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MAX-PLANCK-GESELLSCHAFT

High-brilliance ultra-narrow-band x-rays via electron radiation in colliding laser pulses

Q. Z. Lv

Max-Planck-Institut für Kernphysik

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Outline

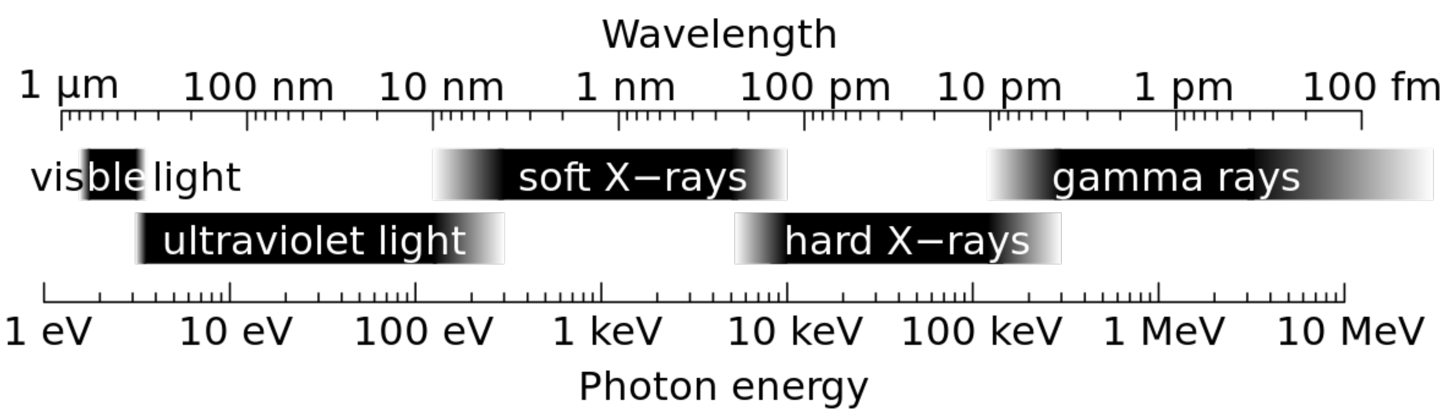
- Motivation
- Colliding laser pulses scenario
- New x-ray source properties
- Summary and Outlook

Motivation: x-ray discovery

- In 1895, Röntgen wrote the first paper about the new x-ray radiation ---- On a new kind of ray: A preliminary communication.

Source: wikipedia

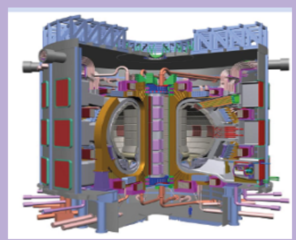
- X-rays: wavelength from 10 picometers to 10 nanometers
  energy about from 100 eV to 100 keV.



Motivation: Applications

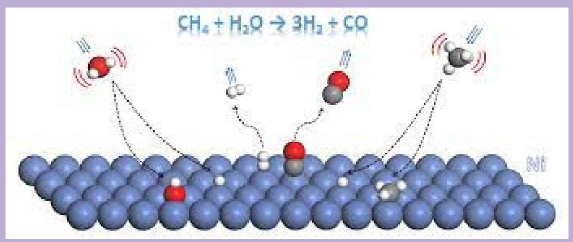
- X-rays have introduced powerful techniques for determining the structure of matter at the atomic length scale:

Physics



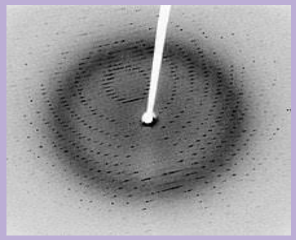
- Atomic/molecular structure
- Plasma diagnostics
- Strong field QED

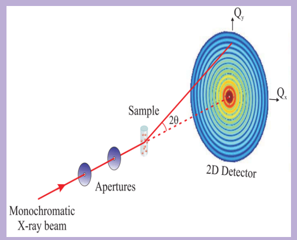
Chemistry



- Real time chemical reaction

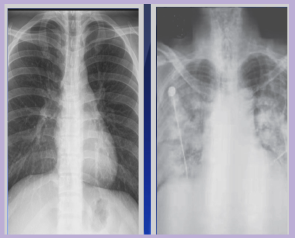
Material Science

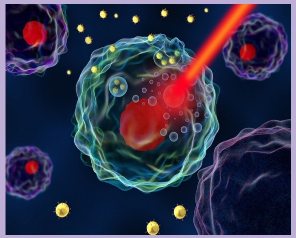




- x-ray crystallography
- x-ray diffraction
- x-ray scattering

Biology and Medicine

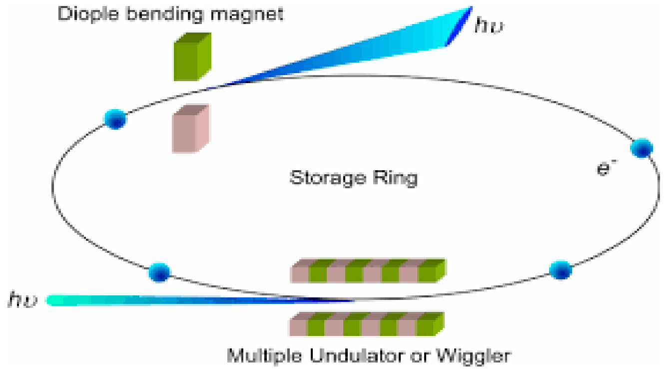


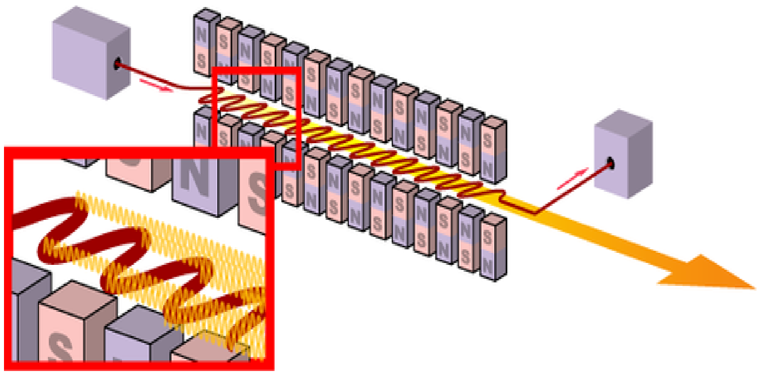


- x-ray therapy
- x-ray diagnosis

Motivation: new generation of x-ray laser

- Synchrotron light source and x-ray free electron laser



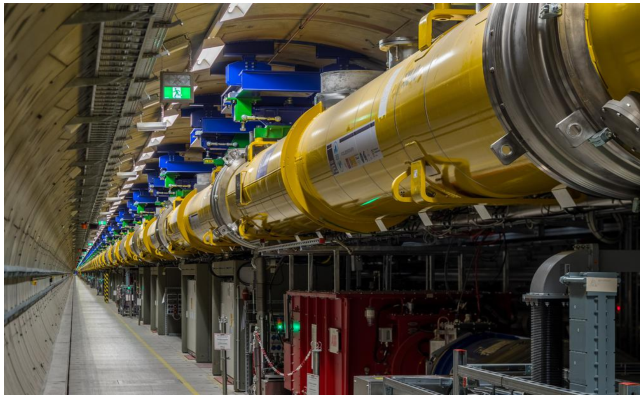


  - a storage ring
  - specialized particle accelerators
  - electrons passes through a magnetic structure
  - the radiation re-interacts with the electrons

- The large size and cost of Synchrotron and XFEL facilities, limit their accessibility to a wide community.

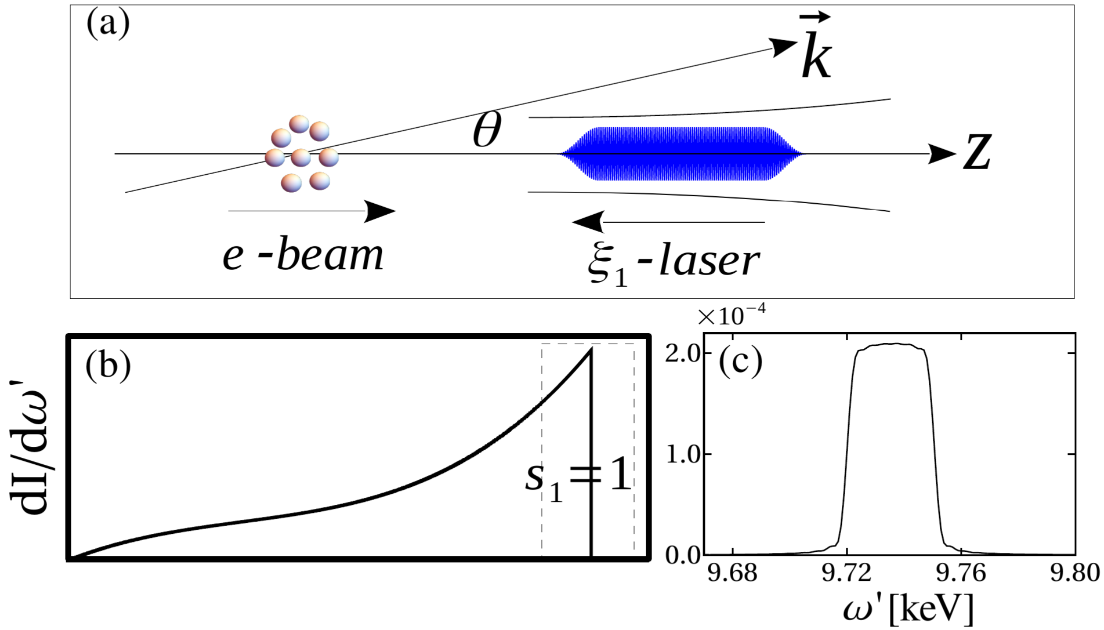
Shanghai SRF: **432 metres**

European XFEL: **3.4 kilometre**



Motivation: Compton scattering source

- Compton scattering (CS) source: relativistic electrons interacting with a single laser pulse.



- the normalized field strength $\xi_1 \sim 1 \longrightarrow s_1 = 1$
- energy is around $\omega' \approx 4\gamma^2\omega_0$
- $\theta \sim \xi_1/\gamma$ with 0.1mrad interval
- the width $\delta\omega'_{CS} \propto \omega_0\gamma^2/\xi_1^2$

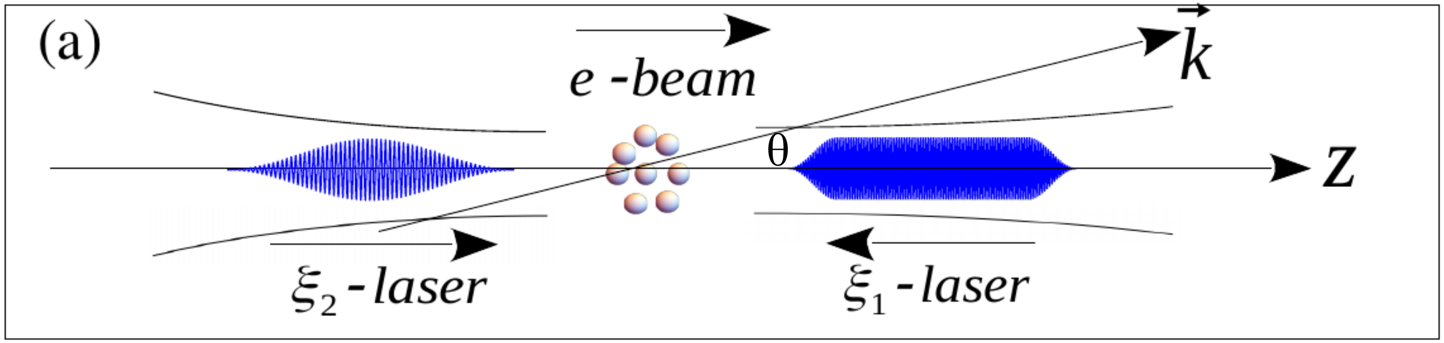
  - Advantage: photon energy in a broad range, compact, affordable ---- experiments[a]
  - Disadvantage: small brilliance, wide bandwidth (BW);

- Different schemes for narrowing the x-ray BW have been proposed [b]:
  - temporal laser pulse chirping and temporally varying laser polarization
  - using a traveling-wave setup

a). G. Sarri et al, Phys. Rev. Lett. 113, 224801 (2014); S. Chen et al, Phys. Rev. Lett. 110, 155003 (2013).
b). D. Seipt et al, Phys. Rev. Lett. 122, 204802 (2019); M. Valialshchikov et al, Phys. Rev. Lett. 126, 194801 (2021); A. Jochmann et al, Phys. Rev. Lett. 111,114803 (2013);

Colliding laser pulses scenario: dynamics

- An new approach: an second laser pulse co-propagating with the electrons is introduced.



➔ ξ_1 , ξ_2 are two counter-propagating waves (CPW) with circular polarization and ω_0

- The classical equation of motion can be solved approximately:

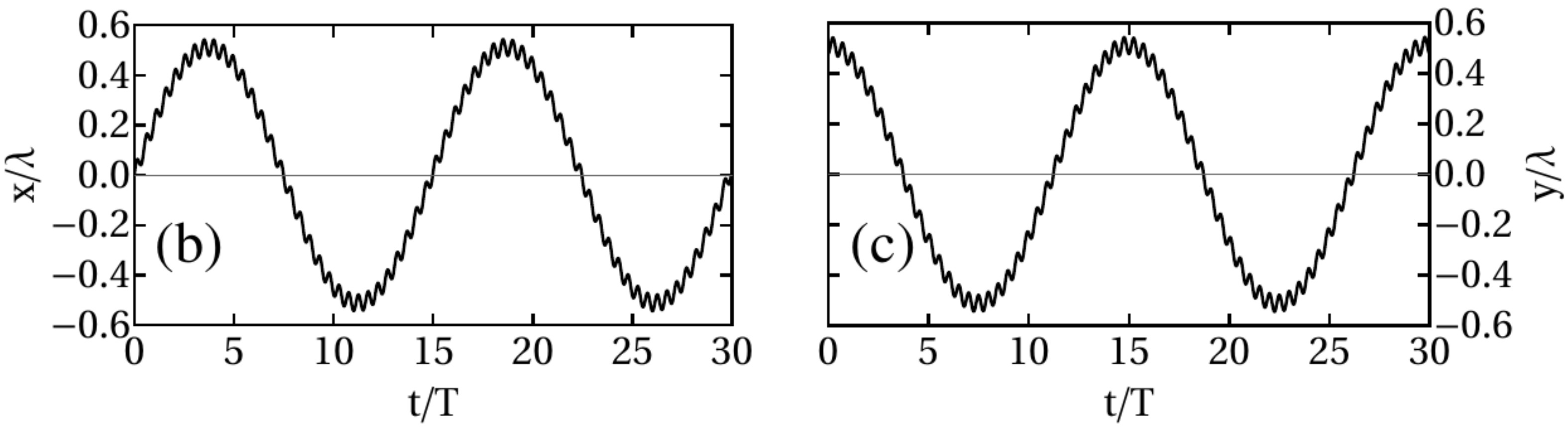
$$P_\mu(\tau) = \bar{P}_\mu - e\left[A_1^\mu(\phi_1) + A_2^\mu(\phi_2)\right] + k_1^\mu\left[\frac{ep\cdot A_1(\phi_1)}{k_1\cdot\bar{P}} - \frac{A_1(\phi_2)\cdot A_2(\phi_2)}{(k_1-k_2)\cdot\bar{P}}\right]$$
$$+ k_2^\mu\left[\frac{ep\cdot A_2(\phi_2)}{k_2\cdot\bar{P}} + \frac{A_1(\phi_2)\cdot A_2(\phi_2)}{(k_1-k_2)\cdot\bar{P}}\right]$$

See the details in the talk by Dr. E. Raicher.

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, Phys. Rev. Research 3, 013214 (2021).
Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, New J. Phys. 23, 065005 (2021).

Colliding laser pulses scenario: dynamics

- The electron motion features two typical frequencies:



  - Because of the Doppler effect:

$$\omega_1 \gg \omega_2 \text{ with } \omega_1 = (1+\bar{v}_z)\omega_0 \,, \omega_2 = (1-\bar{v}_z)\omega_0$$

- The electron can absorb photons in both frequencies for emission.

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, Phys. Rev. Research 3, 013214 (2021).
Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, New J. Phys. 23, 065005 (2021).

Colliding laser pulses scenario: spectra

- The emitted spectrum can be calculated employing the semiclassical operators method:

$$dI = \frac{\alpha}{(2\pi)^2\tau}\left[-\frac{\varepsilon'^2+\varepsilon^2}{2\varepsilon'^2}|\mathcal{T}_\mu|^2 + \frac{m^2\omega^2}{2\varepsilon'^2\varepsilon^2}|\mathcal{I}|^2\right] d^3\mathbf{k}'$$

where $\mathcal{T}_\mu \equiv \int_{-\infty}^{\infty} v_\mu(t)\, e^{i\psi}\, \mathrm{d}t$ and $\mathcal{I} \equiv \int_{-\infty}^{\infty} e^{i\psi}\, \mathrm{d}t$ with $\psi \equiv \frac{\varepsilon}{\varepsilon'} k' \cdot x(t)$, the electron trajectory $x_\mu(t)$ and velocity $v_\mu(t)$.

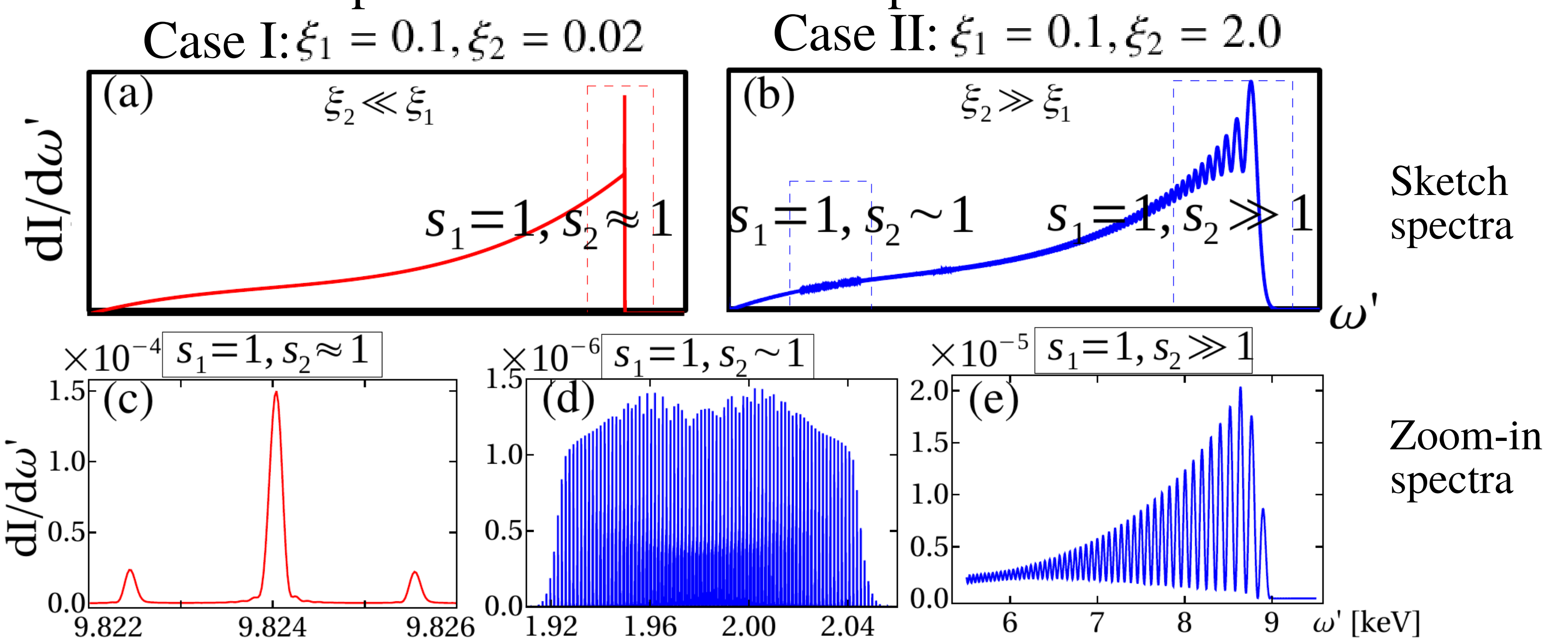
- The time integration can be calculated either analytically or numerically.

- Employing the approximated trajectory, the radiation spectrum can be expressed in the combination of Bessel functions.

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, Phys. Rev. Research 3, 013214 (2021).
Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, New J. Phys. 23, 065005 (2021).

Colliding laser pulses scenario: spectra

- The emission spectrum in the CPW setup:



- $\xi_1 \longrightarrow \chi \longrightarrow$ the general shape; $\xi_2 \longrightarrow$ the zoom-in features.
- Either a single peak or a comb-like x-ray source around keV energy can be realized.
- Peak brilliance in panel (c): $\mathcal{B} \sim 10^{23}$ ph/(s·mrad^2· mm^2· 0.1%BW), 3 orders larger
  in panel (d): $\mathcal{B} \sim 10^{21}$ ph/(s·mrad^2· mm^2· 0.1%BW), 1 order larger

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

Colliding laser pulses scenario: spectra

- The above spectra raise several questions:
  - What determines the peak locations and the spacing between peaks?
  - What determines the width of a single peak?
  - What is the role played by the angle window?
  - How to control the number of harmonics contained in the spectrum?

- To address these questions, let us first look at the phase ψ of the emission, which determines the property of the harmonics:

$$\psi = \psi_{np} t - z_2 \sin(\omega_2 t) - z_1 \sin(\omega_1 t) - z_{12} \sin(\Delta\omega_{12} t)$$

where $\Delta\omega_{12} = \omega_2 - \omega_1$ and $u = \omega'/(\varepsilon - \omega')$ with introducing

$$\psi_{np} = \varepsilon u(1 - \bar{v}_z \cos\theta)\,, z_1 = (mu\xi_1/\omega_1)\sin\theta\,,$$

$$z_2 = (m\xi_2 u/\omega_2)\sin\theta,\ z_3 = 2\omega_0 m^2 \xi_1 \xi_2 u/(\varepsilon\Delta\omega_{12}^2)$$

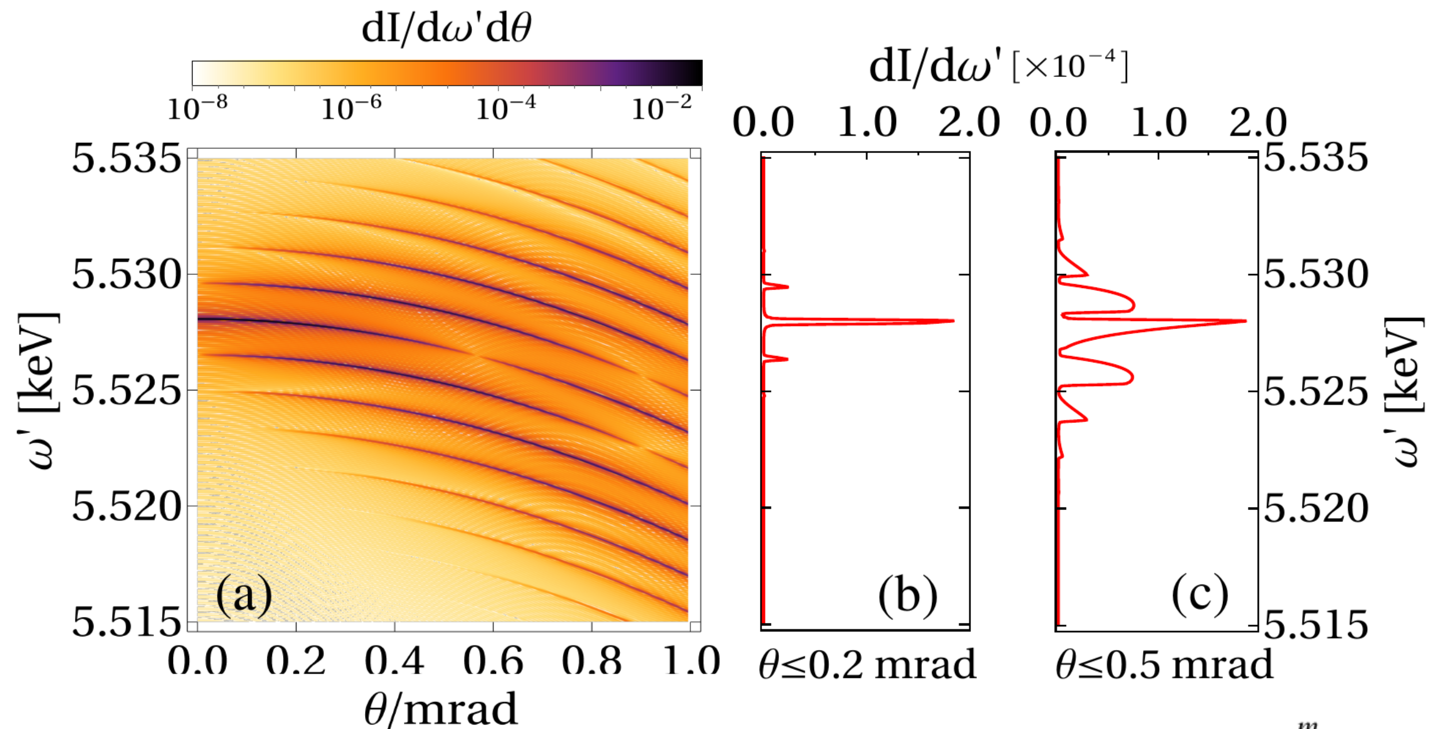
- The time integration gives us the energy-momentum conservation:

$$\cos\theta = \frac{1}{\bar{v}_z}\left[1 - \frac{1}{\varepsilon u}(s_1\omega_1 + s_2\omega_2)\right]$$

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, Phys. Rev. Research 3, 013214 (2021).
Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, New J. Phys. 23, 065005 (2021).

New x-ray source: angular spectra

- Single peak x-ray source: $\xi_1 \gg \xi_2$ (Case I: $\xi_1 = 0.1, \xi_2 = 0.02$)



- The emitted photon energy: $\omega' = \dfrac{\varepsilon(s_1\omega_1 + s_2\omega_2)}{\varepsilon(1 - v_z \cos\theta) + (s_1\omega_1 + s_2\omega_2)} \approx \dfrac{\omega^m_{s_1,s_2}}{1 + 2\gamma_*^2 (1 - \cos\theta)}$,

  the general location: $\omega' \approx 4\gamma_*^2\omega_0$; each line: harmonics with respect to ω_2;

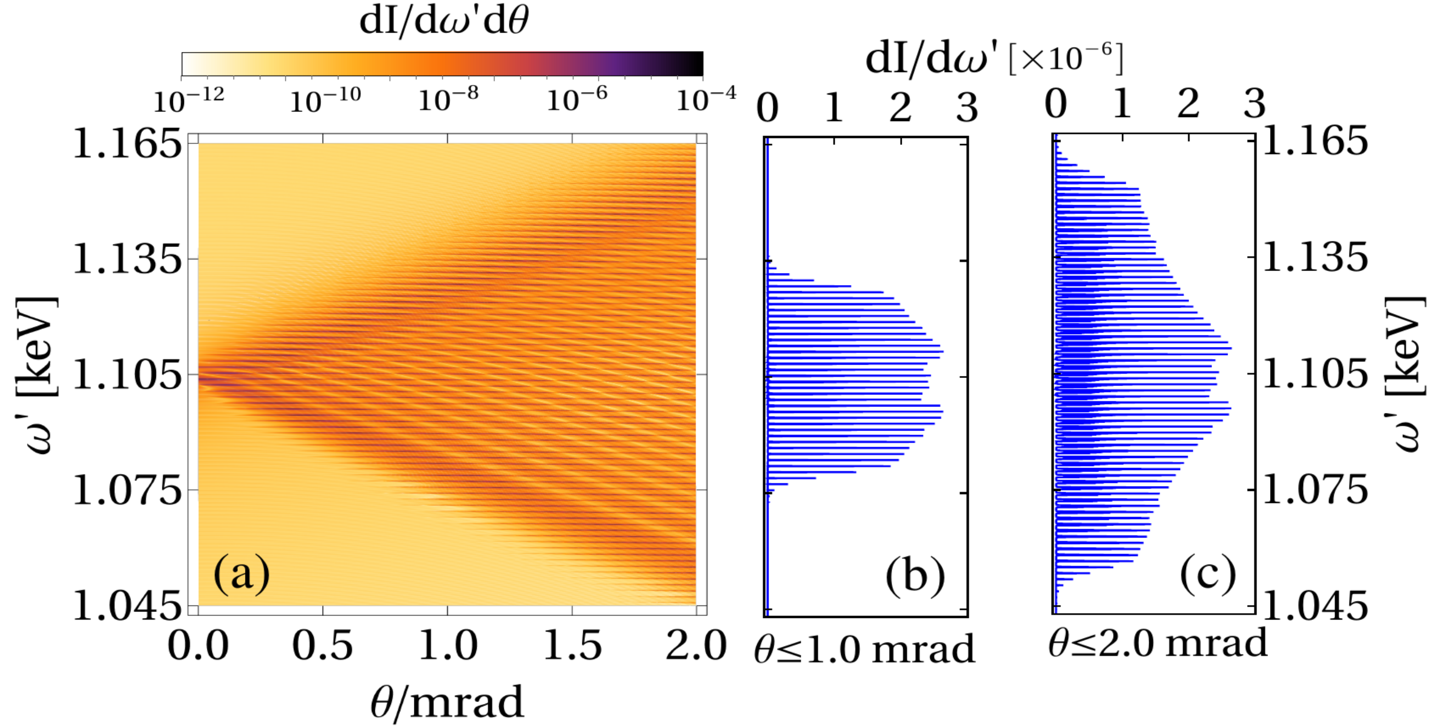
- The space between two peaks: $\Delta\omega' = 2\gamma_*^2\omega_2 \approx \omega_0$, in contrast with the CS, $\sim \gamma^2\omega_1$.

- The width of the spectrum due to the finite angle (θ_w) window: $\delta\omega'_w = \omega^m_{s_1,s_2} (\gamma_*\theta_w)^2$;

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

New x-ray source: angular spectra

- X-ray comb source: $\xi_1 \ll \xi_2$ (Case II: $\xi_1 = 0.1, \xi_2 = 2.0$)



- The central location is also $\omega' \approx 4\gamma_*^2\omega_0$, far away from the main peak $4\gamma^2\omega_0$.
- The number of harmonics is: $\Delta s_2 = \dfrac{2\xi_2\varepsilon\omega_1\theta_w}{\delta\omega_2 m_*^2 + 2\xi_2\varepsilon\omega_2\theta_w} \approx \dfrac{1}{\delta}\left(\dfrac{\theta_w}{\theta_c}\right), \theta_c = \dfrac{m_*}{8m\xi_2}\dfrac{1}{\gamma_*^3}$
- The larger the angle range θ_w, the more harmonics are included.
- Balance between the width of a single harmonic and the range of the total comb.

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

New x-ray source: harmonic width

- The width of the harmonics is affected by two other dynamical factors:
  - The first stems from the characteristics of the electron dynamics. According to the analytical spectrum, the width can be calculated based on $z_2 \sim s_2 \sim 1$as:

$$\delta\omega'_c = \frac{\varepsilon^2\omega_2^2}{2\xi_2^2\omega_1 m^2 + \varepsilon\omega_2^2} \approx \frac{\omega_2}{8}\left(\frac{m_*}{m\xi_2}\right)^2$$

the width $\delta\omega'_c \propto 1/\gamma_*^2$, decreasing with electron energy for CPW
the width $\delta\omega'_{CS} \propto \omega_0\gamma^2/\xi_1^2$, increasing with the electron energy for CS.

  - The second arises from the finite duration of the laser pulses. The photon uncertainty width is mostly determined by the second pulse:

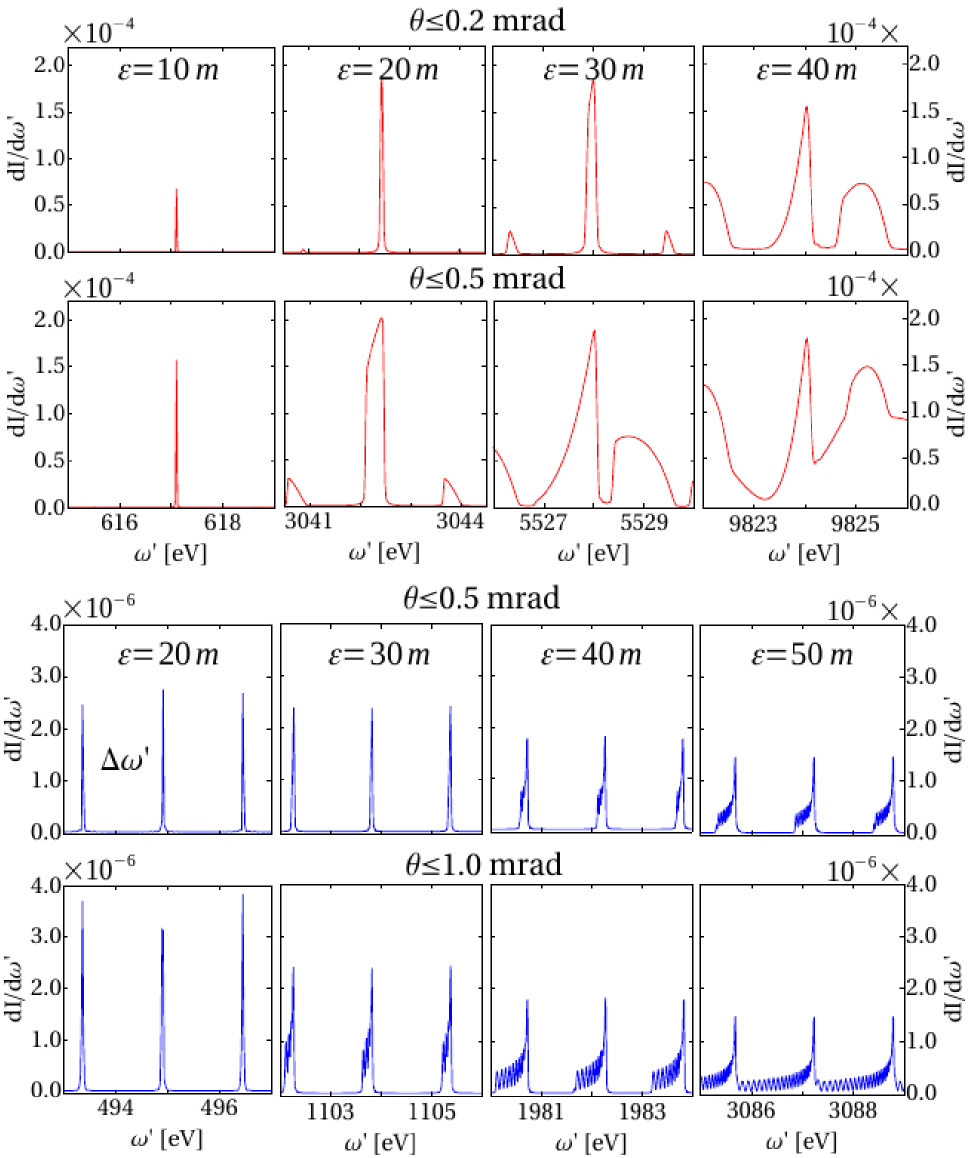
$$\delta\omega'_f = 2\gamma_*^2\omega_2/N_2 = \omega_0/N_2$$

- Controlling the angle range θ_w, one can tune $\delta\omega'_w$ such as not to exceed the dynamical width:

$$\delta\omega'_{in} = \max\left(\delta\omega'_c, \delta\omega'_f\right)$$

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

New x-ray source: harmonic width

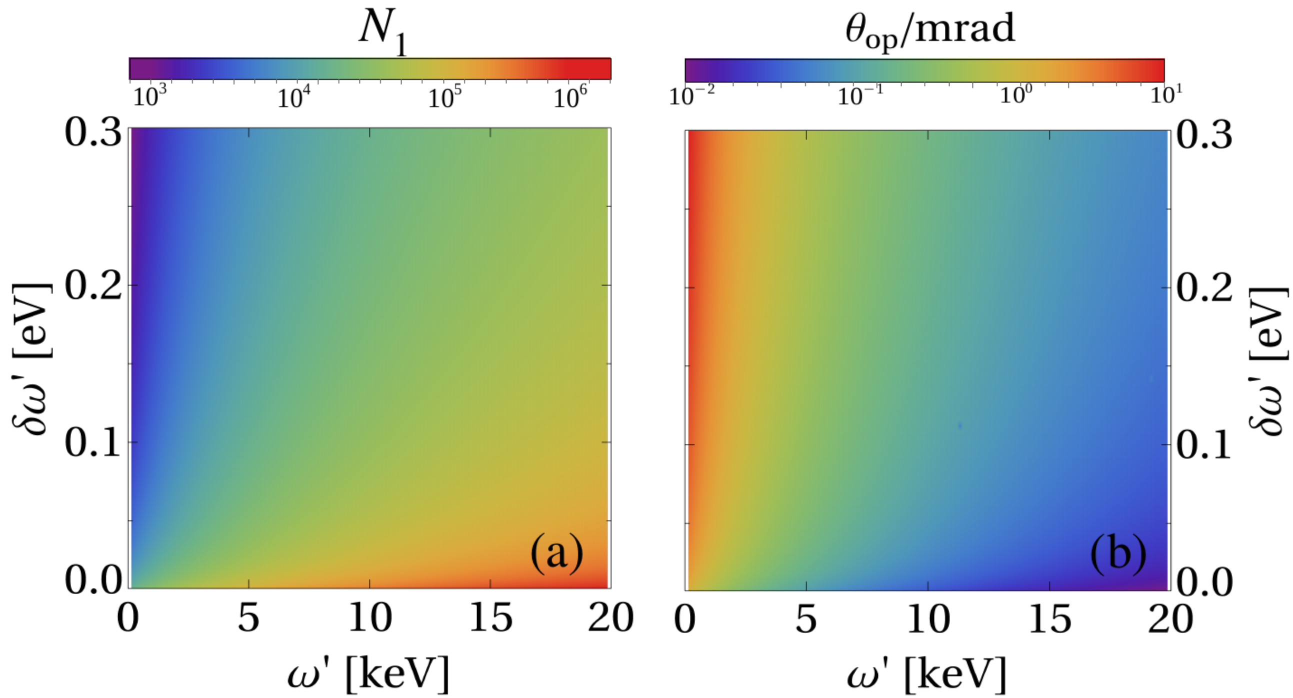


- Case I: $\xi_1 \gg \xi_2$
  - the new satellite peaks arise and the energy roams into spikes;
  - $\delta\omega'_{in} \approx \Delta\omega' \approx \omega_0$; the width is mainly determined by the angle window $\delta\omega'_w$;
  - the relative BW ~ 10^{-4}
- Case II: $\xi_1 \ll \xi_2$
  - $\delta\omega'_{in} \approx \delta\omega'_f \ll \omega_0$, independent of energy and angle
  - the relative BW ~ 10^{-5}
  - large angle causes the noisy background

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

New x-ray source: experimental setup

- Experimental design:
  - Step 1: Case I or II is chosen depending on the preference of the spectral shape;
  - Step 2: Specify the energy ω' and BW $\delta\omega'$ and then the angle window θ_w follows;
  - Step 3: For a given BW, the number of cycles can also be determined;
  - Step 4: For a given laser energy and the required pulse length, the effective mass is obtained and then the electron energy.



According to $z_2 \approx m\xi_2 u\theta/\omega_2 \sim 1$, the optimized angle is $\theta_{op} = m_*^2/(8\gamma\xi_2^2\varepsilon^2)$

Q. Z. Lv, E. Raicher, C. H. Keitel, and K. Z. Hatsagortsyan, arXiv:2106.14099 (2021).

Summary and Outlook

- Summary
  - CPW setup: an extremely narrow BW and collimated x-ray pulse around keV energy, with brilliance by orders of magnitude larger than CS;
  - By tuning the intensity of the two laser pulses, one can produce either a single peak or a comb-like x-ray source, $I \lesssim 10^{18} W/cm^2$;
- Outlook
  - Resonant excitation spectroscopy for highly charged ions;
  - An external XFEL seeder in x-ray regime;
  - Small angle x-ray scattering diagnostics;
  - A way to a hard x-ray frequency comb for ultrahigh precision metrology;
  - ……

Acknowledgments

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

C. H. Keitel

K. Z. Hatsagortsyan

SOREQ
Soreq Nuclear Research Center

E. Raicher