Inverse Compton Scattering Gamma-Ray Source at ASTA

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Outline

• Concept of inverse Compton scattering (ICS) light sources
  • Gamma-ray beams applications
  • Gamma-ray ICS source parameters at ASTA
  • Technical Implementation
  • Conclusions
X-ray light sources

- Synchrotron radiation X-ray light sources are very successful (over a dozen in operation, many under construction/upgrades)
- Ever growing demand from users in many disciplines
- Large facilities based of multi-GeV storage rings
Scaling to optical wavelength

- If undulator is replaced with the laser, one can make a light source much smaller

\[ \lambda_s \propto \frac{\lambda_0}{\gamma^2} \]

\[ \lambda_0 > 1 \text{ cm} \]
\[ \gamma \sim 10^4 \]

Football stadium size facility
Undulator radiation

\[ \lambda_0 \sim 1 \mu \text{m} \]
\[ \gamma \sim 10^2 \]

Room size installation
Inverse Compton Scattering
Inverse Compton Scattering (ICS)

Recoil electron
Scattered photon
Incoming photon
ICS (beam frame)

\[ k_s \approx 4\gamma^2 k_0 \left( \frac{1}{1 + a_L^2 + \gamma^2 \theta_s^2} \right) \]
\[ \sigma_{ICS} \approx \sigma_{th} \quad \text{for} \quad \gamma \ll \frac{\lambda_0}{\lambda_e} \sim 10^5 \]
\[ \sigma_{th} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25} \text{ cm}^2 \]

Incoming photons
Elastic collision
Scattered photons
TS (beam frame)

\[ \hbar \omega < < m_e c^2 \]

ICS

Optical photons
Scattered X-rays
lab frame

\[ \theta_s \sim 1/\gamma \]
ICS vs. undulator radiation

- Good news: ICS is a classical process very similar to the undulator radiation.
- Bad news: need high intensity laser to match undulator radiation efficiency.

\[ \beta_{\perp} \gamma \sim 1 \implies \begin{cases} K_U \approx 1 \\ B \sim 1 \text{ T} \end{cases} \iff \begin{cases} a_L \approx 1 \\ I \sim 10^{18} \text{ W/cm}^2 \end{cases} \]

- 1 J - class, picosecond laser focused to a spot size of \(~ 10 \mu\text{m}\)
**Photoinjector driven ICS**

- Picosecond beams focused to a small spot size means photoinjector e-beam system

\[ N_s \approx \frac{N_0 N_e \sigma_{th}}{A} \]

- 1 nC, 1 J, 10 µm RMS \( \rightarrow \) \( \sim 10^9 \) photons/interaction
Source bandwidth

- Finite intrinsic bandwidth
  - off-axis red-shift
  - 3D laser focus
  - laser bandwidth
  - emittance
  - e-beam energy spread

\[
\lambda_s(\theta) \approx \frac{\lambda_0}{4\gamma^2(1 + \gamma^2\theta^2)}
\]

\[
\frac{\Delta \omega}{\omega} \approx 2 \sqrt{\frac{\Delta \omega_0^2}{\omega_0^2} + \frac{\Delta \gamma^2}{\gamma^2}}
\]

\[
\frac{\Delta \omega}{\omega} \approx \frac{\varepsilon_{nx}^2}{X_f^2}
\]

Red-shift
off-axis

[Courtesy of W. Brown]
Photon yield requirements

- Best photon yield $< 10^9$ per interaction (so far, experimentally at optical wavelength $\sim 10^7$)
- Best spectral brightness $\sim 10^7$ photons in 1% bandwidth
- Most applications require $\sim 10^{10}$-$10^{11}$ cps in 1% bandwidth

- Hence, the optimized ICS operations regime is $10^4$-$10^5$ interactions per second.
ICS for Phase-Contrast Imaging

- Repetition rate to achieve $10^{11}$ cps in 1 % bandwidth:
  - current < 100 A
  - bandwidth limited
  - 1st harmonic only

Burst mode:
- ~ 100 Hz
- 100 bunches per macropulse

SCRF

CW, ~ MHz

NCRF

Minimum Repetition Rate [1/s] vs. Spot size at IP [microns]

- 1 J
- 10 J
- 100 mJ

- current < 100 A
- bandwidth limited
- 1st harmonic only
ICS technical challenges

- A minimum required is $\sim 10^4$ interactions per second, with the 1 J class laser
- Laser re-circulation via optical cavity
- Photoinjector has to operate in a bunch train mode
- E-beam concerns: quality, repeatability and sub-ps synchronization to the laser over pulse train duration
- For practical applications the entire system has to be high fidelity and turn key…

- It is hard to beat X-ray Light Sources
ICS gamma ray source

- **High efficiency** at high energy (~ 1% energy extraction efficiency, like FEL!)
- **Directionality** (~1 mrad)
- **Source brightness** scales like ~ $\gamma^4$
- **Uniqueness** – light sources do not reach MeV energies

[ F.V. Hartemann et al., *PR ST AB* 8, 100702, 2005]
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• **Gamma-ray beams applications**
• Gamma-ray ICS source @ ASTA
• Technical Implementation
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Applications: nuclear threat detection

- Gamma-ICS source can be used to detect concealed special nuclear materials (SNM) via photofission
- Low beam divergence, moderate scattering in atmosphere → stand-off distances up to 1 km!

[J.L. Jones et al., Neutrons Workshop at ONR, October 2006.]
Applications: nuclear waste analysis

- With high degree of monochromaticity nuclear resonance fluorescence (NRF) detection is also possible.
- NRF can also be used for SNM detection (LLNL)

[Photon energy (MeV) vs. photon energy (MeV) graph showing NRF signal for U-238 at 2.176 MeV.

[R. Hajima, Japan Atomic Agency ERL Group (2008).]
Applications: medical isotopes R&D

- ERL based gamma ray sources for isotopes production
- Even more interesting is generation of specific activity radioisotopes via photo-excitation by tuning to specific energy gammas.

<table>
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</table>

[D. Habs, P.G. Thirolf et al ” Medical Application Studies at ELI-NP”, 2012]
Applications: nuclear physics research

γ beam revolution of nuclear physics:
similar to laser revolution of atomic physics in’60s

γ rays: opens new nuclear physics
- measurement of neutron cross section of rare nuclei by inverse process of (γ,n)
- nuclear resonance fluorescence and spectroscopy
- particular excitation
  * nuclear electroweak excitation such as parity measurement
  * isomer creation
  * particular excitation and interaction with inner-shell electrons
- manipulation of nuclei by more than one gamma pulse
  * consecutive excitation to higher levels
  * exploration of exotic nuclear states?
  * quantum control of nuclear states
Applications: gamma ray “optics”

- Observation of “refractive” behavior above 0.7 MeV:
  - potentially new area of active research
  - possibility of making gamma-ray optics
  - possibility of ultra-monochromatic gamma beams (1E-6)

[D. Habs et. al. ” The Refractive Index of Silicon at γ Ray Energies”, PRL 2012]
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Gamma ICS @ ASTA

**E-beam**
- Charge: 3 nC
- Bunch length: ~30 ps
- Normalized emittance: ~5 µm
- Energy: 500-1000 MeV
- RMS spot size @ IP: ~20 µm
- Beta function: ~10 cm

**Laser**
- Pulsed energy: ~1 J
- Wavelength: ~1 µm
- Raleigh range: 5 mm

**Gamma rays (single shot)**
- Total flux: ~1x10⁹
- Gamma-rays energy: 5-20 MeV
- Flux in 1% bandwidth: ~3x10⁷

**Pulse train mode**
- Rep. rate: 3 MHz
- # of bunches in macropulse: ~10,000
- Average flux in 1% BW: ~3x10¹³ cps
- Average power of gamma flux: >10 W

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[C. Prokop, et al., (2011) P. Piot, AARD@ASTA, All Experiment Meetings, Dec. 5, 2011]
Numerical model

- Using W. Brown code simulated initial working point
- About 3% of photons in the 1% bandwidth
- Further optimization is possible
• Comparison of ASTA ICS to other gamma ICS facilities under construction/design stage

[Graph showing peak brilliance scaled to $E_\gamma = 10$ MeV for various facilities: PLEIADES, T-REX, HI$\gamma$S, MEGa-Ray, ERL 1 mA, ERL, ELI-NP.]

Gamma ICS @ ASTA

• Comparison of ASTA ICS to other gamma ICS facilities under construction/design stage:
  • Brilliance is in line with other efforts
  • Tunability could be superior (higher energy reach, ease of adjustment)
  • Cost is smaller, leveraged on the existing facility infrastructure
  • Could be operational in 2014
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Elements of the ICS system

- High duty cycle accelerator
- Laser system (synchronized to the e-beam)
- Laser recirculation cavity
- Final focus system
- Interaction chamber
- Detectors

RadiaBeam has recently conducted a pilot scaled experiment at ATF BNL (DTRA-funded SBIR project)
**High repetition rate accelerator**

- ASTA already has the accelerator
- Standard requirements (managing beam loading, 2\textsuperscript{nd} order dispersion, etc.)

[P. Piot, AARD@ASTA, Dec. 5, 2011]
Laser system

- Start with the photo-injector drive laser (well synched)
- Added amplifier to achieve (> 100 mJ/pulse)
- Spatial filter or adaptive optics for pulse profile control
- Transport, matching and diagnostics are laborious tasks
Laser recirculation

- RING recirculator (I. Jovanovich)
- Worked well at 80 MHz, but may not be so at 3 MHz
Laser recirculation

- Alternative schemes include:
  - 3 MHz cavity w/Pockels Cell
  - Fabry-Perot w/imaging mirrors

M0 – output coupler (90%-99% reflectivity mirror); M1 and M2 – near 100% mirrors; BP – Brewster plate polarizer, Q-sw – fast Pockels Cell

M0 – output coupler (95%-99% reflectivity mirror); M1 flat 100% mirrors; M2 curved 100% mirrors

[R. Tikhopolv]
Final focus system

- Small spot size interaction is critical to ICS efficiency
- PMQ in-vacuum final focus system was developed (~120 T/m); alignment is important

PMQs magnetic measurements stand

2 triplets, to focus the beam and clear it out of the chamber
Final focus system

- Beam tested with the pulse train of 20 x 0.5 nC
- 15 µm RMS spot size at IP as designed
- More recently ATF achieved 6 µm RMS with 300 pC
Interaction chamber design

Avoid damage to the mirrors
A. clearing holes
B. Interaction at angle
C. Chicane-like configuration
Most of other preparatory work for this section has been completed, including cleared out the space from the previous experiments, and moving several cable trays and ceiling lights to accommodate for the spatial filter. As of now there are no beam obstructions remaining throughout the entire hall, and all of the ceiling path breadboards are completed.

5.6 Spatial filter and amplifier installation

The spatial filter was pumped down with a turbo pump with the intent of testing how well it will retain vacuum. The vacuum level reached as low as $2 \times 10^{-4}$ Torr on the attached Pirani Gauge. However, only a few hours after the turbo pump was turned off, the spatial filter was back up to atmosphere. When pumped down again, a leak was detected in both lens/window assemblies. After evaluating the assemblies, the gaskets were determined to be the cause of the leak. Changes in the gasket design were implemented and the gaskets will be remade and retested.

We are still waiting to receive the modified Pockel Cell holder from Germany. Based on the present status information, it should be finished by mid-June.

5.9 I-box installation at ATF

The interaction box installation at the ATF is a major milestone in the project successfully completed during the reporting period. The process started by carefully planning the move of 1,000 lbs chamber in a very space limited experimental hall. The red heads has been installed in place, and the path was cleared. The BNL rigging team has designed a special handling set up (Fig. 1), to enable transport of the chamber while minimizing stress to the welding joints in the system.

Figure 1. Interaction box transportation set-up.
Detector and signal-to-noise

- Detection and clean beam removal are important for improved signal to noise.
- Figures of merit: response time and spectral sensitivity.
- Detection system should include shielding (to protect from e-beam halo bremsstrahlung, and collimation).
- For tuning high signal-to-noise is very important.
Conclusions

- High duty cycle gamma ray ICS source has many interesting applications
- ASTA facility beam parameters offer unique possibility to develop a state-of-the-art gamma ray ICS source at a relatively low cost
- Low but finite: requires dedicated beamline, laser system development, detection system, etc.
- Further system design and optimization could be a fairly straightforward task if it is of interest
- Thank you!