Photon-photon scattering and axion-like particle generation

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Outline

1. Background

2. High field Photon-photon scattering

3. High field axion-like particle generation

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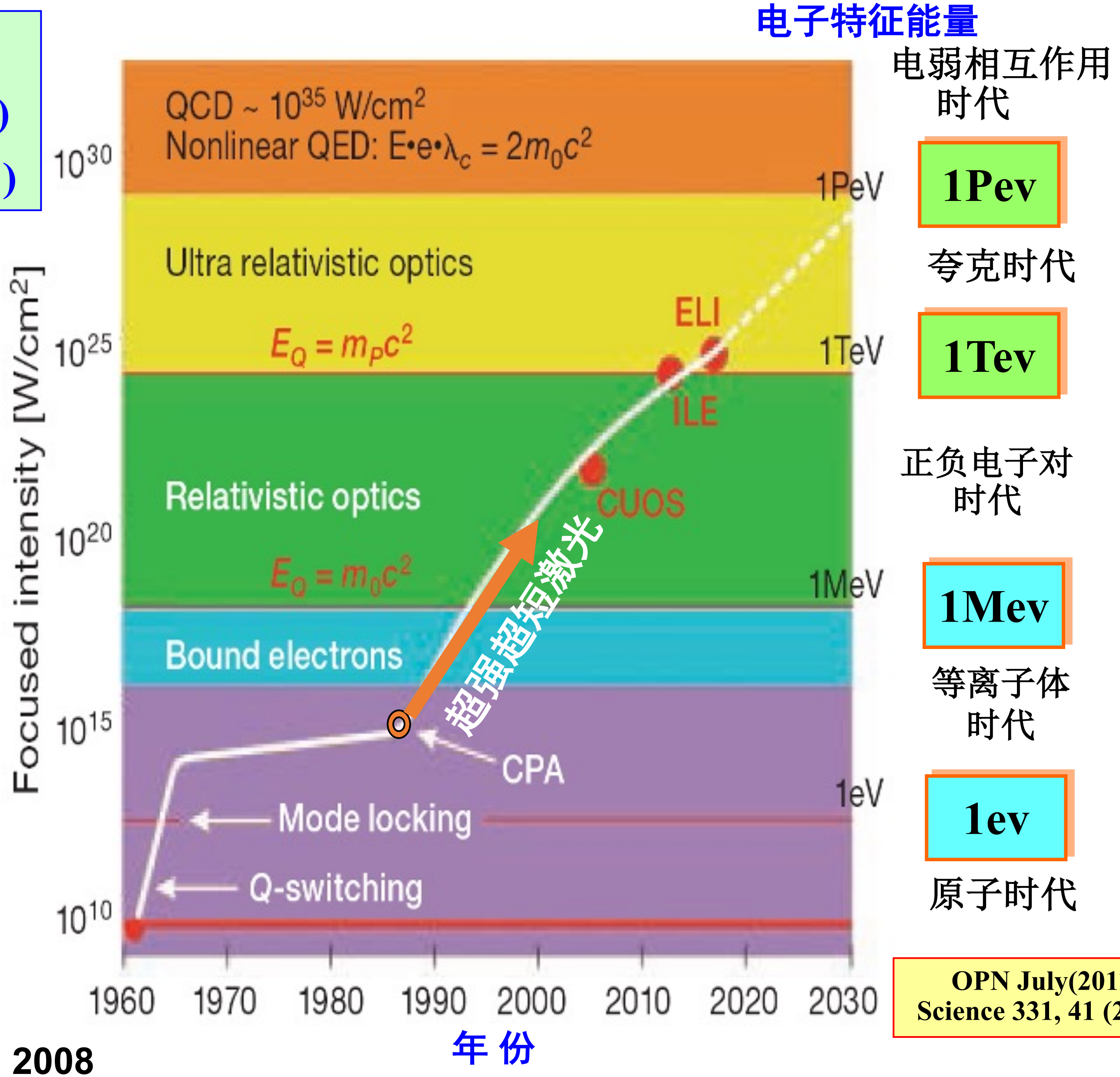
超强超短激光的发展历程与科学新领域的开拓

超强超短激光：
峰值功率> 1TW(10^{12}W)
脉冲宽度<100 fs (10^{-15}s)

超强超短激光最大光强已达 2×10^{22}W/cm^2

宇宙中γ -爆对应的光强10^{20}W/cm^2 *

超强超短激光是人类已知的最亮光源，可以提供前所未有的全新实验手段与极端物理条件。



OPN July(2011)
Science 331, 41 (2011)

* NewScientist April 9, 2008

Optical laser parameters

- Normalized laser amplitude

$$a_0 = \frac{eA_0}{m_e c^2} = \frac{eE_0}{m_e \omega_L c}.$$

When $a_0 = 1$， an electron quivers relativisticly in laser field.

- The corresponding laser intensity is

$$I_0\lambda_L^2 = \delta\left(1.37\times10^{18}\ \frac{\mathrm{W}}{\mathrm{cm}^2}\,\mu\mathrm{m}^2\right) a_0^2,$$

- Laser intensity is different in different reference frame, while the normalized laser amplitude a_0 is a Lorentz invariant quantity.

- At present, the normalized laser amplitude a_0 reaches a$\sim$100.

Optical laser parameters

- The normalized laser amplitude a_0 can be written as

$$a_0 = \frac{eE}{mc\omega_L} = \frac{eE \cdot \lambda_C}{\hbar\omega_L}, \qquad \lambda_C = \frac{\hbar}{mc}.$$

- It describes the photon number which an electron can absorb within a Compton wavelength.

- Therefore, from the QED point of view, the high field （$\boldsymbol{a_0 > 1}$） is better expressed as nonlinear.

Optical laser parameters

- The important parameter for the QED effects is the Schwinge field, describing the absorbed energy by an electron with a Compton wavelength equals the rest energy of an electron.

$$E_s = \frac{m^2c^3}{e\hbar} = \frac{mc^2}{e\lambda_C}.$$

- At this field, pairs can be produced in vacuum.

- At present, while the normalized laser $\boldsymbol{a_0}$ can be easily $> \mathbf{1}$， the laser field is still much smaller than the Schwinge field. Therefore, we discuss **the nonlinear QED physics ($a_0 > 1$) in the weak field region(much smaller than the Schwinge field).**

Why we need XFEL for QED physics?

- Since the optical laser field is still weak compared to the Schwinge field, we need another beam, such as electron beam or gamma beam to boost the QED effects. Here we consider to use XFEL.

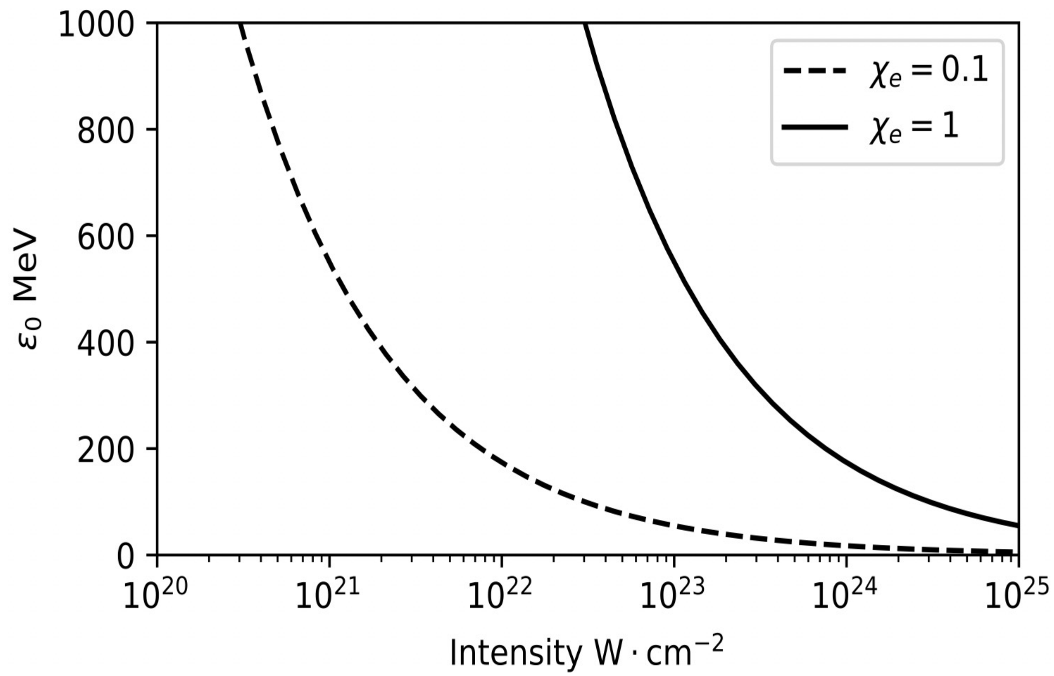
- Compared to electron beams, the XFEL is cleaner without any maters of mass and charge.

- Compared to gamma beams, the XFEL can be measured precisely.

决定高能电子（光子）和强场相互作用QED效应的参数

$$\chi = \frac{1}{E_s mc}\left|F_{\mu\nu}p^{\nu}\right| = \frac{c}{E_s e\hbar}a|kp| = \frac{a}{m^2c^2}|kp|$$

$$\chi = \frac{\gamma}{E_s}|\mathbf{E}_{\perp} + (\boldsymbol{\beta}\times\mathbf{B})|$$



$$\eta = \frac{e\hbar^2}{2m^3c^4}\left|F_{\mu\nu}k^{\nu}\right| = \frac{\hbar}{2E_s mc}\left|F_{\mu\nu}k^{\nu}\right| = \frac{\hbar\omega}{2mc^2E_s}\left|\mathbf{E}_{\perp} + \left(\frac{\mathbf{k}}{k}\right)\times\mathbf{B}\right|$$

Short wavelength laser may provide low cost new generation laser facilities of intensity approaching the Schwinger limit.

1. XFEL with CPA technique may provide attosecond 10 keV laser of focal size less than 10 nm.

2. 10 or 100 PW laser may produce 1EW laser of 1 J and 1 as.

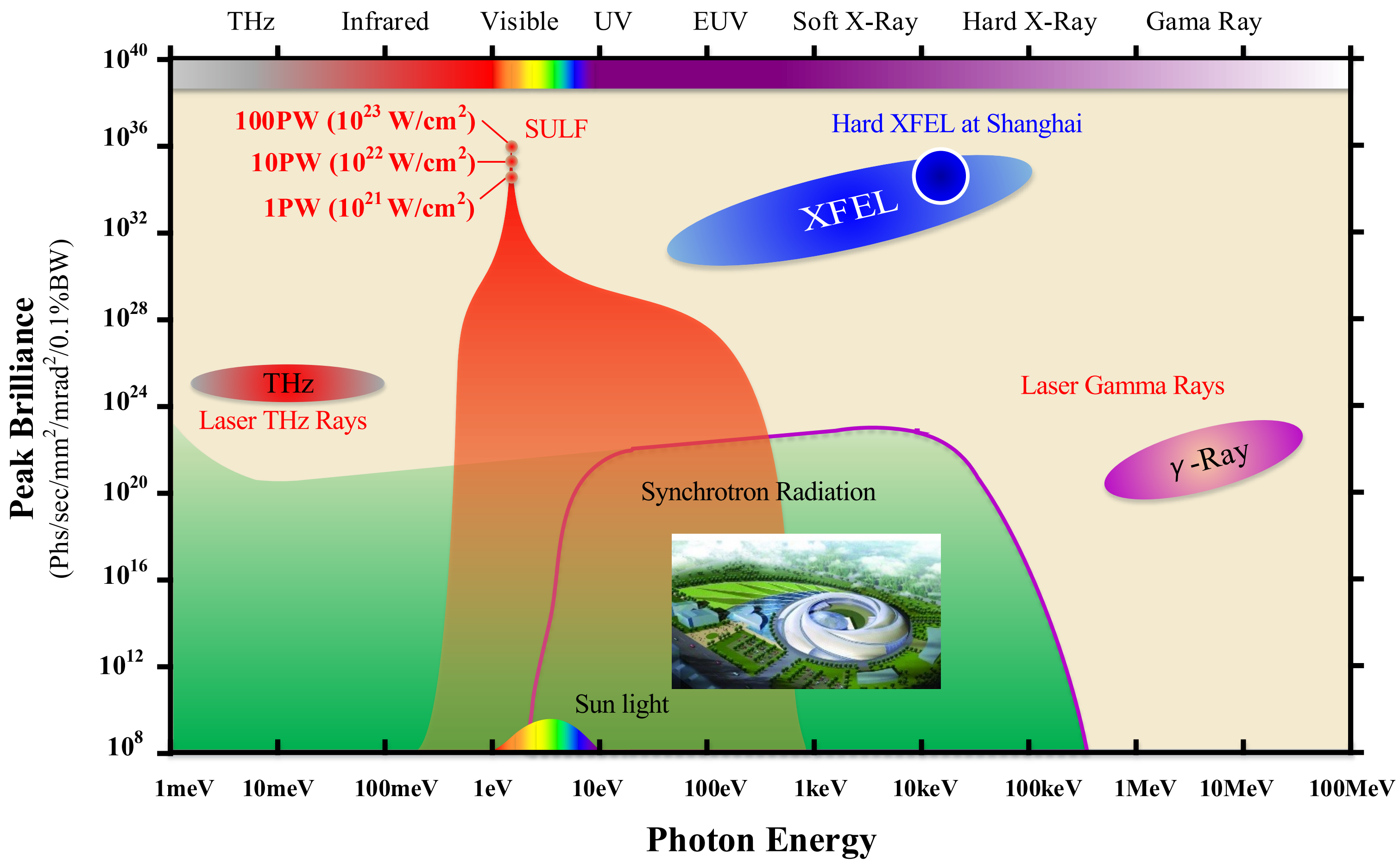
3. Laser-produced ultra-intense gamma radiation may drive a gamma-ray laser.

4. Schwinger limit is not the ultimate limit for laser intensity, since plane wave dose not produce pairs in vacuum.

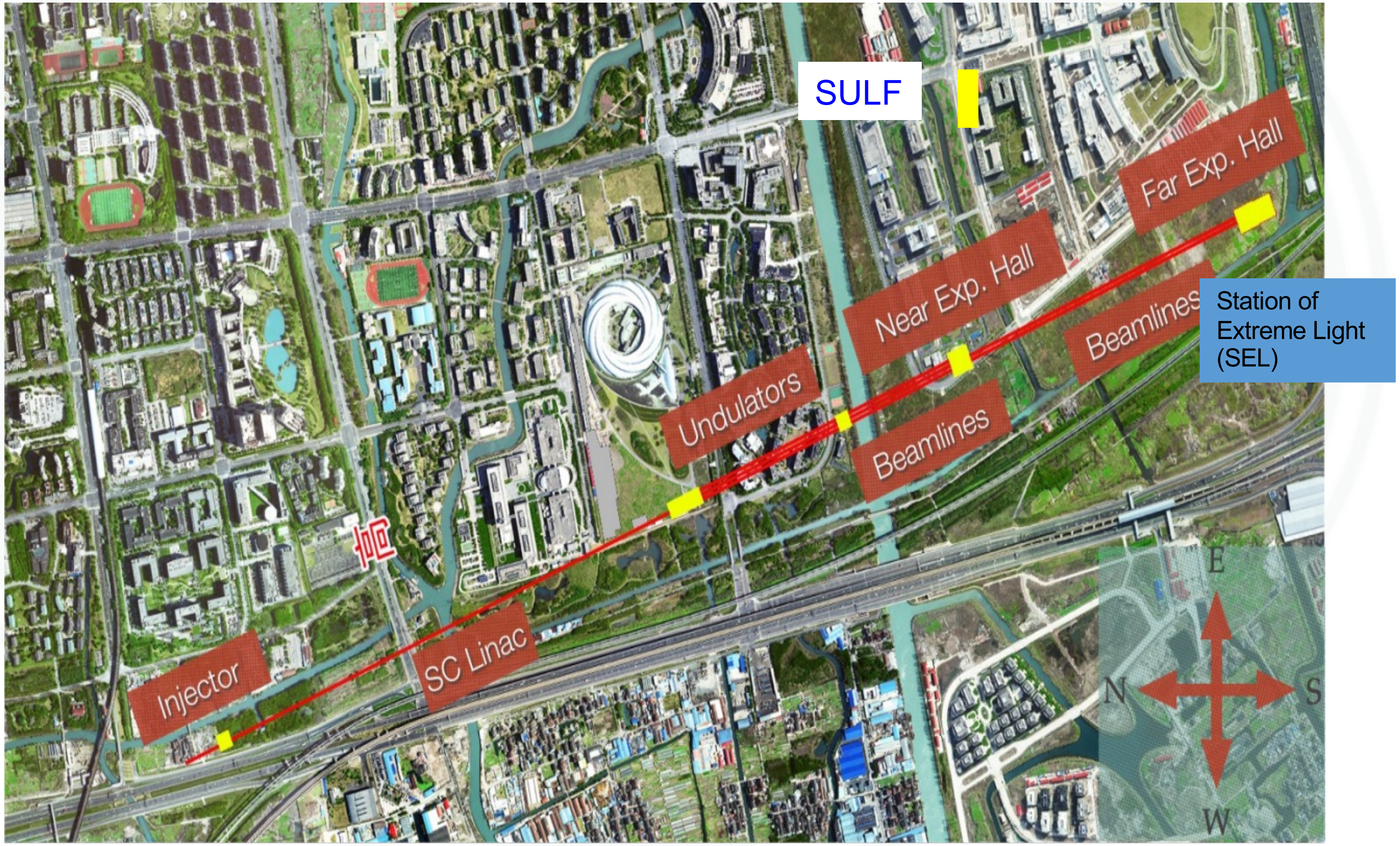
Station of Extreme Light (SEL) at XFEL

The marriage of two most intense light sources：

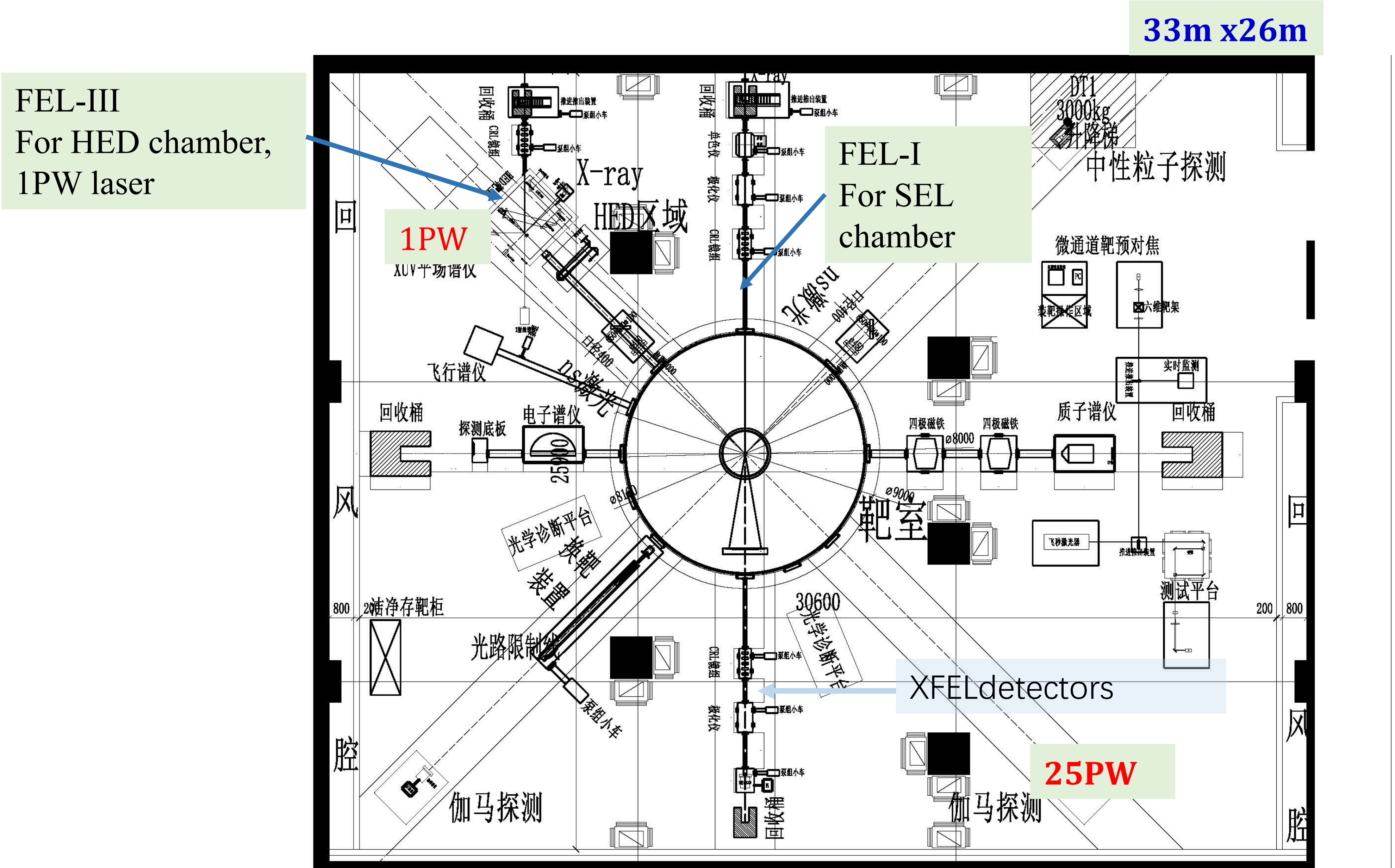
1TW XFEL at 0.1nm + 100PW optical laser at 900nm



The building of Shanghai HIgh repetition XFEL aNd Extreme light facility (SHINE) was started on 27 April, 2018.

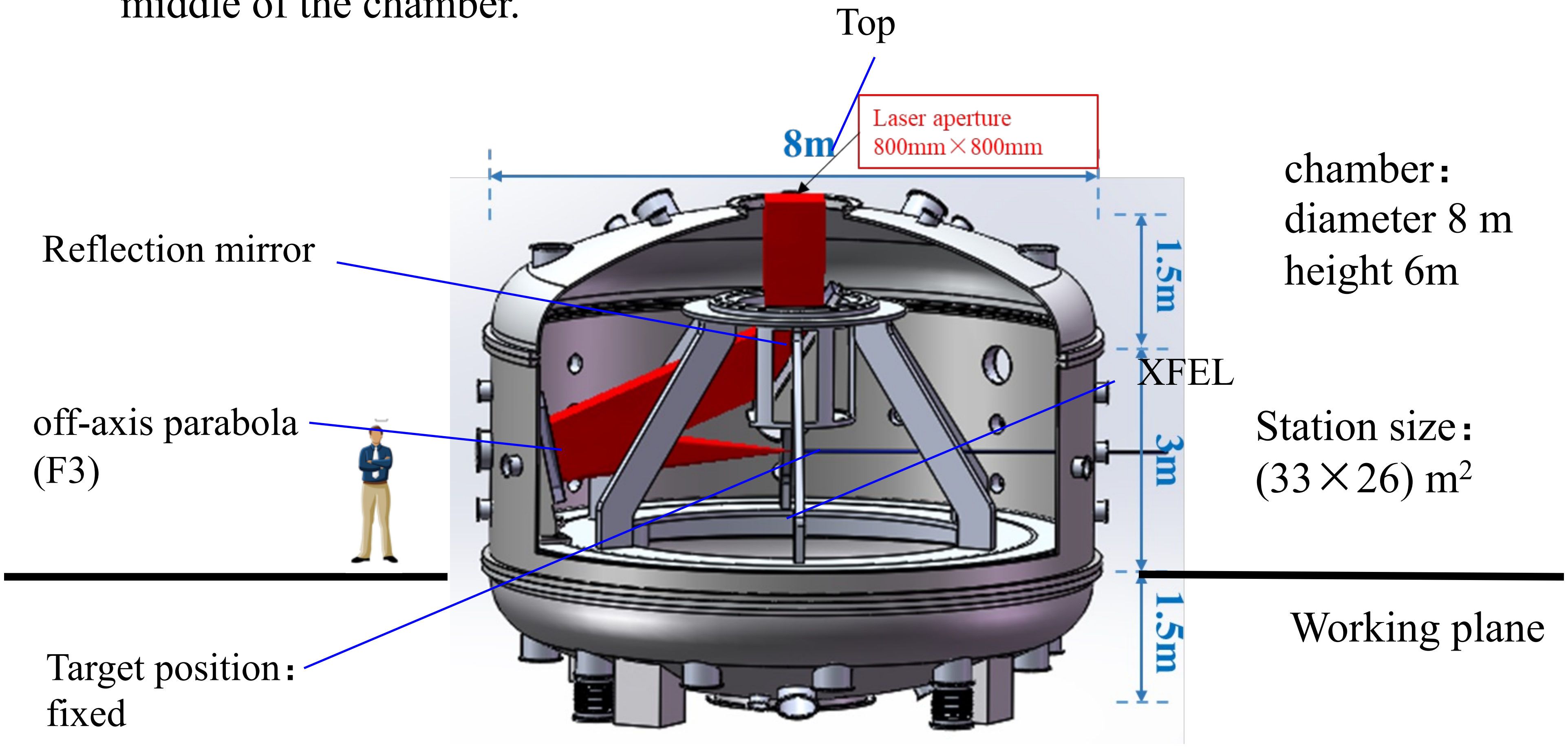


Top view of the experimental area



Interaction chamber

■ 1000x1000 mm^2 100PW laser pulse (1500J/15fs) coming from top is reflected to off-axis parabola near the chamber wall and then focused to XFEL in the middle of the chamber.



The interaction chamber has been installed.

Outline

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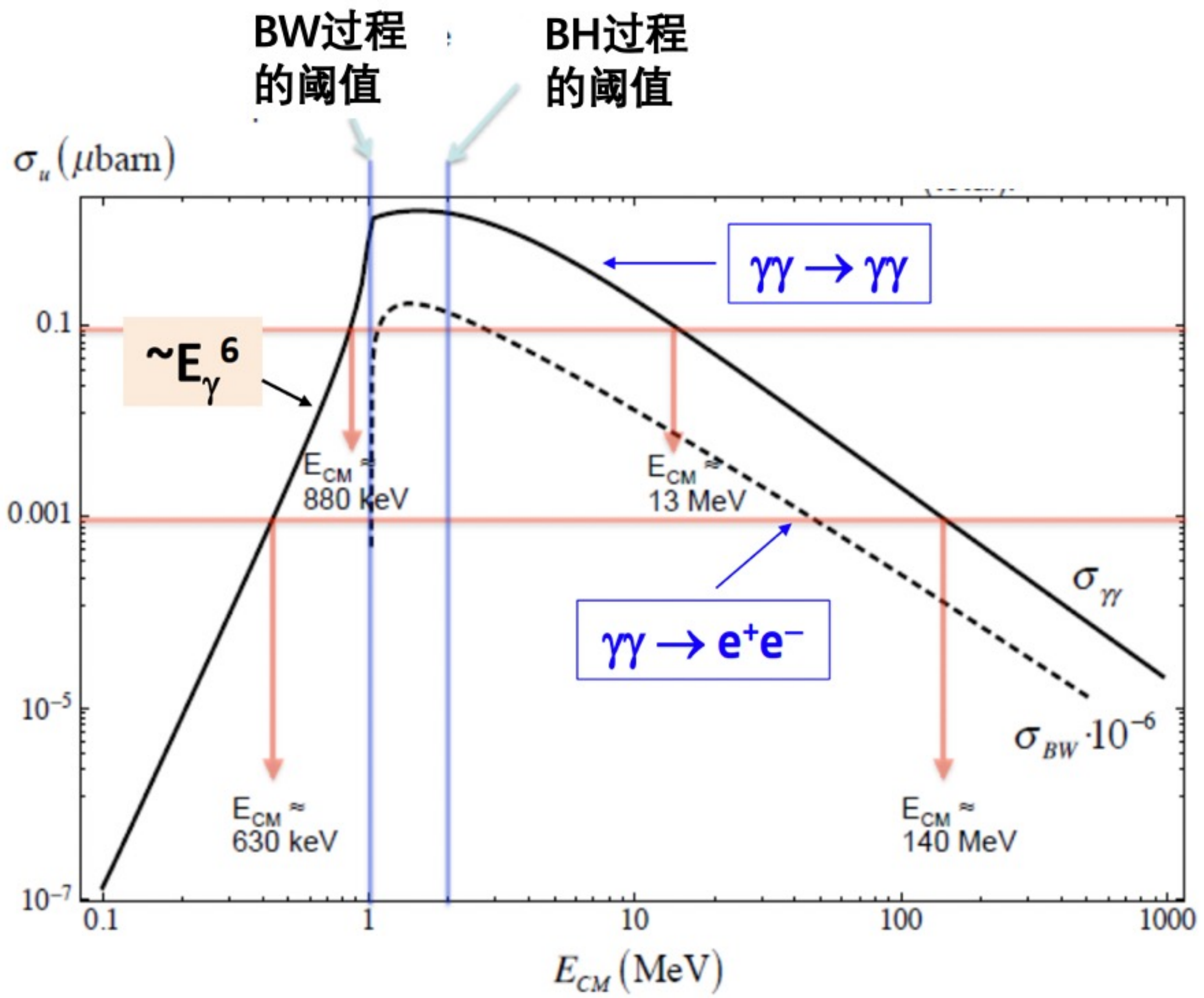
3. High field axion-like particle generation



（单光子）光光总散射截面随质心光子能量的变化

High field Photon-photon scattering

Theoretical methods：

Since the optical laser field is weak compared to the Schwinge field, the Lagrangian density is

$$\mathcal{L}_{EH} = \frac{\xi}{128\pi}\left[4\left(F_{\alpha\beta}F^{\alpha\beta}\right)^2 + 7\left(\widetilde{F}_{\alpha\beta}F^{\alpha\beta}\right)^2\right],$$

Here，the coupling coefficient $\xi = \alpha/(45\pi E_s^2)$,

$$F_{\alpha\beta}F^{\alpha\beta} = -2\left(|E|^2 - |B|^2\right),$$

$$\widetilde{F}_{\alpha\beta}F^{\alpha\beta} = -4E \cdot B.$$

High field Photon-photon scattering

Theoretical methods：

With the Lagrangian density， we have

$$\mathbf{P} = \frac{\partial \mathcal{L}_{EH}}{\partial \mathbf{E}} = \frac{\xi}{4\pi}[2(|\mathbf{E}|^2 - |\mathbf{B}|^2)\mathbf{E} + 7(\mathbf{E}\cdot\mathbf{B})\mathbf{B}],$$

$$\mathbf{M} = \frac{\partial \mathcal{L}_{EH}}{\partial \mathbf{B}} = \frac{\xi}{4\pi}[7(\mathbf{E}\cdot\mathbf{B})\mathbf{E} - 2(|\mathbf{E}|^2 - |\mathbf{B}|^2)\mathbf{B}].$$

Photon-photon scattering can changes the polarization, energy and transverse momentum of the photons.

Detecting vacuum birefringence with XFEL + 100 PW laser

In 1930’ s, W. Heisenberg et al. predicted vacuum birefringence, the QED effect in vacuum. But it has never been observed in laboratory.

In 1940-50’ s, Schwinger et al. established the systematic theory on QED and defined the Schwinger critical field.

In 1960, Maiman invented laser. the Schwinger critical field correspond to the laser intensity 10^{29}W/cm^2. CPA technology helps the quick increase of laser intensity. But, with single ultra intense laser alone, it is still very difficult to study vacuum birefringence.

XFEL provides an excellent solution for us to detect high field vacuum birefringence in laboratory.

Detecting vacuum birefringence with XFEL + 100 PW laser

The refractive factors for the XFEL beam along the laser electric field and magnetic field is

$$n_1 = 1 + c_2\left[\boldsymbol{E}^2 + 2\boldsymbol{E}\cdot\left(\hat{\boldsymbol{k}}\times\boldsymbol{B}\right) + \left(\hat{\boldsymbol{k}}\times\boldsymbol{B}\right)^2\right]$$

$$n_2 = 1 + c_1\left[\boldsymbol{E}^2 + 2\boldsymbol{E}\cdot\left(\hat{\boldsymbol{k}}\times\boldsymbol{B}\right) + \left(\hat{\boldsymbol{k}}\times\boldsymbol{B}\right)^2\right]$$

One efficient way is to collide the two beams to maximize the difference of the refractive factors.

$$\Delta\phi = 2\pi\left(n_1 - n_2\right)\frac{d}{\lambda_X} = \frac{4\alpha}{15}\frac{d}{\lambda_X}\frac{I_L}{I_S}$$

Taking into account the pulse profile in space and time domain, the modified ellipticity of the XFEL beam is

Laser intensity

$$\boxed{\varepsilon = \left|\frac{i\Delta\phi}{2}\right|^2 = \frac{1}{4}\left(\frac{4\alpha}{15}\frac{\pi z_R}{\lambda_X}\frac{I_0}{I_S}\right)^2 G^2(z_R, \tau_R)}$$

Wavelength of XFEL

The phusical design for the experiment of vacuum birefringence has been published .

IOP Publishing

Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **60** (2018) 044002 (11pp)

https://doi.org/10.1088/1361-6587/aaa7fb

Exploring vacuum birefringence based on a 100 PW laser and an x-ray free electron laser beam

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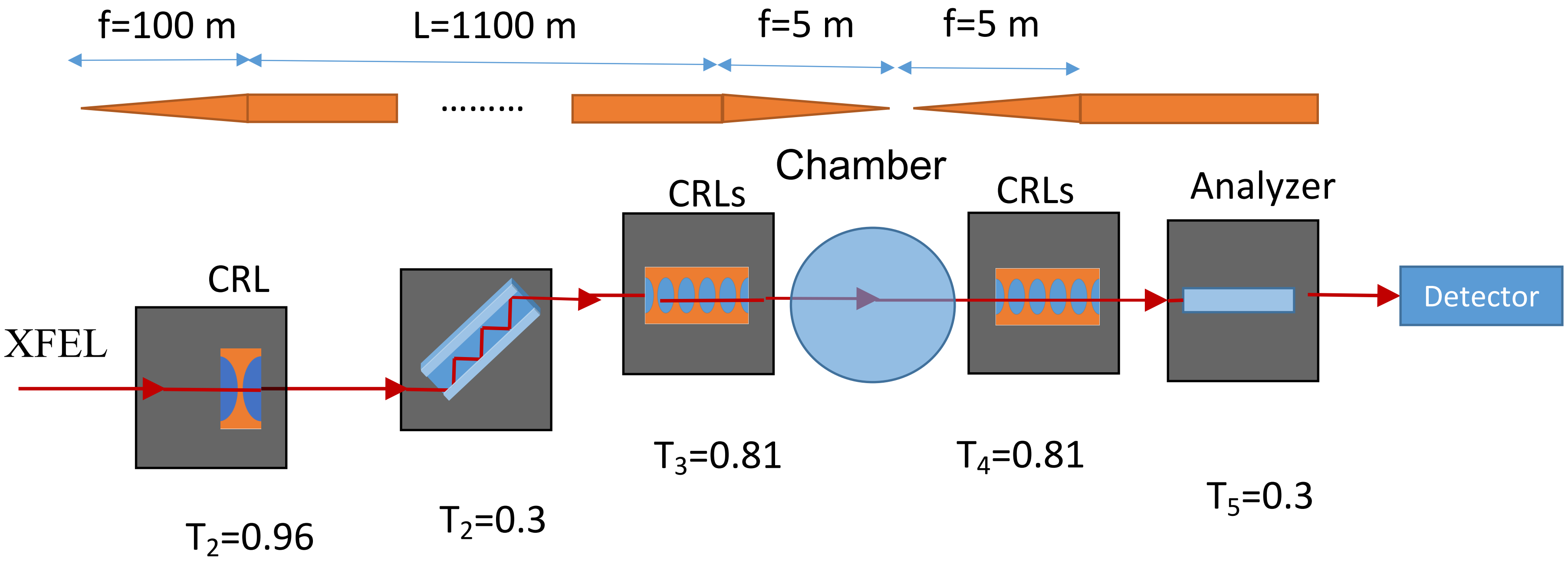
E-mail: bfshen@mail.shcnc.ac.cn

(2018)

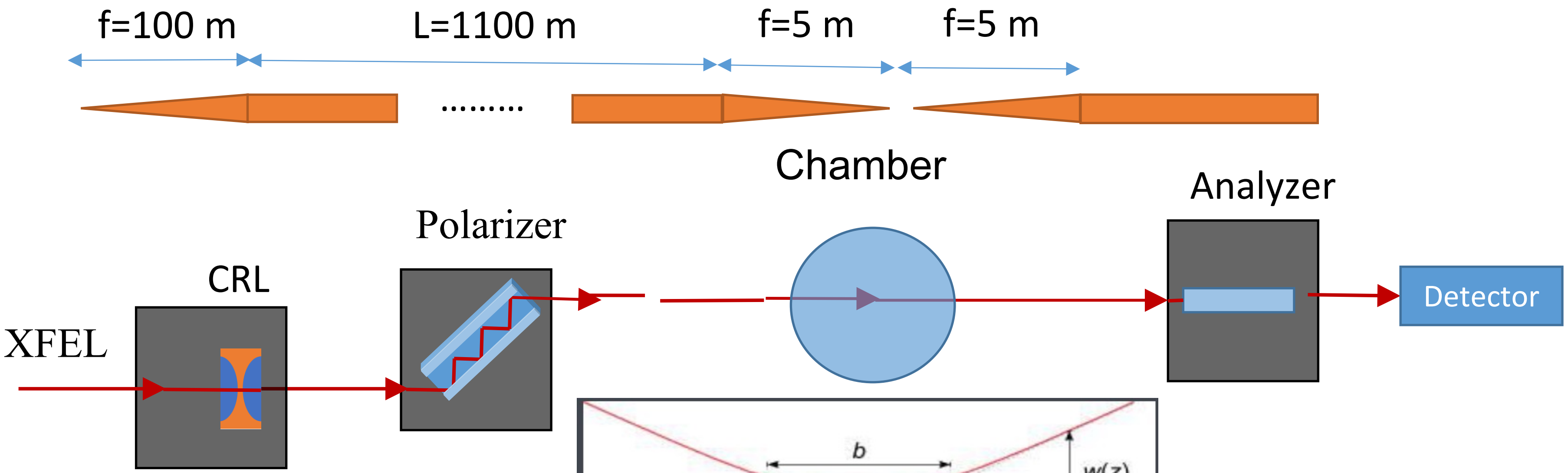
Detecting vacuum birefringence with XFEL + 100 PW laser

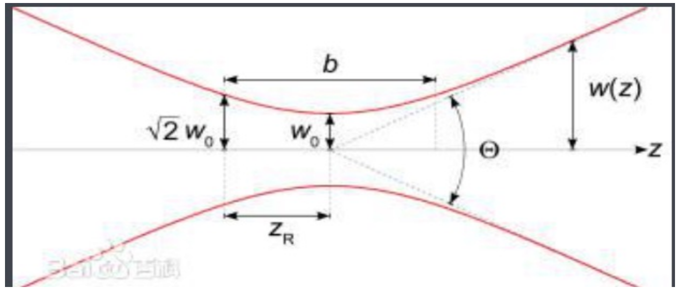


Propagation efficiency： $T=T_1*T_2*T_3*T_4*T_5=0.055$

XFEL Photon number for detection per shot is
10^{12} x 1.74×10^{-10} x 0.055 = 9.6

Detecting vacuum birefringence with XFEL + 100 PW laser





$$z_R = \frac{\pi w_0^2}{\lambda}$$

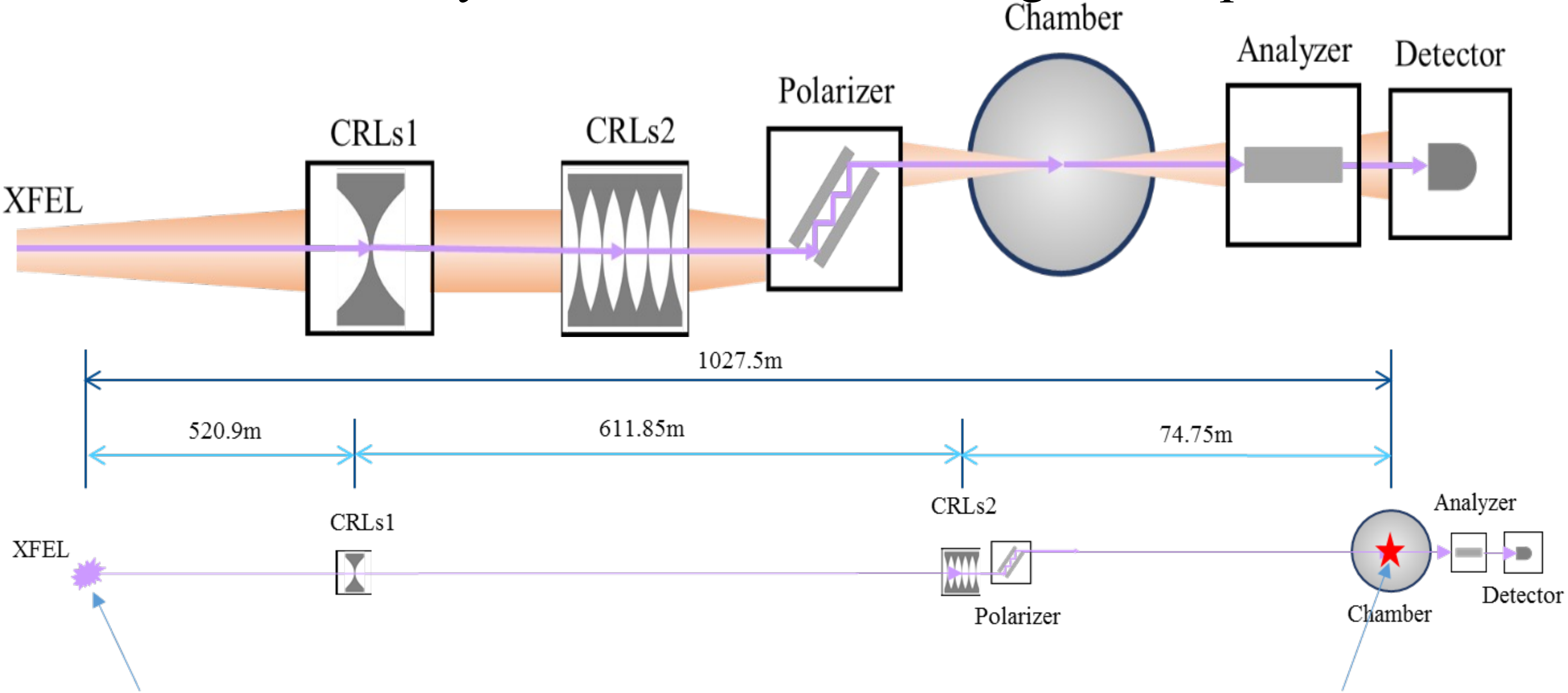
$$\omega(z) = \omega_0\sqrt{1+\left(\frac{z}{z_R}\right)^2} \approx \frac{\omega_0 z}{z_R} = \frac{\lambda}{\pi\omega_0} z = \frac{0.1\text{nm}}{3.14\times 2.5\mu\text{m}} 5\text{m} = 60\mu\text{m}$$

For focal size 5μm

Damage threshold ?

Nuclear Inst. and Methods in Physics Research, A 982 (2020) 164553

XFEL beamline layout for vacuum birefringence experiment



source size(FWHM)： 52μm

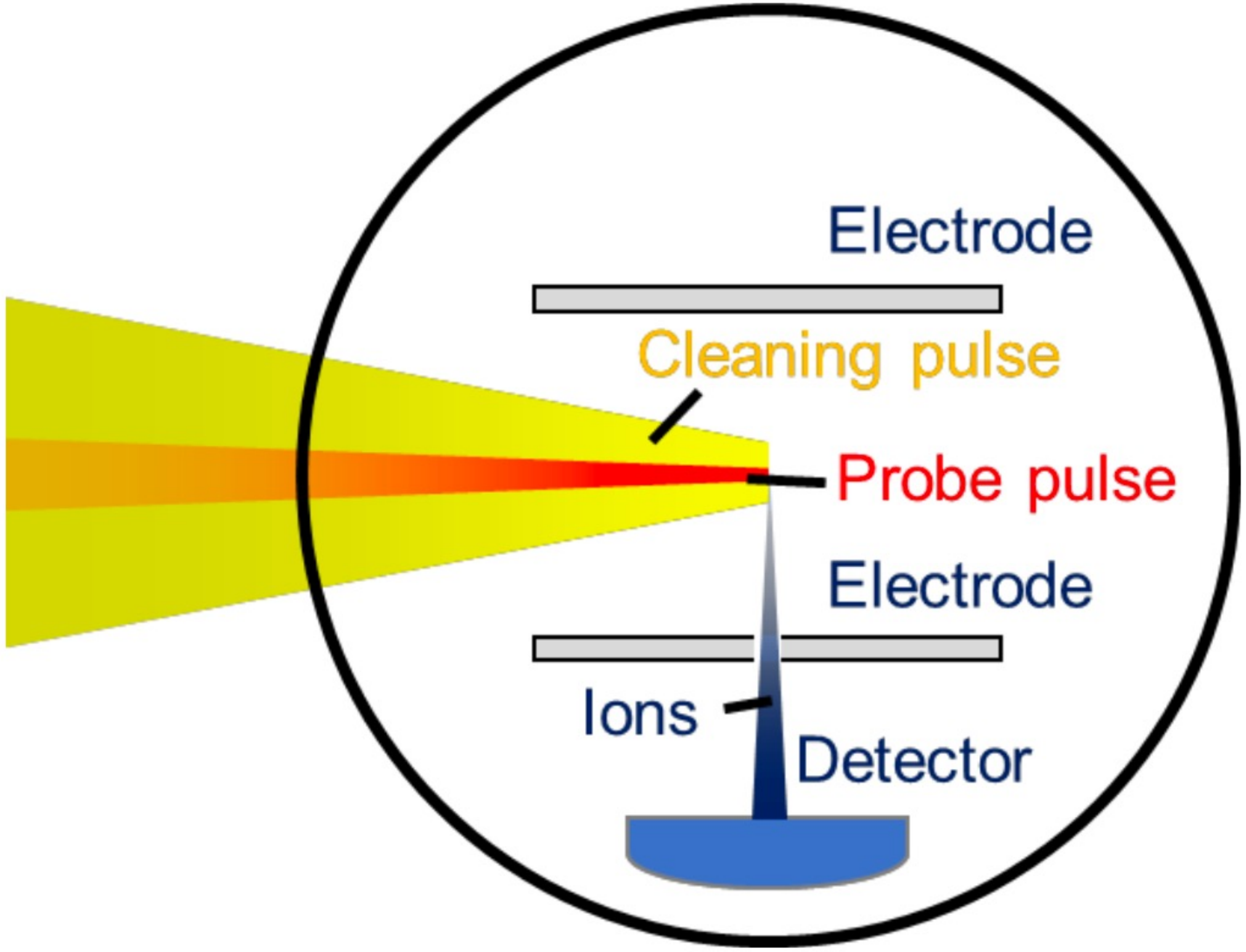
Divergence Angle(FWHM)： 1.2μrad

Focus size(FWHM)： 6.35μm

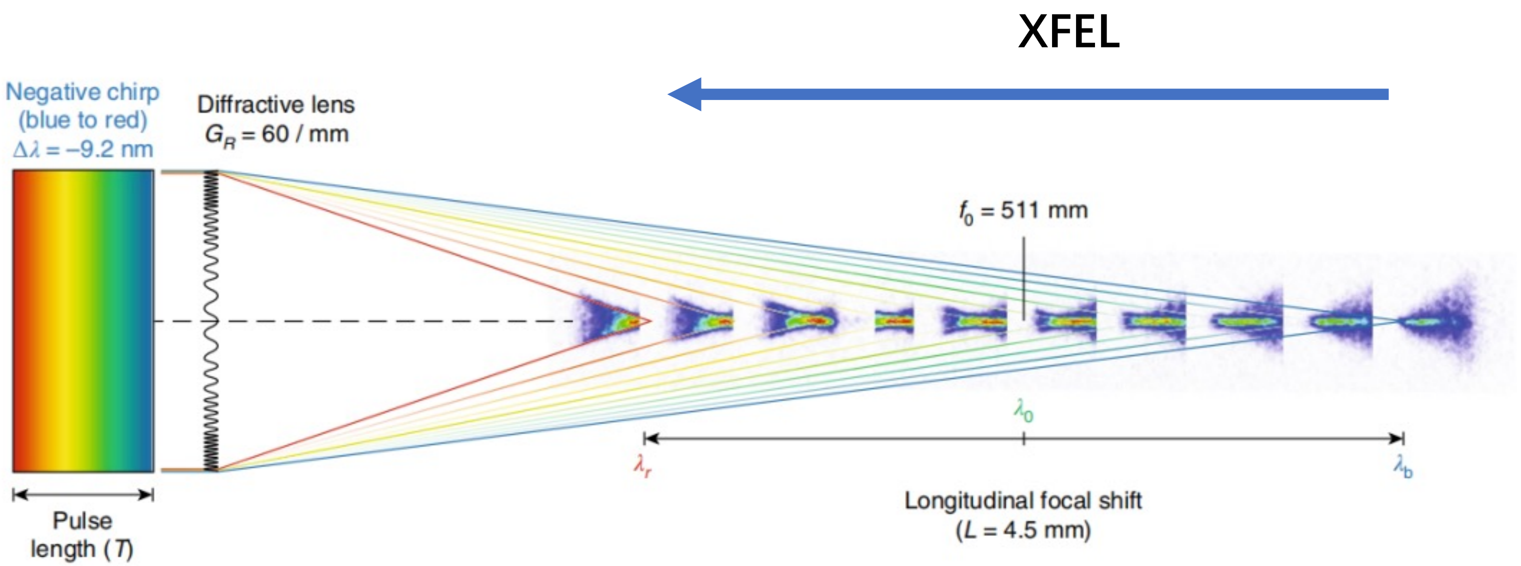
Divergence Angle(FWHM)： 9.82μrad

Nuclear Inst. and Methods in Physics Research, A 982 (2020) 164553

The cleaning method of vacuum is studied to improve the vacuum degree.



Enhancement of vacuum birefringence with pump laser of flying focus



The velocity of the focal spot

$$v = \left(1 + \frac{d\tau}{d\lambda}\frac{d\lambda}{dz}\right)^{-1}$$

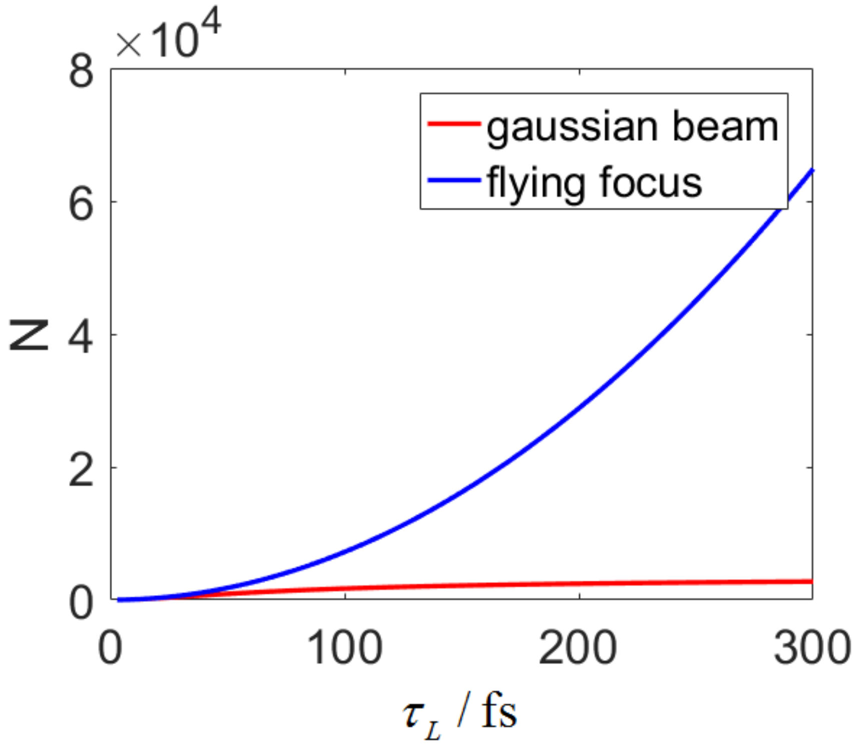
The lights of different frequencies are focused to the different positions.

Froula D H, Turnbull D, Davies A S, et al. Spatiotemporal control of laser intensity[J]. Nature photonics, 2018, 12(5): 262-265.

Enhancement of vacuum birefringence with pump laser of flying focus

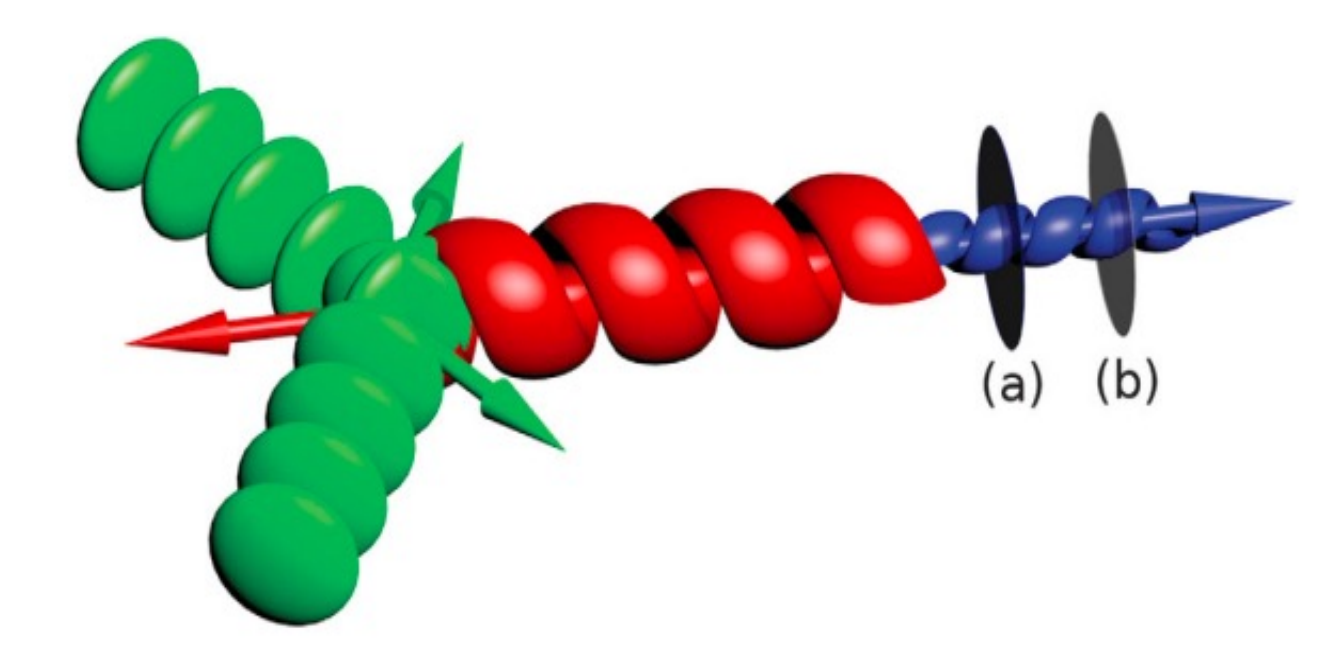
- The velocity of the focal spot is –c.

- The probe light move together with the focal spot, so the interaction area is increased.



B. Jin and Baifei Shen, Phys. Rev. A 107, 062213 – Published 27 June 2023

Angular momentum may be used to increase the signal to noise ratio



Input laser

$$\mathbf{k}_1 = k\mathbf{e}_z + \sqrt{3}k\mathbf{e}_x,$$
$$\mathbf{k}_2 = k\mathbf{e}_z - \sqrt{3}k\mathbf{e}_x,$$
$$\mathbf{k}_3 = -k\mathbf{e}_z,$$

$$l_3 = 1,$$

Scattering light

$$\mathbf{k}_4 = 3k\mathbf{e}_z,$$
$$l_4 = -1,$$

Aboushelbaya R, Glize K, Savin A F, et al. Orbital angular momentum coupling in elastic photon-photon scattering[J]. Physical Review Letters, 2019, 123(11): 113604.

Four wave mixing in vacuum

1. For the case of using XFEL and optical laser, one XFEL photon absorbs two optical photons, emitting a new signal photons.

$$L = \frac{1}{8\pi}(E^2 - B^2) + \frac{\xi}{8\pi}[(E^2 - B^2) + (\mathbf{E}\cdot\mathbf{B})]^2,$$

The photon energy is changed: one can measure the change of 1eV@10keV

2. For planar waves propagating in the same direction, the process of four wave mixing does not happen.

Wave mixing in plasma channel

PHYSICS OF PLASMAS VOLUME 10, NUMBER 11 NOVEMBER 2003

Photon–photon scattering in a plasma channel

Four wave mixing

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$$L=\frac{1}{8\pi}(E^2-B^2)+\frac{\xi}{8\pi}[(E^2-B^2)+(\mathbf{E}\cdot\mathbf{B})]^2,$$

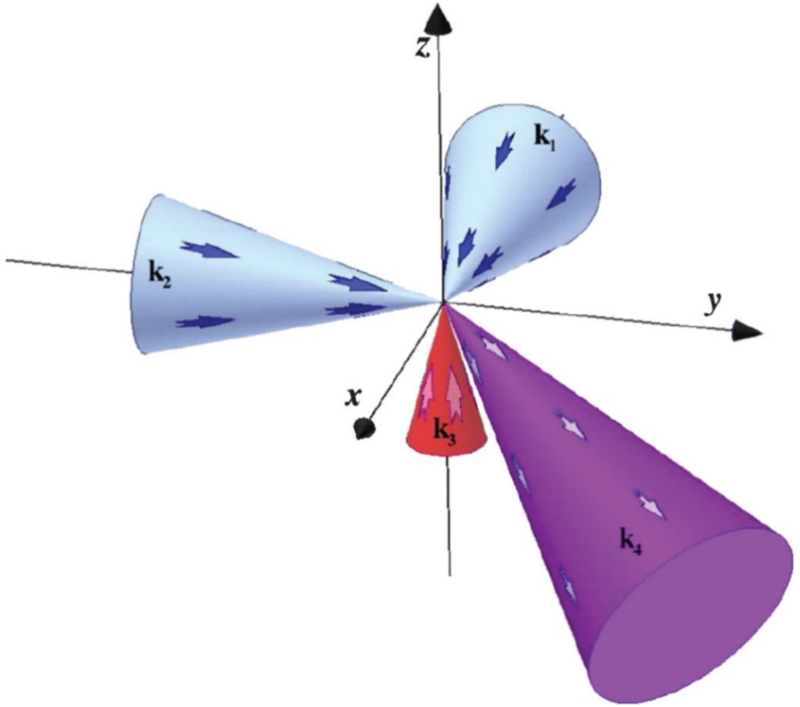
10^{22}W/cm^2 Optical laser
+10^{17}W/cm^2, 1 KeV XFEL

As an example, for $k_1=0$, $\hbar\omega_L=1$ eV, $\hbar\omega_2=1000$ eV, and $\alpha_0=100$ (corresponding to a laser intensity of 10^{22} W/cm^2), we obtain $E_{30}/E_{20}\sim 4\times 10^{-10}$. Thus, for a signal wave of intensity 10^{17} W/cm^2, the detected wave would have an intensity of 1.6×10^{-2} W/cm^2. Such an intensity, as well as the relevant characteristics such as the polarization and the spectra, should be easily detectable if the much stronger channel and signal fields (both are known) are filtered out. In order to avoid severe loss in the strength of the generated wave, the filtering should be sufficiently abrupt.

$$\frac{E_{30}}{E_{20}}=\alpha\frac{\hbar^2(\omega_L-k_1c)\omega_2}{240\pi m_e^2c^4}\alpha_0^2J_0^2, \qquad (14)$$

2003

Wave mixing with three pulses



k1, k2: colliding lasers

K3 probe x-ray

K4: signal

Laser powers

Signal photon

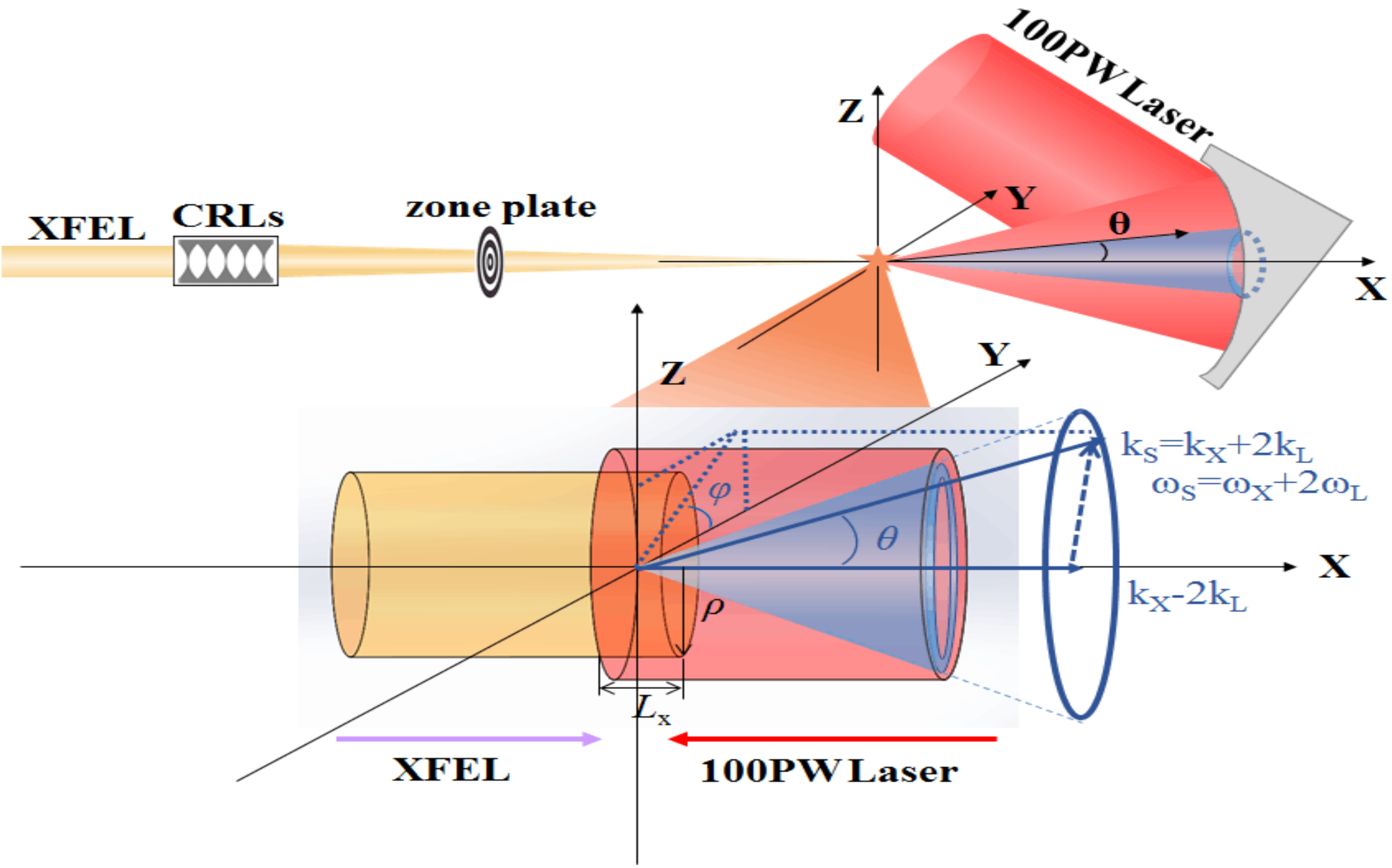
$$N_\gamma \approx 0.25 \frac{P_1[\mathrm{PW}]P_2[\mathrm{PW}]P_3[\mathrm{PW}]}{(\lambda_4[\mu\mathrm{m}])^3}.$$

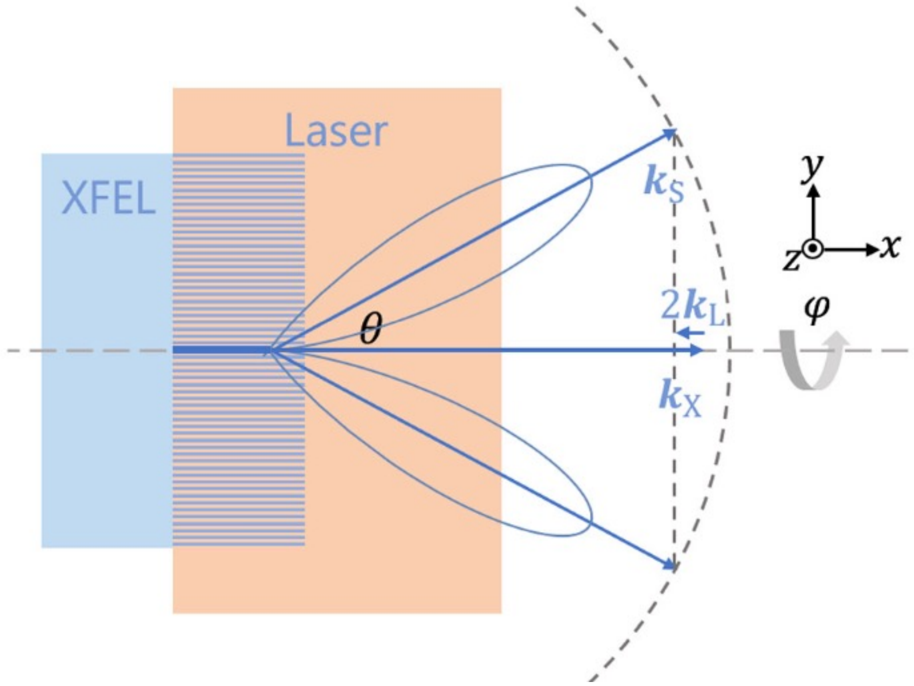
Wave length of X-ray

Phys. Rev. Lett. 96, 083602 (2006).

Phys. Plasmas14, 064503 (2007).

We propose to use colliding XFEL and optical laser to detect the four wave mixing signal

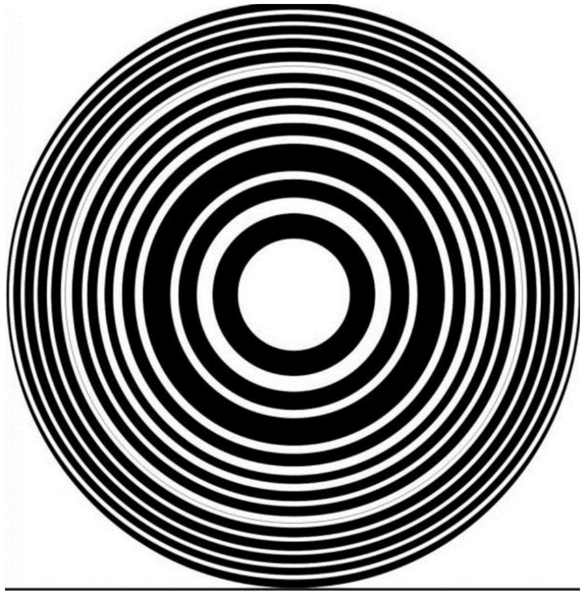




PHYSICAL REVIEW D 100, 013004 (2019)

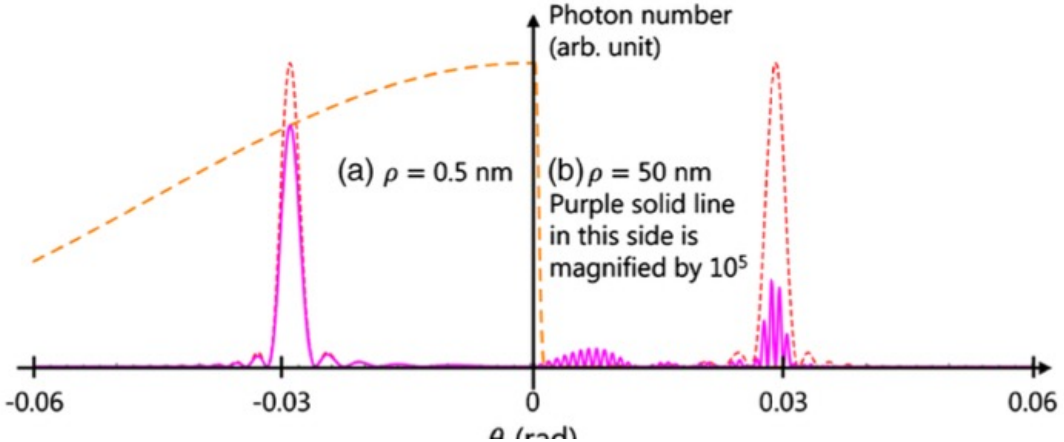
Energy and momentum conservation ？

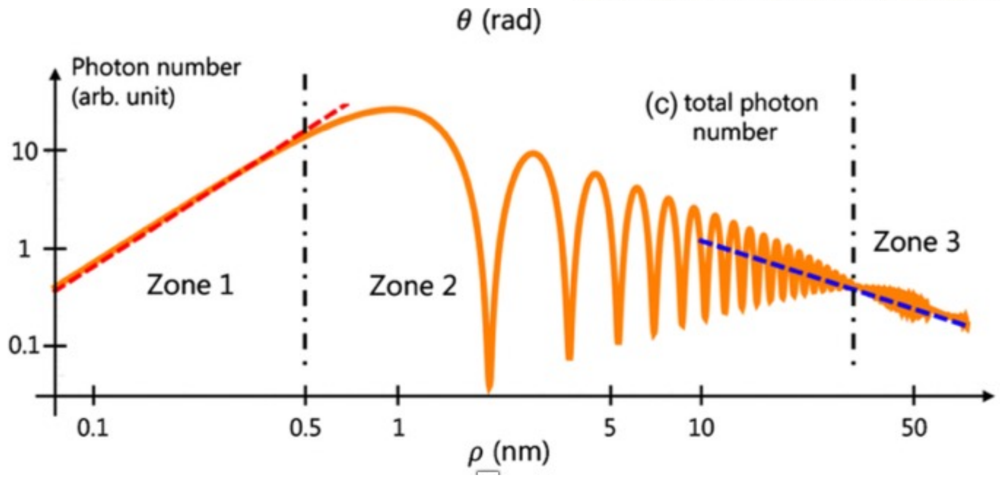
The signal depends on interaction length (Sinc function) and transverse size(Bessel function)



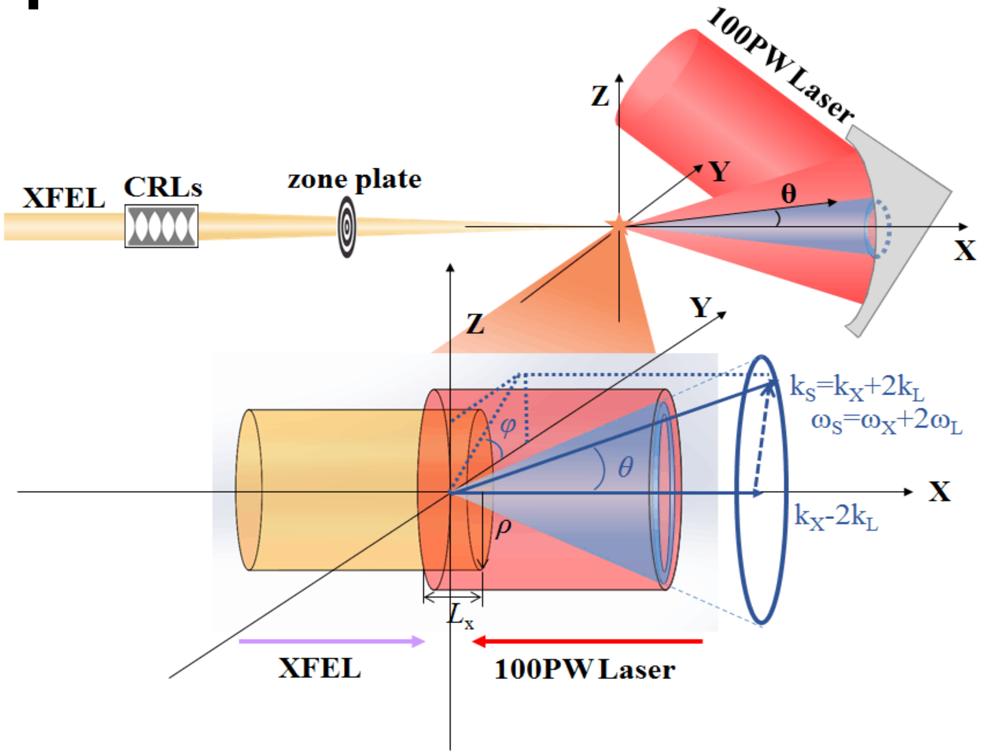
$$\boldsymbol{A}_{\mathrm{S}} = -\frac{1}{2\pi}\boldsymbol{e}_y \cdot \omega_{\mathrm{X}}^2 A_{\mathrm{S}0}\frac{\mathrm{e}^{\mathrm{i}(\omega_{\mathrm{S}} t - k_{\mathrm{S}}|\boldsymbol{x}| + \psi)}}{|\boldsymbol{x}|}\frac{V_{\mathrm{Scatter}}}{k_{\mathrm{S}}\rho\sin\theta}$$

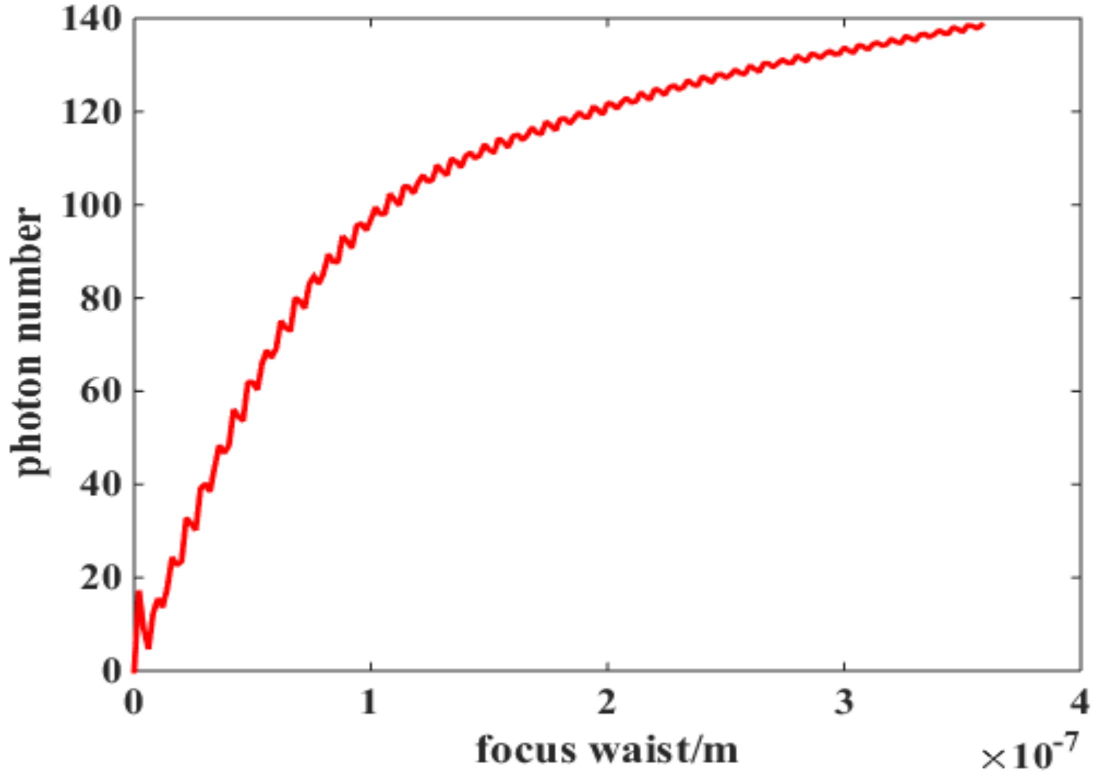
$$\cdot\, \mathrm{sinc}\left\{\frac{1}{2}(k_{\mathrm{S}}\cos\theta - k_{\mathrm{S}x})L_x\right\} \cdot \mathrm{J}_1(k_{\mathrm{S}}\rho\sin\theta).$$





We can use a zone plate to greatly increase the signal photon number.





Here we detect signal photon at different place with different photon energy. The high polarization purity is not required.

Enhancement of vacuum diffraction by interference of signals produced by a probe x-ray free-electron laser with multiple transverse modes

1. Here the focal size of XFEL is larger that the one of the optical laser. The XFEL is diffracted by the optical laser. The propagation direction or the transverse momentum is changed.

2. When multiple transverse modes are used, the diffraction could be enhanced in some angle.

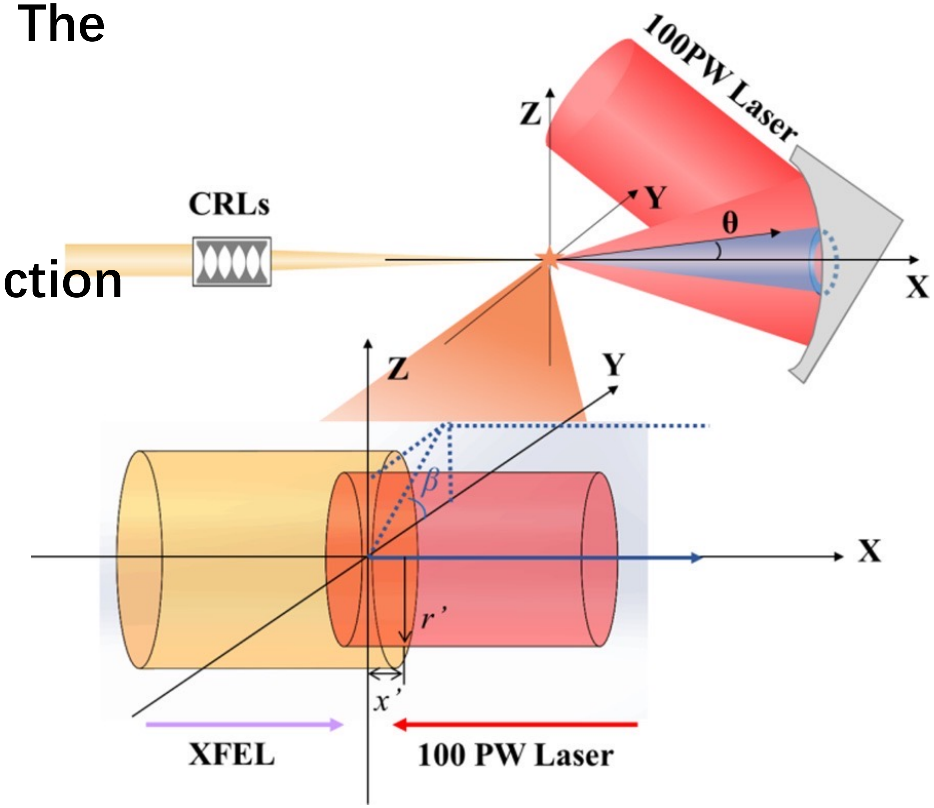


TABLE I. The parameters of the pump laser, XFEL, and scattering signal.

	Wavelength (nm)	Photon energy (eV)	Pulse duration (fs)	Focus size (μm)	Pulse energy (J)
Optical laser	910	1.36	15	5	1500
XFEL	0.096	12914	30		0.002
Signal	0.096	12914	30		

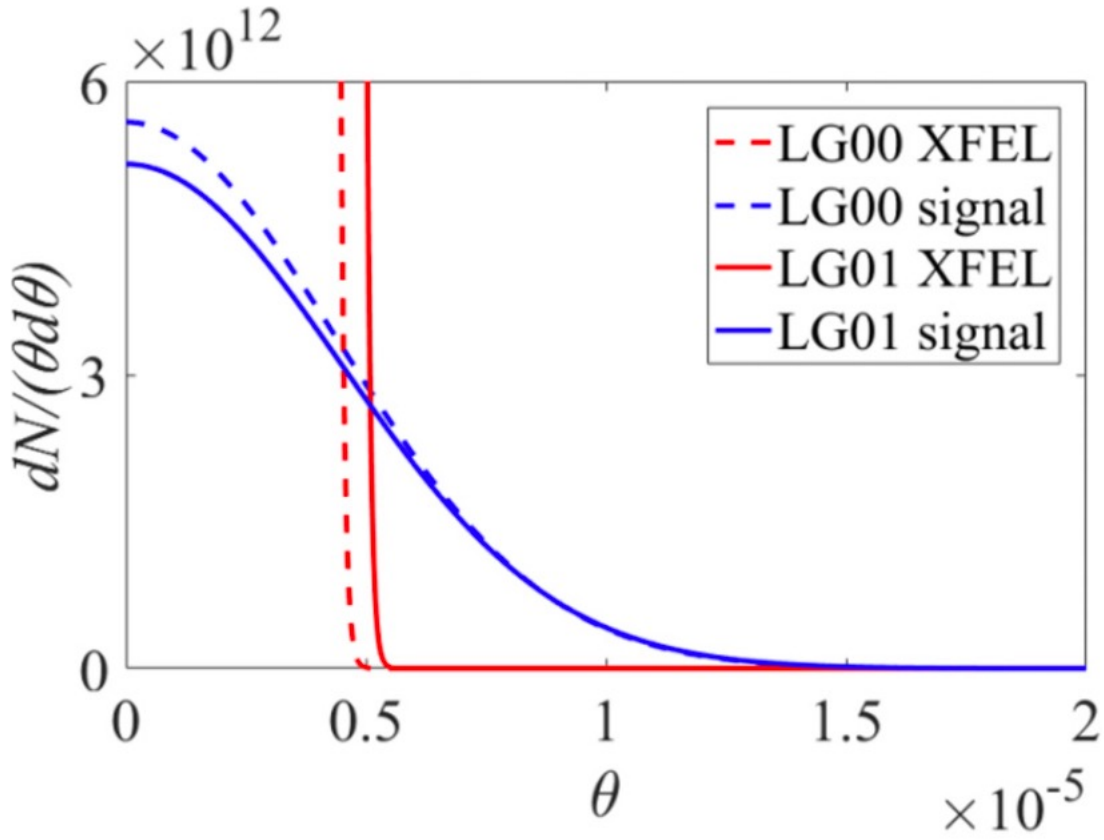
The transverse momentum is changed.

B. Jin and Baifei Shen, PHYSICAL REVIEW A **106**, 013502 (2022)

Enhancement of vacuum diffraction by interference of signals produced by a probe x-ray free-electron laser with multiple transverse modes

The angular distribution of scattering photon for LG (0,0) and LG (0,1) mode is different.

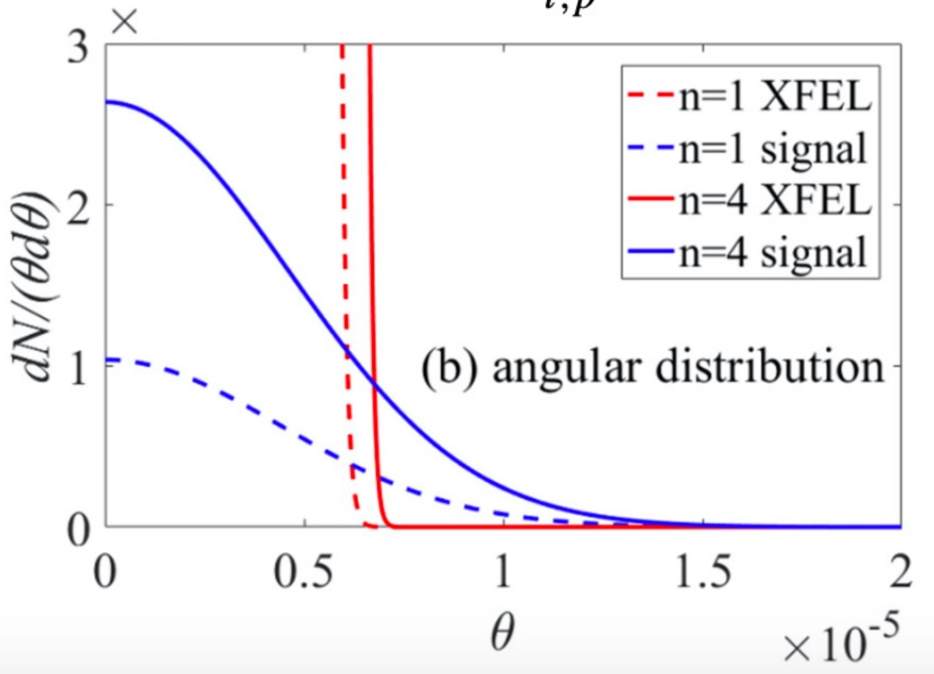
By measuring the angular distribution, we can know the photon-photon scattering.



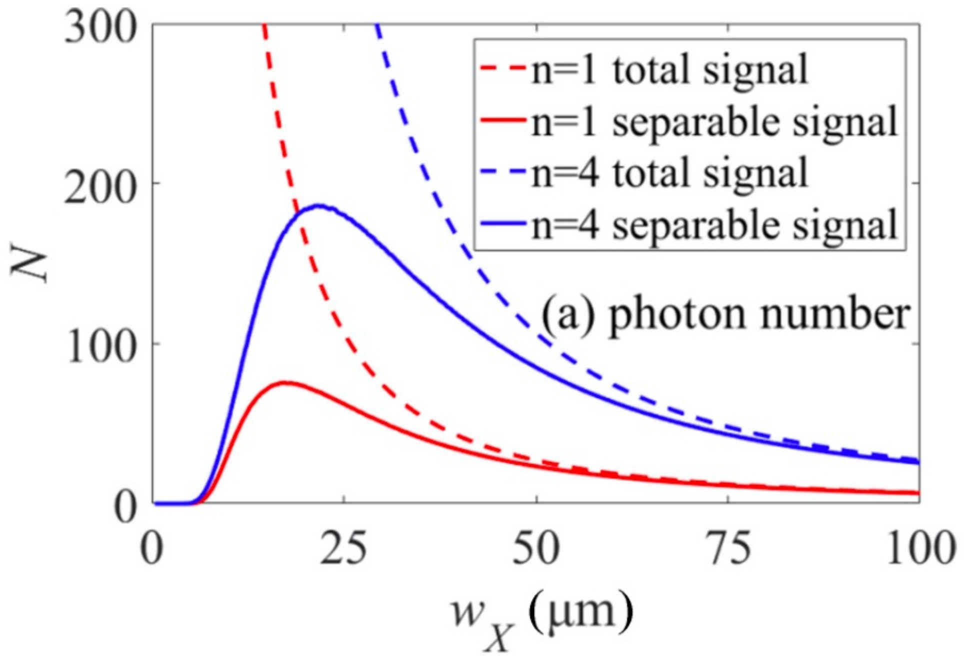
Angular distribution of scattering photon (blue line) and background XFEL (red line) with $w_X = 25$ µm and $w_L = 5$ µm for LG (0,0) mode (dotted line) and LG (0,1) mode (solid line).

Enhancement of vacuum diffraction by interference of signals produced by a probe x-ray free-electron laser with multiple transverse modes

$$A_X(r', x', \beta) = \sum_{l,p} \varepsilon_{l,p} \frac{1}{w_X} \left(\frac{\sqrt{2} r'}{w_X} \right)^{|l|} L_p^{|l|} \left(\frac{2 r'^2}{w_X^2} \right) \exp \left(- \frac{r'^2}{w_X^2} \right) \exp(i l \beta).$$



More X-ray photons are scattered to the larger angle due to the interference between the scattering light from different modes.



Solid lines：detectable photon numbers

Outline

1. Background

2. High field Photon-photon scattering

3. High field axion-like particle generation

Axion-like particle generation in laser-plasma interaction

- In the minimal axion models like the KSVZ model , one axion couples with two photons.

- Viewing from a macroscopic perspective, one can treat this axion-diphoton ('aγγ') process as a three-wave mixing.

- The Lagrangian is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g}{4}\mathcal{F}_{\mu\nu}F^{\mu\nu}\phi - \frac{1}{2}m_{\mathrm{a}}^2\phi^2 + \frac{1}{2}(\partial_\alpha\phi)(\partial^\alpha\phi)$$

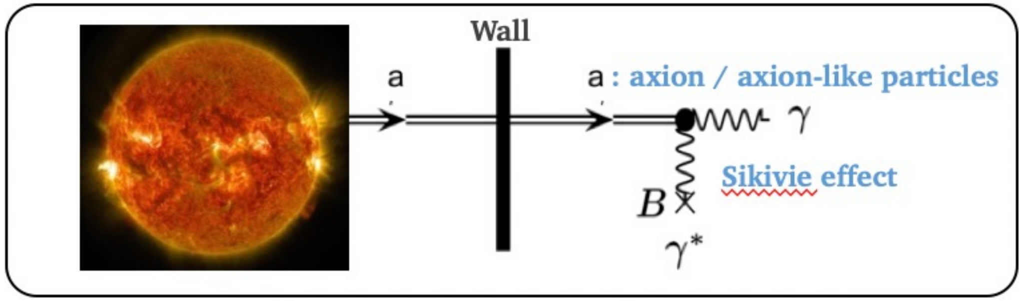
➢ $\boldsymbol{\phi}$ is the potential of the axion-like particle;

➢ g the very weak coupling factor， $\sim 1.320\times 10^{-13}\ \mathrm{GeV}^{-1}$

强场类轴子产生和探测

太阳轴子的探测：

轴子和强磁场相互作用产生光子进行测量



Helioscope, e.g. CAST, (Baby)IAXO

CAST 的目的是探测能量为14 keV 的太阳轴子流。若太阳轴子流存在，一个由长数十米的磁铁提供的强度为数十特斯拉的静磁场可以将一部分轴子转换为 X 射线光子，随后被望远镜尽头的 X 射线探测器发现 。

Summary

PPT由黄杉提供

- LUXE: A groundbreaking experiment for non-perturbative QED
- Data taking is set to start at 2026
- LUXE studies a collision between (in its electron-laser mode)

  16.5 GeV electron and a 40 or 350 TW laser beams

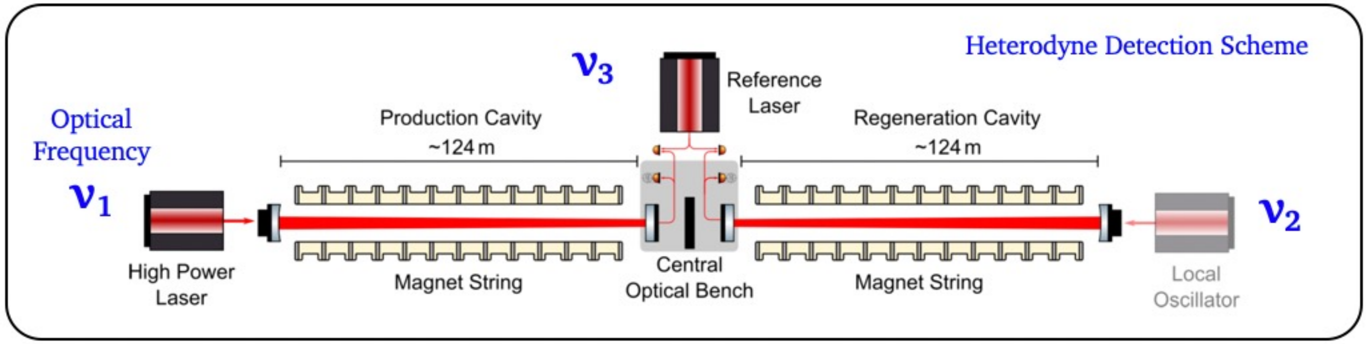
THANKS FOR YOUR ATTENTION!

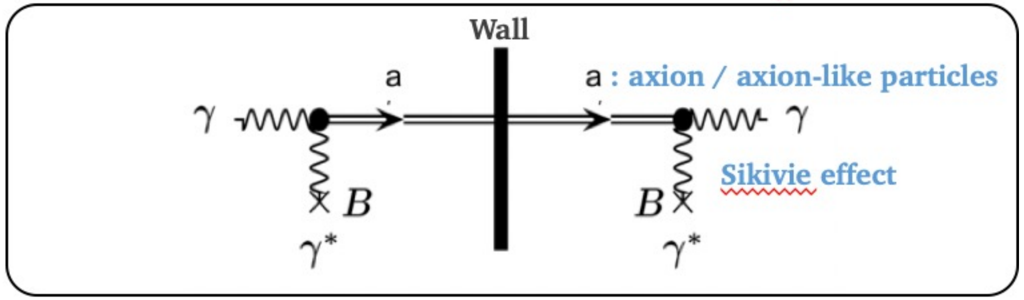
- High-intensity Compton scattering provides a GeV photon flux
  - for BSM physics
  - ... and maybe more
- LUXE-NPOD search can reach the uncharted ALP parameter space for ALP-photon interaction
- ALP/mCP-electron(-photon) studies at the IP

强场类轴子产生和探测

LSW方案 = Light Shining through a Wall

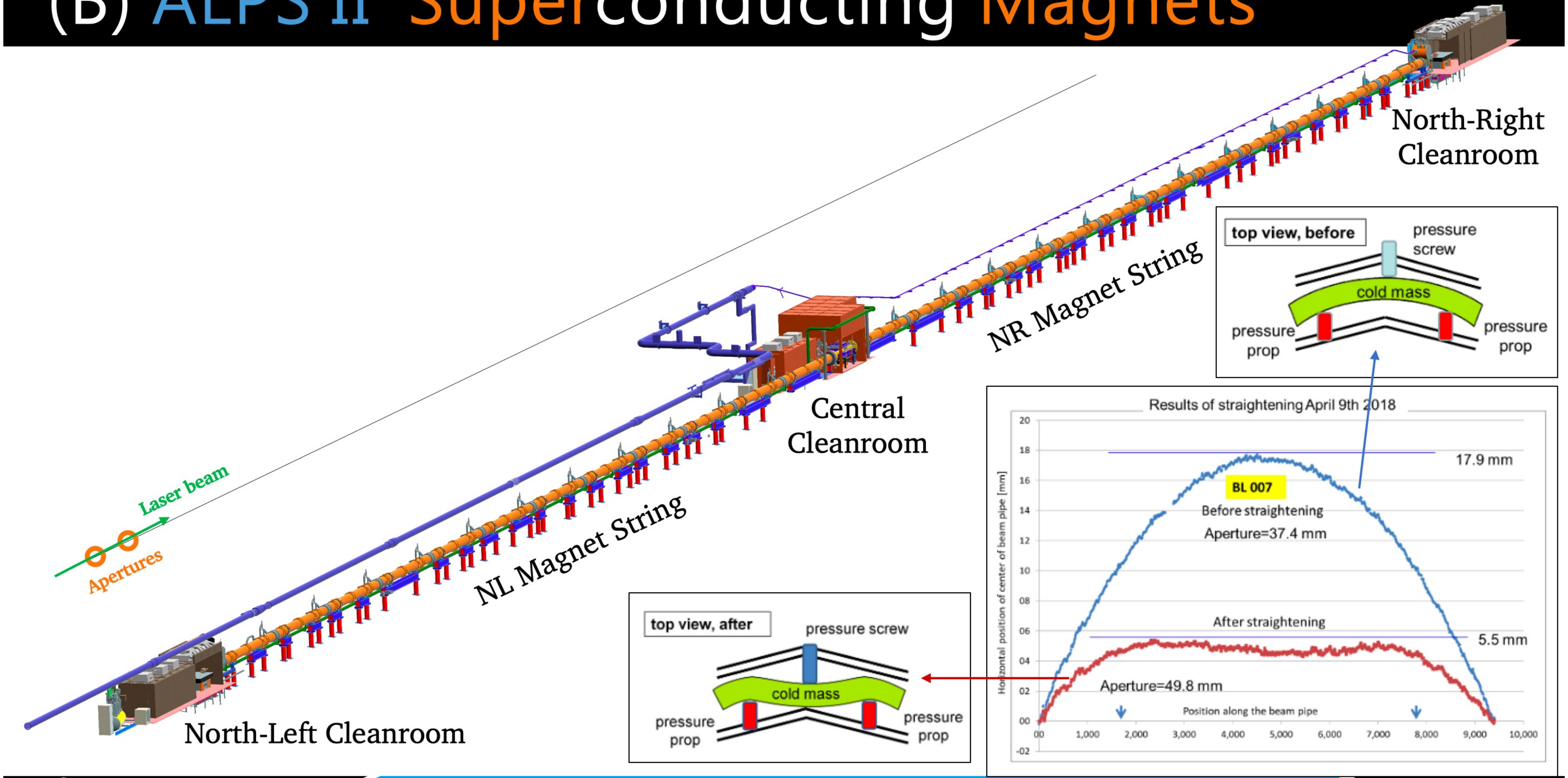
- ➢STEP 1: 光在强磁场下产生轴子流.
- ➢STEP 2: 光和轴子流一起运动；光被墙阻挡，而轴子穿墙而过.
- ➢STEP 3: 轴子在强磁场下被转化为光子.





两步过程的信号是二阶小量

(B) ALPS II Superconducting Magnets



Axion-like particle generation in laser-plasma interaction

- **Electromagnetic interaction may drive the generation of axion-like particle.**

$$(\partial_t^2 - \boldsymbol{\nabla}^2 + m^2)\phi = -g\boldsymbol{E}\cdot\boldsymbol{B}$$

- **At the same time, the production of axion-like particle changes the electromagnetic field.**

$$\boldsymbol{\nabla}\cdot\boldsymbol{E} = g\boldsymbol{B}\cdot\boldsymbol{\nabla}\phi$$

$$\boldsymbol{\nabla}\times\boldsymbol{B} - \partial_t\boldsymbol{E} = g(\boldsymbol{E}\times\boldsymbol{\nabla}\phi - \boldsymbol{B}\partial_t\phi)$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{B} = 0$$

$$\boldsymbol{\nabla}\times\boldsymbol{E} + \partial_t\boldsymbol{B} = 0$$

Axion-like particle generation in laser-plasma interaction

$$(\partial_t^2 - \boldsymbol{\nabla}^2 + m^2)\phi = -g\boldsymbol{E}\cdot\boldsymbol{B}$$

- The intense laser provides much stronger electromagnetic field but much smaller interaction area than static magnetic field.

- The laser field of a=100 is 4 orders larger than the static magnetic field of 100T. It means that the interaction length can reduced from 1km to 10 micrometer.

- One dimensional three wave mixing:

$$\Psi_1 = \psi_1 \exp\{-j(\omega_1 t - k_1 x)\}$$

$$\Psi_2 = \psi_2 \exp\{-j(\omega_2 t \mp k_2 x)\}$$

$$(\partial_{t2} - \nabla_2 + m_{23})\Psi_3 = g_{TWM}\Psi_1\Psi_2$$

$$\omega_{32} = k_{32} + m_{23},\ m_3 \geq 0.$$

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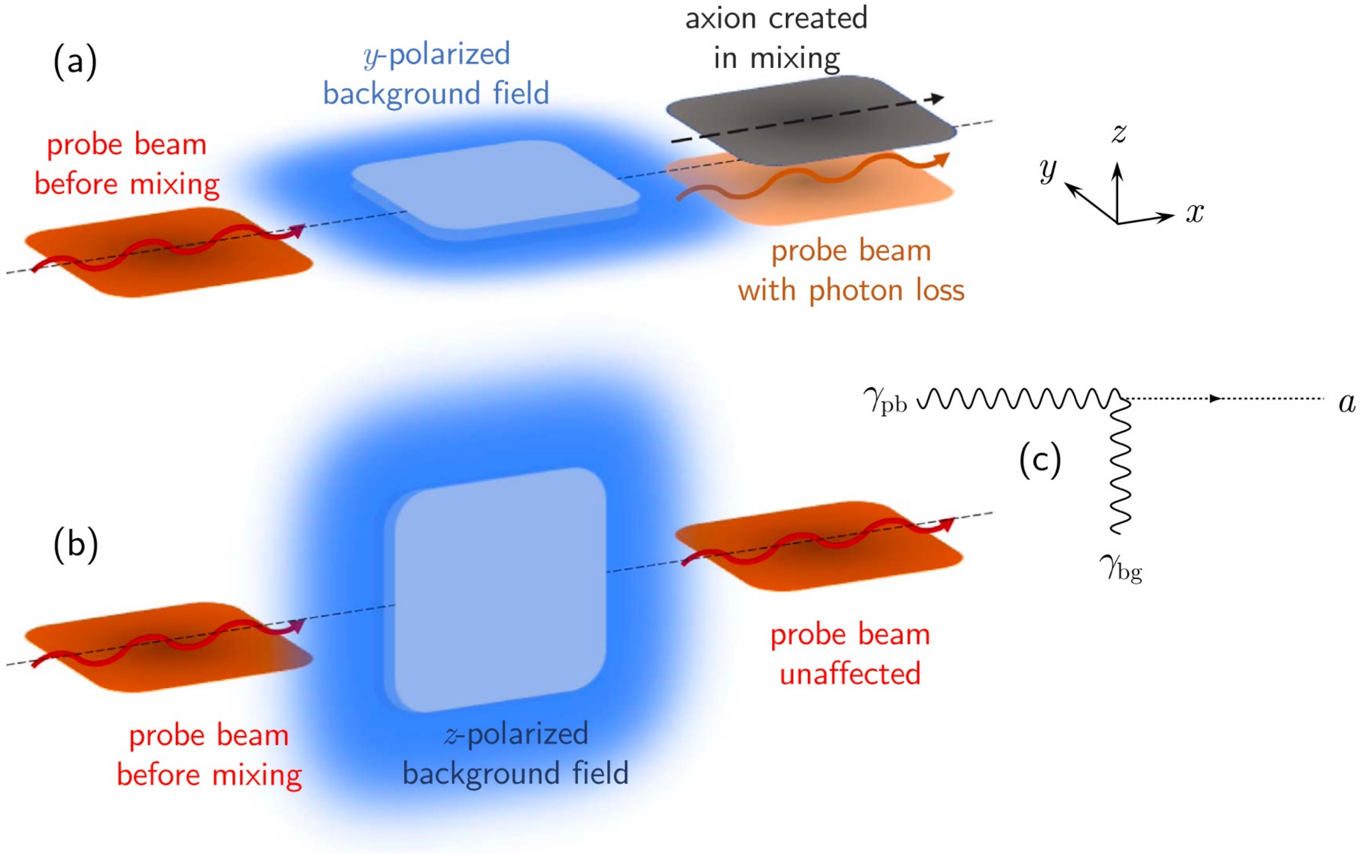
Axion-like particle generation in laser-plasma interaction

We use the B field the probe and the E field of the laser driven plasma to produce the axion-like particles.

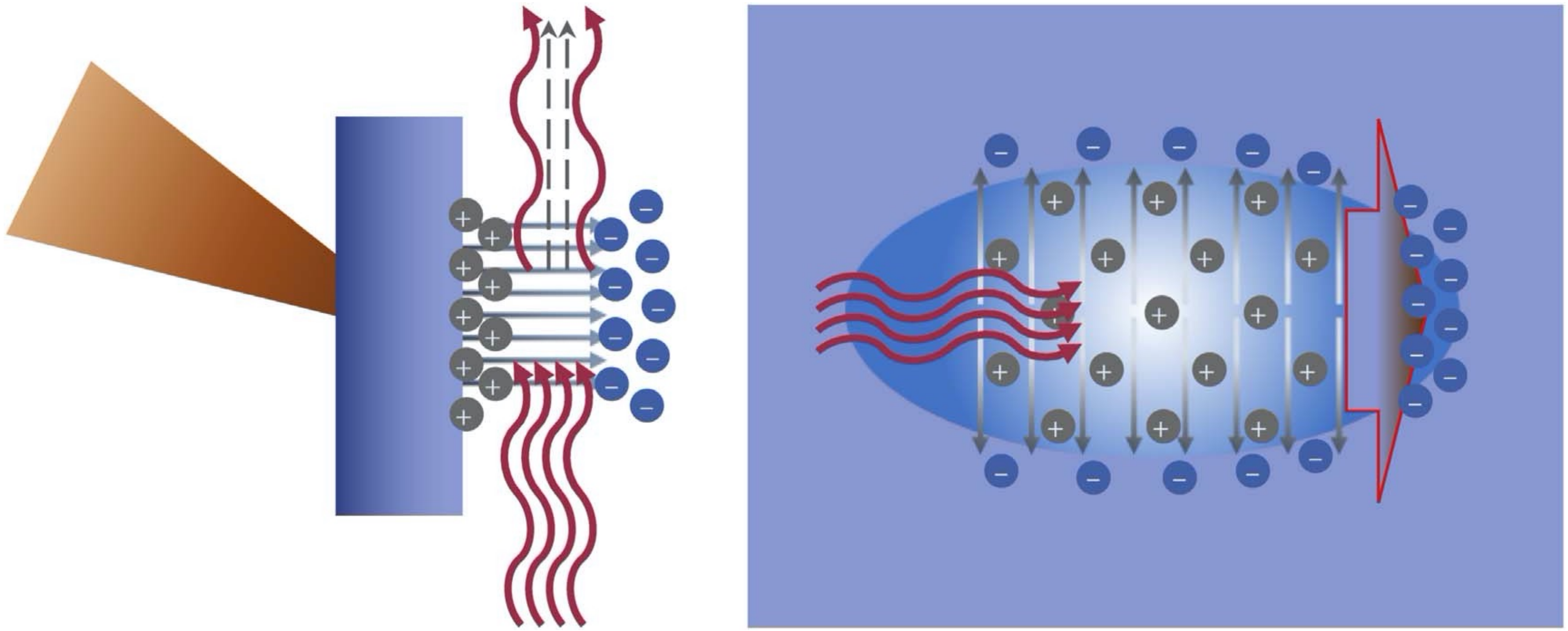
If the polarization direction of probe and the E field direction of the plasma has 45 degree. The polarization direction of the probe is changed when axion-like particles are produced.



The probe could be XFEL

Sketches of the interaction between a magnetically y-polarized probe and electrically (a) y-polarized or (b) z-polarized background field..

Axion-like particle generation in laser-plasma interaction



Two cases are discussed.

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Thank you for your attention

XFEL driven wakefield acceleration

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 101004 (2016)

Particle-in-cell simulation of x-ray wakefield acceleration and betatron radiation in nanotubes

Xiaomei Zhang,[1,2] Toshiki Tajima,[2] Deano Farinella,[2] Youngmin Shin,[3] Gerard Mourou,[4] Jonathan Wheeler,[4] Peter Taborek,[2] Pisin Chen,[5] Franklin Dollar,[2] and Baifei Shen[1]

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T, École Polytech ... u Cedex, France
[5]*Depar ... Leung Center for ... le Astrophysics, N*
University,
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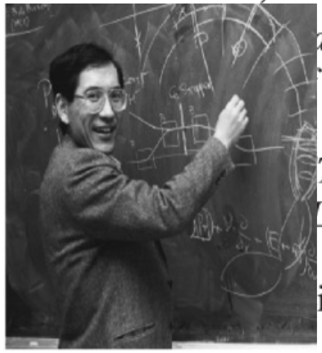
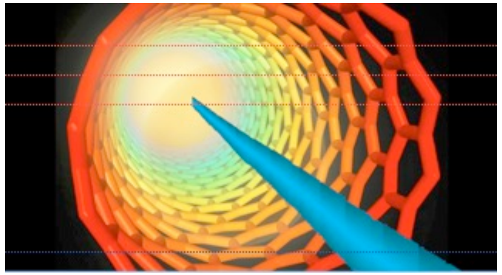




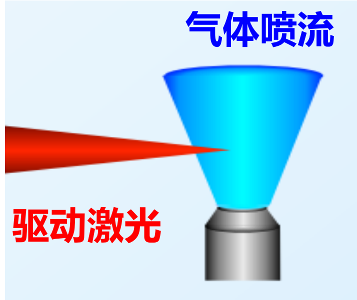
Acceleration gradient can be increased greatly by using crystal or nano tube.

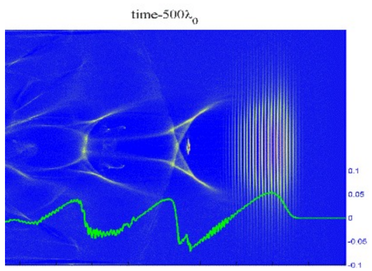
Plasma could provide high acceleration gradient

Conventional accelerator
(gradient= $10^{7\text{-}8}$V/m)

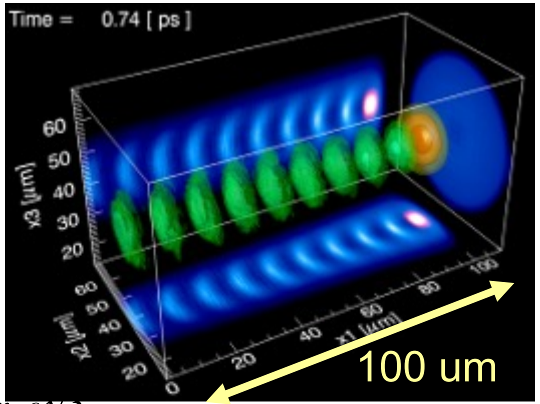
Radiofrequency cavity (1 m-long)

Laser accelerator
(gradient = $10^{11\text{-}12}$V/m)





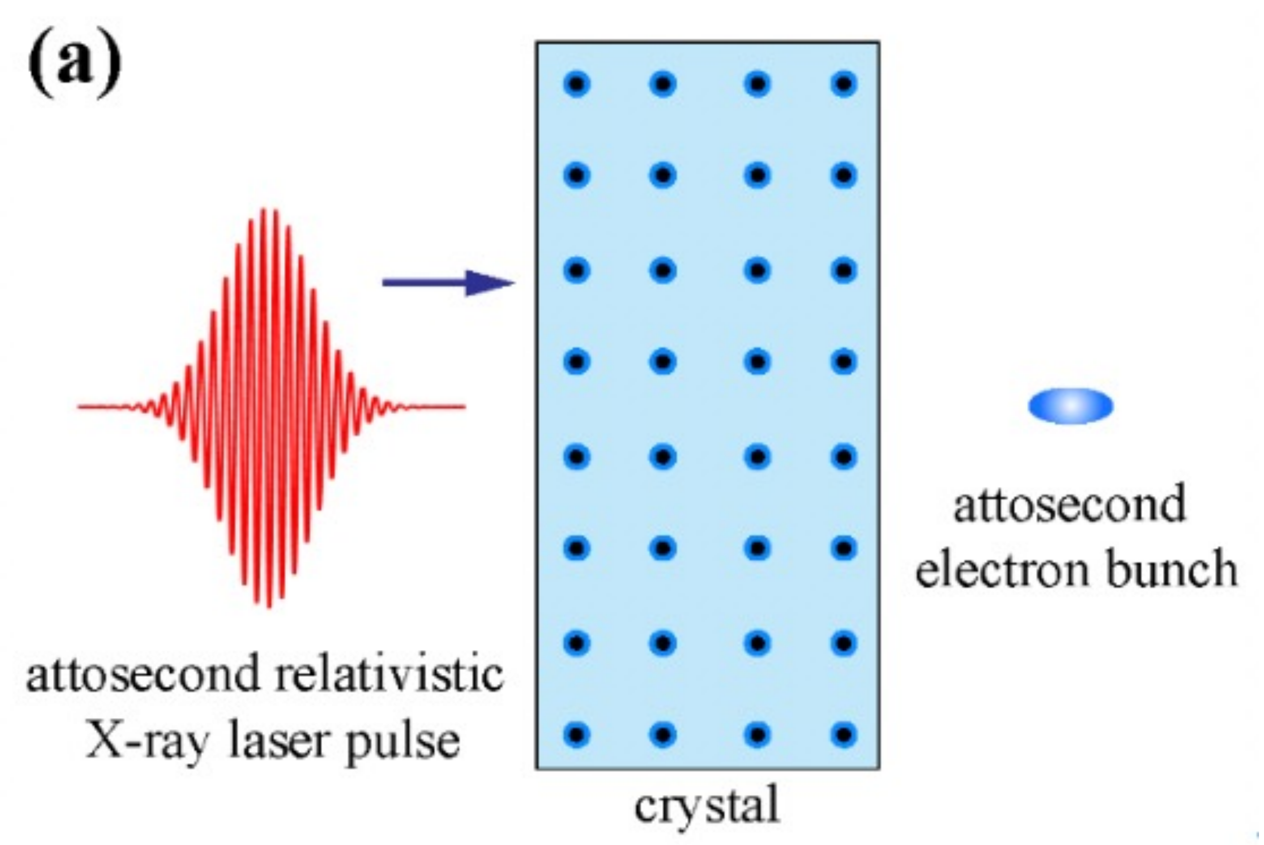
Courtesy of W. Mori & L.O. Silva



$$E_z = \frac{m_e c\,\omega_p}{e} \approx 300\,GV/m$$ (for $n_e=10^{19}$ cm^{-3})

3D PIC simulation of a plasma wave (UCLA)

High–repetition few–attosecond high–quality electron beams generated from crystal driven by intense X–ray laser



The sharp boundary provides good injection control for electron acceleration.