Attosecond Pulse at PAL-XFEL & Weibel instability in a Homogeneous plasma medium

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Outline

• Motivation
• Short Pulse generation in XFEL
  - Train of X-ray radiation pulses at PAL-XFEL
  - Single isolated Terawatt-Attosecond X-ray pulse at PAL-XFEL
• Summary
• Weibel instability in inhomogeneous plasma medium
• Future plan
X-ray free-electron lasers are excellent tools for the study of ultrafast phenomena in atoms and molecules in the fields of physics, material science, chemistry and biology.

However, fs pulses are not sufficiently fast to follow the dynamics of electrons in atoms, molecules and nanoscopic systems in their real time.

To follow the electronic motions, an intense **Attosecond X-ray pulse** is demanded.

**Electron Orbits in Bohr Model**

*For H ground state: $T_{\text{orbit}} \approx 150\ \text{as}$*

$1\ \text{as} = 10^{-18}\ \text{sec}$
High Energy Density matter occurs widely

**Hot Dense Matter (HDM) occurs in:**
- Supernova, stellar interiors, accretion disks
- Plasma devices: laser produced plasmas, Z-pinches
- Directly and indirectly driven inertial fusion experiments

**Warm Dense Matter (WDM) occurs in:**
- Cores of large planets
- Systems that start solid and end as a plasma
- X-ray driven inertial fusion experiments

Short pulse intense X-ray source can create unique initial states in the matter.........
**Possible experiments at HEDS end stations**

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Towards “Ultimate” XFEL Source

![Diagram showing pulse width and wavelength for unattainable and attainable regions, with PAL-XFEL marked.]
Atto-second XFEL (\(< 500\) as)

**Atto-second XFEL Generation**

* ESASE (Enhanced Self-Amplified Spontaneous Emission)

“Increasing the peak current \(I_p\) and keeping the low emittance \(\varepsilon_n\) by lowering the charge can make it possible to reduce \(L_g\).”

\[
L_g \propto \frac{\varepsilon_n^{5/6}}{I_p^{1/2}}
\]

- Beam charge at the gun: 20 pC gives emittance = 0.15 um-rad
- Peak current after the Laser-modulated bunching increased up to \(> 8\) kA \(\rightarrow\) and saturation length is \(L_g\) decreased by 30%
Mode locking technique in FEL

- Optics-free technique synthesizes a comb of longitudinal modes by applying a series of spatiotemporal shifts between the co-propagating radiation and electron bunch.

- These shifts are achieved by repeatedly delaying the electron bunch using the magnetic chicanes between the undulator modules.

- These longitudinal modes become phase locked by modulating the electron beam energy at the mode spacing frequency.

- Each mode acquires sidebands that overlap neighboring modes.

- SASE spectrum at saturation is noisy comprising irregular spikes. Mode locking improve the quality of FEL output over SASE.
Attosecond pulses @ PAL-XFEL

- Shorter undulator than standard one.
- Electron beam delays increases the interaction length.
- Energy modulation provides the modes phase locked giving a train of pulses (Mode locking in FEL).

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Mode locking FEL simulation with PAL-XFEL
A slotted foil in the middle of the bunch compressor to select a small unspoiled part of the electron beam to laser.
The spectrum is discretely multichromatic with a bandwidth envelope increased by approximately 2 orders of magnitude over unseeded FEL amplifier operation.

- Short, high-power pulses phase-correlated over a distance, \( l_{coh} = \lambda / 4\pi \rho \)
- The spectrum is discretely multichromatic with a bandwidth envelope increased by approximately 2 orders of magnitude over unseeded FEL amplifier operation.

- Modulated by SASE envelope, within each lobe of this envelope the radiation spikes have the same phases and hence they are temporally coherent.
Slotted foil used in the last bunch-compressor (BC3)

- Slotted foil used in the bunch compressor, spoils the head and tail parts of the longitudinal distribution of the electron beam [P. Emma, PRL 2004]
- The effect of slotted foil is studied first time on the MLAB-FEL output.

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**Graphs:**

**Graph (a):**
- Normalized Emittance $\varepsilon_{xy}$ (µm)
- Comparison of without and with slotted foil.

**Graph (b):**
- Power (GW) vs. Time (fs)
- Comparison of without and with slotted foil.
Output is reduced to a pulse train with an envelope having a single lobe and the phase of each spike is constant along the output pulse.

Generate broadband, discrete, and coherent spectrum compared to the XFEL’s narrowband spectrum.

High Power-Isolated attosecond pulse @PAL-XFEL

Multi current spikes Case

[Working Principle of the Scheme:
[T. Tanaka, PRL 110, 084801 (2013)].]
Mirror-chicane Working Principle

Chicane-mirror System

Mirror System for optical delay

Optical delay unit

Magnet Chicane

direction of magnetic field

electron trajectory

low energy

high energy

$\theta$

$L_{B}$ $L_{1}$ $L_{2}$
Current Profile & Radiation Profile

(a) Current Profile
- Tail current spike
- Head current spike

(b) Radiation Profile
- Target radiation spike
- Radiation pulse length (µm)

Spectrum
- Photon energy (keV)
- Normalized Spectra (a.u.)
Chirped Optical laser in ESASE section

Unequal spaced current spikes

Increasing variation
Temporal radiation profile and Power spectrum

23 UM # For amplification

- Average power along the undulator.
- After 23 UMs stages is $3.0 \pm 1$ TW, while the average pulse duration is $65 \pm 23$ attosecond at FWHM.

Manuscript ready for submission….
How about without Optical delay and slotted foil?

- Delaying X-ray radiation is technically difficult (however, possible in near future).
- To obtain few attosecond delay, mirror angle < $1^\circ$ and with reflectivity > 90%.
Results

Current Profile (unequally spaced)

Radiation Profile

4 TW /50 as FWHM
Superradiance regime

- At the entrance of the undulator, radiation intensity is proportional to $N$ (number of electrons).
- Later bunching occurs on interacting with the spontaneous radiation resulting emit radiation proportional to $N^2$. This behavior is called “Superradiance”.
- **In super-radiant region**, for large values of $z$, radiation pulse-width varies as the inverse square root $\sim z^{-1/2}$ while the power varies as $z^2$ (rather exponential)
Mode-locked (ML) scheme at PAL-XFEL gives a train of attosecond pulses with $16 \text{ as FWHM}/3.5 \text{ GW}$ in 42 m long undulator.

Mode locked after burner (MLAB) scheme at PAL-XFEL gives a train of attosecond pulses with $1.3 \text{ as FWHM}/3 \text{ GW}$ at 12.4 keV in 43 m long undulator.

Using slotted foil in Mode-locked Afterburner, radiation profile is reduced to a single lobe and the phase of each spike is constant all the way along the output pulse, useful for X-ray crystallography experiments.

Using Chirped laser pulse in ESASE section, Single isolated attosecond pulse ~ 42 as in pulse duration with 3 TW in power is shown in X-ray free electron laser.
Weibel instability in an inhomogeneous plasma medium
Outline

- Understanding microscopic plasma physics is necessary: Plasma waves and their associated instabilities (the Buneman instability, two streaming instability, and the Weibel instability) created in the shocks involve particle acceleration (electrons, positrons, and ions).
- Gamma Ray Bursts (GRB) observations suggest that post-shock magnetic fields are strongly amplified to 100 times in large emission regions.
- However, PIC simulations show that magnetic fields originated from the Weibel instability cannot occupy large regions because of the rapid decay.
- Nonlinear evolution of the Weibel instability has been investigated for uniform plasmas or shocks in uniform plasmas.
  - The Weibel mode decays rapidly.
- We investigate nonlinear evolution of the Weibel instability in an inhomogeneous plasma by using two-dimensional PIC simulations.
The Weibel instability occurs in plasmas with anisotropic velocity distributions.

Ex.) \( T_y > T_x \), counter streaming plasmas

Counter streaming plasma + Magnetic field perturbations, \( \delta B \)

Particle density increases at nodes of \( B_z \)

The streaming plasmas are deflected by \( \delta B \), so that currents are generated.

The currents amplify \( \delta B \) -> unstable
Simulation setup 1

- 2D Electromagnetic Particle in Cell simulation (PIC)
- Periodic boundary condition in both directions x and y.
- Simulation Box Size $L_x = L_y = 120c/\omega_p$, $\omega_p$ is the plasma frequency.
- Cell size $\Delta x = \Delta y = 0.1c/\omega_p$
Simulation Setup 2

- Unmagnetized $e^\pm$ plasmas (first step)
  
  $B = 0, n_{e+} = n_{e-}$

- Two counter-streaming beams in the $x$ direction
  
  Drift velocity $v_d = \pm 0.5 \, c$ (mildly relativistic)

  Thermal velocity $v_{th} = 0.1 \, c$

- Spatial distribution of the $e^\pm$
  
  $n(x, y) = n_0 \{1 + 0.5 \sin 2\pi y / L_x\}$

Especially we consider anisotropic density distributions that is expected in the downstream region of relativistic shocks.
Generation mechanism of the temperature anisotropy in the shock downstream region

High density clump

Isotropic Cold distribution

Upstream regions  Just behind the shock front  downstream regions

R: Length scale of density fluctuations.
where \( r \) and \( \Gamma_d \) are the shock compression ratio and the Lorentz factor of the downstream flow at the shock rest frame.
Time evolution of magnetic fields

In inhomogeneous case
After 1st saturation, magnetic field grows again

Time evolution of the **magnetic field energy density** normalized by the mean initial kinetic energy density, $\varepsilon_B$

- 2nd Peak of magnetic energy density shows that large magnetic fields are maintained for a longer time in case of spatially anisotropic density structure.
- To confirm 2nd peak, temperature anisotropy variation with time and magnetic fluctuations in k-space will be checked.
Time evolution of magnetic fields 2

a) At the 1\textsuperscript{st} saturation
\[ \omega_p t = 17 \]

b) At the 2\textsuperscript{nd} saturation
\[ \omega_p t = 117 \]

c) After the 2\textsuperscript{nd} saturation
\[ \omega_p t = 500 \]

✓ a) Magnetic fields are strongly amplified in the high density region
✓ The typical length scale of magnetic fluctuation at the 1\textsuperscript{st} saturation and the 2\textsuperscript{nd} saturation will be confirmed by k-space.
Magnetic fields produced by the Weibel instability cannot occupy large regions for shocks in uniform plasma.

We investigated nonlinear evolution of the Weibel instability in a nonuniform plasma.

For anisotropic density structure, we observed the 2nd growth of magnetic fields after the 1st saturation.

The 2nd growth of magnetic fields is also due to the Weibel instability.

The temperature anisotropy is produced by the anisotropic density structure after the 1st saturation.

Such a situation can be expected in the downstream region of relativistic shocks.

The 2nd Weibel instability could be important for radiation from GRB, particle accelerations and generation of magnetic fields.
Thank you