Non-linear effects in Compton Sources

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Physics and Applications of High Brightness Beams:
Towards a Fifth Generation Light Source
**Inverse Compton Scattering**

- **Ultra-fast materials characterization**
  - X-rays [keV] for penetrating metals
  - X-ray backlighter, [< ps] resolution
- **Biology and medicine**
  - Breakthrough diagnosis/therapy
  - Phase contrast imaging

- **Intermediate energy [MeV]**
  - Slow positrons (for materials)
  - Nuclear materials detection
- **High energy physics [GeV]**
  - γγ collider, polarized e+
Current ICS project, UCLA at BNL ATF

Standoff detection of special nuclear materials

DETRA: No. HDTRA1-10-1-0073

Active detection of nuclear materials via photo-fission

with use of IFEL & Reserculation

Requirements:

★ ~10-15 MeV ↔ ~ GeV electron
★ photon number > 10^{13} /sec (?)(!) ↔ 10^{10} photons/shot ↔ a_L ~ 1
BNL ATF specification

e-beam:
0.3 nC, $\sigma_x \sim 30 \mu m$, 65 MeV

CO$_2$ laser:
$\sim 1$ TW($a_L \sim 1^*$), $w_0 \sim 40 \mu m$, $Z_R \sim 0.5$ mm, 3 ps, 10.6 $\mu m$

★ Photons/pulse:
$N_\gamma = \sigma_T N_e N_L / \sigma_x^2 4\pi \approx 10^{7-8}$

★ X-ray energy:
$E_{\gamma} = 4\gamma^2 E_L \approx 10$’s of keV

* $a_L = eE_L \lambda_L / 2\pi n_c c^2$

Pre-history of ATF
2006yr
Observation of 2\textsuperscript{nd} harmonic
Kumita et.al.

Ag attenuator used,
\(a_L = 0.35\)

2009yr
K-edge filtering of linear ICS
Williams et. al.

Narrow band linear ICS,
Fe foil used.

Detailed study of non-linear ICS,
using gradually upgraded ATF laser
Recent fresh experiment in BNL ATF
Experimental set-up

Screen: MCP*, φ1"

φ2.5”, f/1 Cu parabola with φ1/16” hole

CO2 laser w0 φ1.5”

φ3” Cu mirror with φ1/4” hole

*MCP: Photonis, KBr coated
Specification of used filters

- **Fe** (5 < $h\nu$ < 7 keV)
  Extraction of 1\textsuperscript{st}

- **Au** (10 < $h\nu$ < 12 keV)
  Extraction of 2\textsuperscript{nd}

- **Al 250 μm** ($h\nu$ > 8 keV)
  > 2\textsuperscript{nd}

- **Al 1000 μm** ($h\nu$ > 12 keV)
  > 3\textsuperscript{rd}

Back scattered value: 7.6 keV, @ 65 MeV, 10.6 μm
Typical Donut shape distribution, linear ICS case

\[5 \text{ keV} < \text{Fe K-edge} < 7 \text{ keV}\]

\[a_L < 0.25 \rightarrow 7.6 \text{ keV}\]

Donut shape = Red-shifted off-axis component
Details of red-shifted fundamental radiation

5 keV < Fe K-edge < 7 keV
\[ \leftrightarrow 0.5 < a_L < 0.7 \]

Estimated \( a_L \sim 0.6 \)

\[ \hbar \omega_{\text{x-ray}} = \frac{4 \gamma^2 \hbar \omega_L}{1 + a_L^2/2 + \gamma^2 \theta^2} \]
Predicts angular-wavelength spectra by classical Lenard-Wiechert approach

\[
\frac{dp}{dt} = eE + e\left(\frac{v}{c}\right) \times H
\]

\[
p_\mu p^\mu = m_e^2 c^2
\]

\[
v = \frac{pc}{\mathcal{E}}
\]

\[E_x = E_{0,s} \sin(k_s z - \omega_s t)\]

1. Particle track

\[E_{\text{LW}} = \frac{m_e}{e} \frac{r_e}{R} \frac{n \times \{(n - v/c) \times w\}}{(1 - n \cdot v/c)^3}\]

2. Field on the screen

3. Fourier transform

\[E_{\text{LW},x}(\omega) = \left| \int_{-\infty}^{\infty} E_{\text{LW},x}(t)e^{i\omega t} dt \right|\]
X-ray distribution for $a_L \approx 0.6$

Predicts angular-wavelength spectra by, classical Lenard-Wiechert approach

In 16 mrad square ($1/\gamma = 8$ mrad @ 65 MeV)

1$^{st}$ ($0 < h\nu < 7$ keV),
Two maxima = Low energy

2$^{nd}$ ($7 < h\nu < 14$ keV),
Peak to peak lobe = 12 mrad

3$^{rd}$ ($14 < h\nu < 25$ keV),
Radiation angle < $1/\gamma$
Narrow band extraction of 2\textsuperscript{nd} component

Mean angle 5 mrad @ 10-12 keV

2\textsuperscript{nd} Harmonic 10-12 keV

x: 8 mrad = 1/\gamma

1/10
Observed higher order harmonics
Discussion of observed harmonics

$1^{st}$ (Fe K-edge) $> 2^{nd}$ (Al 250 μm) $> 3^{rd}$ (1000 μm)

Observed intensity in MCP [a.u.]

Photon number density in theory [a.u.]
Decompose circle shaped lobe

Intensity of 3\textsuperscript{rd} component is comparable to 2\textsuperscript{nd} component, that is 1/10 of fundamental

Al 250 μm (> 8 keV)  
“Circle shaped lobe”

Au filtering (10-12 keV)  
“Crescent lobe“

Al 1000 μm (> 12 keV)  
”On-axis maxima“
& In addition, how is the circular polarization case?

Use of Al 250 μm: > 2\textsuperscript{nd} components

Rotation

For next step of nonlinear ICS
Radiation control of ICS X-ray 2 color?
Two color ICS in nonlinear regime

High frequency laser (TiS, YAG)
Long wavelength laser (CO\textsuperscript{2})

Modulated X, γ-ray

Small amplitude linear motion
Non-linear figure-8 motion
Hybrid motion

\[ E_{x,s} + E_{x,l} = E_{x,s} + E_{x,l} \]

is under investigation.
Small oscillation is, superimposed upon large figure-8

\[ E_{\text{LW}} = \frac{m_e}{e} \frac{r_e}{R} \frac{n \times \{(n - \nu/c) \times w\}}{(1 - n \cdot \nu/c)^3} \]

Hybrid motion

\[ \rightarrow - \frac{m_e}{e} \frac{r_e}{R_0} \frac{w_x(1 - \frac{v_z}{c}) + \frac{w_z v_x}{c}}{(1 - \frac{v_z}{c})^3} \]

with cycle of figure-8 motion

Use of radiation phase

Directed toward observer

\[ E_{x,s} + E_{x,l} \]
Example of non-linear two color spectrum

\[ 4\gamma^2 \hbar (\omega_{L,\text{short}} + n\omega_{L,\text{long}}) \]

**Pulsed extraction of hard X-ray?**

**Multi photon energy?**

Numerically calculated Lienard-Wiechert potential \( E_{LW,x}(t_{\text{screen}}) \) on \((x, y, z) = (0, 0, 0)\)
FIG. 4. Numerically calculated $E_{LW,x}(t_{\text{screen}})$ (a), its on-axis spectrum (b), $E_{LW,x}(h\omega)$ on the screen, that is produced by the ICS interaction of 75 MeV electron beam, CO$_2$ laser, and 200 nm (10.6 $\mu$m/50) laser. $a_{L,CO2}$: 2.0, $a_{L,200\,\text{nm laser}} = 2.0/50 \approx 0.04$ backscattered value: 0.51 MeV.
Experimental Scenario in ATF

Use of existing YAG and CO$_2$

Use of k-edge 25-50 keV, would show 2 lobe shape?
Summary

- Observation of red-shifting & 3\textsuperscript{rd} Harmonic is reported.

- Radiation control of ICS X-ray is proposed.
Gracias, Grazie, Thank you,
Спасибо, 謝謝,
&ご清聴有難う御座います.

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