HIGH-FLUX INVERSE COMPTON SCATTERING SYSTEMS FOR MEDICAL, INDUSTRIAL AND SECURITY APPLICATIONS*

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Abstract

Conventional X-ray sources used for medical and industrial imaging suffer from low spectral brightness, a factor which severely limits the image quality that can be obtained. X-ray sources based on Inverse Compton Scattering (ICS) hold promise to greatly improve the brightness of X-ray sources. While ICS sources have previously been demonstrated, and have produced high-peak brightness X-rays, so far experiments have produced low average flux, which limits their use for certain important commercial applications (e.g. medical imaging). RadiaBeam Technologies is currently developing a high peak- and average-brightness ICS source, which implements a number of improvements to increase the interaction repetition rate, as well as the efficiency and stability of the ICS interaction itself. In this paper, we will describe these improvements, as well as plans for future experiments.

INTRODUCTION

The Inverse Compton Scattering (ICS) process, in which relativistic electrons transfer momentum to the photons of a laser via backscattering, produces very bright, nearly monochromatic X-rays with very small source size and divergence. The physics of ICS has been thoroughly described in the literature [1,2], and has been demonstrated around the world at many labs [3,4]. Furthermore, ICS is currently being developed commercially for medical imaging and protein crystallography applications [5,6]. However, so far the practical use of ICS has been limited by insufficient flux: the current record for average photon flux generated by an ICS system is approximately 10^8 photons/second (at the PLEIADES experiment at Lawrence Livermore National Lab [4]), while most applications require a flux of around 10^{12} photons/second.

A simple estimate of the number of scattered photons in a single ICS interaction can be made under the assumption that the laser and electron beam depths of focus are both longer than either pulse length, and the focal spot sizes are identical:

$$N_\gamma \approx \left[\frac{N_L N_e}{4\pi r_b^2}\right]\sigma_{th}, \qquad (1)$$

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. Due to limitations on the density that can be achieved for both the laser and electron beams, increasing the number of scattered photons per interaction beyond around 10^9 is difficult, and is not likely to result in the several orders of magnitude improvement needed for applications. Increasing the repetition rate of the interaction is thus the most straightforward way of reaching the needed flux.

Some groups have taken this approach to the extreme, by proposing to interact a quasi-CW electron beam (i.e. from a storage ring [6] or superconducting accelerator [7]) with laser pulses stored in a resonant cavity. Unfortunately, this approach increases the complexity of the system and significantly decreases the flux-per interaction, as the brightness of the electron beam and peak power of the laser must be much lower.

Our proposed solution is to increase the repetition rate of the interaction using laser pulse recirculation to recycle the laser through the interaction region, and scattering off an electron bunch train from the photoinjector. Using this method can increase the average flux by a factor of over 100. While the fundamental idea is not novel [8,9], our design for the recirculator and other sub-systems has been carefully considered and optimized. In addition, we have included in our design an innovative Adaptive Optics system to maintain alignment stability at the interaction point (IP).

Table 1: Parameters of the Proposed ICS Sources

Parameter	ATF POC	ICS (Medical)	ICS (Security)
Electron beam energy	70 MeV	40 MeV	550 MeV
Charge per bunch	1 nC		
# of bunches per train	> 50	> 200	
Macro repetition rate	5 Hz	10 Hz	
Bunch length	10 ps		
Beam size at IP	15 µm	10 µm	7.4 µm
Wavelength at IP	532 nm		
Peak laser energy at IP	300 mJ	600 mJ	600 mJ
Pulse duration	10 ps		
X-ray energy	177 keV	50 keV	10.8 MeV
X-ray divergence	7 mrad	13 mrad	1 mrad
# of photons per shot	$1.0\text{x}10^8$	$5.0\text{x}10^8$	$1.0\text{x}10^9$
Average photon flux	$10^{10}\,\gamma$/s	$10^{12}\,\gamma$/s	$10^{12}\,\gamma$/s

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Table 1 lists the parameters of three proposed ICS systems that have been studied at RadiaBeam. The security system is designed to produce a beam of high-energy X-rays for long range detection of special nuclear materials. We have also investigated the design of ICS sources for medical imaging and research applications – as an example we include in the table a design for a 50 keV, 10^{12} photons/second medical ICS source. Finally, we list the parameters of a proposed proof-of-concept experiment to be performed at the Brookhaven National Laboratory Accelerator Test Facility (ATF POC).

In the remaining sections, we describe the sub-systems and components of our ICS systems in more detail, as well as our plans for future development.

LASER PULSE RECIRCULATOR

In order to achieve efficient laser recirculation, the recirculation injection by nonlinear gating (RING) approach [10] will be used due to the advantages that offers unique advantages for beam recirculation in ICS. In RING, shown in Figure 1, the recirculation is established by the injection of the beam via frequency conversion in a thin optical switch (nonlinear crystal). A set of dichroic flat mirrors and off-axis parabolas then recirculate the frequency doubled laser pulse and bring it to a focus at the interaction point. This offers the immediate benefit of frequency up-conversion, in addition to the evident advantages in simplicity and low cost.

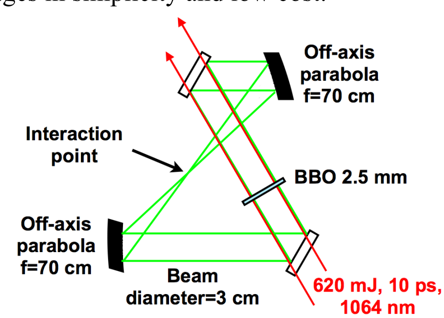

Figure 1: RING pulse recirculator

An important parameter for the RING is the cavity 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). It has been demonstrated to date that cavity *A* factors of ~50 can be achieved, and the needed factors of 100 for ICS should also be achievable with careful selection of the cavity mirrors. Note that due to the RING-down effect, an *A* of 100 requires > 200 recirculations.

Apart from the mirror reflectivity, an important design choice is the size and thickness of the frequency-doubling crystal. Thinner crystals have lower B-integral – the accumulated nonlinear phase shift, which affects the beam quality that can be achieved at focus. A thicker crystal will have higher conversion efficiency. However the increase in efficiency with thickness is limited by the temporal walk-off effect, where the phase-matching between the two frequency components in the crystal is lost by their differing group velocities. The practical solution to optimizing the efficiency and minimizing the B-integral is to reduce the intensity on the crystal and increase the thickness. This requires as large of a crystal aperture as possible.

BEAM CONTROL

Laser Adaptive Optics System

Adaptive Optics (AO) can be used to correct phase front distortions in high energy lasers. In the context of ICS, a phase correction system at the input to the RING would hold a number of advantages, including correction of any final aberrations, optimization of the focal spot, and a means of automatically maximizing the ICS process. The AO system will consist of two primary components: a beam stabilizer quickly corrects for jitter in the beam alignment, using two fast steering mirrors and two position sensitive detectors; and a Shack-Hartmann wavefront sensor and deformable mirror corrects for wavefront aberration.

Electron Beam

RF photo-injector systems are complex and difficult to tune and operate; hence, the development of a self-correcting feedback loop is an essential step towards future commercial systems. Analogous to the laser beam AO system, we will implement electron beam feedback loops to maintain beam quality and alignment at the final focus. We developed a conceptual design for a system to correct for drifts in RF phase, beam position, time of arrival and spot size.

ELECTRON BEAM FINAL FOCUS

Achieving the ~10 μm beam size at the interaction point requires a strong, in-vacuum focusing system. We have designed a baseline final focus system for the electron beam in both the high-energy (security) and low-energy (medical) ICS systems that consists of a permanent magnet quadrupole (PMQ) triplet. The triplet has three quadrupoles in an DFFDD configuration. The PMQ design uses a Halbach geometry [11] with 16 sectors. The high-energy system requires approximately 400 T/m gradients, while the low energy system would use ~50 T/m PMQs. With a remnant field of approximately 1 Tesla (using NdFeB magnets), gradients of up to 500 T/m are achievable with reasonable bore radius and magnet outer radius.

Tuning the strength of the focusing system can be accomplished by varying the longitudinal (z) position of individual PMQs. Individual PMQs will be mounted on precision machined holders, eliminating the need for adjustable alignment movers. The PMQ and holder assembly are then mounted on commercially available, computer controlled vacuum linear stages. The entire system is constrained by a reference rail, and fastened to the vacuum chamber. A rendering of the interaction region, showing the electron beam final focus system and the RING recirculator, is shown in Figure 2.

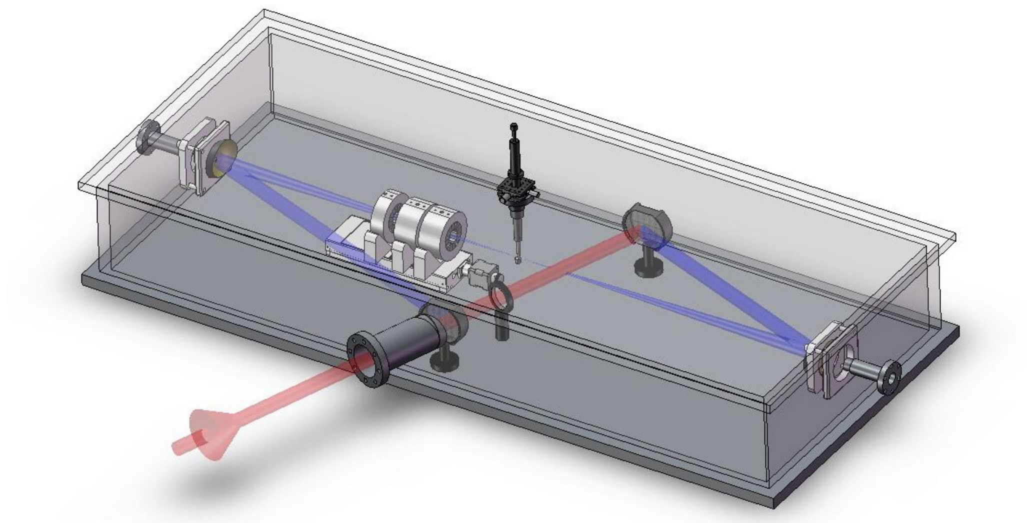

Figure 2: CAD rendering of the interaction region showing a simplified vacuum chamber, the laser path through the RING optics, PMQ final focus assembly, and diagnostic cube.

ACCELERATOR

The photoinjector gun will be an upgraded version of the standard BNL/SLAC/UCLA 1.6 cell design, which is currently offered by RadiaBeam. The gun will produce bunches of 1 nC and 2 µm normalized emittance. A train of ~200 bunches will be generated to match the recirculation frequency of the RING. We will use an active recirculator to generate the drive laser pulse train. The initial pulse is switched in with a Pockels cell, then recirculated and amplified. On each revolution a portion of the pulse energy will be extracted through one partially transmissive mirror, then converted to UV for the photocathode.

The medical ICS system requires a short (< 2 m) booster linac to accelerate from 5 MeV at the output of the gun to 40 MeV. The security ICS system requires acceleration to over 500 MeV. In order to reduce the footprint, we have designed a high-gradient, 50 MV/m, standing wave S-band linac. We chose S-band due to the availability of inexpensive RF components (klystrons, circulators, etc). Using this linac, the security ICS system would be ~12 m long and require only two commercially-available klystrons with SLED.

INTERACTION LASER

Our choice of 10 ps pulse length for the laser and electron beam was driven by an evaluation of the achievable alignment and timing tolerances of the interaction. A shorter laser pulse would allow for tighter focusing and thus lower pulse energies, however this would demand extremely tight spatial and temporal alignment. 10 ps pulse length is an optimal compromise between efficiency and stability. In addition, there are a number of mature laser technologies that can produce the required parameters. We have chosen Nd:YAG because such lasers are commercially available from many sources.

SUMMARY/FUTURE PLANS

We have developed designs for a number of possible commercial ICS systems, based on an robust, inexpensive laser pulse recirculator, automated beam control systems and optimized accelerator technology. The next step is to perform a proof-of-concept experiment to demonstrate our design. We have proposed to perform this experiment at the Accelerator Test Facility at Brookhaven National Lab, using the existing accelerator and Nd:YAG laser. We are currently seeking funding to perform this experiment.

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