Nonlinear Inverse Compton Scattering

Transfer from feasibility study

Y. Sakai(1), I. Gadjev(1), J. Durius(1), P. Musumeci(1), O. B. Williams(1), J. B. Rosenzweig(1)
T. Kumita(2) and Y. Kamiya(3)

(1): University of California, Los Angeles,
(2): Tokyo Metropolitan University, (3): University of Tokyo

October 2014
BNL ATF User Meeting
Inverse Compton Scattering

Relativistic e-beam (Longitudinally heavy: $\gamma m_e c^2$)

Laser (Visible to Infra-red)

$\nu_{ICS} = 4\gamma^2 \nu_L > 10$ keV

- Material science, Biology and Medicine [keV]
  - X-ray penetration, X-ray backlighter, Phase contrast imaging
- Nuclear physics [MeV]
  - Photo fission, Nuclear resonance
- High energy physics [MeV, GeV]
  - $e^+e^-$ linear, $\gamma\gamma$ collider

Photon number is limited to $10^{6-8}$/shot
Nonlinear Inverse Compton Scattering

Due to transverse momentum
Figure-8 motion

Relativistic e-beam

Laser: $a_{L,0} \approx 1$

Use of $a_{L,0} = 1$ laser is required. \( \because a_{L,0} = \frac{eE_L \lambda_L}{2\pi m_e c^2} \)

- Harmonics generation:
  
  \textit{(Multi-photon process in dense photon field)}
  
  $h\nu_{\text{X-ray}} = n 4\gamma^2 \nu_L$

- Red-shift, re-direction:
  
  \textit{(Mass shift effect, $m_{\text{Eff}}^2 = m^2 + m_{L,x}^2$ [Kibbe, 1965yr])}
  
  $h\nu_{\text{X-ray}}' = h\nu_{\text{X-ray}} / (1+a_{L,0}^2/2)$
2011yr: Single shot diffraction of linear ICS
\( \sim 10^8 \) photons/shot [1, 2]

10^4 photons diffracted from Si \(<111>\) crystal

Previous ICS study in BNL ATF

Observation of 2\textsuperscript{nd} harmonic
Ag attenuator used,
\(a_{L,0} \approx 0.3\)
2006yr, Kamiya, Kumita et.al.[3]

Narrow band linear ICS spectrum
Fe K-edge used,
\(a_{L,0} \approx 0.2\)
2009yr, Williams et. al.[4]

Concrete study of fully nonlinear ICS,
using \(a_{L,0} \approx 1\) CO\textsubscript{2} laser and K-edge filter

Experimental condition

**CO₂ laser:** $a_{L0} \approx 0.6$ (~0.3-0.4 TW, ~2-3 J), FWHM ≈ 5 ps, 10.6 μm, $w_0 \approx 40$ μm, $Z_R \approx 500$ μm

**e-beam:** $Q \approx 0.3$ nC, $\sigma_z \approx 300$ μm, $\sigma_x \approx 30$ μm, 65 MeV

**Compton edge:** $h\nu = 4\gamma^2E_L \approx 7.6$ keV

**Photons/Pulse at I.P.:** $N_\gamma = \sigma_T N_e N_L / \sigma_x^2 4\pi \approx 10^9$
Numerical illustrations of radiation pattern

*Lienard-Wiechert potential with $a_{L,0} = 0.6$*

Photon number density distributions of harmonics, in 16 mrad square ($1/\gamma \approx 8$ mrad @ 65 MeV, 10.6 $\mu$m)

1\textsuperscript{st} ($0 < h\nu < 7$ keV), 2\textsuperscript{nd} ($7 < h\nu < 14$ keV), 3\textsuperscript{rd} ($14 < h\nu < 25$ keV)

Geometric features:
- 1\textsuperscript{st}: Radiation angle $< 1/\gamma \approx 8$ mrad (Slightly elliptical)
- 2\textsuperscript{nd}: Distance of crescent lobes center $\approx 10$ mrad
- 3\textsuperscript{rd}: Radiation angle of on-axis component $< 1/(\sqrt{3}\gamma) \approx 4$ mrad
Specification of selected filters

Compton edge: 7.6 keV, @65 MeV, 10.6 μm

- **Fe (5 < \(h\nu\) < 7 keV):** Red-shift of 1\(^{\text{st}}\)
- **Au (10 < \(h\nu\) < 12 keV):** Narrow band 2\(^{\text{nd}}\)
- **Al 250 μm (\(h\nu\) > 8 keV):** > 2\(^{\text{nd}}\)
- **Al 1000 μm (\(h\nu\) > 12 keV):** = 3\(^{\text{rd}}\)

![Lienard-Wiechert model](image)
Observed red-shift (mass shift effect)

Compton edge is red-shifted from 7.6 keV to 5-7 keV

\[ h\nu_{ICS,1}^{st} = \frac{4\gamma^2 \nu_L}{(1+a_{L,0}^2/2)} \rightarrow \therefore a_{L,0} \approx 0.6 \]

\[ \therefore \text{Undulator equation} \]
Harmonics

★ Verification of 2nd harmonic energy

Au L-edge (12 keV)

Narrow band 2nd
2nd + 3rd
3rd (On-axis & lobes)

Verification of 2nd harmonic energy

Relative intensity of 2nd & 3rd

→ Existence of figure-8 motion is verified
Harmonics

★ Verification of 2\textsuperscript{nd} harmonic energy
★ Relative intensity of 2\textsuperscript{nd} & 3\textsuperscript{rd}

Au L-edge (12 keV)        Al 250 μm > 10 keV

Verifying the energy of the 2\textsuperscript{nd} harmonic

Relative intensity of 2\textsuperscript{nd} and 3\textsuperscript{rd} components

→ Existence of figure-8 motion is verified
Harmonics

★ Verification of 2\textsuperscript{nd} harmonic energy
★ Relative intensity of 2\textsuperscript{nd} & 3\textsuperscript{rd}
★ 3\textsuperscript{rd} components

Au L-edge (12 keV)          Al 250 \( \mu \)m > 10 keV          Al 1000 \( \mu \)m > 15 keV
Strong helical motion in Circular polarized laser field

$\frac{1}{4}$ wave plate between regenerative and final amplifier

Off-axis Circular harmonic (> 2$^{nd}$)

Al 250 $\mu$m > 10 keV
Verification of figure-8 motion

Linear
Transverse + Longitudinal motion (Figure-8)

Circular
Transverse motion

CO₂ laser: 10.6 μm, e-beam: 65 MeV, Compton edge: 7.6 keV

Observation vs Lienard-Wiechert model
with estimated $a_{L,0} = 0.6$
Spectrum analysis using Curved Multi-layer [5]

Mo-Si Multi (45) layer thickness: $d \approx 3.3$ nm, Bragg angle $\sim 25$ mrad @ $h\nu = 7.6$ keV

Viewing angle of curved layer $\sim 50$ mrad (covers several keV)

Reflectivity of Multi-layer $\sim 15\%$ @ NSLS X15A

Result in July 2014 run

Single shot double differential spectrum is obtained.

CO$_2$: 9.25 μm, e-beam 61 MeV, Compton edge 7.6 keV

is under investigation
by both Quantum mechanical and Classical approach.
Evidence of on-axis ref-shifting, mass shift, in strong laser field

However: High energy component at 8-10 keV…? etc.
→ CO₂ laser’s spectrum around 9.25 μm?
→ e-beam energy spectra in BL1?
Summary of feasibility study in 2012-2014yr

★ 3rd order harmonic radiation and red-shifting through angular spectrum distribution using foil filters is observed.

★ Single shot double differential spectrum and red-shifting using curved multi-layer grating is observed.
Future plan

(a) Completion of the spectrum study BL1

(b) Design, and preparation for realization of the Two wavelengths nonlinear Gamma-ray ICS in ATF II

(c) Initial investigation of IFEL/ICS scheme using a laser reflector in BL2
Two wavelengths nonlinear ICS
at Gamma-ray regime ~ MeV

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

Small oscillation superimposed upon large figure-8

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

contains high frequency factor

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

with cycle of figure-8 motion

←Use of radiation phase
Directed toward observer

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

Particle motion & X-ray waveform
Controlling a ICS’s radiation kinetics

Pulsed waveform modulation along figure-8 orbit

$$h\nu_{ICS} = 4\gamma^2 h(\nu_{L,Short} + n\nu_{L,Long})$$

(b) Design, and preparation for realization of the Two wavelengths nonlinear Gamma-ray ICS in ATF II

Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{\text{screen}})$ on $(x, y, z) = (0, 0, 0)$
Anticipated $\gamma$-ray spectrum

e-beam: 1 GeV, CO$_2$ 10.6 $\mu$m with $a_{L,0} = 2$, and TW Ti: Sapphire 800 nm case

★Time encoding using laser’s rising phase (tail)

*Initial demonstration can be done using observed red-shifting, ($\Delta\nu \sim 20\%$), in BL1?*

★Spectrum matching to photo fission cross section at $\sim$ MeV

**Collaboration of IFEL/ICS for 10 MeV photon?**
Initial IFEL/ICS combination test using a foil reflector

The IFEL/ICS concept lead by I. Gadjev

\[ \sim 10^{5-6} \text{ ICS photons/shot?} \]

- Al foil thickness = 10s μm,
  (Transparent for 10-30 keV ICS X-rays, & Attenuate Bremsstrahlung)
- Available e-beam charge at \( \sim 80-100 \text{ MeV} \) is \( \sim 30 \% \) (~0.1 nC),
- Rising component of CO\(_2\) laser has 10 \% of its total energy (~0.3 J)
- Laser waist at ICS I.P. \( \sim \) mm?
IFEL/ICS would be, using a laser pulsed train and beams focusing optics in BL2?

Details will be shown in J. B. Rosenzweig’s talk as ICS in ATF II!

\[ \sim 10^{7-8} \text{ ICS photons/shot} \]
Future plan >2015yr

(a) Completion of the observation of double differential spectrum in BL1
   1. Discussions & Details of 9.25 μm laser and e-beam (No beam time)

(b) Design, and preparation for realization of the Two wavelengths nonlinear Gamma-ray ICS in ATF II
   1. Time encoding by using a nonlinear effect in BL1
   2. Synchronization system for mJ level Ti:Sapphire (No beam time)

(c) Initial investigation of IFEL/ICS scheme using a laser reflector in BL2
   For use of focusing optics:
   1. Single linear ICS X-ray verification in BL2, (with energy chirp?).
   2. Generation of double 2-3J CO₂ pulse train in BL2
   3. IFEL/ICS collaboration
Thank you very much,
BNL ATF

ACKNOWLEDGEMENT
This work was supported by the DTRA Contract HDTRA1-10-1-0073, and U.S. Dept. of Energy under Contracts No. DE-FG02-07ER46272, No. DE-FG03-92ER40693 and No. DE-AC02-98CH10886, the US ONR under Contract No. ONR N00014-06-1-0925, and DARPA under Contract No. N66001-11-1-4197. The authors would like to thank all collaborators in BNL ATF and UCLA PBPL. In addition, authors also would acknowledge the invaluable advice and contributions from Dr. P. Siddons, Dr. Z. Zhong (NSLS), Dr. L. Xiao, Dr. D. Cline, and Dr. S. Tochitsky (UCLA)