XFEL diagnostics, detectors, optics

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2. XFEL beam positioning and profiling: MCP and diodes
3. Pulse energy monitoring: gas-based detector, backscattering monitor
4. Pulse profile measurement: scintillating screen, optics, camera
5. Pulse spectrum measurement: grating, X-ray spectrometers
6. Temporal diagnostics: spatial and spectral encoding, THz streaking
7. Summary

Introduction: XFEL jitter

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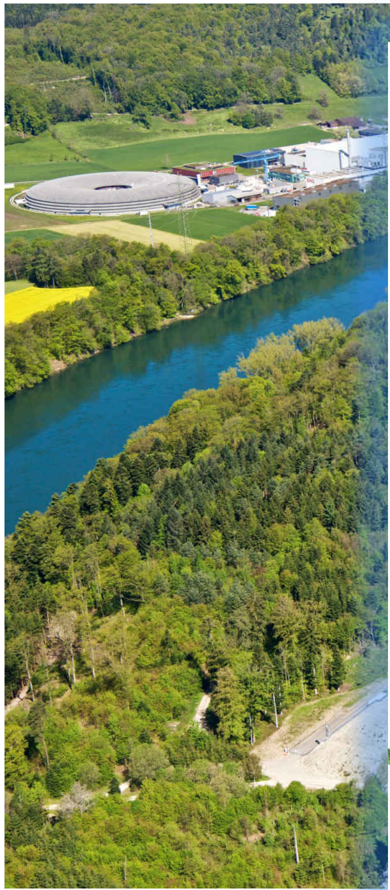

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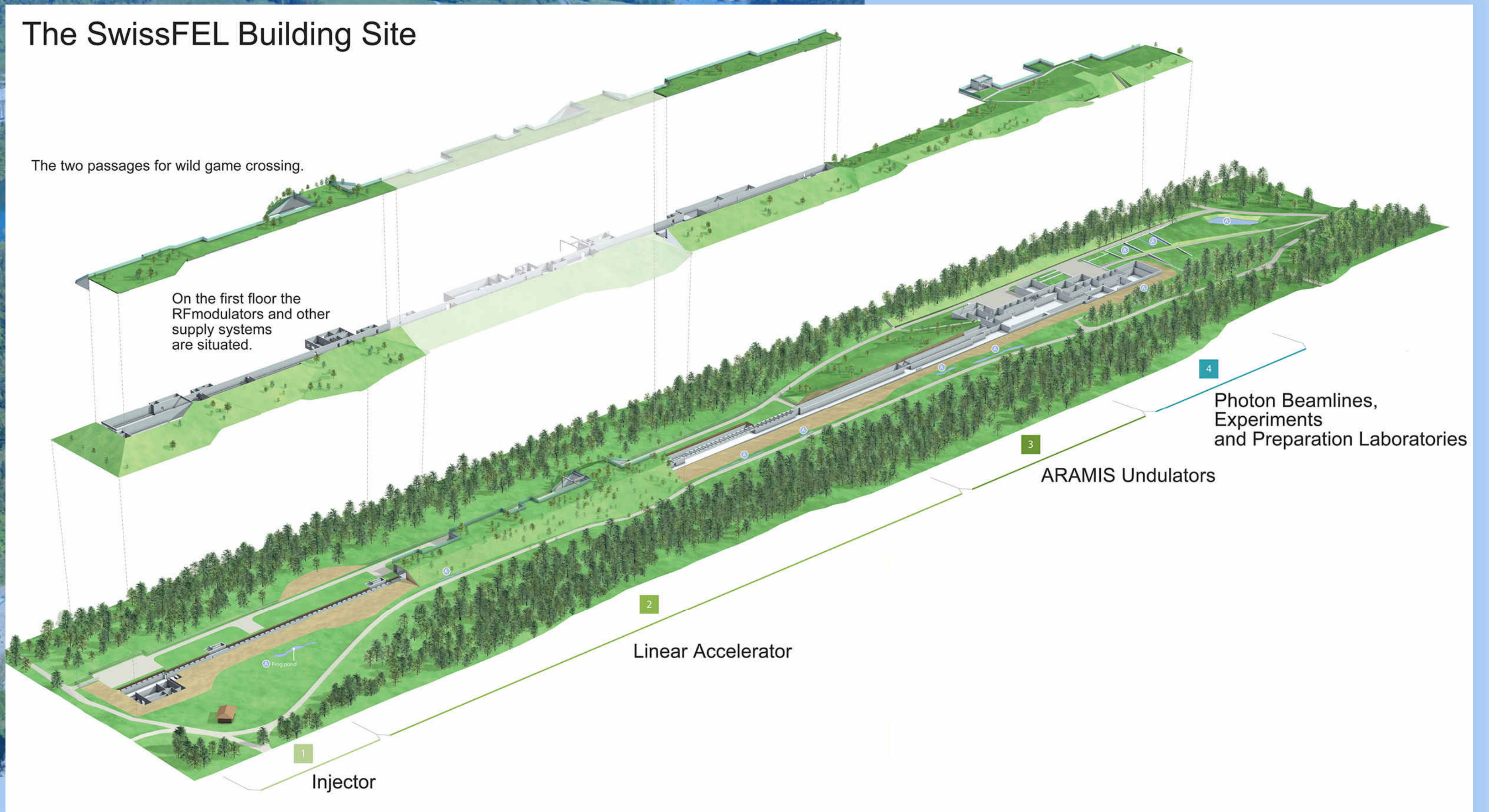

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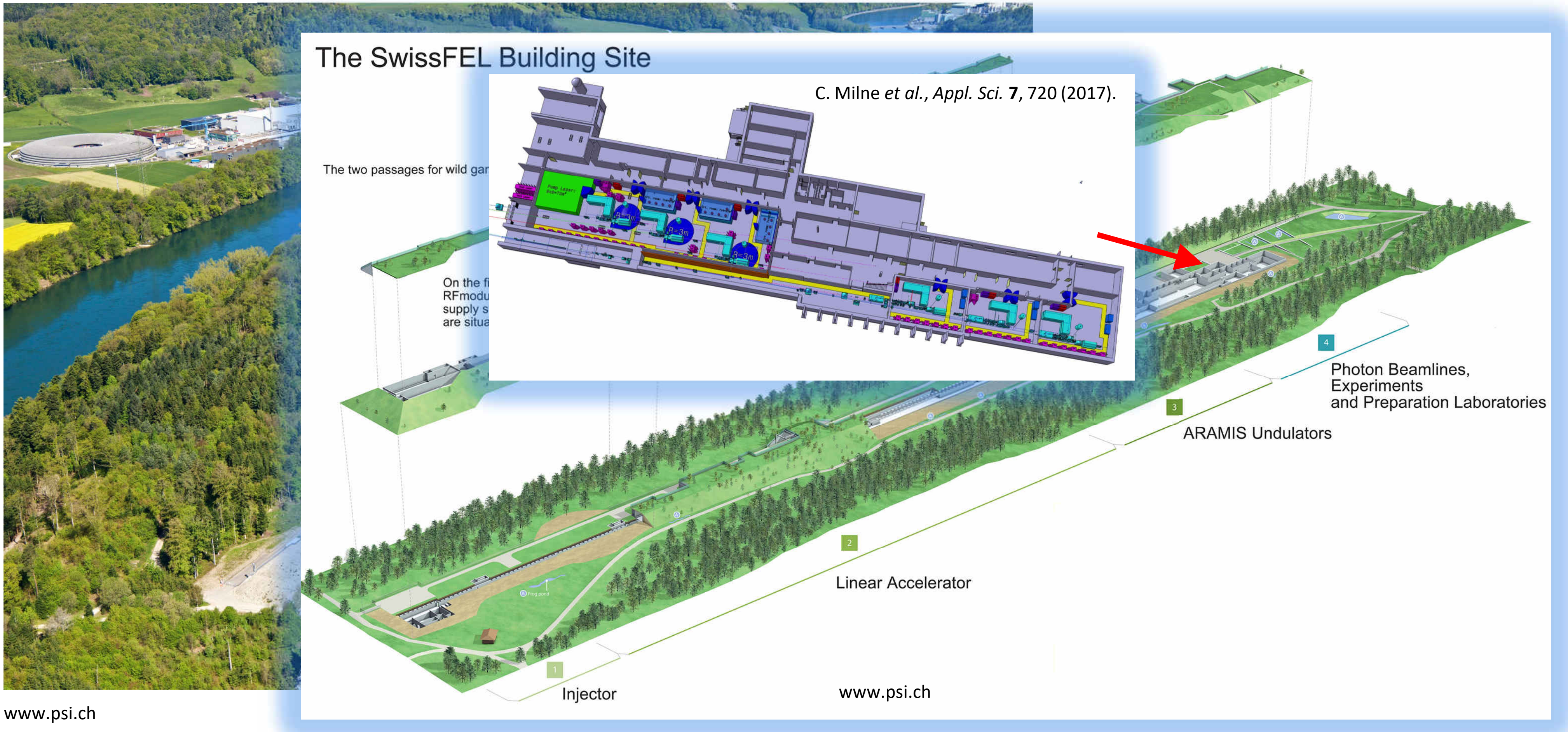

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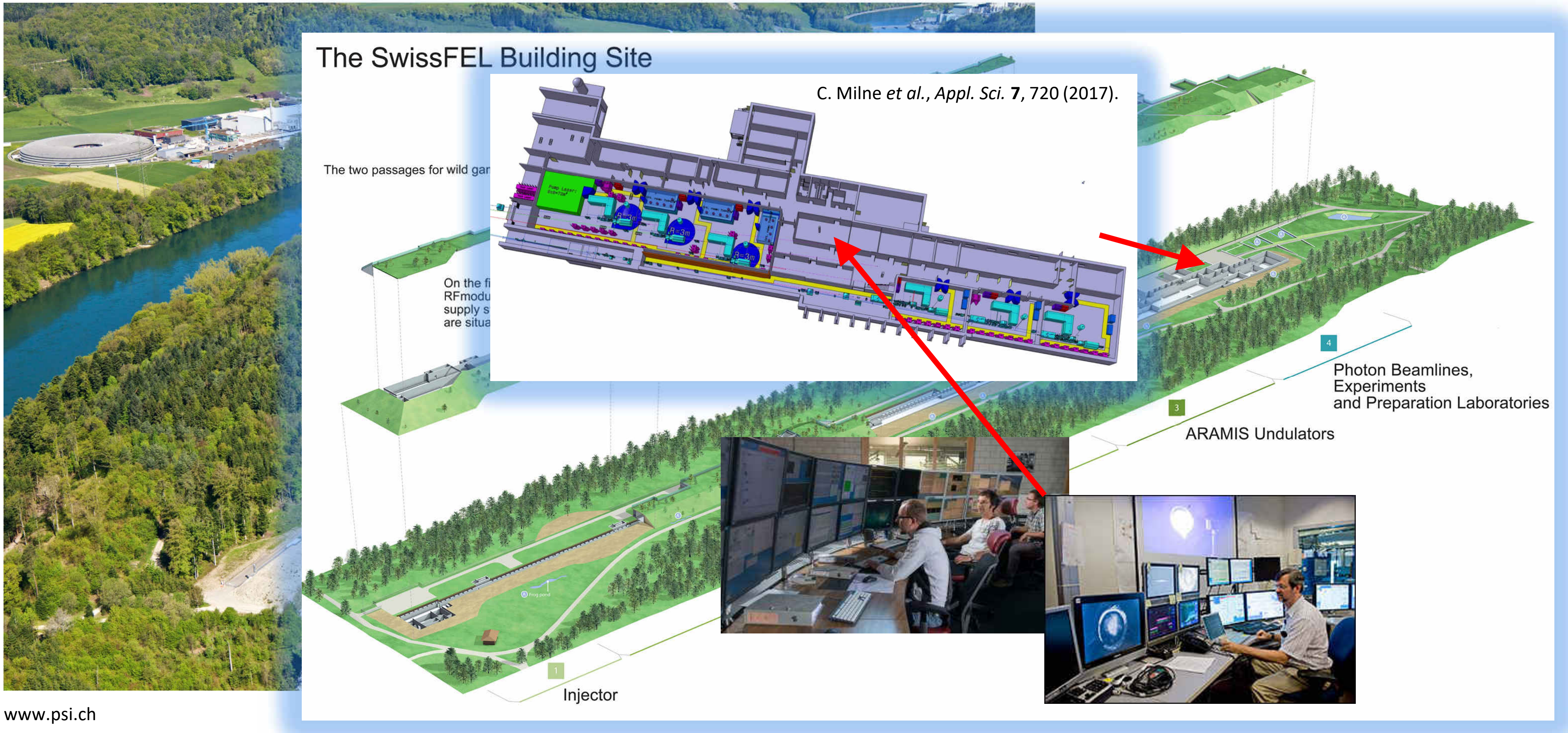

C. Milne *et al.*, *Appl. Sci.* **7**, 720 (2017).

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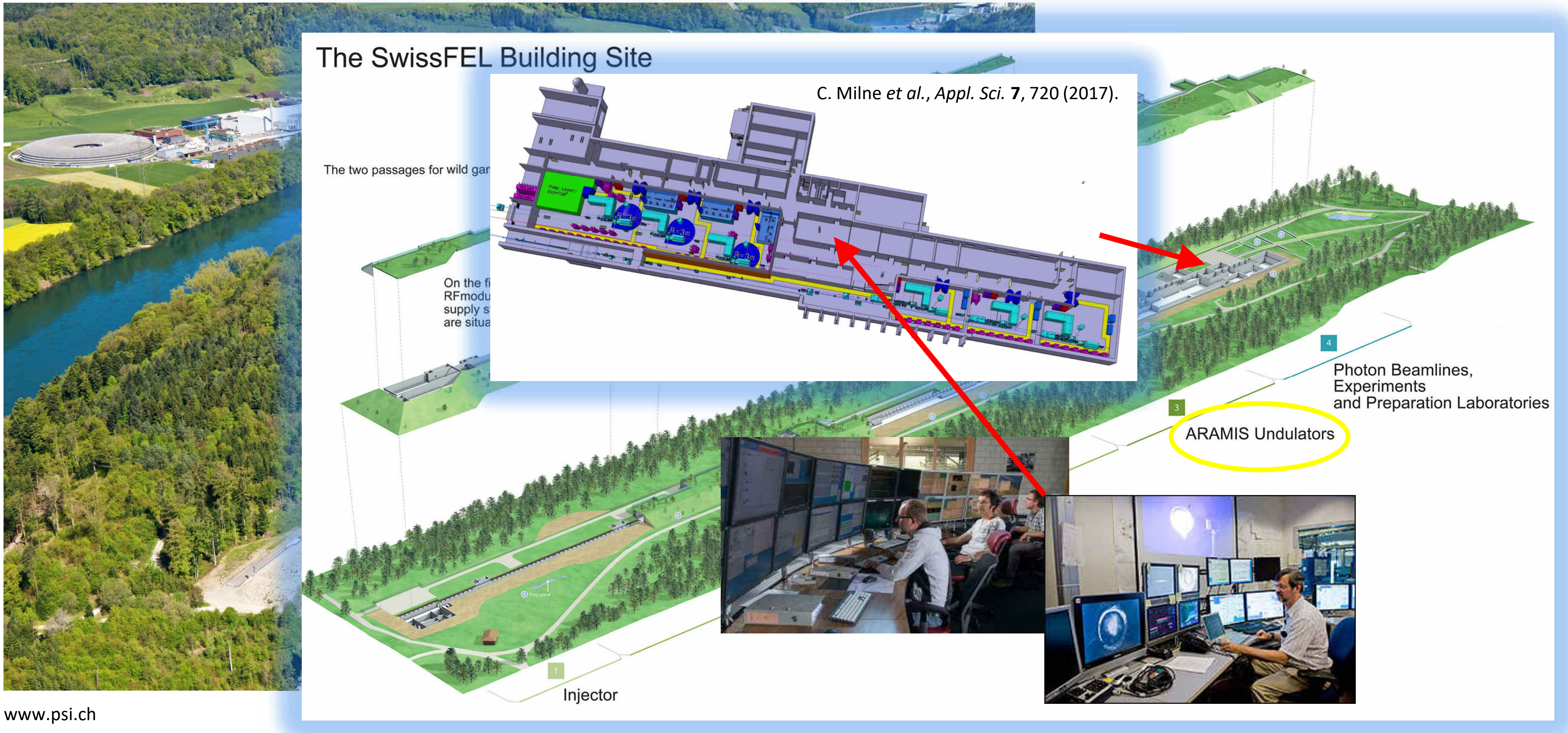

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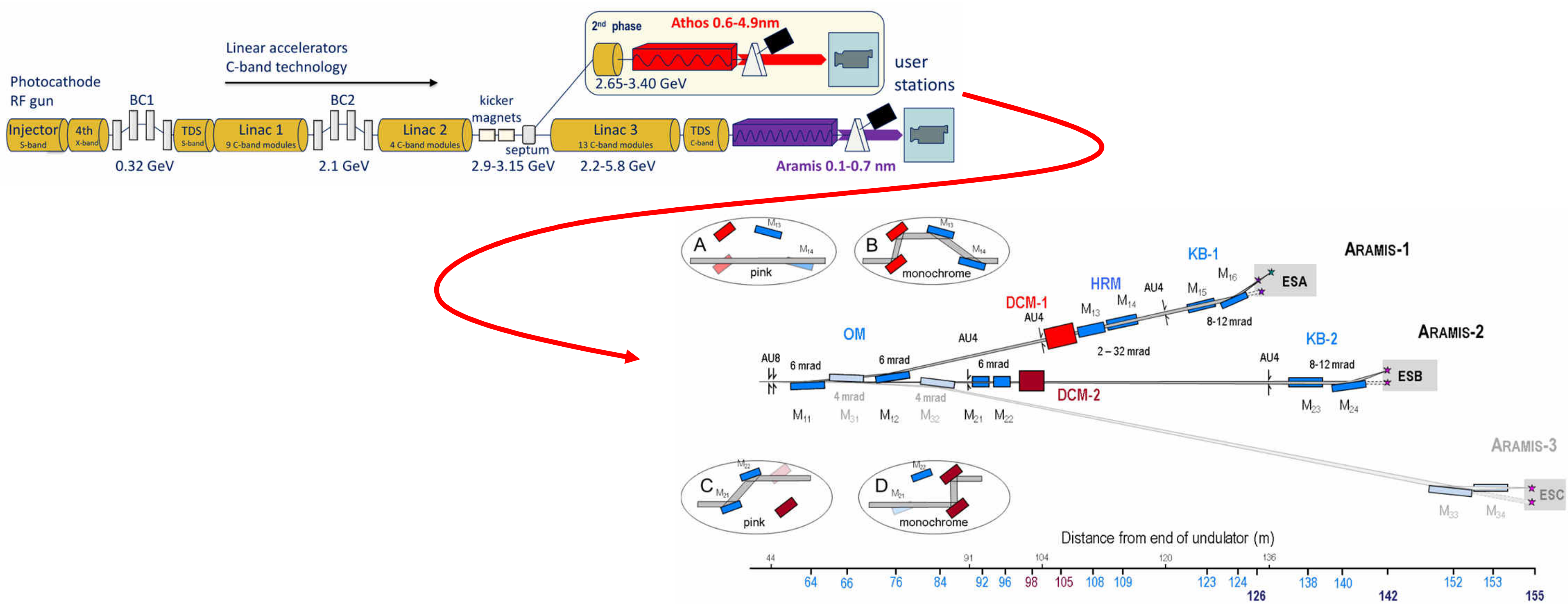

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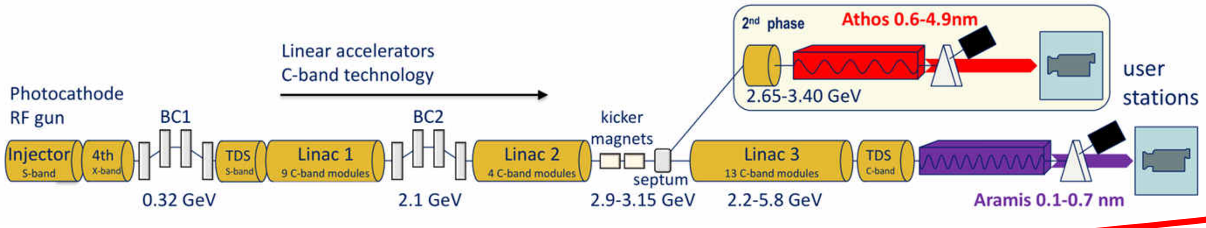

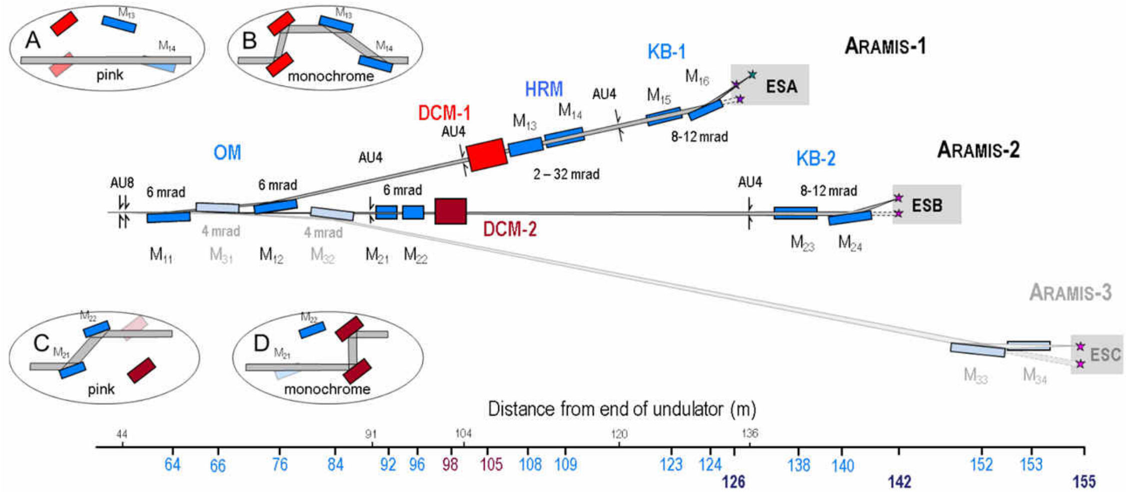

Production of X-ray pulse requires a synchronized work of many devices installed over a long distance.

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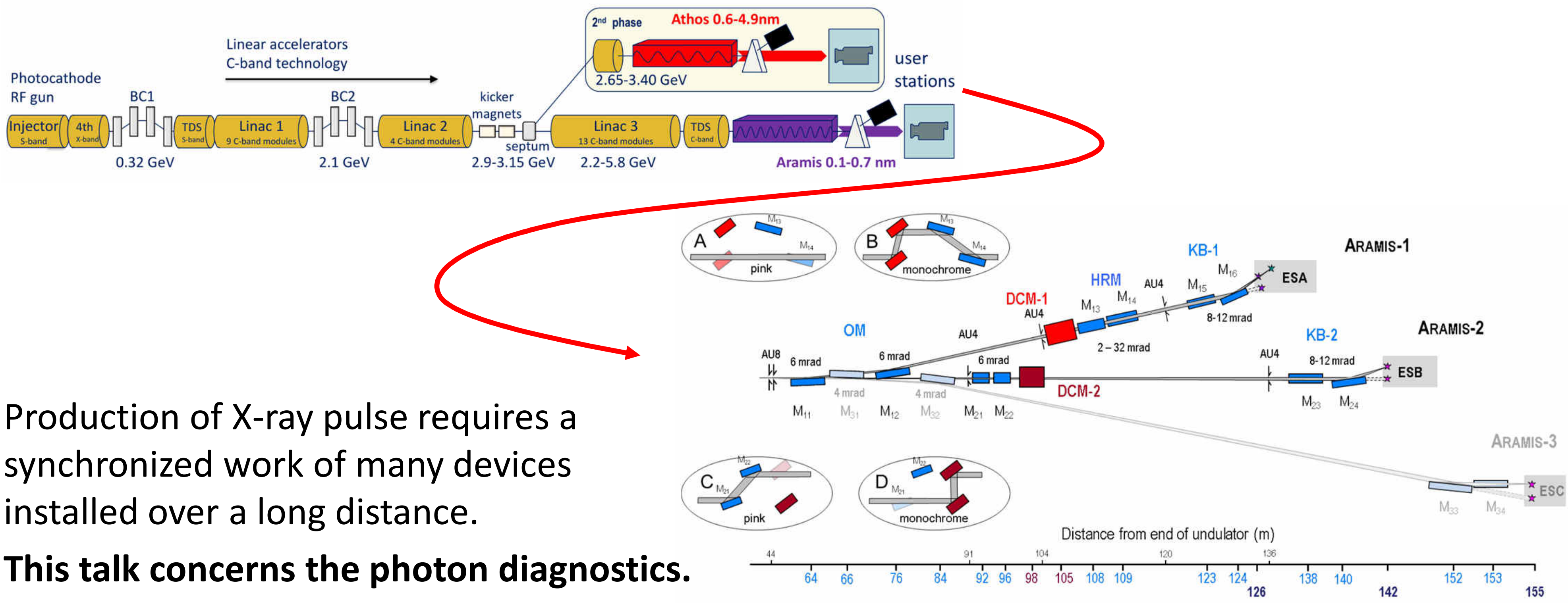

Production of X-ray pulse requires a synchronized work of many devices installed over a long distance.

This talk concerns the photon diagnostics.

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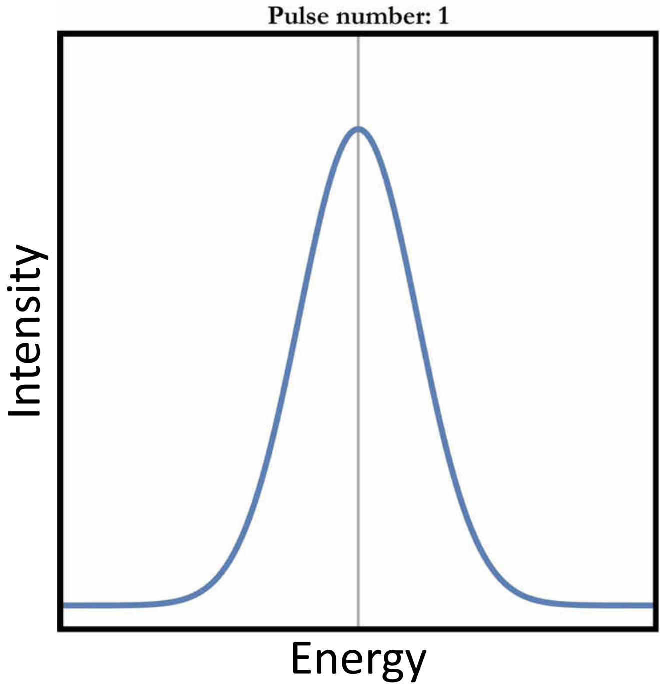
In a model case:



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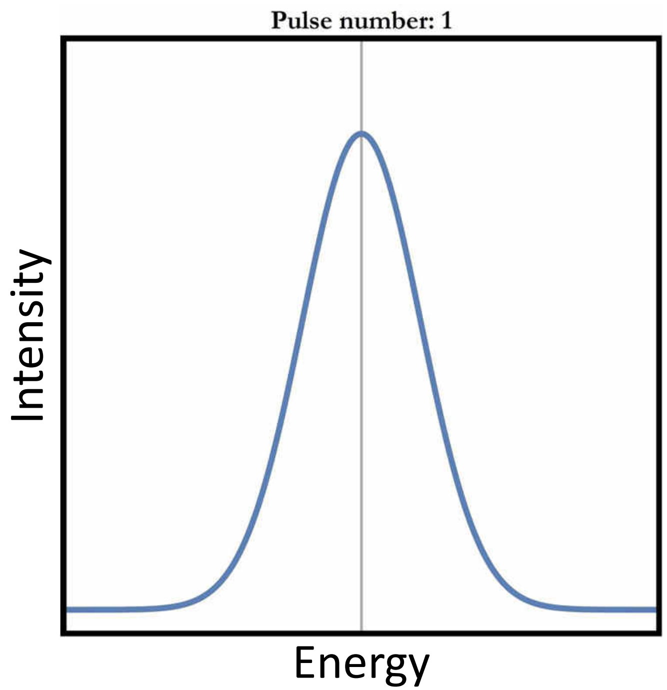

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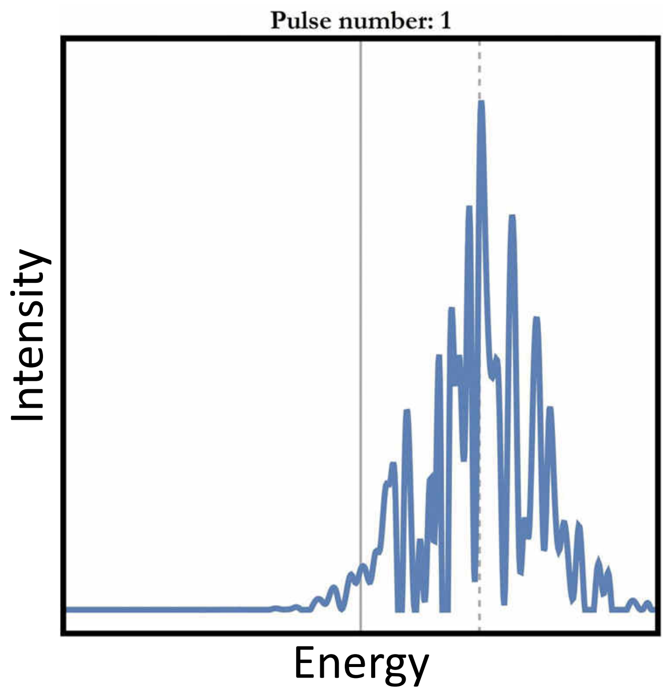

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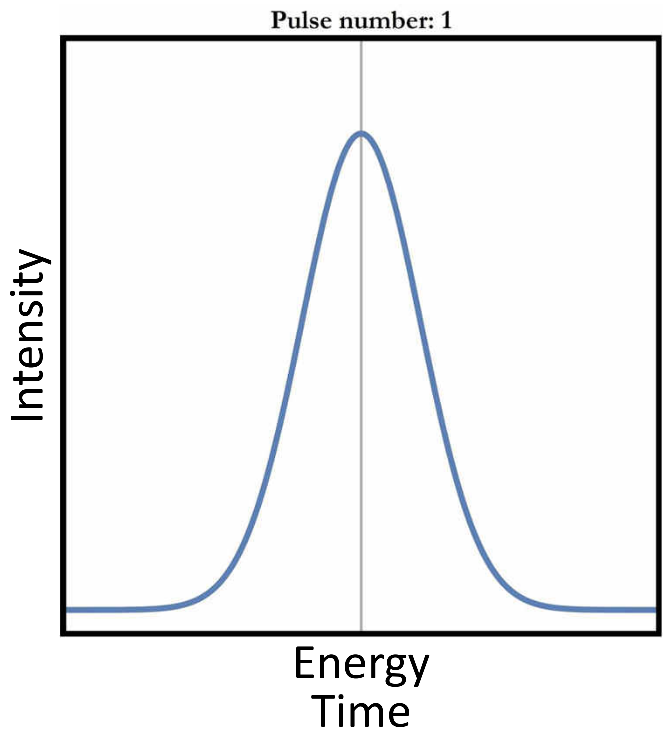

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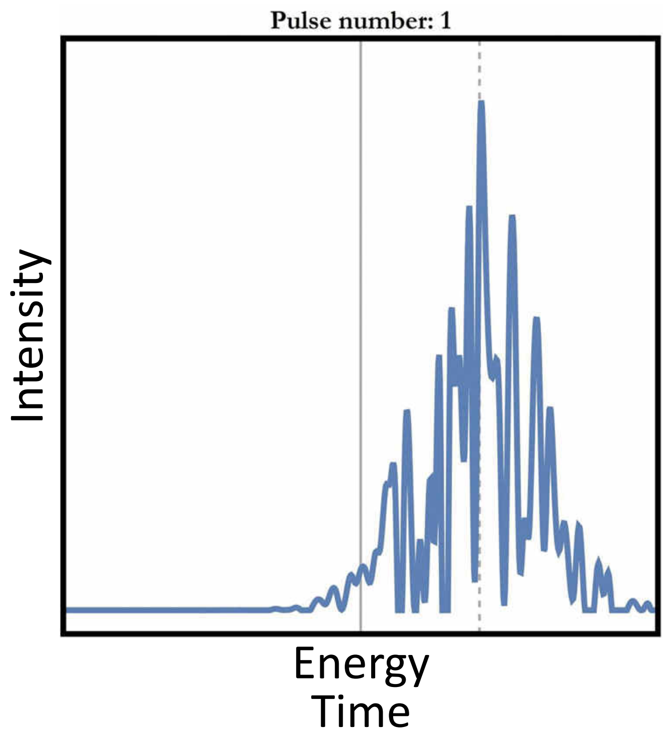

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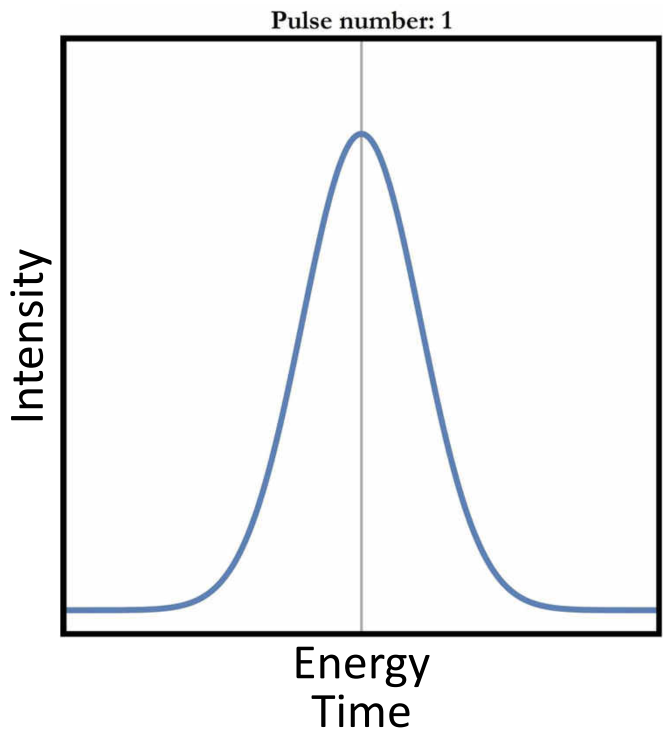

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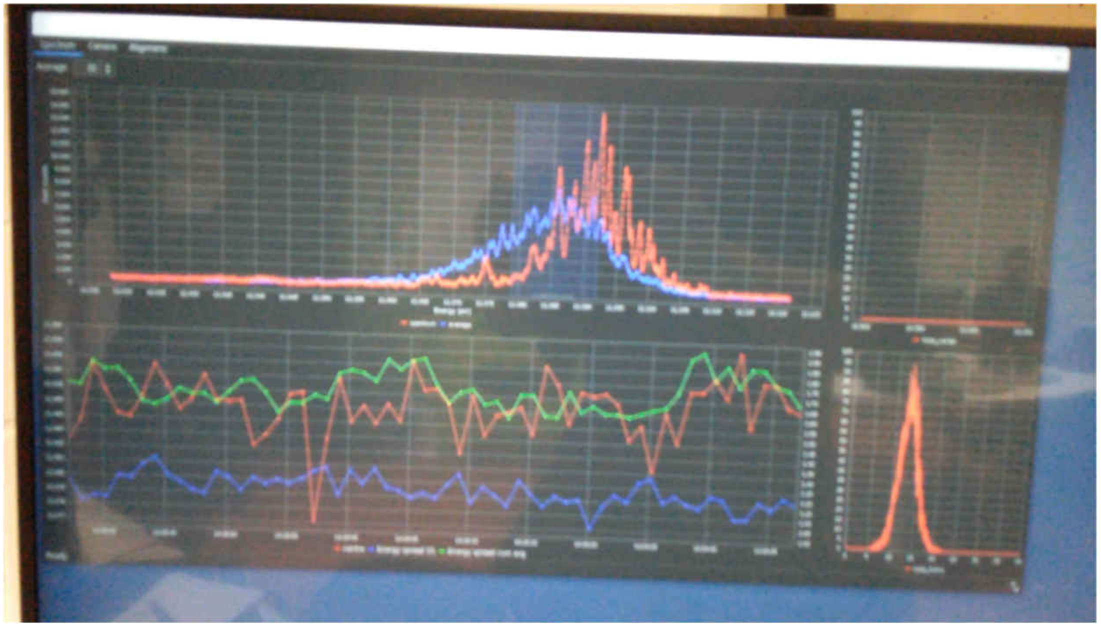

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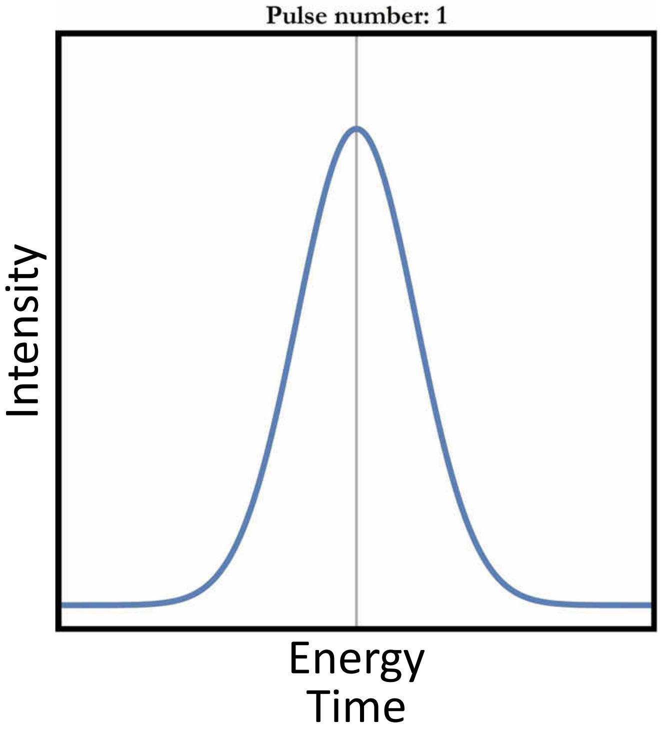

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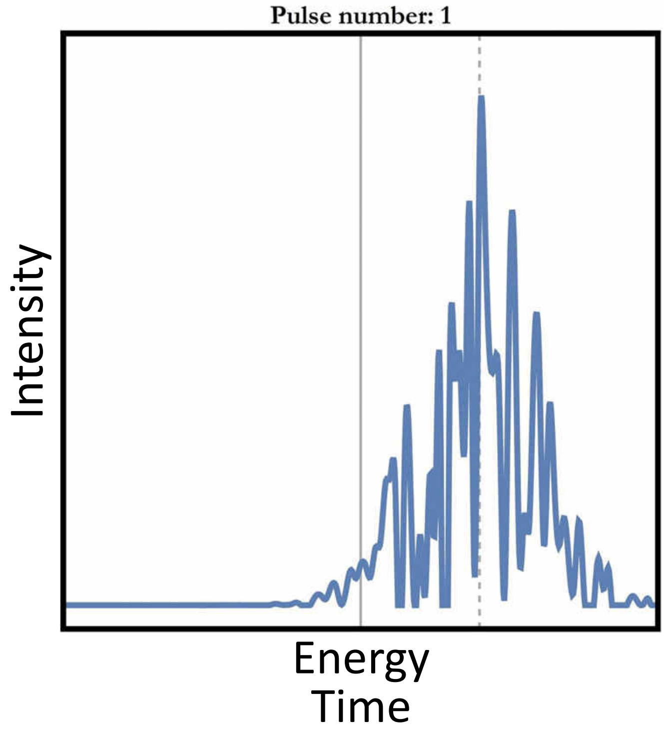

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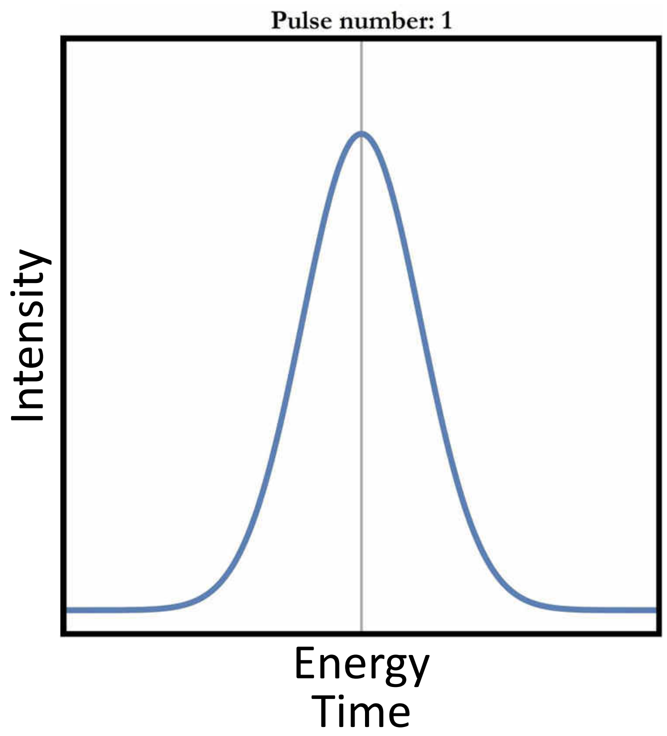

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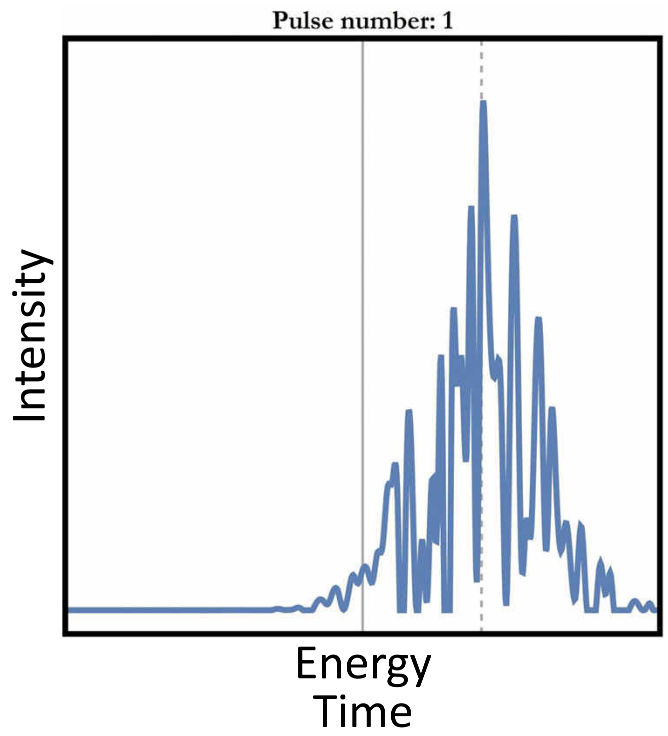

total numer of photons per pulse – area under curve

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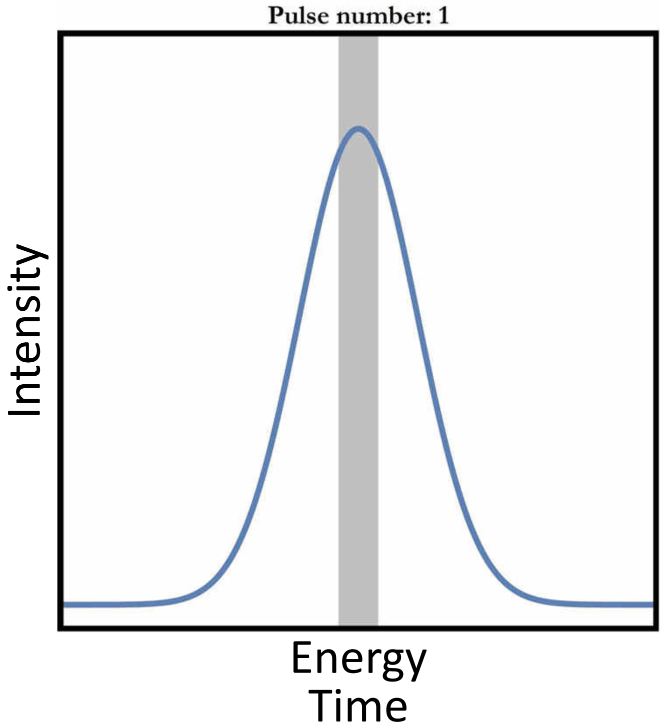

A real XFEL pulse:

Intensity

Energy
Time

total numer of photons per pulse – area under curve, with monochromator

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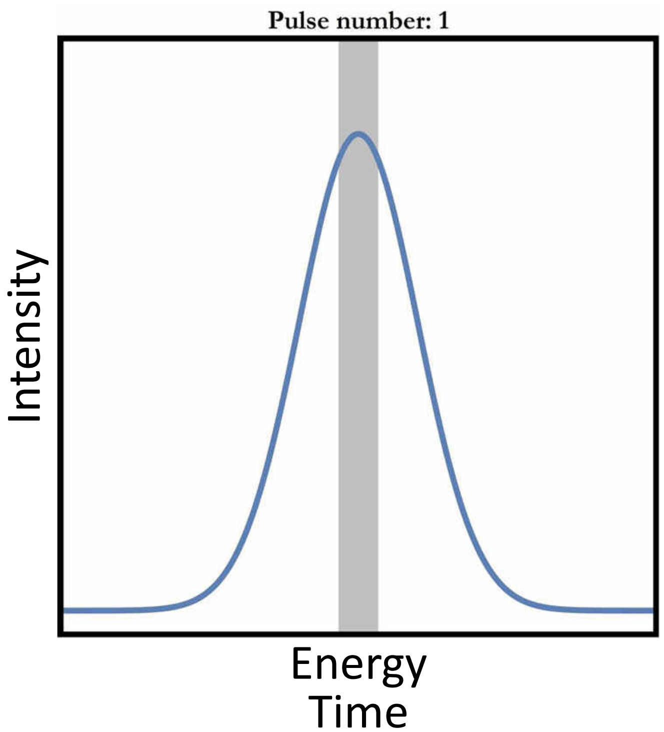

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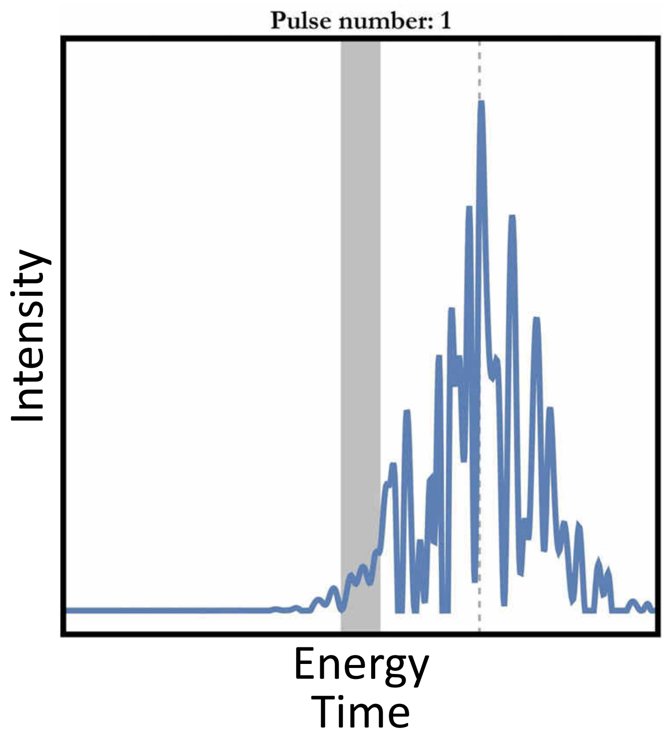

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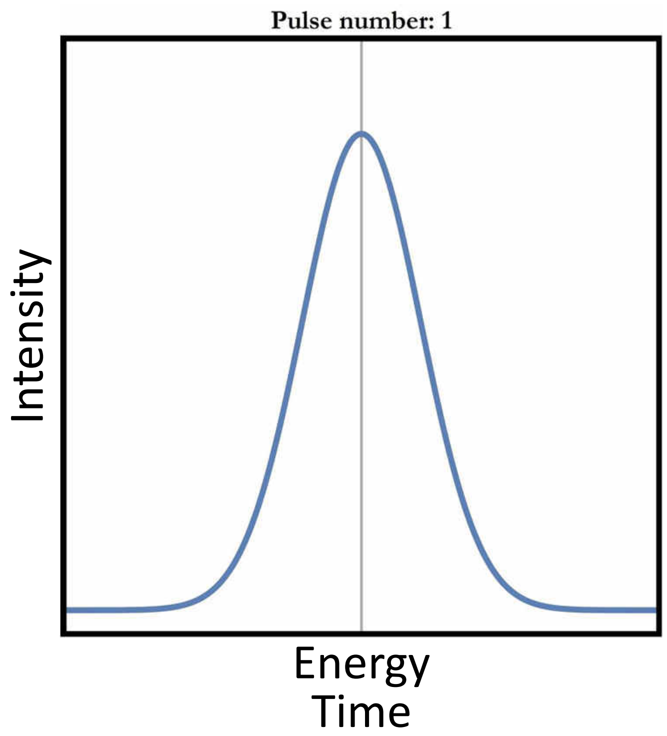

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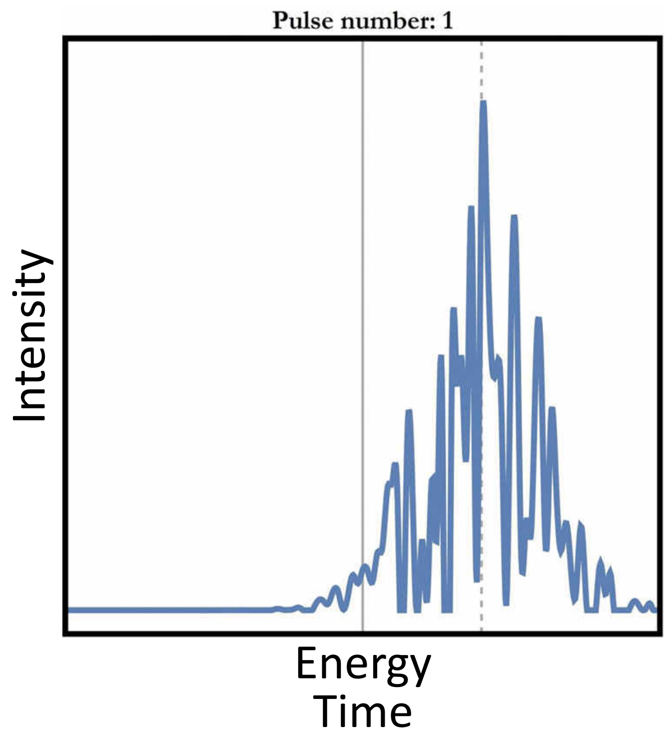

total numer of photons per pulse – area under curve

also: position, size

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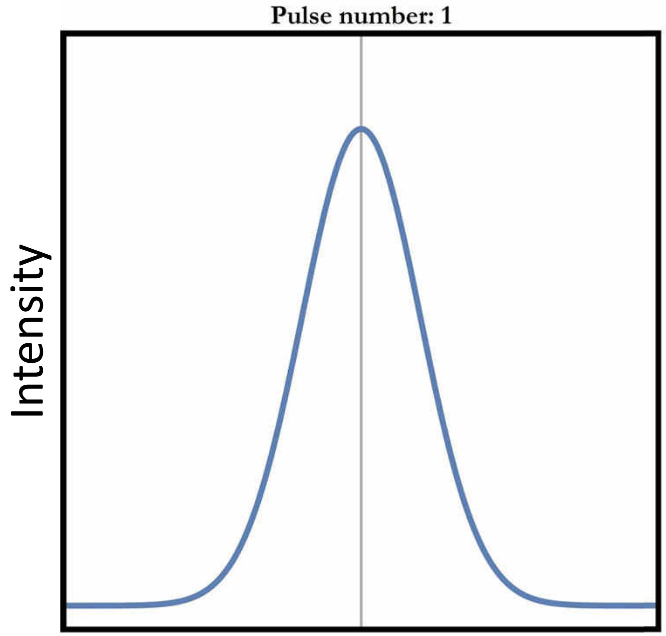

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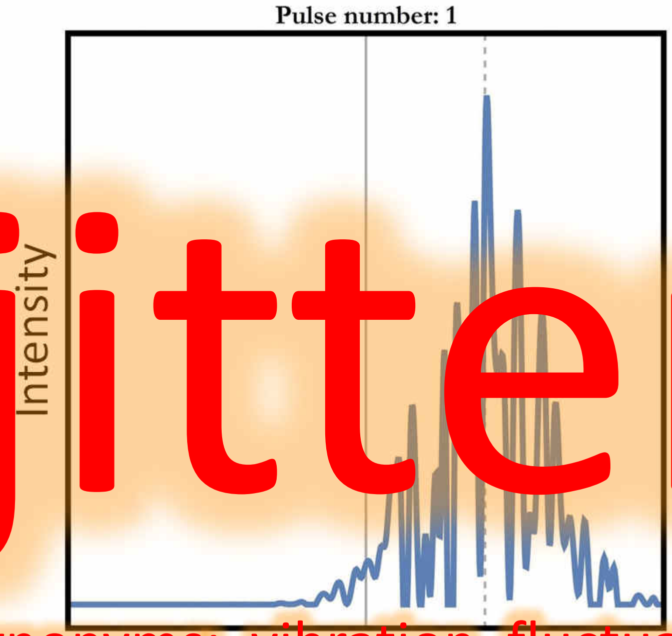


jitter

(synonyms: vibration, fluctuation, oscillation, twitch, tremor, wobble)

total numer of photons per pulse – area under curve

also: position, size

Introduction: Requirements for pulse diagnostics – Machine

Operators and machine experts:

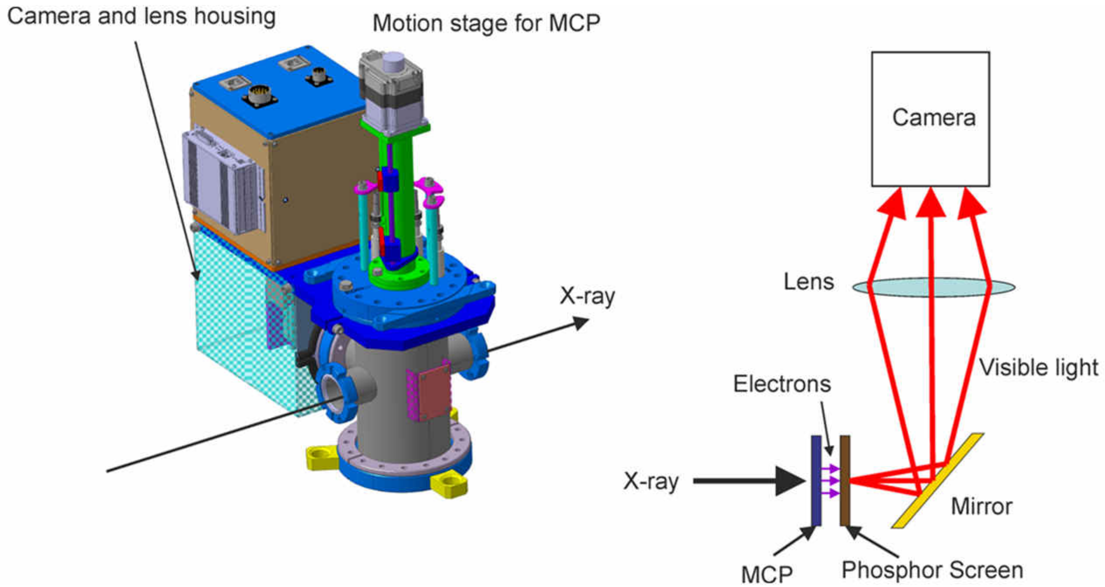
- Want to know machine performance for commissioning, improvement, and monitoring.
- On-line/non-invasive:
  - Pulse energy
  - Spectral distribution
  - Position (Poynting vector)
  - Pulse length
- Invasive
  - Tools for optimization of insertion devices.
  - Devices to measure gain curves of pre-SASE beams.
  - Profile monitors

Introduction: Requirements for pulse diagnostics – Users

Experimental users:

- Want to know the pulse-to-pulse beam parameters for data analysis and signal monitoring.
- On-line/non-invasive:
  - Pulse energy
  - Spectral distribution
  - Position (Poynting vector)
  - Pulse length
  - Arrival time
- Invasive
  - Photon pulse transverse profile.

XFEL beam positioning and profiling: MCP detector, diode



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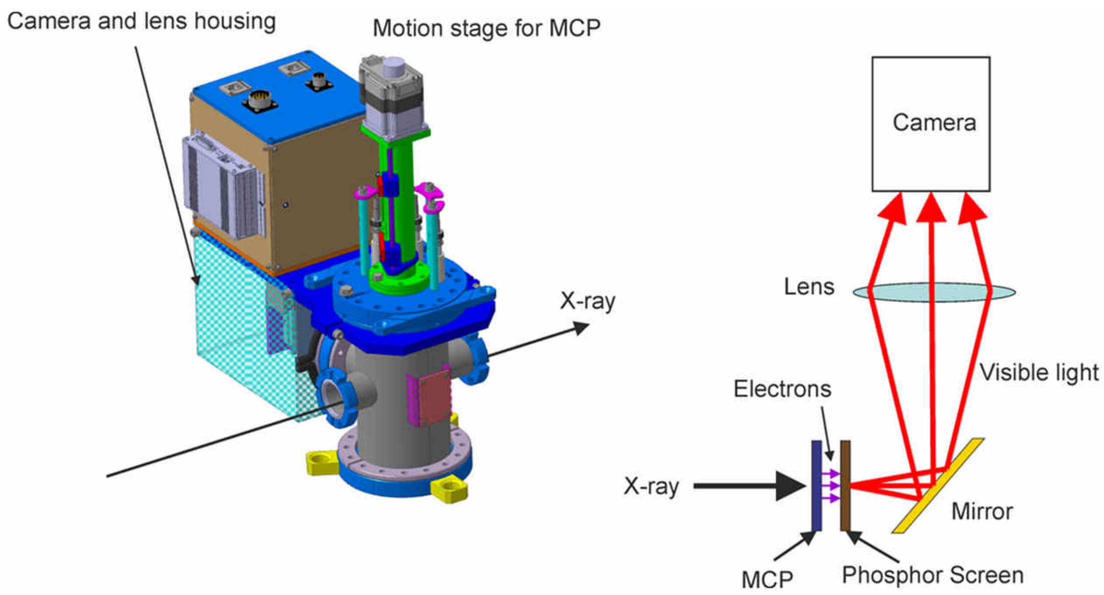
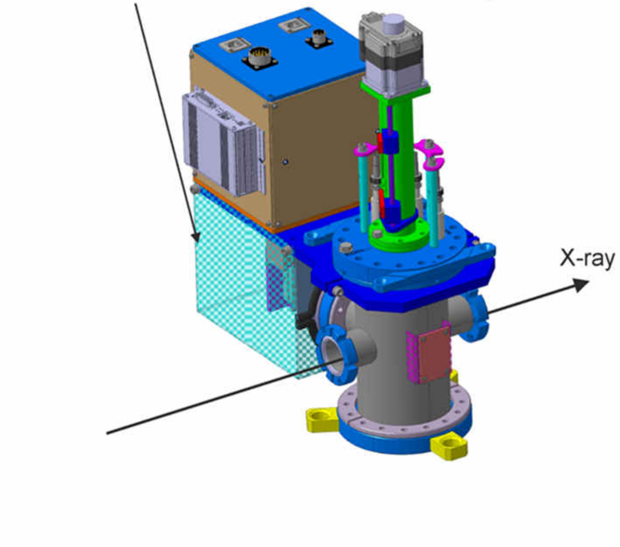
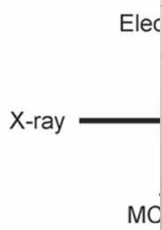


Microchannel plate (MCP) detectors – used in the undulator section.

Undulators should be pointing in the same right direction. To align them, one needs to use a series of MCP detectors to get images of the photon beam as it goes through the subsequent undulators. Although an extremely weak signal needs to be visualized, it does not need to be a shot-to-shot measurement. Without this alignment procedure, the SASE (self-amplified spontaneous emission) is inefficient, and the light may shine all over the place, each undulator emitting the photons in a different direction, causing the light to become diffuse and more jittery.

XFEL beam positioning and profiling: MCP detector, diode





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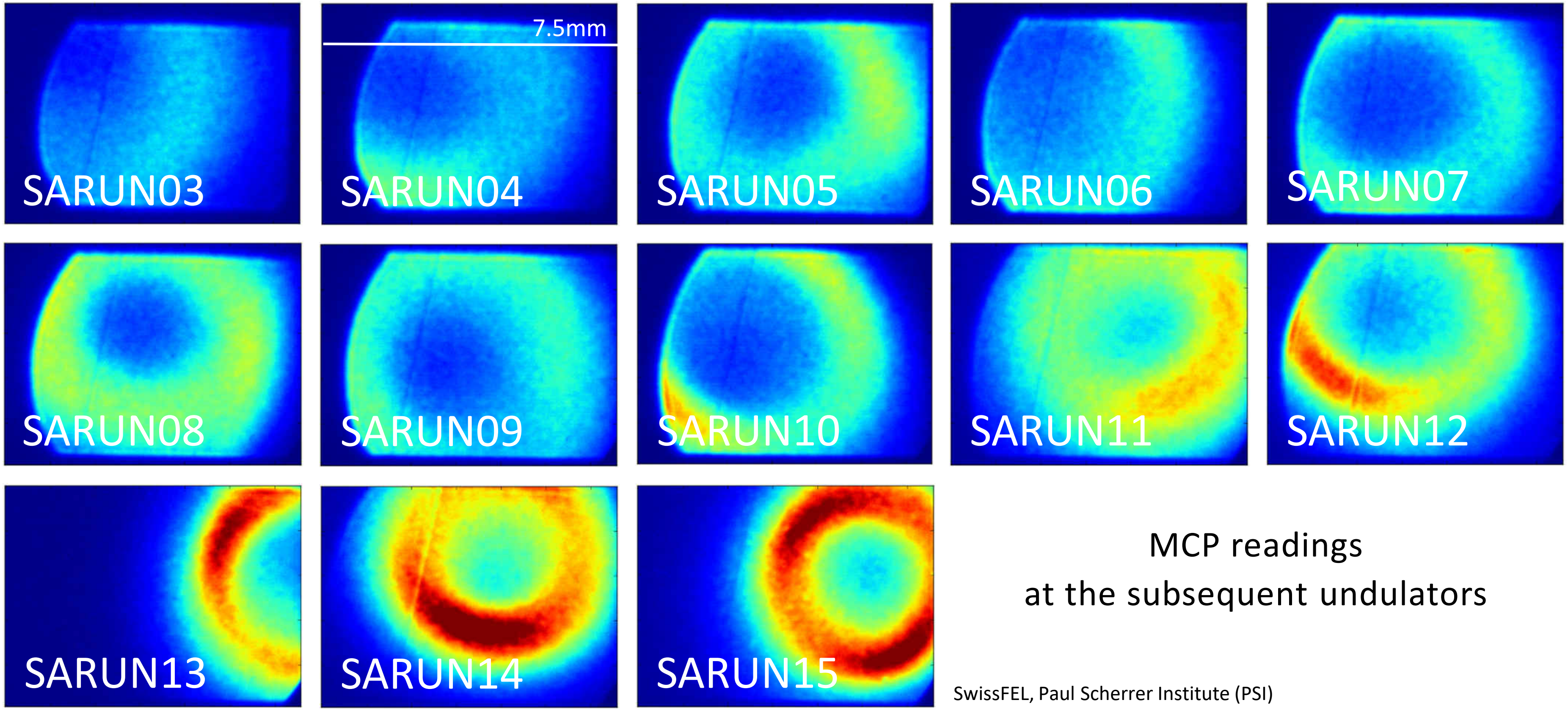
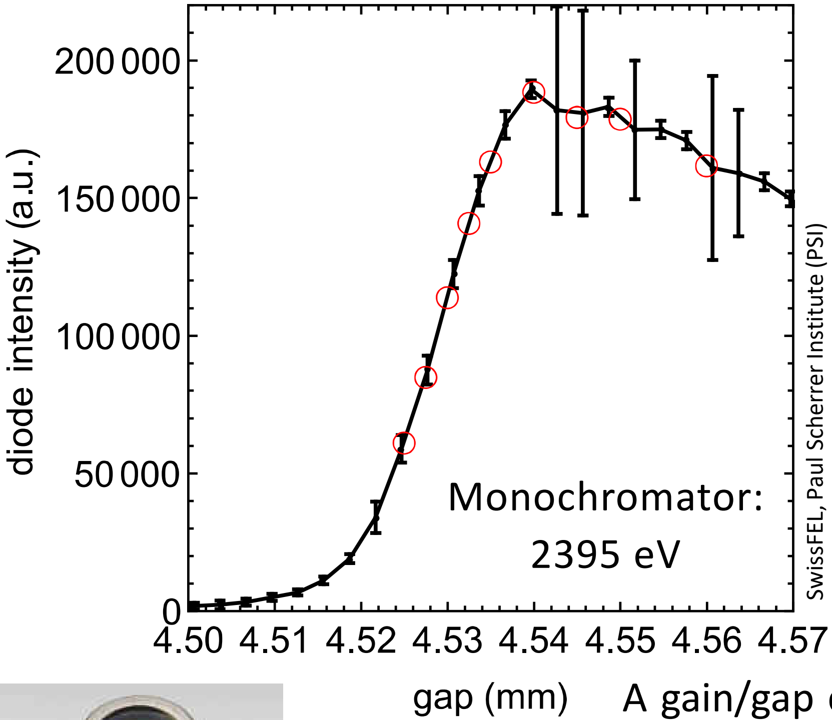


MCP readings
at the subsequent undulators

SwissFEL, Paul Scherrer Institute (PSI)

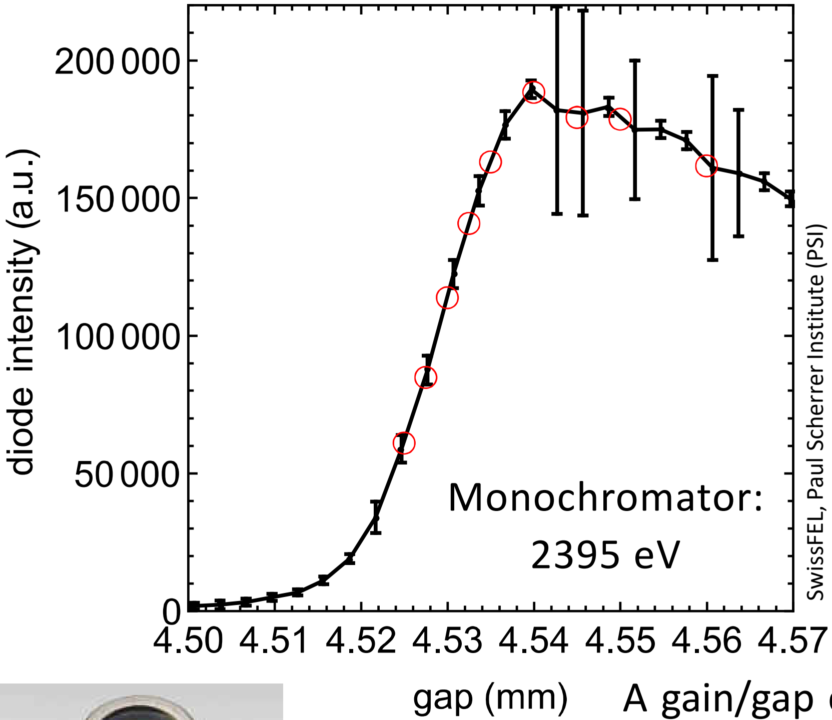
XFEL beam positioning and profiling: MCP detector, diode

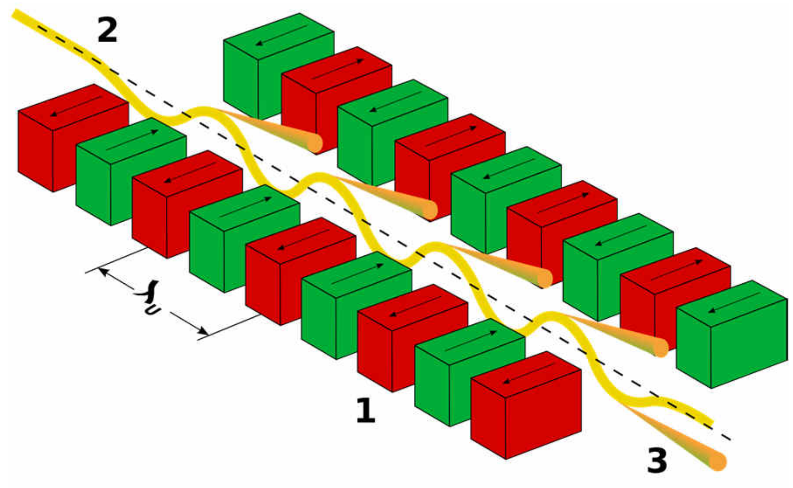



hamamatsu.com

A gain/gap curve is measured to see if the gaps correspond to the correct photon energies. To do this, one sets the monochromator at a certain energy, and scans the gap opening of the undulators, looking at the gain from diodes or MCP detectors for the best performance.

XFEL beam positioning and profiling: MCP detector, diode





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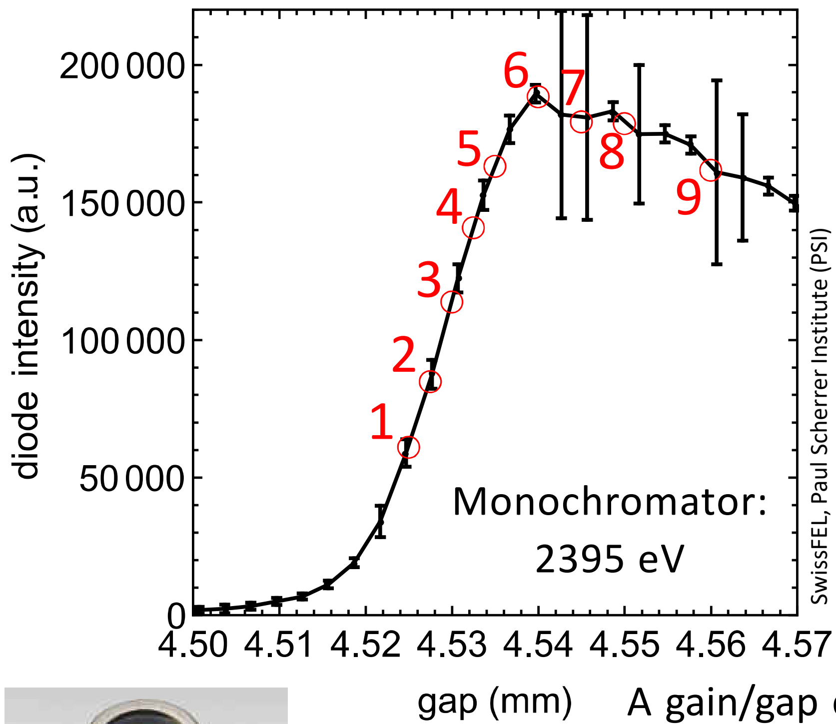
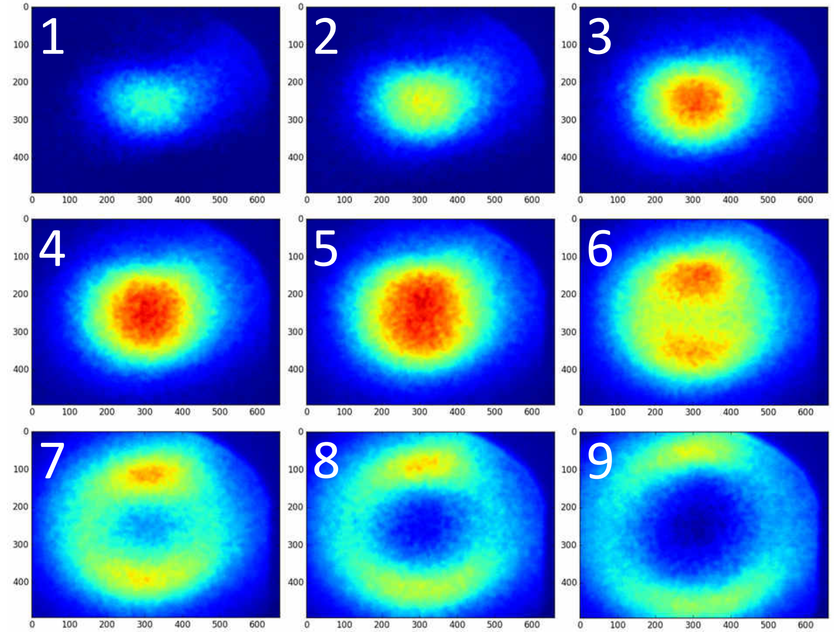


MCP readings



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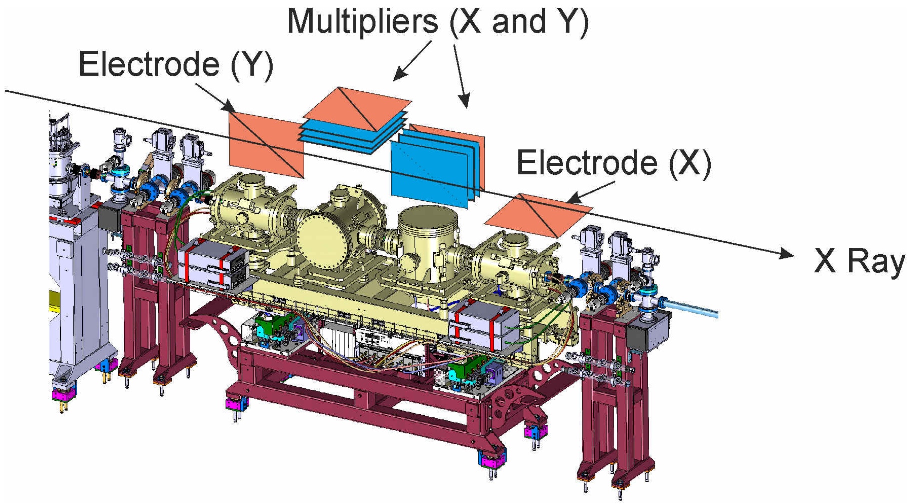
Pulse energy monitoring: gas-based detector, backscattering monitor

- Since the pulse energy changes shot-to-shot, you need to measure the intensity of the FEL beam on a shot-to-shot basis.

- If the beam is monochromatic, the intensity fluctuations can be as much as 100%, i.e. you get no light in some pulses since there is a mismatch between the spectrum of the FEL and the settings of a monchromator. Being able to filter out the bad shots by noting that there was no energy in them becomes invaluable. If you do not have this ability, you do not know if the lack of signal you saw is real (i. e. related to the dynamics in the sample of interest), or you simply did not get the light necessary for the signal.

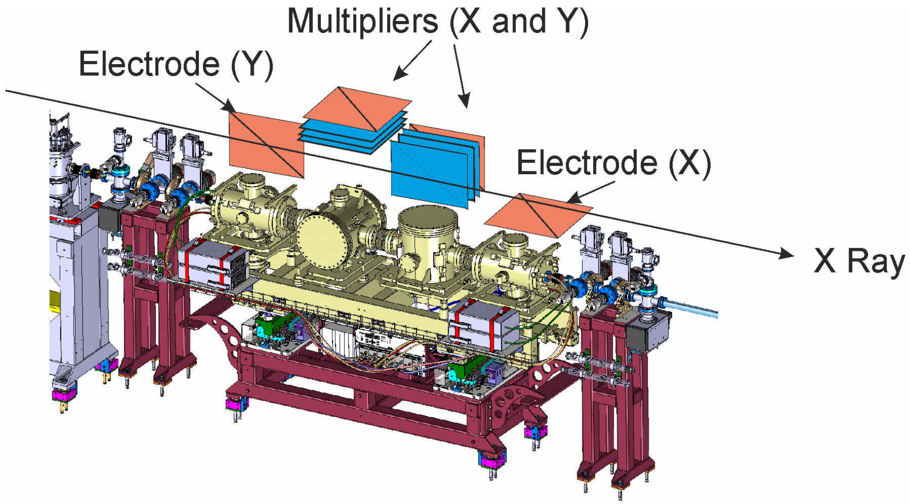
- Most importantly, pulse energy measurement must be non-invasive, to allow users to conduct their experiment at the same time. In other words, the pulse energy must be measured in such a way to allow the light to reach the experiment with minimum interference.

Pulse energy monitoring: gas-based detector, backscattering monitor



- Gas ionization chambers measure pulse energy by counting the number of ions generated in a gas medium.
- Direct current measurements are used for absolute numbers, but are slow.
- Multiplier signal measurements are good for fast measurements, but are relative.
- Fast and slow measurements are combined to get an absolute pulse energy for every pulse.

Pulse energy monitoring: gas-based detector, backscattering monitor



Number of particles detected (electrons or ions), corrected by their expected average charge.

$$N_{\text{photon}} = \frac{N_{\text{particle}}}{Q.E.(\hbar\omega)} = \frac{N_{\text{particle}}}{\sigma(\hbar\omega)\cdot z \cdot \eta \cdot n \cdot a}$$

Quantum efficiency

Cross section

Detector amplification factor

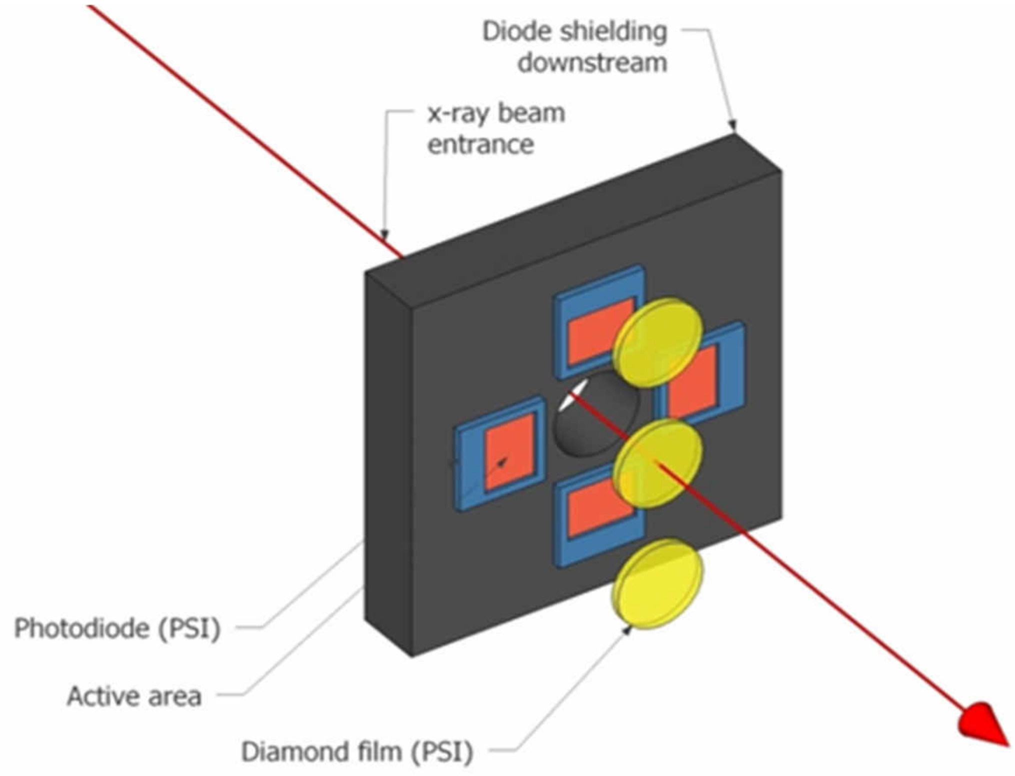
Atomic gas density (requires temperature info)

Detection efficiency

Detector acceptance length

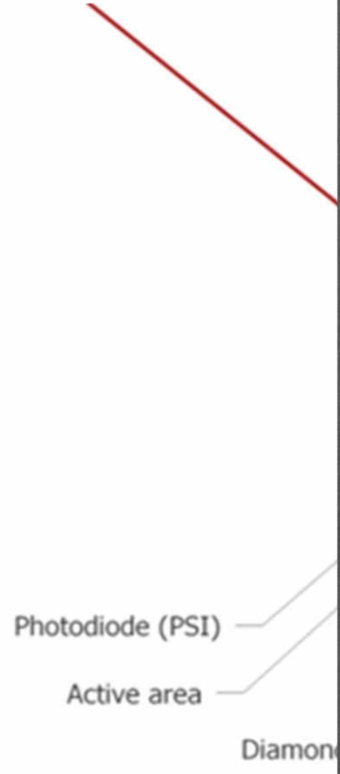
This equation requires a lot of reference data of gas cross-sections and mean charges. If not found in scientific literature, they are typically measured in collaboration with other research facilities.

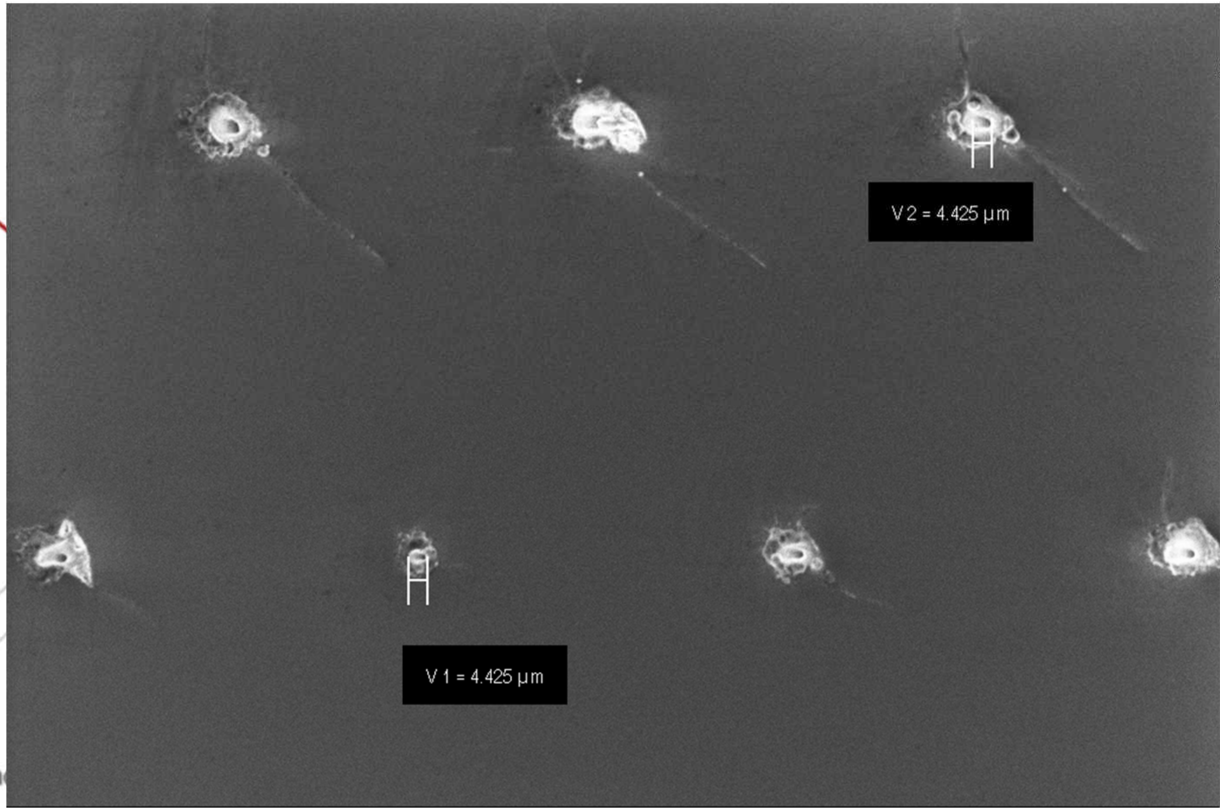
Pulse energy monitoring: gas-based detector, backscattering monitor



- Thin diamond or Si_3N_4 foils let most of the beam through, and the elastically back-scattered photons are detected by the four diodes. Backscattering monitor is used to measure the relative pulse intensity and the position of the beam.
- Here, too, the reference data for the coherent and incoherent scattering of light from the materials are found in old experimental texts, though people have made programs for the evaluation these days.
- Very compact, useful for end-station measurement of pulse energies.

Pulse energy monitoring: gas-based detector, backscattering monitor





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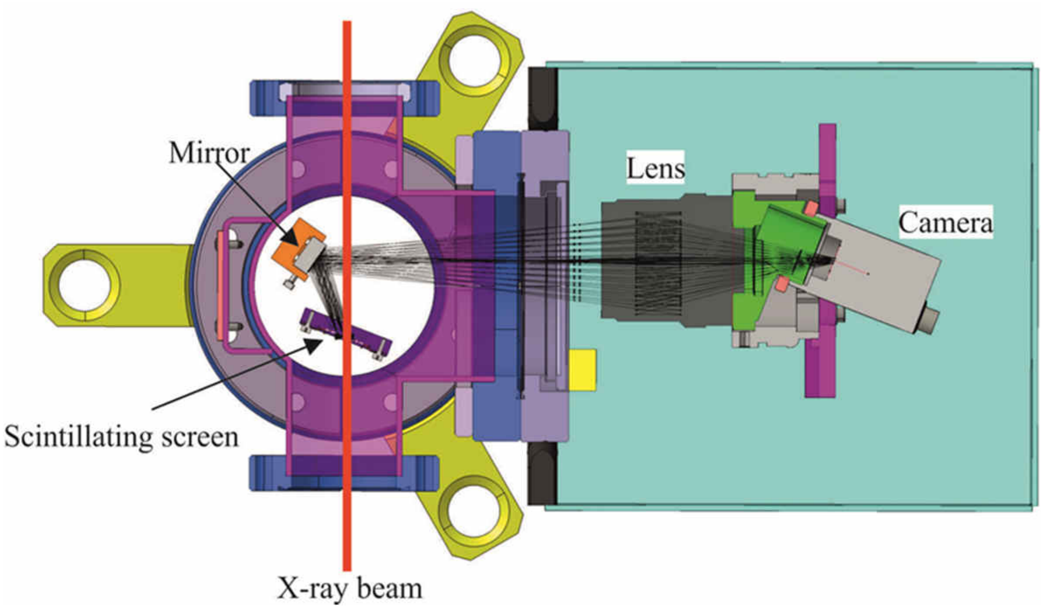
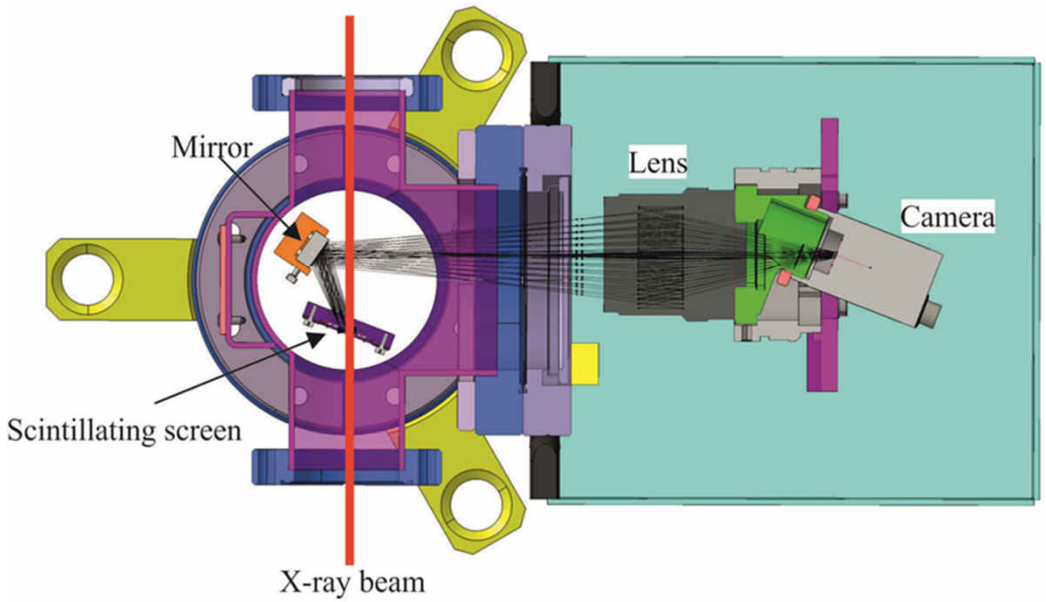
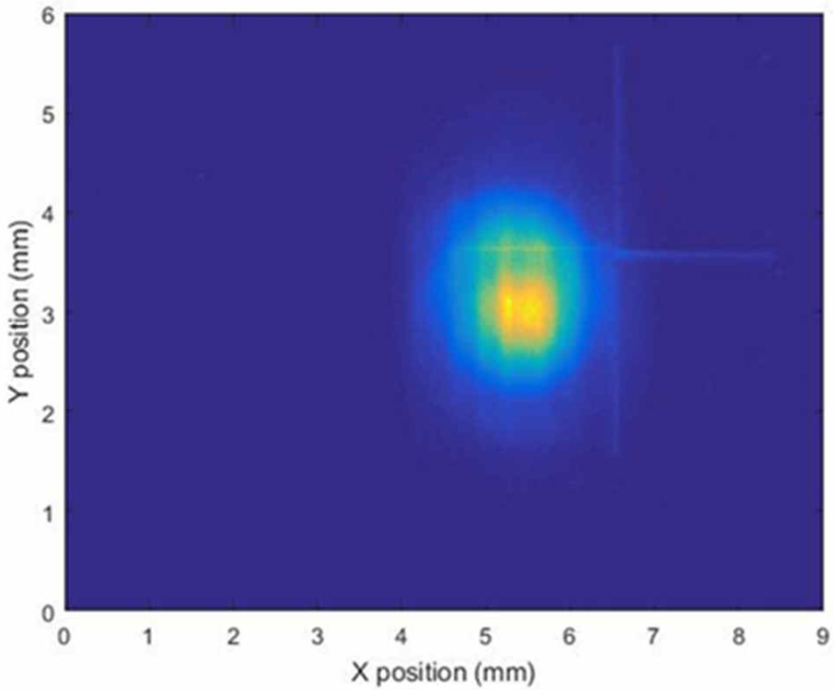
Pulse profile measurement: scintillating screen, optics, camera



Even something as simple as a 2-dimensional visible light-camera (e. g. CCD) can be adapted for better accuracy. In the design shown the mirror and the camera do not move — only the scintillating screen does (because of the XFEL beam damage). The camera always looks at the exact same spot, so any motion detected can only come from the motion of the beam.

Pulse profile measurement: scintillating screen, optics, camera





Pulse spectrum measurement: grating, X-ray spectrometers

Online measurement of the XFEL beam spectra is all about Bragg diffraction. One equation to remember – the Bragg's diffraction law:

$$2d * \sin\theta_B = n\lambda = n\frac{hc}{E}$$

, where d – lattice spacing constant, θ_B – Bragg angle, n – diffraction order (n=1,2,3,…), λ – wavelength, h – Planck's constant, c – speed of light, E – photon energy.

BraggDiffractionWB.nb

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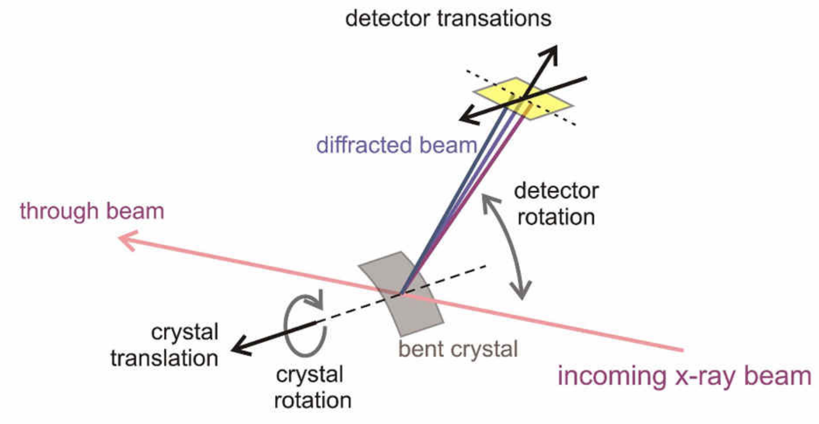

D. Rich *et al.*, *J. Synchrotron Radiat.* **23**, 3 (2016).

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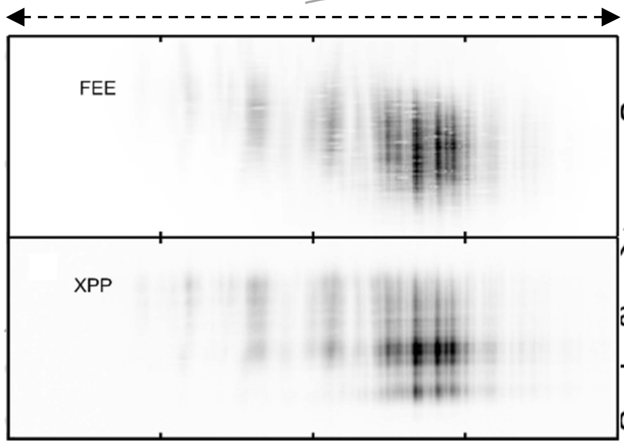

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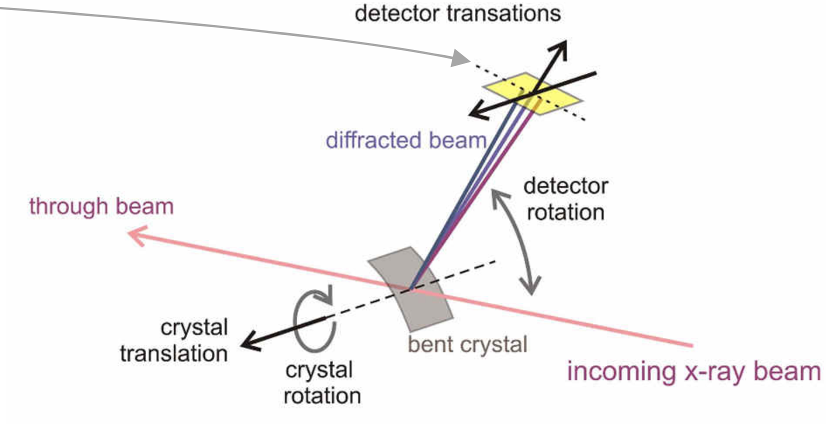

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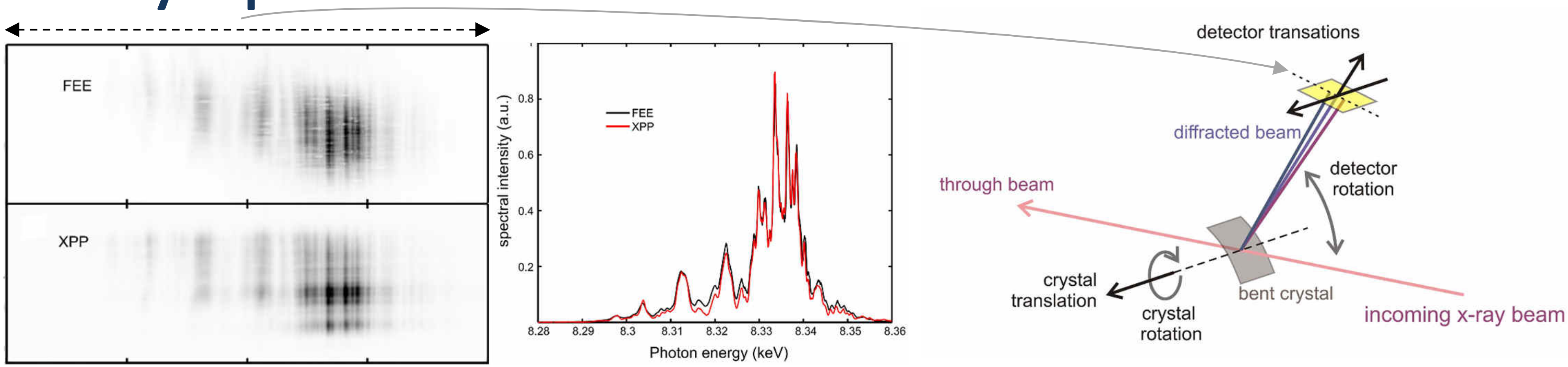

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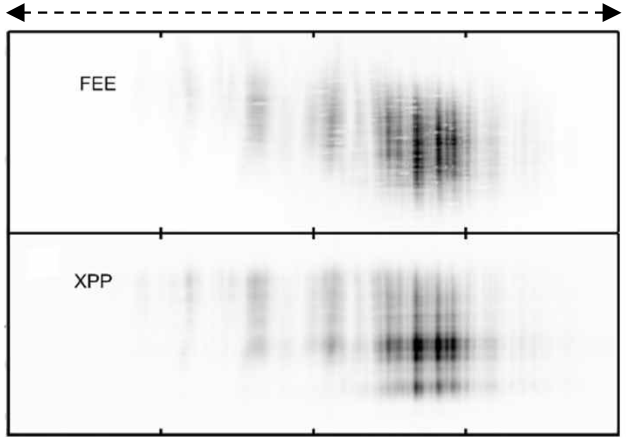

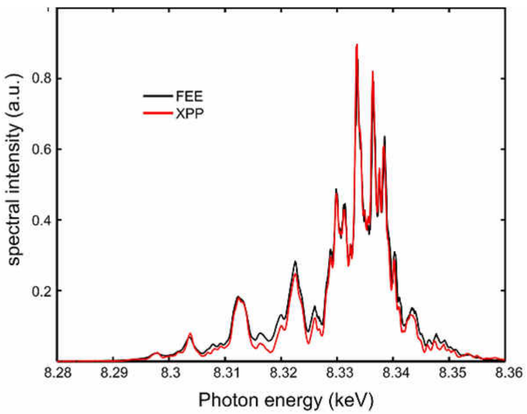

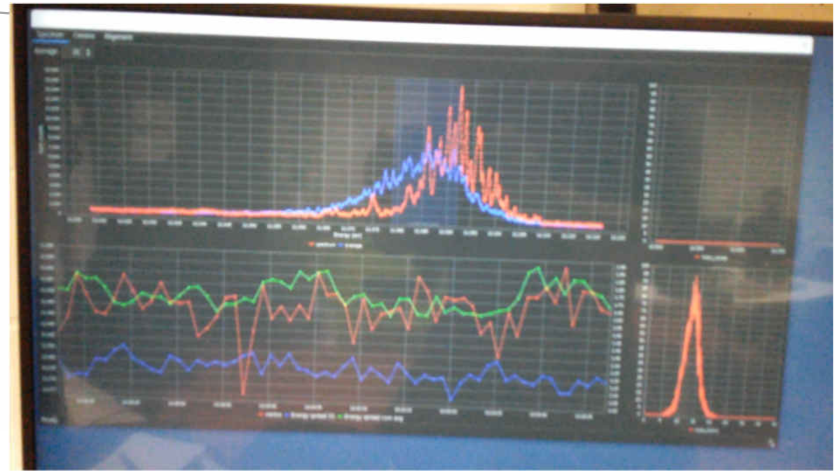

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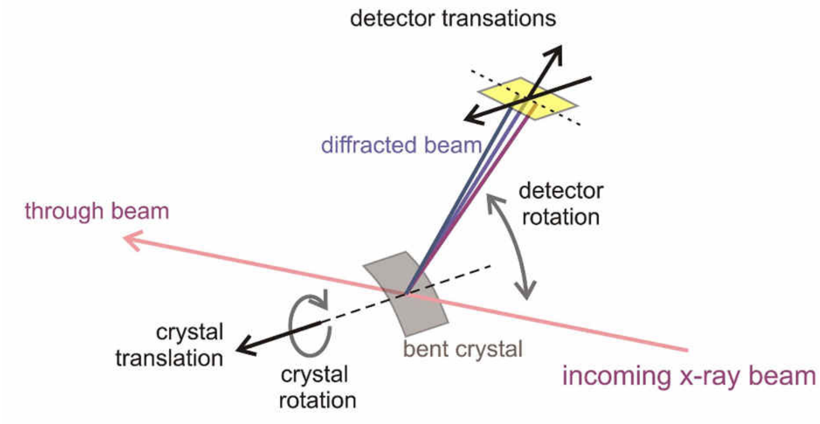
, where d – lattice spacing constant, θ_B – Bragg angle, n – diffraction order (n=1,2,3,...), λ – wavelength, h – Planck's constant, c – speed of light, E – photon energy.



D. Rich *et al.*, *J. Synchrotron Radiat.* **23**, 3 (2016).

Pulse spectrum measurement: grating, X-ray spectrometers

Online measurement of the XFEL beam spectra is all about Bragg diffraction. One equation to remember – the Bragg's diffraction law:

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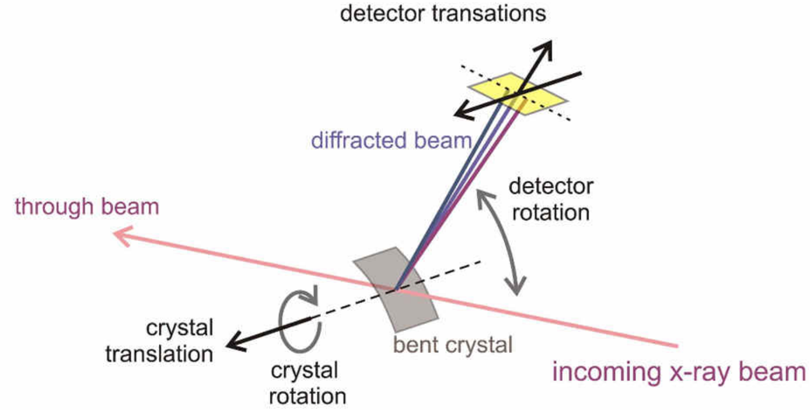
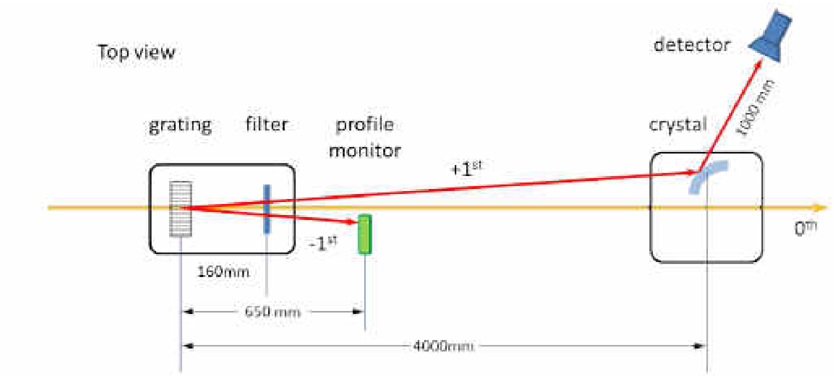


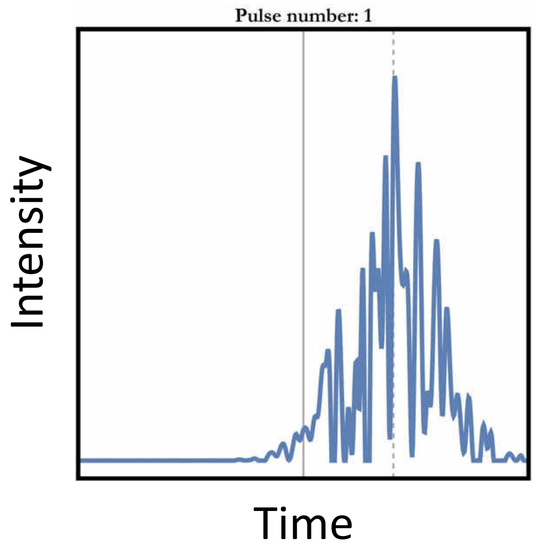
D. Rich *et al.*, *J. Synchrotron Radiat.* **23**, 3 (2016).



Use a grating to split off a part of the beam to shoot onto a bent crystal spectrometer. This allows us to see whole spectrum while letting main beam (>95%) through.

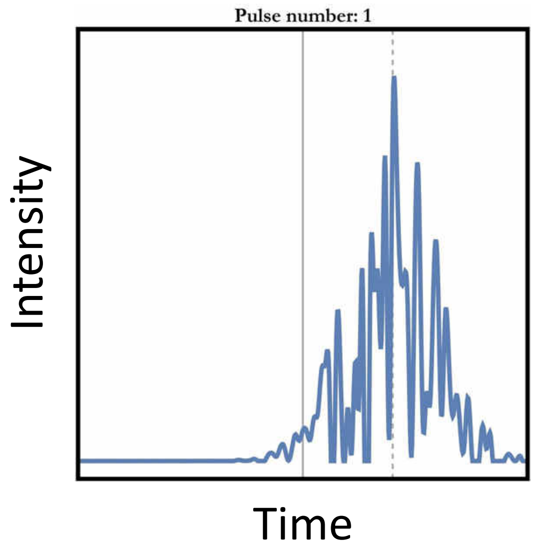
Temporal diagnostics: spatial and spectral encoding, THz streaking

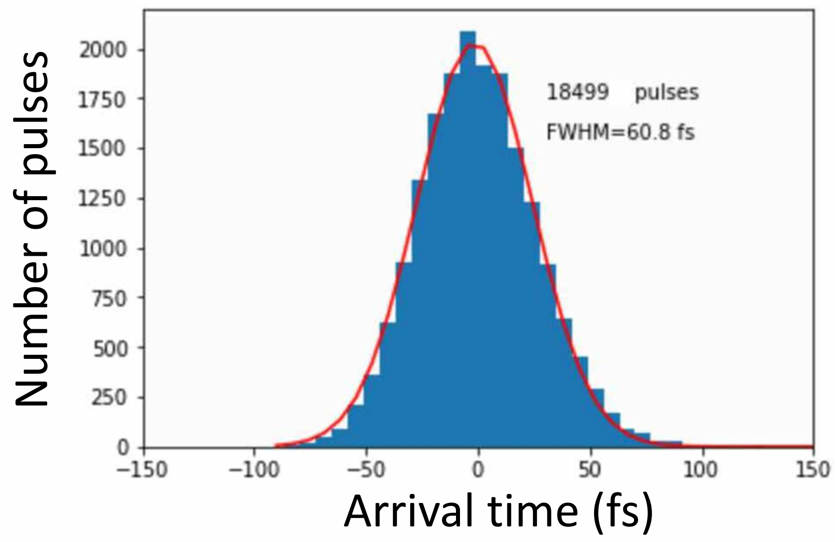
- XFEL pulse arrival time



Temporal diagnostics: spatial and spectral encoding, THz streaking

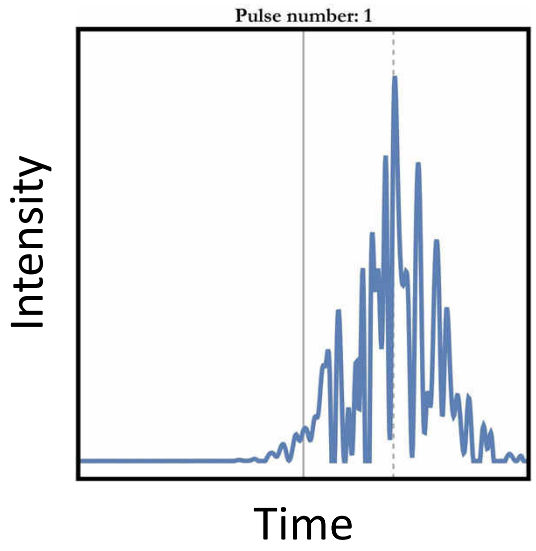
- XFEL pulse arrival time

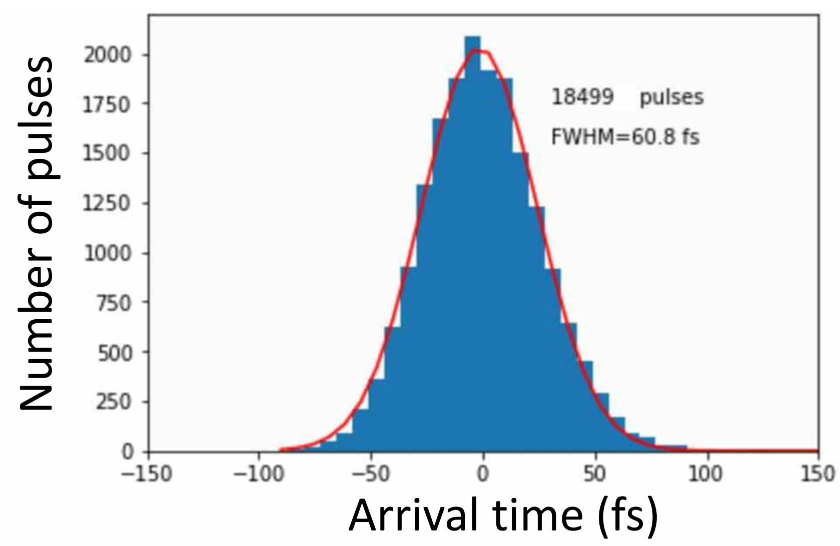




Temporal diagnostics: spatial and spectral encoding, THz streaking

- XFEL pulse arrival time

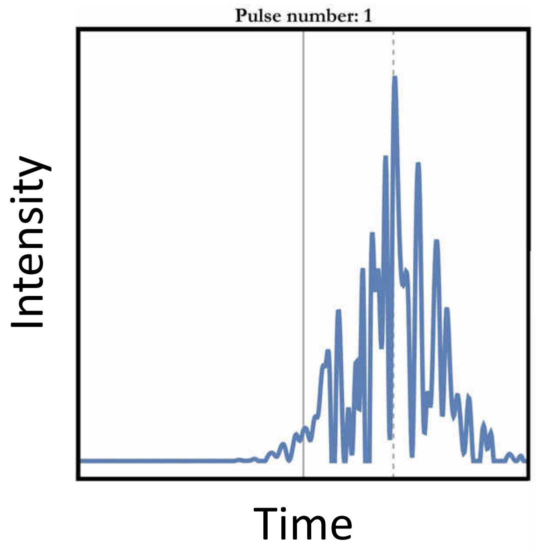




- XFEL pulse duration (or length)

Temporal diagnostics: spatial and spectral encoding, THz streaking

- XFEL pulse arrival time



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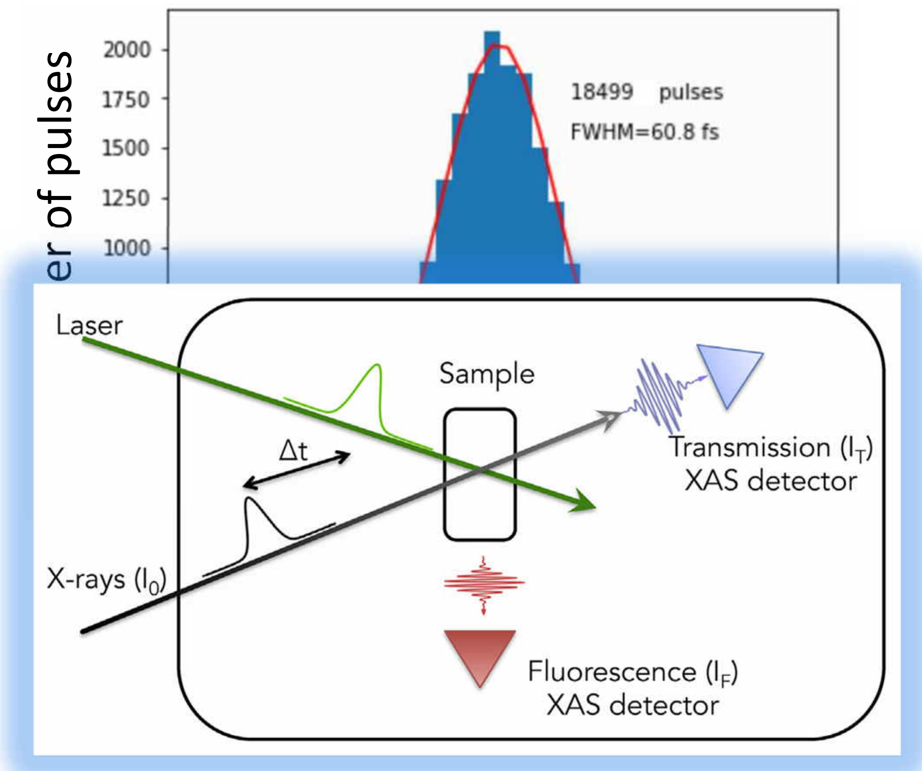
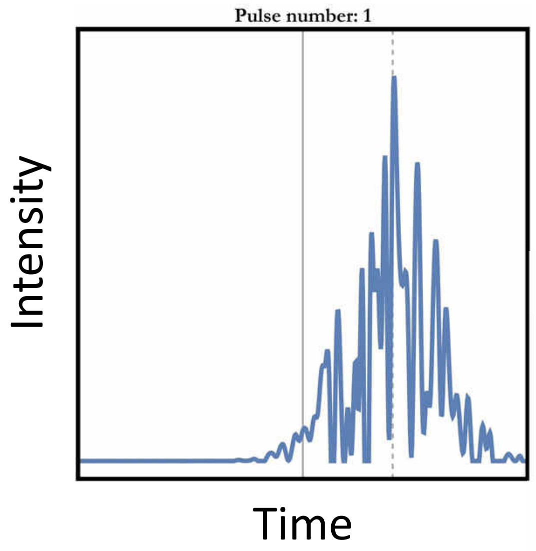
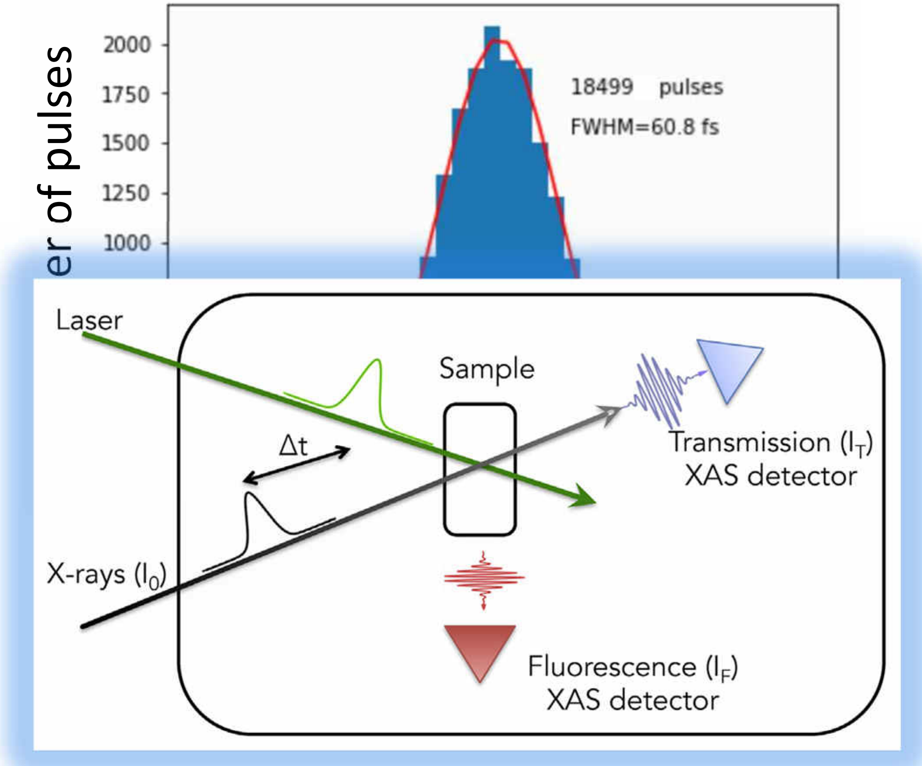


C. J. Milne, T. J. Penfold, M. Chergui, *Coordination Chemistry Reviews* **277**, 44 (2014).

Temporal diagnostics: spatial and spectral encoding, THz streaking

- XFEL pulse arrival time

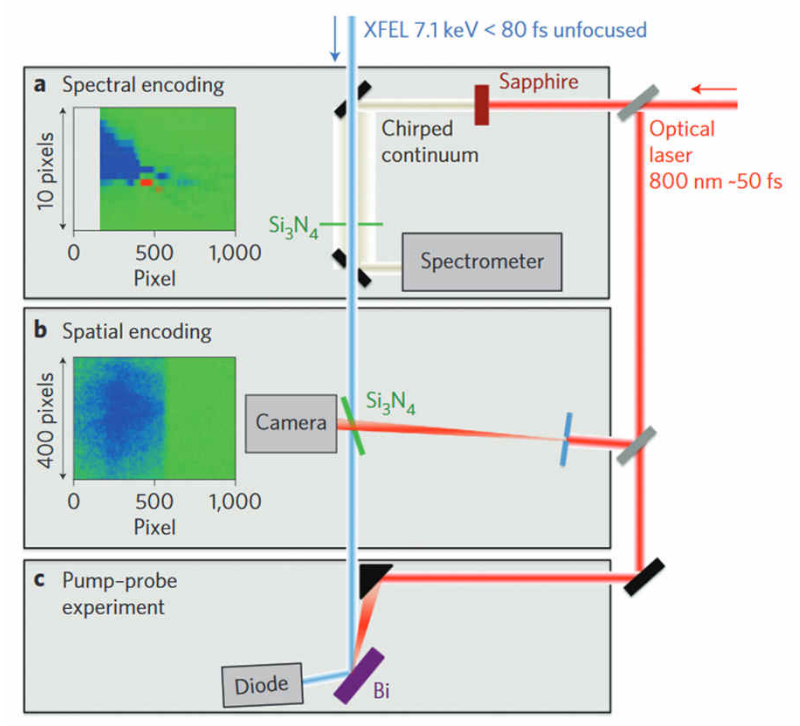




C. J. Milne, T. J. Penfold, M. Chergui, *Coordination Chemistry Reviews* **277**, 44 (2014).

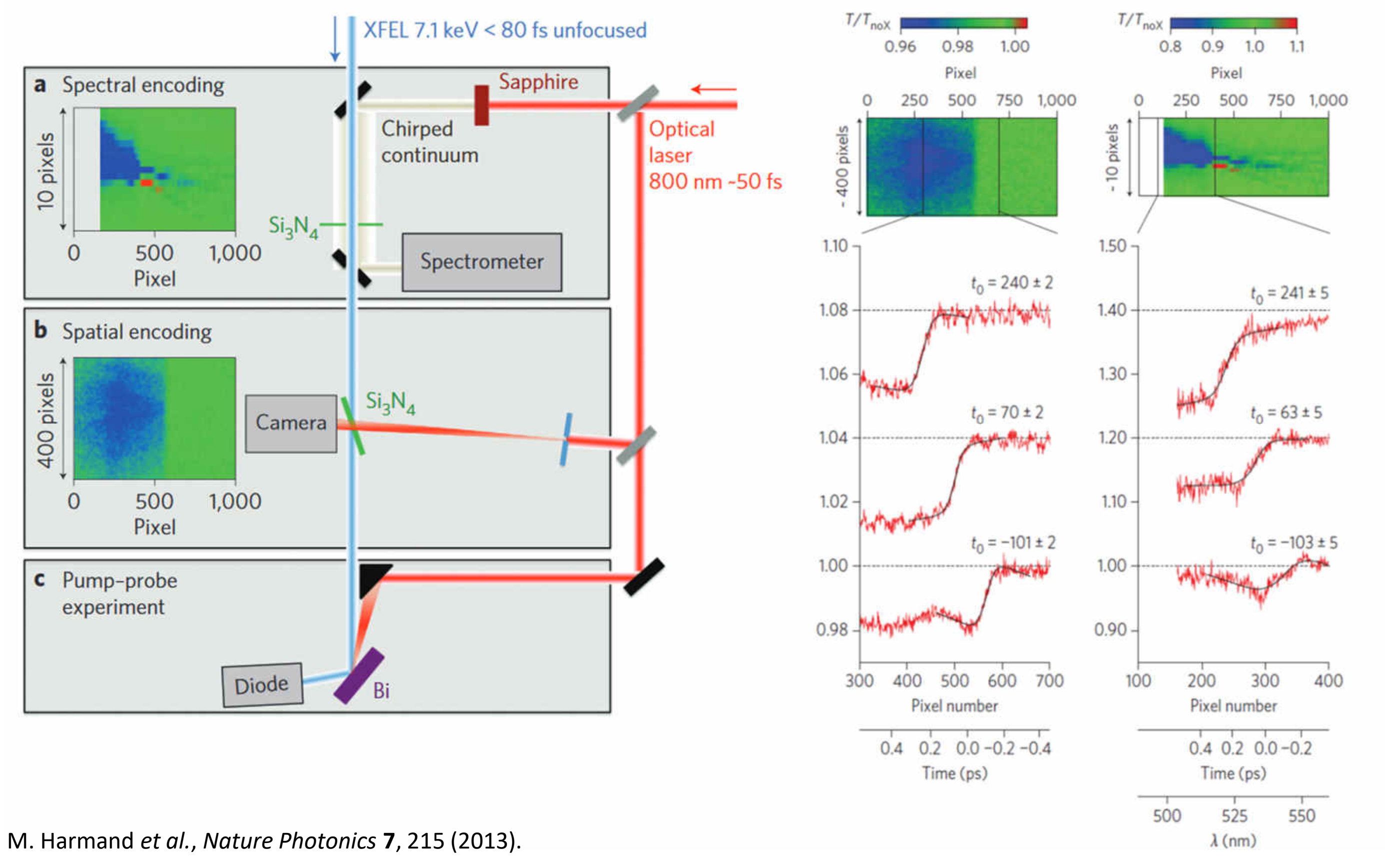
- XFEL pulse duration (or length)
- XFEL pulse time structure

Temporal diagnostics: spatial and spectral encoding, THz streaking



M. Harmand *et al.*, *Nature Photonics* **7**, 215 (2013).

Temporal diagnostics: spatial and spectral encoding, THz streaking



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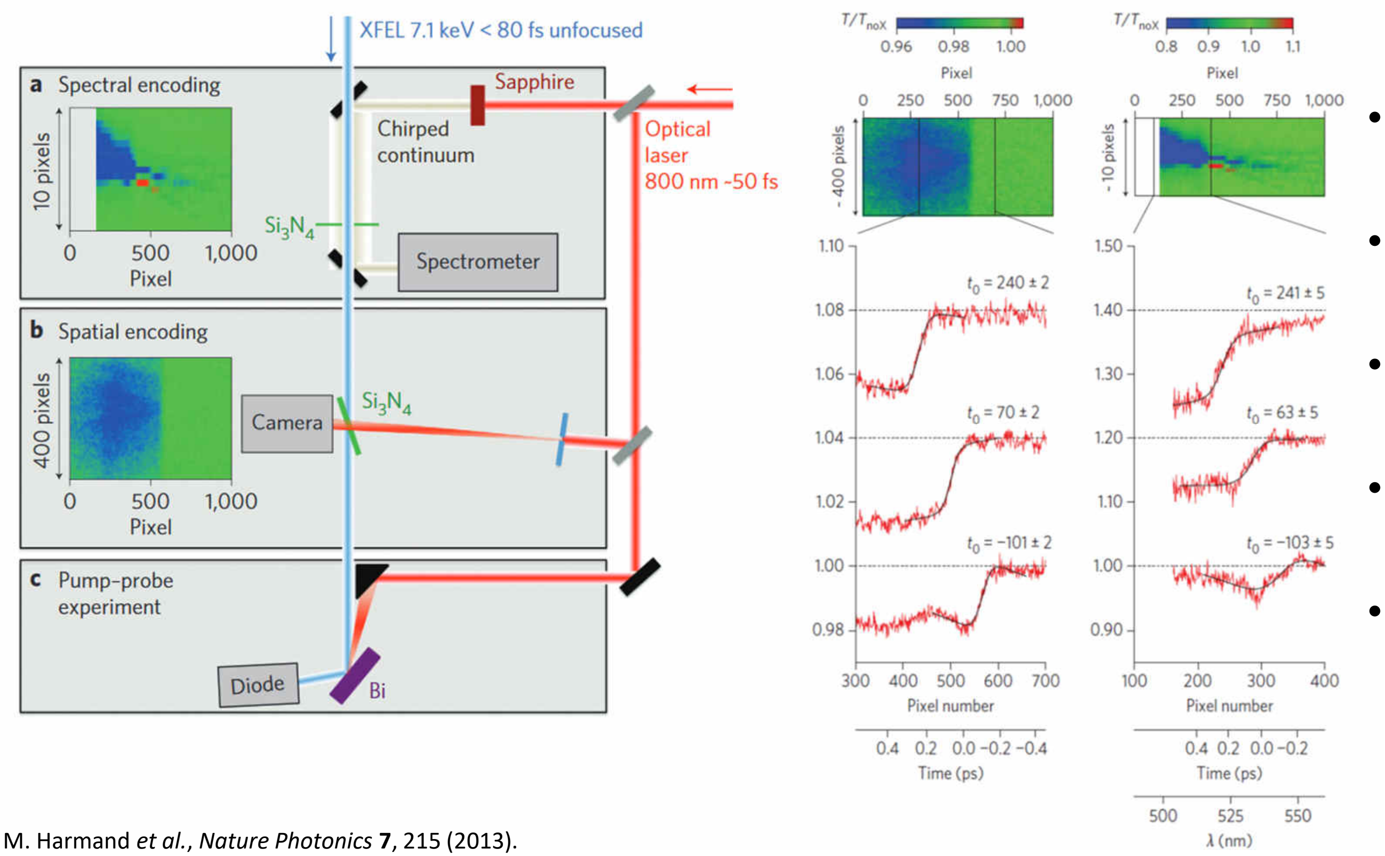
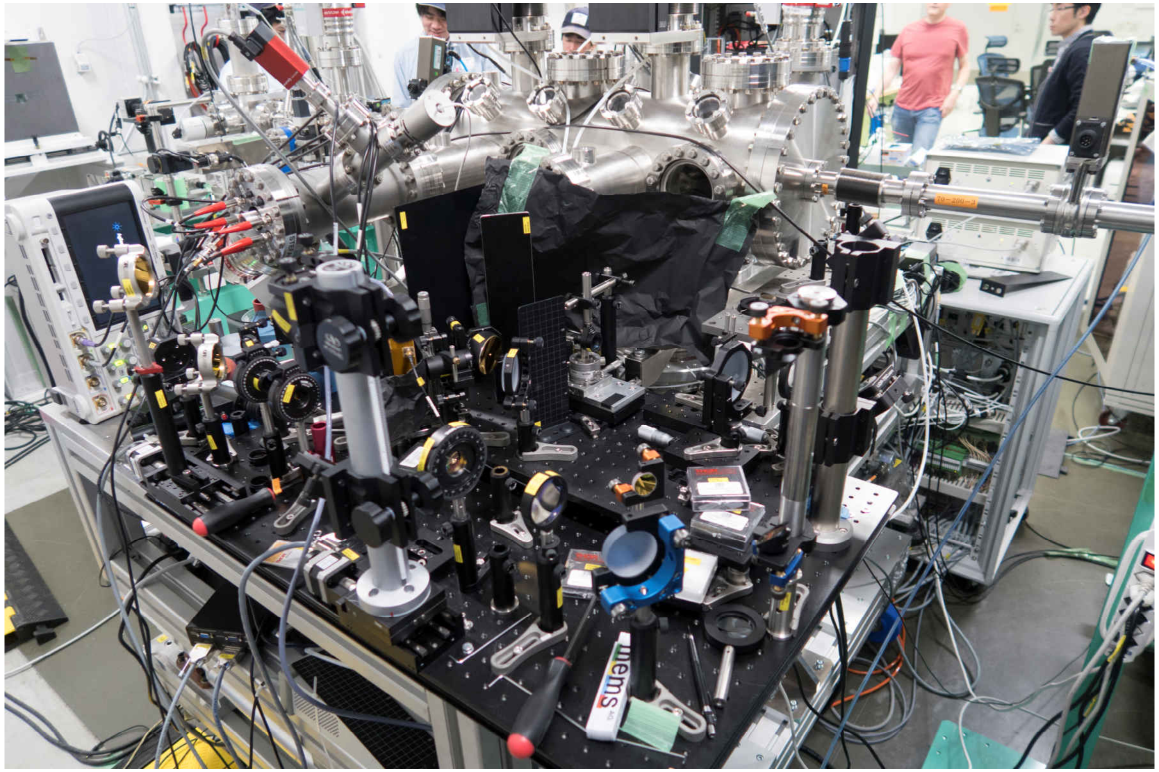
Temporal diagnostics: spatial and spectral encoding, THz streaking



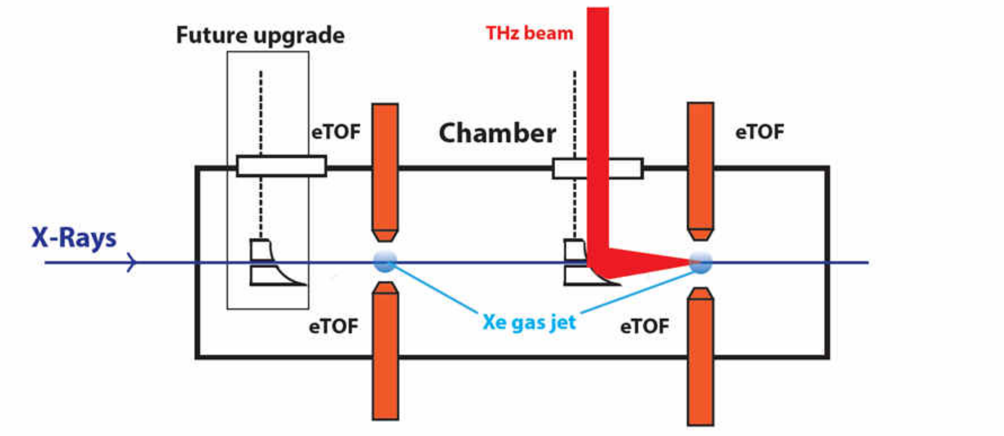
M. Harmand *et al.*, *Nature Photonics* **7**, 215 (2013).

- Can only measure arrival time, not pulse duration.
- Has a large window to work over.
- Can be invasive at low photon energies.
- Reliable tool requiring less setup than the THz streaking.
- Could be hard to find the signal since the edge may be weak.

Temporal diagnostics: spatial and spectral encoding, THz streaking

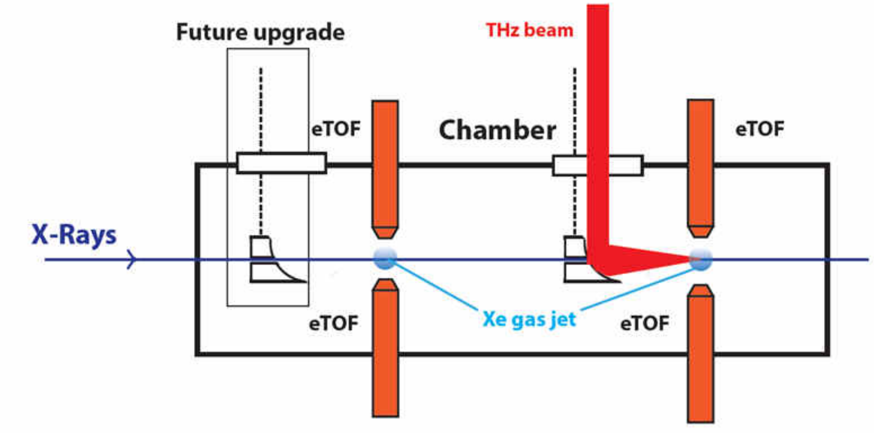


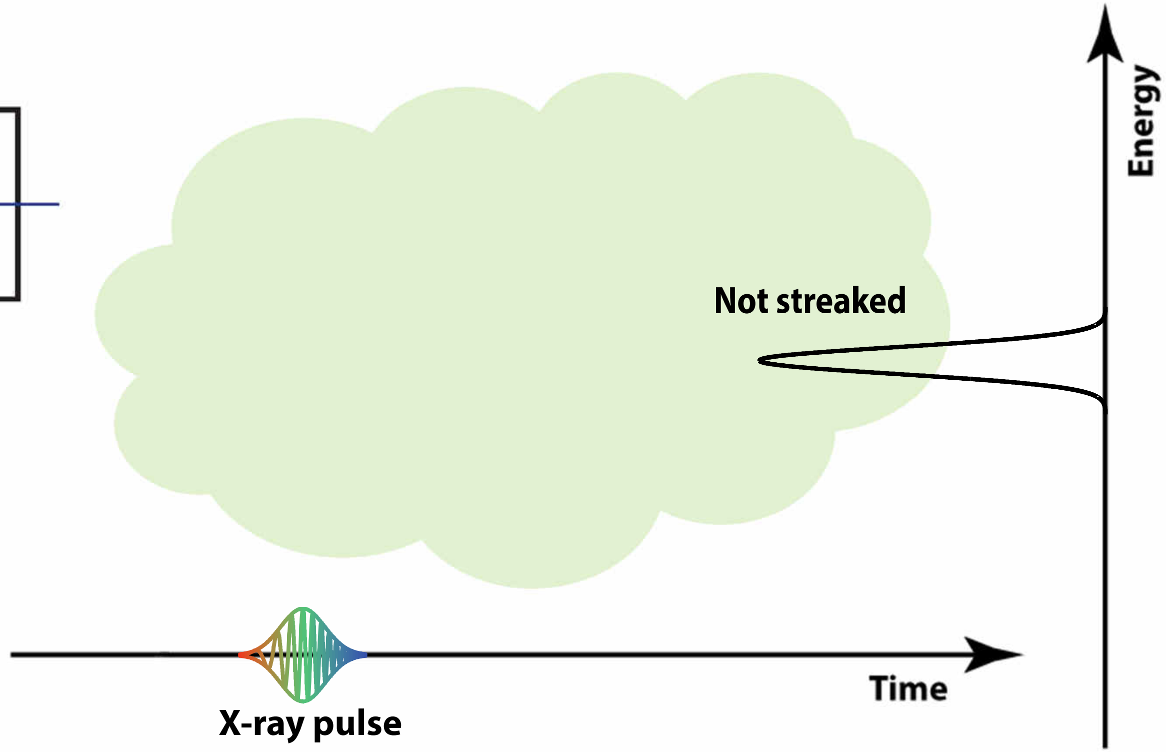
Temporal diagnostics: spatial and spectral encoding, THz streaking



C. Milne *et al.*, *Appl. Sci.* **7**, 720 (2017).

Temporal diagnostics: spatial and spectral encoding, THz streaking





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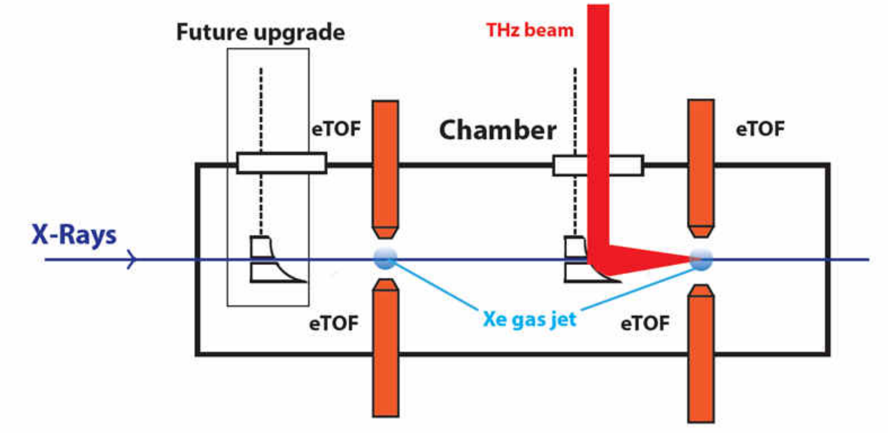
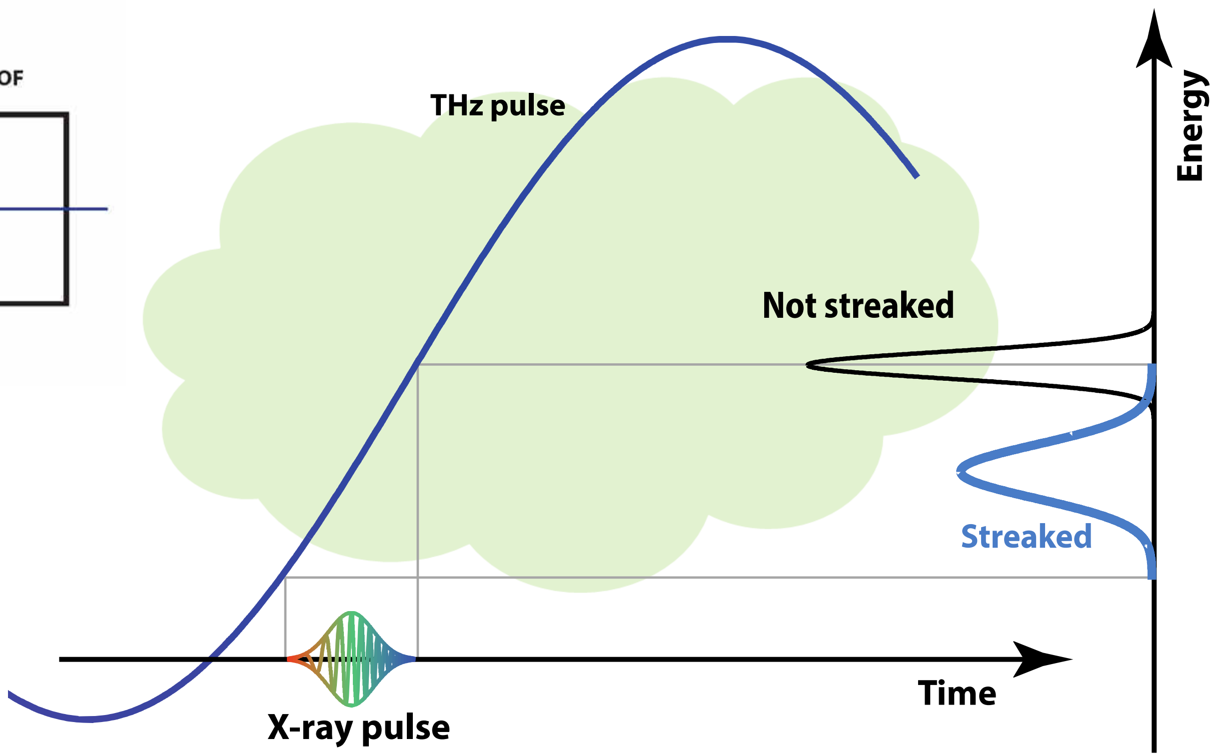
Temporal diagnostics: spatial and spectral encoding, THz streaking





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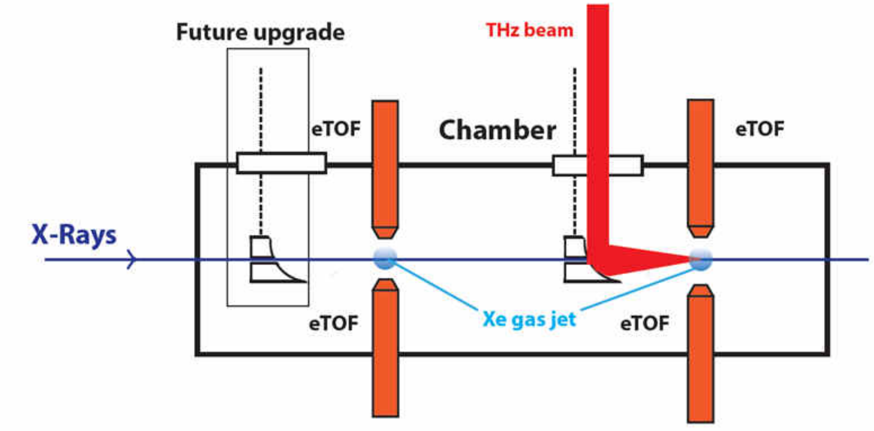
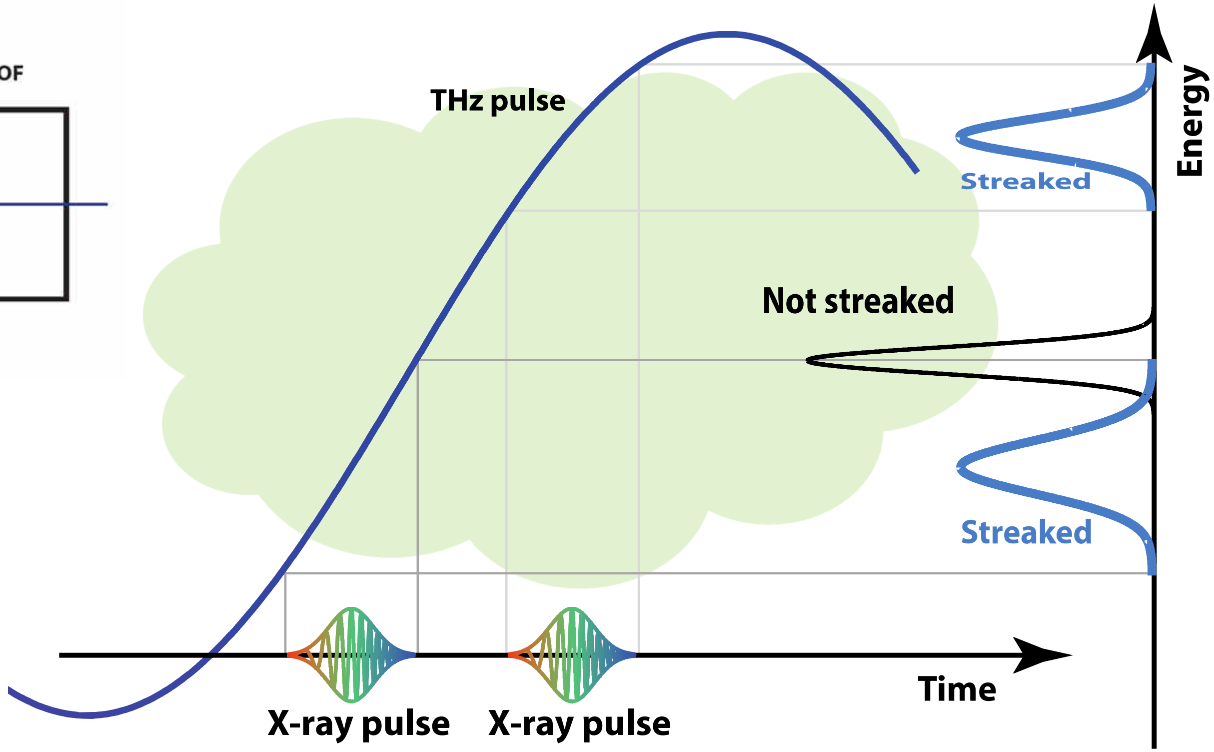
Temporal diagnostics: spatial and spectral encoding, THz streaking





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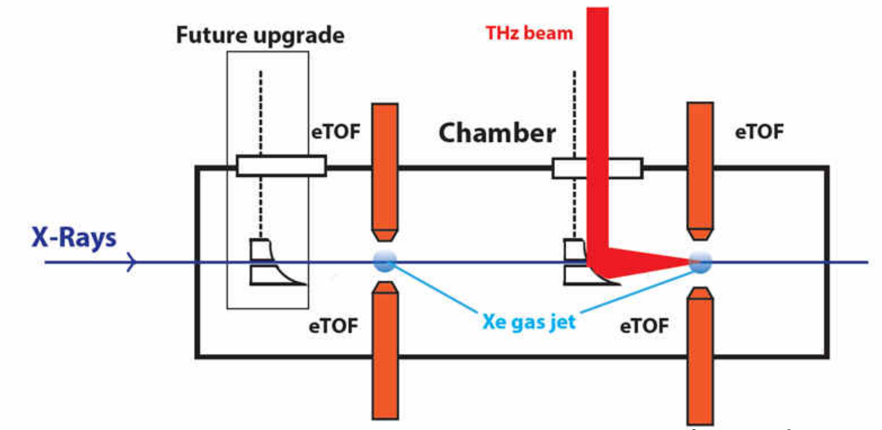
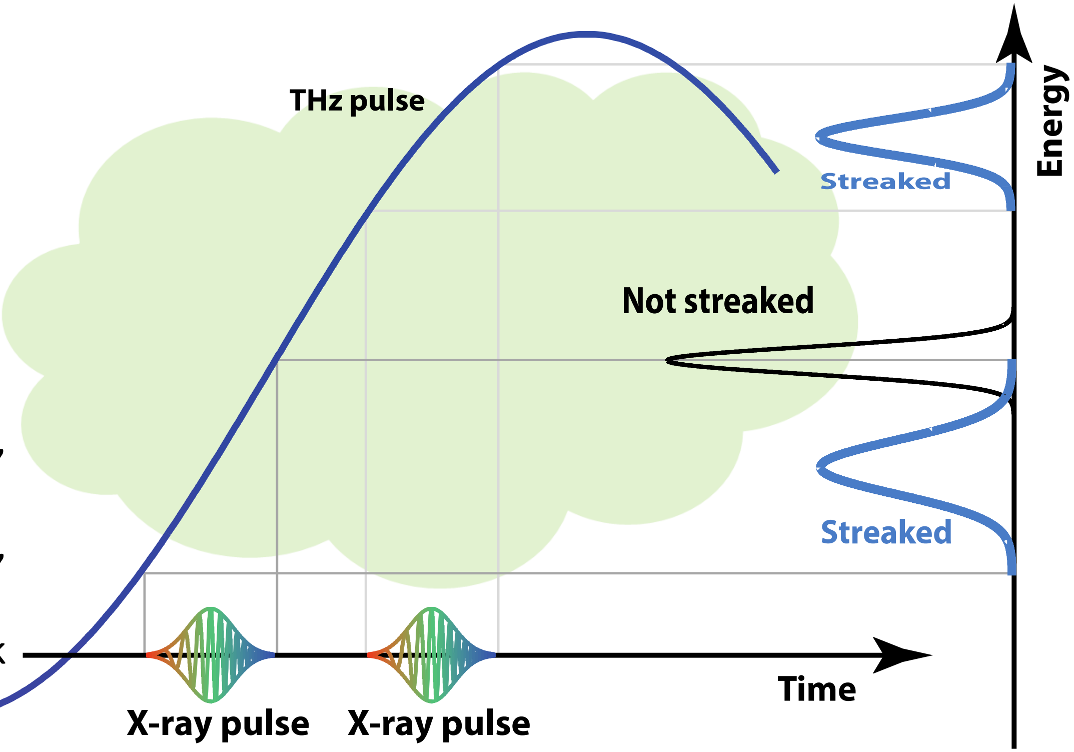
Temporal diagnostics: spatial and spectral encoding, THz streaking





- Very non-invasive e since it is gas-based.
- Can give both arrival time and pulse length, though within a ~600 fs window only.
- Requires lots of work (eTOFs, THz generation, weird mirror geometries).
- Easy to find the signal since it is just a peak moving left and right.

C. Milne *et al.*, *Appl. Sci.* **7**, 720 (2017).

Summary

- Photon Diagnostics are necessary for the proper function and use of current X-ray FELs.
- It is an interesting mix of basic physics, optics, nanofabrication, atomic physics, and engineering, combined with integration with electronics and data systems. Very multi-disciplinary.
- Defining parameters is important — not everything is achievable all the time.
- Once a device is developed, users immediately come up with a way to use them to measure something new and ask for even better devices.