Experimental search for Vacuum Diffraction using high-power laser and XFEL

Yudai Seino, Kyoto university

Experts of our team

Particle physics

: University of Tokyo, KEK

T. Inada, T. Yamazaki, T. Namba, S. Asai, (Y. Seino)

X-ray laser & High-power laser

: SACLA, SPring-8

Y. Inubushi, T. Togashi, T. Yabuuchi, T. Tamasaku, Y. Komura, I. Inoue, T. Osaka, M. Makina, T. Ishikawa

Micro-fabrication

: Osaka University

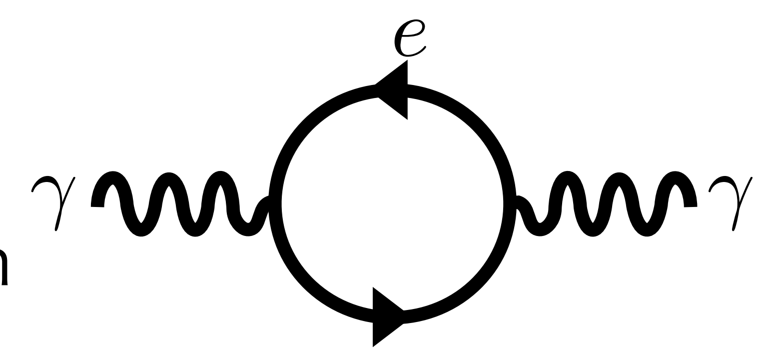
K. Kawai

Search for vacuum polarization

Vacuum polarization

- Process that a photon generates virtual electron-positron pairs
- Predicted by the QED
- Effective lagrangean is Eular-Heisenberg lagrangean

Feynman diagram of vacuum polarization



$$\mathcal{L} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \underline{\frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\boldsymbol{E}}{c}\cdot\boldsymbol{B}\right)^2\right]}$$

$$A_e = \frac{2\alpha^2\hbar^3}{45\mu_0 m_e^4 c^5} = 1.32 \times 10^{-24}\ [\mathrm{T}^2]$$

✔Correction for vacuum polarization

✔Affects the photon-photon interaction

Motivation to search for vacuum polarization

- Verification of QED

  Vacuum polarization is not observed in a real vacuum.

- Search for new particle

  We can also search for new particles beyond the standard model because these also affects the photon-photon interaction.

  ex) Axion, Axion-like particle, Milli charged particle

- Exploration of strong-field QED

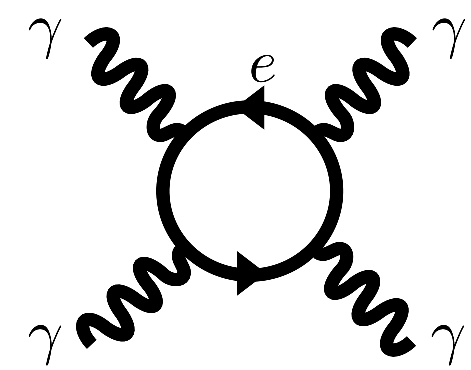
  We want to explore physical phenomena in a strong-field area that have not yet been explored $(O(10^{20\text{~}30})\mathrm{W/cm^2})$.

Phenomena caused by vacuum polarization

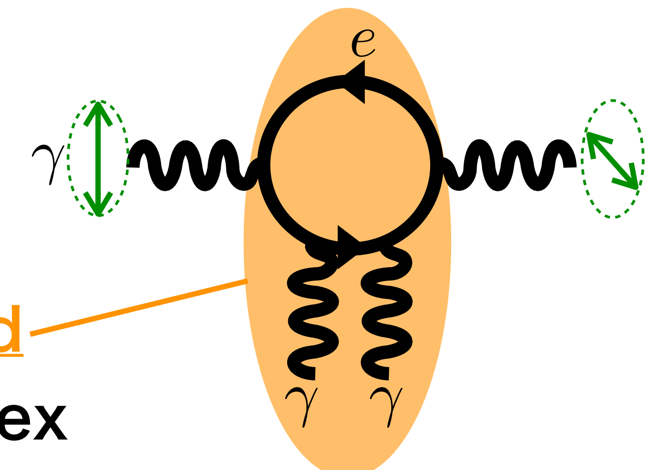
Vacuum polarization causes several physical phenomena.

We can search for vacuum polarization through those phenomena!

1. **Photon-photon scattering**

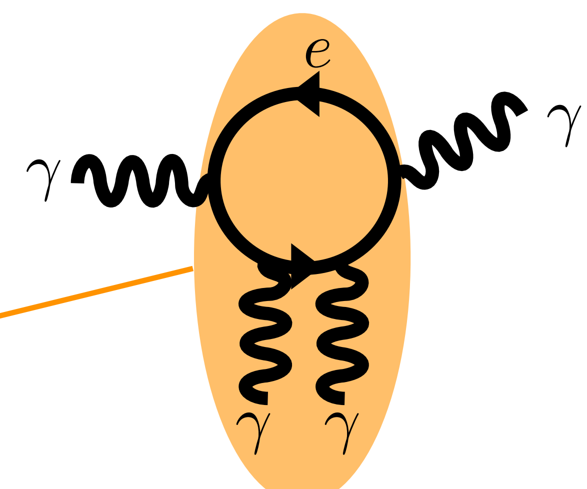


2. **Vacuum birefringence**



Vertical refractive index ≠ Horizontal refractive index

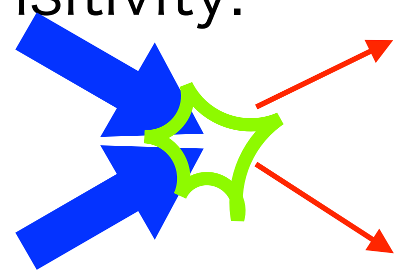
3. **Vacuum diffraction**



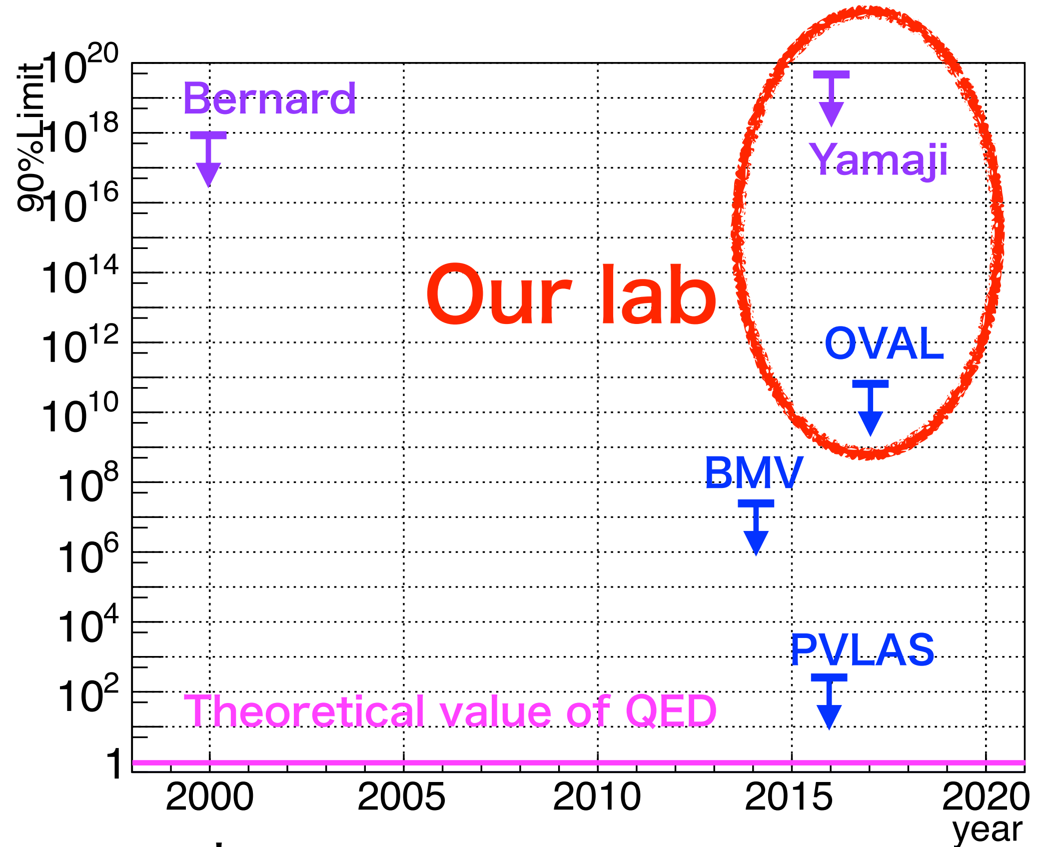
Refractive index ≠1

Previous searches

- **Photon-photon scattering experiment**
  - X-ray free electron laser (XFEL) beams or laser beams are collided, and scattered lights are searched.
  - Sensitivities are 10^{18} worse than theory.
  - Statistic of signal limits the sensitivity.



Sensitivity of previous searches



Photon-photon scattering experiment
Vacuum birefringence experiment

- **Vacuum birefringence experiment**
  - Polarized laser passes a magnetic field of a magnet, and changes of the polarization is searched.
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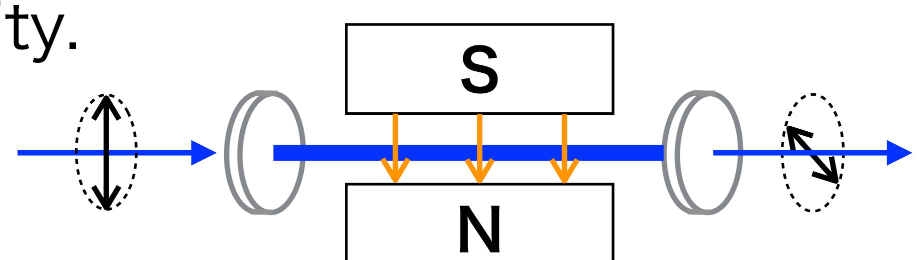
  - Sensitivity is limited since noise is also enhanced by the cavity.



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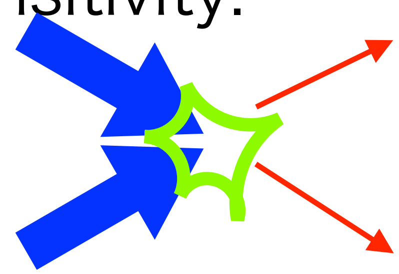
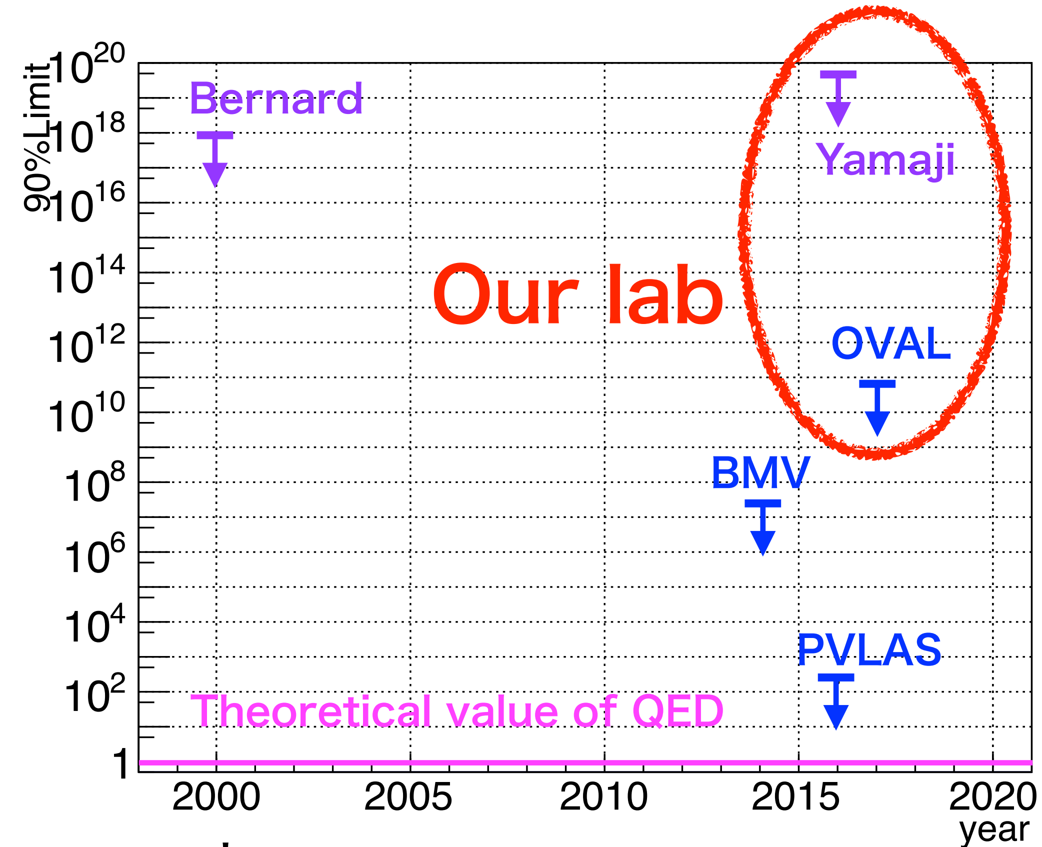


Sensitivity of previous searches



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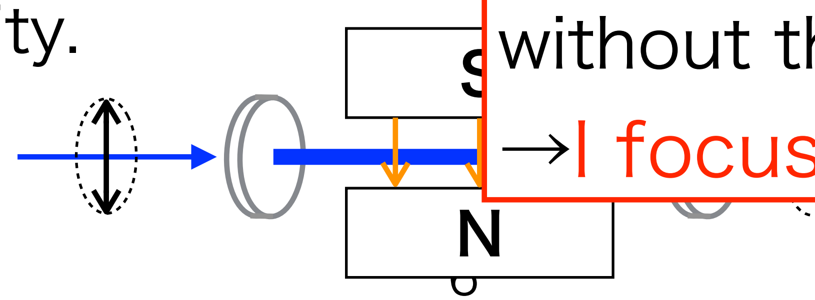
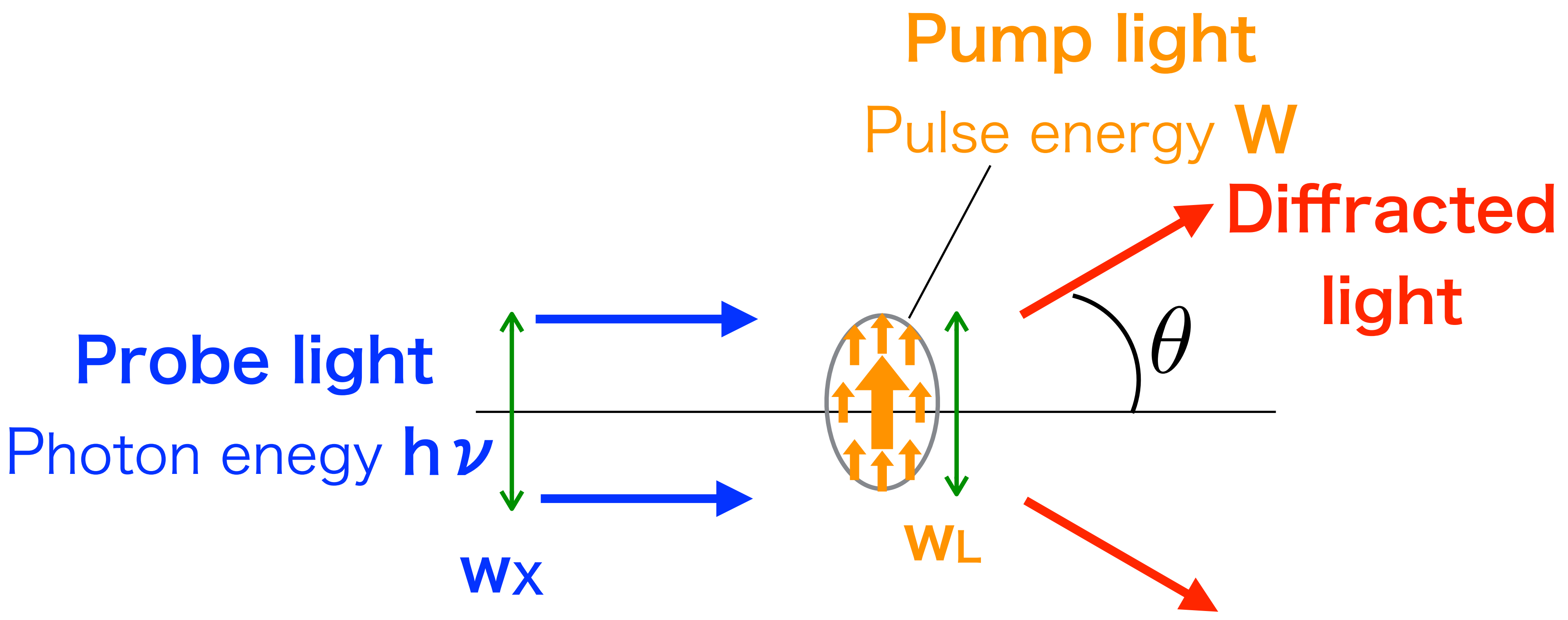


New method to increase signals without the cavity was needed.
→I focused on vacuum diffraction

Vacuum diffraction

Vacuum diffraction

is a diffraction of probe light when there is gradient of refractive index in a vacuum due to a localized electromagnetic field(pump light).



Vacuum diffraction

Smaller pump light is better

because the angular divergence of diffraction will be larger.

Angular divergence $\theta \sim 70\ \mu\mathrm{rad} \times \left(\frac{1\ \mu\mathrm{m}}{w_\mathrm{L}}\right)\left(\frac{8\ \mathrm{keV}}{h\nu}\right)$

I calculate signal of vacuum diffraction
(Y. Seino, et al., Prog. Theor. Exp. Phys. 2020, 073C02)

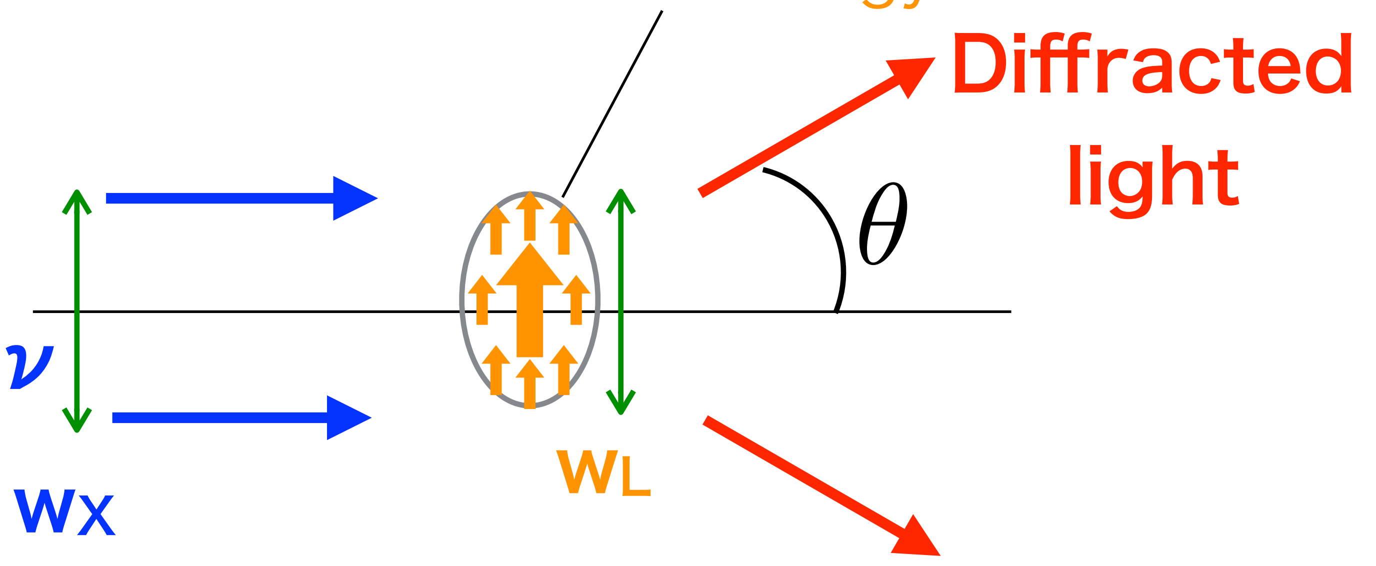
Sensitivity $\propto \frac{(h\nu)^2 W^2}{w_\mathrm{L}^2 (w_\mathrm{L}^2 + w_\mathrm{X}^2)} \times$ (Separation rate of probe light)

Pump light

Pulse energy **W**

Probe light

Photon enegy **h ν**



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High photon energy probe light & high power pump light is good!

Sensitivity $\propto \frac{(h\nu)^2 W^2}{w_\text{L}^2 (w_\text{L}^2 + w_\text{X}^2)} \times$ (Separation rate of probe light)

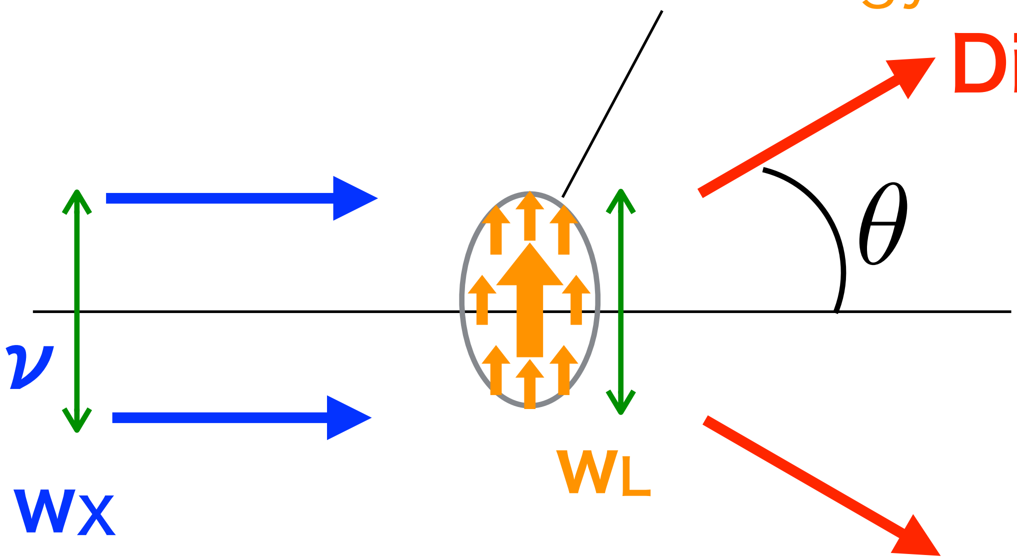
Pump light

Pulse energy **W**

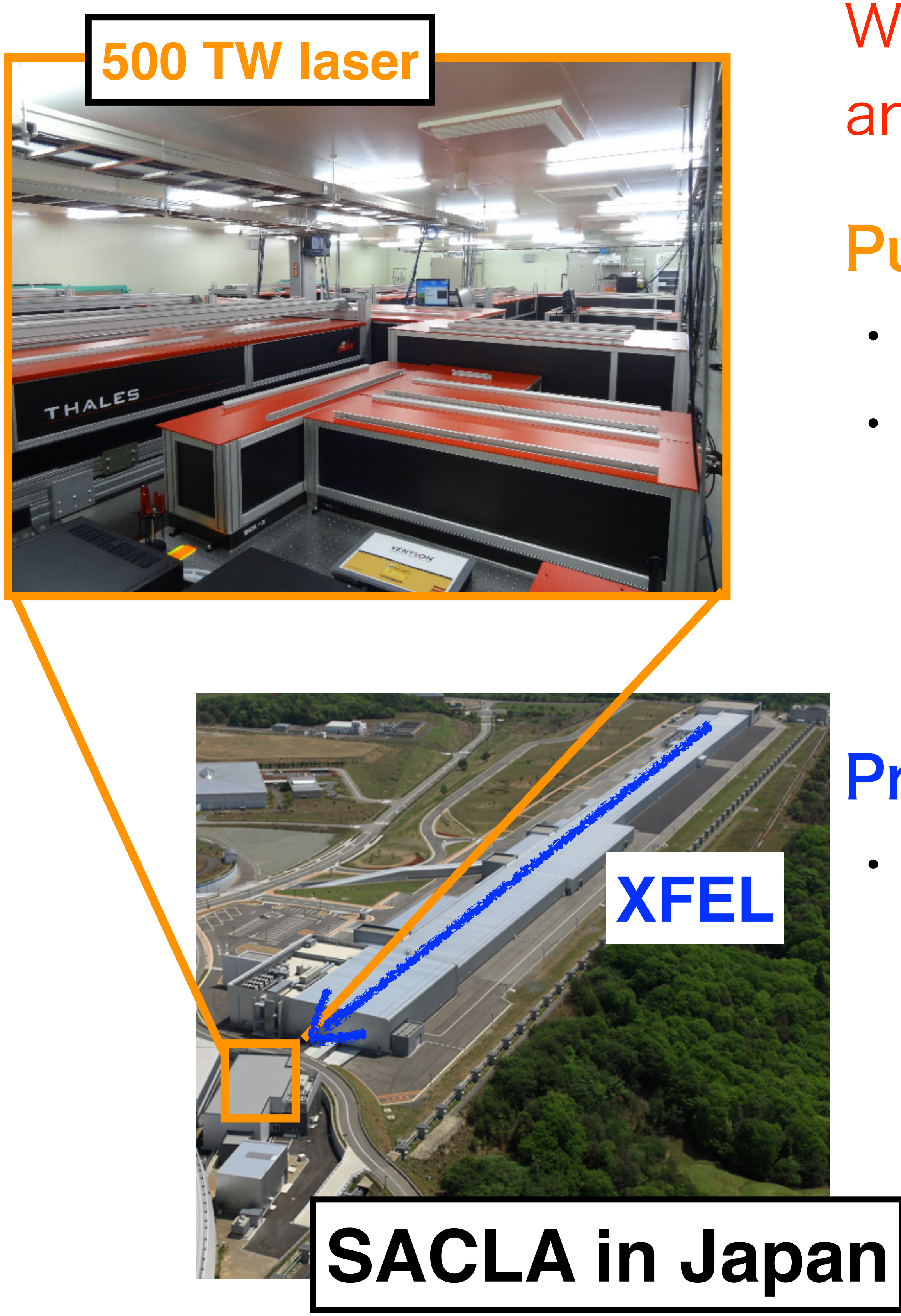
Diffracted light

Probe light

Photon enegy **h** ν



Place for experiment : XFEL facility SACLA



We can use a high power laser
and XFEL at SACLA!

Pump light : 500 TW laser

- We can use from 2018.
- Instantaneously high power laser.
  - Pulse width 30 fs
  - Pulse energy 12.5 J
  - Wave length 800 nm

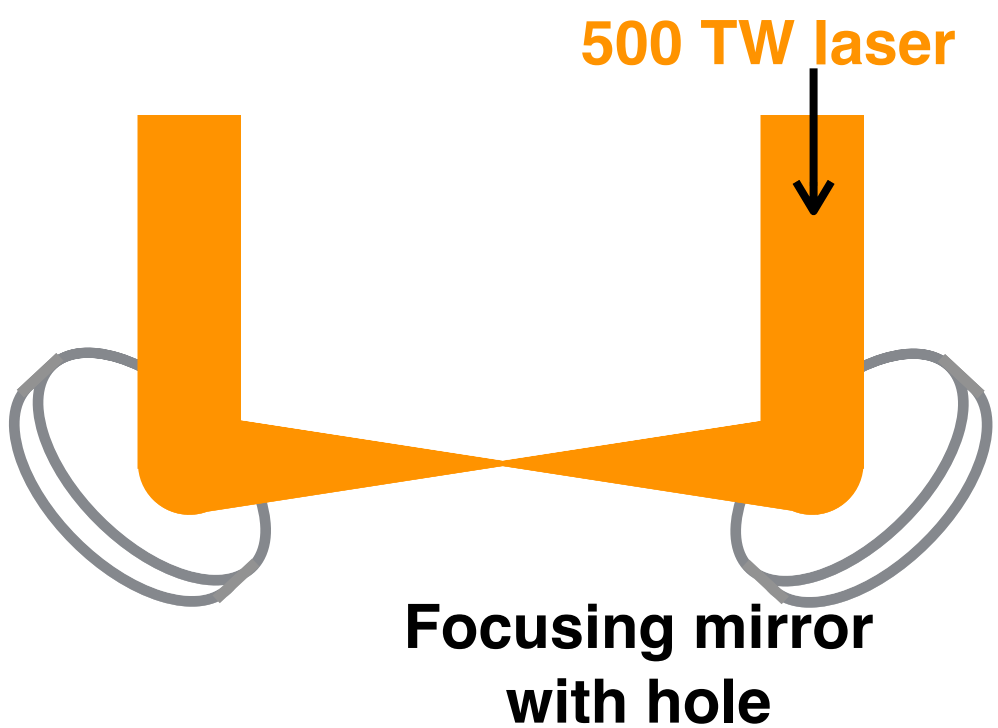
Probe light : XFEL of SACLA

- Instantaneously high power X-ray pulse.
  - Pulse width $\lesssim$ 10 fs
  - Photons 10^{11} photon/pulse

Many experiments using laser and XFEL are proposed!
ex)European XFEL, Shanghai XFEL
・H. Schlenvoigt et al, Phys. Scr. 91 (2016) 023010
・B. Shen et al, Plasma Phys. Control. Fusion 60 (2018) 044002

Experimental setup

- 500 TW laser is focused to 1 μm.

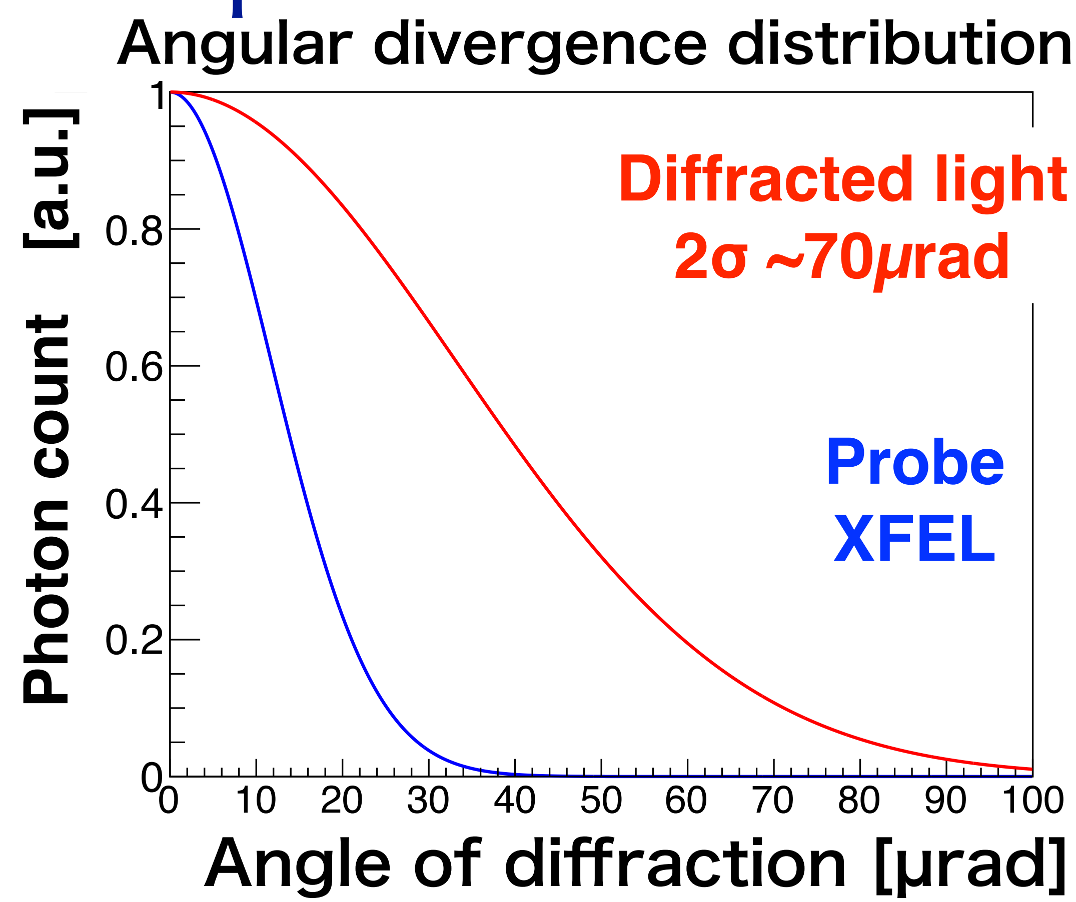


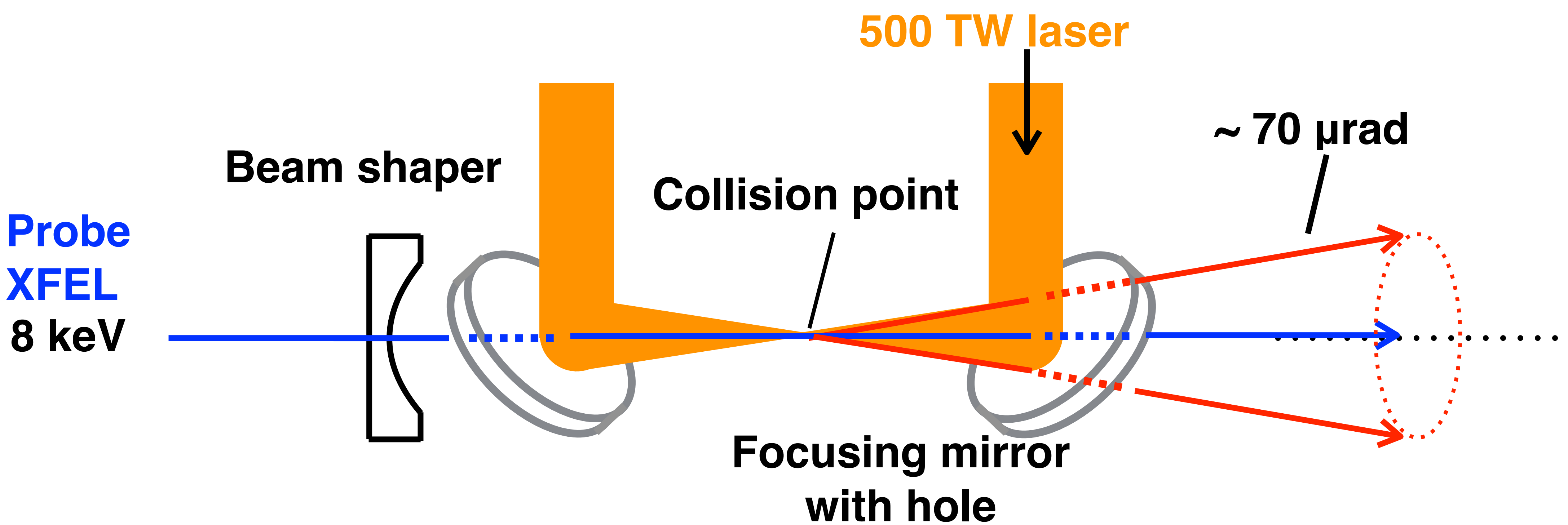
Experimental setup

- XFEL is focused to 2 μm while keeping the angular divergence low.
- Make XFEL pulse collide head-on with 500 TW laser pulses at its focus.
- A part of XFEL pulse is diffracted.

  Probability : ~10^{-12}

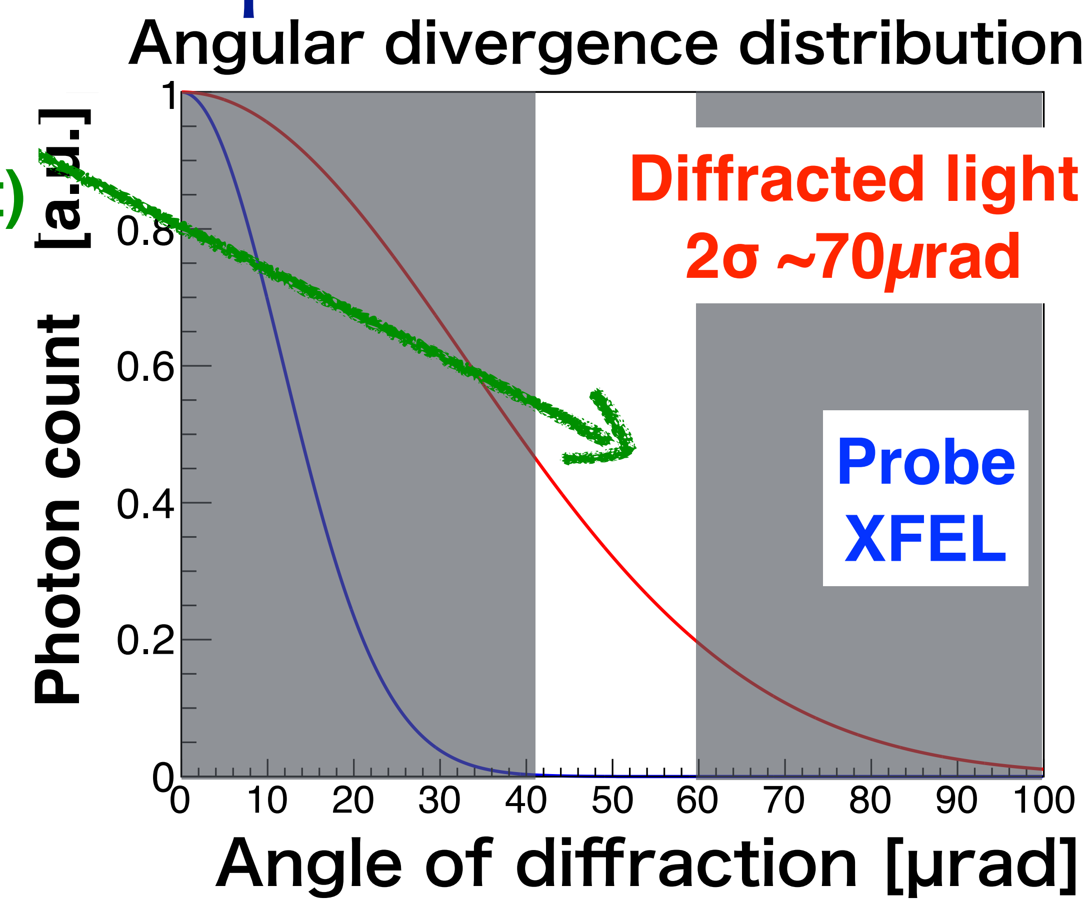
  Angular divergence : ~**70 μrad**

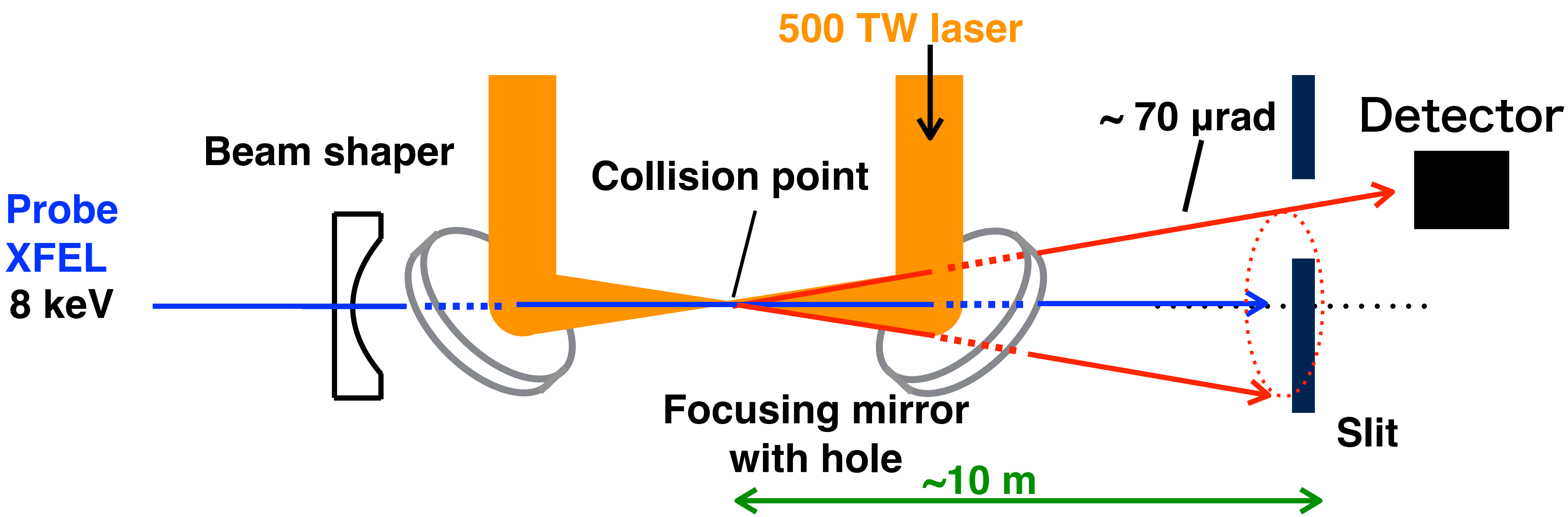




Experimental setup

- Diffracted light is separated from probe XFEL using slit.
- Vacuum diffraction will be observed with ~10 days of data acquisition.
  - 4×10^{11} photons/pulse, 1 Hz
  - Information of polarization is also used.
    (Extinction ratio 2×10^{-10} & Energy width of XFEL 1 eV)





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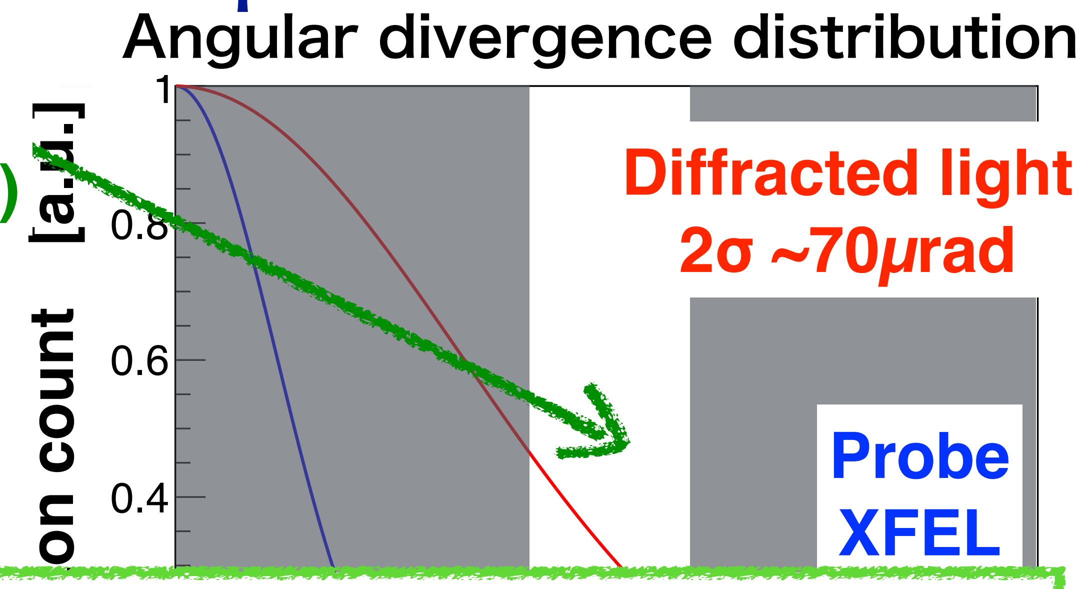


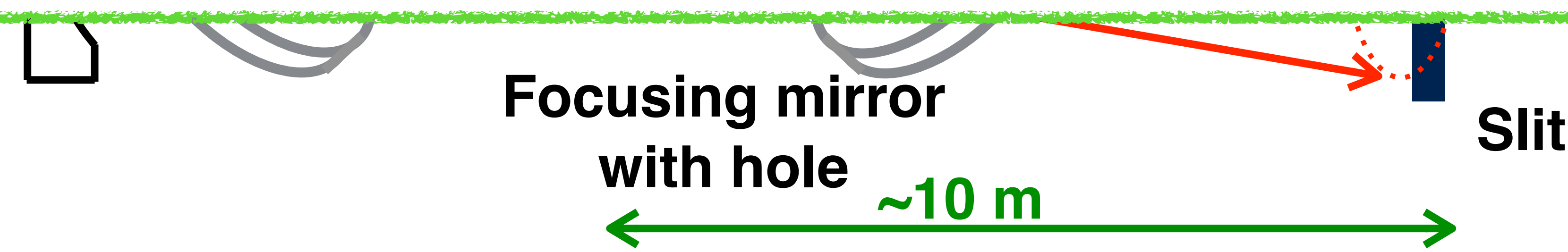
- Because this is new experiment, we did not have know-how.
- 500 TW laser was under development.

⬇

I started my research using a 0.6 TW laser.

The first goals of my research were

- Development of basic experimental techniques
- First search for vacuum diffraction



Key tasks of Research & Development

Key R&D tasks

1. **Focusing of the laser**

   For the strong electromagnetic field and large divergence.

   Goal is **~1 μm**.

2. **Suppressing of backgrounds (BG)**

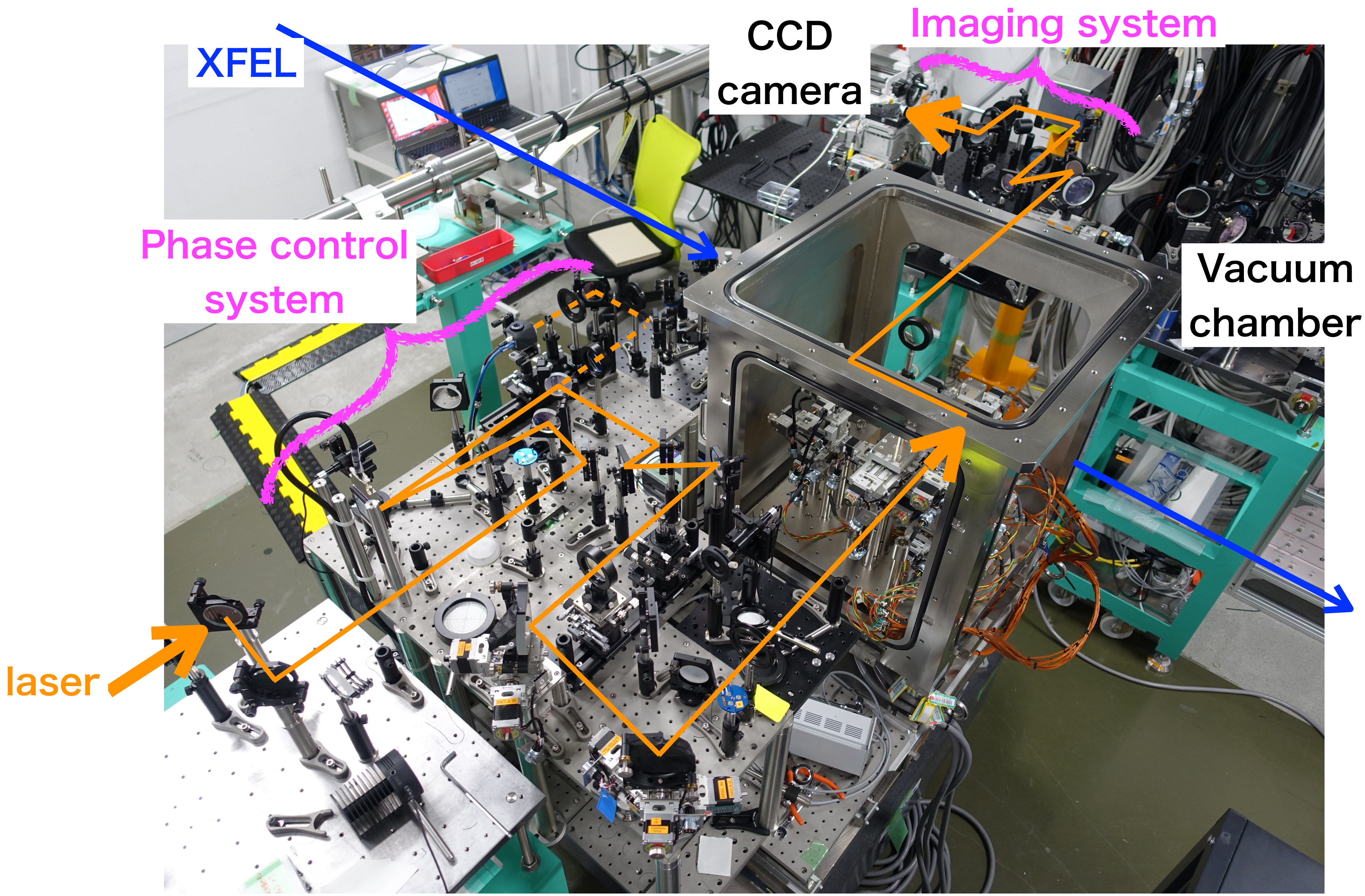
   To remove X rays with large angle in the XFEL pulse

3. **Making both pulses collide**
   - Spatially(**~μm accuracy**)

     Both pulses should be overlapped.
   - Tempolary (**300 fs acuuracy**)

     Both pulses should be collided when the laser pulse is focused.

Picture of optical system for laser



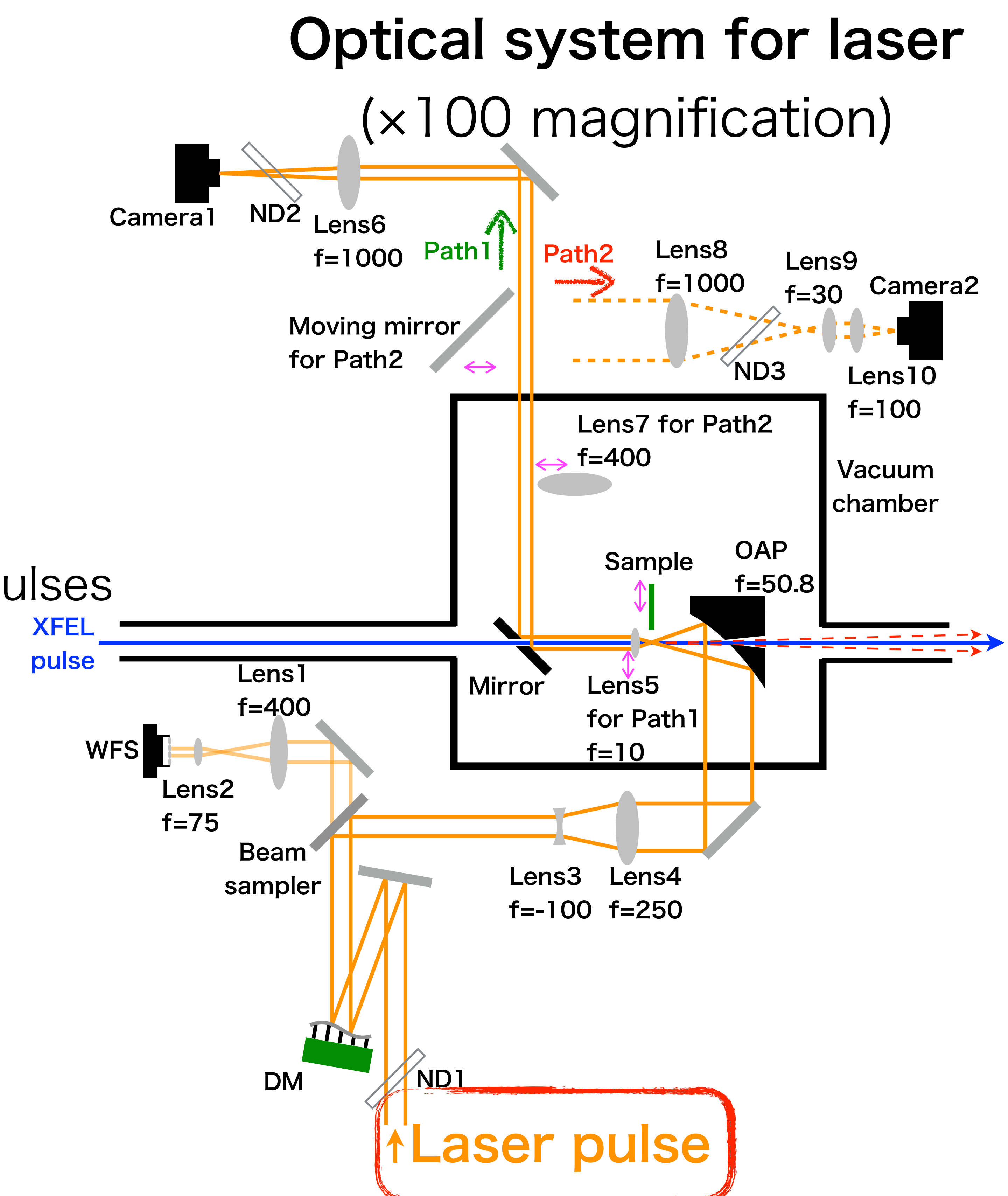
Optical system for laser

- **0.6 TW laser system**
  - Ti:Sapphire laser
  - Pulse energy 3 mJ(upstream)
  - Wavelength 800 nm
  - Pulse width 48 fs

- **Phase control system**
  The focusing image is optimized
  by controlling the phase of laser pulses

- **Focusing system**
  Off axis parabolic mirror with a hole
  (f=50.8mm)

- **Imaging system**
  for focused laser.
  Magnification ×100 & ×8



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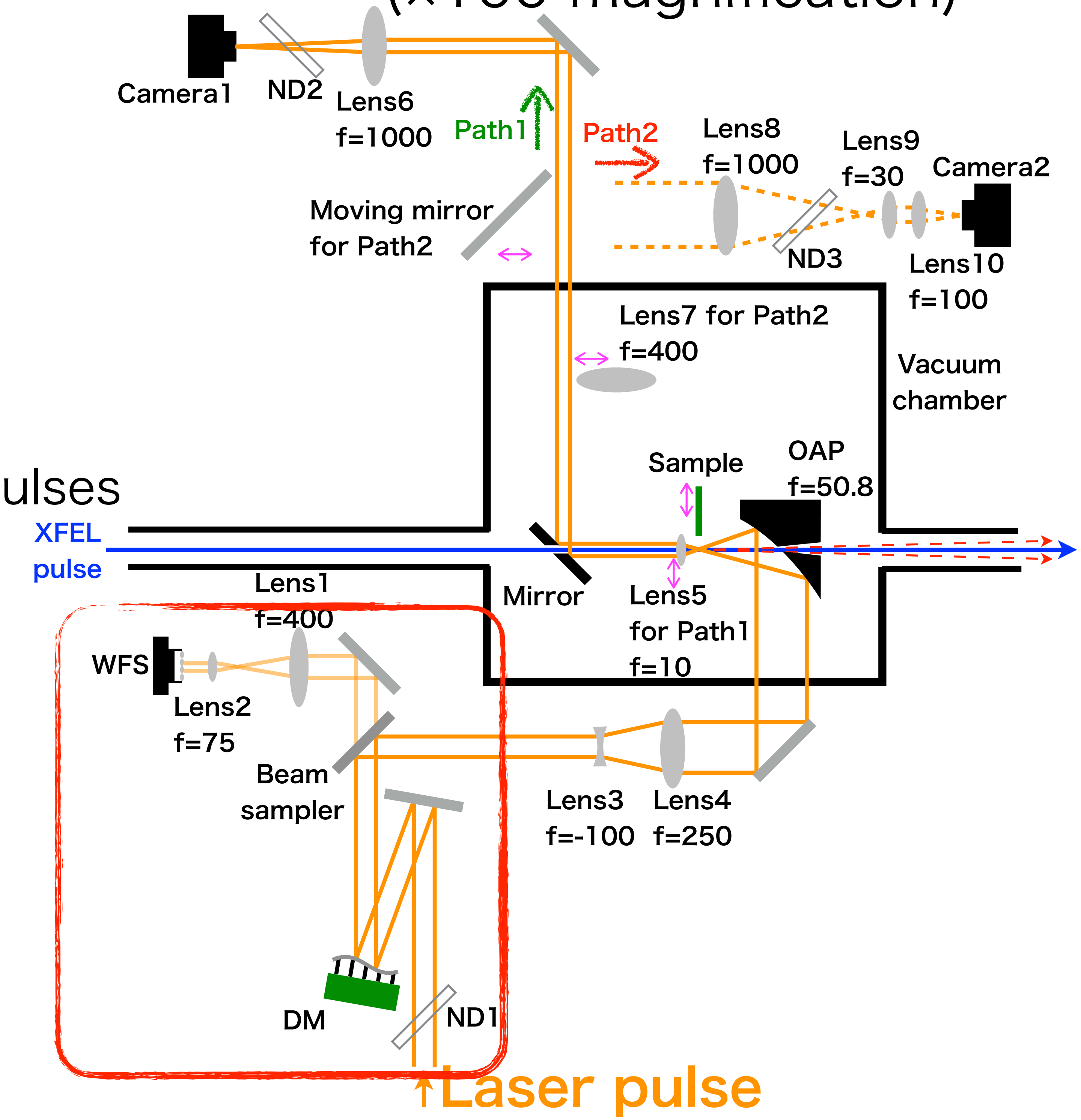
Optical system for laser

(×100 magnification)



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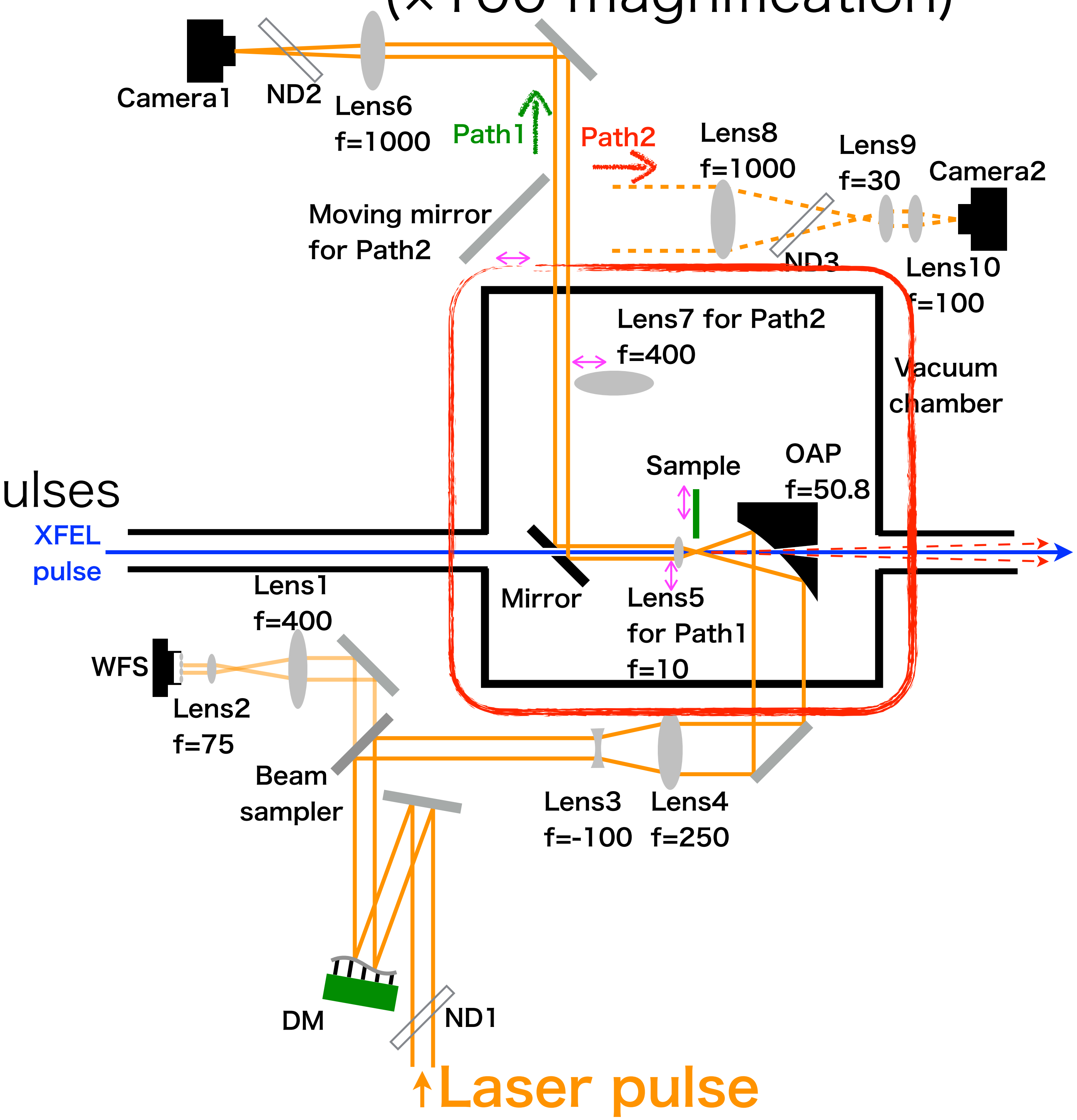
Optical system for laser (×100 magnification)



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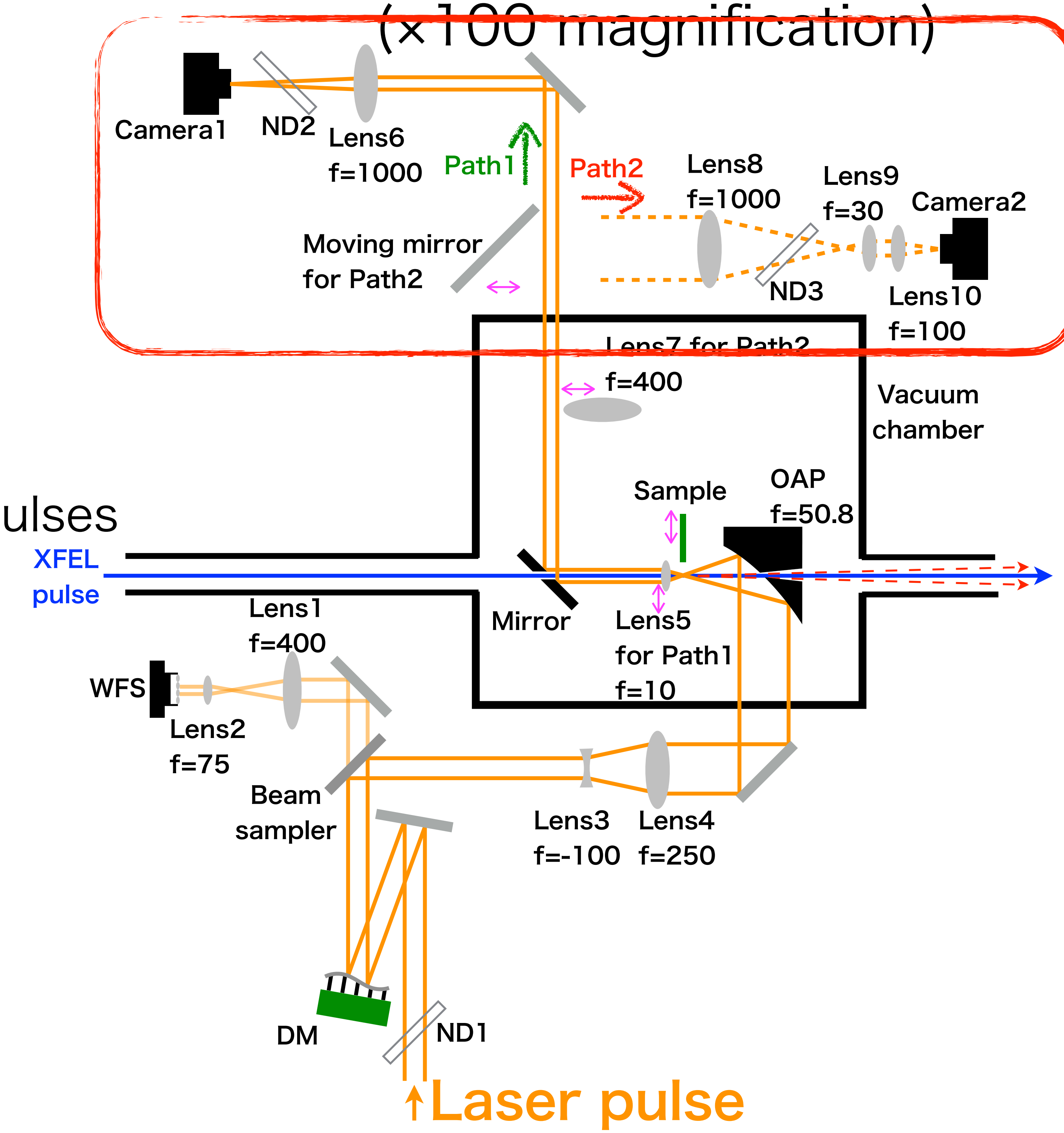
Optical system for laser

(×100 magnification)



R&D task 1 ：Focusing of laser

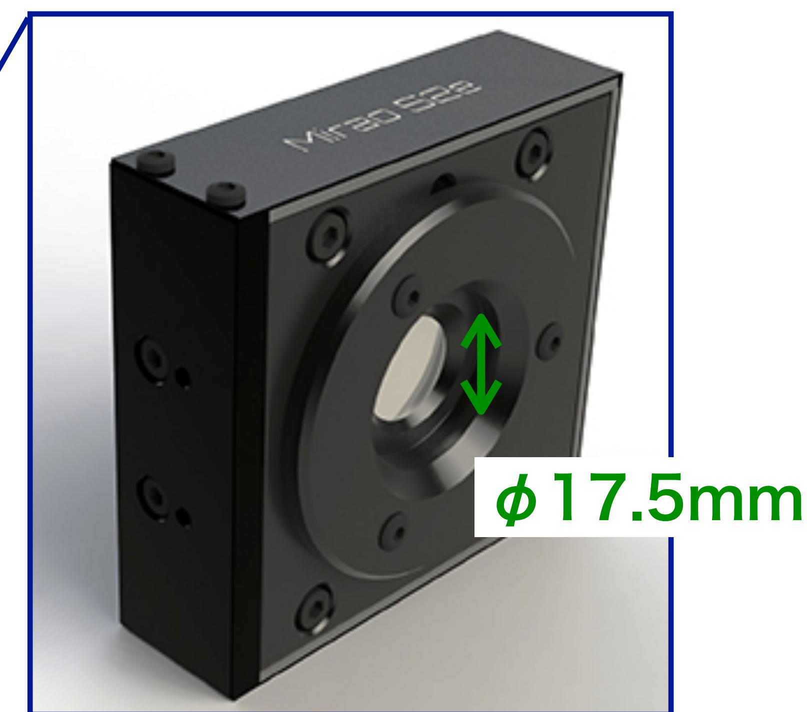
R&D task 1

- Focusing of the laser pulse.
- **Target size is 1 μm**

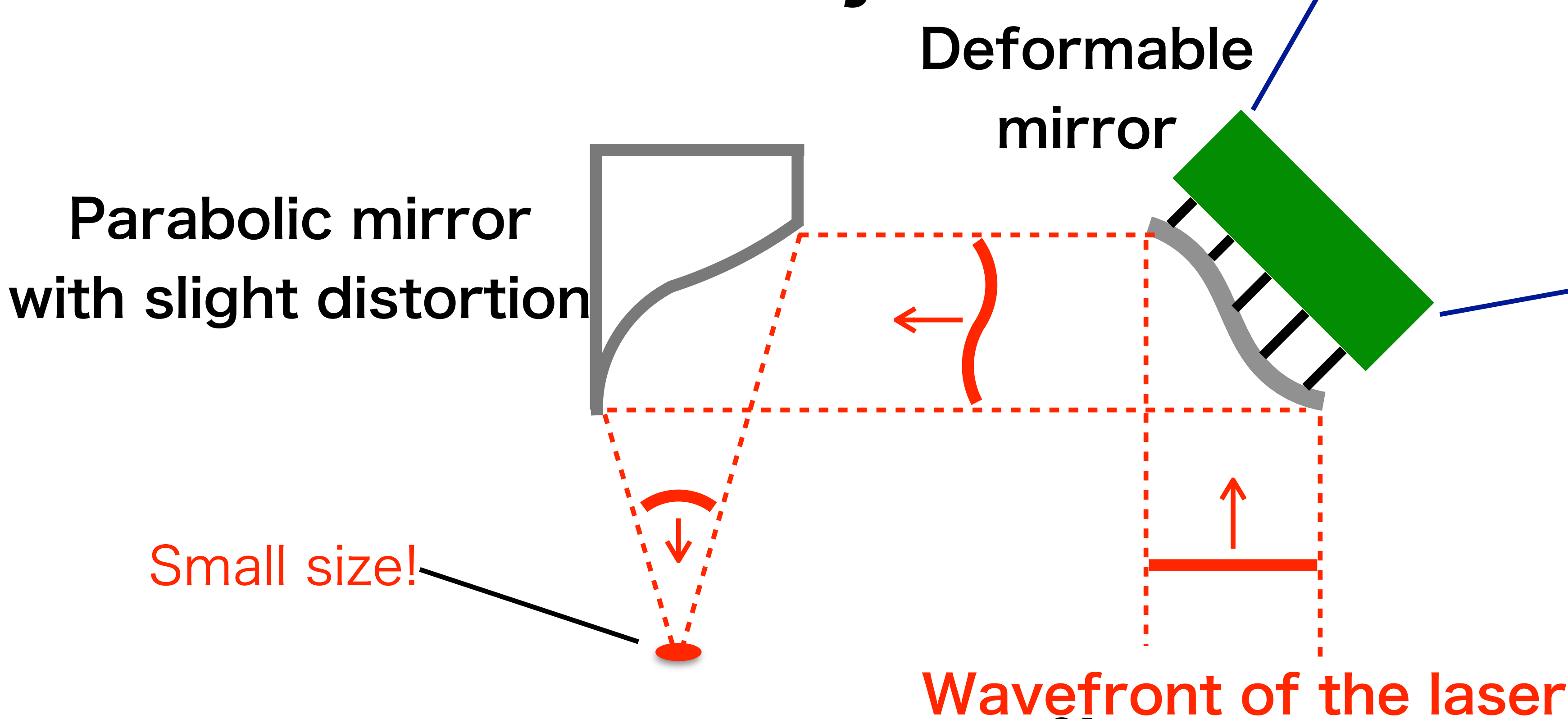
Solution

- Because distortion of the wavefront makes the focal spot size large,
  I controlled phase of the wavefront and optimized focal spot.

Imagine, Mirao 52e



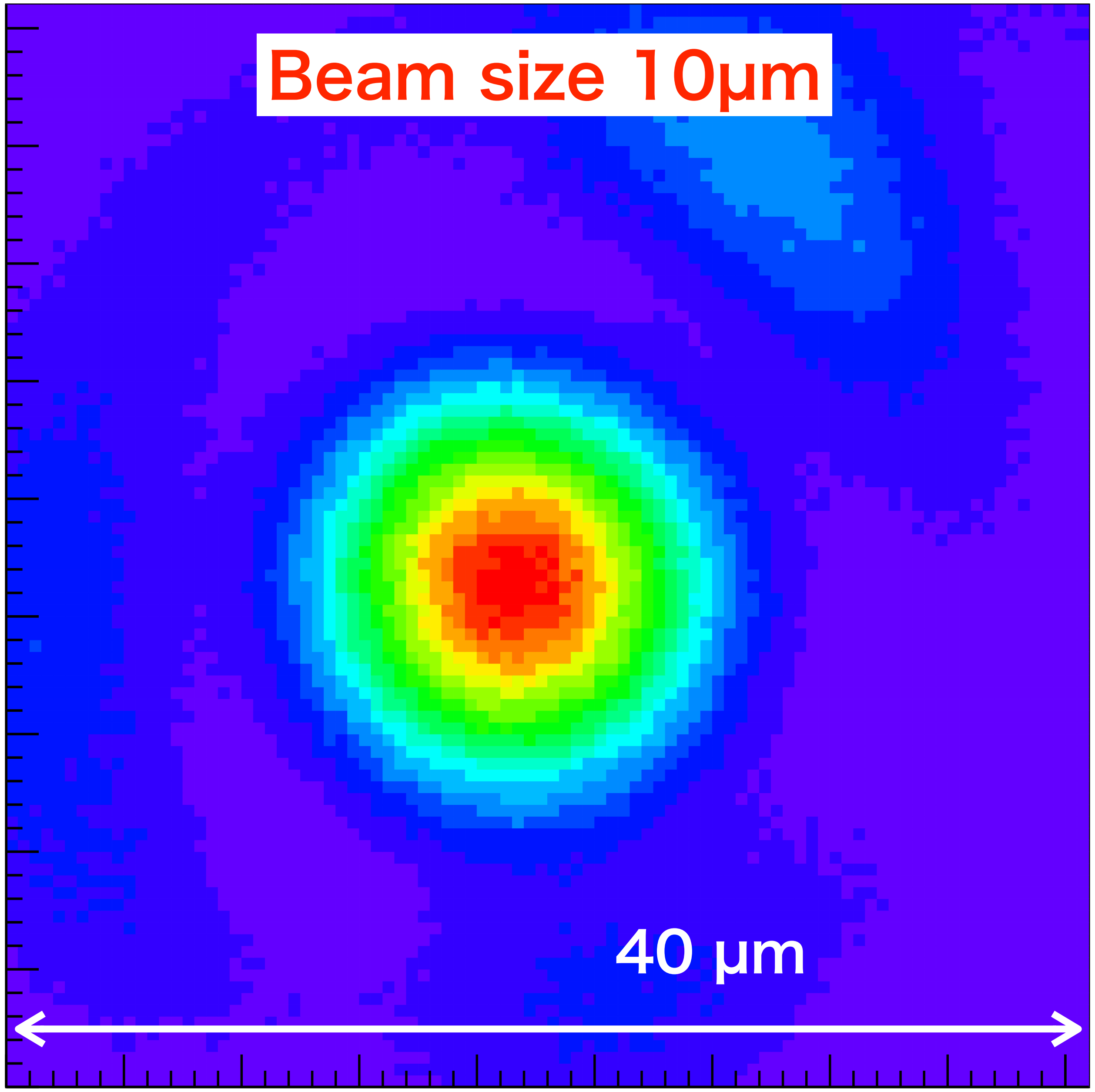
<u>Phase control system</u>



Surface of the mirror is controlled by 52 actuators.

Improvement of the laser size

No phase control

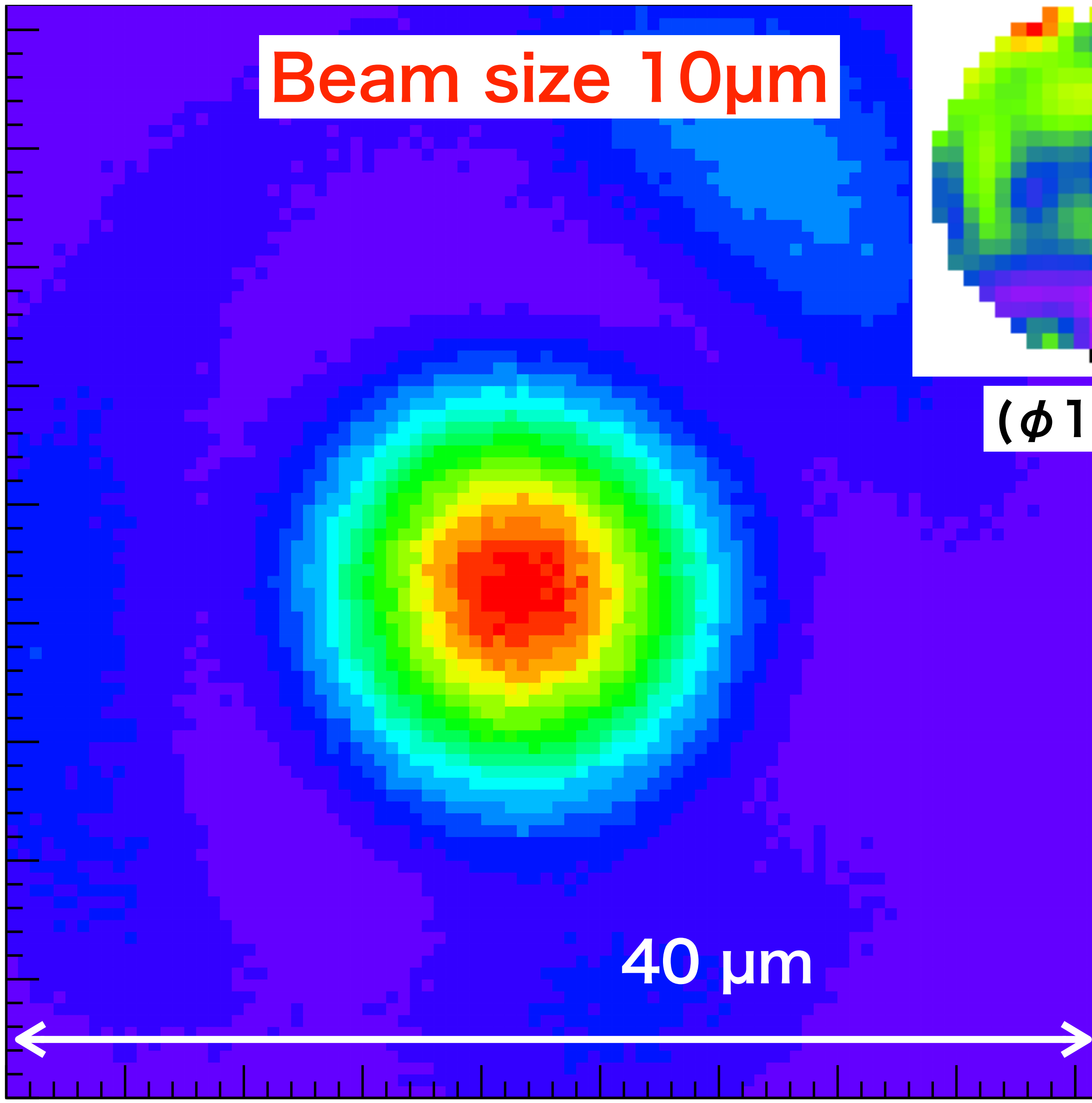


(Focal length 102mm)

With phase control

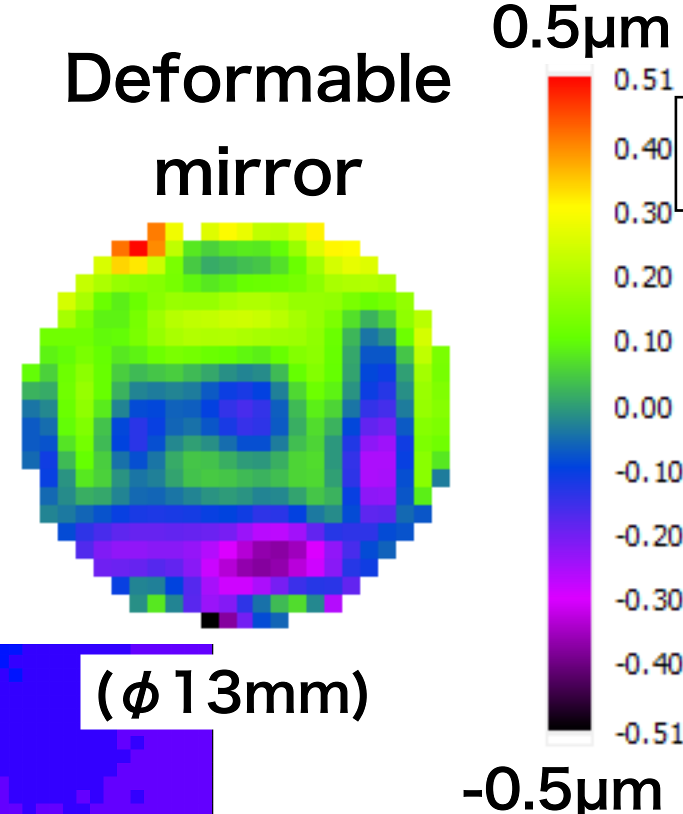
Improvement of the laser size

No phase control



(Focal length 102mm)

Deformable mirror

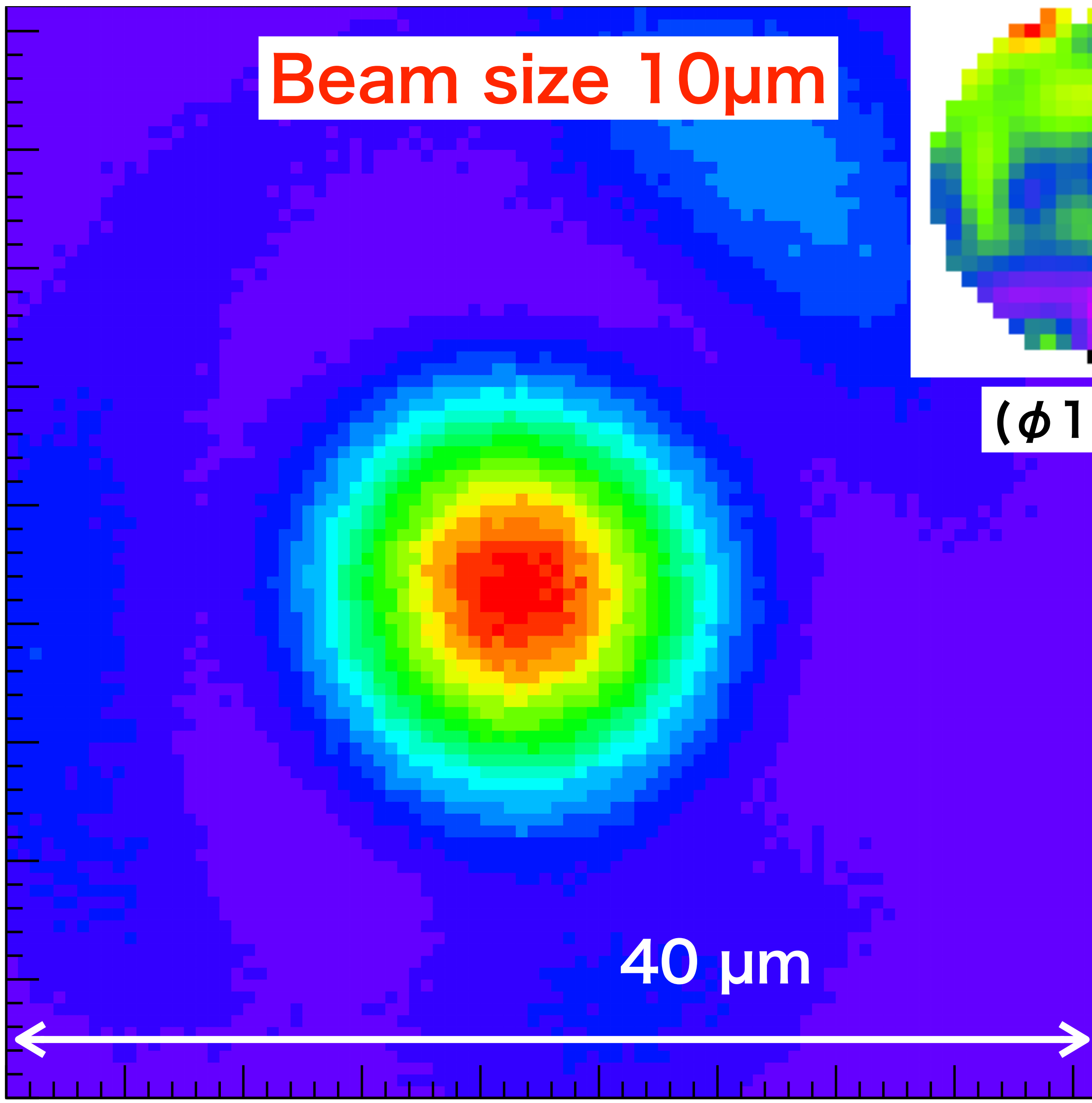


(ϕ13mm)

With phase control

Improvement of the laser size

No phase control



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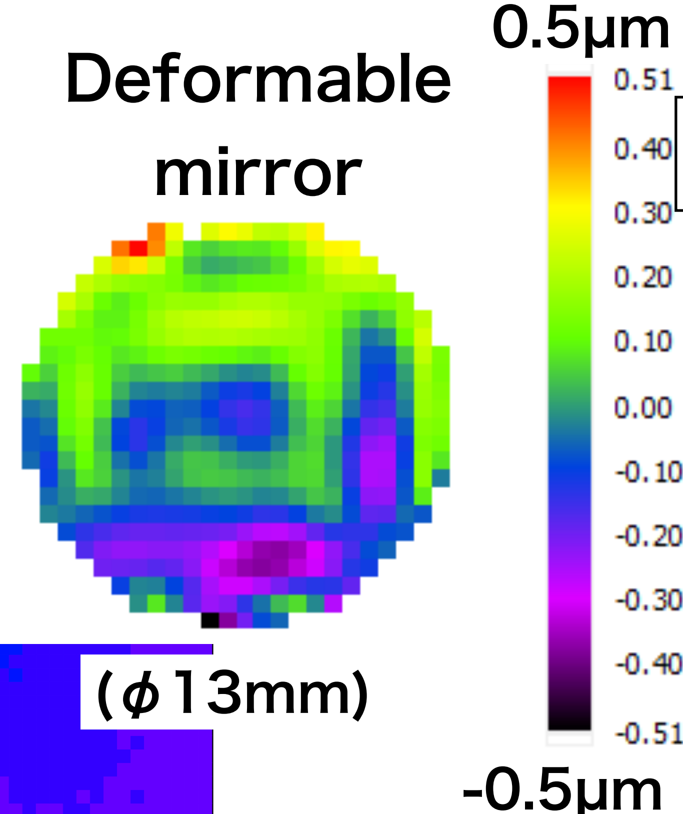
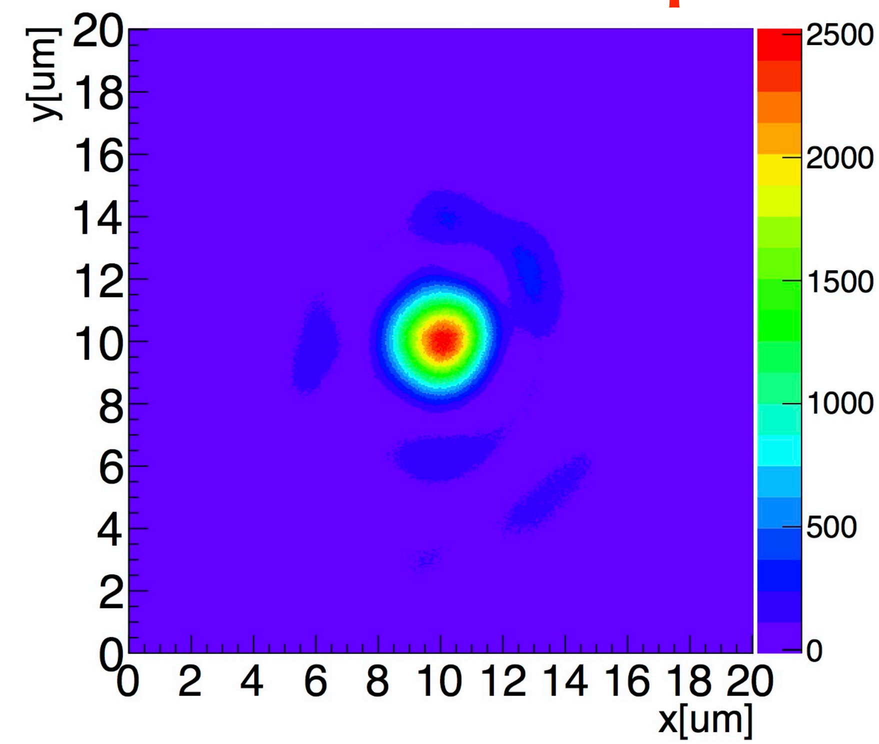


(φ13mm)

With phase control

Beam size 1.9μm



(Focal length 51mm)

Beam size becames 1.9 μm!

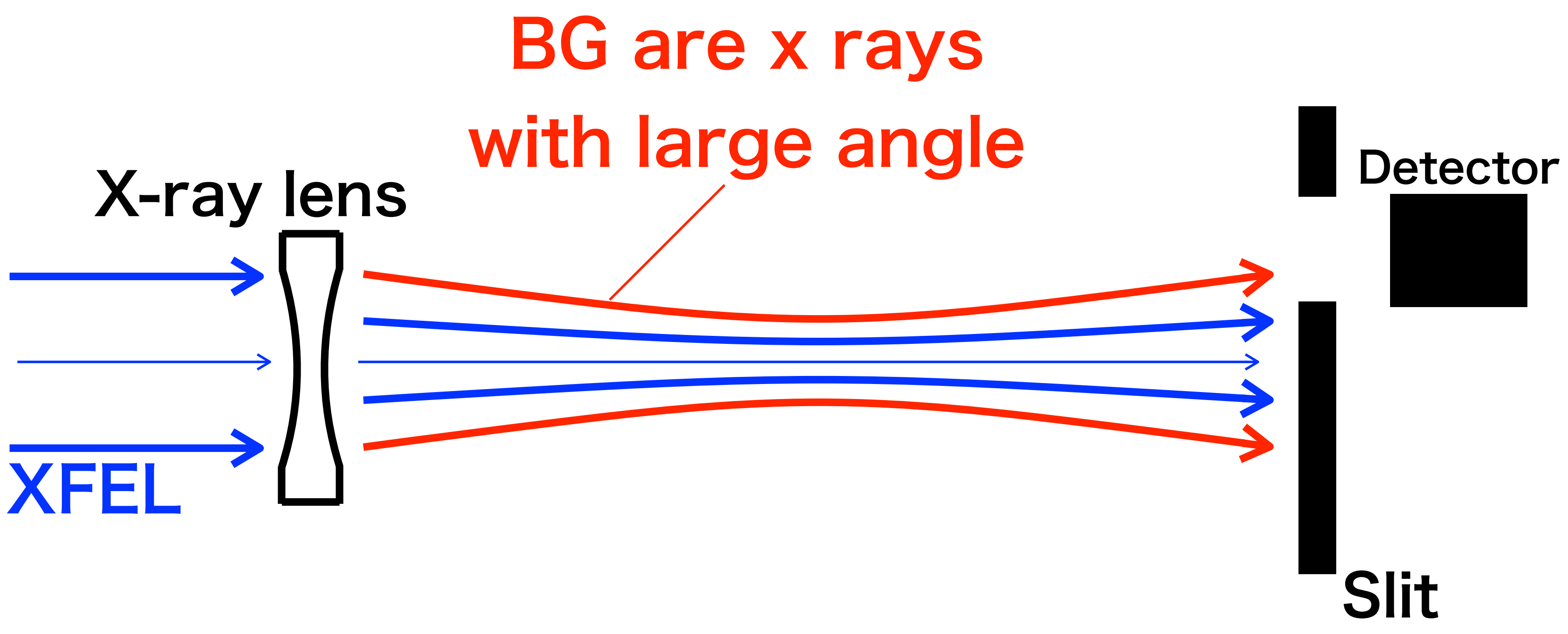
R&D task2：Development of beam shaper for BG suppression

R&D task 2

- Suppression of BG
- Target value is **BG/(XFEL intensity) < 1e-5**

Solution

- BG source：X rays which has large angle in XFEL beam
- Removal by silts generate another BG



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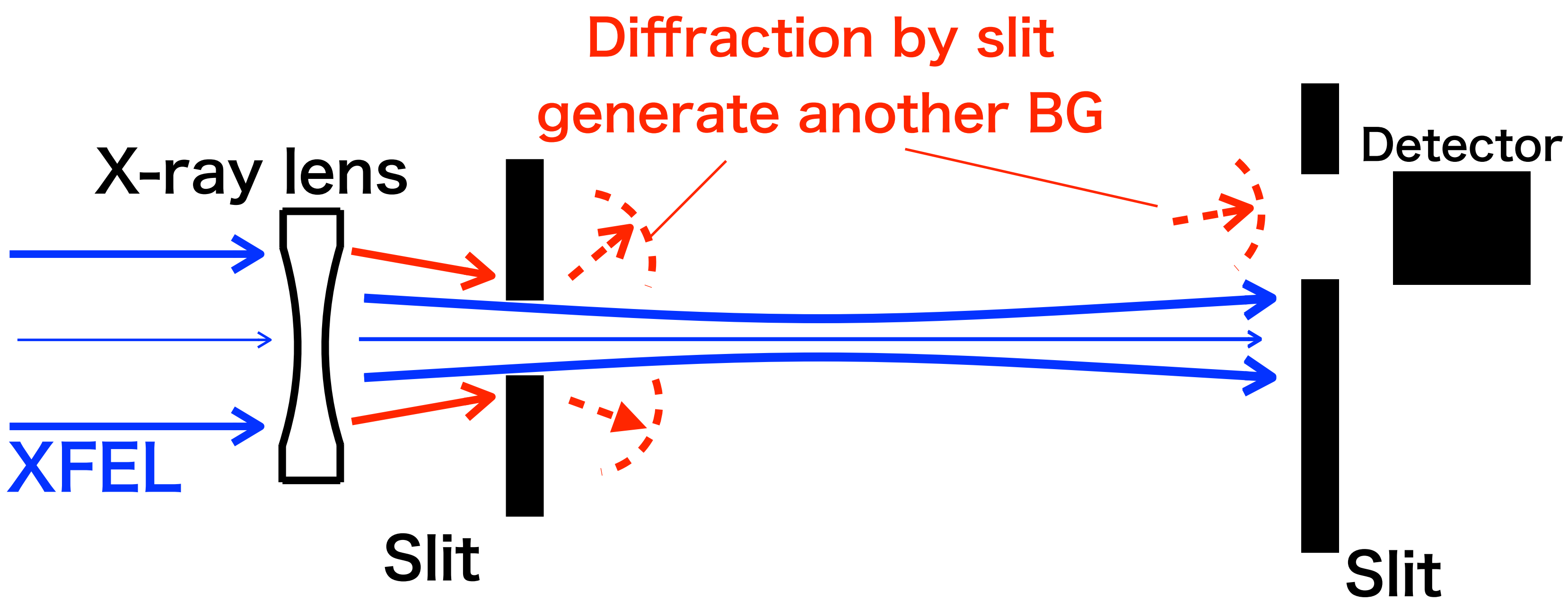


First I tried like this

but BG suppression was 1e-2 . . .

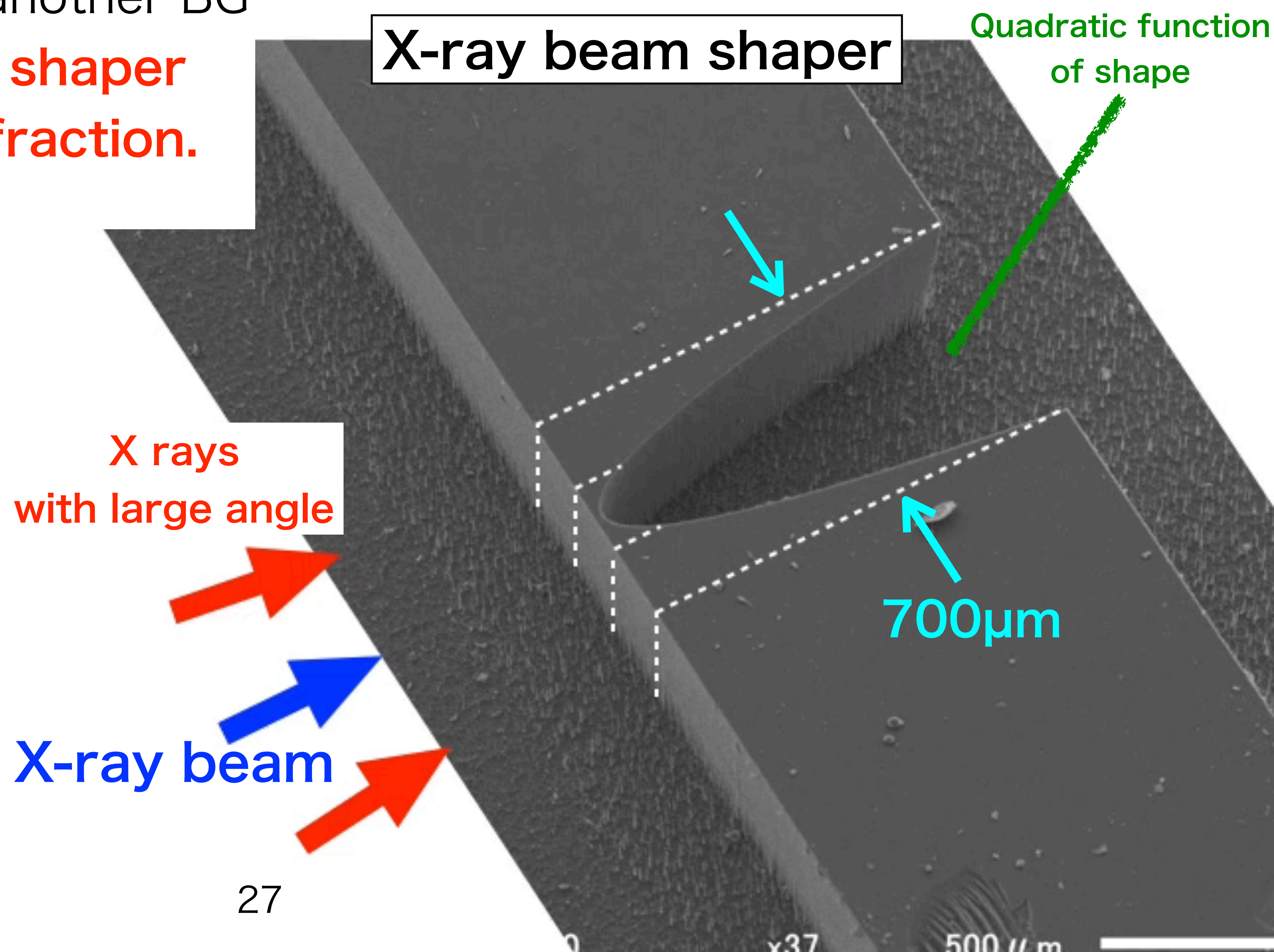
R&D task2：Development of beam shaper for BG suppression

R&D task 2

- Suppression of BG
- Target value is **BG/(XFEL intensity) < 1e-5**

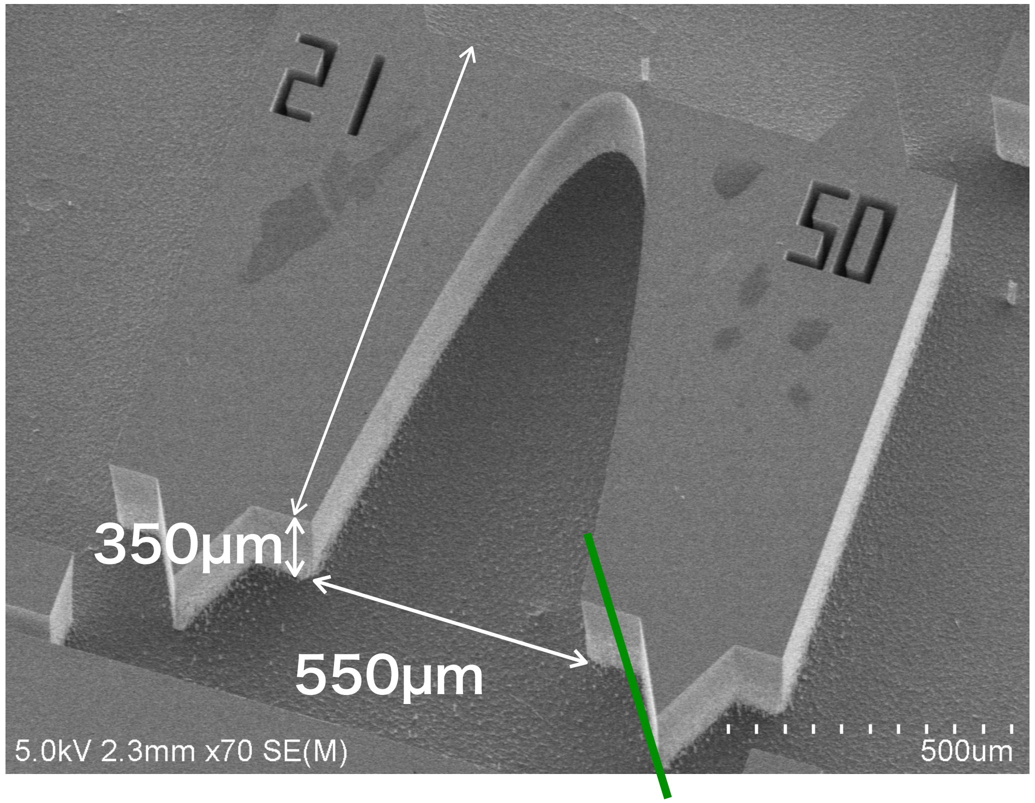
Solution

- BG source：X rays which has large angle in XFEL beam
- Removal by silts generate another BG
- **I invented an x-ray beam shaper to absorb BG without diffraction.**



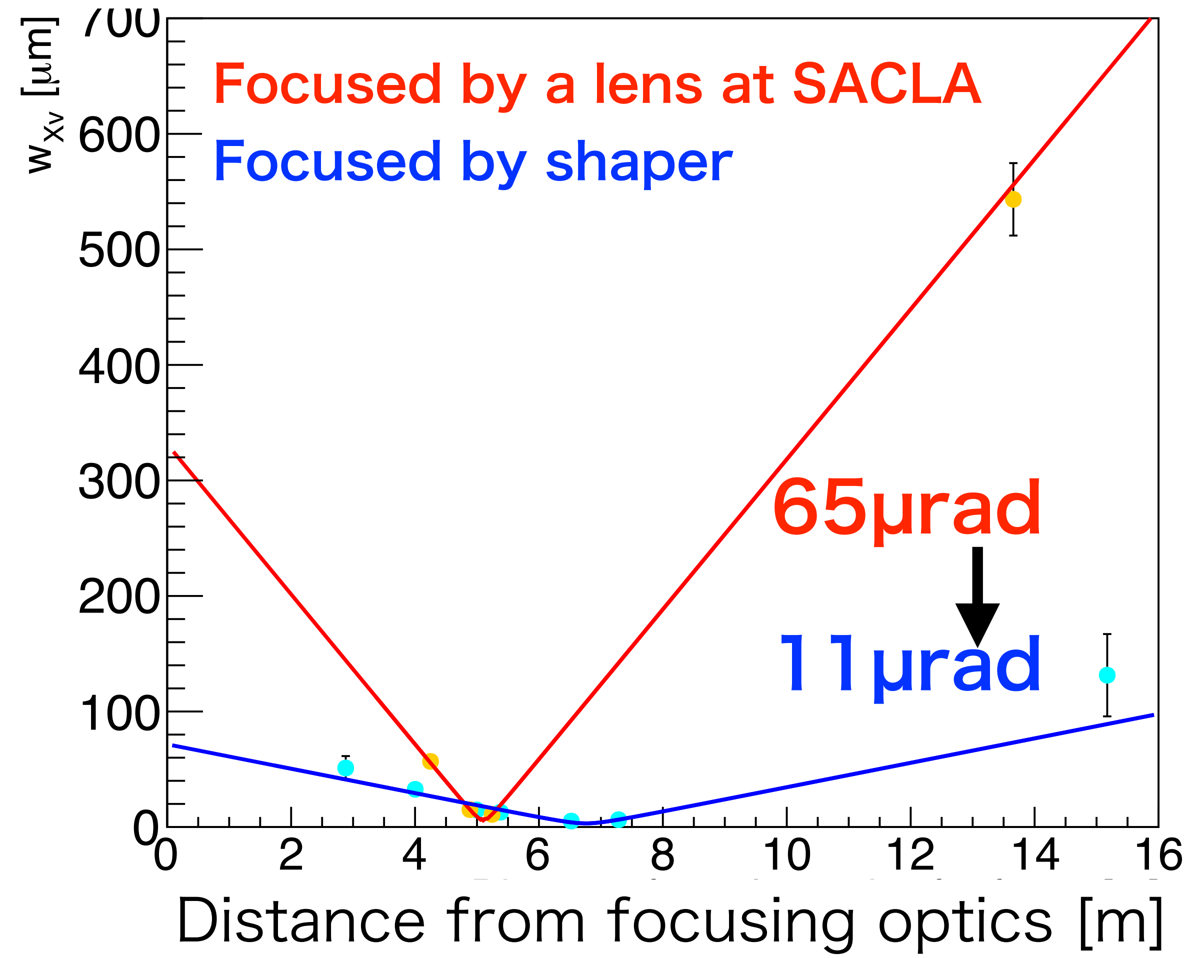
Shaper

SEM image of shaper



Quadratic function of shape

Focused XFEL beam at SACLA



Shaper

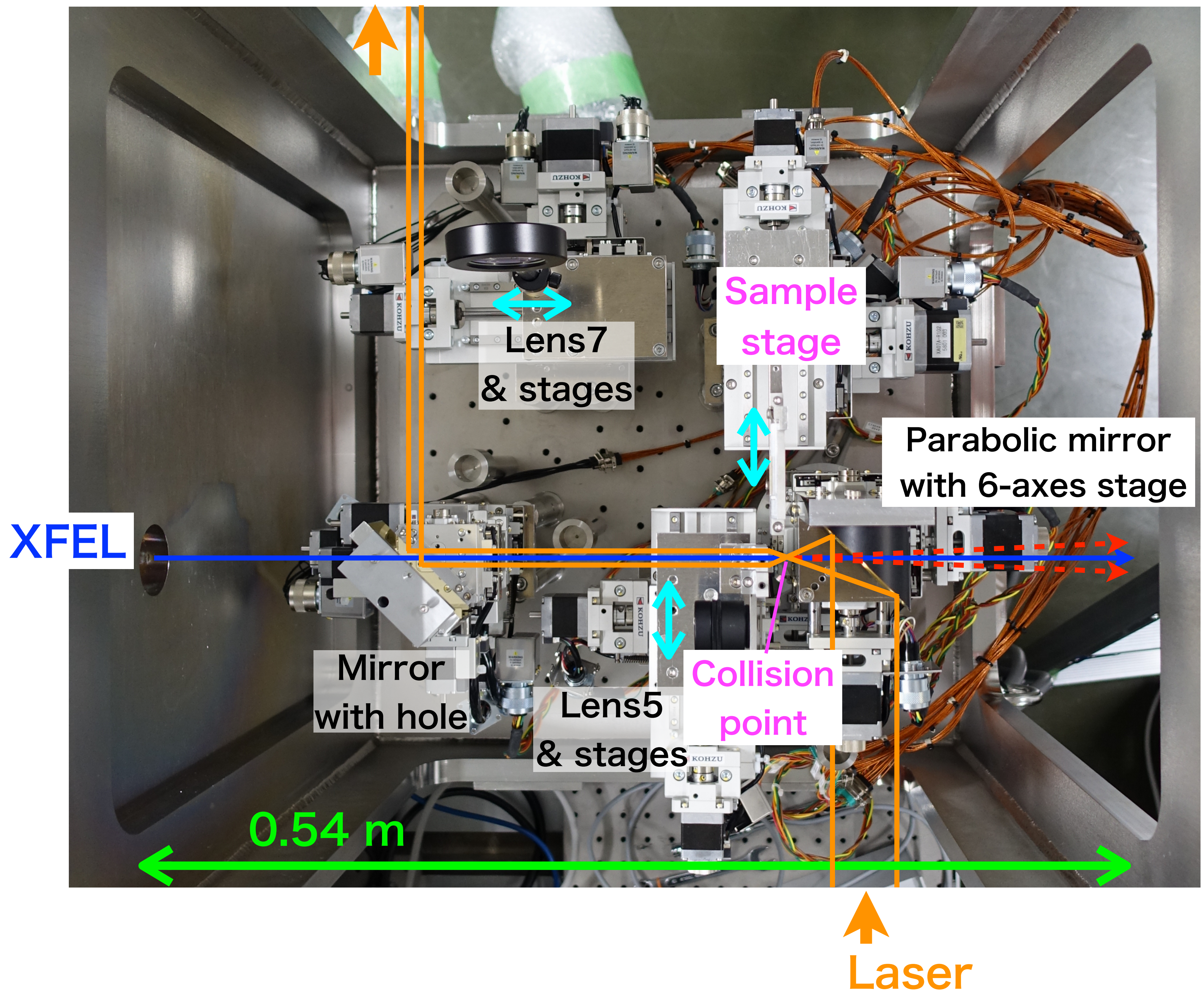
- Si substrate is processed by ion etching
- One-dimension focusing. f=5.4m
- Transmitted beam has gaussian profile
- Angular divergence becomes smaller since beam becomes thin without diffraction

Angular divergence

- Divergence of XFEL beam focused by shaper becomes smaller.
- BG is suppressed as expected. (BG rate $1\times10^{-2}\rightarrow$ **3×10^{-5}**)

R&D task 3 : Techniques for collision

Top view of vacuum chamber



- A sample at collision point was used to align position and timing of laser pulse.
- Degree of vacuum : 3×10^{-3} Pa

R&D task3-1 : Collision technique (Space)

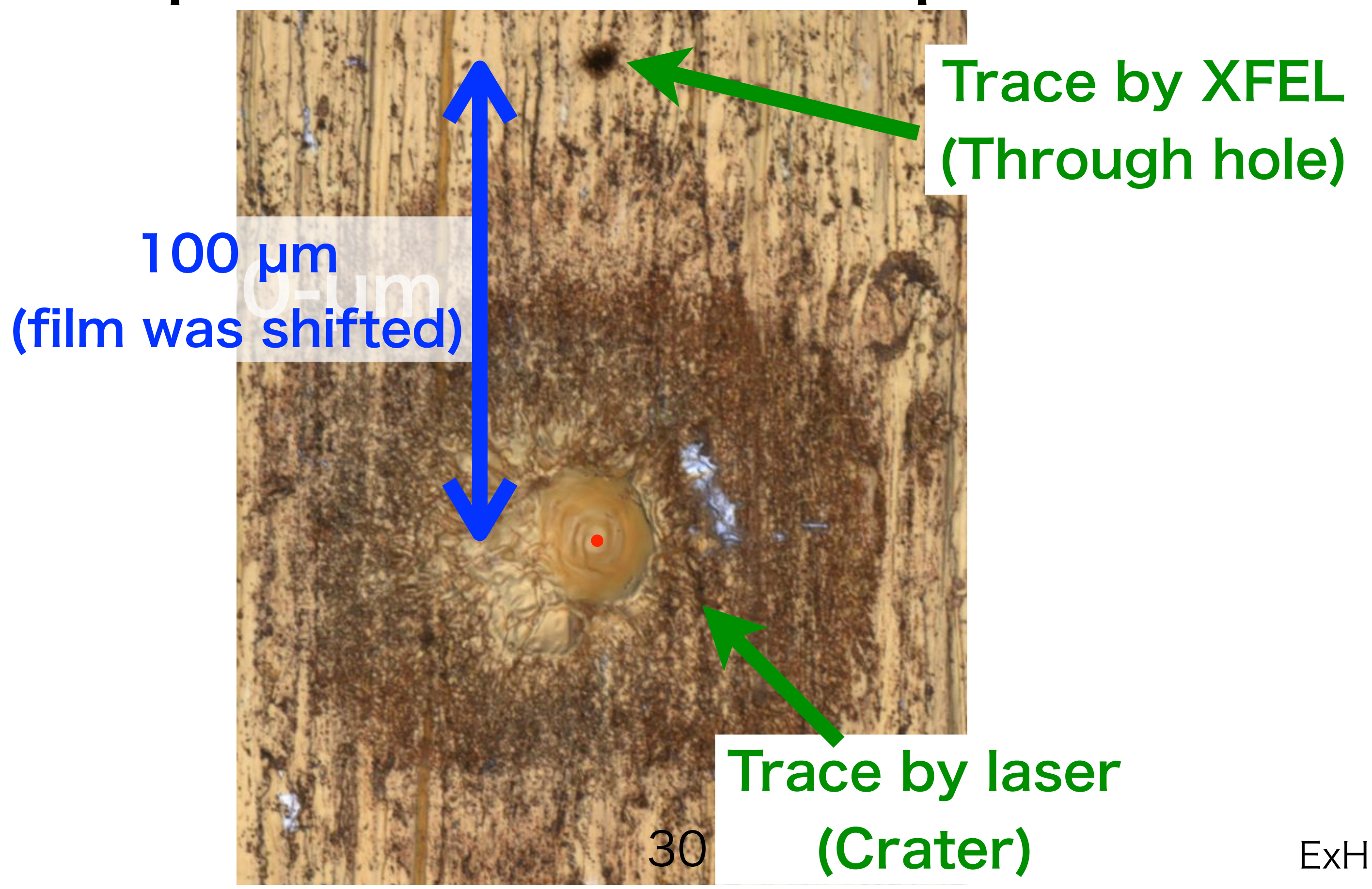
R&D task3-1

- Both pulses should be overlapped.
  Target of accuracy is **below XFEL size(15μm)**
- Key point is measurement of relative distance of both pulses

Solution

- To guarantee the overlap certainly, irradiation traces of both pulses were made on the sample placed at the collision point and both positions were compered.

Picture of gold film(20μm) placed at the collision point



R&D task3-1：Collision technique (Space)

R&D task3-1

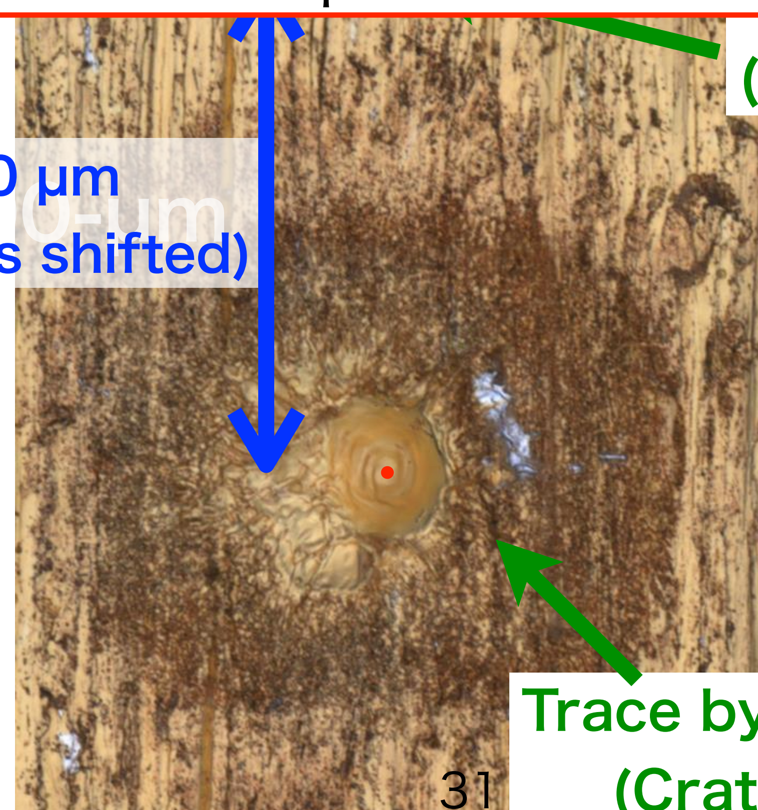
- Both pulses should be overlapped.
  Target of accuracy is **below XFEL size(15μm)**
- Key point is measurement of relative distance of both pulses

Solution

- To guar… ere made
  on the s… ompered.

- Accuracy of measurement of relative distance was
  Horizontal：**±4.2 μm**
  Vertical　：**±3.7 μm**

→Accuracy is smaller than target value (XFEL size, 15μm).
We can collide both pulses!



R&D task3-2：Collision technique (timing)

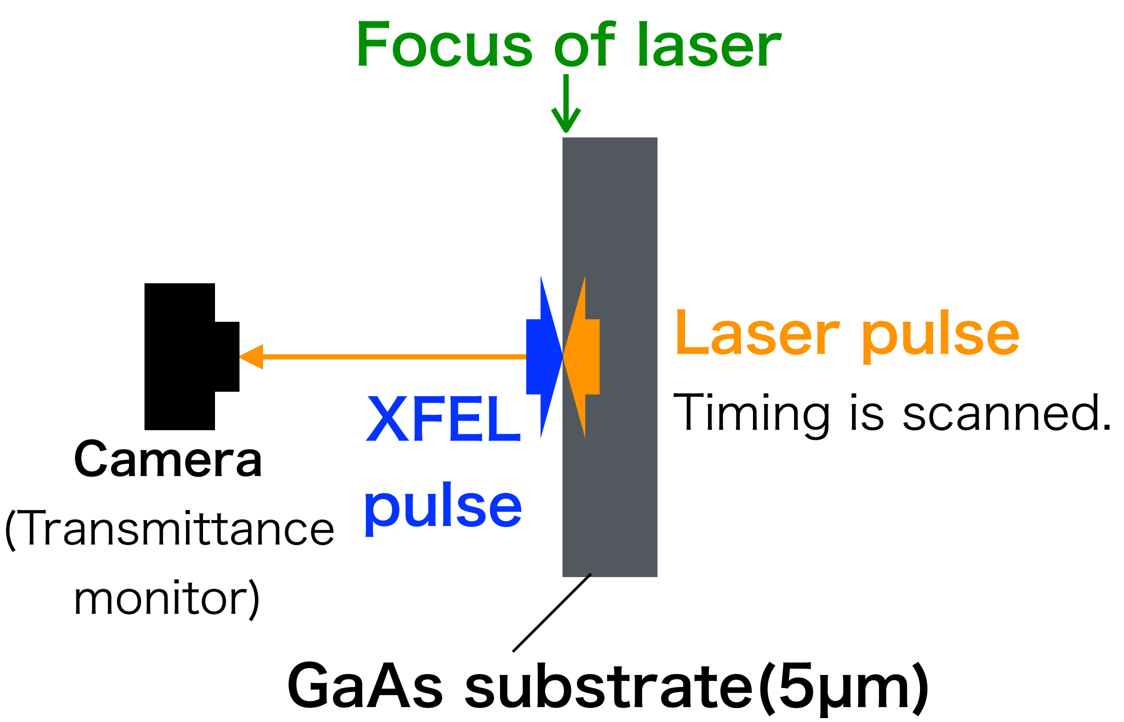
R&D task3-2

- Both pulses should be collided when the laser pulse is focused.
  Target of accuracy is **300 fs** (=jitter size)

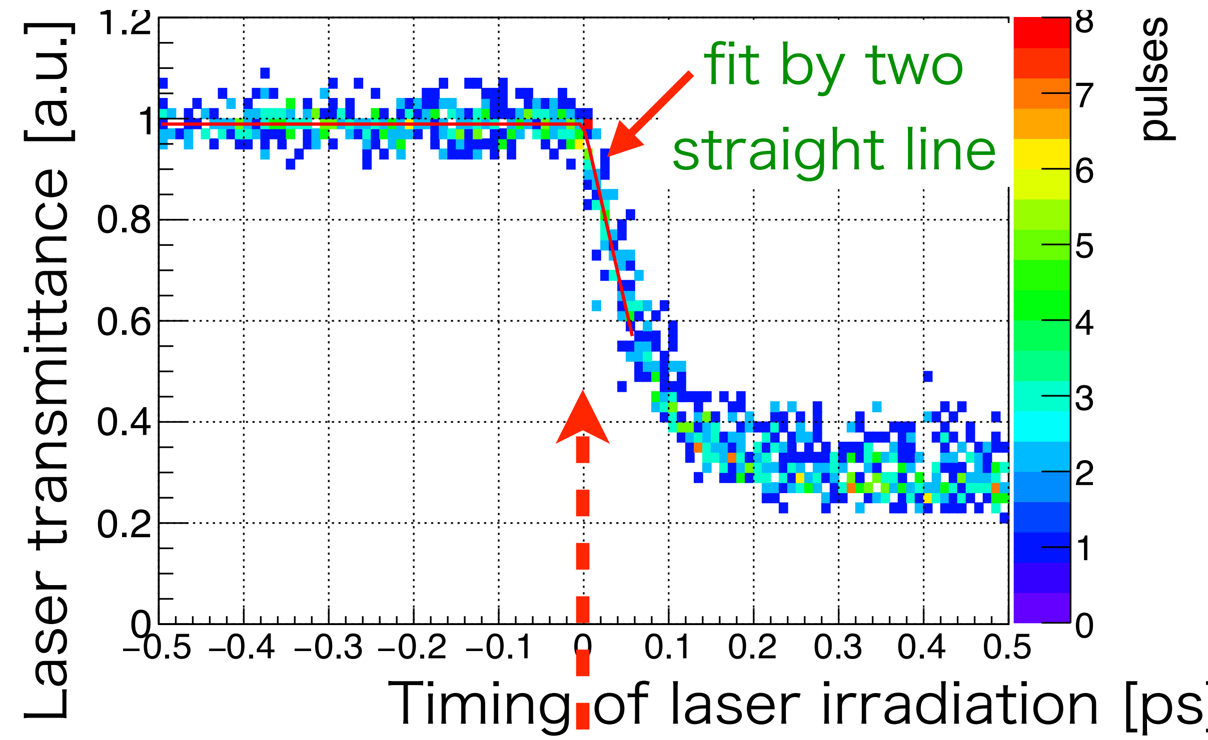
Solution

- I used **fast change(<100 fs) in transmittance** of GaAs.

Timing alignment setup



Laser transmittance measurement



- GaAs becomes opaque when x rays are absorbed.
- GaAs substrate is placed at focus of laser, and both pulses are irradiated.
- Timing when transmittance decrease is searched, scanning timing of irradiation of the laser.

Transmittance decrease
⇒Both pulses are irradiate at the same time

R&D task3-2：Collision technique (timing)

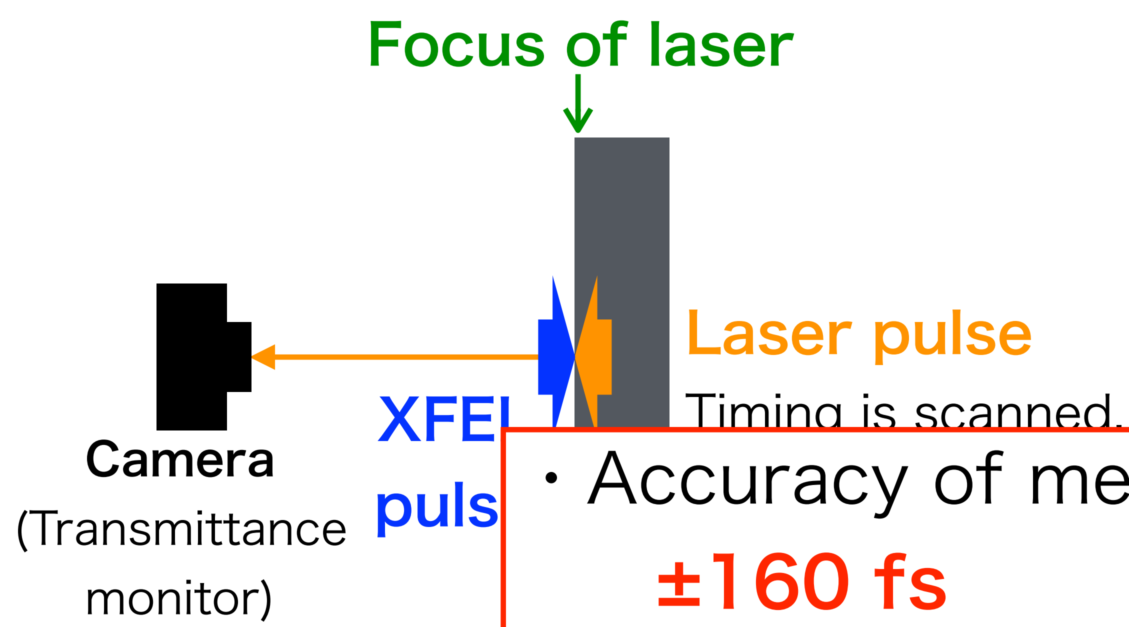
R&D task3-2

- Both pulses should be collided when the laser pulse is focused.
  Target of accuracy is **300 fs** (=jitter size)

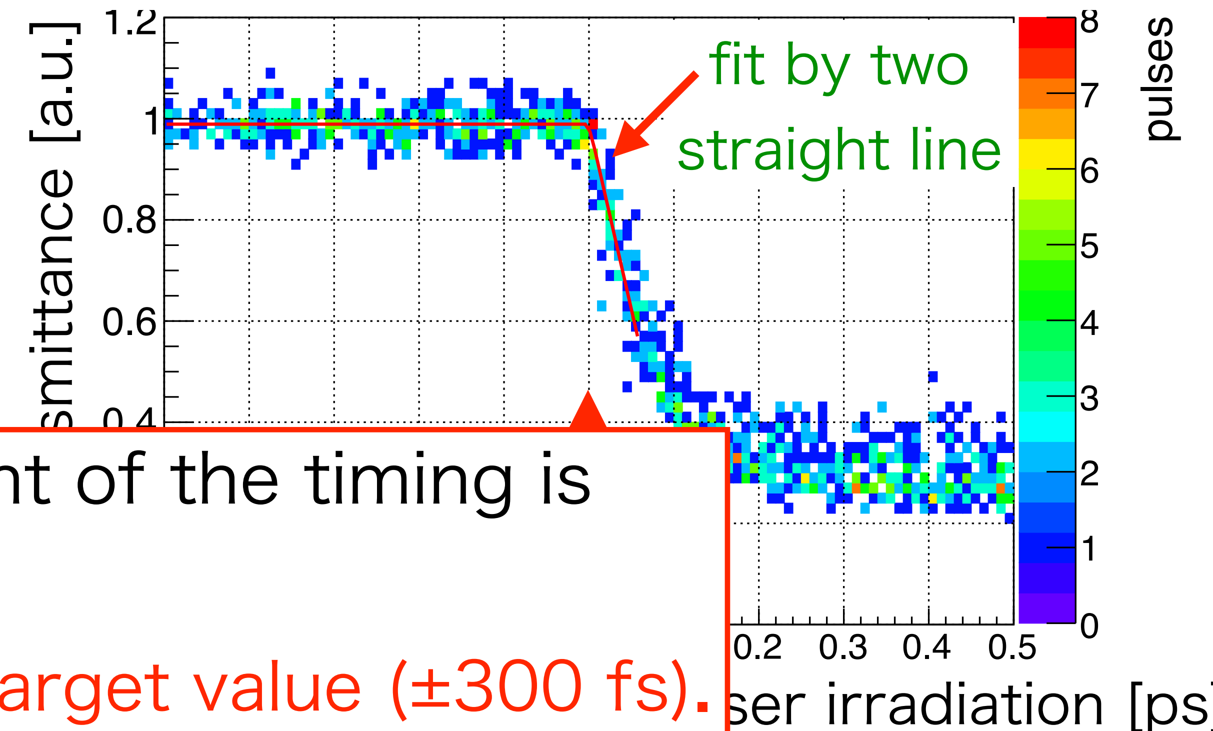
Solution

- I used **fast change(<100 fs) in transmittance** of GaAs.

Timing alignment setup



Laser transmittance measurement



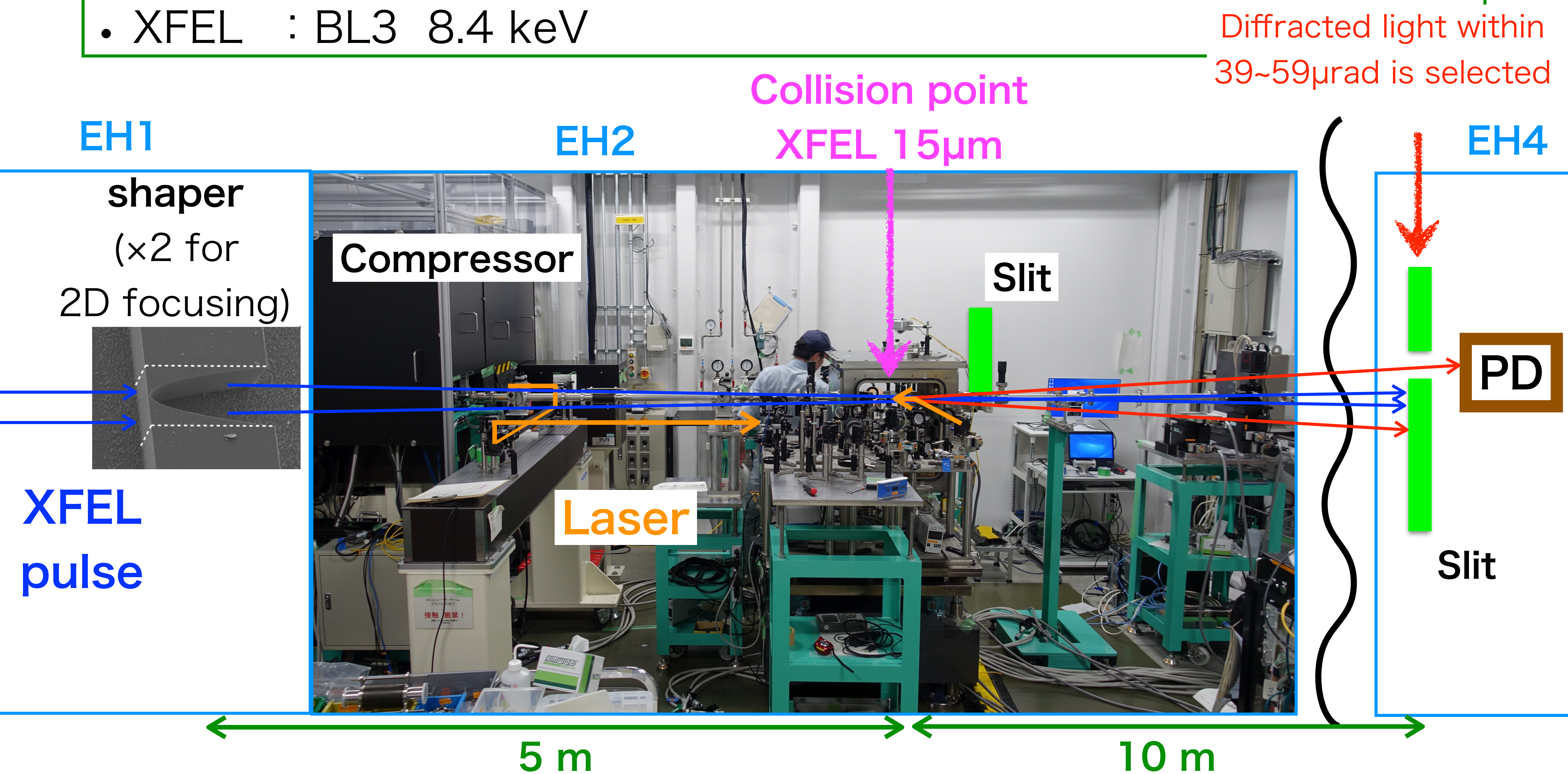
- Accuracy of measurement of the timing is **±160 fs**
  →Accuracy is smaller than target value (±300 fs).
  We can collide both pulses!

- GaAs become
- GaAs substrate is placed at focus of laser, and both pulses are irradiated.
- Timing when transmittance decrease is searched, scanning timing of irradiation of the laser.

Transmittance decrease
⇒Both pulses are irradiate at the same time

Vacuum diffraction experiment at SACLA

- Beam time：2019/06/27 ～ 07/01　(96hour)
- Purpose is first search for vacuum diffraction
- Laser　：0.6 TW laser (0.47mJ at focus)
- XFEL　：BL3　8.4 keV

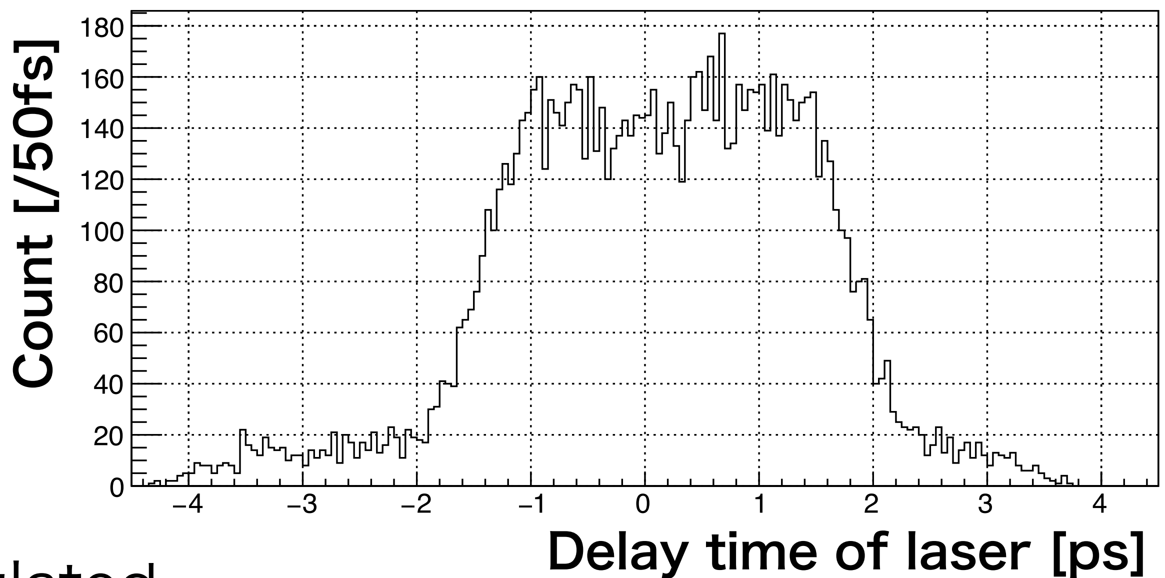


Measurement of diffracted x rays & expected signal

Measurement of diffracted x rays

- Diffracted x rays were measured after the alignments.
- Datas w/wo laser were acquired alternately.
  (XFEL 30Hz, Laser 15 Hz)
- Irradiation timing of the laser was scanned.
  (interval of each scan step is 0.3 ps)
- 22050 shots of data was obtained.
- XFEL intensity was $N=3.46\times10^{9}$ photons/pulse

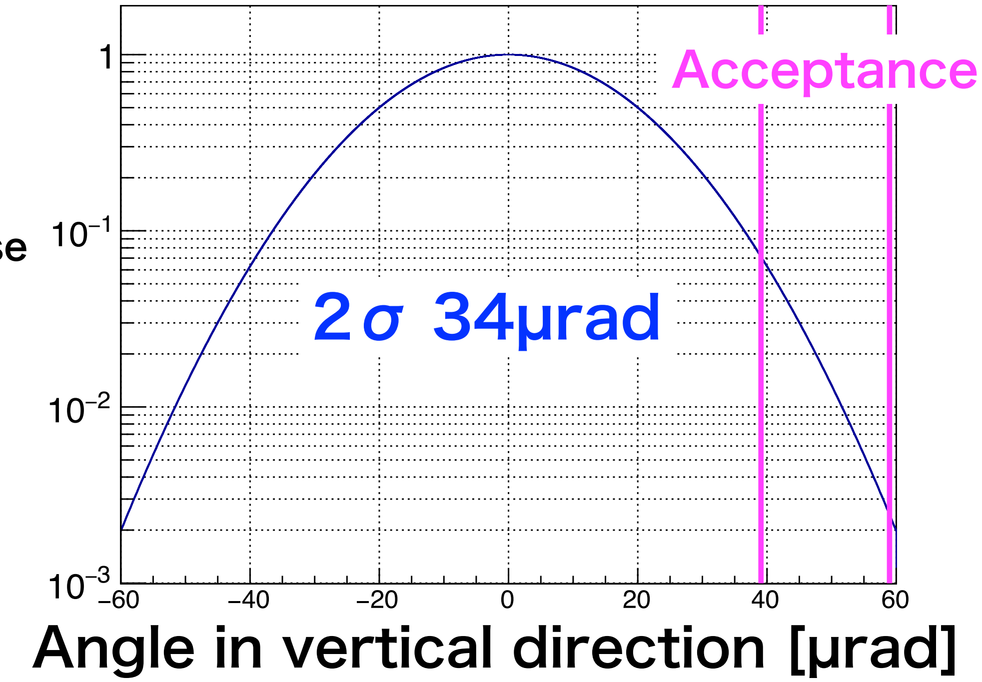
Timing distribution of data



Expected signal

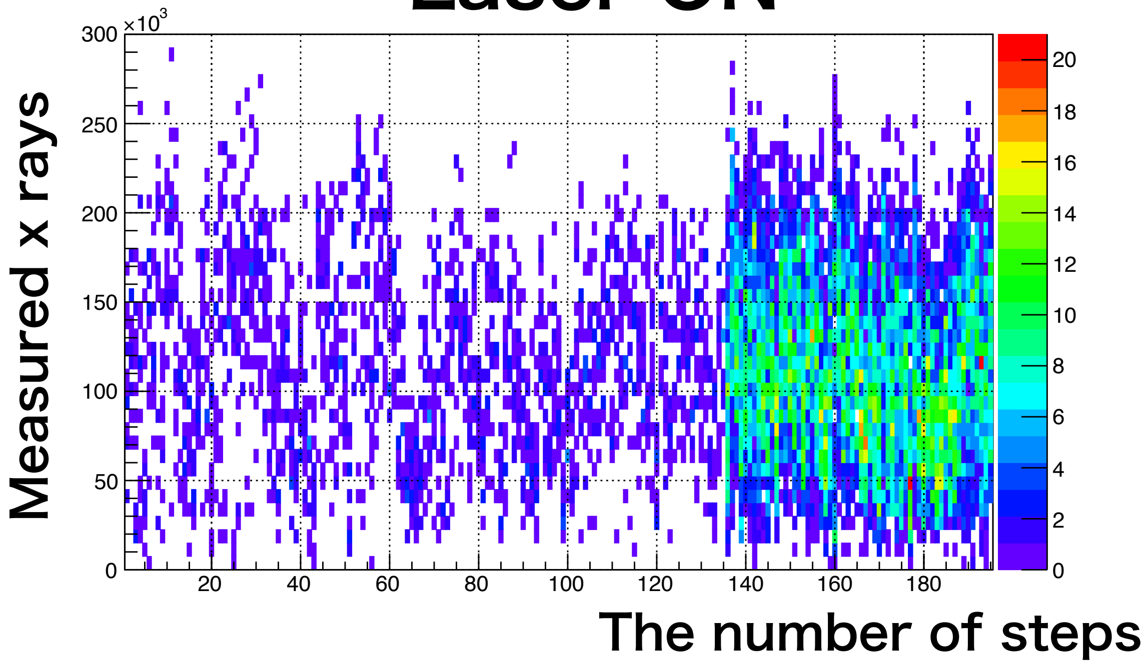
- Angular distribution of signal is effectively calculated by considering XFEL profile and divergence.
- Probability of diffraction : $\mathbf{P=2.1\times10^{-22}}$
  Acceptance : $\mathbf{A=9.5\times10^{-3}}$
  →Expected signals : $\mathbf{NPA = 7.0\times10^{-15}}$ **photons/pulse**
- Timing distribution of signal is also calculated by using measured laser images

Signal angular distribution (Vertical)

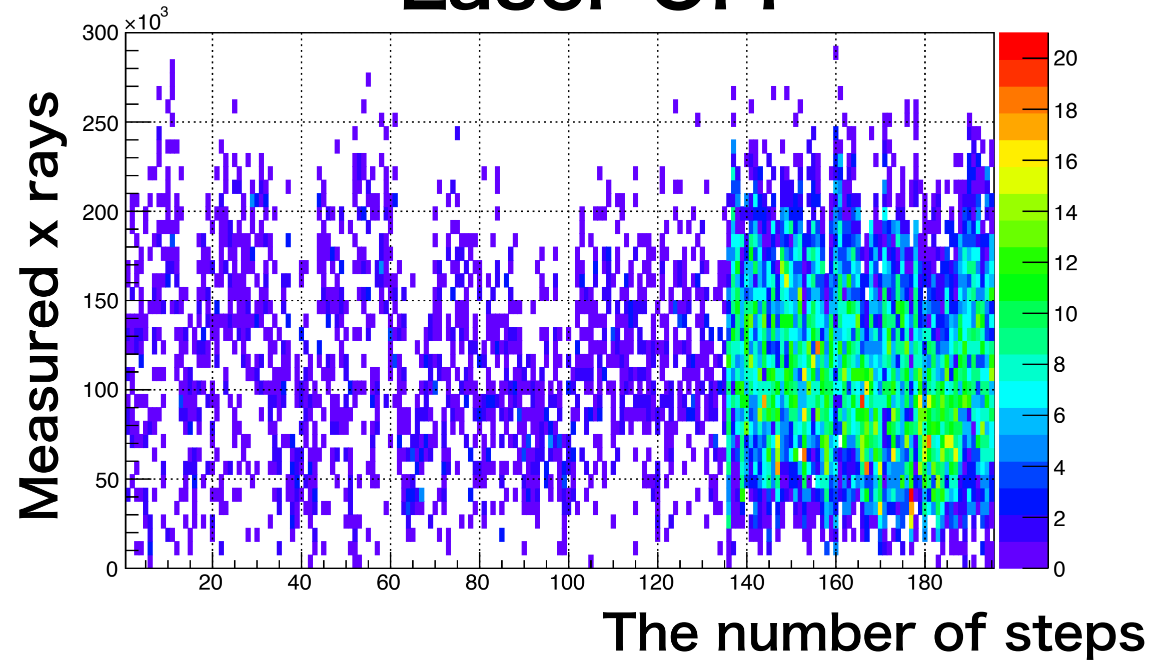


Measured x rays and limit

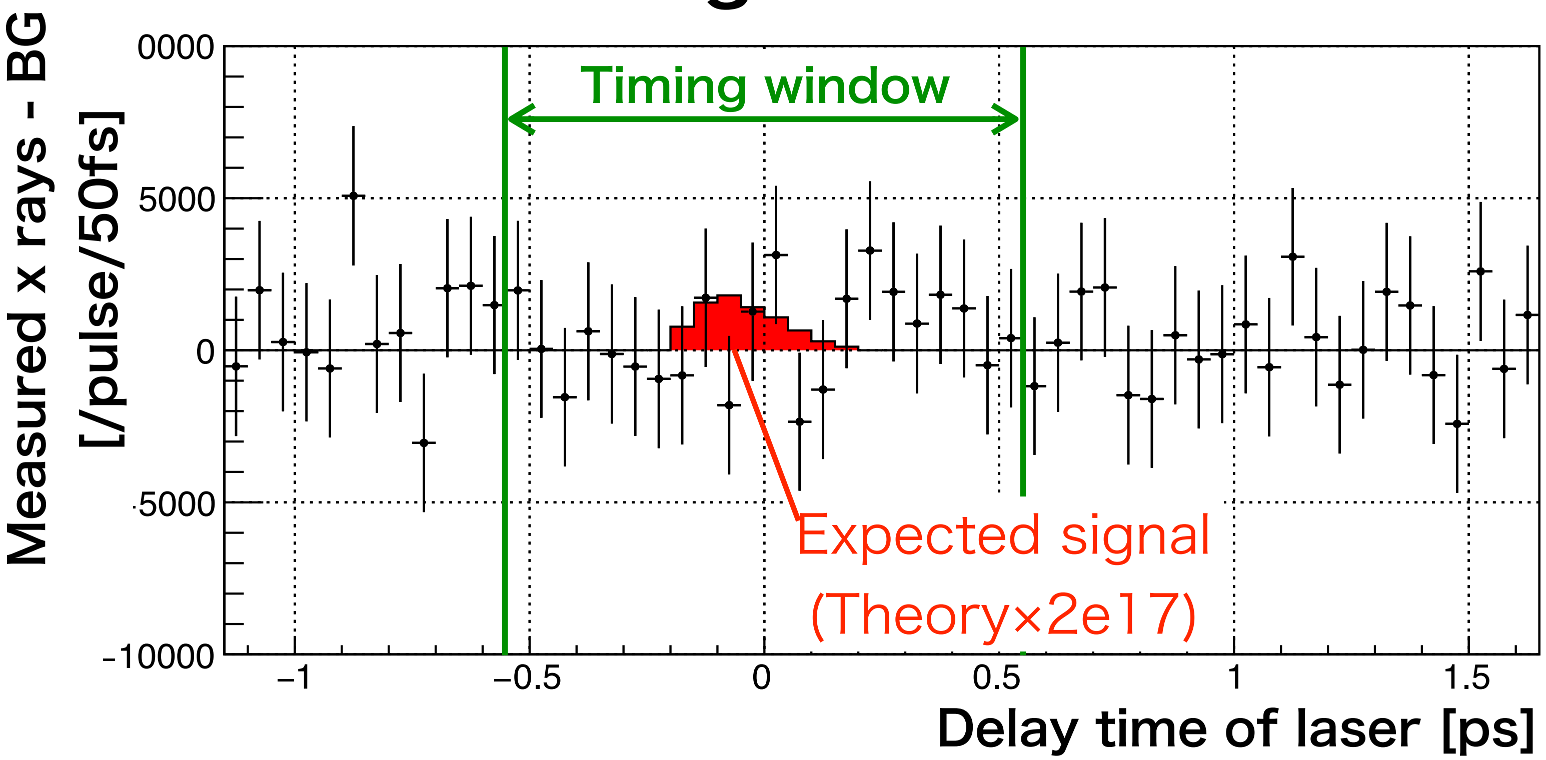
Laser ON



Laser OFF

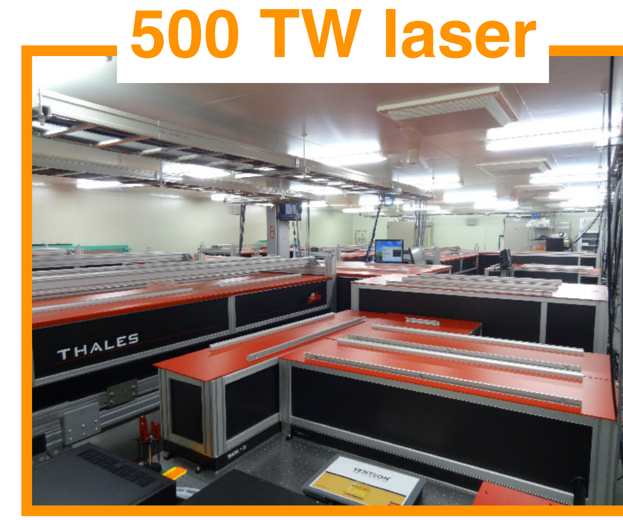


Timing distribution



- Measured x rays are upper.
- BG data (laser OFF) was subtracted in timing distribution.
- Photons in timing window is 0 constant
  $(1.02 \pm 1.07) \times 10^4$ photons
- First experimental limit for vacuum diffraction is obtained
  (Measured photons)/(Theory) $<$ **2.3×10^{18}** (90% C.L.)

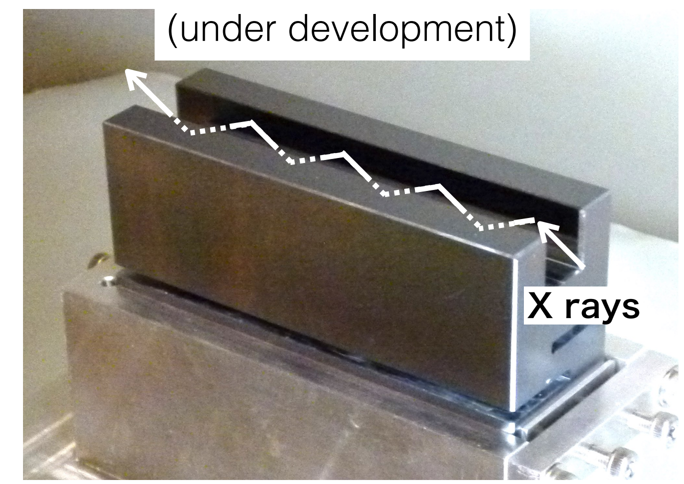
Future prospects



Main upgrades

- **Increase of signal**
  Use SACLA 500 TW laser(12.5 J)
  Signal increases $(12.5/0.47\times10^{-3})^2$ = 7×10^8
- **BG suppression**
  My experiment can induce vacuum diffraction and vacuum birefringence at the same time.
  By using both effect to suppress BG, sensitivity increase 5×10^9.

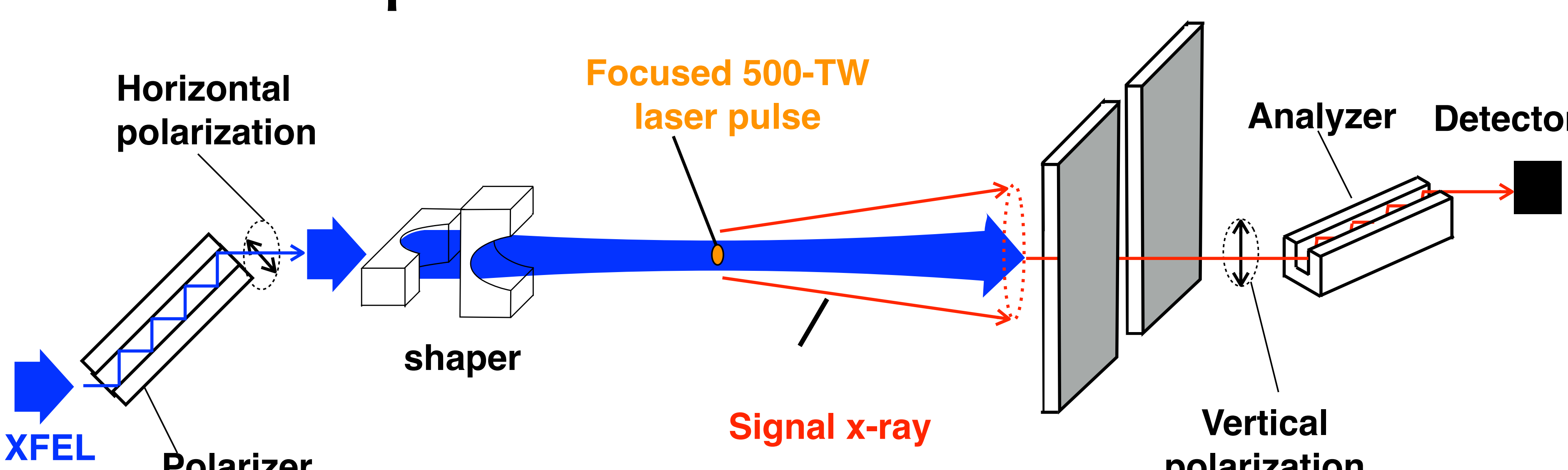
Polarizer
(under development)



Future experiment

By these upgrades, signal and BG will be 4.1 photons, 1.6±0.2(stat)photons by 20 days DAQ. Vacuum diffraction will be observed!

Setup of future experiment



Summary

- Vacuum polarization is predicted by QED and affects photon interaction.
- Sensitivity of previous researches are limited by some reasons.

- Vacuum diffraction experiment overcomes these problems.
- For the experiment, I developed
  - Focusing system of laser with phase control system
  - X-ray beam shaper for BG suppression
  - Alignment techniques to collide both pulse spatially and temporally
- Vacuum diffraction was searched by using SACLA XFEL and 0.6 TW laser
- Though signal was not obtained, first experimental limit was obtained.

  (Measured photons)/(Theory) $< 2.3 \times 10^{18}$ (90% C.L.)

- Vacuum diffraction will be observed by using 500 TW laser of SACLA