CRISP 4

Fast Bunch Profile Monitoring with broadband THz Spectroscopy of Coherent Radiation at FLASH

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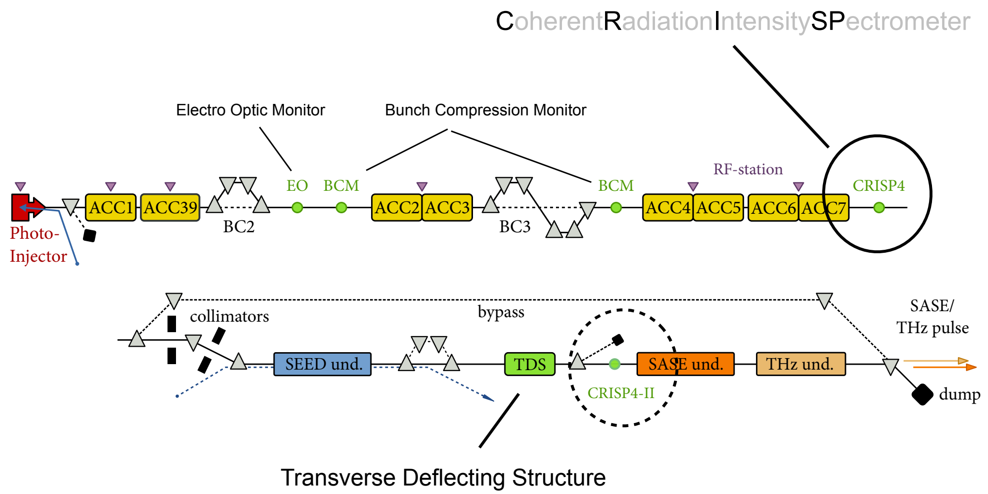
ICFA Workshop on Future Light Sources
Thomas Jefferson National Accelerator Facility, March 5-9, 2012

HELMHOLTZ ASSOCIATION

DESY

Longitudinal Diagnostics at FLASH



Coherent Radiation : Basics

wavelength space configuration space

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

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

*bunch **form factor** from normalized 3-D space charge distribution S*

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

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

complex function

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

longitudinal form factor

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

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

the task (2005)

- machine side : roll-over compression, large fluctuation
- single shot technique seemed mandatory

- up to then attempts with **scanning spectrometers** (interferometers) not terribly successful

at present :

linearized compression, machine much more stable

constant complains from users about photon pulse length „instability“

needs for online monitoring of bunch compression

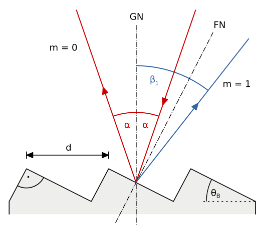
Grating spectrometer : fundamentals

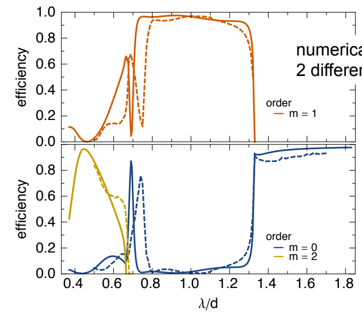
diffractive grating + parallel read out : single shot spectrometer

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 (far to narrow for our purpose)

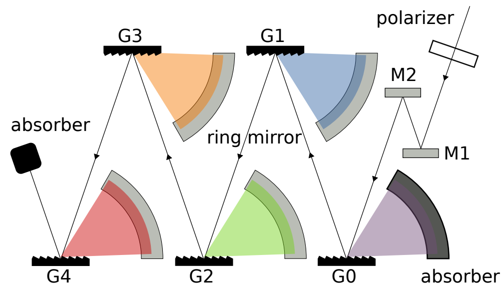
reflective blazed gratings in specific geometry :
high efficiency for specific orders (eg. m=1)
with sharp transition m = 0 (specular) to m=1 (diffractive)





numerical calculations
2 different commercial codes

multi-stage grating spectrometer



gratings as pre-filter and
dispersive device
from short to long wavelengths

4 stages : 1 decade in λ
(parallel)

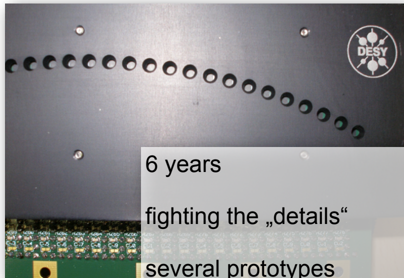
2 x 4 stages : 2 decades in λ
(sequentially)

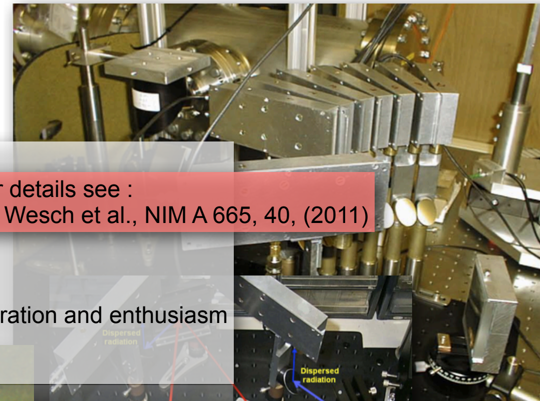
- dispersed radiation covers large angles : how to focus ?
- broad band detectors, sensitive enough and fast
- optics entirely diffraction dominated
- delicate alignment task

monitoring : relative intensities ok

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

from idea to instrument ..





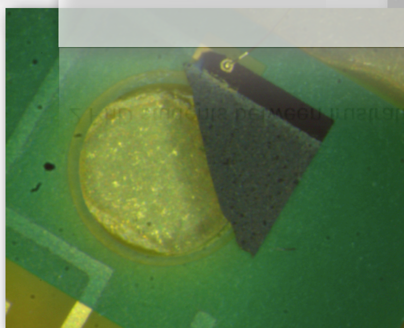
6 years

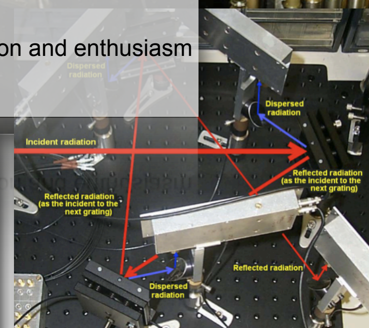
fighting the „details“

several prototypes

2 PhD students between frustration and enthusiasm

for details see :
S. Wesch et al., NIM A 665, 40, (2011)





mechanical set up of 4 stage device

precision machining, no breadboard

2 x 5 gratings on remote controlled stages

2 spectrometers in one

4 ring mirrors

electronics plane comes on top

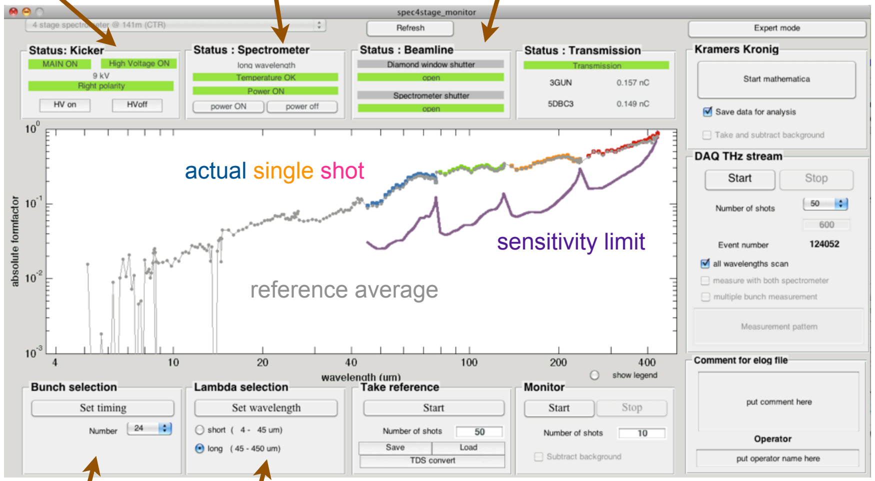
in vacuum, no window to THz beamline

CRISP4 as an online-tool

kicker

spectrometer

beamline



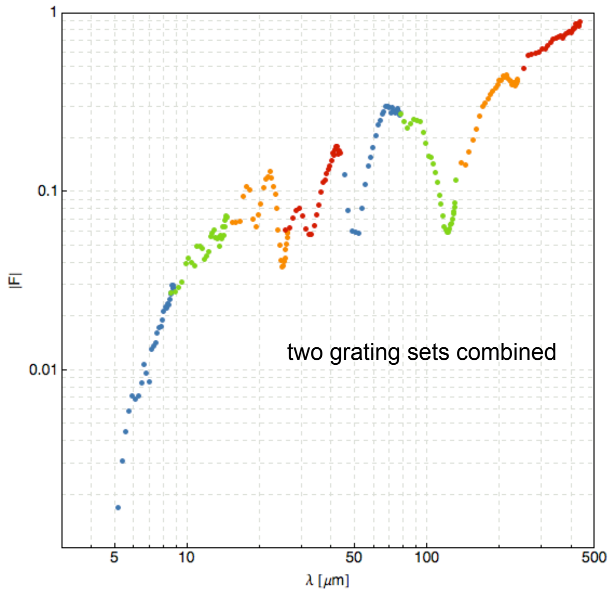
DAQ

data taking

bunch number

grating set

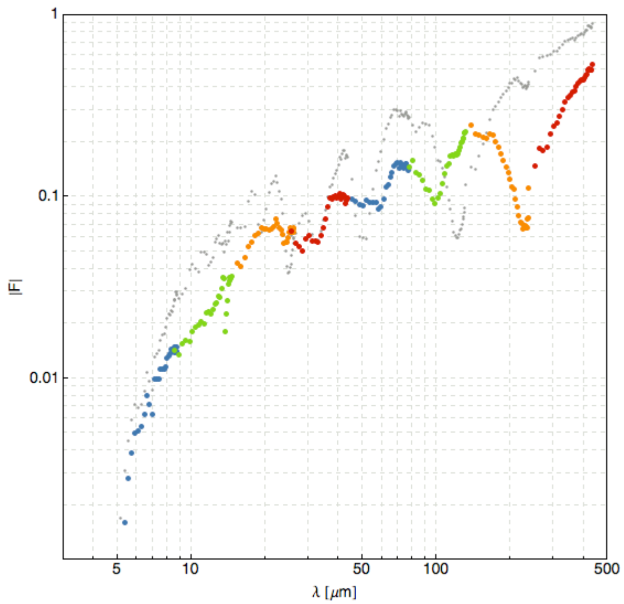
finally : broad band form-factors (modulus)



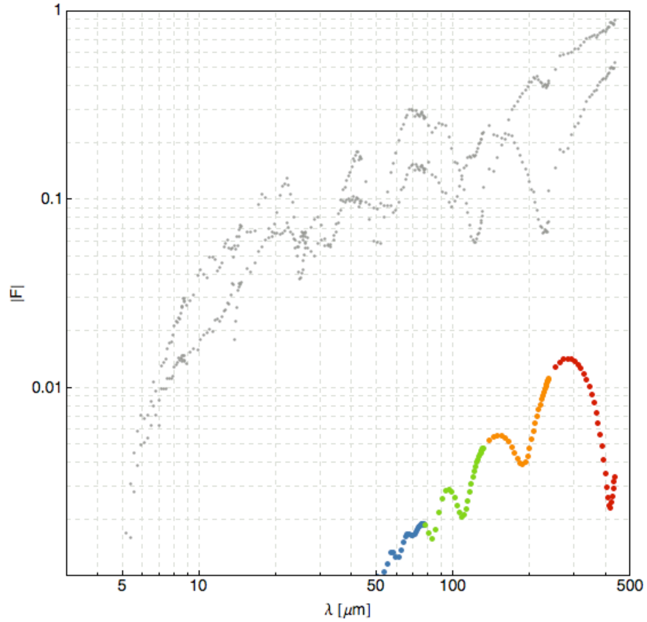
a „typical“ bunch...

no monotonic curve
characteristic „features“
reveal bunch structure

broad band form-factors (modulus)

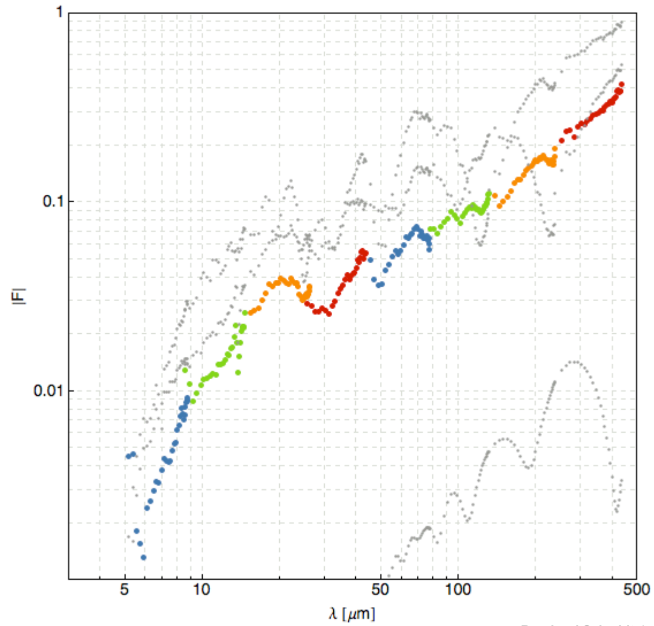


broad band form-factors (modulus)



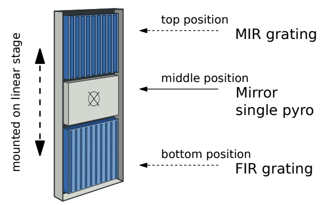
a VERY long bunch

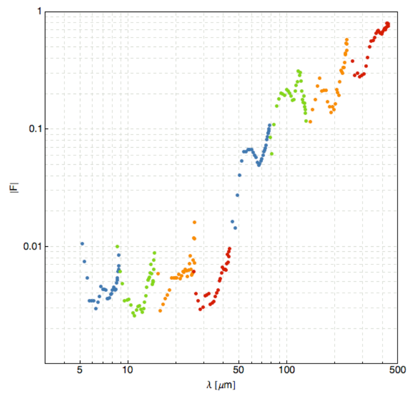
broad band form-factors (modulus)



alignment, a crucial point

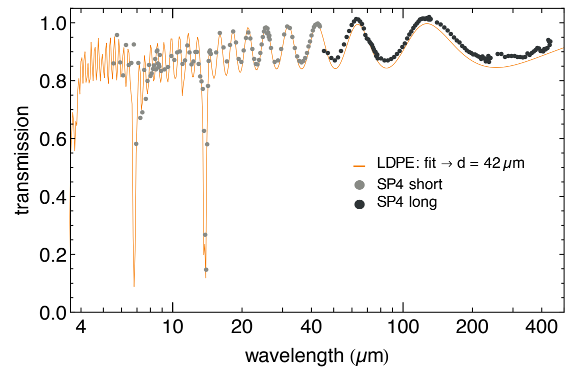
- internal alignment done automized with radiation (... 1 h , done rarely)
- beam position on screen has to be stable (orbit feedback)
- otherwise...





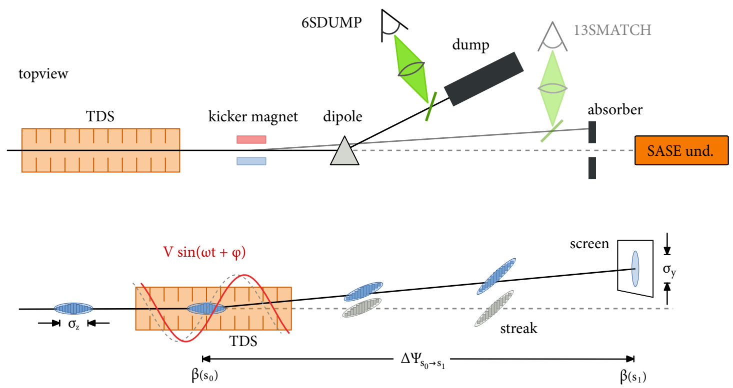
wavelength calibration

transmission through
LDPE foil
- etalon effect
- absorption lines



performance studies : benchmark with TDS

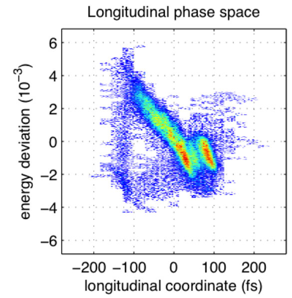
> comparison with time domain technique (TDS)



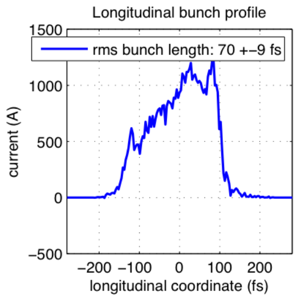
- uses always dispersive arm due to strong COTR in „direct" path
- not applicable during FEL operation
- resolution depends on streak power and machine optics

TDS : by no means trivial ..

camera image
- longitudinal phase space



current profile inside
viewfield

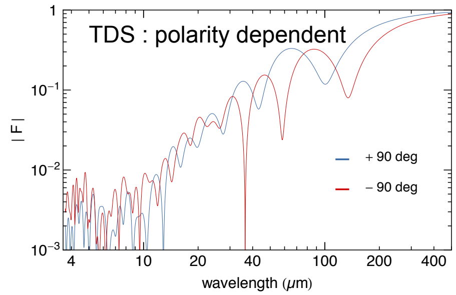


TDS : problem of internal z-y correlations

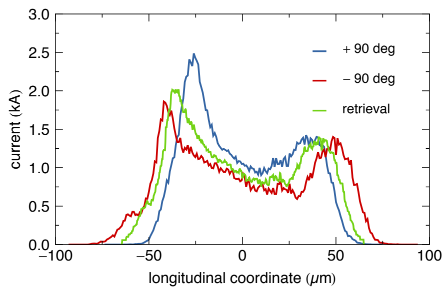
procedure :

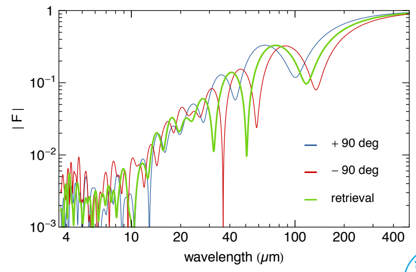
- take TDS profile
- calculate |F|
- compare with CRISP4 data

- first attempt shocking !

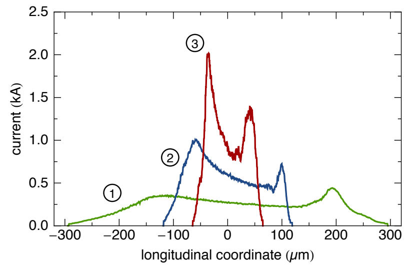


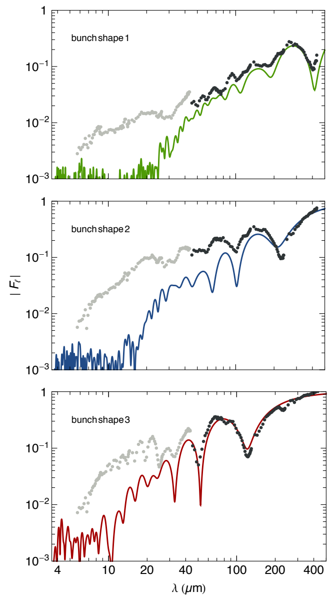
reliable data need „tomography“ (cf. Hendrik Loos, SLAC)





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 !

Compare in time domain : the phase problem

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

complex function, S(z) is real

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

we measure neither Re nor Im but |F| !

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

$$\boxed{\log(F) = \log|F| + i\phi(\lambda)}$$

can we use Kramers-Kronig to retrieve the missing phase ??

to some extend : yes ...

(Lay, Happek, Sievers 1994)

retrieve the phase.

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

„minimal“ phase, „canonical“ phase

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

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

measured values

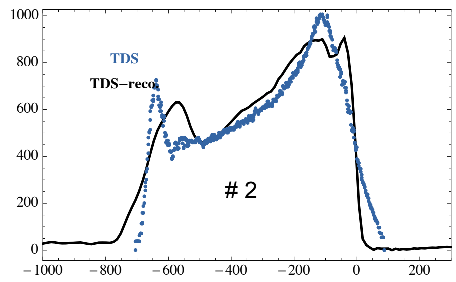
„minimal“ or „canonical“ bunch profile

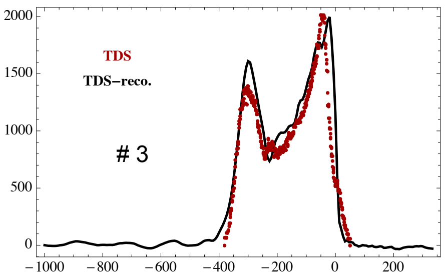
the known „caveats“

KK phase tends to produce leading spikes (short wavelengths to the front..)

it produces the „most compact“ profile compatible with the measured spectrum

test with measured profiles : profile - FF - KKphase - back





- comes out „front sharpened“ and „inverted in time“

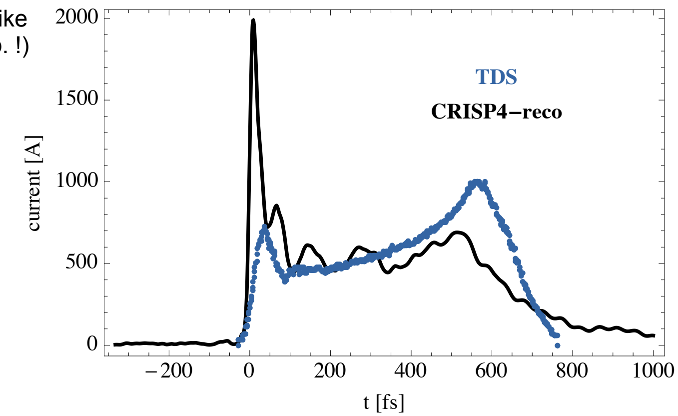
but otherwise ok !

from the measured FF : TDS bunch #2

- avg. current agrees
- total bunch length agrees

- reco has strong leading spike
  (short wavelengths comp. !)

- tail after 800 fs
  (TDS field field of view !)



TDS bunch #3

- avg. current agrees
- total bunch length agrees

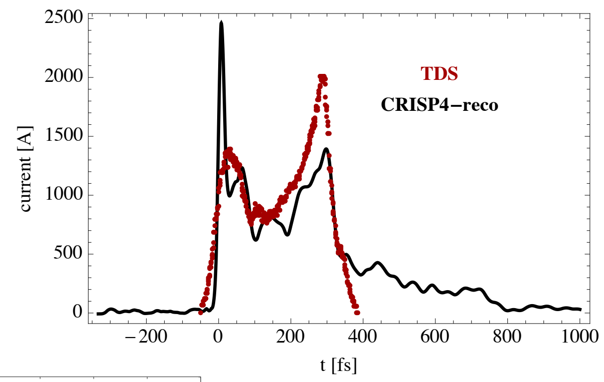
- reco has strong leading spike
- tail after 400 fs

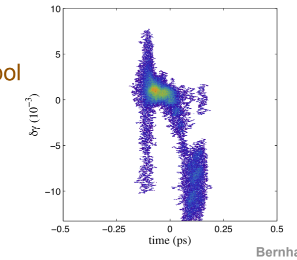
are the leading spikes
purely artificial ?

- probably not !

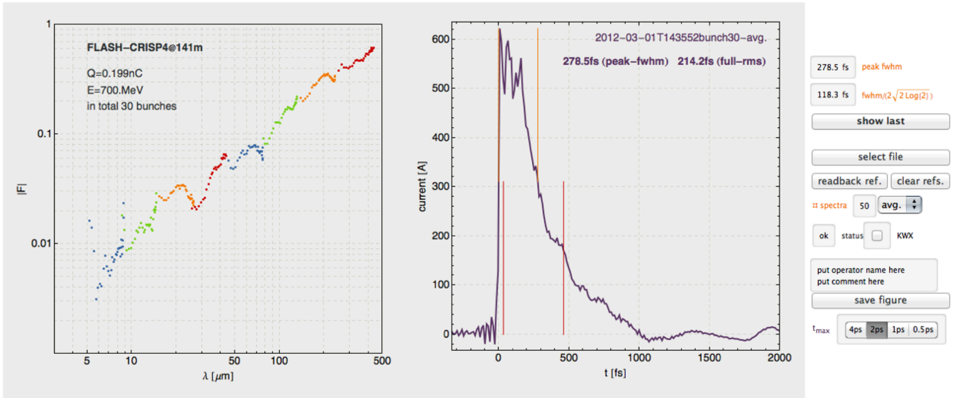
large energy spread

60 m + R_{56}(5mm) between
CRISP4 + spectrometer dipol

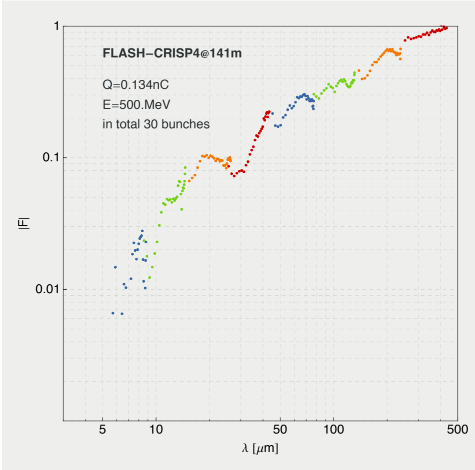


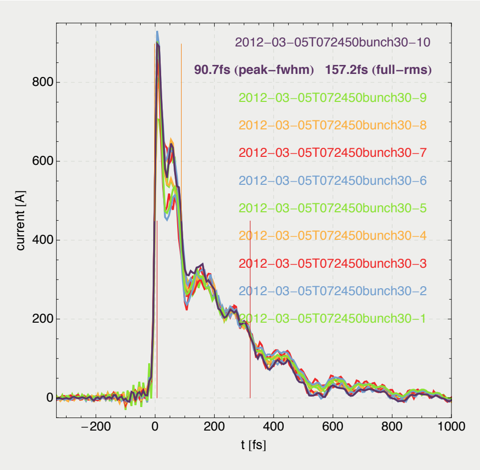


Phase Retrieval Tool : now used in control room



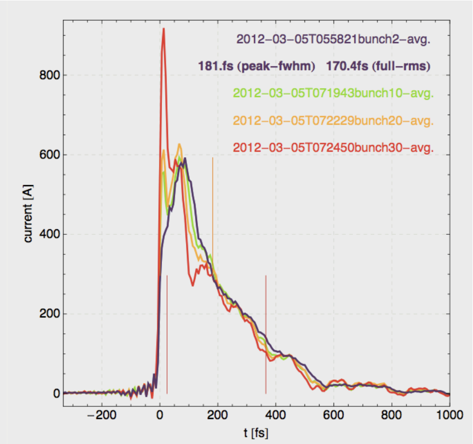
reproducibility



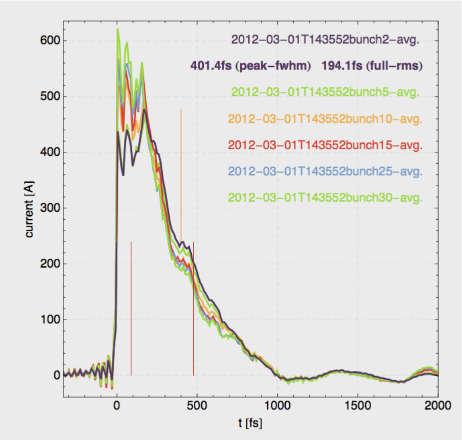


bunch profile along the bunch train

Q = 0.137 nC
E = 500 MeV

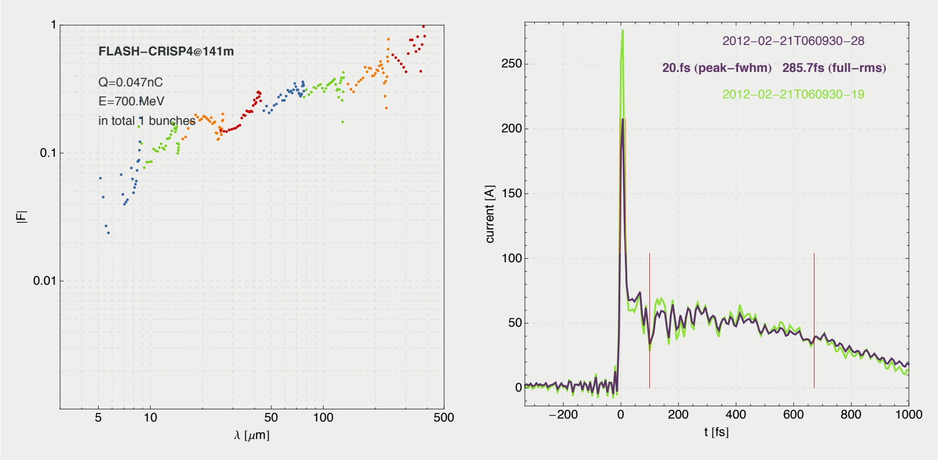


Q = 0.200 nC
E = 700 MeV



CRISP4 works with 50 pC

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



Summary and credits

- we have developed a broad band spectrometer for coherent radiation
- (quasi) single shot („double shot") capable down to Q < 100pC
- now available (and used !) as online tool in the control room
- perfectly complements the time domain (TDS) installation

+ second item (CRISP42) using transition OR diffraction radiation in commissioning phase
+ foreseen for FLASH-2 and XFEL (17.5 GeV, diffraction radiation)

CREDITS !

Lex van der Meer for the idea of staging gratings..

Hossein Delsim-Hashemi for building the first prototype with 2 stages, inventing the ring-mirror and solving many initial problems (and killing my ideas of transmission gratings)

Stephan Wesch for solving the innumerable problems from prototype to working 4-stage device, especially for his brilliance and endurance getting the absolute calibration done

all our engineers and technicians for doing their best and sometimes more