Overview of High Intensity Gamma-ray Source – Capabilities and Future Upgrades

Y. K. Wu

FEL Laboratory, TUNL and
Department of Physics, Duke University

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Outline

- Overview of Compton Photon Sources
- High Intensity Gamma-ray Source Capabilities
- HIGS Development Projects
- Scientific Research at HIGS and Impact
Gamma-rays

Energy and Average Brightness of Undulators and XFELs

**LCLS (Operational, hard x-rays mode)**
- **λ**: 1.3 – 6.2 Å (9.6 – 2.0 keV)
- 120 Hz
- **2x10^{12} ph/pulse**
- **2.4x10^{14} ph/s**
- **BW (FWHM): 2 – 5 \times 10^{-3}**
- **Pulse duration (rms): 23 fs**
- **Peak Brightness: 2.0 \times 10^{33} phs/sec/mm^2/mrad^2/0.1\%-BW**
- **Avg Brightness: 1.6 \times 10^{22}**

**TESLA SASE FEL (Design)**
- **λ**: 1 – 5 Å (12.4 – 2.5 keV)
- **1.8x10^{12} ph/pulse**
- **1.0x10^{17} ph/s**
- **Peak Brightness: 8.7 \times 10^{33}**
- **Avg Brightness: 4.9 \times 10^{25}**

Compton Scattering

Compton Photon Energy

\[ E_\gamma \equiv h\omega' = \frac{h\omega(1 - \beta \cos \theta_i)}{1 - \beta \cos \theta_f + \frac{\hbar\omega}{\gamma_e}(1 - \cos \theta_{ph})} \]

**Head-on Collision:** \[ E_\gamma^{\text{max}} \approx (\gamma(1 + \beta))^2 \hbar\omega \approx 4\gamma^2 \hbar\omega \]

Compton Scattering

Compton Photon Beam Flux

Compton Photon Sources = Electron-Photon Colliders

\[ \frac{dN_\gamma}{dt} \sim \frac{\sigma}{A_{\text{eff}}} f N_e N_{\text{laser}} \]

Thomson cross-section:
\[ \sigma_0 = 6.6524 \times 10^{-29} m^2 \]

\[ d\sigma = 8\pi r_e^2 \frac{dy}{x^2} \left[ \left( \frac{1}{x} - \frac{1}{y} \right)^2 + \left( \frac{1}{x} - \frac{1}{y} \right) + \frac{1}{4} \left( \frac{x}{y} + \frac{y}{x} \right) \right] \]

\[ x = \frac{2y\hbar \omega (1 - \beta \cos \theta_i)}{mc^2}, \quad y = \frac{2y'\omega' (1 - \beta \cos \theta_f)}{mc^2} \]

Energy Distribution of Compton Gamma-beam

Monochromatic electron and photon beams

Compton Scattering

Emittance Effect (Scaled)

E-beam Energy Spread Effect (Scaled)

Collimator Effect

Operation Principle of HIGS

Two electron bunches + two FEL pulses

V.N. Litvinenko et al. PRL v. 78, n. 24, p. 4569 (1997)
HIGS Capabilities

1. HIGS Accelerator Facility Overview

2. HIGS Capabilities

- Energy Range and Tuning
- Gamma-ray Intensity
- Energy Resolution
- Gamma-ray Beam Stability
- Helicity Switch
Switchyard for OK-4 and OK-5 Wigglers

1. Preserve existing HIGS capabilities
2. Enable high-energy operation (>100 MeV)
HIGS Capabilities: Energy Range
Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)

Gamma-ray energy range
1 – 100 MeV
(FEL: 1060 to 190 nm)
HIGS Capabilities: Energy Tuning

240 nm Mirror Wavelength Tuning

$E_{ebeam} = 627$ MeV, OK–4, single bunch, $\sim 17$ mA, June 4, 2010
Compton Gamma-ray Sources

HIGS/TUNL, Duke University, US

Facility/Project: HIGS
Institution: TUNL and Duke University
Country: US
Energy (MeV): 1 – 100
Accelerator: Storage Ring, 0.24 – 1.2 GeV
Laser: FEL, 1060 – 190 nm (1.17 – 6.53 eV)
Total flux: $10^7$ – $2 \times 10^{10}$ g/s (max ~10 MeV)
Status: User Program
Research: Nuclear physics, Astrophysics, National Security

Accelerator Facility
160 MeV Linac pre-injector
160 MeV – 1.2 GeV Booster injector
240 MeV – 1.2 GeV Storage ring
FELs: OK-4 (lin), OK-5 (circ)
HIGS: two-bunch, 40 – 120 mA (typ)
**HIGS Capabilities: High Energy Operation**

**New Gamma-ray Energy Region: 70 – 100 MeV**

HIGS Circularly Polarized Gamma-ray Beam on 2010–09–29
\[ \lambda \text{ (OK–5 FEL)} = 192 \text{ nm}; \text{ SR Energy} = 1040 \text{ MeV}; \text{ Collimation } D = 12 \text{ mm} \]

- **Peak**: ~73 MeV
- **FEL**: 192 nm
- **E-beam**: 900 MeV
- **Peak**: ~97 MeV
- **FEL**: 192 nm
- **E-beam**: 1040 MeV

**Flux on target (D=12mm)**: \(1.3 \times 10^6\) (\(\gamma/s\))

**Total flux (4pi)**: \(2 \times 10^7\) (\(\gamma/s\))

**Significance**
- Opened new research frontiers: precise measurements of electric and magnetic polarizabilities, and spin polarizabilities of nucleons
HIGS Capabilities: Total Flux

HIGS User Flux Capabilities with OK-5 FEL

HIGS – World’s Most Intense Compton $\gamma$-ray Source

Peak Performance of HIGS

Total Flux: $>2 \times 10^{10} \gamma/s$, around 10 MeV
Spectral Flux: $>1,000 \gamma/s/eV$, around 10 MeV
### HIGS Capabilities for User Programs in 2013

#### HIGS Capabilities: Collimated Flux for User Research

#### Parameter | Value | Comments
---|---|---
E-beam Configuration E-beam current [mA] | Symmetric two-bunch beam 50 - 120 | High flux configuration
Gamma-ray Energy [MeV] | 1 – 100 | with mirrors 1064 to 190 nm Available with existing hardware Extending wiggler current to 3.5 kA

(a) No-loss mode

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Total flux [γ/s]</th>
<th>Collimated flux (ΔE/E~5%) [γ/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 3 MeV</td>
<td>1 x 10^8 – 1 x 10^9</td>
<td>6 x 10^6 – 6 x 10^7</td>
</tr>
<tr>
<td>3 – 5 MeV</td>
<td>6 x 10^8 – 2 x 10^9</td>
<td>3.6 x 10^7 – 1.2 x 10^8</td>
</tr>
<tr>
<td>5 – 13 MeV</td>
<td>4 x 10^8 – 4 x 10^9</td>
<td>2.4 x 10^7 – 2.4 x 10^8</td>
</tr>
<tr>
<td>13 – 20 MeV</td>
<td>1 x 10^9 – 2 x 10^9</td>
<td>6 x 10^7 – 1.2 x 10^8</td>
</tr>
</tbody>
</table>

(b) Loss mode

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Total flux [γ/s]</th>
<th>Collimated flux (ΔE/E~5%) [γ/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 – 54 MeV</td>
<td>&gt; 2 x 10^8</td>
<td>&gt; 1 x 10^7</td>
</tr>
<tr>
<td>55 – 65 MeV</td>
<td>~ 2 x 10^8</td>
<td>~ 1 x 10^7</td>
</tr>
<tr>
<td>66 – 100 MeV</td>
<td>~ 0.7 x 10^8</td>
<td>~ 0.4 x 10^7</td>
</tr>
</tbody>
</table>

#### Additional Comments:

- (a) With present configuration of OK-5 wigglers separated by 21 m, the circular polarization is about ½ the values here.
- (b) The flux in loss mode is mainly limited by injection rate.
- (c) Thermal stability of FEL mirror may limit the maximum amount of current can be used in producing FEL lasing, thus flux.

#### Highest Total Flux: >2x 10^{10} γ/s @ 9 – 11 MeV
HIGS Capabilities: Energy Spread

High Energy-Resolution Operation

356 MeV e–beam, Asymmetric bunch pattern \#0 = 5 mA and \#32 = 57 mA
738 nm OK4 lasing, 0.5" collimator, Run \#55, 11–01–2007

Gamma-ray Beam Energy Resolution

- High-resolution operation: asymmetric electron bunches, lower flux
- High-flux operation: typical 3 – 5% (or larger), selected by collimation
240 nm Mirror: 61 MeV \( \gamma \)-Beam Production

61 MeV, \( \gamma \)-ray, Cir., \( E_{\text{ebeam}} = 926 \text{ MeV} \), Col. \( D=12 \text{ mm} \), Mar. 2011

Highest energy gamma-ray beam delivered for experiments: 61 MeV, \(^6\)Li Compton Scattering
HIGS Capabilities: Beam Pointing Stability

Stability of Electron/Photon Collision Angle

Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5 µrad (peak to peak) during this operation, this value corresponds to 150 µm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision point. Typically, the collimator radius of the γ ray beam is 6 mm to 15 mm, therefore the misalignment caused by the beam orbit is about 2.5% to 1.0% of radius of the beam.
OK-5 Helicity Switch

Eb = 484 MeV, OK5W lasing, 770 nm, two bunch

Higgs Capabilities: Helicity Switch

2009-12-11
5.7 MeV
3-year HIGS Operation Summary


Accelerator Operation Reliability:  ~96%

<table>
<thead>
<tr>
<th>Activities</th>
<th>Beamtime</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIγS user research</td>
<td>4859</td>
<td>56.8%</td>
</tr>
<tr>
<td>UV research</td>
<td>251</td>
<td>2.9%</td>
</tr>
<tr>
<td>Acc. R&amp;D</td>
<td>760</td>
<td>8.9%</td>
</tr>
<tr>
<td>Acc./FEL/HIγS setup and tune</td>
<td>2356</td>
<td>27.5%</td>
</tr>
<tr>
<td>Unscheduled downtime</td>
<td>332</td>
<td>3.9%</td>
</tr>
<tr>
<td>Total scheduled beamtime</td>
<td>8558</td>
<td>100%</td>
</tr>
</tbody>
</table>
HIGS Development (2013 – )

New Capabilities Development in Two Fronts

- **Energy Front**
  
  FEL ~175 nm => 100 – 120 MeV gamma-ray beams
  
  FEL ~150 nm => 120 – 158 MeV gamma-ray beams

- **Intensity Front:** *Next Generation Compton Source at HIGS: HIGS2*
  
  - Hadronic parity violation
  
  - Nuclear astrophysics
  
  - Dark-matter search
HIGS with VUV FEL Operation

1. 66 – 100 MeV, 190 nm FEL: two OK-5 wigglers
2. 100 – 120 MeV, 175 nm FEL: two OK-5 wigglers
3. 120 – 158 MeV, 150 nm FEL: three OK-5 wigglers
The HIGS2 Concept

Next Generation High Intensity Gamma-ray Source (HIGS2)


Projected Performance
- ~2 micron FP cavity: 2 – 12 MeV
- Total Flux: few $10^{11} – 10^{12}$ gamma/s
- Pol: Linear, or Circular (rapid switch)
- Energy resolution (FWHM): < 0.5%

Research Programs
- Hadronic Parity Violation
- Nuclear Astrophysics
- Dark-matter Search
HIGS Capabilities vs Nuclear Physics Programs

1. 2007 Long-Range Plan for Nuclear Science in the USA (NSAC);
2. Courtesy of C. Howell, TUNL

To be developed
100 – 158 MeV

HIGS
1 – 100 MeV

Areas of Applications Research
- National Security: SNM detection
- Materials: Novel scintillators
- Energy: Nuclear waste
- Medical: Isotope production
- Industrial: product inspection