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High-power laser pulse recirculation for inverse Compton scattering-produced γ-rays

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Abstract

Inverse Compton scattering (ICS) of high-power laser pulses on relativistic electron bunches represents an attractive method for high-brightness, quasi-monoenergetic γ-ray production. The efficiency of γ-ray generation via ICS is severely constrained by the small Thomson scattering cross-section. Furthermore, repetition rates of high-energy short-pulse lasers are poorly matched with those available from electron accelerators, resulting in low repetition rates for generated γ-rays. Laser recirculation has been proposed as a method to address those limitations, but has been limited to only small pulse energies and peak powers. Here we propose and experimentally demonstrate an alternative method for laser pulse recirculation that is uniquely capable of recirculating short pulses with energies exceeding 1 J. ICS of recirculated Joule-level laser pulses has a potential to produce unprecedented peak and average γ-ray brightness in the next generation of sources.

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1. Introduction

Inverse Compton scattering (ICS) exhibits some favorable characteristics not present in other methods for generation of X-rays and γ-rays, such as directionality and quasi-monochromaticity [1]. The resulting potential for high brightness of sources based on ICS is of significant interest for numerous applications, including high-energy physics [2], nuclear transmutation and spectroscopy [3–6], and medical diagnostics and treatment [7,8]. The projected brightness of such sources increases nonlinearly with the photon energy [9], which significantly improves their brightness and utility at energies $\gtrsim 1\,\mathrm{MeV}$.

In addition to the monochromaticity and directionality, other desired characteristic of ICS-produced γ-rays include high peak power (photon number in unit time per pulse) and high average power (repetition rate). High peak power is desirable in applications that require good temporal resolution, such as time-resolved radiography, as well as applications in which reduced integration time may produce improved signal-to-noise ratio. High average power would be of great benefit in applications in which the integrated energy (photon number) delivered to the sample is essential, such as nuclear transmutation/spectroscopy and medical applications. In those applications high average power reduces the operation time or, alternatively increases the scanning rate.

ICS-based γ-ray sources are based on the combination of two different technologies: electron accelerators and high-energy short-pulse lasers. The relativistic electron bunches are normally generated by conventional linear electron accelerators [2,10], preferably equipped with low-emmittance photoinjectors. High-energy short laser pulses can be produced by modern solid-state chirped-pulse amplification systems [11]. In the recent period, some convergence of two technologies has occurred with the demonstration of monoenergetic laser-based electron accelerators [12], with increasing prospects for their use in all-laser-driven γ-ray production via ICS [13].

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In the ICS interaction, the small Thomson scattering cross-section limits the efficiency of conversion of incident laser photons to γ-rays. Typical backscattered fraction of the incident photons is $<10^{-9}$, so that the ICS interaction region is essentially transparent to laser photons. Furthermore, a significant technology gap in repetition rate exists between linear accelerators and high-energy short-pulse lasers. While the linear accelerators are capable of producing electron bunches in bursts with repetition rates of ~GHz, typical joule-level short-pulse lasers are limited to ~10-Hz repetition rates.

Recirculation of the laser pulse has been previously proposed as a method to bridge some of this technology gap. For the future International Linear Collider (ILC), 2820 micropulses in a macropulse are proposed, generated by resonant cavity build-up and recirculation [2,14]. Recirculation of high-energy short pulses by resonant cavity coupling requires interferometric alignment accuracies and high-energy laser sources with high repetition rates, or the use of multiple such sources.

In this paper we propose and experimentally demonstrate a novel method for high-energy laser pulse recirculation based on the injection and trapping of a single incident laser pulse in a passive optical cavity, akin to "burst-mode" operation. This method circumvents the B-integral limitations of conventional optical switching by the use of a thin nonlinear switch based on frequency conversion in a nonlinear crystal. Following the nonlinear pulse injection, subsequent recirculation is shown to be capable of increasing the average power and brightness of ICS-based γ-ray sources by a factor of ~100. Further, this recirculation method, termed recirculation injection by nonlinear gating (RING), is scalable to >100-J, ps pulses, well beyond the capability of alternative recirculation methods.

In addition to the proof-of-principle experimental demonstration, we provide the estimate of the effect of RING recirculation on the spectral and spatial characteristics of the recirculating pulse, of relevance for the characteristics of generated γ-rays. It is also shown how the RING method can be applied to generation and recirculation of tunable laser pulses, as well as for simultaneous recirculation of multiple laser frequencies, which can enable simple tunable or polychromatic γ-ray sources. The use of RING is compatible with the current paradigm of ICS-based γ-ray sources, offering a significant improvement in average power and possible reduction in laser energy and electron accelerator energy. The concept is complementary to the much costlier development of higher repetition rate lasers, and it could also be used in conjunction with higher repetition lasers when they become available.

2. Laser recirculation methods and limitations

Laser recirculation has been used for numerous applications, primarily motivated by the need for higher power output. The use of laser recirculation is intertwined with the development of the resonant cavity which enables the laser action itself. Approaches to laser recirculation demonstrated to date can be classified by several criteria, and here we mention some of the important examples, their features and limitations.

Intra-cavity components can include only passive elements which result in power (energy) loss and rely on external coupling of the light. Alternatively, a cavity can also include a gain element such as a laser or a parametric device, which can compensate for the cavity power loss [15]. For most ICS applications of interest, the recirculated laser pulse is short and the required pulse energy is high, which is incompatible with direct amplification in a compact laser amplifier due to spectral and spatial modification of the propagating pulse. The nonlinear phase accumulation (B-integral) due to self-phase modulation of the medium from an intense optical pulse can be written as

$$\phi^{(2)}(x,y)=\frac{2\pi}{\lambda}\int_0^L n_2 I(x,y,z)\,\mathrm{d}z \tag{1}$$

where $\phi^{(2)}$ is the accumulated B-integral, λ is the laser center wavelength, n_2 is the nonlinear refractive index of the material, $I(x,y,z)$ is the pulse intensity, and L is the length of the medium along pulse propagation direction z. In a typical laser amplifier, the accumulated B-integral per pass is incompatible with direct amplification and recirculation of a short energetic laser pulse. In such cases the use of chirped-pulse amplification [11] would be preferable, but would require a sensitive, complicated setup exhibiting average power limitations due to intra-cavity pulse stretching and compression.

Passive optical cavities are designed to exhibit minimum loss and require continuous or pulsed coupling of an external laser source into the cavity via resonant cavity coupling [16] or via a dedicated optical switch [17]. In resonant coupling, a stringent phase requirement exists for the light incident into the cavity for the constructive interference to occur. For cw light, this corresponds to the incident light spectral overlap with existing cavity modes. For pulsed light, the phase of the incident pulse needs to match the phase of the recirculating pulse and the repetition rate of the incident pulses needs to be identical or a subharmonic of the recirculating pulse. These interferometric requirements correspond to sub-100 nm positioning of optical components for optical frequencies. In a non-resonant coupling scheme, an optical switch such as an electro-optic or acousto-optic modulator can be used to actively modulate the pulse using an external electric or magnetic field [17], or modulate the properties of the switch itself to trap the pulse in the cavity. Conventional linear switches require interaction lengths of several cm and thus encounter the problem identical to active cavities when used with energetic short laser pulses. For even modest pulse energies, the required apertures of such switches that result in acceptable nonlinear phase accumulation are prohibitively large.