Search for Vacuum Diffraction Using high power laser and X-ray Free Electron Laser SACLA

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Vacuum diffraction
caused by a nonuniform polarization of vacuum

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

ex) Under a magnetic field $n = 1 + \mathbf{9\times10^{-24}B^2}$, B [T]

This effect has not been observed!

~When there is a nonuniform electromagnetic field in the vacuum~

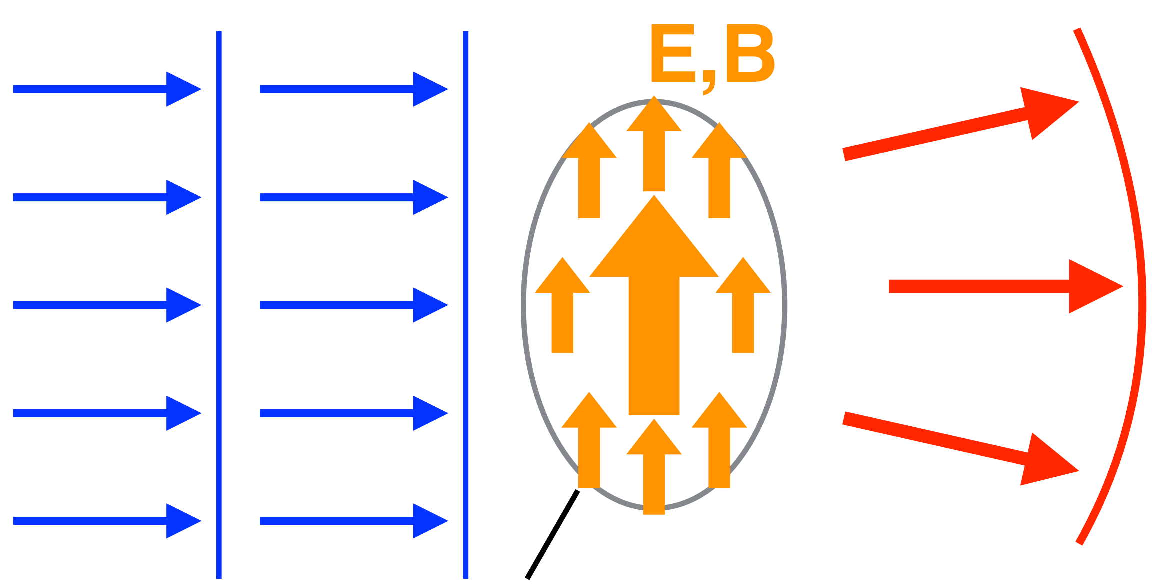
→An electromagnetic field makes a nonuniform polarization.

→Photons transversing the vacuum could be diffracted slightly.

→**Vacuum diffraction**

In the vacuum

light



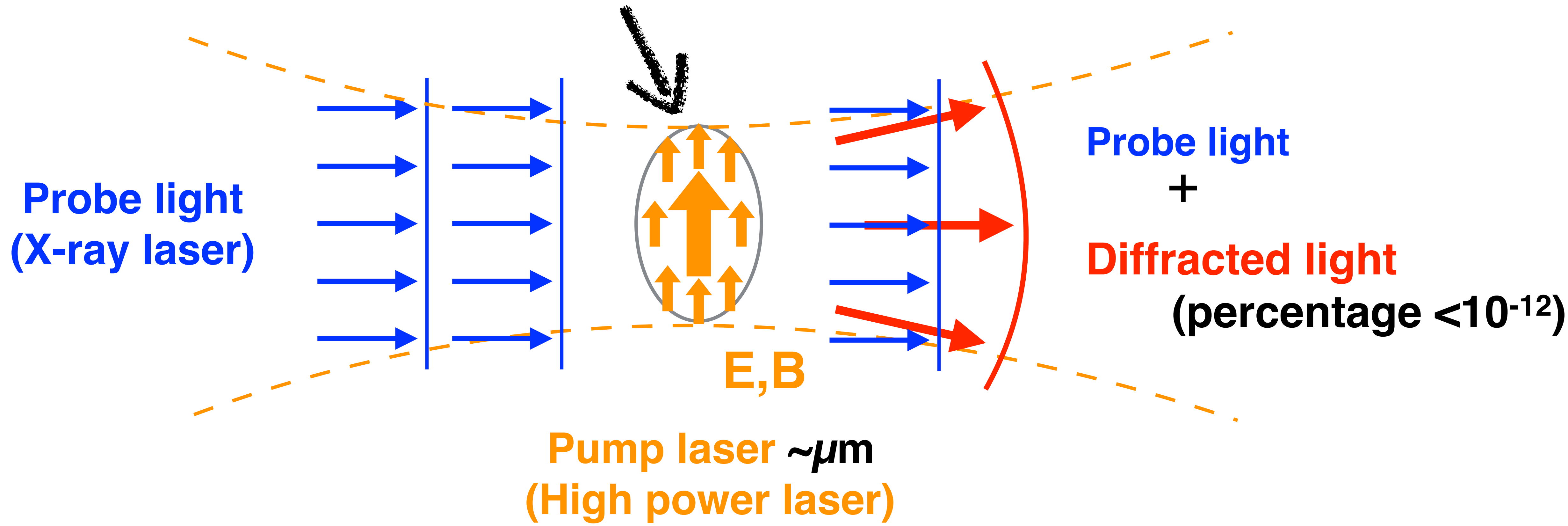
Nonuniform strong electromagnetic field

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.
✔Laser is small focused.



Reasons to use high power laser

1. Strong electromagnetic field : **~10^6 T**
2. Focal spot makes small nonuniform electromagnetic field : **~1 μm**

Anglar distribution of vacuum diffraction

Anglar distribution of Diffracted light at collision point

$$\frac{\mathrm{d}N_{\mathrm{diffracted}}}{\mathrm{d}\cos\theta} \sim \frac{JE \ldots}{w_{\mathrm{L}}^2(w_{\mathrm{L}}^2 \ldots}$$

$$\times\, (Ew \ldots$$

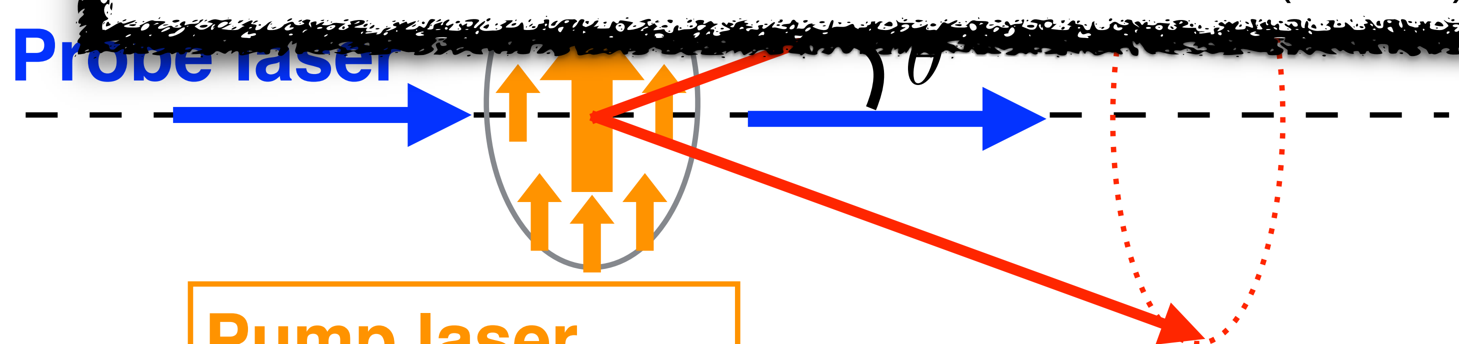
$$w^2 = \frac{w_{\mathrm{L}}^2 w_{\mathrm{X}}^2}{w_{\mathrm{L}}^2 + 2w_{\mathrm{X}}^2}$$

PRD 94, 013004 (2016)

Calculation about vacuum diffraction effect

- **"Light Diffraction by a Strong Standing Electromagnetic Wave"**
  A. Di Piazza et. al, PRL 97, 083603(2016)
- **"Light by light diffraction in vacuum"**
  D. Tommasini et. al, PRA 82, 011803(R) (2010)
- **"Probing vacuum birefringence using x-ray free electron and optical high-intensity lasers"**
  F. Karbstein et. al, 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}

Anglar distribution of vacuum diffraction

Anglar distribution of Diffracted light at collision point

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

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

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

PRD 94, 013004 (2016)

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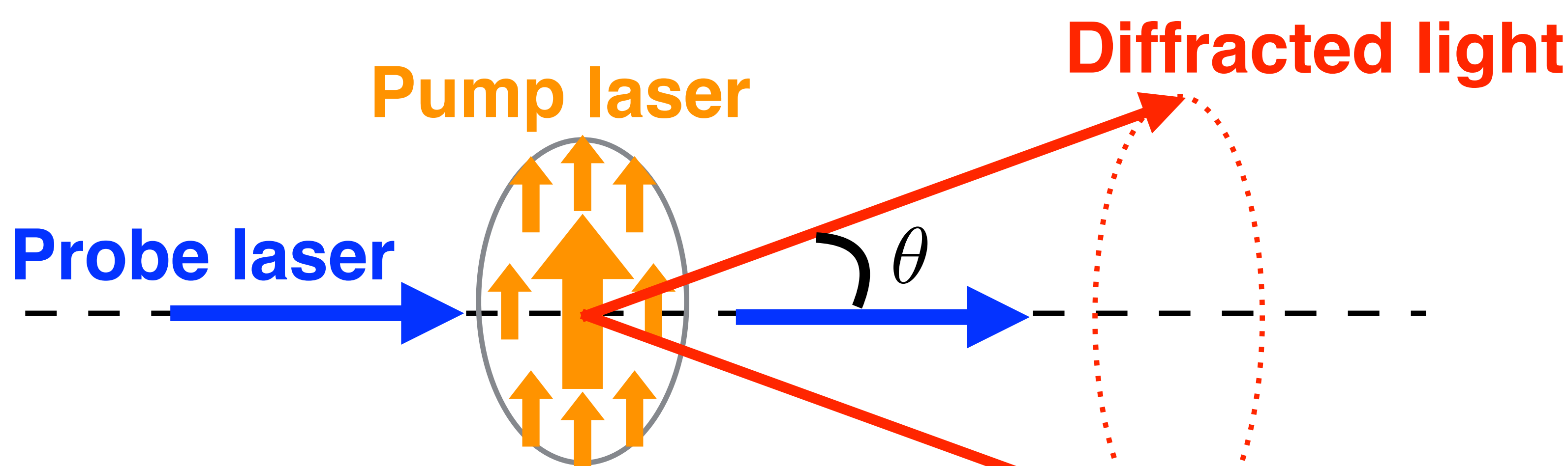

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PRD 94, 013004 (2016)

Parameter

Probe laser energy E : **10 keV**

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

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

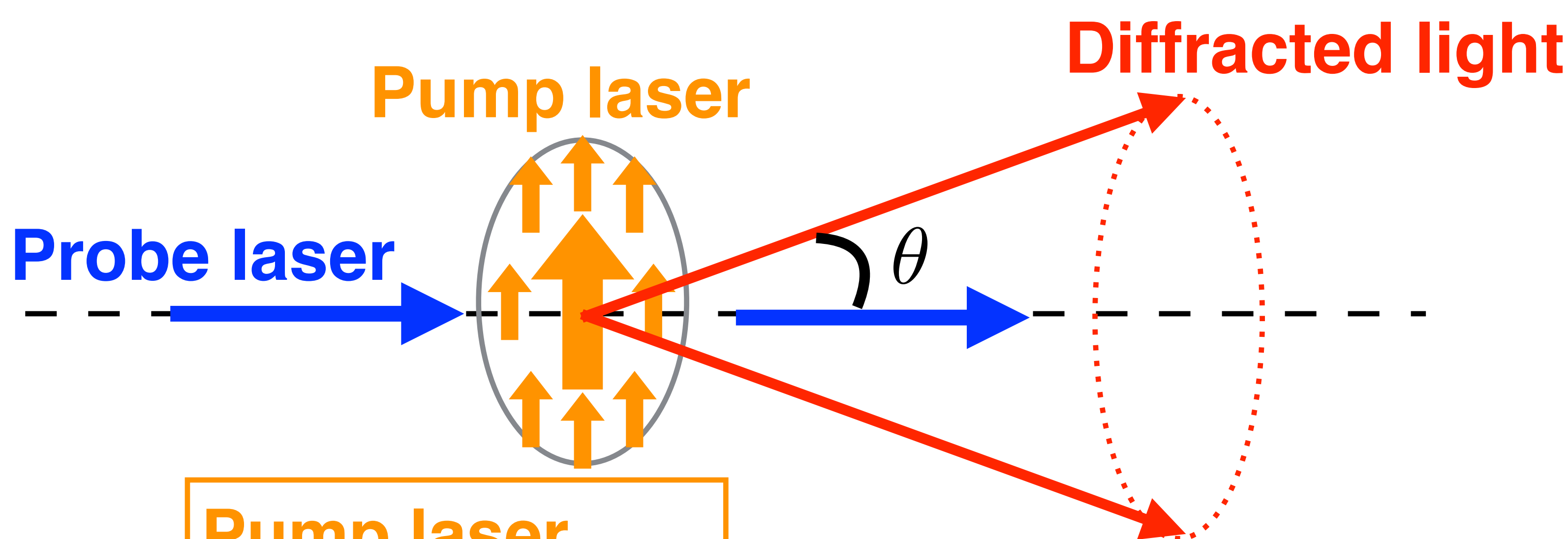
Probe X-ray laser (Gaussian beam)

Photon number : N

Photon flux : J

Photon energy : E

Beam waist : w_{X}



Pump laser

Pulse energy : W

Beam waist : w_{L}

Anglar distribution of vacuum diffraction

Anglar distribution of Diffracted light at collision point

$$\frac{dN_{\mathrm{diffracted}}}{d\cos\theta} \sim \frac{JE^2W^2}{w_L^2(w_L^2+2w_X^2)} \times (Ew)^2 e^{-\frac{1}{2}(Ew\theta)^2}$$

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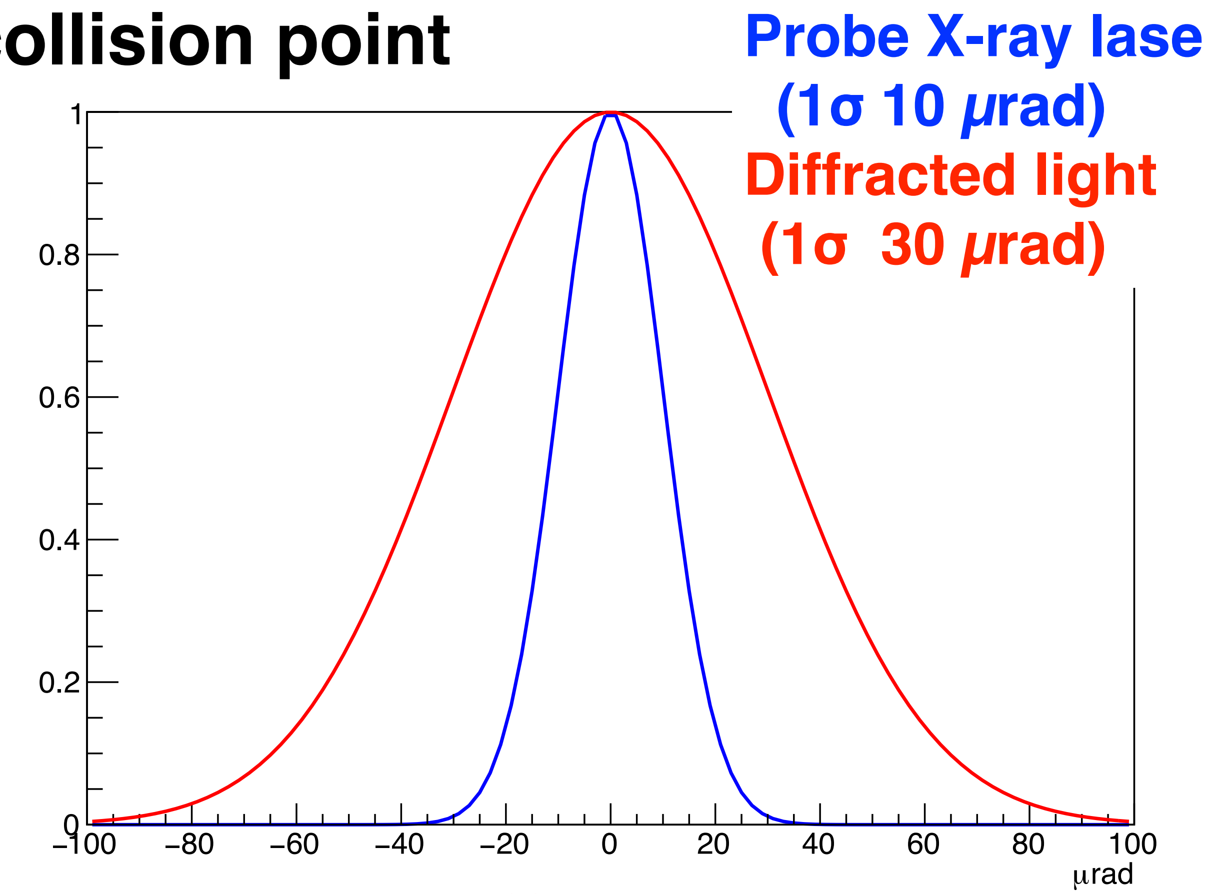
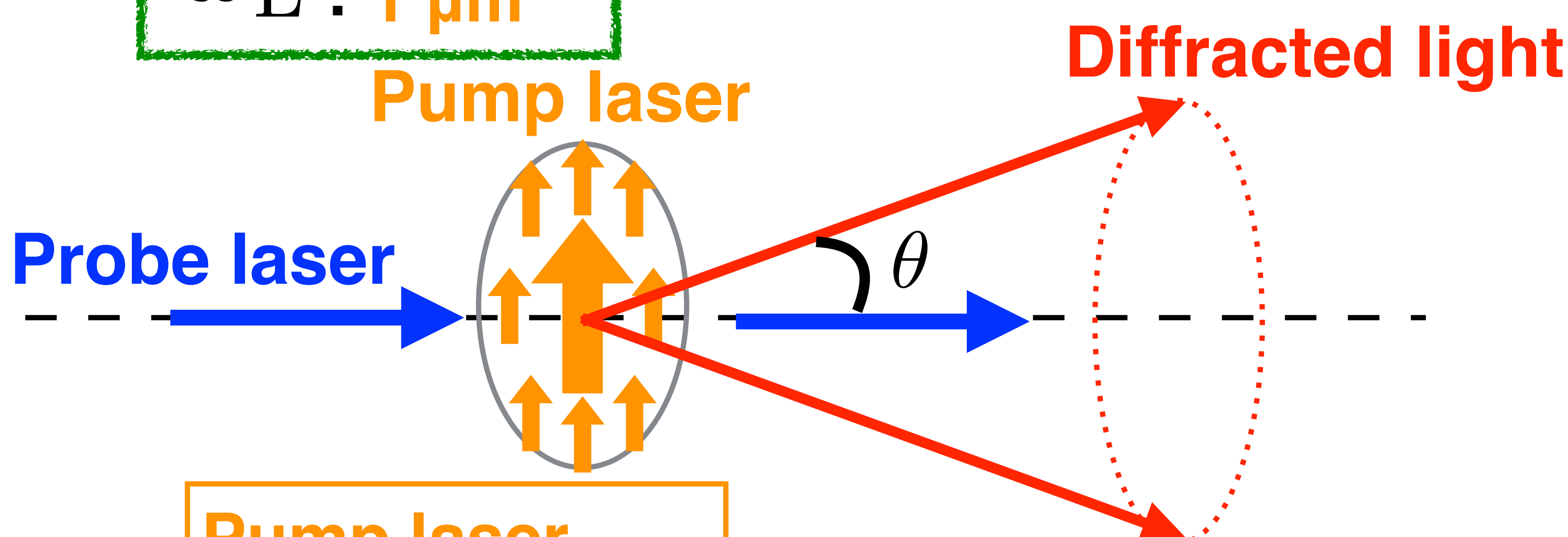
PRD 94, 013004 (2016)

E : **10 keV**
w_X : **2 μm**
w_L : **1 μm**



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

X-ray Free Electron Laser(XFEL) facility SACLA

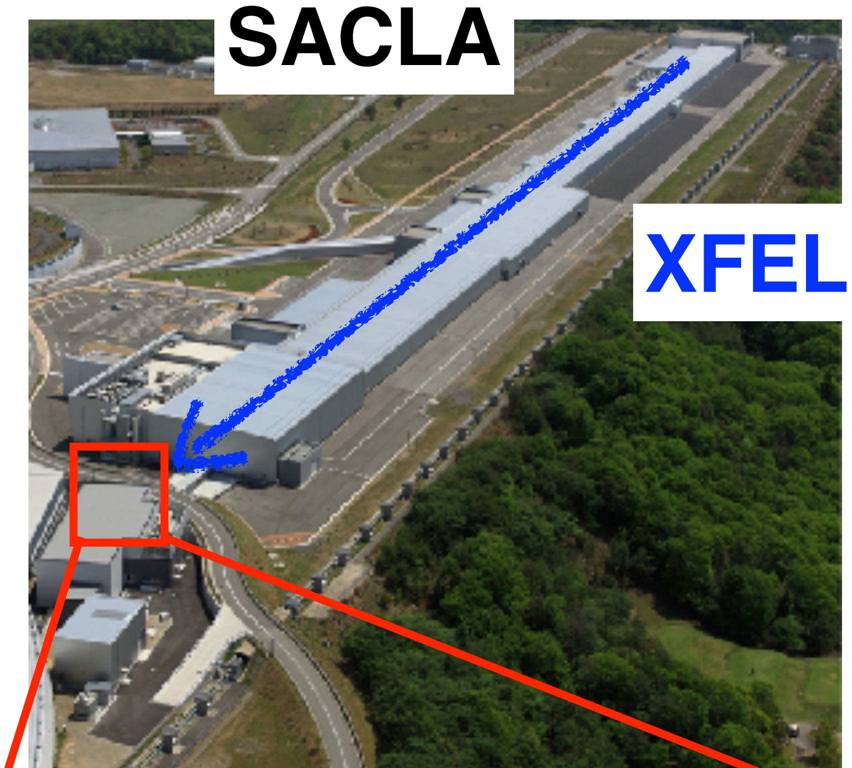
- We can use XFEL and high power laser at SACLA !

Probe

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

Performance of the XFEL

- Photon number : 3×10^{11} photons/pulse @10 keV
- Pulse width : <10 fs
- Beam waist : 300 μm
  1 μm (after focusing)

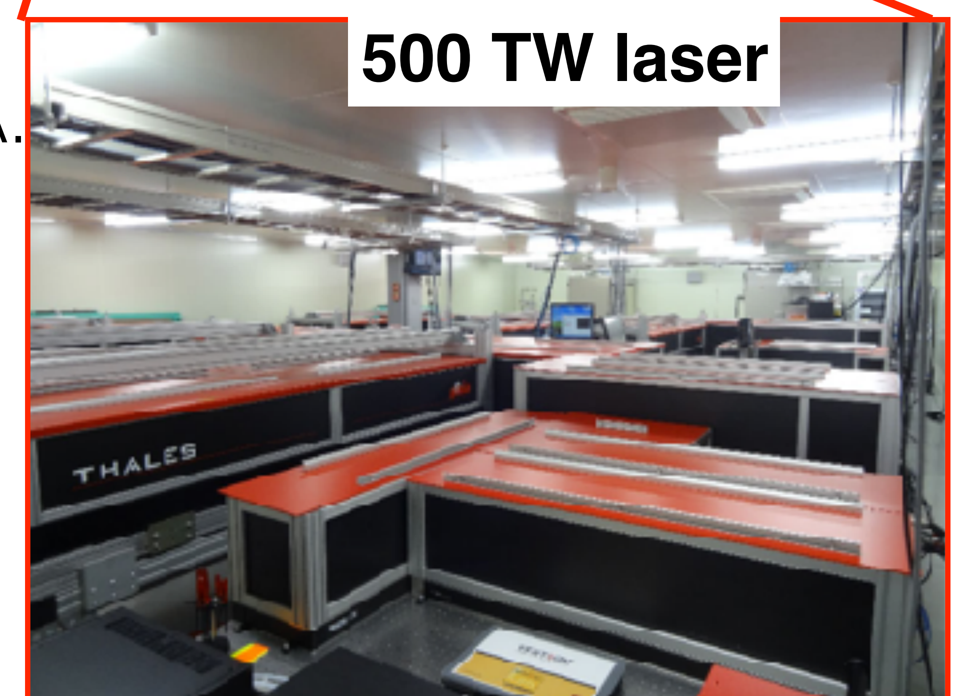


Pump

We can use a high power laser with XFEL at SACLA.
A 500 TW laser is under installation.

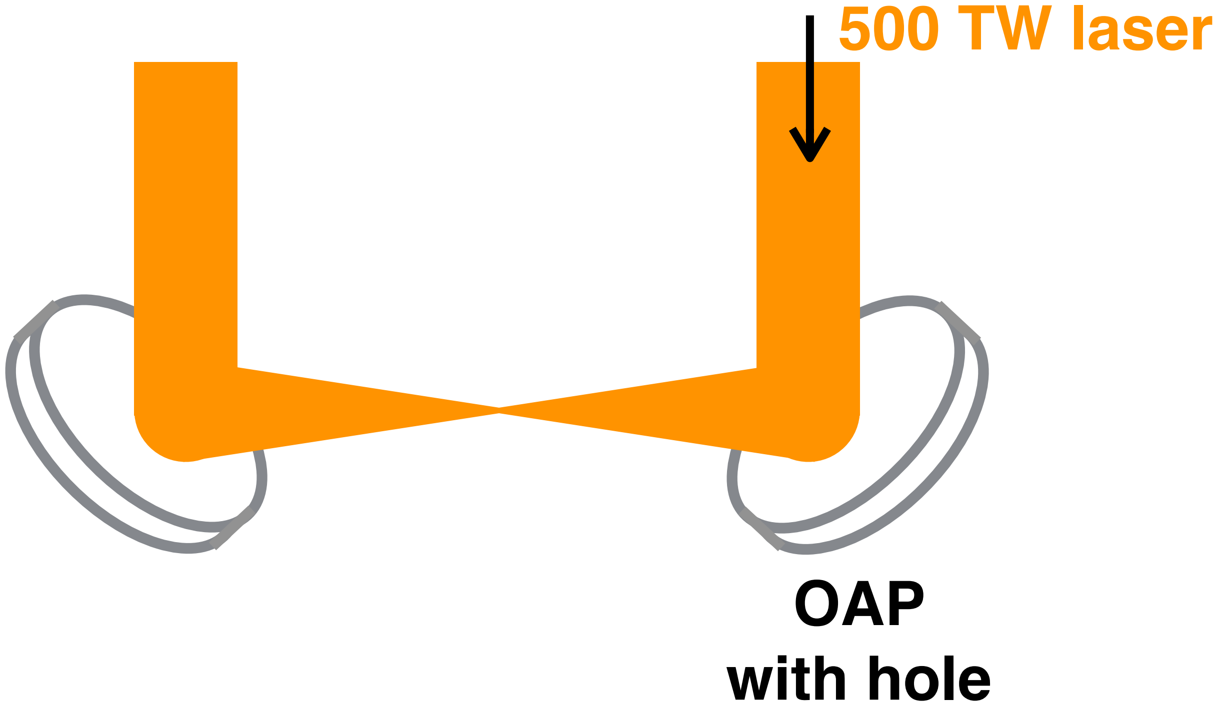
Performance of the 500 TW laser

- Wave length : 800 nm
- Pulse energy : 12.5 J
- Pulse width : 25 fs
- Rate : 1 Hz



Experimental setup

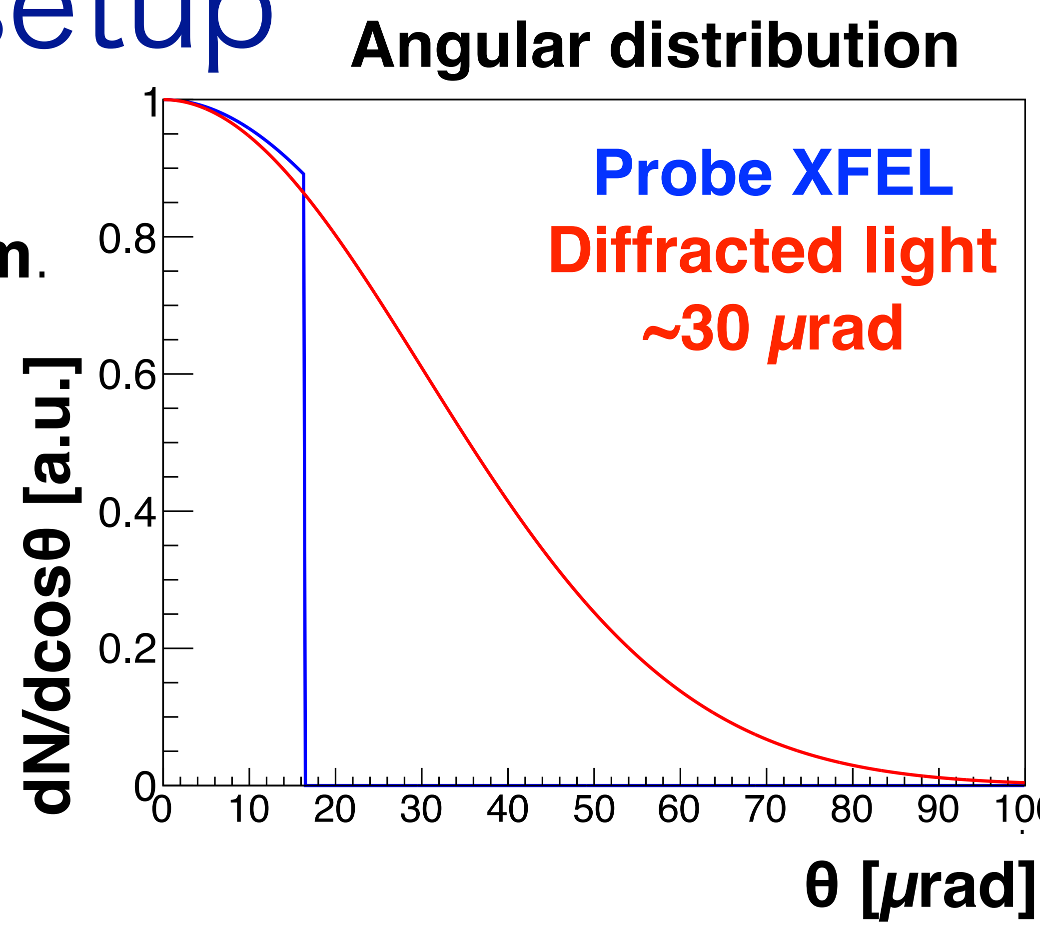
- The **500 TW laser** is focused to **1 μm**.

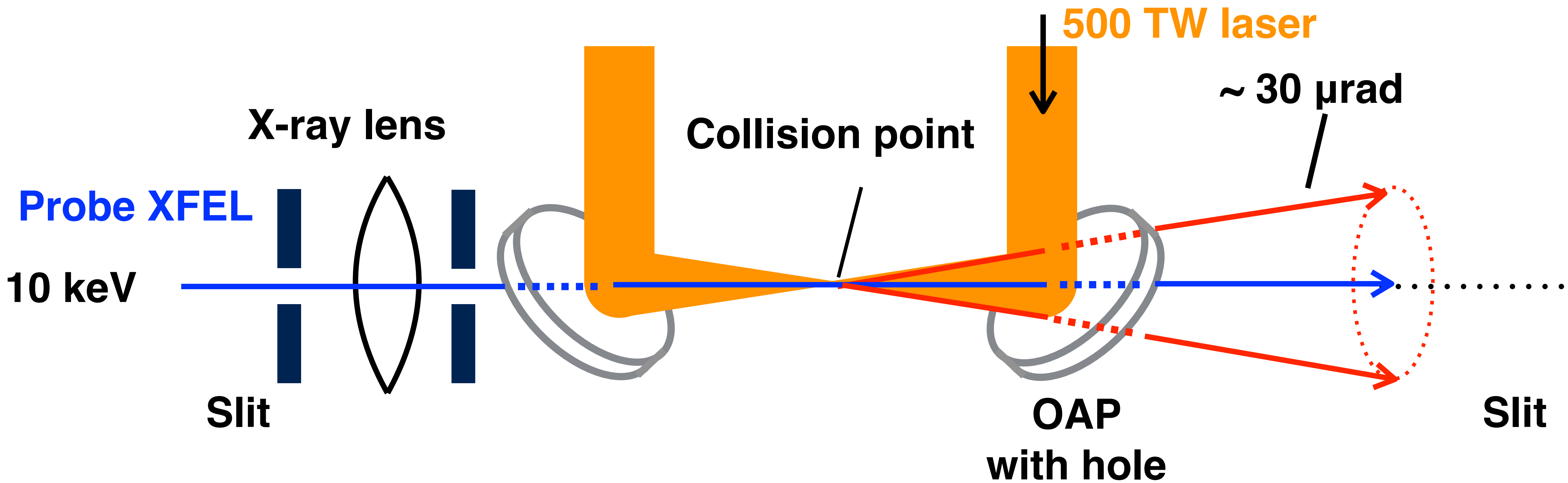


Experimental setup

- Anglar divergence of the **probe XFEL** is suppressed by slits and the **probe XFEL** pulse is focused to **2 μm**.
- The **focused XFEL pulse** and the **500 TW laser pulse** collide each other at the focal point.
- The probe XFEL were **diffracted**.

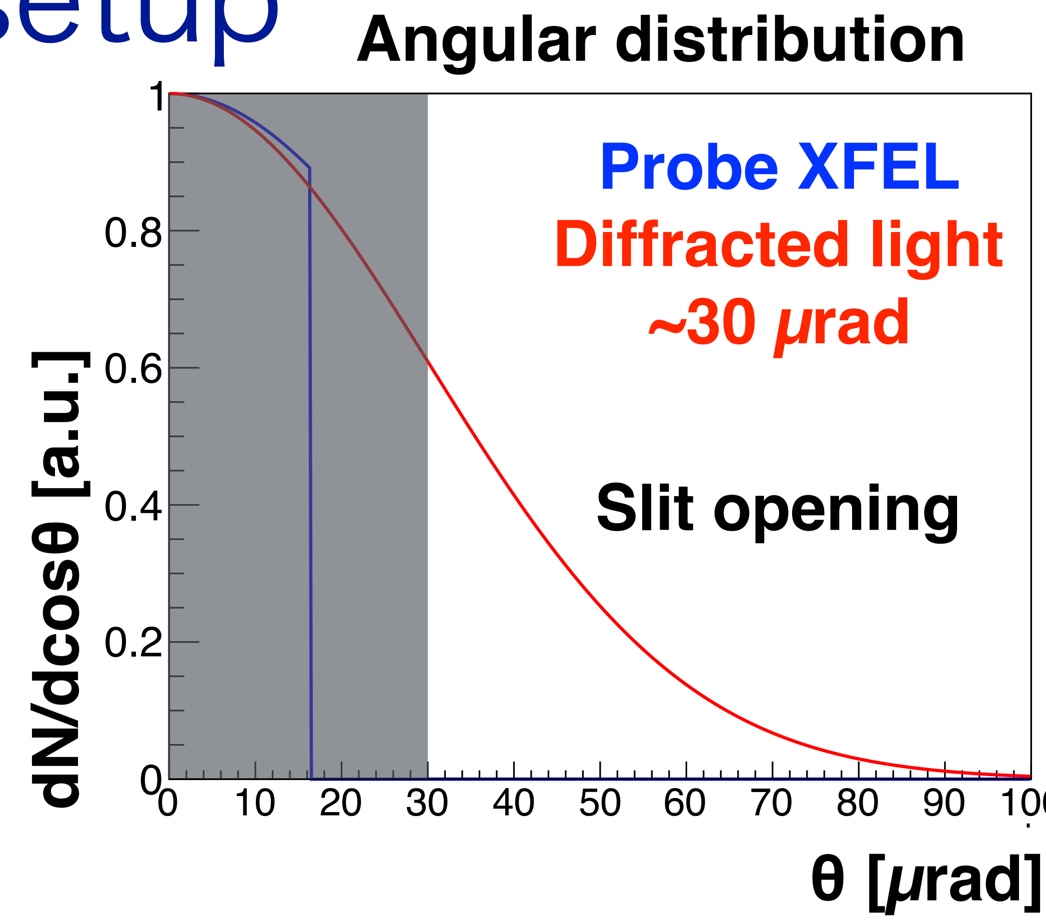
  Probability : ~$\mathbf{10^{-13}}$ Angler divergence : ~**30 μrad**

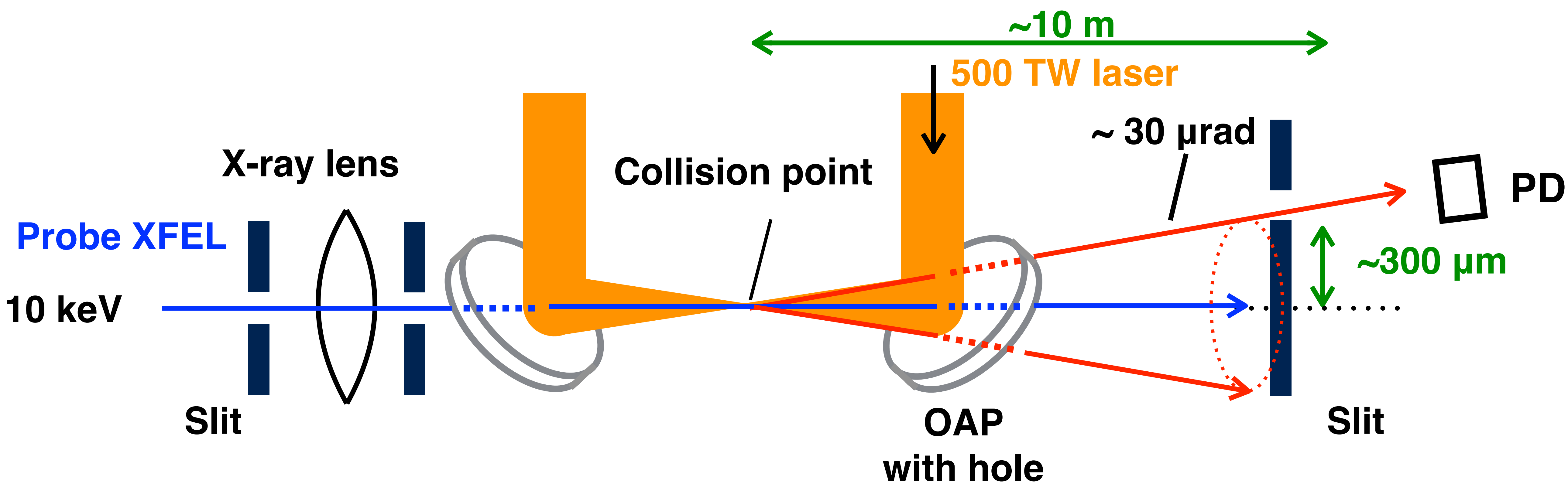




Experimental setup

- We detect only diffracted light by setting slit.
- For 2 days DAQ, signal light reach **~200 photons**.





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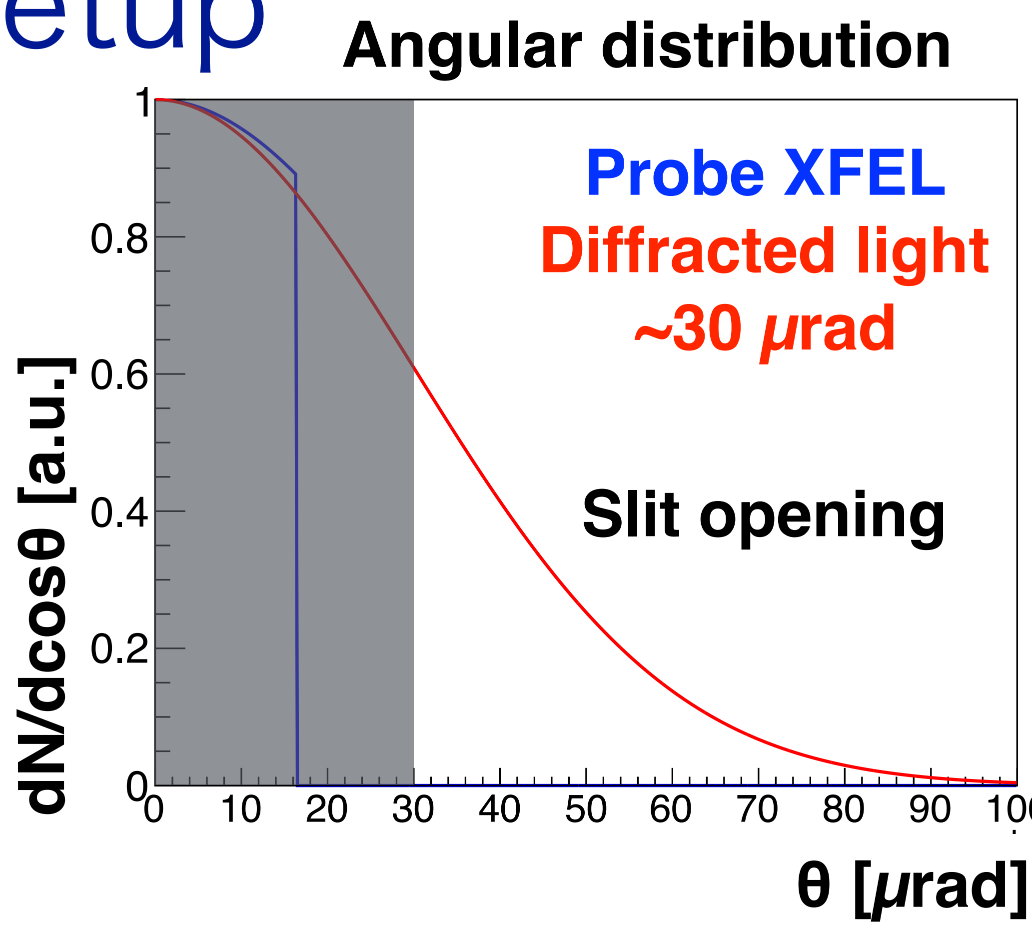
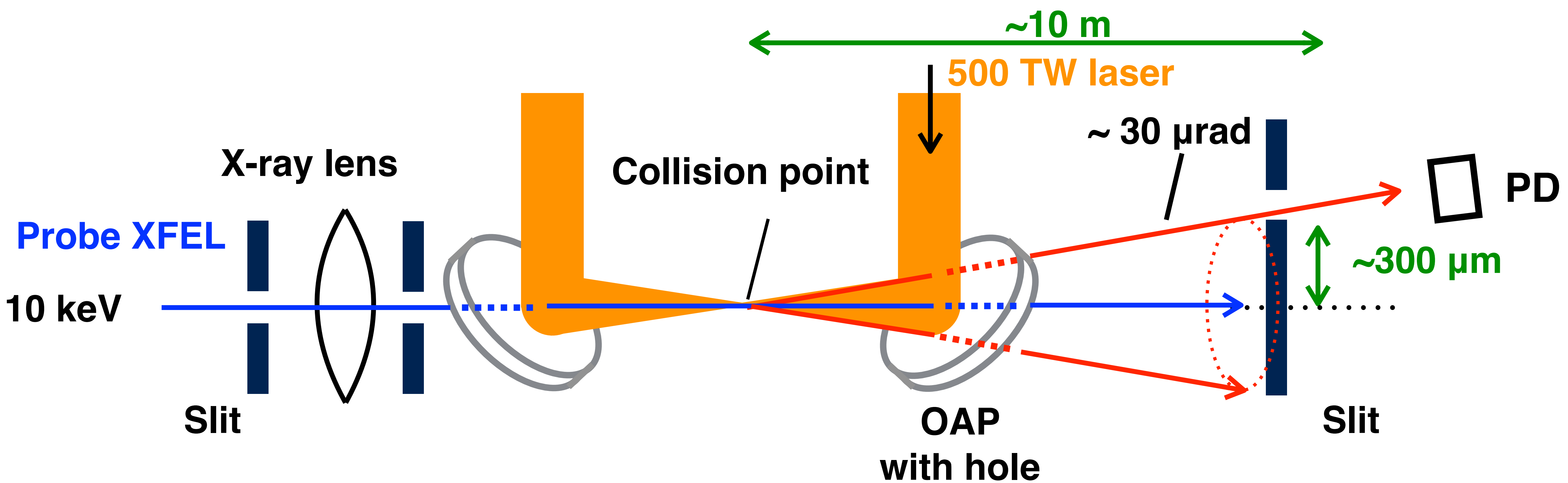


We can observe vacuum diffraction.

(If collision and BG suppression is successful)



Requirements for vacuum diffraction observing

- **Points to get enough signals**

  - Size of the pump laser and the probe XFEL **~1 μm**
  - Spacial alignment (absolute position, fluctuation) **~μm**
  - Timing alignment (absolute timing, jitter) **~ps**

- **Back ground suppression**

  BG are produced by the probe XFEL beam(3×10^{11} photons/pls)

Target value	Laser	Laser pulse energy	Focused laser size	Spacial precision	Timing precision	BG suppression rate
Final experiment **(Observation of VD)**	500 TW	12.5 J	1 μm	1 μm	0.3 ps	10^{-16}

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Final experiment **(Observation of VD)**	500 TW	12.5 J	1 μm	1 μm	0.3 ps	10^{-16}
1st step experiment	2.5 TW	0.1 J	10 μm	10 μm	3 ps	10^{-16}

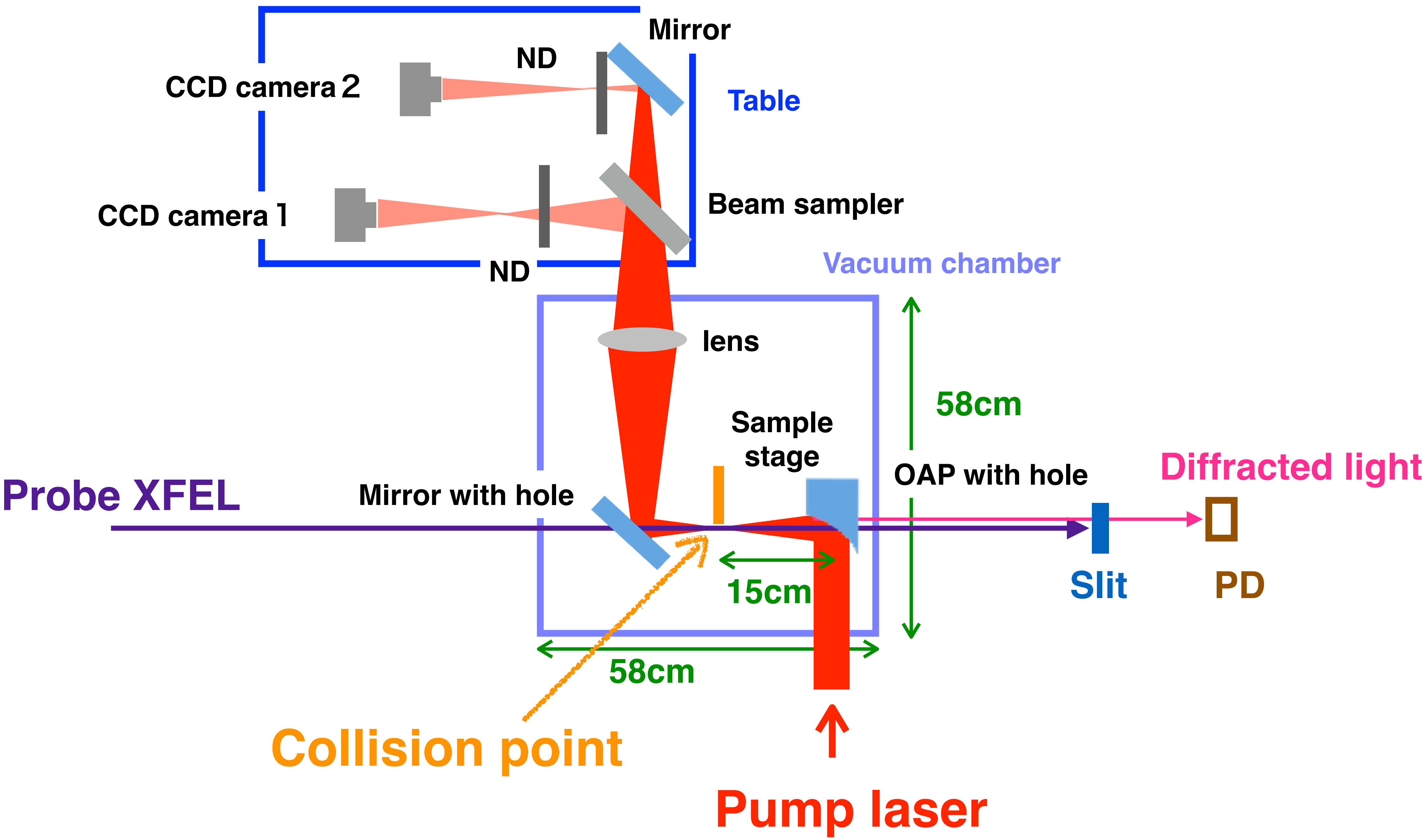
- We can already use 2.5 TW laser at SACLA.
- Firstly we made test experiment with large laser size(10 μm) to check current techniques for above contents.
- First vacuum diffraction experiment.

1st step experiment in November 2016

We made a 1st step experiment at SACLA in November 2016.

Beam time : 2.5 days

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



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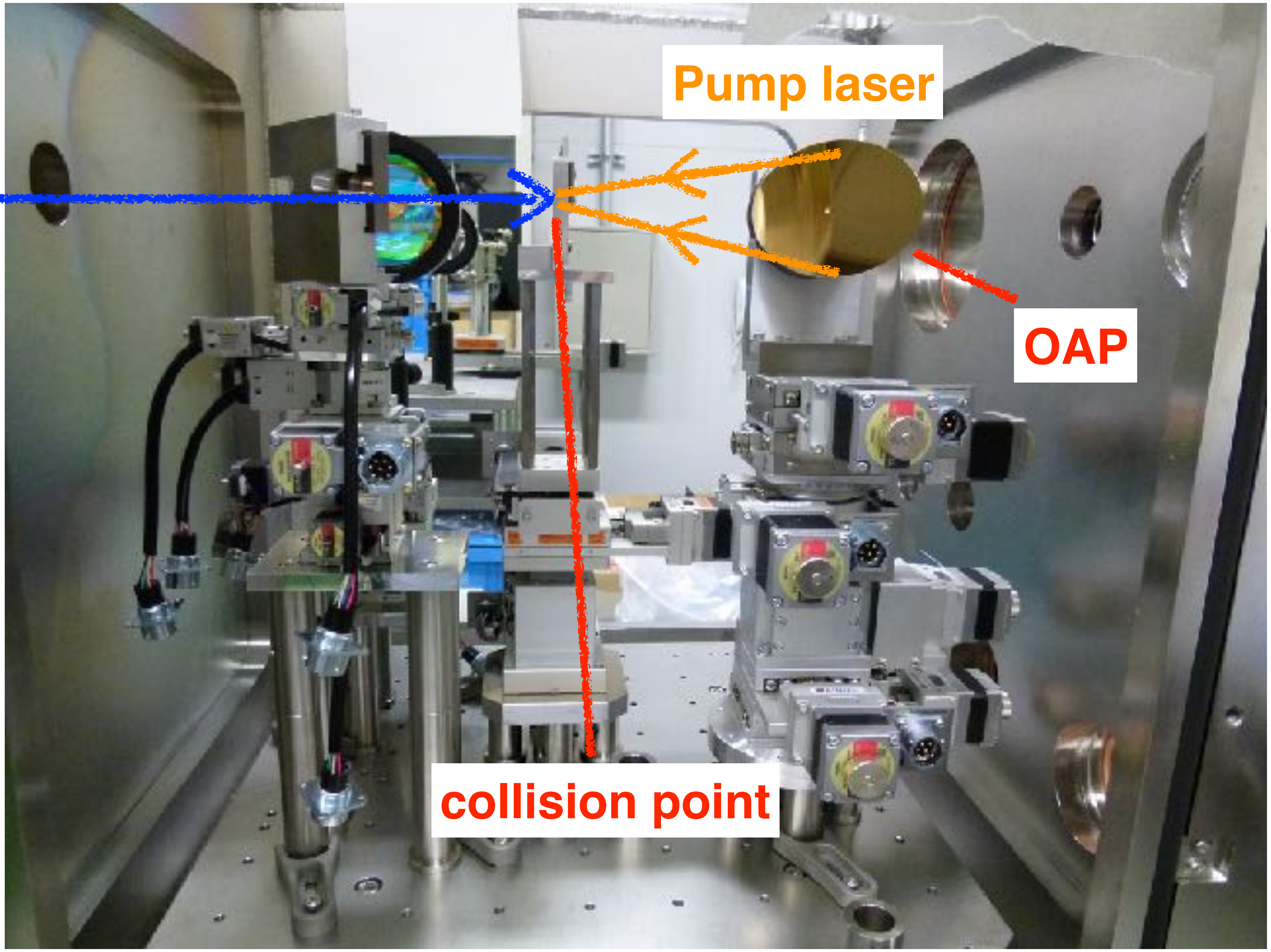
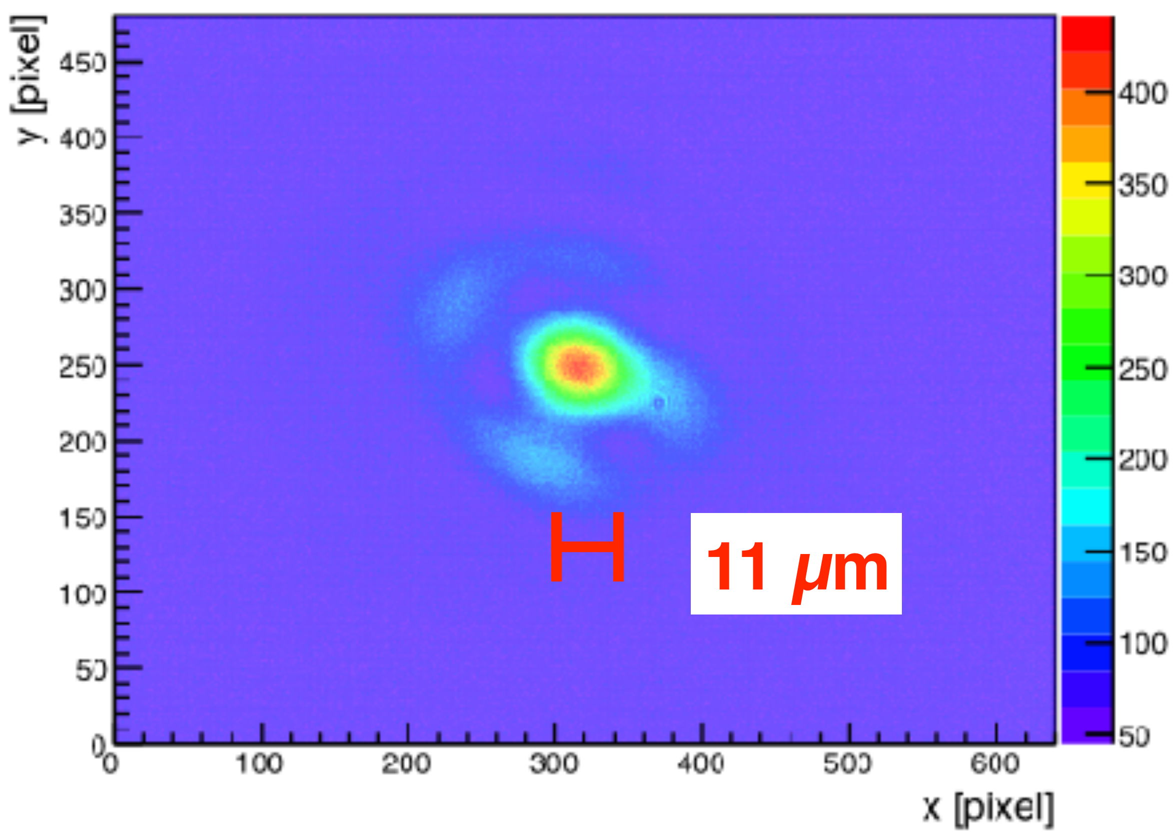
Vacuum chamber

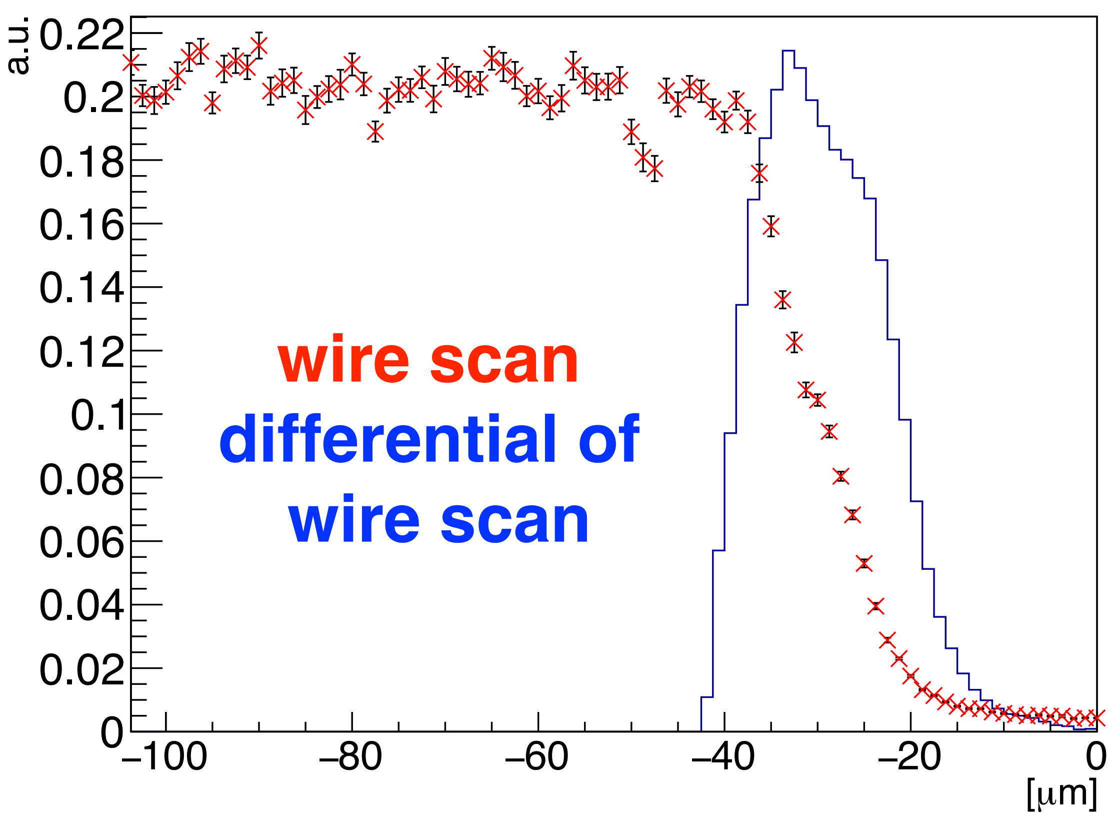


Pump laser and probe XFEL size

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



Wire scan result of the probe XFEL



Beam size of pump laser
FWHM : 11 μm (V)
→Enough size as 1st step experiment.

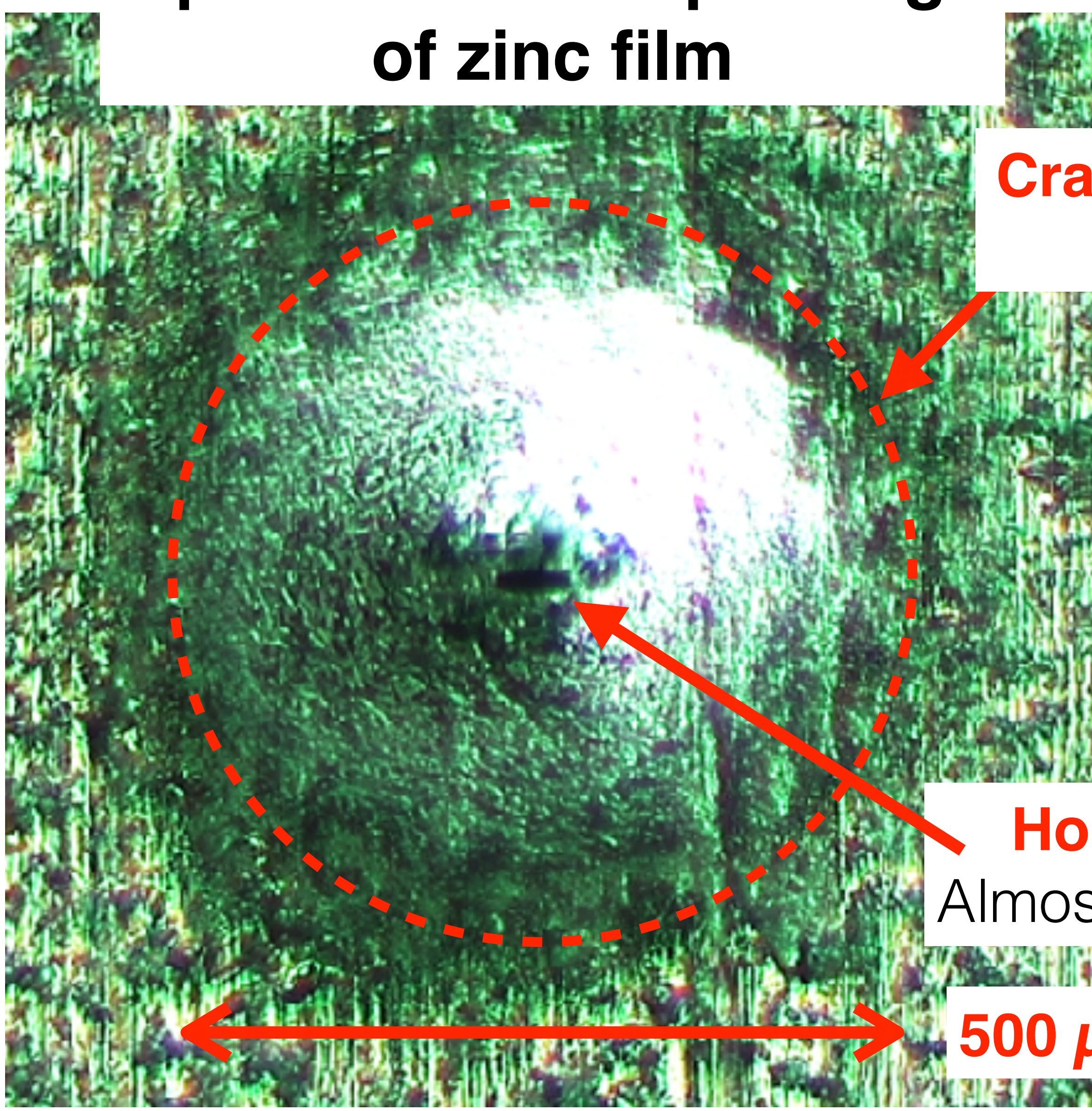
To cover the pump laser size, we adjust XFEL size to 20 μm.
Beam size of probe XFEL
FWHM : 20 μm (V)

Spacial guarantee

Spacial alignment method

Probe XFEL and pump laser are irradiated to a zinc thin film(20 μm) set at the collision point and both make <u>irradiation traces</u>. We adjust and overlap the position of the irradiation traces using an optical microscope.

Optical microscope image of zinc film



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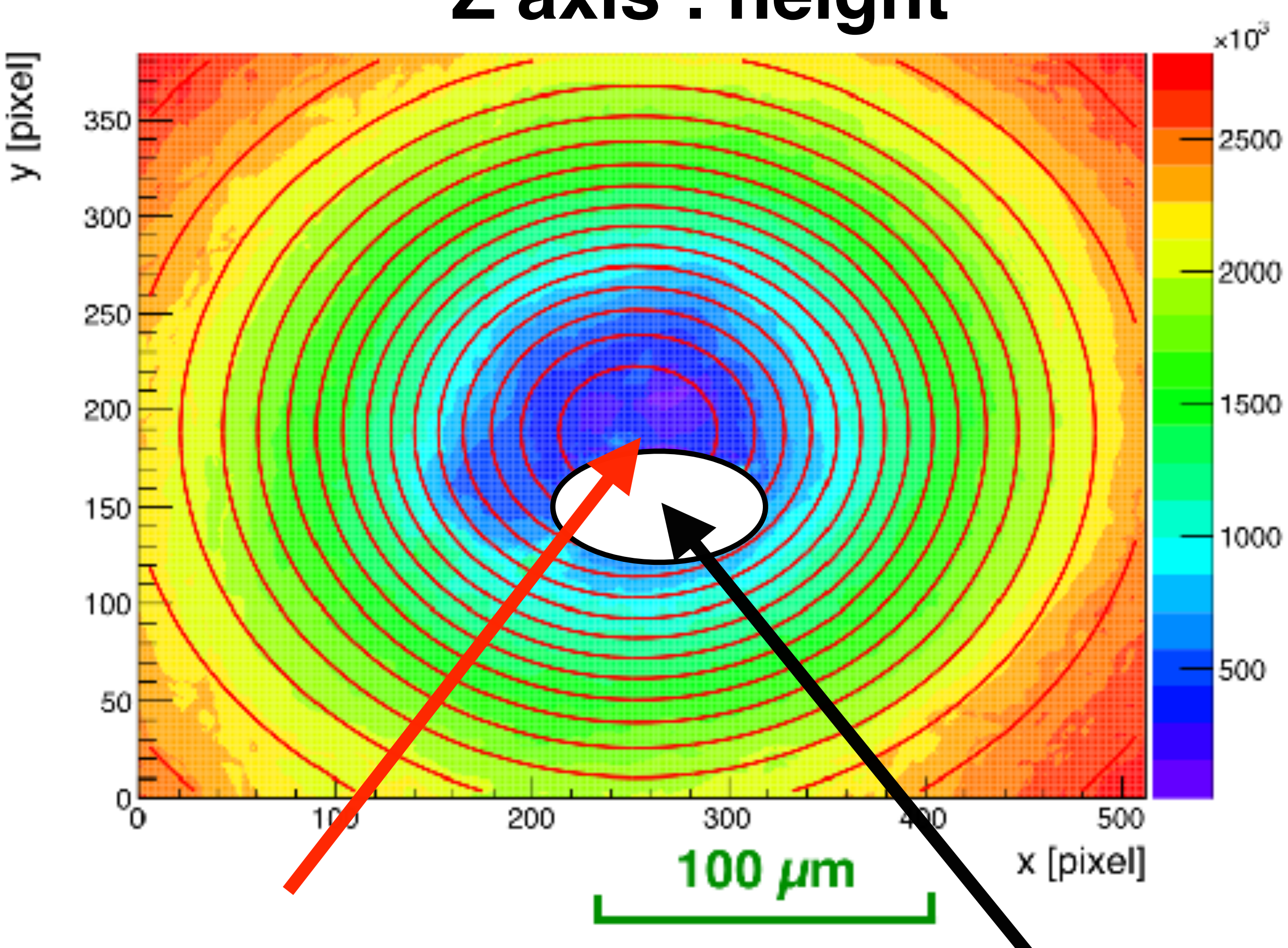
Laser microscope image
Z axis : height



Center of pump laser

Center of probe XFEL

After beam time, I measured relative distance of irradiation traces using laser microscope.

Measurement precision : ±4 μm

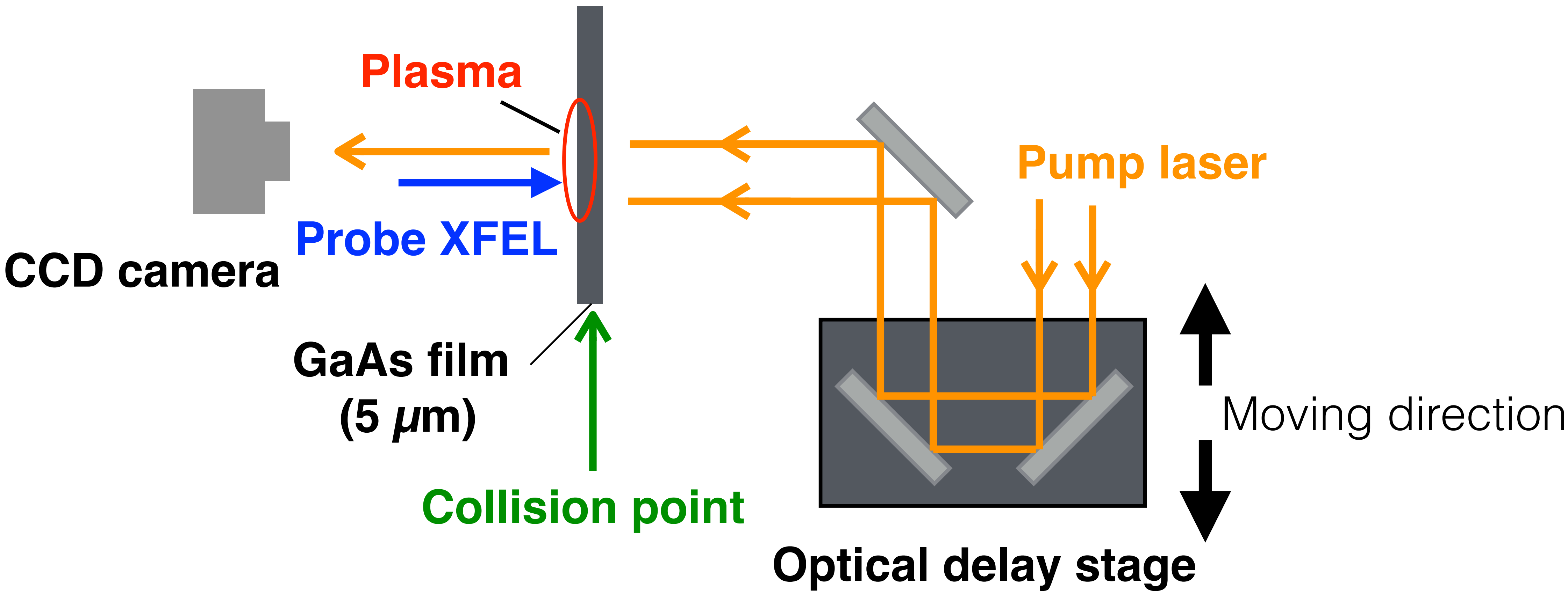
→Spacial precision is better than ±10 μm!

Timing guarantee

Timing alignment method

1. GaAs film was put at collision point and XFEL and the pump laser are irradiated.
2. We applied optical delay to the pump laser and monitored laser transmittance by CCD camera.

When XFEL and laser are irradiated at same timing
XFEL is irradiated to the GaAs film
→Some GaAs atoms become plasma(~ps).
→Laser transmittance decrease
because laser light can not through plasma.



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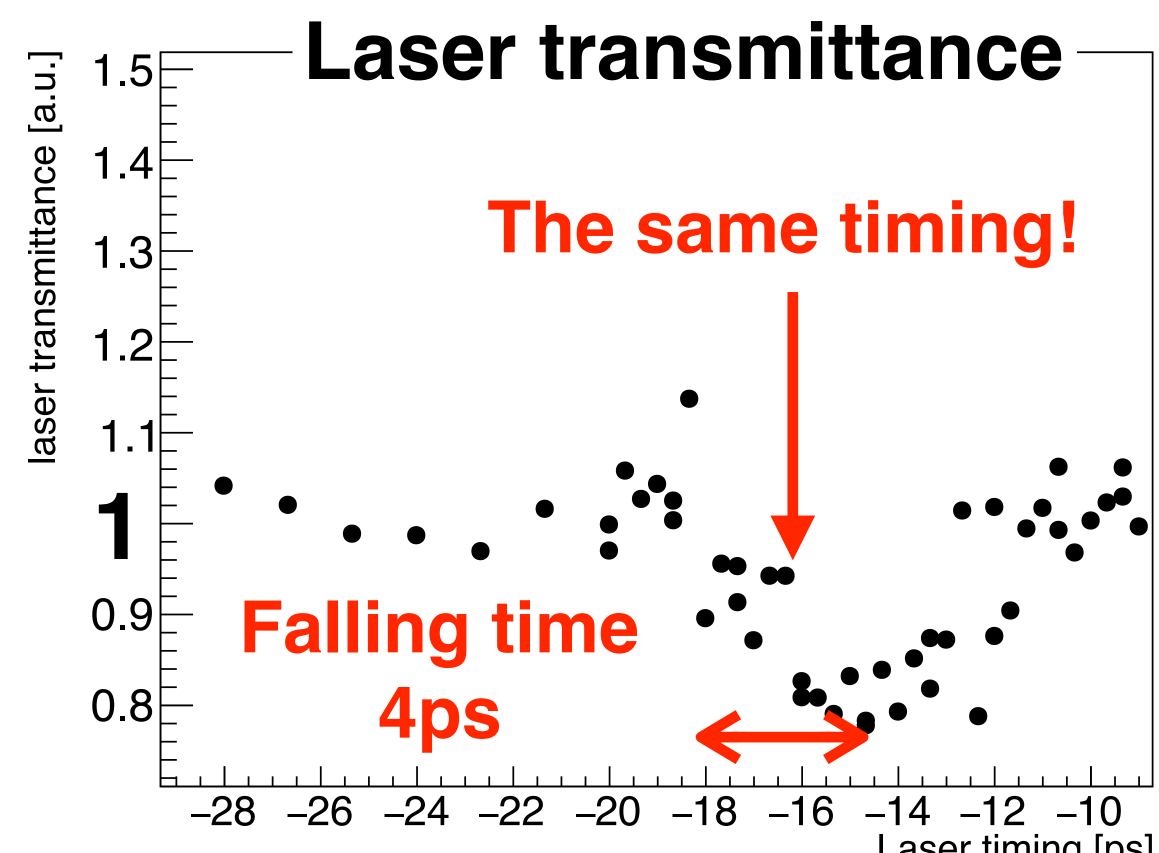
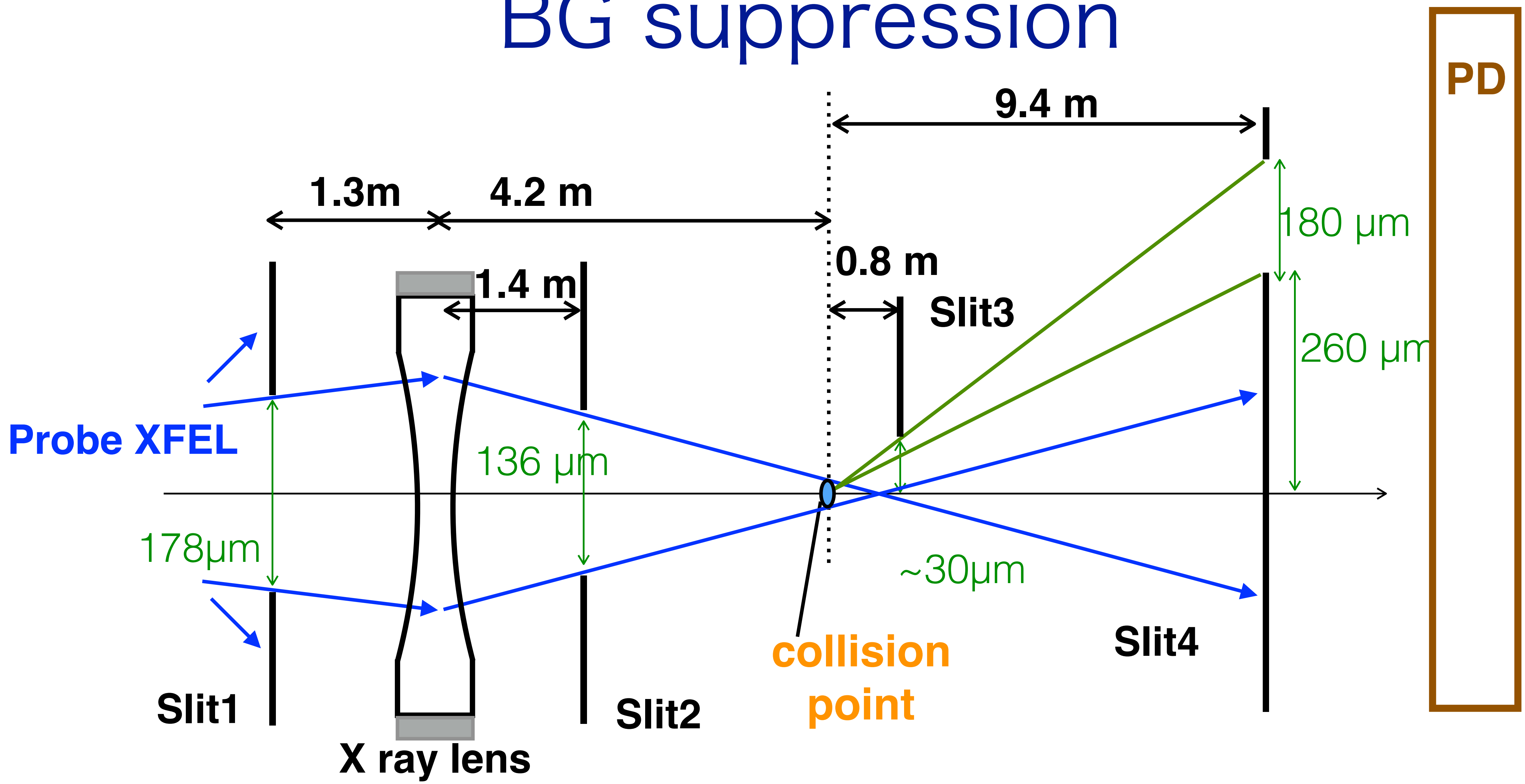


The timing uncertainty : ±2 ps
→Timing precision is better than ±3 ps!

BG suppression



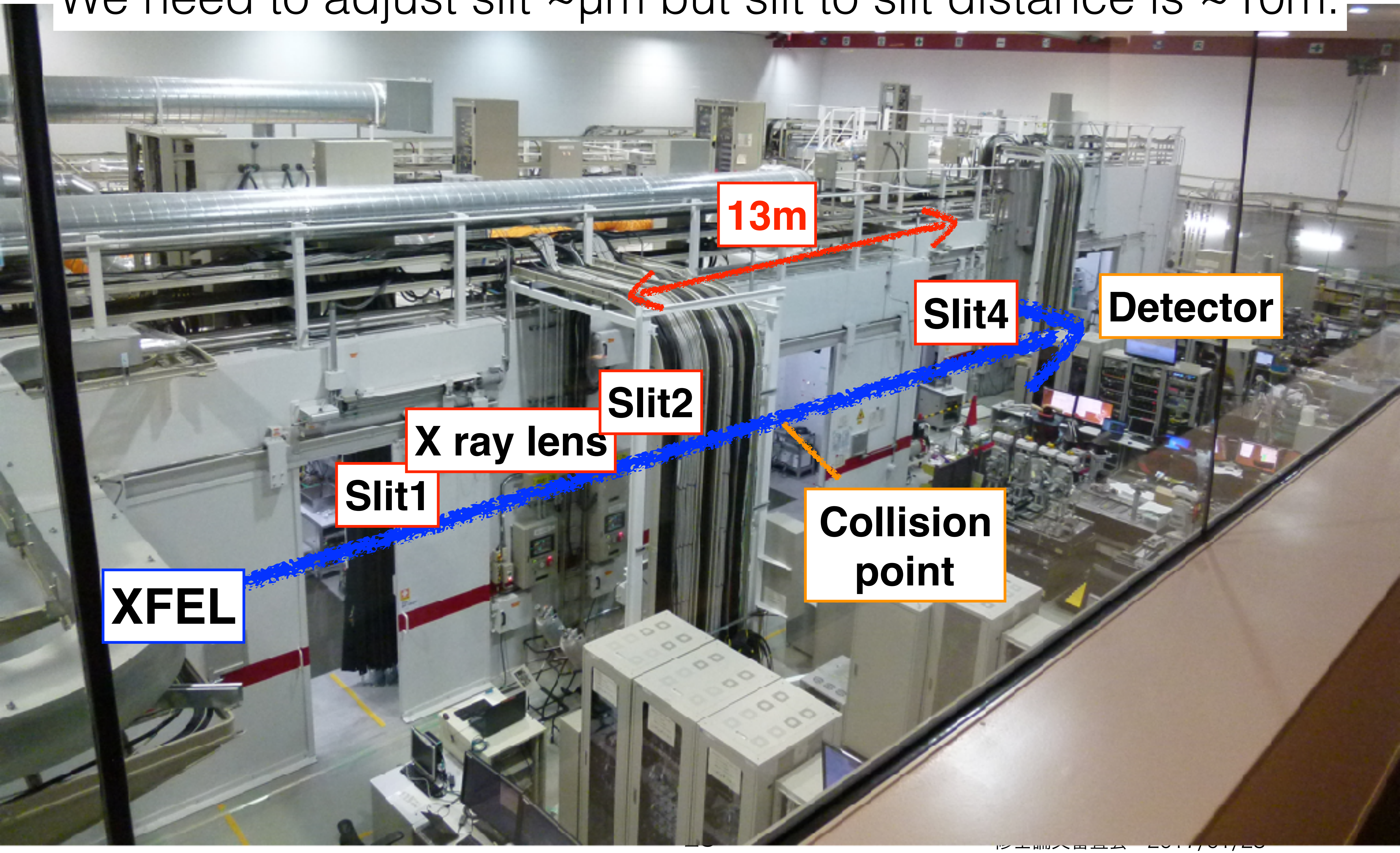
For BG suppression, we used slits.

Two strategies for BG suppression

1. Suppression of probe XFEL angular divergence by Slit1,2.
2. We set a Slit3 in a place to cut x rays scattered by slit2, lens, etc.

Experimental hall

We need to adjust slit ~μm but slit to slit distance is ~10m.



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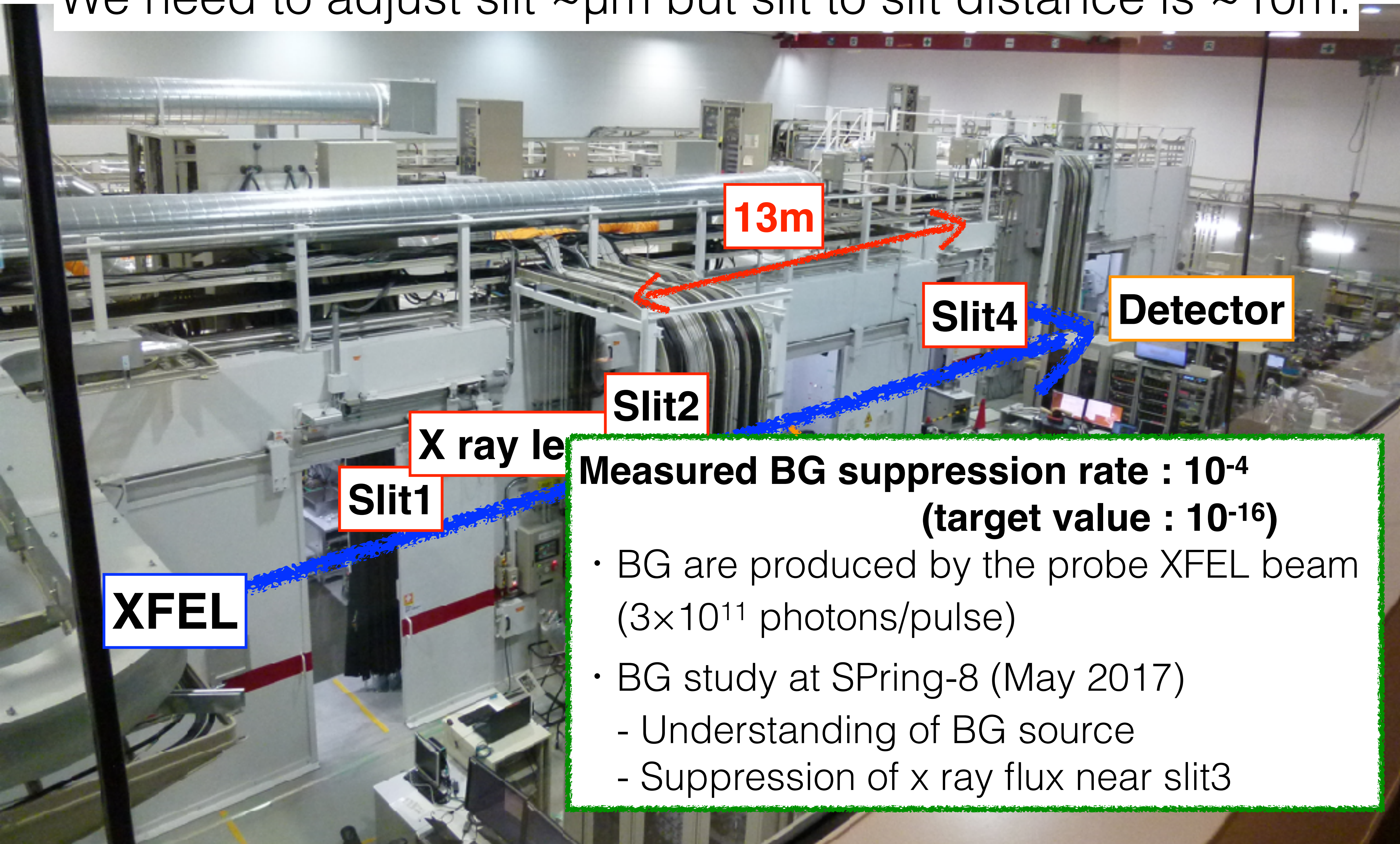

Measured BG suppression rate : 10^{-4}

(target value : 10^{-16})

- BG are produced by the probe XFEL beam (3×10^{11} photons/pulse)
- BG study at SPring-8 (May 2017)
  - Understanding of BG source
  - Suppression of x ray flux near slit3

Result of Nov. test experiment

	Focused laser size	Spacial precision	Timing precision	BG suppression rate
Target value	10 μm	10 μm	3 ps	10^{-16}
Result	11 μm	4 μm	2 ps	10^{-4}

From this experiment, sensitivity was 4×10^{34} times worse than QED theoretical value. This result is not good but this is first trial for vacuum diffraction.

Future plan

BG study at SPring-8(May 2017)

- Identification of BG source
- Change of slit geometry, BG suppression 10^{-4} —> 10^{-16}

Improvements of following items(2017~)

- Laser : 2.5 TW —> 500 TW
- Focused laser size : 11 μm —> 1 μm
  Introduction of deformable mirror
- Spacial alignment precision : 4 μm —> 1 μm
  Using new metal film or high resolution detector
- Timing alignment precision : 2 ps —> 0.3 ps
  Alignment using Si_3N_4 film

VD experiment using 500 TW laser(2018~)

- 500 TW laser & beam waist 1 μm
- The probe XFEL beam waist 2 μm
- 2 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 a nonuniform 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.