Light-by-light scattering at SACLA/SPring-8

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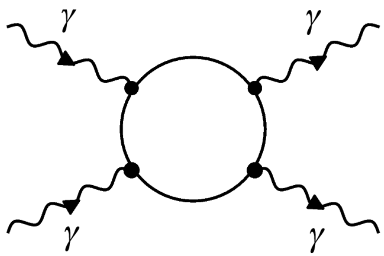
Based on

- *Y. Seino et al, arXiv (in preparation)*
- *T. Inada et at, arXiv:1707.00253*

Probing strong-field QED in electron-photon interactions
Aug. 23 2018, DESY

Light-by-light scattering using XFEL
x-ray + x-ray scattering

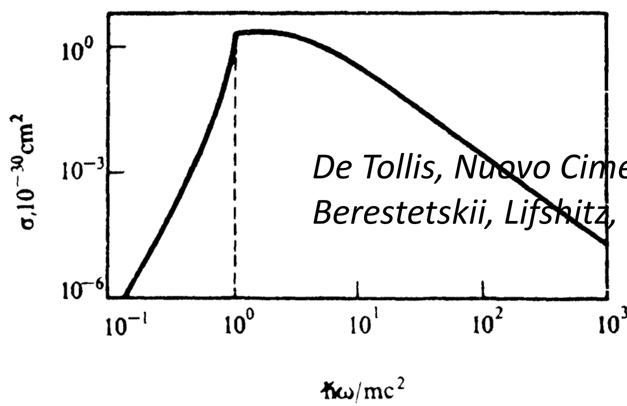
- 5 years ago



started with x-ray + x-ray scattering

- Two reasons

$\sigma \propto \omega^6$ $(\omega < m_e)$



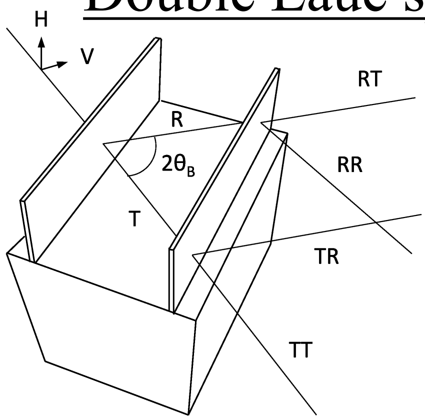
XFEL-SACLA

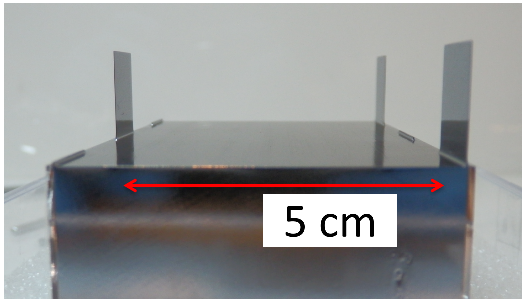
- How to prepare two x-ray beams → two beamlines?

Light-by-light scattering using XFEL x-ray + x-ray scattering

- Branch one beam by a crystal

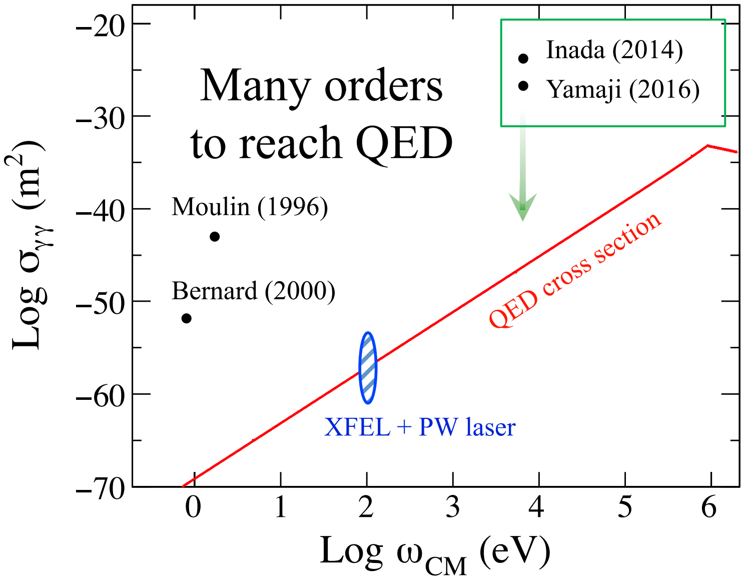
Double Laue splitter (Si440)





Crossing precision ~ 1 Å

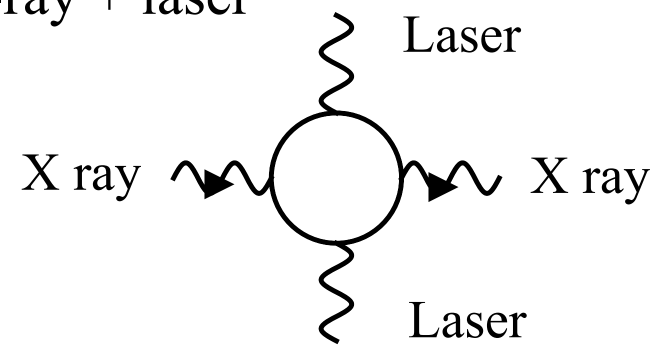
- Intensity reduction by a bandwidth:
  SASE XFELs ~ 50 eV ↔ crystals: 0.1 eV
  → 3 orders (6 orders in sensitivity to σ)
- Using only an XFEL power is not sufficient



Light-by-light scattering using XFEL
x-ray + laser scattering

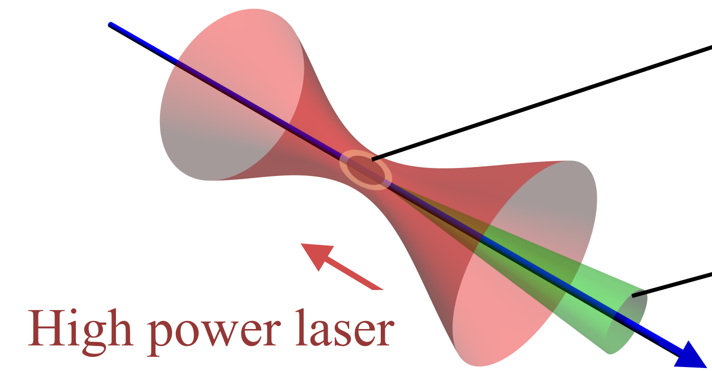
- X-ray + laser

*Heinzl et al., Opt. Comm. **267** (2006)*
*Di Piazza et al., PRL **97** (2006)*



- No beam branching of x rays
- Intense laser field

- Pump-probe experiment without a sample



1 PW laser, 1-3 μm focus:
Strong vacuum polarization
Refractive index $\Delta n \sim 10^{-12}$-10^{-11}

Signal x rays
- **Diffraction**: scattering
- **Birefringence**: polarization flip

Light-by-light scattering using XFEL
x-ray + laser scattering

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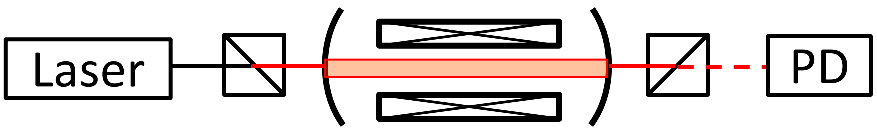
Vacuum Magnetic **Birefringence**:
PVLAS, BMV, OVAL



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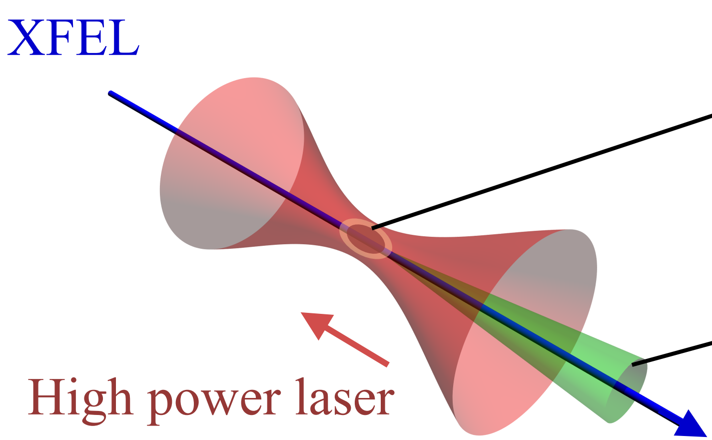
Focusing (spatial modulation)
→ Vacuum **Diffraction**



1 PW laser, 1-3 μm focus:
Strong vacuum polarization
Refractive index $\Delta n \sim 10^{-12}$-10^{-11}

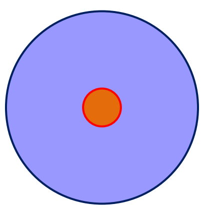
Signal x rays
- **Diffraction**: scattering
- **Birefringence**: polarization flip

Vacuum diffraction Probability and angle

- Diffraction: the increase of an angular div.
  signal div > probe div. but the ratio (probability) is tiny

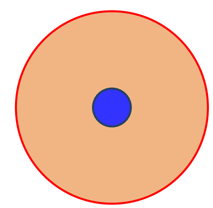
- Cross section of the focal spot

XFEL size ≫ laser size



Wasting most of the probe power
→ Signal ratio decreases

XFEL size ≪ laser size



Probe doesn't feel/see the laser size
→ Signal div. ≈ probe div.

XFEL size ~ laser size: large probability and large increase of div.

Vacuum diffraction Probability and angle

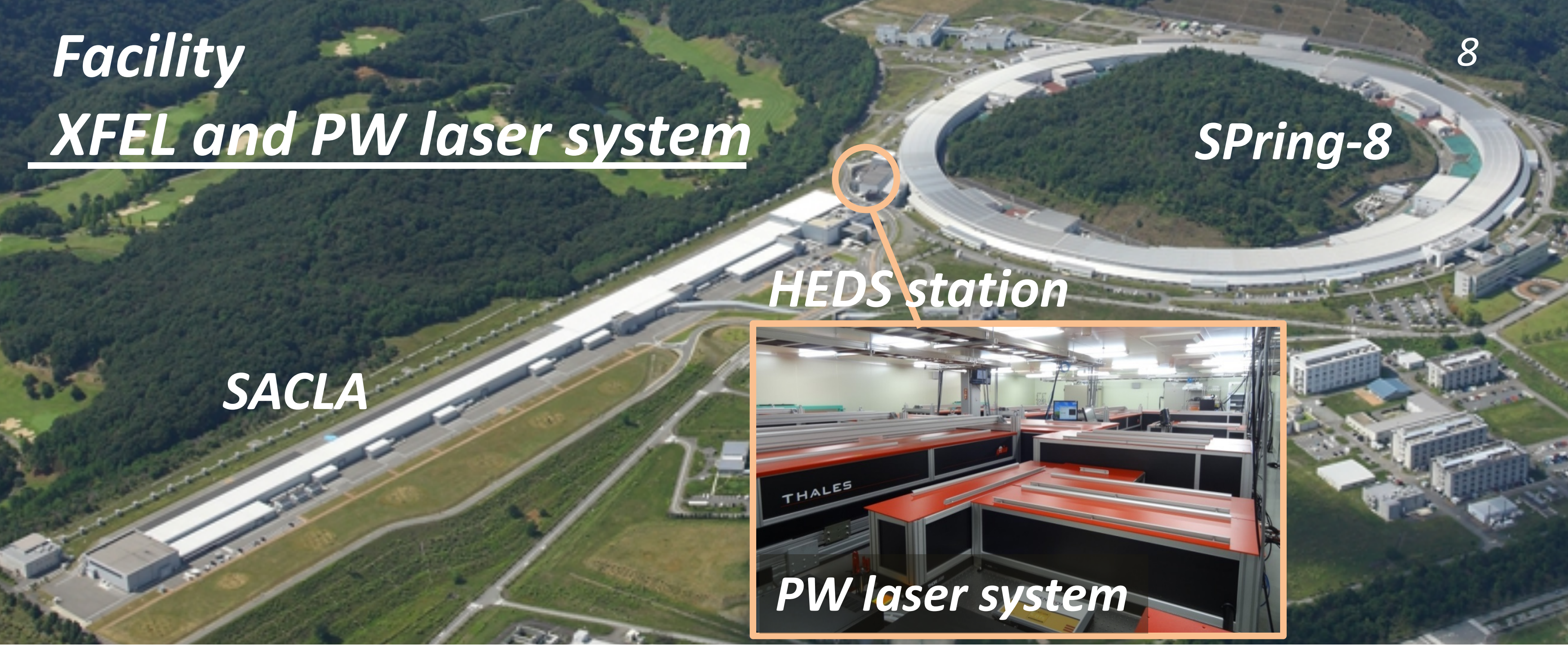
- Focusing a PW laser
  - diffraction limit ~ 1 μm: HERCULES, 0.3 PW

- Focusing an XFEL
  - KB mirror: 1 μm
  - CRL: a few μm

Suppose 1 μm focus to both probe (10 keV) and pump (1 PW),
the diffraction probability ~ 10^{-10} → 10^{6} photon/day

Detailed calc.: *Karbstein & Sundqvist, PRD **94** (2016)*

Facility
XFEL and PW laser system



Probe	XFEL-SACLA
Wavelength	4-29 keV
Pulse energy	0.5 mJ/pulse (~10^{11} photon/pulse)
Angular divergence	0.8 μrad (V/H)
Pulse width	10 fs
Repetition	60 Hz

Pump	PW laser
Wavelength	800 nm
Pulse energy	12.5 J/pulse ×2
Pulse width	25 fs
Repetition	1 Hz

User operation started in 2018

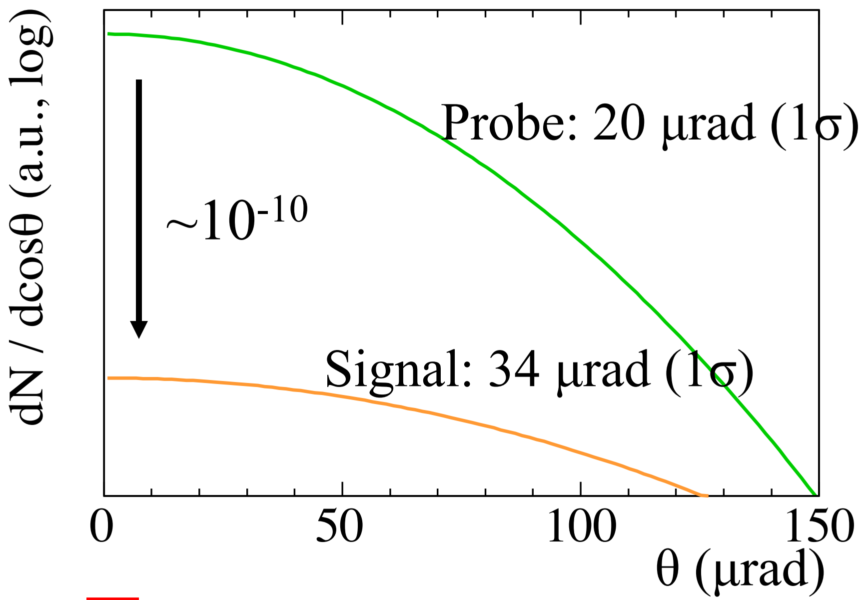
So far we've seen that we can expect a sizable number of signals in XFEL + laser setup.
→ How to detect it?

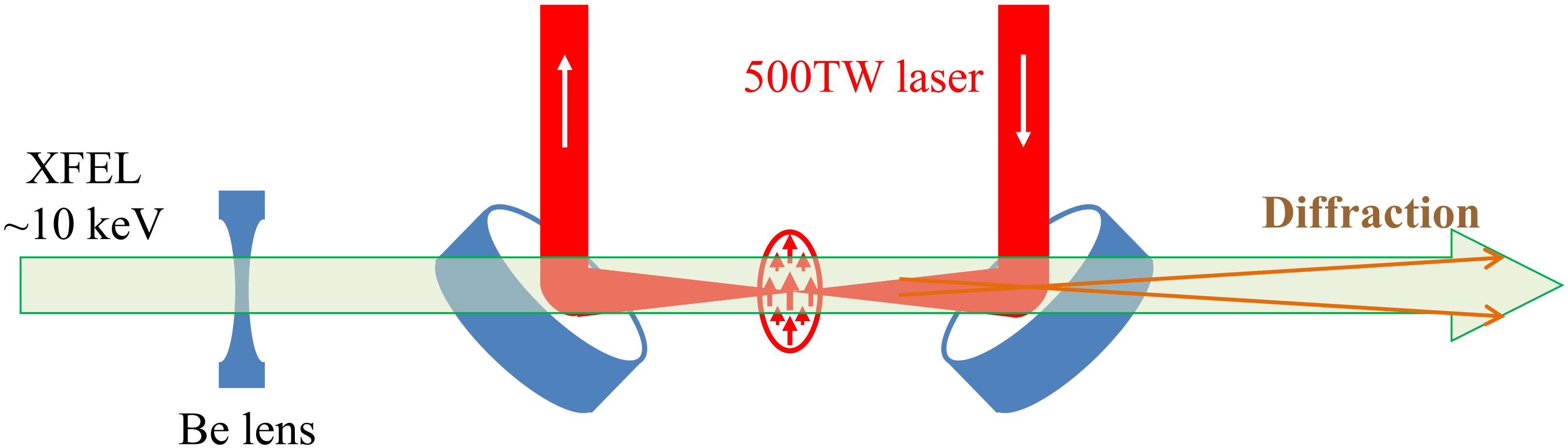
Briefly, I want to go over
- conventional approaches
- polarimeter approach

Comparison of current approaches
Situation

- Probe divergence < signal divergence
  ex: 1 μm focus for both
  20 μrad < 34 μrad

- but the signal is tiny: $\sim 10^{-10}$

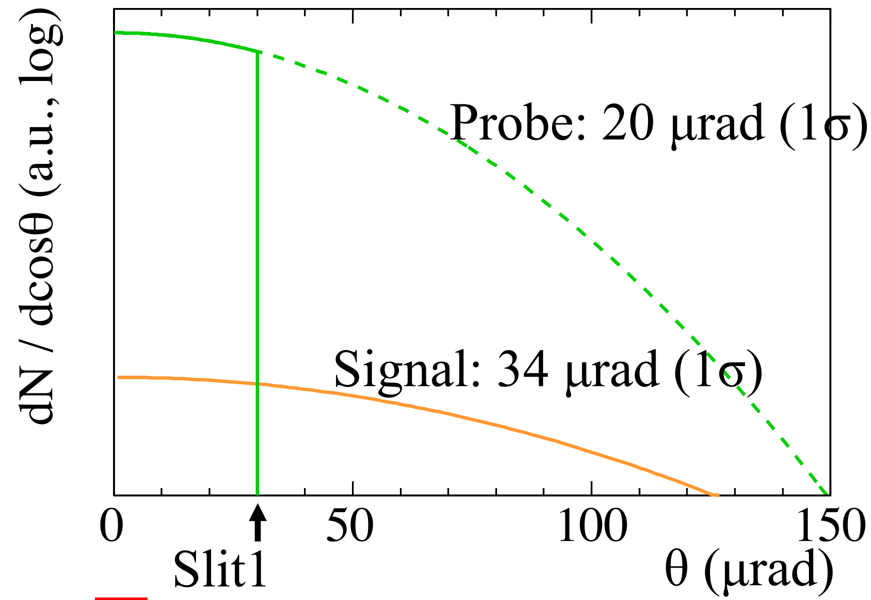


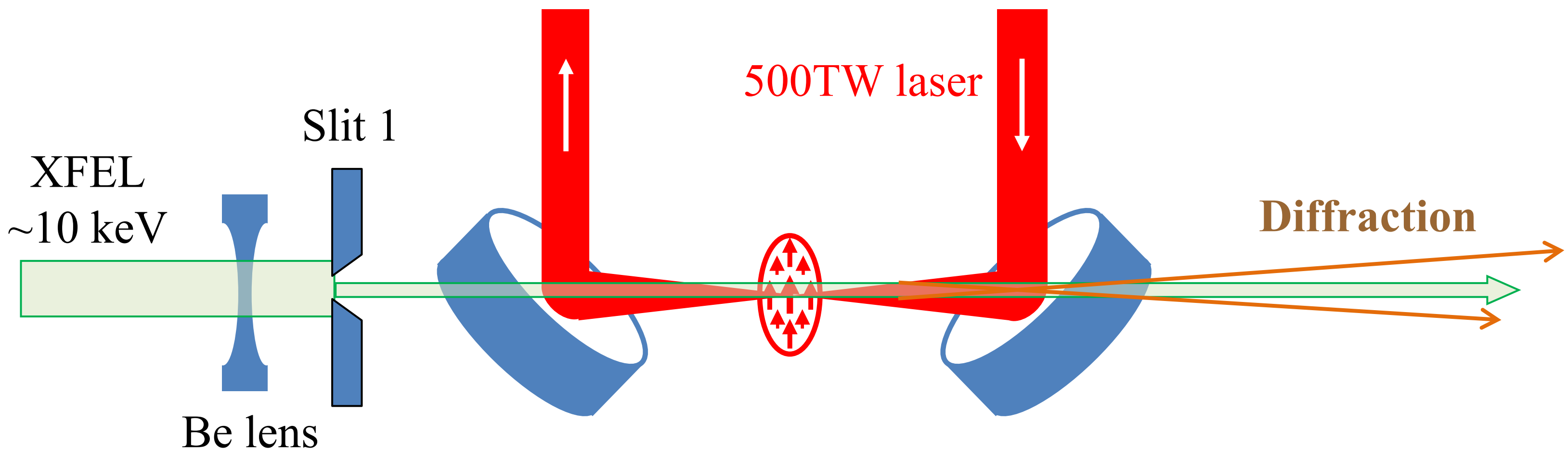


Comparison of current approaches
Slit collimation

Conventional SAXS approach
slit collimation

use only the central fraction (small div.)



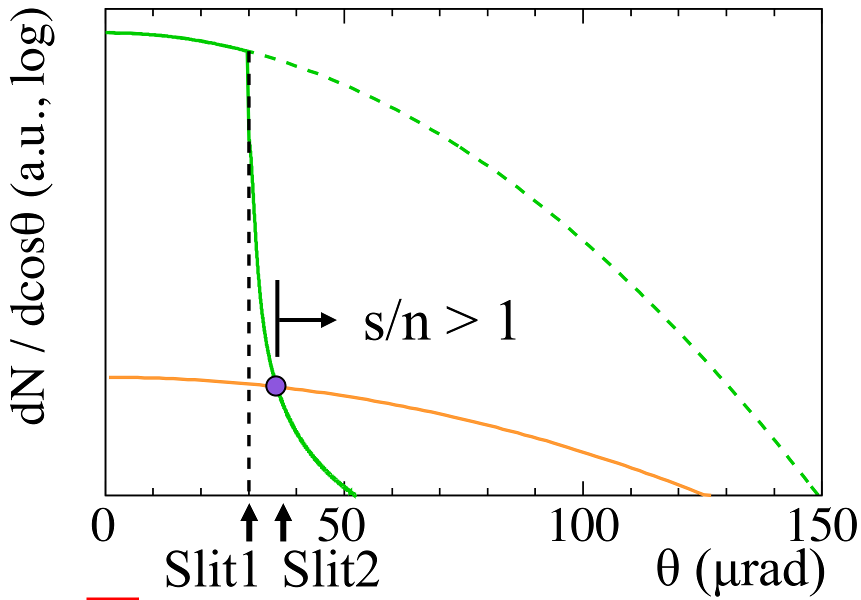


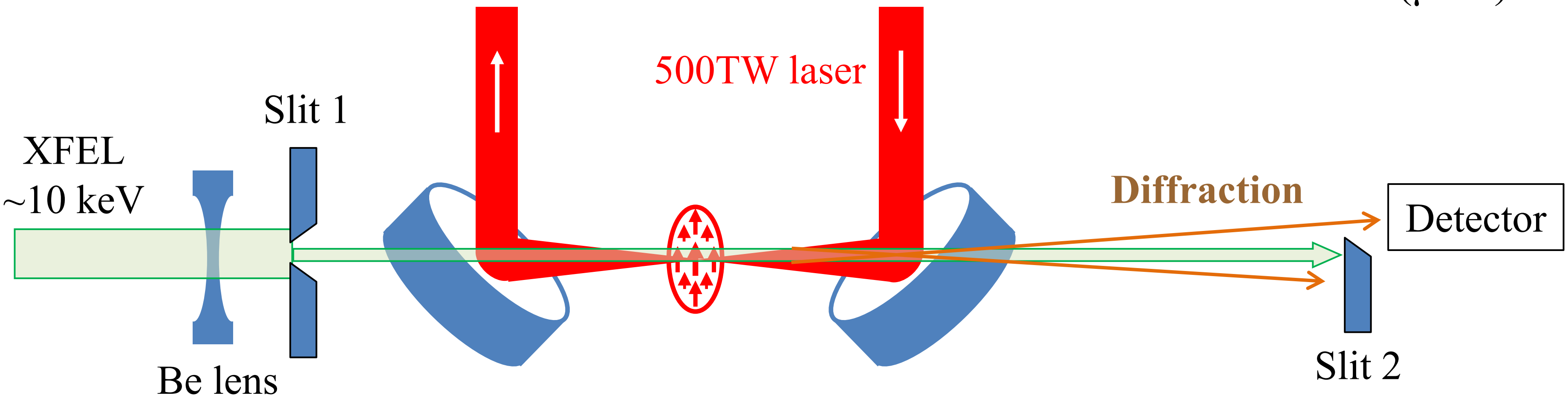
Comparison of current approaches
Slit collimation

- Forward scattering from slit1
  - SAXS: reduce it by other slits
  - High s/n region in large angles

- Slit2 blocks the direct beam
  detector picks up only that region

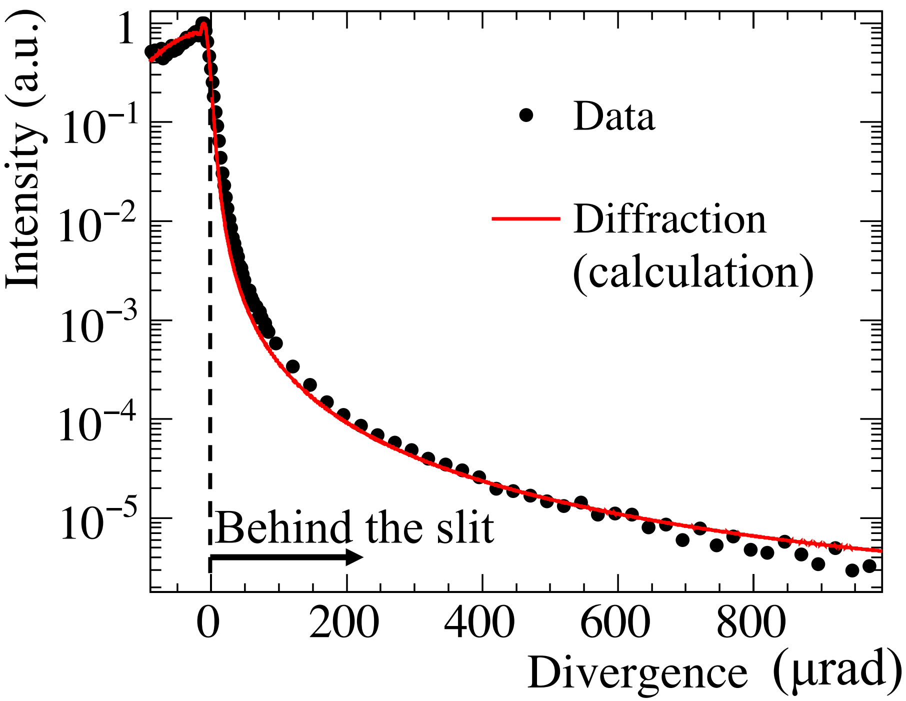
- Good for synchrotron experiments





Comparison of current approaches
Slit collimation

- XFELs have good spatial coherence
  Fresnel/Fraunhofer diffraction occurs at a slit aperture

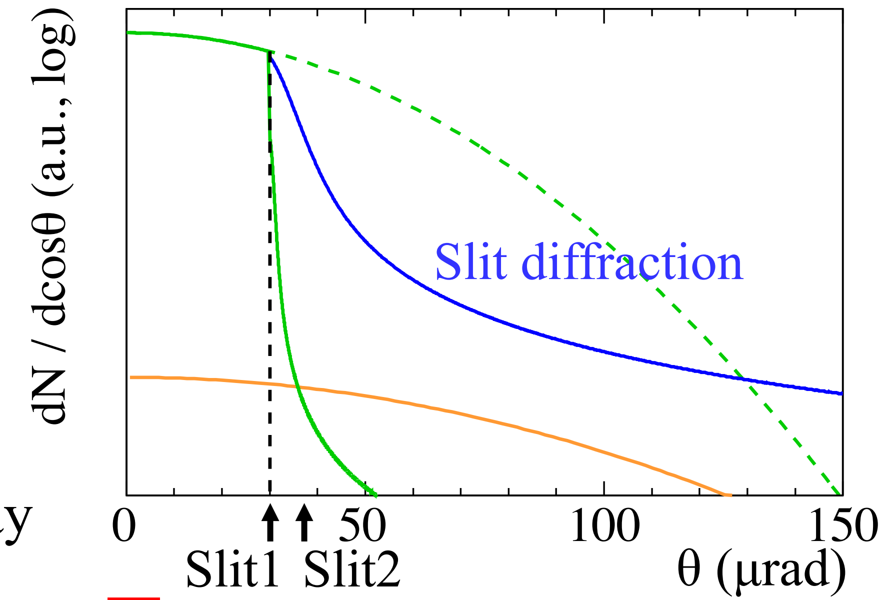


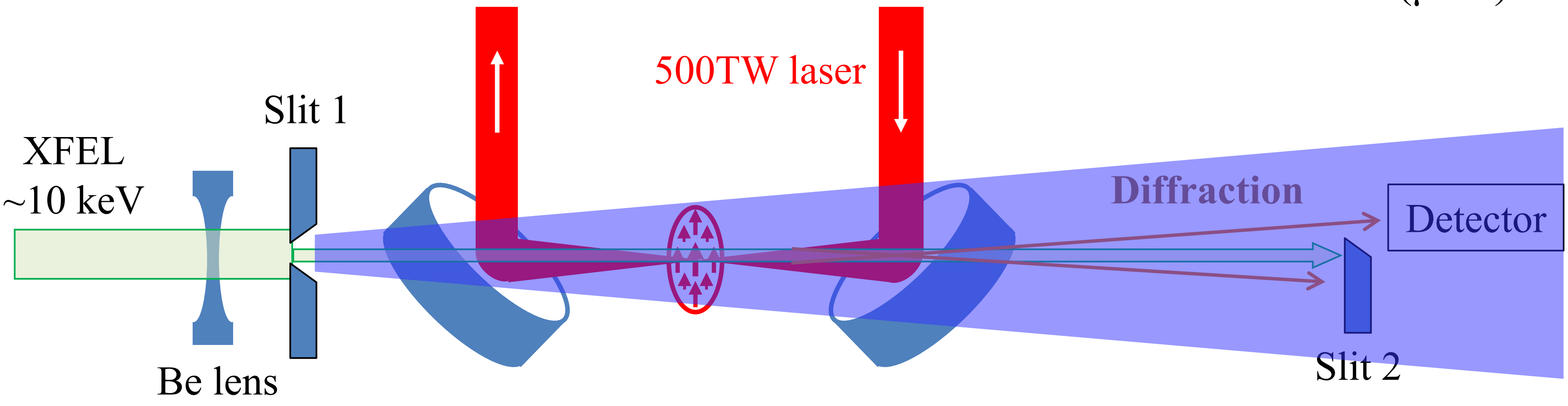
- Backgrounds at large angles

Comparison of current approaches
Slit collimation

In an XFEL experiment, slit collimation
- helps to reduce probe div. for some angles,
- but **adds** div. in large angles

Simple slit collimation seems very hard.
We need more studies to find a better way

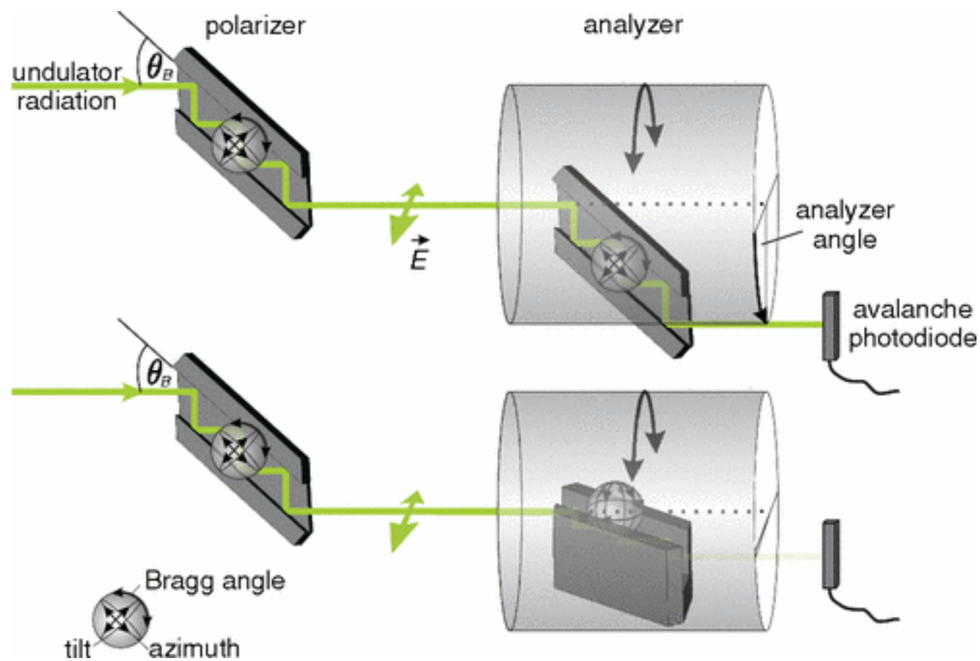




Comparison of current approaches
Crystals

- Conventional SAXS approaches
  - Slit collimation
  - Bonse-Hart camera
    two channel-cut crystals

- HED/HIBEF: polarization flip
  - Flip ratio: 7%
  - θ_B: Brewster's → s-pol.
    x-ray polarizer
  - Extinction ratio: $6 \cdot 10^{-10}$



*Karbstein & Sundqvist, PRD **94** (2016)*
*Schlenvoigt et al, Phys. Scr. **91** (2016)*

*Marx et al, PRL **110** (2013)*

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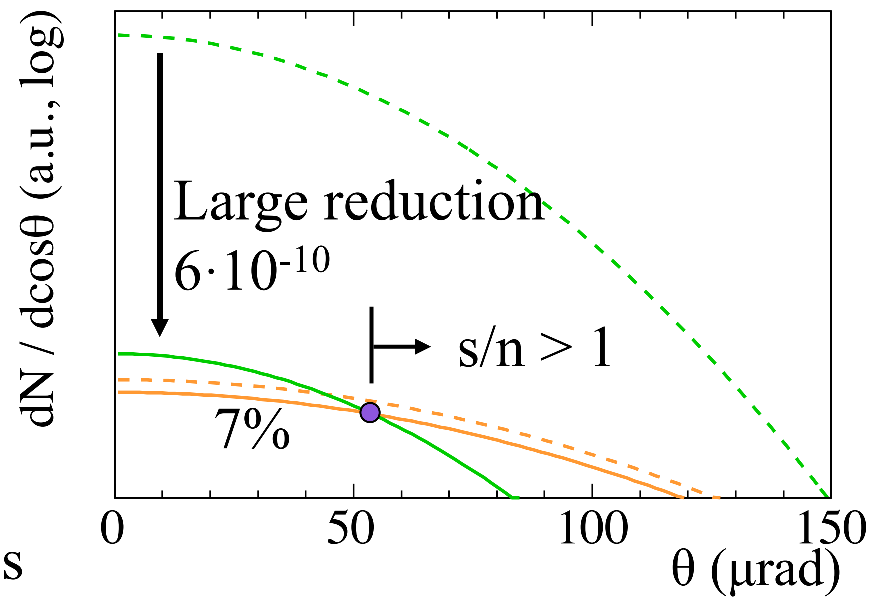

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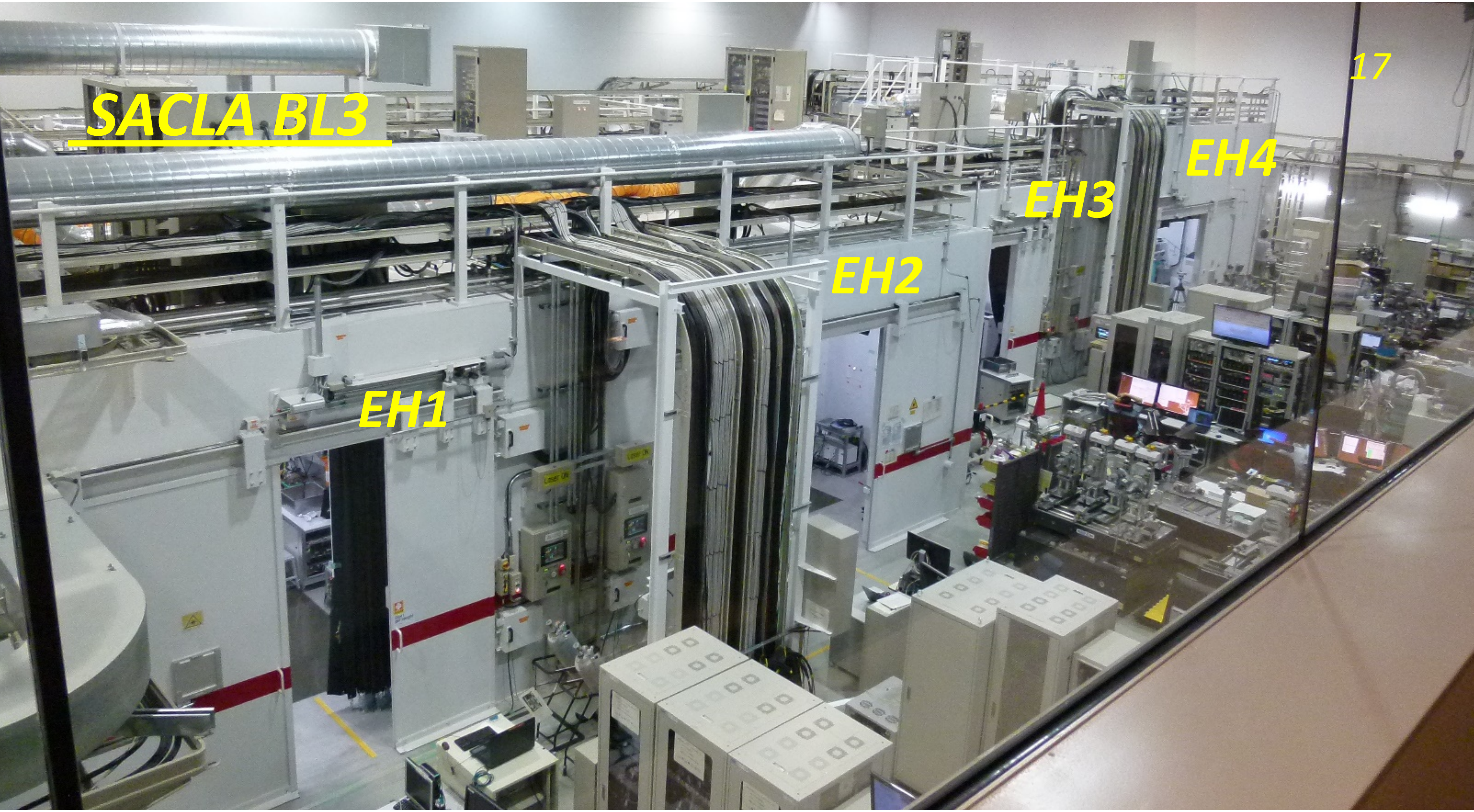


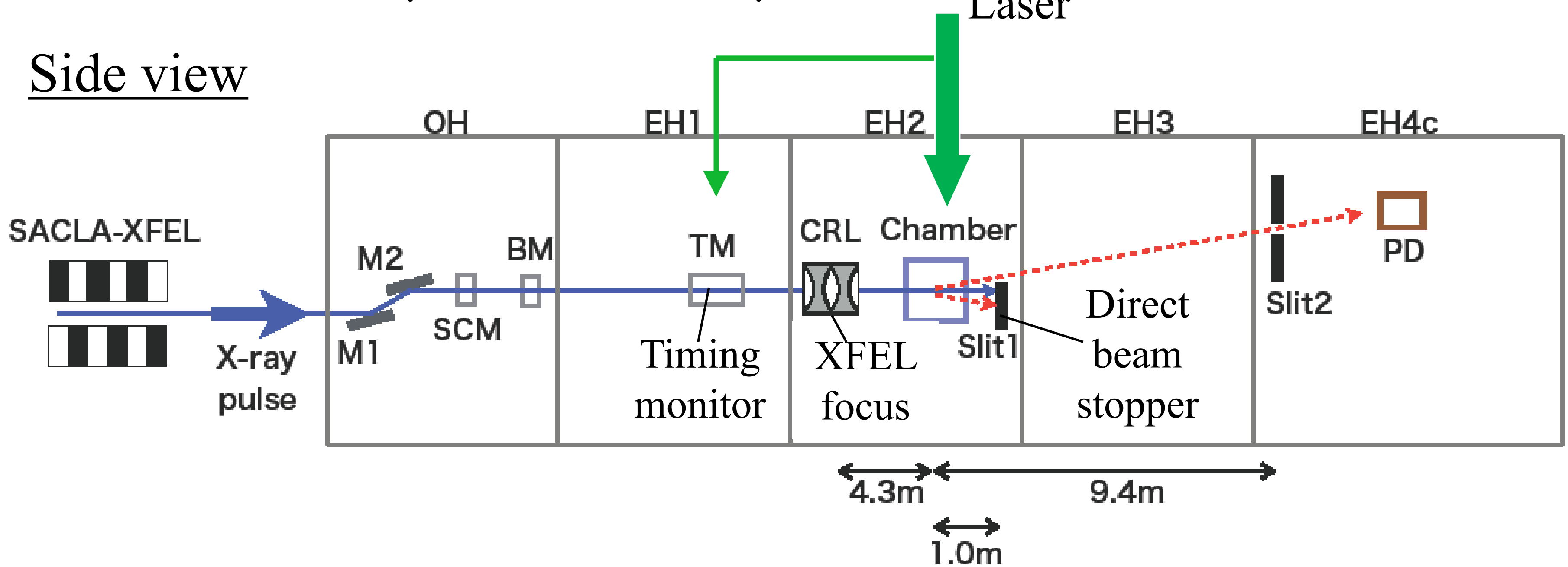
From now on, I want to show the current status of our test measurements.
It’s **very hard** to make a collision of two focused femto-pulses
→ Not yet a well-established method

Test measurement using 2.5 TW prototype laser

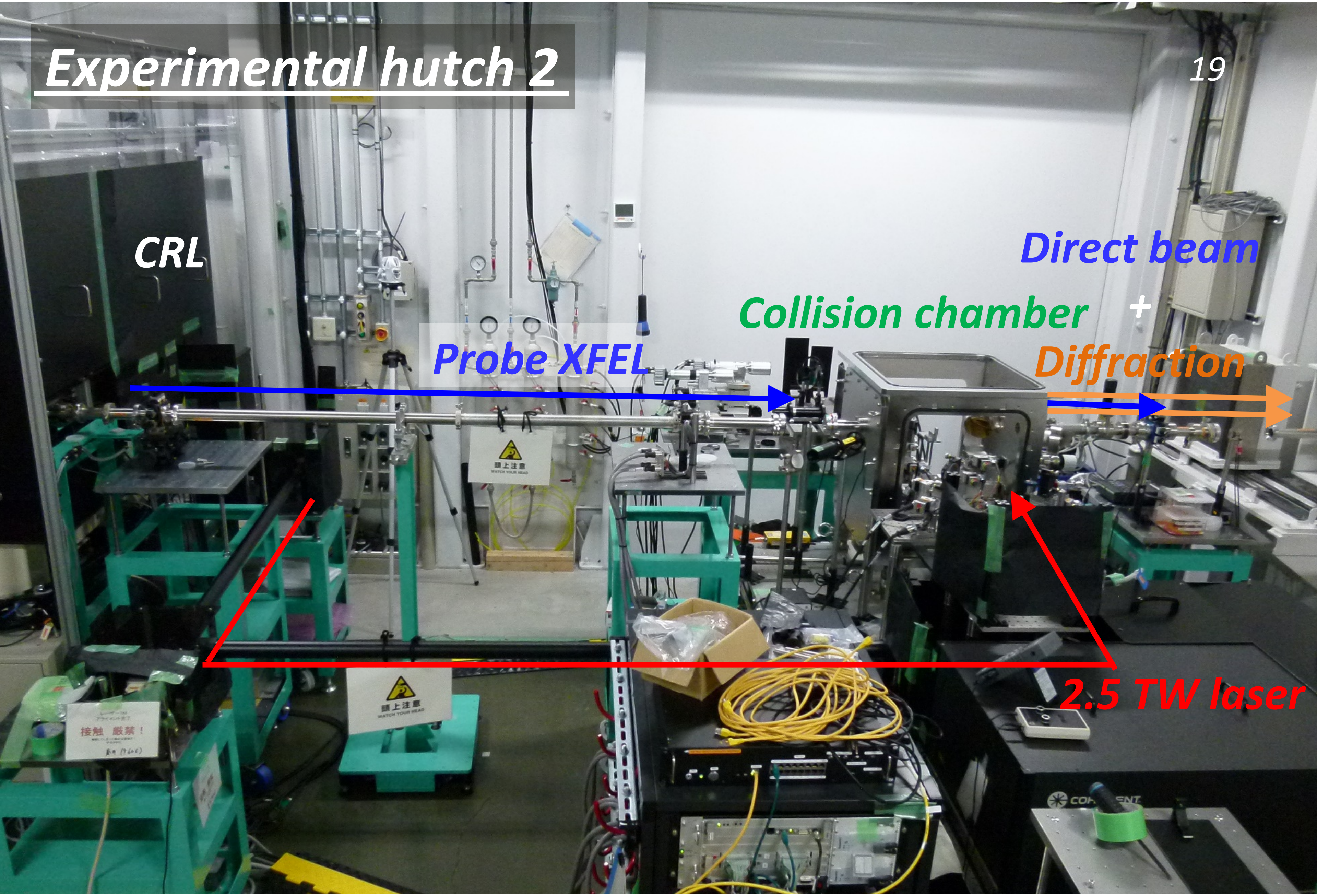
Beamtime: December 18-20 2017

- Main purpose: collision between XFEL and laser
  - study the accuracy of temporal/spatial adjustment
- No slits for angular collimation
- Beam size (2σ) at the collision point
  Laser: 10 μm, XFEL: 60 μm

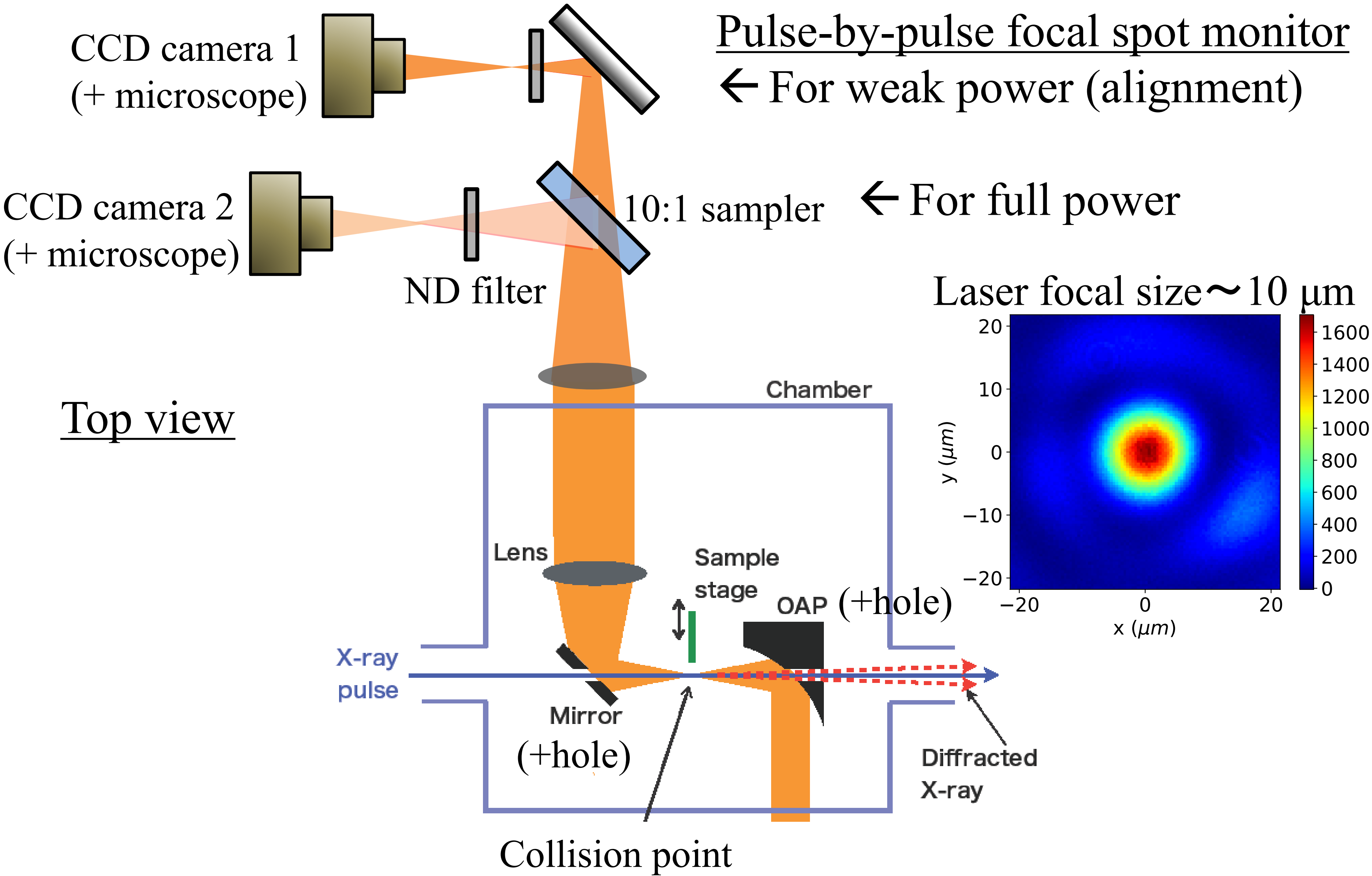
<u>Side view</u>

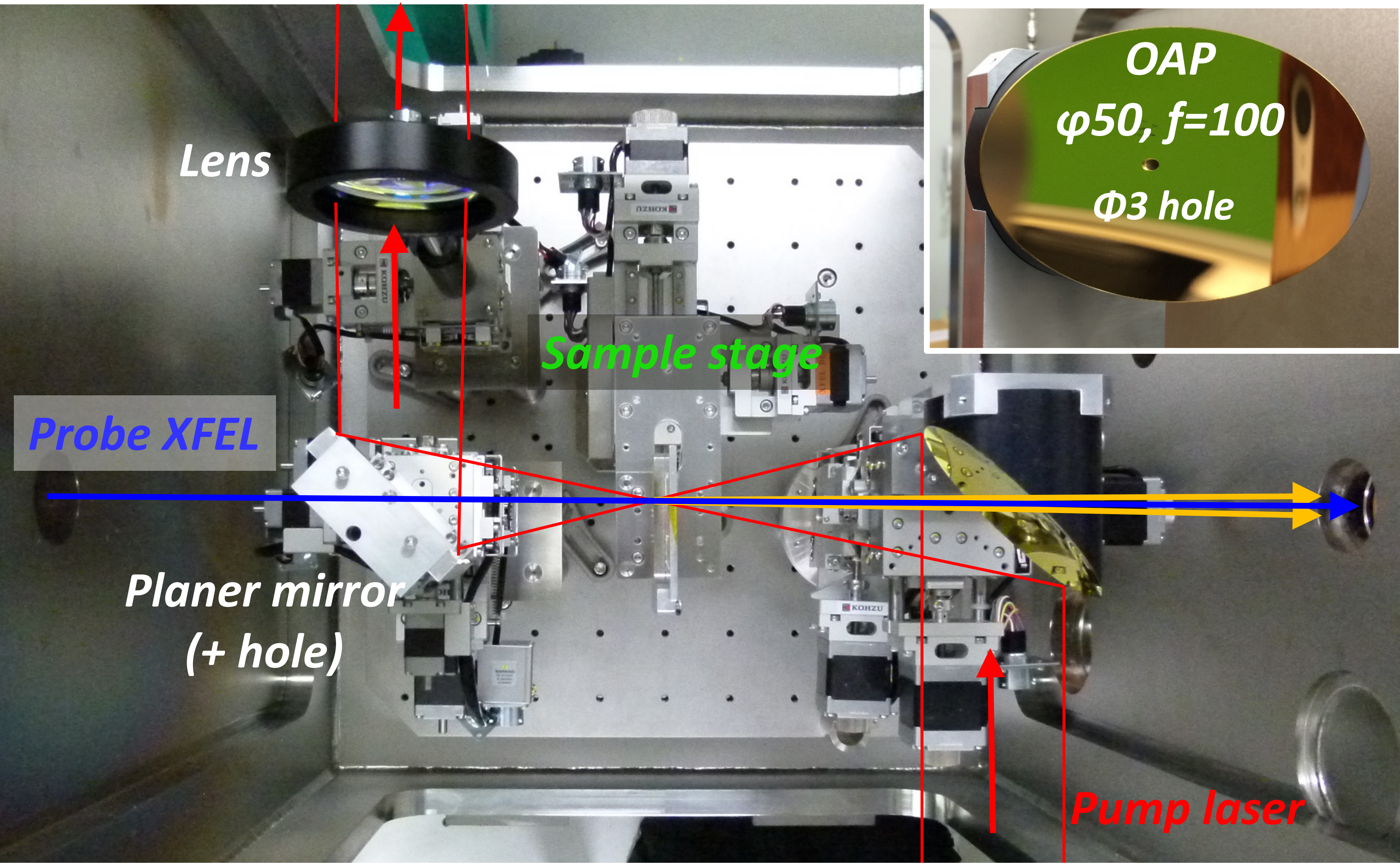


Experimental hutch 2



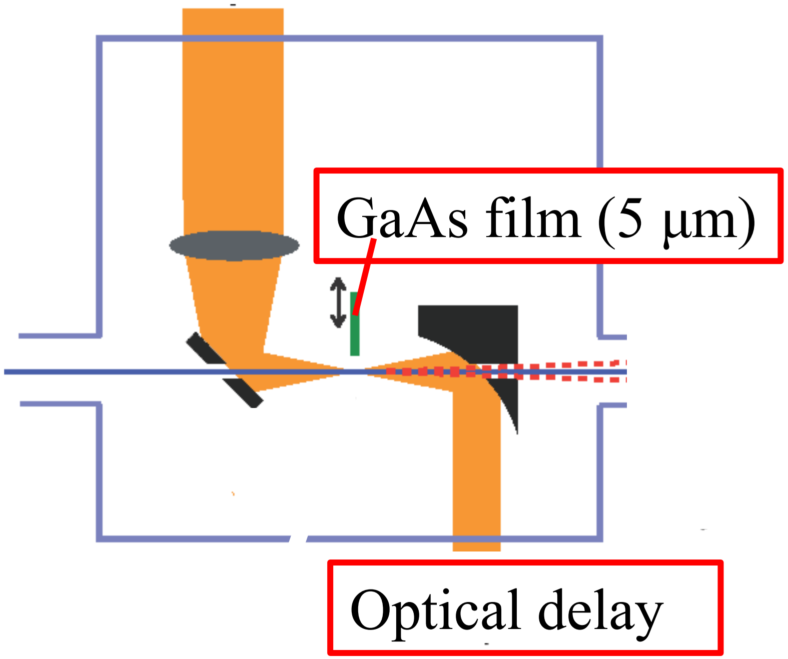
Optics around collision point



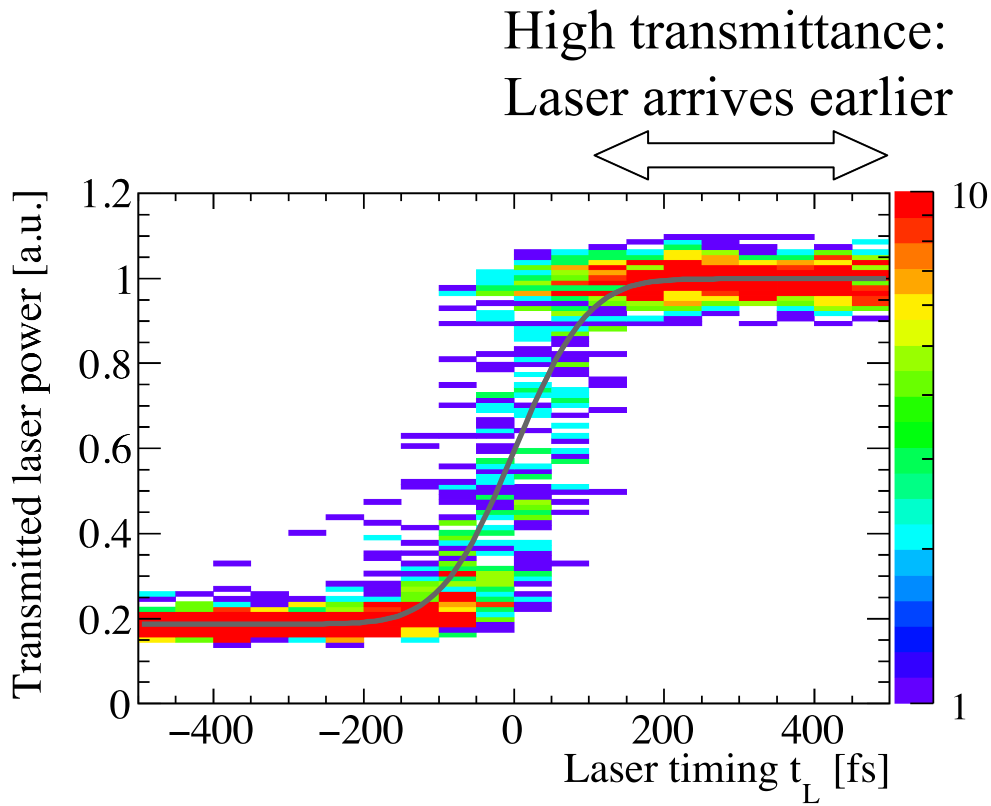


Many stages with motors to adjust the focal position and its size

Temporal adjustment



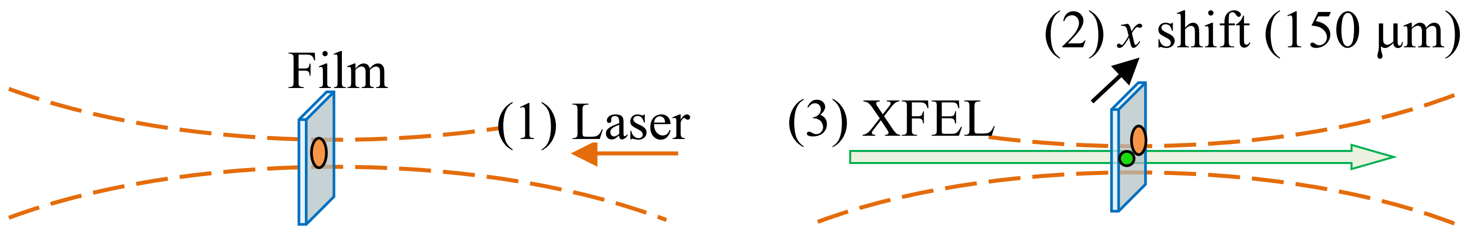
- GaAs: high transmittance to the laser
- It decreases if XFEL arrives at the film before the laser (x-ray photoionization)
- Scan the laser delay

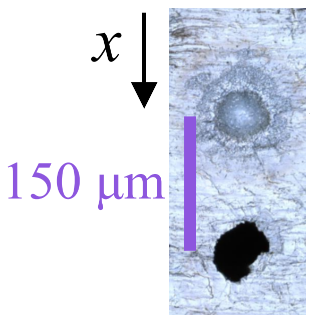


- Fit it to an error function:
  σ = **77±4 fs** ↔ $\pm z_{R\,L}/c$=20 fs
- Convolution of laser/XFEL pulse width and response time of GaAs
- Intrinsic timing jitter ~100 fs

Spatial adjustment Overlap

- Set a zinc film (25 μm) to the sample stage:
  E_{abs}=9.7 keV, E_{XFEL}=9.8 keV
- Irradiate both laser and XFEL → spot on the film: shift it to avoid overlap

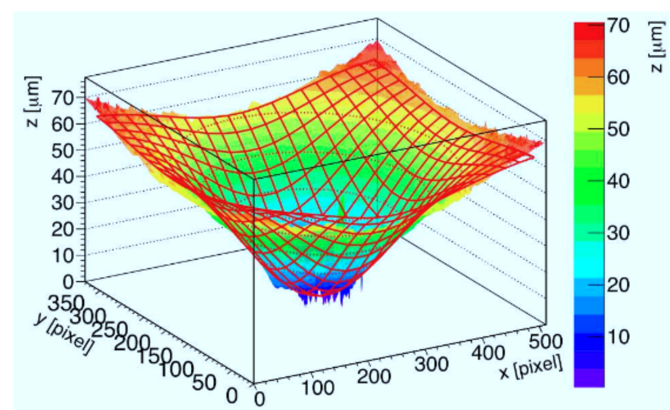




Laser 10 μm **at the focus**: 3 shots

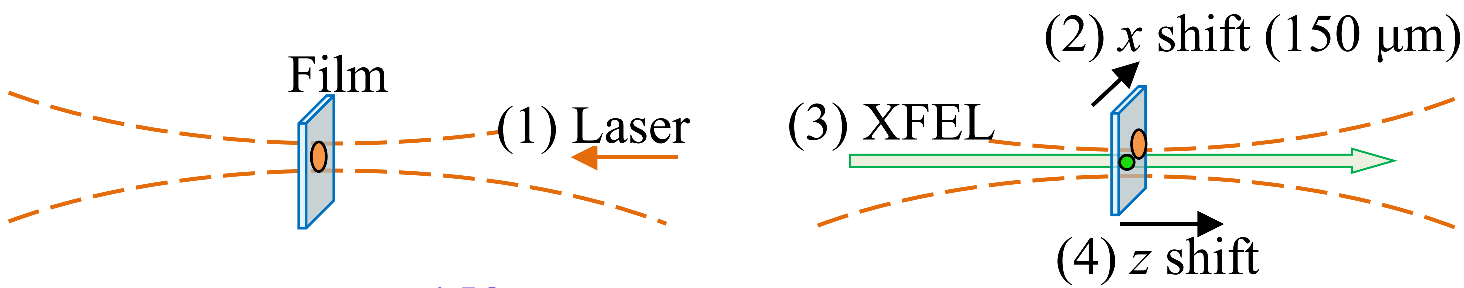
XFEL 60 μm: 100 shots

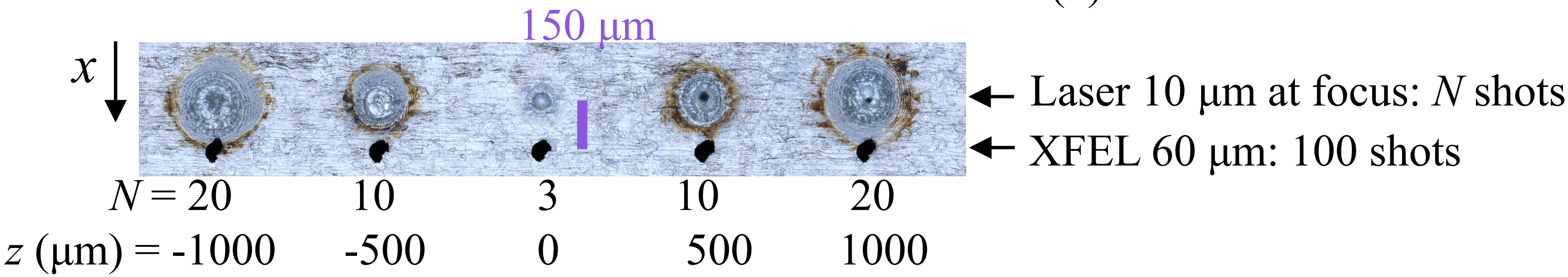
- Take the height profile by a laser microscope
- Fit the laser shape to a 2d-Gaussian
  center position: **1-2 μm** accuracy



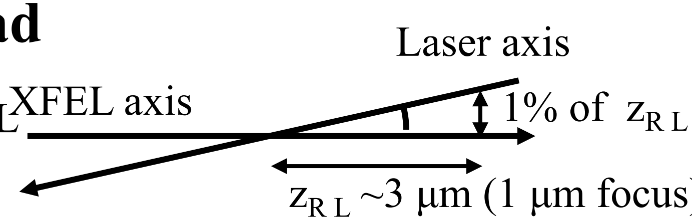
Spatial adjustment
Colinearity

- Repeat it by changing the film position along the laser axis z
  $z_{R\,X} >> z_{R\,L}$: XFEL size does not change



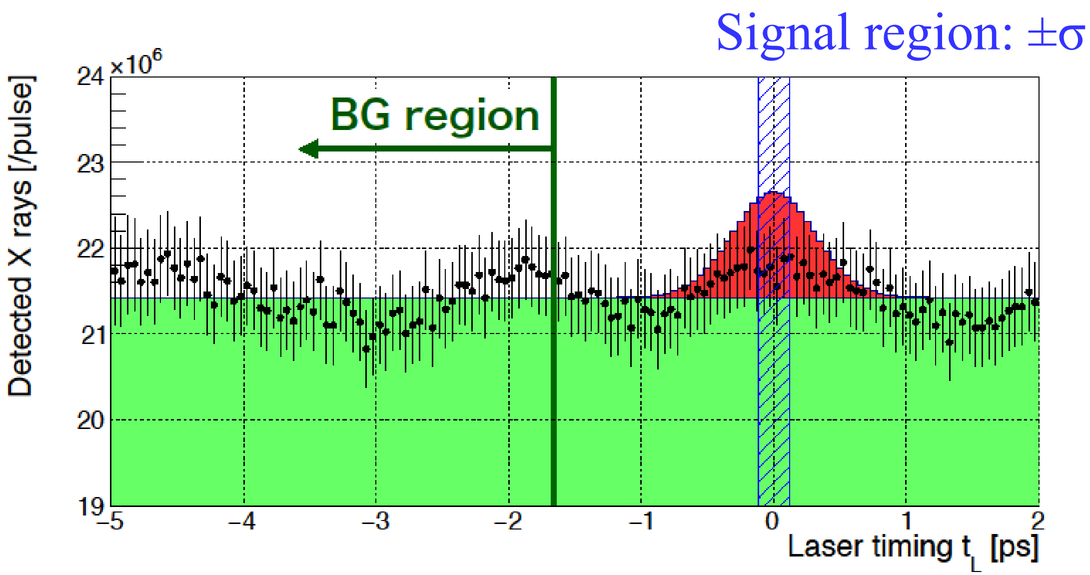


- Repeat the same image processing for each pair of patterns
  - Collinearity between the two axes ~ **10 mrad**
  - Transversal beam shift over $z_{R\,L}$: 1% of $z_{R\,L}$
    it gets negligible for a small $z_{R\,L}$



Test run

- Carried out a test run and checked DAQ system



- The count was consistent with the background's

Full details: the arXiv (*Y. Seino et al.*) coming soon

Summary & further works

- X-ray + X-ray scattering → X-ray + laser scattering
  - can expect sizable signals
  - detection: slit collimation, x-ray polarizers

- How to make a collision of the two focused femto-pulses
  Current status using GaAs and Zn films
  - accuracy of temporal adjustment ~ 100 fs
  - accuracy of spatial adjustment ~ 1-2 μm

- In this and next year, we need to
  - focus a PW laser
  - use a deformable mirror to correct wavefronts
  - study/reduce (unexpected) background sources

Thank you