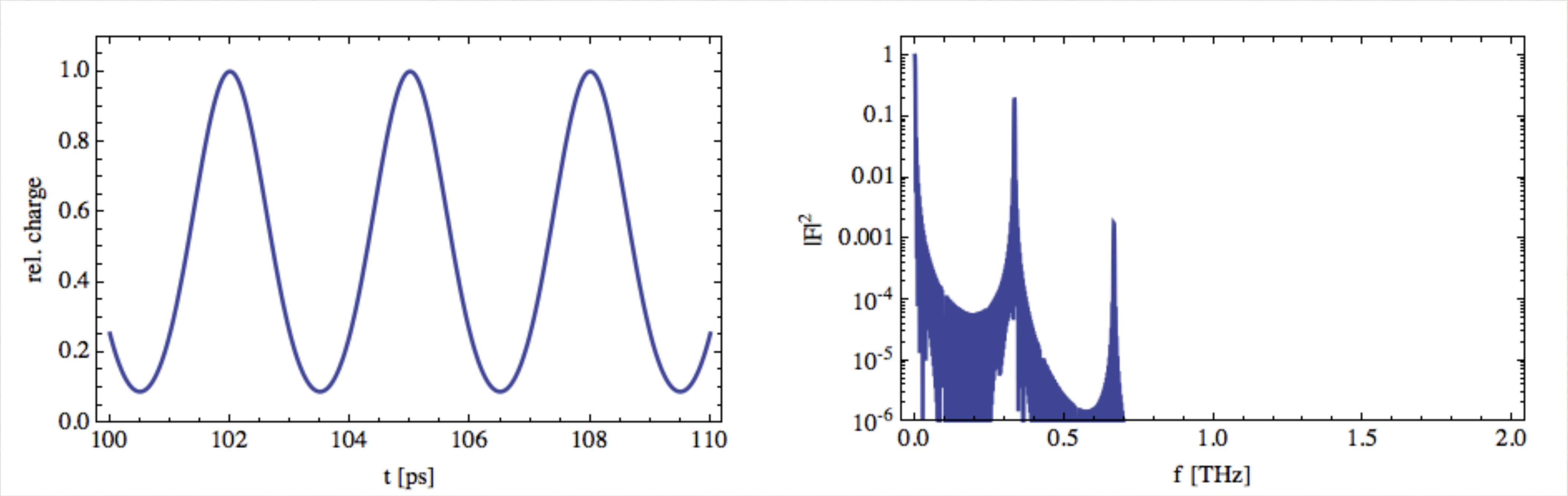
$$F^2 = \frac{e^{-4\pi^2 f^2 \sigma_b^2} (\cos(2\pi f (m+1) t_p) - 1)}{(m+1)^2 (\cos(2\pi f t_p) - 1)}$$

additionaly :
„T-function" for CTR, two mirrors, detector focussing

total charge 16 nC, t_p= 3 ps, $m = 100$, $\sigma_{x,y} = 1mm$, $\gamma = 450$

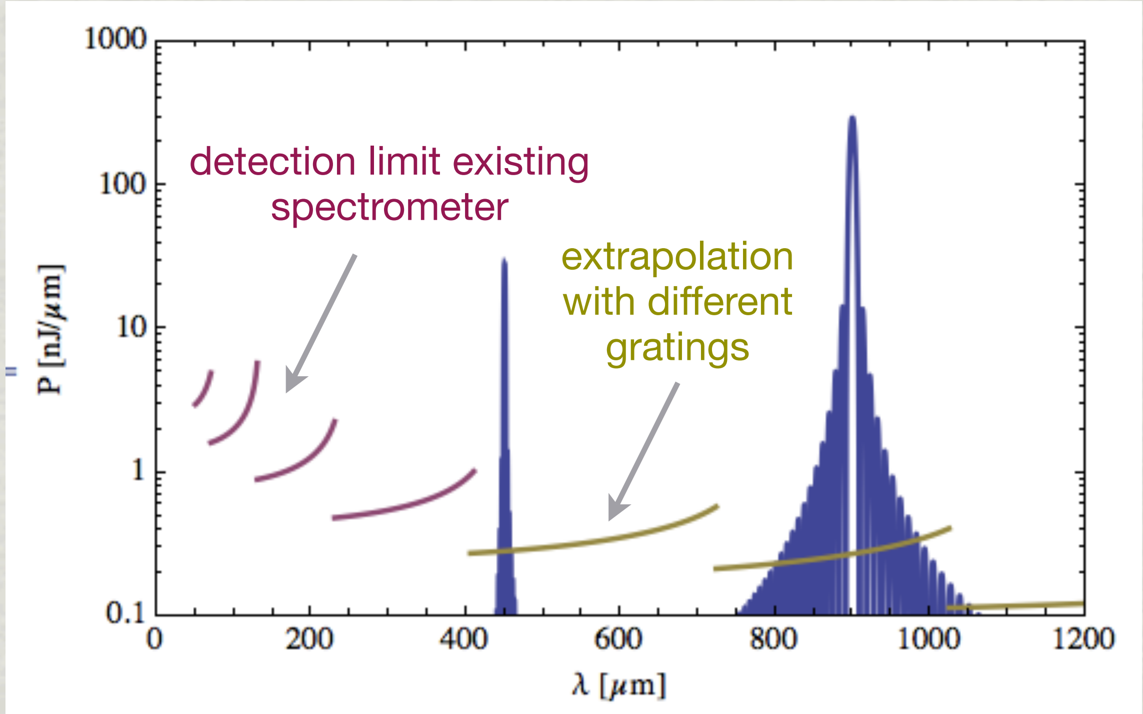
radiation intensity at detector (CTR, mirrors etc.)

strong modulation, 100 periods



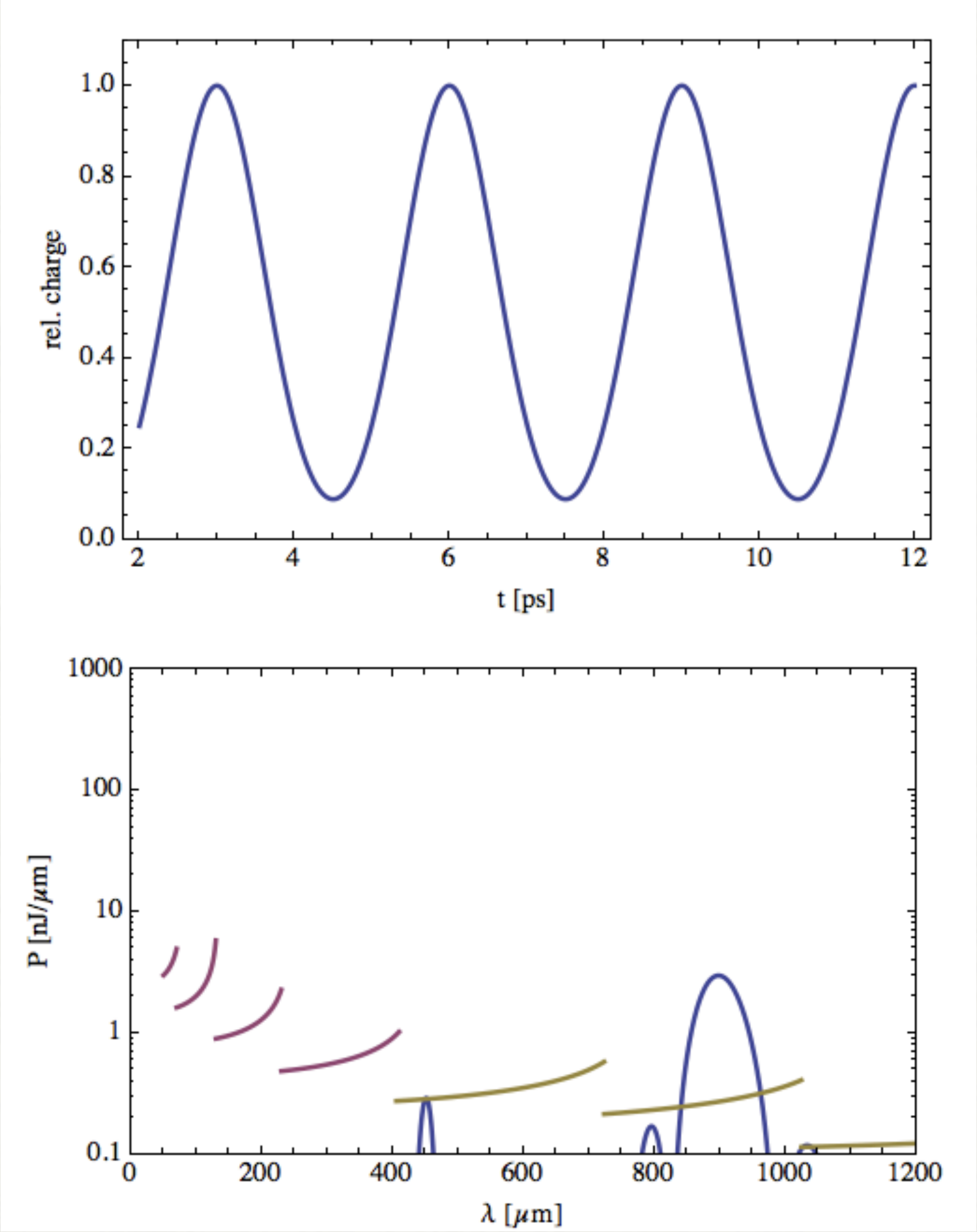
enormous signal at fundamental !

if wavelength known, single stage might be enough

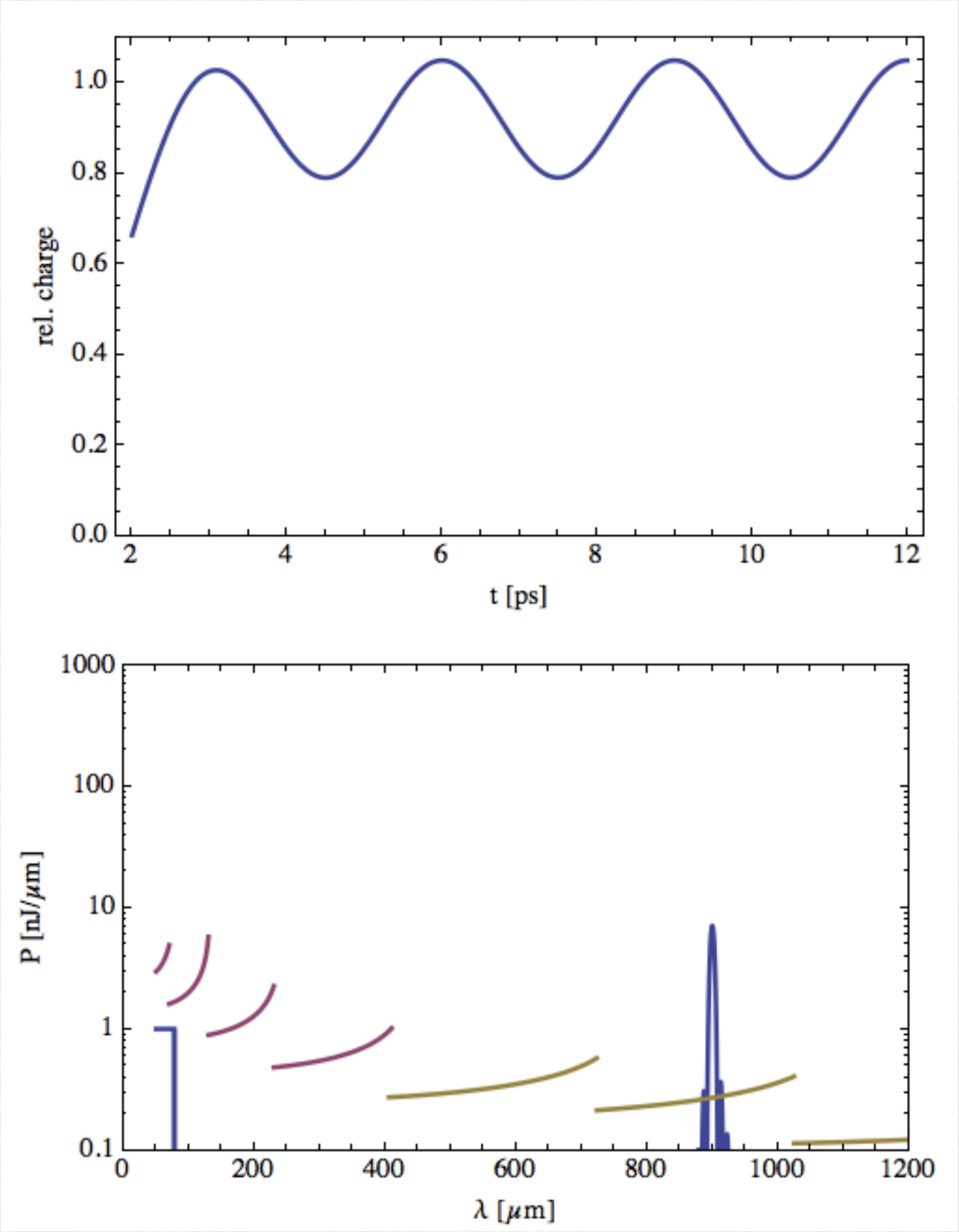


radiation intensity at detector -II

strong modulation, 10 periods



weak modulation, 100 periods



the combined approach : EO-THz-spectrometer

- use long (~100 ps) Fourier limited laser
- interaction with THz pulse in EO material
- up-convert THz frequency to optical
- use high resolution **optical** spectrometer
- side bands reveal periodic bunch structure

S. Jamison Appl. Phys.B 91, 241–247 (2008)

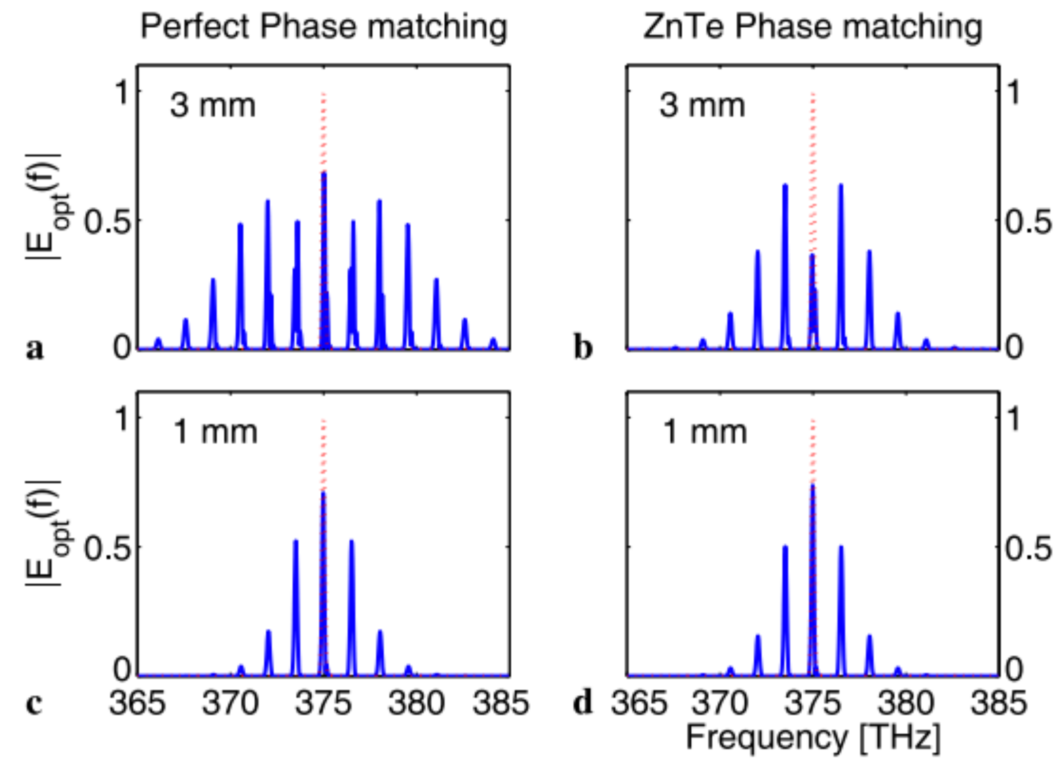
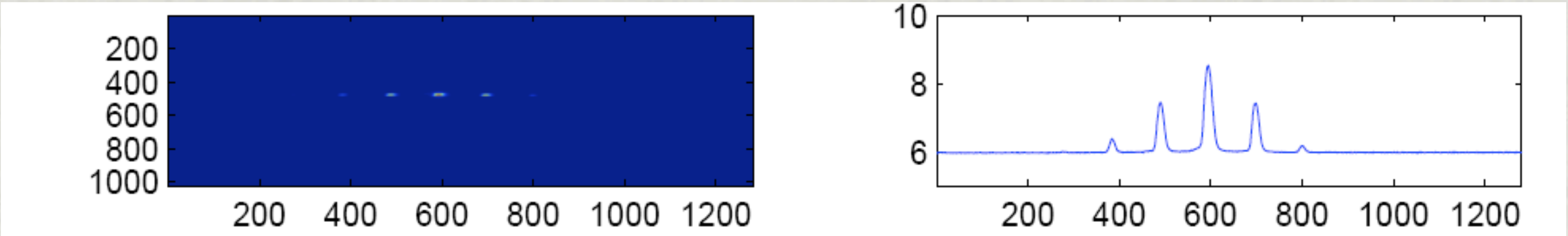


FIGURE 2 Optical spectra following the interaction with a quasi-monochromatic $\omega = 1.5$ THz pulse, with a peak field strength of 5×10^5 V m^{-1}, and for interaction lengths of 1 mm and 3 mm; (**a**) and (**c**) assume perfect phase matching, while (**b**) and (**d**) include phase matching as expected for ZnTe material properties. In each plot, the *dotted line* is the input optical spectrum

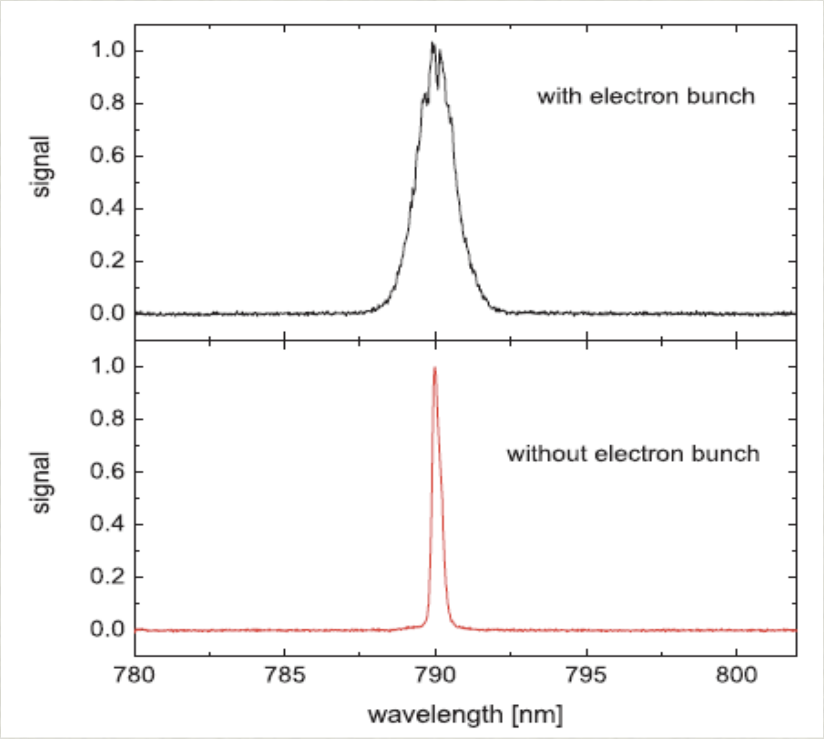
EO-THz-spectrometer demonstrated



120 µm THz wave

experimental demonstration by
Giel Berden (FELIX) & Steve Jamison (Daresbury)
publication in preparation...

Coulomb field



could be simple and reliable set-up
no „close to beam“ crystal, could use focused CTR
no short-pulse laser required
especially suited for periodic signals

summary

- the problem to detect the mm substructure is solvable
- different experimental techniques applicable
- nothing from the shelf, may be OTR + streak camera ?
- no „obvious show-stoppers“ expected

Thanks for attention


DC
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The FLASH
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1
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JUNE '09
2010
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