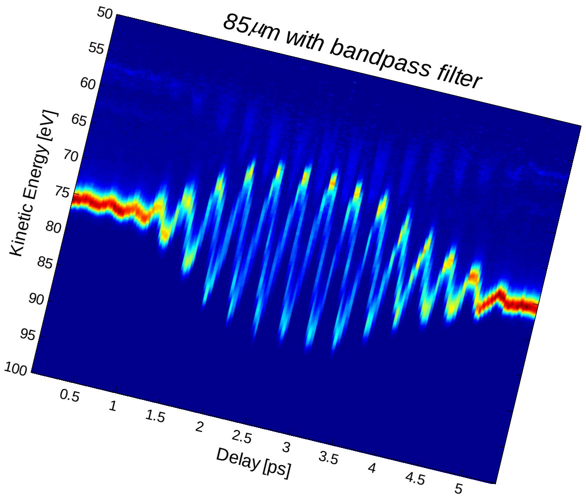
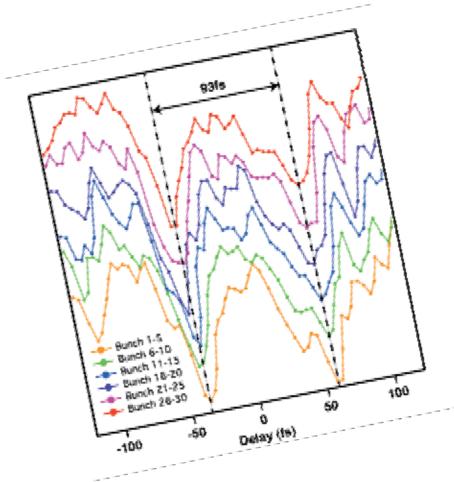
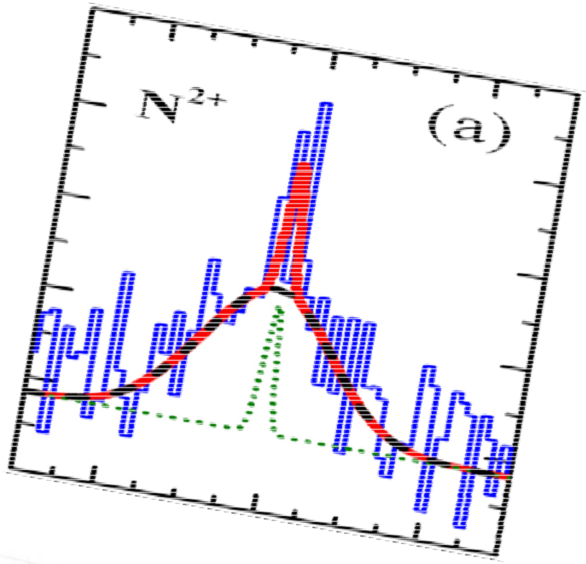
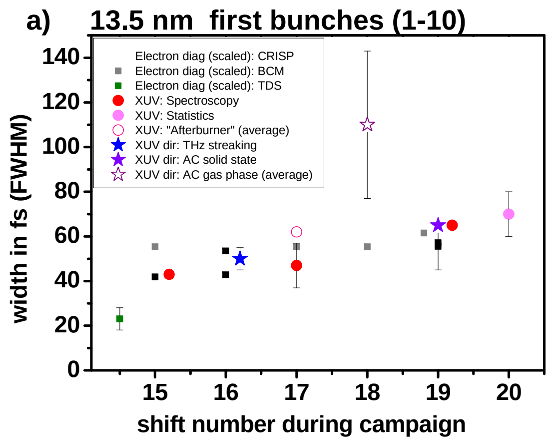
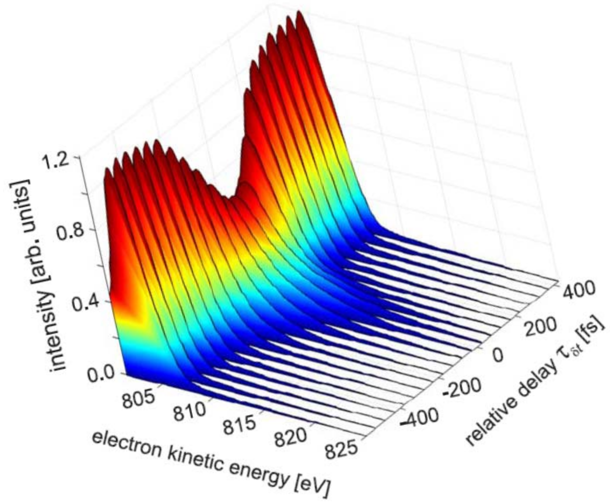
Simultaneous Measurement of Electron and Photon Pulse Duration at FLASH











HELMHOLTZ
ASSOCIATION

Stefan Düsterer / DESY

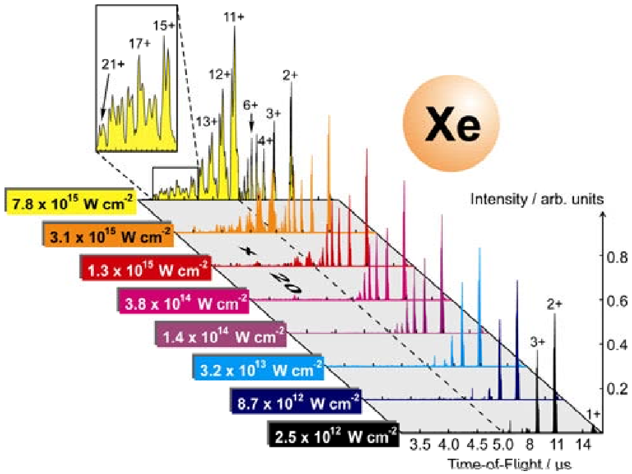
DESY

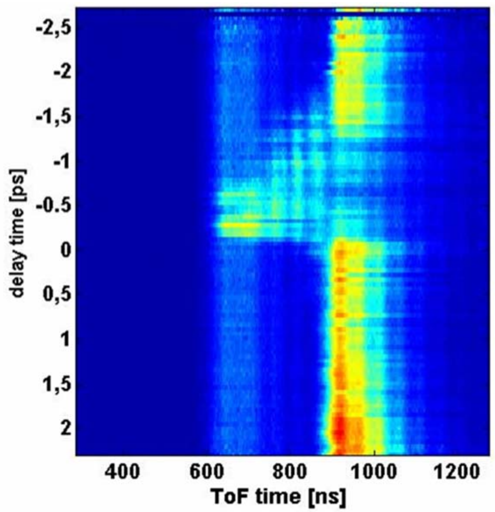
Why measure FEL pulse durations ?

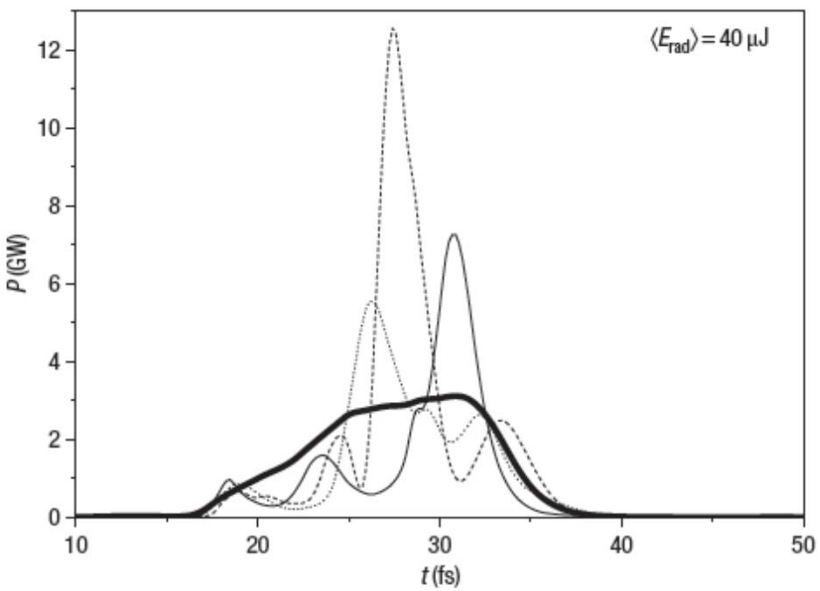
> **FEL characterization**

> **non-linear physics**

> **Ultra-fast Dynamics:**
> **Pump – probe experiments**







Goals for the short pulse studies

1. Can we setup the FEL to a **defined** pulse duration
2. Calibrate **“indirect”** methods against **“direct”** ones
3. Measure the scaling factor between **photon** pulse length and **electron** bunch length
4. Find out **advantages / disadvantages** of different methods

Members of the pulse duration team

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Extended paper submitted

Outline

- Electron beam diagnostics
  - Transverse Deflecting Structure (TDS)
  - THz spectroscopy (CRISP)
  - Bunch Compression Monitor (BCM)
- Indirect photon based methods
  - Spectral characteristics
  - Pulse energy fluctuations - statistics
  - Mapping SASE to visible light: “afterburner”
- Direct photon based methods
  - Autocorrelation
  - Optical Cross-correlation
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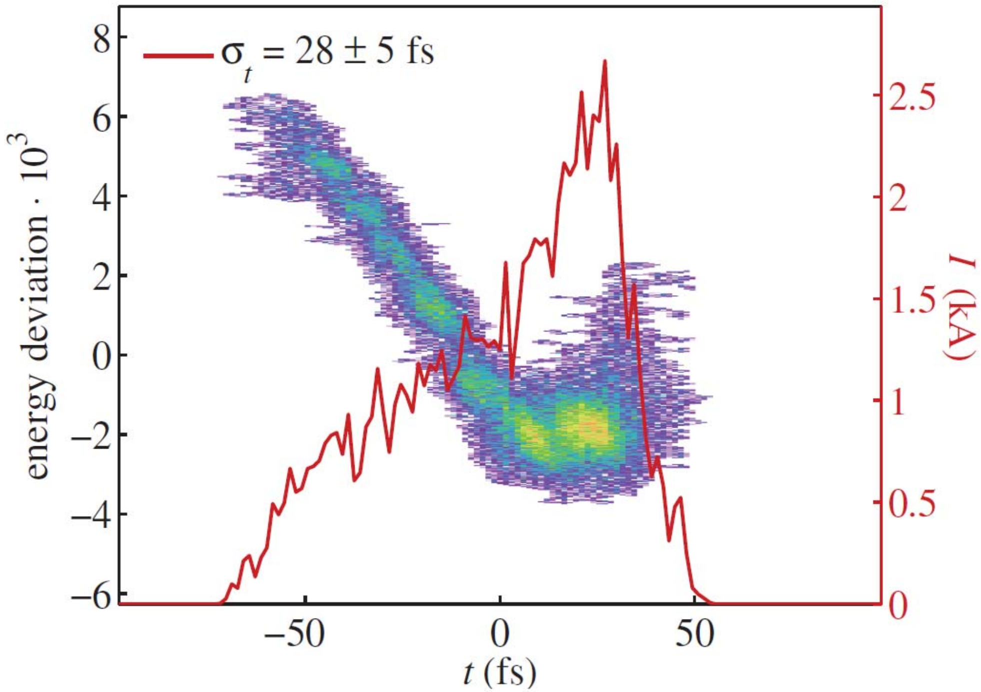
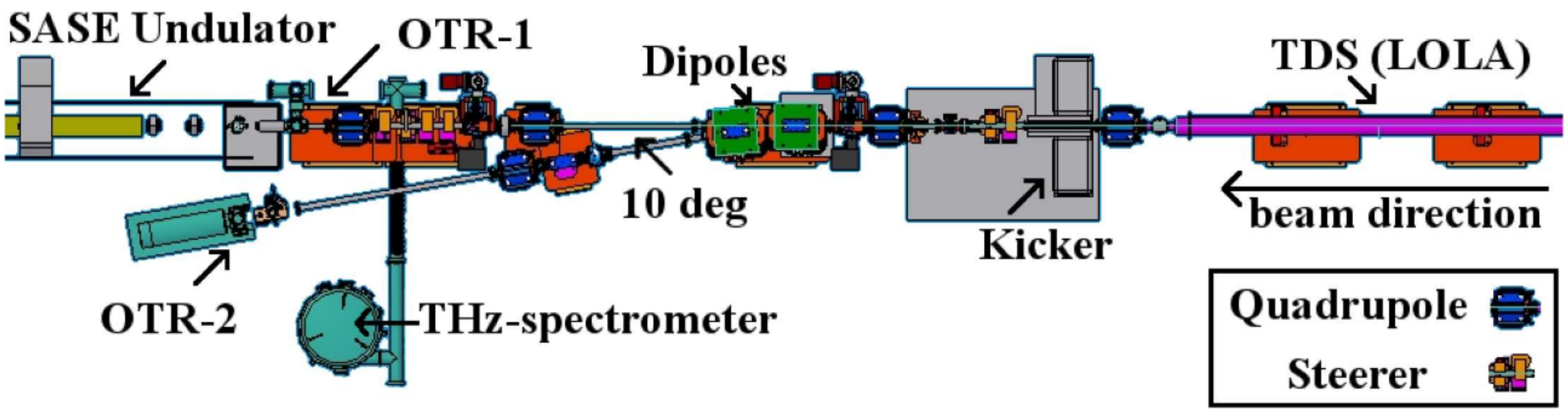
Electron Diagnostics: Transverse deflecting cavity (TDS)



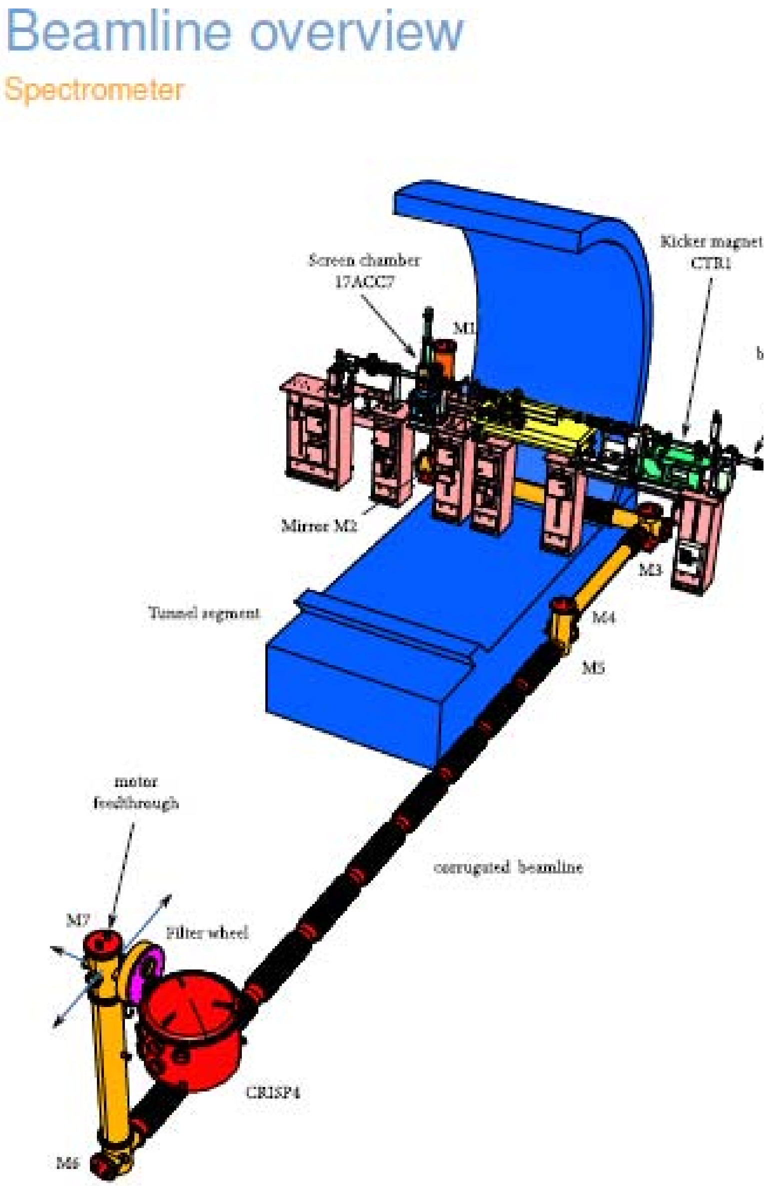
PRO:
- very good resolution (few fs)
- (meanwhile) online diagnostic
- Arbitrary pulse in bunch train can be measured

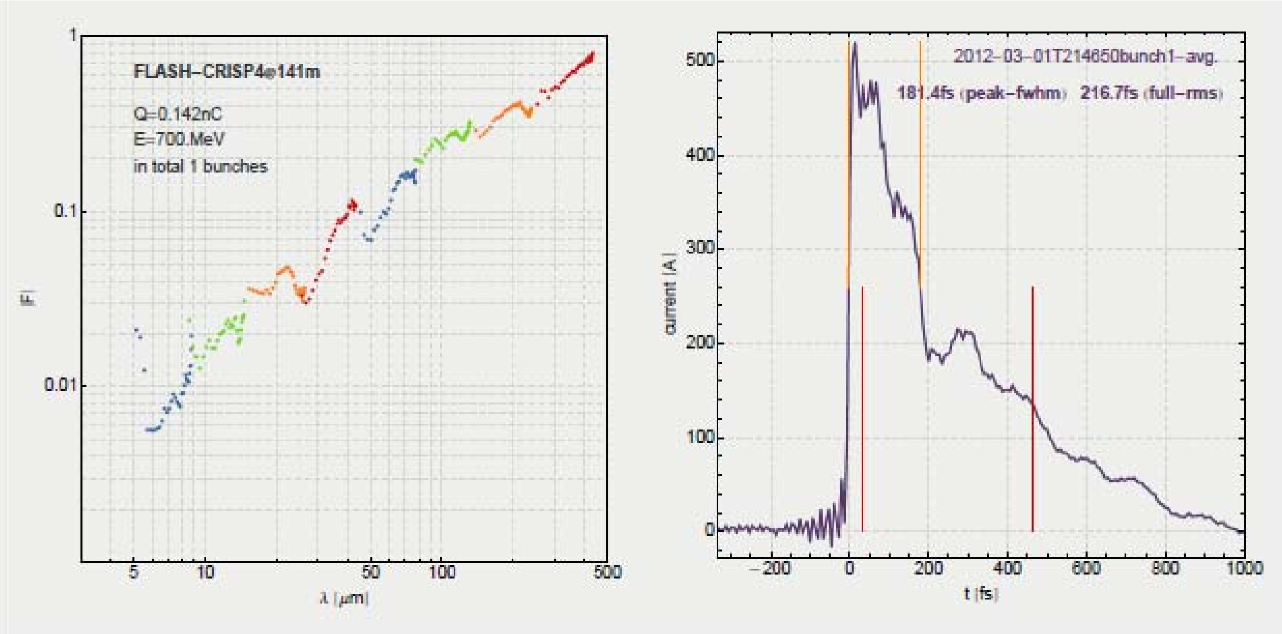
CON:
- only 1 bunch out of bunch train – destructive !
- dispersive measurements (chirp) not online



Courtesy: M. Yan, Ch. Gerth

Electron Diagnostics: CRISP





PRO:

- reconstructed bunch shape for single bunches
- Arbitrary pulse in bunch train can be measured

CON:

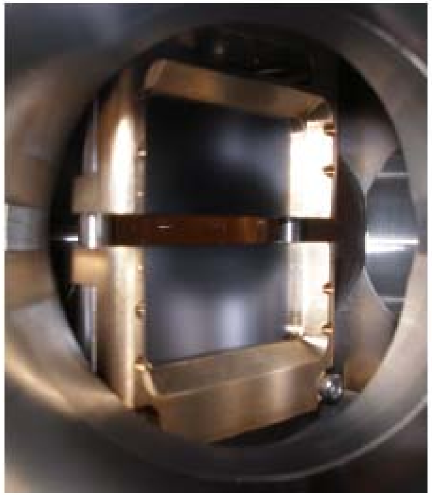
- Needs complicated math to get to bunch shape
- only 1 bunch out of bunch train – destructive !

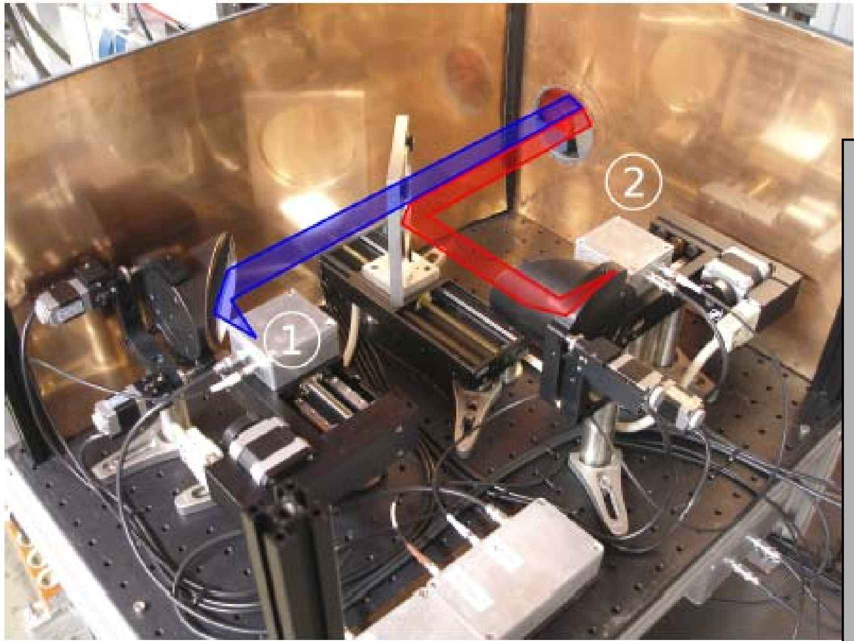
Courtesy: E. Hass, B. Schmidt

Electron Diagnostics: Bunch Compression Monitor (BCM)

Setup

BCM (Beam Compression Monitor)

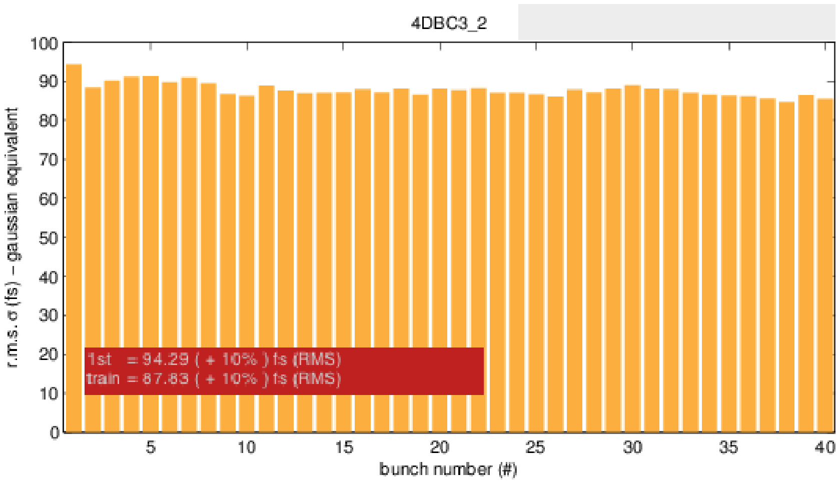




Courtesy of S.Wesch

PRO:
- parasitic
- bunch resolving

CON:
- no info about bunch shape
- Dependent on integration area (detector response)



$$I_{\rm coh} = \int \frac{dU_{\rm coh}}{d\lambda} {\rm d}\lambda.$$

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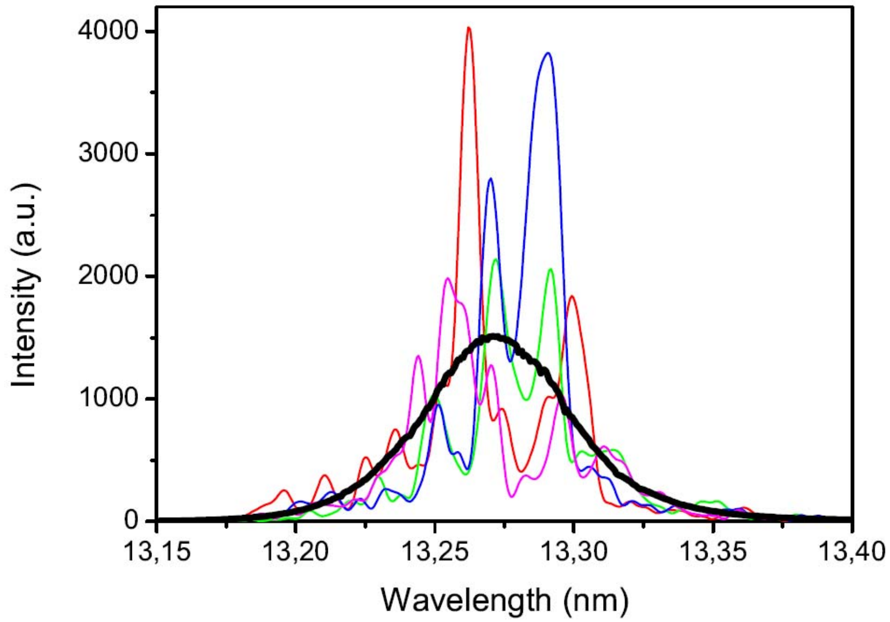
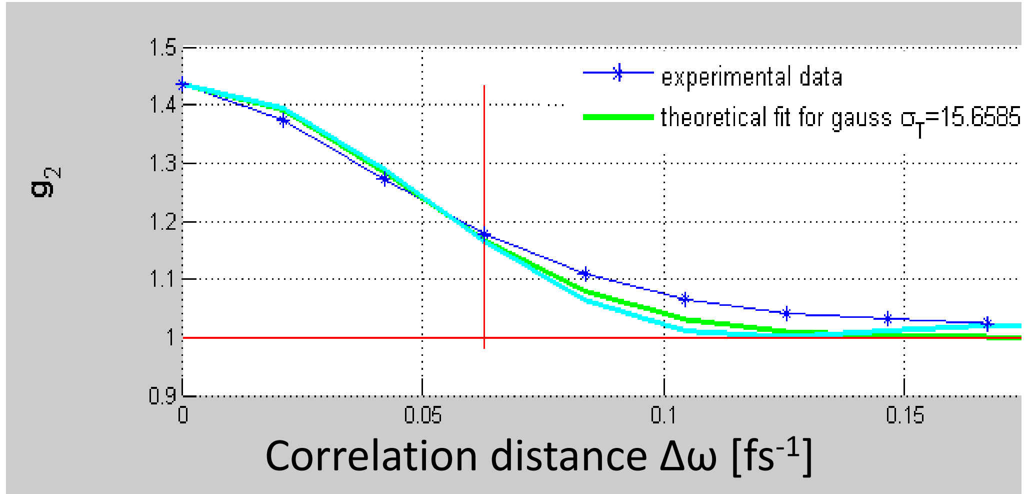
Indirect PHOTON methods: spectral correlations





$$g_2(\omega,\delta\omega)=\frac{\langle|\tilde{E}(\omega-\delta\omega/2)|^2|\tilde{E}(\omega+\delta\omega/2)|^2\rangle}{\langle|\tilde{E}(\omega-\delta\omega/2)|^2\rangle\langle|\tilde{E}(\omega+\delta\omega/2)|^2\rangle}.$$

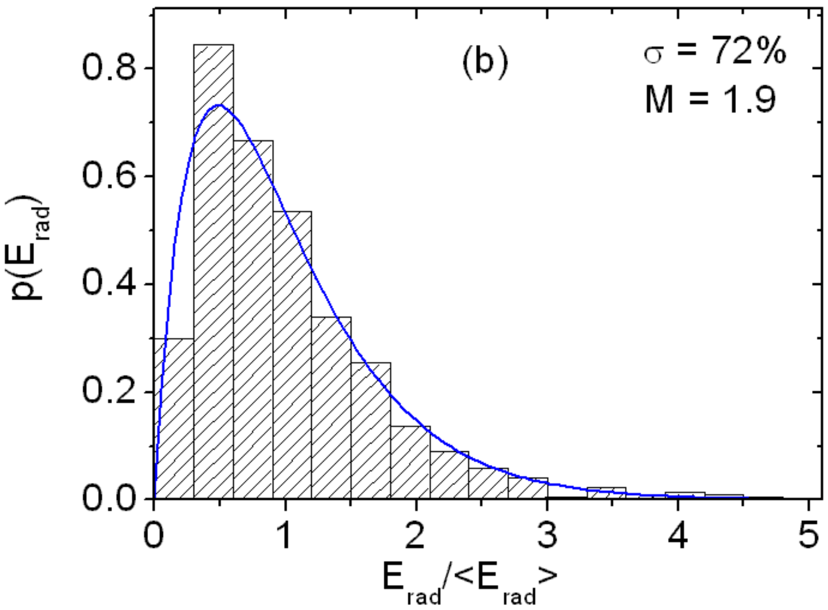
PRO:
- Rel. easy to use
- bunch resolved

CON:
- not parasitic (at Flash)
- assumptions needed for reconstruction

Courtesy N. Gerasimova, R. Engel

A. A. Lutman, et al. Phys. Rev. ST Accel. Beams **15**, 030705 (2012).

Indirect PHOTON methods: Statistical fluctuations



PRO:
- rel. easy to use
- Relies on well tested theory

CON:
- Only valid for **linear regime**
- Only **lower limit for pulse dur.** in saturation
- remove machine-related fluctuations
- Spatial and temporal modes are mixed

$$\tau_{fel} = M\tau_{coh}$$

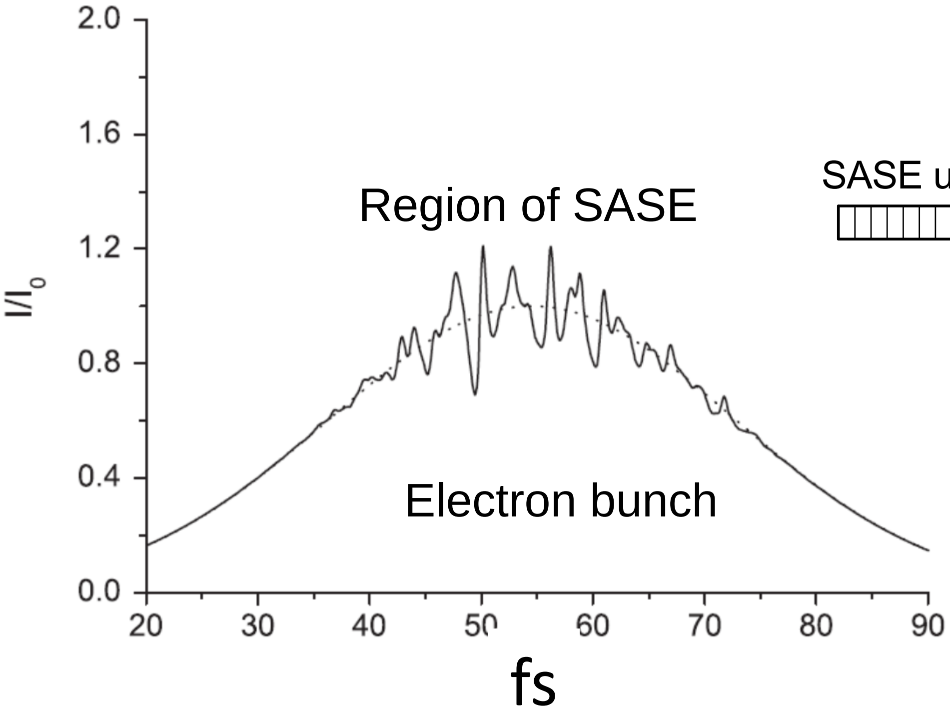
$$p(W) = \frac{M^M}{\Gamma(M)}\left(\frac{W}{< W >}\right)^{M-1}\frac{1}{< W >}\exp\left(-M\frac{W}{< W >}\right)$$

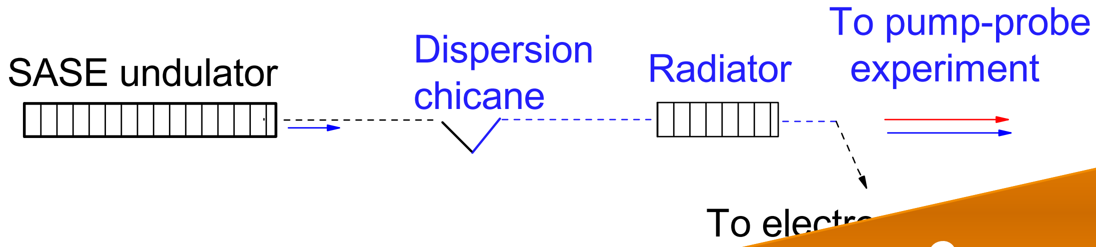
$$M^{-1} = \sigma_W^2 =< (W- < W >)^2 > / < W >^2$$

Ackermann et al., Nature Photon.1(2007)336

Courtesy: E. Schneidmiller, M. Yurkov

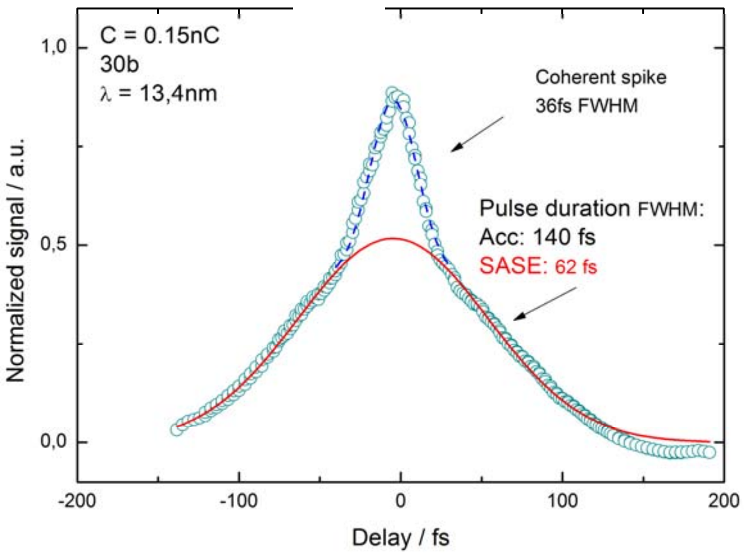
Indirect PHOTON methods: “afterburner”





- **Optical pulse has the same envelope as FEL pulse**

Saldin, Schneidmiller, Yurkov, Phys. Rev. ST-AB 13(2010)030701



PRO:
- rel “simple to use”
- *in principle* parasitic

CON:
- difficult for very short pulses
- (up to now) averaging technique

Courtesy: N. Stojanovic

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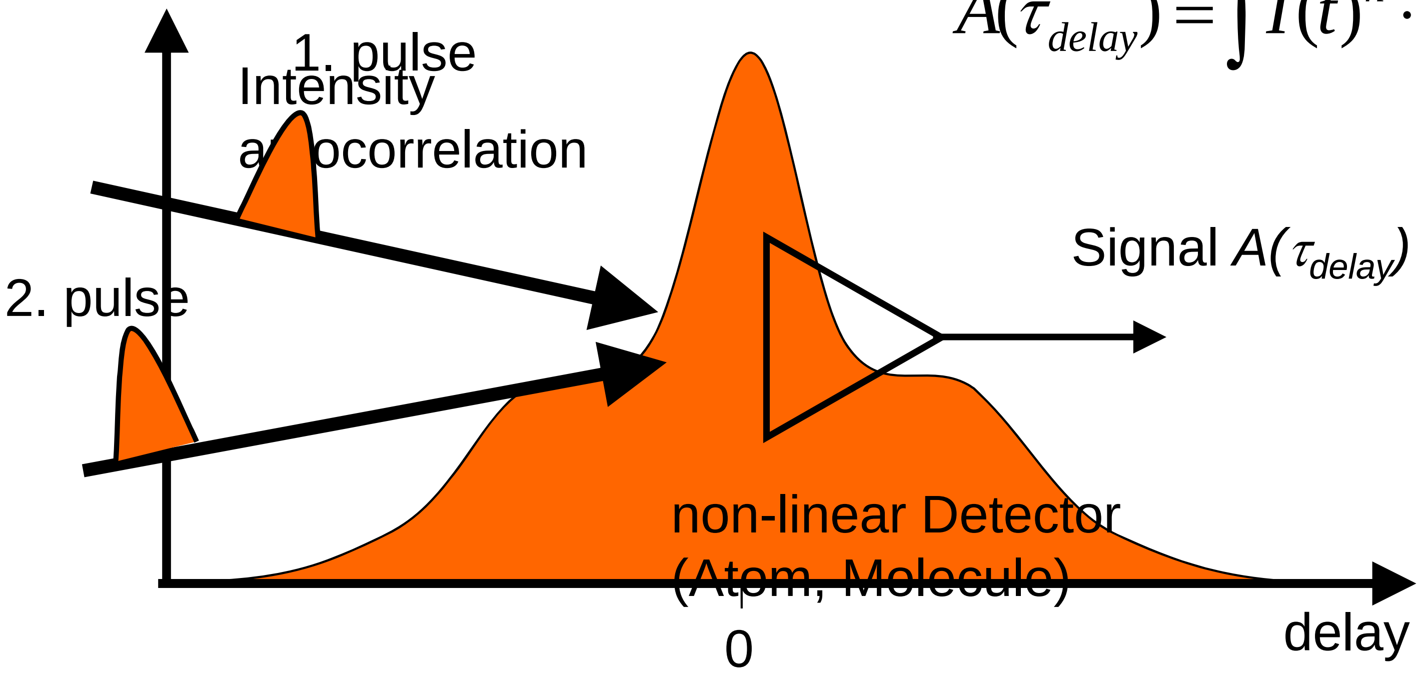
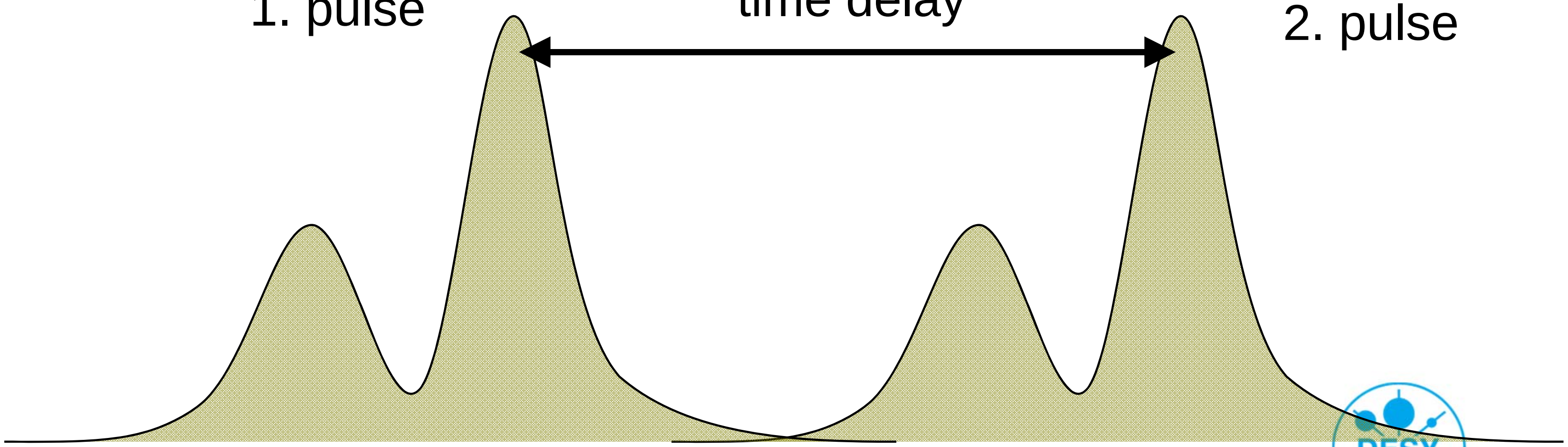
Direct PHOTON methods: auto correlation

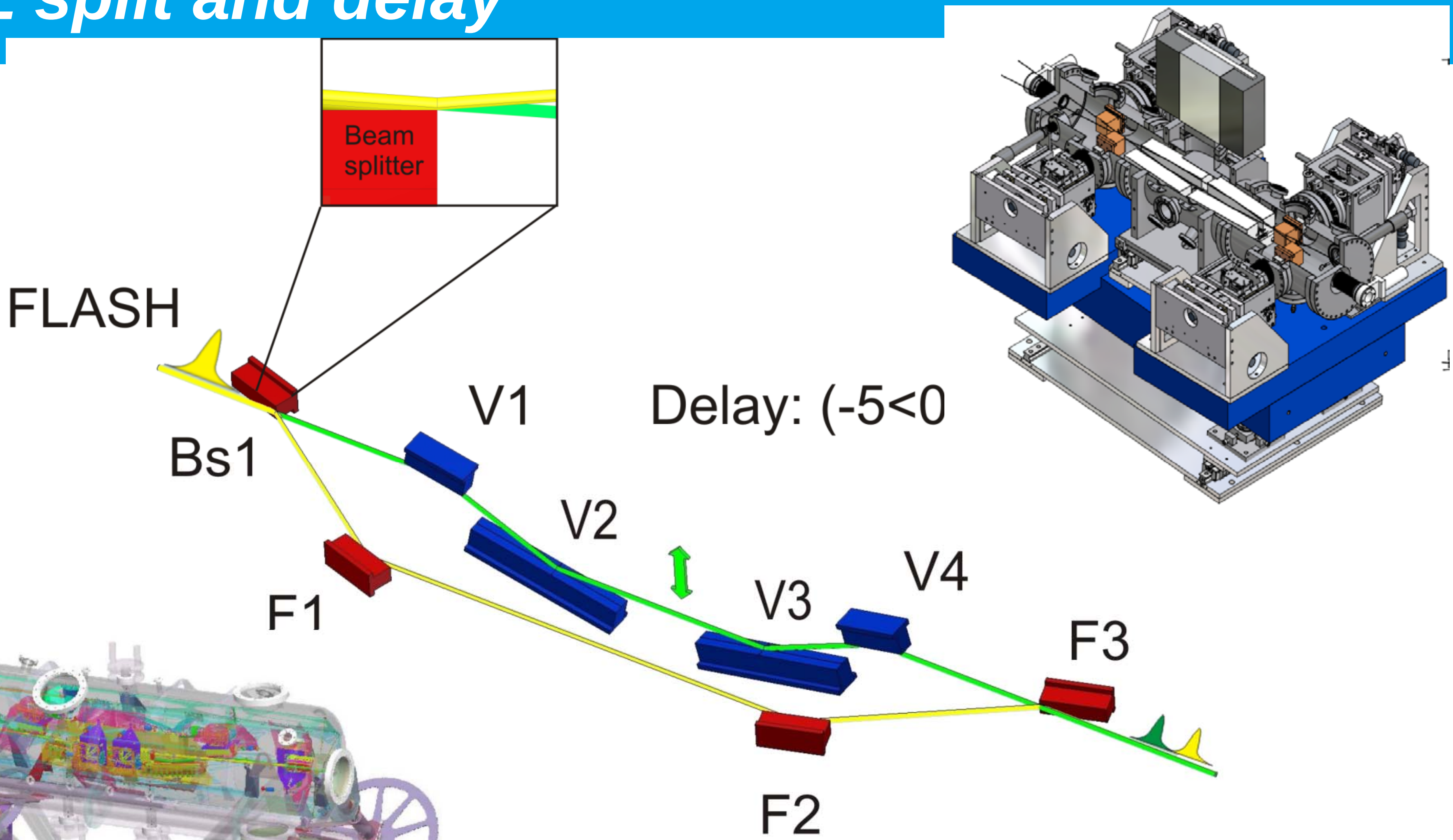
$$A(\tau_{delay}) = \int I(t)^n \cdot I^n(t-\tau_{delay})dt$$

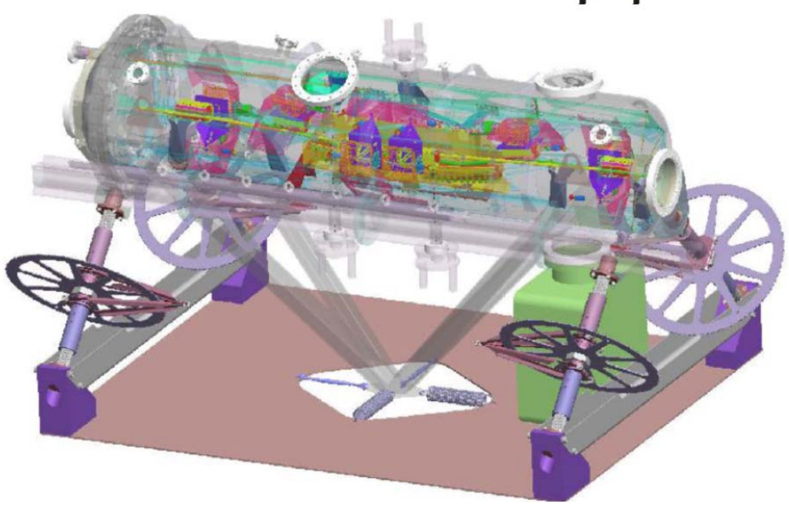




Courtesy R. Moshammer

FEL split and delay

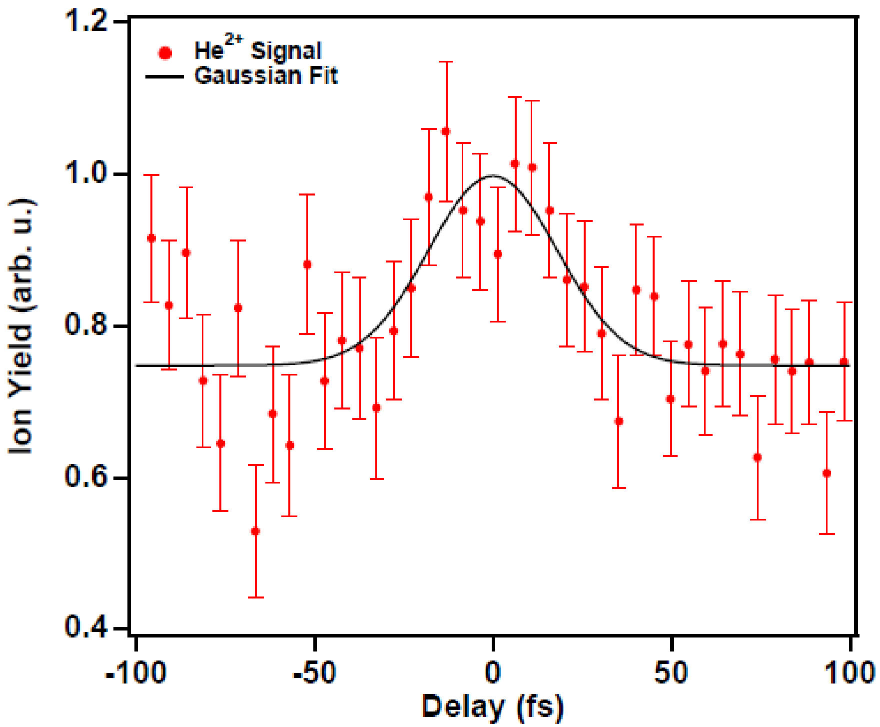




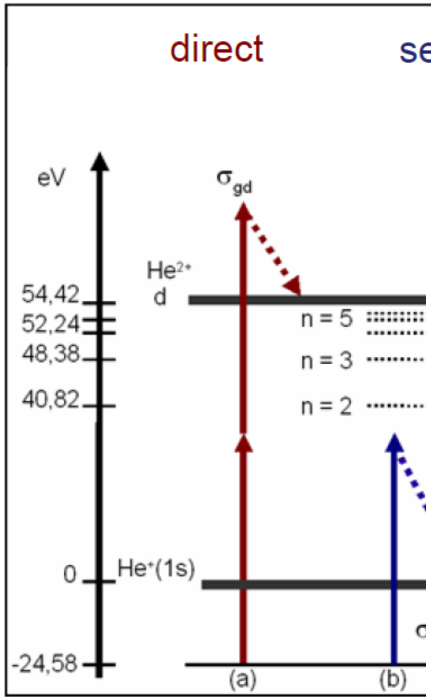
Uni Münster, BESSY, PTB, DESY

R. Mitzner, et al. Optics Express 16, 19909 (2008);
F. Sorgenfrei, et al, Rev. Sci. Instrum. 81, 043107 (2010)

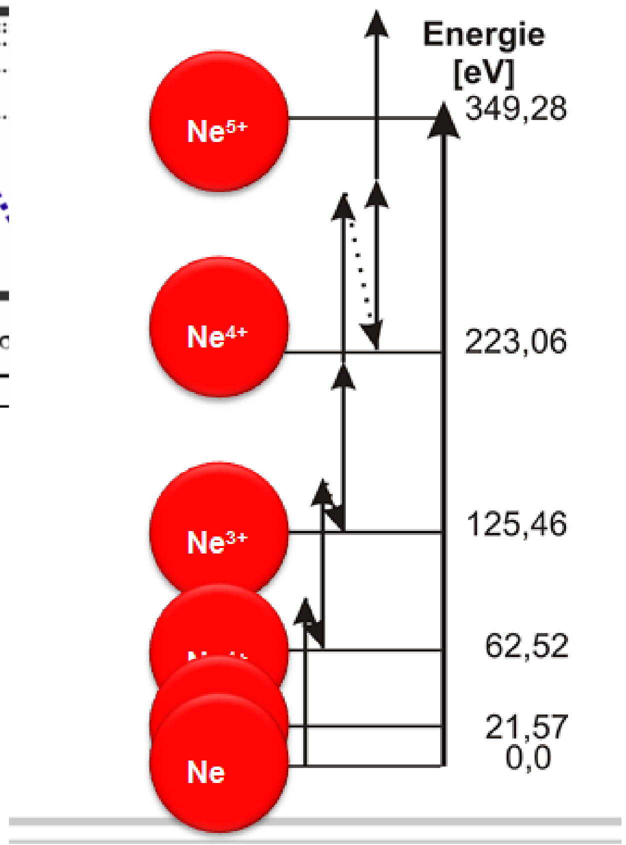
Direct PHOTON methods: auto correlation



Pathways to He^{2+} at 24 nm



13 nm (~92 eV)



Pro

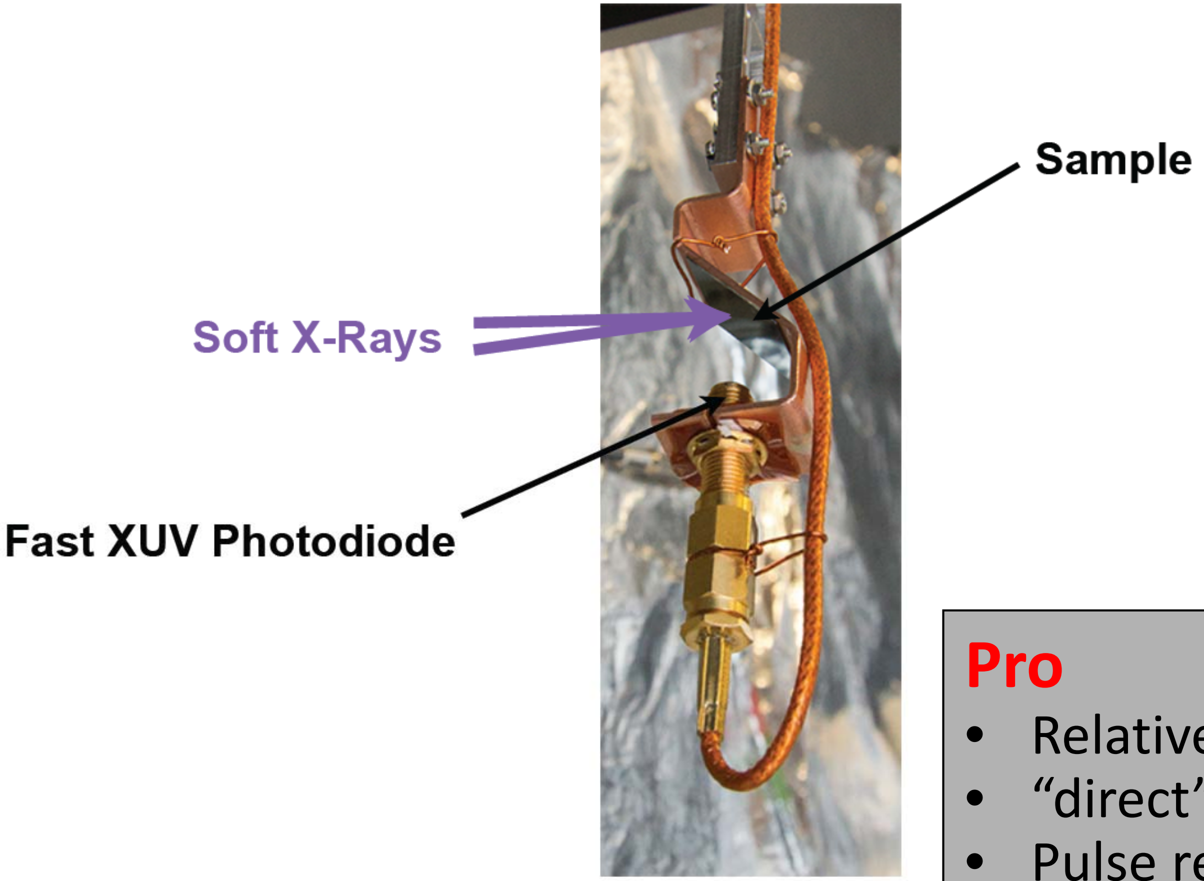
- "direct" measurement (for known reactions)

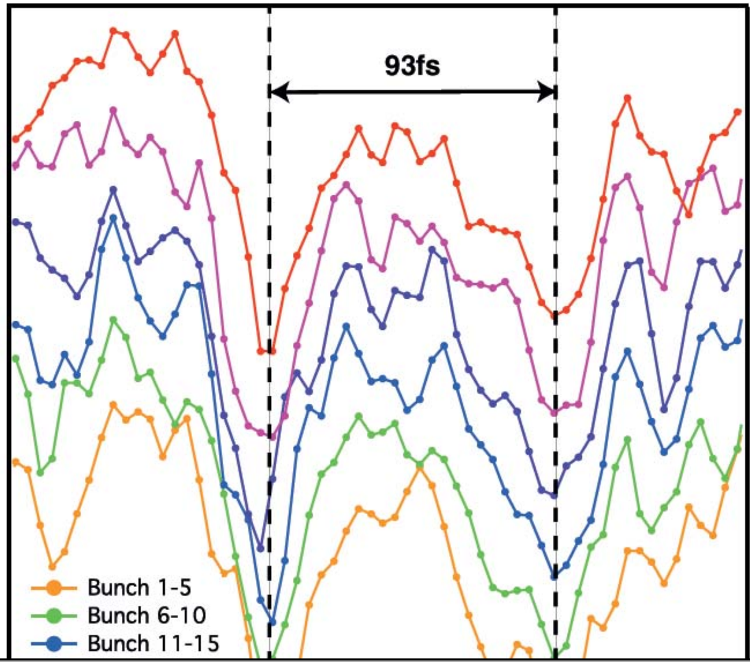
Con

- **Experimentally challenging** (takes long time)
- (up to now) averaging technique
- **well defined for < 25 nm**
- For XUV several path lead to same ionization state -> Simulations needed

Direct PHOTON methods: XUV reflectivity

X-Ray Reflectivity of Si_3N_4





Pro

- Relatively easy to implement
- "direct" measurement
- Pulse resolving

Con

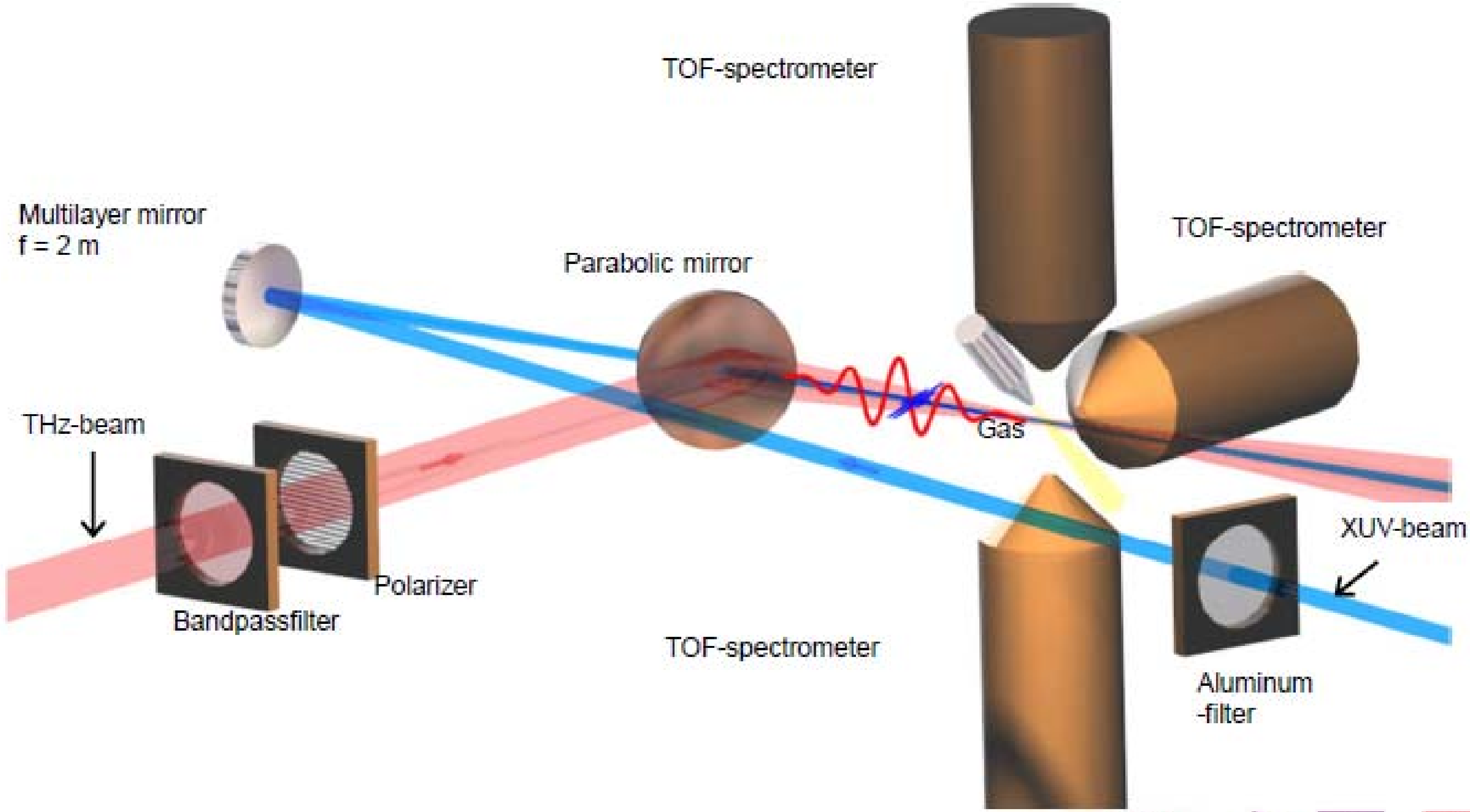
- Scanning technique (needs averaging over several minutes.)
- Not parasitic
- Applicable parameter range not known (so far)

Courtesy F. Sorgenfrei

Direct PHOTON methods: Undulator based THz streaking

THz streak camera for femtosecond XUV pulse length measurement

Experimental setup



LEXI

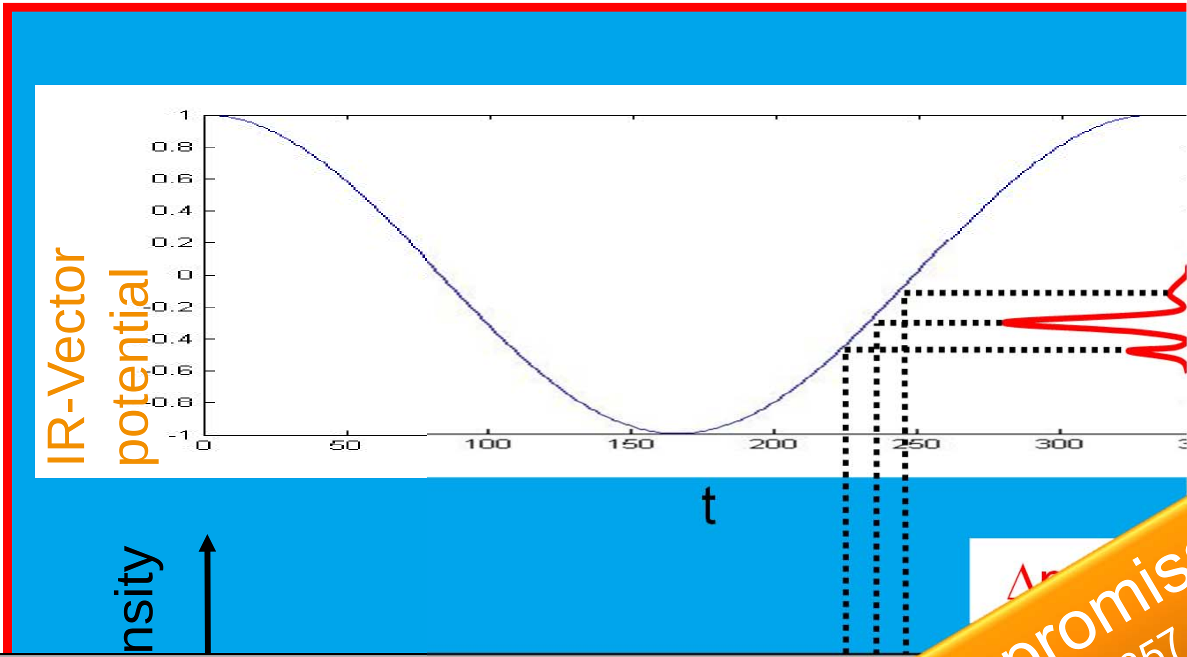
JOACHIM HERZ STIFTUNG

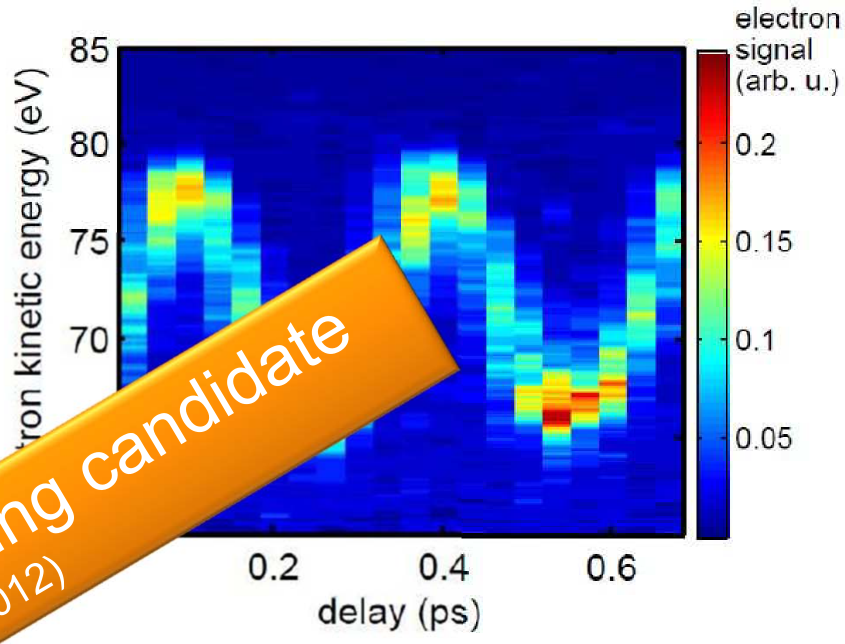
UHH

Courtesy M. Drescher

DESY

Direct PHOTON methods: Undulator based THz streaking



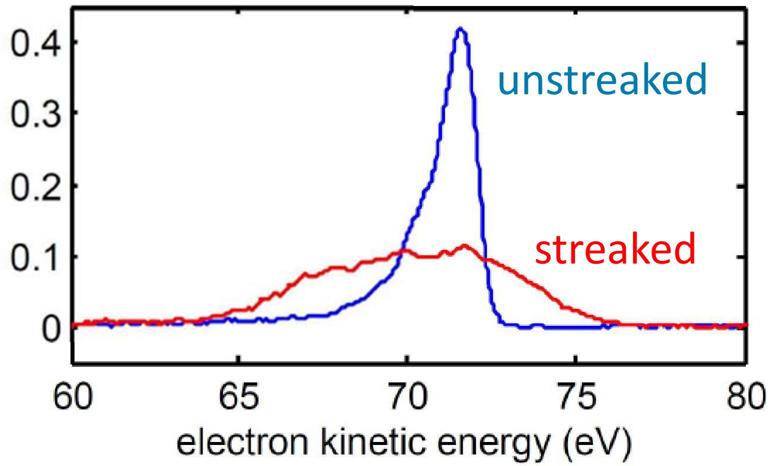


PRO:
- **single shot pulse duration in ... ture !!**
- works for VUV to x-ray
- Can measure chirp

CON:
- experimentally dem...ng
- needs multilayer focusing - only for specific wavelength
- Problems with very low charge

Laser based THz – promissing candidate

Grguras et al, Nature Photonics **6**, 852-857 (2012)



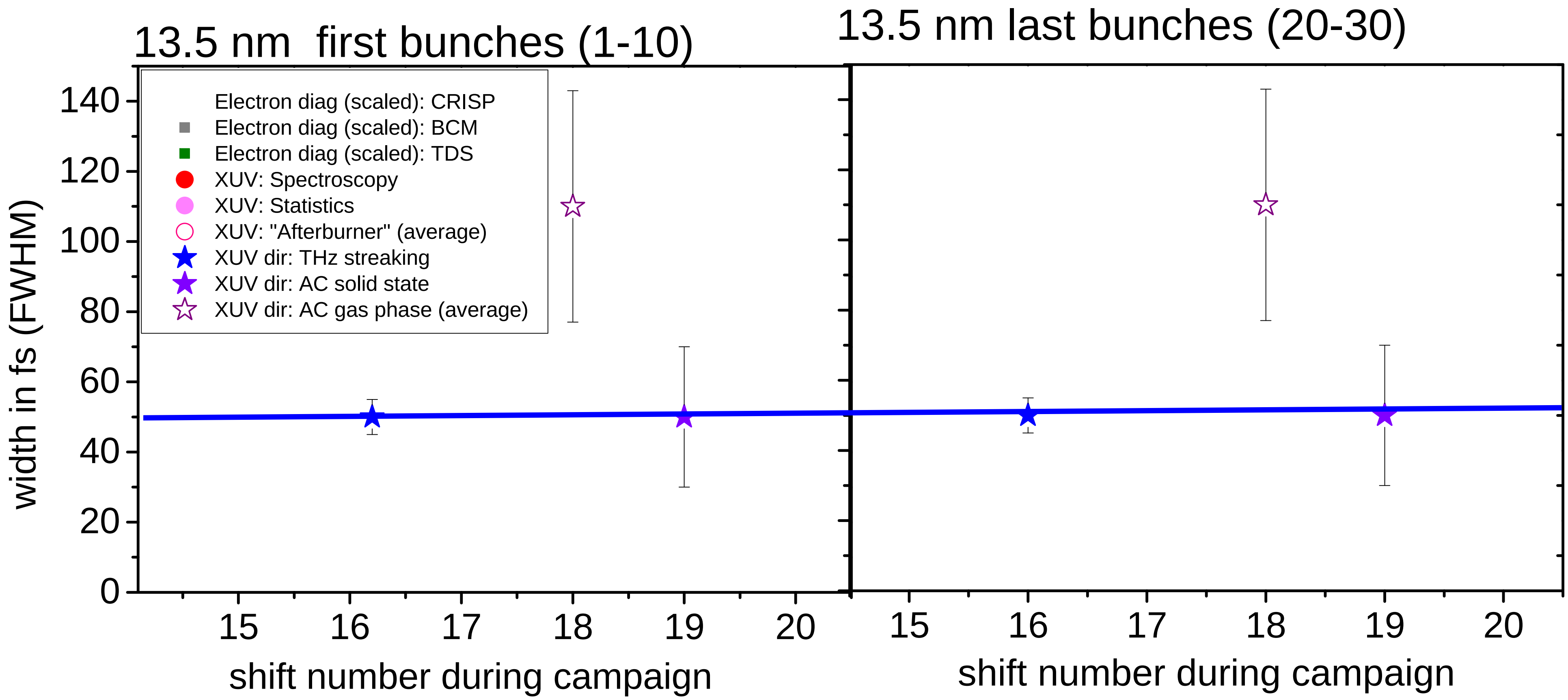
Courtesy M. Drescher

What was measured ???

Machine parameters:

- 13.5 nm, 150 pC, ~ 50 µJ, 30 bunches, 250 kHz
  -> goal ~ 50 fs
- 24.0 nm, 130 pC, ~ 50 µJ, 30 bunches, 250 kHz
  -> goal ~ 50 fs with gradient

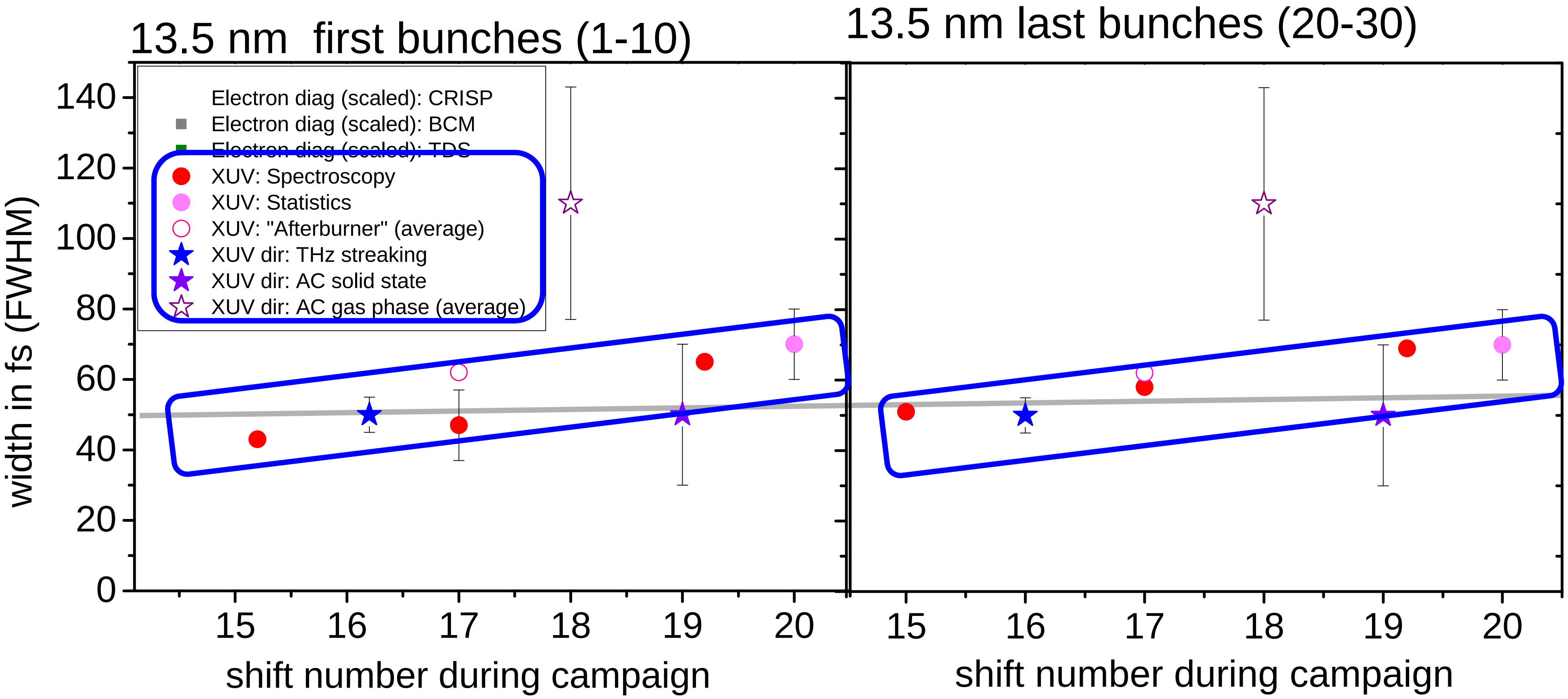
Direct photon methods (13.5 nm)



Machine parameters:

- **13.5 nm, 150 pC, ~ 50 µJ, 30 bunches, 250 kHz -> goal ~ 50 fs**

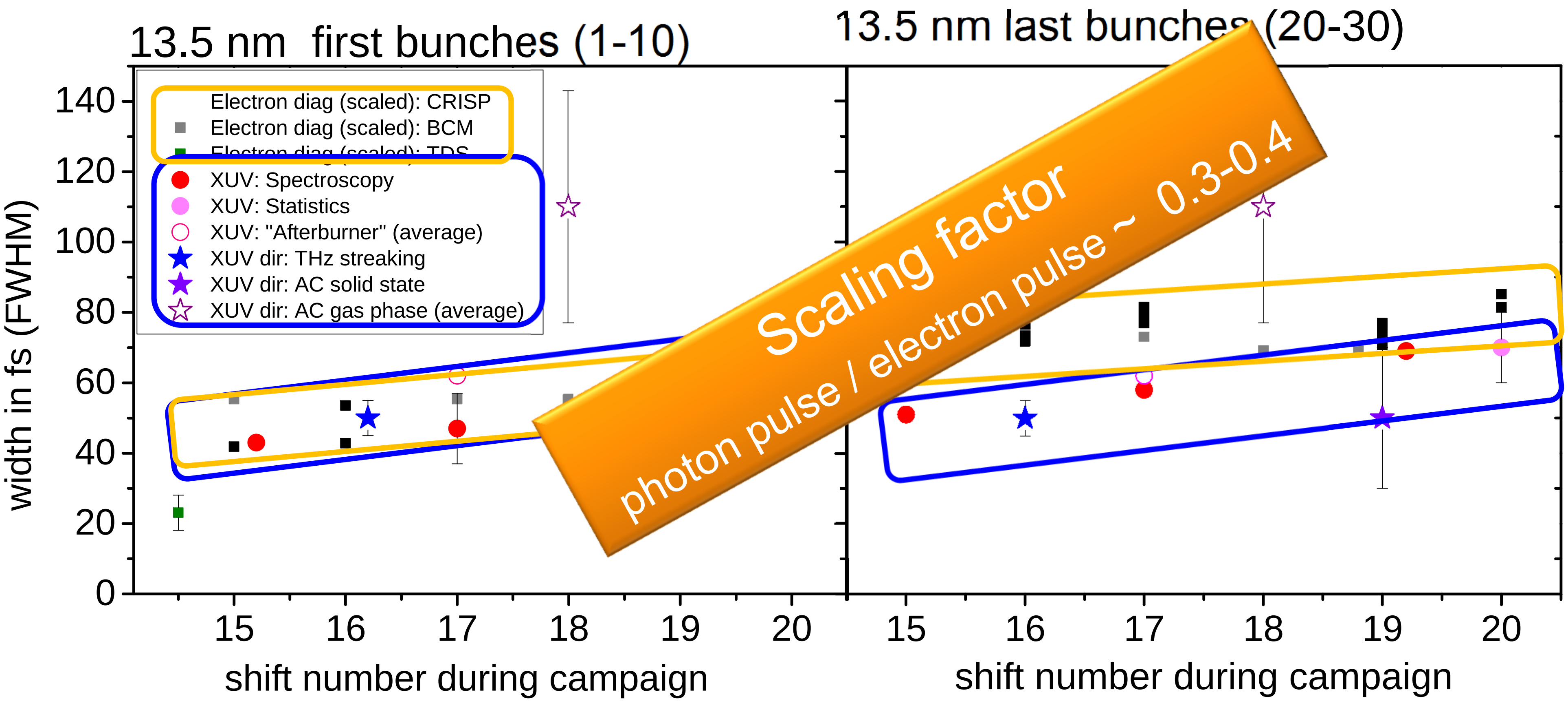
Direct and indirect photon methods (13.5 nm)



Machine parameters:

- **13.5 nm, 150 pC, ~ 50 µJ, 30 bunches, 250 kHz -> goal ~ 50 fs**

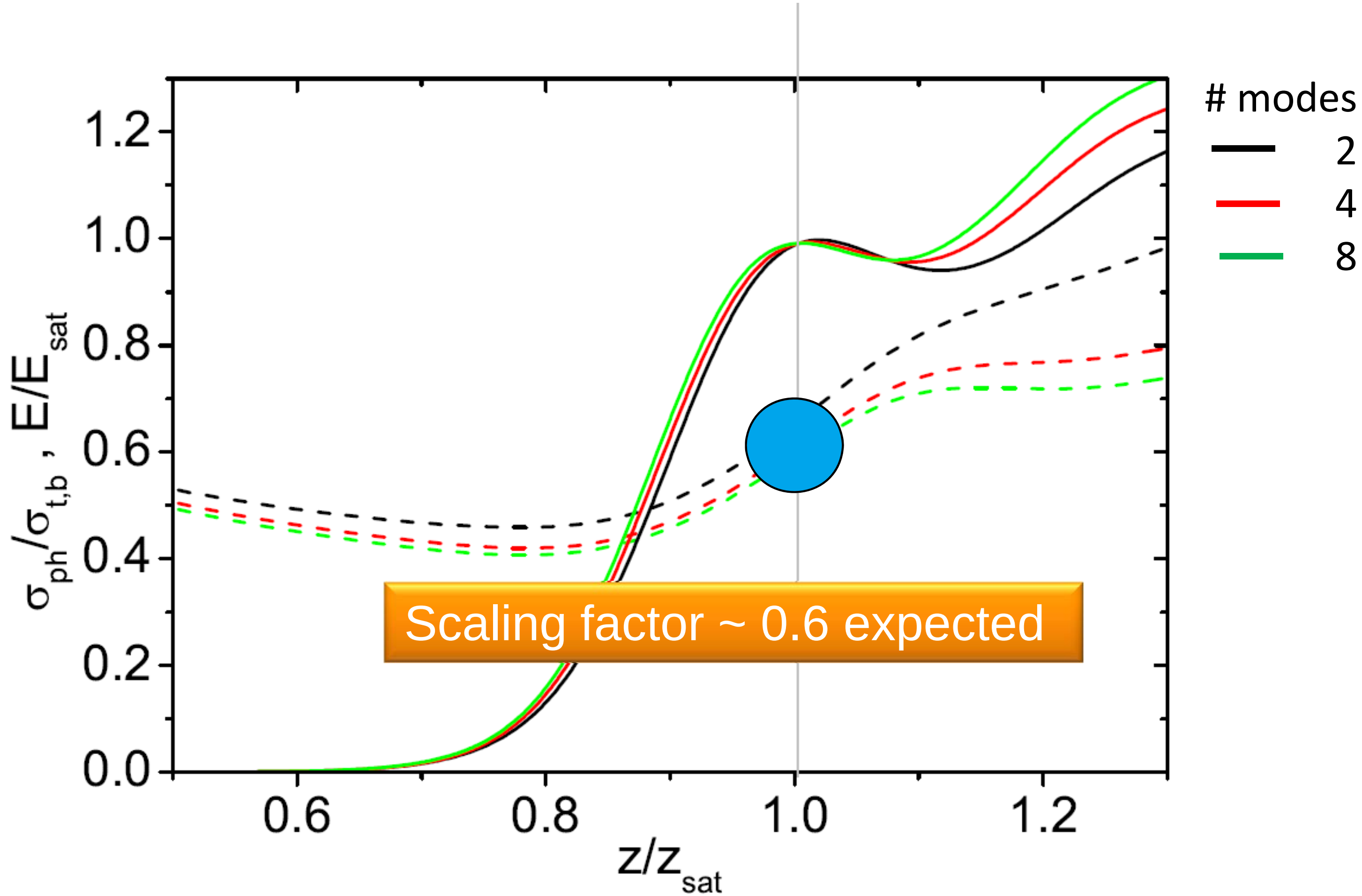
Photon and electron methods (13.5 nm)



Machine parameters:

- **13.5 nm, 150 pC, ~ 50 µJ, 30 bunches, 250 kHz -> goal ~ 50 fs**

Simulation with Gaussian model (FAST)



1D simulation with Gaussian longitudinal electron profile

E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instr. Meth. A **429 ,** 233 (1999).

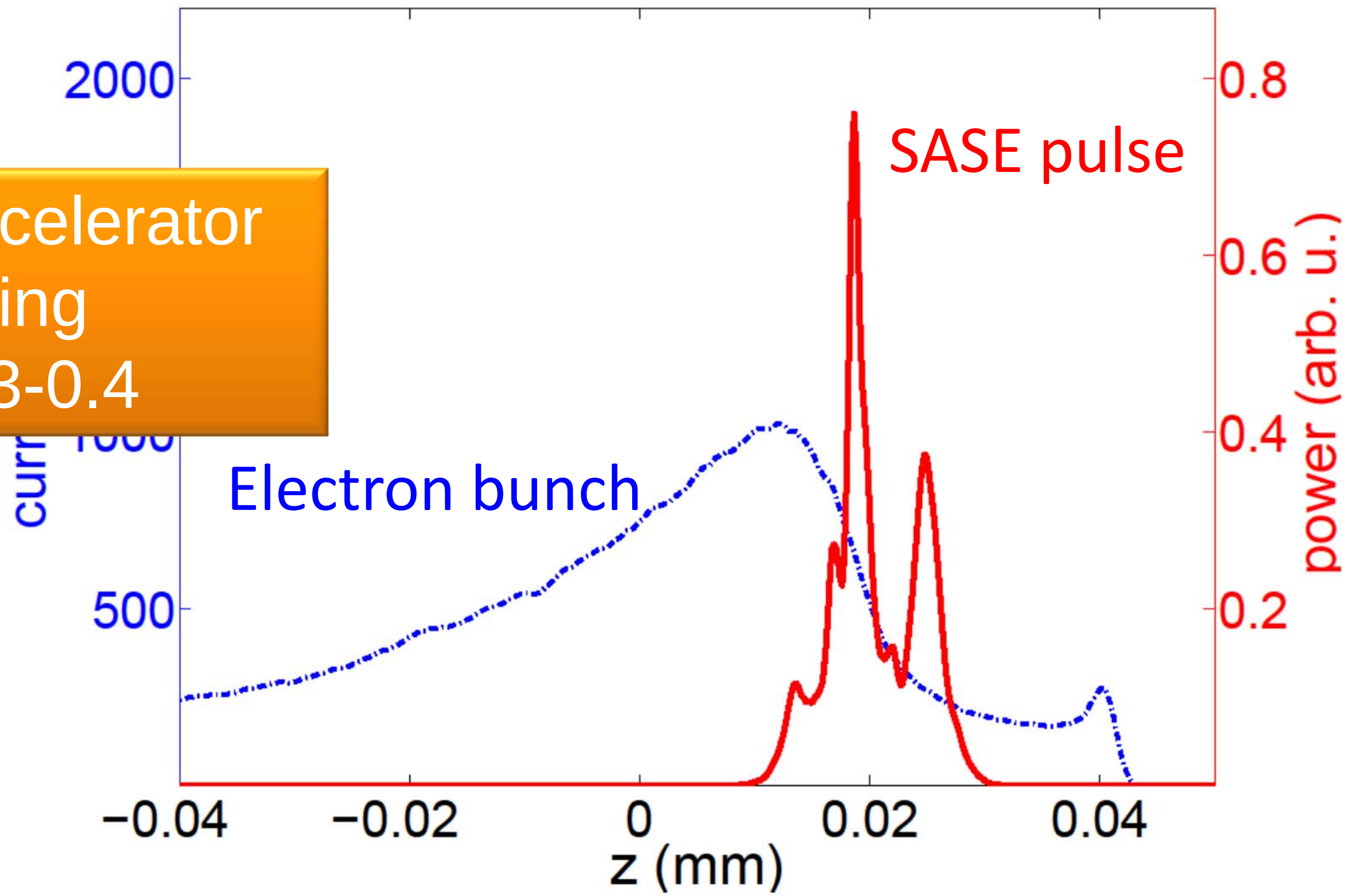
C. Behrens, et al. Phys. Rev. ST Accel. Beams **15**, 030707 (2012)

Courtesy M. Yurkov, E. Schneidmiller

Start-to-end simulation (Astra, CSRtrack & Genesis)

Simulation by M. Rehders

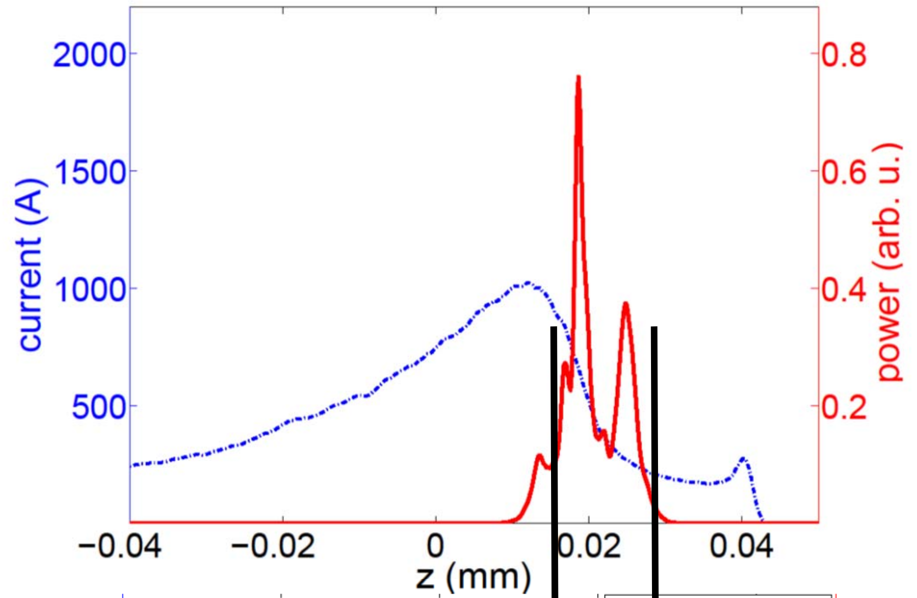
Poster / paper MOP059 .

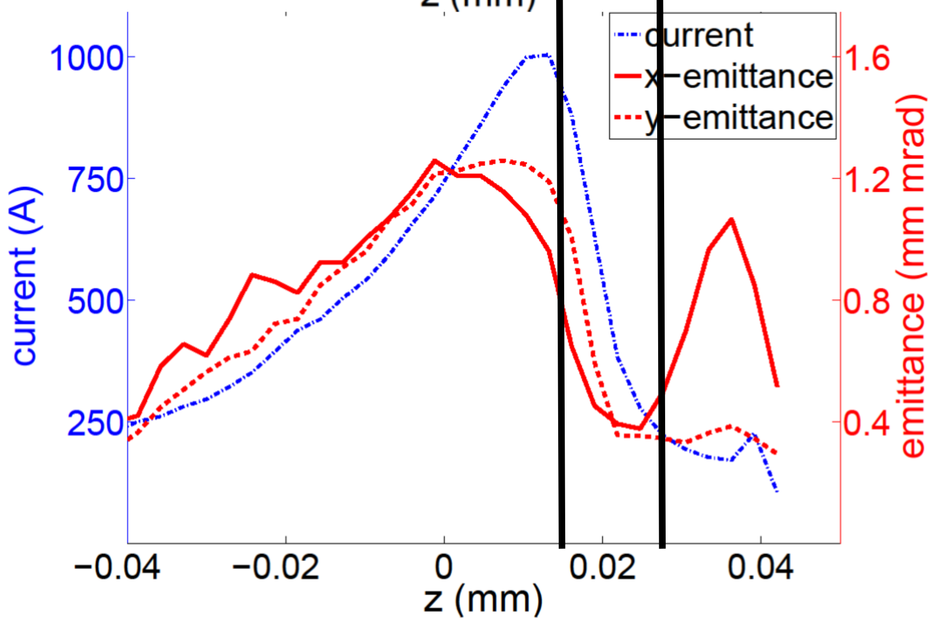


For the actual accelerator settings the scaling parameter is ~ 0.3-0.4

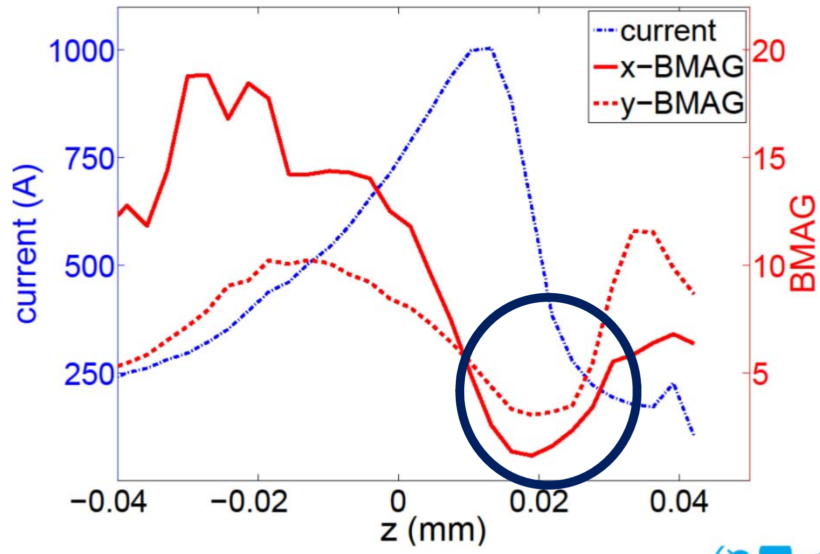
Start-to-end simulation (Astra, CSRtrack & Genesis)

Simulation by M. Rehders Poster / paper MOP059 .





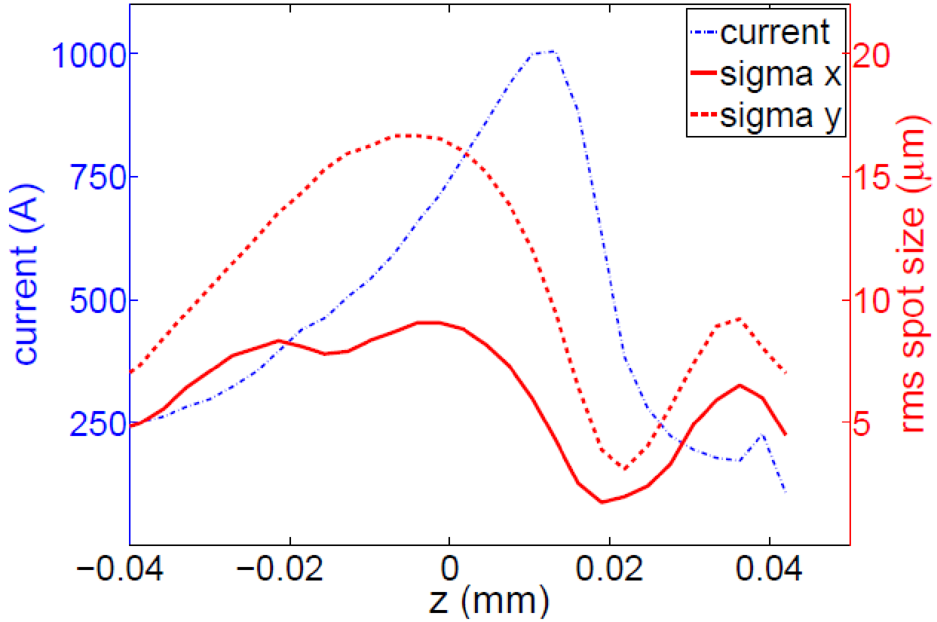
Only the leading part of the bunch has low emittance and good matching



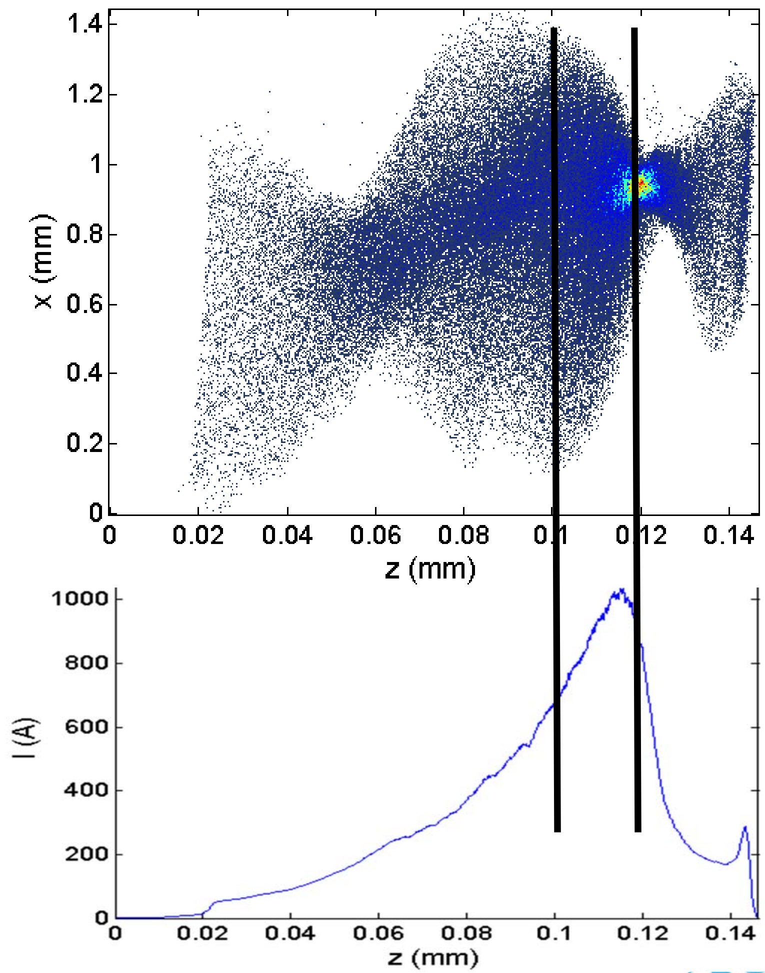
DESY

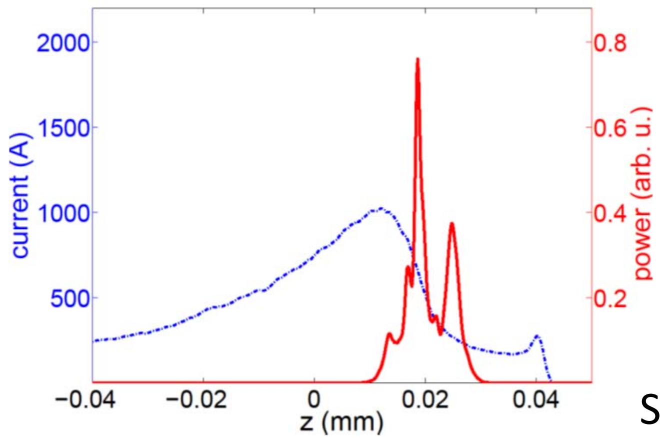
Start-to-end simulation (Astra, CSRtrack & Genesis)

Spatial electron distribution



One example for a non-Gaussian particle distribution.





Simulation by M. Rehders

Summary 13.5 nm run

> **Goal parameters reached** (50 fs, 50 µJ)

> **Very good agreement between direct and indirect photon based methods**

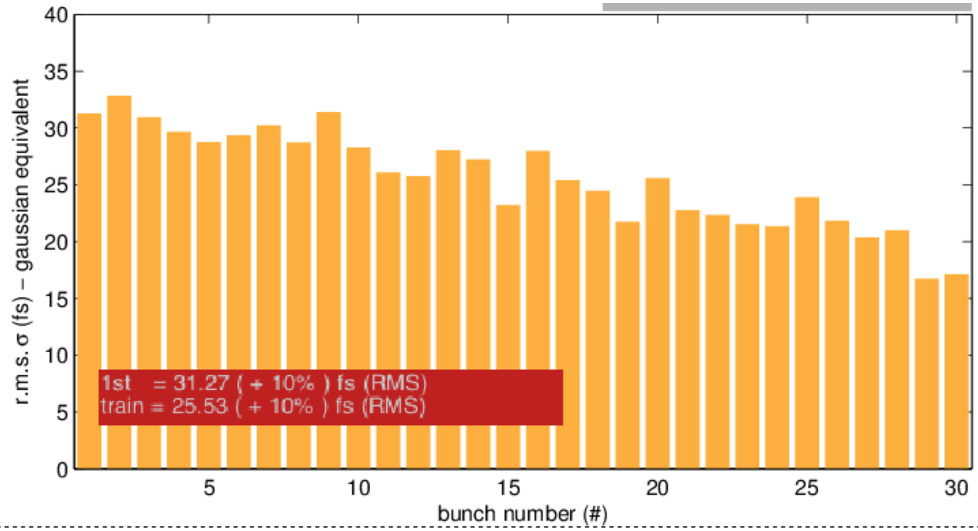
> scaling factor (photons/electrons) 0.3-0.4   - can be explained with simulations.

24 nm case

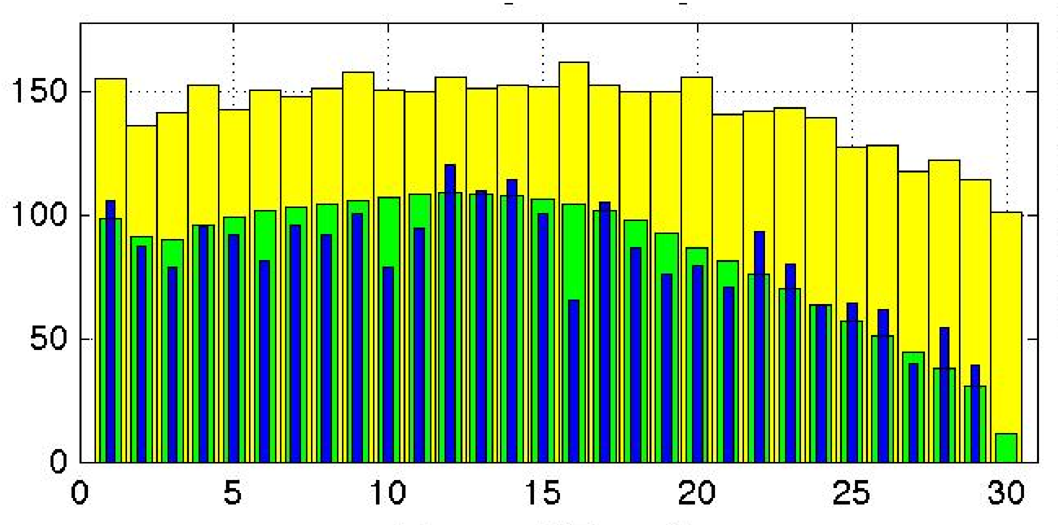
Machine parameters:

- **24 nm, 150 pC, ~ 50 µJ, 30 bunches, 250 kHz**
  -> goal ~ 50 fs with gradient

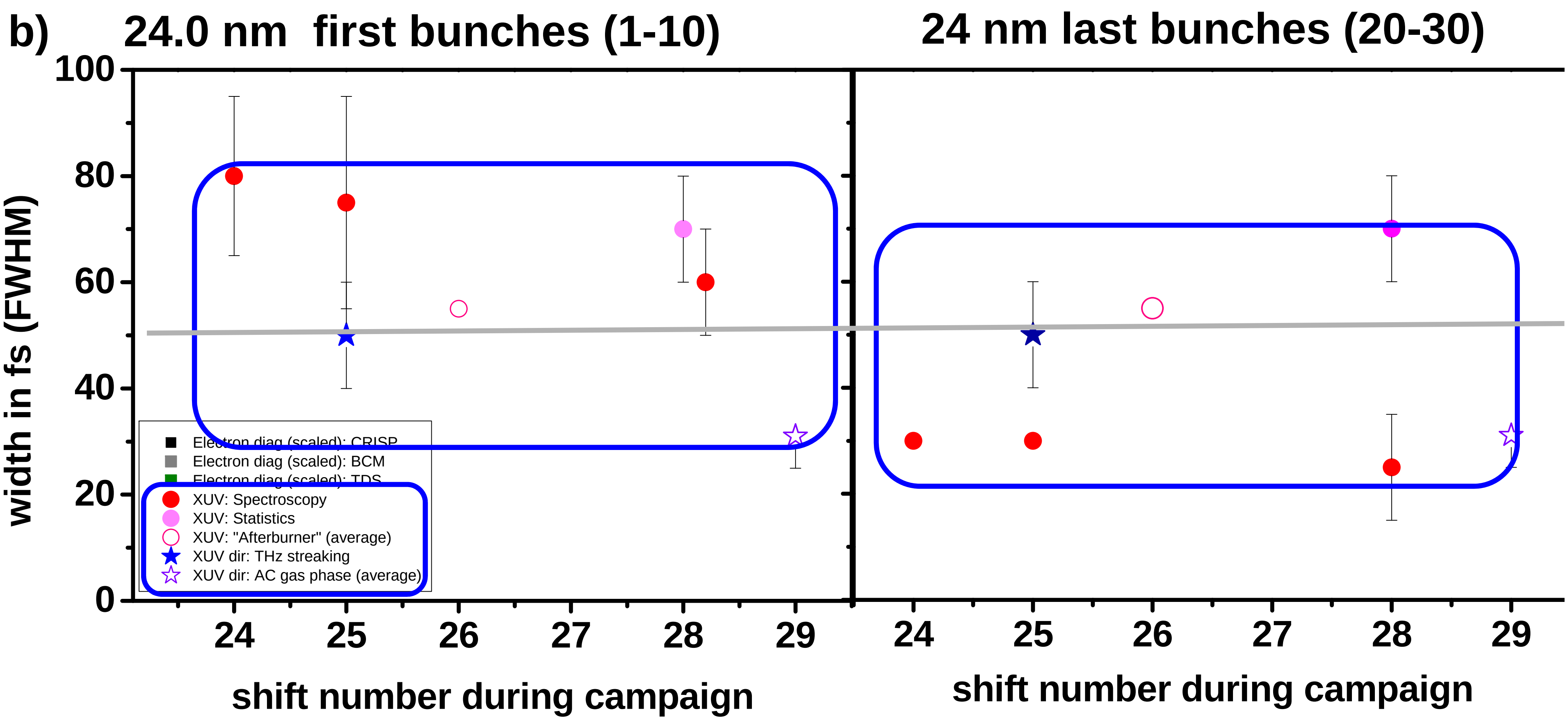
Bunch length (BCM)



Pulse energy (GMD)



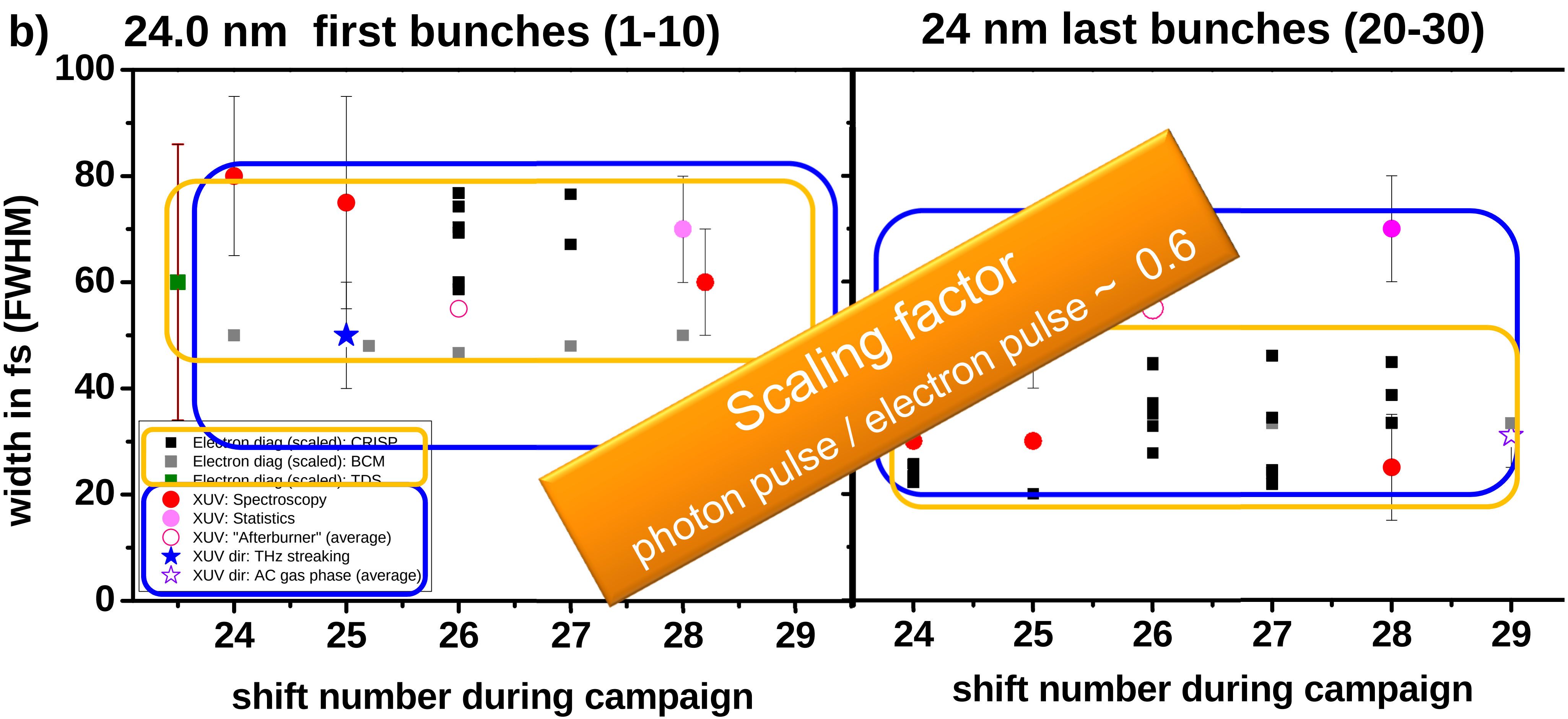
Direct and indirect photon methods (24 nm)



Machine parameters:

- **24.0 nm, 130 pC, ~ 50 µJ, 30 bunches, 250 kHz**

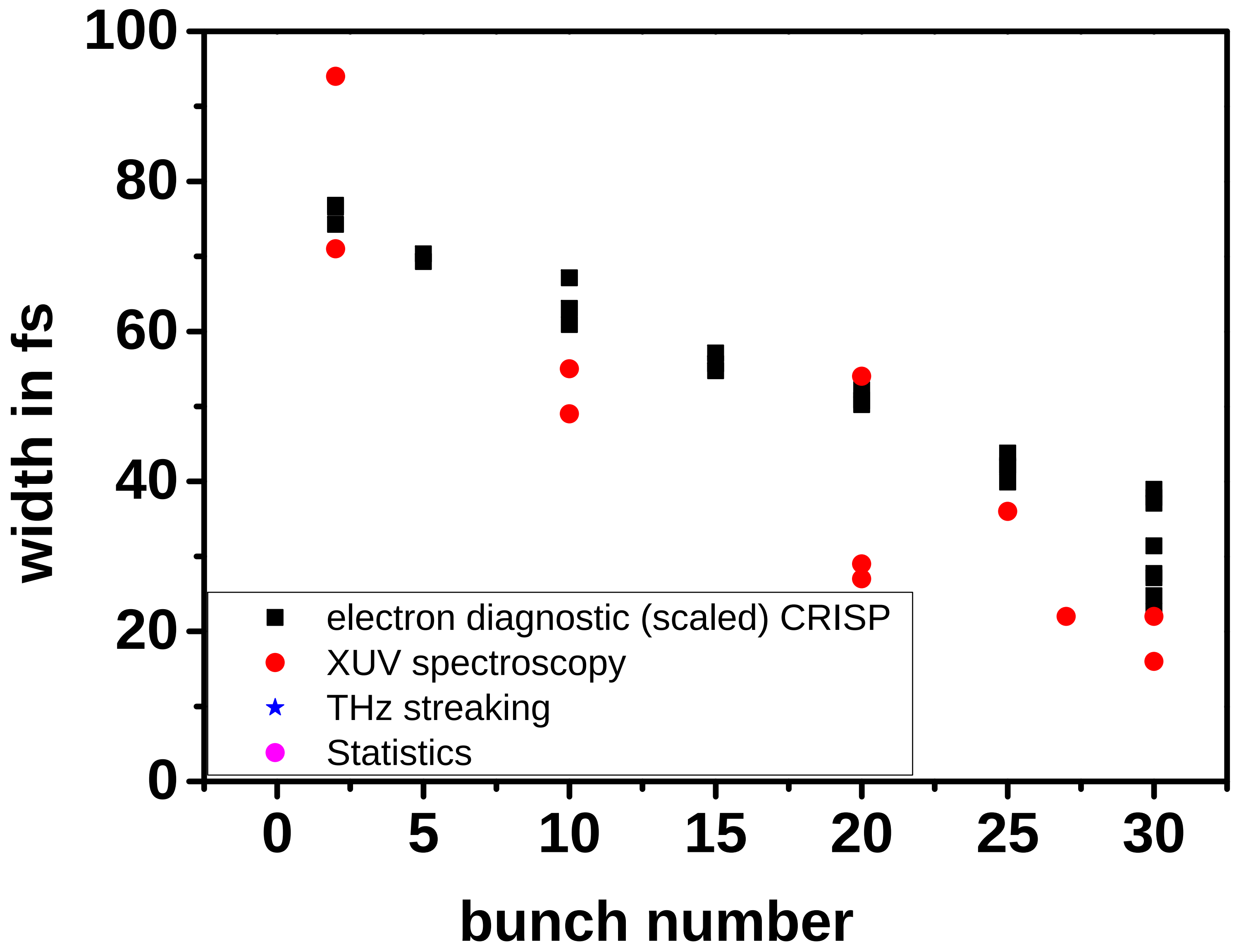
Photon and electron methods (24 nm)



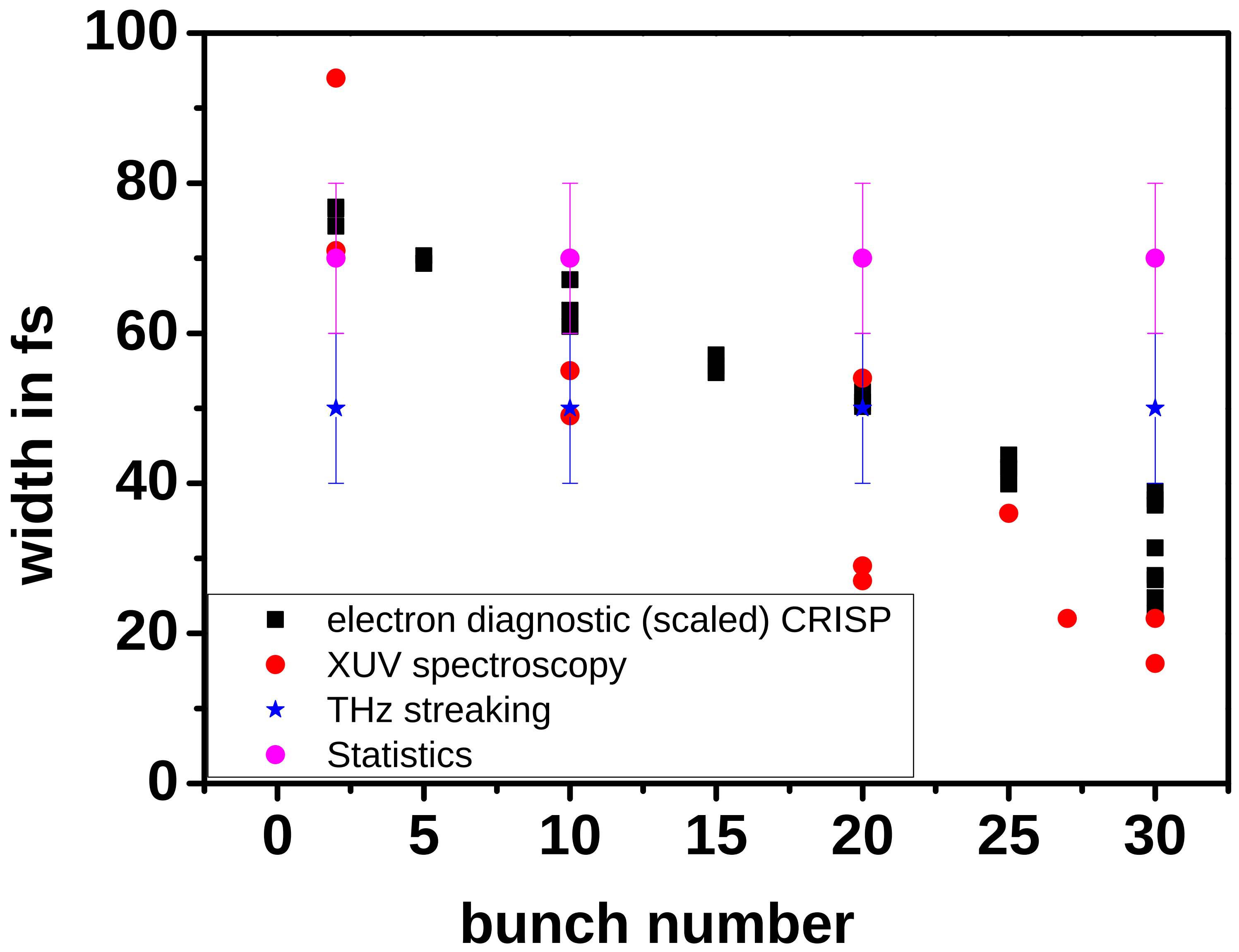
Machine parameters:

- **24.0 nm, 130 pC, ~ 50 µJ, 30 bunches, 250 kHz**

24 nm run - pulse duration gradient ?



24 nm run - pulse duration gradient ?



Summary 24 nm run

> **Goal parameters reached:** 50 fs +-30fs, 50 µJ

> Large scatter of measurements

> scaling factor (photons/electrons) ~ 0.6

> Limits due to assumptions used by different techniques (Gaussian photon pulses, sensitivity to chirp …)

> Not enough information available to reconstruct cause for discrepancies

> New test measurements needed

Summary

- No pulse length diagnostic for ALL needs
- Electron bunch length diagnostics:
  - Good monitor for changes (drifts)
  - Estimate for XUV pulse duration (upper limit for short wavelength)
- Photon pulse length diagnostics
  - Direct methods are demanding – indirect methods still challenging
  - **Very good agreement between direct and indirect m** parameters)
  - Large error bars for varying pulse par
- scaling factor (photons/electr) 0.3 – 0.6

20 page detailed article submitted
S. Düsterer. M. Rehders et al (2014)

DESY

Outlook

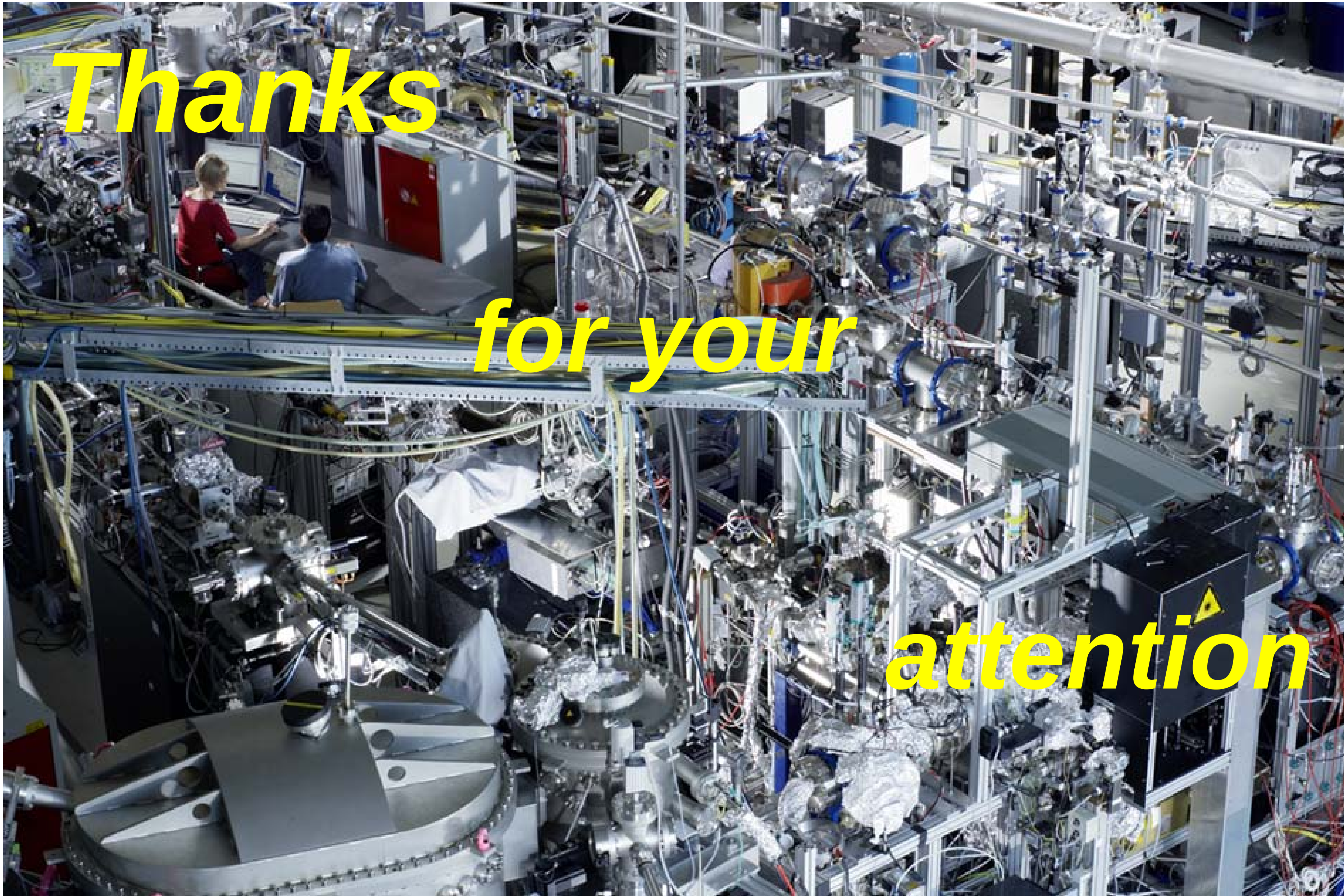
Better knowledge about XUV pulse duration / shape @ FLASH:

> focus on pulse length photon diagnostics:

- Direct: Laser based THz streaking (own setup designed / collaboration PSI, XFEL …)
- Direct: XUV-optical reflectivity changes (ongoing measurements, e.g. Nat Comm. 4 1731 (2013))
- Indirect: Afterburner (THA04)
- Indirect: Spectral analysis (evaluation of "online" pulse duration tool)

> Single mode operation (TUB04)

> Seeding options …


Thanks
for your
attention