Short Bunch Diagnostics - Can We Measure Below the Femtosecond?

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EPSRC
Engineering and Physical Sciences Research Council

CLIC

Electron bunch temporal profile diagnostics with femtosecond resolution

(selective discussion due to time constraints, with apologies to those whose work has been omitted)

The need for femtosecond longitudinal diagnostics

1. Advanced Light Sources: 4^{th} & 5^{th} generation

Free-Electron Lasers kA peak currents required for collective gain

τ = 200fs FWHM, 200pC (<2008, standard) $\Rightarrow$ 10fs FWHM,10pC (increasing interest)

Low-emittance storage rings *τ = 10-200 ps rms, ε_H = 150-300 pm.rad (MAX-IV, ESRF II)*

2. Particle Physics:

Linear Colliders (ILC, CLIC) e^+-e^- and others

short bunches, high charge, high quality - *for high luminosity*

- *~150fs rms, ~1nC stable, known (smooth?) longitudinal profiles*

3. LPWA & variants:

Laser-plasma accelerators produce ultra-short electron bunches!

- *1-5 fs FWHM (and even shorter in principle), ~ 20pC + future FELs*

Significant influence on bunch profile from …

wakefields, space charge, CSR, collective instabilities… machine stability & drift

$\Rightarrow$ ***must have a single-shot diagnostic***

Two distinct classes of diagnostics

Grouped by similar physics and capabilities / limitations

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

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

"Radiative" Techniques

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

propagating & non-propagating

Spectral domain:

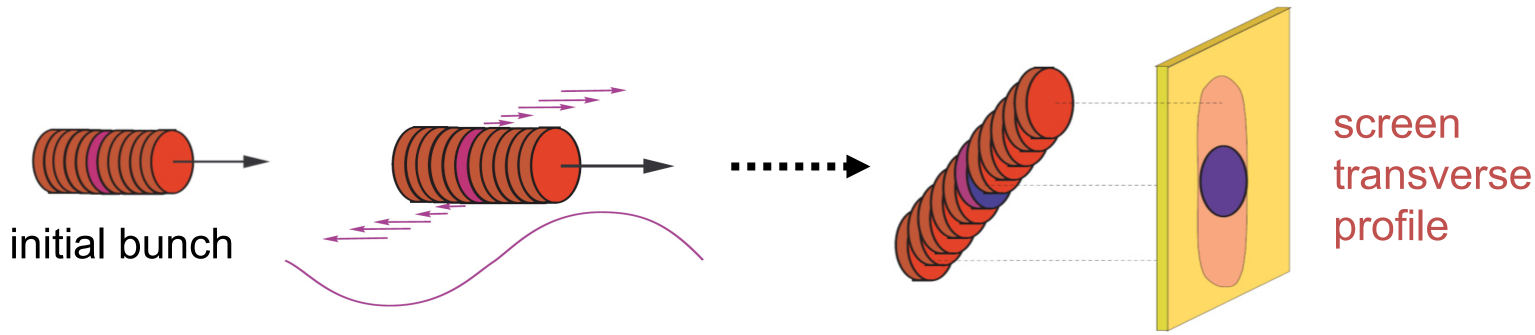
- CTR, CDR, CSR (spectral characterisation)
- Smith-Purcell
- Electro-Optic

Time domain:

- CTR, CDR (autocorrelation)
- Optical Replica/Transposition
- Electro-Optic

Class 1. Direct Particle Techniques

RF zero-phasing



cavity:
z-dependent accel/deceleration

beam optics:
energy dispersion

- Introduce energy chirp to beam via "linear" near-zero crossover of RF
- Measure energy spread with downstream spectrometer ⇒ infer initial bunch profile

time resolution dependent on:

- gradient of energy gain
- dispersion of spectrometer (needs to be high!)
- initial energy spread (needs to be low!)

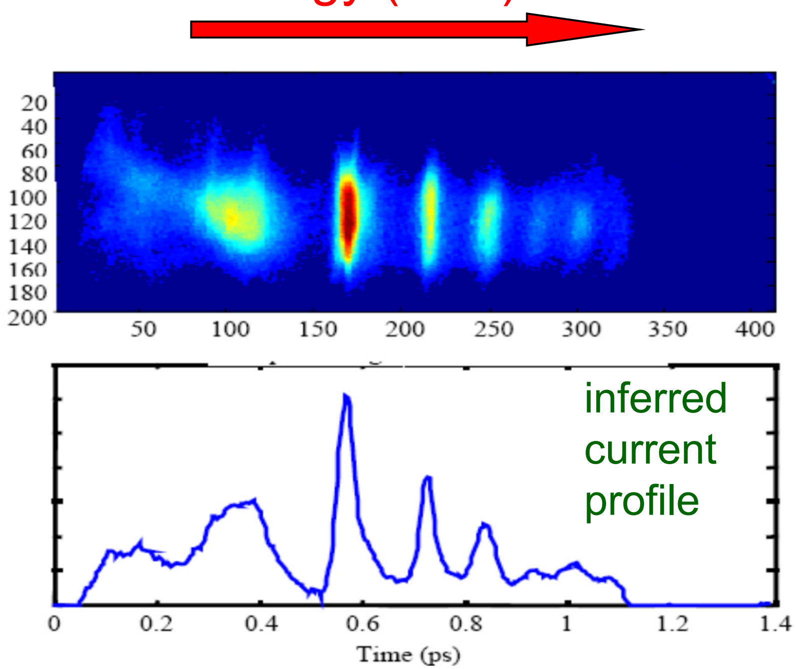
initial γ–z correlation ?

Disadvantage - destructive to electron beam

RF zero-phasing examples

DUV-FEL: at 75 MeV

energy (time)

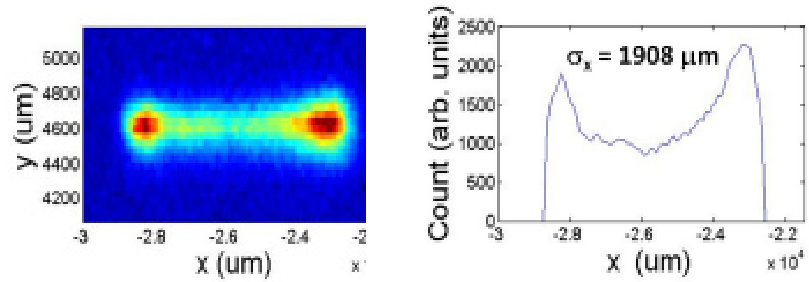


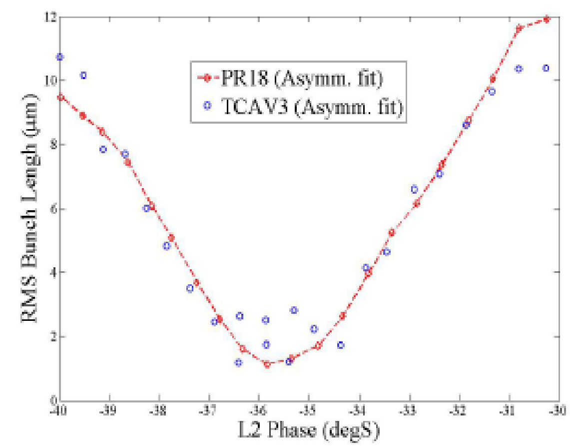
time resolution of ~50 fs

W. Graves et al., PAC 2001, Chicago, 2224

SLAC LCLS: at 4.7 GeV

- 550m of linac at RF zero crossing!
- 6m dispersion on A-line spectrometer



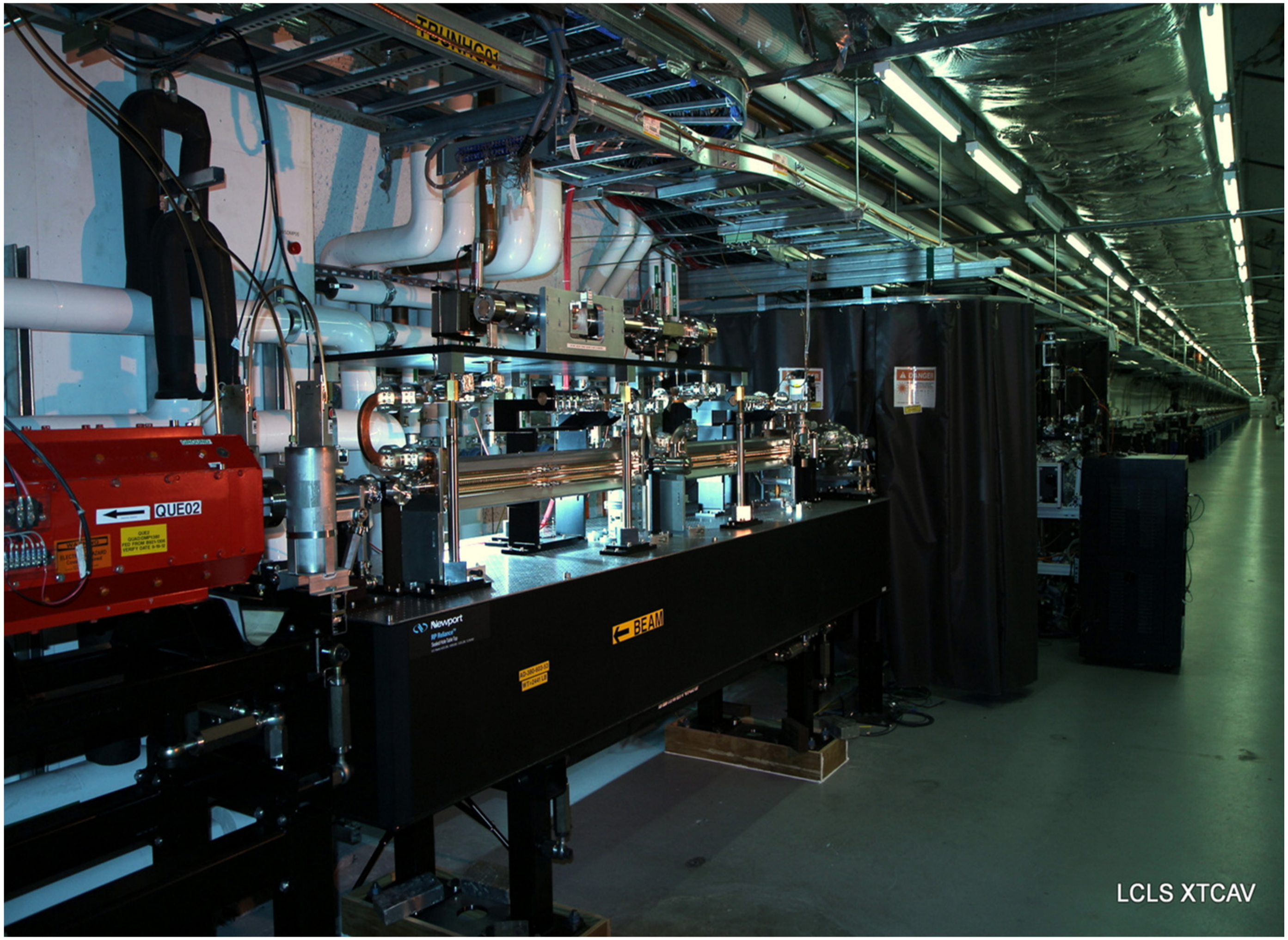


TCAV3

~ 1 fs rms bunch length at 4.7 GeV

Z. Huang et al. PAC 2011, FEL2013

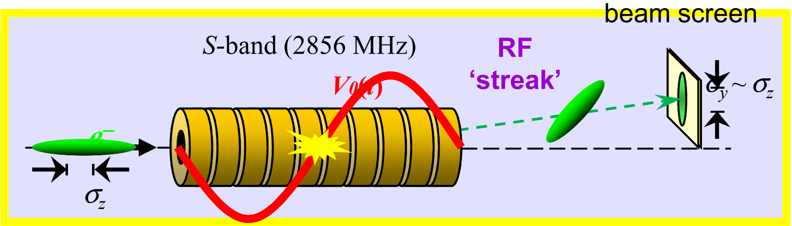
SLAC LCLS X-band Transverse Deflecting Cavity (XTCAV)



SLAC NATIONAL ACCELERATOR LABORATORY

Slides courtesy of Pat Krejcik, SLAC

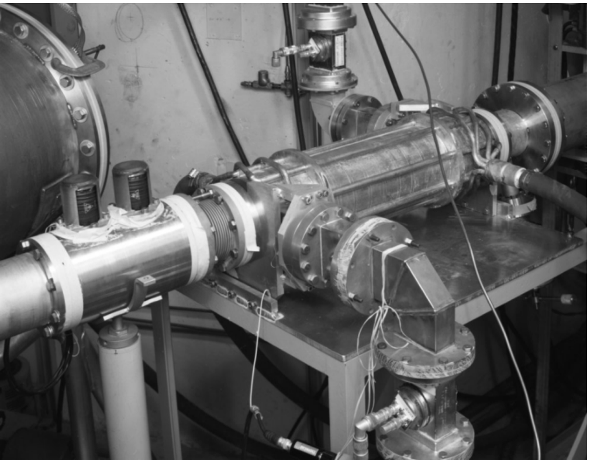
Transverse Deflecting Structures

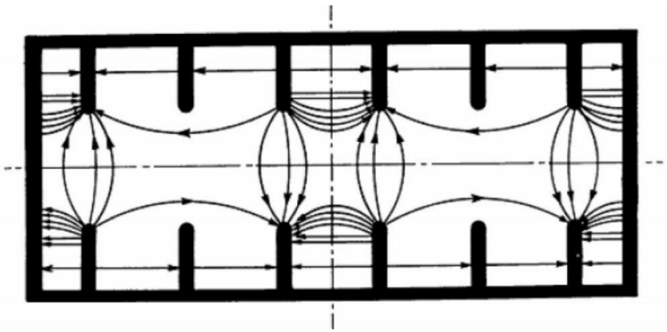


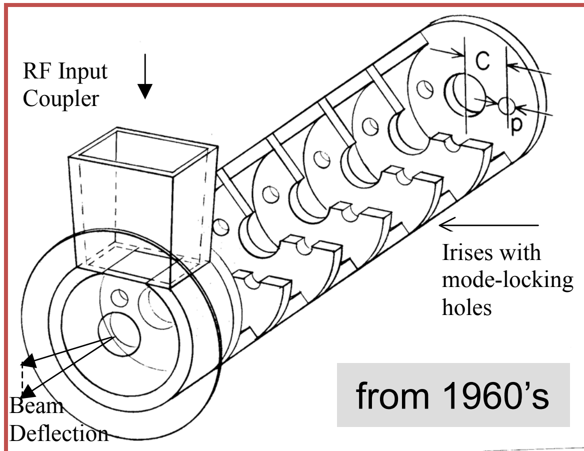
- Well-established technique at SLAC to measure bunch length
- Uses a time-varying transverse electric field to "streak" the beam across a monitor screen
- 3 m-long S-band 2856 MHz ('LOLA')structures built in the 1960's
- Installed in the LCLS linac, but are invasive to operation for photon users

Diagnostic capabilities linked to beam optics

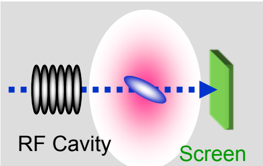
Disadvantage - destructive to electron beam

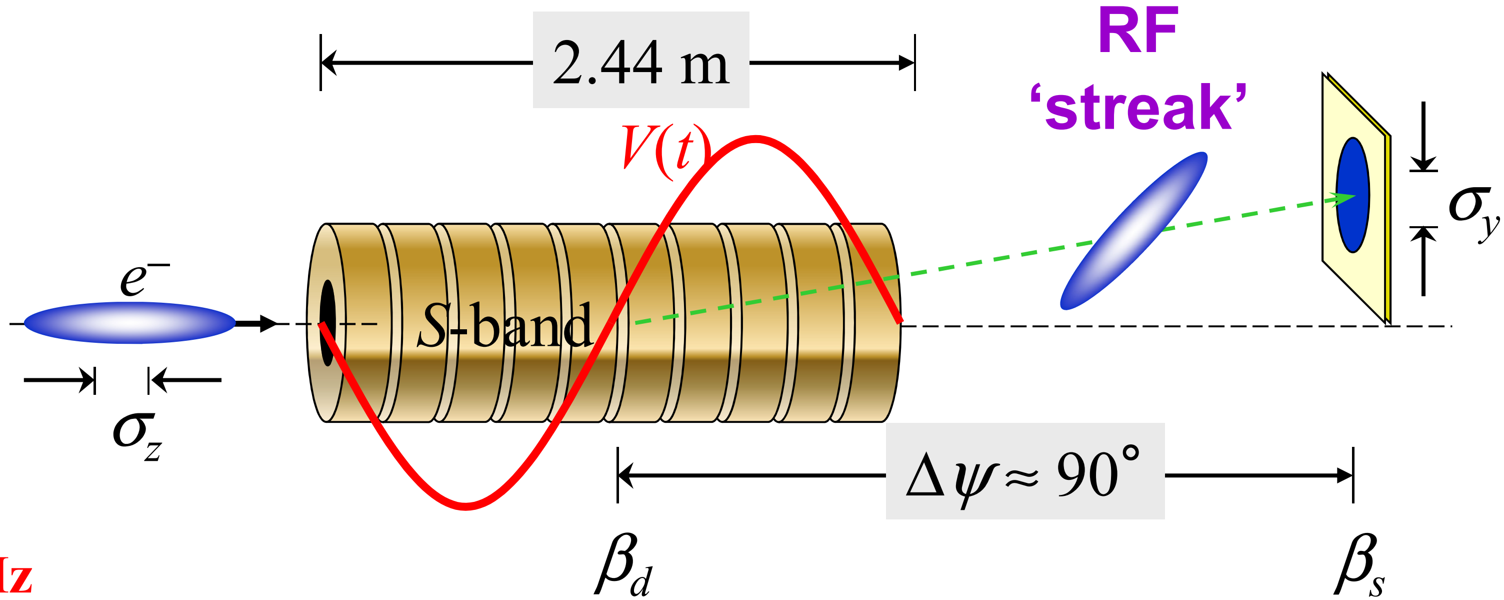






Transverse Deflector Cavity (TDC)





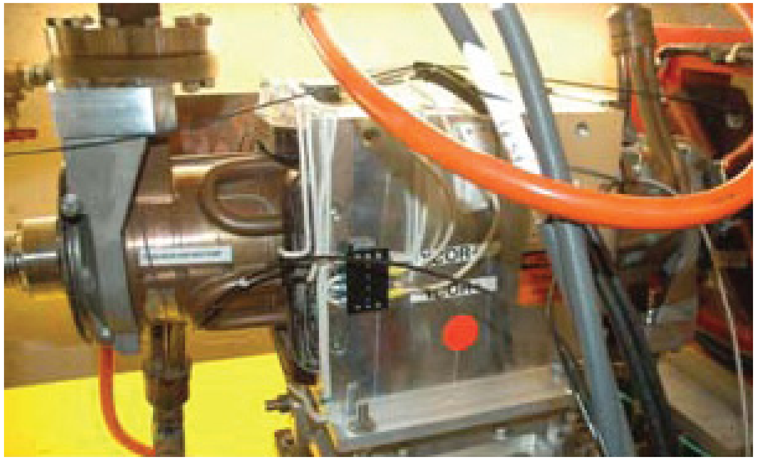
$V_0 > 20$ MV
$f_{RF} = 2856$ MHz
$E_S = 13.6$ GeV

$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left(\frac{k_{RF} e V_0}{E_s} \sin\Delta\psi \cos\phi \right)^2$$

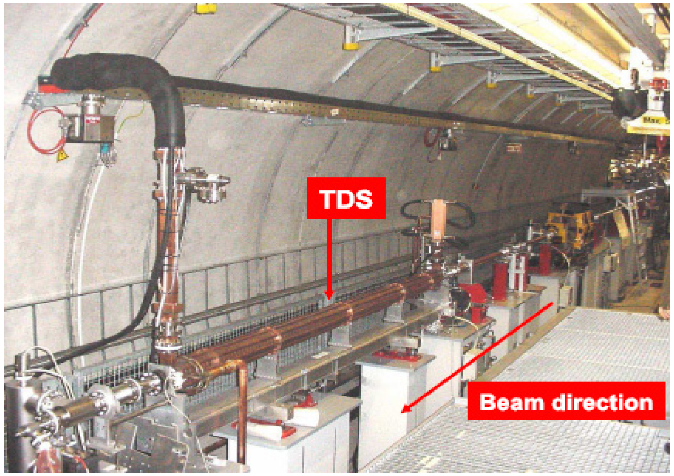
- Map time axis on to transverse coordinate
- Simple calibration by scan of cavity phase

TDC @ LCLS, FLASH & SPARC

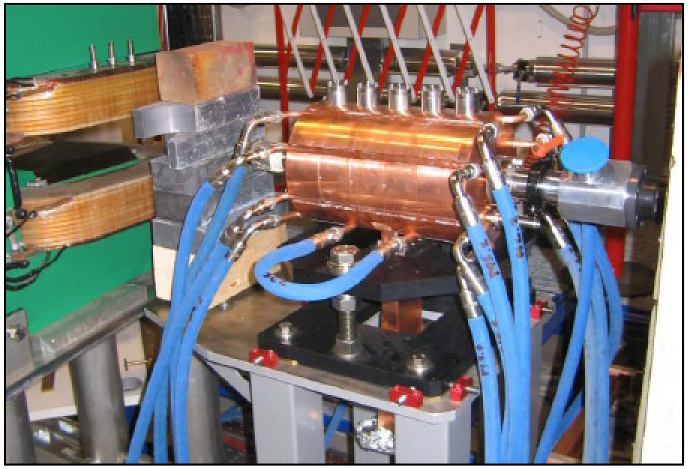
low-energy TW RF deflector @ LCLS



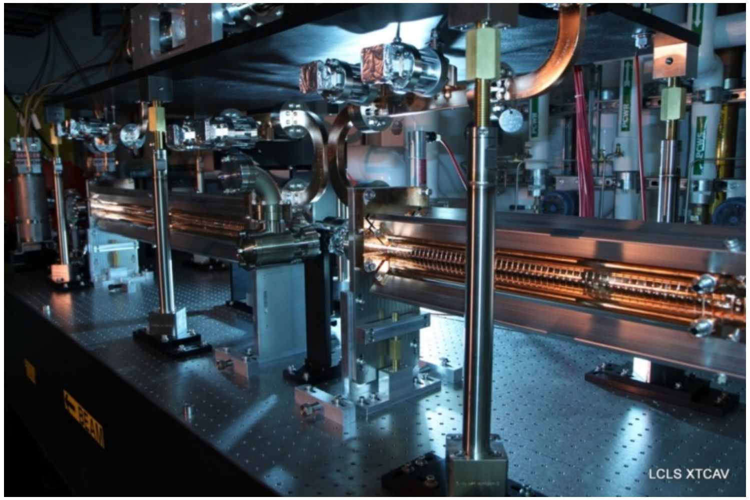
TW RF deflector @ FLASH



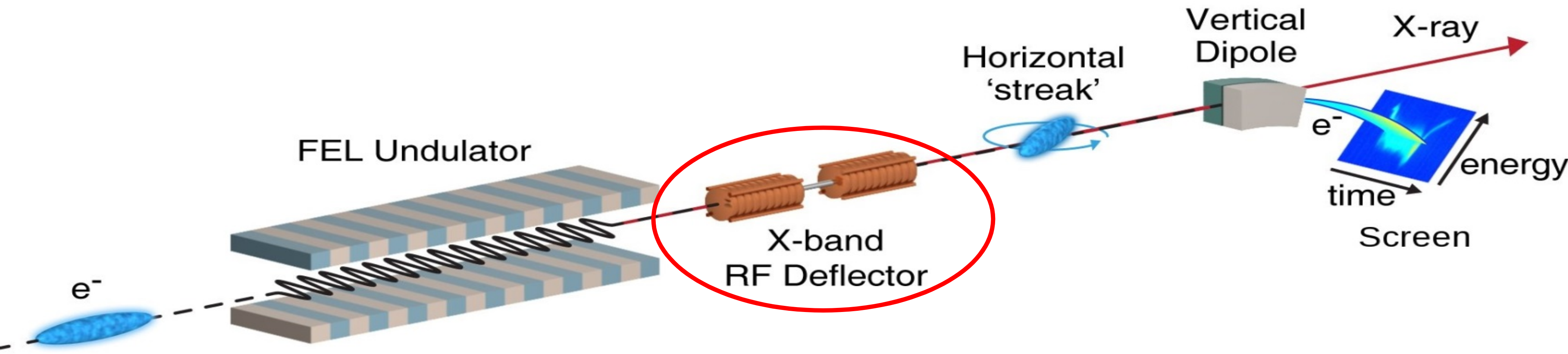
SW RF deflector @ SPARC



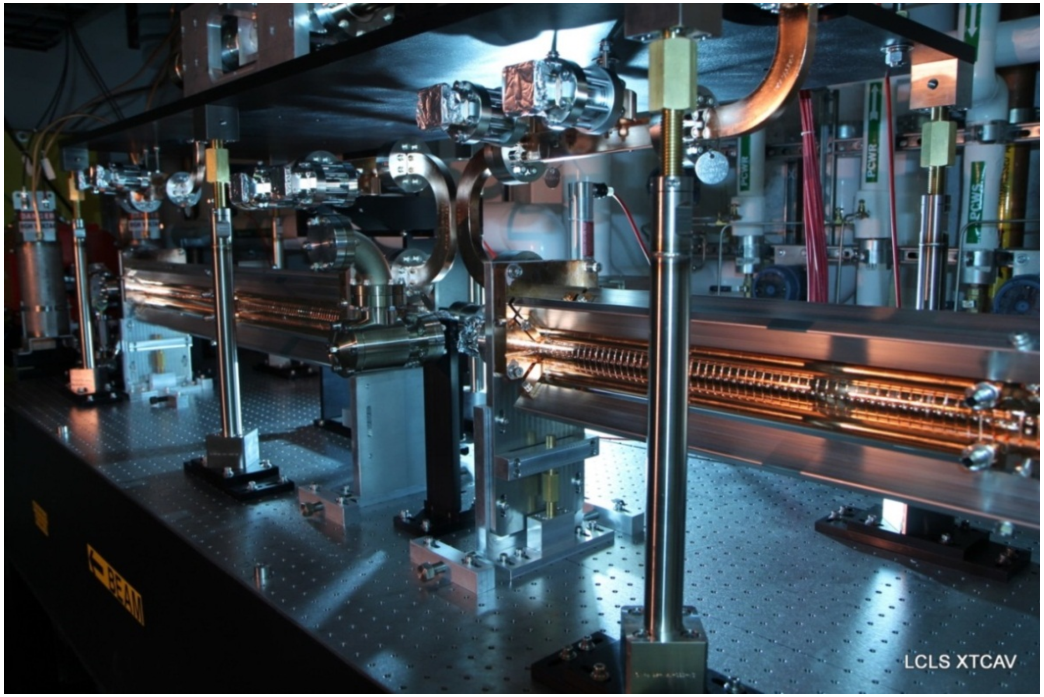
X-band TDC @ LCLS



LCLS: Horizontal XTCAV plus Vertical Spectrometer

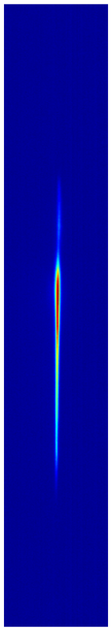


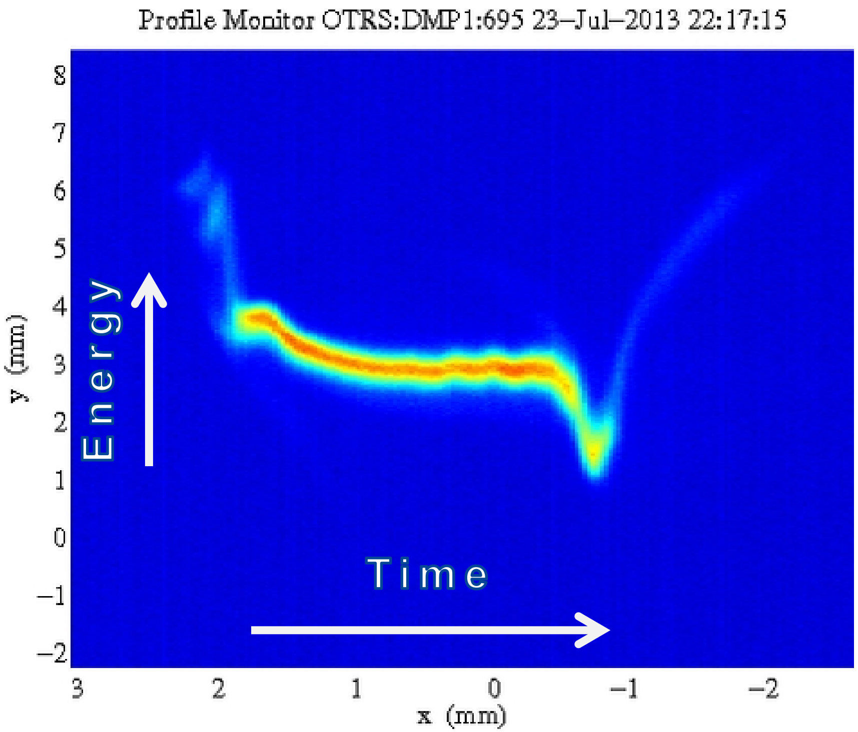
Imaging the temporal profile of the electron beam by horizontally streaking with an RF deflecting cavity and measuring the time-dependent energy via a vertical spectrometer.

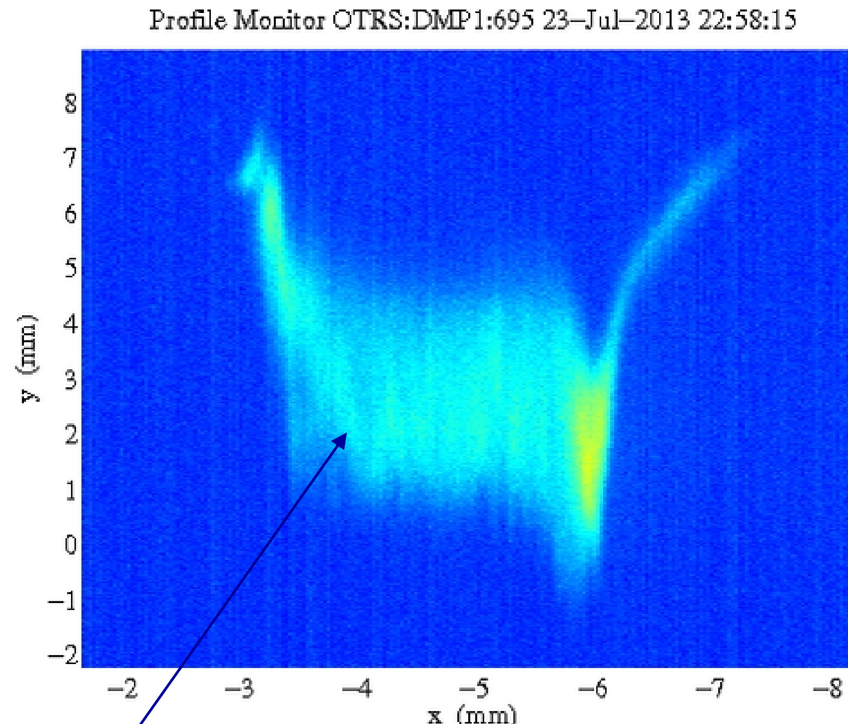


FEL energy spectrum at 4.7GeV, 150pC

Three images at the electron dump spectrometer screen







XTCAV Off

XTCAV On
FEL Suppressed
(baseline)

XTCAV On
FEL On
~1mJ FEL pulse energy

Transfer of energy to photons causes electron energy loss and spread

3 new important features:

- **Operates at 11.424 GHz**

  ⇒ 8 times better temporal resolution

  - 4 from shorter λ and 2 from V gradient
  - allows measurement of slice emittance

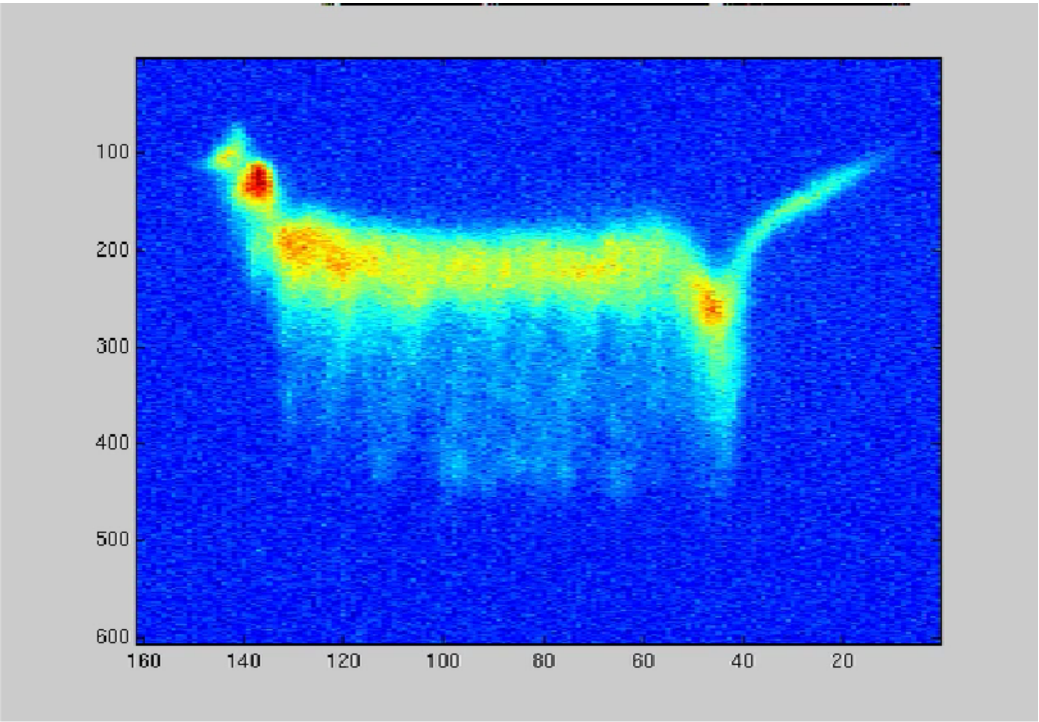
- **Located downstream of the undulator**

  ⇒ cannot interfere with photon operation

  - Continuous non-invasive operation
  - Every shot analyzed at 120 Hz

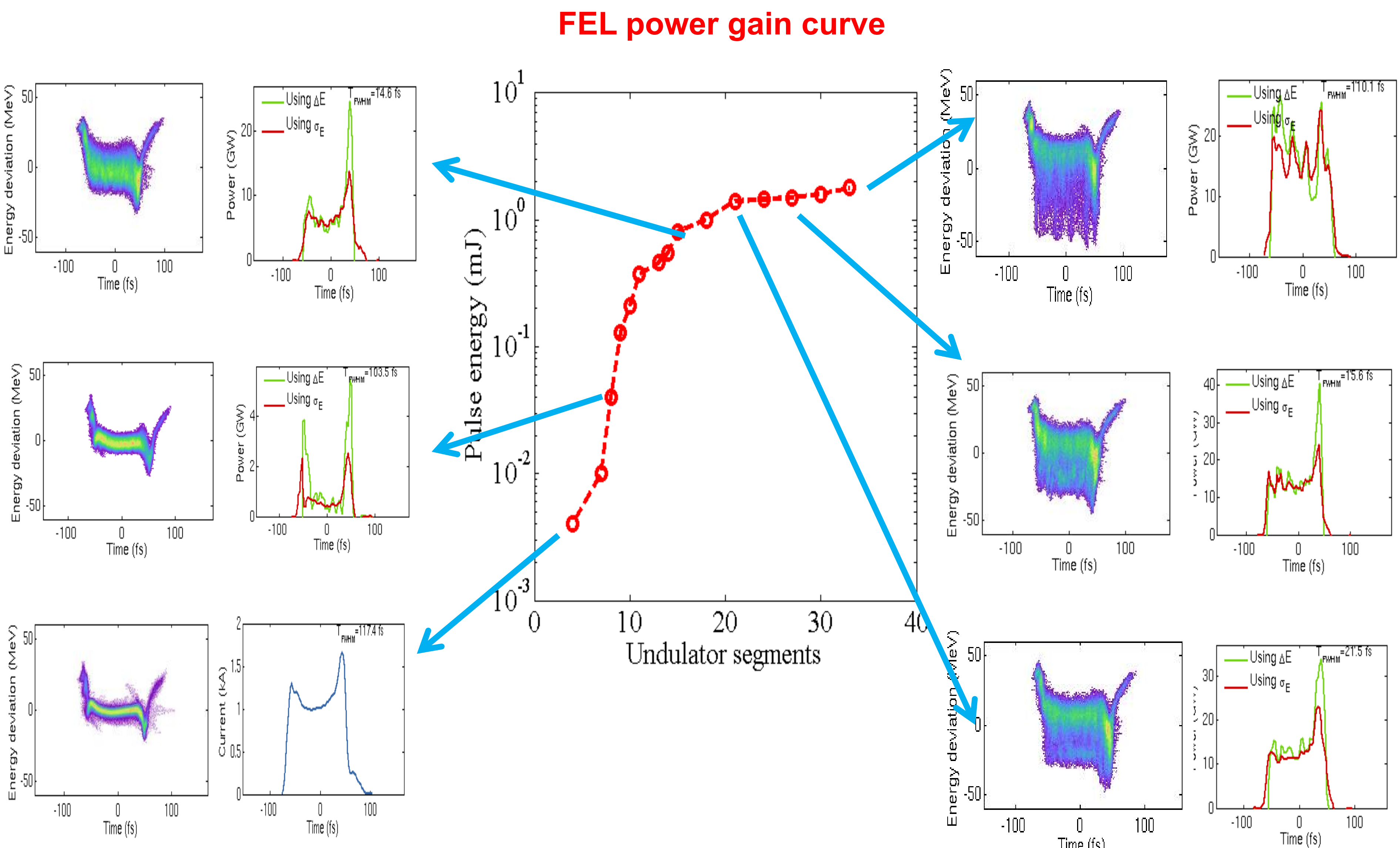
- **Reconstructs temporal profile of x-ray beam from e-loss profile of electrons**

20 consecutive shots (1keV, 150pC)

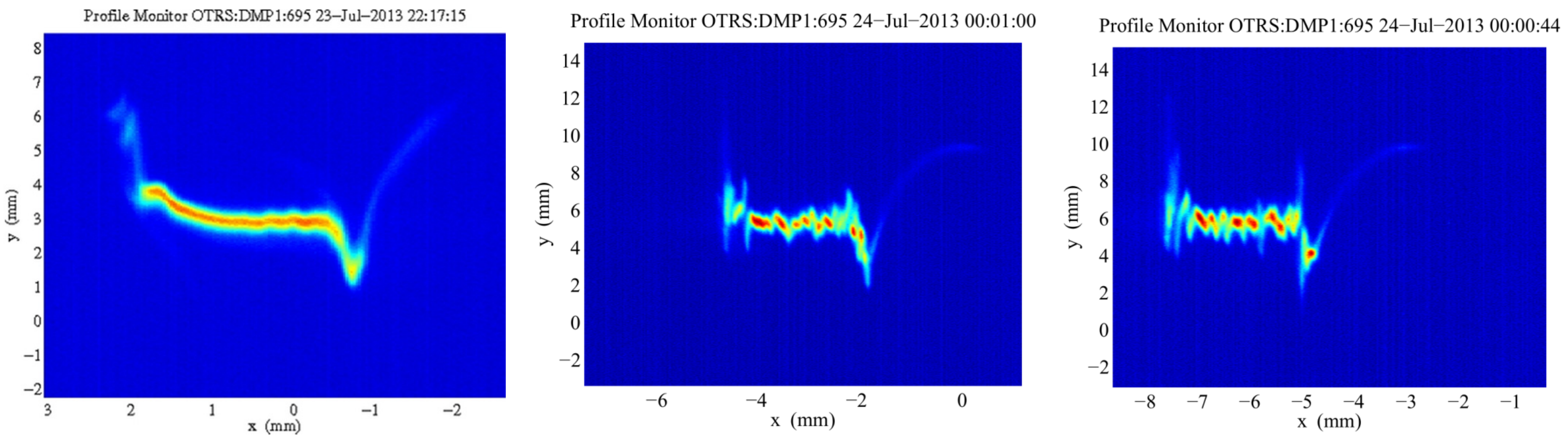


Demonstrated resolution of 0.8 ± 0.2 fs

Evolution of SASE along the FEL Power Gain Curve at 4.7GeV, 150pC (1keV)



Direct Observation of Microbunching Instability with XTCAV



Decreasing gain on the Laser Heater

Class 2. “Radiative” Techniques

"Radiative" Techniques

General Methodology: Cause bunch to radiate coherently

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

- emission response
- phase matching

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

- Dispersion
- Attenuation
- Diffraction…

Measure spectrum, intensity time profile

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

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

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

- detector response
- missing phase information *

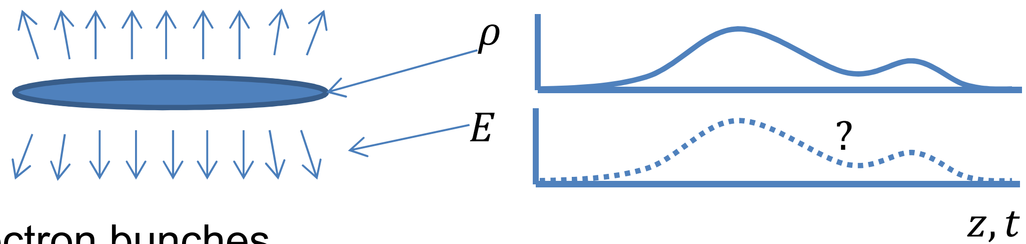
Infer charge density

Techniques & limitations:

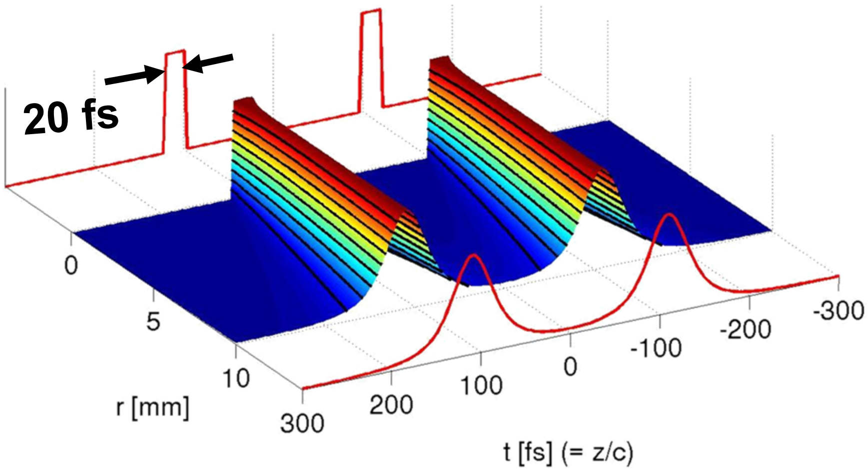
CSR/CTR :	propagation effects; detector response; missing phase
CDR :	as for CSR/CTR; plus emission response
Optical Replica:	emission response (? radiating undulator)
Electro-Optic:	detector response

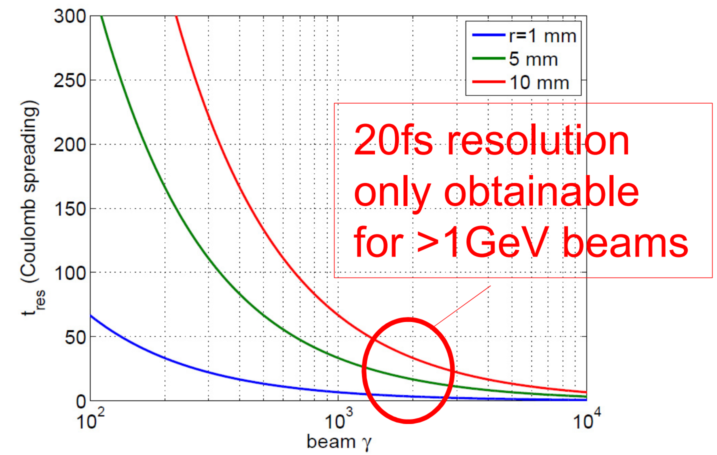
Common Problem - Field at Source

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:

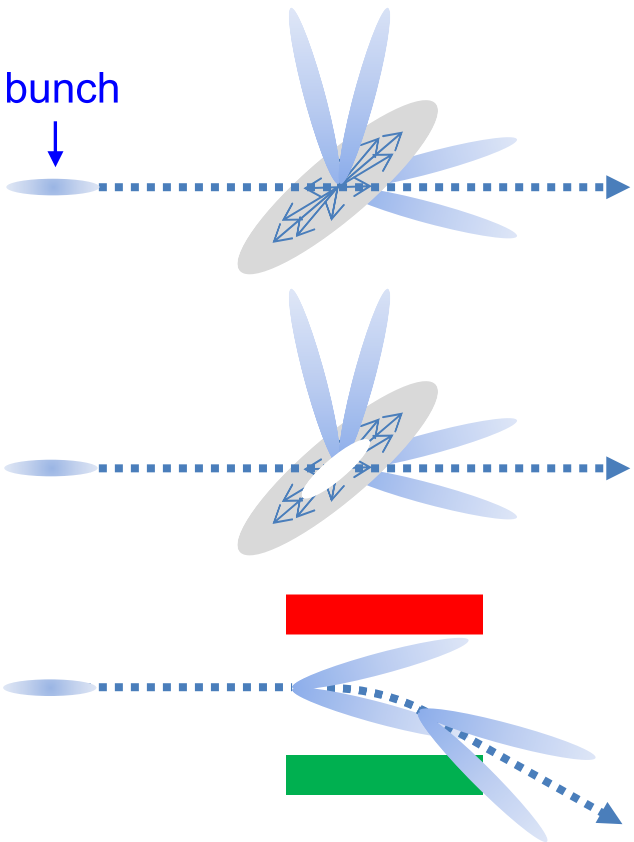
$$\delta t \sim 2r / c\gamma$$

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

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

Spectral domain radiative techniques

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



Coherent Transition Radiation (CTR)
Bunch field sets up currents 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
Need to divert the beam!

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

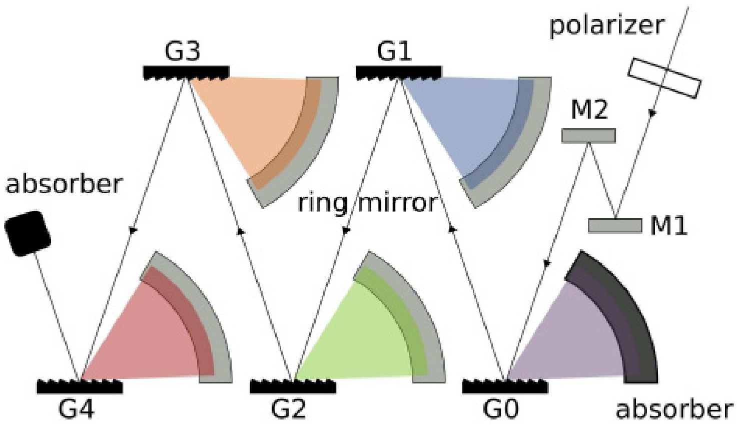
Usually only *spectrum* measured, but temporal measurements also possible (EO) …

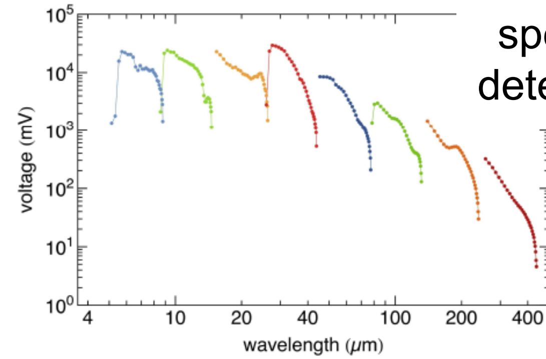
no direct detectors are fast enough!

Good example: single-shot CTR spectrometer at DESY FLASH

cascaded dispersive grating elements, and pyroelectric detector arrays

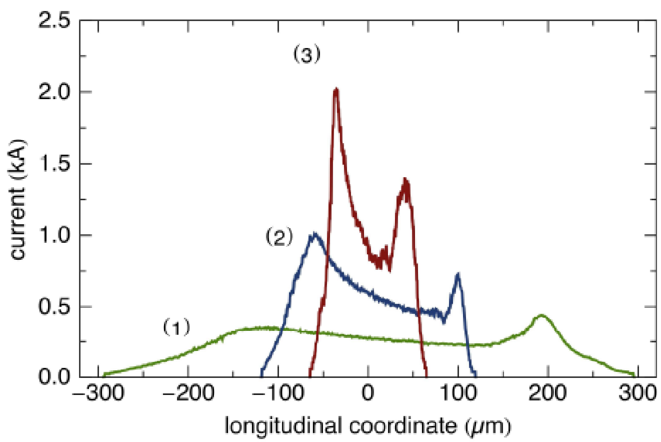
E. Hass et al., Proc. SPIE 8778, May 2013



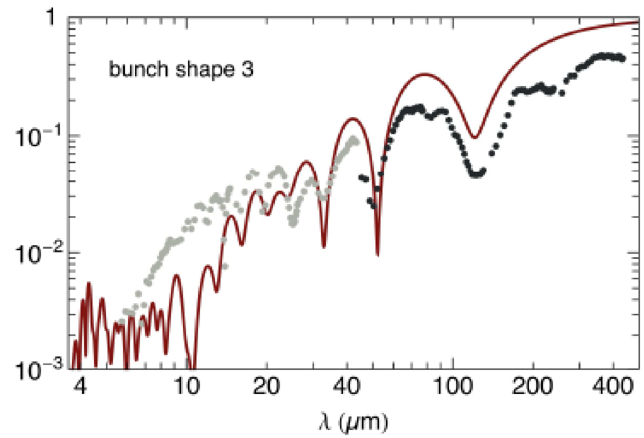


spectrometer & detector response

Deflecting cavity bunch profiles



Measured & calculated spectra

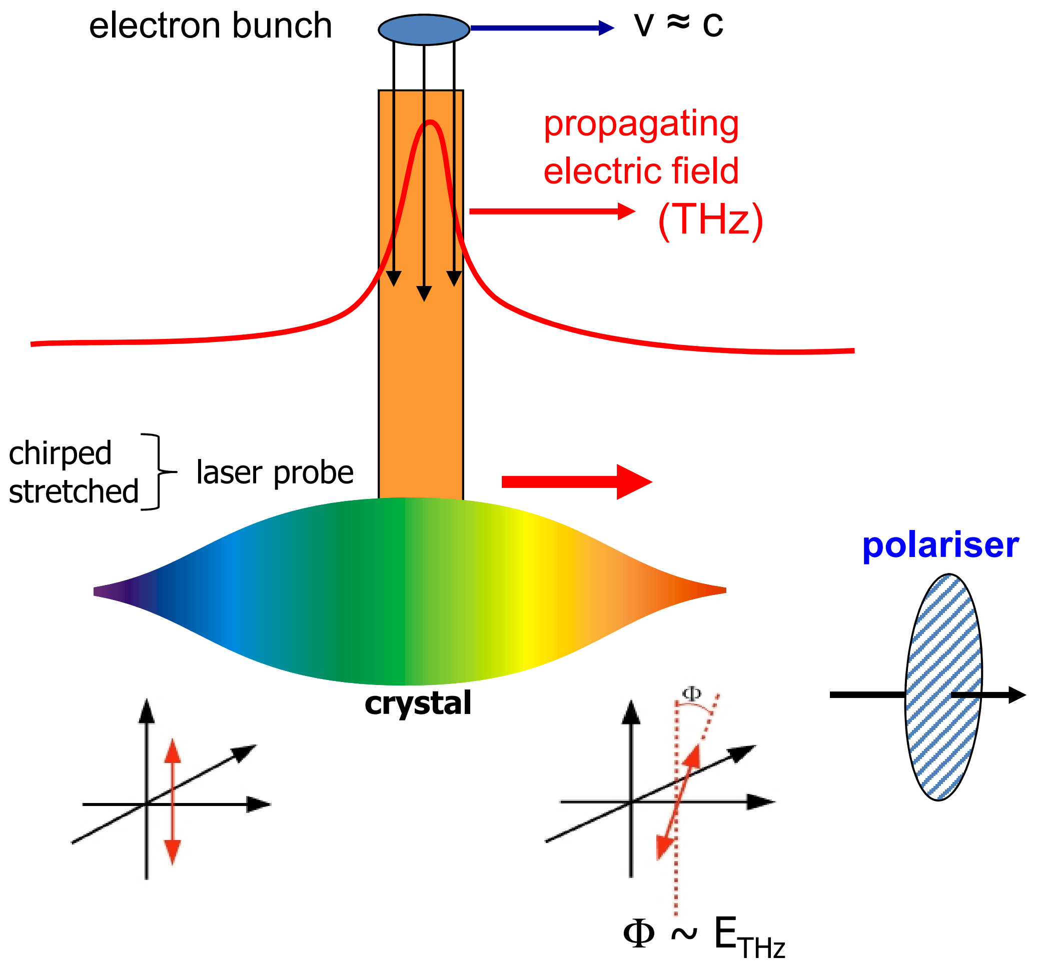


Similar concepts applied at HZDR ELBE facility (O. Zarini et al, LA^{3}NET workshop, Dresden, April 2014) and at SLAC LCLS (T. J. Maxwell et al, PRL 111, 184801, 2013)

Concept of Electro-Optic profile diagnostic

Principle: Convert Coulomb field of e-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

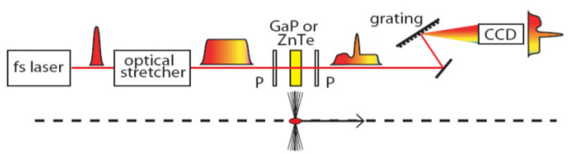
Yields: temporal intensity variations in a single laser pulse

Range of Electro-Optic Techniques

complexity / cost

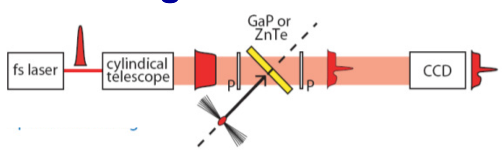
demonstrated
time resolution

Spectral Decoding



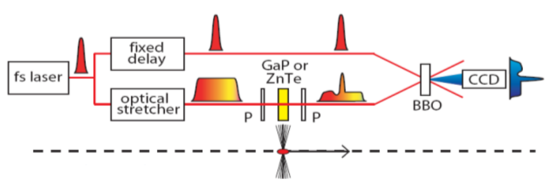
- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

Spatial Encoding



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

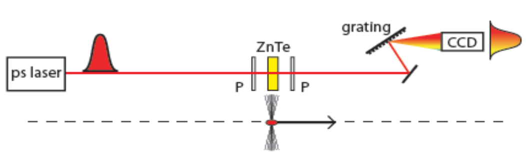
Temporal Decoding



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

New Technique:

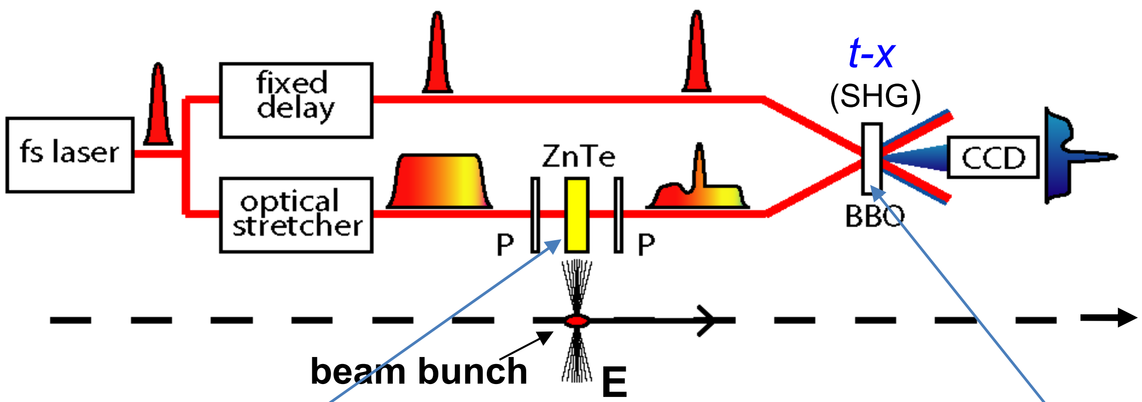
Spectral Upconversion / EO Transposition



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

Single-shot Temporal Decoding (EOTD)

(currently gives best EO time resolution, circa 80 fs)



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)

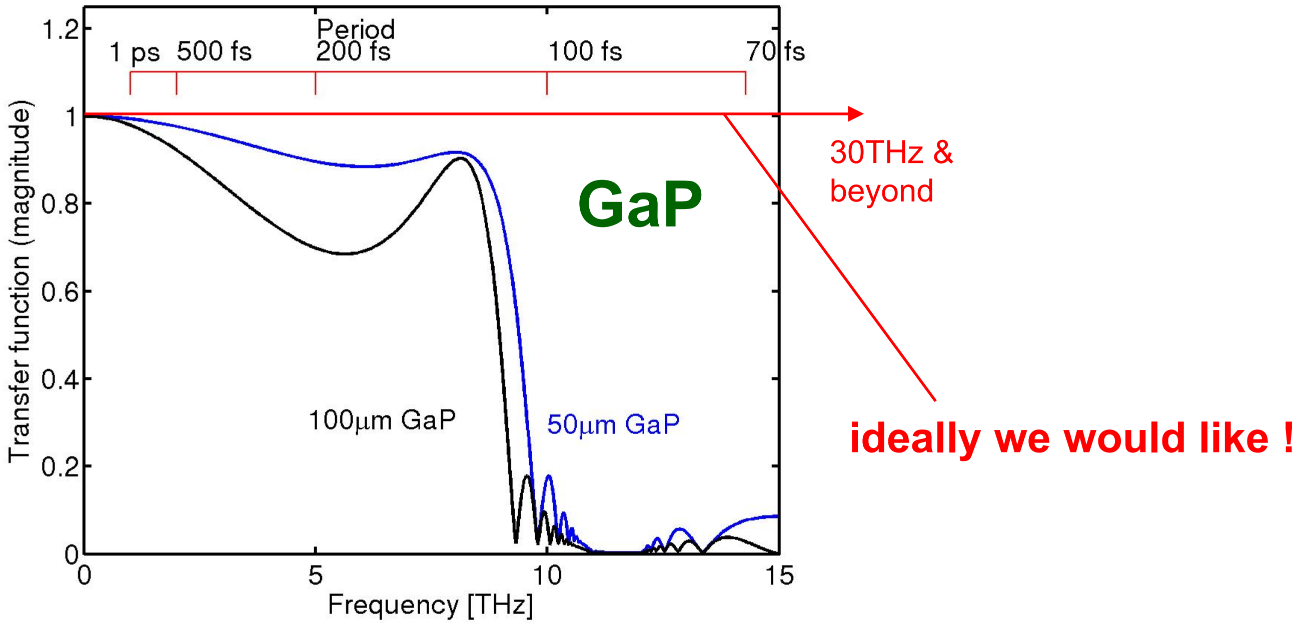
Stretched laser pulse leaving EO crystal measured using original short pulse via single-shot cross correlation in BBO crystal

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

Fundamental Problem: Encoding Time Resolution

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

1. velocity mismatch of Coulomb field and probe laser
2. 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

   - termed "silver-glass nanocomposites"

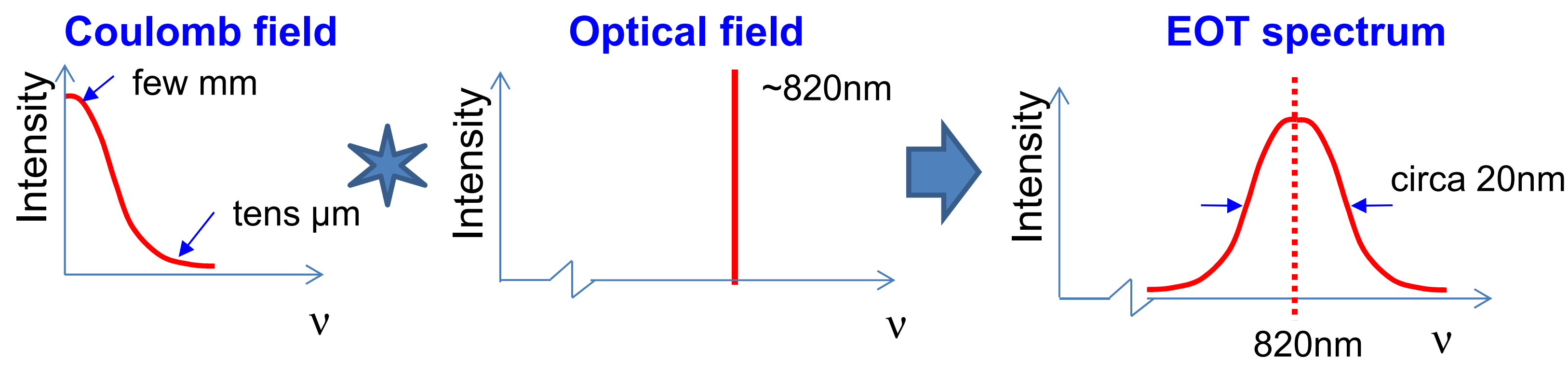
EO Transposition

A more rigorous description of the EO effect is <u>nonlinear frequency mixing</u>

⇨ sum & difference frequencies between laser & THz generated within crystal

Frequency Domain

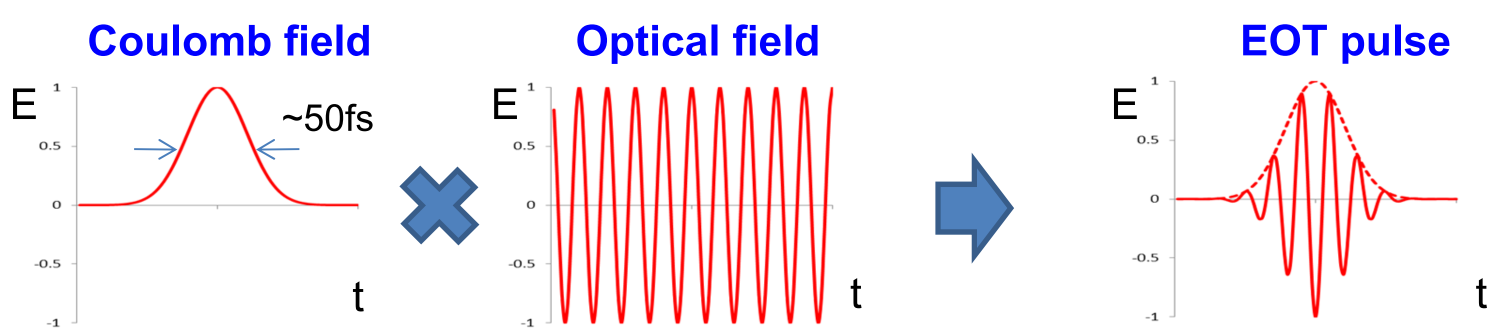
$$\tilde{E}^{\mathrm{opt}}_{\mathrm{out}}(\omega) = \tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega) + i\omega a \tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega) * \left[\tilde{E}^{\mathrm{Coul}}(\omega)\tilde{R}(\omega)\right]$$



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

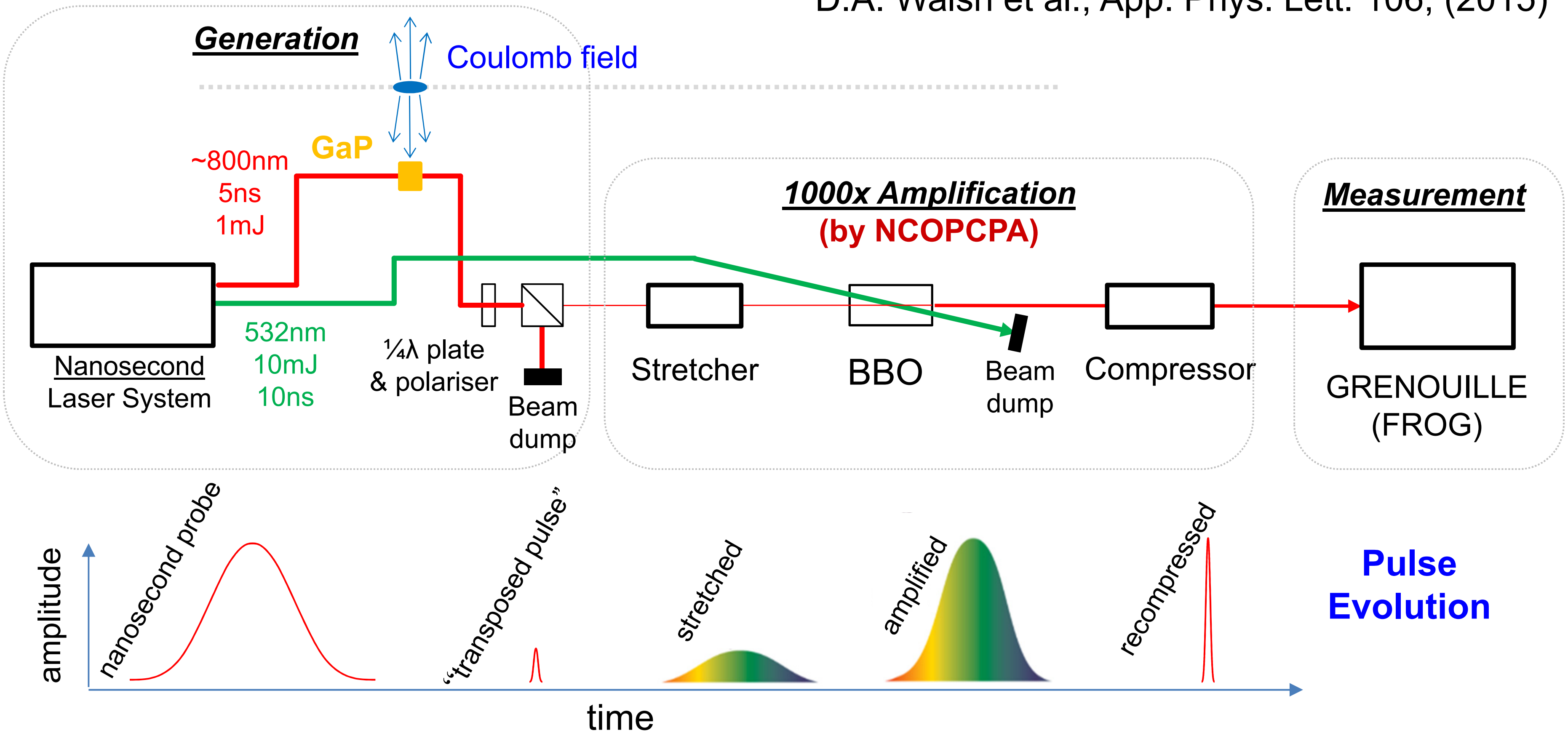
S. P. Jamison et al. Opt. Lett. **31** 1753 (2006)

Time Domain



EO Transposition System (2014-15)

D.A. Walsh et al., App. Phys. Lett. 106, (2015)



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 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 <u>spectrally resolved autocorrelation</u>

What we want to know → $E(t) = Re\left(\sqrt{I(t)}e^{i(\omega_0 t - \phi(t))}\right)$ **<-Fourier->** $\tilde{E}(\omega)=\sqrt{S(\omega)}e^{-i\varphi(\omega)}$

"Carrier" frequency

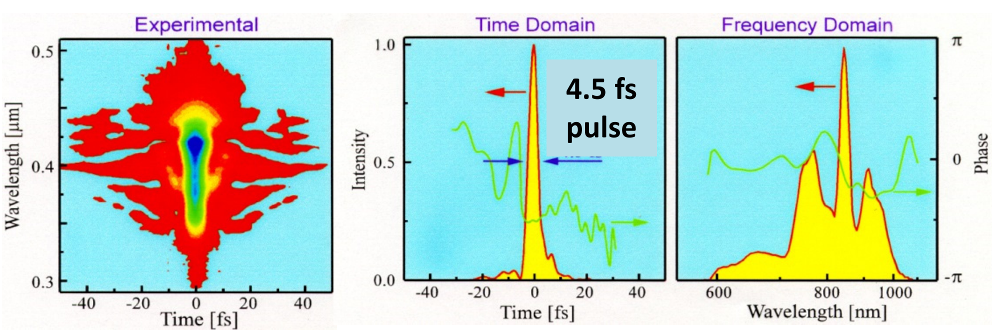
Can't measure

Spectrum

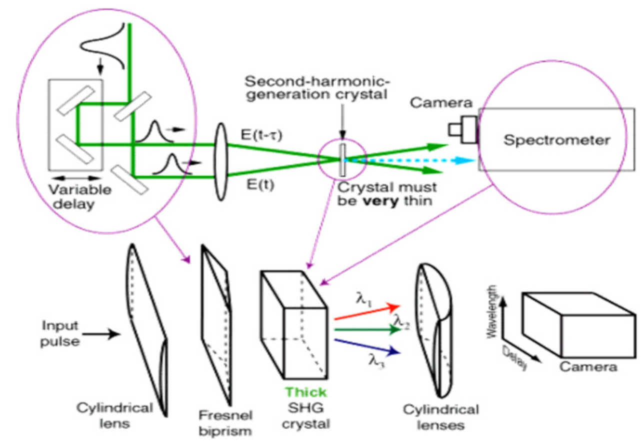
Spectral Phase

Can be retrieved!

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

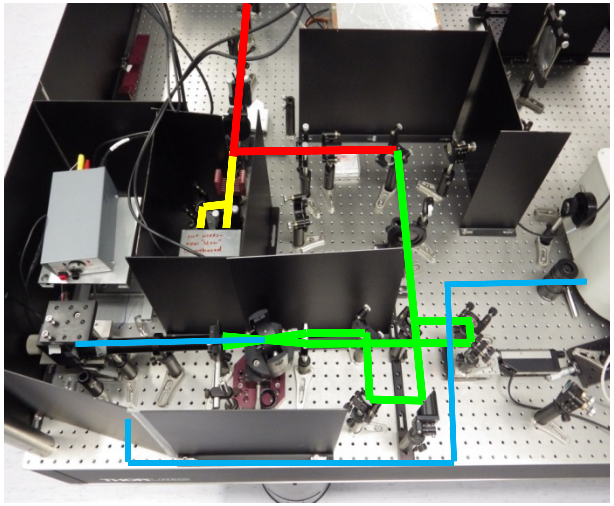


Baltuska, Pshenichnikov, and Weirsma, J. Quant. Electron., 35, 459 (1999).

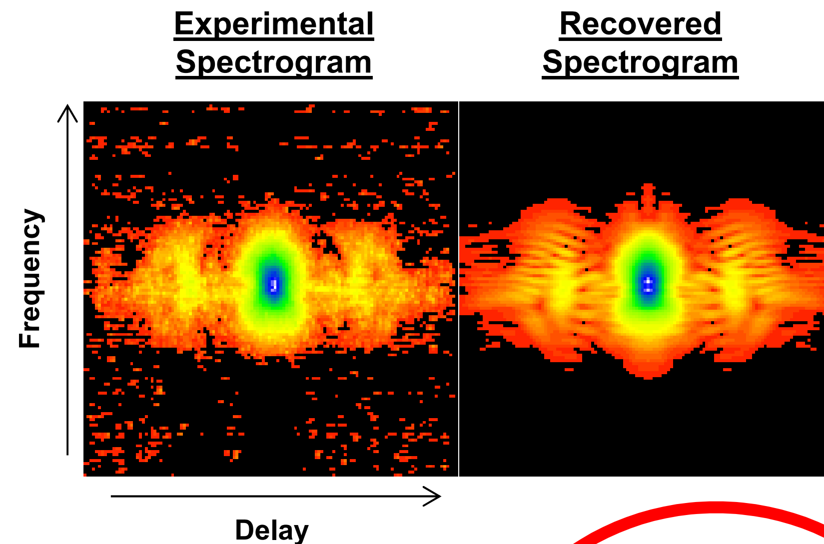


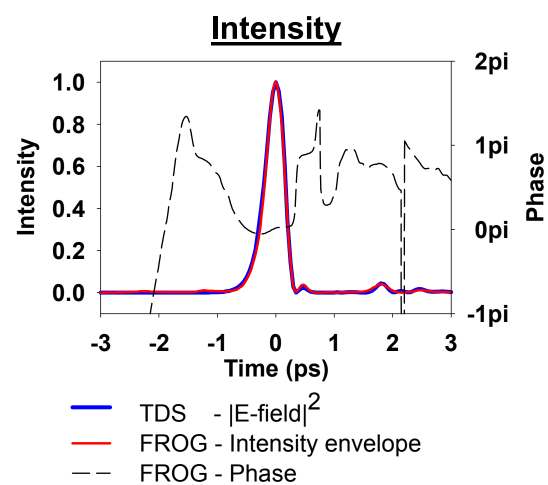
- Most sensitive "auto gating" measurement
- Self-gating avoids timing issues (<u>no need</u> for a femtosecond laser)
- Requires minimum pulse energy of <u>~1 μJ</u>

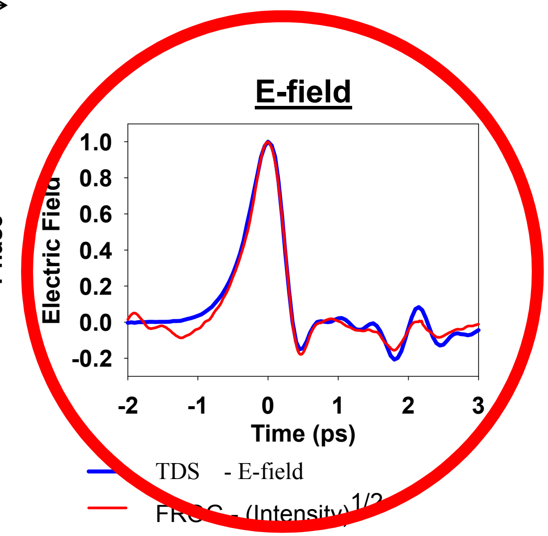
FROG Measurement



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



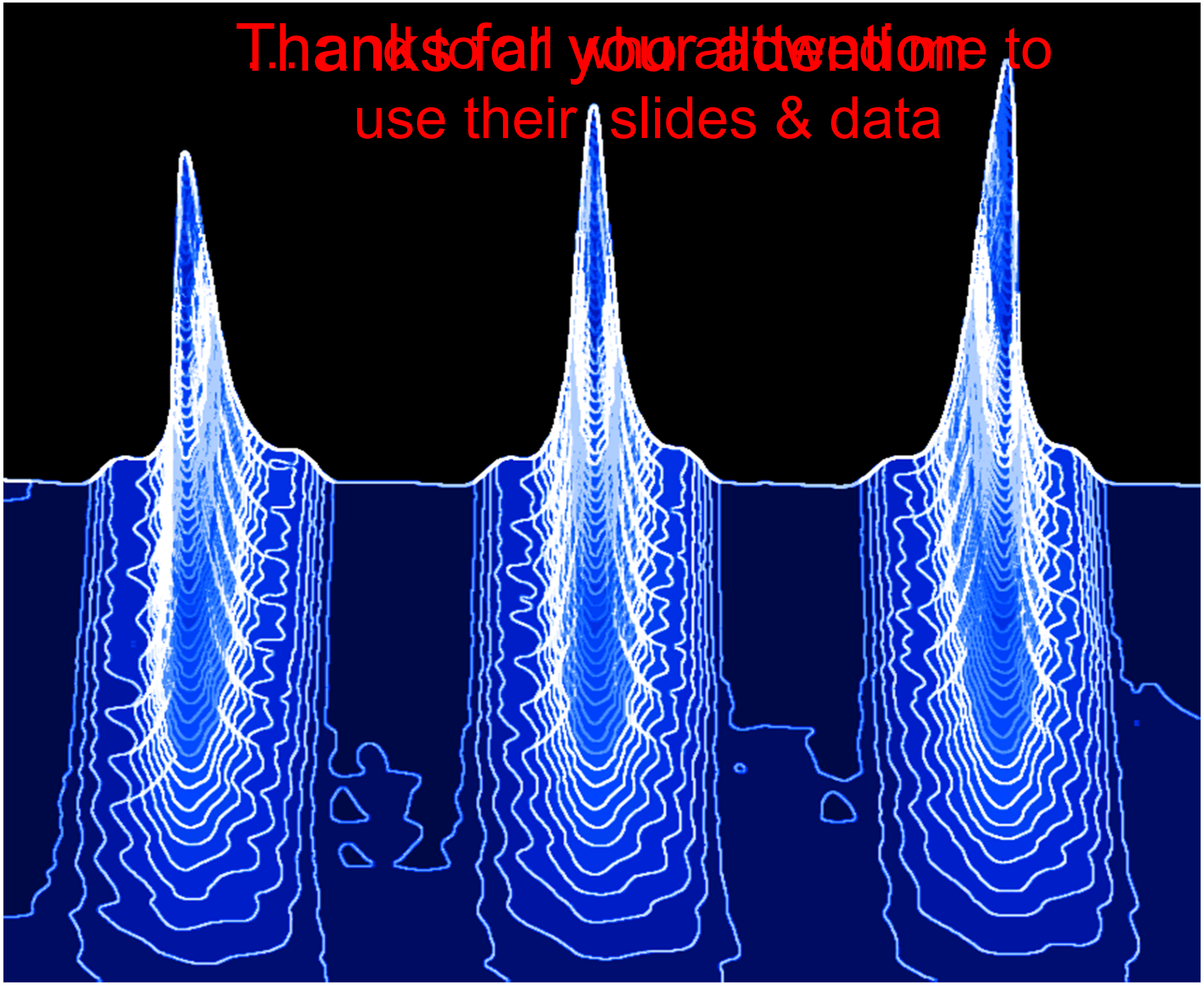




0.55 ps pulse measured with a 10 ps transform limited probe!

Summary of ultra-short bunch techniques

- Transverse deflection cavity / zero crossing
  - <5 fs resolution capability, in principle
  - large infrastructure for high energies
  - destructive techniques, in general
- 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 alternative materials (?) and in FROG-like techniques
  - non-destructive and compact techniques (can be retro-fitted)
  - can approach 1-10 fs capability in principle


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

SPARE SLIDES FOLLOW

1. Publications from our group

Role of misalignment-induced angular chirp in the electro-optic detection of THz waves
D. A. Walsh, M. J. Cliffe, R. Pan, E. W. Snedden, D. M. Graham, W. A. Gillespie and S. P. Jamison
Optics Express, 22, 12028-12037 (2014)

Design of an electro-optic bunch length monitor for the CERN-CTF3 probe beam
R. Pan, T. Lefevre, S. P. Jamison, and W. A. Gillespie
Physical Review STAB (2012)

Upconversion of a relativistic Coulomb field terahertz pulse to the near infrared
S.P. Jamison, G. Berden, P.J. Phillips, W.A. Gillespie and A.M. MacLeod
Applied Physics Letters 96 (23) 231114-231114-3 (2010)

Electro-optic time profile monitors for femtosecond electron bunches at the soft x-ray free-electron laser FLASH
B. Steffen, V. Arsov, G. Berden, W.A. Gillespie, S. P. Jamison, et al
Physical Review STAB **12**, 032802:1-16 (2009)

Limitations of electro-optic measurements of electron bunch longitudinal profile.
S.P. Jamison, G. Berden, W.A. Gillespie, P.J. Phillips, and A.M. MacLeod.
Proceedings of 11th European Particle Accelerator Conference (2008) 1149-1151.

Single shot longitudinal bunch profile measurements at FLASH using electro-optic detection techniques.
P.J. Phillips, W.A. Gillespie, S.P. Jamison, V. Arsov, H. Schlarb, B. Schmidt, P. Schmuser, B. Steffen, G. Berden, A.F.G. van der Meer, and A.M. MacLeod.
Proceedings of 11th European Particle Accelerator Conference (2008) 1242-1244.

Single-shot longitudinal bunch profile measurements at FLASH using electro-optic detection.
B. Steffen, E.-A. Knabbe, H. Schlarb, B. Schmidt, P. Schmuser, W.A. Gillespie, P.J. Phillips, G. Berden, A.F.G. van der Meer, A.M. MacLeod
Proceedings of FEL 2007, Novosibirsk, Russia (2007) 310-313.

Benchmarking of electro-optic monitors for femtosecond electron bunches.
G. Berden, W.A. Gillespie, S.P. Jamison, E.-A. Knabbe, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmidt, P. Schmuser, and B. Steffen
Physical Review Letters **99** (2007) 164801.

Single shot longitudinal bunch profile measurements by temporally resolved electro-optic detection.
P.J. Phillips, W.A. Gillespie, B. Steffen, E.-A. Knabbe, B. Schmidt, P. Schmuser, S.P. Jamison, G. Berden, A.F.G. van der Meer, and A.M. MacLeod
Proceedings of DIPAC 2007, Venice, Italy (2007) 221-223.

Single shot longitudinal bunch profile measurements at FLASH using electro-optic techniques.
G. Berden, A.F.G. van der Meer, S.P. Jamison, B. Steffen, E.-A. Knabbe, B. Schmidt, P. Schmuser, A.M. MacLeod, P.J. Phillips, and W.A. Gillespie.
Proceedings 10th European Particle Accelerator Conference (2006) 1055-1057.

Time resolved single-shot measurements of transition radiation at the THz beamline of FLASH using electro-optic spectral decoding.
G. Berden, A.F.G. van der Meer, S.P. Jamison, B. Steffen, E.-A. Knabbe, B. Schmidt, P. Schmuser and W.A. Gillespie.
Proceedings of 10th European Particle Accelerator Conference (2006) 1058-1060.

Femtosecond resolution bunch profile measurements.
S.P. Jamison, G. Berden, A.M. MacLeod, B. Steffen, P.J. Phillips, and W.A. Gillespie.
Proceedings of 10th European Particle Accelerator Conference (2006) 915-919.

Temporally-resolved electro-optic effect.
S.P. Jamison, A.M. MacLeod, G. Berden, D.A. Jaroszynski, and W.A. Gillespie.
Optics Letters, **31** (2006) 1753.

Electro-optic techniques for temporal profile characterisation of relativistic Coulomb fields and coherent synchrotron radiation.
S.P. Jamison, G. Berden, A.M. MacLeod, D.A. Jaroszynski, B. Redlich, A.F.G. van der Meer, W.A. Gillespie.
Nuclear Instruments and Methods in Physics Research A **557** (2006) 305-308.

Real-time, single-shot temporal measurements of short electron bunches, terahertz CSR and FEL radiation.
G. Berden, B. Redlich, A. van der Meer, S.P. Jamison, W.A. Gillespie.
Proceedings of 7th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (2005) 69-71.

High temporal resolution, single shot electron bunch-length measurements.
G. Berden, B. Redlich, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, W.A. Gillespie.
Proceedings 26th international FEL confrence (2004) 343-346.

High temporal resolution, single shot electron bunch-length measurements.
G. Berden, B. Redlich, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, W.A. Gillespie.
Proceedings 9th European Particle Accelerator Conference (2004) 2697-2699.

Electro-optic technique with improved time resolution for real-time, nondestructive, single-shot measurements of femtosecond electron bunch profiles.
G. Berden, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, B. Redlich, and A.F.G. van der Meer.
Physical Review Letters **93** (2004) 114802.

Single shot electron-beam bunch length measurements.
G. Berden, G. Knippels, D. Oepts, A.F.G. van der Meer, S.P. Jamison, X. Yan, W.A. Gillespie, J.L. Shen, and I. Wilke.
Proceedings of 6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (2003) 20-24.

[**Chirped-laser based electron bunch length monitor.**]
G. Berden, G. Knippels, D. Oepts, A.F.G. van der Meer, S.P. Jamison, X. Yan, W.A. Gillespie, J.L. Shen, and I. Wilke.
Proceedings of the 2003 Particle Accelerator Conference (2003) 519-523.
[**Time-domain terahertz science improves relativistic electron-beam diagnostics.**]
I. Wilke, A.M. MacLeod, W.A. Gillespie, G. Berden, G.M.H. Knippels, and A.F.G. van der Meer.
Optics & Photonics News **13** (2002) 16.
[**Real-time single shot electron bunch length measurements.**]
I. Wilke, W.A. Gillespie, G. Berden, G.M.H. Knippels, and A.F.G. van der Meer.
Nuclear Instruments and Methods in Physics Research A **483** (2002) 282-285.
[**Single-shot electron-beam bunch length measurements.**]
I. Wilke, W.A. Gillespie, G. Berden, G.M.H. Knippels, and A.F.G. van der Meer.
Physical Review Letters **88** (2002) 124801.

2. Other relevant publications in these areas

[**Extending electro-optic detection to ultrashort electron beams**]
M. H. Helle, D. F. Gordon, D. Kaganovich and A. Ting
Physical Review Special Topics - Accelerators and Beams **15** (5), 052801 (2012)
[**Single-shot spatiotemporal measurements of ultrashort THz waveforms using temporal electric-field cross correlation**]
N. H. Matlis, G. R. Plateau, J. van Tilborg, and W. P. Leemans
J. Opt. Soc. Am. B 28, 23-27 (2011)
[**Few-femtosecond time-resolved measurements of X-ray free-electron lasers**]
C. Behrens, F-J. Decker, Y. Ding, V.A. Dolgashev, J. Frisch, Z. Huang, P. Krejcik, H. Loos, et al
Nature Communications, 5.3762 (Apr 2014)
[**TADPOLE for longitudinal electron-bunch diagnostics based on electro-optic upconversion**]
J-P. Schwinkendorf, S. Wunderlich, L. Schaper, B. Schmidt and J. Osterhoff, NIM A 740 (2014) 222-225
[**Femtosecond x-ray pulse temporal characterization in free-electron lasers using a transverse deflector**]
Y. Ding, C. Behrens, P. Emma, J. Frisch, Z. Huang, H. Loos, P. Krejcik and M-H. Wang
PRSTAB: **14**. 120701 (2011)
[**Bunch length measurements in CTF3**]
A. Dabrowski, S. Bettoni, H.H. Braun, R. Corsini, T. Lefevre et al
Proceedings of LINAC08, Victoria, BC, Canada
[**Transverse deflecting structures for bunch lengthy and slice emittance measurement on SwissFEL**]
P. Craievich, R. Ischebeck, F. Loehl, G.L. Orlandi, E. Prat, Proceedings of FEL2013, New York, NY, USA

Energy slicing analysis for time-resolved measurement of electron-beam properties
E. Allaria et al. Phys.Rev.ST Accel.Beams 17 (2014) 1, 010704
Single-shot fs electron bunch diagnostic (using CTR)
O. Zarini et al., LA3NET workshop, Dresden, April 2014
Coherent radiation spectrum measurements at KEK LUCX facility
M. V. Shevelev et al, NIMA 11, 771 (2014)
Longitudinal bunch profile diagnostics with coherent radiation at FLASH
E. Haas, C. Gerth, B. Schmidt, S. Wesch and M. Yan
Proc. SPIE 8778, Advances in X-ray Free-Electron Lasers II: Instrumentation, 87780M (2013)
Measurement of <20 fs bunch length using coherent transition radiation
I. Nozawa et al. Phys.Rev.ST Accel. Beams 17 (2014) 7, 07280
Coherent Radiation Spectroscopy of Few-Femtosecond Electron Bunches Using a MIR Prism Spectrometer
T. J. Maxwell et al. Phys. Rev. Lett. 111 (2013) 18, 184801 SLAC-PUB-15692
Transverse deflecting structures for bunch lengthy and slice emittance measurement on SwissFEL
P. Craievich, R. Ischebeck, F. Loehl, G.L. Orlandi, E. Prat
Proceedings of FEL2013, New York, NY, USA
Novel nondestructive shot-by-shot monitor to measure 3D bunch chargedistribution with femtosecond EO sampling
H. Tomizawa, S. Matsubara, H. Dewa, A. Mizuno, T. Taniuchi, K. Yanagida, and H. Hanaki.
Proceedings of FEL 2010, Malmo, Sweden, 2010.
Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation
P. Karataev et al., J. Phys. Conference Series, 236(1):01202 (2010)
Coherent Radiation Diagnostics for Short Bunches
O. Grimm, Particle Accelerator Conference (PAC 07), Albuquerque, New Mexico, (2007) p.2653
Spectral sidebands on a narrow-bandwidth optical probe as a broad-bandwidth thz pulse diagnostic
J. van Tilborg, D.J. Bakker, N.H. Matlis, and W.P. Leemans. Optics Express, 19(27), December 2011
Electro-optic methods for longitudinal bunch diagnostics at FLASH
Bernd R Steffen. PhD thesis, Hamburg University, 2007
Measurements of coherent diffraction radiation and application for bunch length diagnostics in particle accelerators
M. Castellano, V. A. Verzilov, L. Catani, A. Cianchi, G. Orlandi, and M. Geitz.
Phys Rev E, 63(056501), 2001
Electron bunch shape measurement using coherent diffraction radiation
B. Feng, M. Oyamada, F. Hinode, S. Sato, Y. Kondo, Y. Shibata, and M. Ikezawa.
Nuclear Instruments and Methods in Physics Research A, 475:492-497, 2001

Kramers-Kronig Phase Reconstruction

$$|\tilde{E}_{\rm det}(\omega)|^2 \propto |\tilde{E}_{\rm source}(\omega)|^2 T(\omega, \gamma, \cdots)$$

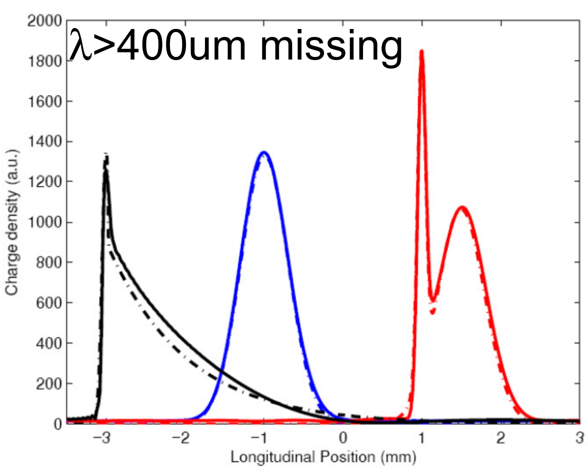
Transfer function must be known (from calculation or experiment)

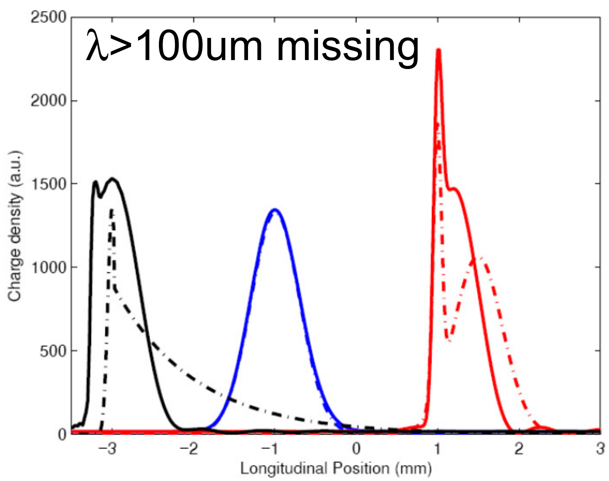
phase to be inferred (via K-K relations)

$$\tilde{E}_{\rm source}(\omega, \underline{\boldsymbol{x}}) \propto \int \rho(t, \underline{\boldsymbol{x}}) e^{i\omega t} dt$$

Missing data & incorrect calibration can influence results

Always have very long wavelengths missing! (diffraction)





original
reconstructed

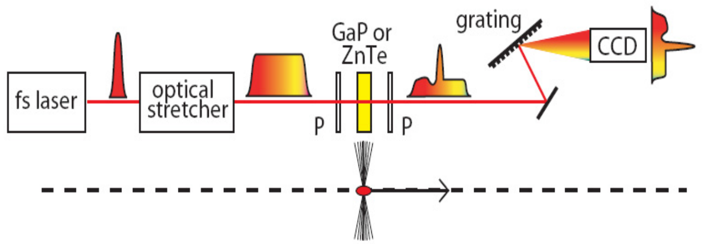
O. Grimm, P. Schmuser
Tesla-FEL 2006-04

Solution for phase not unique:

Retrieves the "minimum" phase only
e.g. could not retrieve a chirped pulse

Without other information (accel phys simulation?) leaves uncertainty in reliability of profile

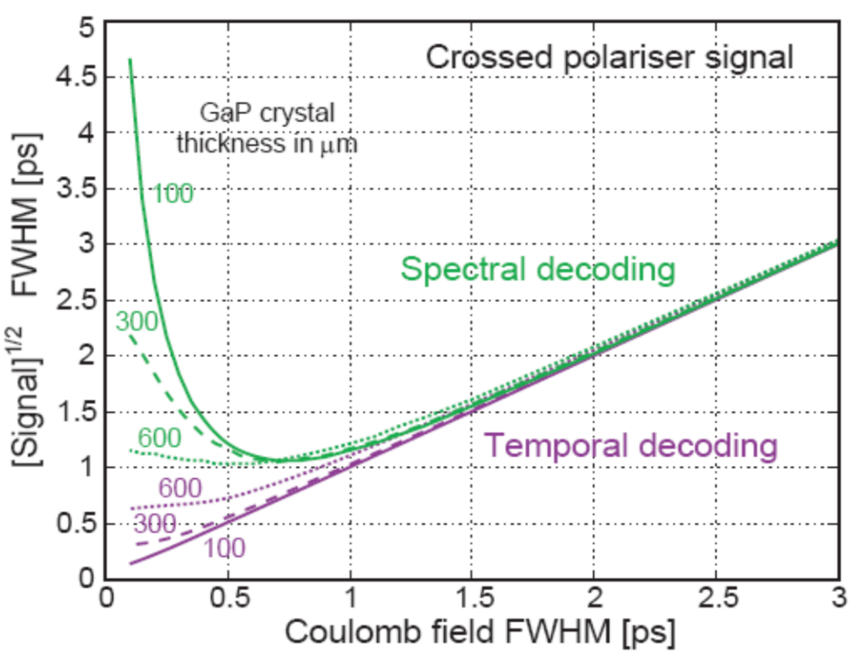
Spectral Decoding (EOSD)



Attractive simplicity for low time resolution measurements e.g. injector diagnostics

Rely on t-λ relationship of input pulse for interpreting output optical spectrum.

Resolution limits come from the fact that the EO-generated optical field doesn't have the same t-λ relationship



temporal resolution limits:

EOSD limited by chirp

Can relate to FWHM durations…

$$\tau_{\mathrm{lim}} = \sqrt{12\pi\beta}$$

$$\tau_{\mathrm{lim}} = 2.61\sqrt{T_0 T_c} \quad \text{; for a Gaussian pulse}$$

Conclusion:
Unlikely to get better than 1.0 ps (FWHM) with Spectral Decoding

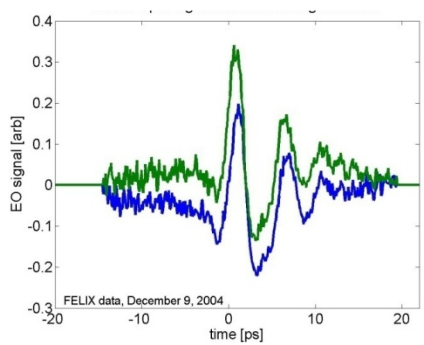
General status of electro-optic systems

Many *demonstrations*...

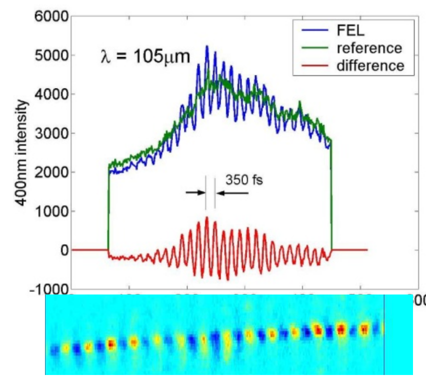
Accelerator Bunch profile -	FLASH, FELIX, SLAC, SLS, ALICE, FERMI ....
Laser Wakefield experiments -	CLF, MPQ, Jena, Berkley, ...
Emitted EM (CSR, CTR, FEL) -	FLASH, FELIX, SLS, ...

Temporal Decoding @FLASH

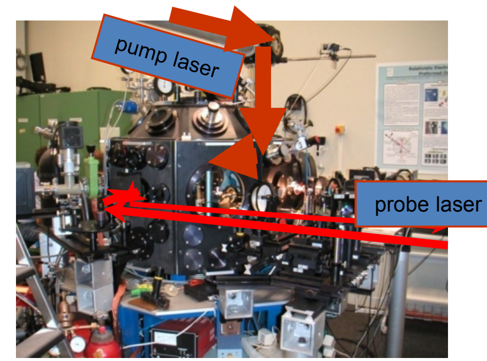
CSR @FELIX



Mid-IRFEL lasing @FELIX



Laser Wakefield @ M-P Garching



Few facility implementations: remaining as experimental / demonstration systems

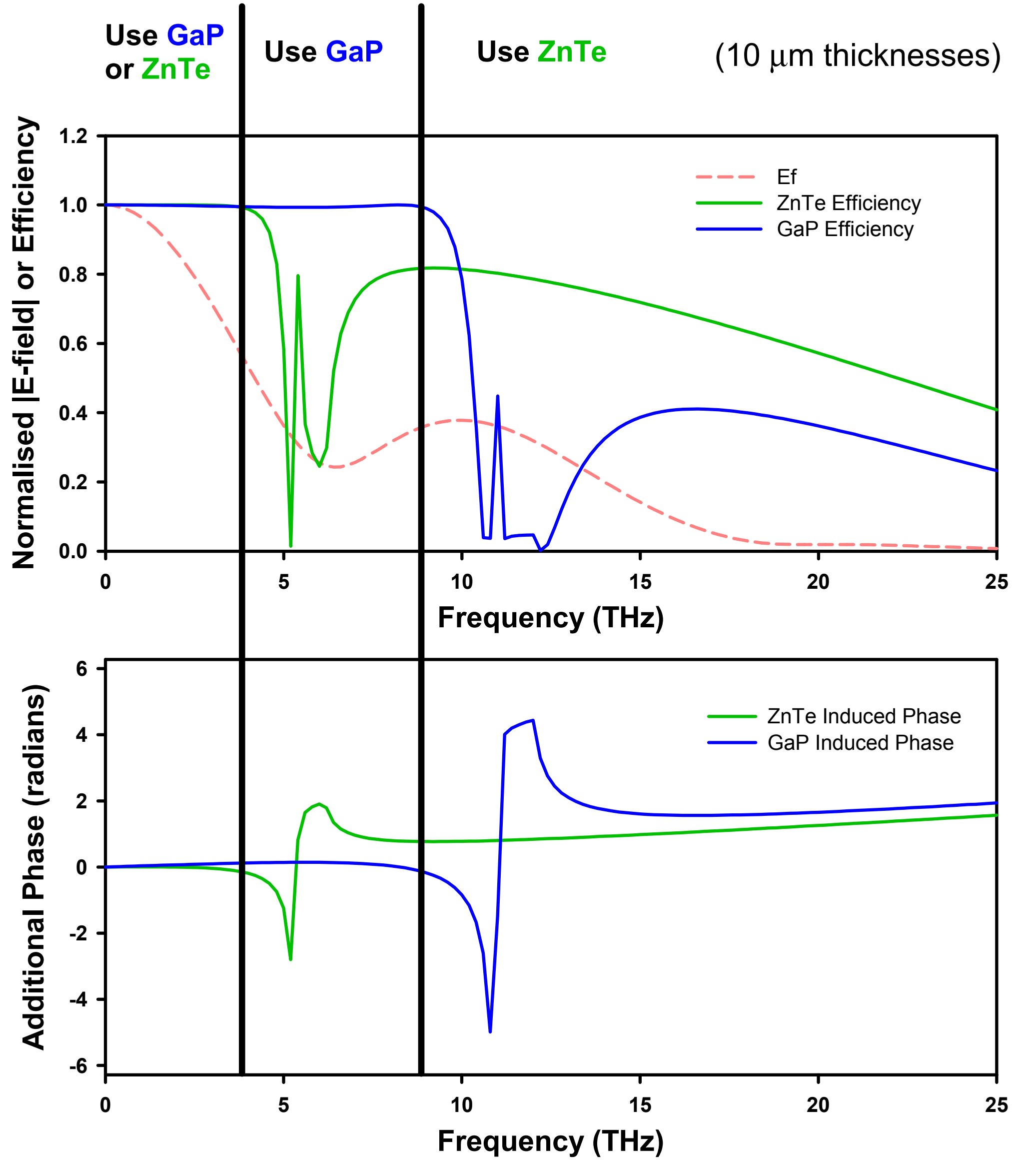
- Complex & temperamental laser systems
- Time resolution “stalled” at ~100fs

Phys Rev Lett **99** 164801 (2007)
Phys. Rev. ST **12** 032802 (2009)

Spectral Compositing of Multiple Crystals

- Phasematching not the whole story
  - Dips caused by absorption near phonons
  - Phase distortions near absorptions become very large
  - Distortions in $\chi^{(2)}$ near absorptions
- Discard data around the absorption lines
- Fill in the blanks with different crystals

In theory seems sound.
Not yet demonstrated.



EO Temporal Resolution Limitations

EO transposition scheme is now limited by materials

- Phase matching and absorption bands in ZnTe & GaP
- Other materials are of interest, such as DAST or poled polymers, but there are questions over their lifetime in accelerator environments

Collaborative effort with MAPS group at the University of Dundee on development of novel EO materials

- Potential to produce a significant enhancement of nonlinear processes through embedded metallic nanoparticles
- THz field induced second harmonic TFISH enhancement being investigated.
- Surface nonlinear effects …

A key property of the EO Transposition scheme may be exploited

- FROG (Grenouille) retrieves the spectral amplitude and phase
- At frequencies away from absorptions etc. the spectrum should still be faithfully retrieved
- Potential to run two, "tried and tested", crystals with complementary response functions side by side to record FULL spectral information!

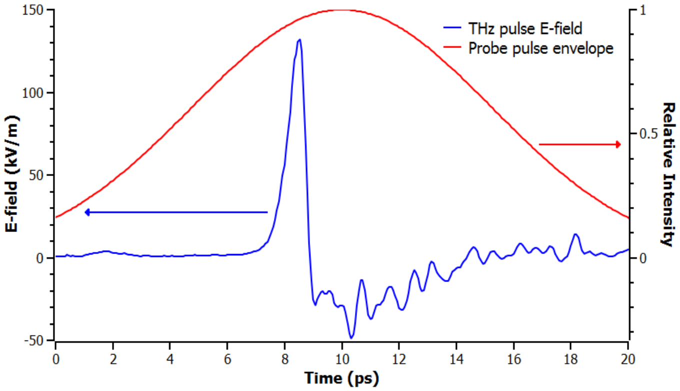
Transposed Pulse Measurements

Input pulses

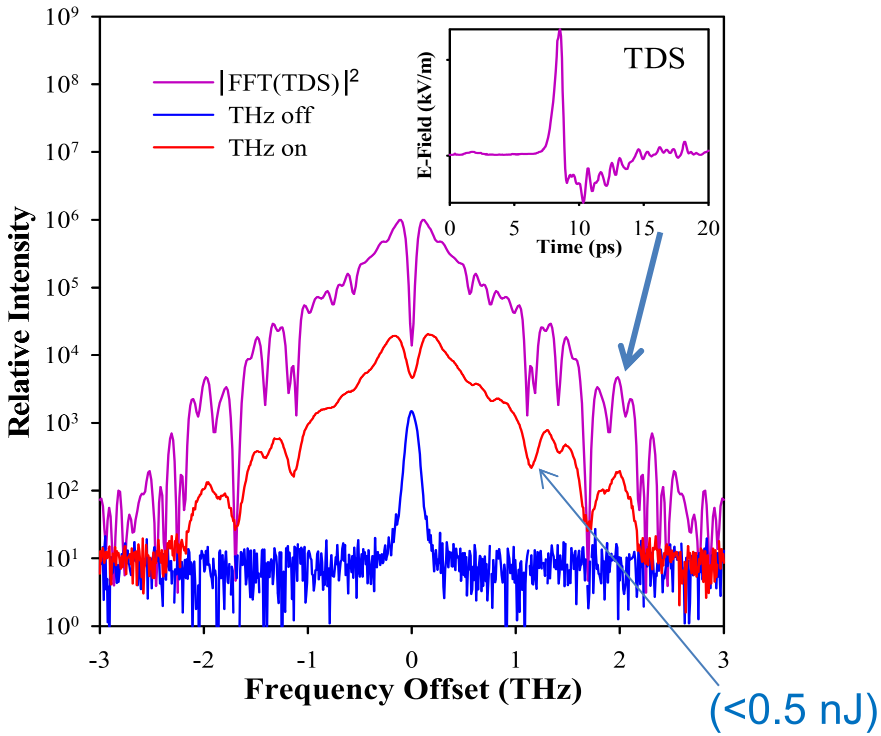
Optical probe length Δt ~ 10 ps

Optical probe energy S ~ 28 nJ

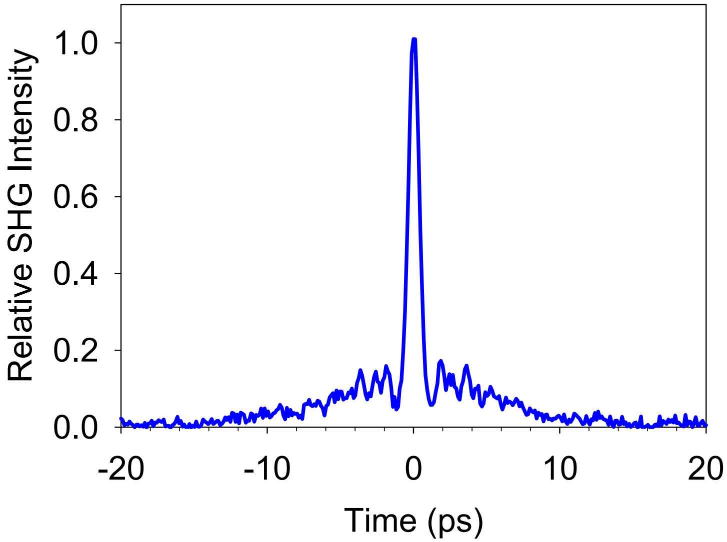
THz field strength E ~ 132 kV/m



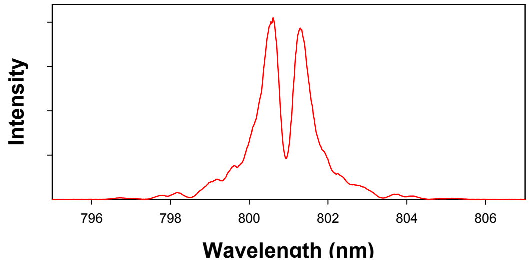
Spectral Measurement

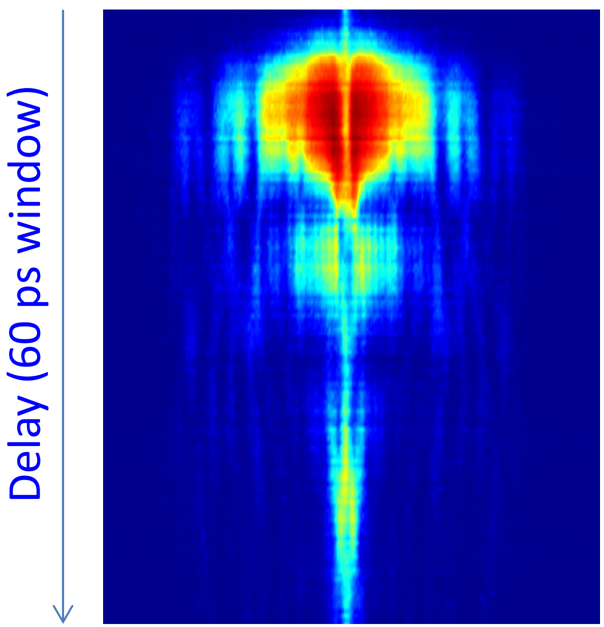


Autocorrelation



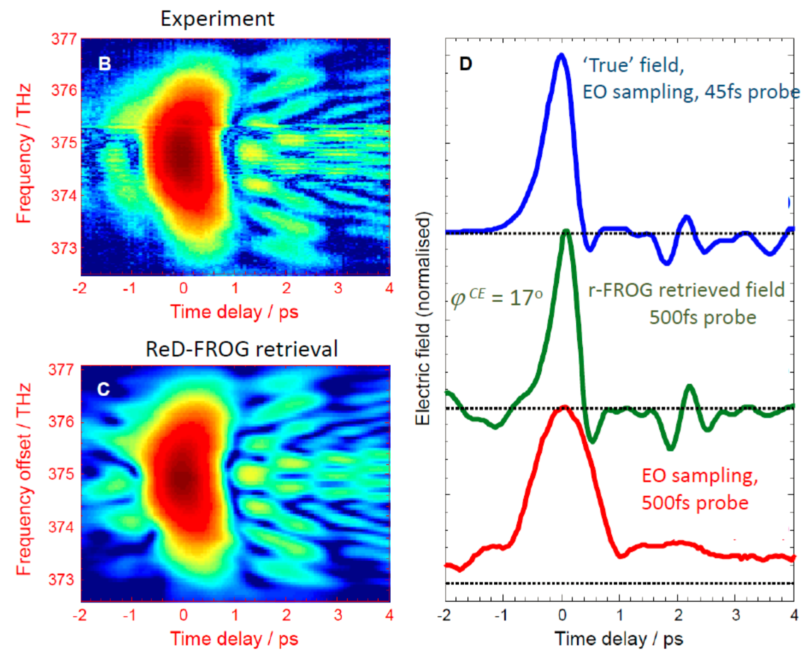
New THz Measurement Scheme
(an absolute phase FROG!)





This looks like a spectrogram!

- This is a FROG where both SFG and DFG mechanisms are present and spectrally overlap.
- A FROG algorithm was modified to account for this.
- Essentially, the interference pattern between SFG and DFG in the trace reveals the absolute phase.



Theory extended to optical pulses and is being published (**arXiv:1501.04864** **[physics.optics]**)