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研究課題名（英文）Relativistic Flying Mirror Gamma Ray Source

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研究成果の概要（和文）：コウモリはその位置を決定するために超音波を使用します。 彼らのエミッター（鼻）とレシーバー（耳）は両方とも動いているので、彼らは二重ドップラー効果を経験します。 アインシュタインは、これが光速近くで動く鏡から反射された光で起こり得ると予測しました。 プラズマ中を伝播するレーザは、相対論的ミラーから反射するレーザパルスがミラーを著しく乱さないほど低い強度を有する場合、レーザ光を反射、圧縮、およびアップシフトする破壊プラズマ波（相対論的ミラー）を生成することが示されています。数値シミュレーションにより、強いレーザーパルスでも相対論的ミラーで反射し、はるかに短い波長の光を生成できることを示しました。

研究成果の学術的意義や社会的意義
Relativistic mirrors reflecting high intensity laser pulses can generate ultrashort high-intensity short wavelength light. This has applications for imaging of ultra-short phenomena. This upshifted laser light could be used to generate electron-positron pairs from vacuum.

研究成果の概要（英文）：Bats use ultrasound to determine their position. Because their emitters (nose) and receivers (ears) are both moving, they experience the double Doppler effect. Einstein predicted this can occur with light reflected from a mirror moving near light speed. Lasers propagating in plasma have been shown to generate breaking plasma waves (relativistic mirrors) which reflect, compress, and upshift laser light where the laser pulse reflecting off the relativistic mirror had low intensity to not significantly perturb the mirror. We showed via numerical simulations that even strong laser pulses can reflect off relativistic mirrors and generate much shorter wavelength light.

研究分野： laser plasma interaction

キーワード： plasma　mirror　relativisitic

１．研究開始当初の背景

Petawatt (PW, 10^{15} W) lasers having 10's of femtoseconds duration (fs, 10^{-15} s) have been and are being developed. When these lasers are focused to spot sizes of micron order, ultra-high intensities ~ 10^{22} W/cm^2 are achieved. Multi-PW lasers will produce intensities ~ 10^{23} to 10^{24} W/cm^2. At these intensities we and other groups have shown that greater than 30% of the laser energy can be converted into γ-ray photons when multi-PW lasers interact with high energy electrons and solid targets (radiation reaction dominant regime). Since the resulting γ-rays are of the order of the laser pulse duration (10's of fs), these sources generated from solid targets are expected to reach ultra-high PW levels and have photon energies in the 10's of MeV range. However, the energy range is broad and the angular distribution is expected to be within a relatively broad cone based on classical (~30°) and quantum mechanical calculations (~80°). We have shown that extremely short coherent light pulses with photon energies greater than optical levels focused to extremely small spots can be achieved from the interaction between plasma and ultra-short laser pulses via relativistic flying mirrors with relatively compact laser systems. The relativistic mirror is a breaking plasma wave generated by an ultra-short high power laser propagating in plasma. A laser pulse counter-propagating to this mirror is up-shifted in frequency and shortened in length by it. We realized that combining reaching the radiation reaction dominated regime with an ultra-high intensity laser pulse counter-propagating with a relativistic flying mirror that a tightly focused γ-ray beam is possible due to the naturally focusing nature of the mirror.

２．研究の目的

Up to now the reflection from the mirror of low intensity counter-propagating optical laser pulses has been studied. At high intensity high order harmonics are generated in the up-shifted laser light. At ultra-high intensity the interaction can become radiation reaction dominant where a large portion of mirror's energy stored in electrons is converted to radiation up to γ-rays. We clarified the extent to which the up-shifted and shortened high intensity counter-propagating laser pulses can be focused by using the naturally focusing nature of relativistic mirrors in a variety of configurations using multi-PW lasers. We determined how much the angular distribution can be reduced as opposed to solid targets.

３．研究の方法

Using particle-in-cell (PIC) simulations and nonlinear plasma theory we sought to obtain the smallest spot possible for the incoherent γ-rays. We clarified the types of basic and applied physics problems, which can be pursued with such a source.

４．研究成果

Previously relativistic mirrors (breaking plasma waves) generated by high intensity laser pulse propagating in a plasma have been shown both theoretically, numerically, and experimentally to be able to upshift laser light propagating in the direction opposite to the mirrors to higher frequencies. Only weakly relativistic laser pulses were considered so as not to strongly perturb the mirrors. We have shown by high resolution one dimensional simulations that even nearly relativistic intensity laser pulses can be reflected off the relativistic mirrors, upshifted and

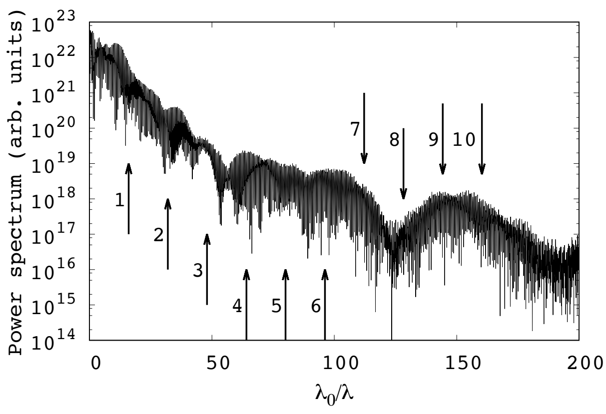

Figure 1. Spectrum of the reflected laser pulse where the wavelength, λ, is normalized to that of the original laser pulse λ_0 with intensity 1.5×10^{17} W/cm^2. Arrows indicate the position of the harmonics of the relativistic upshift factor. Numbers next to arrows refer to the harmonic order. (generated from simulation data from 雑誌論文④)

produce relativistically upshifted harmonics [雑誌論文④]. The relativistic upshift, which depends on the phase velocity of the nonlinear plasma wave, was found to agree with analytical estimates of Schroeder et al. [Phys. Rev. Lett. 107, 145002 (2011)]. In the interaction the nearly relativistic intensity laser pulse is relativistically upshifted and produces relativistically upshifted harmonics with wavelengths below 20 nm from an originally 3 micron laser pulse approximately 160 times shorter than the original laser wavelength [雑誌論文④] (Figure 1). When the intensity of the laser pulse is too strong, the reflected spectra do not have clear harmonic peaks [雑誌論文④]. Since we discovered that relativistic harmonic generation from the high intensity pulse interaction with the relativistic mirror occurred, we decided to concentrate on this for the project instead of the gamma ray production as in the original plan, since such a source would be invaluable for short wavelength coherent radiation. Two dimensional simulations have shown that strong laser pulses can be reflected and focused by the breaking plasma waves generated by another laser pulse. In addition, via collaborations it has been shown both theoretically and numerically with three dimensional particle-in-cell simulations including quantum electrodynamics effects that a high energy electron beam can generate a clean and bright source of GeV photons with high efficiency when scattered off multiple colliding laser pulses in a geometry of optimal focusing below PW levels [雑誌論文①]. Such a source could be applied to fundamental studies in nuclear and quark-gluon physics [雑誌論文①].

５．主な発表論文等

〔雑誌論文〕（計　　４件）

① Magnusson Joel, Gonoskov Arkady, Marklund M, <u>Esirkepov Timur Zh</u>, <u>Koga James K</u>, Kondo Kiminori, Kando Masaki, Bulanov Sergei V, Korn Georg, Bulanov Stepan S, Laser-particle collider for multi-GeV photon production, Phys. Rev. Lett., accepted (2019)(refereed) https://journals.aps.org/prl/accepted/fe070Y3bL3712c6a029f3dd88b3c78b636123e971

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③ <u>Koga James K</u>、Bulanov Sergei V、<u>Esirkepov Timur Zh</u>、Kando Masaki、Bulanov Stepan S、Pirozhkov Alexander S, Corrigendum: Relativistically upshifted higher harmonic generation via relativistic flying mirrors (2018 Plasma Phys. Control. Fusion 60 074007), Plasma Physics and Controlled Fusion 60, 099501 (2018) (refereed) https://doi.org/10.1088/1361-6587/aad012

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〔学会発表〕（計　　８件）

① <u>J. K. Koga</u>, S. V. Bulanov, <u>T. Zh. Esirkepov</u>, M. Kando, S. S. Bulanov, A. S. Pirozhkov1 A. Bierwage, P. Valenta, Focusing and Up-shift of Ultra-high Intensity Lasers Reflected by Relativistic Flying Mirrors, 2nd Asia-Pacific Conference on Plasma Physics(国際学会), 11/14/2018

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④ <u>James K. Koga</u>, Relativistic Harmonics and Relativistic Flying Mirrors, レーザープラズマ科学のための最先端シミュレーションコードの共同開発・共用に関する研究会, 1/10/2018

⑤ <u>James K. Koga</u>, Focusing and up-shift of laser light by relativistic flying mirrors in the high power and large wavelength difference regime, 59th Annual Meeting of the APS Division of Plasma Physics(国際学会), 10/26/2017

⑥ <u>James K. Koga</u>, Radiative Electron Dynamics in Multiple Laser Pulse Fields and Applications, Sixth International Conference on High Energy Density Physics (ICHED2017)(プレナリー), 6/9/2017

⑦ James Koga, Reflection of Strong Long Wavelength Laser Pulses from Relativistic Mirrors, レーザープラズマ科学のための最先端シミュレーションコー ドの共同開発・共用に関する研究会, 1/10/2017
⑧ James Koga, Relativistic flying mirrors in the nonlinear and large wavelength difference regime, 58th Annual Meeting of the APS Division of Plasma Physics(国際学会), 11/3/2016

〔図書〕（計　　件）

〔産業財産権〕
○出願状況（計　　件）

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国内外の別：

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名称：
発明者：
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〔その他〕
ホームページ等

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