RE-CIRCULATED INVERSE COMPTON SCATTERING X-RAY SOURCE FOR INDUSTRIAL APPLICATIONS*

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Abstract

An experiment is under way at the Accelerator Test Facility (ATF) at BNL to demonstrate inverse Compton scattering in a pulse-train regime. A photoinjector generated electron beam pulse train is scattered by a recirculating laser pulse in a novel resonant configuration termed Recirculation Injection by Nonlinear Gating (RING). The goal of the experiment is to demonstrate strong enhancement of the ICS photon flux through laser recirculation. The project status is presented, and the long-term outlook is discussed with emphasis on the medical and security applications.

INTRODUCTION

There is a growing applications-driven demand in the research, industrial, medical and defense communities for compact X-ray sources capable to match the spectral brightness of the large synchrotron radiation facilities. One promising approach is to develop a compact linac driven Inverse Compton Scattering (ICS) system [1,2]. The ICS process produces X-rays with extremely high peak spectral brightness, while the system footprint allows deployment in hospitals, universities, or on mobile platforms, where the real estate is at a premium. Besides the compact footprint, the important feature of ICS is a favorable scaling towards higher photon energies [3], thus ICS is the technology of choice for applications in the multi-MeV spectral range. RadiaBeam Technologies, in collaboration with Accelerator Test Facility at BNL and Penn State University, is developing a compact, high average power multi-MeV ICS source for active interrogation of special nuclear materials (SNM). A pilot experiment is underway at the ATF to demonstrate average power enhancement of the ICS by using the novel RING laser recirculation technique.

For a head on relativistic electron-photon collisions, the scattered 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 much below unity to reduce parasitic emission at harmonic wavelengths). As a consequence, the minimum (on-axis) value of the ICS bandwidth is determined by the incoming electron and photon beam energy spreads (bandwidth), and angular divergences within the interaction region; however, the overall ICS source bandwidth is most often defined by a cut-off integration angle. As a consequence, varying the acceptance angle offers a trade-off between ICS source monochromaticity and directionality on the one hand, and an overall photon flux available altogether.

A simple estimate of the total number of photons produced per interaction can be made under the assumption that the laser and electron beam depths of focus (Rayleigh length, Z_R, and minimum beta-functions β_x, β_y respectively) are longer than either pulse lengths to minimize the "hour-glass" effect on the luminosity:

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

where r_b is the electron/laser beam rms radius at the focus, σ_{th} 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 number of photons produced per interaction, one must increase the density of electrons and laser photons. This requires a high quality, high peak power laser, and a low emittance, high peak current electron beam (produced by a photoinjector electron gun). Due to practical limitations on the density that can be achieved for both beams, increasing the number of photons per interaction beyond around 10^8 is difficult. On the other hand, most of the applications, such as phase-contrast medical imaging, or active interrogation at large stand-off distances require fluxes on the order of 10^{11}-10^{12} cps, which can only be achieved in ICS using a bunch train operation.

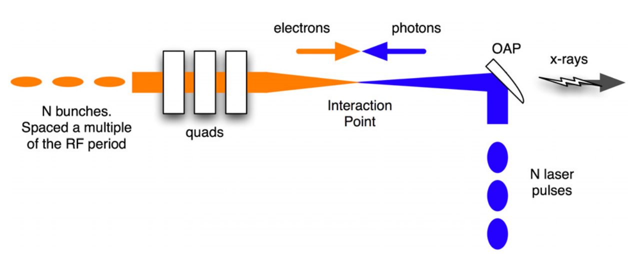

Figure 1: A conceptual diagram of the multi-bunch ICS.

EXPERIMENTAL SETUP

The photoinjector electron beam facilities have already demonstrated a bunch train mode operation [4], where a macropulse composed of up to 100 bunches 10s of ns

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apart; thus allowing overall flux enhancement by 2 orders of magnitude compare to a single shot operation (Fig. 1). On the other hand, high power lasers are typically single shot devices; hence laser recirculation on a 10s of ns timescale is necessary to take advantage of the bunch train regime. RadiaBeam is presently engaged into the pilot experiment to demonstrate for the first time strong enhancement of ICS flux in a bunch train regime using novel RING laser recirculation technique.

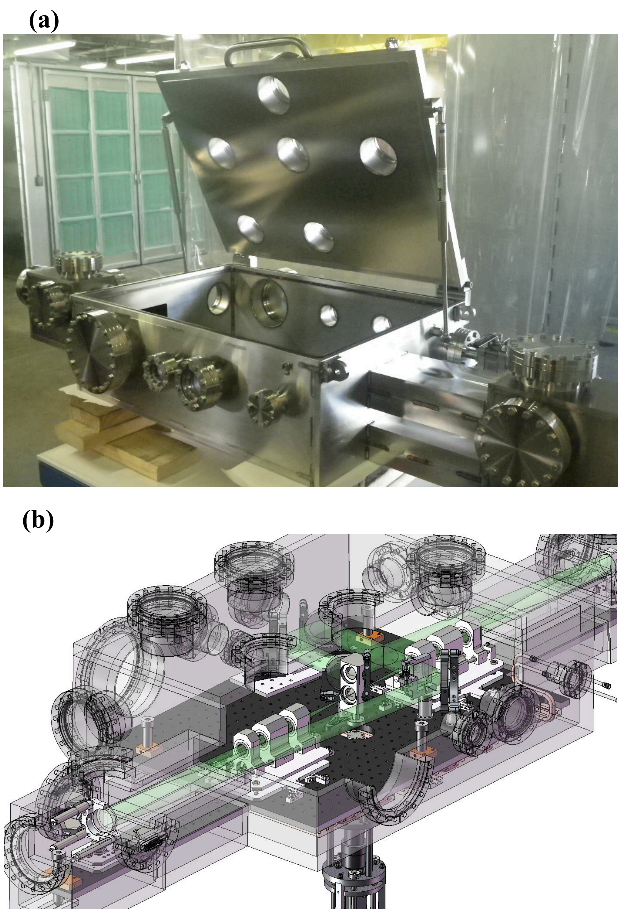

Figure 2: A photograph of the ICS interaction chamber prior to initial UHV test (a); and a CAD model of a full ICS assembly (b), showing vacuum chamber, diagnostics, laser beam envelope, PMQs and RING optics.

The recirculated ICS interaction chamber is shown in Fig. 2(a). The electron beam bunch train enters into the resonator through sub-mm openings in the spherical mirrors, where it propagates through permanent magnet quadrupole (PMQ) focusing triplet, to achieve 15 μm RMS size at the interaction point (IP), Fig. 2(b). After the IP the beam is matched to propagate through the opening in the output mirror, and eventually guided via bending magnet into the beam dump.

The 100 mJ IR laser beam is injected into the interaction chamber and passes through the doubling crystal inside the RING resonator. As a consequence, the 2nd harmonic (green) is trapped within the RING cavity. As the ICS process cross-section is very low, the losses in the resonator are strictly dominated by the resonator finesse. Quantitatively the RING cavity can be characterized by the enhancement factor *A*, which is the ratio of integrated recirculated power to the injected, frequency-doubled power (i.e. the power of the first pulse) [5]. It has been demonstrated to date that cavity *A* factors of ~50 can be achieved, though in the case of POC test this cavity enhancement factor is slightly reduced due to additional losses associated with the e-beam openings in the mirrors. For the ATF experiment, parameters of electron and laser beams, and projected ICS performance are shown in Table 1. This would be the first ever demonstration of the picosecond timescale re-circulated electron-laser interactions in a bunch train mode, and special efforts are dedicated to the issues of stability, and average flux optimization over many bunches.

If the results are successful, the follow up work may include development of a stand-alone system, aimed at achieving average photon flux of 10^{11}-10^{12} cps. The low-energy (LE) version of such system (30-40 MeV e-beam, 10s of keV X-rays) would find a number of applications in medicine, such as phase-contrast imaging; whereas high energy (HE) version is an ideal gamma ray source for a long-range stand off detection of special nuclear materials. Practically achievable parameters of such systems are also listed in Table 1 for comparison.

Table 1: Parameters of the Proof-of-concept (POC) ICS Experiment at ATF, and of the Future Practical Systems for Medical (LE) and Security (HE) Applications

Electron Beam	**POC**	**LE**	**HE**
Energy [MeV]	70	40	550
Charge per bunch [nC]	0.5	0.5	0.5
Bunch length, FWHM [ps]	40	20	10
Spot size at IP, RMS [μm]	15	15	8
Micropulse separation [ns]	12.5	12.5	12.5
No. pulses per bunch train	1-50	100	100
Macropulse rep. rate [Hz]	1-3	100	100
Laser Beam			
Wavelength [nm]	532	532	532
Spot size at IP, RMS [μm]	15	15	8
Synchronization jitter [ps]	< 1	< 1	< 1
Energy per pulse [mJ]	120	600	600
Pulse duration, FWHM [ps]	40	20	10
RING enhancement factor	20-30	20	50
Macropulse rep. rate [Hz]	1-3	100	100
Compton photons			
Peak energy [keV]	177	50	10.800
Maximum photon flux/shot	$2x10^7$	$1x10^8$	$4x10^8$
Maximum average flux [cps]	$2x10^9$	$2x10^{11}$	$2x10^{12}$
Angular acceptance [mrad]	< 1	< 10	< 1
Photon flux transmitted [cps]	$\sim10^8$	$\sim10^{11}$	$\sim10^{12}$

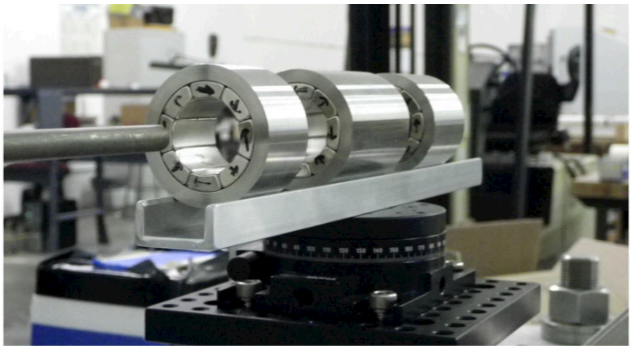

Figure 3: PMQ triplet on the test stand. The 3D Hall probe enables 3D field map measurements, which can be imported into ELEGANT for beam dynamics simulations.

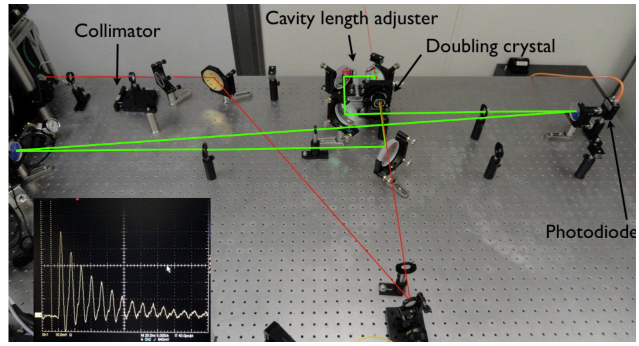

Figure 4: Initial bench top test of the RING resonator. An injected 1064 µm laser beam (red line) generates 2[nd] harmonic (green line), which is trapped inside the cavity.

PRESENT STATUS

At present the interaction chamber shown in Fig. 2 is being assembled and prepared for the installation. The PMQ triplet is fabricated and tested (Fig. 3), the results are in a good agreement with initial RADIA simulations (within 2% of the design parameters). The field maps are being measured for the final errors analysis and beamline tune corrections before installation into the vacuum chamber. The defocusing PMQ triplet is also being built, to enable e-beam clearance through the downstream opening in the optical resonator cavity mirror.

The RING resonator is being bench tested (Fig. 4), and the effects of mirror openings, radiation damage, and reflection losses, as well as on alignment tolerances, has been studied extensively, in order to optimize overall optical enhancement factor. The radiation test performed at ATF involved mirrors exposure to many hours of direct impact by the focused 50 MeV electron beam, and demonstrated no measureable damage to the reflective coating. The alignment tolerance and mirror opening tests also showed very good initial results, and so far the predominant source of optical losses inside the resonator is a doubling crystal mismatch. The new optimized crystal has been ordered, and once available (early April), it is expected to enable RING optical enhancement factor on the order of 20-30.

The initial e-beam bunch train generation experiments have also been performed at the ATF. The photoinjector drive laser beam was modified to enable pulse train generation, and a train of 20 electron bunches, 300 pC each, 12.5 ns apart was generated with a good pulse-to-pulse stability and repeatability. Beam loading effects has been observed in the dispersive section of a beamline; and plans are in place to mitigate beam loading problem via fine-tuning the relative phase of the ATF linacs to compensate for the energy loss in sub-sequent bunches.

The installation completion and initial experimental work is scheduled to start in May 2011. Initially, the optimization will be performed in a single shot regime, with the goal of obtaining on the order of $\sim 10^7$ photons per ICS interaction (limited by the laser pulsed energy available). Once the single shot regime is fully optimized, the multi bunch operation will commence. The initial goal is to demonstrate recirculation with 20 pulses per train, and eventually test the upper limits of the recirculation capabilities using 50 pulses per train.

CONCLUSION

The POC re-circulated ICS experiment is underway at ATF BNL, to demonstrate average flux enhancement by recycling laser pulse to interact with electron beam in a pulse train mode. If the results are successful, the follow up work may include development of a stand-alone system, aimed at achieving average photon flux of 10^{11}-10^{12} cps. The low-energy version of such source would find a number of applications in medicine and research, and due to a small footprint can be offered to hospitals and universities, as an in-house solution for high spectral brightness X-rays, which are otherwise only available at the synchrotron radiation light sources. The high-energy version of the ICS system is an ideal gamma ray source for defense and homeland security applications. To take a full advantage of such system, however, an additional development work is necessary, to reduce the 500-700 MeV ICS electron beam driver footprint to a practical size. These efforts, including Inverse Free Electron Laser (IFEL) and high gradient Radio Frequency (RF) accelerators developments are reported elsewhere [6,7].

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