Bunch Length Diagnostics: Current Status & Future Directions
Part 2

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Two distinct classes of diagnostics

Grouped by similar physics and capabilities / limitations

1. Direct Particle Techniques

$\rho(t) \rightarrow \rho(x)$

longitudinal $\rightarrow$ transverse imaging

RF zero-phasing

$\rho(t) \rightarrow \rho(\gamma) \rightarrow \rho(x)$

Transverse Deflecting Cavities

$\rho(t) \rightarrow \rho(x') \rightarrow \rho(x)$

2. "Radiative" Techniques

$\rho(t) \rightarrow E(t)$

propagating & non-propagating

Spectral domain:

- CTR, CDR, CSR (spectral characterisation)
- Smith-Purcell
- Electro-Optic

Time domain:

- CTR, CDR (autocorrelation)
- Optical Replica
- Electro-Optic + Transposition
- Other techniques

Class 2. “Radiative” Techniques

Here we cause the Coulomb field of the electron bunch to radiate in a controlled manner, and subsequently infer the bunch profile from the emitted radiation spectrum.

"Radiative" Techniques

General Methodology: Cause electron bunch to radiate coherently

$$\rho(t, x_0) \longrightarrow E_{\text{rad}}(t, x_0)$$

- emission response
- phase matching

'Propagate' to observation position $\longrightarrow E_{\text{rad}}(t, x)$

- Attenuation
- Dispersion
- Diffraction…

long wavelengths significantly affected by diffraction

Measure spectrum, intensity time profile

$$|\tilde{E}_{\text{rad}}(\omega, x)|^2$$

$$E^2_{\text{env}}(t, x)$$

$$E_{\text{rad}}(t, x)$$

- detector response
- missing phase information

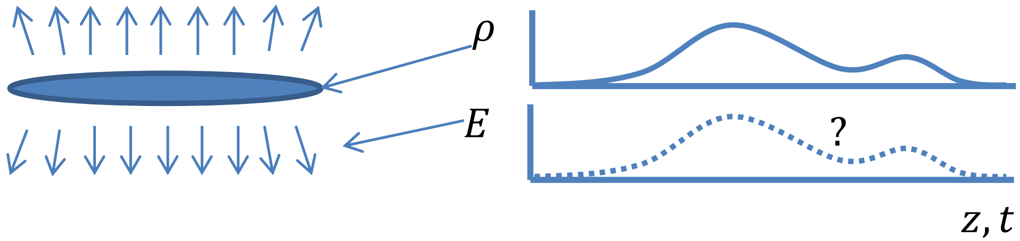
Infer charge density

Techniques & limitations:

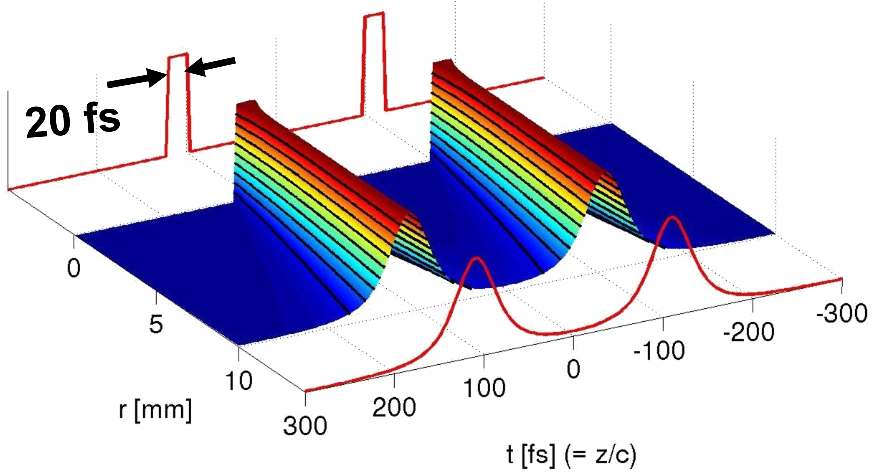
CSR/CTR :	propagation effects; detector response; missing phase
CDR :	as for CSR/CTR; plus emission response
Optical Replica:	emission response (? radiating undulator)
Electro-Optic:	detector response

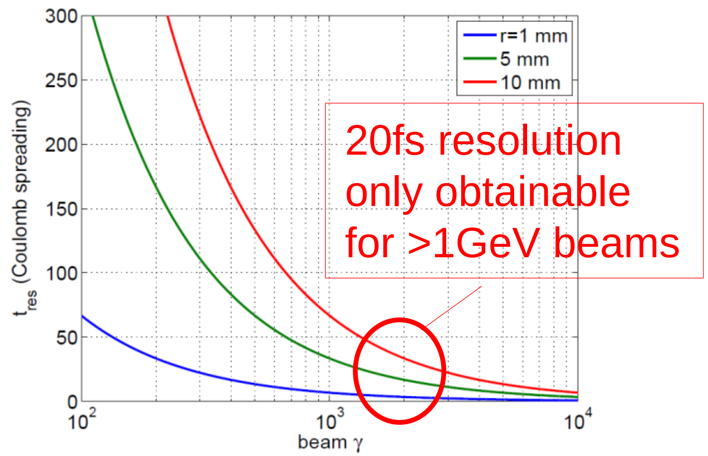
Common Problem - Field at Source

Field radiated or probed is related to Coulomb field near the electron bunch



20fs electron bunches,
200fs separation, $\gamma = 1000$





High γ is an advantage!

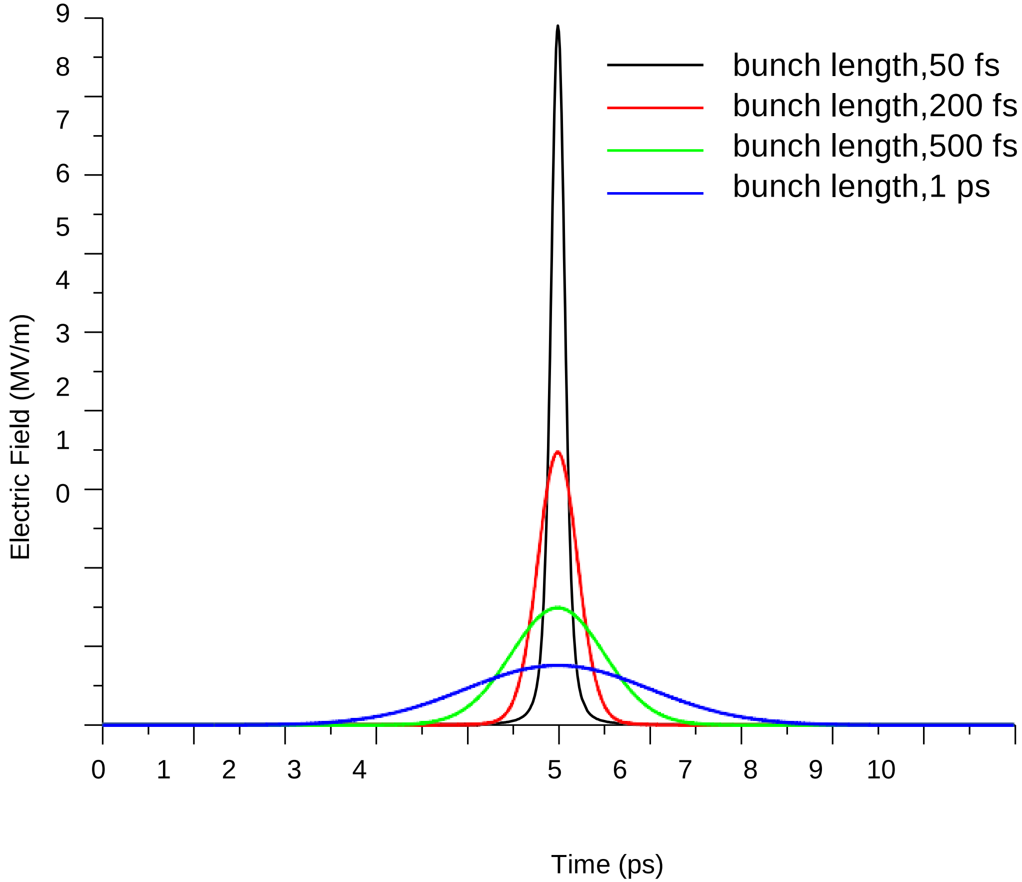
Time response & spectrum of field is dependent on spatial position, r :

$$\delta t \sim 2r / c\gamma$$

$\Rightarrow$ ultrafast time resolution requires close proximity to bunch

(N.B. equally true of CTR, CDR, Smith-Purcell, Electro-Optic, etc.)

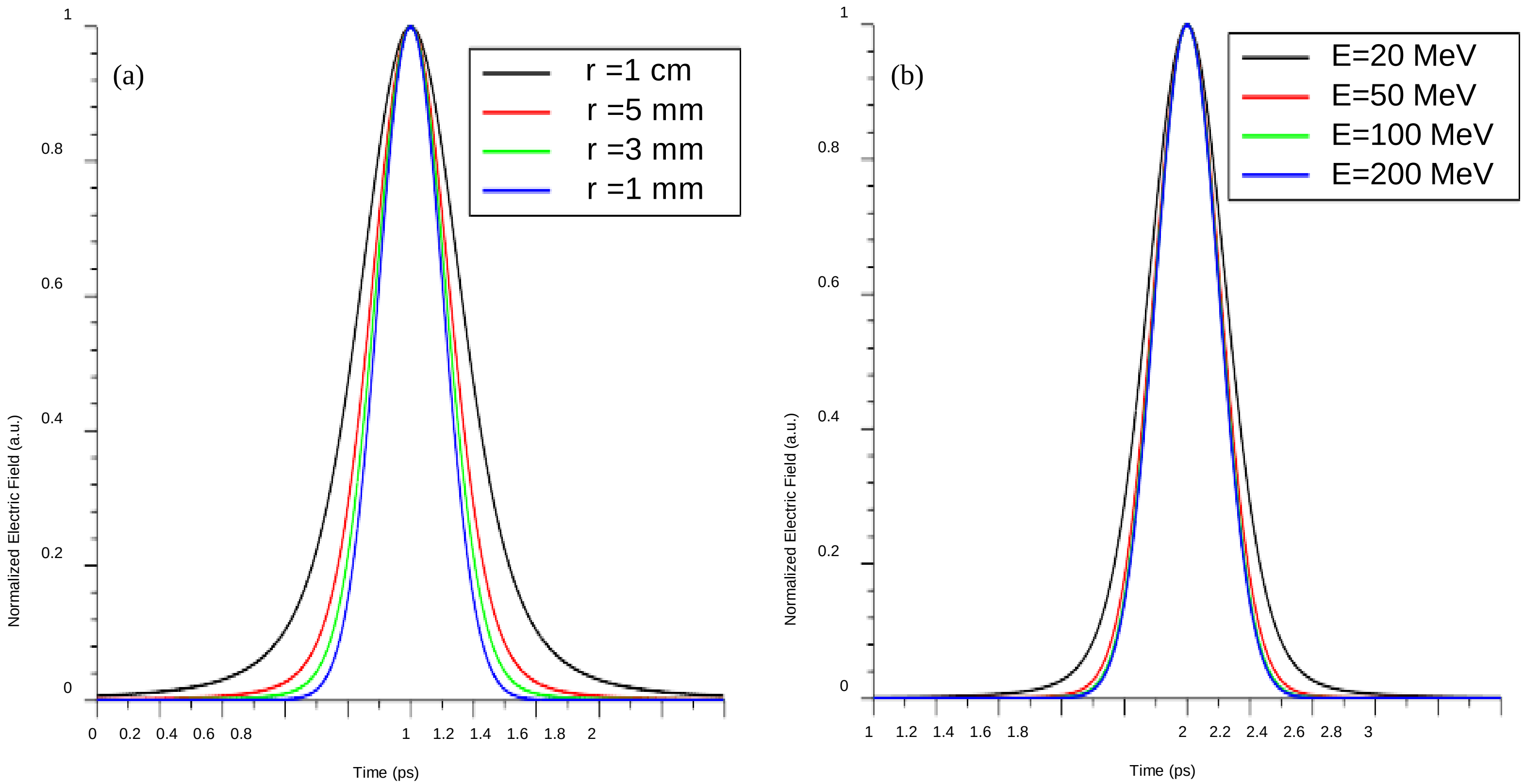
Transverse E-field of a relativistic electron bunch



Transverse electric field of a relativistic bunch (Q = 160 pC, 110 MeV, ρ = 5 mm) with Gaussian distribution for different $\sigma_z = c\sigma_t$. The parameter σ_t takes the values of 50, 200, 500 and 1000 fs (rms), with larger values corresponding to broader curves.

Pompili

Transverse E-field of a relativistic electron bunch



(a) Transverse electric field of a relativistic bunch (Q = 160 pC, 100 MeV, σ_t = 100 fs) with Gaussian distribution at different observation point distances r. Larger values of r correspond to broader curves; (b) Same as in (a) but the varying parameter is the beam energy. Now larger values correspond to narrower curves. The distance here is fixed to $r = 1$ mm.

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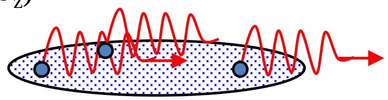
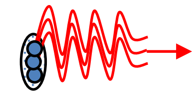
Coherent Radiation

long bunch ($\lambda<\sigma_z$)



short bunch ($\lambda>\sigma_z$)



For wavelengths *shorter than* the bunch length, the particles within the bunch radiate incoherently, with power emitted proportional to number of particles. However, for wavelengths *equal to or longer than* the bunch length, particles emit radiation coherently with the emitted power dependent on the bunch length, and scaling as the square of the number of particles.

incoherent term ⇓ coherent term ⇓

$$S(\omega) = S_p(\omega)\,[N + N(N-1)F(\omega)]$$

with form factor

$$F(\omega) = \left| \int_{-\infty}^{\infty} \rho(s)\, e^{-i\frac{\omega}{c}s}\, ds \right|^2$$

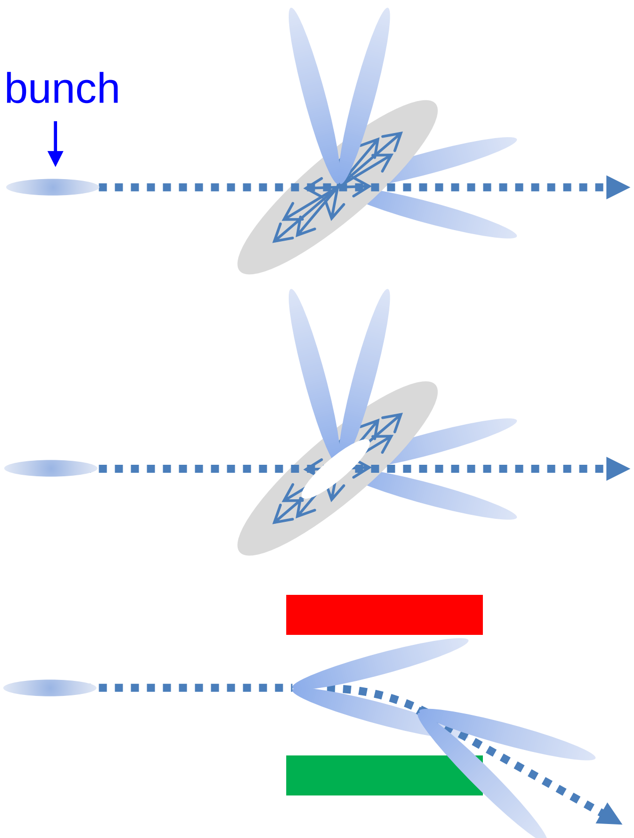
where $S(\omega)$ represents the radiation spectrum, Sp(ω) the single particle spectrum, N the number of particles and $F(\omega)$ the longitudinal bunch form factor, which depends on the longitudinal particle distribution $\rho(s)$.

Measuring the power spectrum therefore allows the form factor to be calculated from which an indirect measurement of the bunch length is possible.

What is obtained, however, is the form factor rather than the longitudinal distribution.
In order to reconstruct the longitudinal bunch profile it is necessary to perform an inverse-Fourier transformation using phase recovery algorithms making use of the Kramers–Kronig relation.

2.1 Spectral domain radiative techniques

Radiation emitted in forward/backward cones (not TEM_{00} !)



Coherent Transition Radiation (CTR)
Bunch field sets up currents in foil which re-radiate
Can think of as a reflection of the Coulomb field.
“Destructive”

Coherent Diffraction Radiation (CDR)
Similar to CTR but with a hole in angled screen
Can lose shorter wavelengths
Also Smith-Purcell radiation (SP) similar, but extra complication due to interference

Coherent Synchrotron Radiation (CSR)
.. or “edge” version, CER
But need to divert the beam!

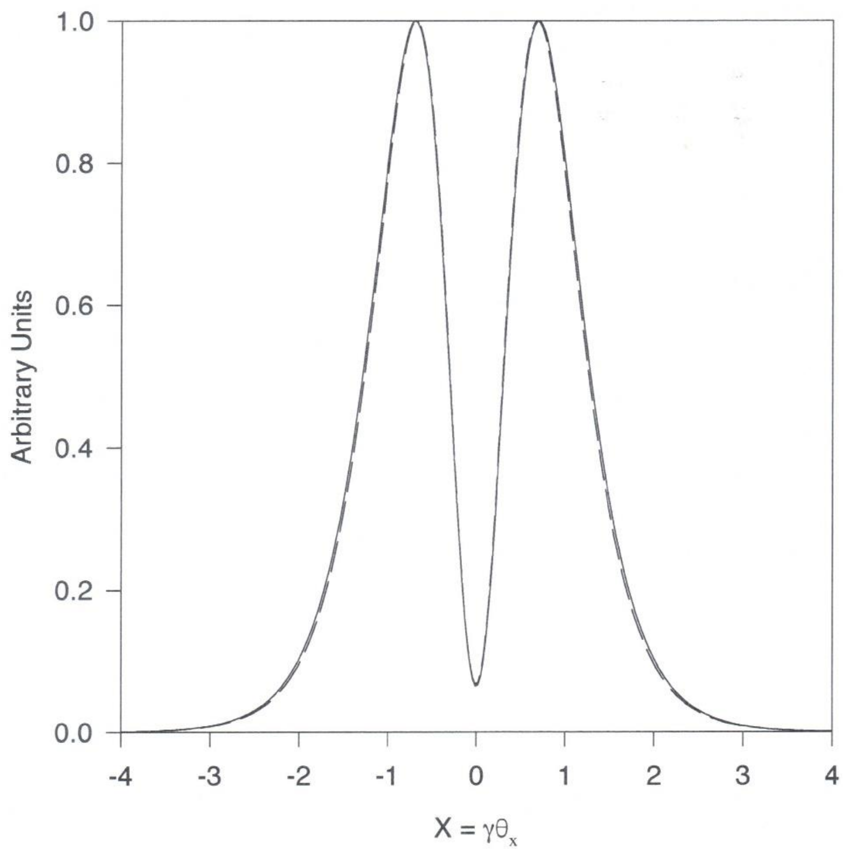
Bunch form factor $\Rightarrow$ $F(\lambda) \equiv \left| \int_{-\infty}^{\infty} f(z) e^{-i\frac{2\pi z}{\lambda}} dz \right|^2$ $\Rightarrow$ mid-IR to far-IR spectrum (wide)

Usually only *spectrum* measured, but temporal measurements also possible (EO) …

no direct detectors are fast enough!

What is Transition Radiation?

TR, OTR, CTR



Typical double-lobed angular distribution of TR

Definition: Radiation which occurs when a charge moving at constant velocity crosses a boundary between media with different dielectric constants

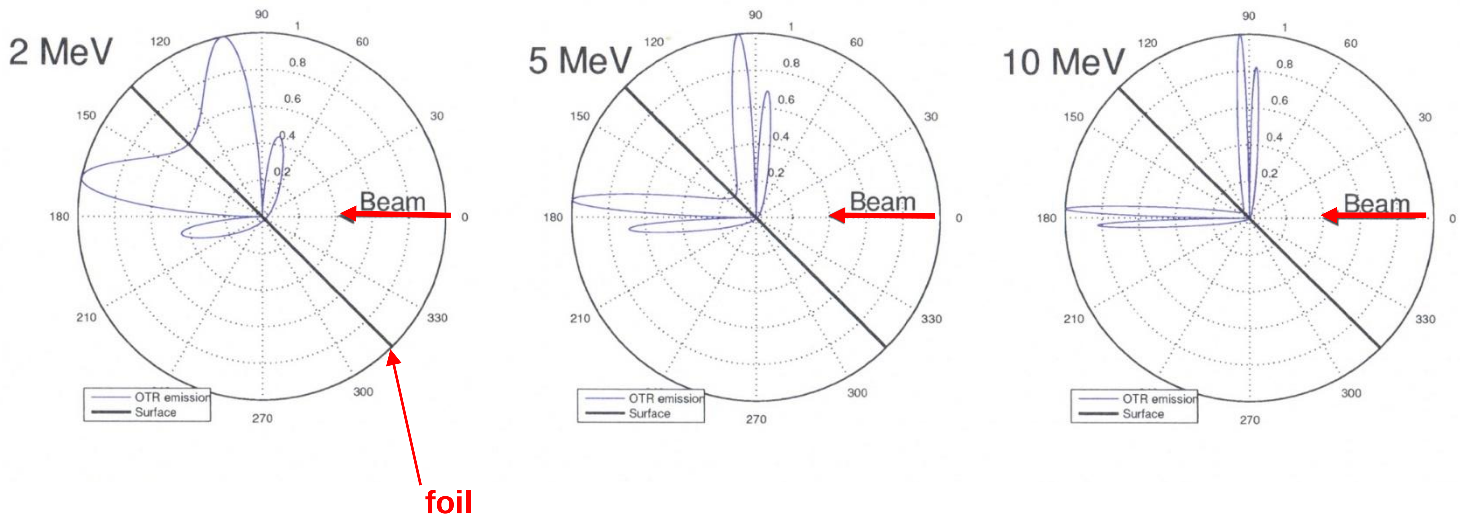
- simple idea: Radiation from collapsing dipole formed by moving charge and its image
- more exact: Radiation formed by suddenly disappearing and appearing surface charge distribution as charge crosses boundary (femtosecond time scale)
- virtual photons: Reflection and refraction of virtual photons of all frequencies (up to plasma frequency) at the interface

Transition Radiation at low electron beam energy

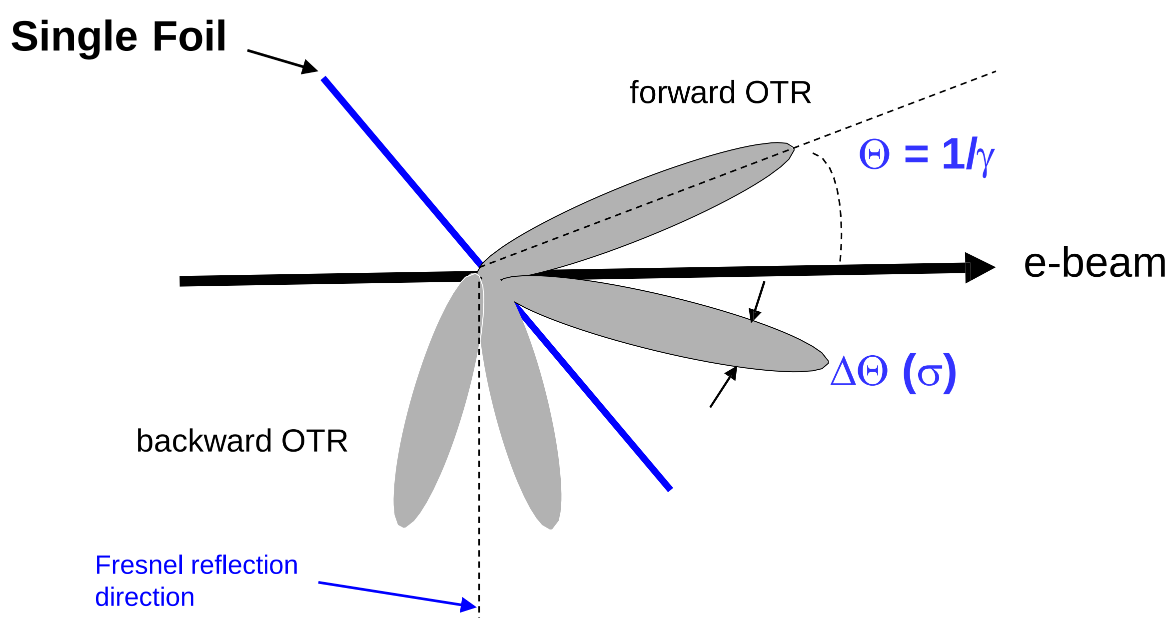
The angular distribution in the plane containing the particle velocity vector and the normal to the surface is given by:

$$\frac{d^2W}{d\omega d\Omega} = \left(\frac{e^2 v^2}{2\pi^2 c^3}\right) \cdot \left[\frac{\sin(\theta - 2\varphi)}{\left[1 + \frac{v}{c}\cos(\theta - 2\varphi)\right]} + \frac{\sin\theta}{\left[1 - \frac{v}{c}\cos\theta\right]} \right]^2$$

Important in the OTR device design

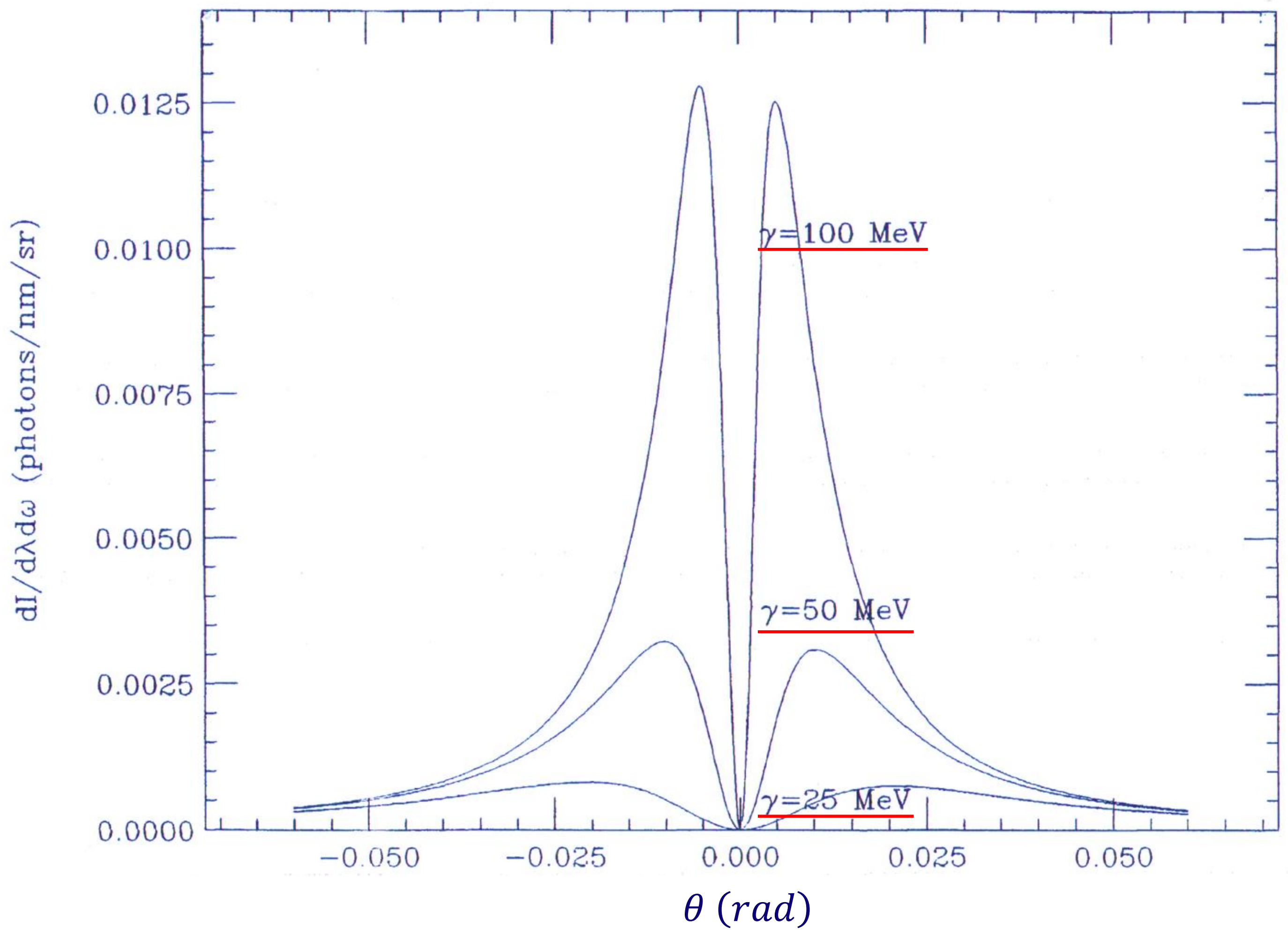


Beam Diagnostic using Angular Distribution of Single Foil OTR or CTR



At high γ get simplified relation: $$\Rightarrow \frac{d^2 I^{(S)}}{d\omega d\Omega} = \frac{e^2}{\pi^2 c} \frac{\theta^2}{(\gamma^{-2} + \theta^2)}$$

angular distribution is a function of angle, energy, angle, divergence and energy spread, but is independent of beam size or position.

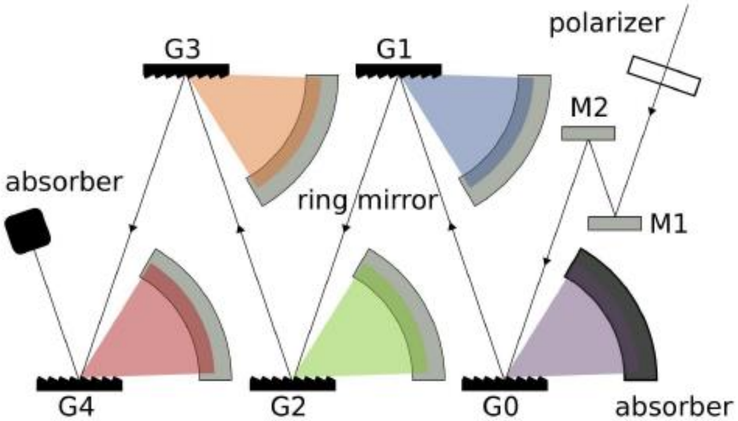


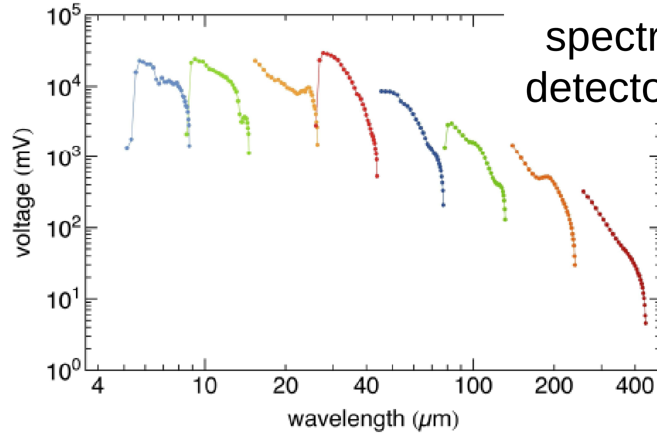
Angular distribution of transition radiation
as a function of energy

Good example: single-shot CTR spectrometer at DESY FLASH

cascaded dispersive grating elements, and pyroelectric detector arrays

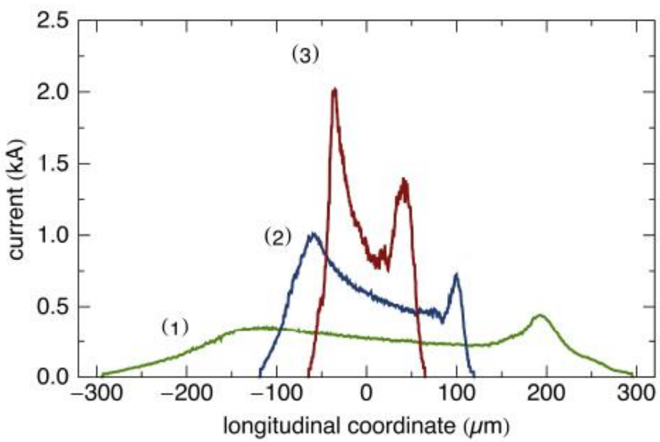
(E. Hass et al., Proc. SPIE 8778, May 2013)



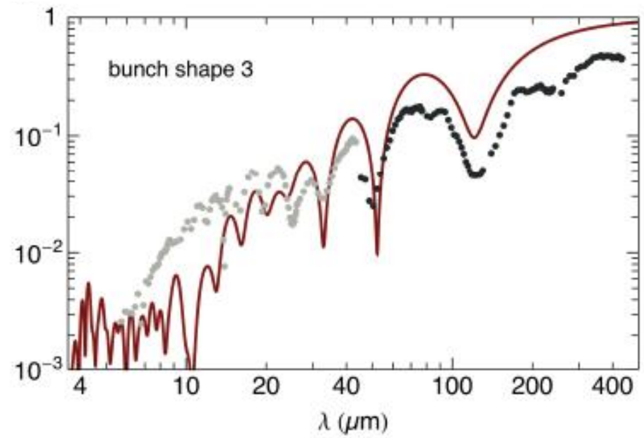


spectrometer & detector response

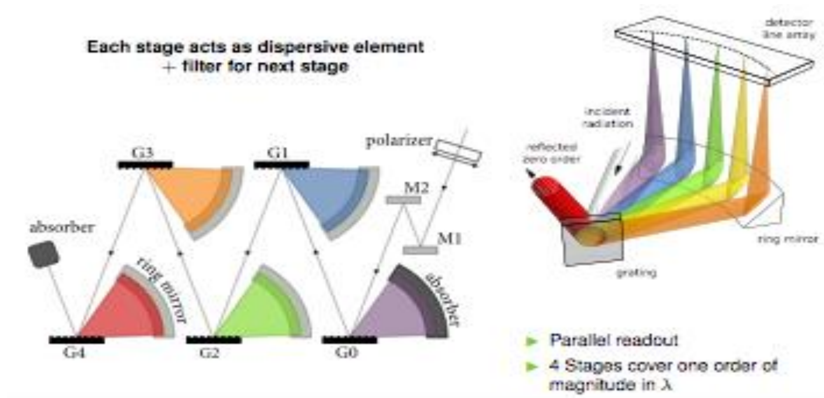
Deflecting cavity bunch profiles



Measured & calculated spectra

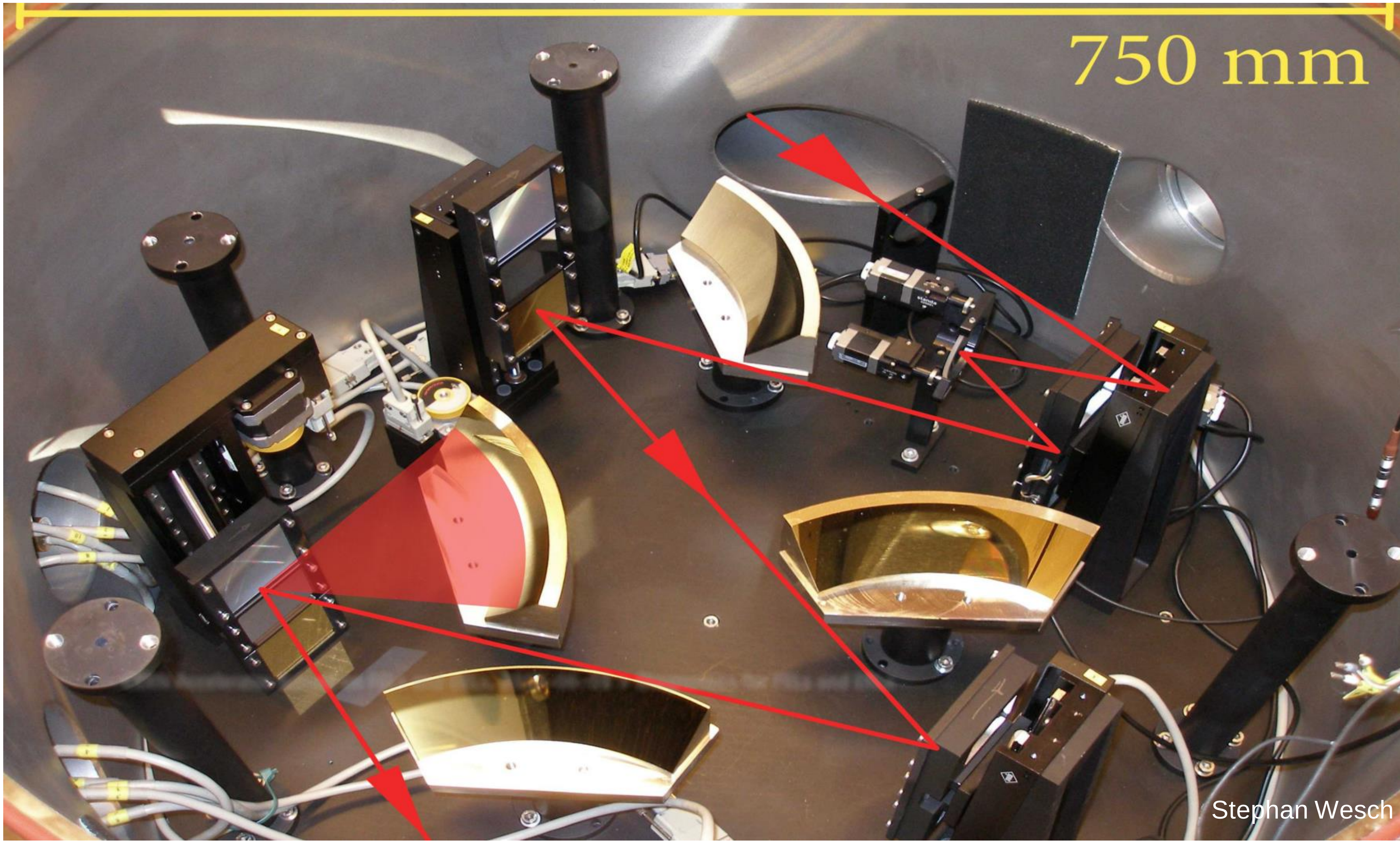


Similar concepts applied at HZDR ELBE facility (O. Zarini et al, LA³NET workshop, Dresden, April 2014) and at SLAC LCLS (T. J. Maxwell et al, PRL 111, 184801, 2013)

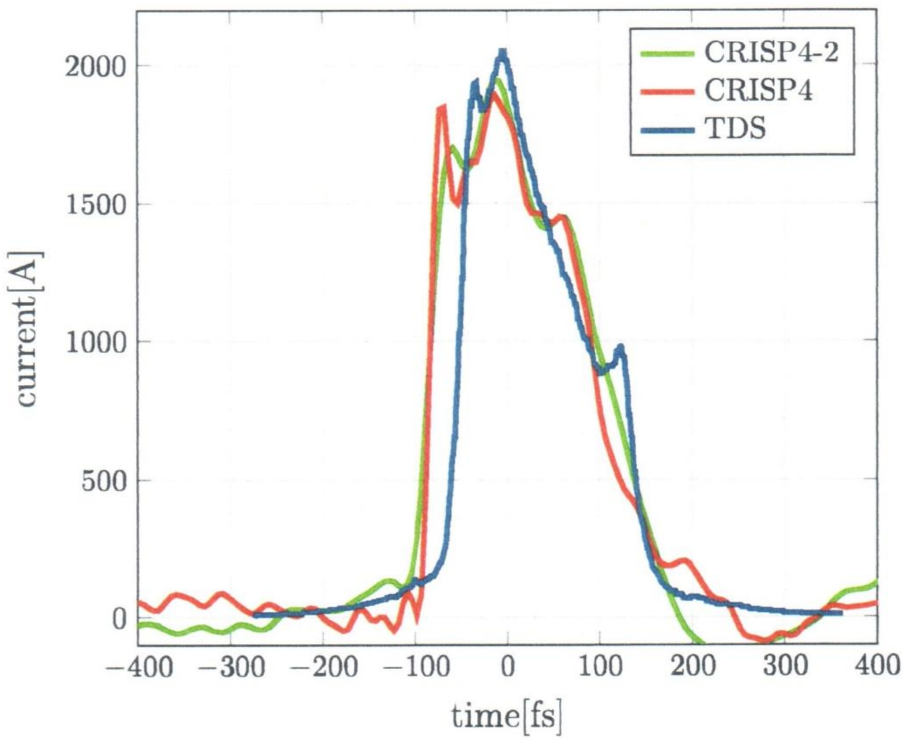


single-shot CTR spectrometer at DESY FLASH

- 5 consecutive dispersion gratings
- 120 parallel readout channels
- can be operated in either short (5 - 44μm) or long (45 - 430μm) mode



single-shot CTR spectrometer at DESY FLASH



Temporal profiles measured with the TDS (-) and the CTR spectrometers [CRISP 4 (-) and 4-2 (-)]

FWHM $\sim 180\ fs$

Note that these measurements are not strictly single-shot, since the spectrometers require two measurements with different grating sets to cover the full wavelength range (2 orders of magnitude).

Reconstruction requires use of *Kramers-Kronig based* phase retrieval technique.
Bear in mind: this is the shortest pulse compatible with the spectrum.

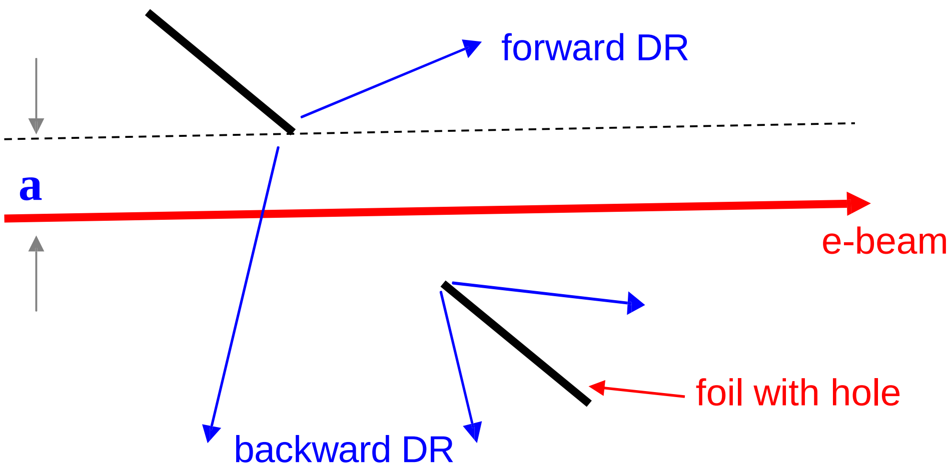
Diffraction Radiation

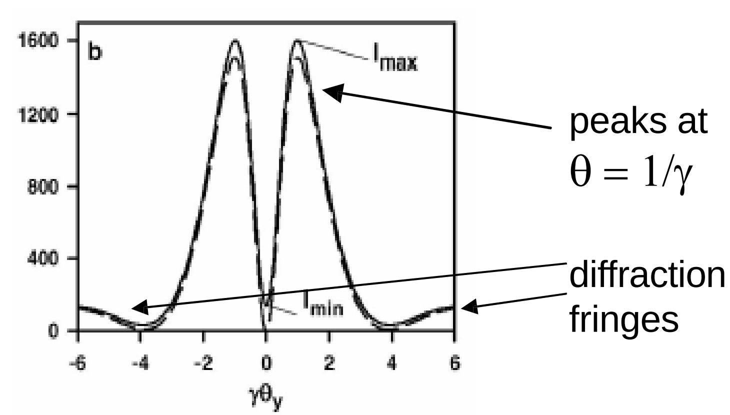
produced by interaction of the field of a constant velocity charge with a boundary
(hole of arbitrary shape in foil)

Impact Parameter: $\alpha = \gamma\lambda/2\pi$,

is the range of the radial field of the charge: $E_e \sim K_1\,(r/\alpha)$

(1) when $a \sim \gamma\lambda$, DR is produced and angular distribution is frequency dependent





(2) when $a \ll \gamma\lambda$ DR = TR; particle doesn't see hole, and no diffraction wings

Smith-Purcell Radiation

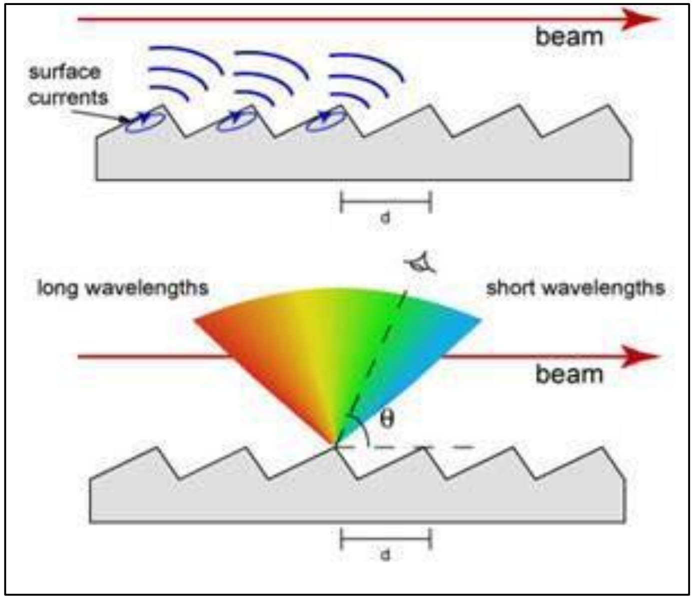
Smith-Purcell radiation is produced when a charged particle beam interacts close to a parallel periodic metallic structure (spatially coherent DR**).**

The structure, or 'grating', causes a wide angular dispersion of wavelengths according to the relationship (radiation resonance condition):

$$\lambda = \frac{d}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$

where d is the period of the grating, *n* is the emitted order of radiation, β = v/c and θ is the observation angle.

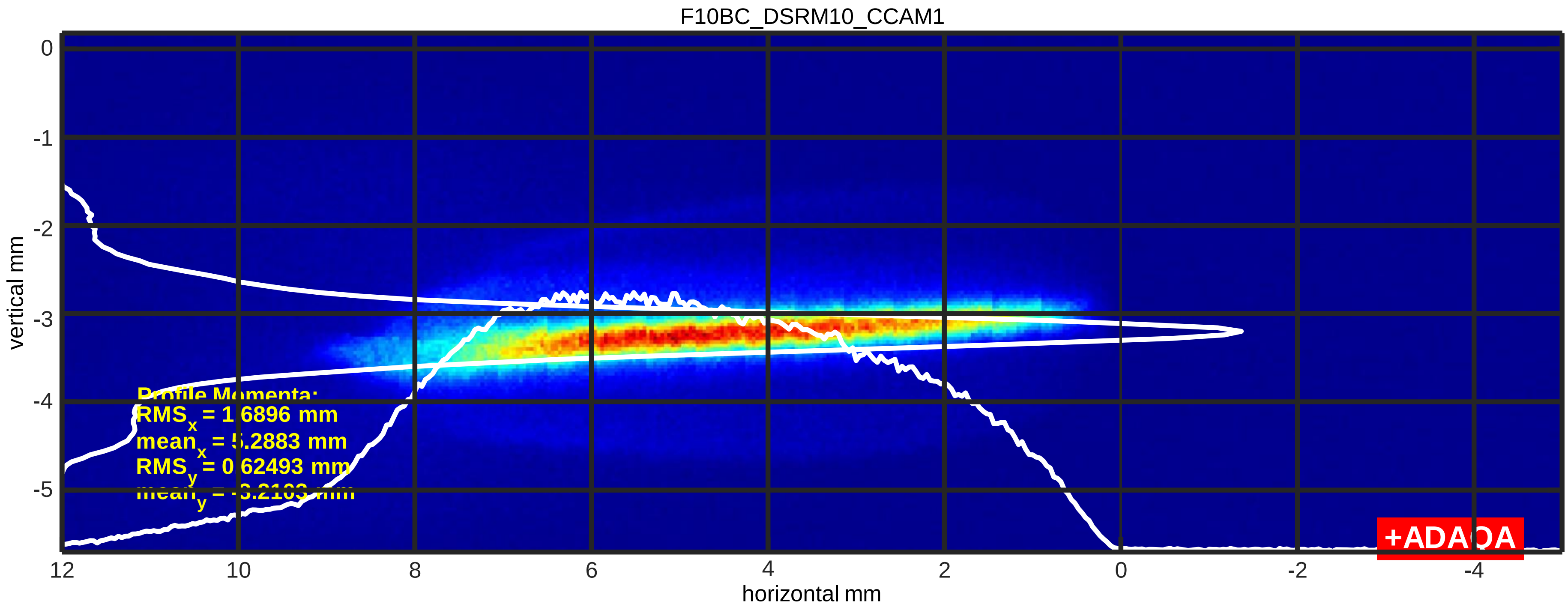
- The broad wavelength range depends on the grating period, and can be selected
- *Coherent enhancement* occurs for bunch lengths shorter than, or equal to, the emitted wavelengths
- Bunch profile not explicitly determined from the data; instead, experimental spectra are compared to calculated spectra based on trial bunch profiles
- Sub-ps bunch lengths measurable.



Synchrotron Radiation (SR and CSR)

can be used to measure very small beam sizes

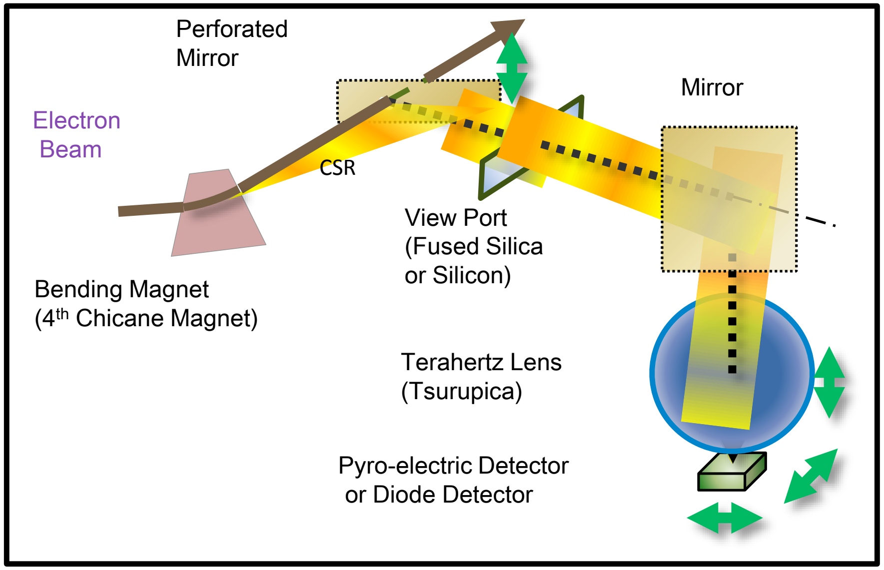
Measurement at the SwissFEL Injector Test Facility

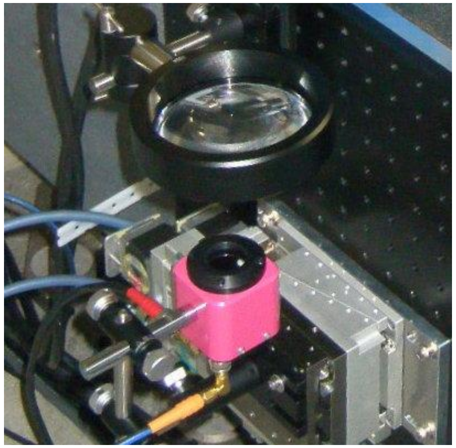


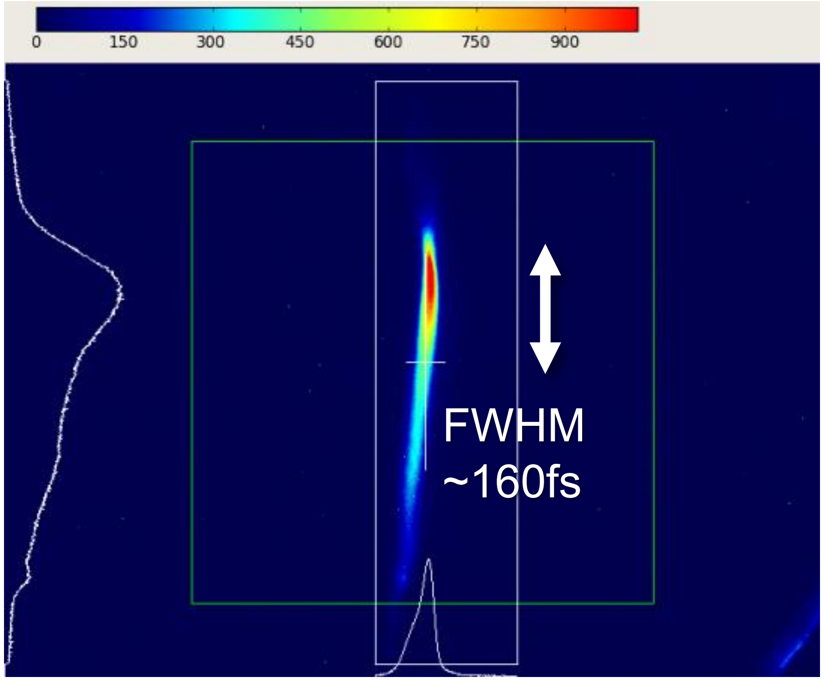
Gian Luca Orlandi

Image from synchrotron radiation monitor

CSR measurement at SACLA (free electron laser at SPring8 in Japan)

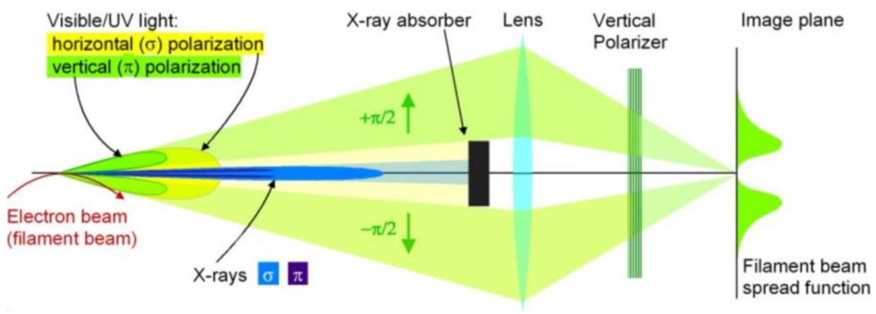


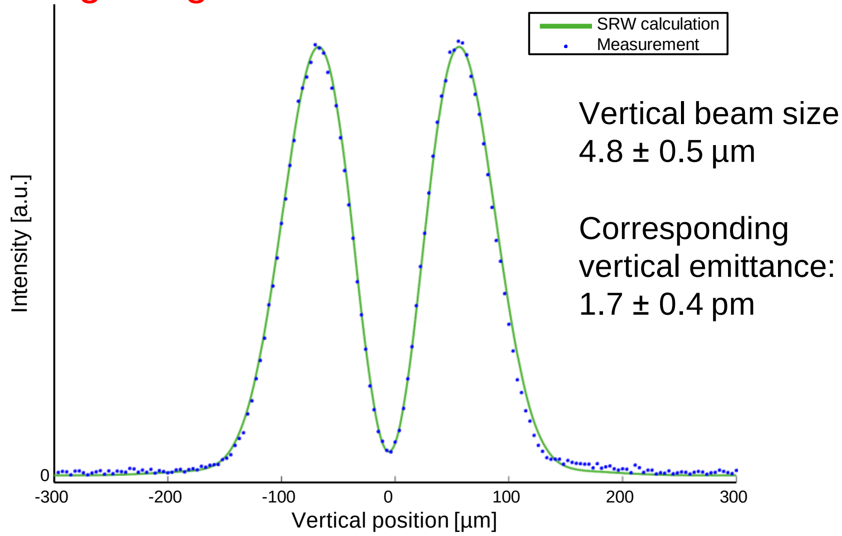


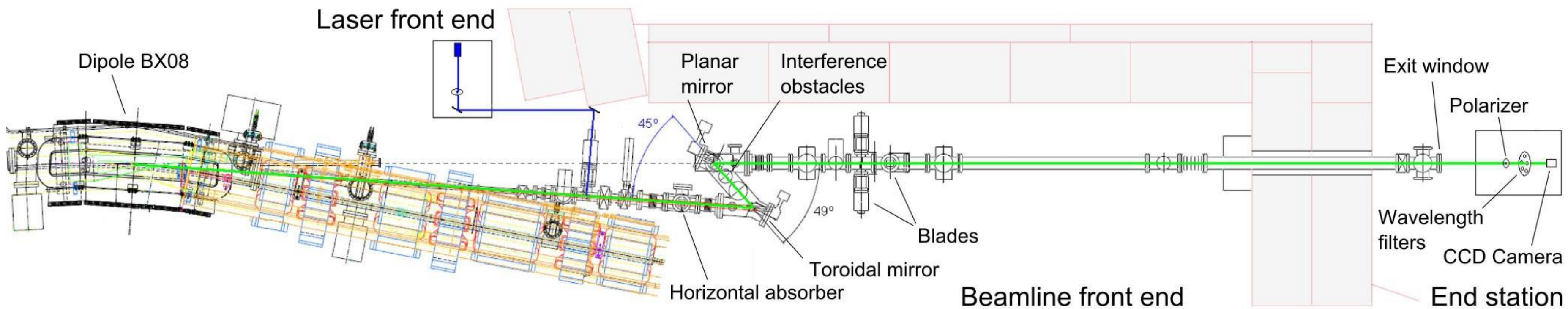


Yuji Otake

Measurement of synchrotron radiation in SLS storage ring:







Angela Saa Hernandez, ALERT 2014 Workshop, and J. Breunlin et al., Proceedings of IPAC2014

Measurement principle: interference of vertically polarized synchrotron light.
Measurement of very small beam sizes possible, even at a large distance.

Requirement: very good knowledge of the beam shape (here: Gaussian)

2.2 Electro-Optic Methods of Bunch Distribution Measurement

Here we use ultrafast laser sampling and electro-optic crystals to “copy” the Coulomb field distribution of the electron bunch on to a synchronised pulsed laser beam.

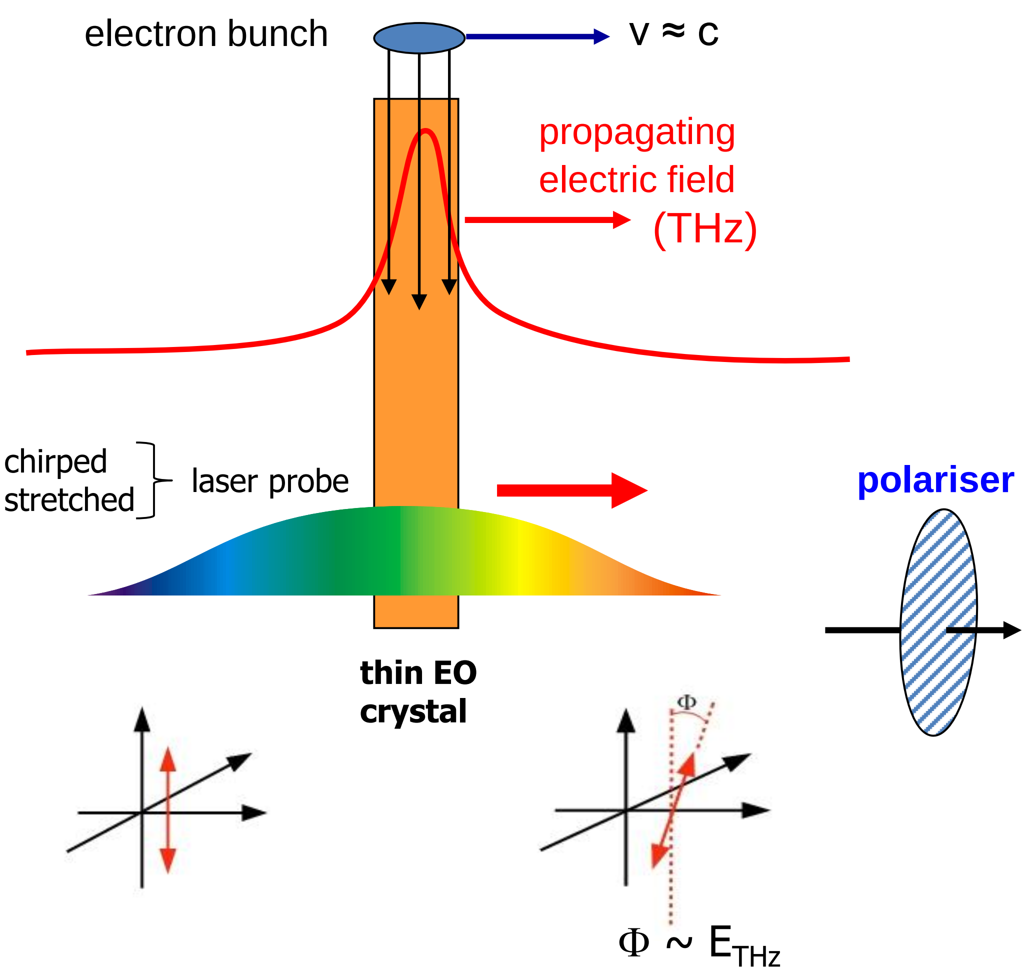
A range of standard techniques in ultrafast optics are then used to “decode” the encoded laser pulse, extracting a “true” time-resolved longitudinal beam bunch distribution.

In principle, this yields a non-intercepting bunch profile monitor.

Concept of Electro-Optic profile diagnostic

Principle: Convert Coulomb field of electron bunch into an optical intensity variation

Encode: Coulomb field on to an optical probe pulse - from Ti:Sa or fibre laser



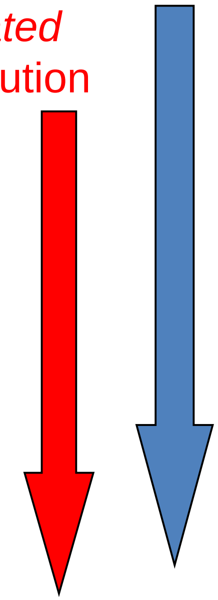
Decode: temporal intensity variations in single laser pulse via single-shot cross correlation in a BBO crystal

Yields: temporal intensity variations in a single laser pulse

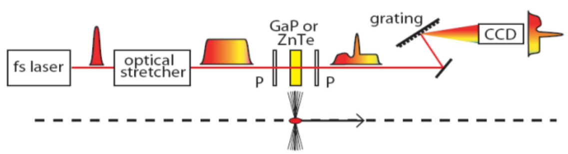
Wide Range of Electro-Optic Techniques

complexity / cost

demonstrated time resolution

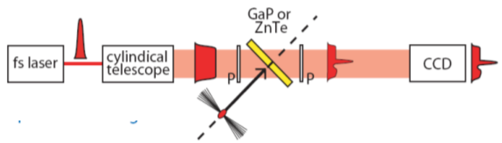


Spectral Decoding



- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

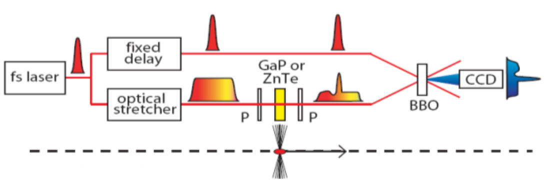
Spatial Encoding



- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

A.L.Cavalieri et al, Phys. Rev. Lett. 94, 114801 (2005)

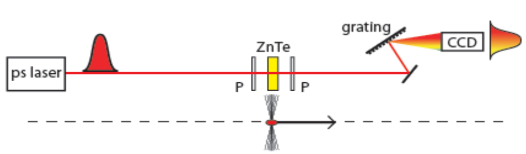
Temporal Decoding



- Long pulse + ultrashort pulse gate
- Spatial readout (cross-correlator crystal)
- Use time-space relationship

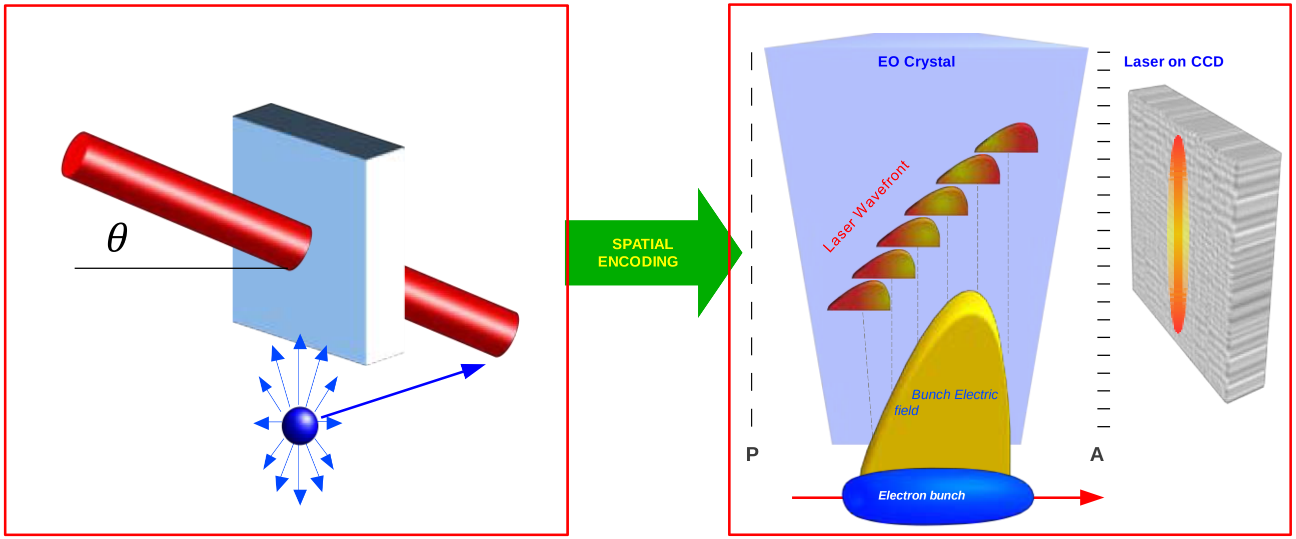
New Technique:

Spectral Upconversion / EO Transposition



- Simplified laser systems
- Quasi-monochromatic optical input (long pulse)
- Spectral readout
- Uses FROG-related techniques to recover bunch info

EO spatial encoding/decoding



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(a) The electron bunch is traveling in a plane below the laser beam and the EO crystal. The horizontally expanded laser pulse passes through the polarizer P and the EO crystal in the beam-pipe.

(b) Since the laser hits the EO crystal at an angle, different spatial components of the laser pass through the crystal at different times and acquire a different polarization.

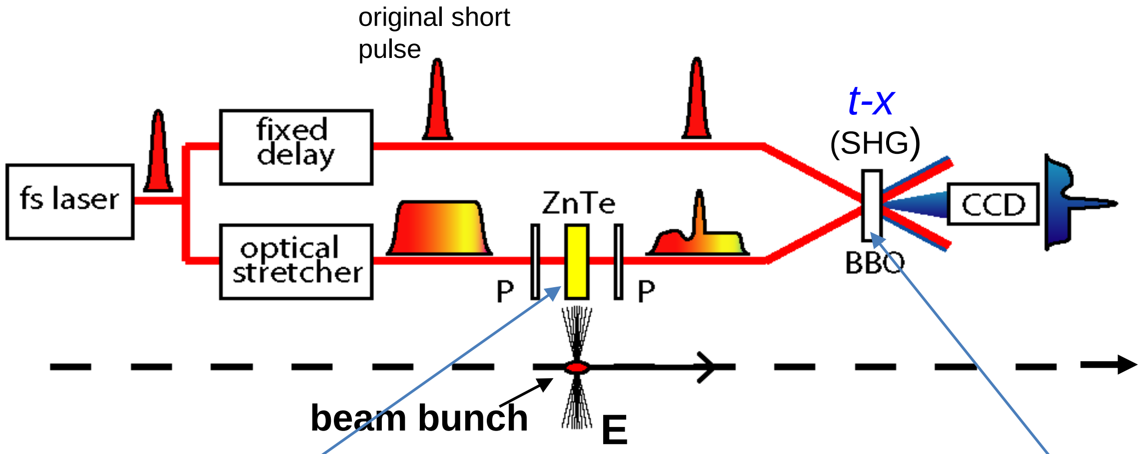
The analyser A turns the spatial modulation of the polarization into a spatial intensity modulation which is detected by the CCD camera.

Relies on spatially uniform EO material

A.L. Cavalieri, et al., Phys. Rev. Lett. 94 (2005) 114801

Single-shot Temporal Decoding (EOTD)

(currently gives best EO time resolution)



Temporal profile of probe pulse → **Spatial image of SHG pulse**

Thin EO crystal (ZnTe or GaP) produces a *optical temporal replica* of Coulomb field

Measure optical replica with *t-x* mapping in 2nd **Harmonic** Generation (SHG)

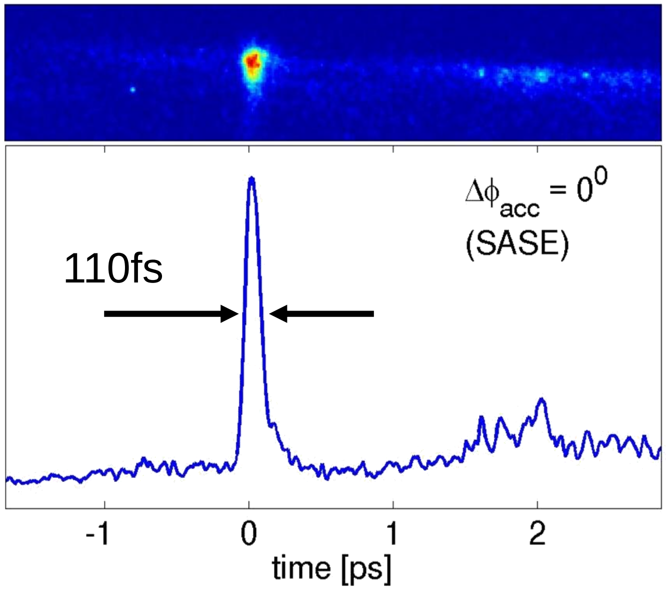
Stretched laser pulse leaving EO crystal measured using original short pulse via single-shot cross correlation in BBO crystal

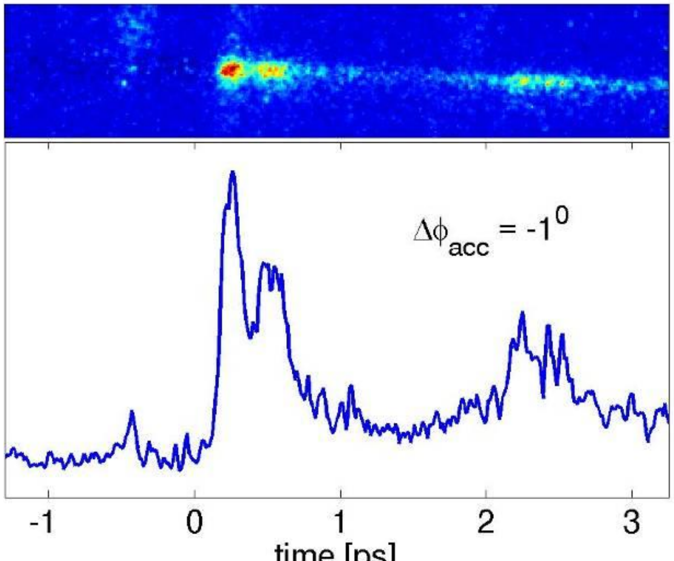
Large (~1mJ) laser pulse energy required (via Ti:Sa amplifier)

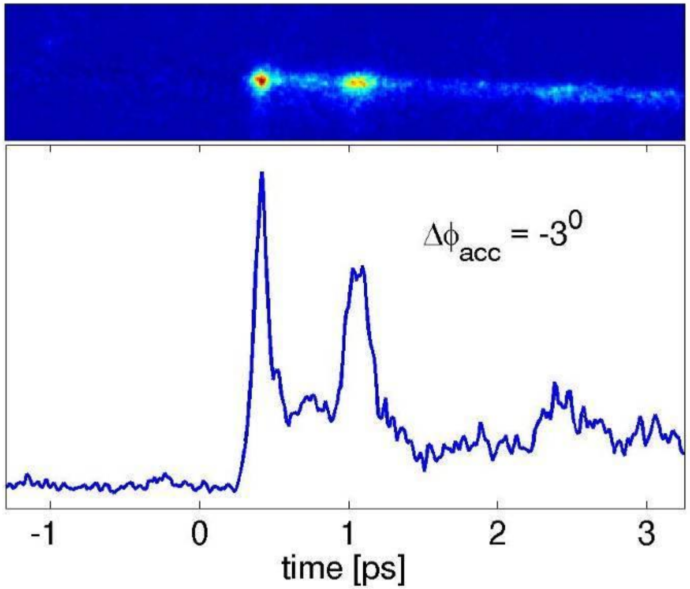
Berden et al. Phys Rev Lett. **99** (2007)

Temporal decoding at FLASH

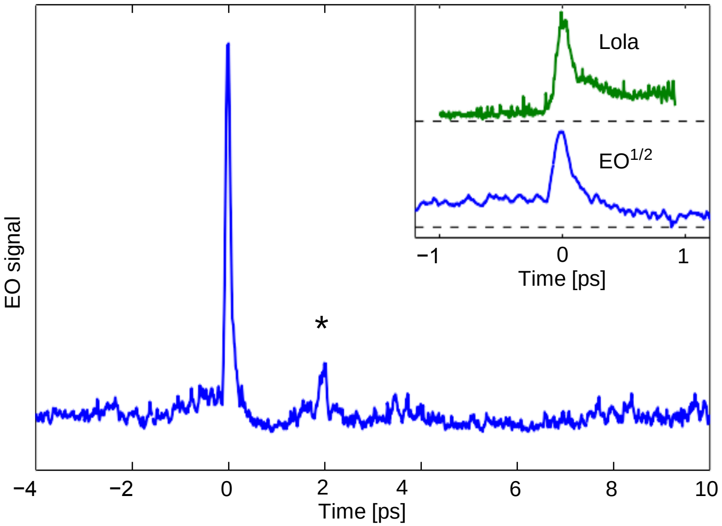
- real time profile monitoring with accelerator settings
- ZnTe EO crystal...





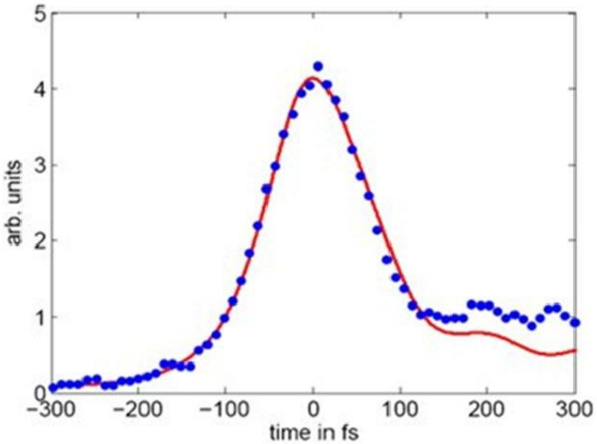


EO measurements at DESY FLASH

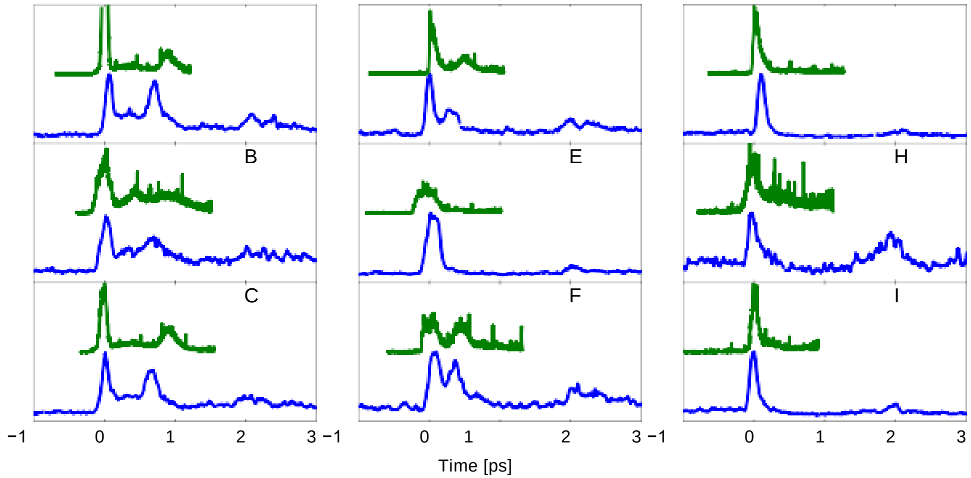


Single-shot electro-optic temporal decoding measurement of a single electron bunch measured under SASE conditions of the FEL. The signal labeled with an asterisk is due to a reflection of the Coulomb field of the bunch in the electro-optic crystal.

The inset shows the longitudinal electric field profile of the electron bunch togheter with a transverse deflection LOLA measurement of the following electron bunch in the bunch train.



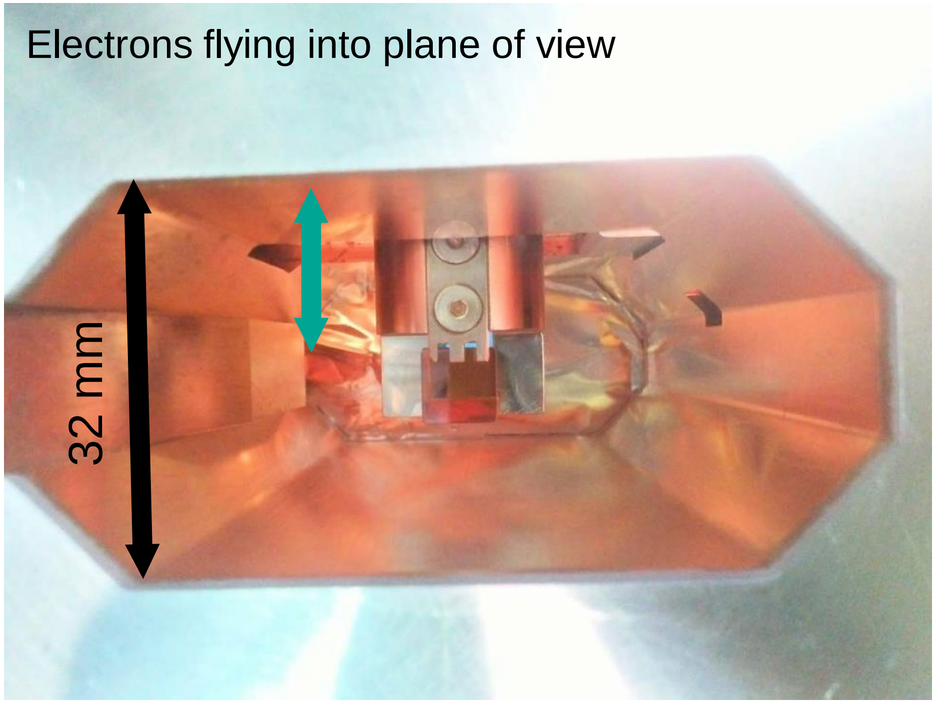
experimental and theoretical bunch profiles



Three single-shot EOTD (-) and LOLA measurements (-) of single electron bunches for three different phases of one of the DESY FLASH accelerator modules.

A phase of 10.94° corresponds to maximum compression of the bunch as required for SASE operation. The other two phases correspond to over-compression.

The FLASH EO setup has been transformed from an experiment to a reliable diagnostic. Shown here: electro-optical monitor at the ANKA storage ring, designed in a KIT-DESY-PSI collaboration.

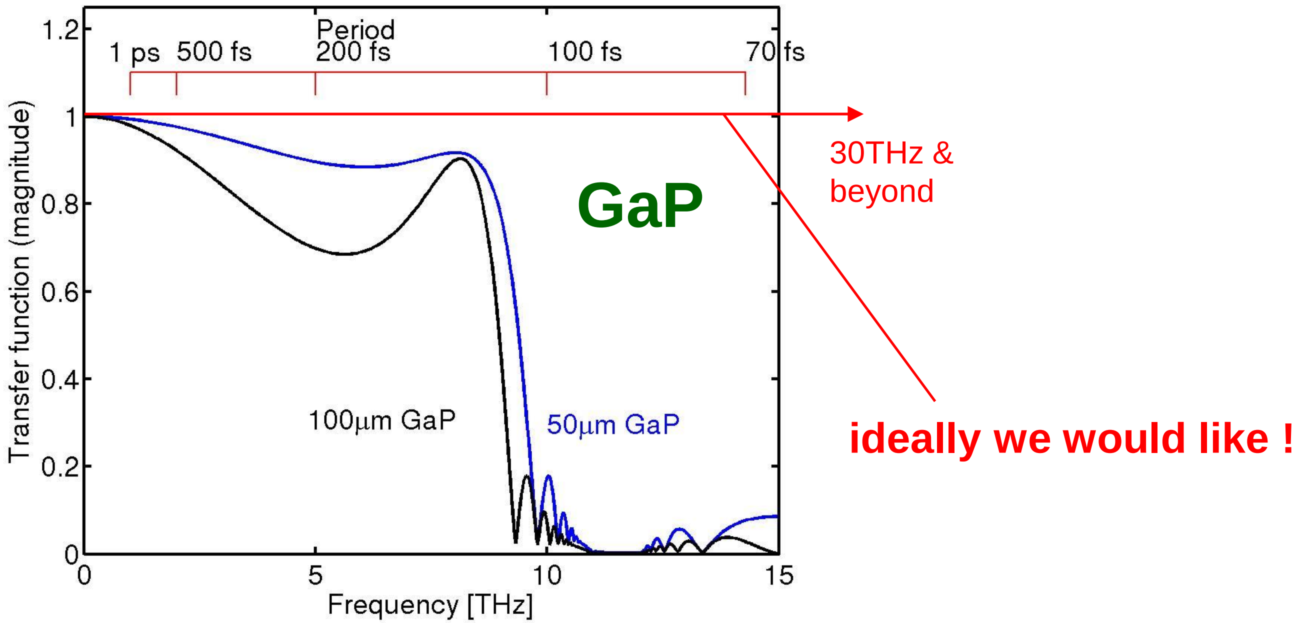


Nicole Hiller et al., Proceedings of IPAC 2014

Fundamental Problem: Encoding Time Resolution

material frequency response, R(ω), of typical GaP crystal

1. velocity mismatch of Coulomb field and probe laser
2. phonon resonances in EO material
3. frequency mixing efficiency, $\chi^{(2)}(\omega)$



May be soluble by:

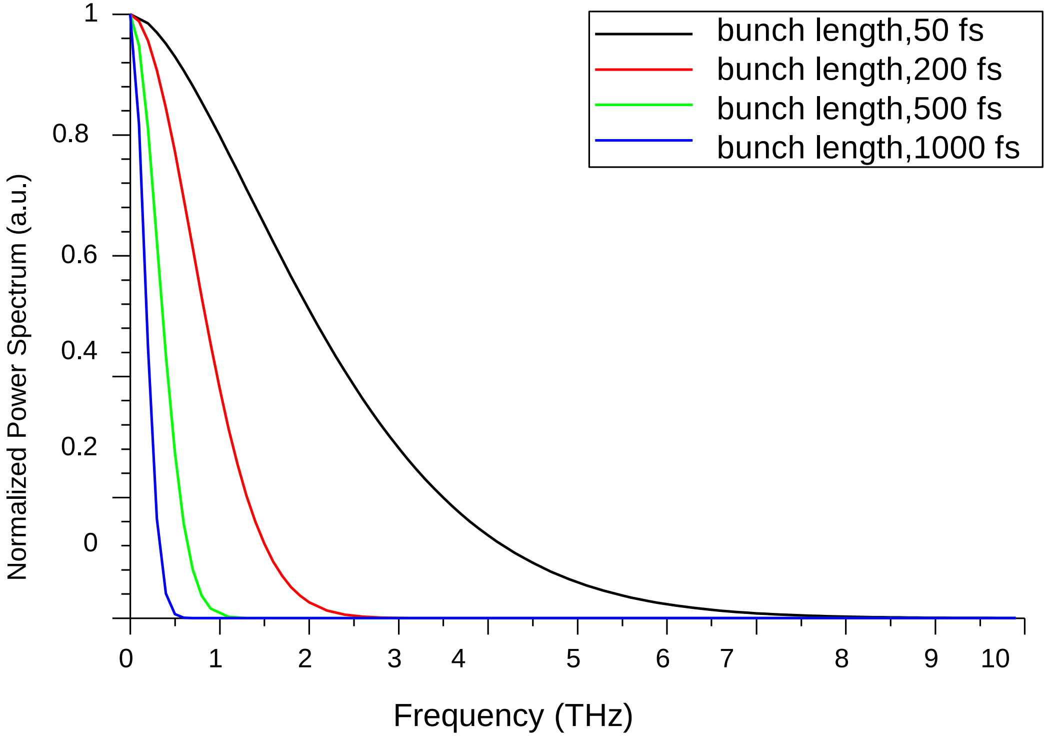
1. Organic crystals (e.g. DAST, DSTMS, OH1) or poled polymeric materials
2. Artificially-created "metamaterials" under development at University of Dundee

   - "silver-glass nanocomposites"

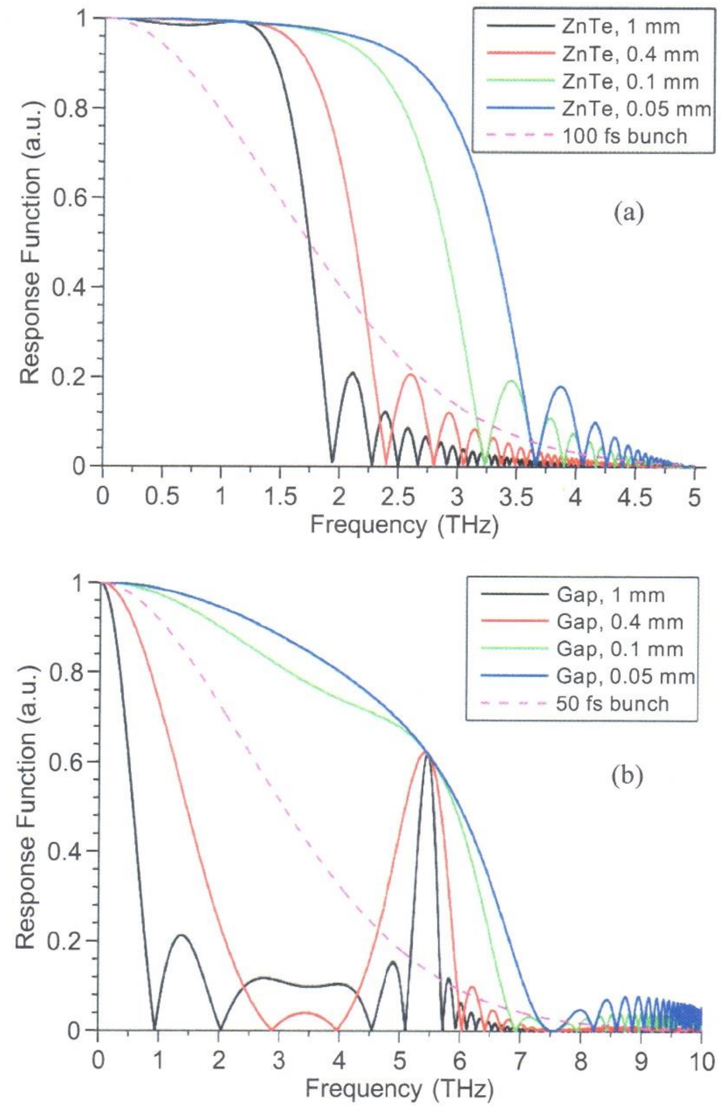
Other EO materials

More exotic electro-optic materials with higher electrooptic coefficients do exist, however they have multiple resonances and their dispersion relations are extremely complex.

e.g. Y. Takahashi, H. Adachi, T. Taniuchi, M. Takagi, Y. Hosokawa, S. Onzuka, S. Brahadeeswaran, M. Yoshimura, Y. Mori, H. Masuhara et al., J. Photochem. Photobiol., A 183, 247 (2006).



Normalized electric field power spectrum of a 160 pC Gaussian bunch with energy 110 MeV, located at *r* = 5 mm distance from the observer. The bunch lengths (rms) are 50, 200, 500 and 1000 fs.



(a) EO response function of ZnTe for crystal thicknesses of 50 μm, 100 μm, 400 μm and 1 mm.
The power spectrum (----) of a 100 fs electron bunch is showed for comparison.
(b) EO response function of GaP for crystal thicknesses of 50 μm, 100 μm, 400 μm and 1 mm.
The power spectrum (----) of a 50 fs electron bunch is shown for comparison.

Pompili

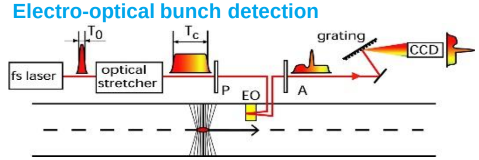
Electro-Optical bunch length detection at the E-XFEL

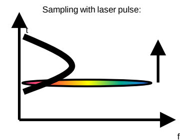
Slides courtesy of Bernd Steffen, E-XFEL

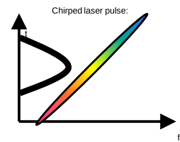
Electro-optical bunch length Detection at the E-XFEL

Bernd Steffen, Christopher Gerth (DESY)

Electro-optical bunch detection



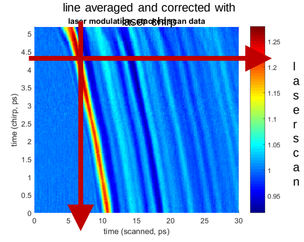


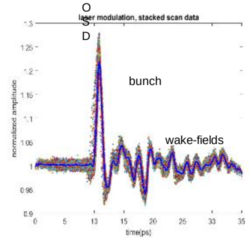


Measurements from XFEL-BC1 (700MeV, after compression)

EO Spectral Decoding + laser time scan

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

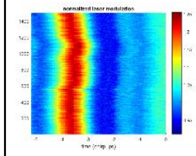




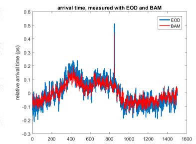
Stacked with laser timing delay

All data presented here measured with a Ytterbium fiber laser at 1030 nm, a 2 mm thick GaP crystal and a KALYPSO2 detector.

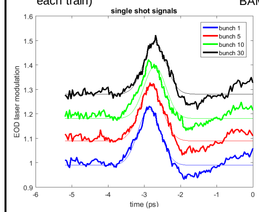
EO Spectral Decoding single shot data



EOD signal from 1500 consecutive bunches (1st of each train)

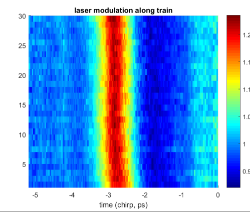


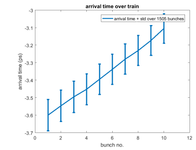
…and their arrival time measured with EOD and BAM

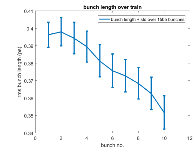


Single shot EOD traces and fitted Gaussians from the same bunch train

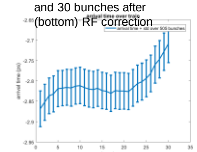
EOD traces of all 30 bunches of a bunch train with 1.13 MHz repetition rate

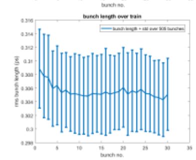




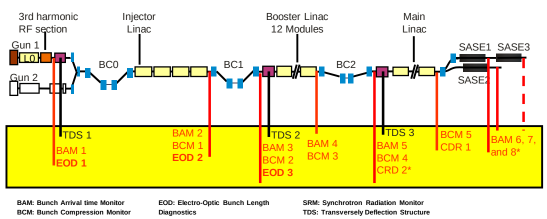


Arrival time and bunch length from fitted Gaussians for 10 bunches before (top) and 30 bunches after (bottom) RF correction





Longitudinal diagnostics at the E-XFEL



BAM: Bunch Arrival time Monitor
BCM: Bunch Compression Monitor
CRD: Coherent Radiation Spectrometer
EOD: Electro-Optic Bunch Length Diagnostics
SRM: Synchrotron Radiation Monitor
TDS: Transversely Deflection Structure

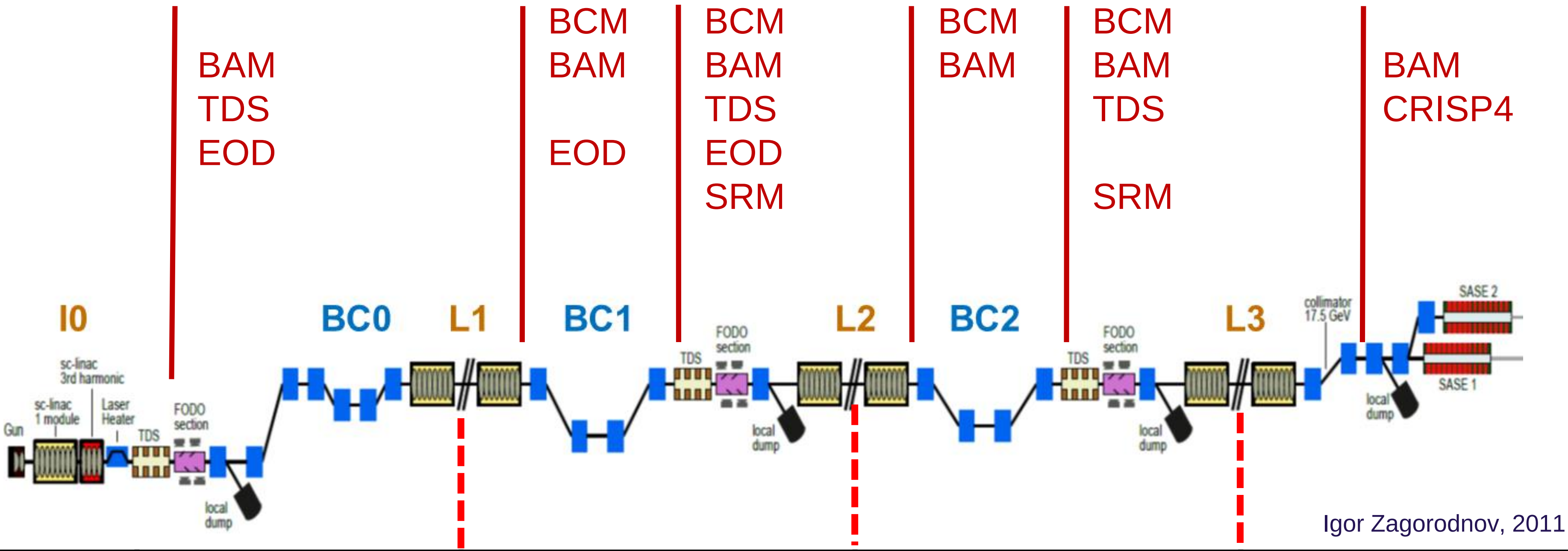
KALYPSO 1 MHz detector

(more on the poster by M. CASELLE)

- Currently under development at KIT
- Based on the GOTTHARD chip developed at PSI
- First prototypes in operation, new version in development
- 256 pixel linear PDA in InGaAs (1 µm - 2.5 µm) or Si (200nm -1 µm)
- 54MHz clock via 16 ADCs
- 1.2MHz continuous line rate or 5 pulses with 54MHz
- FPGA … feed…

HELMHOLTZ | GEMEINSCHAFT

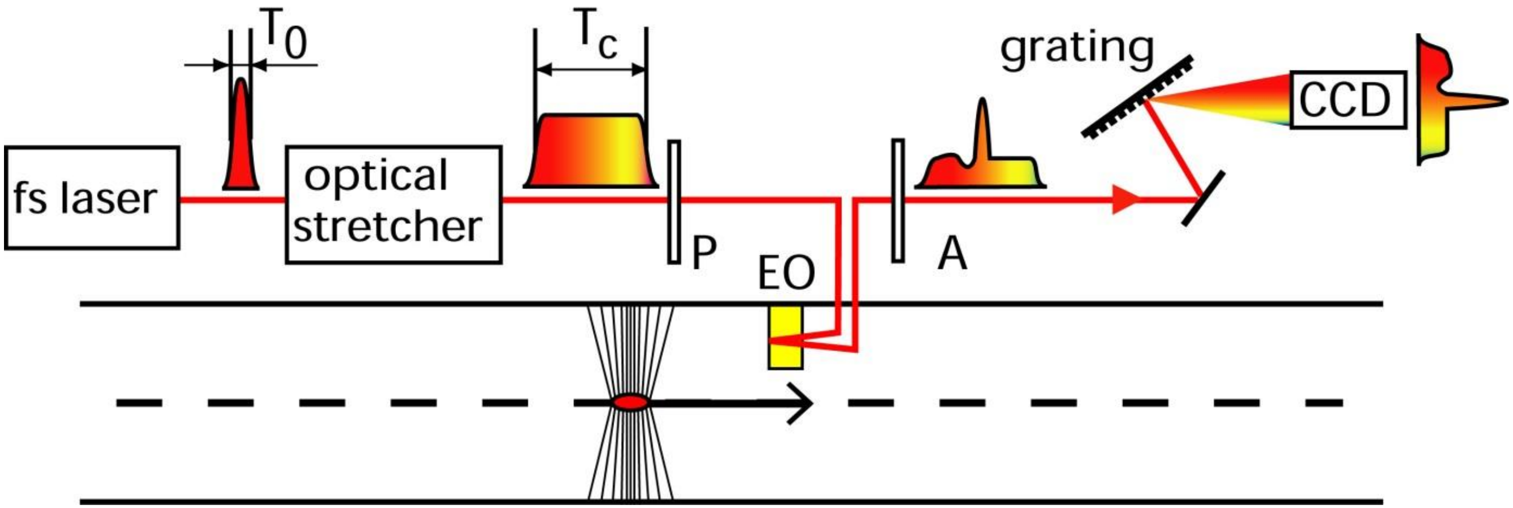
Longitudinal Diagnostics at the European XFEL



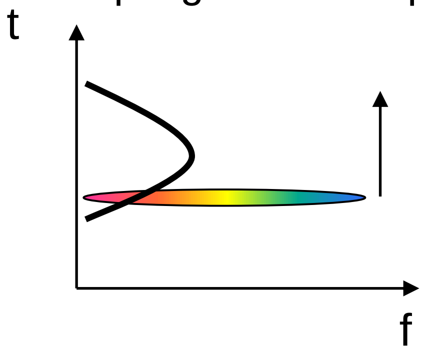
Energy	130MeV	600MeV	2.5GeV	17.5GeV

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

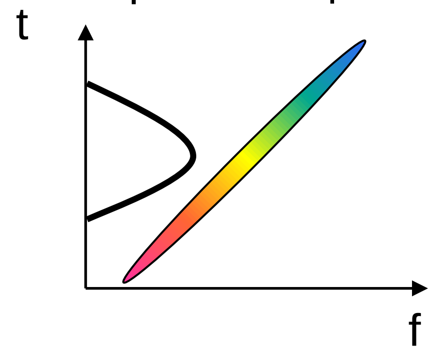


Sampling with laser pulse:



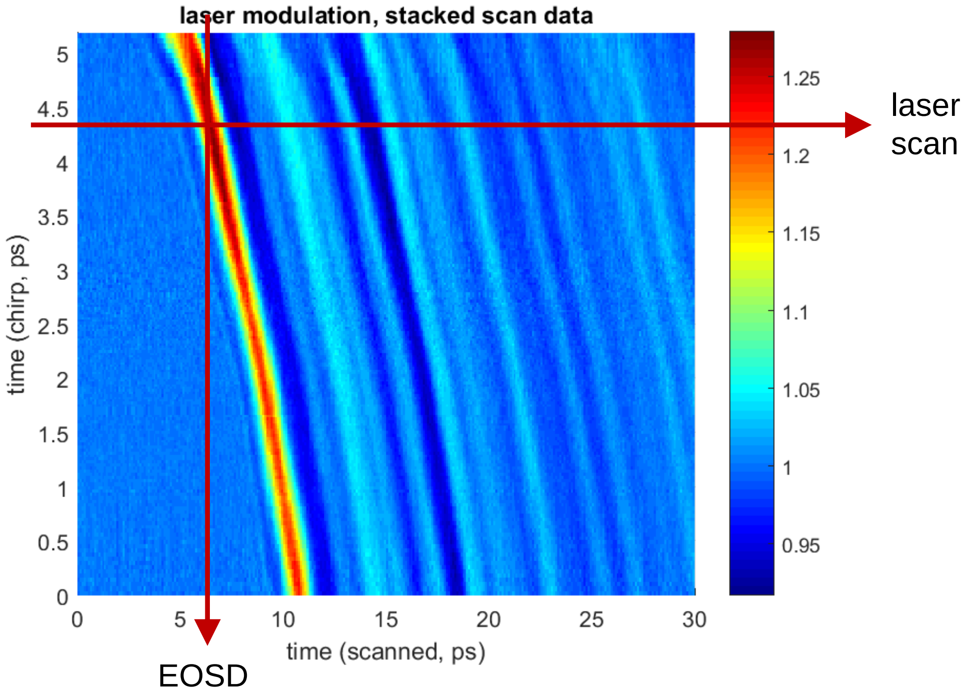
→ Sample electron bunch with many laser pulses

Chirped laser pulse:



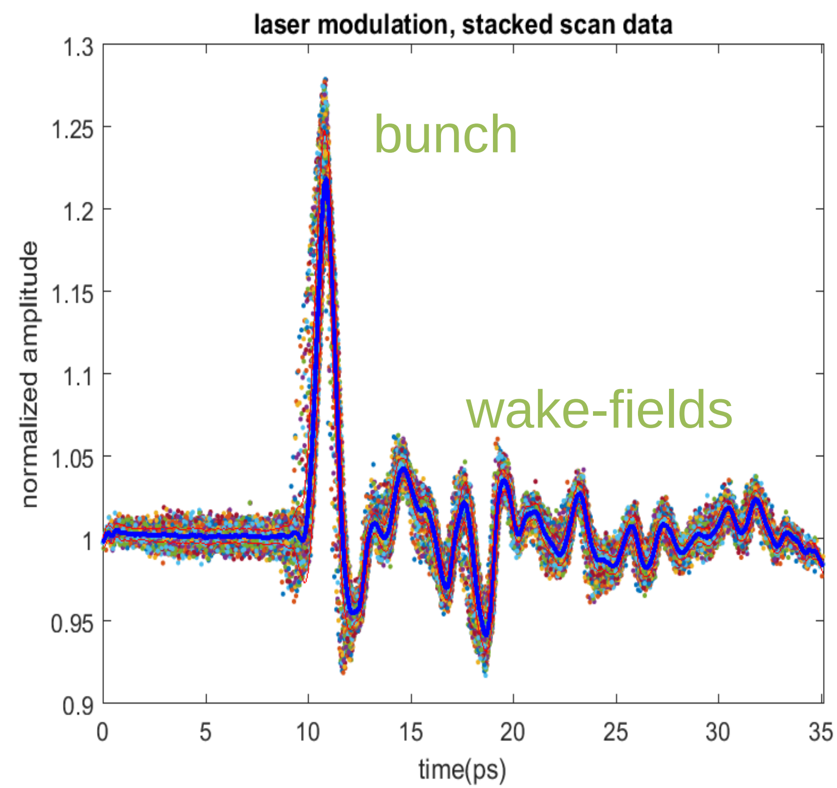
→ Defined relation between time and frequency

Measurements from XFEL-BC1: Laser time scans

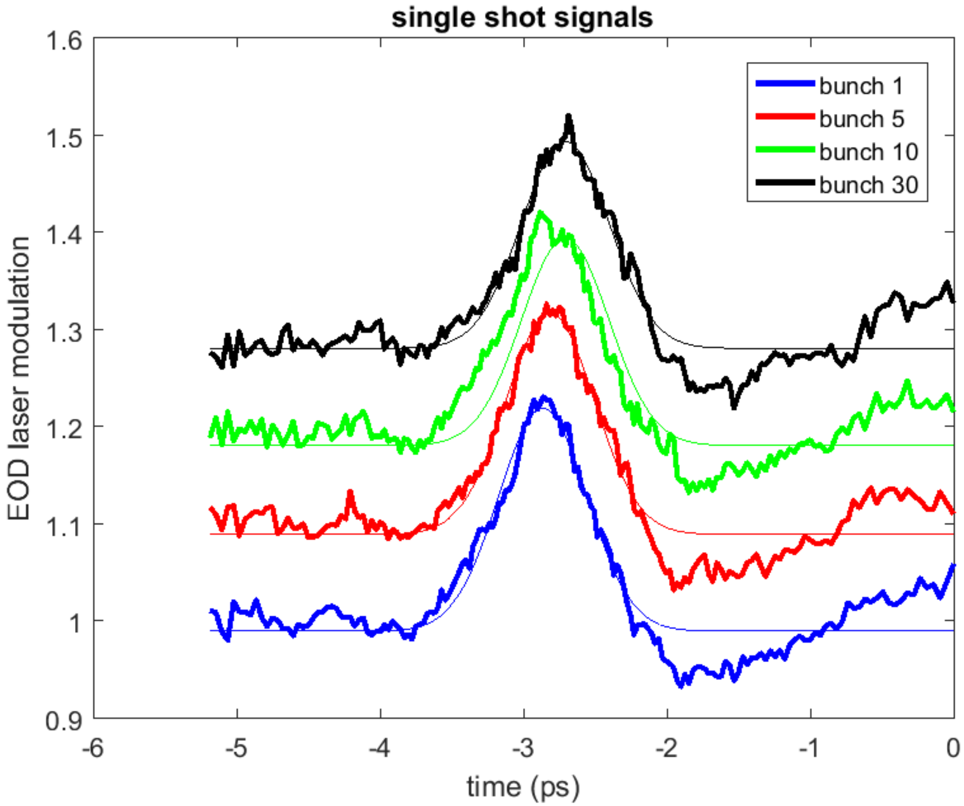


Raw signal from 5 bunches each line averaged and corrected with laser chirp

Stacked data

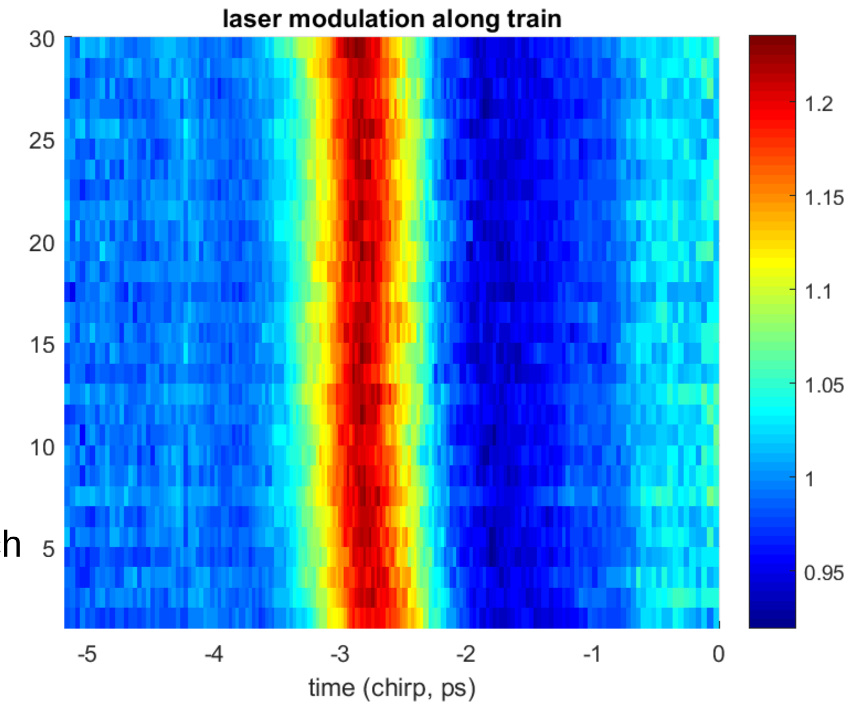


Measurements from XFEL-BC1: Single-shot EO Spectral Decoding

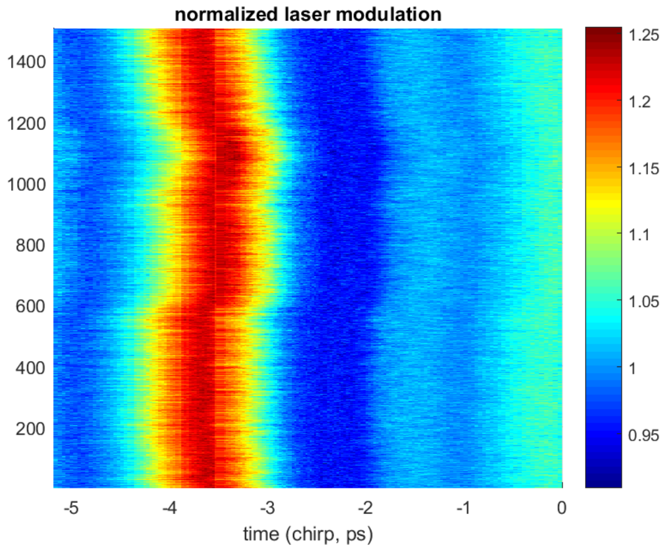


Single-shot EOD traces and fitted Gaussians from the same bunch train

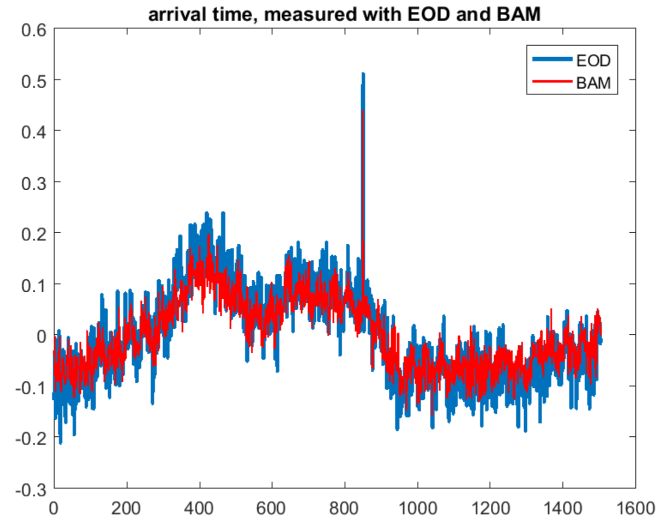
EOD traces of all 30 bunches of a bunch train with 1.13 MHz repetition rate



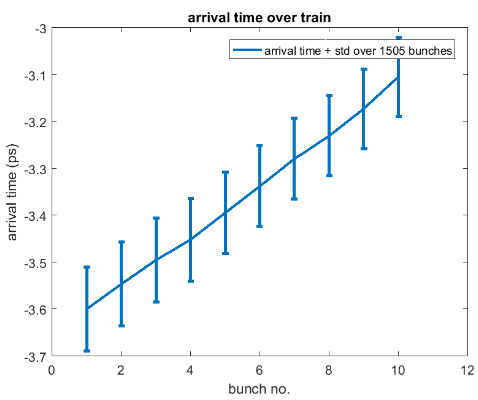
Measurements from XFEL-BC1: Single-shot EO Spectral Decoding

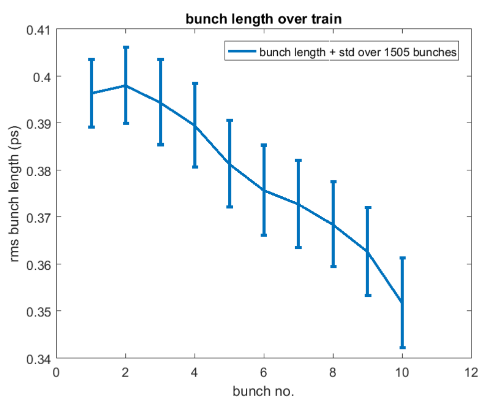


EOD signal from 1500 consecutive bunches (1st of each train)

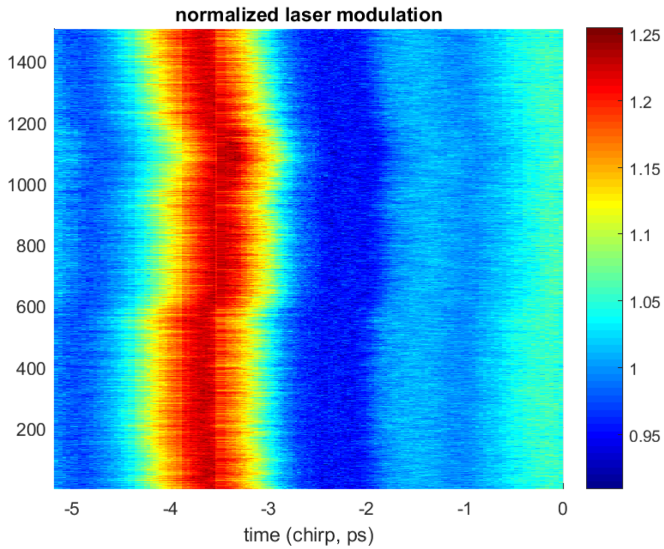


…and their arrival time measured with EOD and BAM

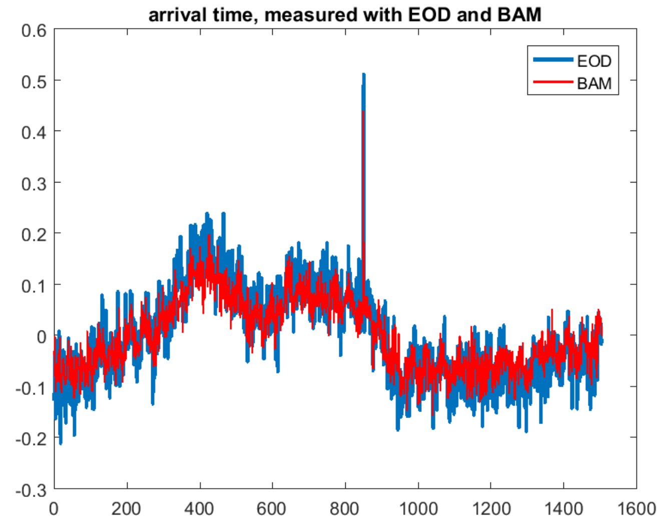




Machine Stability



EOD signal from 1500 consecutive bunches (1st of each train)



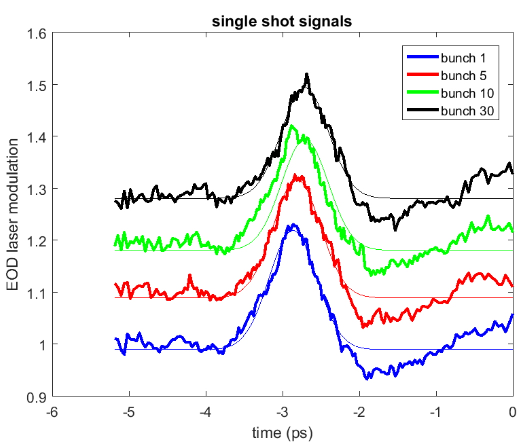
…and their arrival time measured with EOD and BAM

BAM + EOD

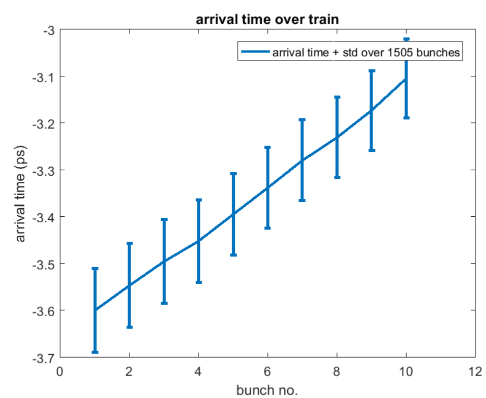
Arrival time jitter

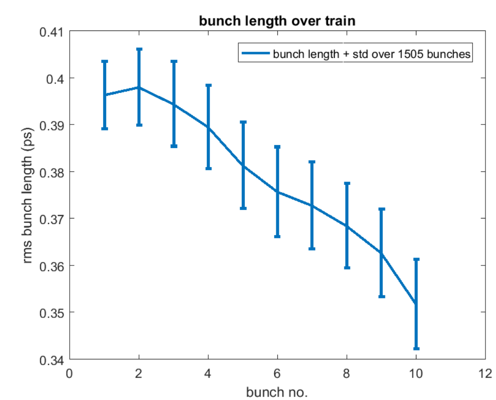
usually **30fs**

(after last compression stage)



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





Arrival time and bunch length from fitted Gaussians for 10 bunches

Alternative approach: Daresbury-Dundee Group (2008 ff)

Different approach to EO encoding / decoding

yielding an alternative measurement method: EO Transposition

Rather than utilising the idea of induced birefringence within the EO crystal, a more rigorous description of the EO effect involves nonlinear frequency mixing

S. P. Jamison et al. Opt. Lett. **31** 1753 (2006)

⇨ sum & difference frequencies generated within EO crystal

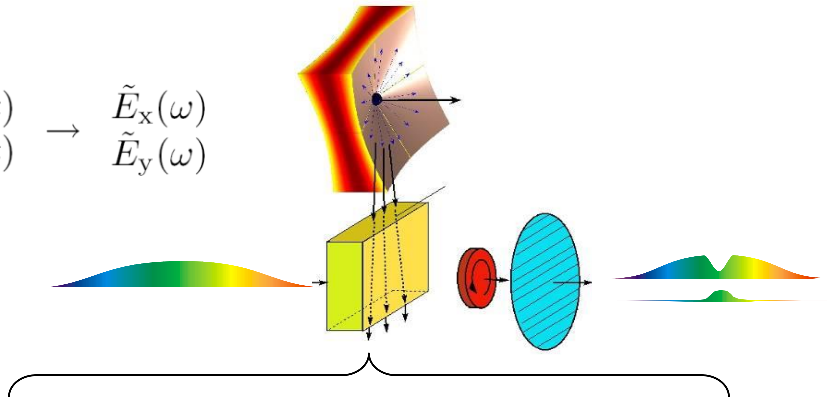
The idea is to generate a reliable method of EO bunch measurement that:

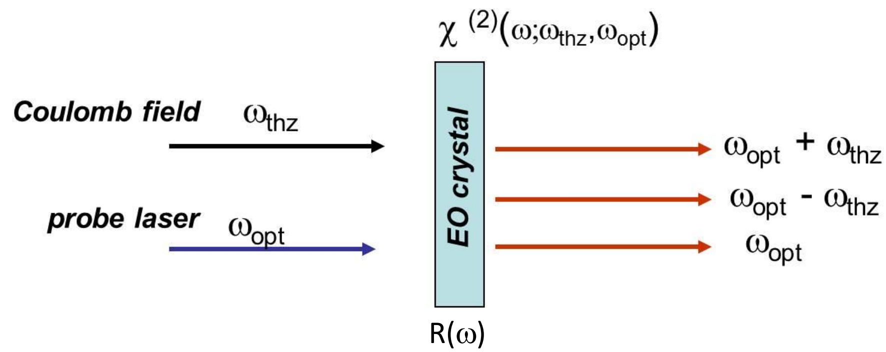
- does not rely on sensitive, ultrafast lasers and optics
- uses reliable (nanosecond) laser systems
- does not suffer from the frequency bandwidth problems that infect EO measurements on ultrashort (< 50 fs) bunches

Instead of using an ultrashort (50fs) laser pulse, we substitute a quasi-monochromatic 800nm 5ns pulse !

Back to the physics of EO encoding...

$$E_x(t) \quad \tilde{E}_x(\omega)$$
$$E_y(t) \rightarrow \tilde{E}_y(\omega)$$





$$\tilde{E}^{\rm opt}_{\rm out}(\omega) = \tilde{E}^{\rm opt}_{\rm in}(\omega) + i\omega a \tilde{E}^{\rm opt}_{\rm in}(\omega) * \left[\tilde{E}^{\rm Coul}(\omega)\tilde{R}(\omega)\right]$$

Coulomb spectrum shifted to optical region

$$E^{\rm opt}_{\rm out}(t) = E^{\rm opt}_{\rm in}(t) + a\left[E^{\rm Coul}(t) * R(t)\right]\frac{\rm d}{{\rm d}t}E^{\rm opt}_{\rm in}(t)$$

envelope — optical field

Coulomb pulse temporally replicated in optical pulse

$R(\omega)$ = *frequency response of thin EO crystal*

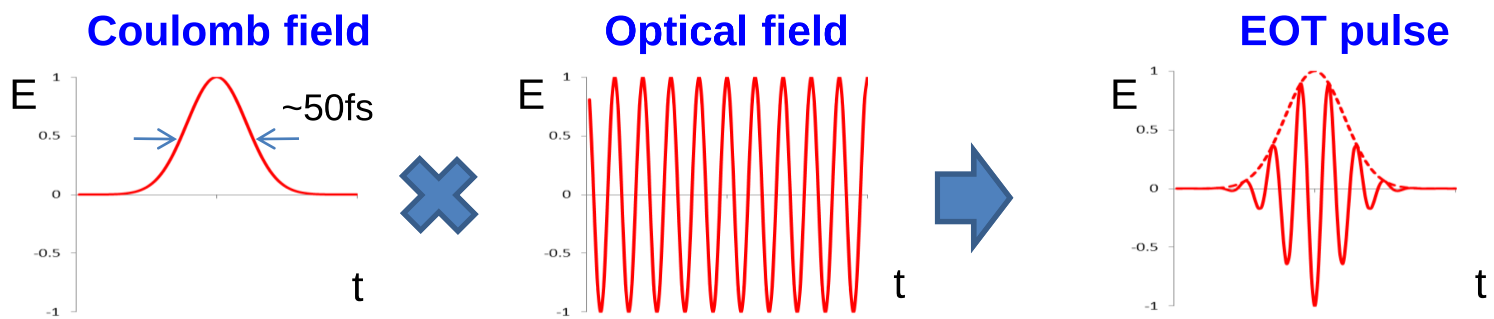
$E^{\rm Coul}(\omega)$ = *frequency spectrum of bunch Coulomb field*

$E_{in}^{opt}(\omega)$ = *frequency bandwidth of input probe laser*

Consider modulating a 50fs Coulomb field pulse on to an 800nm single frequency probe (optical carrier)

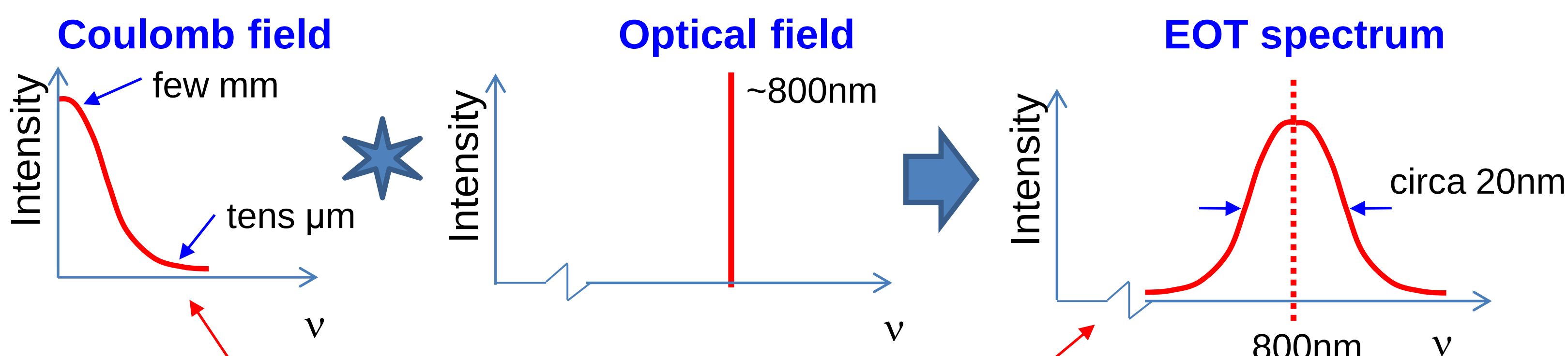
$$E^{\mathrm{opt}}_{\mathrm{out}}(t) = E^{\mathrm{opt}}_{\mathrm{in}}(t) + a\,\underbrace{\left[E^{\mathrm{Coul}}(t) * R(t)\right]}_{\text{envelope}}\,\underbrace{\frac{\mathrm{d}}{\mathrm{d}t}E^{\mathrm{opt}}_{\mathrm{in}}(t)}_{\text{optical field}}$$

Time Domain



Frequency Domain

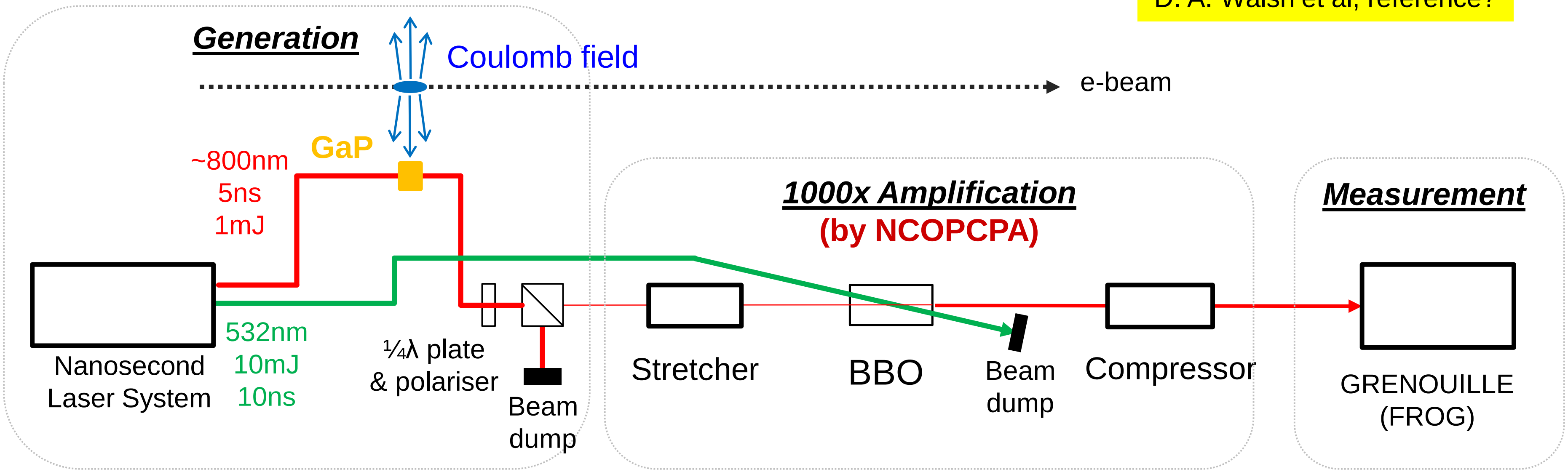
$$\tilde{E}^{\mathrm{opt}}_{\mathrm{out}}(\omega) = \tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega) + i\omega a\tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega) * \left[\tilde{E}^{\mathrm{Coul}}(\omega)\tilde{R}(\omega)\right]$$

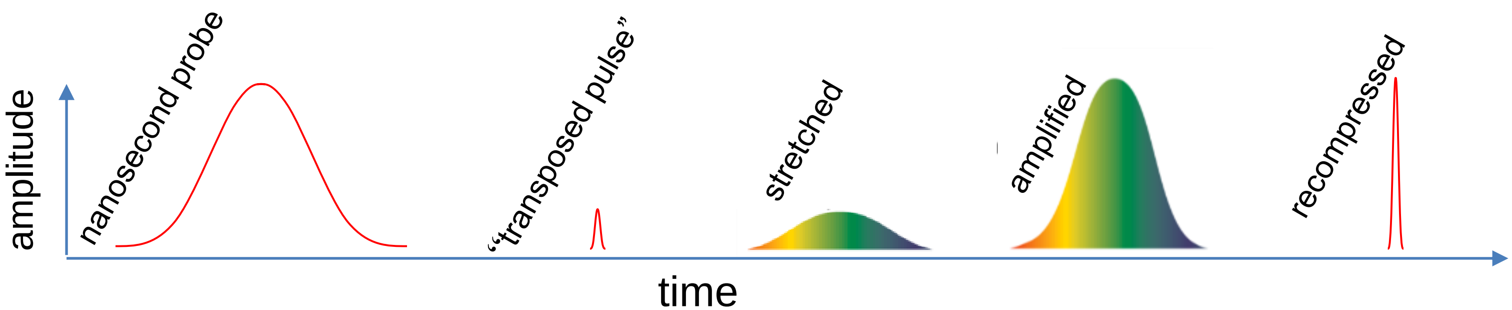


converts non-propagating ~100% bandwidth field into ~2.5% optical spectrum, including DC component

EO Transposition System

D. A. Walsh et al, reference?





Pulse Evolution

1. Nanosecond laser-derived single-frequency probe brings reliability
2. "Electro-Optic Transposition" of probe encodes temporal profile
3. *Non-collinear optical parametric chirped pulse amplification (NCOPCPA)* amplifies signal
4. Full spectral amplitude and phase measured via FROG / Grenouille technique
5. Coulomb field, and hence bunch profile, calculated via time-reversed propagation of pulse

Characterisation of Transposed Pulse

Considerations: Needs to be **single shot, unambiguous, and for low pulse energy**

Solution: Grenouille (frequency resolved optical gating), a **Standard and robust** optical diagnostic

Retrieves spectral intensity and phase from spectrally resolved autocorrelation

What we want to know

$$E(t) = Re\left(\sqrt{I(t)}e^{i(\omega_o t-\phi(t))}\right)$$

"Carrier" frequency

Can't measure

<-Fourier->

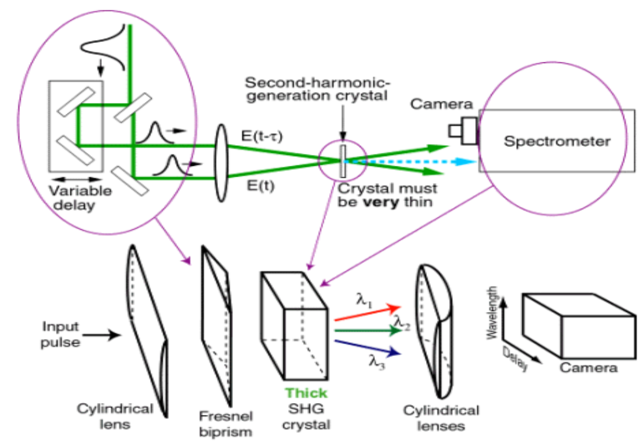
$$\tilde{E}(\omega)=\sqrt{S(\omega)}e^{-i\varphi(\omega)}$$

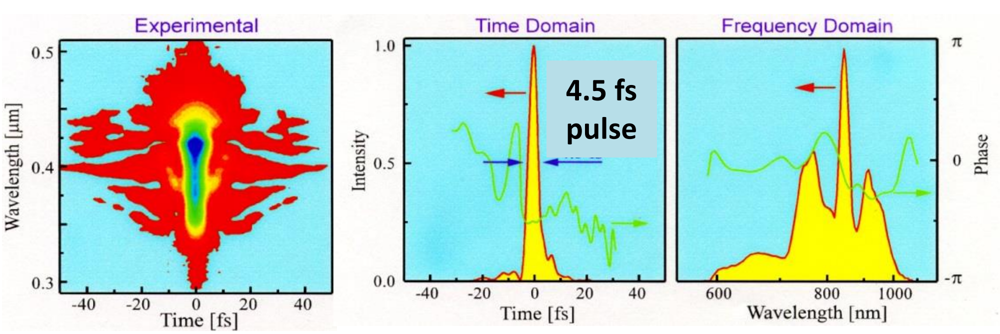
Spectrum

Spectral Phase

Can be retrieved!

$$I(\omega,t) \propto \left|\int E(t)\,E(t-\tau)e^{-i\omega t}dt\right|^2$$

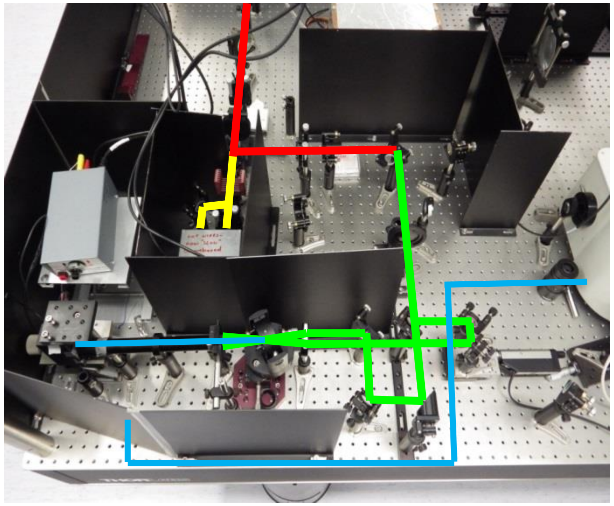




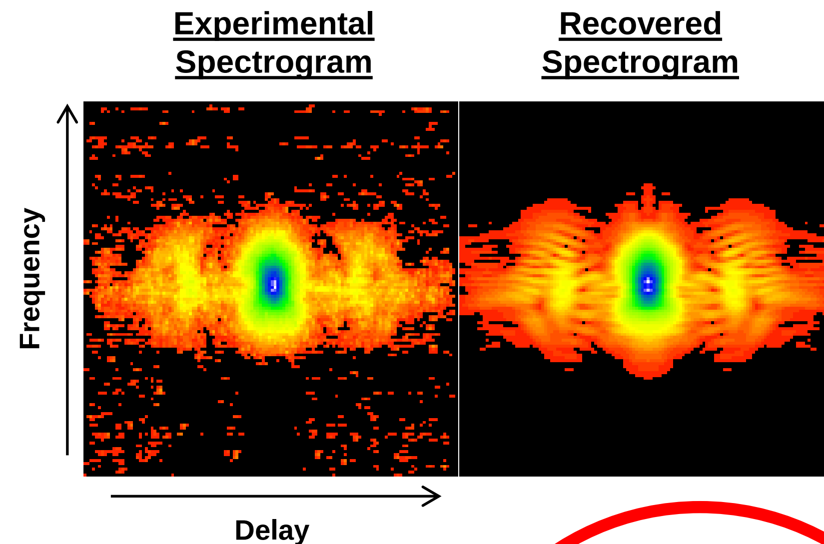
- Most sensitive "auto gating" measurement
- Self-gating avoids timing issues (no need for a femtosecond laser)
- Requires minimum pulse energy of ~1 μJ

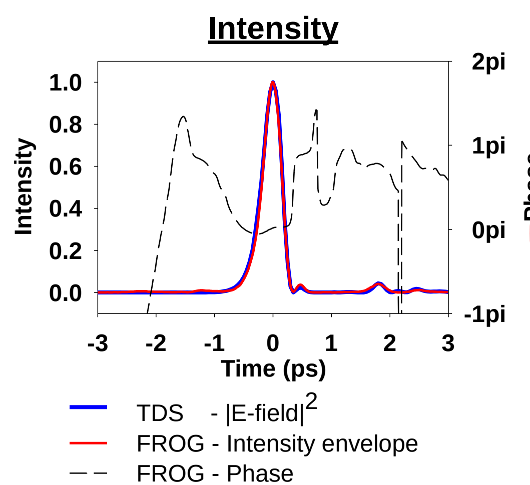
Baltuska, Pshenichnikov, and Weirsma, J. Quant. Electron., 35, 459 (1999).

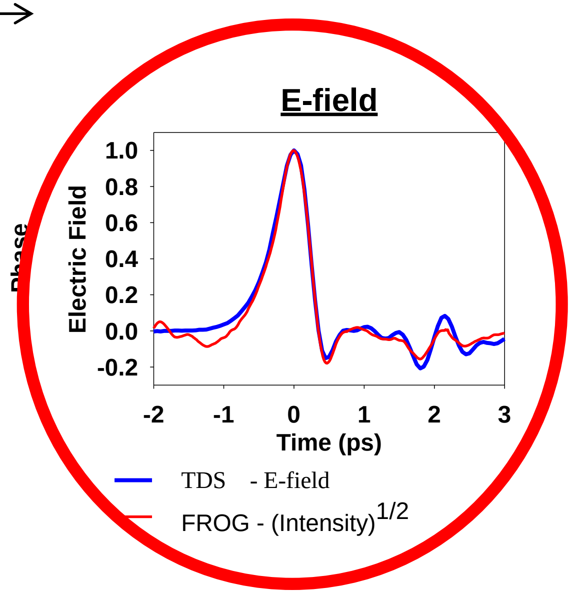
FROG Measurement



PCO dicam pro ICCD camera
256x frame integration
30x software averaging







0.55 ps pulse measured with a 10 ps transform limited probe!

Very brief review of other techniques

Measurement of ultrashort FEL X-ray pulses (LCLS)

Strong requirement to measure temporal structure (as well as duration) of few-femtosecond X-ray pulses from short-wavelength FELs

Use near-infrared (NIR) streaking spectroscopy techniques at SLAC LCLS

Well-established technique for attosecond pulses in the XUV spectral region

Non-invasive scheme with sub-fs resolution

Provides an upper bound on the X-ray pulse duration

Single-shot technique required for consecutive SASE X-ray pulses

Principle:

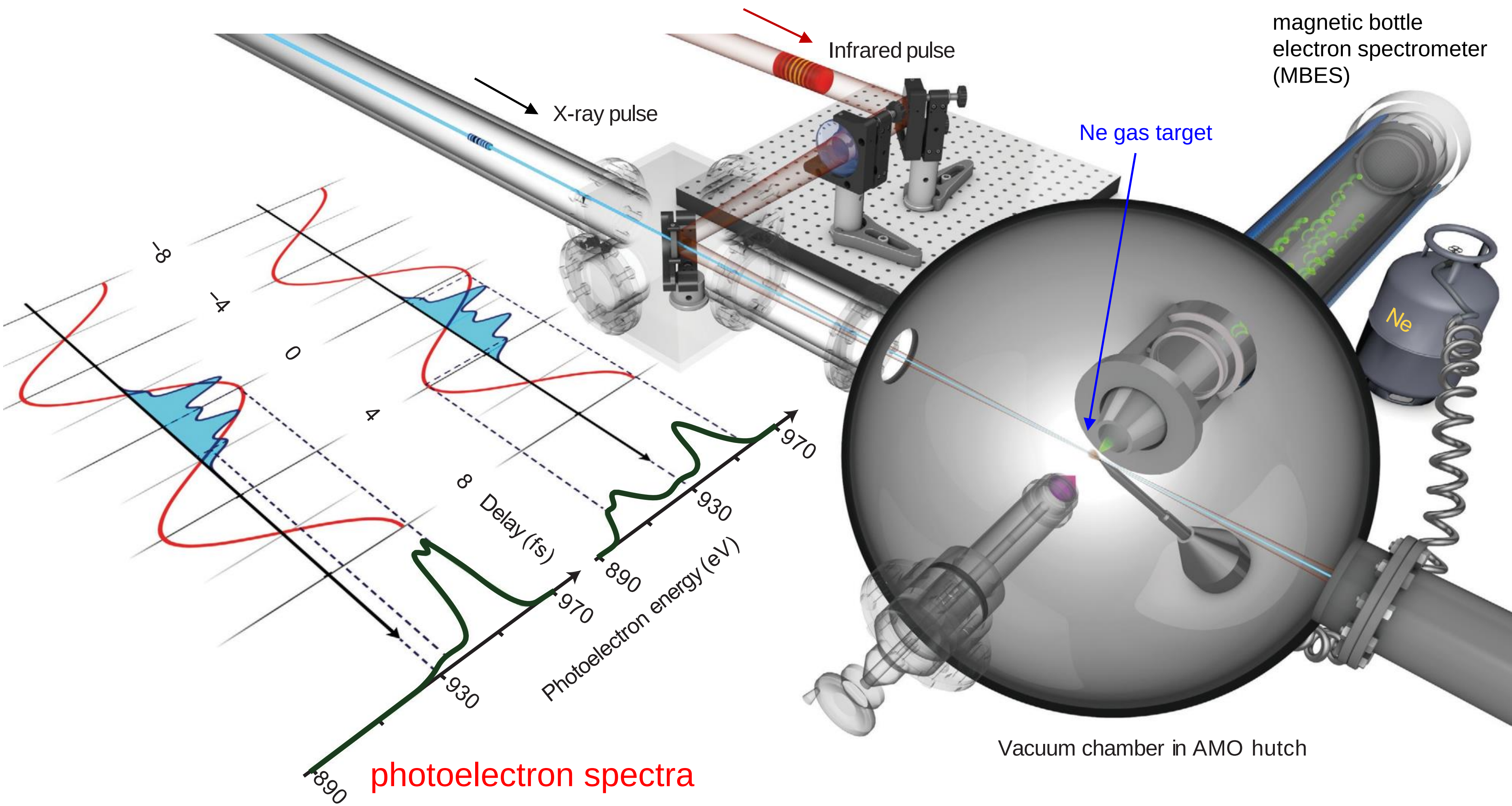
NIR laser field, coarsely synchronised to the X-ray pulse, is spatially overlapped with the X-ray beam in a dilute gas target

Ne gas atoms ionised by FEL and resulting photoelectrons detected in a magnetic bottle electron spectrometer (MBES)

Thus, temporal profile of X-ray pulse is mapped on to energy domain

Complex analysis can extract the X-ray profile

NIR Streaking Spectroscopy Technique at the LCLS

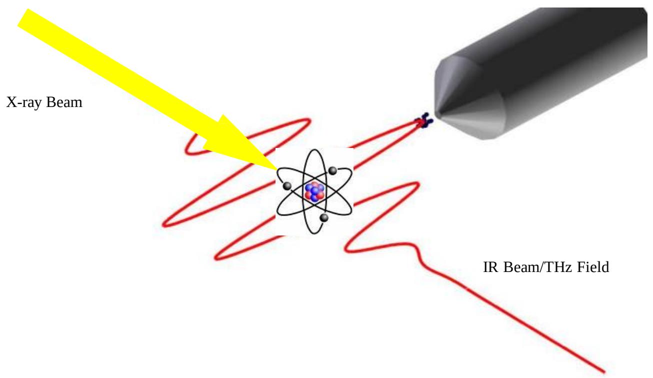


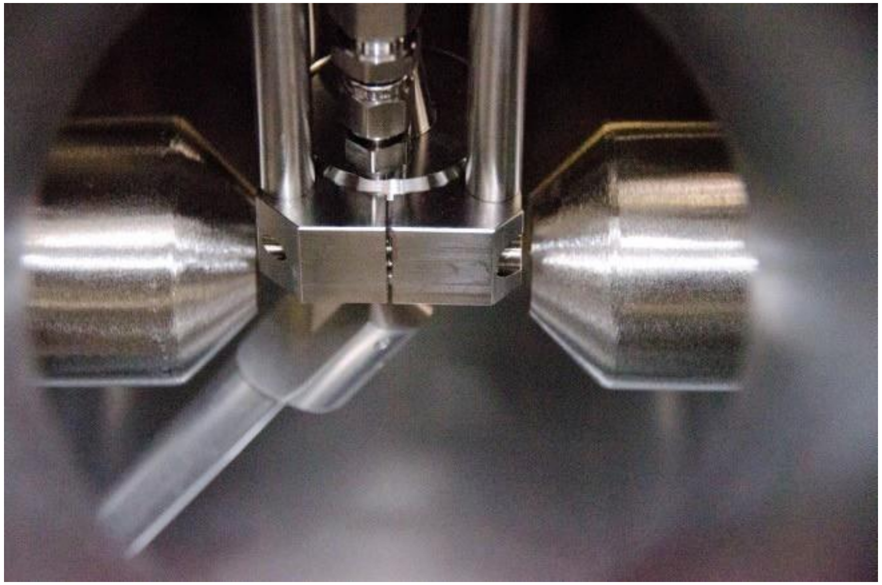
Wolfram Helml, Andy Maier et al. Nature Photonics 8 (2014)

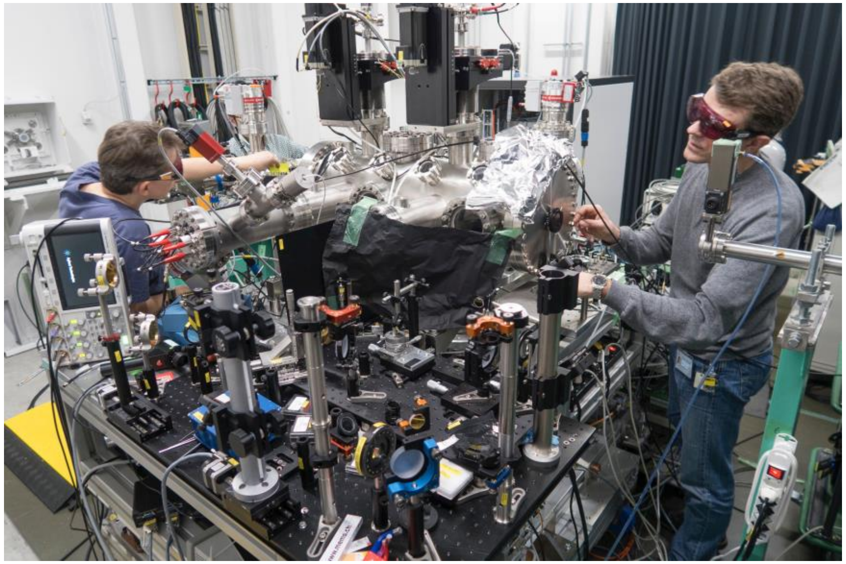
Measurements at LCLS confirm sub-cycle pulse length

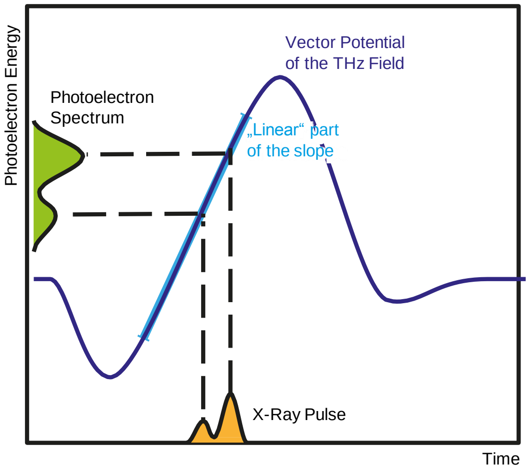
THz Streak Camera installed at SACLA

Measurement principle: X-ray photons ionise a gas
Photoelectron spectrum is equal to photon spectrum minus binding energy
Additional (THz) electromagnetic field streaks the photoelectrons

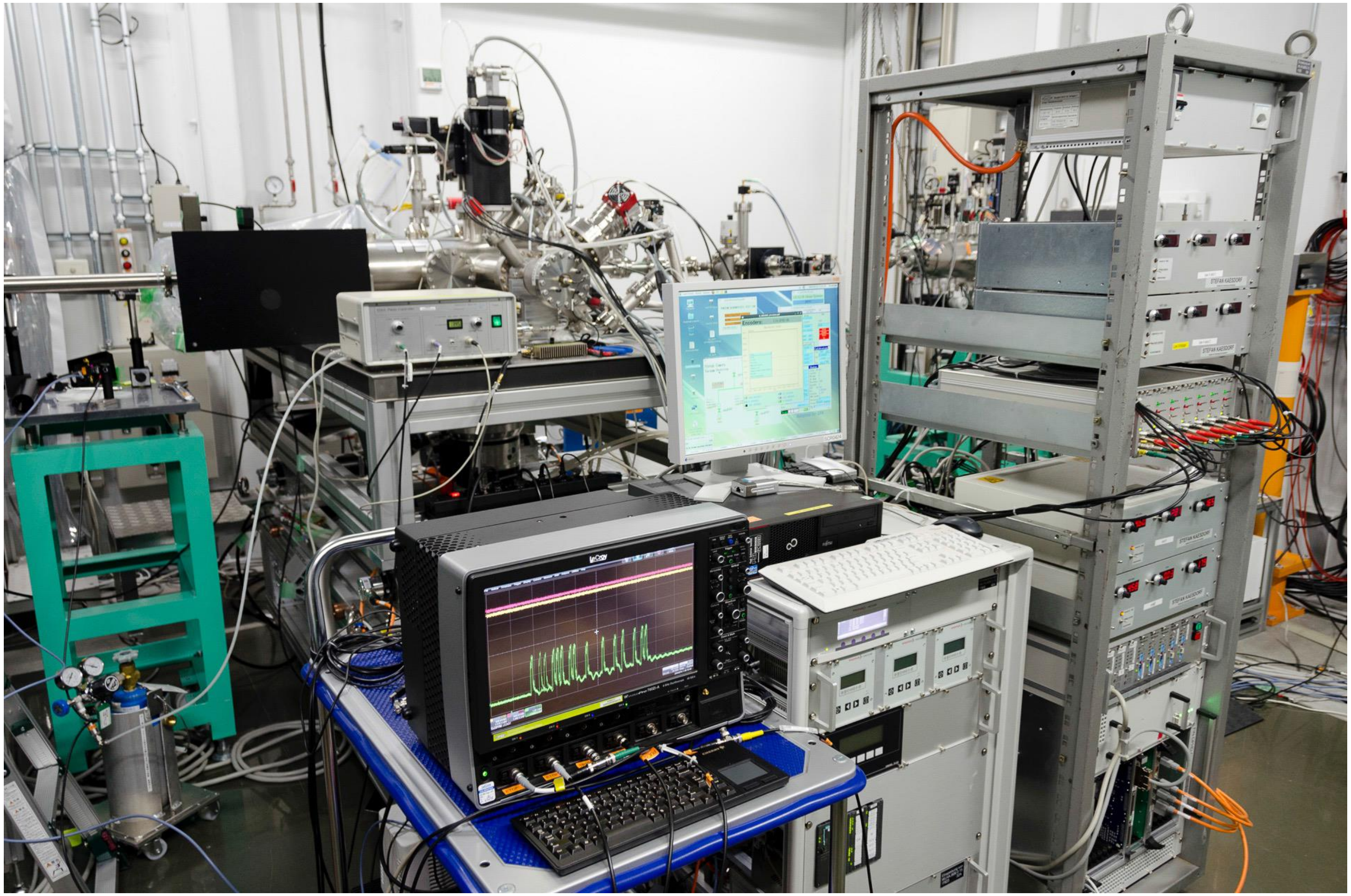








Pavle Juranić



Terahertz streak camera:

Ionise Xenon clusters, measure photoelectron spectrum.

Modulation of this spectrum by terahertz field derived from the pump laser

Summary of ultra-short bunch techniques

- Transverse deflection cavity / zero crossing
  - <5 fs resolution capability, in principle
  - large infrastructure for high energies; requires significant beamline space
  - destructive techniques, in general.   “semi-parasitic” (sacrifices 1 bunch)
  - gives access to slice parameters of electron beam

- Radiative spectral techniques
  - demonstrated with extreme broadband & single-shot capability
  - empirical tune-up, stabilisation problems

- Electro-optic upconversion / transposition
  - converts extreme broadband signal into manageable optical signal
  - partially limited by materials and optical characterisation
  - solution in multiple-crystal detectors / alternative materials (?) and in FROG-like techniques
  - non-destructive and compact techniques (and can be retro-fitted)

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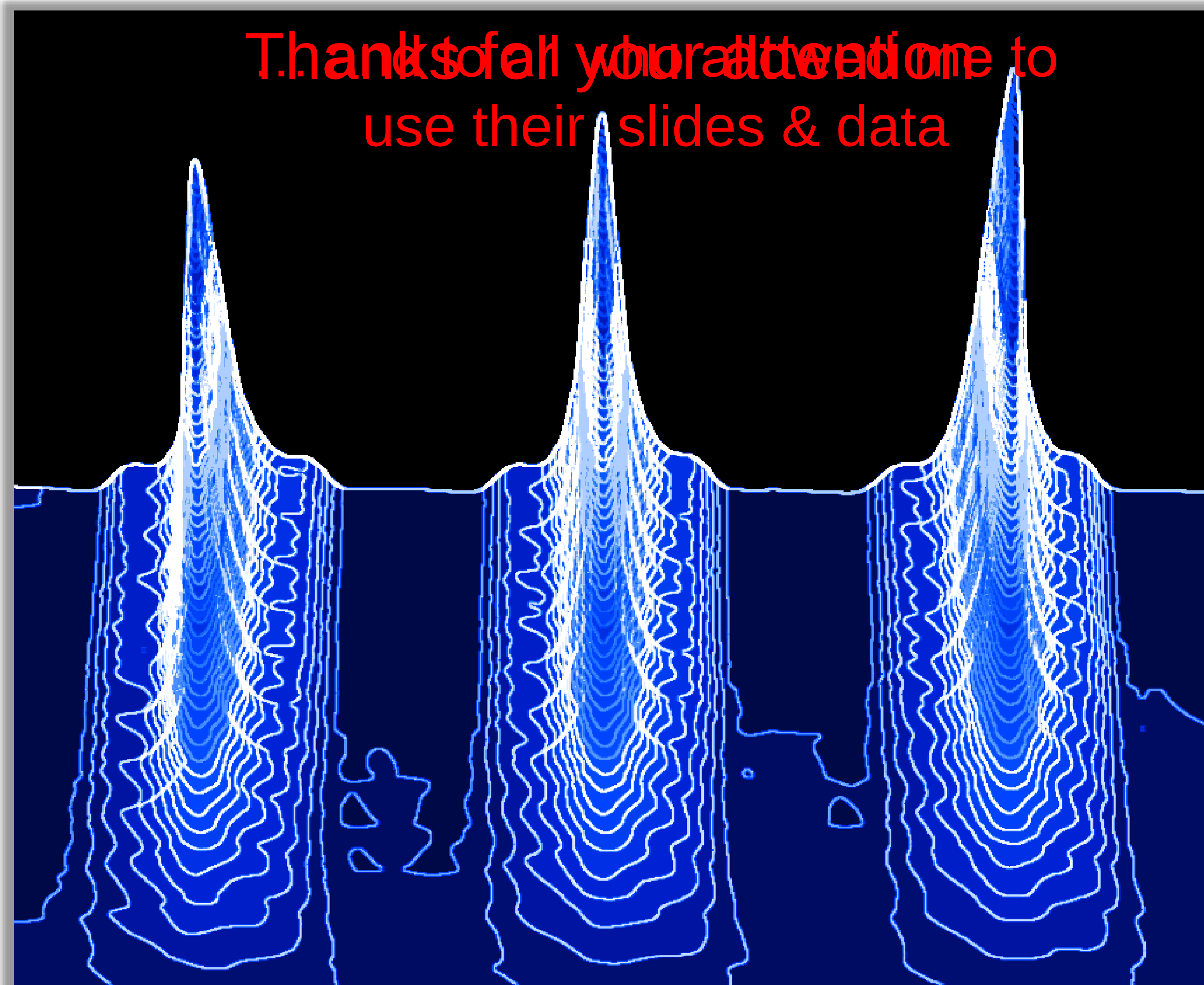
Other individual photos, etc., are individually listed.

… or at least this was not your response.


Thanks for your attention
…and to all who allowed me to
use their slides & data

Partial List on Short Bunch Diagnostics Publications

Role of misalignment-induced angular chirp in the electro-optic detection of THz waves
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