FEL 2006, Berlin

Diagnostics for X- and XUV-FELs

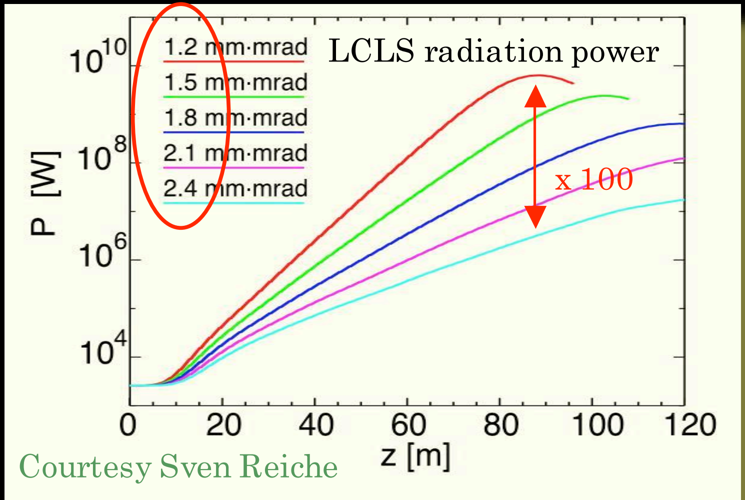
- diagnostics specific for single pass FEL
- especially demanding areas, new developments

- no photon diagnostics
- personal perspective

Bernhard Schmidt

bernhard.schmidt@desy.de

The case for diagnostics



" a single pass FEL is a non-forgiving machine" (S.R.)

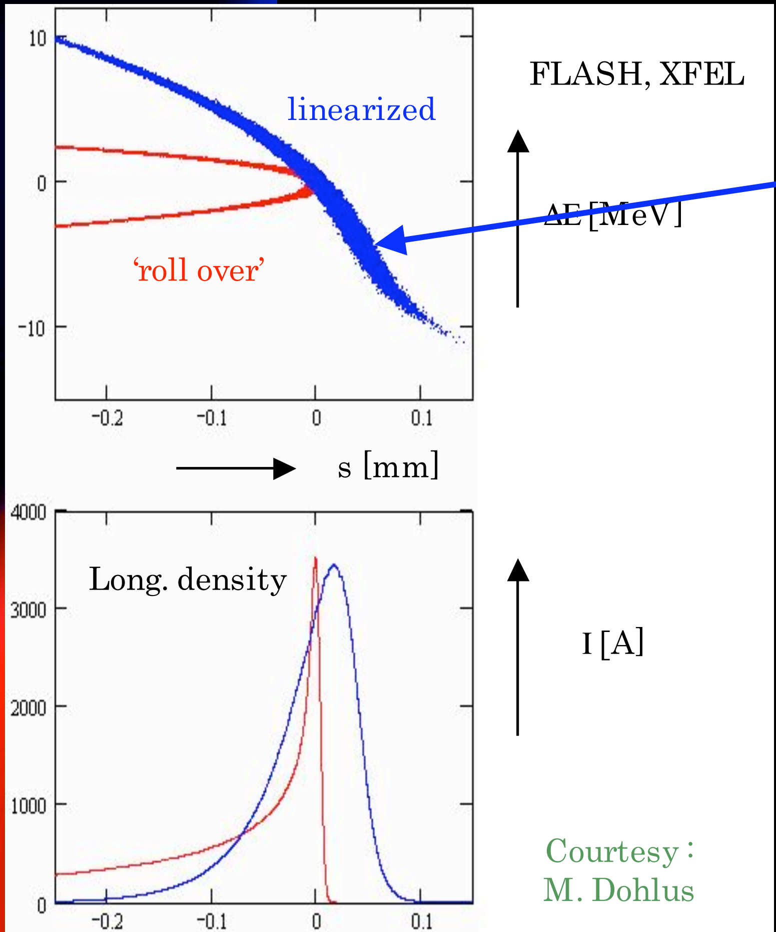
FEL power depends exponentially on beam parameters (peak current, emittance…)

Measure, control and stabilize beam parameters such that optimum FEL performance is achieved

Slow : human experience
Fast : intra-bunch feedback for SC machines

Longitudinal phase space

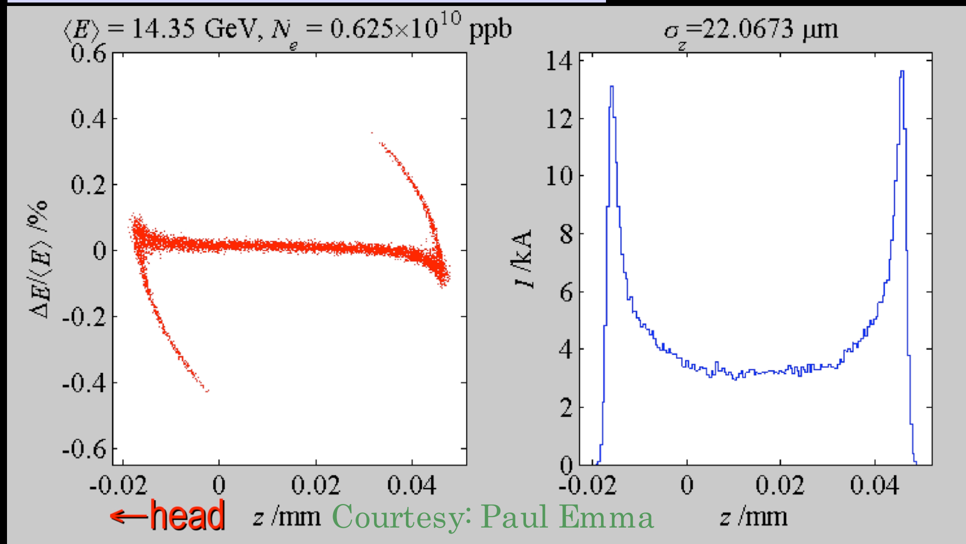
Bunch compression for high peak currents has non-linear components ➔ complex phase space distributions



Very demanding parameter control !

Phases < 0.01°
Fields < 10^{-4} ....

Expected long. Bunch shape at LCLS, 'double horn' due to wake fields

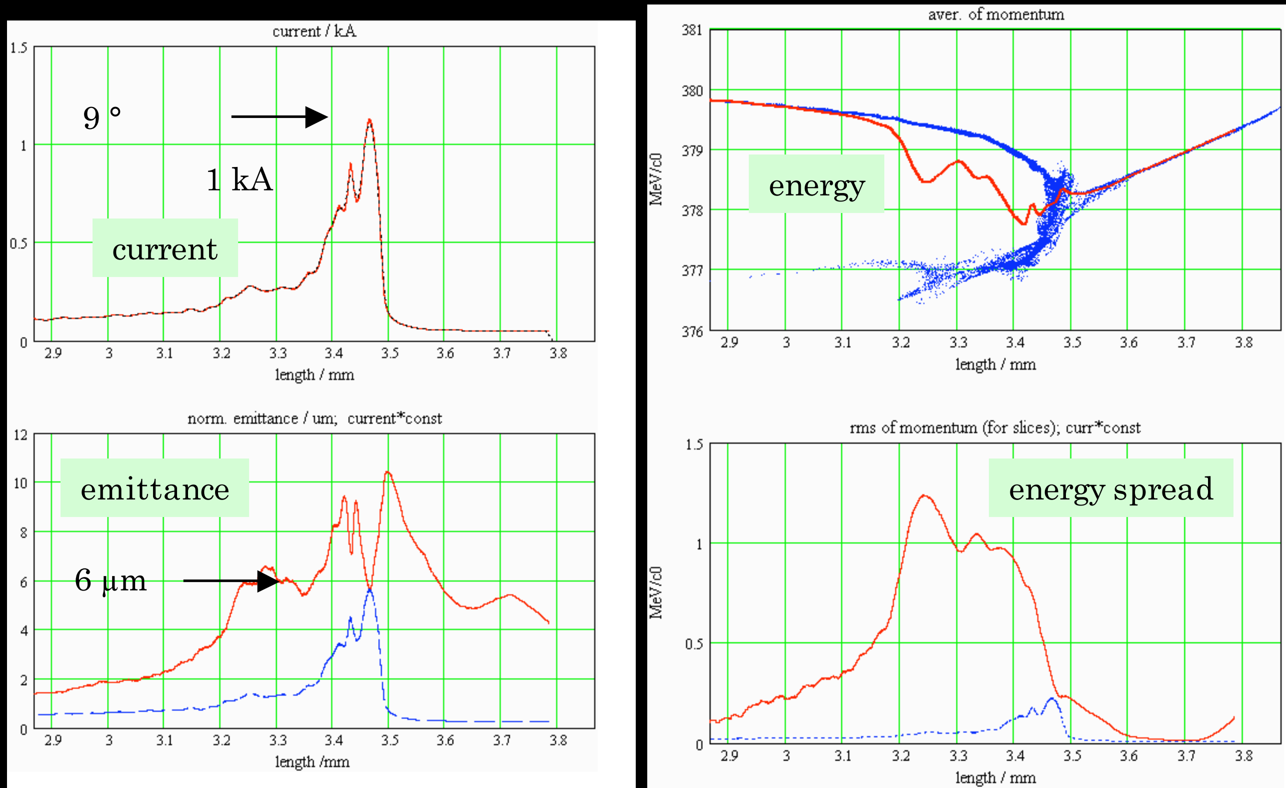


Only fraction of the total charge will 'lase', diagnostic has to be sensitive to this fraction

Including coherent effects : CSR & space charge

FLASH, nonlinear compression

S2e simulations, Martin Dohlus,Thorsten Limberg



Projected parameters are of limited use !
Diagnostics has to reveal details of the bunch structure
slice emittance, bunch profile, slice energy spread, bunch position

... bunch to bunch basis

The ideal diagnostics

- ultimate resolution
- comprehensive
- immediate feedback on single bunch
- non - invasive

.. will remain a dream

Status and perspectives of a few key technologies

BPM - 1

Warm sections - Cold sections (XFEL) - Undulators

Resolution :

10 µm, resonant stripline, button

"workhorse"

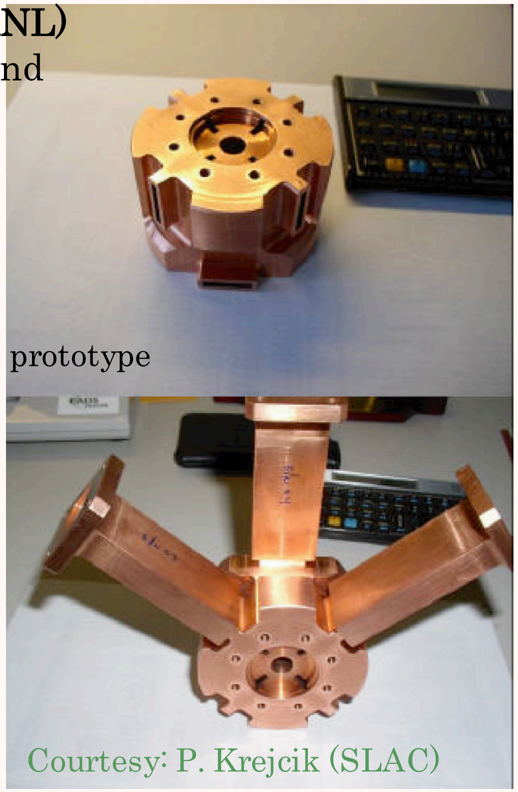
<< 1µm for 1 Å

Similar developments in Italy (ELLETRA) (P.Craievich et al. , THPPH025) and Japan (Spring8) (T. Shintake, MOBAU05)

Cavity BPM's

LCLS (SLAC,ANL)
8.26 GHz, X-band
Goal :
< 100 nm/nC

H.D. Nuhn et al
THBAU02

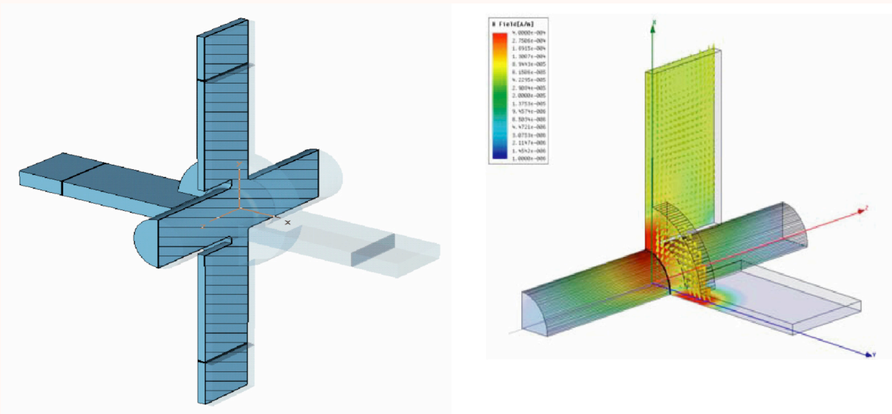


prototype

Courtesy: P. Krejcik (SLAC)

XFEL (PSI, DESY)
4.38 GHz, C-band
Goal :
< < 1 µm/nC

D. Noelle et al
THPPH014



Courtesy: B. Keil (PSI)

Challenge : design, fast signal processing, mechanical precision, alignment and stability ..

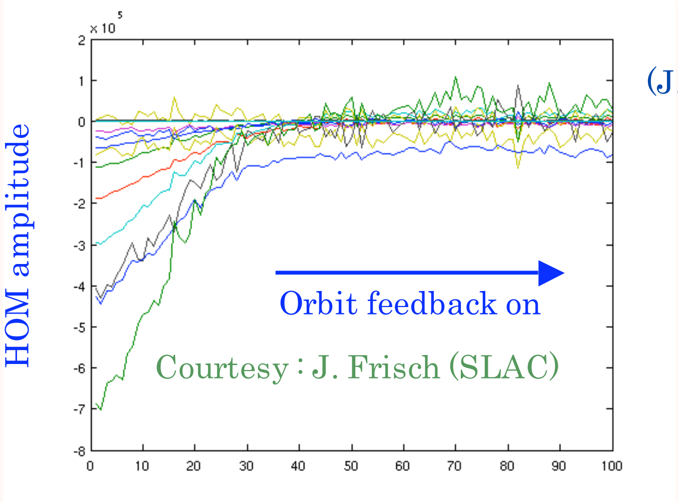
BPM-2, specialities

Beam induced HOM in SC cavities for BPM

Complex 'spectrum' of different modes depends on beam position and angle

Expected : resolution ~1 μm

EPAC06, Talk by J. Frisch



System Test at FLASH
(J. Frisch, N. Baboi, M. Ross..)

Achieved ~ 7 μm res.

+ beam angle
+ timing

Large aperture BPM inside BC chicane

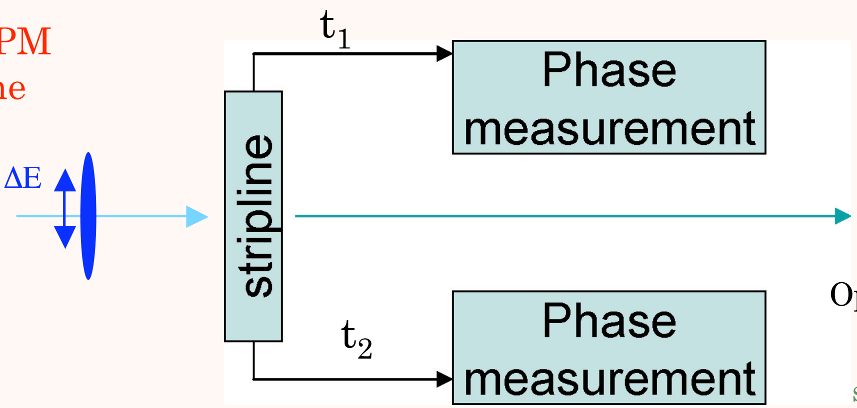
Example:

ΔE : 10^{-4}

Δx : 35 μm

Δt : 60 fs

energy feedback needed



Courtesy : K. Hacker (DESY)

Resolution required
Δx: ~ 5 μm
Δt: ~ 15 fs !

~~RF~~ ?

Optical detection seems feasible

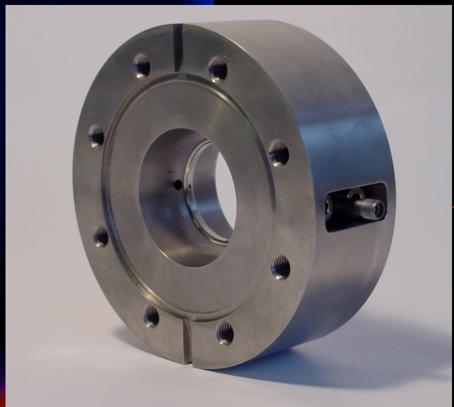
single bunch !

TUPPH054

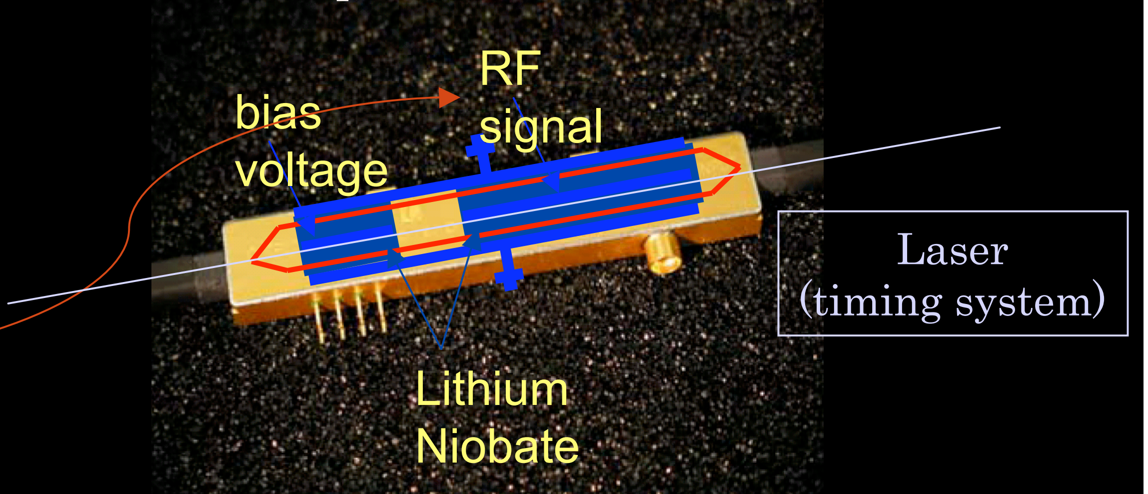
Alternative : image SR in the UV range from chicane dipole (C. Gerth, THPPH011)

Arrival time monitors

Pick up (ring electrode)

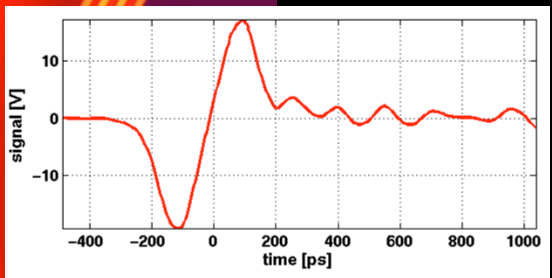


Electro-Optic Modulator

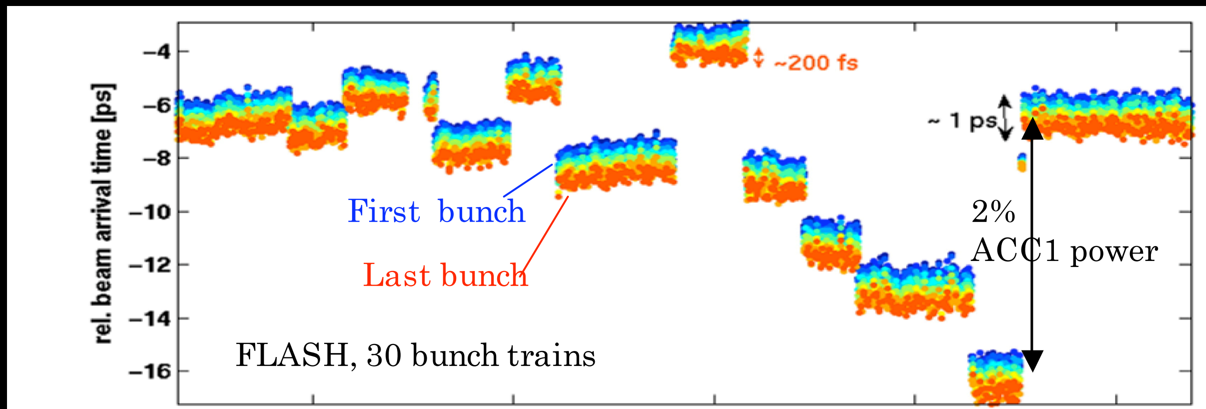


Caveat : center of charge !

Resolution
direct electrical mixing : ~ 300 fs
Electro-optic : ~ 30 fs demonstratet (EPAC, talk by F. Löhl)



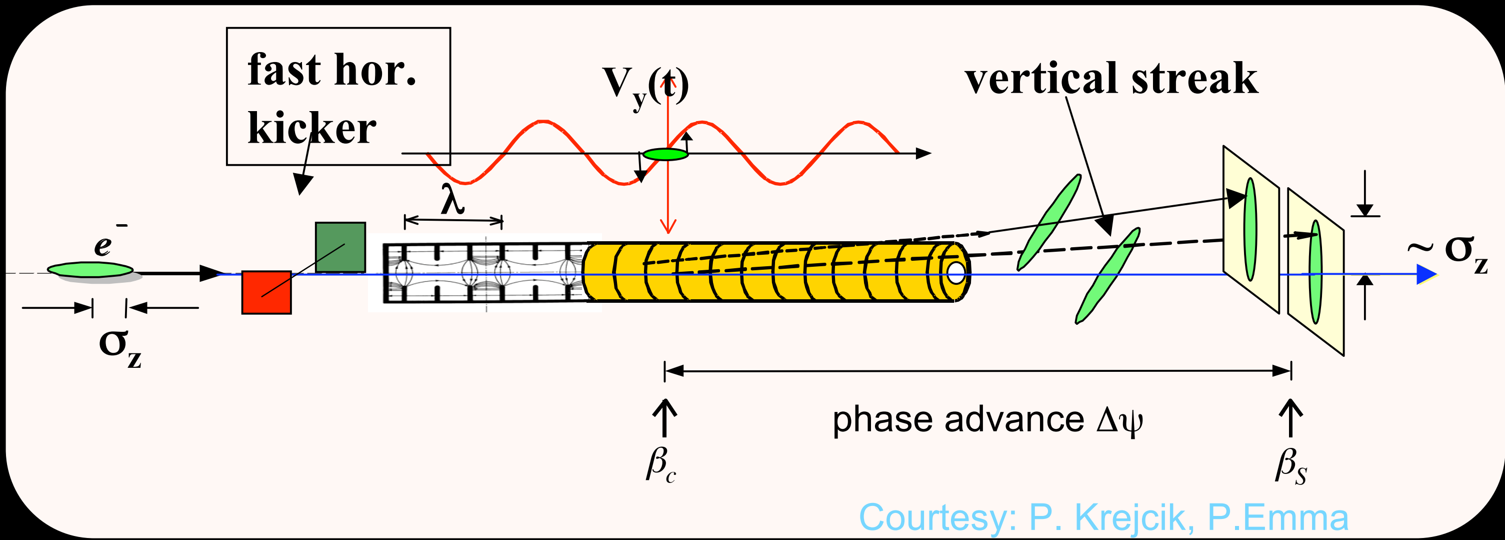
Phase detection at zero crossing



Courtesy : F. Löhl (DESY)

Transverse deflecting cavities (TCAV)

- Adds z-position dependend transverse kick to bunch
- Phase advance to screen ➔ vertical streak of longitudinal bunch structure



adding fast horizontal kicker ➔streak image on off-axis screen

- single bunch capable
- not multi-bunch capable
- 'semi-parasitic' (sacrifice 1 bunch)
- slow read out (imaging)

$$\Delta y = \Delta z \frac{eV}{E_0} \frac{2\pi}{\lambda_{HF}} \sqrt{\beta_c \beta_S} \sin(\Delta\psi)$$

$$\Delta y >> \sigma_y^{initial}(screen) \rightarrow \text{small } \beta_S$$

$$\Delta y \propto \sqrt{\beta_S \beta_C} \rightarrow \text{large } \beta_C$$

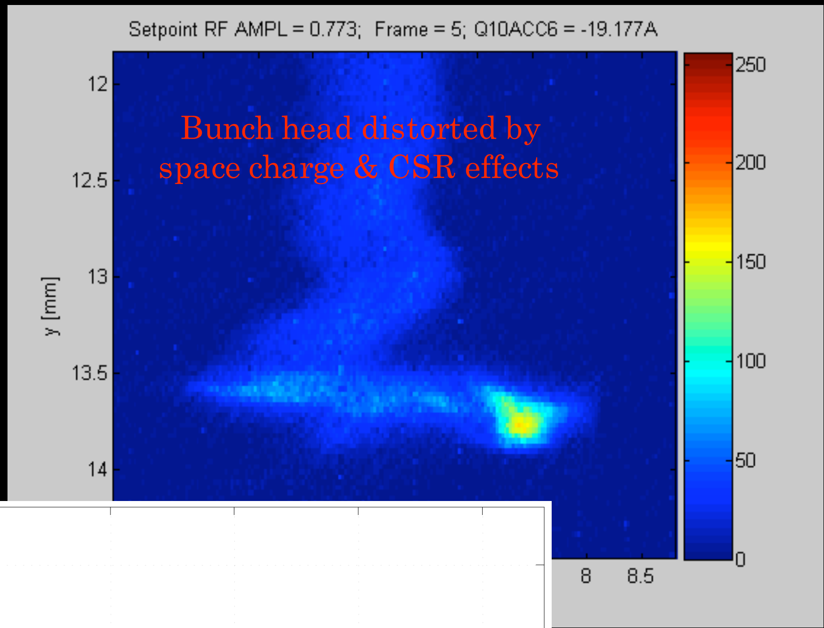
Resolution depends on cavity power, beam energy and machine optics

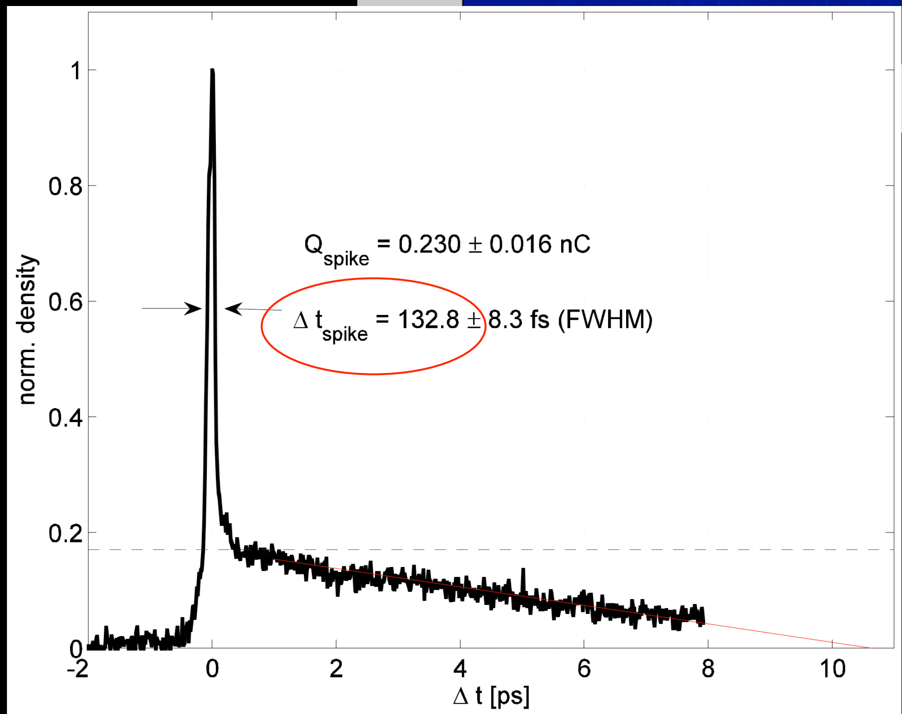
SLAC - DESY collaboration (M. Ross, J. Frisch, M. Hüning, H. Schlarb a.m.o.)

TCAV installation at FLASH

$E_0 = 600$ MeV
$\sqrt{\beta_C \beta_S} = 50$ m
$\Delta\psi = 18°$

$\nu_{HF} = 2.856$ GHz
$\lambda_{HF} = 105\ mm$
$L = 3{,}66\ m$
$V_{eff} = 25\ MV$
$P_{HF} = 18\ MW$

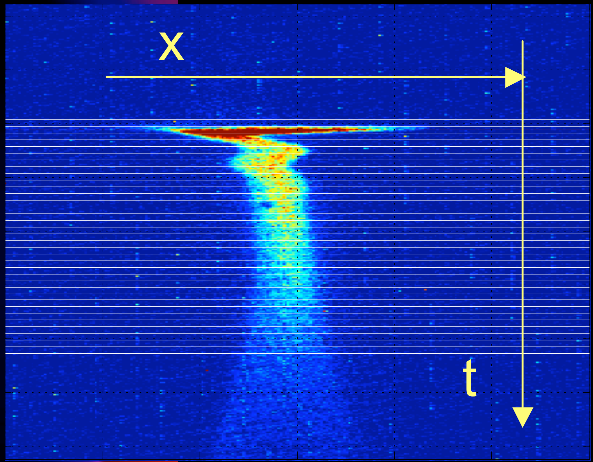


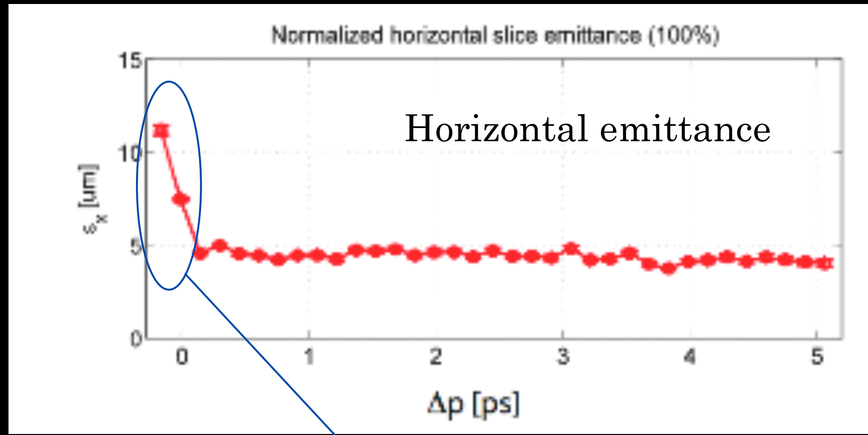


Typical Resolution
: 20-50 fs

TCAV for slice emittance and slice energy spread

(Examples !)

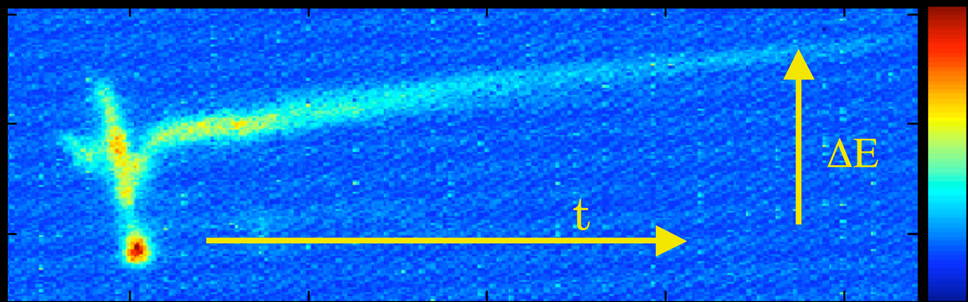




- Longitudinal slices of 250um or 154fs

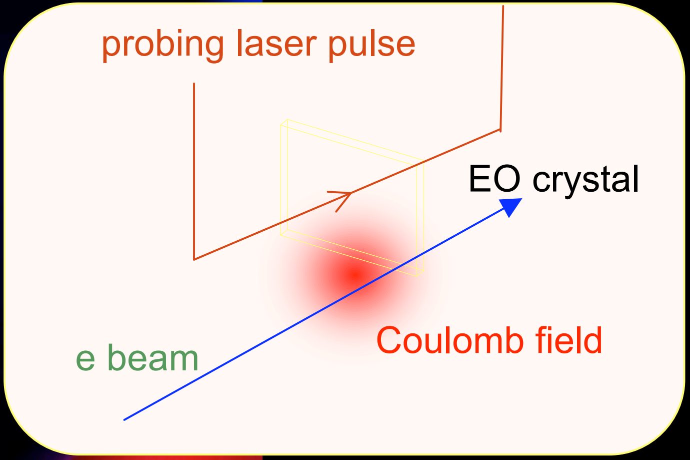
apparently too large for lasing !!

slicing >> width of spike(s) ➔ “projected” emittance



courtesy: M. Röhrs

Electro - Optic (EO) Techniques



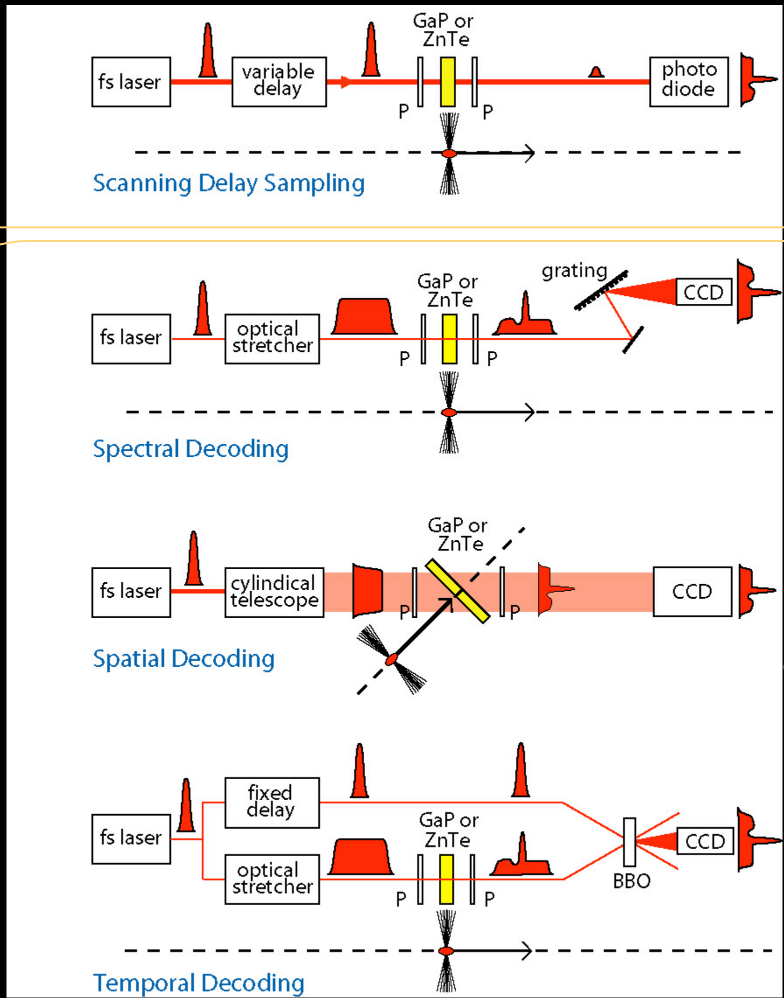
Intra-beamline measurement of the bunch Coulomb field

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

Limitations:

- high frequency cut-off due to finite distance to beam
- velocity mismatch of FIR and optical propagation in EO crystal
- phonon resonances of EO material

Decoding the probing laser pulse

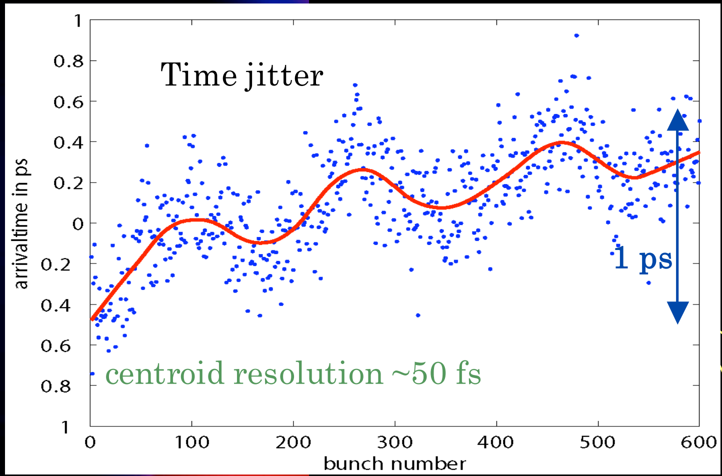


scanning technique
NOT single shot
inadequate if jitter ≥ pulse lengths

single shot techniques
different complexity and resolution

Courtesy: Giel Berden (FELIX), Bernd Steffen (DESY)

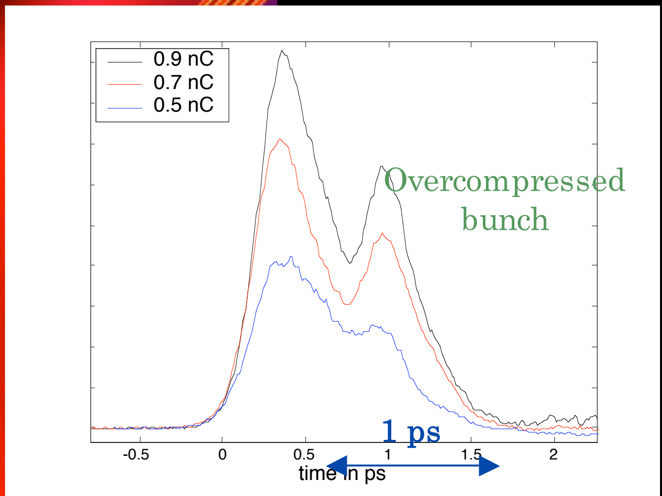
Spectral decoding



Optical pulse:
Δλ 60-80 nm, chirped to 1-2 ps
nJ energy (oscillator)
Read out:
Polarizer + gated CCD camera
Rep. Rate: Hz

Structures ~ 300 fs
Centroid of spike ~ 50 fs

Courtesy B. Steffen

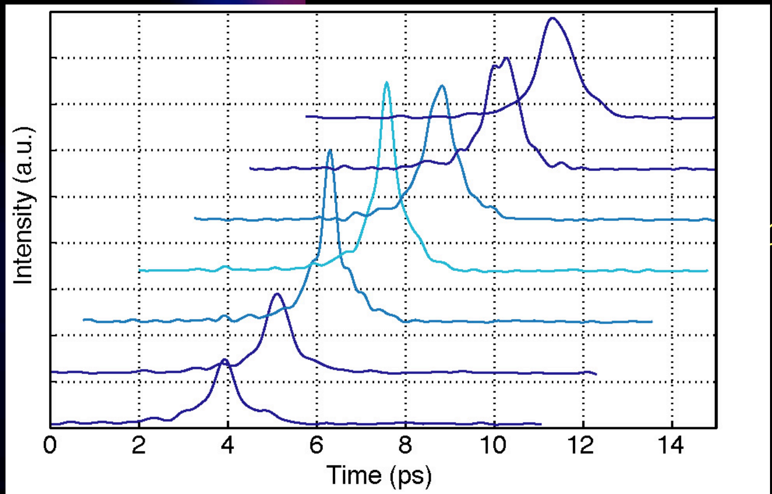


pro:
Relatively simple set up
No high power laser
contra:
Resolution intrinsically limited due to frequency mixing between FIR (E-field) and Optical (probe pulse) fields ➔
Broadening & artificial structures

Application:
Spike arrival time, coarse features

Future developments:
multi - bunch capability with fast read out (line detector)
Online monitor with simplified robust laser system (fibre laser)

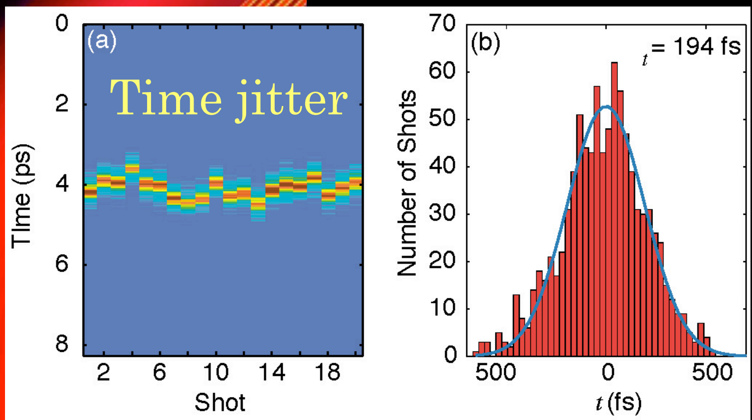
Spatial decoding



fwhm ~270 fs

Optical pulse:
Δλ 60-80 nm, SHORT
nJ energy (oscillator)
Read out:
Polarizer + gated camera
Rep. Rate Hz

pro:
Moderate laser power
No methodical limitations
contra:
Relies on spatially uniform EO material
Needs complex optics and
imaging system inside accelerator

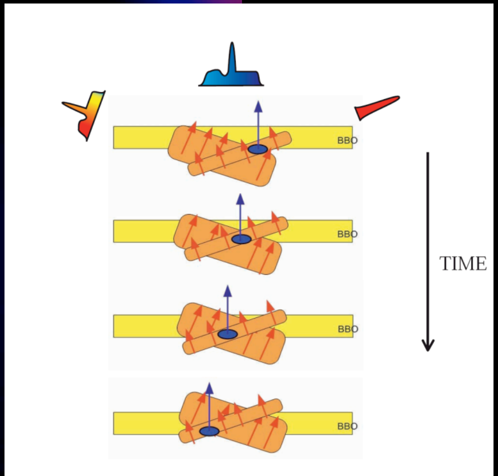


Data from
SLAC-FFTB (A. Cavalieri et al.)

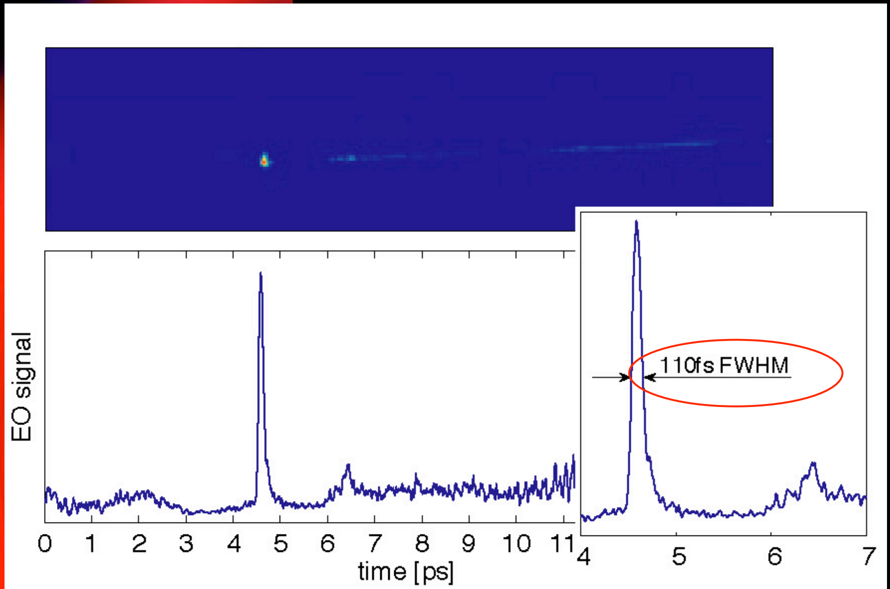
Similar experiment at FLASH with GaP, ~100 fs resol. achieved
(Armin Azima et al.)

FEL 2006, Berlin

Temporal decoding



Optical pulses:
Δλ 60-80 nm, stretched to few ps, nJ energy
\+ short pulse , several μJ energy
Read out:
Optical SH generation in non-colinear geometry
Imaging with intensified CCD
Rep. Rate Hz

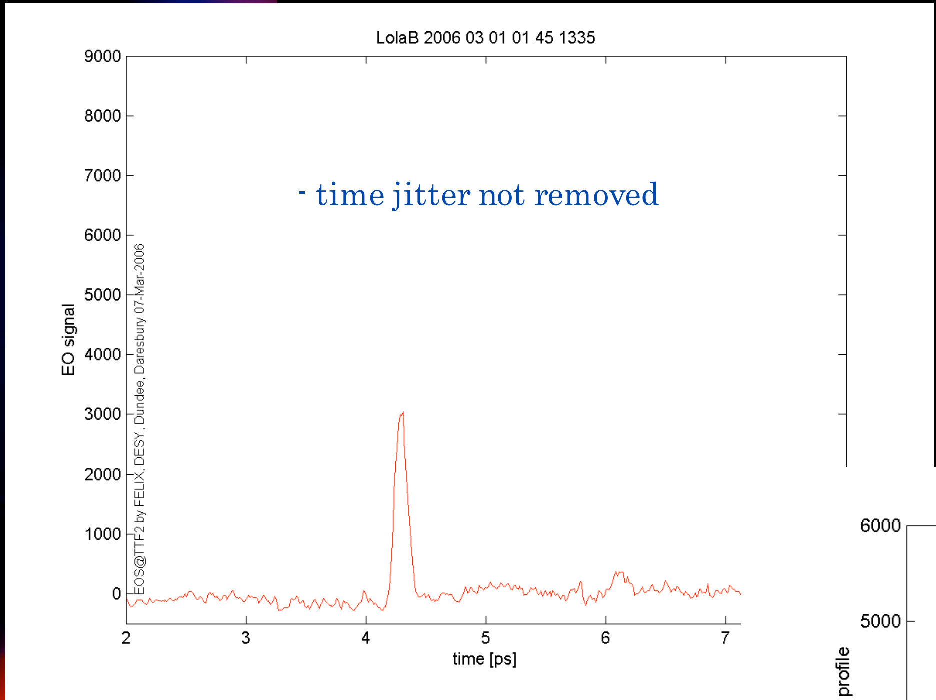


pro:
No methodical limitations
Superior resolution demonstrated (so far)
contra:
High power laser system (amplifier)
Needs complex optics and
imaging system inside accelerator

Data from: FLASH
Giel Berden (FELIX)
Steve Jamison (Daresbury)
Jonathan Philips (Aberdeen Dundee)
Bernd Steffen (DESY)
et al.

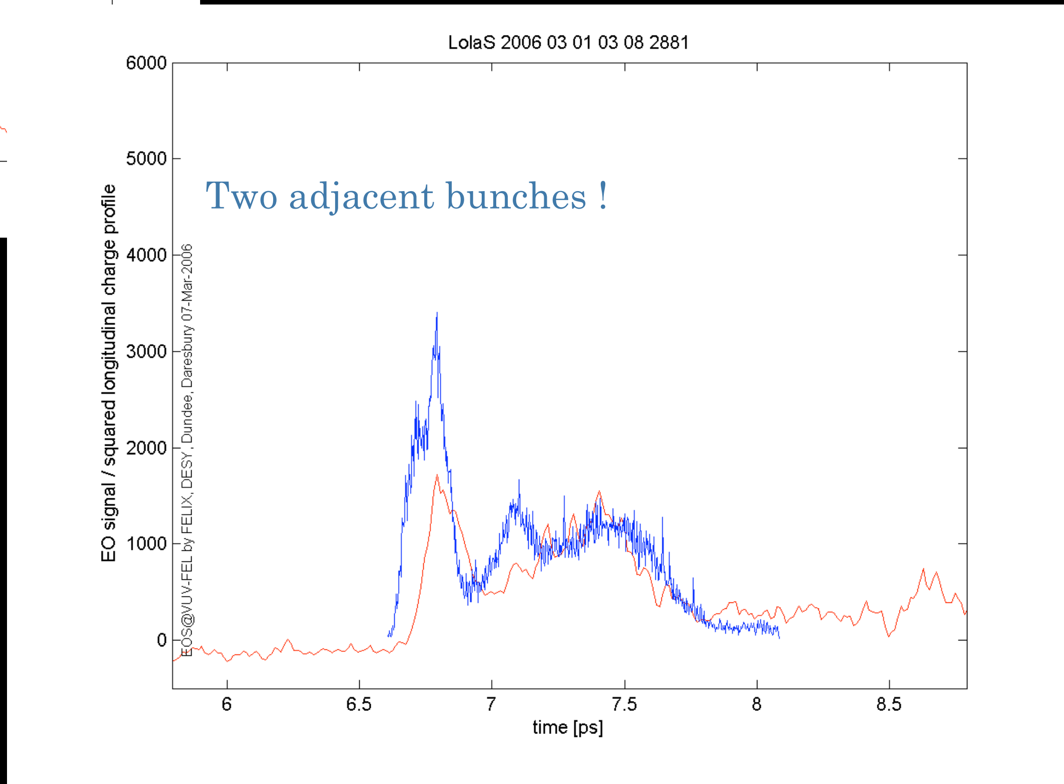
EO movies

DESY - FLASH, Courtesy Bernd Steffen et al.



EO-TD online, raw data
Optimal SASE compression

EO-TD compared with TCAV data
(jitter removed off-line)
Over-compressed beam



Make the electrons radiate ...

COHERENTLY

spectral energy density

source characteristics (CSR,CTR,CER, CDR,SP..)

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

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

normalized charge densitiy

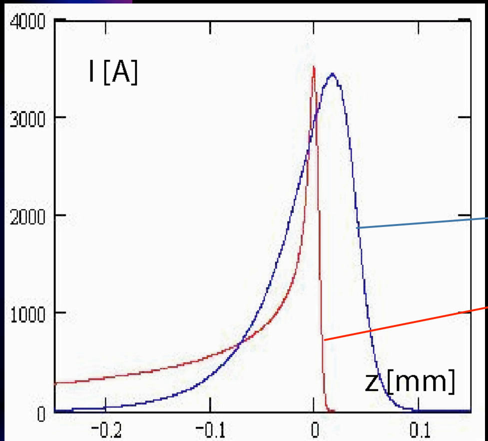
- integral intensity

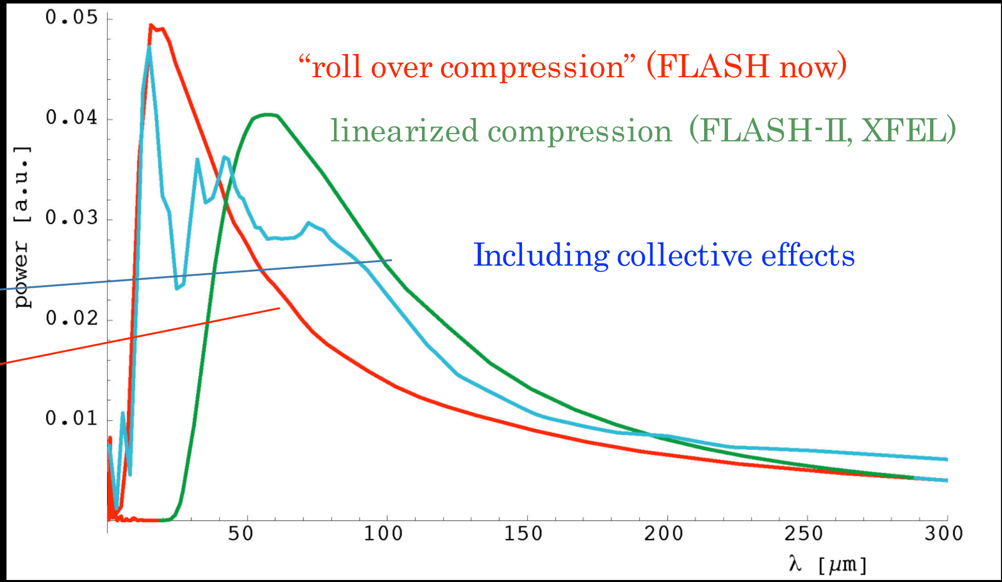
➡ 'compression factor', effective bunch length

- spectral resolved intensity

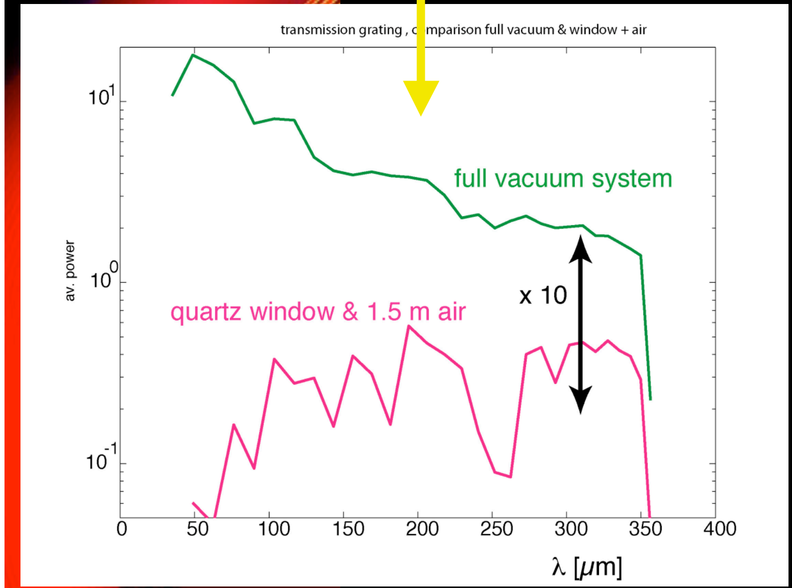
➡ + bunch structure, 'longitudinal fingerprint'

Wavelength range of relevance





Experimental data



Depending on compression scheme , 1 - 200 μm
Coherent effects create spectral substructure
Micro-bunching can produce ~ few μm coherent radiation

Technical implications

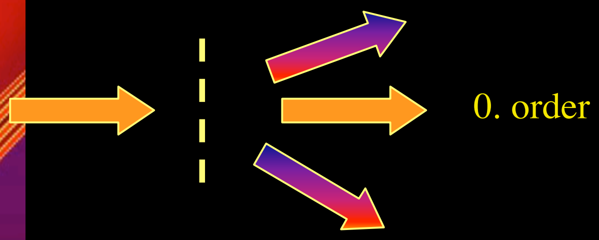
- CDR problematic at low beam energies, short wavelength cut off
- CVD diamond windows to accelerator vacuum
- NO radiation transport in (humid) air
- Broad wavelength range to cover, SINGLE SHOT

Spectroscopy...

Classical : Michelson type interferometers
- scanning devices, no single shot
- complex unfolding procedure (autocorrelation function)

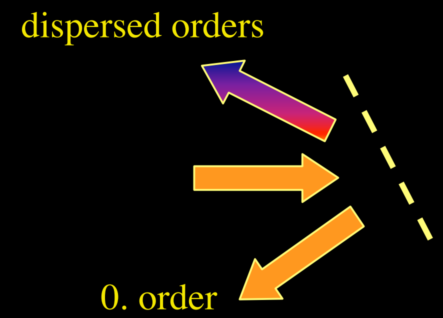
Single shot spectrometers:
dispersive elements & multichannel detector

Transmission Gratings



+ can have large free spectral range (1 decade)
- limited to $\lambda > 50\ \mu m$
- poor dispersion efficiency (~15%)

Reflective Gratings



staging

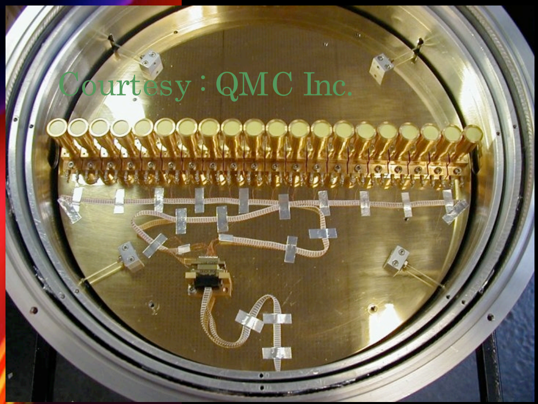
- small free spectral range (< 1 octave)
+ ANY λ
+ high dispersion efficiency (> 90%)

Single shot multichannel detectors ?

Various new ideas, benefit from IR - astronomy

HgCdTe array ?

Hot electron bolometer array ?

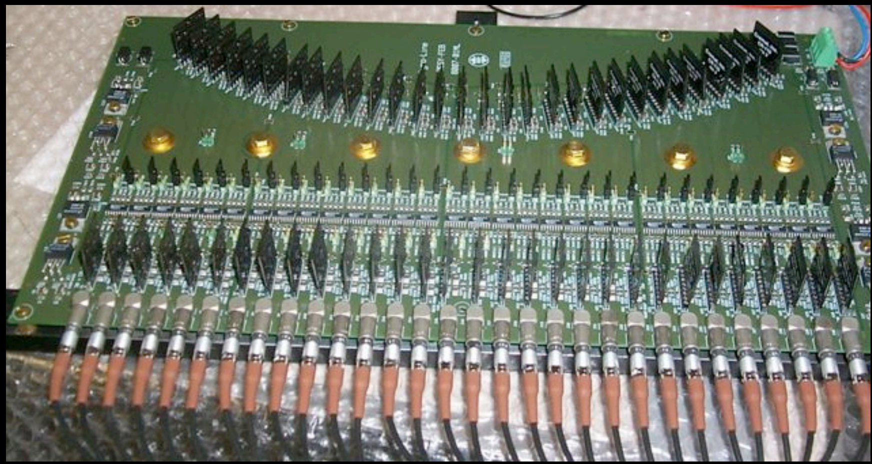


+ commercial
+ fast
+ sensitiv
- cryogenic device
- very expensive

Requirements :

- fast, 200 ns for XFEL bunch spacing
- uniform spectral response
- broadband (1 μm - 1mm)
- robust ?

Recent development at DESY



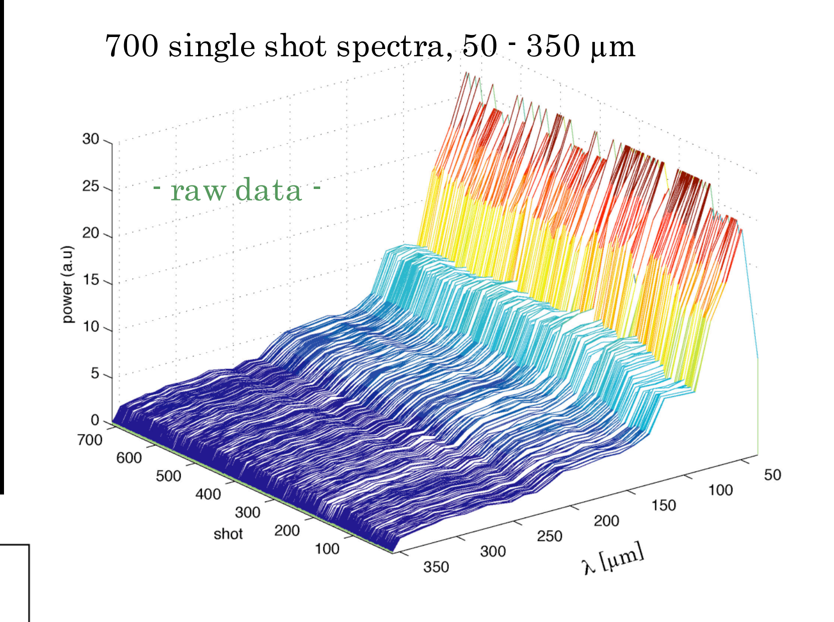
Pyro-electric line detector

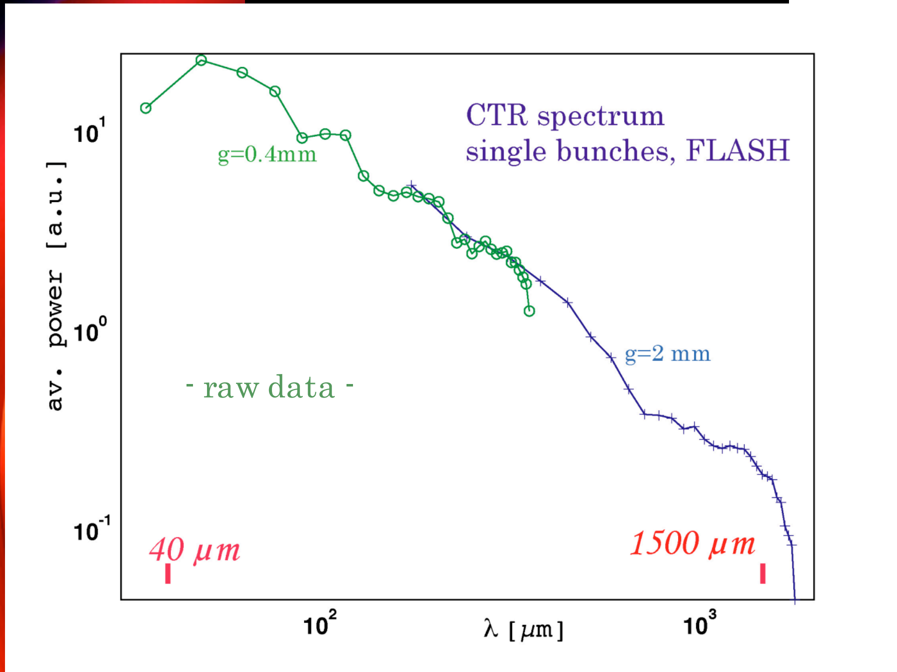
+ 30 channels
+ room temperature
+ no window, works in vacuum
+ fast read out
+ sensitivity ~ 300 pJ (S/N=5)
+ smooth response function (suppressed resonances)

Single Shot CTR spectra - transmission gratings

1 bunch from 30 bunch train
kicked to off-axis screen

Small fluctuations
Strongly peaked at short wavelengths

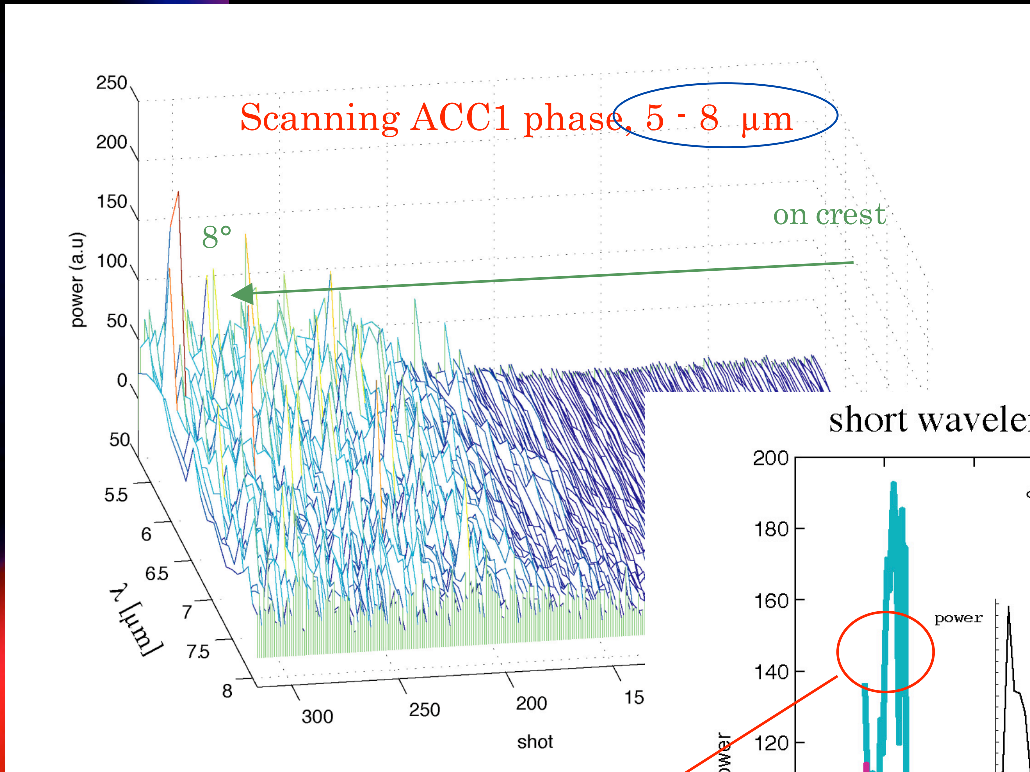




Two gratings cover 40 µm - 1.5 mm range

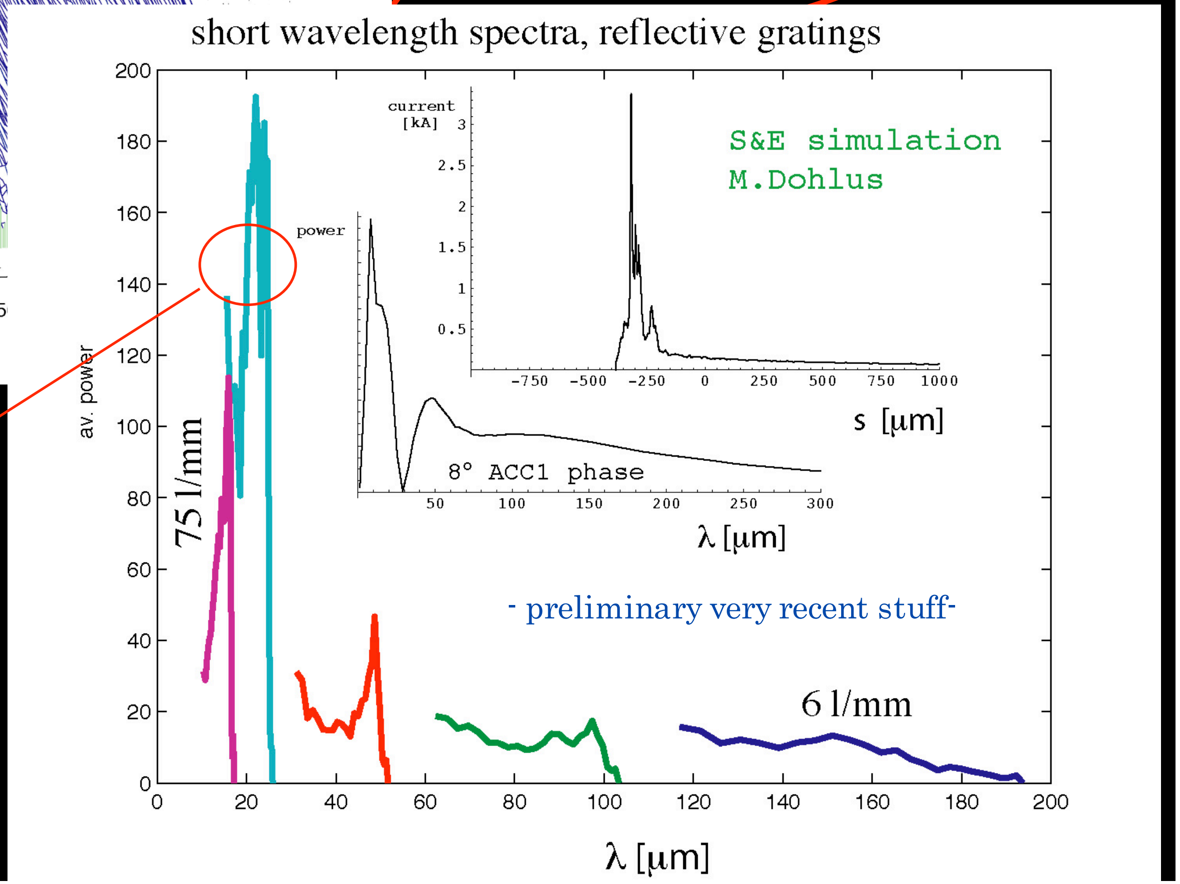
H. Delsim-Hashemi et al. THPPH018

Single shot spectra - reflective gratings - short wavelengths



More structure, more fluctuations
NO destinct phase regimes
No clear spectral shape, spikes
More compression, more spikes
Two distinct phase regimes
Microbunching of bunch structure
produce CTR @ ~ 20 µm

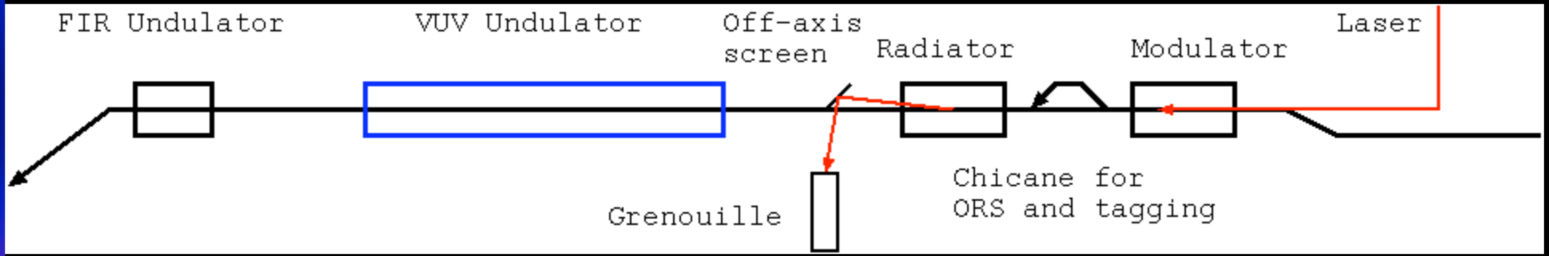
Short wavelength single
shot spectra "fingerprint"
of bunch structure



Corresponds to
~70 fs spike length

outlook : the optical replica system

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



"seed" the bunch with optical wavelength

cause coherent emission of light pulse in radiator that mimics the longitudinal shape of the electron bunch (optical replica)

analyse the optical pulse by FROG system (fs resolution)

+ powerful diagnostic instruments exist for optical pulses (FROGS, Grenouilles ..)
+ direct 'image' of longitudinal structure with fs resolution
- needs "heavy" infrastructure (high power laser two undulators, beam transport..)
- tricky spatial - temporal alignment of laser pulse and bunch

Installation at FLASH in 2007

DESY - Univ. Stockholm - UU/ISV collaboration

N. Javahiraly et al. TUBAU05

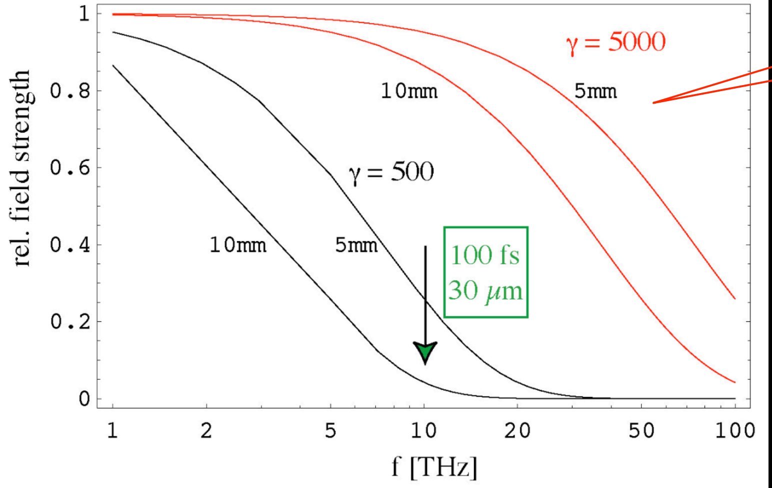
Summary ?

Diagnostic at the fs / μm scale is a challenging and fascinating business

Thanks to all
who have
contributed
material and
other input to
this talk..

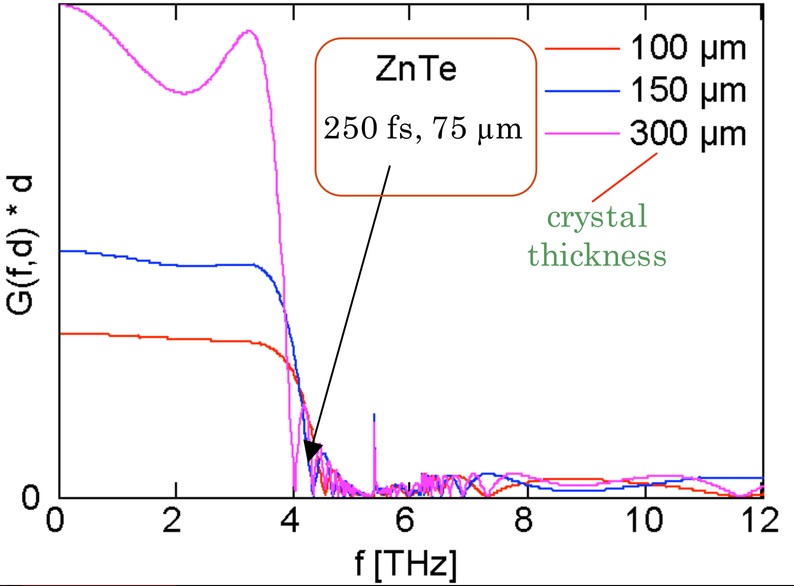
courtesy : www.bws-photo.de

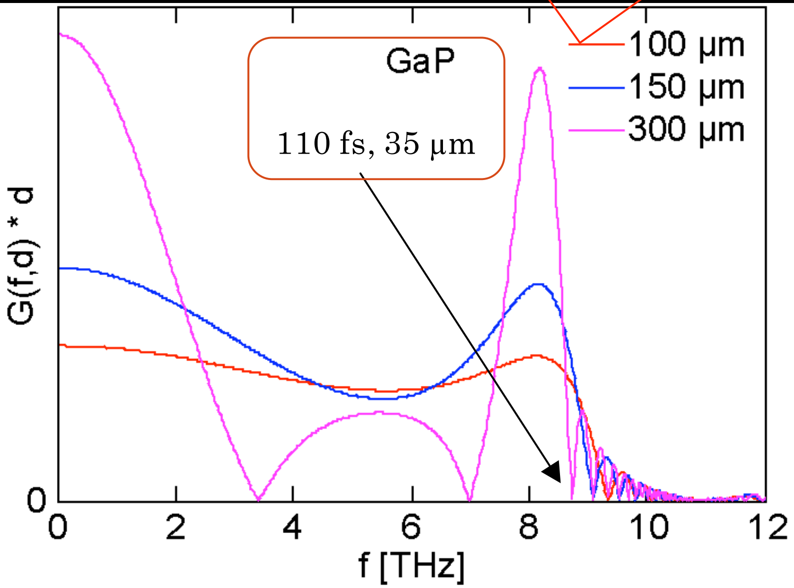
Limiting factors



High frequencies ➔ get close to beam
Especially for low energy beams

High frequencies ➔ thin GaP crystalls ➔ small signals

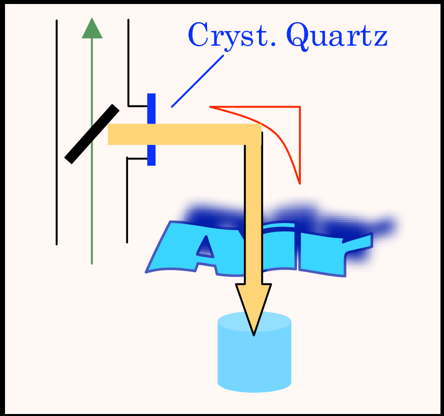




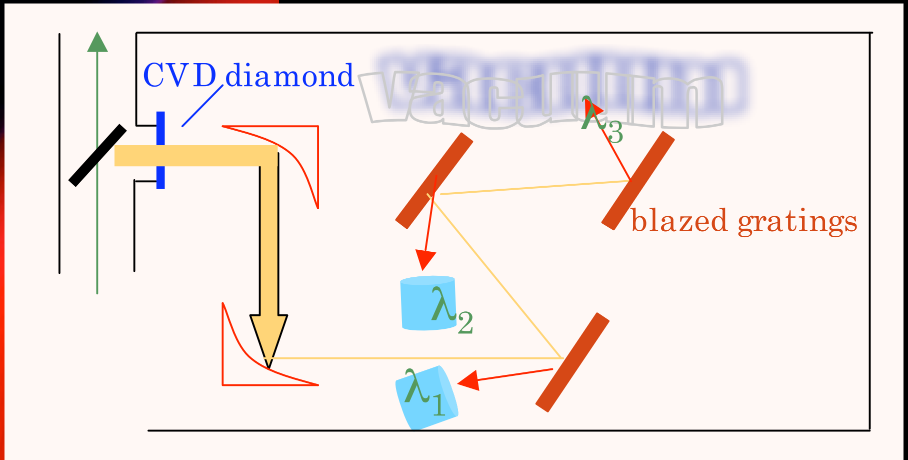
Bunch compression monitors

The 'classical' compression monitor

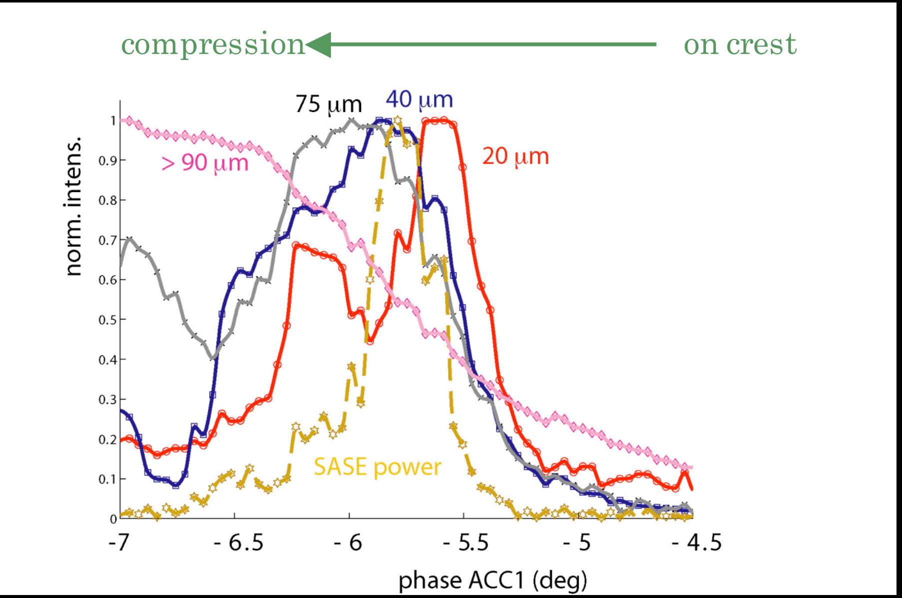
- integral intensity, > 100 μm
- overall compression strength
- robust, simple, workhorse



The 'advanced' compression monitor (EPAC, H.Delsim-Hashemi)



ABCM phase scan (FLASH), CTR
single bunch kicked from train



- wavelength specific intensity (bands)
- reveals 'long. features' of the bunch
- complex, still experimental