Femtosecond Resolution Bunch Profile Diagnostics

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HELMHOLTZ
ASSOCIATION

DESY

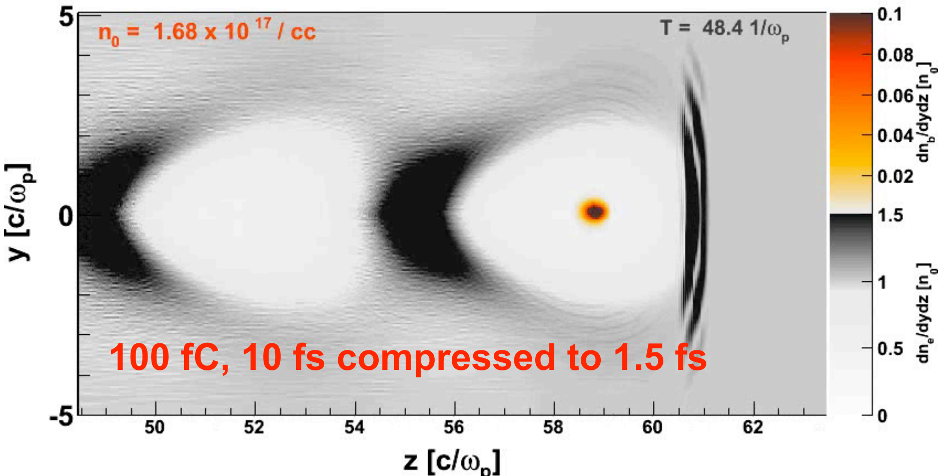
driving forces

fs bunches driving fs x-ray pulses :

below ps & nC
↓
few fs & few pC

plasma wakefield experiments :

the fs & fC challenge



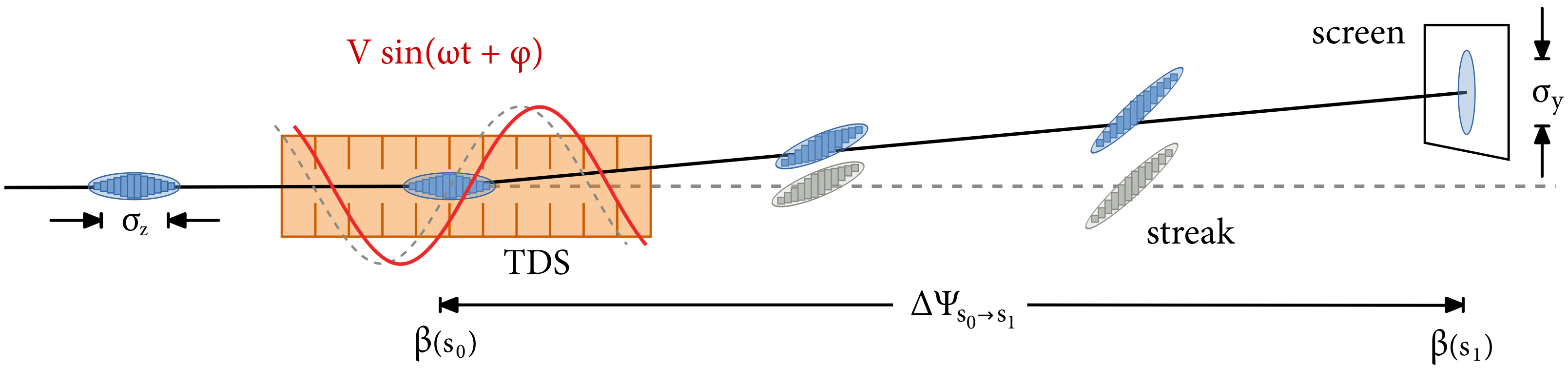
J. Grebenyuk *et al.*, in preparation

- status of established technologies
- progress towards online monitoring
- exciting experiments
- new and demanding ideas

Transverse Deflecting Structures (TDS)

well established - versatile - high resolution - bulky - expensive

RF - transverse deflector at zero crossing



imprint y'(s) → $R_{y\,y'}$ → measure y(s)

$$R_t = \sqrt{\frac{\epsilon}{\beta_0}} \frac{E_b}{eV\omega_{RF} sin(\Delta\Psi)}$$

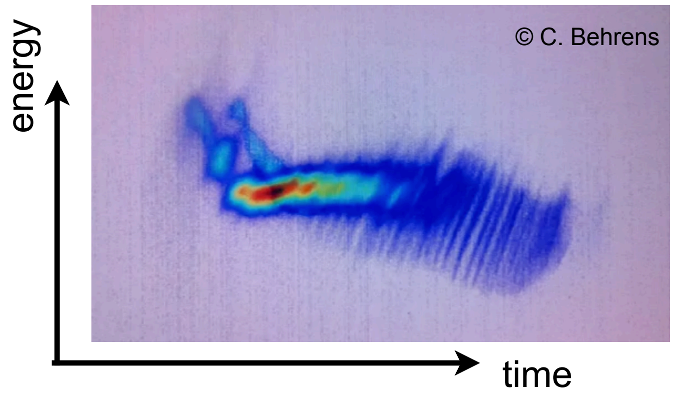
time resolution

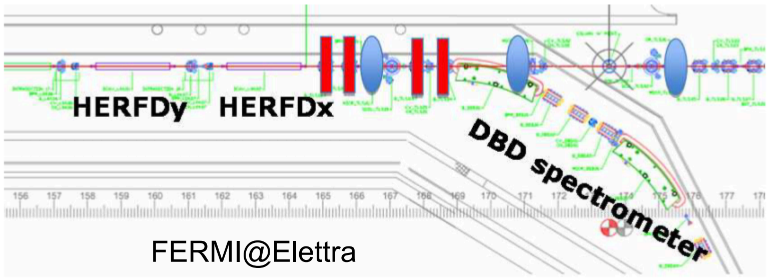
limited by beam emittance
streak power and RF-frequency
beam optics

longitudinal phase space

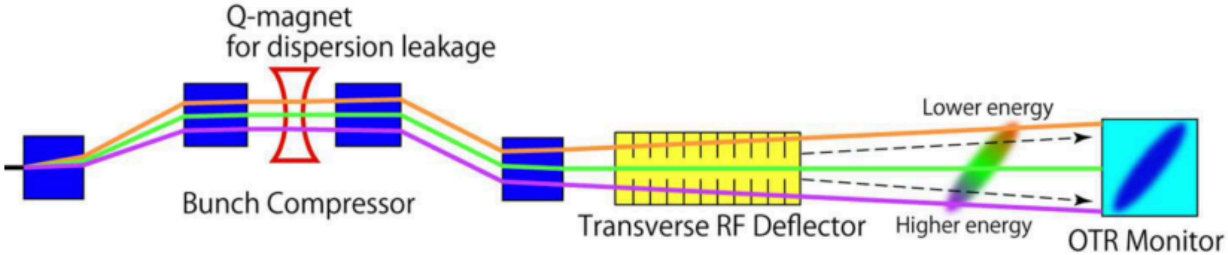
combine TDS with orthogonal dispersion

FLASH, LCLS, FERMI: TDS + Dipol spectrometer





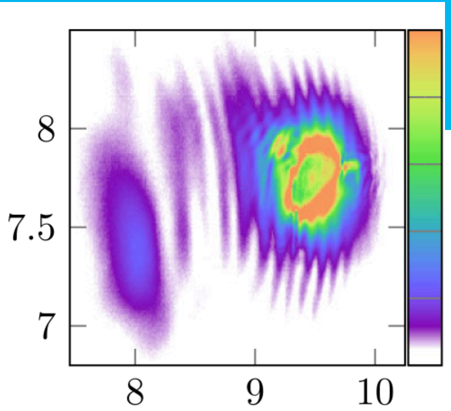
SACLA: TDS + „dispersion-leakage“ from compressor



see H. Maesaka: MOIC02

imaging problems

TDS imaging suffers form COTR due to micro-bunching

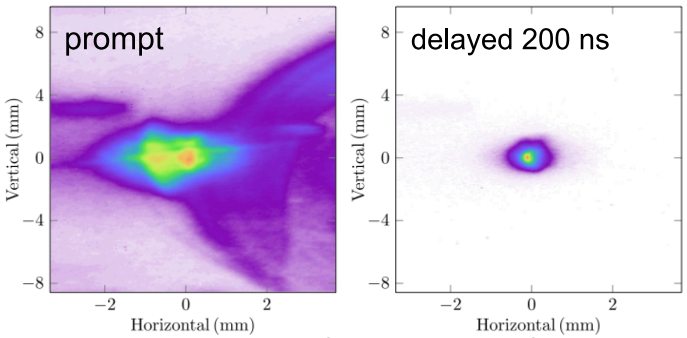


replace metallic screen by scintillator
→ still COTR from surface

delayed image using gated camera

mask central OTR cone

S. Matsubara
MOCC04



C. Behrens et al. , PRSTAB 15, 062801 (2012)

use dispersive arm (FLASH, LCLS..)
→ but no operation parallel to FEL

- disregard imaging, use wire scanners (LCLS)

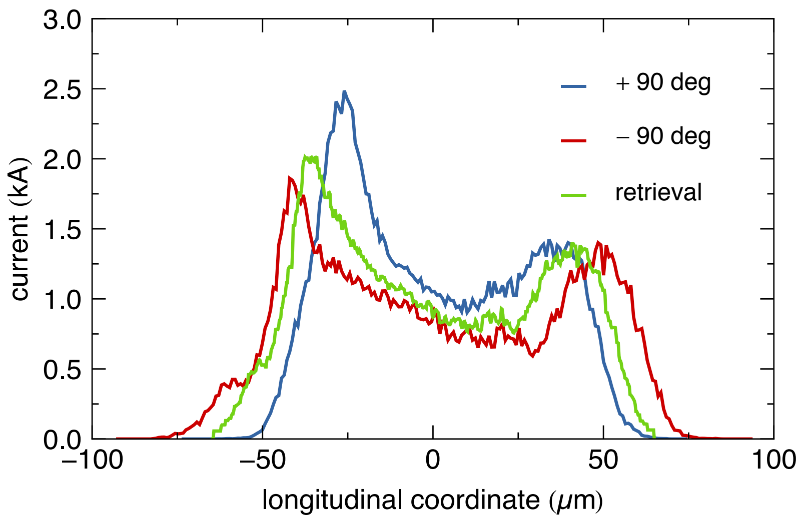
resolution & complications

- induces energy spread
- wakefields

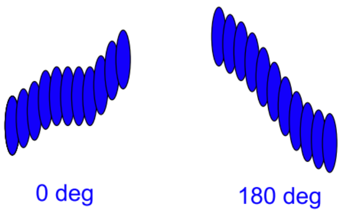
⟶ minor effects for high energies

non-vanishing problem : intrinsic (y'-z) correlations

retrieval from 2 streak polarities (ref. H. Loos)
(substantially different bunch profiles)



data from FLASH © S. Wesch

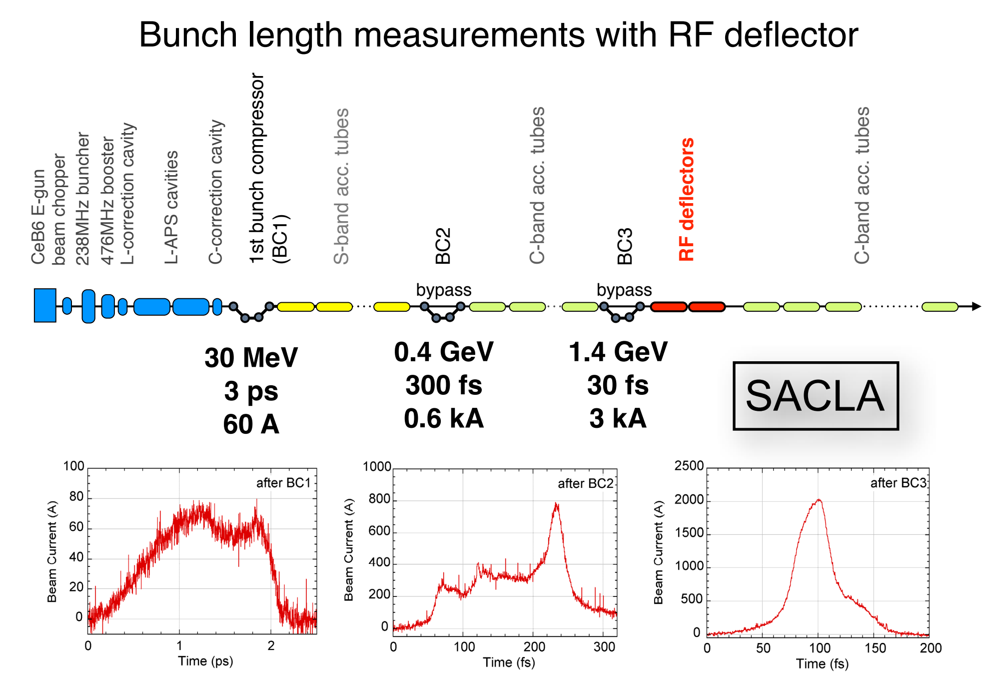


bias free measurements need at least two opposite streaks

att.: TDS is not longer single shot

way to the future

machine	f-RF	V_{max}	E_{beam}	resolution
FLASH	2.8 GHz (S)	25 MV	1.2 GeV	~10 fs
FERMI	3.0 GHz (S)	20 MV	1.2 GeV	< 20 fs
SACLA	5.7 GHz (C)	60 MV	1.4 GeV	~ 10 fs
XTCAV@LCLS	11.4 GHz (X)	46 MV	< 13.6 GeV	~1 fs exp.



K. Togawa et al., Proceedings FEL2011, p.259

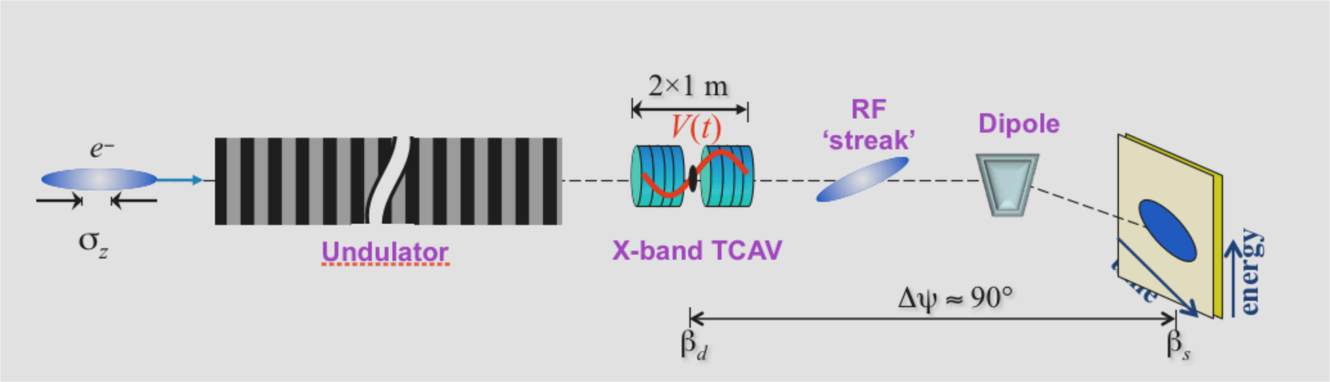
H. Maesaka: MOIC02

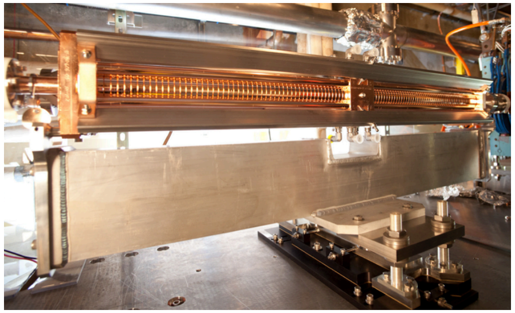
time resolution ~10 fs limited by beam size at screen

the XTCAV project at LCLS

XTCAV + spectrometer behind undulator

P. Krejcik, TUPA41

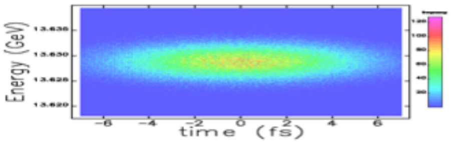




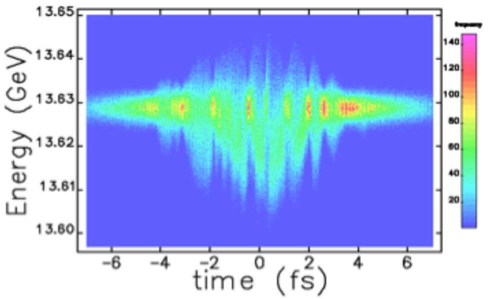
derive photon pulse profile
from long. phase space measurement

expected performance

FEL Off
E-beam only



FEL On
Electron+Photon beam



© P. Krejcik et al.

status : structures installed
RF-power next spring

beating the limits : new ideas

„the ideal z-mapper“

D. Xiang, Y. Ding
Phys. Rev. ST Accel. Beams 13, 094001 (2010)

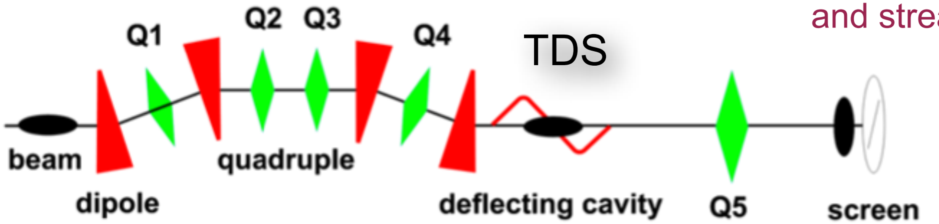


FIG. 1. Scheme for longitudinal-to-transverse mapping.

by careful adjusting the chicane parameters
and streaking strength of TDS

y(s) = f k z

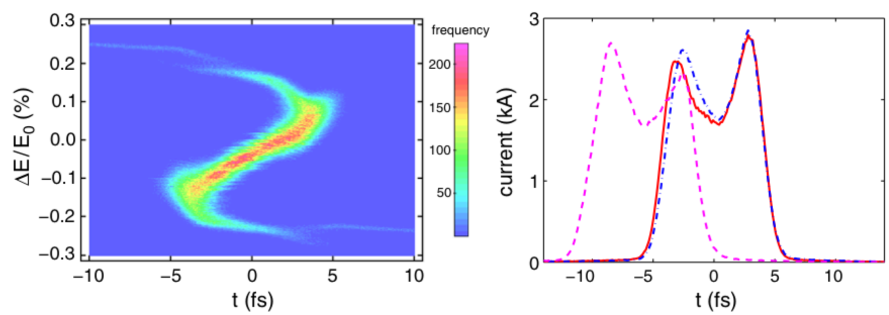
$$R = R_b R_s = \begin{bmatrix} 0 & 0 & fk & 0 \\ 1/f & -R_{12}/f & 0 & 1/fk \\ 0 & 1/k & 1 & 0 \\ -k & kR_{12} & 0 & 0 \end{bmatrix}.$$

+ free from correlation problems
+ resolution limited by second order terms

- resolution scales with δE^2
- bulky, complex, needs tight balancing

ex: 0.2 fs for δE=0.1%

simulation result



optical - streaking

TDS

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 072802 (2011)

Longitudinal profile diagnostic scheme with subfemtosecond resolution for high-brightness electron beams

G. Andonian,[1,2] E. Hemsing,[1] D. Xiang,[3] P. Musumeci,[1] A. Murokh,[2] S. Tochitsky,[4] and J. B. Rosenzweig[1]
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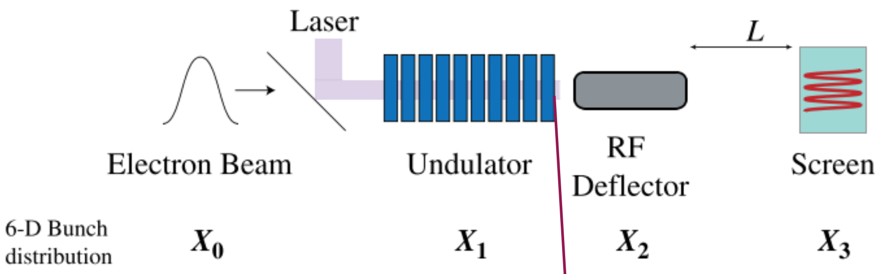
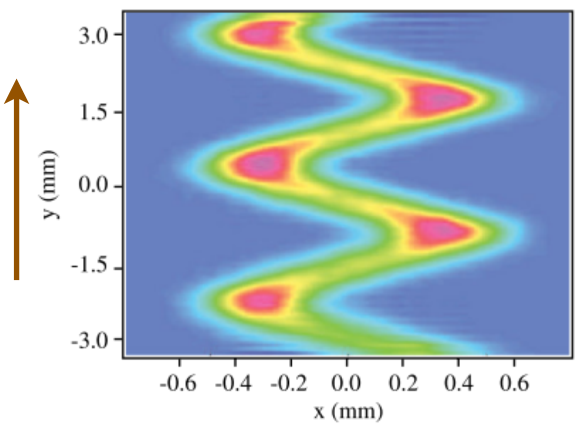
(Received 10 March 2011; published 13 July 2011)

laser + TDS : high resolution + large dynamic range

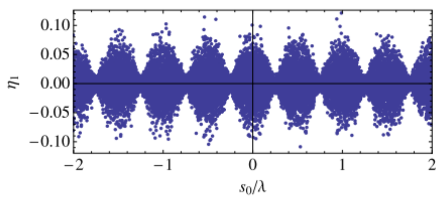


TDS
streak



laser
streak

energy



divergence

$$\Delta x' \sim \gamma^{-2}\sqrt{P_L}$$

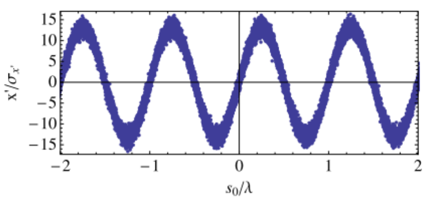


TABLE I. Simulation parameters for the UCLA Neptune case.

Beam energy	E	12.9 MeV
Normalized emittance	ϵ_n	1.0 mm mrad
Energy spread	σ_γ	5×10^{-3}
Undulator peak field	B_0	1.02 T
Undulator period	λ_u	9 mm
Undulator length	L_u	9 cm
Undulator parameter	K	0.855
Laser wavelength	λ	10.6 μm
Laser waist	w_R	250 μm
Laser power	P_L	300 MW

CO_2 laser

high beam energy -> GW (TW) laser power

proposed proof of concept
experiment at UCLA

Coherent Radiation

Spectral distribution of „bunch radiation“ with $N_e >> 1$

For all direct radiation processes : incoherent and coherent contribution

Synchrotron -
Edge -
Transition - *Radiation*
Diffraction -
..

$$\frac{dU}{d\lambda d\Omega} = \left(\frac{dU}{d\lambda d\Omega}\right)_1 \left(N + N^2 \left|F_{3d}(\lambda,\Omega)\right|^2\right)$$

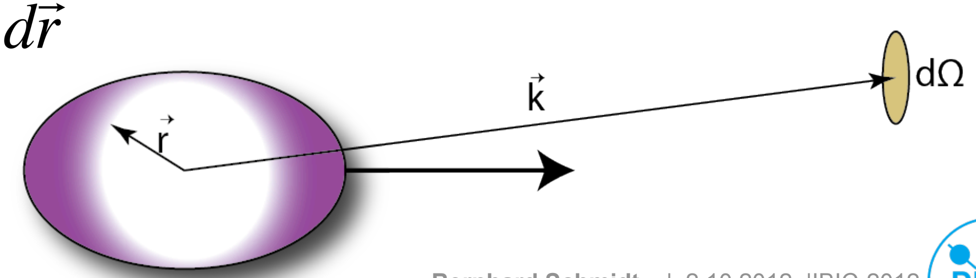
single electron spectrum

Form factor
reveals charge distribution

wavelength space configuration space

$$F_{3D}(\vec{k}) = \int S_{3D}(\vec{r}) e^{-i\vec{k}\vec{r}}\, d\vec{r}$$

$$|\vec{k}| = \frac{2\pi}{\lambda}$$



Coherent Radiation: Basics

$$F_{3D}(\vec{k}) = F(\lambda)\ F_T(\lambda,\theta)$$

***IF** no long. - trans. correlation : factorize*
F_T for fixed θ , only weak λ dependence

attn.: fails for $\sigma_r \geq \gamma\lambda/(2\pi)$

complex function

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) e^{-2\pi i z/\lambda} dz$$

longitudinal form factor

coherent radiation intensity

$$\frac{dU}{d\lambda d\Omega} \approx \left(\frac{dU}{d\lambda d\Omega}\right)_1 N^2 \left|F(\lambda)\right|^2$$

$\left(\frac{dU}{d\lambda d\Omega}\right)_1$ single electron contribution

$$F(\lambda) = |F(\lambda)| e^{-\phi(\lambda)}$$

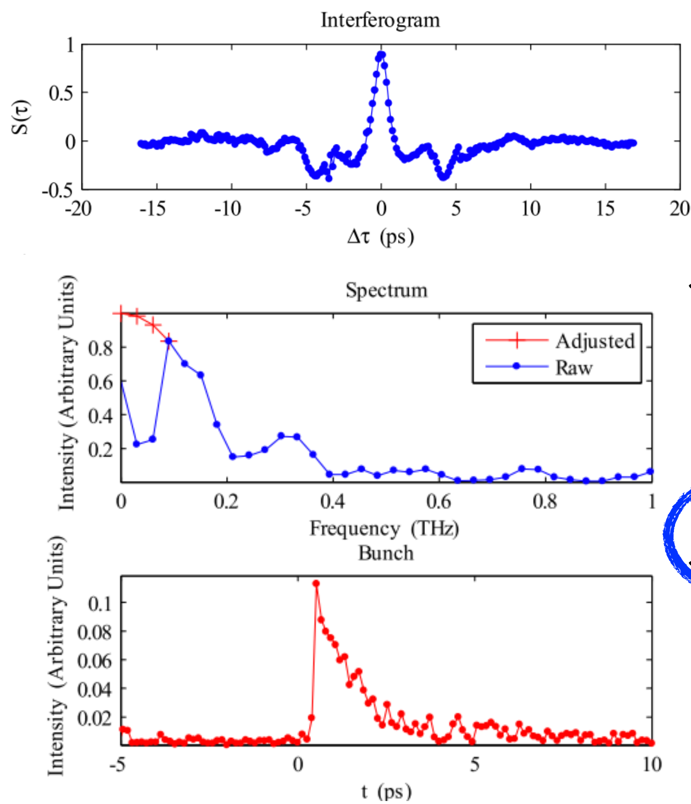
notice : the **phase** is missing !

measuring techniques

Lai, Happek, Sievers (1994)

interferometer : scanning device, simple (one channel readout)..

temporal autocorrelation function



$S(\Delta\tau)$

$\mathcal{F}$ -Transform

$P(f)$

K-K phase
$\mathcal{F}$ -Transform

$I(t)$

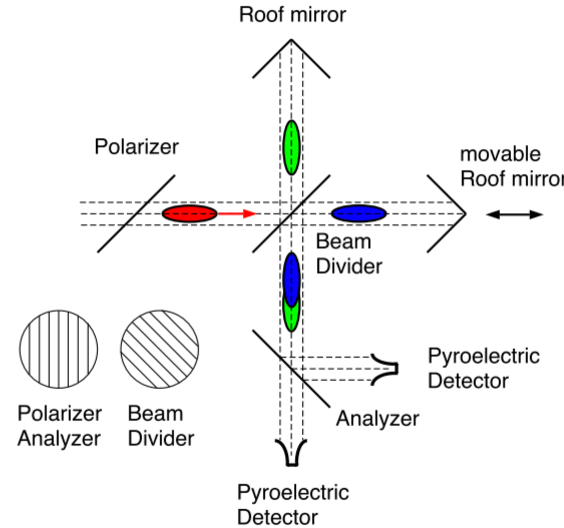


Figure 1: The Martin Puplett interferometer.

- not single shot
- diffraction limits resolution

single shot spatial auto correlator

CR

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 043302 (2012)

Demonstration of a real-time interferometer as a bunch-length monitor in a high-current electron beam accelerator

J. Thangaraj,[1,a)] G. Andonian,[2,3] R. Thurman-Keup,[1] J. Ruan,[1] A. S. Johnson,[1]
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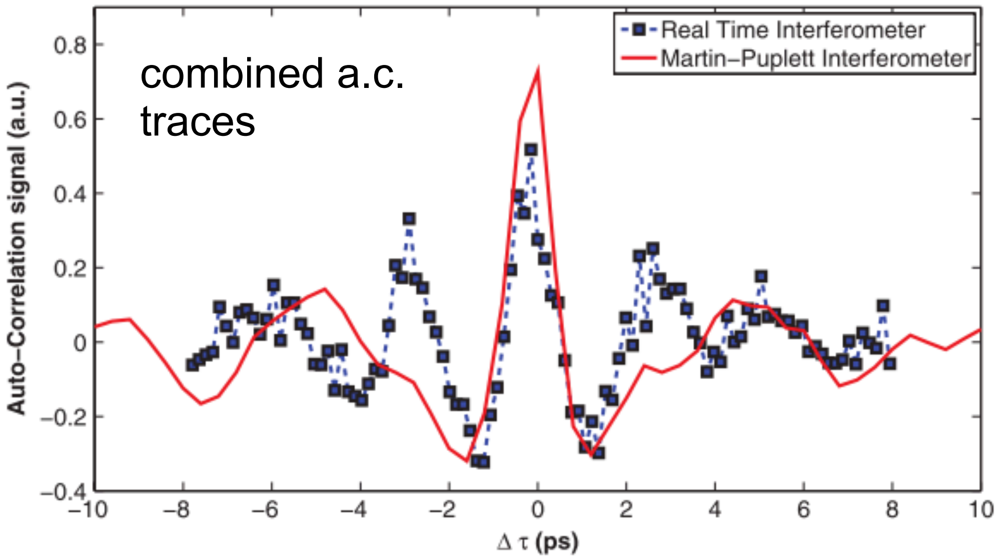
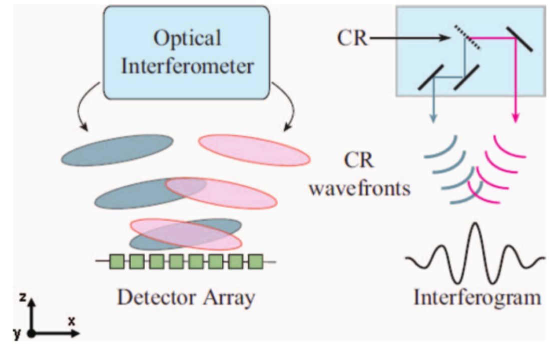
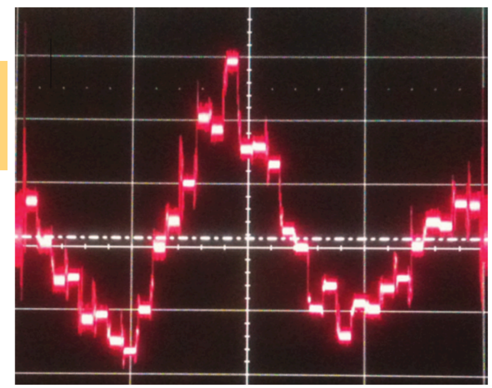




G. Andonian
TUPA39



data taken at A0 photoinjector (Fermilab)

resolution determined by transverse beam size and mixing angle

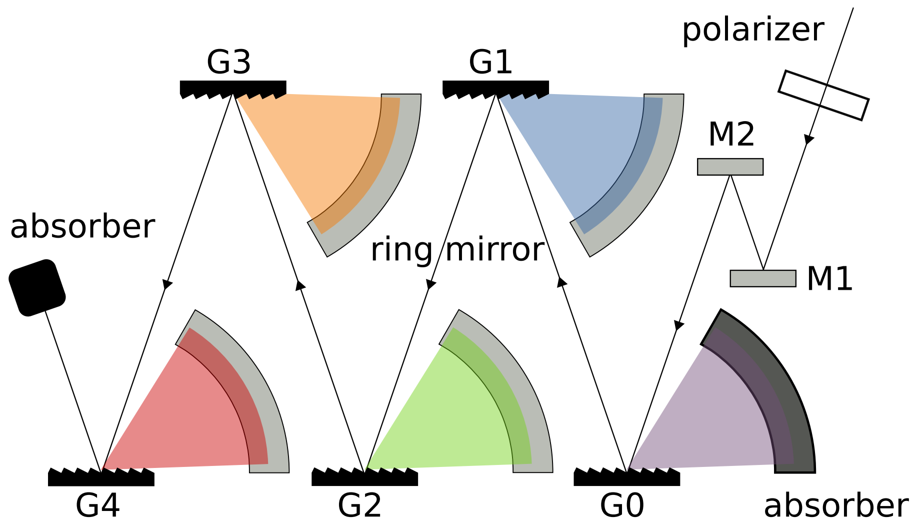
CRISP4 : four stage grating spectrometer

CRD

diffractive grating + parallel read out : single shot spectrometer

but : higher order problem ! λ/2 in 2. order and λ in 1. order have same diffraction angle

- pre-filter short wavelengths
- only factor 2 in λ with one grating possible , needs cascaded grating stages



4 stages : 1 decade in λ (parallel)

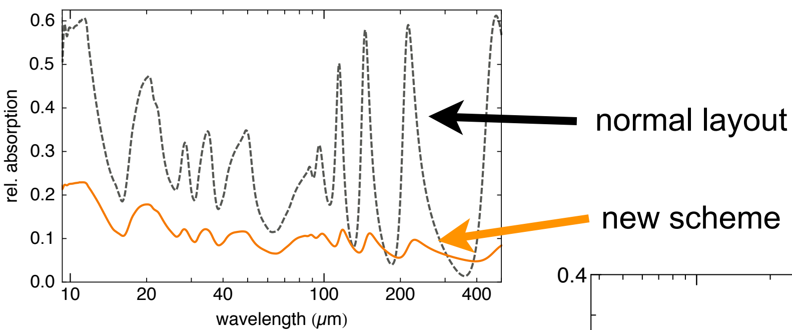
2 x 4 stages : 2 decades in λ (sequentially)

monitoring : relative intensities ok

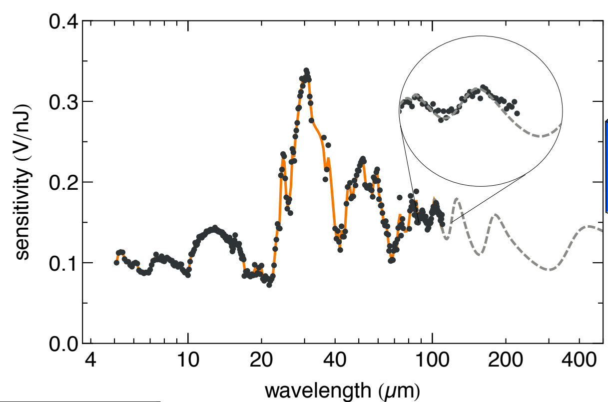
form factor :
absolute intensity as function of λ required ! Needs detailed understanding of all components

installation & calibration

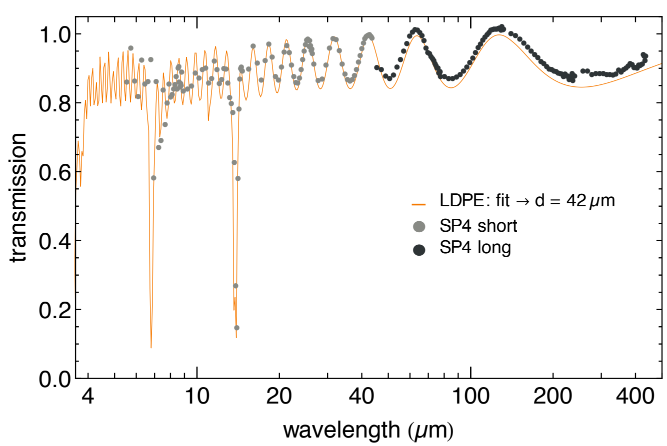
absolute |F| measurement needs
full understanding of all details

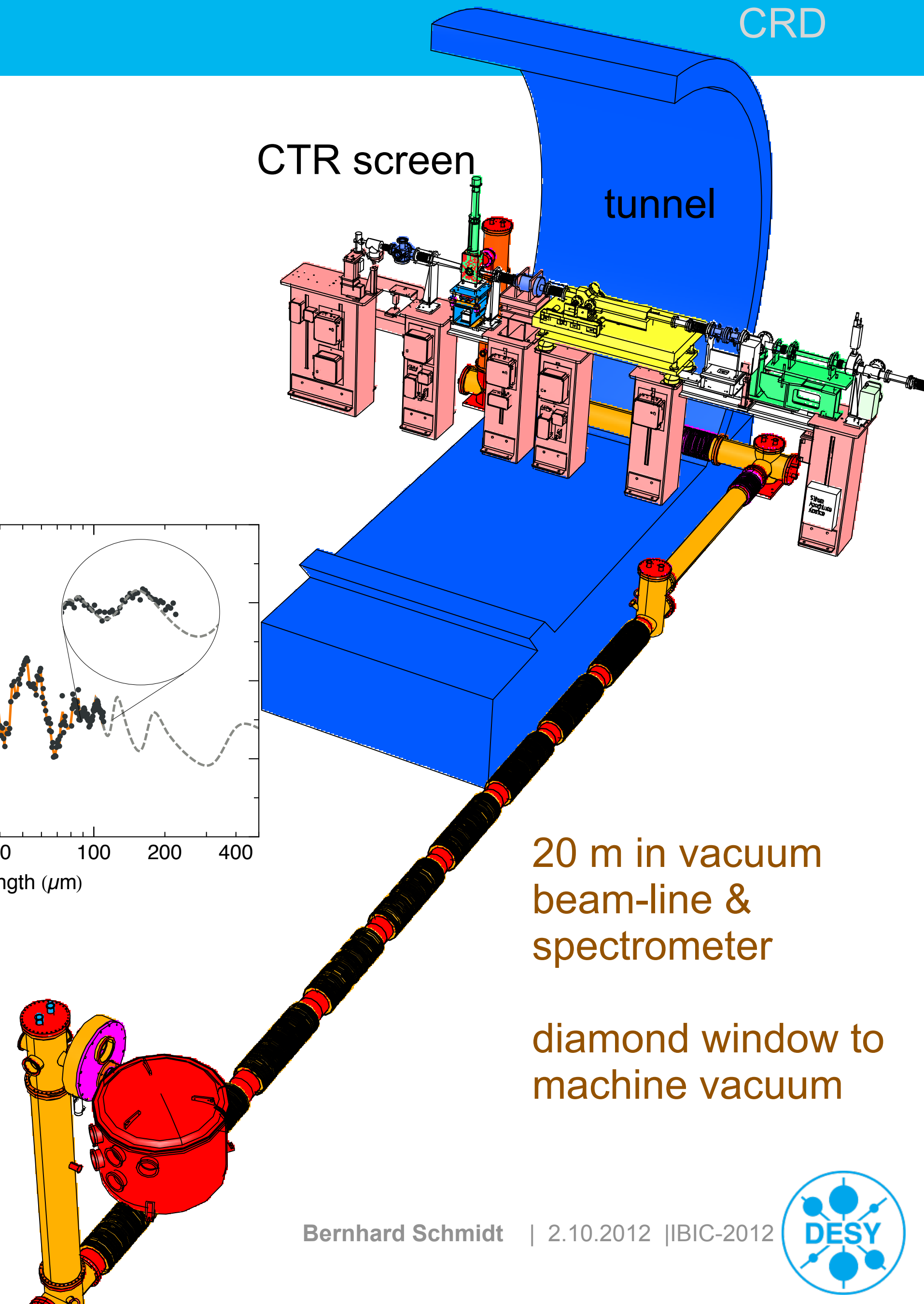


120 channels pyroelectric detectors



wavelength calibrated..





20 m in vacuum
beam-line &
spectrometer

diamond window to
machine vacuum

CRISP4 now an online-tool

CRD

Nuclear Instruments and Methods in Physics Research A 665 (2011) 40–47

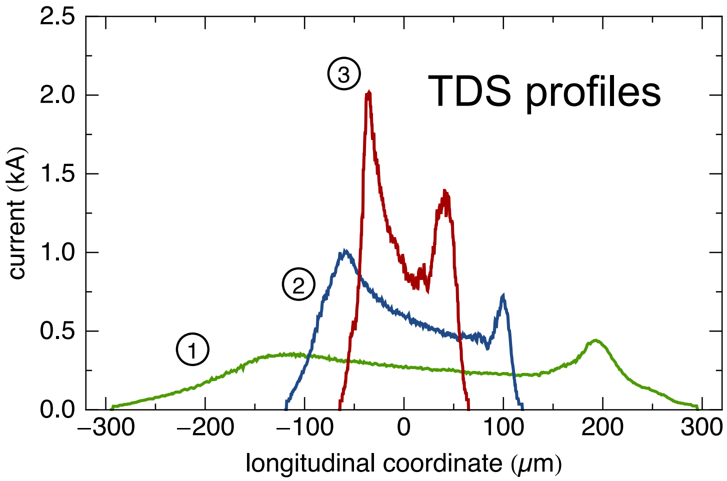
A multi-channel THz and infrared spectrometer for femtosecond electron bunch diagnostics by single-shot spectroscopy of coherent radiation

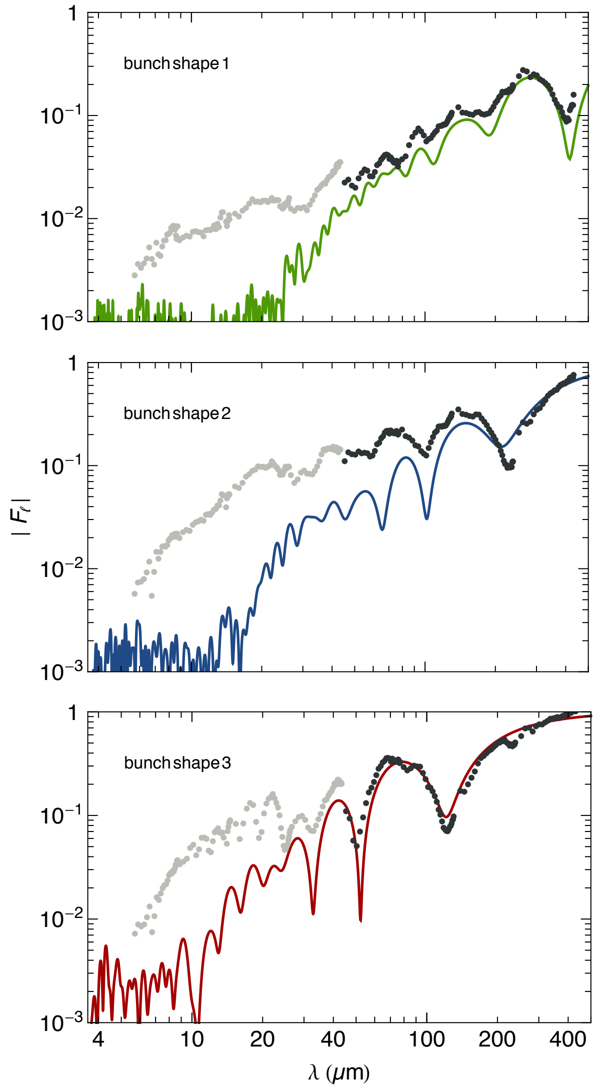
Stephan Wesch*, Bernhard Schmidt, Christopher Behrens, Hossein Delsim-Hashemi, Peter Schmüser

Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany

regularly used as online tool for monitoring and compression control

compare TDS and CRISP4 : |form factors|





- very good agreement for long wavelengths

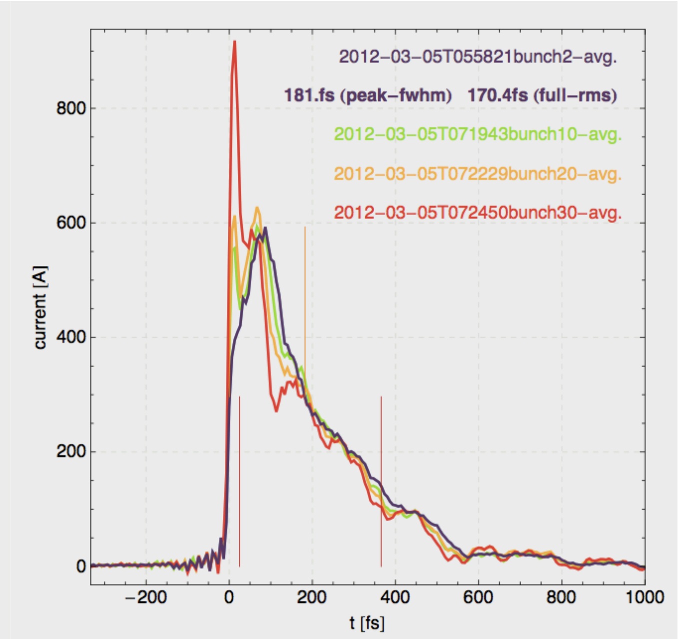
- TDS profiles show less short wavelength content

  - smoothed and averaged by tomography
  - finite resolution
  - TDS and CRISP4 are 60 m apart !

reconstructed shapes (KK-phase)

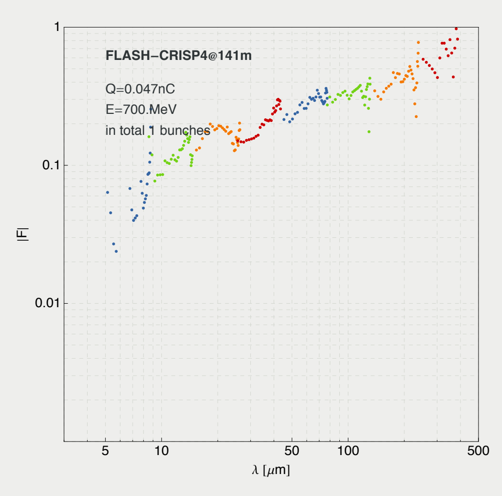
CRD

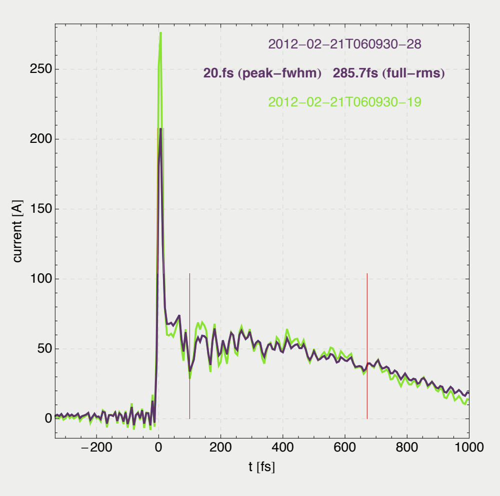
Q = 0.137 nC
E = 500 MeV



reconstructed profiles along bunch train

- single bunch with 47 pC
- very sharp leading spike (**8.5 fs rms**) on long tail





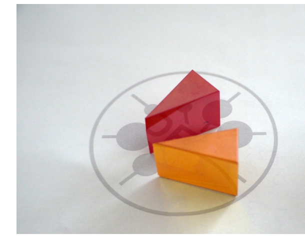
(using Krames-Kronig relation, not unique, „a possible bunch shape")

outlook CR methods

shorter bunches, less charge... (few fs - pC bunches)

wavelength range 1 µm - 20 µm *can be covered by prisms ! (KRS-5 or ZnSe)*

more sensitive detectors (ex. **HgCdTe** arrays)



T. Maxwell
TUPA47

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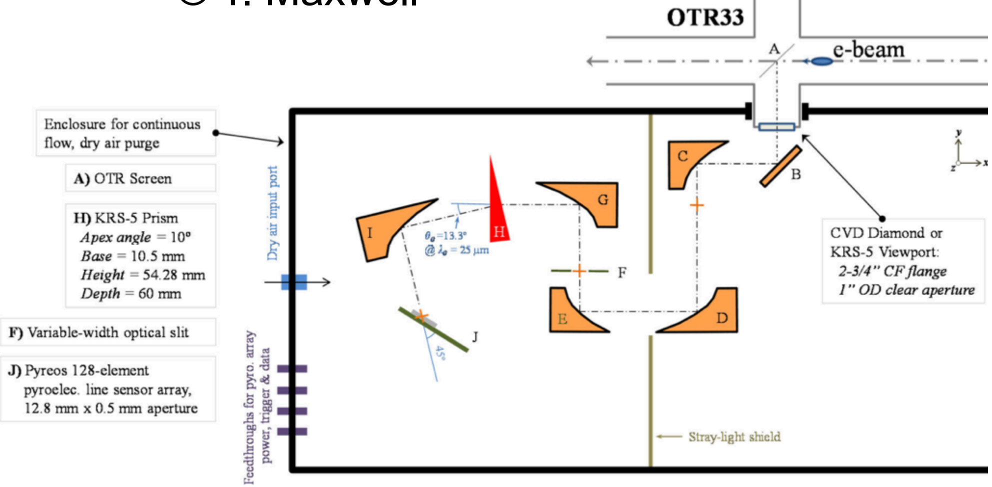
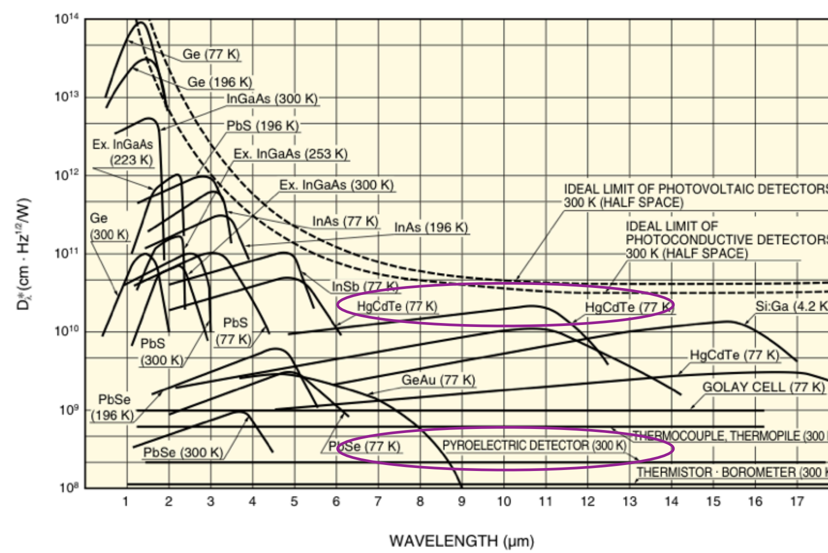




Optical Replica Synthesizer

proposed by Saldin, Schneidmiller and Yurkov in 2004

Nuclear Instruments and Methods in Physics Research A 539 (2005) 499–526

A simple method for the determination of the structure of ultrashort relativistic electron bunches

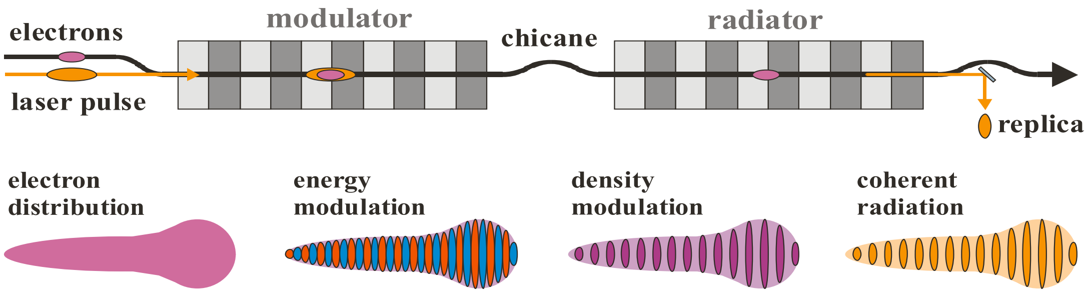
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov*

Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, Hamburg 22607, Germany

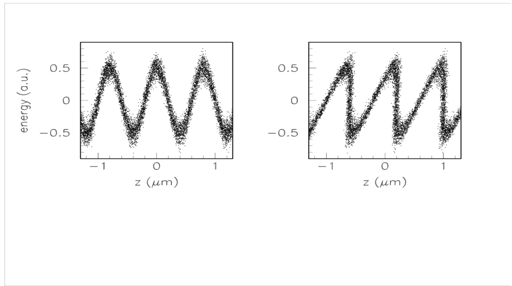
Received 3 August 2004; received in revised form 2 November 2004; accepted 2 November 2004
Available online 2 December 2004

„Operating range of proposed diagnostic technique nicely includes that of most ultrashort XFEL injector linacs, so it should be ideal for most everyday diagnostics as well as many more exotic ones“.

- *overlap beam with laser pulse in resonant undulator (modulator)*
- *generates energy modulation*
- *transform into density modulation by small chicane (R56)*
- *produce **coherent radiation** pulse at laser wavelength in second undulator*
- *measure temporal profile of „optical replica pulse“ with established optical methods (FROG,..*



© S. Khan



ORS limitations

ultimate resolution limit : phase slippage

$$\sigma_t \geq N_u \lambda / c$$

5 periods, 800nm → 13 fs

beam constraints :
beam size in undulators small (diffraction limit)

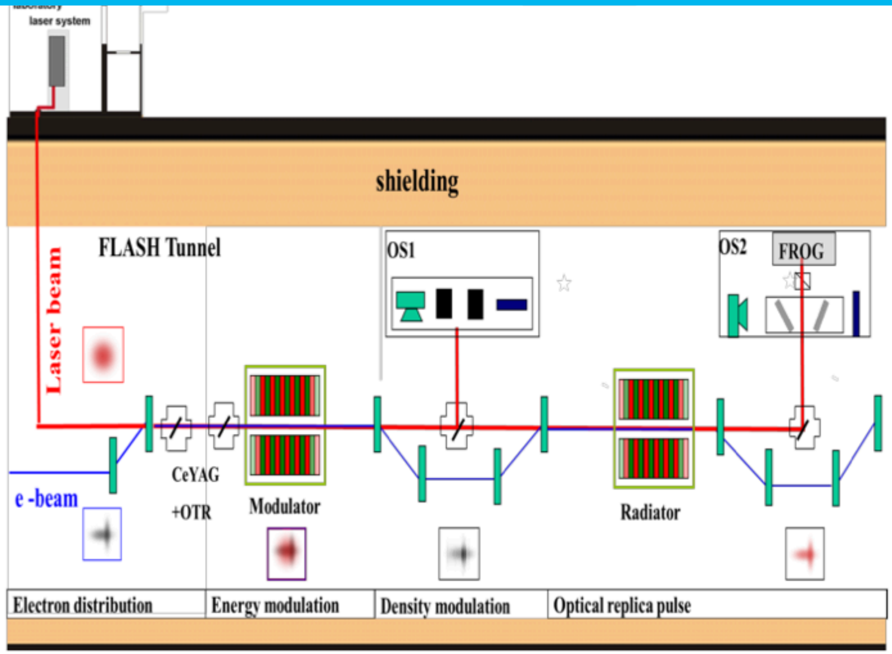
$$\sigma_x \ll \sqrt{\lambda L_u / (2\pi)}$$

5 periods, 1 m → σ_x << 350 µm

longitudinally „smooth“ beam (no microbunching)

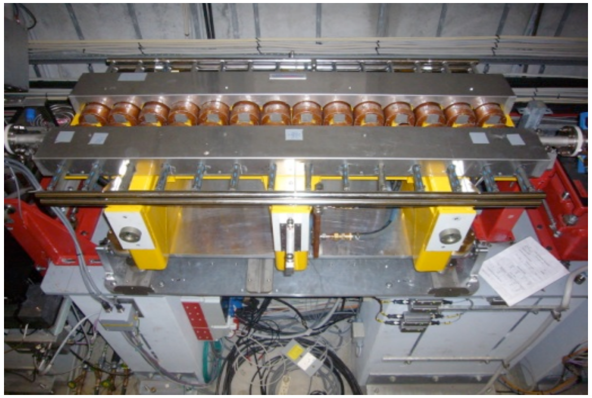
technical contraints :
spatial and temporal overlap of laser and beam
time jitter laser to beam << laser pulse length
sufficient laser power to overcome intrinsic energy spread
sufficient radiated power for FROG operation

ORS installation at FLASH



G. Angelova et al, PRSTAB **11**, 070702 (2008)

E_{beam}	$700\ MeV$
q	$0.5 - 1.2\ nC$
σ_x	$0.3\ mm$
$N_u \lambda_u$	$5 \cdot 0.2\ m$
λ_L	$800\ nm$
P_L	$0.5\ mJ$
σ_L	$400\ fs$
$R56$	$170\ \mu m$

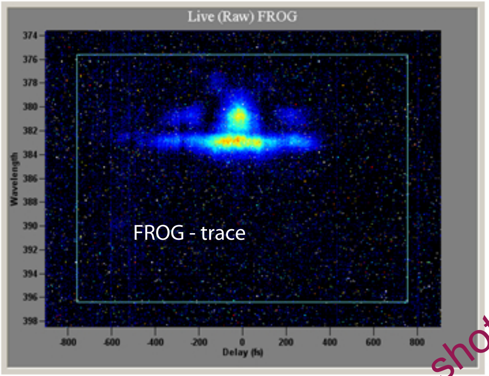


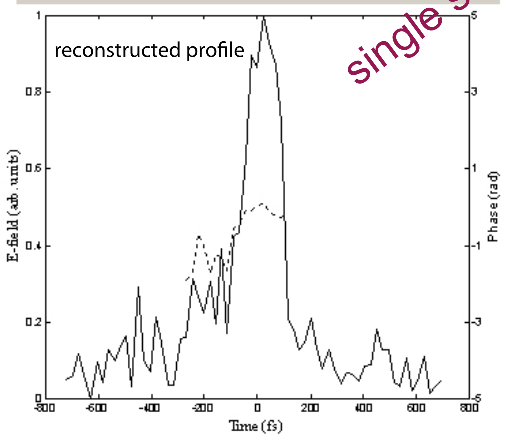
two orthogonal undulators

ORS@FLASH : first run 2007-2008

temporal and spatial overlap established

moderate signal for ~150 fs FWHM bunches



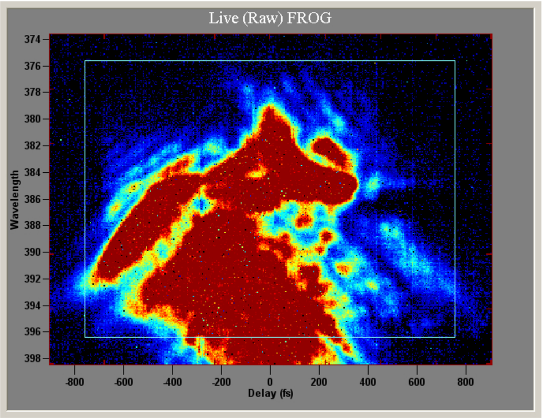


Proc. FEL-2009

RESULTS FROM THE OPTICAL REPLICA SYNTHESIZER AT FLASH

P. Salén, M. Hamberg, P. van der Meulen, M. Larsson, Department of Physics, Stockholm University, Sweden
G. Angelova-Hamberg, V. Ziemann, Department of Physics and Astronomy, Uppsala University, Sweden
H. Schlarb, F. Löhl, E. Saldin, E. Schneidmiller, M. Yurkov, DESY, Hamburg, Germany
J. Bödewadt, A. Winter, Universität Hamburg, Germany
S. Khan, DELTA, TU Dortmund, Germany
A. Meseck, Helmholtz-Zentrum für Materialen und Energie, Berlin, Germany

slightly more compression:



dominated by COTR from intrinsic microbunching ☹

ORS@FLASH : new plans

avoid COTR by using **270 nm** seed beam (below COTR „cut-off")

needs „transient grating (TG) FROG
with reflective optics

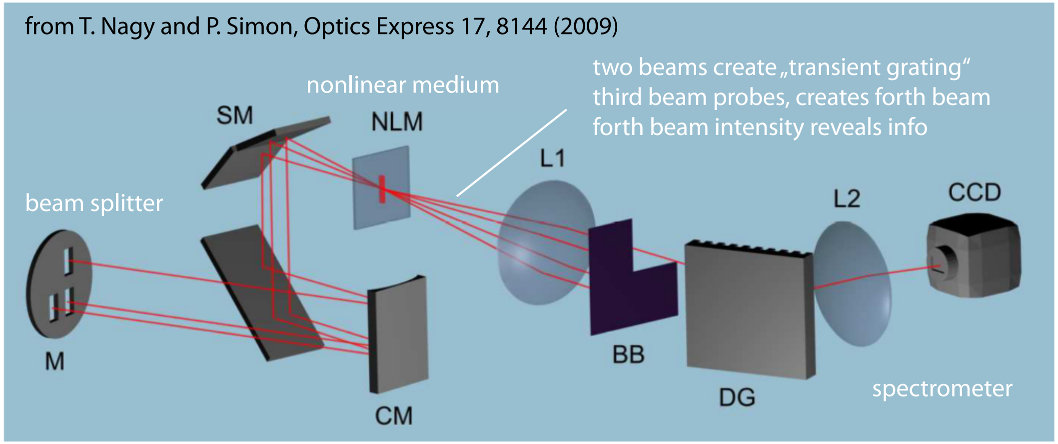
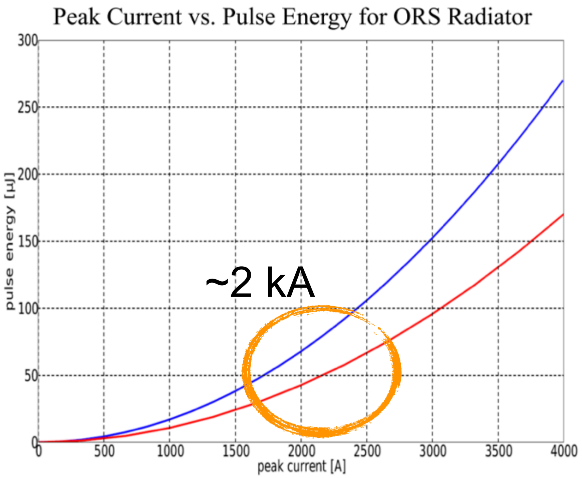


Fig. 2. The single-shot all-reflective TG FROG arrangement. (For the labels see text.)

Proc. FEL-2012
OPTICAL REPLICA SYNTHESIZER TO BE RECOMMISSIONED WITH 270 NM SEED AT FLASH

Kirsten Hacker*, Robert Molo, Shaukat Khan, Technische Universitaet Dortmund, Germany
Peter Salen, Peter Van der Meulen, Stockholm University, Sweden
Gergana Angelova Hamberg, Volker Ziemann, Uppsala University, Sweden

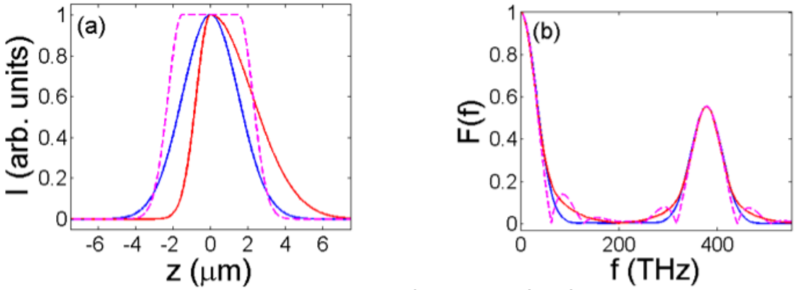


ORS ideas, plans, status

interesting technique of non-vanishing complexity
requires considerable technical infrastructure
still in experimental phase

Dao Xiang : IPAC 2012 : the „simplified ORS“

no second undulator, no FROG → OTR screen + spectrometer



simulation © D. Xiang, SLAC

OTR spectrum reveals bunch shape

„up-converted“ THz spectrum

including phase problem !

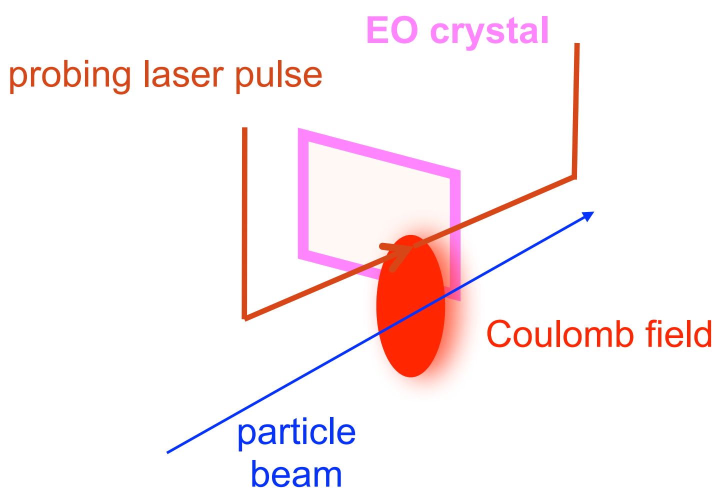
Electro Optic Methods : Basics

Intra-beamline measurement of the bunch Coulomb field

VOLUME 85, NUMBER 16 PHYSICAL REVIEW LETTERS 16 OCTOBER 2000

Subpicosecond Electro-optic Measurement of Relativistic Electron Pulses

X. Yan,* A. M. MacLeod, and W. A. Gillespie
School of Science and Engineering, University of Abertay Dundee, Bell Street, Dundee DD1 1HG, United Kingdom
G. M. H. Knippels, D. Oepts, and A. F. G. van der Meer
FOM–Instituut voor Plasmafysica "Rijnhuizen," P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands
W. Seidel
Forschungszentrum Rossendorf, Institute for Nuclear and Hadron Physics, P.O. Box 51 01 19, 01314 Dresden, Germany
(Received 31 May 2000)

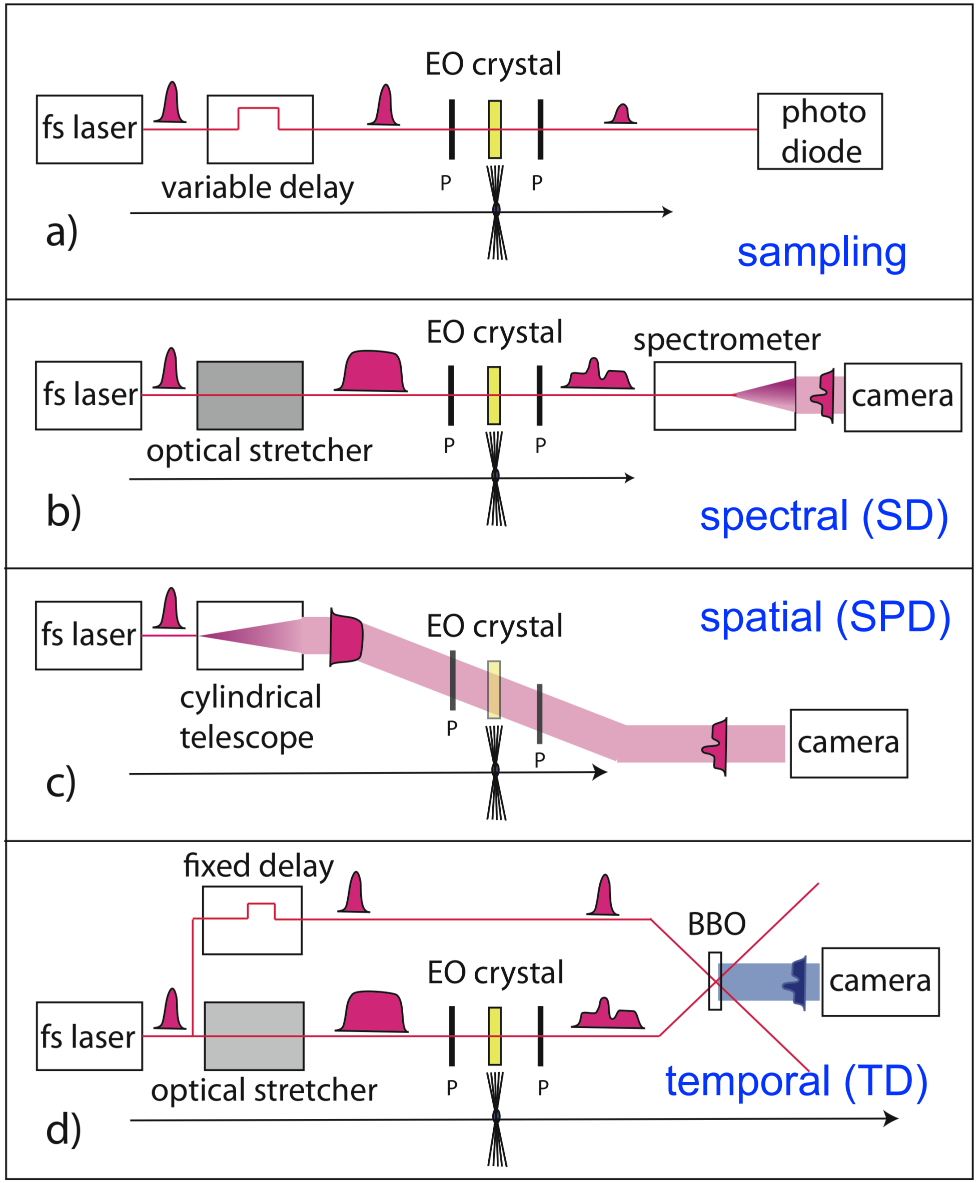


- Field induced refractive index change
- Polarization-modulation of probing laser
- Temporal structure of Coulomb field i.e. (beam current)
  ➔ impressed to ellipticity of optical pulse

$$\text{signal} \sim E_r(t) \overset{\gamma \gg 1}{=} \frac{I(t)}{2\pi b \epsilon_0 c}$$

$I(t) = \text{current}$

EO decoding schemes



- classical
- needs very short laser pulse
- **time jitter << bunch length**
- multi-shot (scanning)

- linearly chirped laser pulse
- **converts time → wavelength**
- technically simple
- systematic distortions and bias

- **cross-correlation technique in vaccum**
- detection system (imaging) close to beam
- bias free up to „crystal limits“

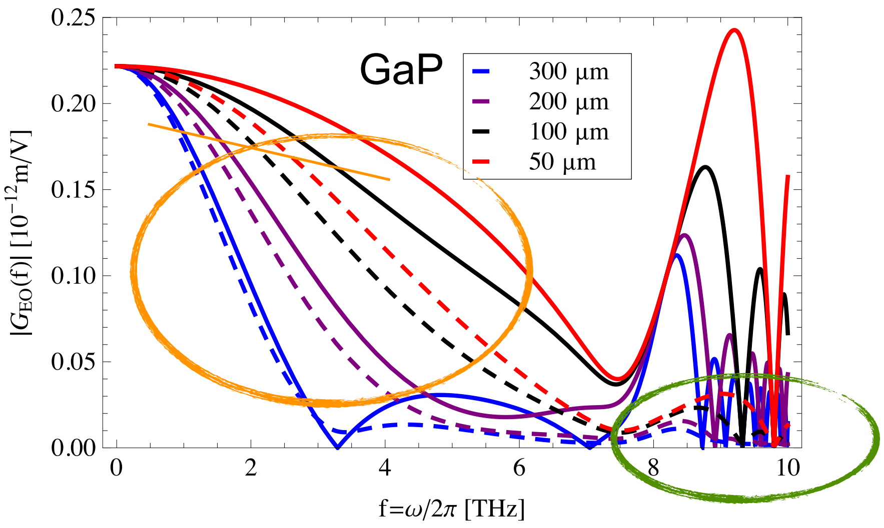
- **probe + sample pulse**
- SHG needs considerable power
- more demanding
- bias free up to „crystal limits“

Electro optic : resolution limits

Limits from anorganic EO material : phonon resonances & phase slipping

avoid „slipping“ by thin crystals
less signal

the EO „response function“, λ=800 nm



$\sigma_b \geq 50$ fs - GaP

$\sigma_b \geq 100$ fs - ZnTe

short bunches ⇢ high frequencies
excite phonon resonances
complex response, ringing...

status spectral decoding EO-SD

Problem :

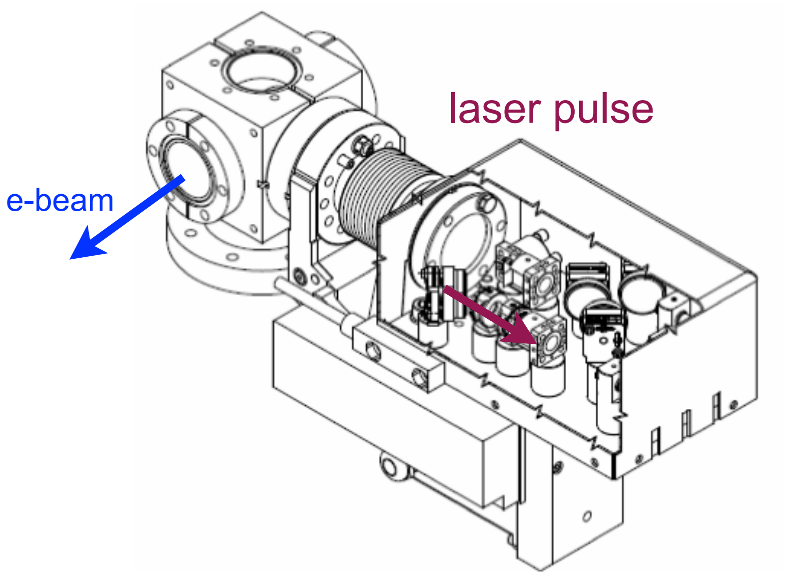
frequency mixing of bunch field an laser **distorts the „linear chirp“** (the „time scale“).

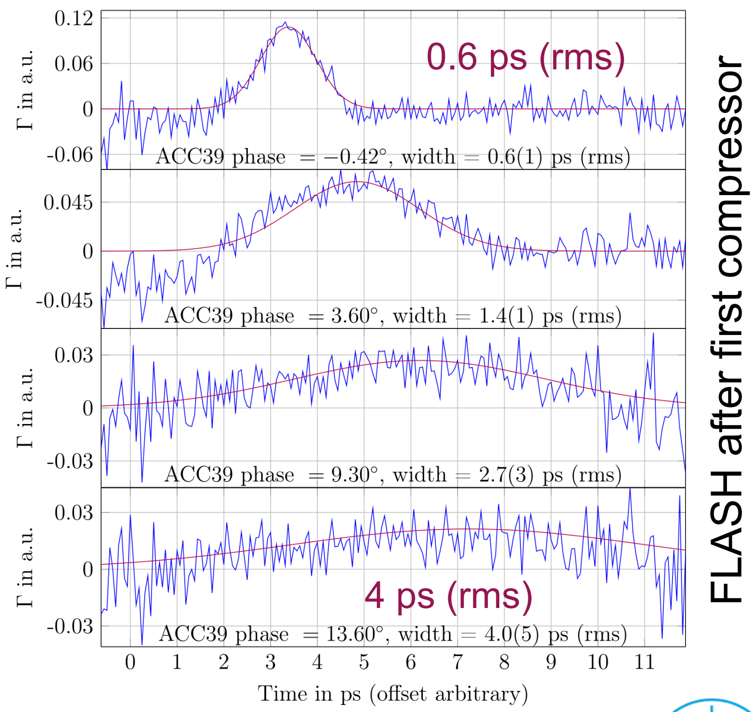
→ SD restricted to „long“ bunches. 100 µm GaP : $\sigma_b \geq 350$ fs

But : technically less demanding, robust, compact

Example : online monitor developed at PSI & DESY (Proc. DIPAC 09, B.Steffen,V. Schlott, F. Müller)

- Yb fibre laser (1030 nm) avoids delicate TiSa
- almost perfect phase matching, thick crystals allowed
- read out by commercial InGaAs spectrometer (fibre coupled)





drawback: finding the temporal overlap is (still) cumbersome

Spatial Decoding

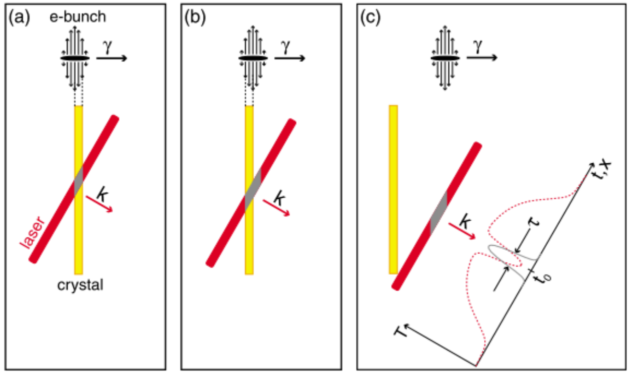
EO

first demonstrated at SLAC, 2005

PRL **94,** 114801 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

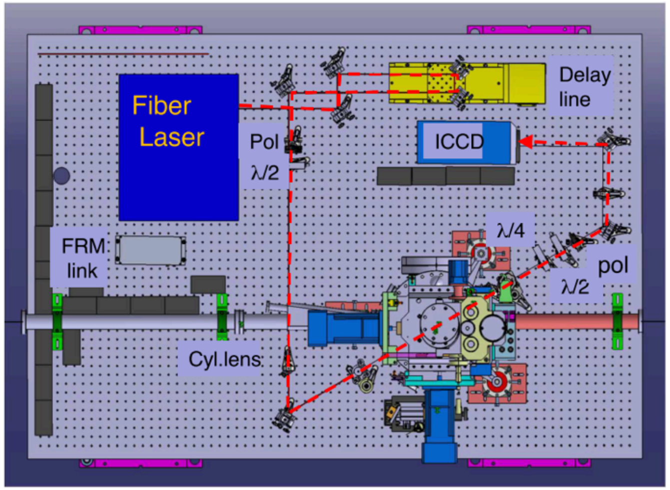
Clocking Femtosecond X Rays

A. L. Cavalieri,[1] D. M. Fritz,[1] S. H. Lee,[1] P. H. Bucksbaum,[1] D. A. Reis,[1] J. Rudati,[2] D. M. Mills,[2] P. H. Fuoss,[3] G. B. Stephenson,[3] C. C. Kao,[4] D. P. Siddons,[4] D. P. Lowney,[5] A. G. MacPhee,[5] D. Weinstein,[5] R. W. Falcone,[5] R. Pahl,[6] J. Als-Nielsen,[7] C. Blome,[8] S. Düsterer,[8] R. Ischebeck,[8] H. Schlarb,[8] H. Schulte-Schrepping,[8] Th. Tschentscher,[8] J. Schneider,[8] O. Hignette,[9] F. Sette,[9] K. Sokolowski-Tinten,[10] H. N. Chapman,[11] R. W. Lee,[11] T. N. Hansen,[12] O. Synnergren,[12] J. Larsson,[12] S. Techert,[13] J. Sheppard,[14] J. S. Wark,[14] M. Bergh,[15] C. Caleman,[15] G. Huldt,[15] D. van der Spoel,[15] N. Timneanu,[15] J. Hajdu,[15] R. A. Akre,[16] E. Bong,[16] P. Emma,[16] P. Krejcik,[16] J. Arthur,[17] S. Brennan,[17] K. J. Gaffney,[17] A. M. Lindenberg,[17] K. Luening,[17] and J. B. Hastings[17]

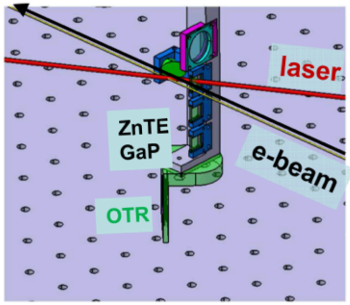


M. Veronese, BIW12

TUPA43



FIRST EOS measurements
Spatial encoding scheme
Fiber Laser : 780nm –FW 100fs
ZnTe, GaP, OTR, YAG



recent example

single shot technique, resolution not limited by frequency mixing
ideal for arrival time monitoring !

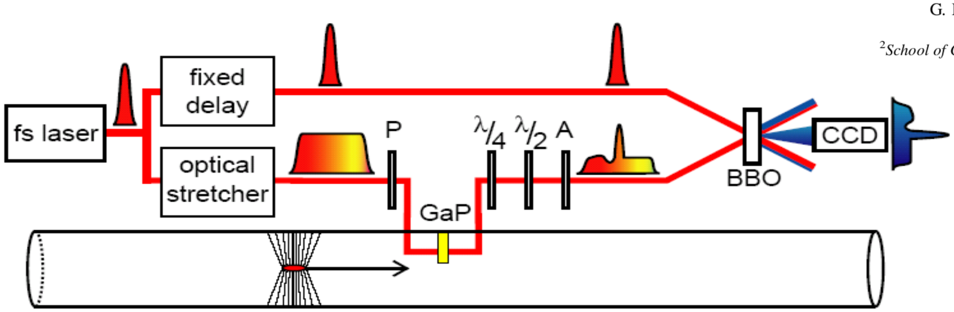
Temporal decoding

VOLUME 93, NUMBER 11 PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2004

Electro-Optic Technique with Improved Time Resolution for Real-Time, Nondestructive, Single-Shot Measurements of Femtosecond Electron Bunch Profiles

G. Berden,[1] S. P. Jamison,[2,*] A. M. MacLeod,[2] W. A. Gillespie,[2] B. Redlich,[1] and A. F. G. van der Meer[1]
[1]*FOM Institute for Plasma Physics "Rijnhuizen," Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands*
[2]*School of Computing and Advanced Technologies, University of Abertay Dundee, Bell Street, Dundee DD1 1HG, United Kingdom*
(Received 22 April 2004; published 9 September 2004)

gate pulse

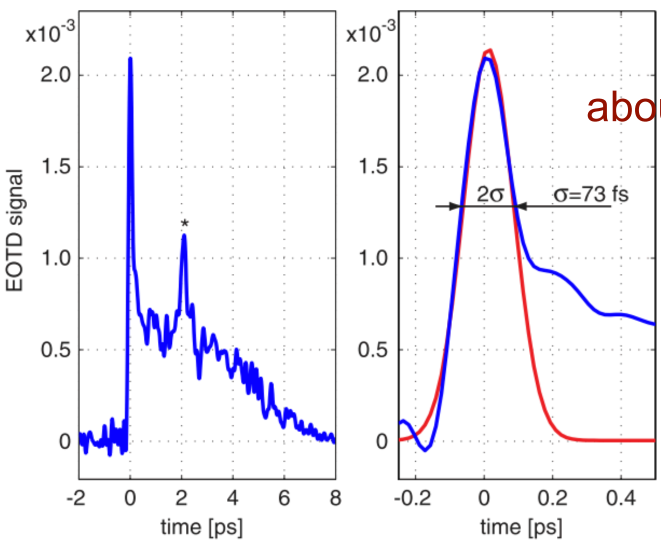


cross correlation in BBO crystal

needs > μJ laser power (2.order process)

complex optics

rather experiment but monitor



about crystal limit

B. Steffen et al., PRSTAB 12, 032802 (2009)

EO : new ideas

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 052801 (2012)

Extending electro-optic detection to ultrashort electron beams

M. H. Helle,* D. F. Gordon, D. Kaganovich, and A. Ting
Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375, USA
(Received 29 September 2011; revised manuscript received 23 February 2012; published 3 May 2012)

overcome problems
with resonances

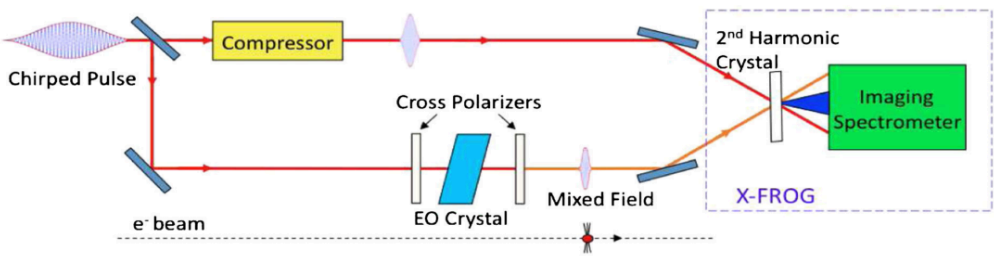


FIG. 2. BMX-FROG setup used to measure ultrashort charged particle bunches.

add spectrometer to EO-TD set-up

simulated FROG images

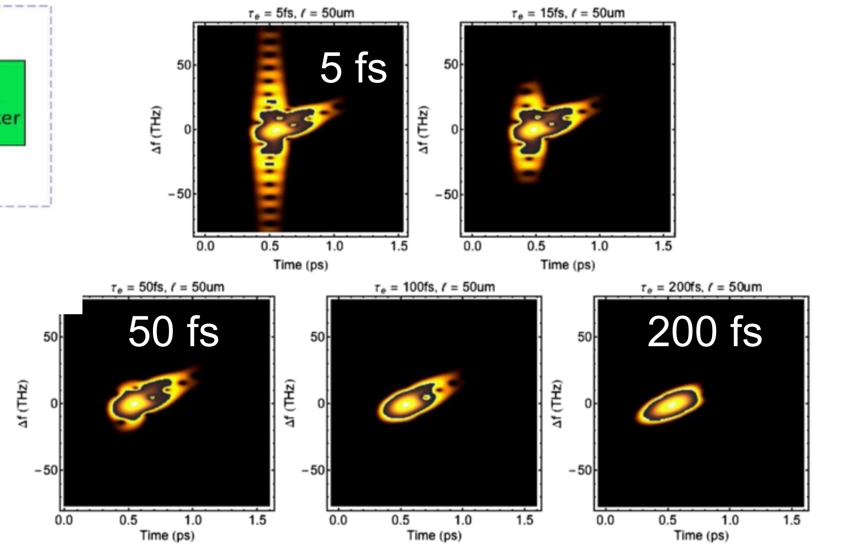
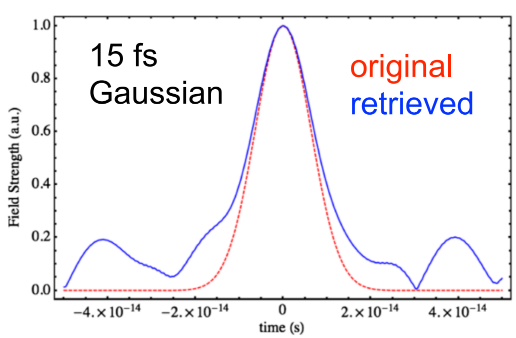


FIG. 5. Simulation results for various bunch lengths measured using a 50 μm crystal with a chirped probe. Each image is plotted using its own normalized false color scale.



caveat:
- needs very precise knowledge of crystal response
- inversion of complex profiles ?

EO : frequency up-conversion

WEPC80 Proceedings of FEL2009, Liverpool, UK

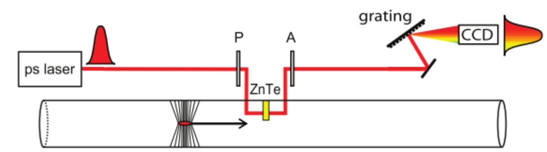
LONGITUDINAL ELECTRON BEAM DIAGNOSTICS VIA UPCONVERSION OF THZ TO VISIBLE RADIATION

G. Berden, A.F.G. van der Meer, FELIX / FOM Institute 'Rijnhuizen', Nieuwegein, NL

S.P. Jamison, ASTEC, Daresbury Laboratory, STFC, UK

A.M. MacLeod, Abertay University, Dundee, UK

W.A. Gillespie, P.J. Phillips, Dundee University, Dundee, UK

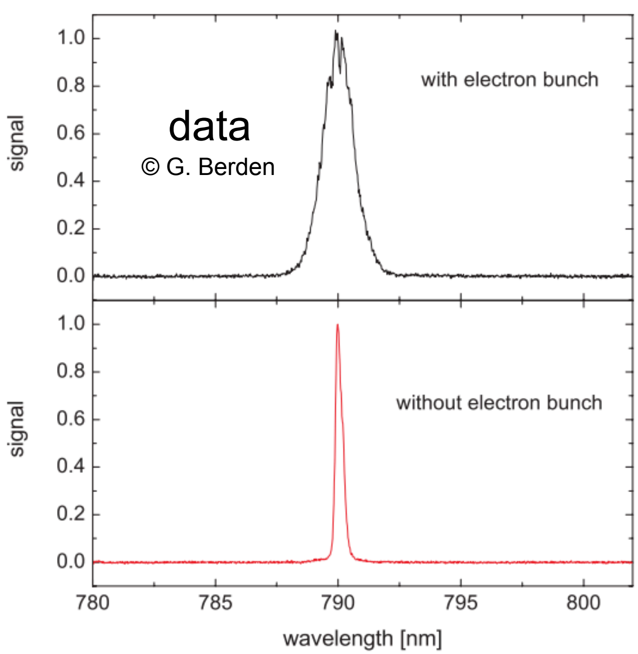


most simple set-up

needs **narrow band (long) laser pulse**

spectral broadening („side bands") by THz spectrum of bunch

no phase information (yet) ! (as with CTR spectra..)



a really ambitious project

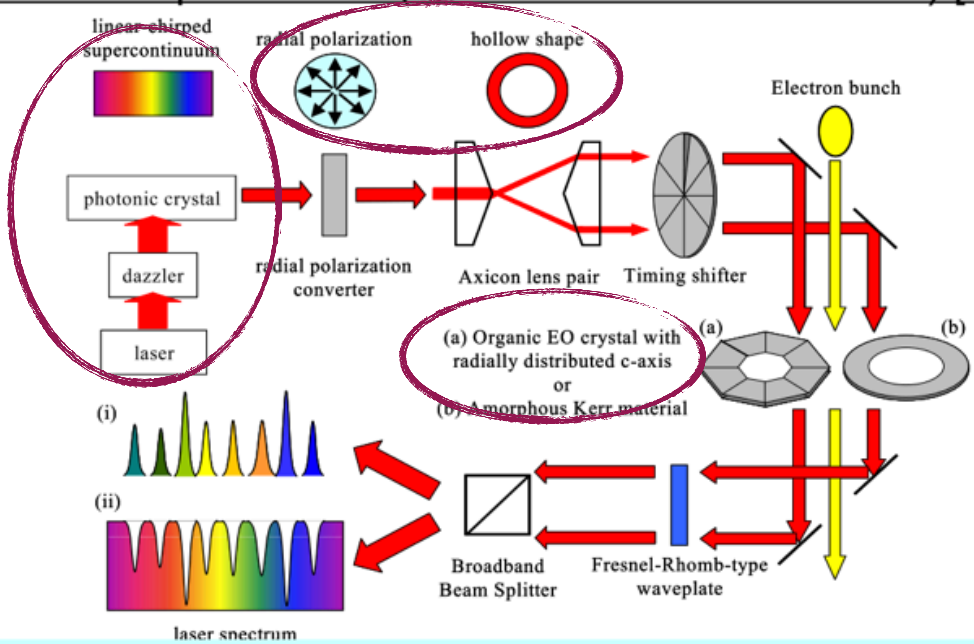
WEPPH053 Proceedings of FEL 2007, Novosibirsk, Russia

NON-DESTRUCTIVE SINGLE-SHOT 3-D ELECTRON BUNCH MONITOR WITH FEMTOSECOND-TIMING ALL-OPTICAL SYSTEM FOR PUMP & PROBE EXPERIMENTS

H. Tomizawa, H. Hanaki, Accelerator Division, Japan Synchrotron Radiation Research Institute (JASRI/SPring-8), Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan
T. Ishikawa, The Institute of Physical and Chemical Research (RIKEN Harima/SPring-8), Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan

talk by Y. Okayasu
MOCC03

3D bunch shape monitor (One element of 3D-BCDM) [1]



codes time & radial information into spectrum

several new an challenging concepts !

under development

Supercontinuum generation: Photonic crystal fiber
Supercontinuum propagation: Spectrum modulation by DAZZLER + Developments of optics
radial polarization: Liquid crystal
Hollow shape: Axicon mirror pair

Summary

- progress in TDS technology towards ~ 1 fs regime

- coherent radiation methods made it to online monitors, perspectives for shorter bunches

- electro-optic methods : more experiment than monitors, interesting approaches ahead

- ORS : proof of feasibility still missing, complex technology

- interesting new ideas and concepts waiting to be tested

Thank you and all contributors !

there is always room for the discovery of wonderful new techniques...

additional stuff

fs resolution achieved: „zero phasing“

Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA THP183

MEASUREMENT OF FEMTOSECOND LCLS BUNCHES USING THE SLAC A-LINE SPECTROMETER *

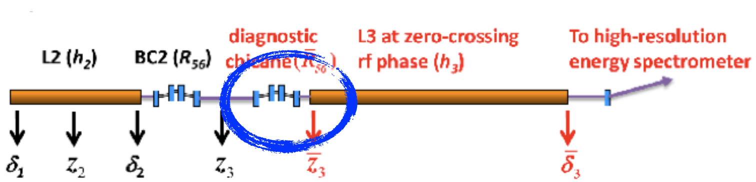
Z. Huang, A. Baker, C. Behrens†, M. Boyes, J. Craft, F.-J. Decker,
Y. Ding, P. Emma, J. Frisch, R. Iverson, J. Lipari, H. Loos, D. Walz
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

dedicated experiment at LCLS

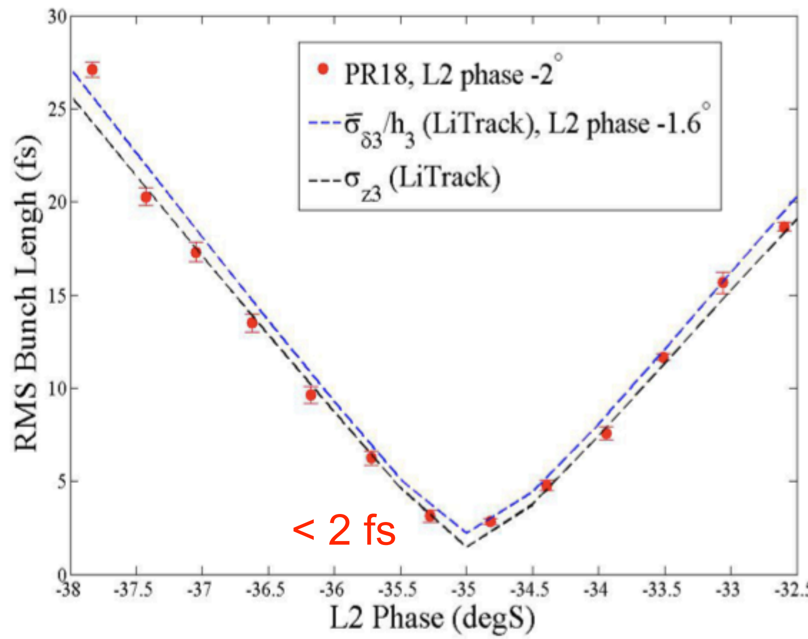
running linac at „zero phase“

chirp maps time → energy

high resolution(10^{-4}) „A-line“ spectrometer



compensates
intrinsic energy spread



Back to time domain : the phase problem

(Lay, Happek, Sievers 1994)

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) e^{-2\pi i z/\lambda} dz$$

complex function, S(z) is real

Kramers-Kronig relation: connects real and imaginary part (for a certain class of S !)

$$\phi_m(\lambda_0) = -\frac{2}{\pi}\lambda_0 \int_0^{\infty} \frac{\log\left(\left|F(\lambda_0)\right| / \left|F(\lambda)\right|\right)}{(\lambda_0^2 - \lambda^2)} d\lambda$$

needs |F(λ)| over a wide range ..
but neither „0“ nor „infinity“..
extrapolation needed (long wavelengths)

$$S_m(z) = \frac{2}{c\lambda^2} \int_0^{\infty} \left|F(\lambda)\right| \cos\left(\frac{2\pi}{\lambda} + \phi_m(\lambda)\right) d\lambda$$

measured values

„minimal“ or „canonical“ bunch profile

EOSD: early days

VOLUME 88, NUMBER 12 PHYSICAL REVIEW LETTERS 25 MARCH 2002

Single-Shot Electron-Beam Bunch Length Measurements

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(Received 10 September 2001; published 6 March 2002)