Photon diagnostics @ FLASH

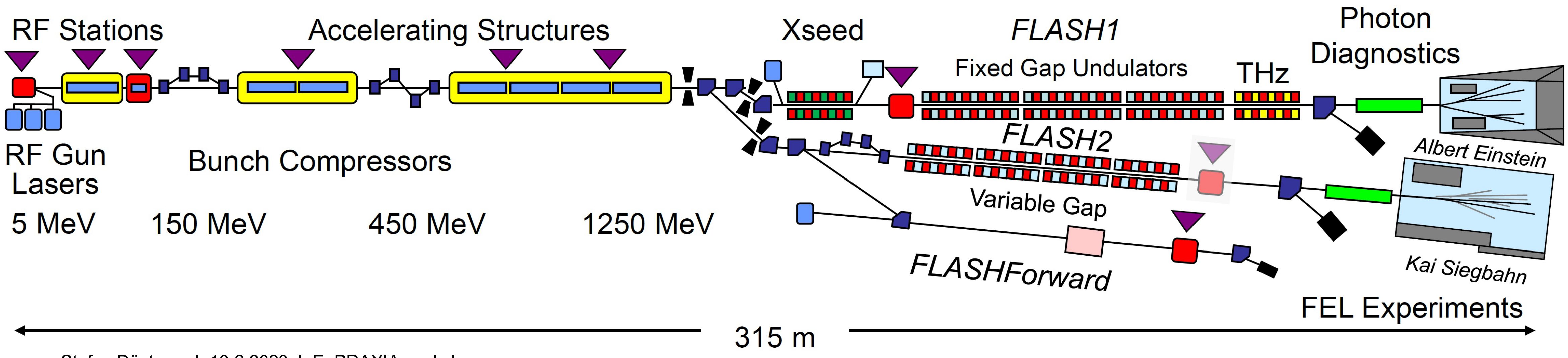
WP13 EuPRAXIA electron and photon diagnostics workshop

Stefan Düsterer for the FLASH team
13.06.2023

FLASH Photon beam parameters

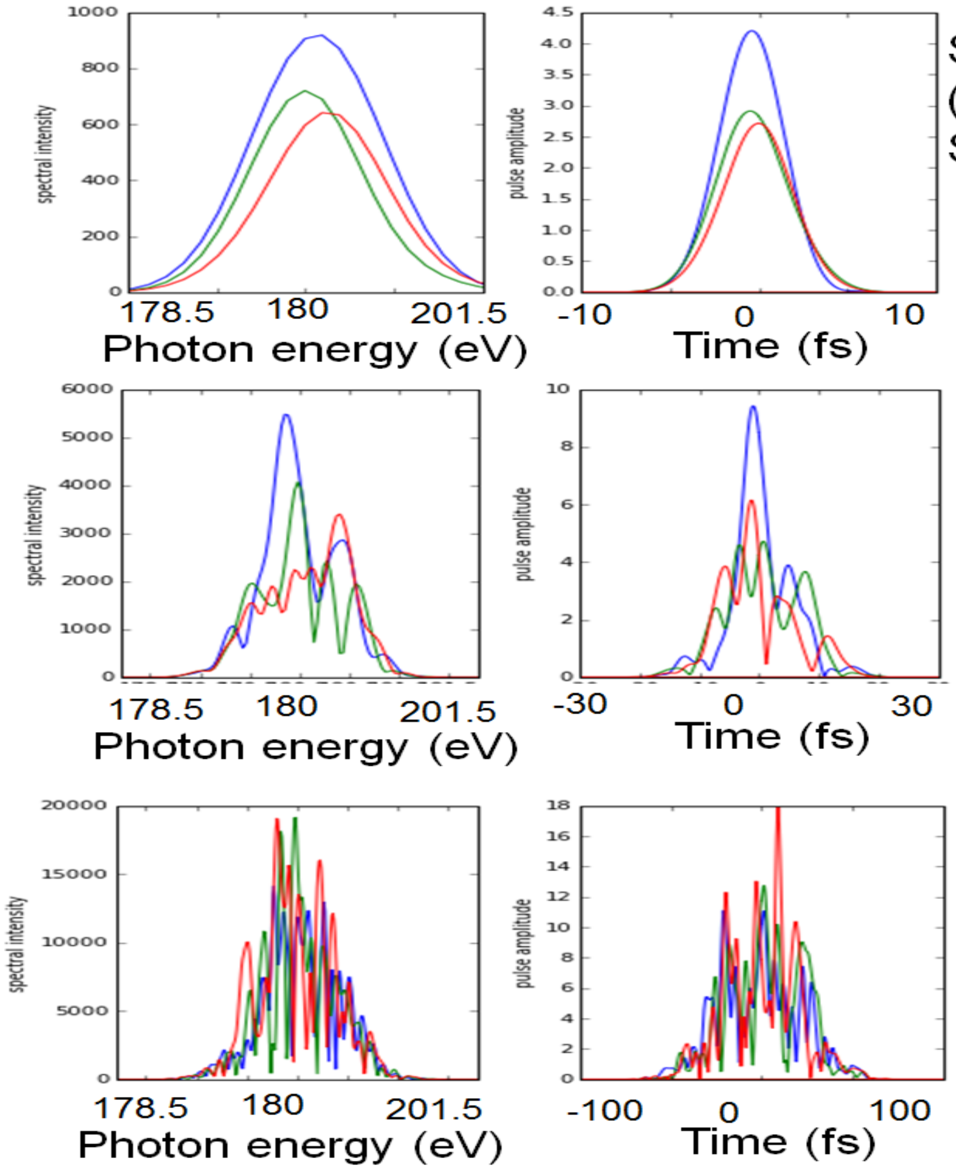
Photon beam Parameters	FLASH1	FLASH2
Photon energy fundamental (eV)	24 – 290 eV	14 – 300 eV
Wavelength fundamental (nm)	4.2 – 51 nm	4 – 90 nm
Photon pulse duration (FWHM)	<30-200 fs	<30-200 fs
Single photon pulse energy (average)	1 – 500 μJ	1 – 1000 μJ
Spectral width (FWHM)	0.7 – 2 %	0.5 – 2 %
Pulses per second**	10 - 5000	10 - 5000

**shared between FLASH1 and FLASH2



SASE pulses (Self-Amplified Spontaneous Emission)

Simulation



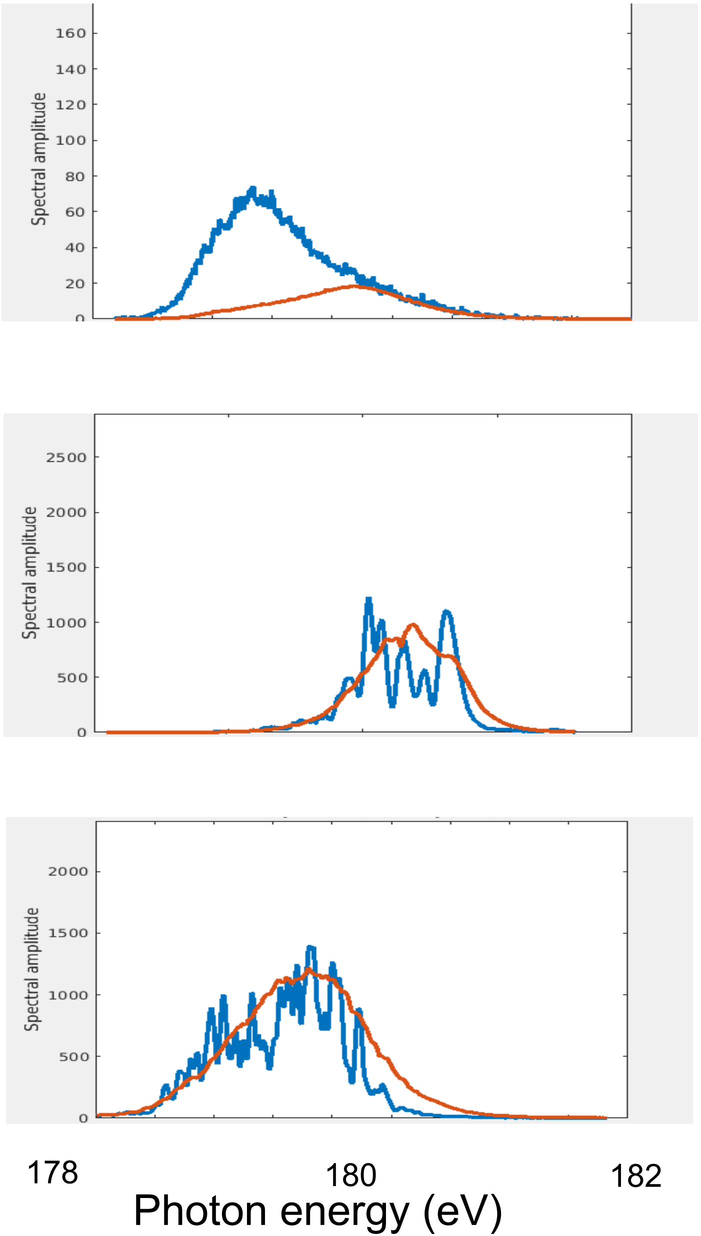
Single spike
(currently) shortest
SASE FEL pulses

5-10 fs

~30 fs

~80 fs

Spectral measurements

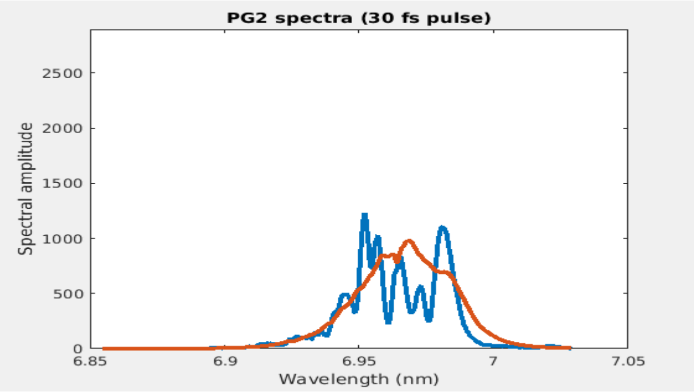


Diagnostic tools for FELs.

What kind of diagnostic tools do users need to make efficient use of FELs?

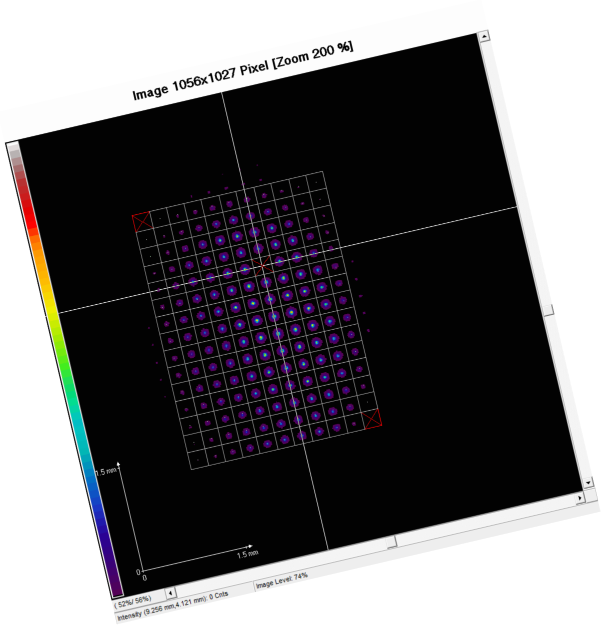
Due to the SASE specific shot-to-shot fluctuation the users need most this information for every single pulse => online, non-destructive

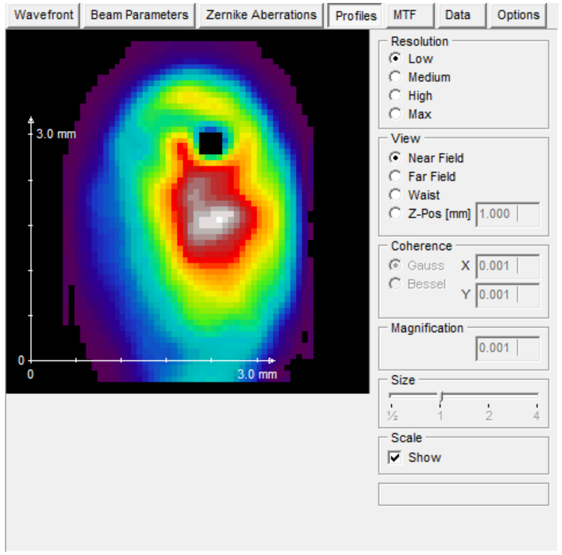
- focus size
- beam position
- pulse energy
- spectral distribution
- temporal radiation pulse properties
- coherence
- polarization

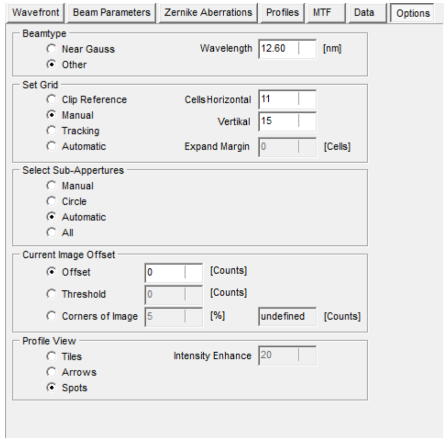


Focus size and position

Wave front sensors



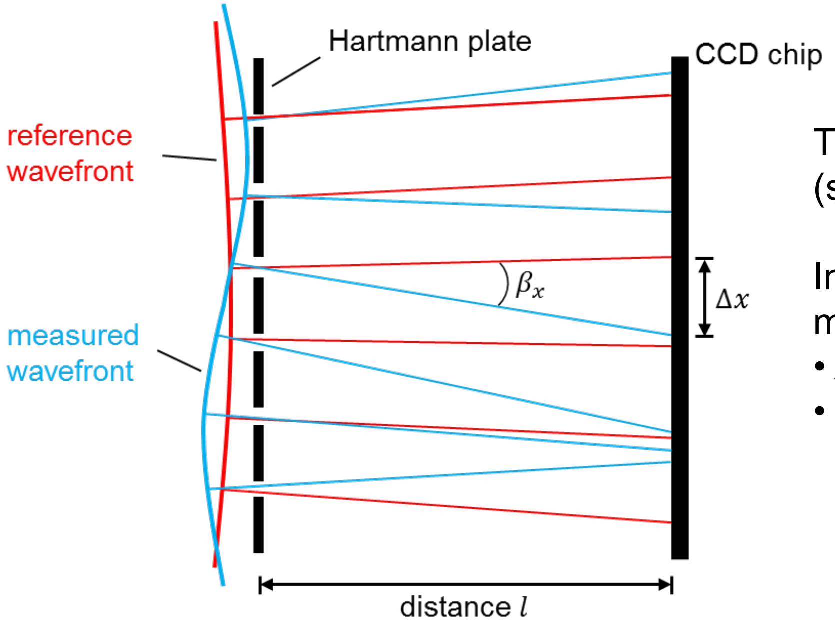




B. Keitel et al . J. Synchrotron Rad. **23**, 43-49 (2016);

Wavefront sensors (WFS) at FLASH

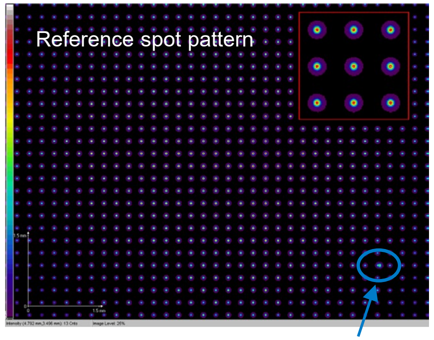
Operation principle



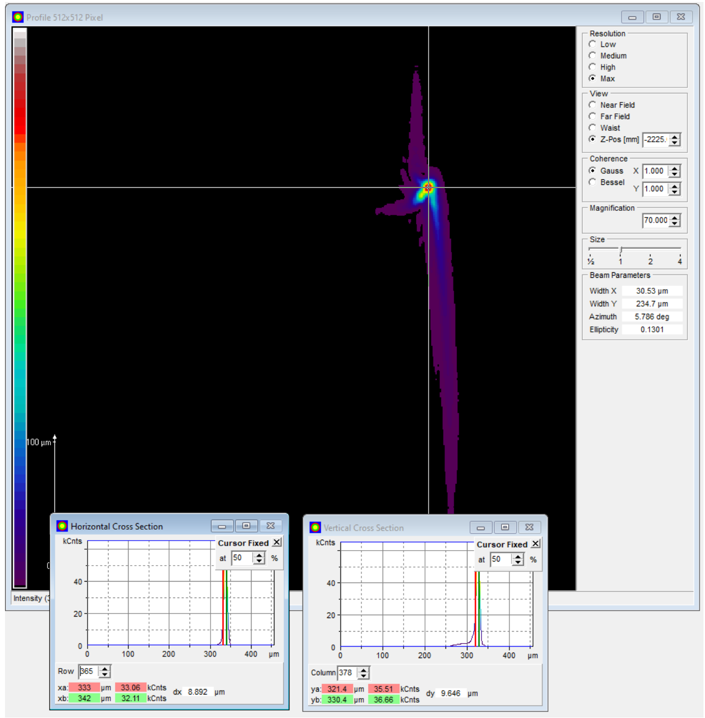
The actual beam is compared to a reference wave (spherical wave).

Intensity and phase information in single shot measurements:

- Amplitude of each spot → local intensity
- Position of each spot → local slope, wavefront phase



Alignment pinhole



Software MrBeam (by IFNANO) allows evaluation of

- Intensity profile / beam size
- Waist position and size
- Wavefront and Zernike aberrations
- Beam divergence
- Beam quality product M^2
- Pointing stability
- Back propagation of intensity profiles for any position in the beam
- Back propagation of partial coherent beam using Gaussian or Besselian coherence functions is available

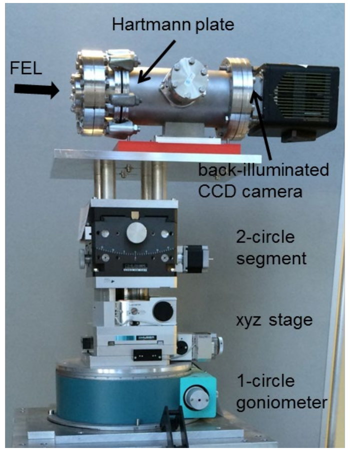
Courtesy B. Keitel

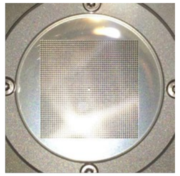
Wavefront sensors (WFS) at FLASH

Continuous collaboration with industry since 2005

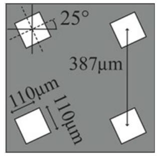
imagine optic (France)

- Since 2005 first WFS for the XUV wavelength range (8 - 40 nm) in operation at FLASH
- Since 2019 in-vacuum WFS with high NA for highly divergent XUV beams

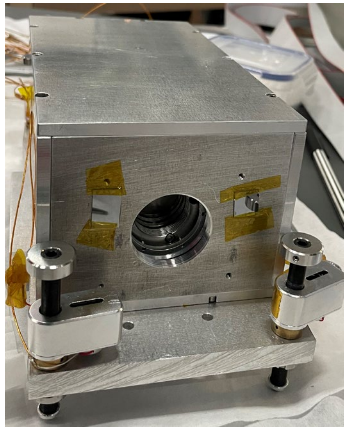




Hartmann plate



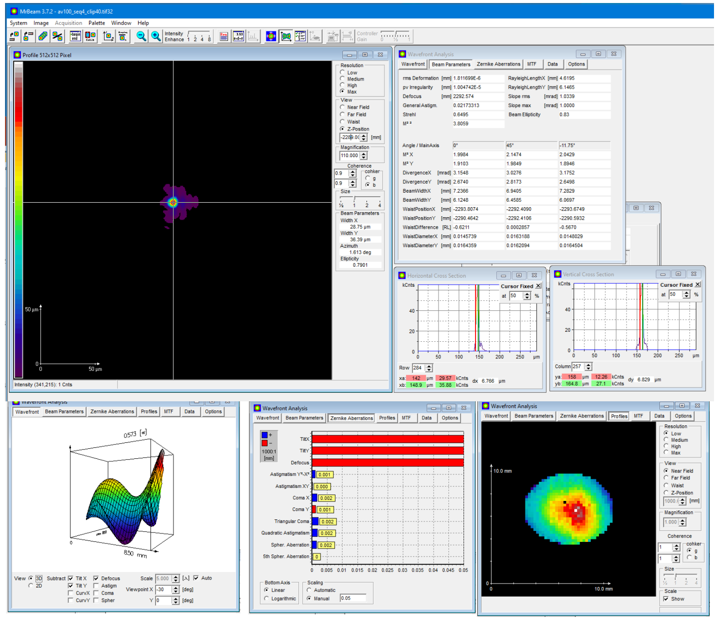
First WFS at FLASH, still in operation

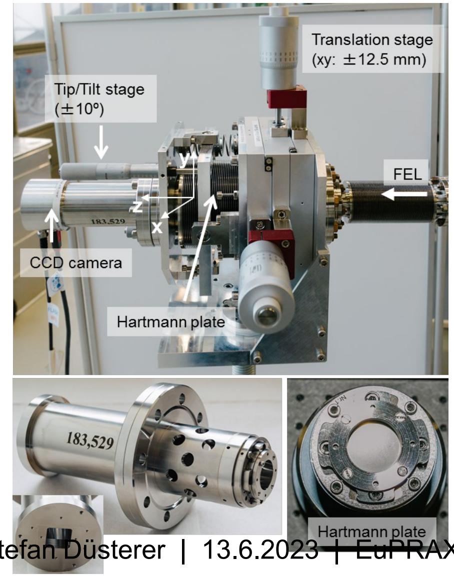


Fully in-vacuum WFS

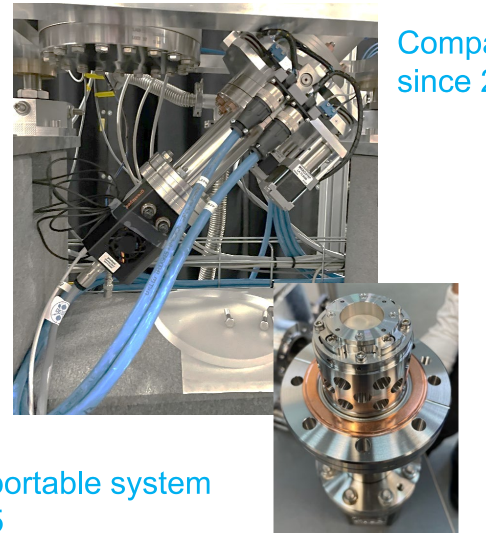
IFNANO INSTITUT FÜR NANOPHOTONIK (Göttingen) together with ProOpto (Spin-off company)

- In 2006 start of development for compact XUV (4 – 30 nm) WFS





Compact portable system since 2015



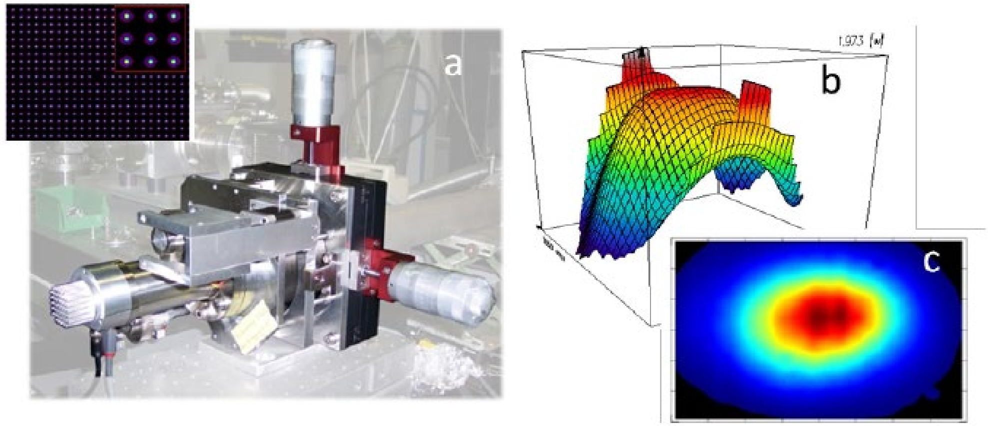
Compact integrated system since 2023

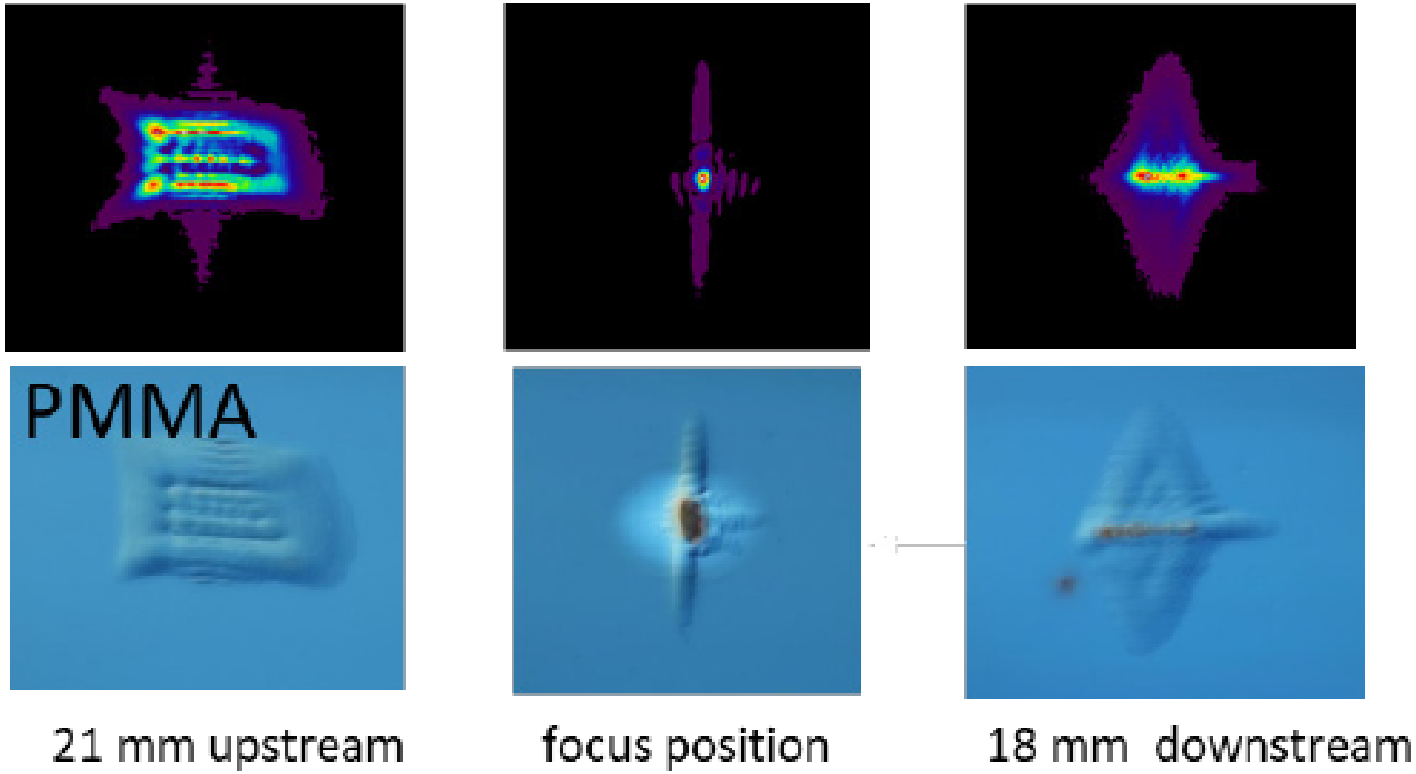
WFS for visible (350 – 1100 nm)

Courtesy B. Keitel

Wavefront sensor benchmarking

Compare to imprints

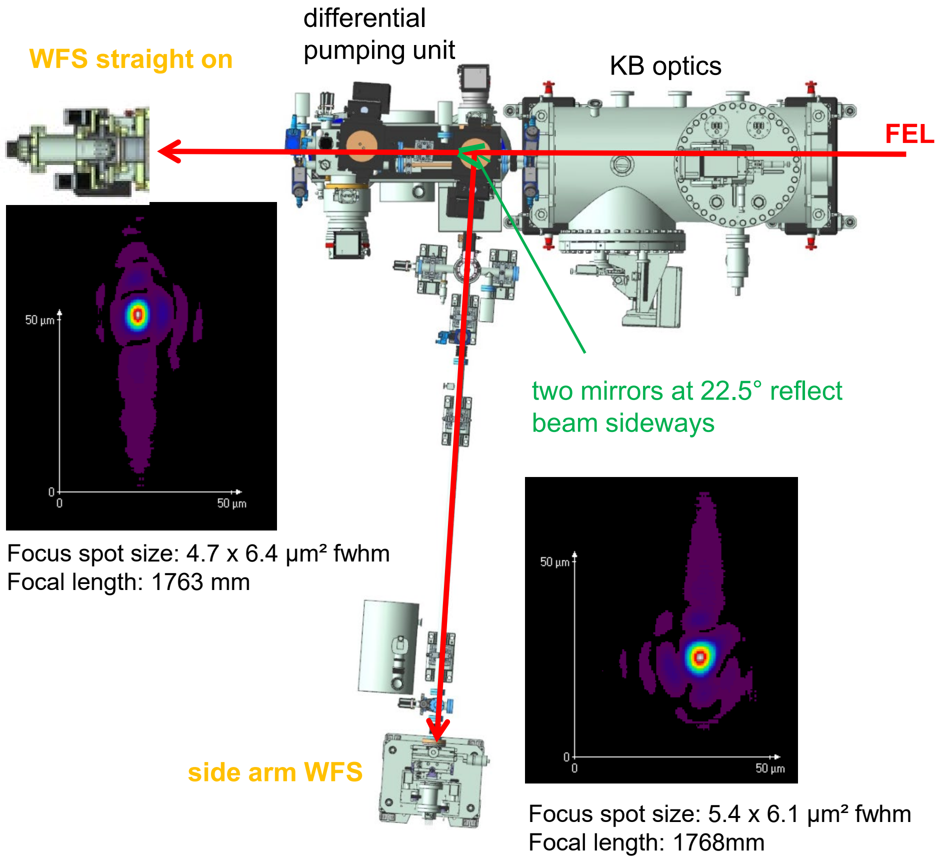


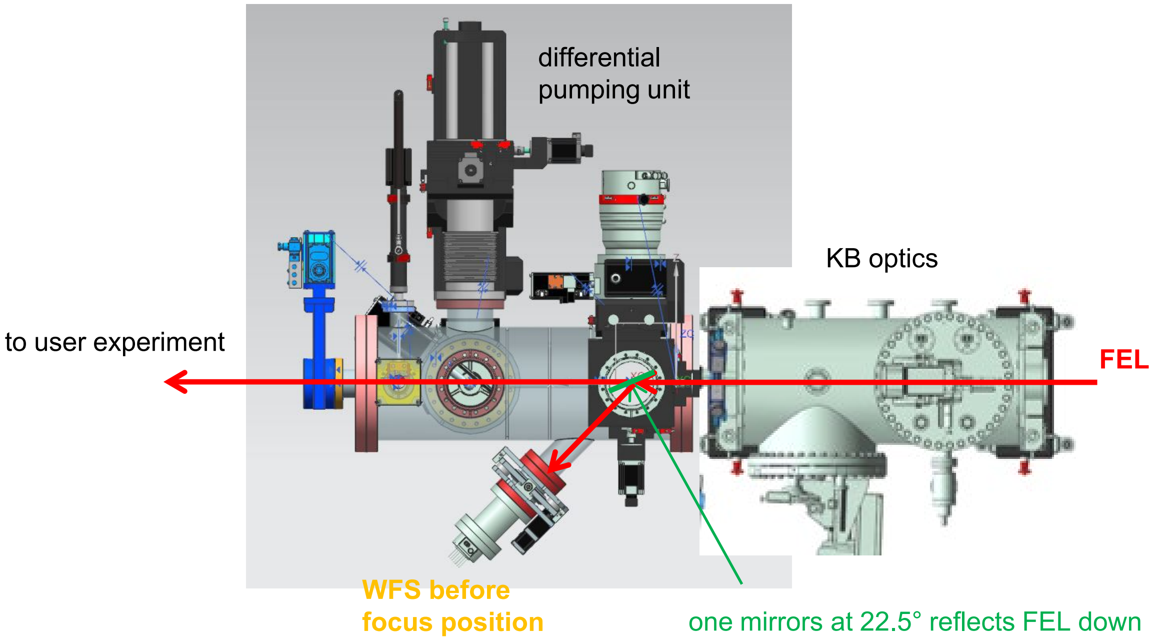


Courtesy B. Keitel

Wave front sensors need space …

Permanent wave front sensing setup incorporated at beamline FL23 and FL24 at FLASH2





Successful first proof-of-principle demonstrator:

- WFS in the side arm for alignment of KB optics without disturbing users
- two mirrors at 22.5°
- limited wavelength range (8 nm up to 40 nm)
- focus positions between 1.5 m and 3.5 m can be measured
- conform results in the side arm and straight direction

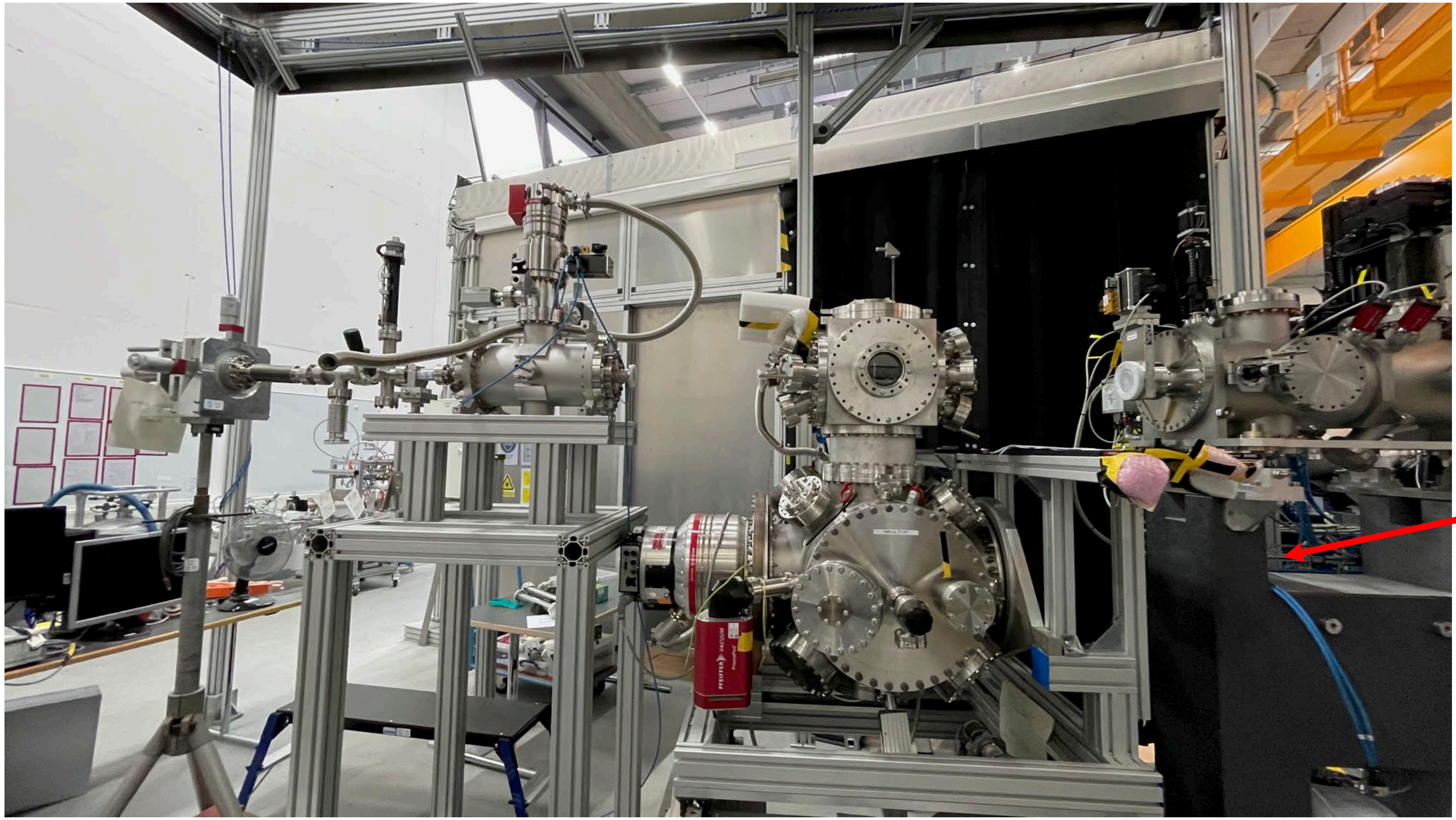
New design:

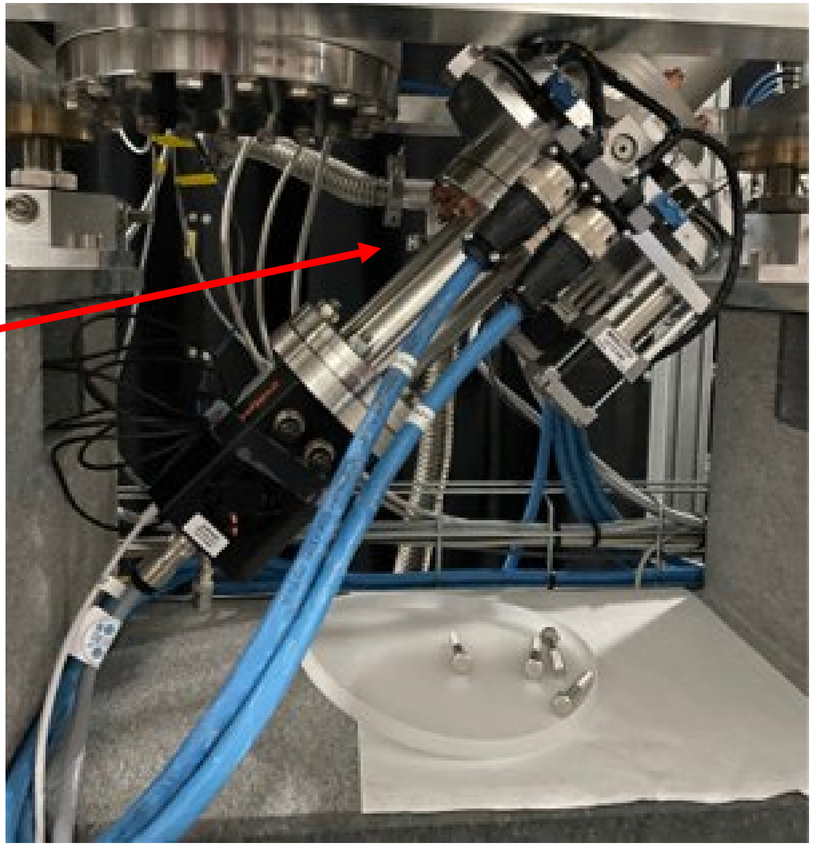
- need to incorporate WFS into every beamline using bendable KB optics
- WFS be located 45° beneath the differential pumping unit
- one mirror under 22.5° increases intensity
- WFS is located **before focus** position to avoid a large arm

Courtesy B. Keitel

Compact WFS

Integrated in the focussing chamber

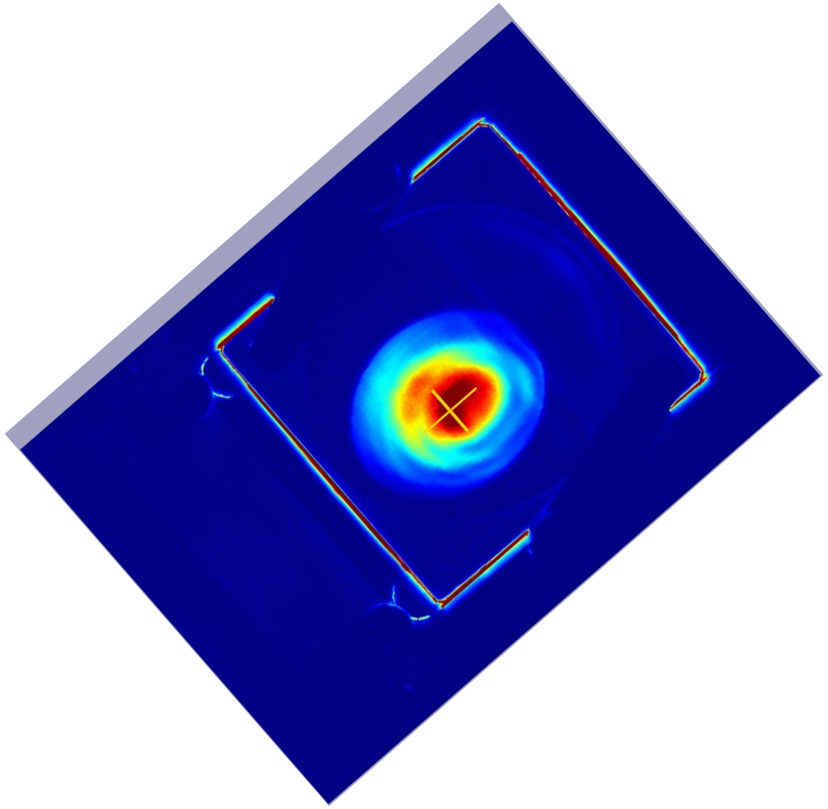


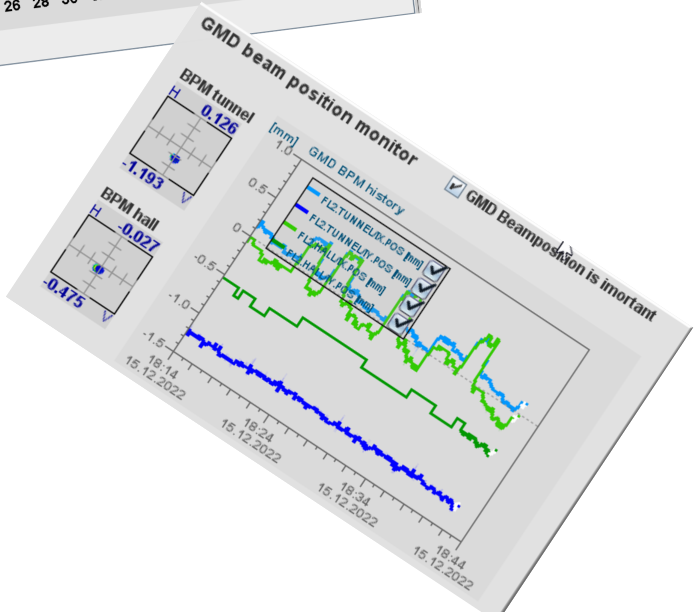


Courtesy B. Keitel

Beam position and pulse energy

Screens and “GMD”

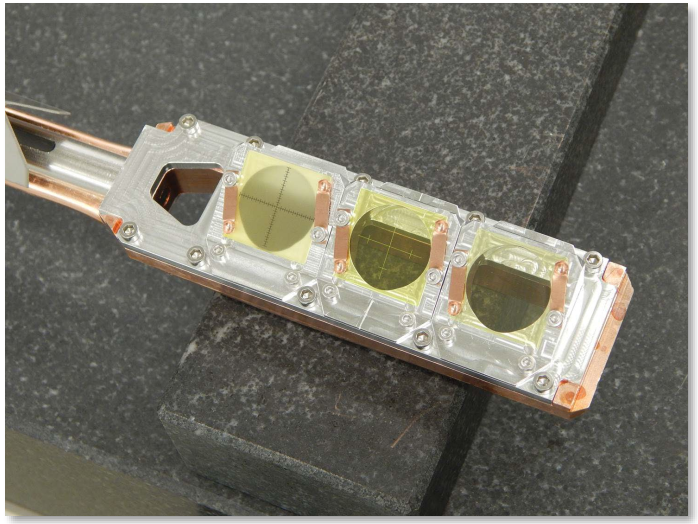


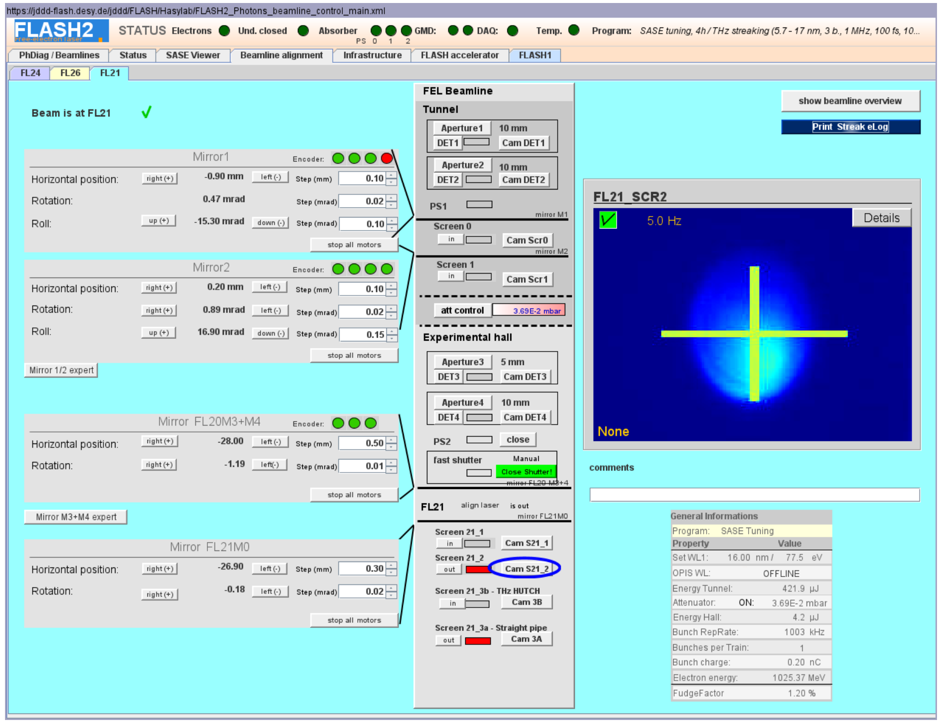


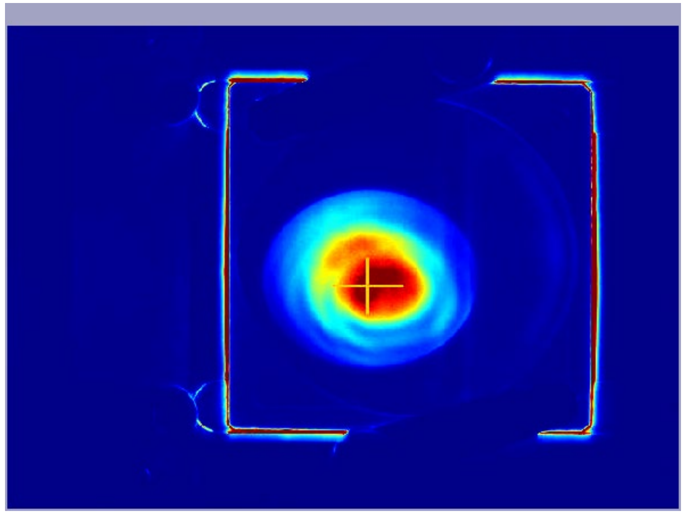
Beam position / shape

Important for machine setup and beamline alignment

- **Ce:YAG crystals (no powder due to aging)**
- motorized and pneumatic
- mounted at 30 deg
- **Diamond** are more robust screens for small, intense spots

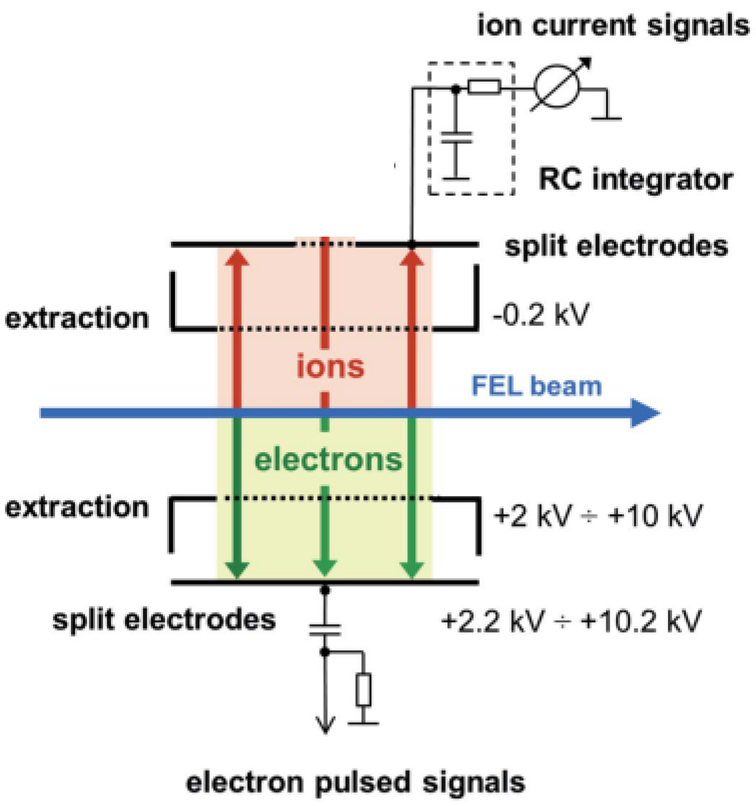


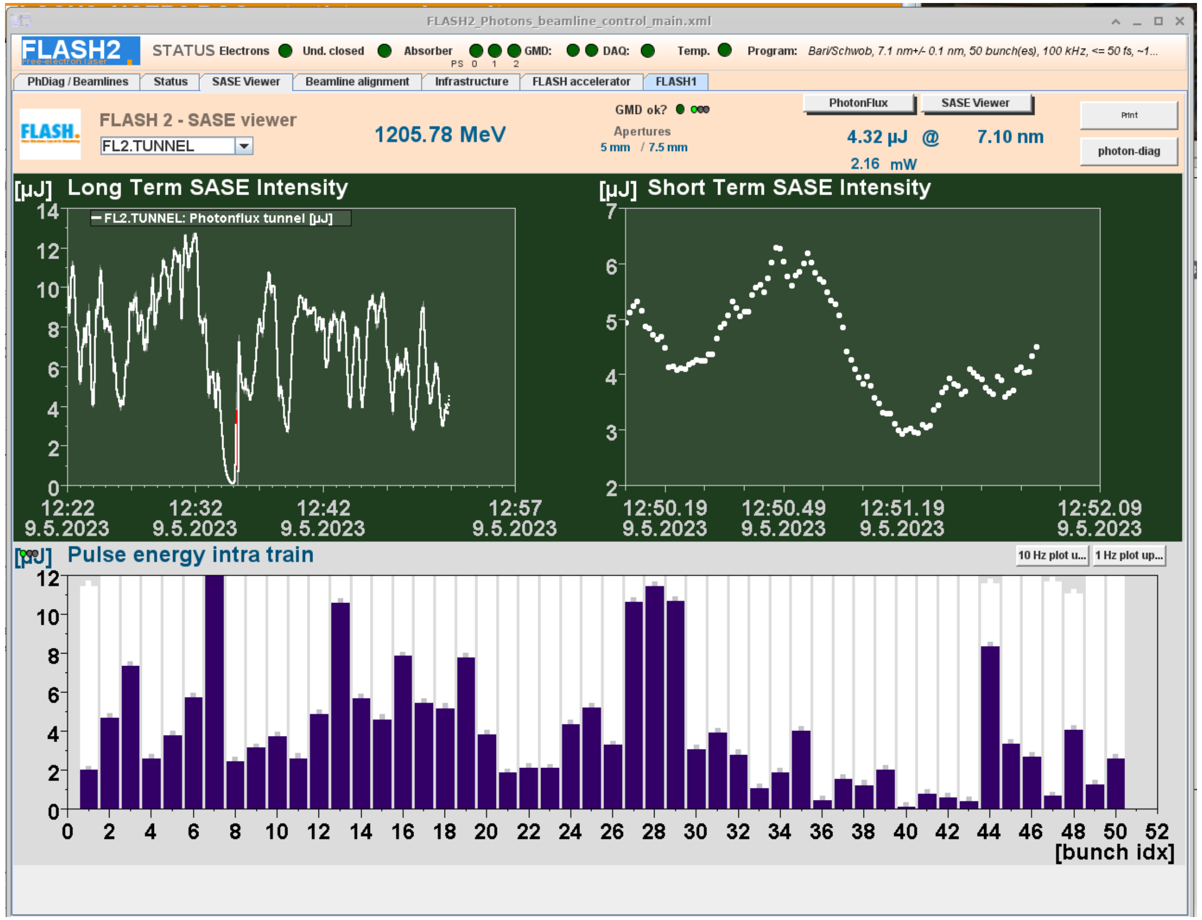




Pulse energy

Gas monitor detector (GMD)

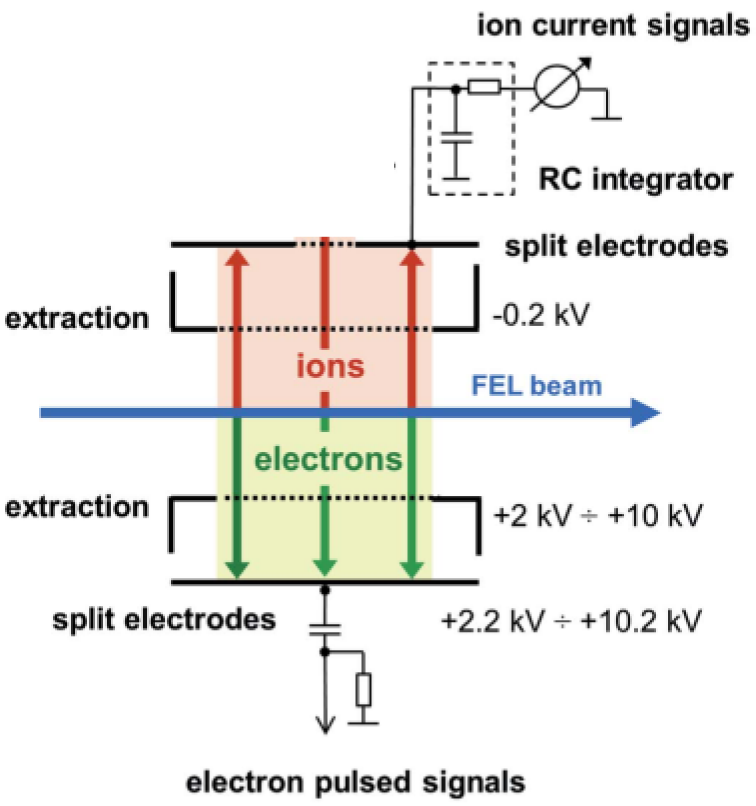




A. A. Sorokin et al, J. Synchrotron Rad. **26**, 1092-1100 (2019);

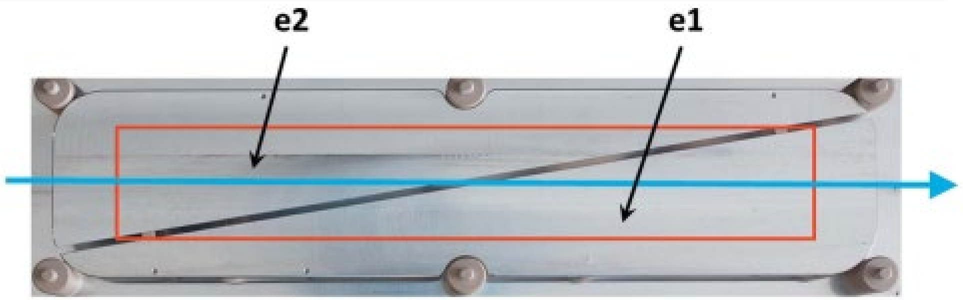
Pulse energy

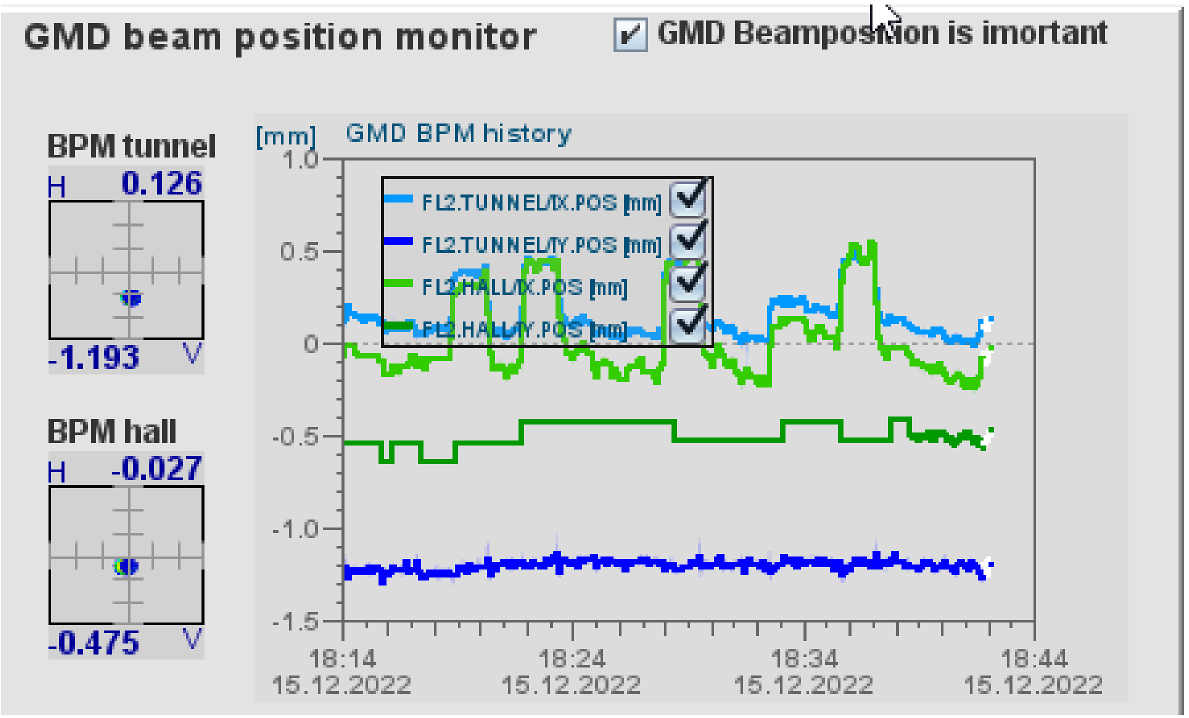
Gas monitor detector (GMD)



A. A. Sorokin et al, J. Synchrotron Rad. **26**, 1092-1100 (2019);

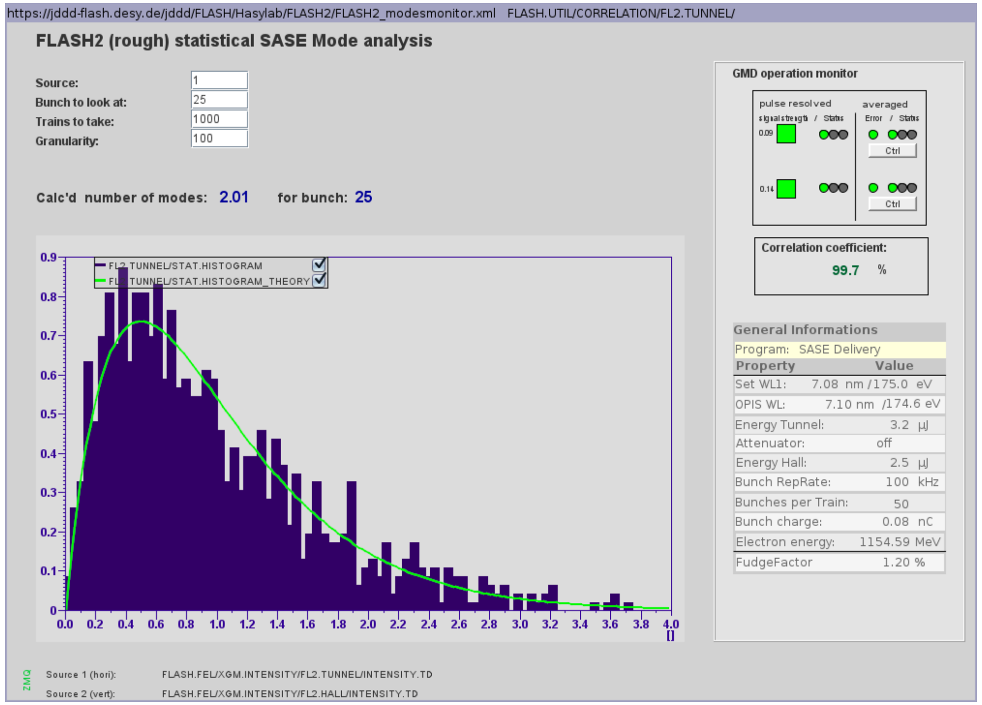
Split electrodes … allows to measure the beam position

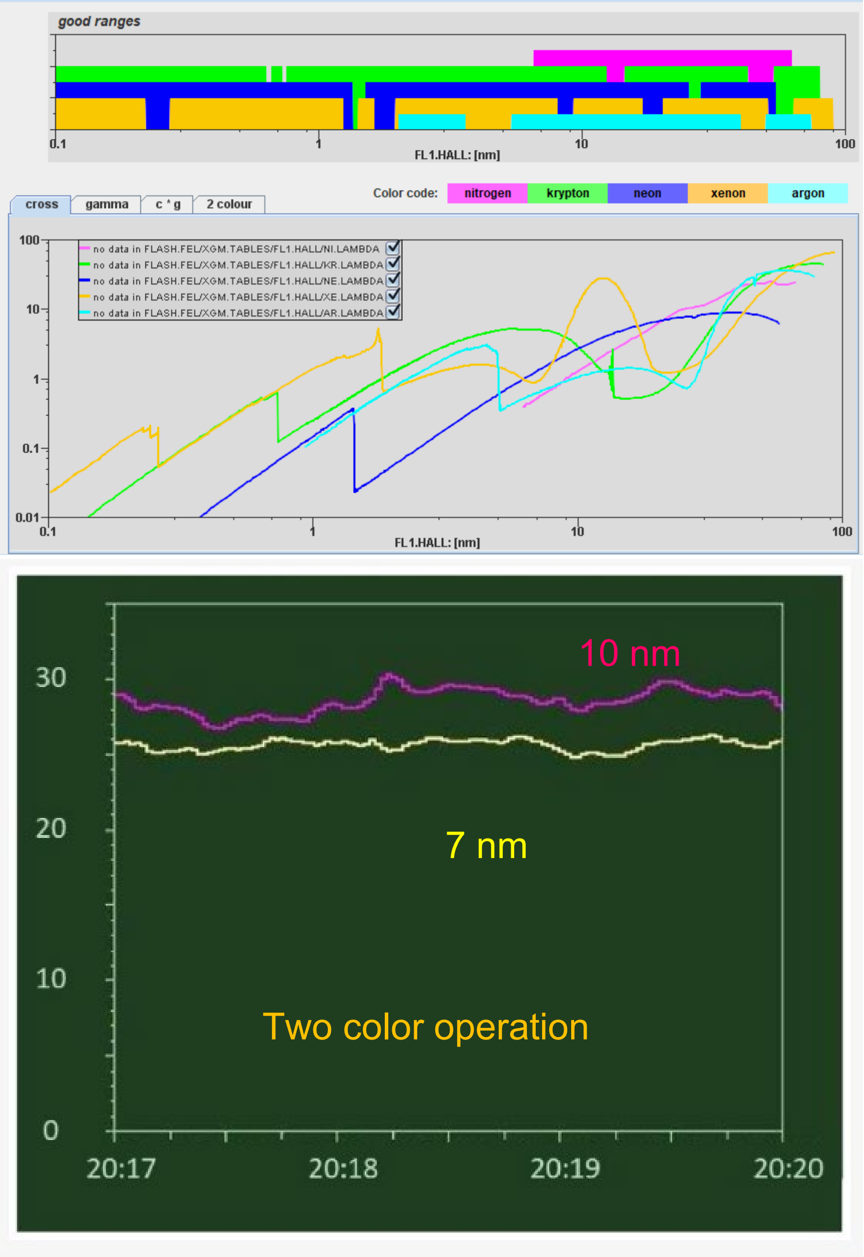




GMD in action

Statistical pulse energy analysis -> number of SASE modes

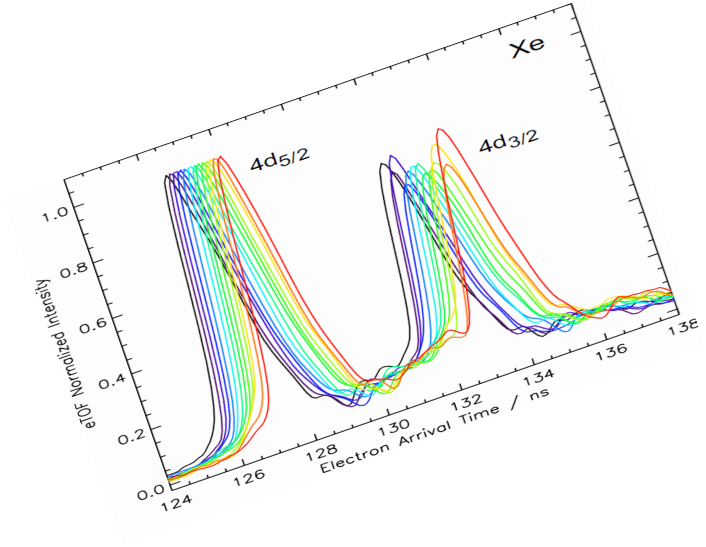


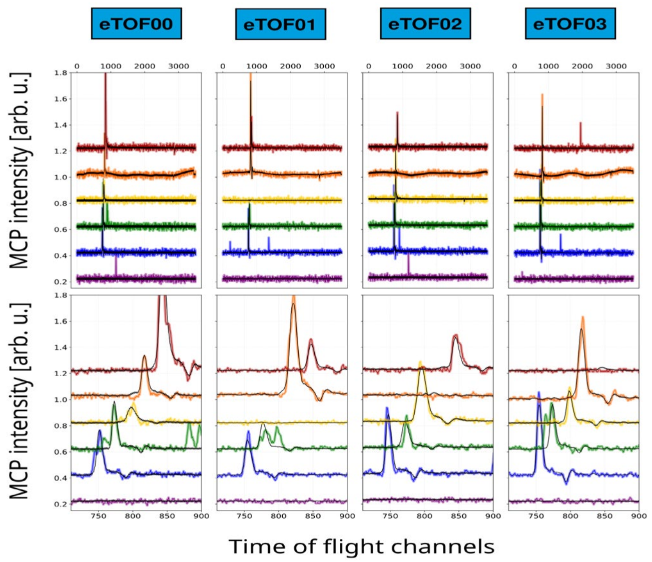


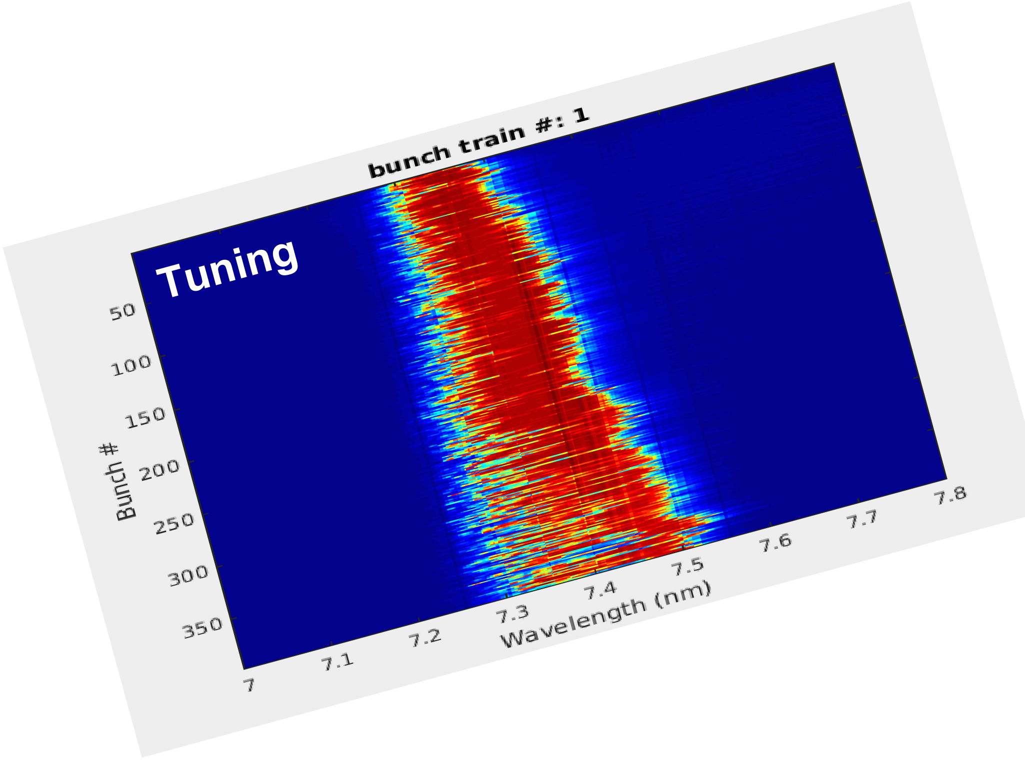
E. Schneidmiller, Appl. Sci. **13**, 67 (2023)

Spectrum

Photo ionization and MHz line camera





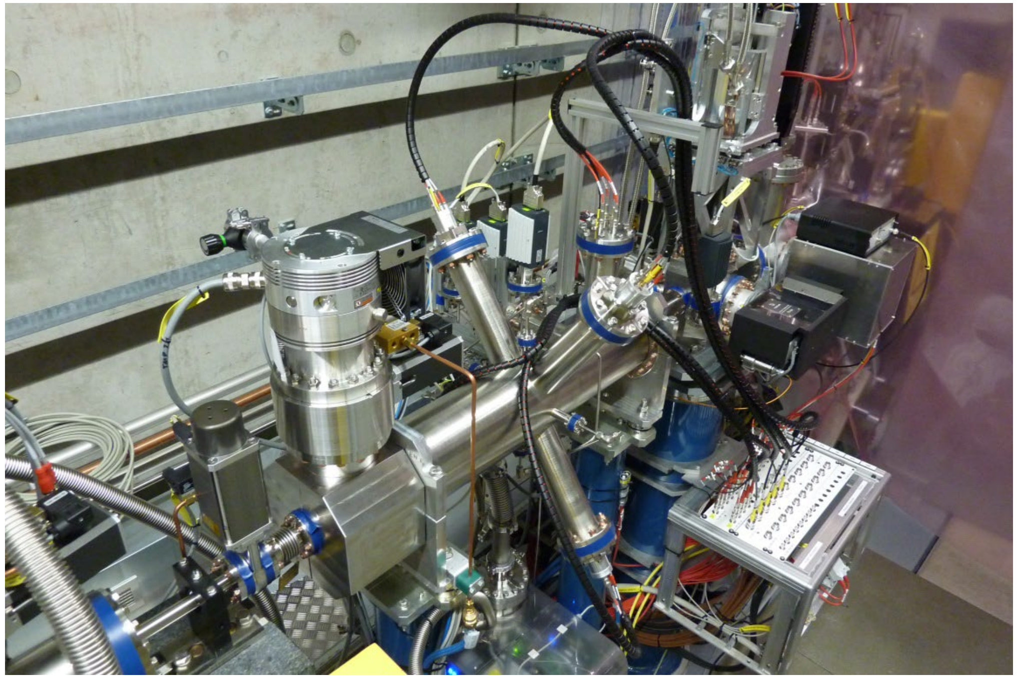


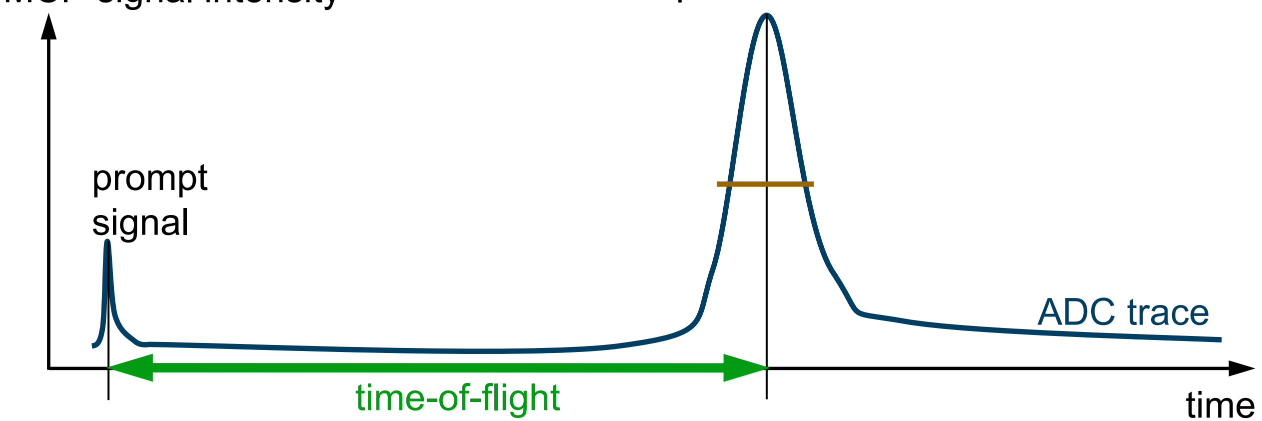
Online Photoionization Spectrometer (OPIS) @ FLASH2.

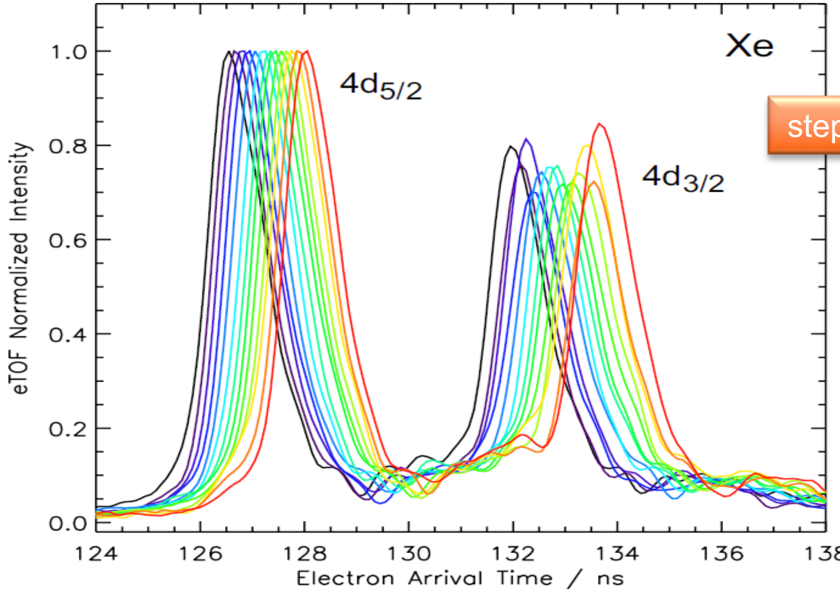
Measure the wavelength with photo electron spectroscopy

- No optical elements which can be damaged or degrade
- Basically 100% transmission
- Self-calibration capability using Auger electrons
- **Low signal level** to avoid space charge

M. Braune, et al , J. Synchrotron Rad. **25**, 3-15 (2018);



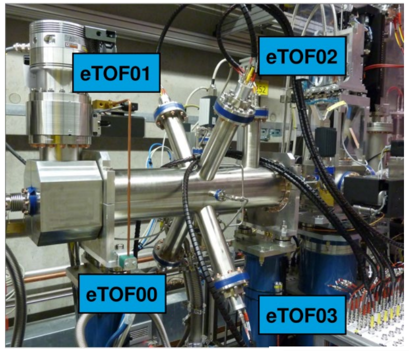




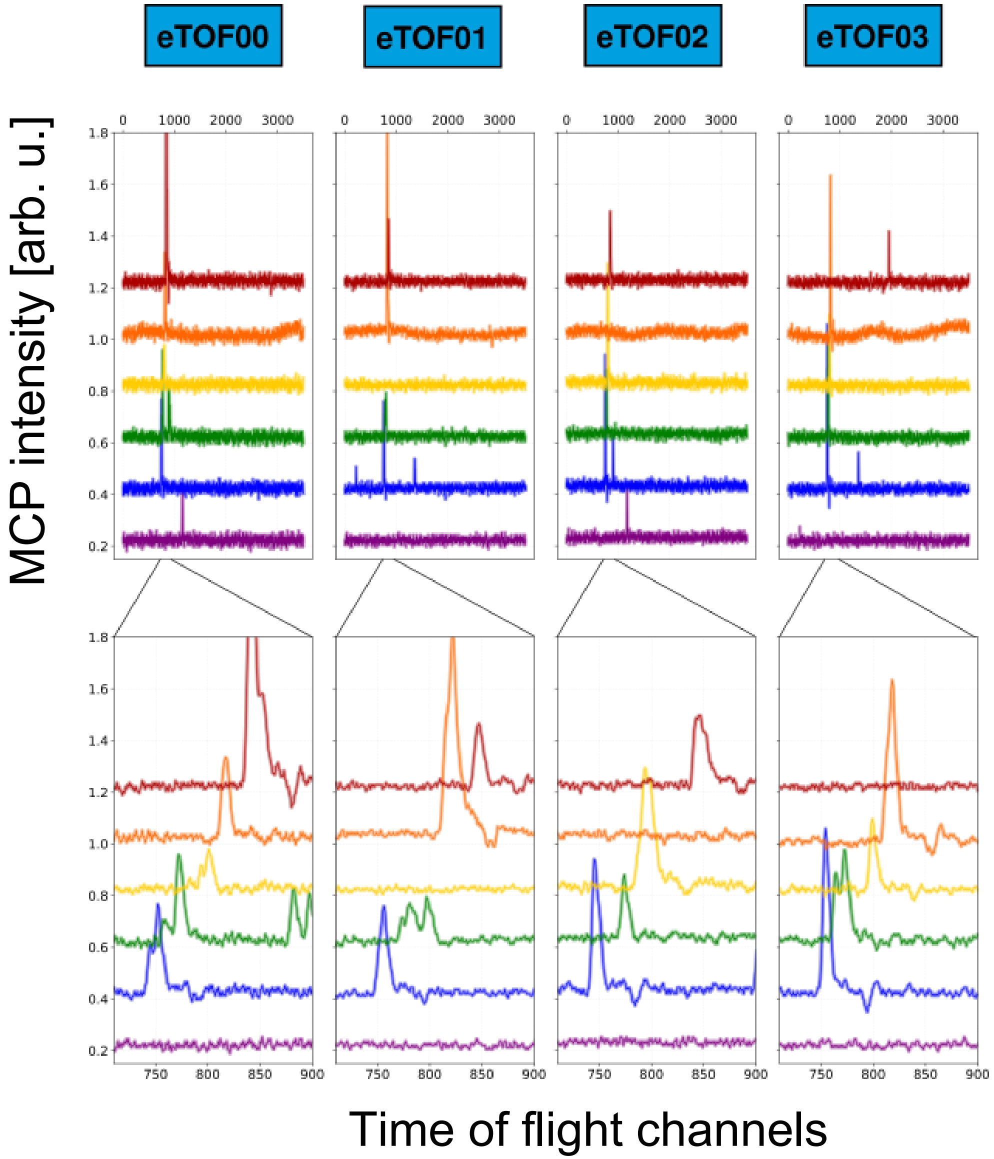
steps of $\Delta h\nu$=0.05 eV

Courtesy M. Braune

OPIS: Raw data

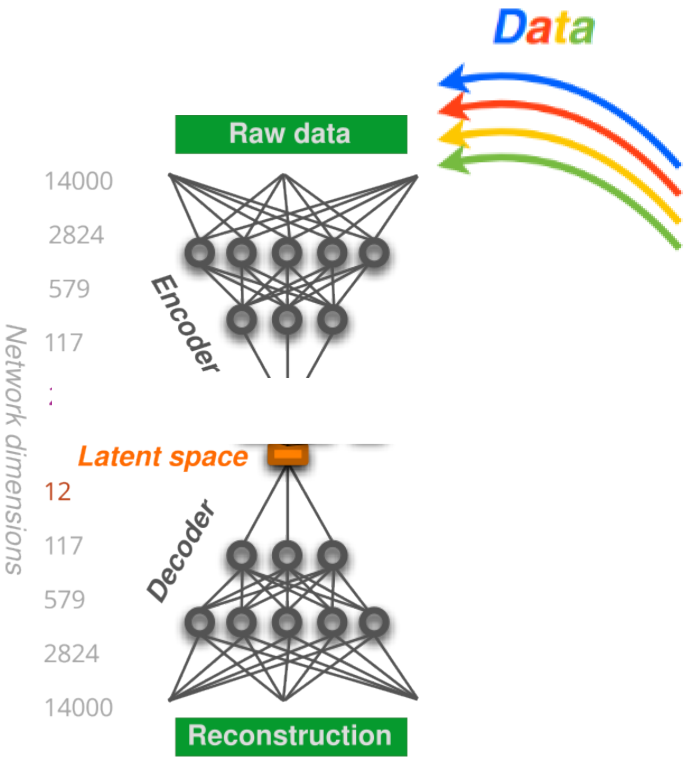


$$E_{pho} = E_{kin} + E_{bin}$$

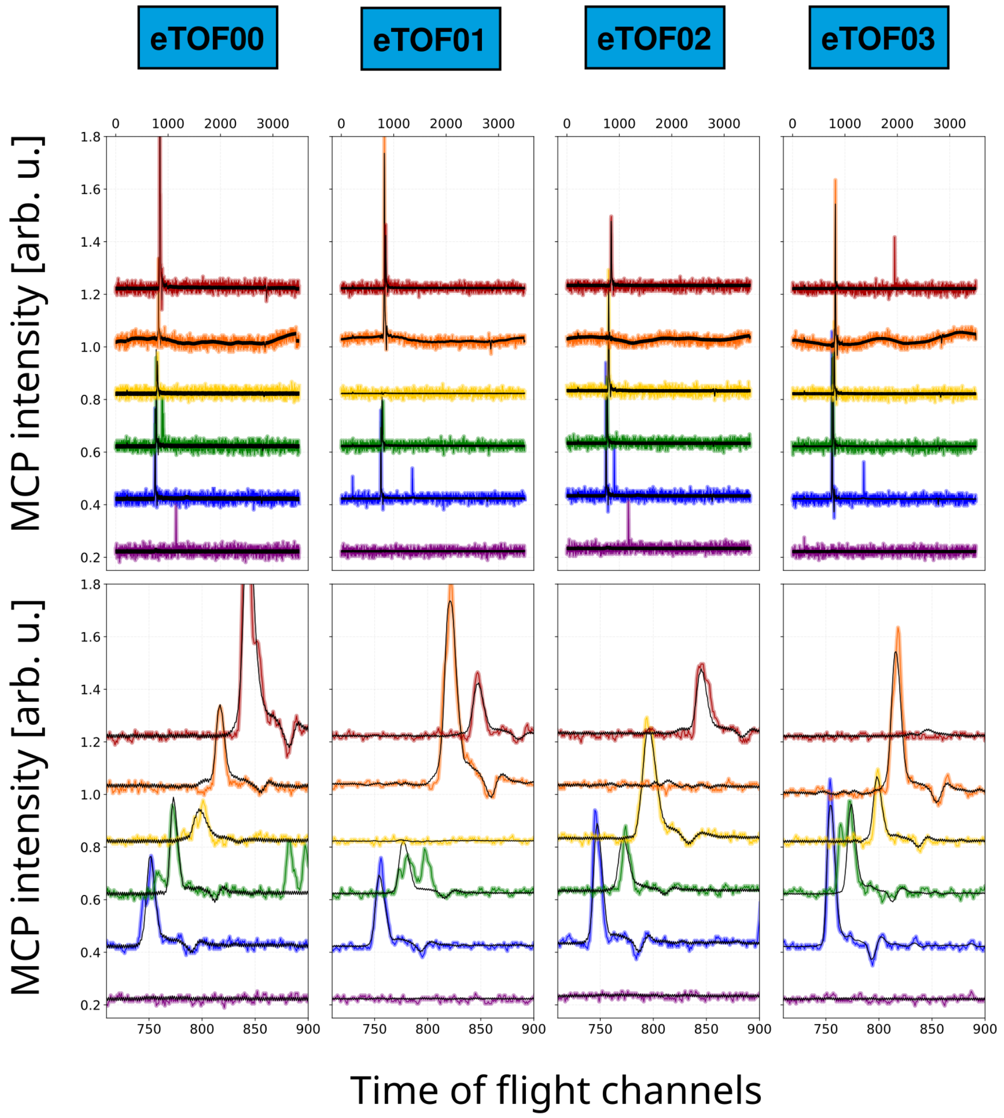


OPIS: Reconstruction

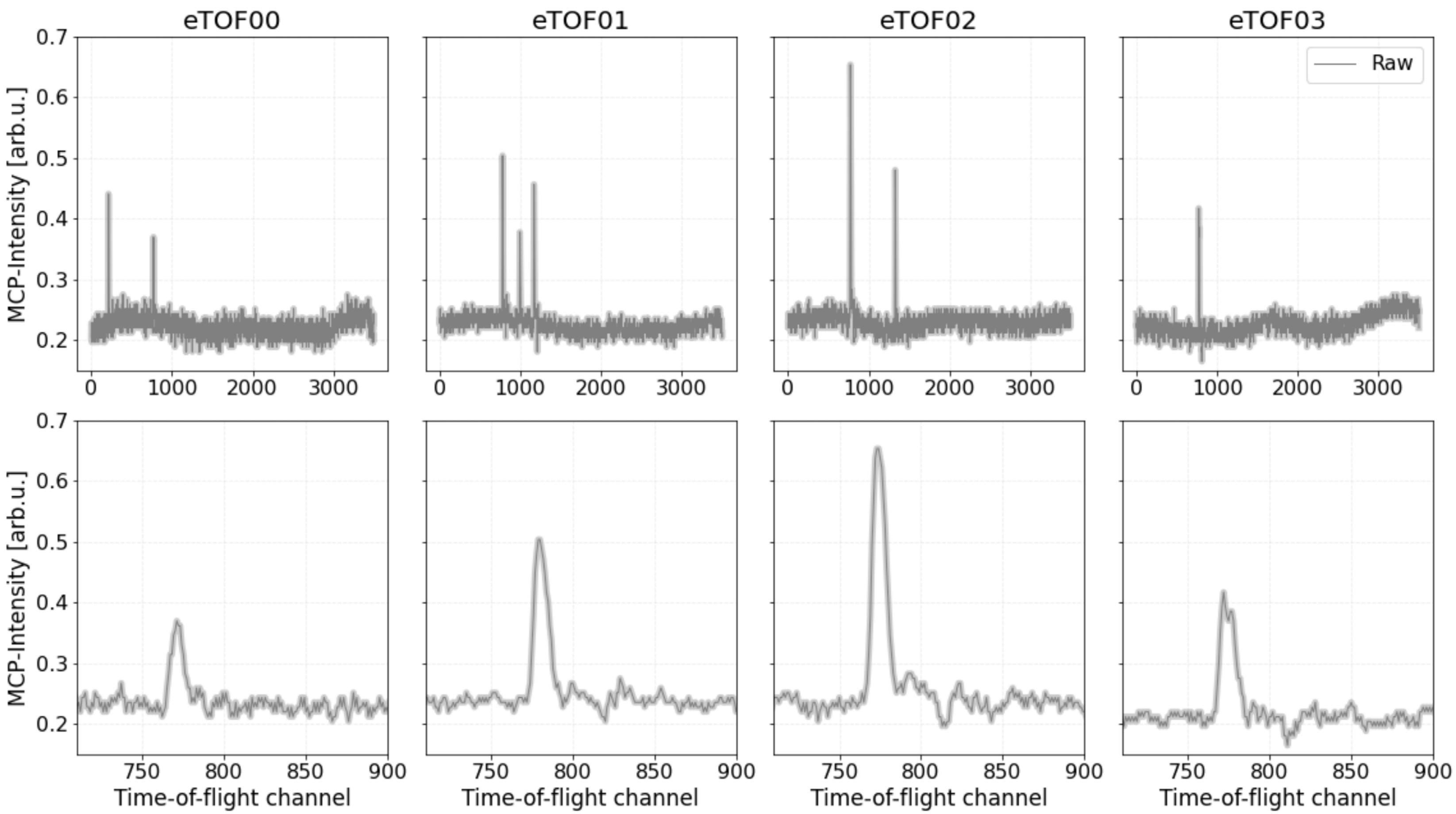
G.Hartmann, et al Sci. Rep. **12,** 20783 (2022);



Reconstructed Data

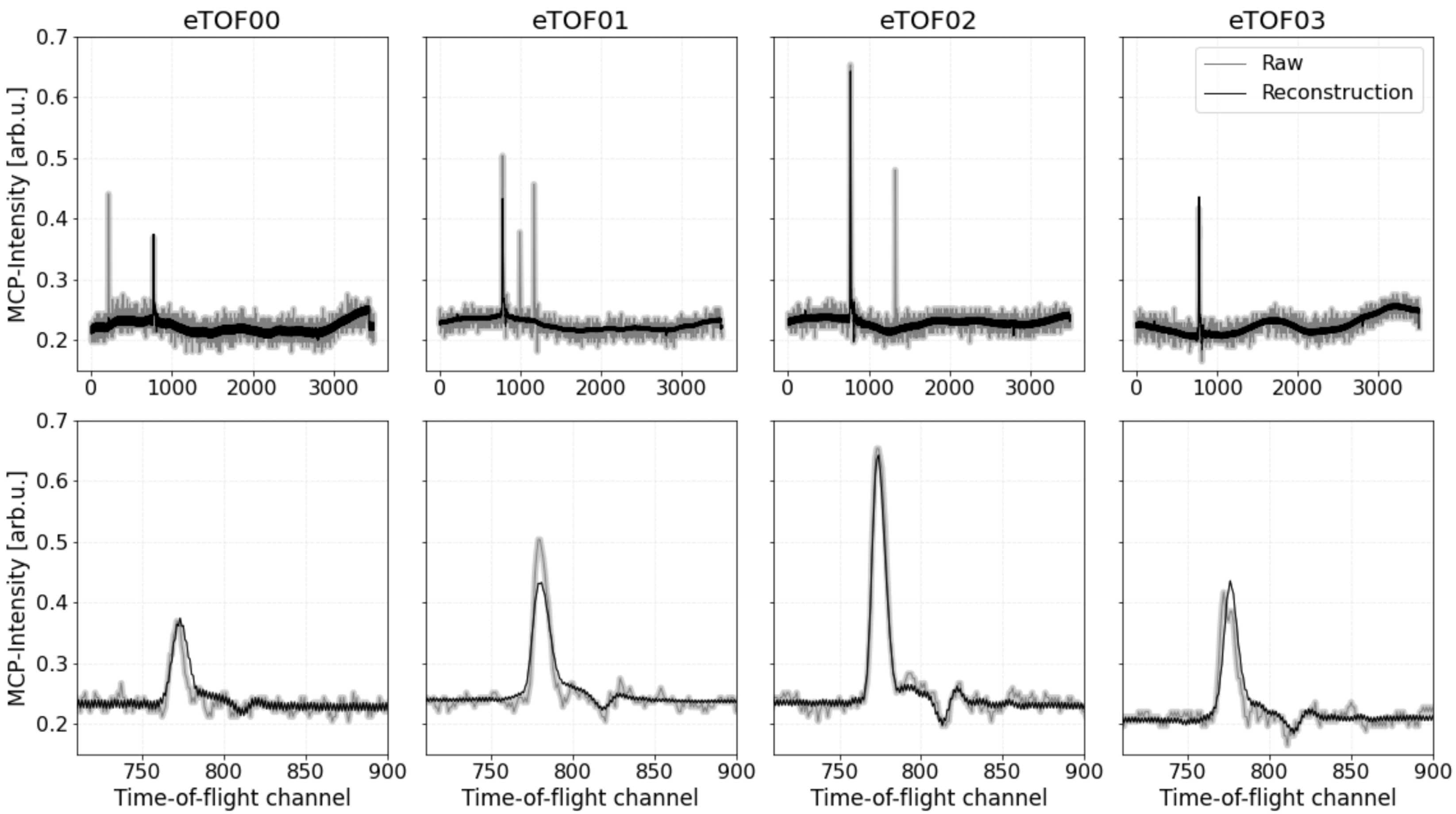


OPIS: Data cleaning



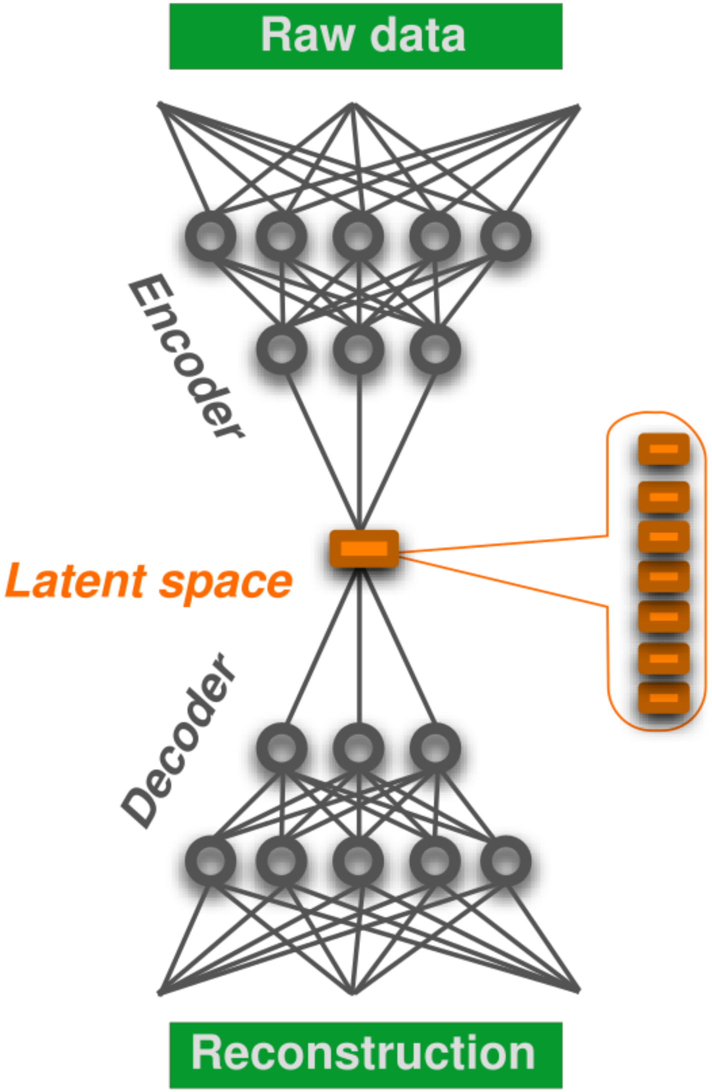
G.Hartmann, et al Sci. Rep. **12,** 20783 (2022);

OPIS: Data cleaning



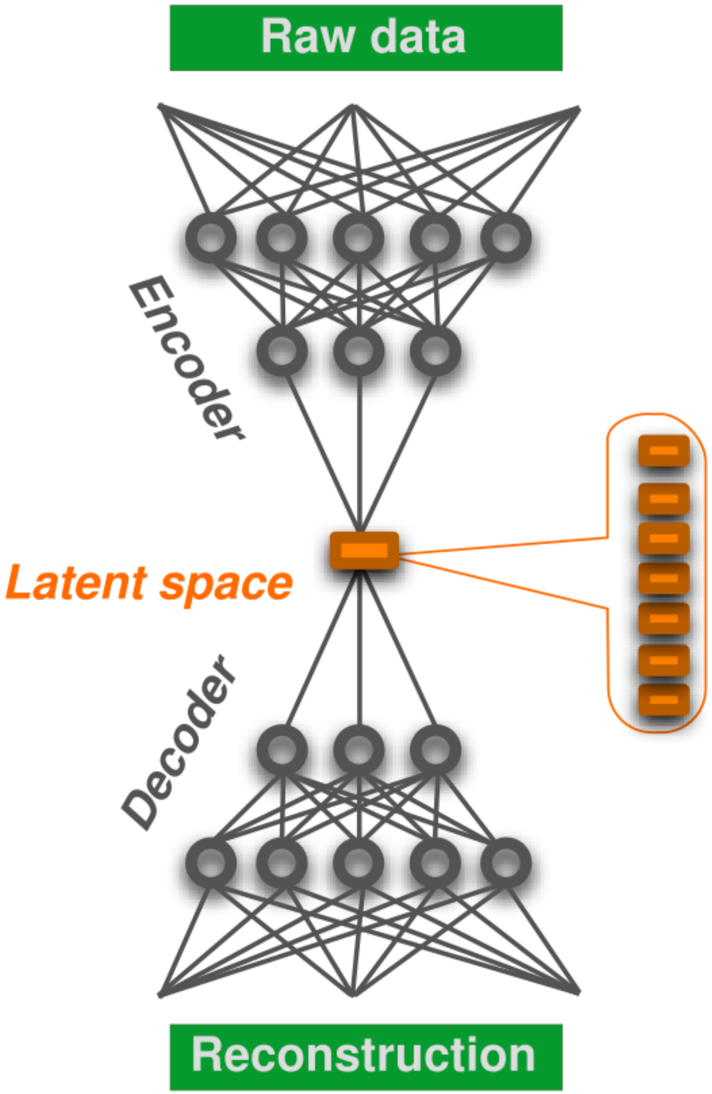
G.Hartmann, et al Sci. Rep. **12,** 20783 (2022);

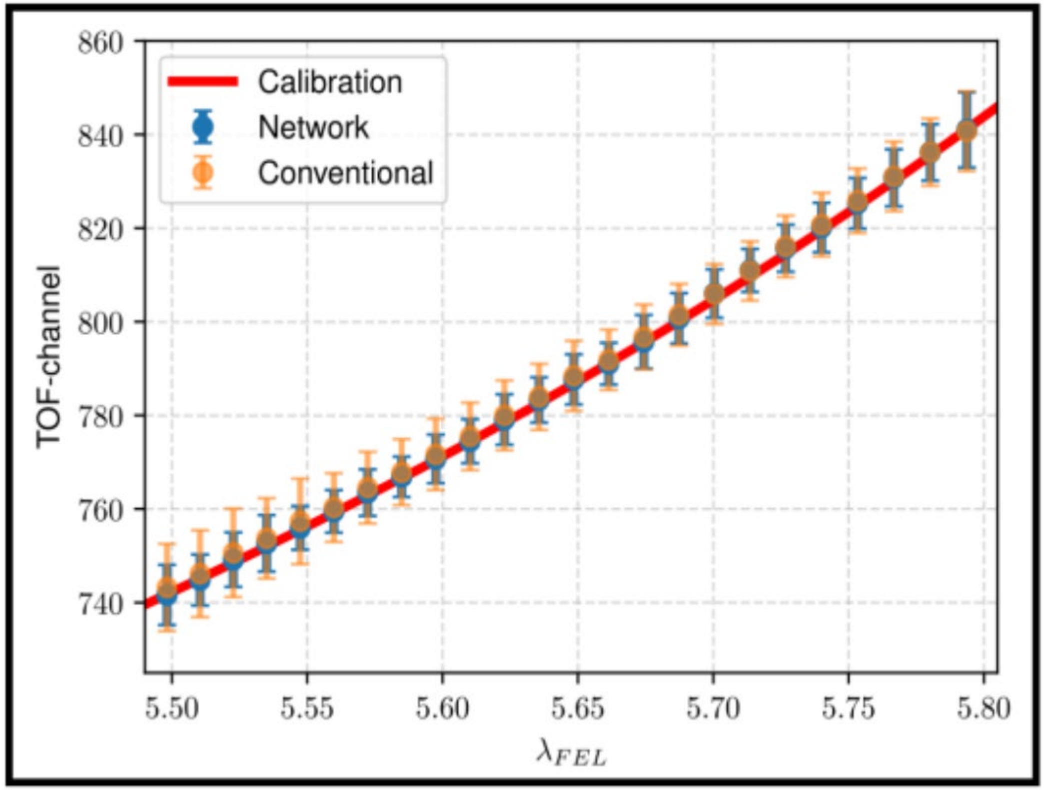
OPIS: Latent space



- Wavelength
- Intensity
- Baseline
- Interleaving
- Pointing

OPIS: Obtain central wavelength





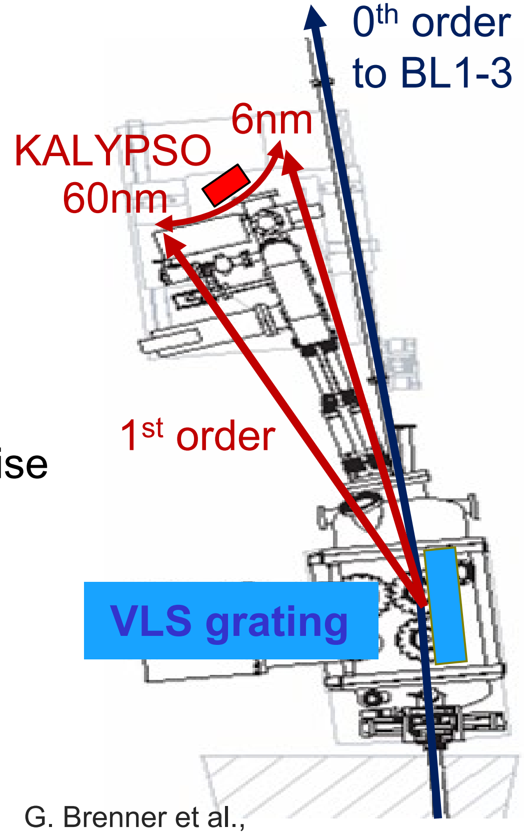
G.Hartmann, et al Sci. Rep. **12,** 20783 (2022);

VLS-Spectrometer with MHz line camera

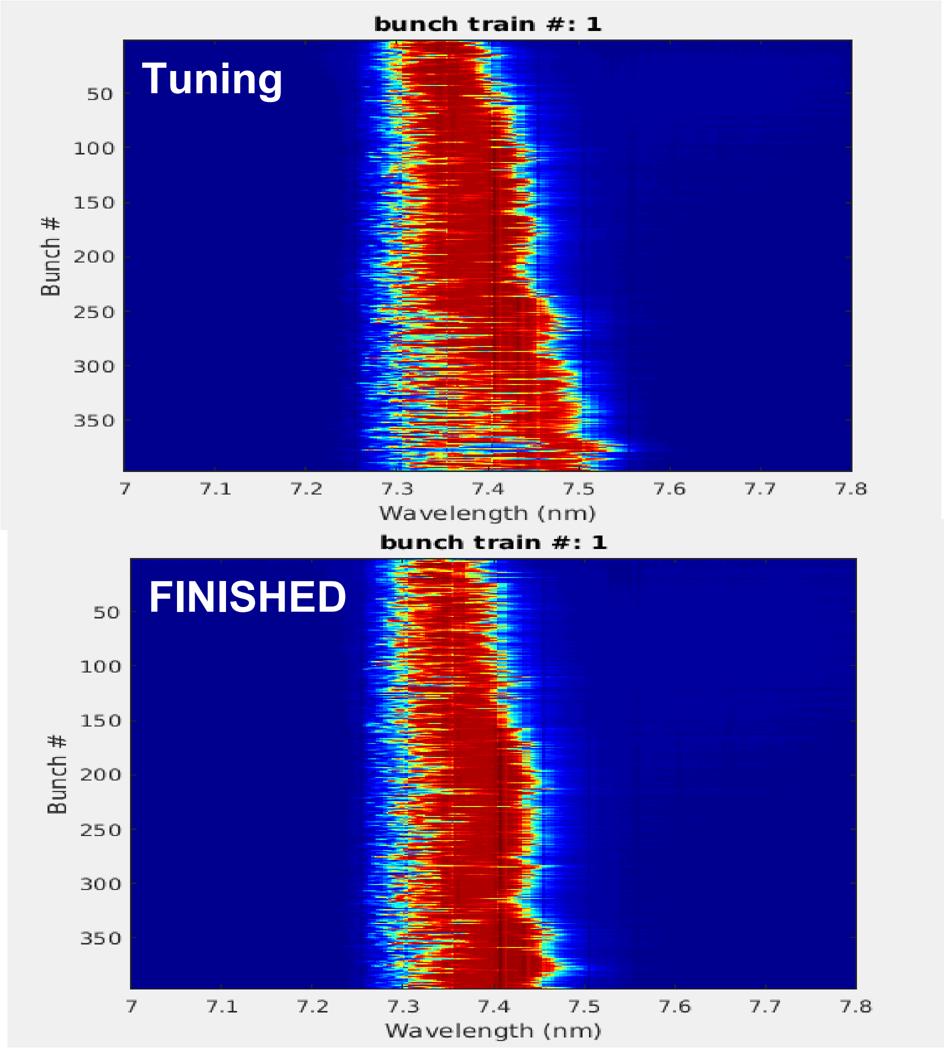
> KALYPSO:

- 256 pixels, 50 µm pitch
- 14 bit ADC, 2.7 Mfps

- Developed within ARD Matter & Technology between KIT, DESY and HZDR
- Low-latency continuous read-out with up to 2.7 MHz rep rate => cw and feedback capability
- Under development version 3:
  up to 1024 pix, up to 5 MHz, better signal-to-noise



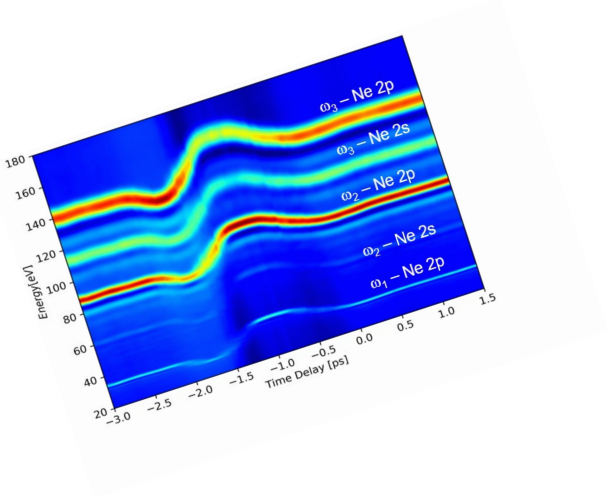
G. Brenner et al.,
Nucl. Instr. and Meth A **635**, 99–103 (2011).

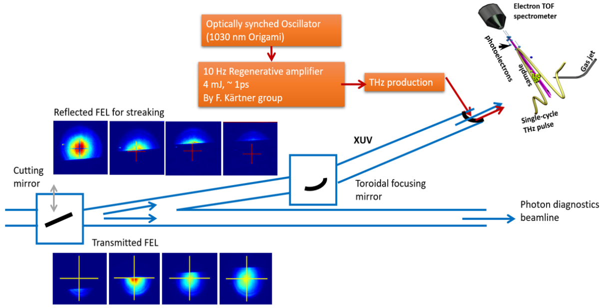


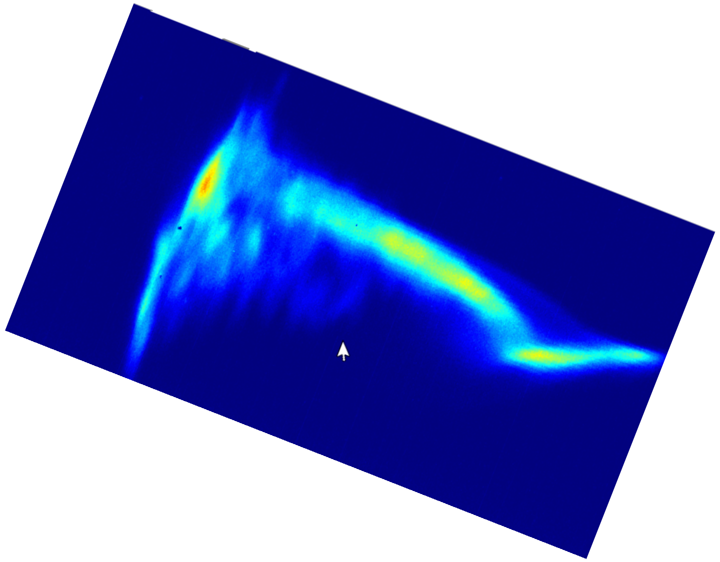
C. Gerth, et al. J. Synchrotron Rad. **26**, 1514 - 1522 (2019);

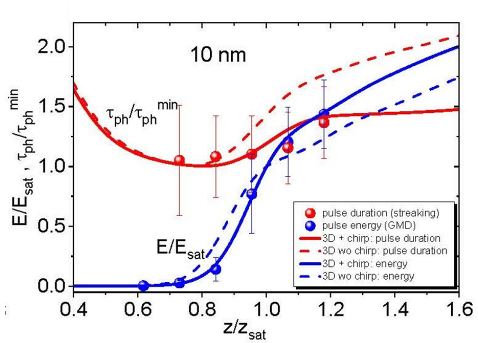
Temporal properties

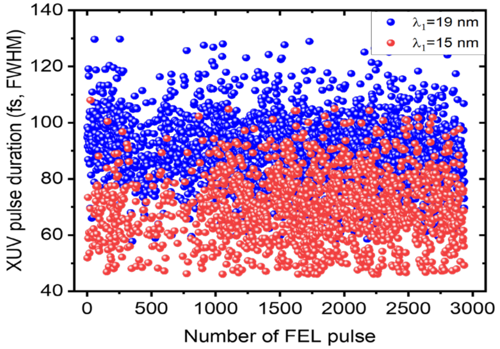
Pulse duration and arrival time



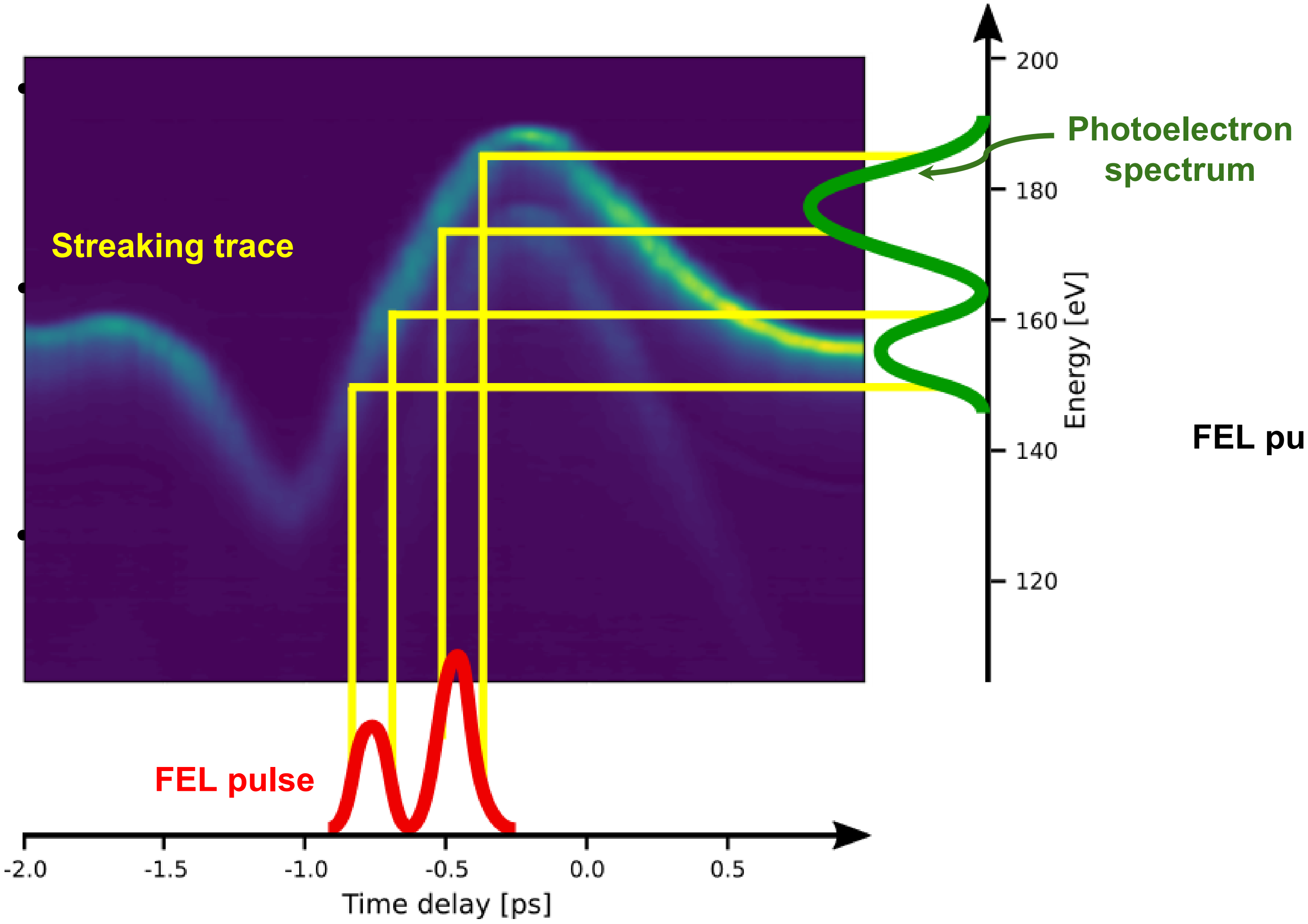


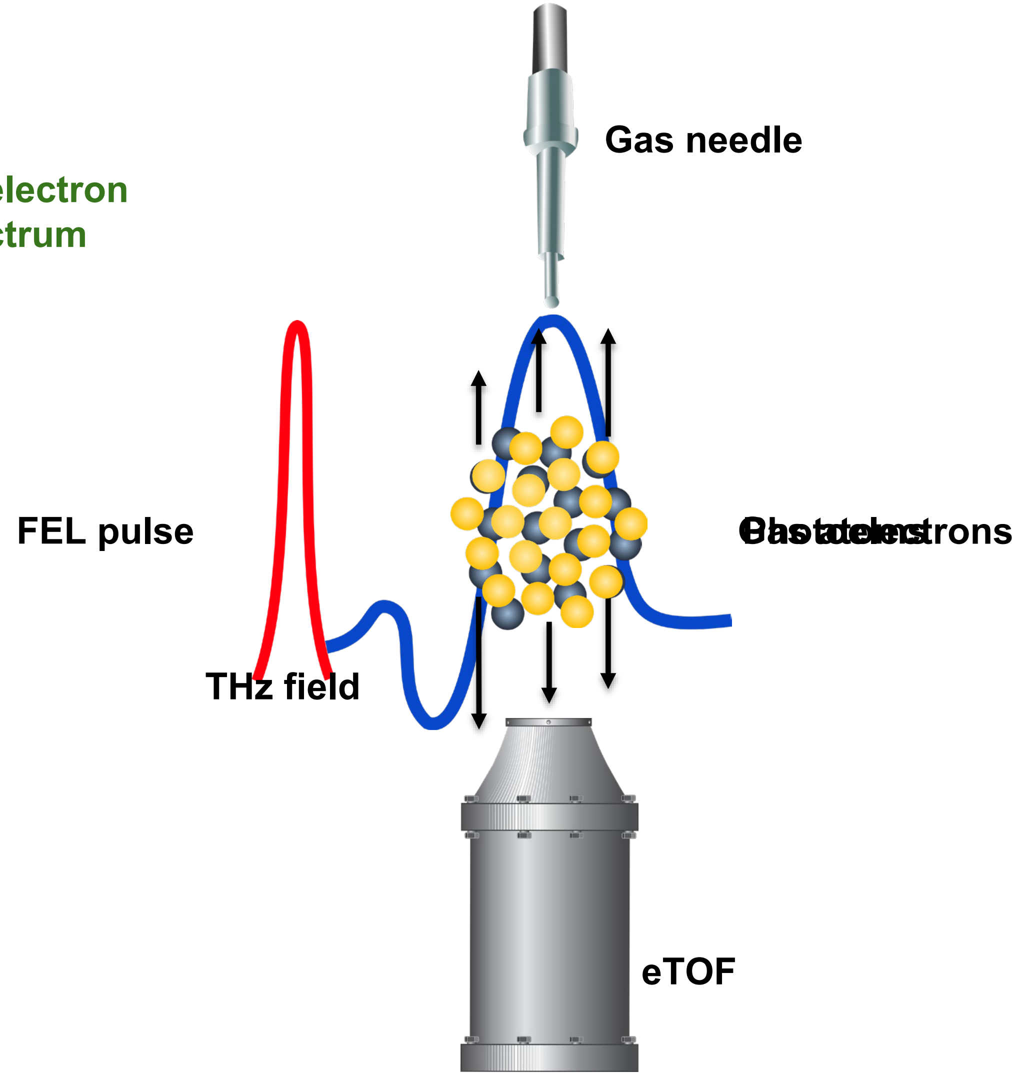






THz streaking principle

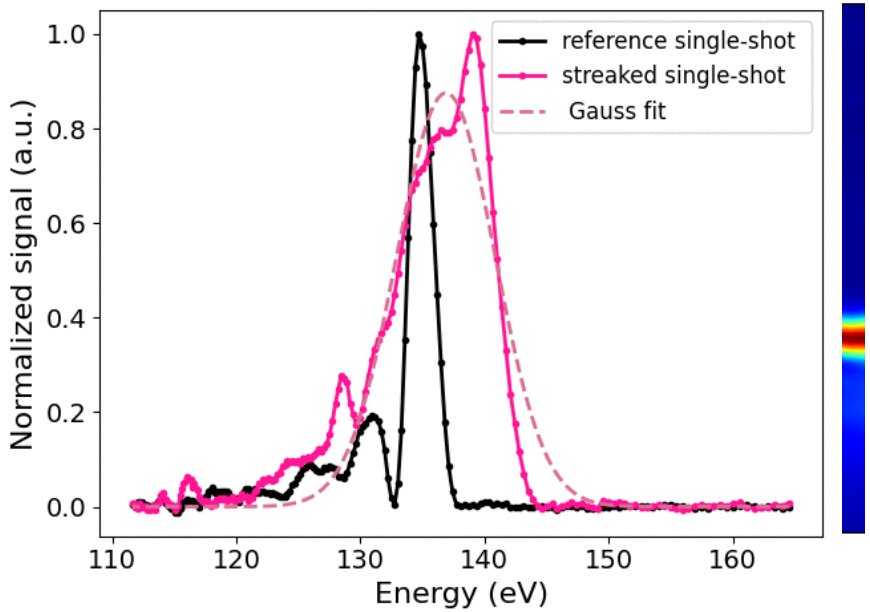




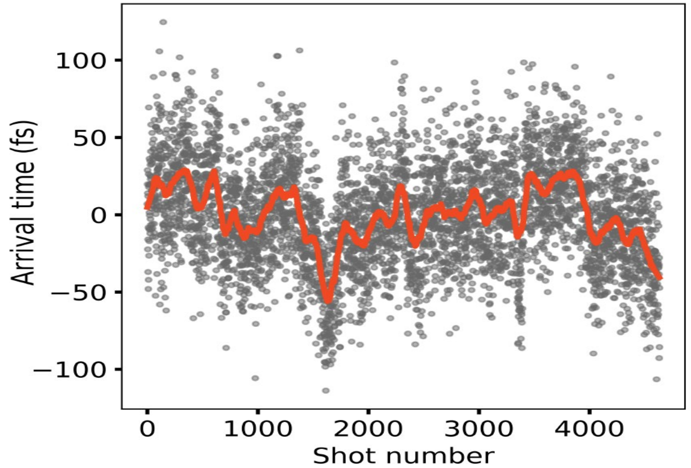
U. Frühling et al. Nat. Photonics 3, 523 (2009)
I. Grguraš et al. Nat. Photonics 6, 852 (2012)

THz Streaking - observables

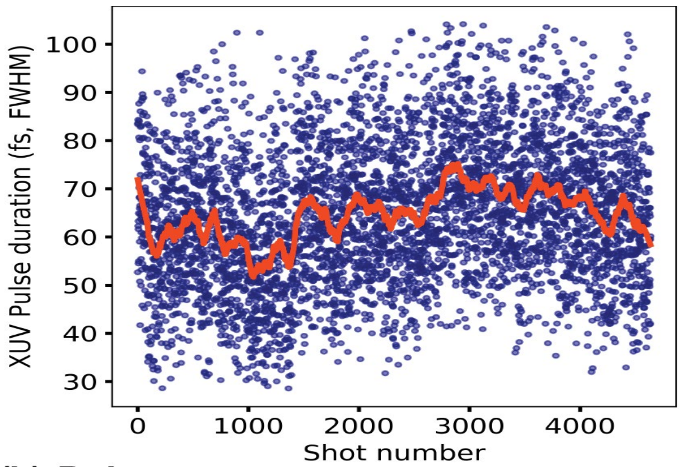
What can we learn from the signal?



- Single shot XUV arrival time



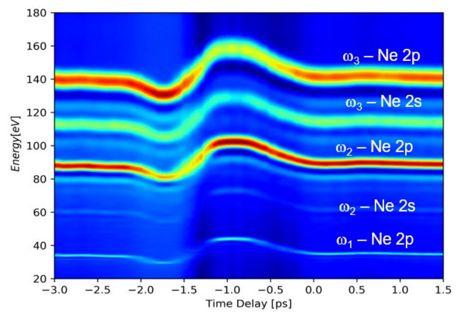
- Single shot XUV pulse duration

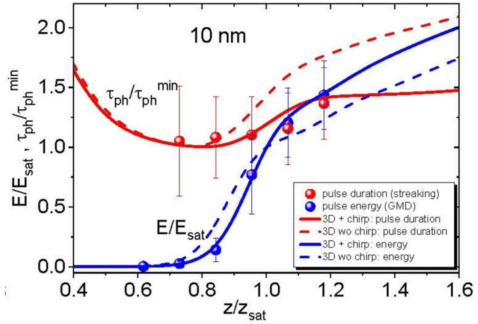


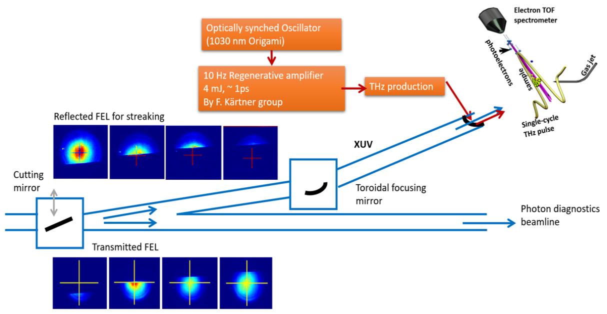
THz streaking at FLASH

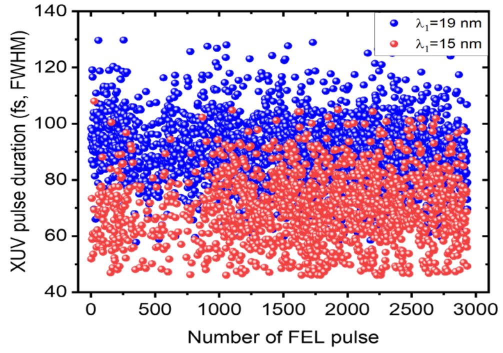
Summary of the last years

- **Short and long pulses**
  R.Ivanov at al., Journal of Physics B, 53 (2020)
- **Correlation to other pulse parameters**
  I.Bermudez at al., Optics Express 29, 10491-10508 (2021)
- **Pulse duration along the gain curve**
  M. Bidhendi, Appl. Sci. **12**, 7048 (2022)
- **Arrival time studies**
  R.Ivanov at al., J. Synchrotron Rad., 25 (2018)
  R.Ivanov et al, Opt. Express 31, 19146 (2023)
- **"parasitic measurement" option**
  R.Ivanov et al, Opt. Express 31, 19146 (2023)
- **2 color operation**
  E. Schneidmiller, Appl. Sci. **13,** 67 (2023)
- Pulse duration of FEL harmonics
- Comparison to electron diagnostic (TDS)



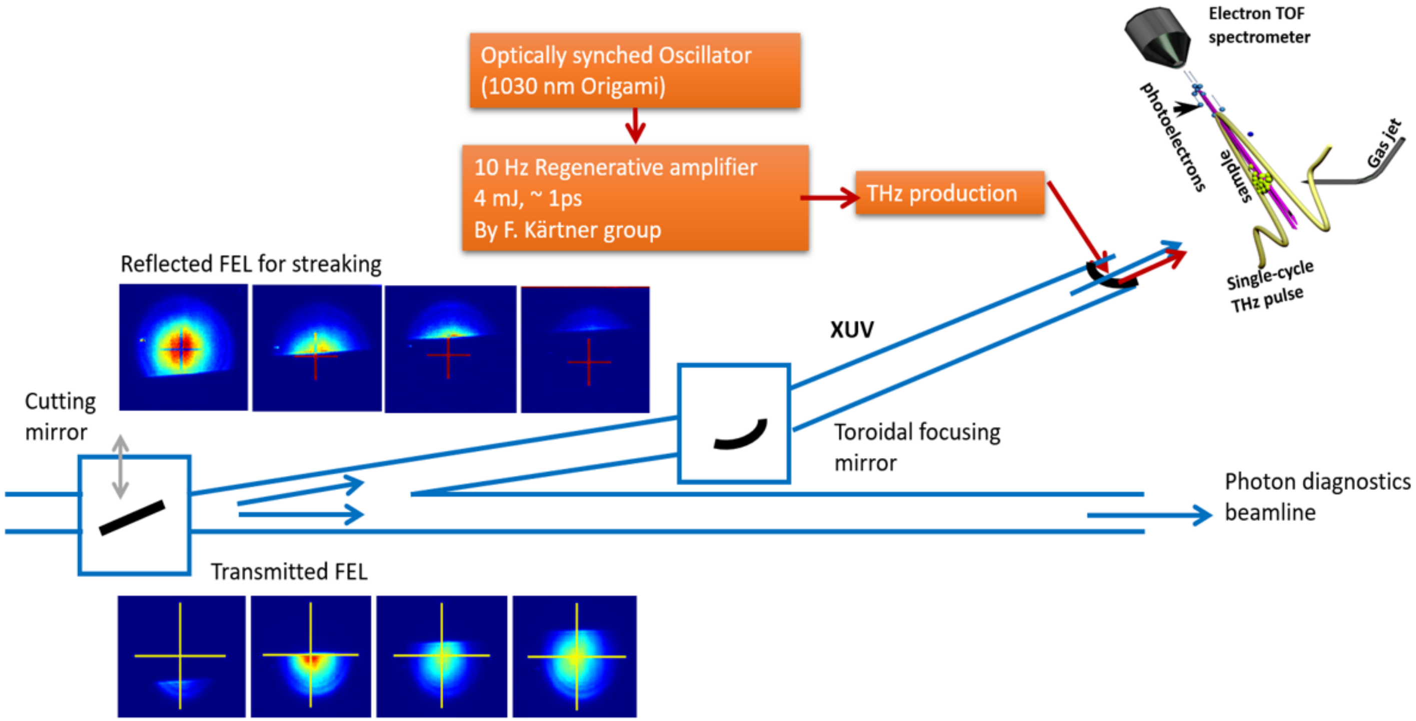


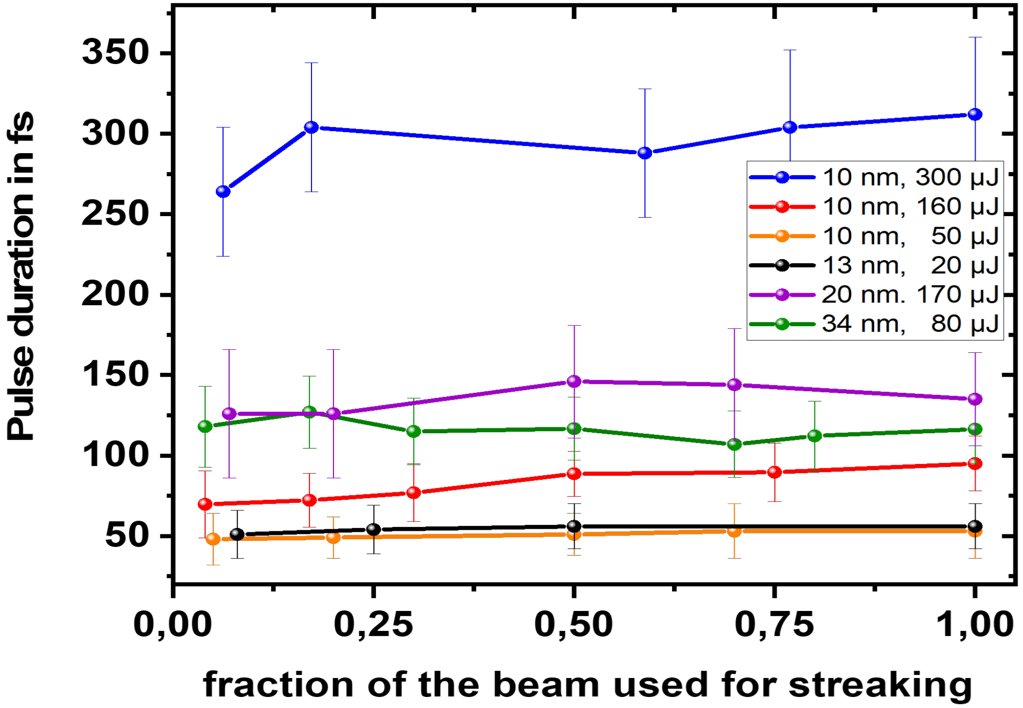




Testing "parasitic" measurements

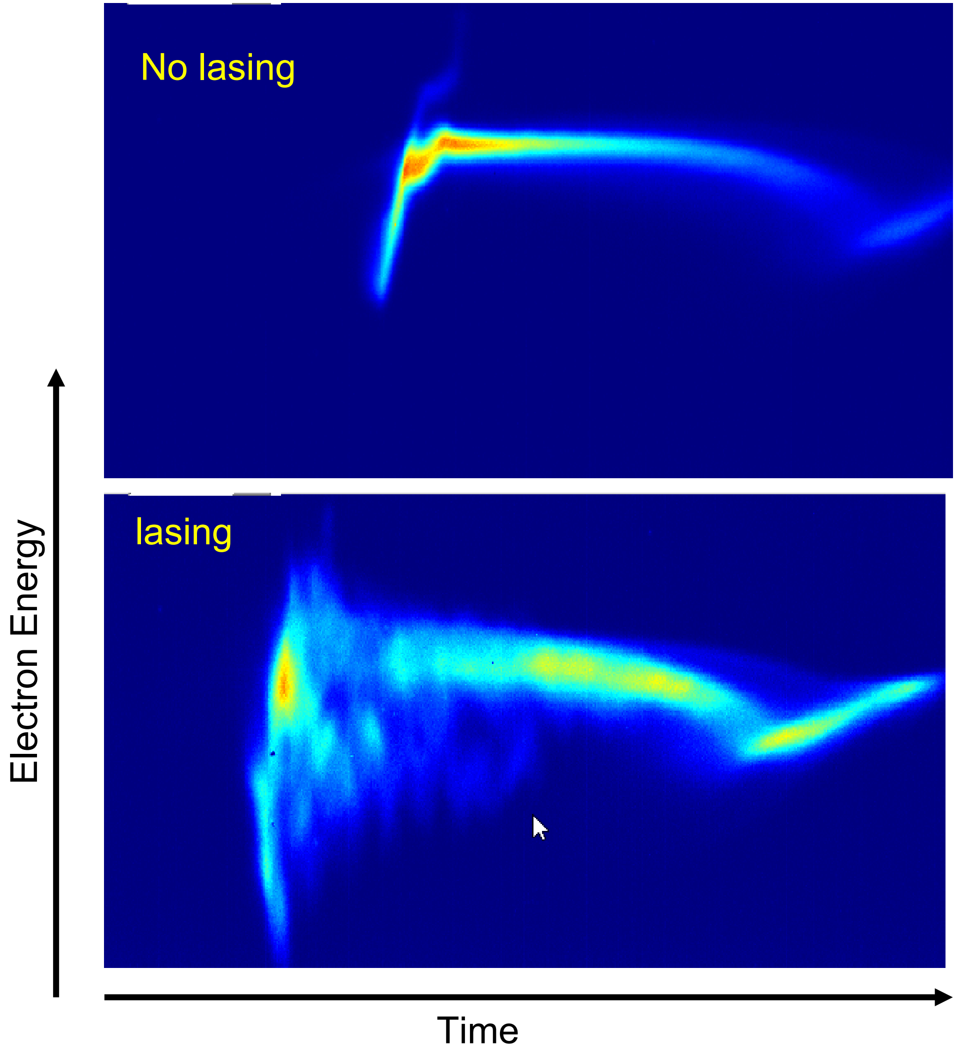
Use only a small fraction of the FEL beam

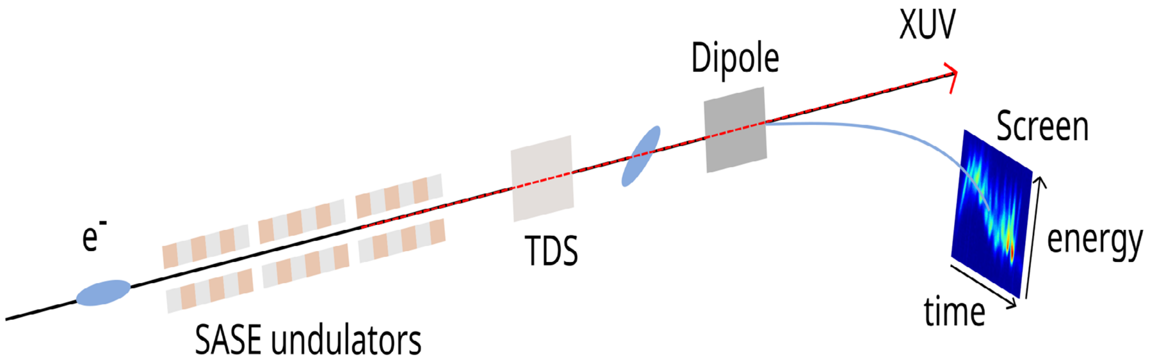




Comparison TDS vs THz streaking

Use electron diagnostics to measure XUV pulse duration / shape

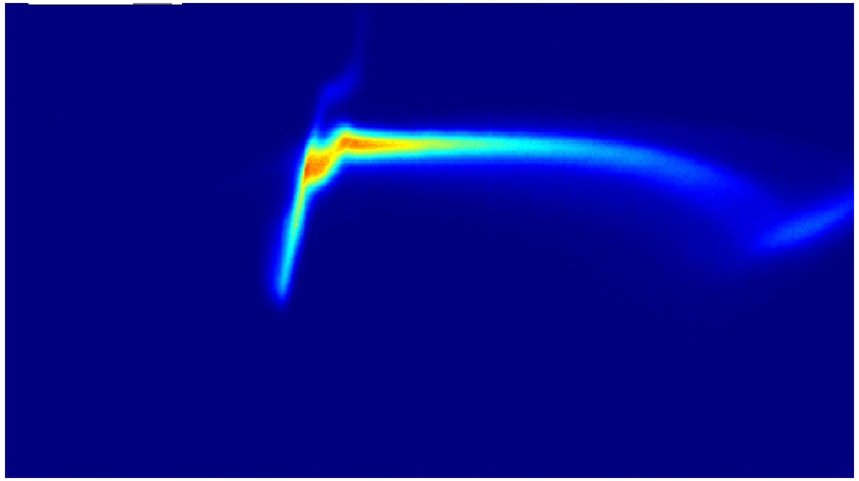


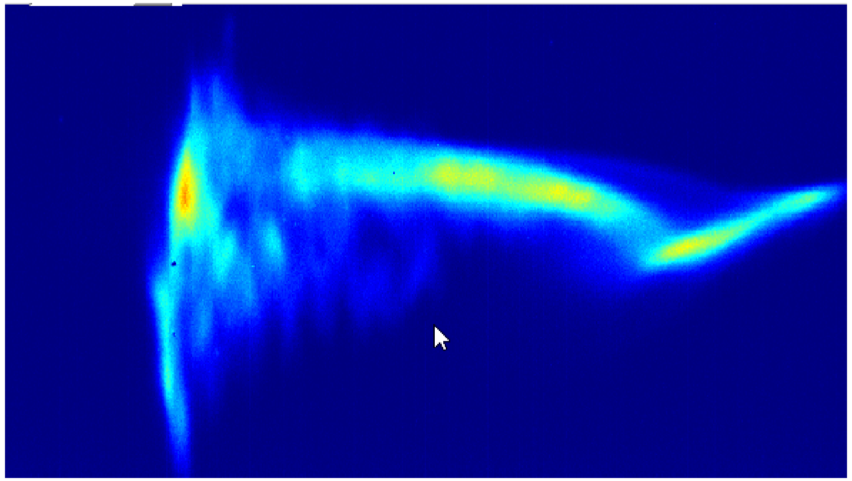


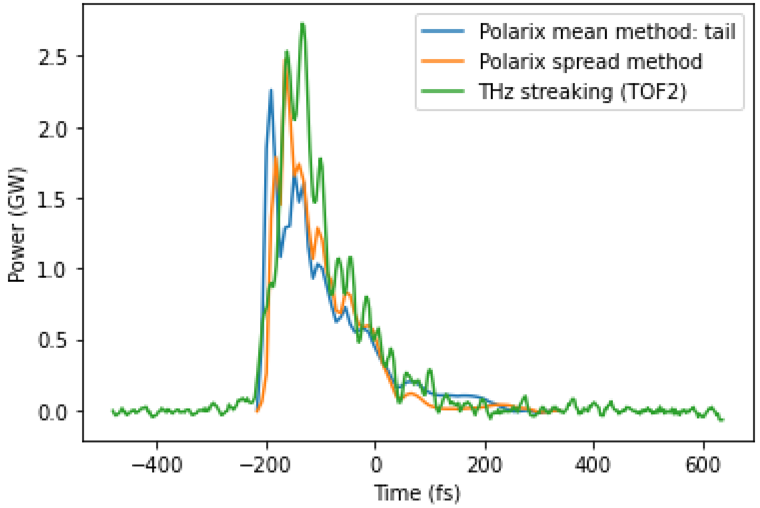
C. Behrens at al, Nature Communications **5**, 3762 (2014)

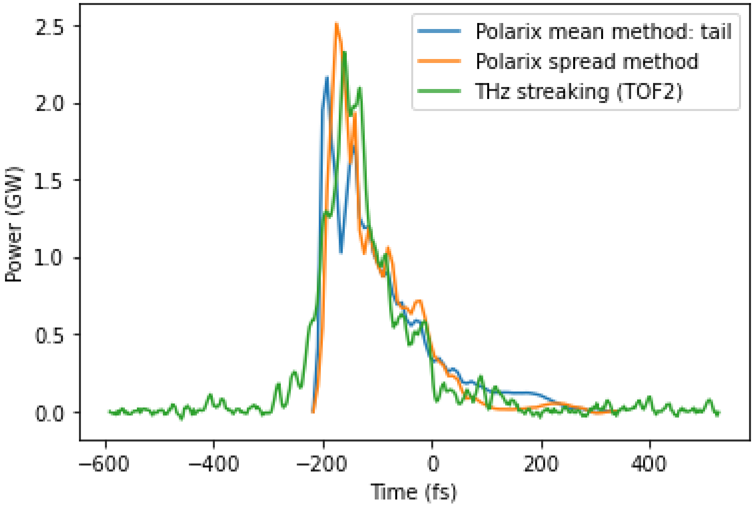
Comparison TDS vs THz streaking

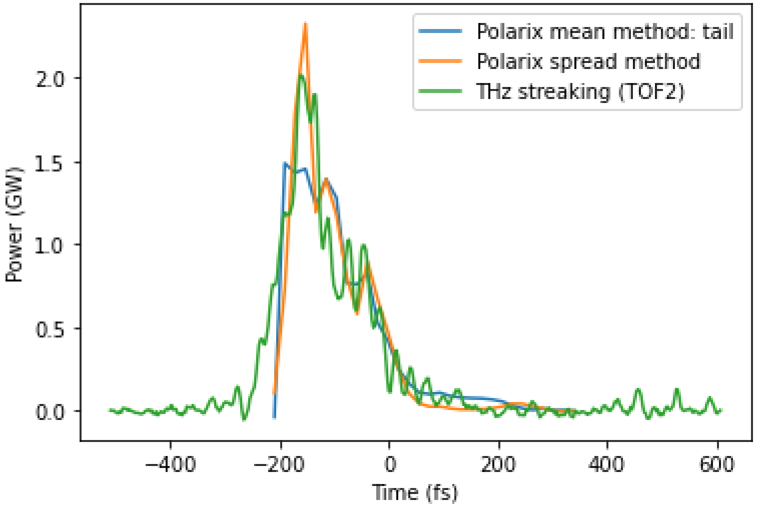
Recent data … work in progress …











Thanks to Ch. Behrens and G. Goetzke

Summary

SASE FEL needs pulse resolved diagnostics !

- **Focal spot size / position**
- **Energy, pointing**
- **Spectrum**
- **Pulse duration (~ 30 fs to ~ 300 fs)**

- **Next steps**
  - More automated analysis (AI …)
  - More non-invasive and "little-invasive" diagnostics
  - Measure very short pulses (0.5-20 fs) -> angular streaking
  - After 2025 … **FLASH1 -> SEEDED HIGH REPRATE FEL**

Thanks to

Acknowledgments

M. Bidhendi, R. Ivanov, I. Bermudez, M. Yurkov, E. Schneidmiller, G. Brenner, J. Roensch-Schulenburg , M. Kuhlmann, U. Frühling, M. K. Czwalinna, M. Brachmanski, S. Kreis, J. Müller, S. Schulz, A-L Calendron, M. Degenhardt, B. Keitel, K. Tiedtke, M. Braune, G. Goetzke, Ch. Behrens …

J. Liu

G. Hartmann,
P. Feuer-Forson

N. Kabachnik
A. Kasansky

F. Kaertner, M. Pergament,
M. Kellert, S. Reuter

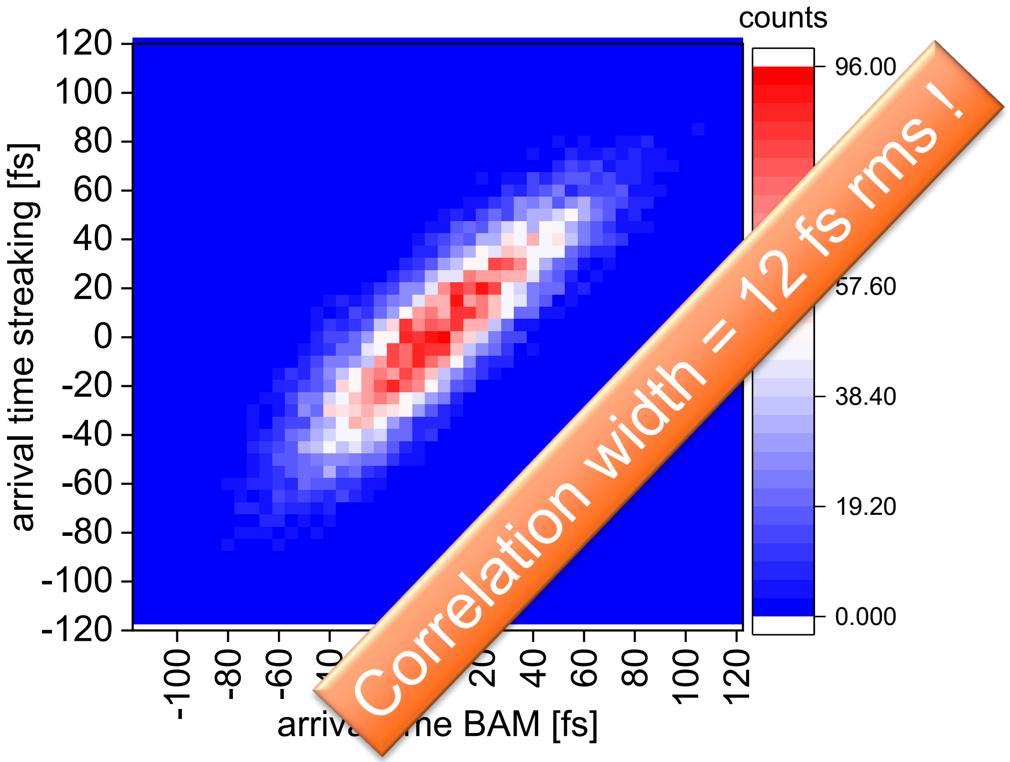
Thanks

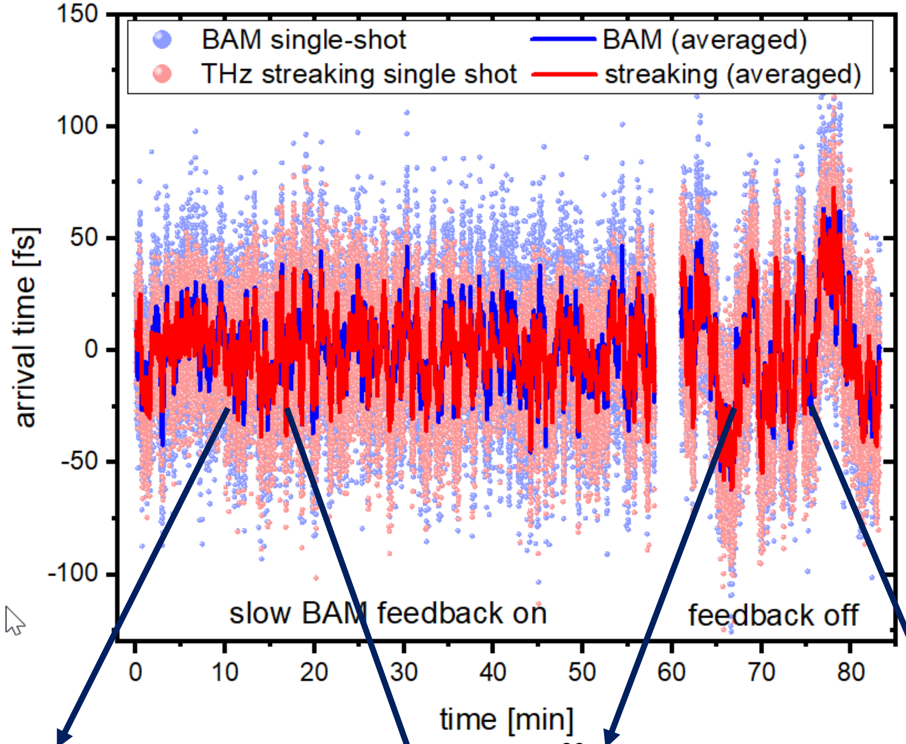
for your

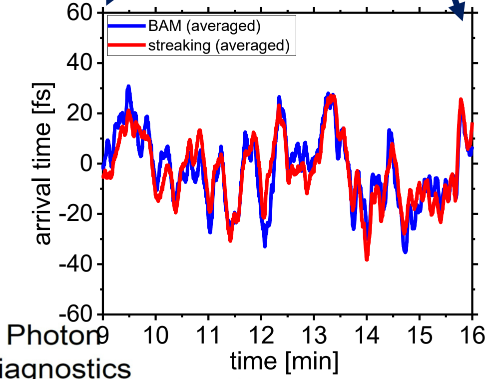
attention

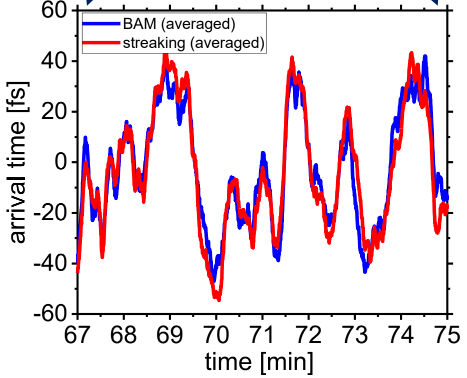
Arrival time measurements

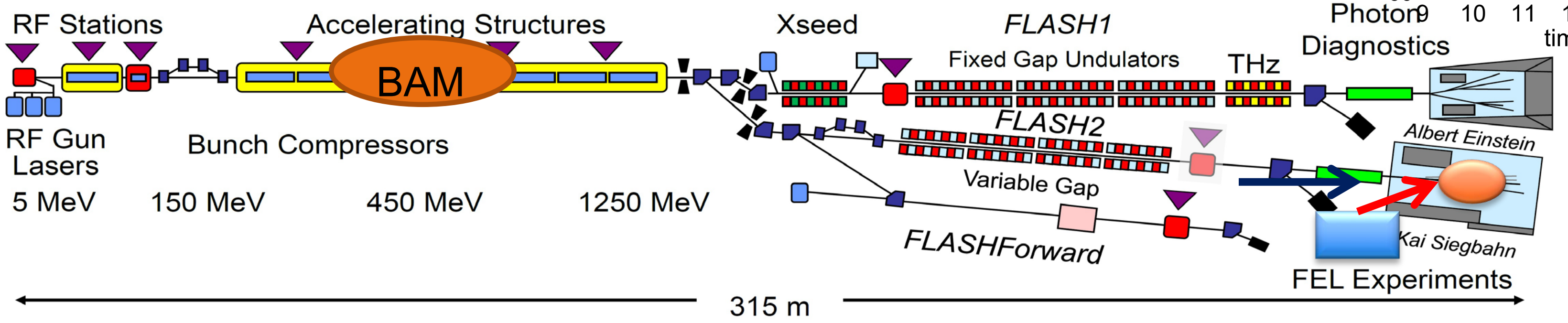
Precision for pump-probe







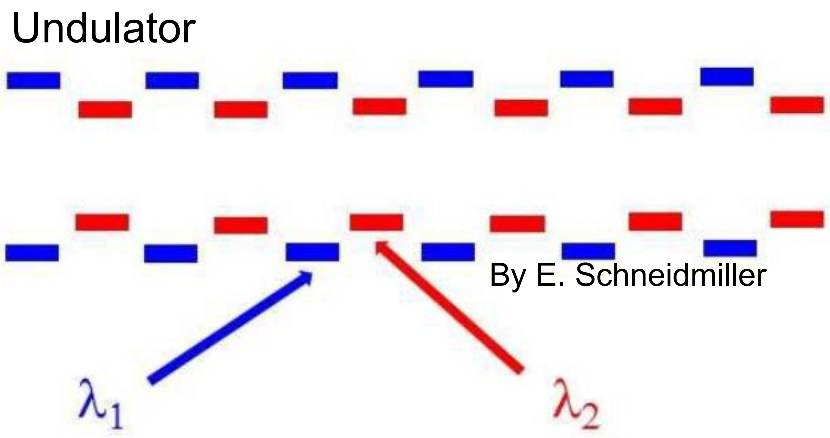




R.Ivanov et al, Opt. Express **31**, 19146 (2023)

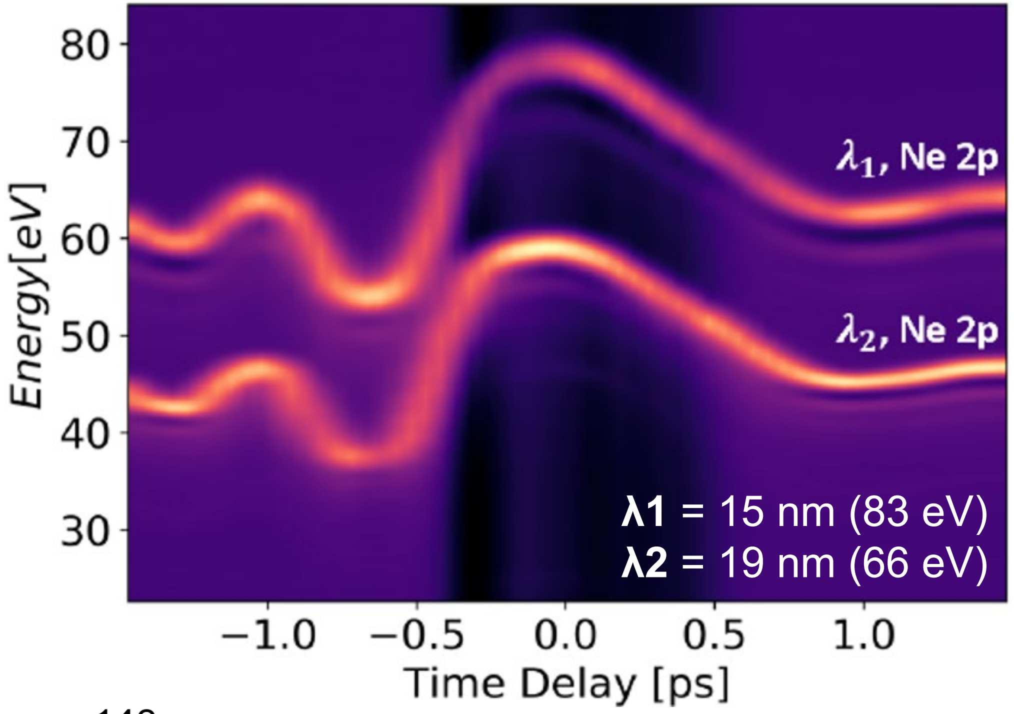
Two-color operation @ FLASH2

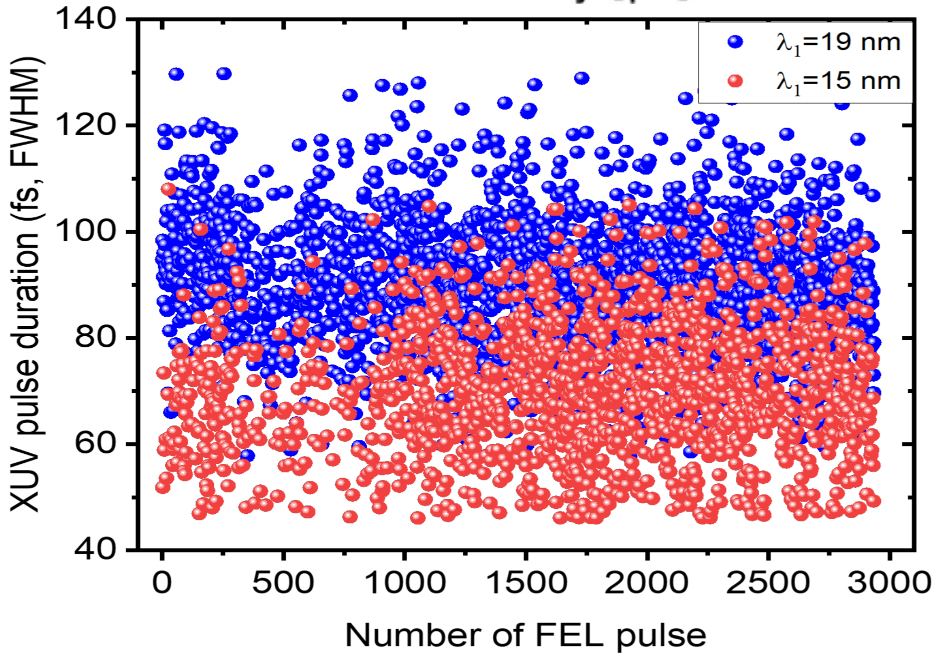
2 pulses with 2 colors from the same electron bunch



Short WL = 15 nm (82 eV); ~ 70 fs (FWHM)
Long WL = 20 nm (62 eV). ~ 90 fs (FWHM)

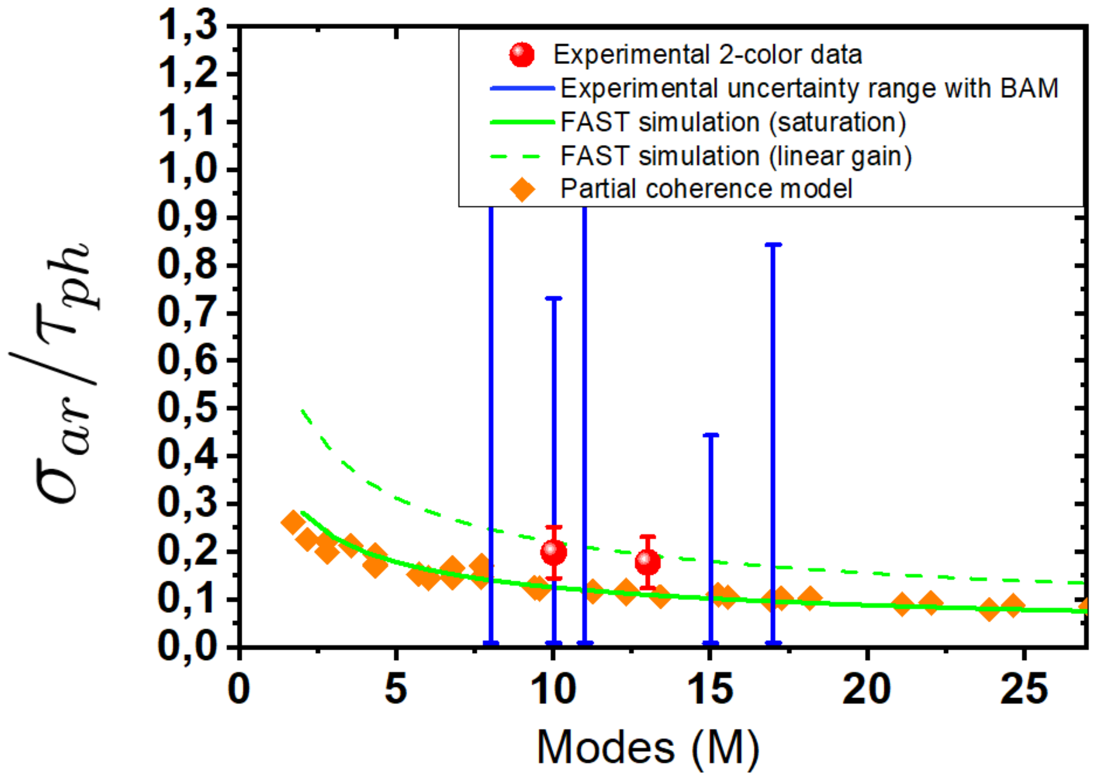
E. Schneidmiller et al., Appl. Sci. **13,** 67 (2023)



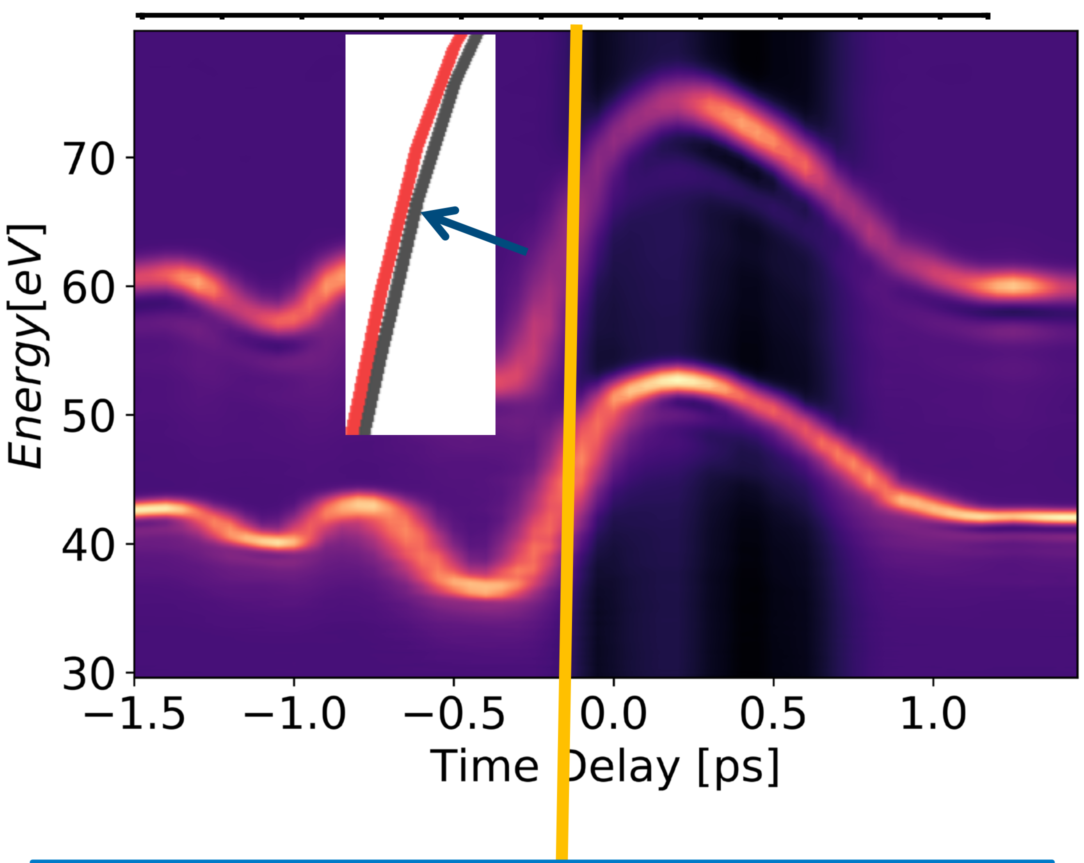


Two-color operation @ FLASH2

Arrival time fluctuations

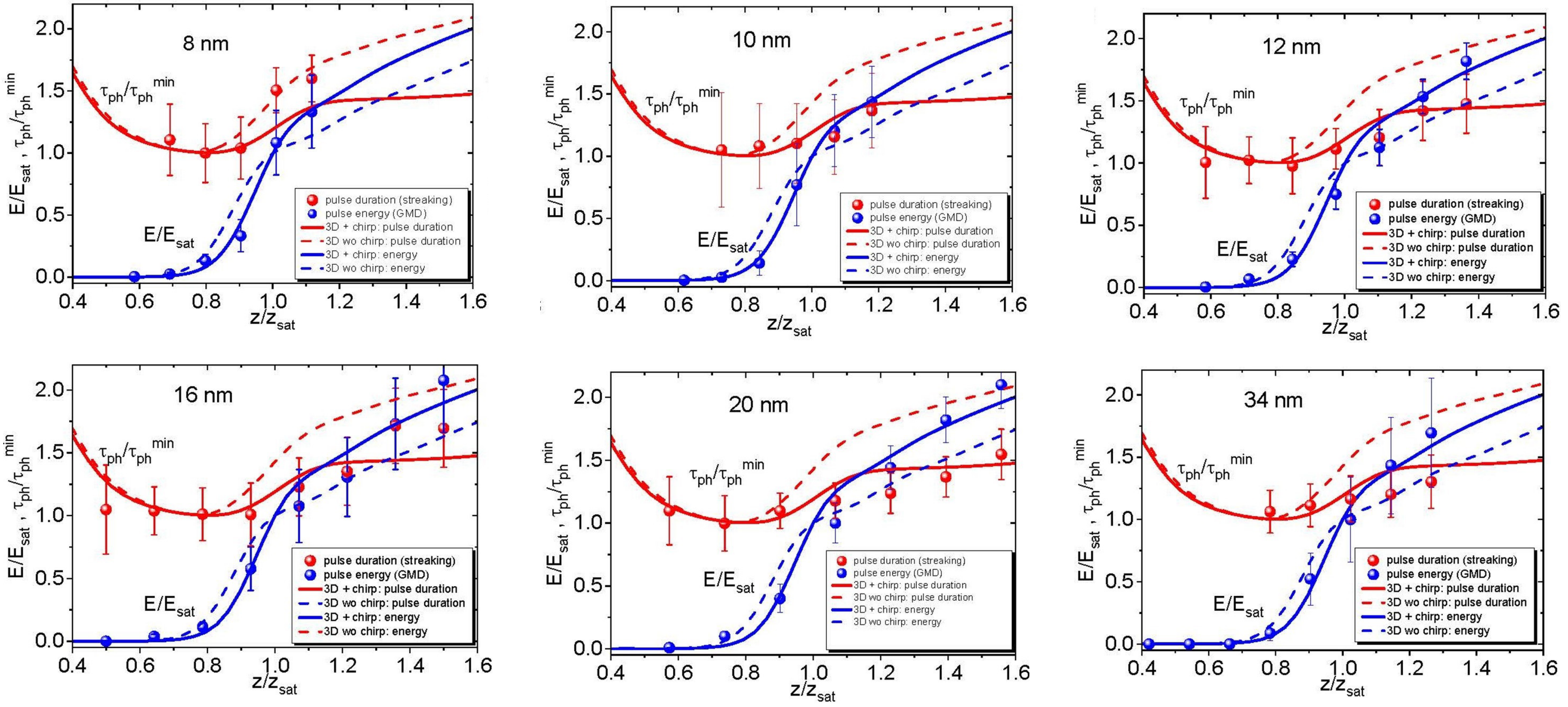


Relative arrival time



Longer wavelength pulses arrive on average ~ 15 fs later

Evolution of pulse energy and pulse duration

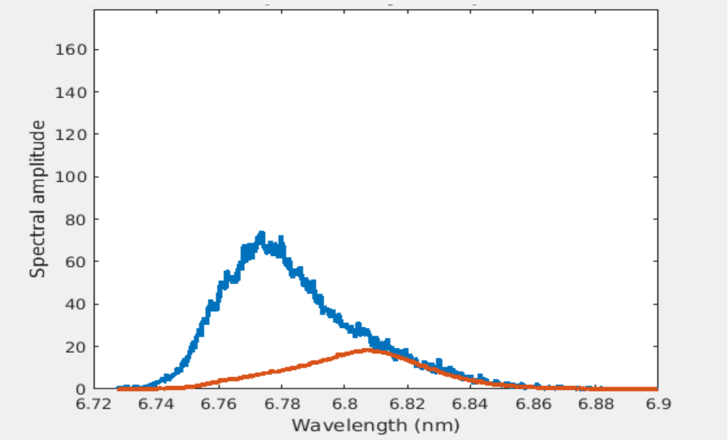


M. Bidhendi et al. Appl. Sci. 12, 7048 (2022)

Error sources @ different pulse duration ranges

a) Fluctuating SASE XUV spectrum

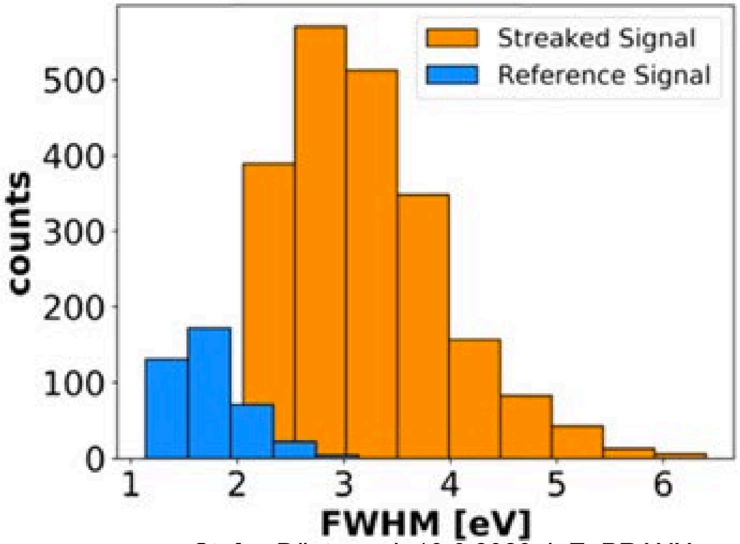
Measured XUV spectrum



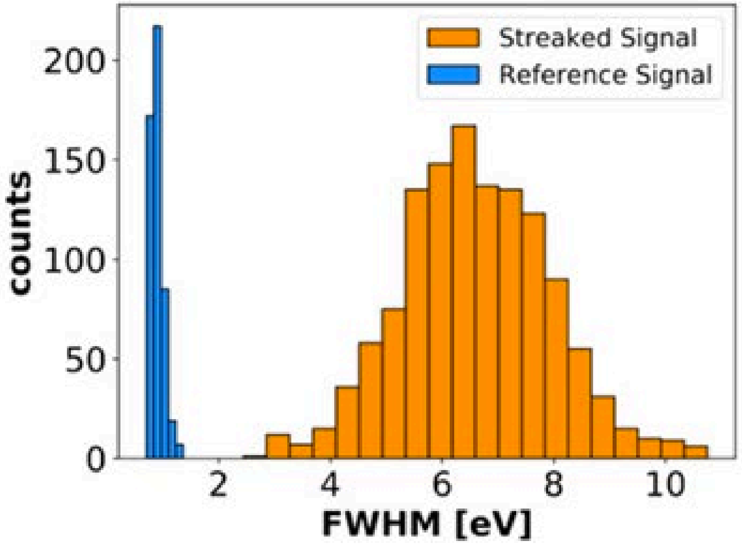
$$\tau_{xuv} = \sqrt{\frac{\sigma^2{}_{streak} - \sigma^2{}_{reference}}{s^2}}$$

Streaking speed: s~ 0.1 eV/fs

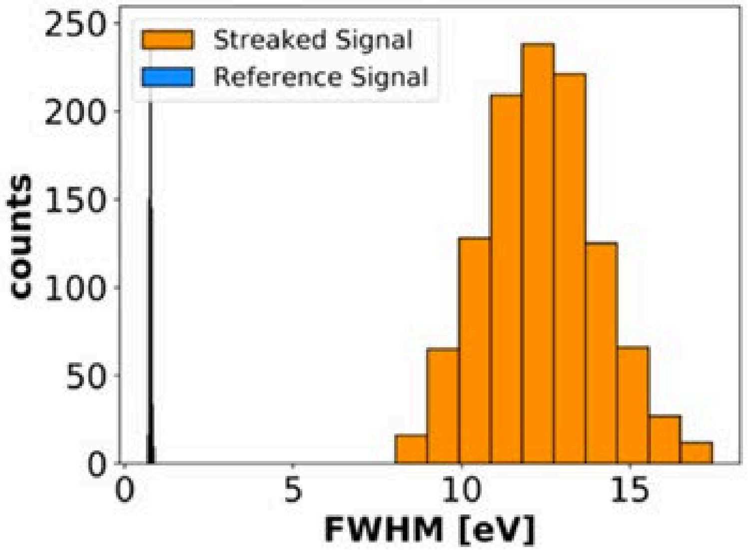
τ_{FEL} < 30 fs (FWHM)



30 fs < τ_{FEL} < 200 fs (FWHM)

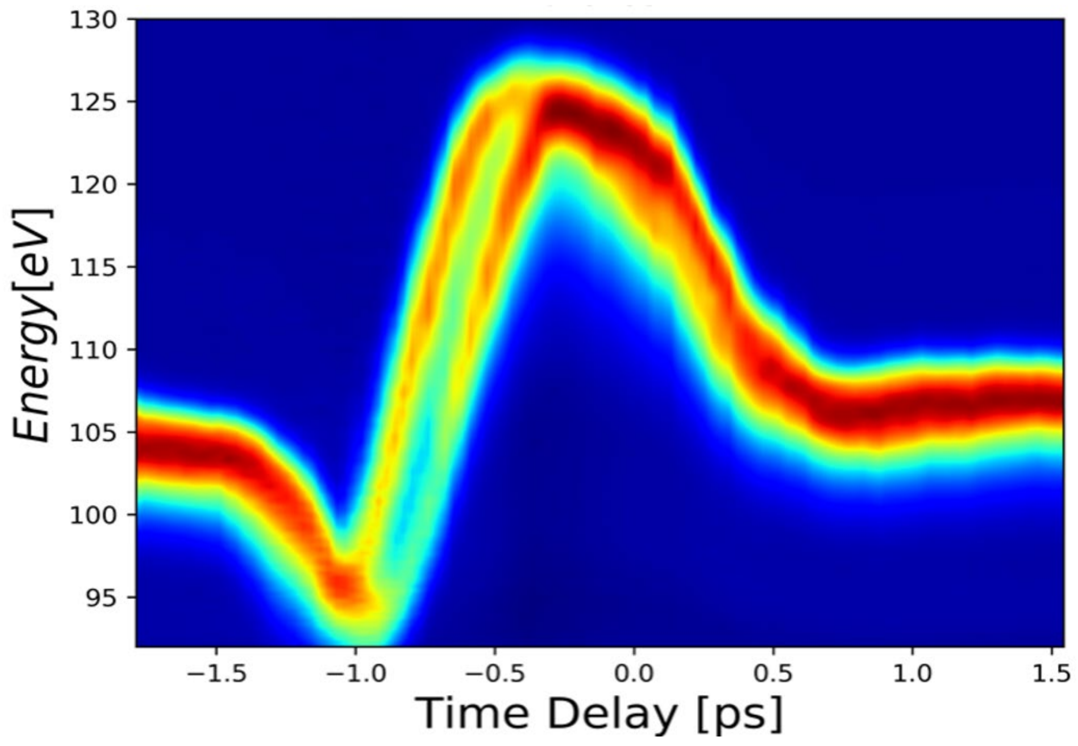


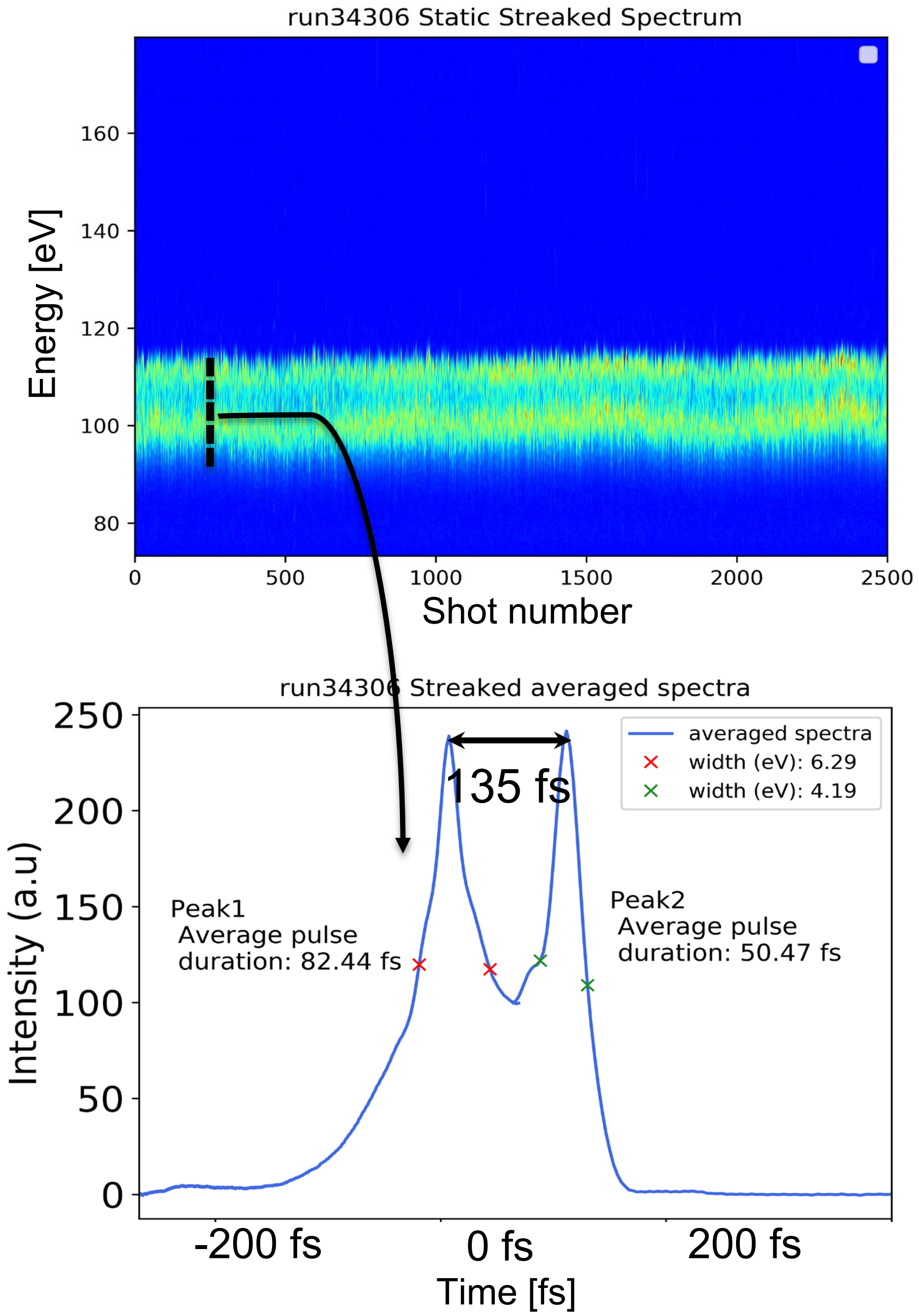
τ_{FEL} > 200 fs (FWHM)



Special operation modes

Double pulse in deep saturation regime

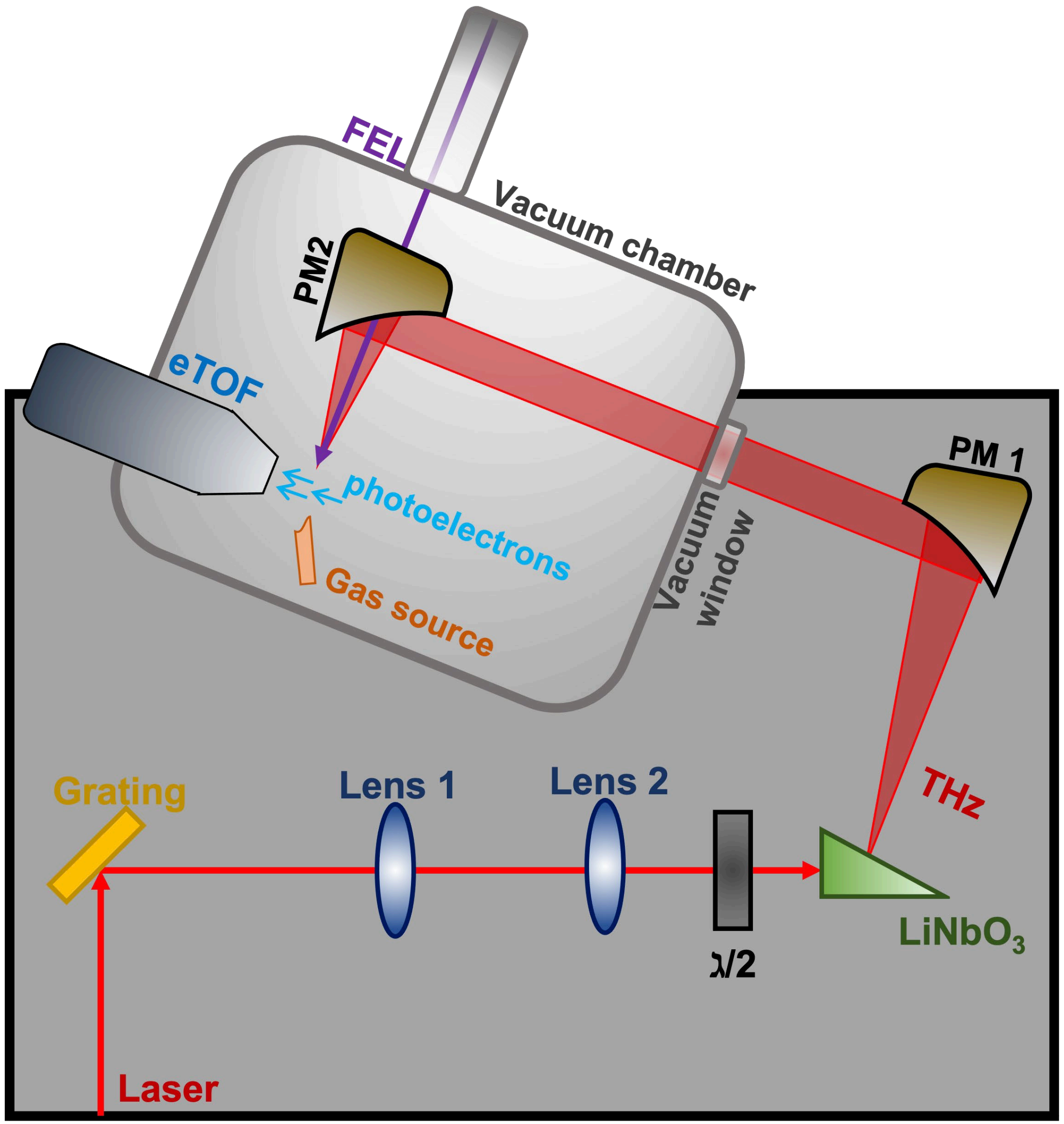




THz generation

Schematic layout of the THz-streaking setup. It consists of two parts:

- the THz production via tilted pulse-front in a LiNbO3 crystal using an IR laser (1030 nm)
- and the UHV chamber located above the optical table, where the FEL and THz beams are collinearly overlapped and focused into the interaction region



I. Bermudez, PhD thesis (2022).

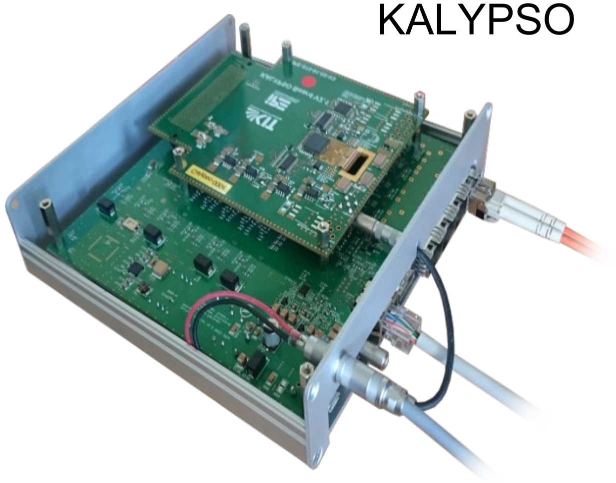
Further detectors

- HAMP, XGMD, Round-Robin GMD
- KALYPSO

  Parameters for current version 2.1
  - 256 pixels, 50 µm pitch
  - 14 bit ADC, 2.7 Mfps

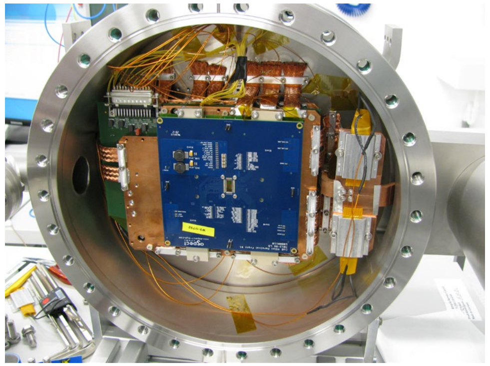
  Parameters for prototype version 2.5
  - 1024 pixels, 25 µm pitch
  - 14 bit ADC, 2.2 Mfps

KALYPSO



Other DESY groups:

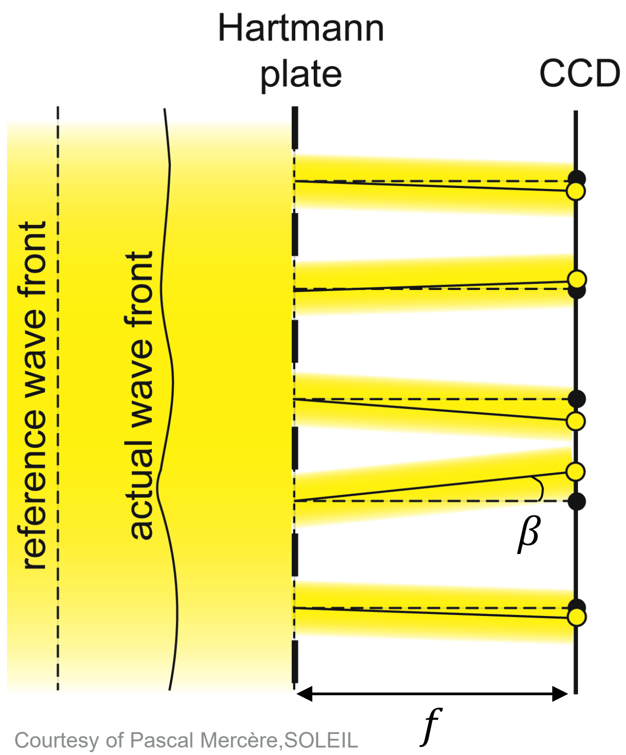
- Polarimeter („CookieBox“), P04 @PETRA III
  16-eTOF spectrometer instrument for monitoring the polarization by measuring the photoelectron angular distribution
- Percival (“Pixelated Energy Resolving CMOS Imager, Versatile and Large”)
  back-thinned to access its primary energy range of 250eV to 1keV, the roughly 10x10cm2, 3520 x 3710 pixel monolithic sensor up to 120Hz



Percival
(courtesy C. Wunderer)

Wavefront sensors (WFS) at FLASH

How a wavefront sensor works



Courtesy of Pascal Mercère,SOLEIL

Wave front reconstruction:

The displacement of the spot centroid $(x_c,y_c)_{ij}$ with respect to a known reference position $(x_r,y_r)_{ij}$ is a measure for the spatial average of the Poynting vector S. $(\beta_{x,y})_{ij}$ approximates the wavefront gradient.

$$S_t \propto \begin{pmatrix} \frac{\partial w}{\partial x} \\ \frac{\partial w}{\partial y} \end{pmatrix}_{ij} = \beta_{ij} = \frac{1}{f}\begin{pmatrix} x_c - x_r \\ y_c - y_r \end{pmatrix} ij \qquad \beta^{x,y}(x,y;z_0) = \frac{\partial w(x,y;z_0)}{\partial x,y} = \sum_{k=1}^{L} c_k(z_0)\frac{\partial P_k(x,y)}{\partial x,y}$$

The wavefront is reconstructed by a modal approach, via a least squares fit with a polynomial basis P_k. Zernike polynomials are well suited for the reconstruction at FLASH due to the circular beam shape and good representation of typical focusing mirror aberrations.

Numerical propagation:

Since the sensor records both intensity and phase, it allows also the prediction of intensity distributions for any position in the beam course by numerical propagation. The IFNANO software MrBeam features Fresnel-Kirchhoff propagation:

$$I(x,y,z) = \left| \frac{ik}{2\pi z} \iint_{\infty} \sqrt{I(x',y')}\, e^{ikw(x',y')} \cdot e^{\frac{ik\left[(x-x')^2+(y-y')^2\right]}{2z}} dx'dy' \right|^2$$