Search for Vacuum Diffraction Using X-ray Free Electron Laser SACLA

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Vacuum diffraction
caused by the reflective index slope of vacuum

<u>QED predicts that a refractive index of the vacuum changes from 1 under a strong electromagnetic field.</u>

ex) Under a magnetic field $n = 1 + \mathbf{9 \times 10^{-24} B^2}$, B [T]

This effect has not been observed!

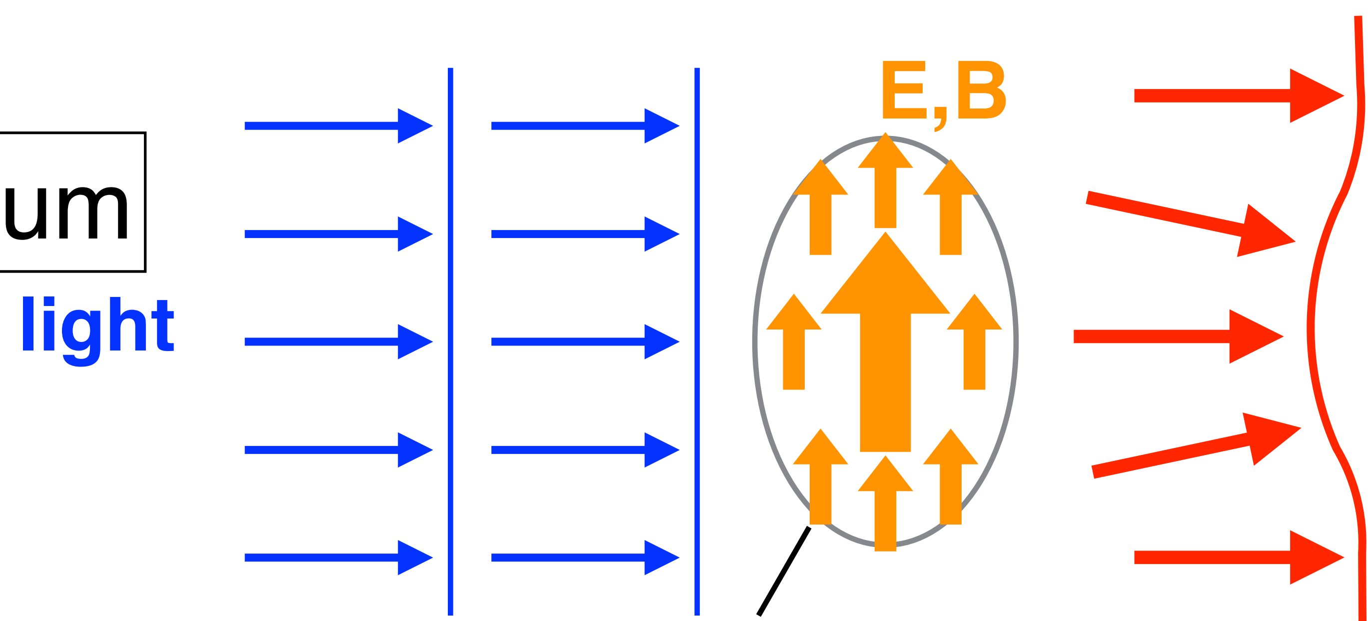
~When there is an ununiform electromagnetic field in the vacuum~

→An electromagnetic field makes a slope of a refractive index in the vacuum!!

→Photons transversing the vacuum could be diffracted slightly.

→**Vacuum diffraction**

In the vacuum



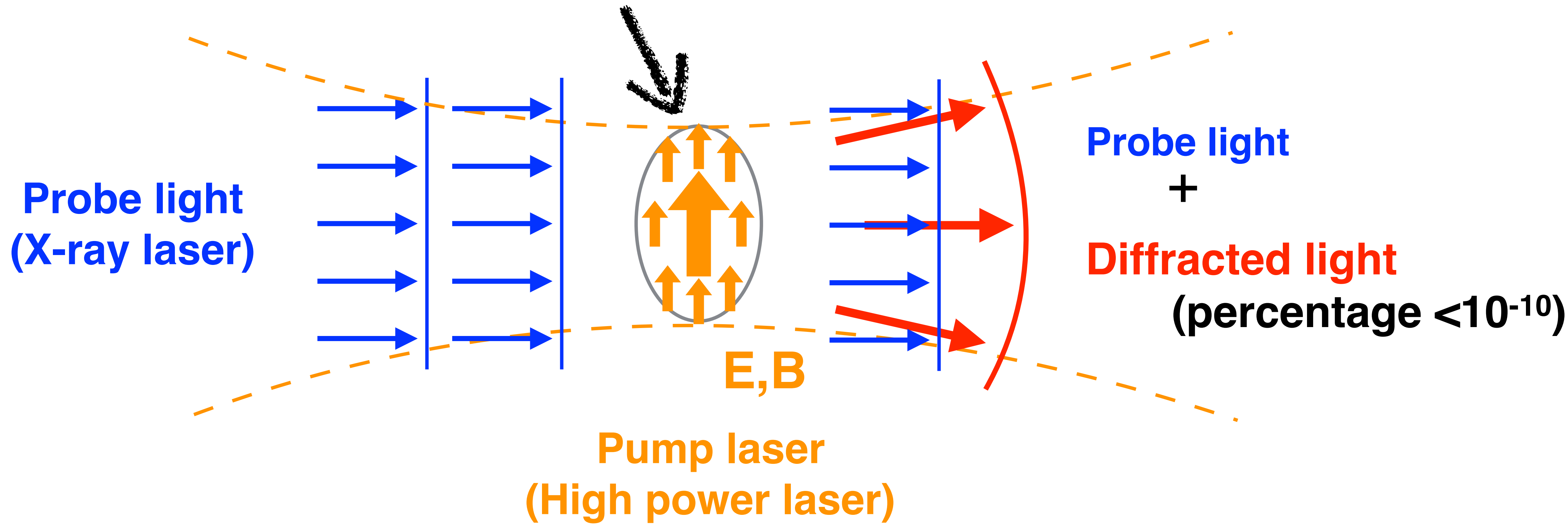
Ununiform strong electromagnetic field

A key point is to make this field.

→We use a high power laser.

Vacuum diffraction with high power laser

✔We use a high power pulsed laser to pump the vacuum.
✔A strong electromagnetic field is made by focused laser.



Vacuum **D**iffraction and **V**acuum **B**irefringence are properties of the vacuum.

VD experiment
Effect : Momentum change of light
Pump : High power laser(10^6T)
Probe : X-ray laser(next slide)

VB experiment(previous talk)
Effect : Polarization change of light
Pump : Strong magnet(20T)
Probe : Usual laser

Angle distribution of vacuum diffraction

Angle distribution of Diffracted light at collision point

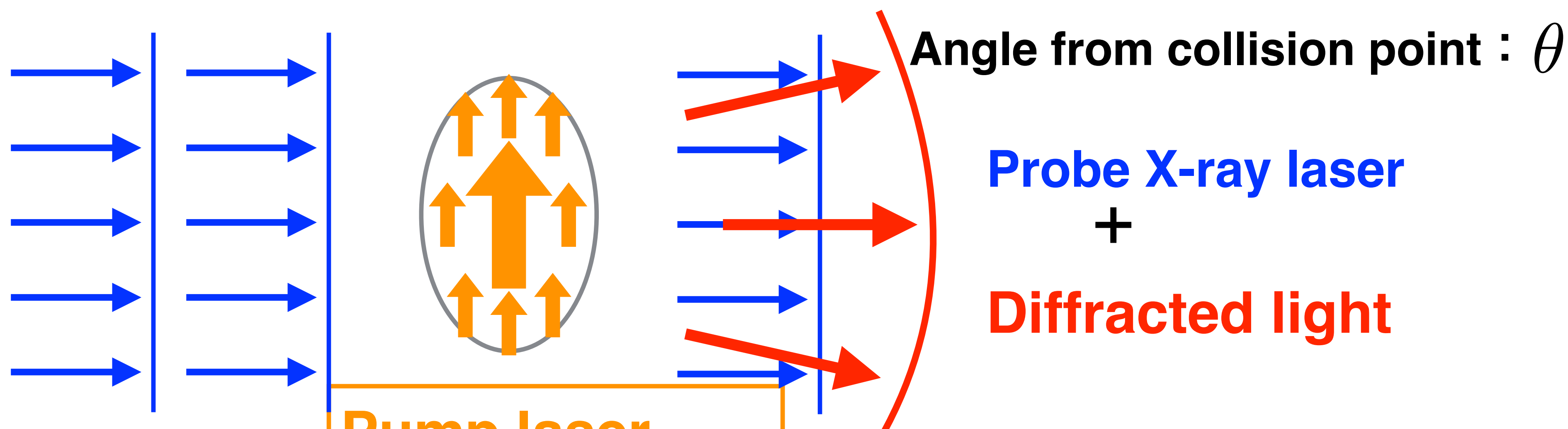
$$\frac{\mathrm{d}N_{\mathrm{diffracted}}}{\mathrm{d}\cos\theta} \sim \frac{\underline{E}^2 \underline{J} W^2}{w_{\mathrm{L}}^2 (w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2)} E^2 w^2 e^{-\frac{1}{2}(Ew\theta)^2}$$

$$w^2 = \frac{w_{\mathrm{L}}^2 w_{\mathrm{X}}^2}{w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2}$$

Probe light
:High energy & pulsed laser is good.
→Pulsed X-ray laser

PRD 94, 013004 (2016)

Probe X-ray laser (Gaussian beam)
Photon number : N
Photon flux : J
Photon energy : E
Beam waist : w_{X}



Pump laser
Pulse energy : W
Beam waist : w_{L}

Angle distribution of vacuum diffraction

Angle distribution of Diffracted light at collision point

$$\frac{\mathrm{d}N_{\mathrm{diffracted}}}{\mathrm{d}\cos\theta} \sim \frac{E^2 J W^2}{w_{\mathrm{L}}^2 (w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2)} E^2 w^2 e^{-\frac{1}{2}(\underline{Ew\theta})^2}$$

$$\underline{w^2 = \frac{w_{\mathrm{L}}^2 w_{\mathrm{X}}^2}{w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2}}$$

Probe laser energy E **: 10 keV**

Probe laser beam waist w_{X} **: 2 μm**

Pump laser beam waist w_{L} **: 1 μm**

PRD 92, 071301(R) (2015)

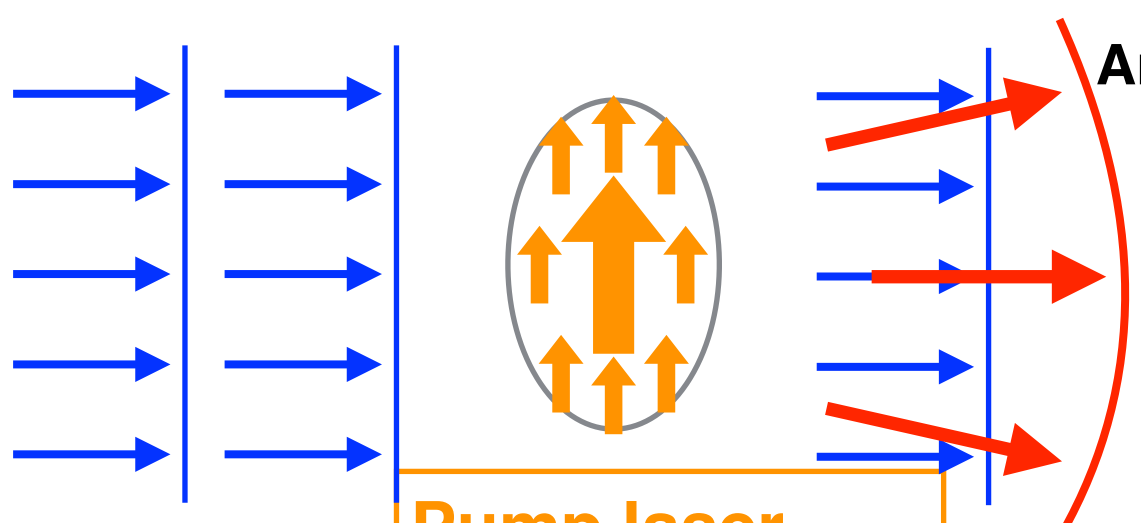
Probe X-ray laser (Gaussian beam)

Photon number : N

Photon flux : J

Photon energy : E

Beam waist : w_{X}



Angle from collision point : θ

Probe X-ray laser

+

Diffracted light

Pump laser

Pulse energy : W

Beam waist : w_{L}

Angle distribution of vacuum diffraction

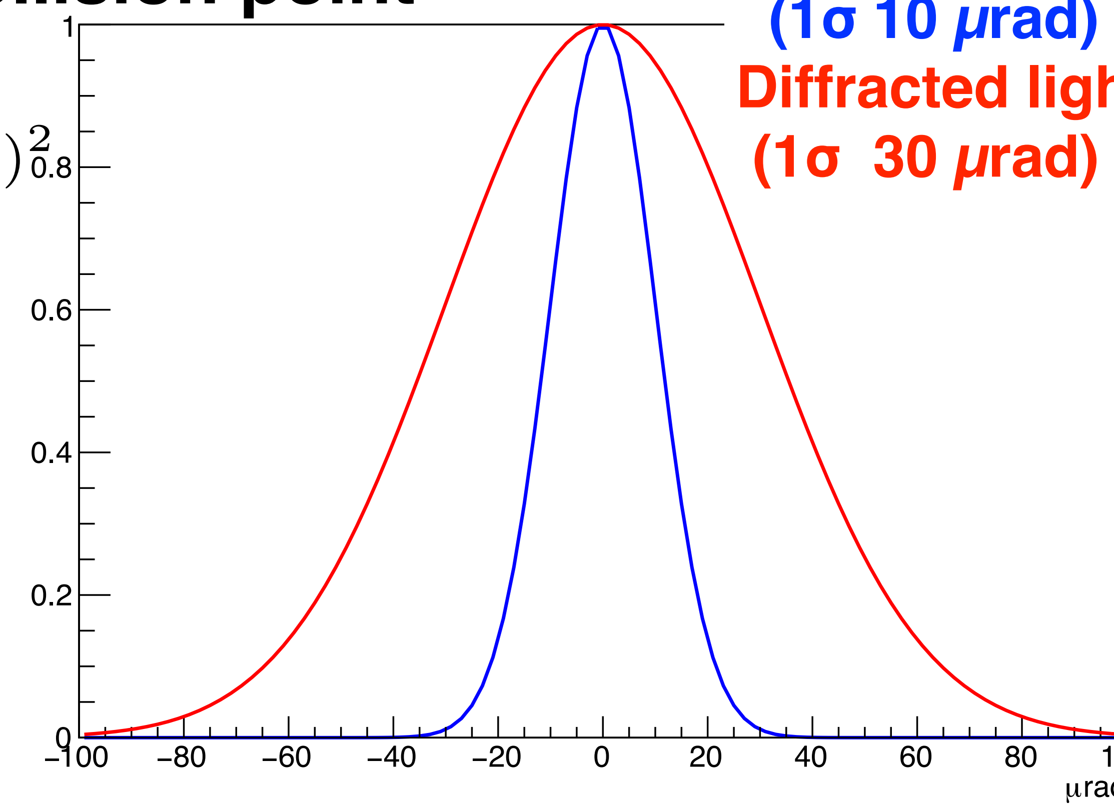
Angle distribution of Diffracted light at collision point

$$\frac{\mathrm{d}N_{\mathrm{diffracted}}}{\mathrm{d}\cos\theta} \sim \frac{E^2 J W^2}{w_{\mathrm{L}}^2(w_{\mathrm{L}}^2+2w_{\mathrm{X}}^2)} E^2 w^2 e^{-\frac{1}{2}(Ew\theta)^2}$$

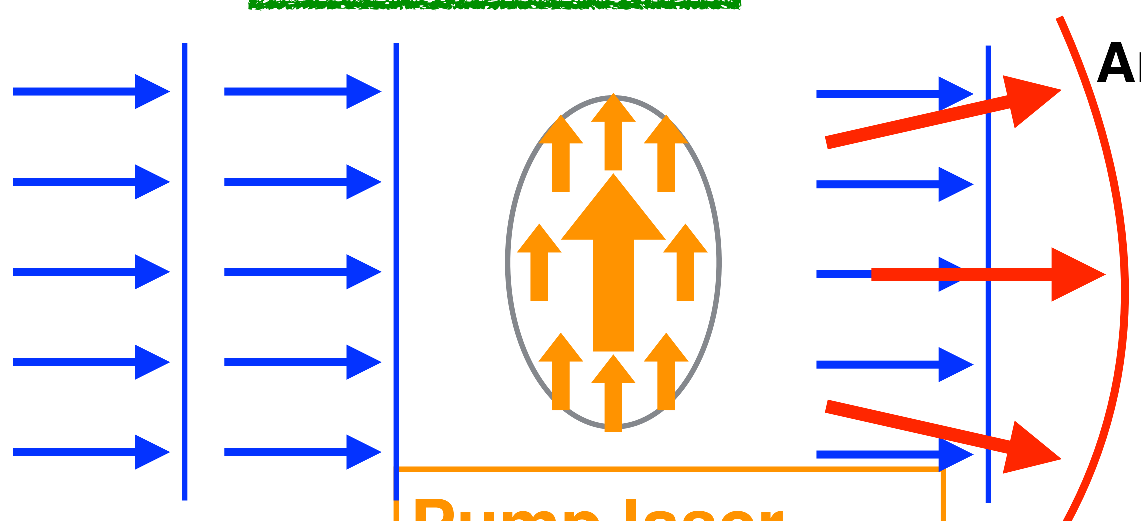
$$w^2 = \frac{w_{\mathrm{L}}^2 w_{\mathrm{X}}^2}{w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2}$$

E : **10 keV**
w_{X} : **2 μm**
w_{L} : **1 μm**

PRD 92, 071301(R) (2015)



Probe X-ray laser (Gaussian beam)
Photon number : N
Photon flux : J
Photon energy : E
Beam waist : w_{X}



Angle from collision point : θ

Probe X-ray laser
+
Diffracted light

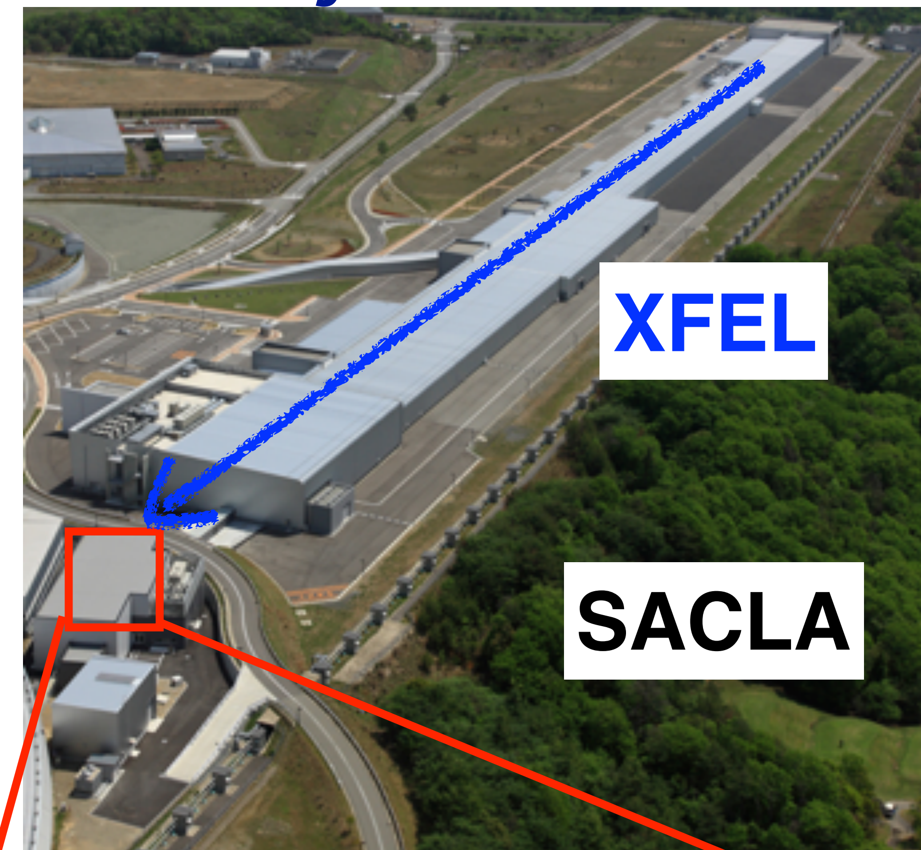
Pump laser
Pulse energy : W
Beam waist : w_{L}

X-ray Free Electron Laser(XFEL) facility SACLA

Probe

We use an **XFEL** of SACLA.
XFEL is X-ray laser.

Performance of the XFEL	
・Photon number	: 5×10^{11} photons/pulse @10 keV
・Pulse width	: <10 fs



Pump

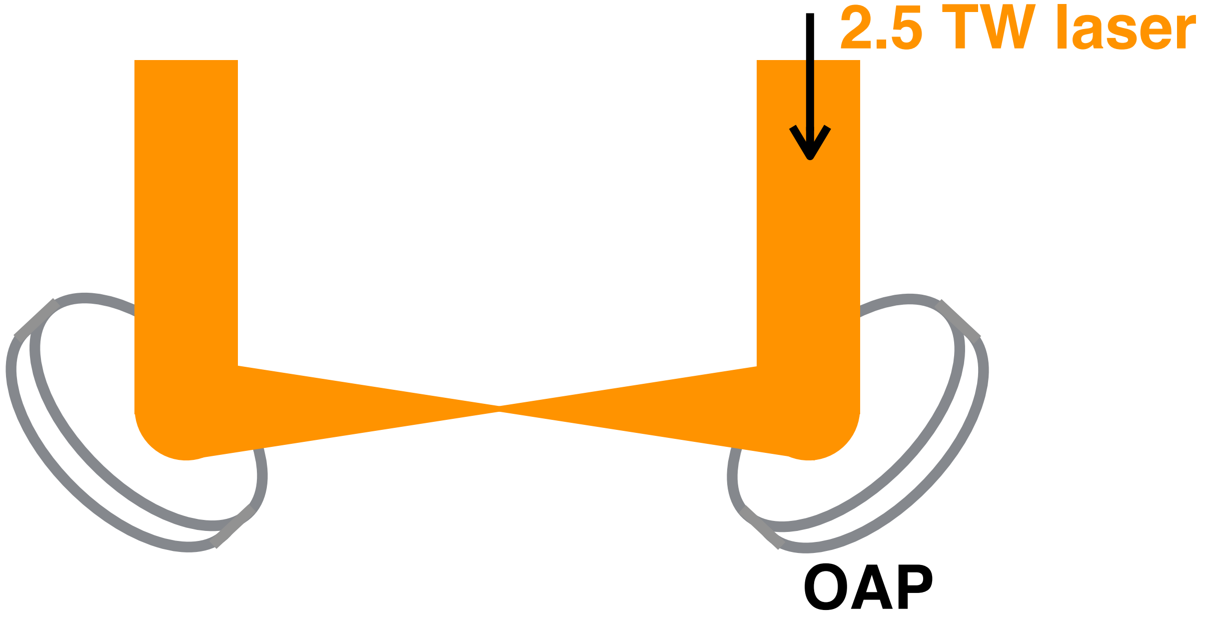
We can use a high power laser with XFEL at SACLA.
We can already use a **2.5 TW laser** and
a **500 TW laser** is under installation.

Performance of the 500 TW laser	
・Wave length	: 800 nm
・Pulse energy	: 12.5 J
・Pulse width	: 25 fs
・rate	: 1 Hz

500 TW laser

Setup of test experiment

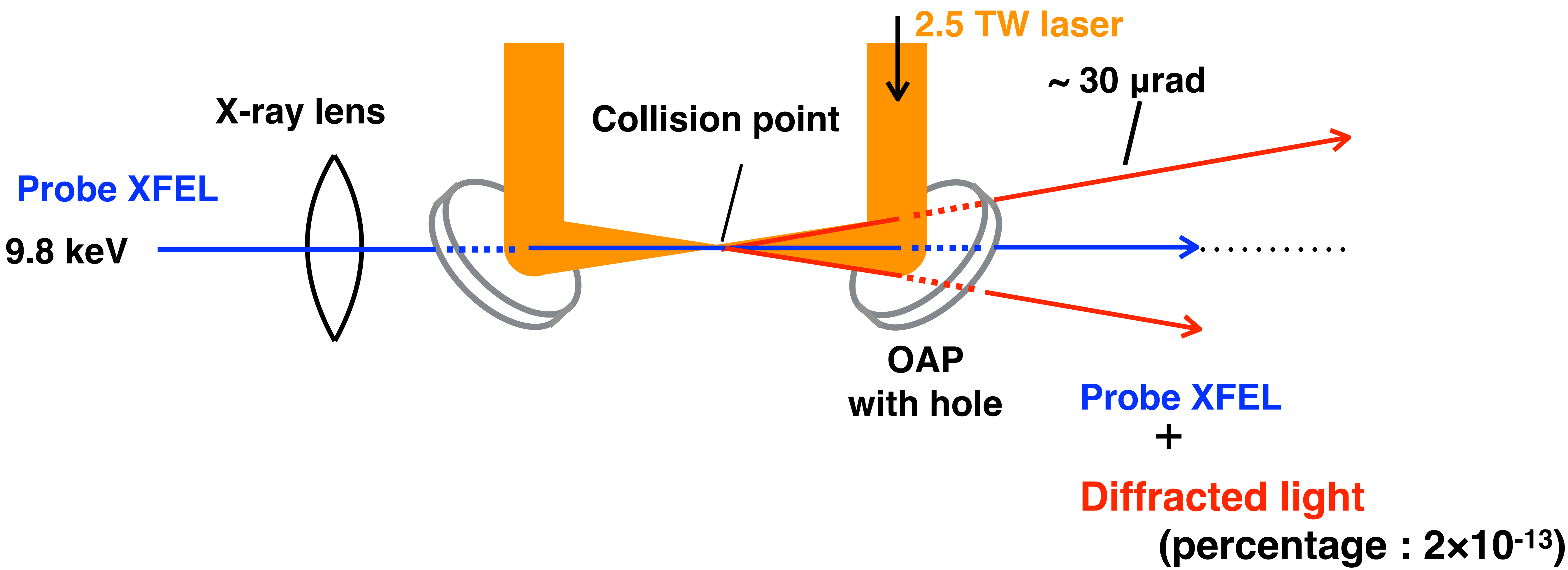
①The **2.5 TW laser** is focused to 10 μm.



Setup of test experiment

①The **2.5 TW laser** is focused to 10 μm.

②The **focused XFEL pulse** and the **2.5 TW laser pulse** collide each other at the focal point.

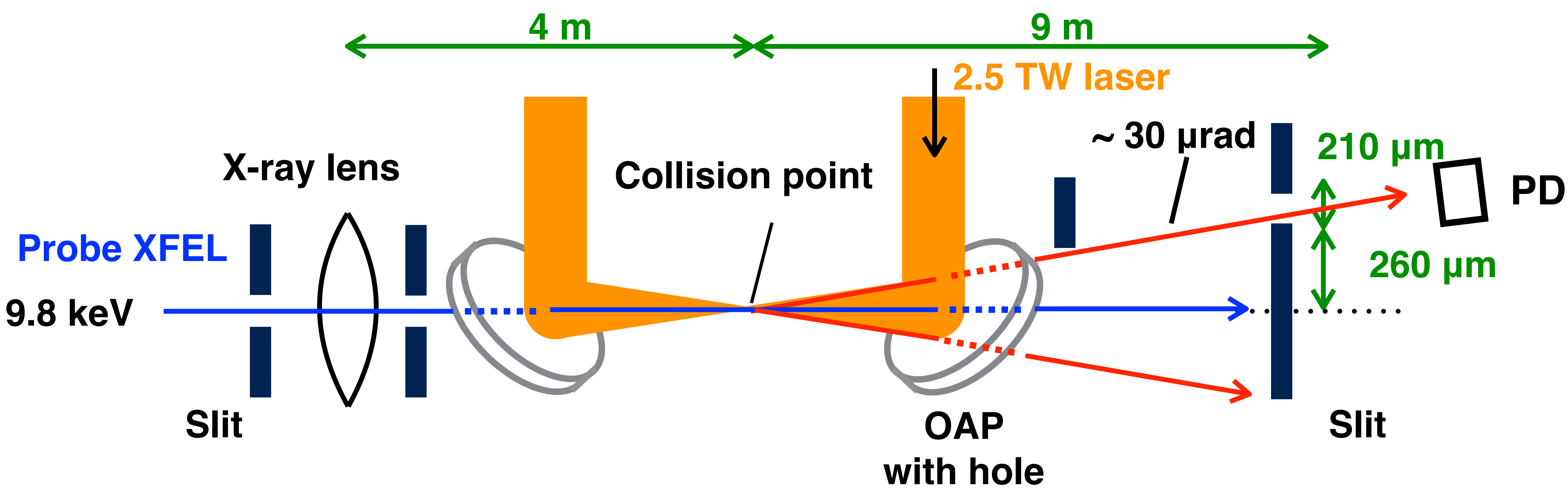


Setup of test experiment

①The **2.5 TW laser** is focused to 10 μm.

②The **focused XFEL pulse** and the **2.5 TW laser pulse** collide each other at the focal point.

③We put the slits to shut out **X rays** which enter to the detector and to detect only diffracted **signal light**.(~30 μrad)

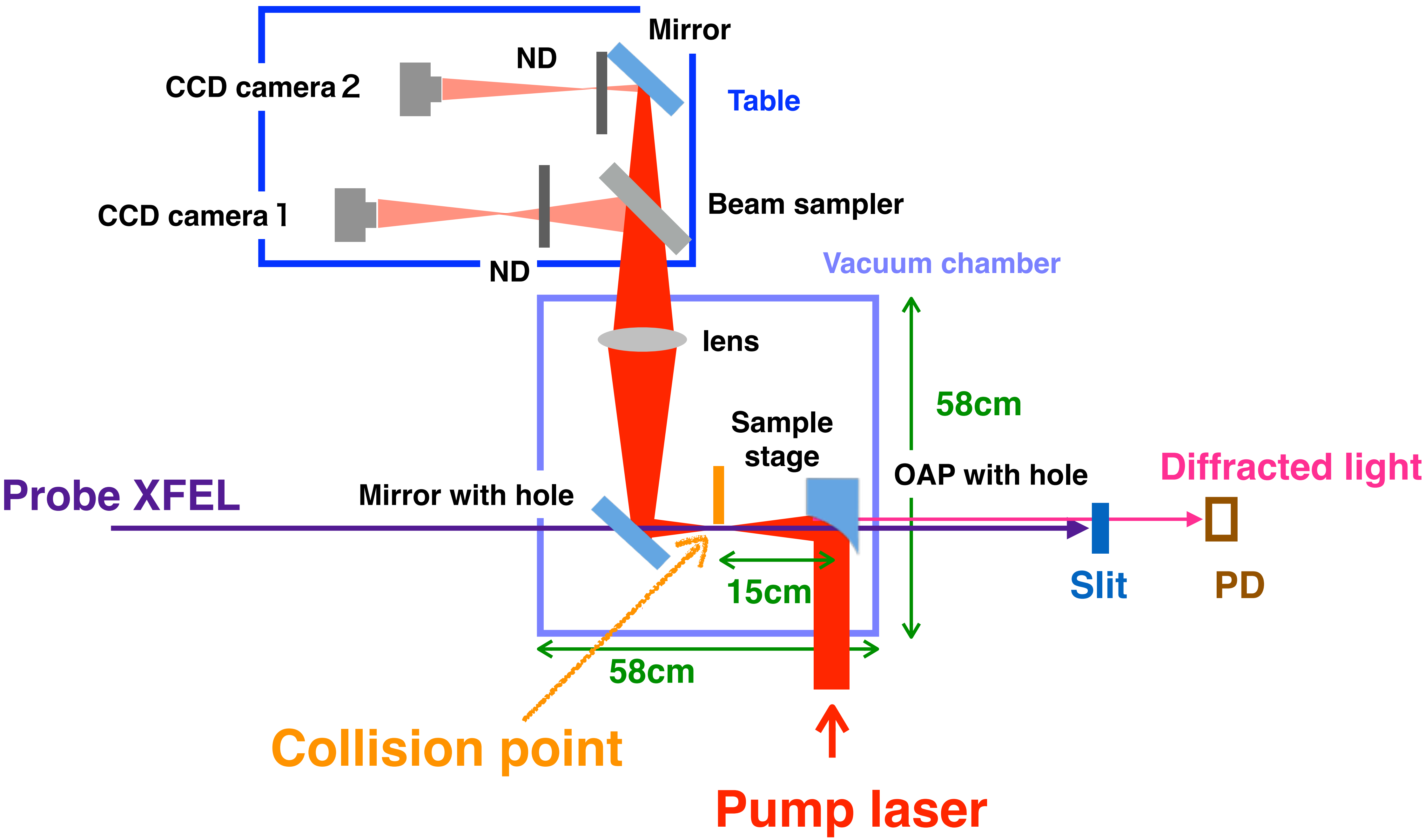


Experiment in November 2016

We made the vacuum diffraction experiment at SACLA in November 2016.

Beam time : 2.5 days

Parameters : Probe XFEL : 9.8 keV, Pump laser : 2.5 TW



Experiment in November 2016

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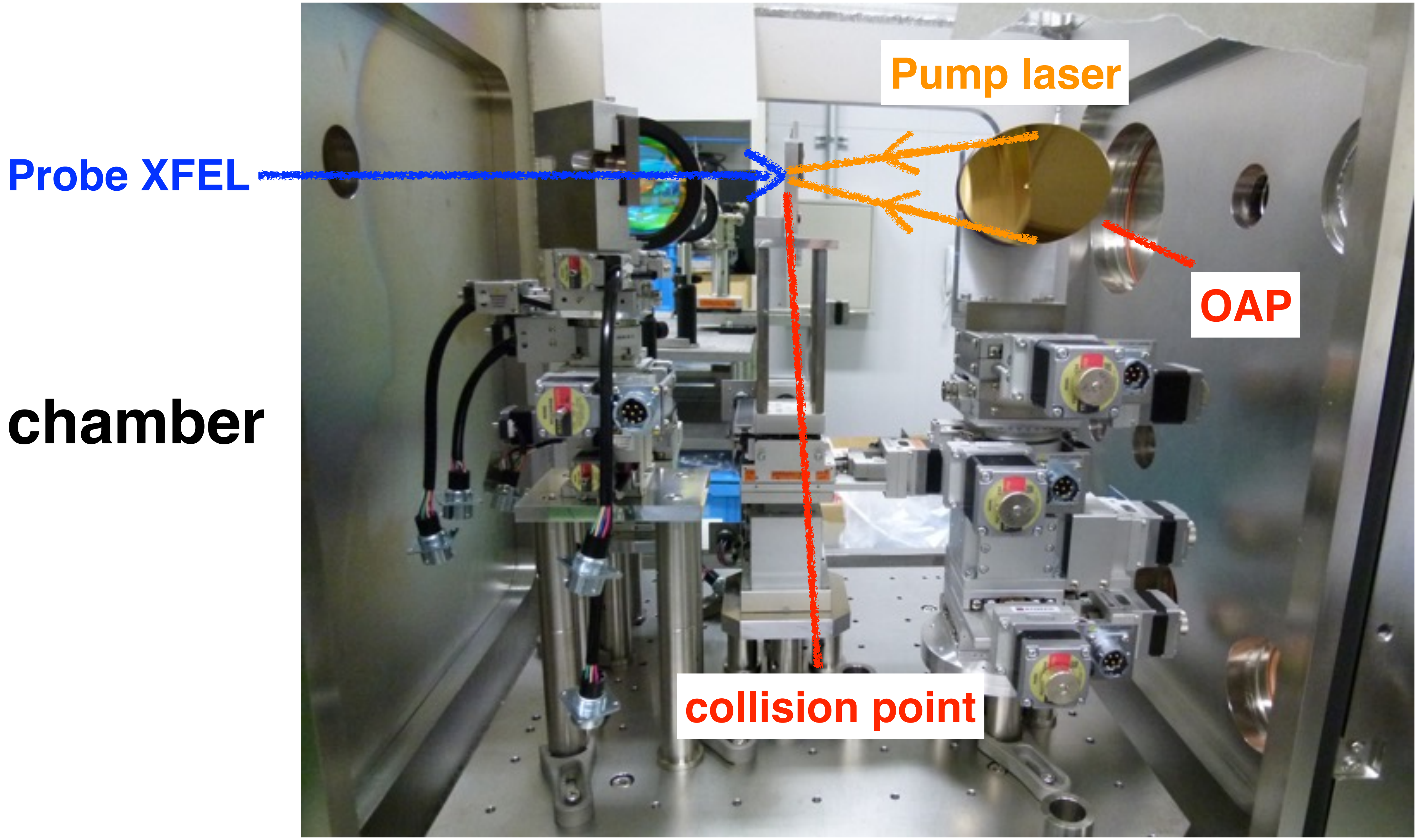
Vacuum chamber



Important points of VD experiment

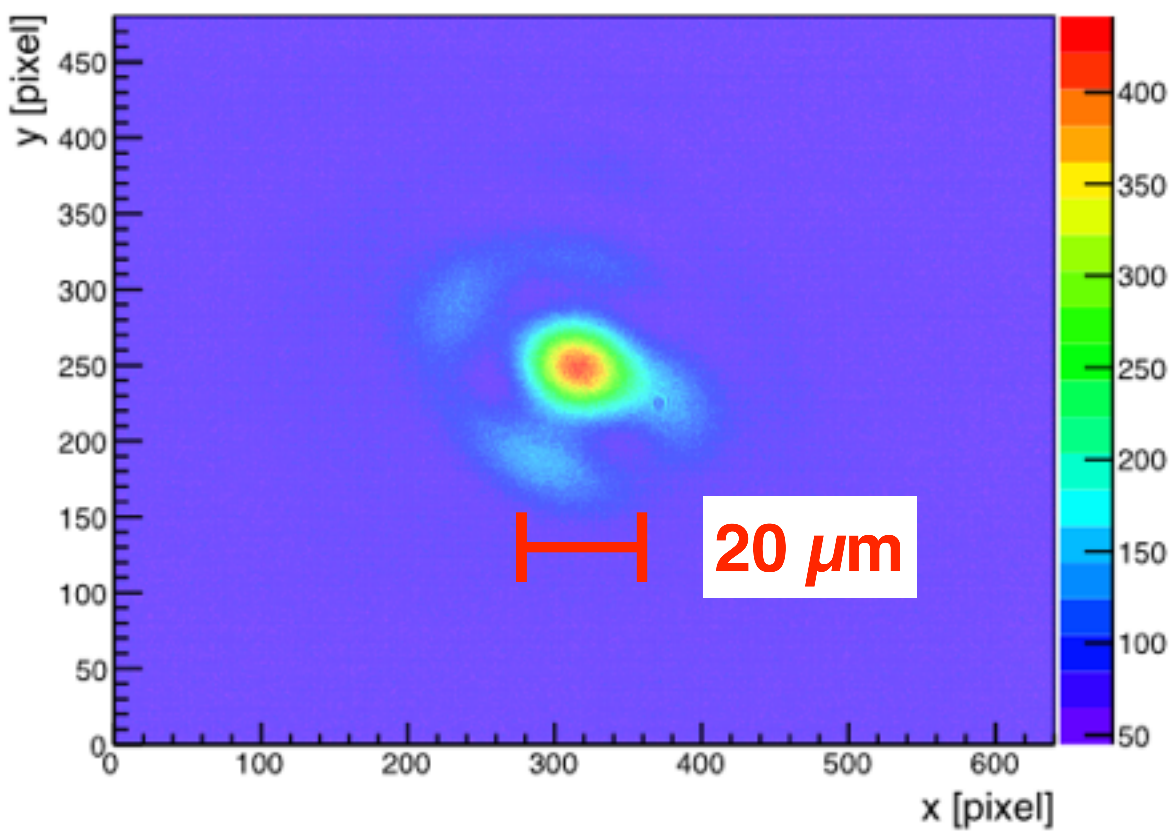
- **Size of the pump laser and the probe XFEL**

- **Space and timing guarantee of the collision**

- **BG suppression**

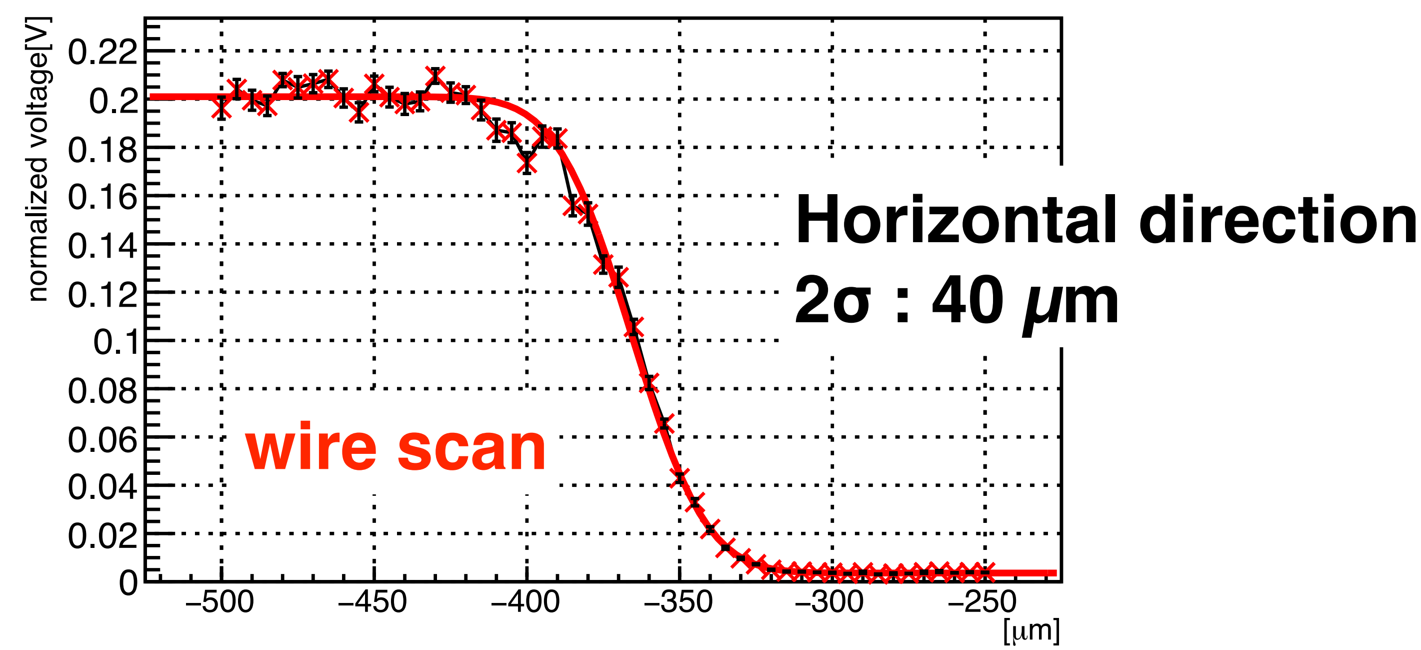
Pump laser and probe XFEL size

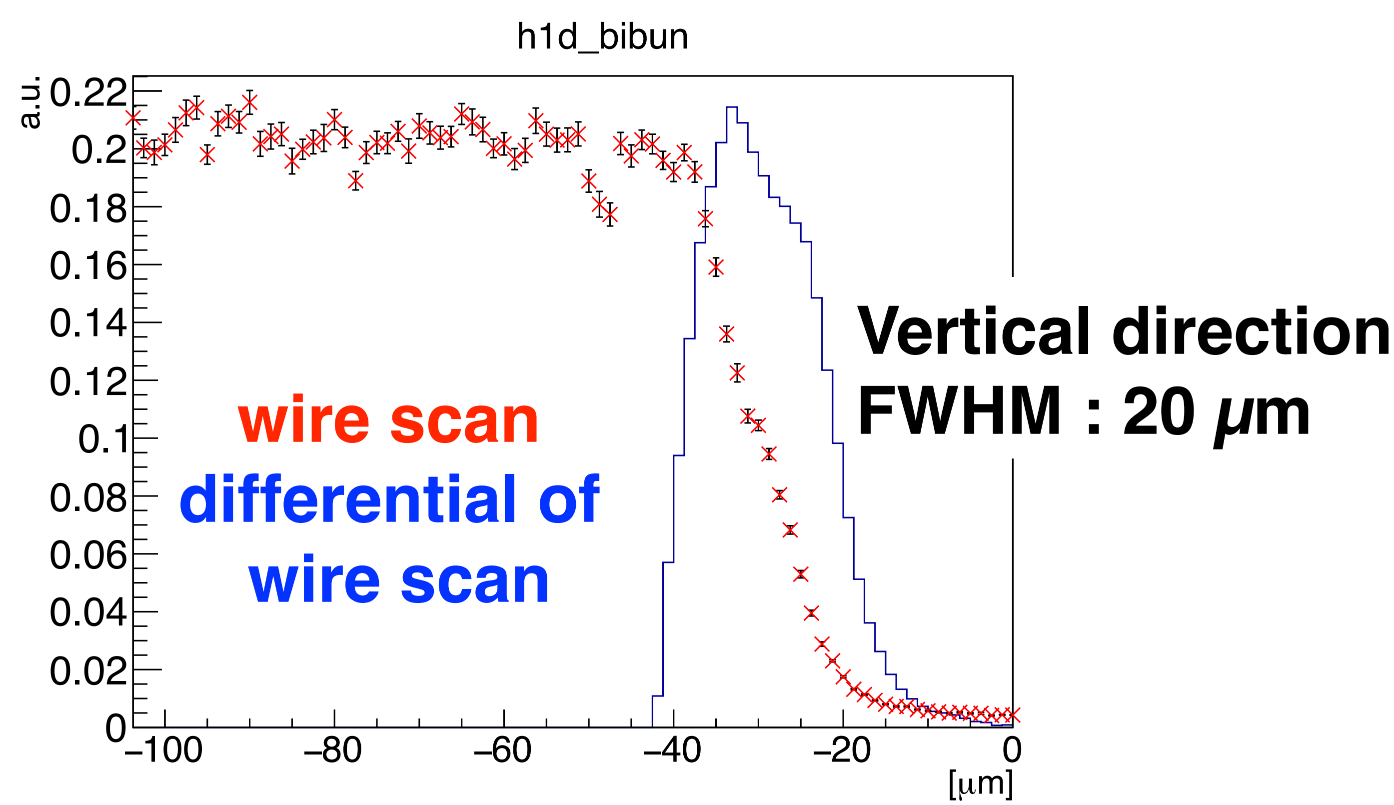
Pump laser image of CCD camera
Low power (~nJ)



Beam waist : 12 μm
→Enough size as first step experiment

Wire scan result of the probe XFEL



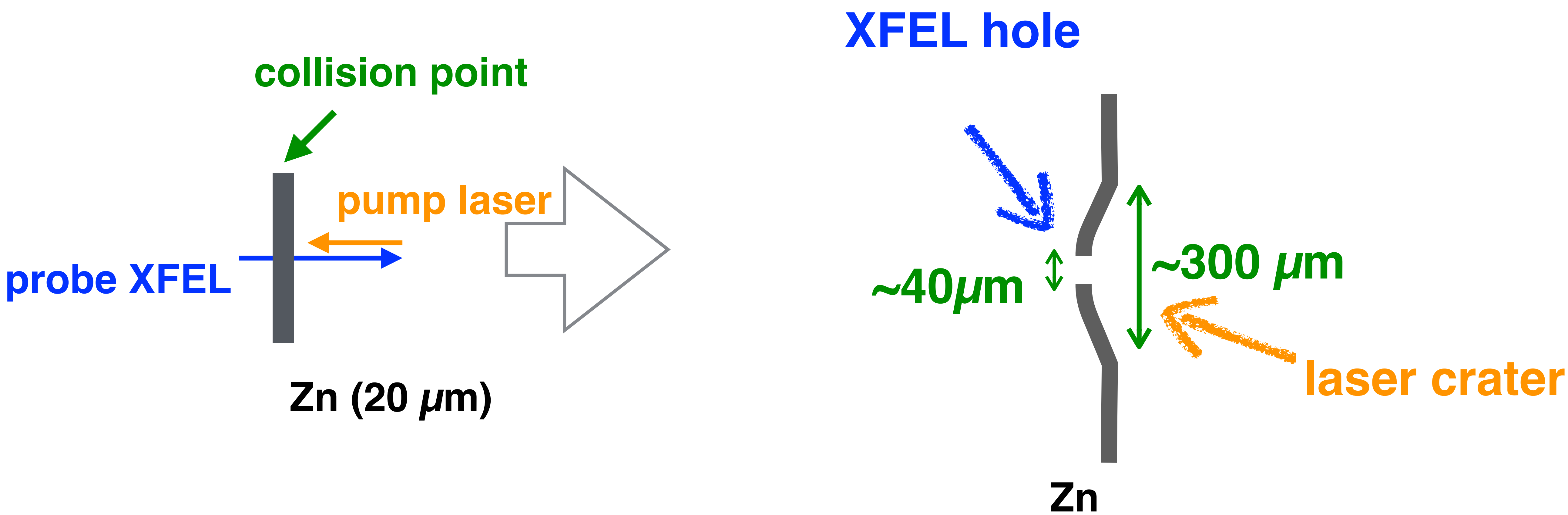


Spacial guarantee

We used Zn film to check the collision of the pump laser and the probe XFEL. A hole made by the probe XFEL and a crater made by the pump laser were used to guarantee the collision.

How to check the colliision

1. Zn thin film(20 μm) was set at the collision point and irradiated the pump laser and the probe XFEL.
2. Zn thin film was checked by a laser microscope after the experiment.



Spacial guarantee

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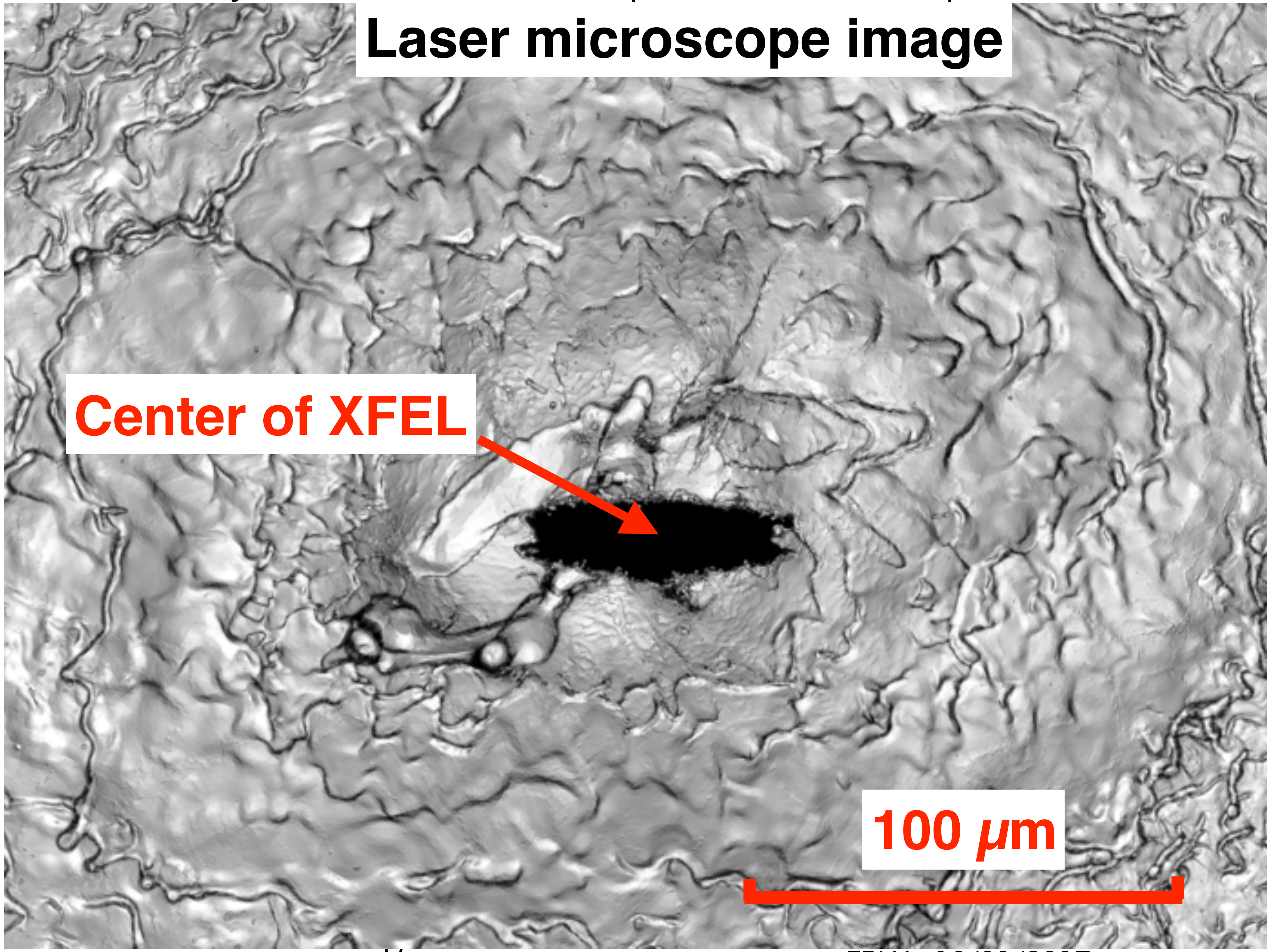

Spacial guarantee

How to check the colliision

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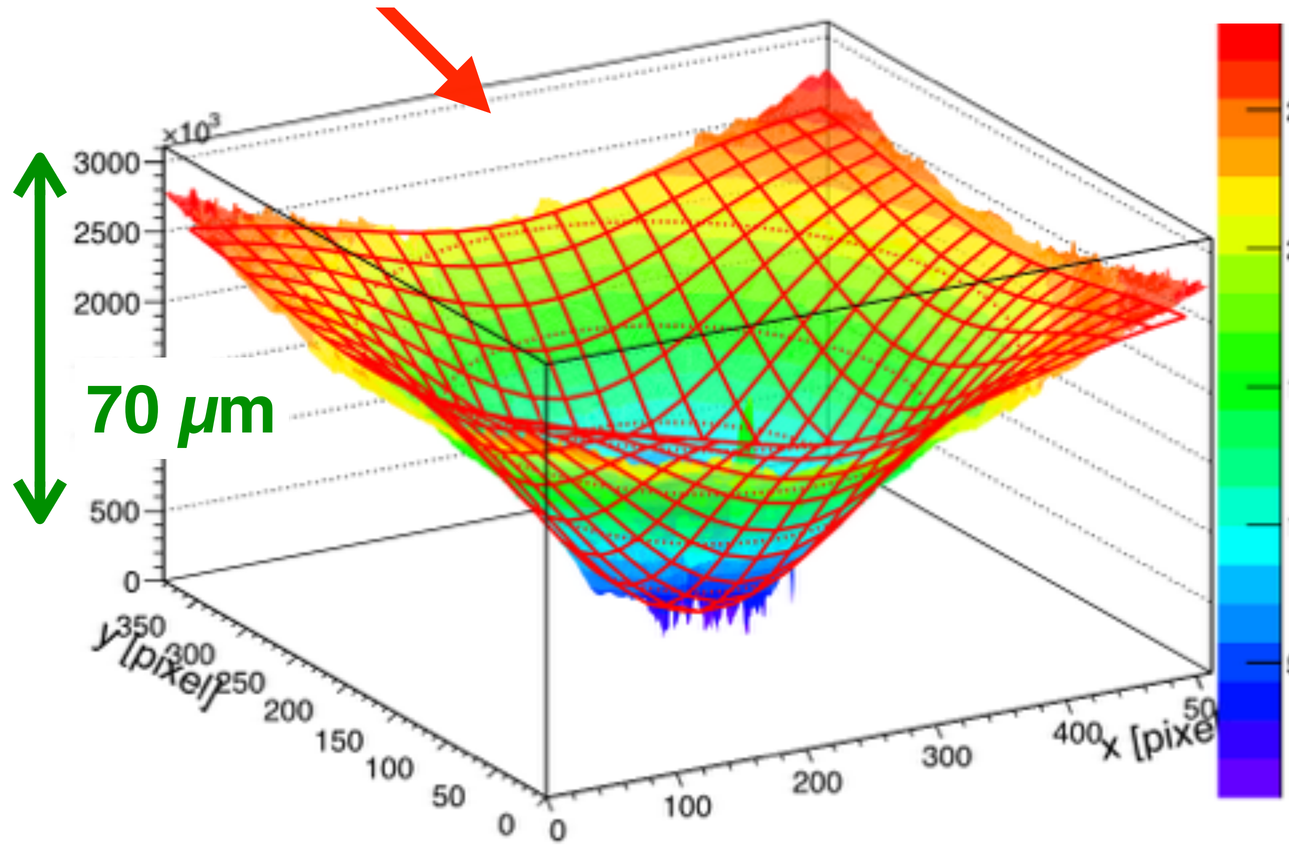
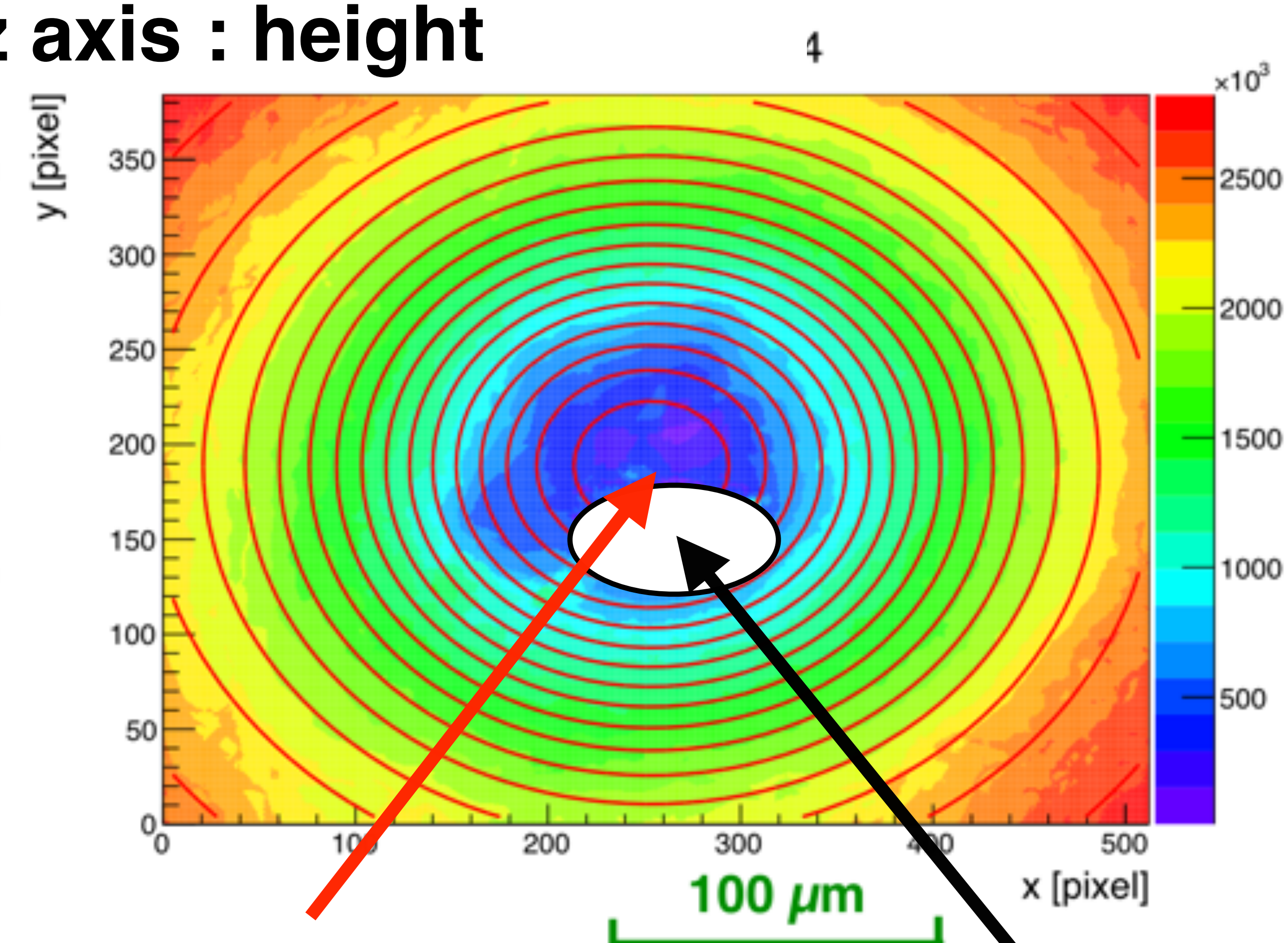
The crater on the Zn film.
This is fitted by 2D Gaussian



Same laser microscope image
z axis : height



Center of laser

Center of XFEL

Spacial guarantee

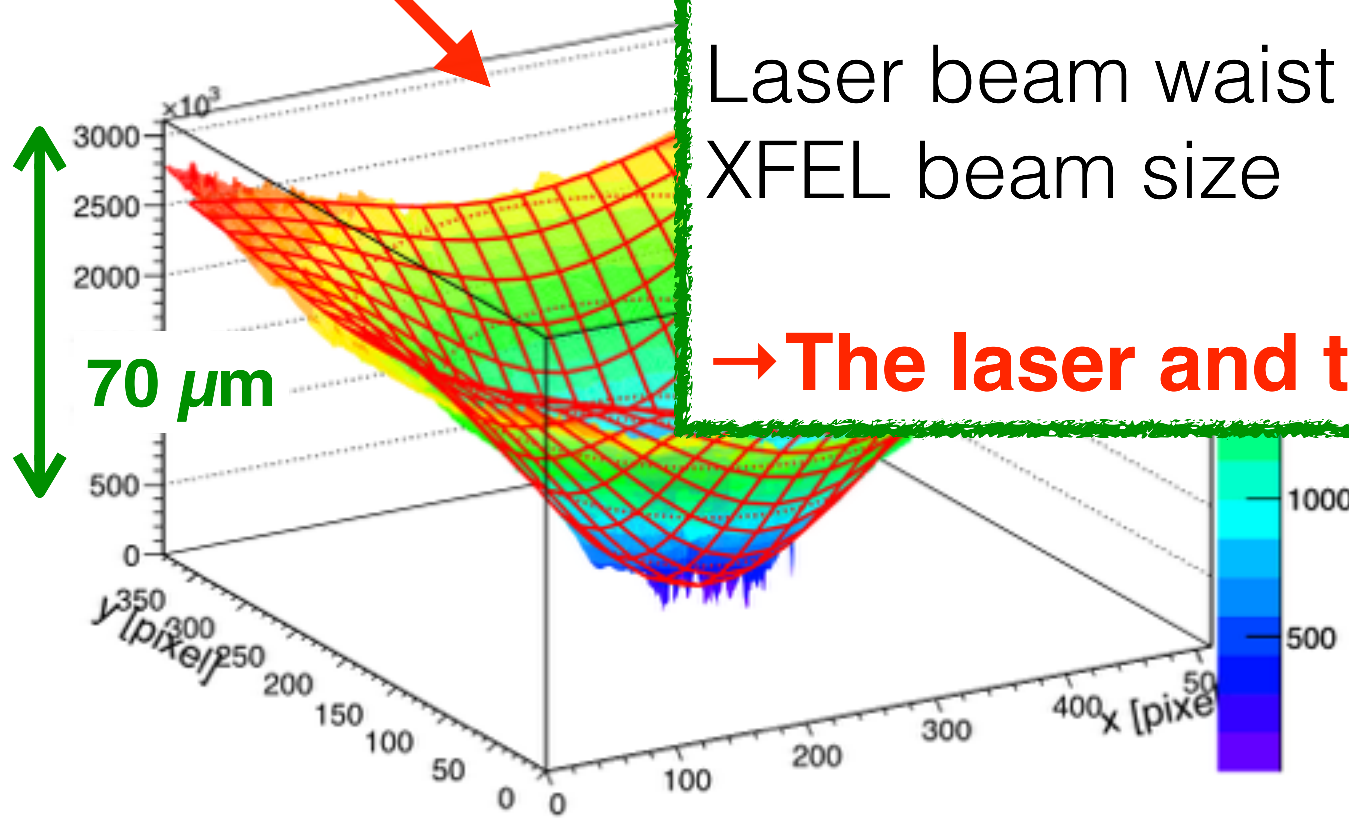
How to check the colliision

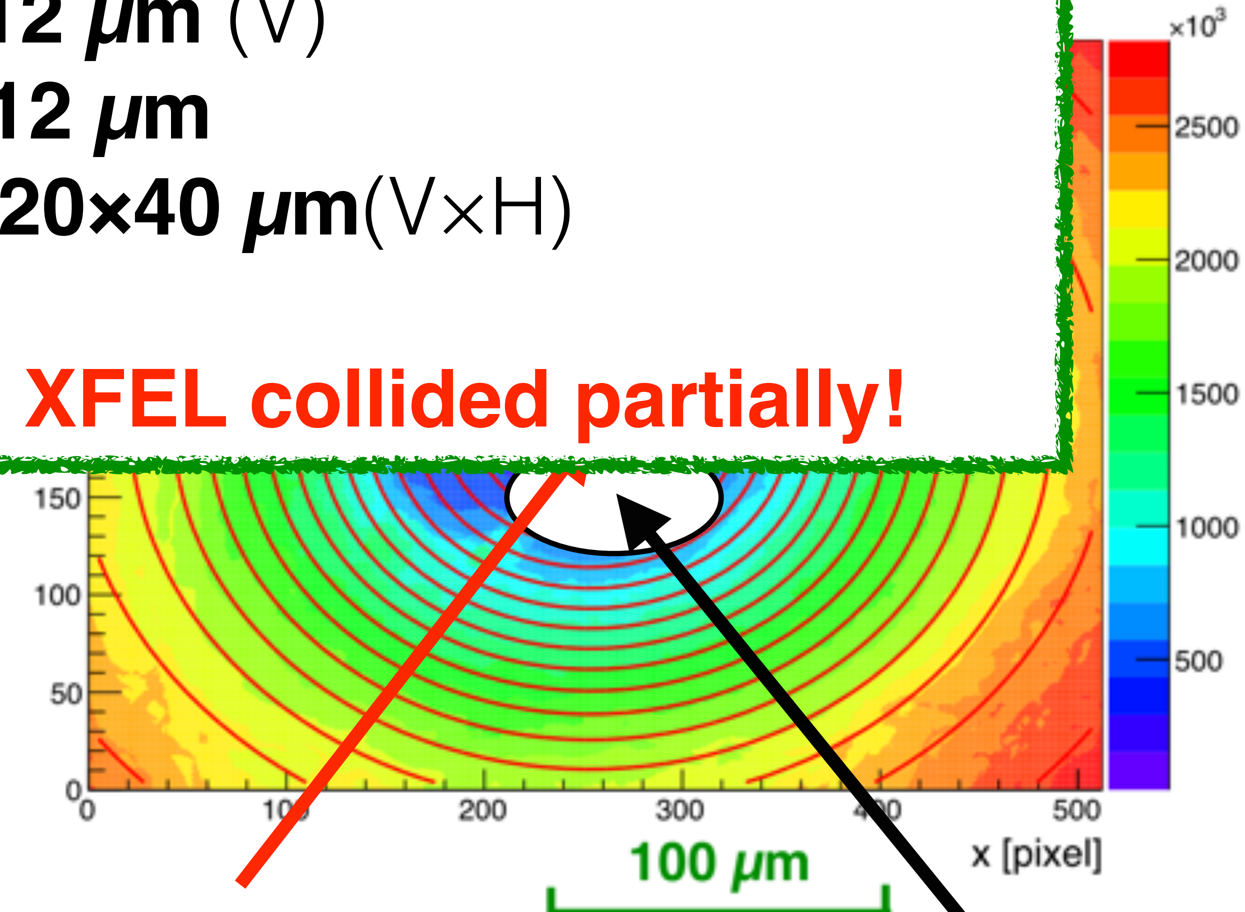
1. Zn thin film(20 μm) was set at the collision point and irradiated the pump laser and the probe XFEL.
2. Zn thin film was checked by a laser microscope after the experiment.

The crater on the Zn
This is fitted by 2D G

Distance from the XFEL center to the laser center
: **12 μm** (V)
Laser beam waist : **12 μm**
XFEL beam size : **20×40 μm**(V×H)

→The laser and the XFEL collided partially!



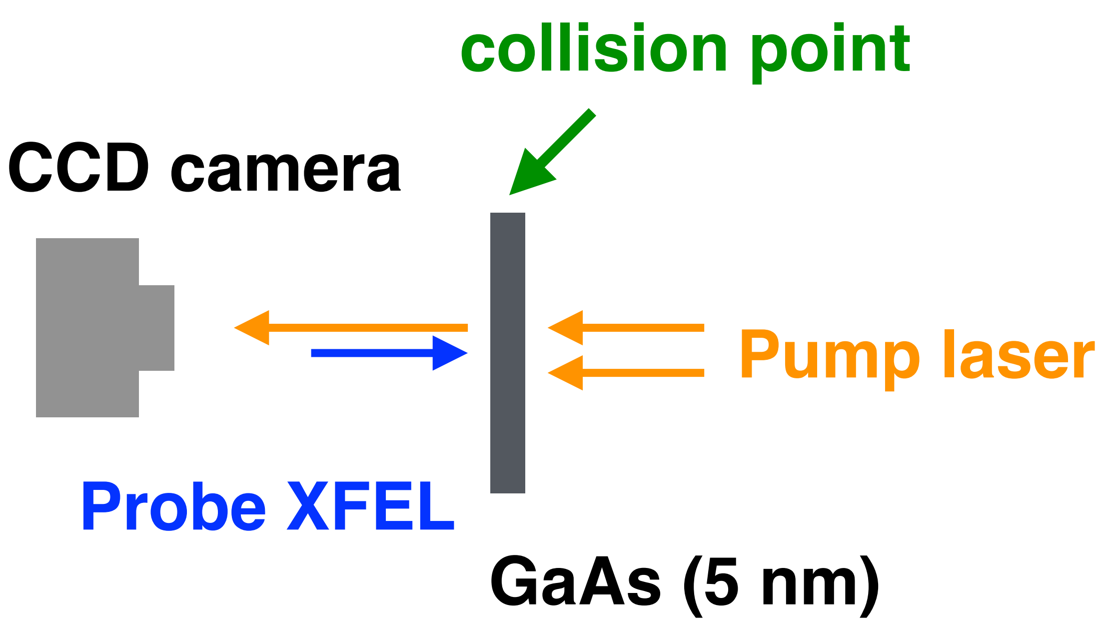


Center of laser

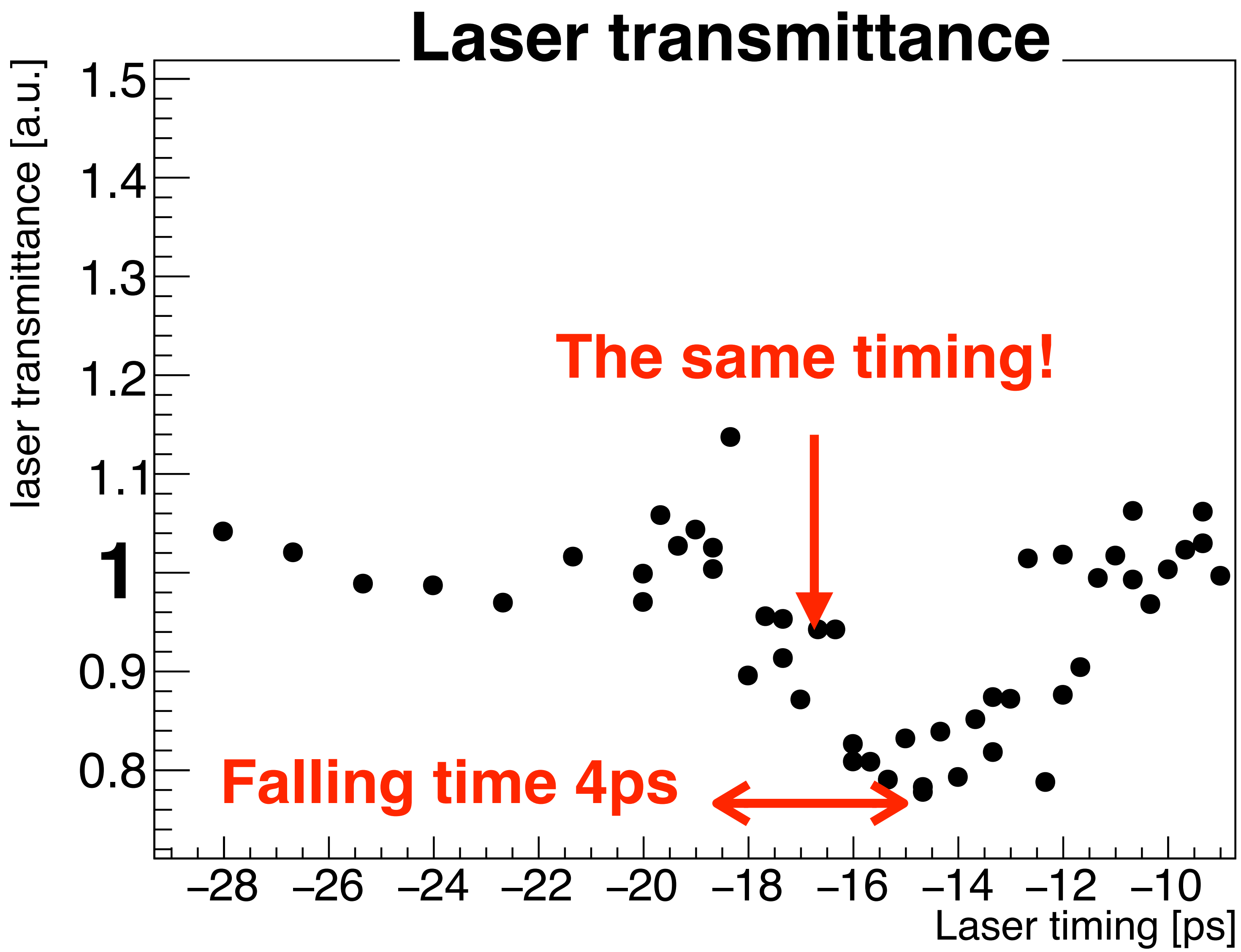
Center of XFEL

Timing guarantee

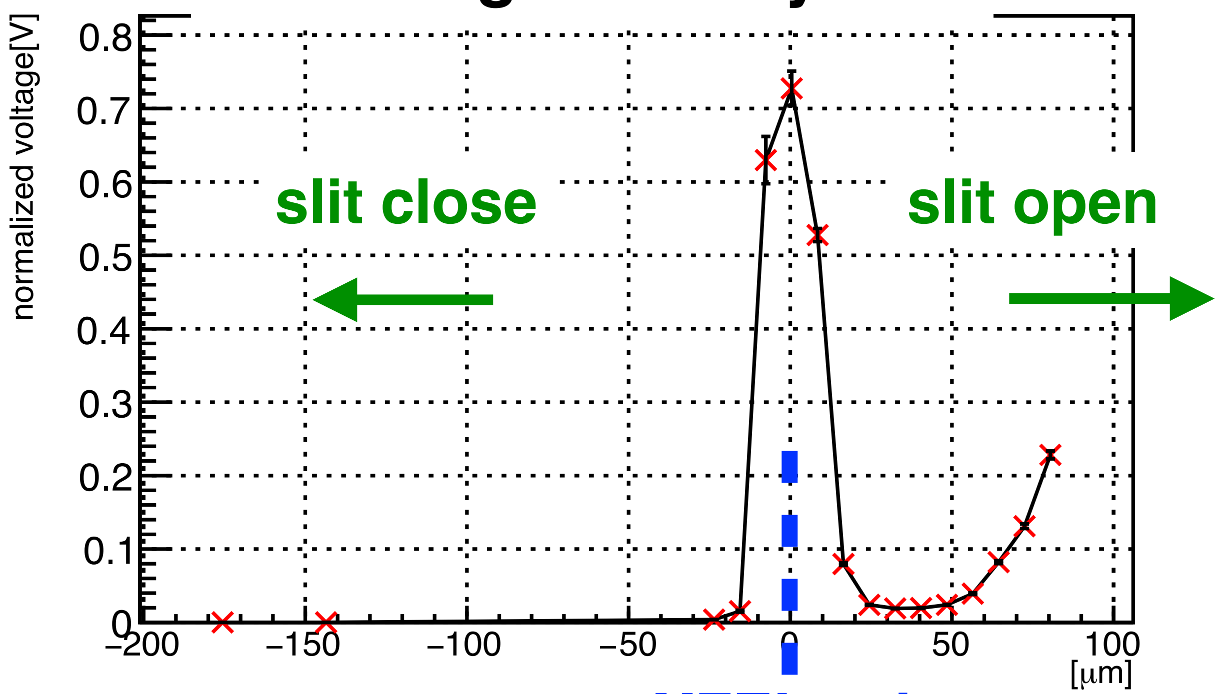
To check the collision timing, we use a GaAs thin film.
If the probe XFEL is irradiated to the GaAs, charge carrier density of GaAs increase and a opacity changes.
Hence, when the pump laser and the probe XFEL are irradiated at same timing, the pump laser transmittance changes(**decreases**).



A requirement of timing **: ±3 ps**
The timing uncertainty **: ±2 ps**
→Timing guarantee is enough!

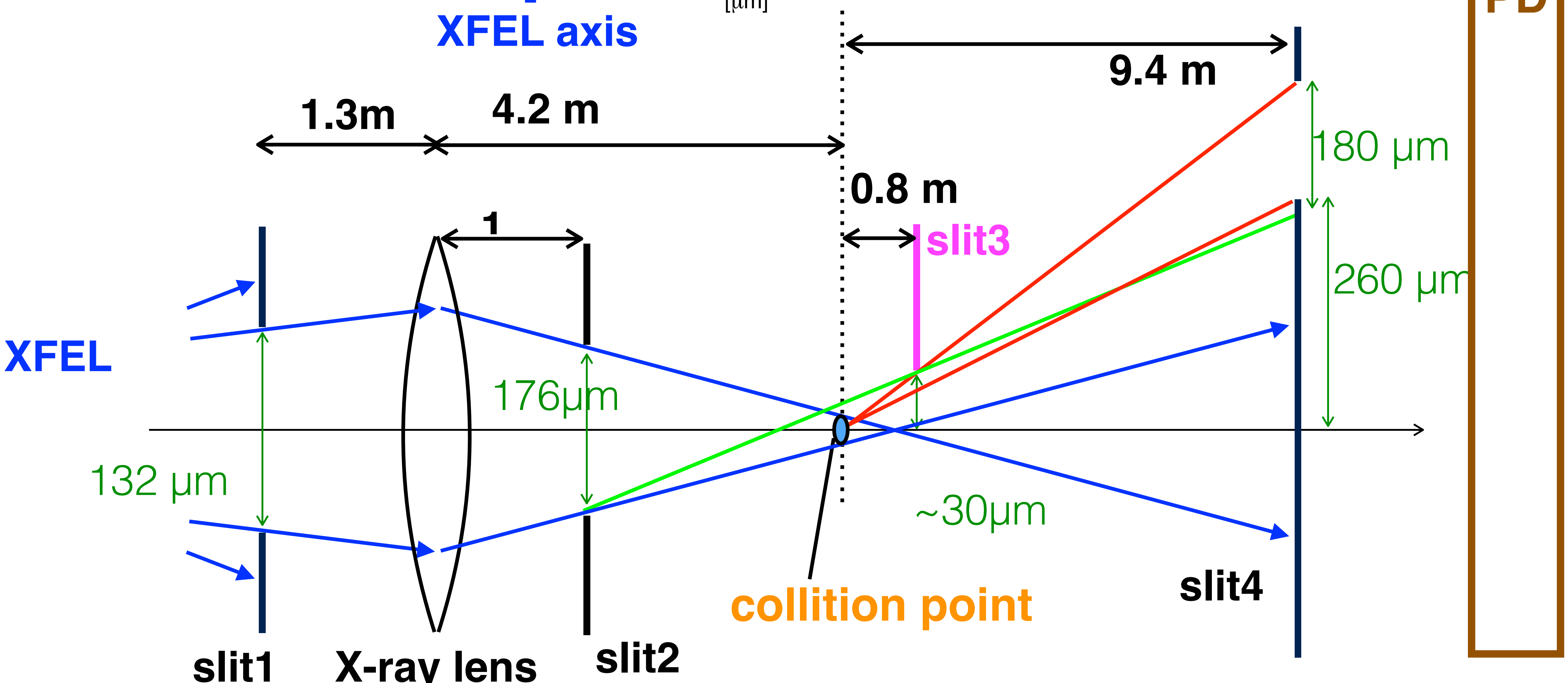


BG suppression



We tuned the position of slit3 for the BG suppression.

1. Slit1,2,4 were set.
2. Knife edge scan by slit3.
3. Slit3 was set.



BG suppression

We took Main Run and BG Run data.
(Repetition frequency of the probe XFEL is 30 Hz and the pump laser is 10 Hz)

Main DAQ (10 Hz) : XFEL with the laser. —> 2.93×10^{6} photons/pulse
BG DAQ (20 Hz) : XFEL without the laser. —> 2.94×10^{6} photons/pulse
(X rays at the collision point is 3×10^{10}photons/pulse)

Finally we subtracted photon counts of BG DAQ from Main DAQ.
Result of BG suppression was $\mathbf{10^{-6}}$.
(10^{-16} suppression is required for final step experiment)

Final Result

I am calculating a sensitivity of the test experiment.
I will present about the result at the JPS in March 2017.

Future plan

VD experiment with the small focused laser and the XFEL(2017)
- Laser beam waist 1 μm
- XFEL beam waist 2 μm

BG study at SPring-8(2017)

We do not understand the source of BG now.

SPring-8 : Synchrotron radiation facility
Steady X-ray beam

VD experiment using 500 TW laser(2018)
- 500 TW laser & beam waist 1 μm
- The probe XFEL beam waist 2 μm
- 1 day DAQ

Reach QED theoretical value.
First observation of vacuum diffraction!!

Summary

- QED predicts that a strong electromagnetic field changes a refractive index of the vacuum. Photons transversing an ununiform electromagnetic field could be diffracted.

- We use a high power laser to make a strong electromagnetic field.
- XFEL is used as probe beam.

- We made the vacuum diffraction experiment in November 2016, but the sensitivity was not enough to reach QED theoretical value.

- We will make the vacuum diffraction experiment using the 500 TW laser. It will be the first observation of vacuum diffraction.