Femtosecond resolution bunch profile diagnostics

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Femtosecond longitudinal diagnostics

Radiative Spectral Techniques

- CTR, CDR, CSR spectral characterisation
- CTR, CDR autocorrelation
- Smith Purcell

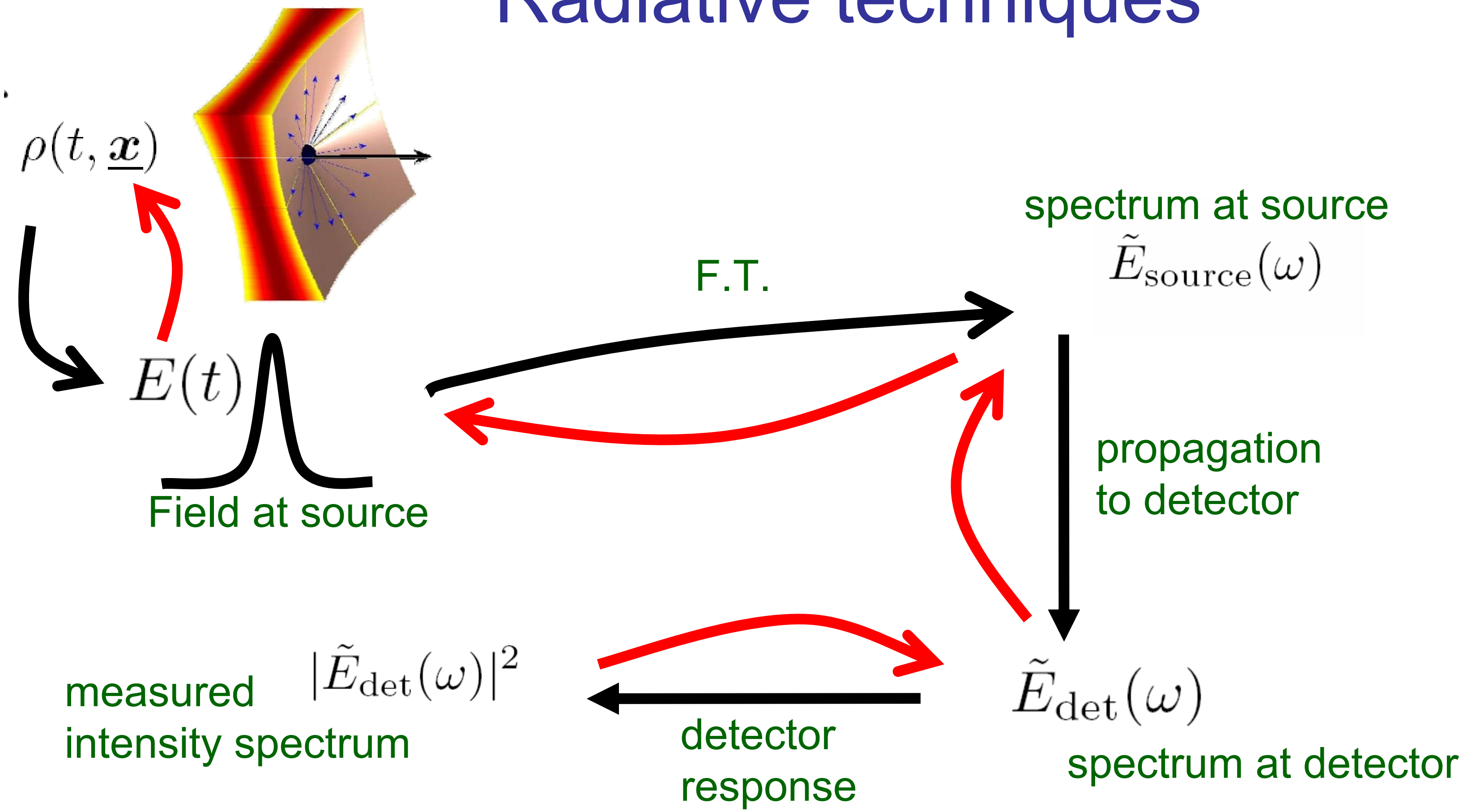
Electro-optic Techniques

- Scanning/Sampling
- Temporal decoding
- Spectral decoding
- Spatial encoding

Direct Particle Techniques

- RF zero-phasing
- Transverse deflecting cavities
- Optical replicas

Radiative techniques



$\rho(t, \underline{\boldsymbol{x}})$

$E(t)$

Field at source

F.T.

spectrum at source

$\tilde{E}_{\mathrm{source}}(\omega)$

propagation
to detector

$\tilde{E}_{\mathrm{det}}(\omega)$

spectrum at detector

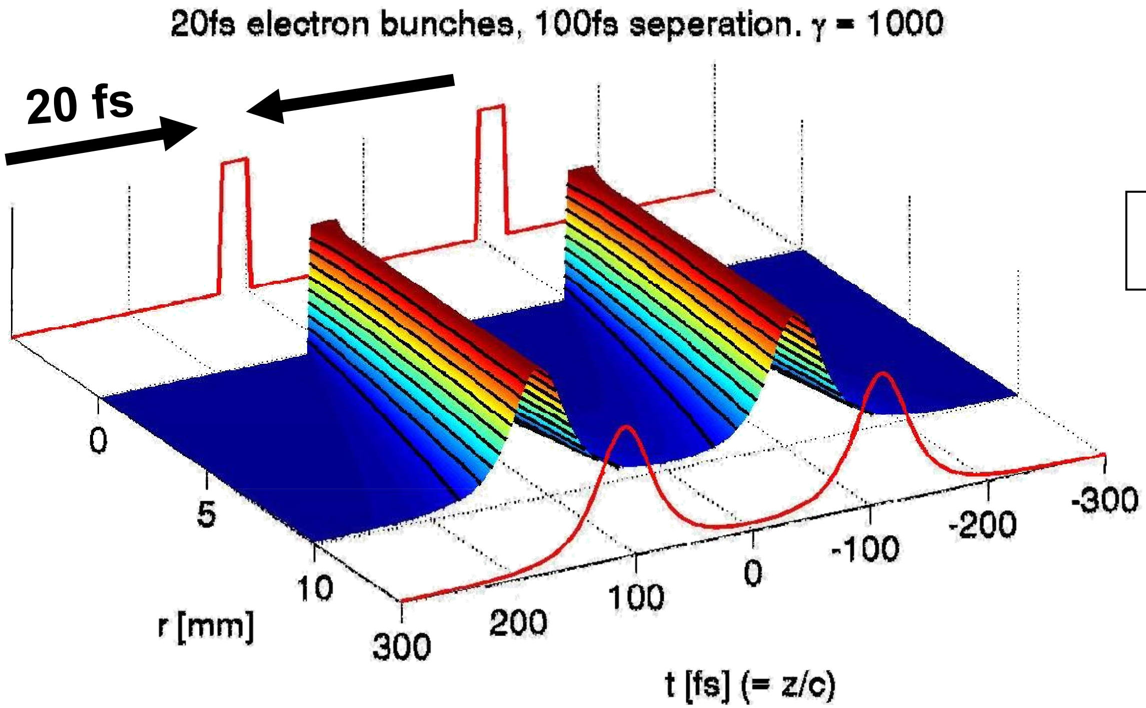
detector
response

measured
intensity spectrum

$|\tilde{E}_{\mathrm{det}}(\omega)|^2$

- Transfer function (radiator to detector)?
- Spectral Phase???

Field at Source



$\gamma = 1000$

Spectrum of field dependent on spatial position:

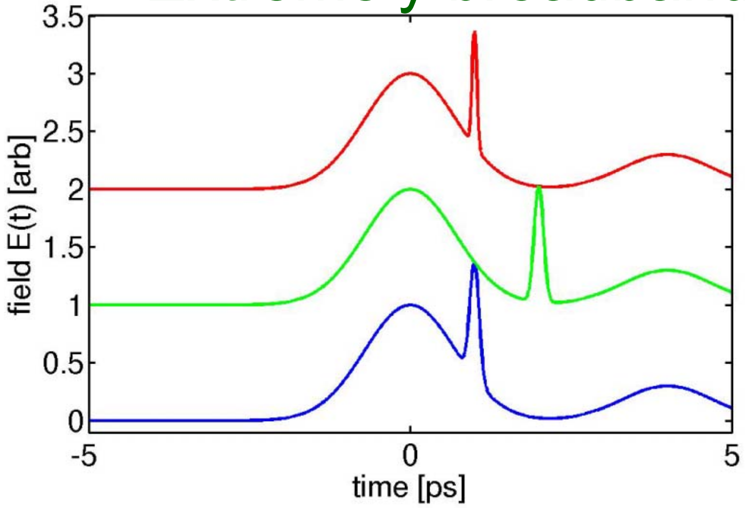
$$\delta t \sim 2R/c\gamma$$

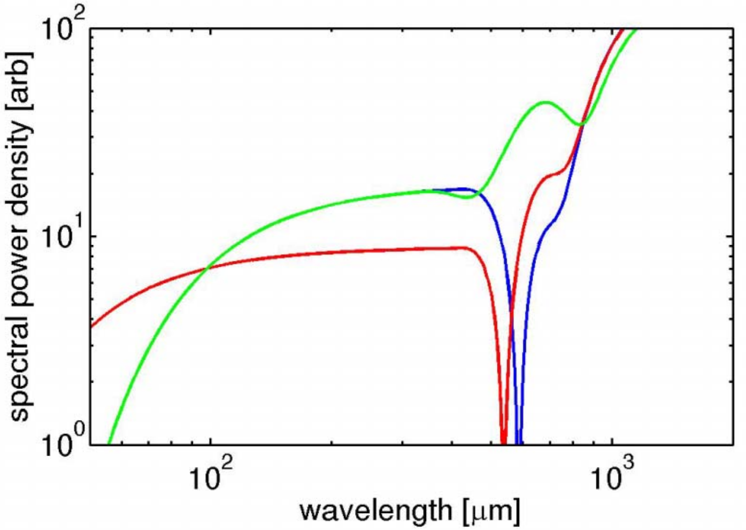
Ultrafast time resolution needs close proximity to bunch

(equally true of CDR, Smith-Purcell, Electro-optic etc)

Field at Source

Extremely broadband spectrum from short pulses.





More than an order of magnitude in frequency / wavelength

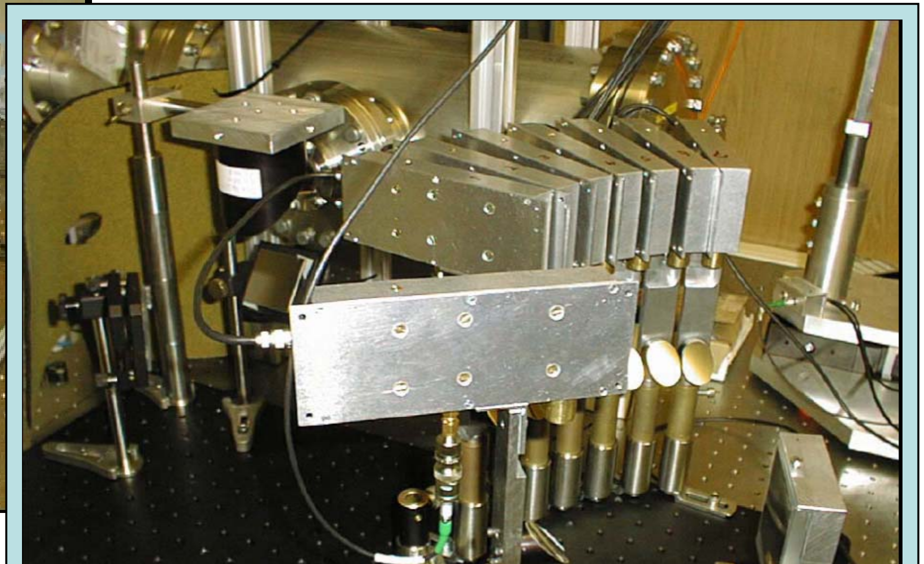
Short wavelengths contain the fast structure information

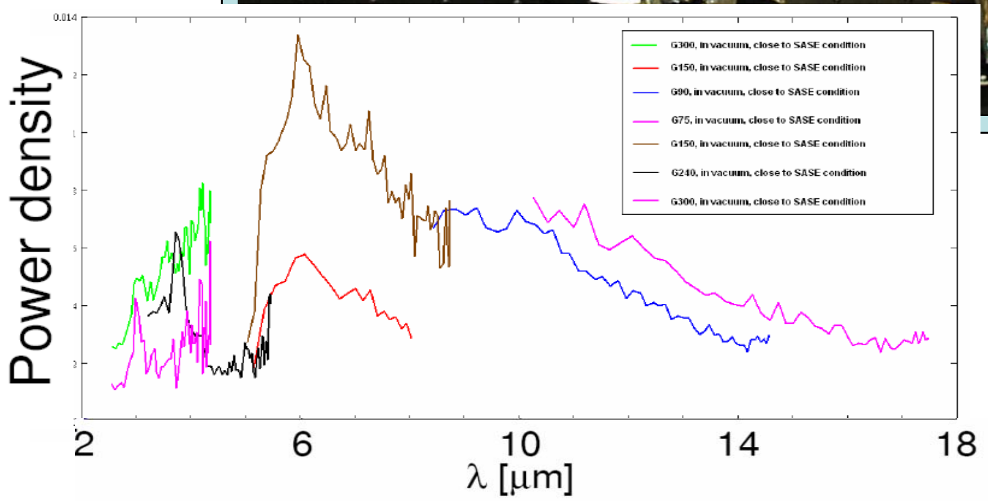
long wavelengths needed for bunch reconstruction

diffraction grating spectrometer... (CTR at FLASH)

scanning spectral measurement

single-shot spectrograph

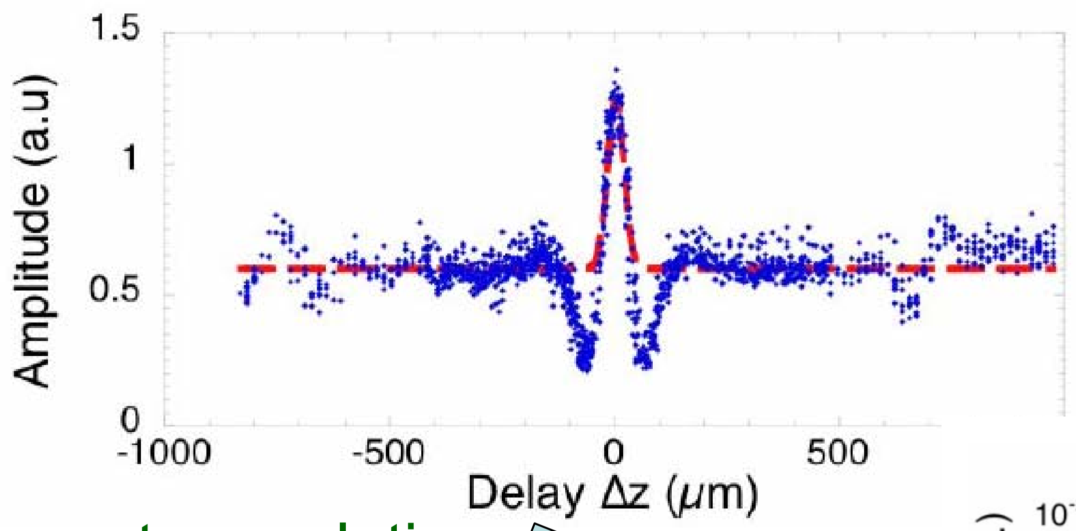


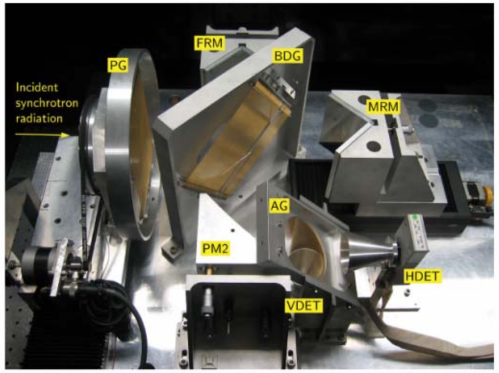


H. Delsim-Hashemi et al.
FALS'06, EPAC'06

Michelson-Morley interferometer...

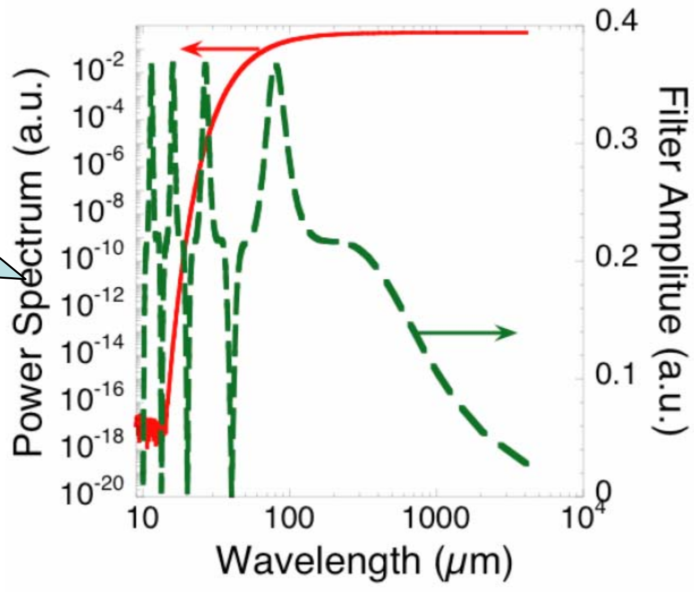
(CTR at SLAC/FFTB)





autocorrelation

Determined 210 fs FWHM



spectrum
corrected for
transmission

Muggli et al. PAC'05

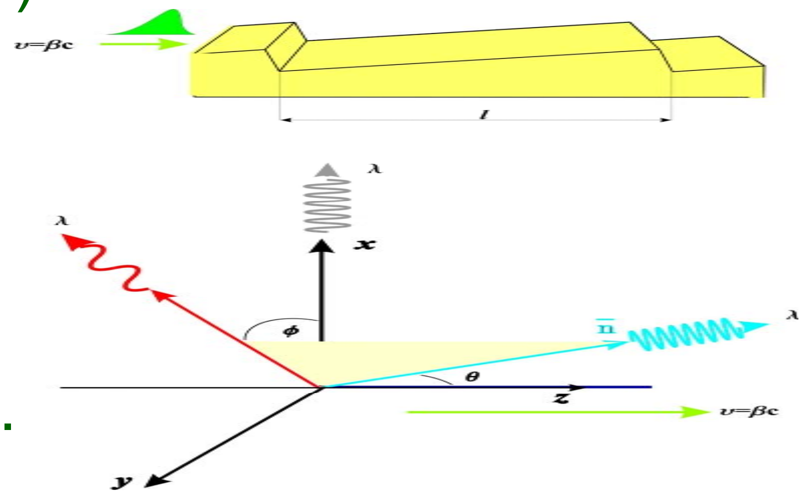
Smith-Purcell radiation

Grating structure in beamline

both radiator, and spectral dispersive element

Can enhance radiated power
(α number of grating periods)

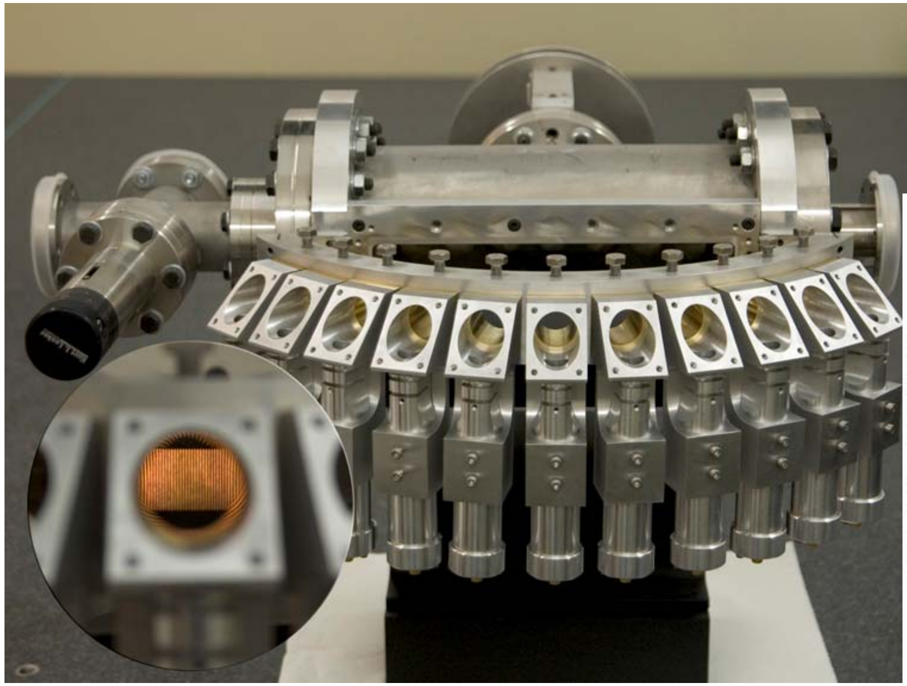
$$\lambda_n = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



Grating period chosen to optimise radiation at wavelengths of interest.

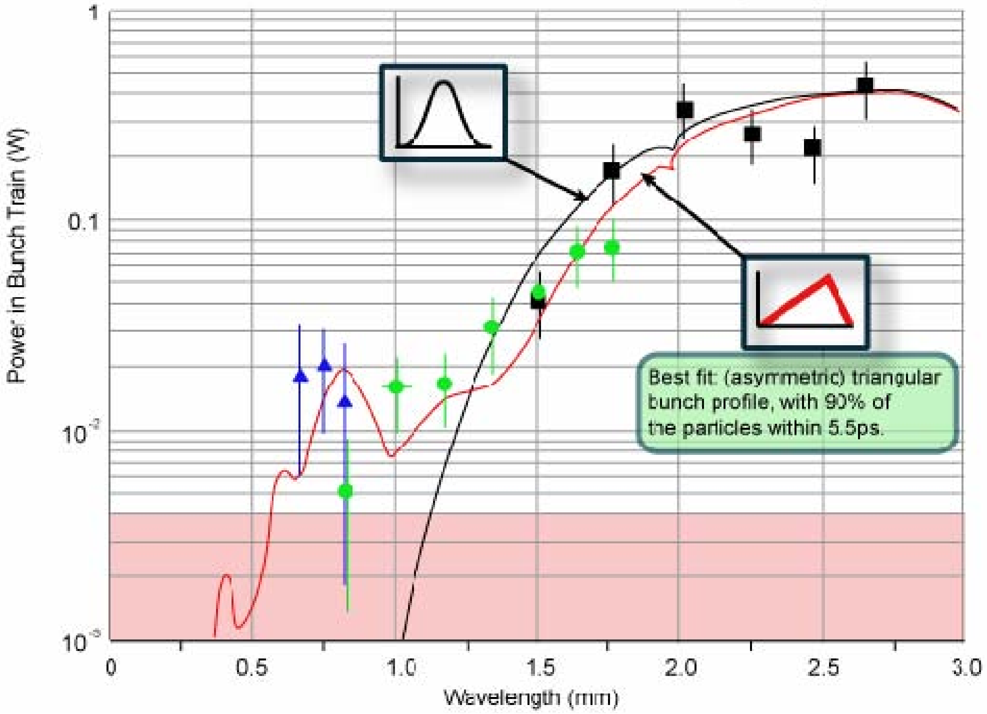
- Non-invasive method
- Compact & robust experimental equipment
- Relatively inexpensive and simple setup.

Multi-element detector for S-P radiation



Doucas, Blakemore
EPAC'06: TUPCH042, TUPCH043

FELIX data, 45MeV, 200pC



Best fit: (asymmetric) triangular bunch profile, with 90% of the particles within 5.5ps.

See also Korbly et al. Phys. Rev. ST; 9 (2006) 22802

Kramers-Kronig Phase Reconstruction...

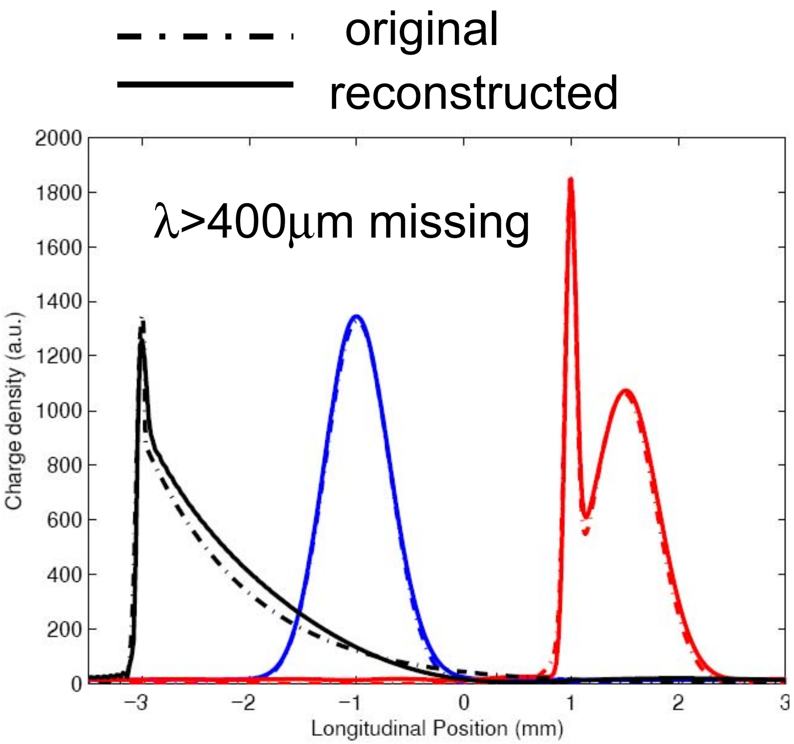
$$\underbrace{|\tilde{E}_{\mathrm{det}}(\omega)|^2} \propto |\tilde{E}_{\mathrm{source}}(\omega)|^2 \boxed{T(\omega,\gamma,\cdots)}$$

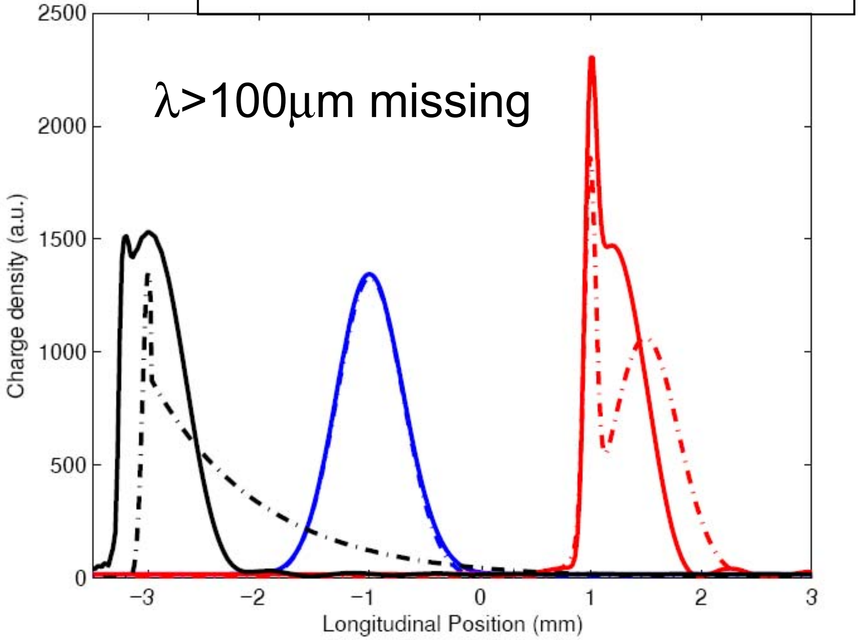
Transfer function must be known
(from calculation or experiment)

phase to be inferred
(via K-K relations)

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

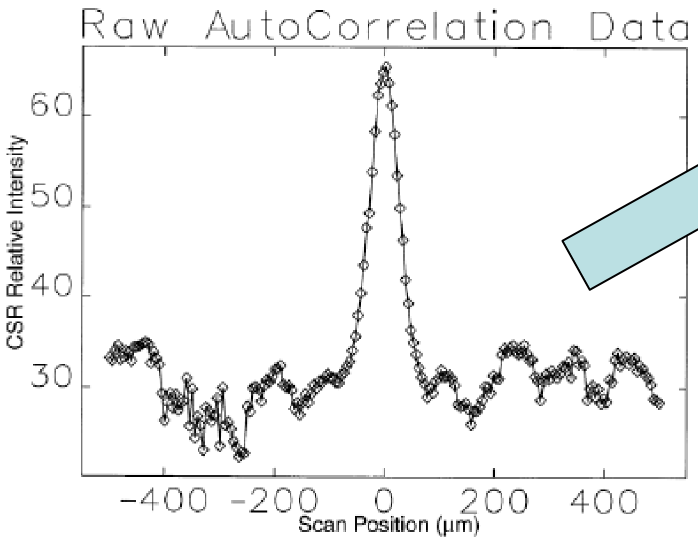
O. Grimm, P. Schmüser
Tesla-Fel 2006-04





Kramers-Kronig Phase Reconstruction...

An example from APS...

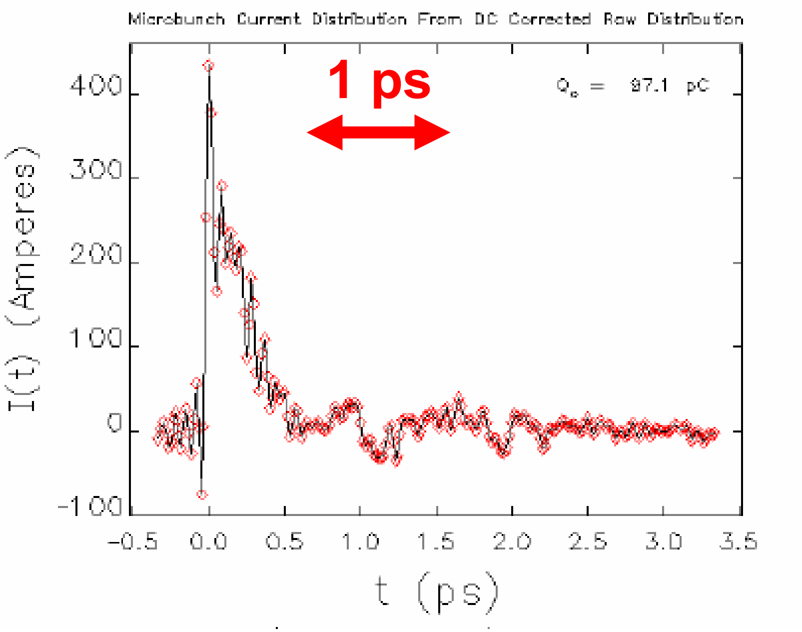


auto-correlator / interferometer data...

...intensity spectrum...

...Kramer-Kronig phase retrieval...

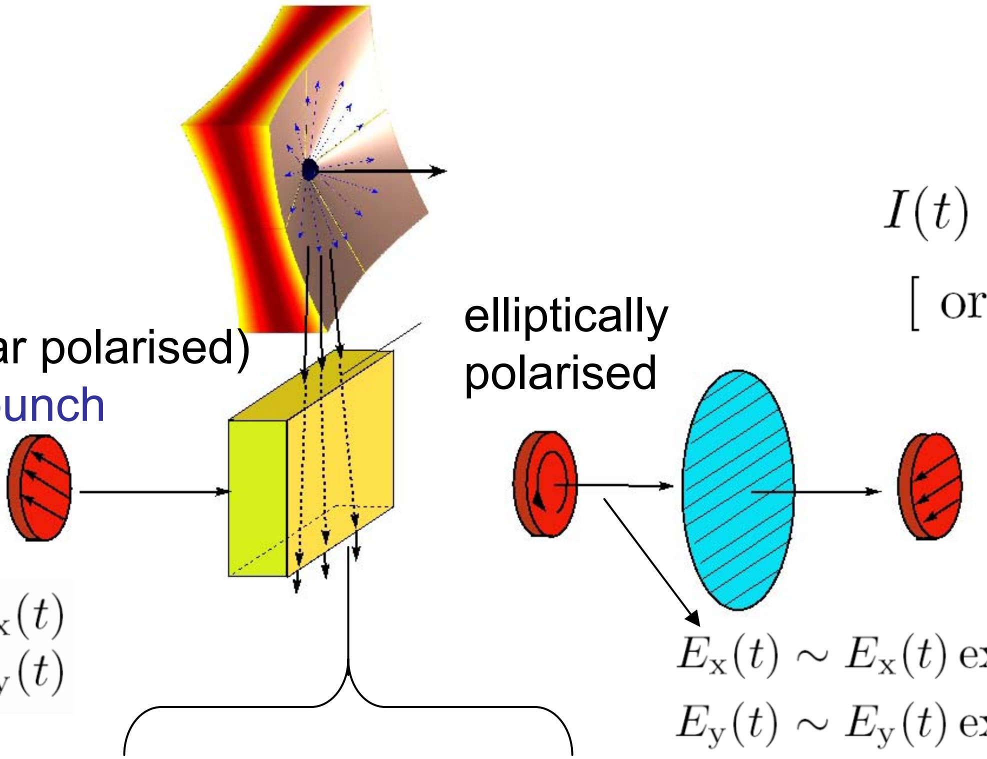
...inferred bunch profile.



Lumpkin et al, FEL 2005

Electro-optic Techniques

Refractive index α Coulomb Field



laser pulse (linear polarised)

Comoving with bunch

elliptically polarised

$$I(t) \propto E_{\mathrm{Coul}}(t)$$

$$[\ \text{or} \quad \propto E^2_{\mathrm{Coul}}(t) \quad]$$

$$E_{\mathrm{x}}(t)$$
$$E_{\mathrm{y}}(t)$$

$$E_{\mathrm{x}}(t) \sim E_{\mathrm{x}}(t)\exp(i\omega t - i\eta\omega z/c)$$
$$E_{\mathrm{y}}(t) \sim E_{\mathrm{y}}(t)\exp(i\omega t - i\eta\omega z/c)$$

$$\eta_{\mathrm{x}}(t) = \eta_0(t) + \alpha_{\mathrm{x}} E_{\mathrm{Coul}}(t)$$
$$\eta_{\mathrm{y}}(t) = \eta_0(t) + \alpha_{\mathrm{y}} E_{\mathrm{Coul}}(t)$$

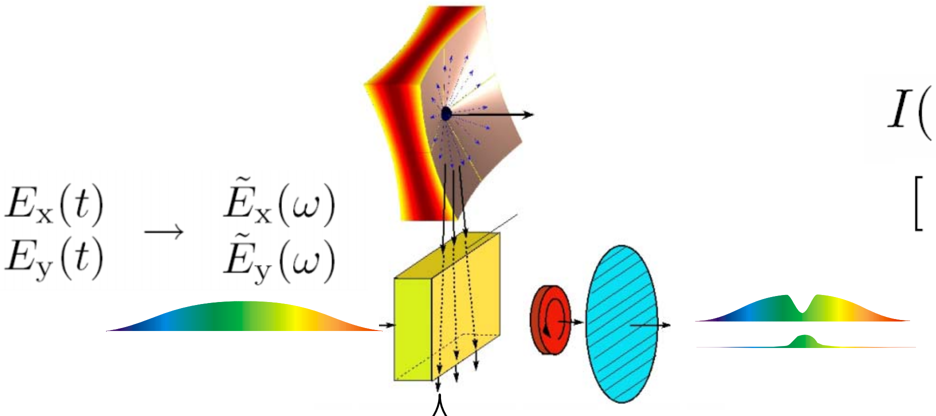
Chirped optical pulses?
E(ω,*t*) ?

Electro-optic Techniques....

shifting Coulomb spectrum to optical region

OR

creating an optical “replica” of Coulomb field



$$I(t) \propto E_{\mathrm{Coul}}(t)$$

$$[\text{ or } \propto E^2_{\mathrm{Coul}}(t) \quad]$$

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

Coulomb spectrum combined with optical spectrum

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

Coulomb pulse replicated in optical pulse

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

Coulomb spectrum shifted to optical region...

Far-infrared (CTR etc)	Optical “replica” of Coulomb field
$\delta\lambda/\lambda \sim 1$	$\delta\lambda/\lambda \sim 0.05$
$\lambda \sim 50\ \mu\text{m} – 1000\ \mu\text{m}$ (missing DC component)	$\lambda \sim 800$ nm
“single-cycle” pulse	standard optical pulse

gained

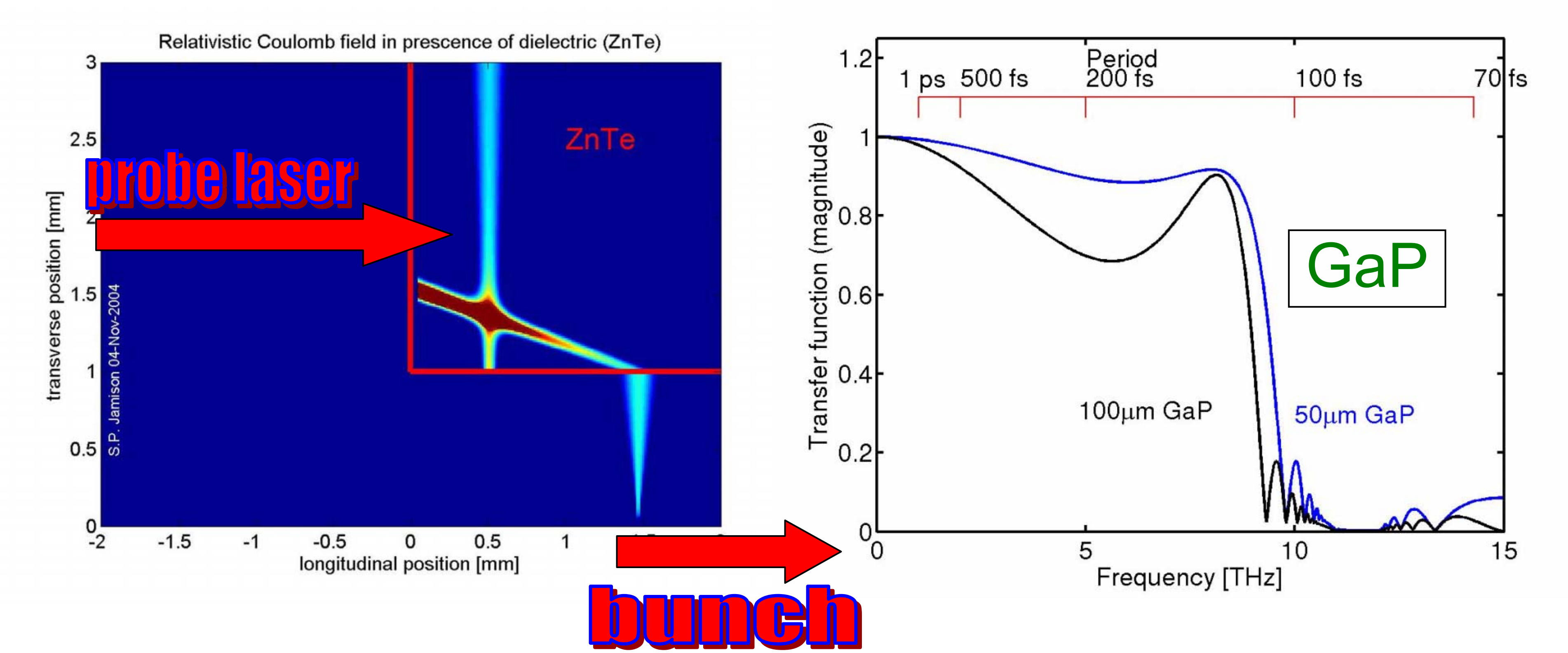
- Optical propagation easy [but not always! (fibres)]
- Narrower bandwidth : eases windows problems, absorption, etc
- Ultrafast optical time-domain detection a standard technology
- Single-shot optical spectral measurement trivial
- DC component converted to optical region...it is detected

lost

- Conversion process may need calibration...
  (important for sub 300fs FWHM bunches)
- Cost... (may change with fibre lasers)

Encoding Time Resolution...

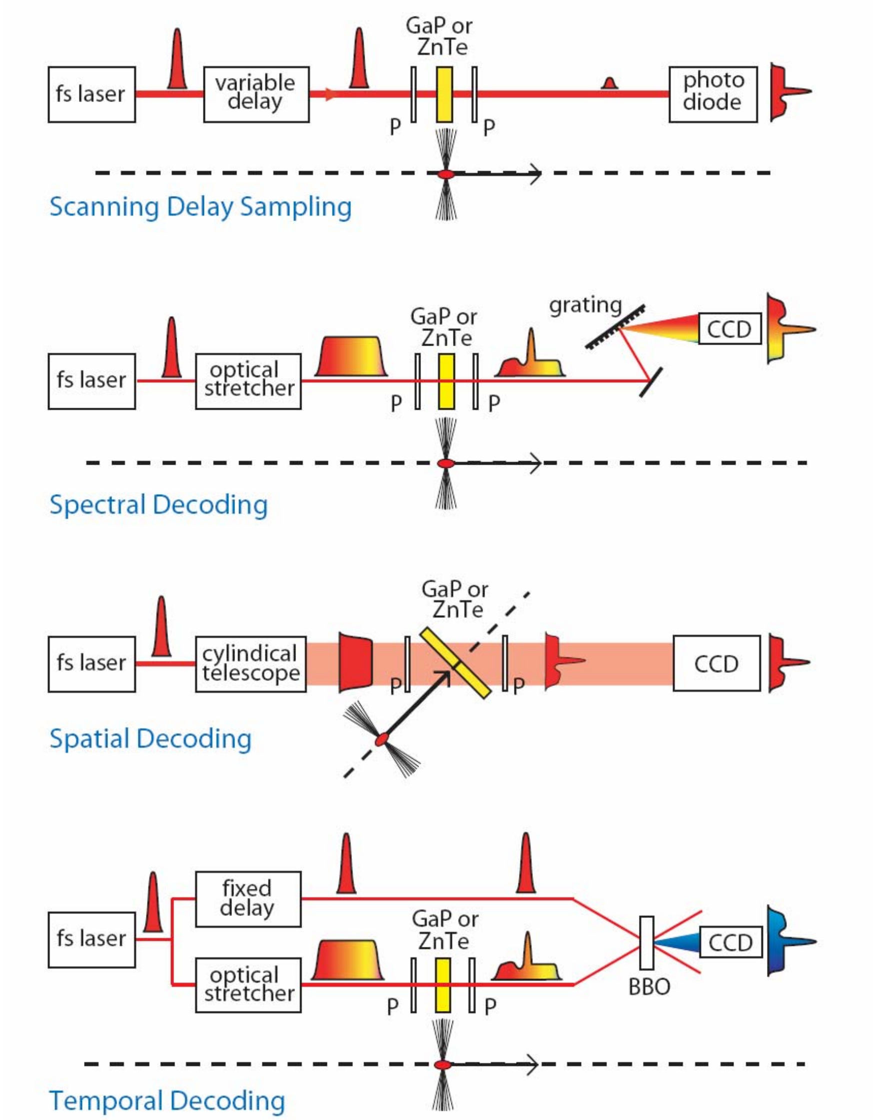
material response, R(ω)



Uniform response <8THz (λ >40 μm)

⇒ Faithful reproduction of > 150 fs (FWHM) bunches

Decoding methods...



FELIX,
DESY
SLS
BNL
...

FELIX
DESY
BNL
...

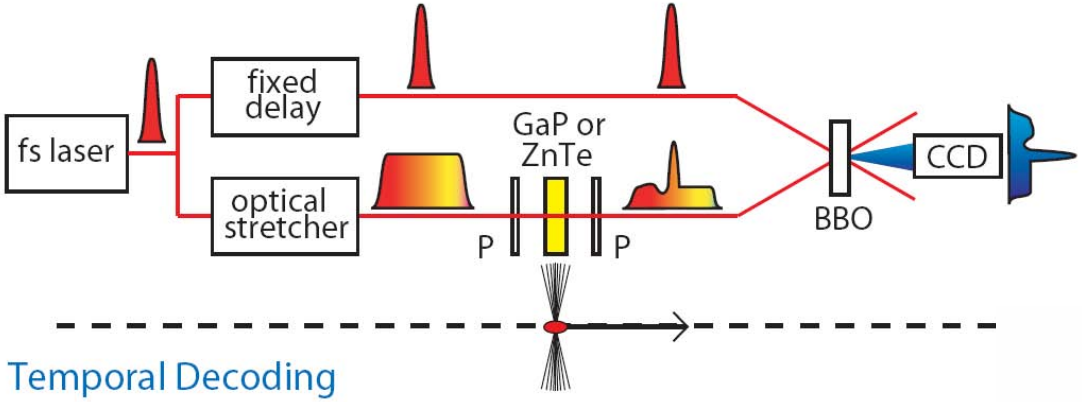
SLAC
DESY

FELIX
DESY

increasing complexity

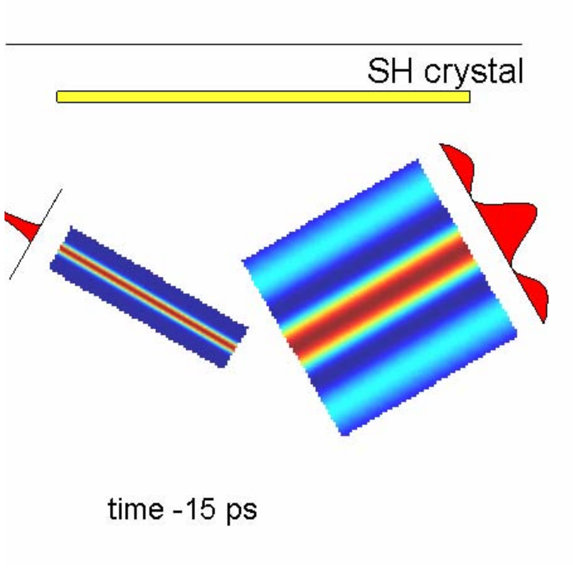
demonstrated time resolution

An example... Temporal decoding



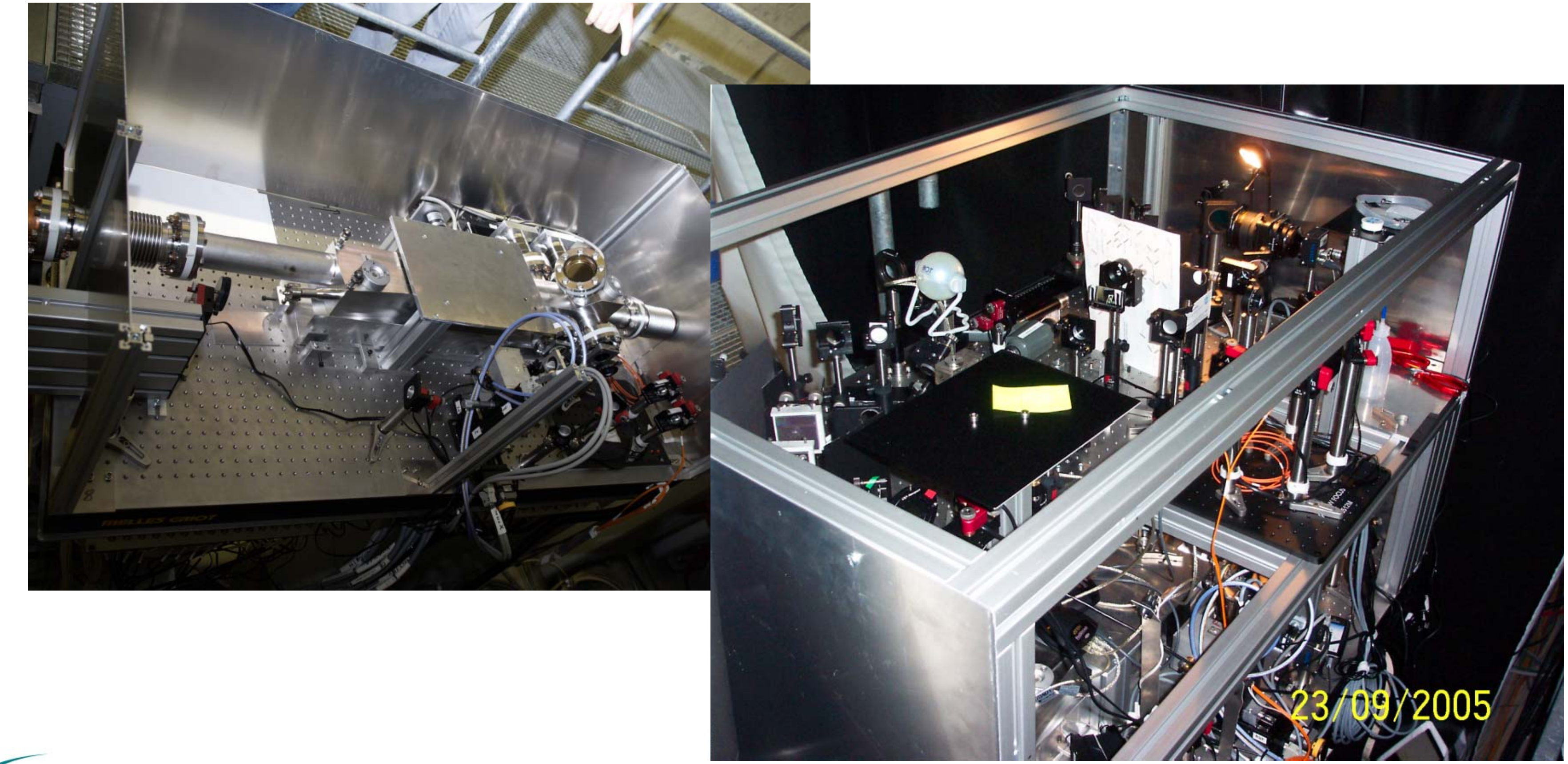
- Optical probe chirped to ~15 ps
- Samples field at single point
  (in beamline)
- Probe intensity profile measured
  (longitudinal to transverse mapping)

Integrated SH intensity

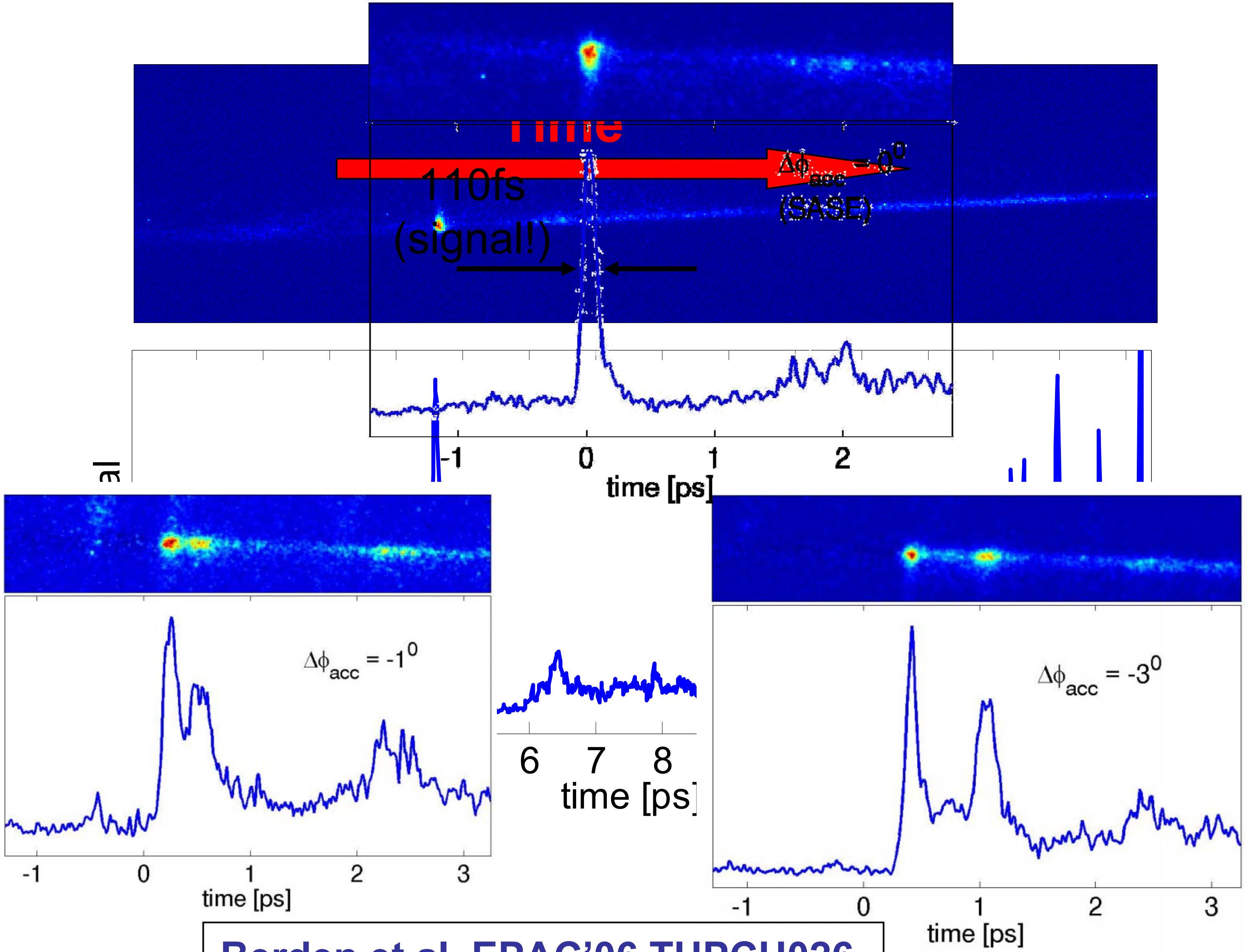


Temporal decoding at FLASH

- situated at 140m point on TTF, at “EOS” station
  (also used for spectral decoding EO and scanning delay EO)
- beam energy 450 MeV
- adjacent to LOLA transverse deflection cavity

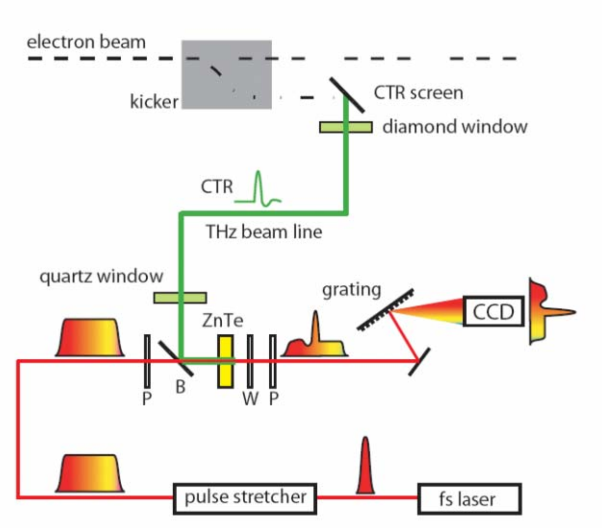


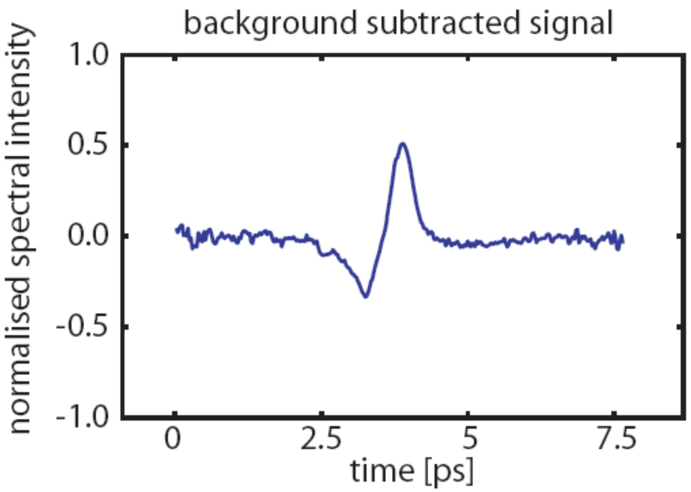
Temporal decoding at FLASH



Berden et al. EPAC’06 TUPCH026

Electro-optic measurements of CTR

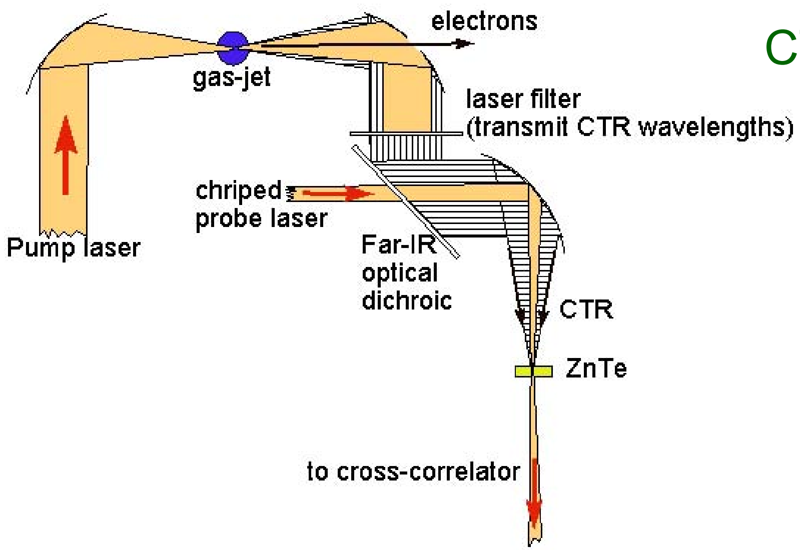


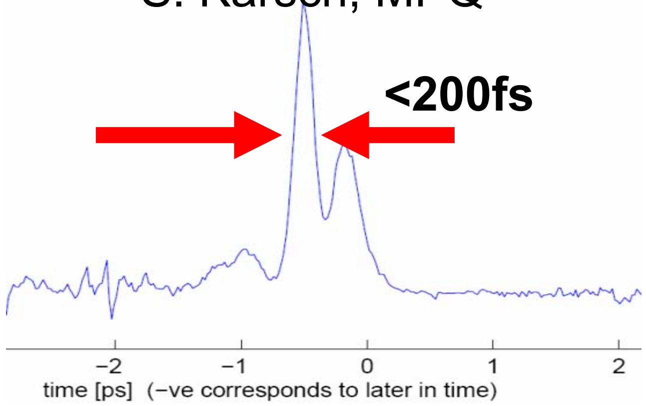


Steffen et al. EPAC'06 TUPCH027

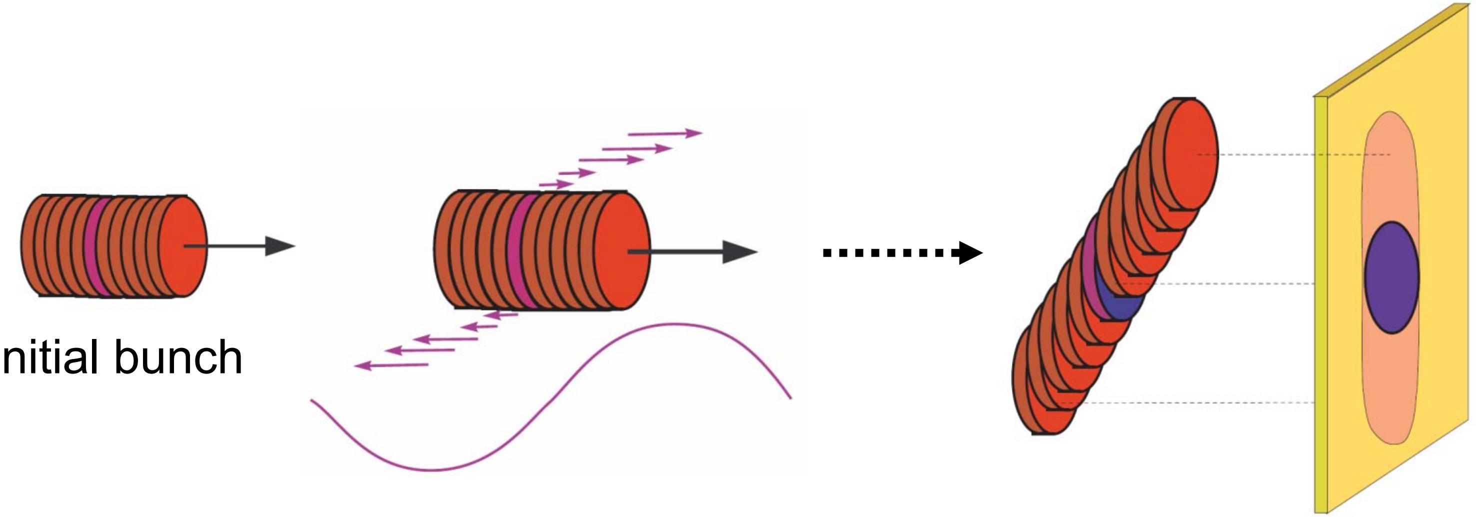
CTR from laser wakefield acceleration expts.

(Rutherford Central laser facility, 2005)
S. Karsch, MPQ





RF zero phasing



initial bunch

screen
transverse
profile

cavity
z-dependent acceleration

beam optics
energy dispersion

- Introduce energy chirp to beam
- Measure energy spread

⇒ infer initial bunch profile

RF-zero phasing

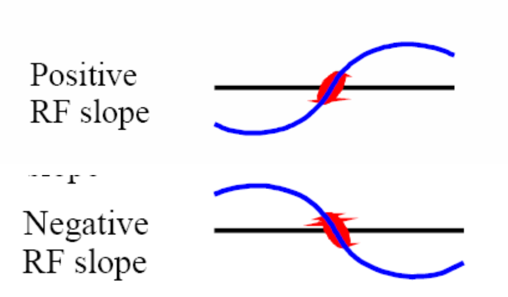
time resolution dependent on

- gradient of energy gain
- dispersion of spectrometer
- initial energy spread

what about bunches with an initial energy – z correlation?

initial linear chirp...

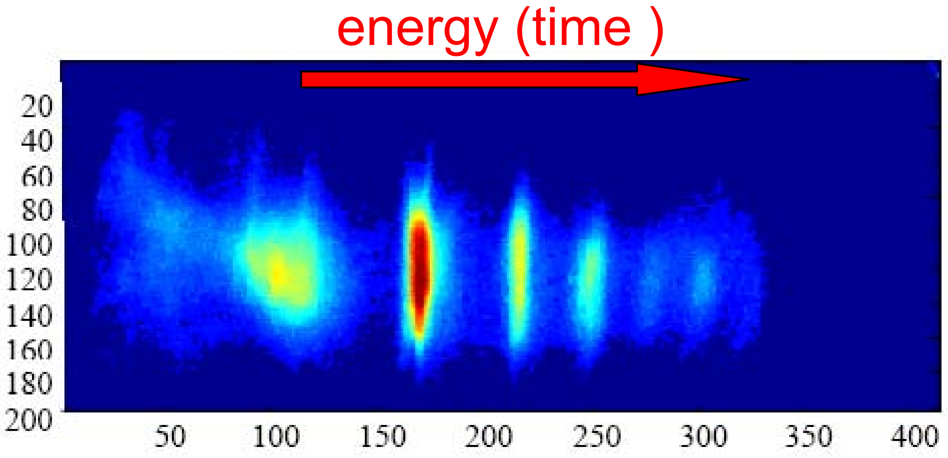
measure both positive and negative chirp



complicated Energy-z correlation may dealt with by tomography

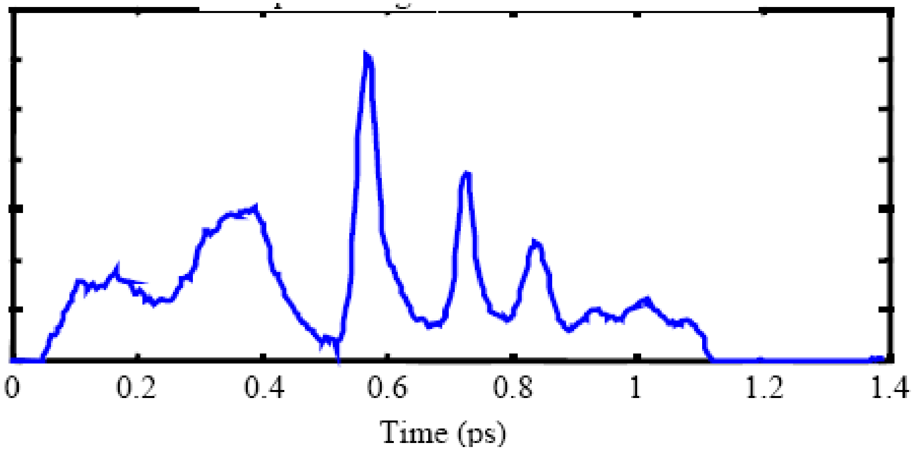
(e.g. Loos, NIMA **557** 309 (2006))

Example of zero-phasing profile from DUV-FEL



(75MeV beam)

Beam profile
after dispersion

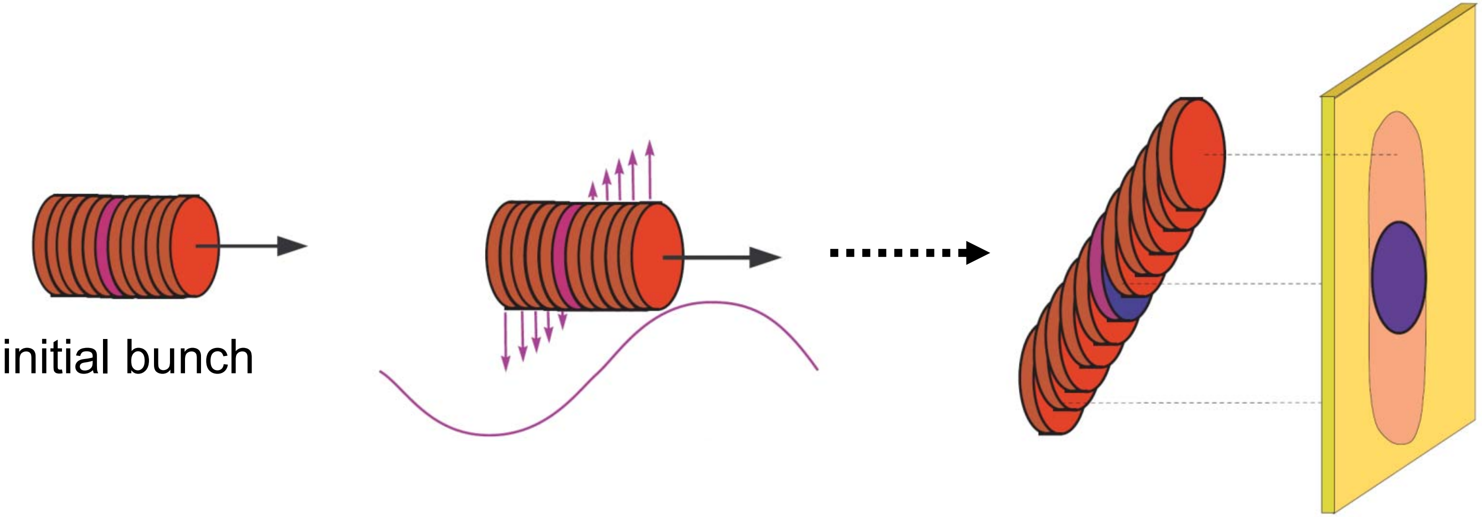


inferred
current
profile

Time resolution of 8 fs !

Graves et al. PAC'01

Transverse deflecting cavities



initial bunch

OTR screen
transverse
profile

Cavity
Transverse kick

$$\Delta y'_{\mathrm{cav}}(z) = \frac{eV}{pc}\sin(\frac{2\pi z}{\lambda_{\mathrm{cav}}} + \phi)$$

beam optics
Transverse streak

$$\Delta y_{\mathrm{screen}}(z) = \left\{\sqrt{\beta_{\mathrm{c}}\beta_{\mathrm{s}}}\sin(\Delta\psi)\right\}\Delta y'_{\mathrm{cav}}(z)$$

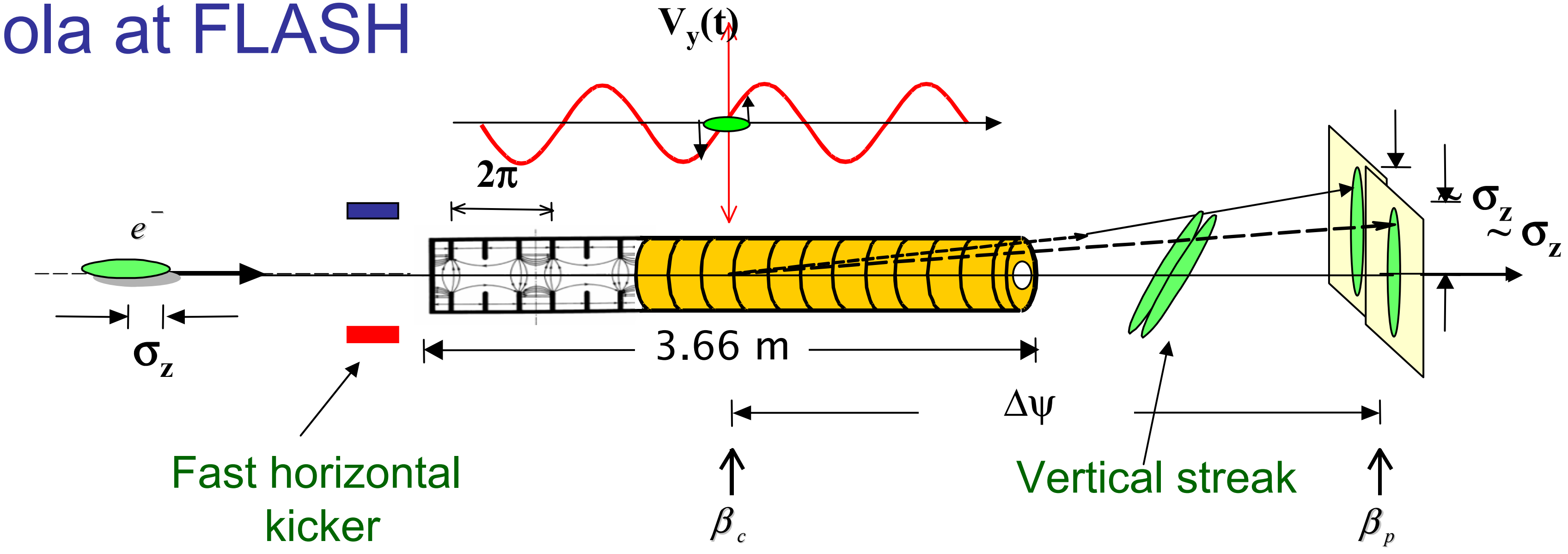
- Resolved time structure when: $\Delta y(z) \geq \sigma_y$
- Diagnostic capabilities linked to beam optics

Transverse deflecting cavities...

"Lola" cavities from SLAC... (from 1960's)

Deflection independent of
transverse position within cavity

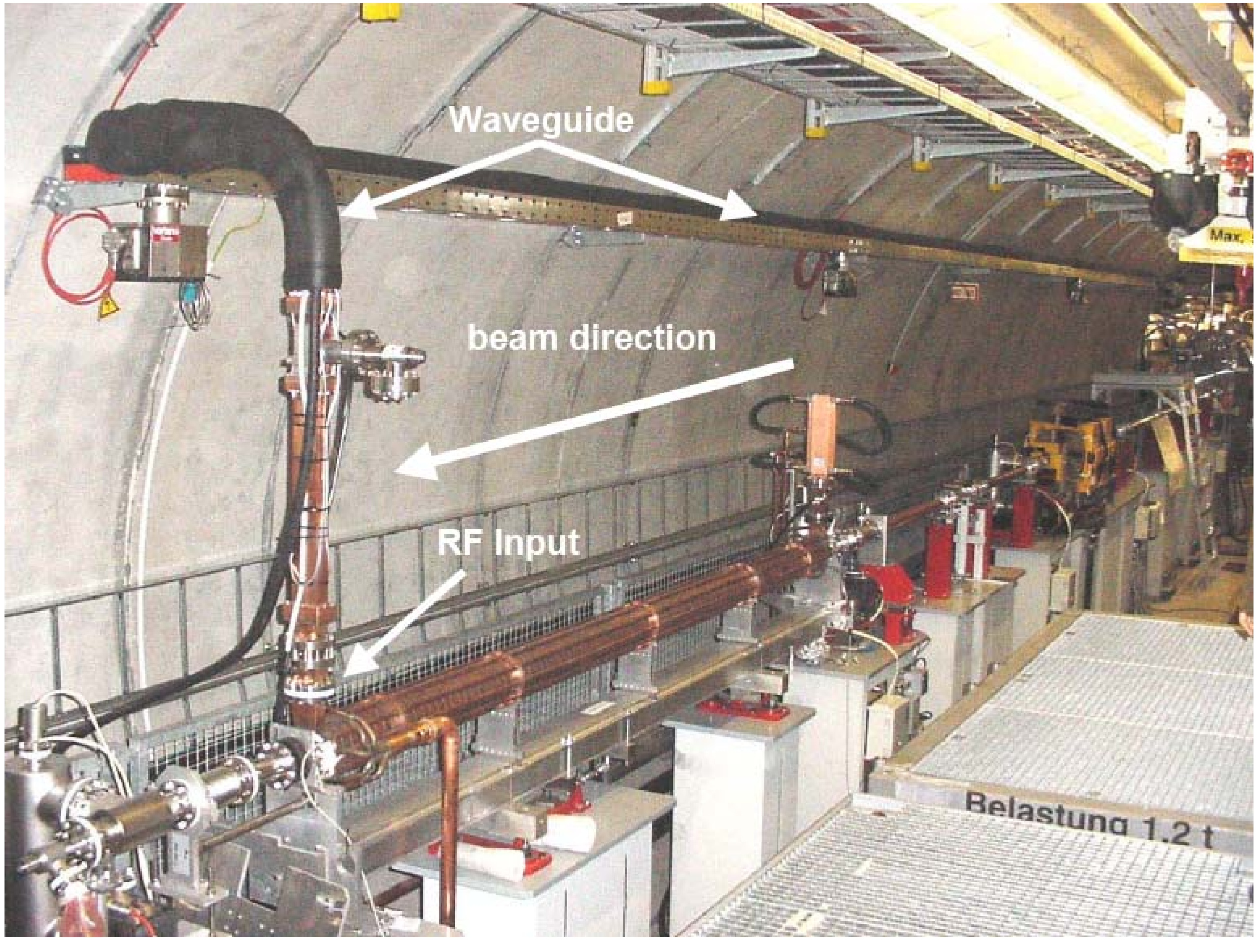
Lola at FLASH



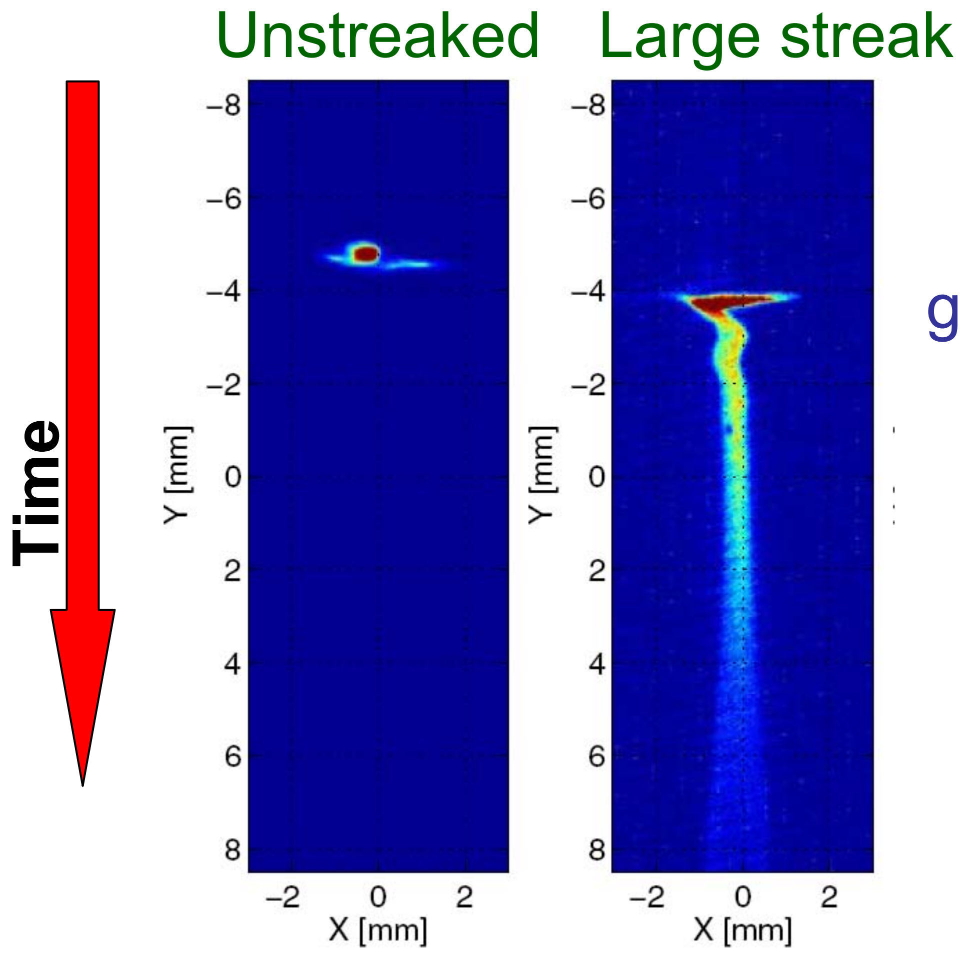
Fast horizontal
kicker

Vertical streak

Lola at FLASH



Lola at FLASH



Only resolve temporal structure streaked greater than transverse profile

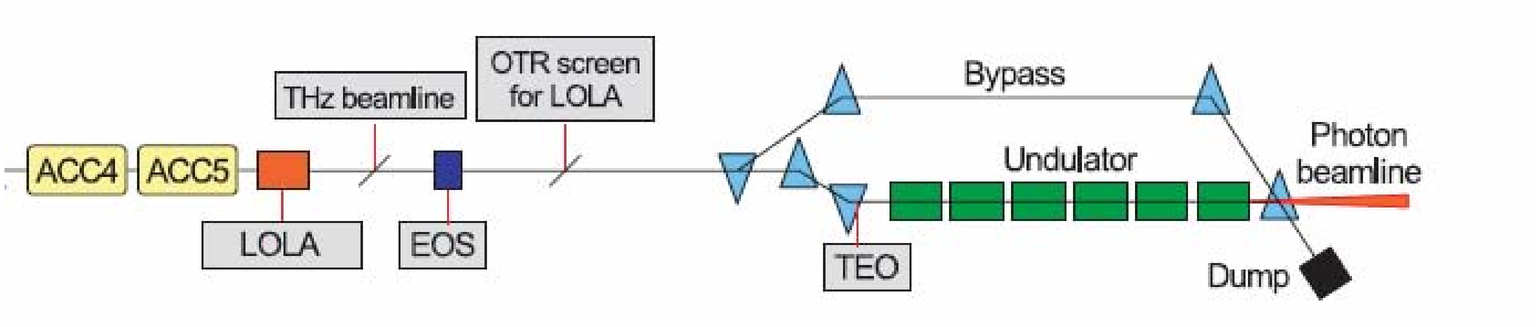
- maximum streak at screen ~ 72 fs / mm
- beam size at screen ~ 200 µm

Time resolution ~ 15 fs !!!

Can spatially image beam in orthogonal axis
⇒ slice emittance, energy slice, z-y correlation, ...

Hüning et al. FEL’05
Röhrs et al. FEL’05

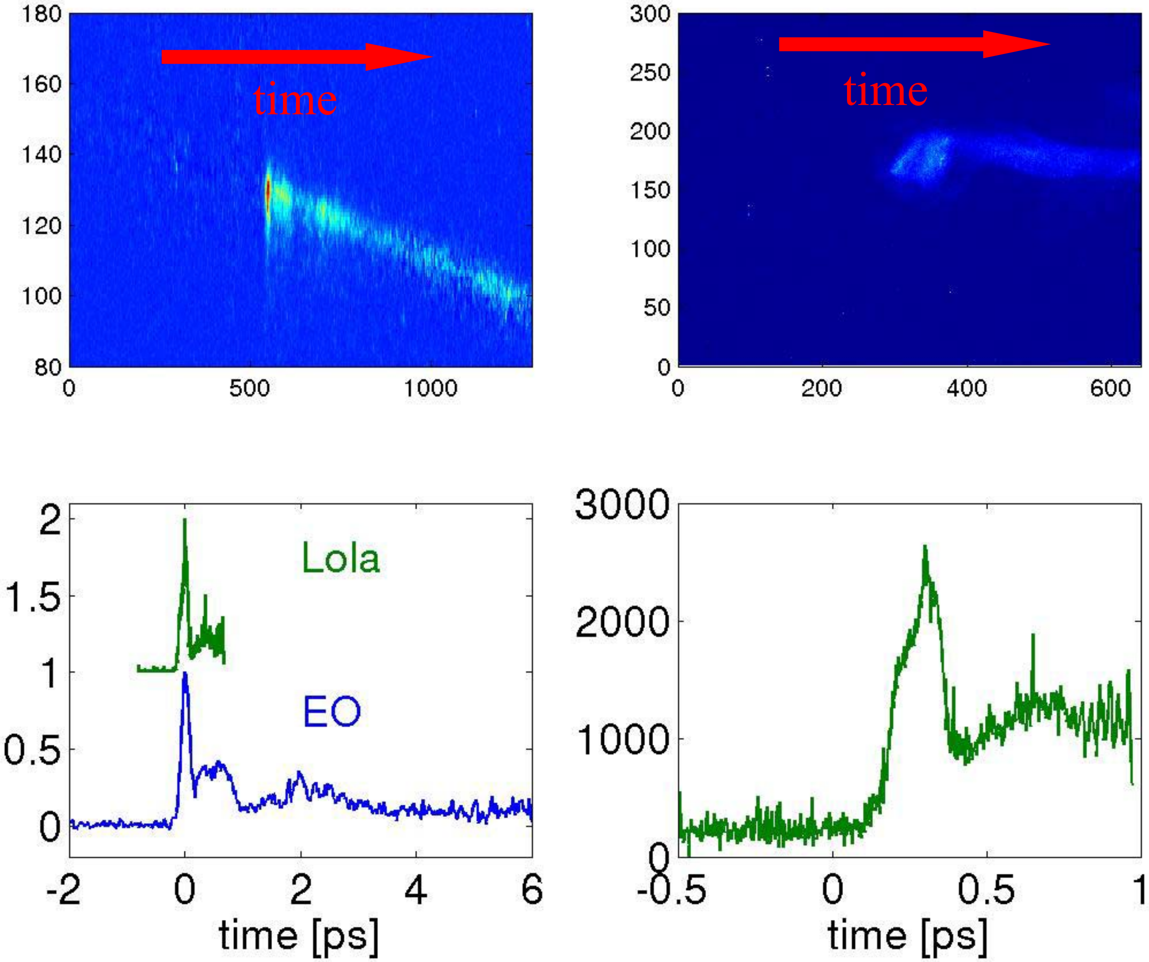
Bench-marking of longitudinal diagnostics



- EO Spatial Encoding (TEO)
- EO Temporal Decoding + Spectral Decoding
- Spectral measurements of CTR and CDR
- Lola transverse deflecting cavity

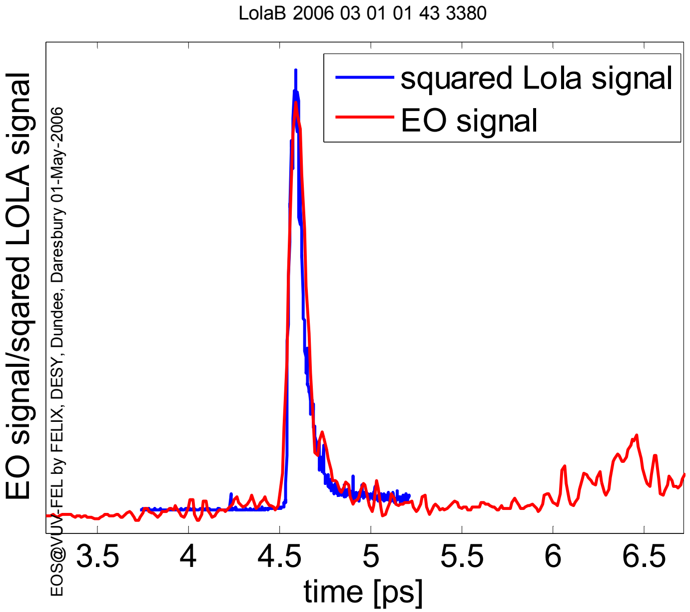
Comparison of EO and LOLA signals

EO (temporal decoding)   High resolution Lola

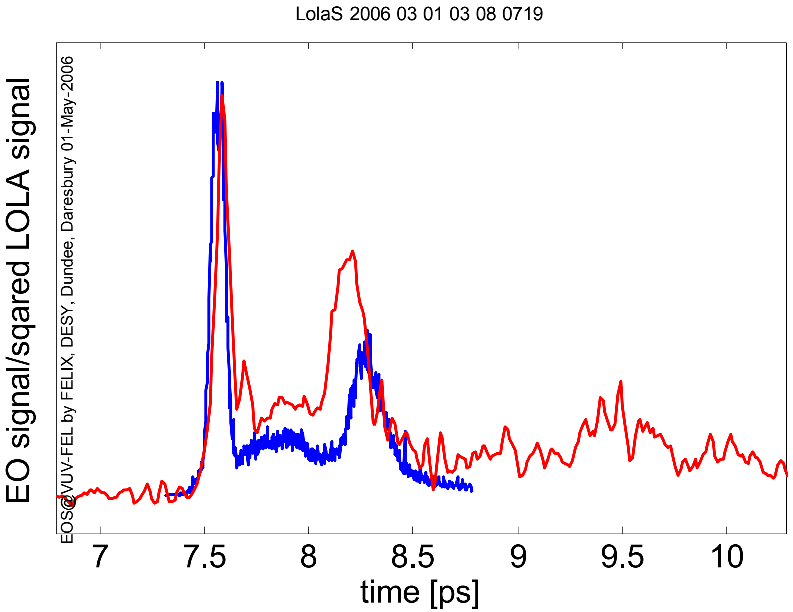


Berden et al. EPAC'06 TUPCH026

Comparison of EO and LOLA signals



SASE conditions



ACC1 phase 3° overcompression

Within bunch train: { EO at first bunch
LOLA at second bunch

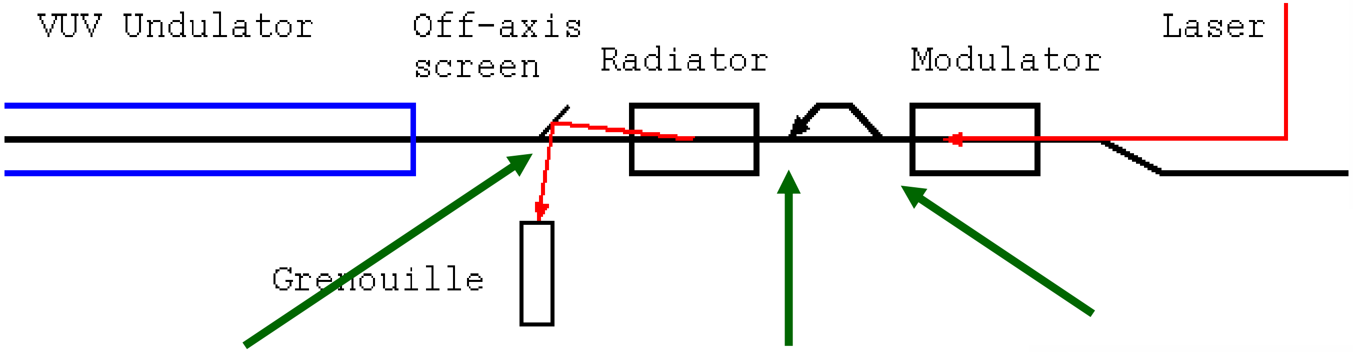
Berden et al. EPAC'06 TUPCH026

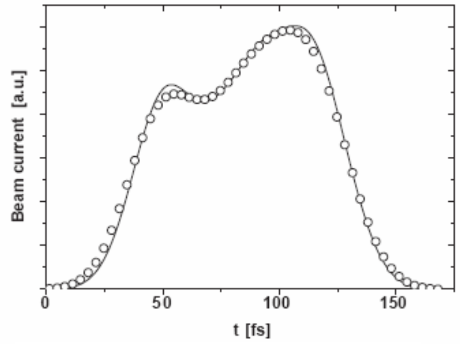
Future diagnostics...

Optical Replica Synthesizer

Concept: Saldin, Schneidmiller, Yurkov: NIM A 539 (2005) 499

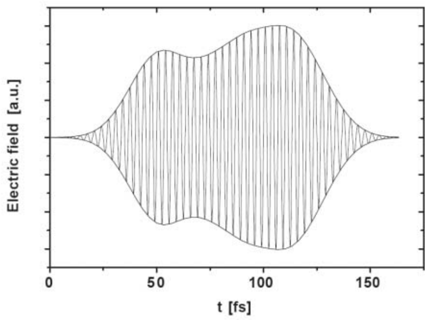
Proposed expt. at FLASH: Zeimann et al. EPAC'06 TUPCH081



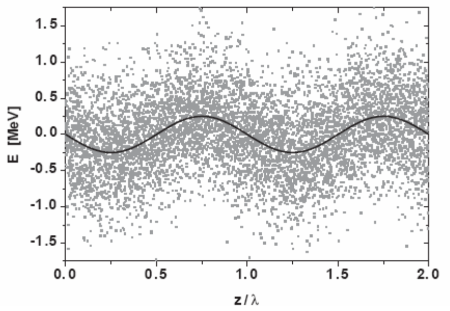


bunch profile

radiated optical field



density modulation



energy modulation at seed wavelength

Optical Replica Synthesizer

Experiments at FLASH

(Stockholm University / DESY / Uppsala University)

Seed laser:

- Frequency doubled Er fibre oscillator
- Ti:S amplifier

- Pulse duration: 2 ps
- Pulse energy: 250 μJ
- Transverse diameter ~ 750 μm
- λ ~ 770nm
- E_{laser} ~ 1.8×10^8 V/m

Undulators:

(spring 2007)

- 5 periods
- B ~ 0.4 T
- Electro-magnet undulator

V. Zeimann et al. EPAC'06 TUPCH081

Optical Replica Synthesizer

Time resolution determined by slippage

5 optical periods slippage between bunch and emitted undulator radiation

λ = 800 nm

$\Rightarrow \tau_{res} \sim$ 15 fs

Separation of radiation from electrons

off axis orbit in radiator...

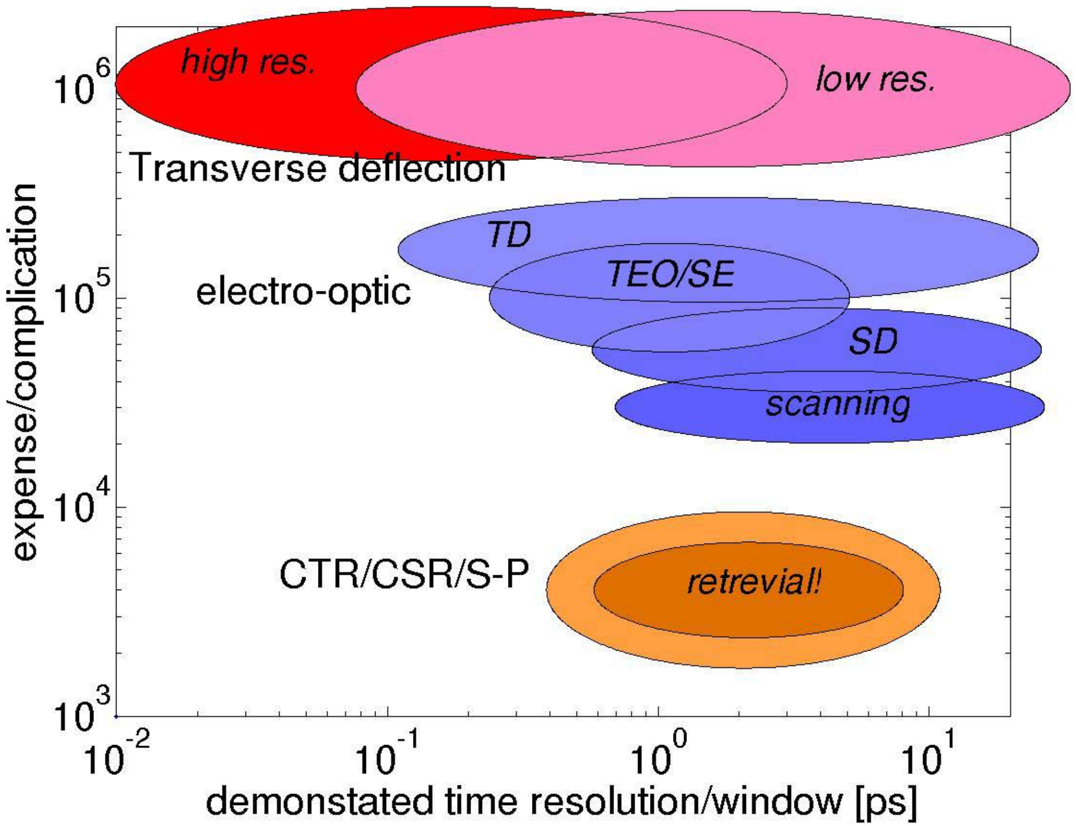
problems with tilted wave-fronts

collection mirror with hole....

diffraction?

Summary...

- Many techniques
- No unique best solution...
- ~10 fs resolution demonstrated



thanks to...

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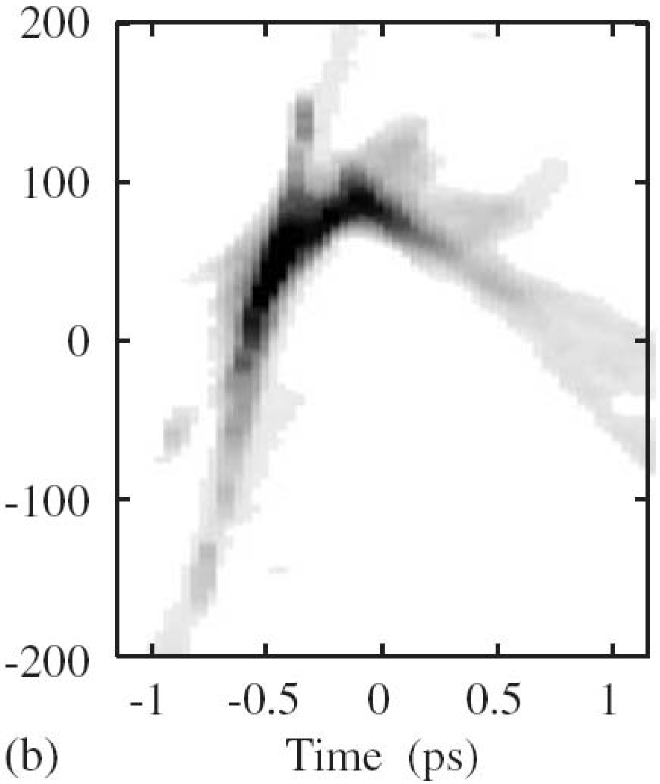
Stefan Karsch
Bernd Steffen
Ernst-Axel Knabbe
Bernhard Schmidt
Hossein Delsim-Hashemi
Oliver Grimm
Peter Schmüser
Holger Schlarb
Volker Zeimann

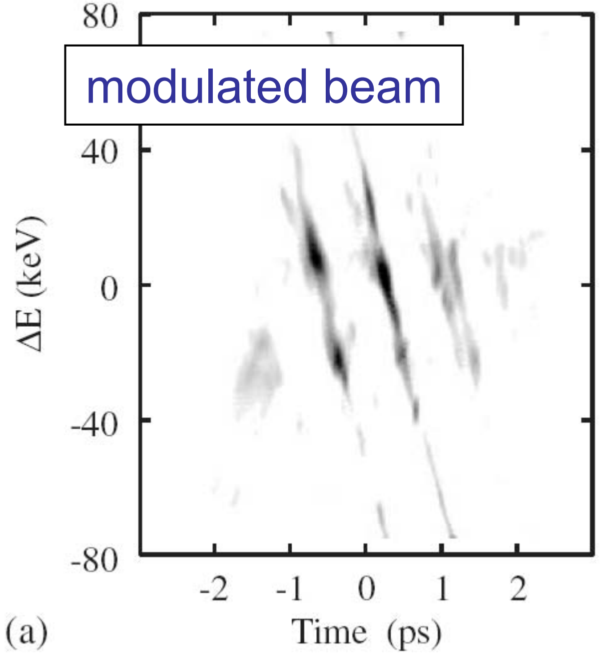
and to everyone whose results I have shown..

complicated Energy-z correlation - tomography

- Set of zero phasing (or similar) measurements
- Numeric inversion to initial energy-time correlation



Tomographic measurements from DUV-FEL (75MeV)



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