INVERSE COMPTON SCATTERING EXPERIMENT IN A BUNCH TRAIN REGIME USING NONLINEAR OPTICAL CAVITY *

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Abstract

Inverse Compton Scattering (ICS) is a promising approach towards achieving high intensity, directional beams of quasi-monochromatic gammas, which could offer unique capabilities in research, medical and security applications. Practicality implementation of ICS sources, however, depends on the ability to achieve high peak brightness (~0.1-1.0 ICS photons per interacting electron), while increasing electron-laser beam interaction rate to about 10,000 cps. We discuss the results of the initial experimental work at the Accelerator Test Facility (ATF) at BNL to demonstrate ICS interaction in a pulse-train regime, using a novel laser recirculation scheme termed Recirculation Injection by Nonlinear Gating (RING). Initial experimental results and outlook are presented.

INTRODUCTION

There is a growing applications-driven demand in the research, industrial, medical and defense communities for compact room-size X-ray sources capable to match the spectral brightness of the large synchrotron radiation facilities. One promising approach is to develop a linac driven Inverse Compton Scattering (ICS) system [1,2]. The ICS process generates X-rays with extremely high peak spectral brightness, while the system footprint could be small enough to allow deployment in hospitals, universities, and even on mobile platforms.

For a head-on relativistic electron-photon collision, the scattered ICS photon wavelength is given by,

$$\lambda_s \approx \frac{\lambda_L}{4\gamma^2}\left(1+\frac{{a_L}^2}{2}+\gamma^2\theta^2\right), \qquad (1)$$

where λ_L is an incoming laser wavelength, γ is a Lorentz factor, θ – scattered angle; and $a_L \cong 0.85\lambda_L[\mu m]{I_{18}}^{1/2}$ is a normalized vector potential (typically kept below unity to reduce harmonics excitation). Most of the ICS photons are generated within the Lorentz cone of $1/\gamma$; hence, with the moderate energy electron beam and an optical laser, ICS source can produce quasi-monochromatic, directional and tunable X-ray beams. Besides the relatively compact footprint, the important feature of ICS sources is a very favorable ($\sim\gamma^4$) extracted power density scaling at higher energies [3], which should make ICS the technology of choice for generation of hard X-rays and multi-MeV gamma ray beams.

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With the properly matched electron and laser beams, the maximum number of photons produced per interaction can be approximated as,

$$N_\gamma \approx \left[\frac{N_L N_e}{4\pi {r_b}^2}\right]\sigma_{th}, \qquad (2)$$

where r_b is the electron/laser beam rms radius at the focus, σ_{th} is the Thomson cross-section, and N_L and N_e are the number of photons and electrons per pulse, respectively. Thus, in order to increase the ICS flux, one must optimize both laser and electron beams brightness at the interaction point (IP). This requires a high quality, high peak power laser, and a low emittance, high peak current electron beam (such as produced by a photoinjector electron gun). Due to practical limitations on the IP density that can be achieved for both beams, increasing the number of ICS photons generated per interaction beyond ~ 10^8-10^9 range is difficult. Yet, per our estimate, most of the practical applications require photon fluxes on the order of 10^{12} cps. Hence, practical implementation of the ICS sources requites 10^3-10^4 interactions per second, which with the state-of-the-art technology could only be achieved when a bunch train electron beam interacts with the re-circulated laser beam.

As a part of the development program towards high average power ICS systems, RadiaBeam Technologies, in collaboration with Accelerator Test Facility (ATF) at BNL and Penn State University, conducted a pilot experiment to demonstrate ICS interaction in a pulse-train regime, using a novel laser recirculation scheme termed Recirculation Injection by Nonlinear Gating (RING) [4]. While the ultimate objective of generating pulse trains of hard X-rays has not yet been achieved, a number of encouraging experimental results has been demonstrated, including ultra-small electron beam generation and successful RING 2nd harmonic cavity commissioning.

EXPERIMENTAL SETUP

The experiment is hosted at the Accelerator Test Facility at BNL. The electron beam is generated with the 1.6-cell SLAC/BNL/UCLA type photoinjector, and accelerated with the two SLAC-type linac section, to achieve a nominal energy in the range of 50-70 MeV. After acceleration the beam is injected into the dog leg transport line, which directs it to one of the three users beamlines. RadiaBeam ICS experiment was located at the upstream section of the ATF user Beamline 1.

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Bunch Train E-beam Generation

Productions of bunch train electron beams at ATF starts with the photoinjector drive laser. For this experiment a 20-pulse laser train was generated, with about 60 µJ of UV per pulse on the cathode, 12.5 ns apart. The resulting photoinjector output generated a pulse of 20 electron bunches with the total charge of 30 nC (1.5 nC per pulse on average) on crest of the RF phase, and 15 nC (0.5 nC per pulse) at about 30° injection phase, where the beam quality was optimized (Fig. 1).

The pulse-to-pulse energy variation within the train were 20%, with the variations mimicking the UV laser pulse train profile. Further uniformity improvement was possible, but not necessary for the experimental purposes. A systematic energy chirp of electron beam pulses in the train was observed due to beam loading in the linac (3% energy spread over 20 pulses, vs. ~ 0.1% energy spread of the individual pulses), as shown in Fig. 1 (right). While beam loading could in principle have a negative effect on the ICS source performance, purpose build high current linacs routinely mitigate this issue by tailoring RF macropulse profile and linac coupling coefficients to compensate for the beam loading effects.

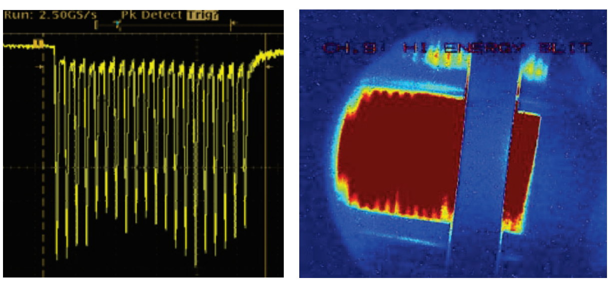

Figure 1: E-beam bunch train on the Faraday cup (left) and on a YAG:Ce screen after the bending magnet (right).

Re-circulated Laser Beam

The seed IR pulse of up to 20 mJ was sliced off the photoinjector drive laser and made available for the ICS experiment. An optical transport and matching line was constructed to bring the seed pulse into the experimental hall. A Continuum Nd:YAG amplifier was purchased and installed at the experimental hall. Initial tests indicated 20% gain uniformity over 1” rod area, with the average gain of about 3 x per pass. The seed pulse was transported twice through the amplifier to achieve up to 200 mJ in IR. An 8-meter long in-vacuum spatial filter was fabricated and installed, to improve M^2 of the laser beam at the entrance of the interaction chamber.

A ~100 mJ IR laser beam is injected into the interaction chamber and via doubling crystal into the RING resonator. The 2^{nd} harmonic (532 nm) is generated in the crystal and trapped inside the RING cavity. As the ICS process cross-section is very low, the losses in the resonator are strictly dominated by the reflection losses at the mirror, transmission losses at the crystal, and losses associated with the electron beam clearance holes in the mirrors.

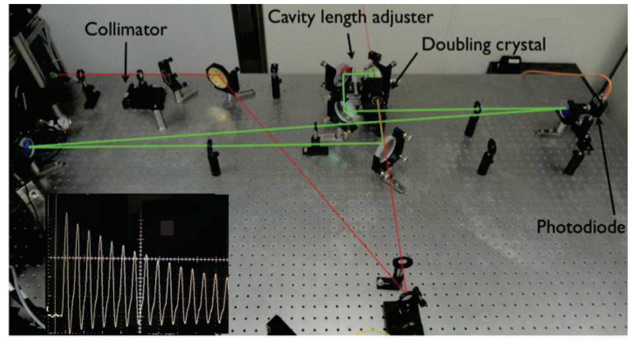

Figure 2: Bench test of RING cavity: IR pulse generated 2^{nd} harmonic in the crystal, and green pulses are trapped in the cavity. The photodiode shows 3.5% losses per pass.

The bench top test layout of the RING system is shown in Fig. 2. The cavity includes spherical focusing mirrors, a doubling crystal, cold mirror, and a translation stage to manipulate timing between the pulses. Quantitatively a RING cavity can be characterized by the enhancement factor (in our case ~ 25), which is the ratio of integrated recirculated power to the injected one in the first frequency-doubled pulse. A new and encouraging result was an excellent spatial overlap of the consecutive pulses at the focal point (stable position and profile to the limits of the measurements).

Interaction Chamber

The recirculated ICS interaction chamber (Fig. 3) is a 2 meter long UHV vessel comprised of the two side sections for RING focusing mirrors and a main section around the interaction point (IP). The e-beam bunch train clears entrance and exit of the chamber through sub-mm openings in the resonator spherical mirrors.

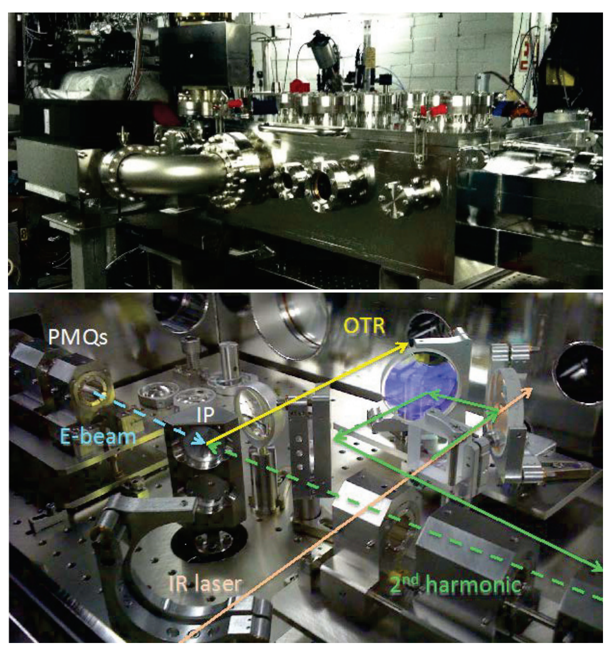

Figure 3: ICS interaction chamber (top) external view, and (bottom) inside of the main section of the chamber, showing the IR and green laser paths, IP, e-beam matching PMQ triplets, and OTR diagnostics.

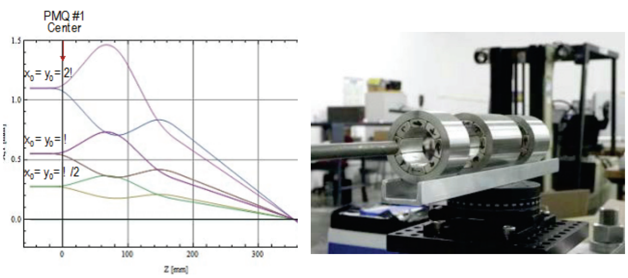

Figure 4: Design (left) and bench tip measurements (right) of the in-vacuum PMQ focusing triplet.

Inside the chamber the electron beam propagates through PMQ focusing triplet (Fig. 4), to achieve 15 μm RMS size at the IP, and through identical triplet it clears the chamber. A dual position/dual arm diagnostic system enables electron beam profile and position measurements with YAG and OTR screens, as well as simultaneous measurements of the laser spot at the IP (although not at full power).

EXPERIMENTAL RESULTS

The interaction chamber, and laser transport and amplification line were installed at the ATF in July 2011, and the experimental measurements were conducted through November 2011. The results (Table 1) were only partially successful, but the experiment had to be postponed due to schedule and budgetary constrains.

Electron beam nominal design parameters were achieved in as single pulse mode (Fig. 5), as well as in a pulse train mode. In-vacuum PMQ focusing triplets were successfully commissioned and enabled to comfortably achieve the target 15 μm RMS spot size and good beam propagation through the system. In addition, at a later time (April 2012) the same PMQ triplet was shown to generate an ultra-small 6 μm RMS spot sizes at ATF [5].

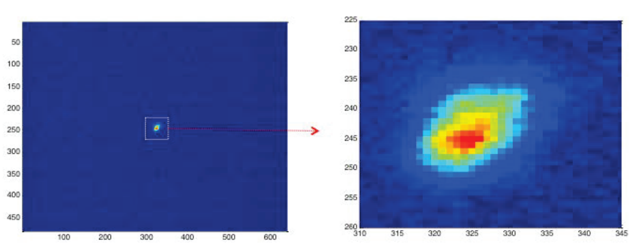

Figure 5: 15-μm RMS electron beam measured at IP using OTR diagnostic wafer. The pixels on the magnified image (right) are 3x3 μm.

On the other hand, the laser system took longer than planned to commission. The laser transport line length and complexity made it difficult to properly match the laser beam through the spatial filter and amplifier, and into the interaction chamber. The best spot size achieved at the IP was on the order of 100 μm RMS, significantly larger than the design value. Further improvement was relatively straightforward but labor intense, and did not fit into the compressed experimental schedule.

Even more importantly, the experimental progress was significantly hindered by the initially poor choice of the detection scheme for the experiment. The conventional scintillating diagnostics was dominated by the broad band X-ray noise from e-beam scattering and bremsstrahlung, and planned improvement of signal-to-noise ratio through spectrally resolved measurements of 180 keV X-rays turned out to be beyond the available experimental capabilities. When the problem was realized it was not possible, within the time remaining, to make necessary experimental modifications to reduce noise, such as placing the downstream bending dipole closer to the IP, such as was done at PLEIADES facility at Livermore [6]. Without a robust X-ray detection scheme, the single pulse data were inconclusive, and the bunch-train experiment was postponed.

Table 1: Summary of Experimental Parameters, Planned and Achieved (italicized values are estimated)

	Planned	**Achieved**
Electron beam (energy)	70 MeV	70 MeV
Charge per pulse	0.5 nC	0.5 nC
Pulses per bunch train	20	20
Spot size at IP, RMS	15 μm	15 μm
Laser Beam (wavelength)	532 nm	532 nm
Energy per pulse	100 mJ	50 mJ
Pulses per bunch train	> 20	1
Spot size at IP, RMS	15 μm	100 μm
ICS photons (peak energy)	180 keV	*180 keV (?)*
# of photons per pulse	$2x10^7$	*$5x10^5$ (?)*
# of photons per train	$2x10^8$	N/A

CONCLUSION

We report the first experimental attempt to operate ICS X-ray source in a bunch train mode. Electron and laser pulse trains were demonstrated separately, and the electron beam studies showed high quality electron beam at the IP. In the next round of experiment, pending funding availability, it is planned to improve the known issues in the laser transport system and detection to achieve design performance.

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