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Picosecond Pulse Recirculation for High Average Brightness Thomson Scattering-based Gamma-ray Sources

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Picosecond Pulse Recirculation for High Average Brightness Thomson Scattering-based Gamma-ray Sources

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ABSTRACT

Pulse recirculation has been successfully demonstrated with the interaction laser system of LLNL's Thomson-Radiated Extreme X-ray (T-REX) source. The recirculation increased twenty-eight times the intensity of the light coming out of the laser system, demonstrating the capability of increasing the gamma-ray flux emitted by T-REX. The technical approach demonstrated could conceivably increase the average gamma-ray flux output by up to a hundred times.

INTRODUCTION

The T-REX source has recently been shown to produce gamma-rays enabling the detection of different isotopes through Nuclear Resonance Fluorescence (NRF) [1-2]. This source is the first of MEGa-rays – first source of ultra-high brightness monoenergetic gamma-rays.

The main challenge in exciting nuclear resonance fluorescence is with the sub-electron-volt narrowness of the absorption spectrum for the process. MEGA-rays are based on Thomson scattering of high intensity laser photons by a relativistic electron beam. Optimizing different parameters produces gamma-rays of high enough spectral density to detect re-radiated NRF photons from the isotopes under investigation. Conceivable applications for the technology include nuclear material detection, radioactive waste management, and radioactive waste transmutation.

Nuclear material detection by fluorescent imaging is attractive because of low false positives and low false negatives in comparison to current detection schemes. Even more attractive is the fact that inconclusive results are not mistaken for negative or positive ones. This allows for high-confidence inspection routines for ports and other possible illegal entry points for nuclear materials.

Radioactive waste management poses the challenge of knowing the exact isotopic composition of said waste. Tempting examination targets range from spent nuclear fuel pellets all the way to long-term nuclear waste storage containers. With fluorescent imaging, the targets' isotope composition could be determined. This determination requires NRF excitation of all the isotopes present. Only a tunable gamma-ray source can successively excite all the isotopes to undergo NRF. Furthermore, the gamma-ray source has to be sufficiently bright to make the NRF re-radiation detectable. Finally, the spatial distribution of each isotope is of interest. Tomographic reconstruction enables visualization of this spatial distribution. The gamma-ray source is quasi-collimated (sub-milliradian divergence), so it meets the requirements that tomographic reconstruction algorithms have for the sources.

Photo-fission is an extremely promising technique for dealing with radioactive waste. The idea is to induce fission among toxic and highly radioactive isotopes through photon absorption. Eliminating highly undesirable isotopes from radioactive waste would greatly alleviate problems with radioactive waste disposal.

All the applications described above require a high-brightness; high-spectral-density; and tunable, low-divergence source of MeV gamma-rays. T-REX is the first demonstrated source to have all those characteristics. Alternative sources of MeV gamma-rays use synchrotron light or bremsstrahlung. These sources are fifteen orders of magnitude less bright then T-REX.

T-REX consists of two arms – the accelerator producing the electron beam and the laser system which produces the high-intensity laser beam. These two beams meet at the interaction point to produce gamma-rays. We present results of the proof-of-concept experiment. This experiment proves the feasibility of an upgrade to the interaction point. The upgrade allows for the recirculation of the laser light. This recirculation has been demonstrated to increase twenty-eight times the amount of light interacting with the electron beam. The technical approach taken for the upgrade engineered is termed Recirculation Injection by Non-linear Gating (RING).

Section II will describe the theory behind T-REX and RING. Section III will describe RING together with the experimental setup for the RING viability demonstration. Section IV will present measurements demonstrating the viability of the RING upgrade to T-REX. Section V will present the conclusions.

II Theory

The T-REX source utilizes Compton scattering high intensity laser photons of a relativistic electron beam. Let us derive the Compton scattering formula from first principles. An electron with momentum $\vec{u}$ interacts with a photon of frequency ν. Let the electron's momentum after the interaction be $\vec{v}$ and the scattered photon's frequency be ν_0. We further assume that the electron and the photon undergo a head-on collision: that the electron moved in the +z direction and the photon moved in the –z direction prior to interaction. The outgoing photon's momentum is at angle θ with z-axis. Figure 1 illustrates the geometry of the problem:

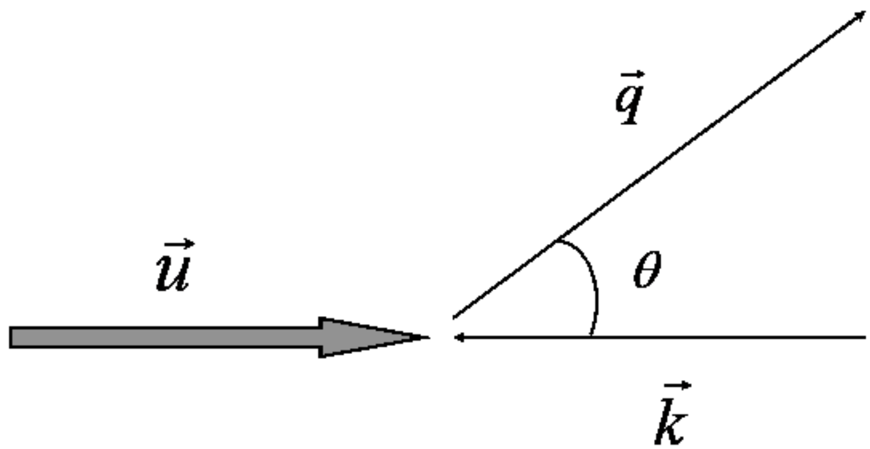

Figure 1. Momenta of the electron ($\vec{u}$) and the photon ($\vec{k}$) before the scattering, and the momentum of the photon ($\vec{q}$) after the scattering.

Here are the corresponding 4-vectors:

$$
\begin{aligned}
u_\mu &= \gamma \cdot m \cdot c \cdot (1,0,0,\beta) \\
k_\mu &= h \cdot \nu \cdot \frac{1}{c} \cdot (1,0,0,-1) \\
q_\mu &= h \cdot \nu_0 \cdot \frac{1}{c} \cdot (1, \sin(\theta), 0, \cos(\theta)) \\
v_\mu &= u_\mu + k_\mu - q_\mu
\end{aligned} \tag{1}
$$

The last equation in (1) is the conservation of 4-momentum applied to the problem. It is the recoiling photon's 4-momentum. Let us find the length of the 4-vectors on both sides of the last equation in (1):

$$v_\mu \cdot v^\mu = (u_\mu + k_\mu - q_\mu)\cdot(u^\mu + k^\mu - q^\mu)$$
$$v_\mu \cdot v^\mu = u_\mu \cdot u^\mu + k_\mu \cdot k^\mu + q_\mu \cdot q^\mu + u_\mu \cdot k^\mu + k_\mu \cdot u^\mu - u_\mu \cdot q^\mu - q_\mu \cdot u^\mu - k_\mu \cdot q^\mu - q_\mu \cdot k^\mu$$

Now let us apply the following properties of 4-vectors:

- For the electron: $v_\mu \cdot v^\mu = u_\mu \cdot u^\mu = m^2 \cdot c^2$
- For the photon: $k_\mu \cdot k^\mu = q_\mu \cdot q^\mu = 0$
- For any two 4-vectors: $a_\mu \cdot b^\mu = b_\mu \cdot a^\mu$

Applying these gives:

$$m^2 \cdot c^2 = m^2 \cdot c^2 + 0 + 0 + 2\cdot(u_\mu \cdot k^\mu - u_\mu \cdot q^\mu - k_\mu \cdot q^\mu)$$
$$u_\mu \cdot k^\mu - u_\mu \cdot q^\mu = k_\mu \cdot q^\mu$$

Now plugging in for all 4-vectors from (1):

$$\gamma \cdot m \cdot h \cdot \nu + \gamma \cdot \beta \cdot m \cdot h \cdot \nu - \gamma \cdot m \cdot h \cdot \nu_0 + \gamma \cdot \beta \cdot m \cdot h \cdot \nu_0 \cdot \cos(\theta) = \frac{h^2 \cdot \nu \cdot \nu_0}{c^2}\cdot(1+\cos(\theta))$$
$$\nu + \nu \cdot \beta - \nu_0 + \nu_0 \cdot \beta \cdot \cos(\theta) = \frac{1}{\gamma}\cdot\frac{h}{m\cdot c}\cdot\frac{\nu}{c}\cdot \nu_0 \cdot (1+\cos(\theta))$$
$$\nu_0 = \frac{1+\beta}{1-\beta\cdot\cos(\theta) + \frac{1}{\gamma}\cdot\frac{h}{m\cdot c}\cdot\frac{\nu}{c}}\cdot \nu$$
$$\nu_0 = \frac{1+\beta}{1-\beta\cdot\cos(\theta) + \frac{1}{\gamma}\cdot\lambda_c\cdot k}\cdot \nu$$

We substituted for Compton's wavelength $\lambda_c = \dfrac{h}{m\cdot c}$ and $k = \dfrac{\nu}{c}$. Now we need to do small-angle approximation together with high-γ approximation:

$$\cos(\theta) \approx 1 - \frac{\theta^2}{2}$$
$$\beta = \sqrt{1-\frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\cdot\gamma^2}$$

After doing a little algebra, one can get:

$$\nu_0 \approx \frac{4\cdot\gamma^2}{1+\gamma^2\cdot\theta^2 + 4\cdot\gamma\cdot\lambda_c\cdot k}\cdot\nu \qquad (2)$$

This is the general result for Compton scattering for the geometry described in Figure (1). T-REX uses electrons with high γ values, which makes the spectrum of light coming out of it fairly narrow, both in energy and in angle. Furthermore, controlling γ controls the energy of the up-shifted photons. Thus, almost all the requirements of the gamma-ray source mentioned in introduction are met. The only requirement that the gamma-ray source has yet to meet is the number of gamma rays emitted per second. This could be achieved by recirculation of the light at the interaction point.

The recirculation is achieved by using the RING cavity. Let us calculate the cavity enhancement, i.e. how much more light could be made available if instead of a single pulse, there is a train of pulses getting to the interaction point. It is important to remember that the laser pulse is very short, so there is no interference between different reflections and re-reflections of the main pulse. Let us assume L to be roundtrip loss, and I_0 to be the intensity of the first pulse in the cavity (the intensity we would have gotten at the interaction point without RING). Every cavity roundtrip knocks down the intensity by a factor of $1-L$. To get the total intensity available we need to sum the infinite geometric series:

$$I = \sum_{n=0}^{\infty} I_0 \cdot (1-L)^n = \frac{I_0}{L}$$

This gives the enhancement factor of:

$$\frac{I}{I_0} = \frac{1}{L} \tag{3}$$

The roundtrip loss is a combination of loss to non-unity reflectivity of the mirrors, absorption losses, diffraction losses, and other losses in the cavity and the amount of light turned into gamma-rays by scattering. T-REX has on the order of 10^{18} photons trying to interact with 10^{10} electrons. This means that photon loss due to scattering is insignificant when compared to other losses. Mirrors can easily have reflectivity better than 99.5%. L could be estimated at 0.01. Such loss means RING enhancement could easily result in a hundredfold increase in the light at the interaction point. This, in turn, makes for a hundredfold increase in the gamma-ray output from T-REX.

III Experimental Setup

Figure 2 is a photograph of the experimental chamber utilized in the proof-of-concept RING experiment. The chamber is evacuated and supplied with high-transmission windows to let in a laser pulse with a wavelength in infrared range. The frequency doubler (a 2ω converting crystal) creates a green pulse out of available infrared light. Mirrors 1 and 2 form a laser cavity for the green pulse to show recirculation. All diagnostic measurements are made on the green light's leakage through the back of Mirror 2.

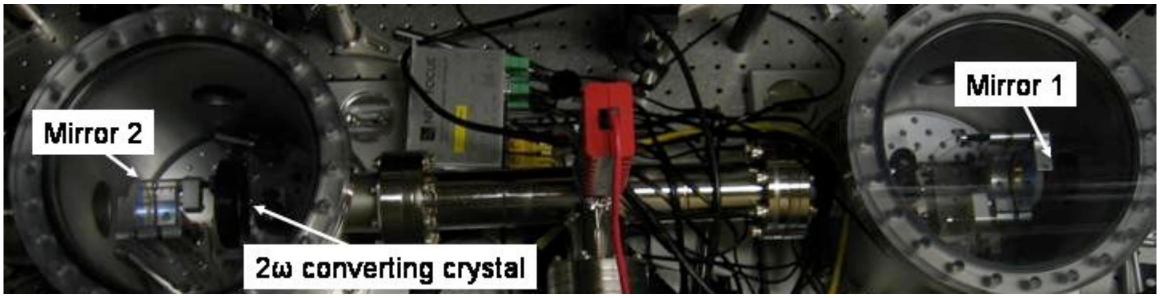

Figure 2. RING proof-of-concept experimental chamber.

The vacuum chamber provides for remote adjustment of the mirror's pointing, cavity length, and the doubling crystal's tip and tilt. This allows all possible adjustments to be made while the cavity is under vacuum. The mirror-to-mirror size of the cavity is $750mm$. Both mirrors are concave with radii of curvature around $750mm$, making the cavity self-imaging. Thus there is a focus in the middle of the cavity to mimic focusing at the interaction point. The vacuum is desirable to minimize non-linear phase accumulation and optical breakdown.

Of interest is the enhancement provided by the cavity. Therefore, the main measurement needed is the intensity of the light leaking through Mirror 2 and outside of the chamber versus time. A fast diode is illuminated by the leakage. The diode's response is fed into the fast oscilloscope, thus providing an intensity-versus-time trace. The total enhancement would be the ratio of the energy in all the pulses in the train over the energy of the first pulse.

This setup is designed to demonstrate production, recirculation, and enhancement of the green light only. A real RING upgrade to T-REX or any other MEGa-ray would require linear accelerators capable of producing multiple-electron bunches per single original (infrared) laser shot.

Noteworthy is the fact that the cavity length could be adjusted to match the repetition rate of the electron bunches interacting with green light. The cavity in Fig. 2 was designed to provide a roundtrip time of $5ns$. Any optics needed to prepare the green light for the profile needed can easily fit in the lasing cavity. Figure 3 is the design scheme proposed for a RING upgrade to a Compton-based gamma-ray source.

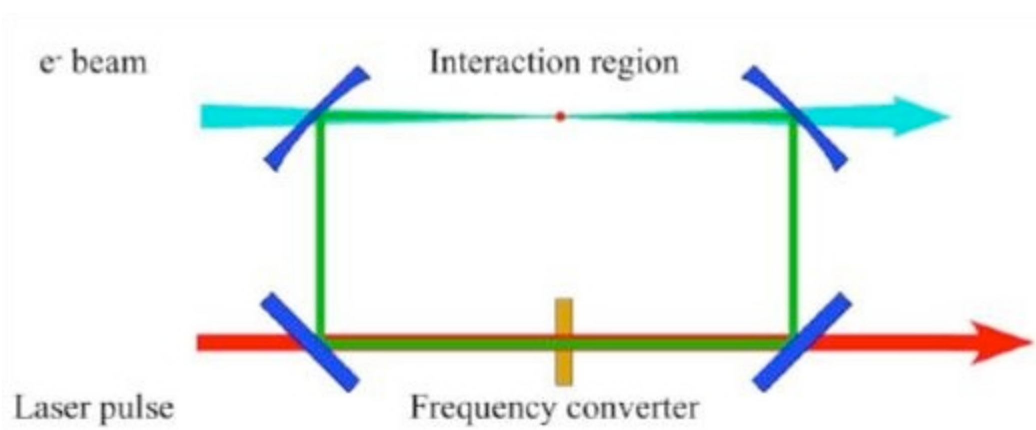

Figure 3. Design scheme for RING upgrade.

The red color denotes the original infrared pulse. The green color is the green pulses that are trapped in the cavity to be focused down in the interaction region. The electron beam (teal arrow) comes in through small holes in the two mirrors depicted on top to interact with the green light.

IV Experimental Results

Figure 4 shows the trace of the energy on the diode vs. time; an enhancement factor of twenty-eight is calculated from the data.

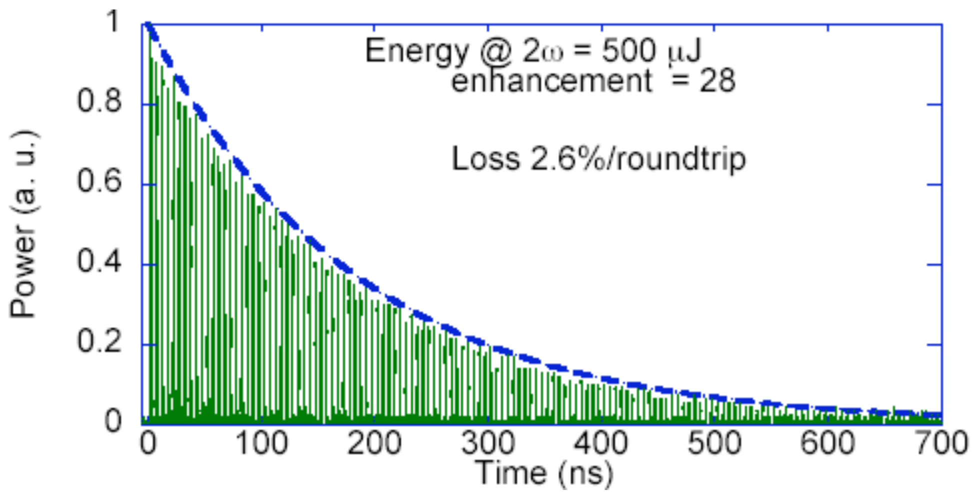

Figure 4. Intensity of green light in the cavity vs. time.

The green beam had the following parameters: wavelength $\lambda = 532nm$, energy of the first pulse $E = 500mJ$, duration of the first pulse $\tau = 10ps$, and effective roundtrip loss $L = 2.6\%$.

CONCLUSION

The RING upgrade to the laser system of a T-REX gamma-ray source has been demonstrated to be viable. Furthermore, laser energy in the green portion of the spectrum has been shown to be enhanced by a factor of twenty-eight. This work opens up possibilities for recirculating cavities around the interaction points of MEGa-rays.

Nevertheless, there are some challenges remaining with the Joule-scale beam recirculation. The main challenges are:

- Optical damage and nonlinear phase accumulation from high fluence and high pulse intensity.
- High thermal gradient on nonlinear crystal.
- High sensitivity to wavefront aberrations.

Let us discuss proposed ways around the difficulties. High fluence and high pulse intensity could be engineered around through increasing beam size. Since both problems are reduced with an increased beam cross-section, this solution seems to be straightforward. This solution comes with the price. A larger beam size means higher sensitivity to wavefront aberrations. The adaptive optics approach might counteract aberrations, i.e., a deformable mirror with a feedback loop could ensure the wavefront quality needed. All these difficulties seem to be surmountable through careful engineering.

The next big challenge to the RING is the demonstration of compatibility with the next generation gamma-ray source under development at LLNL. This source has a higher rep rate ($120Hz$ instead of $10Hz$) and a higher per pulse energy (up to $9J$). Modeling of the RING system needs to be done by incorporating those new parameters. Furthermore, RING upgrade compatibility would have to be experimentally demonstrated again with this new laser.

With the work completed, it is safe to assume that the RING is a viable upgrade to any MEGa-ray. It is a relatively cheap and simple way of enhancing gamma-ray flux by order(s) of magnitude. Insufficient total and spectral brightness is the main problem with the gamma-ray sources currently in operation. RING-type upgrades can provide just the flux enhancement needed to make a viable NRF-based system for nuclear detection, radioactive waste management and photo-fission.

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