Proposal ID: 312815

Harmonic Nonlinear Inverse Compton Scattering

Nonlinear ICS by $a_0 > 1$, CO$_2$ (9.2um) laser with Nd:YAG laser (1um)

BNL ATF user meeting
March 2, 2023

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Collaborator: Zhong Zhong, BNL NSLS

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BNL ATF Experiment Renewal: Experiment Goals {Return Of “Nonlinear”}

AE70: Nonlinear Compton, AE87: Hard X-ray ICS, AE##: Nonlinear Inverse Compton Scattering

- Strong field physics: Bi-harmonic Compton interaction with ATF’s CO₂ laser
- Hard X-ray optics developments: DDS measurement & Focusing or Collimation
- X-ray OAM investigation: Higher order harmonics by circular polarized CO₂ laser

Relativistic e-beam

\[ a_{L,0} \equiv \sqrt{-e^2 A_\mu A^\mu / m_e c^2} = eE_{L,0} (\lambda L/2 \pi) / m_e c^2 \]

Linear laser polarization

Nonlinear ICS: \( a_L \sim 1 \), Transverse motion → Relativistic, nontrivial longitudinal oscillation**
Slow down electron’s velocity, or Effective mass increase

★ Red-shifting and BW increase:

Photon absorption by electron = Mass shift

\[ h\nu_{X\text{-ray}} \rightarrow h\nu_{X\text{-ray}} / (1+a_L^2/2+\gamma_0^2 \Theta^2) \]

★ Harmonic generation/angular dependence:

Multi-photon process in dense photon field

\[ h\nu_{X\text{-ray}} = 4\gamma^2 h\nu_L n \]
AE70 experiment in BNL-ATF, 2014yr

BNL-ATF Beam parameters (as of 2014yr):

- CO₂ laser: \( a_L \approx 0.6 \) to \( 1.0 \)
  - \((-0.4-0.8 \) TW, \( > 3 \) J), FWHM \( \approx 3.5 – 5.0 \) ps,
  - \( 10.6 \) \( \mu \)m, \( w_\theta \approx 40 \) \( \mu \)m, \( Z_R \approx 500 \) \( \mu \)m

- Electron beam: \( E = 65 - 70 \) MeV
  - \( Q \approx 0.3 \) nC, \( \sigma_z \approx 300 \) \( \mu \)m, \( \sigma_x \approx 30 \) \( \mu \)m, \( \varepsilon_N \approx 1 \) mm mrad, \( \beta \approx \) a few cm

Compton edge: \( h\nu = 4\gamma^2E_L \approx 7 - 10 \) keV

Photons / pulse: \( N_\gamma \approx 10^9 \) (World record *)
Observed red-shift (*Direct evidence of the figure-8 motion*)

7.6 keV < Fe k-edge
Off-axis component

\[ a_{L,0} < 0.25 \]

\[ h \nu_{ICS,1}^{3} = 4 \gamma^{2} v_{L}/(1+a_{L,0}^{2}/2) \rightarrow 0.5 < a_{L,0} < 0.7 \]

Angular distribution of harmonic radiation: *Linear polarization case*

Au L-edge (12 keV)  
Al 250 μm > 10 keV  
Al 1000 μm > 15 keV

-8 -6 -4 -2 0 2 4 6 8

Normalized intensity

-8 -6 -4 -2 0 2 4 6 8

Normalized intensity

-8 -6 -4 -2 0 2 4 6 8

Normalized intensity

Narrow band 2\textsuperscript{nd}  
2\textsuperscript{nd} + 3\textsuperscript{rd}  
3\textsuperscript{rd}

★On axis components of 3\textsuperscript{rd} harmonics ↔ Direct evidence of the longitudinal motion

Details of the ICS X-ray spectrum: Mo/Si curved Multi-layer spectrometer - AE70

Mo-Si Multi (45) layer thickness: $d \approx 3.3$ nm

- Bragg angle: 
  $\sim 25$ mrad

- Angle acceptance:
  $\sim 50$ mrad

- Reflectivity $\sim 15\%$ @ NSLS X15A (Z. Zhong)

Projection of deflected ICS X-ray in a single shot at $h\nu < 10 \text{ keV}$ \textit{(AE70)}

Laser energy 1.5 J, $a_L = 0.7$

Laser energy 3.0 J, $a_L = 1$

Bi-harmonic nonlinear Compton interaction

Pulsed waveform modulation of Hard X-ray component at less than $< 10^{-18}$ s time scale (Cycle of 10 keV X-ray)

Observation of Red-Blue shifts & $h\nu_{L,YAG} \pm n h\nu_{L,CO_2}$

Fourier Transform $\rightarrow$

Numerical estimate of bi-harmonic spectrum by ATF parameter (CO2: 9.2um, Nd: YAG 1064nm)

$e$ (70 MeV)

- High frequency laser (YAG)
- Infra-red Long wavelength laser (CO2)

Modulated $\gamma$-ray

$\text{CO}_2$ component $< 10 \, \text{keV}$, YAG center component $30 \sim 80 \, \text{keV}$

- No-Filter
- Au-100$\mu$m
- Au-200$\mu$m

Only $\text{CO}_2$’s component  
Bi-harmonic YAG’s component
Experimental set up

Bi-harmonic Compton laser optics:

- Input of CO$_2$ laser and YAG laser are opposite
- CO$_2$ laser final optic has D ½ or ¼ inch hole
Experimental set up

Bi-harmonic Compton laser optics:
Input of CO$_2$ laser and YAG laser are opposite & CO$_2$ laser final optic has D ½ or ¼ inch hole

HOW TO DO

ALIGNMENT & TIMING

OF TWO LASER & e-beam

*ICS
≈ Experiment of Alignment in real life

Note:
Vacuum laser transport needs to be stable.
Next: ICS by circular polarized laser – OAM X-Gamma ray?

Linear case:
- e-beam
- Spin
- Laser

Nonlinear case (multi photon process):
- e-beam
- 1st (circular pol)
- 2nd, 3rd (OAM?)
- 2nd, 3rd (OAM?)

NOTE: OAM X-ray can be also generate by FEL & Linear ICS by OAM laser.
Harmonic generation by circularly polarized CO\textsubscript{2} laser, in AE70

\(\frac{1}{4}\) wave plate between regenerative and TW amplifier (Without compressor grating)

<table>
<thead>
<tr>
<th>Al 250 (\mu\text{m}):</th>
<th>Linear, 2\textsuperscript{nd}</th>
<th>Elliptical, 2\textsuperscript{nd}</th>
<th>Circular, 2\textsuperscript{nd}</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Al 1000 (\mu\text{m}):</th>
<th>Linear, 3\textsuperscript{rd}</th>
<th>Circular, 3\textsuperscript{rd}</th>
</tr>
</thead>
</table>

Gamma-ray vortices can be generated by only ICS

{Strong demands in Nuclear Photonics community:

REF Y. Taira, T. Hayakawa, M. Katoh, Scientific Reports volume 7, 5018 (2017)}

\(\rightarrow\) Detailed spectrum distribution needs to be measured at 10s keV range.
Single shot DDS measurement at X-ray energy of 87.5 keV > 10s keV

Quantitative study

→ Thick Laue Bent Crystal Efficiency > Bandwidth

Multi layer crystal: 5 – 20 keV (CO₂’s ICS component)
Thick crystal: 20 keV – 200 keV (YAG’s ICS component)

* Radius of curvature R: 2.5 m
* Thickness: 1 mm
* Bragg angle at 85 keV: ~ 22 mrad
* Crystal to MCP screen 0.3 m
* Expected dispersion at screen: 10-20 mm:
* Band width: ~ 10 keV
* Reflectivity (Efficiency): ~10%

Stats: Diffraction not observed yet in 87.5 keV Hard X-ray ICS run time.
→ First, 2nd – 3rd Harmonic radiation at 20–30 keV range should be examined. Much higher detector efficiency, with more photon flux.
Recover, or almost new installation of, nonlinear CO$_2$ ICS set up 1.5 year:
1. Complete laser vacuum transport. <On going now>
2. Installation of CO$_2$ laser optics with Regen signal at mJ; Establish alignment method <Summer 2023 yr>
3. CO$_2$ laser high power test (Protection of YAG system & source CO$_2$ laser) <2023-24 yr>
4. Benchmarking $a_{1,0}$ measurement of upgraded 5 TW CO$_2$ laser through harmonic components of nonlinear ICS <2024 yr>

Single shot DDS measurement by Bent crystal 2$^{nd}$, 3$^{rd}$ order harmonic (CO$_2$ laser) At ~30 keV range <2024 yr>

Recover Nd: YAG laser optics for Bi-harmonic Compton <2025 yr>

87.5 keV hard X-ray DDS measurement by Bent crystal <2025 yr>

OAM study, Circularly polarized CO$_2$ laser. Depend on the polarization rotator <TBD>

Thank you
### Electron Beam Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>MeV</td>
<td>50-65</td>
<td>Full range is ~15-75 MeV with highest beam quality at nominal values</td>
<td>70 MeV</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>nC</td>
<td>0.1-2.0</td>
<td>Bunch length &amp; emittance vary with charge</td>
<td>0.3 nC</td>
</tr>
<tr>
<td>Compression</td>
<td>fs</td>
<td>Down to 100 fs</td>
<td>A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(up to 1 kA peak current)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse size at IP ((\sigma))</td>
<td>(\mu)m</td>
<td>30 – 100 (dependent on IP position)</td>
<td>It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.</td>
<td>&lt; 30 um</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>(\mu)m</td>
<td>1 (at 0.3 nC)</td>
<td>Variable with bunch charge</td>
<td>&lt; 2 mm mrad</td>
</tr>
<tr>
<td>Rep. Rate (Hz)</td>
<td>Hz</td>
<td>1.5</td>
<td>3 Hz also available if needed</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Trains mode</td>
<td></td>
<td>Single bunch</td>
<td>Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.</td>
<td>Single bunch</td>
</tr>
</tbody>
</table>
## CO₂ Laser Requirements

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Regenerative Amplifier Beam</strong></td>
<td>Wavelength</td>
<td>μm</td>
<td>9.2</td>
<td>Wavelength determined by mixed isotope gain media</td>
<td>9.2 um</td>
</tr>
<tr>
<td></td>
<td>Peak Power</td>
<td>GW</td>
<td>~3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Mode</td>
<td>---</td>
<td>Single</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Length</td>
<td>ps</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Energy</td>
<td>mJ</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M^2$</td>
<td>---</td>
<td>~1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repetition Rate</td>
<td>Hz</td>
<td>1.5</td>
<td>3 Hz also available if needed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>---</td>
<td>Linear</td>
<td>Circular polarization available at slightly reduced power</td>
<td>Linear &amp; Circular</td>
</tr>
</tbody>
</table>

**CO₂ CPA Beam**

*Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>μm</td>
<td>9.2</td>
<td>Wavelength determined by mixed isotope gain media</td>
<td>9.2 um</td>
</tr>
<tr>
<td>Peak Power</td>
<td>TW</td>
<td>5</td>
<td>~5 TW operation will become available shortly into this year’s experimental run period. A 3-year development effort to achieve &gt;10 TW and deliver to users is in progress.</td>
<td>Max. aL&gt;1</td>
</tr>
<tr>
<td>Pulse Mode</td>
<td>---</td>
<td>Single</td>
<td></td>
<td>Single</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>ps</td>
<td>2</td>
<td></td>
<td>2 ps</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>J</td>
<td>~5</td>
<td>Maximum pulse energies of &gt;10 J will become available within the next year</td>
<td>Max</td>
</tr>
<tr>
<td>$M^2$</td>
<td>---</td>
<td>~2</td>
<td></td>
<td>&lt;&lt; 0.05</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>0.05</td>
<td></td>
<td>Linear &amp; Circular</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td>Linear</td>
<td>Adjustable linear polarization along with circular polarization can be provided upon request</td>
<td></td>
</tr>
</tbody>
</table>
# Other Experimental Laser Requirements

## Ti:Sapphire Laser System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Stage I Values</th>
<th>Stage II Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Wavelength</td>
<td>nm</td>
<td>800</td>
<td>800</td>
<td>Stage I parameters are presently available and setup to deliver Stage II parameters should be complete during FY22</td>
<td>TBD</td>
</tr>
<tr>
<td>FWHM Bandwidth</td>
<td>nm</td>
<td>20</td>
<td>13</td>
<td>Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.</td>
<td>500 fs possible?</td>
</tr>
<tr>
<td>Compressed FWHM Pulse Width</td>
<td>fs</td>
<td>&lt;50</td>
<td>&lt;75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chirped FWHM Pulse Width</td>
<td>ps</td>
<td>≥50</td>
<td>≥50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chirped Energy</td>
<td>mJ</td>
<td>10</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressed Energy</td>
<td>mJ</td>
<td>7</td>
<td>~20</td>
<td>20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.</td>
<td></td>
</tr>
<tr>
<td>Energy to Experiments</td>
<td>mJ</td>
<td>&gt;4.9</td>
<td>&gt;80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power to Experiments</td>
<td>GW</td>
<td>&gt;98</td>
<td>&gt;1067</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Nd:YAG Laser System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>1064</td>
<td>Single pulse</td>
<td>1064</td>
</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>5</td>
<td></td>
<td>100-200 mJ</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>14</td>
<td></td>
<td>FWHM 14ps</td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>532</td>
<td>Frequency doubled</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Special Equipment Requirements and Hazards

• All item has been registered in ESR of AE87.
## Experimental Time Request

### CY2023 Time Request

<table>
<thead>
<tr>
<th>Capability</th>
<th>Setup Hours</th>
<th>Running Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Only</td>
<td></td>
<td>1 week (In EH. Only regen)</td>
</tr>
<tr>
<td>Laser* Only (in Laser Areas)</td>
<td></td>
<td>16 hours</td>
</tr>
<tr>
<td>Laser* + Electron Beam TWCO2 only in EH</td>
<td>100</td>
<td>1 week (CO2 – ebeam Timing). 1 hour (Damage test)</td>
</tr>
</tbody>
</table>

### Total Time Request for the 3-year Experiment (including CY2023-25)

<table>
<thead>
<tr>
<th>Capability</th>
<th>Setup Hours</th>
<th>Running Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Only</td>
<td></td>
<td>2 weeks X 6 = 480 hours</td>
</tr>
<tr>
<td>Laser* Only (in Laser Areas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser* + Electron Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Laser = Near-IR or LWIR (CO$_2$) Laser