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研究課題名（英文） A compact coherent x-ray source development using relativistic high-order harmonics from laser-gas jet interactions

研究代表者
Esirkepov　Timur (Esirkepov, Timur)

国立研究開発法人日本原子力研究開発機構・原子力科学研究部門・量子ビーム応用研究センター・研究副主幹

研究者番号：１０３７０３６３

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研究成果の概要（和文）：解析的手法及びマルチパラメトリックPICシミュレーションを用いて、高強度レーザーによって高濃度プラズマ中に形成される特異点が放出する高次高調波生成について研究する。適合するプラズマプロフィールを用いて、高次高調波生成のコントロールが可能であることを示すことができる。それによって非常に効率の良いパラメータ領域を見出した。最近の実験で、J-KARENレーザーによる高次高調波の発生源が点状であることが観測されたが、このことを、専用シミュレーションによって説明することができた。

研究成果の概要（英文）：High-order harmonics generation due to singularities formed by an intense laser in underdense plasma is investigated with the help of analytical methods and multi-parametric PIC simulations. A control over the onset of the high-order harmonics generation is demonstrated using tailored plasma profiles. A highly efficient generation regime is found. A dedicated simulation explained recent experimental finding of point-like x-ray sources in plasma irradiated by the J-KAREN laser.

研究分野：数物系科学

キーワード：プラズマ　レーザー　相対論的相互作用　相対論的自己集中　船首波　Particle in Cell法　クラスタサーバ

１．研究開始当初の背景

Recently emerged multi-terawatt lasers have demonstrated an ability to produce XUV radiation, x-ray and gamma-ray in the interactions with matter. Among these effects, the high-order harmonic generation (HHG) can provide unprecedented temporal and spatial resolution demanded by numerous applications.

Recently we discovered a new regime of HHG by multi-terawatt laser in tenuous plasma. It requires a tightly focused laser pulse with the intensity of $I_0=a_0^2\ I_R\ (\lambda[\mu\mathrm{m}])^2$, where the laser dimensionless amplitude is $a_0=eE/m_e\omega c >> 1$ and $I_R=1.37\times10^{18}\ \mathrm{W/cm^2}$, and an underdense plasma with density well below critical density, $n_e << n_{cr} = 10^{21}\ \mathrm{cm^{-3}}$. Here λ, $\omega=2\pi c/\lambda$ and E are, respectively, the laser wavelength, frequency and electric field, e and m_e are the electron charge and mass, c is the speed of light in vacuum. Such the laser pulse excites a nonlinear Langmuir (wake) wave and a bow wave [T. Zh. Esirkepov, Y. Kato, S. V. Bulanov, Phys. Rev. Lett. 101, 265001 (2008)]. A multi-stream plasma flow creates an electron density spike (density singularity) which is driven by the laser pulse and generates high-order harmonics. A strong localization of the electron spike and its robustness to oscillations imposed by the laser are explained by catastrophe theory [A. S. Pirozhkov, M. Kando, T. Zh. Esirkepov, et al., Phys. Rev. Lett. 108, 135004 (2012)].

This mechanism uniquely explains HHG in the experiments with the 9 TW J-KAREN laser (JAEA, Japan) and the 120 TW Astra Gemini laser (CLF RAL, UK). The experimentally demonstrated harmonic signal in the “water window” region (2.3-4.4 nm) with an outstanding brightness comparable to the 3rd generation synchrotron light sources opens the way to a compact coherent x-ray source built on a university laboratory scale repetitive laser and an easily accessible, replenishable, and debris-free gas jet target.

It is difficult to determine the HHG timing, energy and divergence because an electron density spike formation is the result of instability. In this project I proposed that the desired control can be achieved by using tailored plasma density profiles. In a scheme shown in Fig. 1, the laser pulse waist propagating through a plasma density jump suddenly changes, so that the bow wave position quickly relocates inside a higher intensity region of the laser pulse. This leads to the quick enhancement of HHG. Here the density jump location determines the onset of HHG while the plasma density gradient and value allow controlling the HHG timing, energy and divergence.

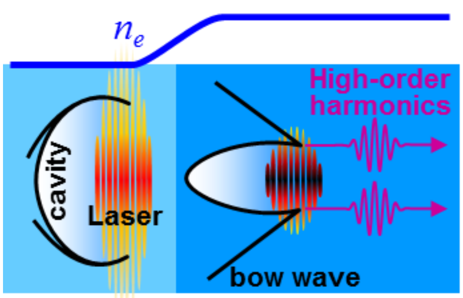

図 1. A tailored plasma density profile controls the HHG onset.

２．研究の目的

This project had the following purposes:
(1) investigate the HHG due to plasma caustics formation for various experimentally feasible plasma density profiles and characteristics of the laser pulse.
(2) determine the scalings of the HHG energy, brightness and beam divergence.
(3) formulate optimal strategies for future experiments and for realizing a compact coherent x-ray source.
(4) investigate, with unprecedented resolution, nonlinear processes observed in the research on HHG, such as wave breaking, electron injection, coherent structures formation, electron betatron oscillation, etc.

３．研究の方法

The research was done using (1) analytical methods and (2) numerical simulations, using (3) newly built Linux cluster.
(1) The simulation parameters were chosen using the theory of a paraxial laser beam, relativistic self-focusing and a Langmuir wave excitation. The minimum scale length of the plasma density jump has been estimated using the theory of gas dynamics.
(2) For simulations, I used my 2D & 3D Relativistic Electro-Magnetic Particle-mesh (REMP) code based on the particle-in-cell method. The dependences on the laser and plasma parameters were obtained using multi-parametric simulations, where processor subsets of a multi-processor computer simultaneously performed similar tasks with different sets of initial parameters. Moving window technique was used to follow the laser pulse in plasma in order to reduce memory

requirements at higher resolution.

(3) The computer cluster “Shkaf2” was built for numerical simulations and data analysis (including visualization).

４．研究成果

(1) Owing to this grant, I assembled the computer cluster “Shkaf-2” comprising of 32 nodes (see Table 1 and Fig. 2). Its performance is 5 times greater than the previous cluster “Shkaf” built in 2009 using the grant 若手研究(B) 21740302 “Bow wave in laser plasma and electron acceleration” (2009-2011).

Table 1. Computer cluster “Shkaf-2” (32 nodes, 128 cores)

Performance	2.1 TFlops (LINPACK), 2.97 TFlops (nominal)
Memory	1024 GB
Disk	96 TB
Network	Gigabit Ethernet 1Gb/s
Power	2.4 kW (idle), 3 kW (load)
Software	Linux Debian Intel Cluster Toolkit 3.2 Intel Fortran Compiler 11.1

Each node is a personal computer (PC) made of the motherboard Gigabyte B75M-D3H, CPU Intel Core i5-3470S (4 cores, 2.9GHz, nominal performance 92.8GFlops, TDP 65W), RAM Winchip WJNCHIP-D3-1600C11 (8GBx4), HDD Western Digital WD30EZRX 3 TB, LAN 10/100/1000 base-T (on-board, MTU=7200). The nodes are connected by a switch DELL PowerConnect 6248 (core type, 184 Gb/s). Linux Debian (currently version 6.0.7 “Squeeze”) was installed on each node; Intel Cluster Toolkit 3.2 and Intel Fortran Compiler 11.1 was installed on the master node. The cluster is equipped with 4 uninterruptable power supply units (UPS) controlled by an additional low-end PC under Windows (so called front end).

I installed the REMP code, data management, and post-processing package. Auxiliary software for the cluster management was developed. The cluster performance was tuned with Intel Cluster Toolkit and measured with LINPACK package.

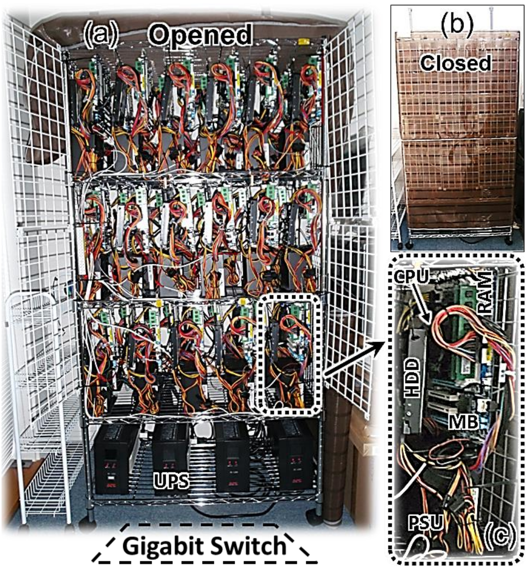

図 2. Computer cluster “Shkaf-2”. (a) Case opened, 32 computer units (nodes) on 3 shelves (in 2 rows); UPS=uninterruptable power supply; gigabit switch is beneath the floor. (b) Case closed. (c) One node: MB=motherboard, CPU=central processor unit, RAM=random-access memory, HDD=hard disk drive, PSU=power supply unit.

(2) Using the cluster “Shkaf-2”, I performed multi-parametric 2D PIC simulations of the high-order harmonic generation for various tailored plasma density profiles and different laser pulse parameters. The plasma density was from 10^{18} to 10^{20} cm^{-3} at maximum. The density jump was from 2 to 5 times in magnitude, on the length from 1 to 50 μm. The laser power was from 100 TW to 1 PW, the beam f-number was from 1.5 to 20, the pulse duration was from 15 fs to 70 fs. Basing on the parameter survey, I performed a 3D PIC simulation. The investigated domain of parameters includes the conditions accessible in the future experiments with the newly constructed JKAREN-P laser at KPSI.

(3) I found the scalings of the high-order harmonic generation in the domain of the plasma and laser parameters. The characterization of the high-order harmonic emission energy, brightness and divergence enabled to formulate optimal strategies for future experiments and for realizing a compact coherent x-ray source.

In particular, I successfully confirmed the possibility of controlling the HHG onset using a tailored plasma density profile. This is shown in Fig.3, where HHG occurs immediately after the laser pulse propagated through the density jump.

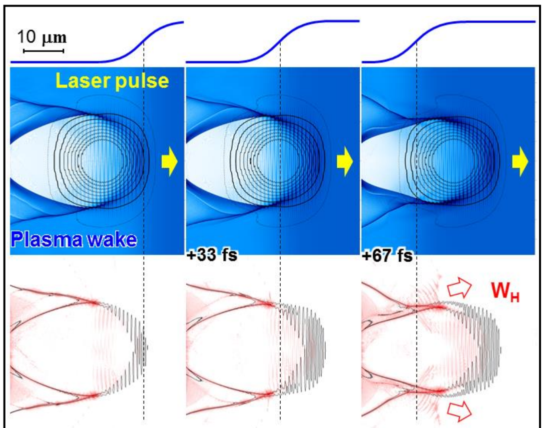

図 3. PC simulation. Top: laser pulse (energy 5 J, duration 35 fs, focal spot 10 μm) propagates through a plasma density jump (density up 2 times, on the length of 5 μm, $n_{e,max}$ = 0.01n_{cr}). Bottom: irradiance W_H of electromagnetic field for frequencies > 4ω. $W_{H,max}$ =10^{-6} in units of I_R. Detaching wave train is the high-order harmonic emission.

More importantly, I found the most efficient, so far, variant of the high-order harmonic generation mechanism due to formation of density singularities. At a sufficiently high plasma density, the laser pulse waist can be larger than the local Langmuir wavelength. This causes the laser pulse filamentation. When the laser pulse propagates through a density jump with increasing density, and the filamentation condition is suddenly satisfied, the electron density spike is formed just inside the laser pulse, where the laser intensity is near maximum. This leads to an efficient generation of high-order harmonics.

Fig. 4 illustrates this effect. The laser and plasma parameters are the same as in Fig. 3 except a 5 times greater plasma density. Behind the density jump, the local Langmuir wavelength is two times less than the laser pulse focal spot. Therefore the laser pulse begins to filament. Electron density spikes are formed in the region of high laser intensity. They emit trains of short pulses, corresponding to high-order harmonics. The emission irradiance is two orders of magnitude higher than in Fig. 3. These results will be soon submitted for publication.

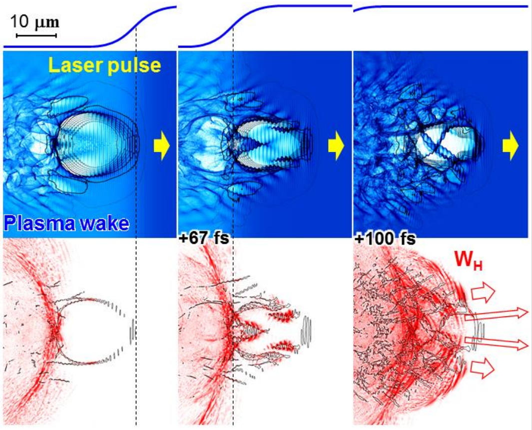

図 4. PC simulation. Top: the same laser pulse as in 図 3 propagates through a plasma density jump with $n_{e,max}$ = 0.05n_{cr}). Bottom: irradiance W_H of electromagnetic field for frequencies > 4ω. $W_{H,max}$ =10^{-4} in units of I_R. Detaching wave train is the high-order harmonic emission.

A valuable by-product of my investigations is a large amount of high-resolution data on nonlinear processes occurred in the laser-plasma interaction, such as wave breaking, electron injection, coherent structures formation, electron betatron oscillation, etc.

(4) Using the cluster "Shkaf-2", I performed dedicated simulations, which explained recent experimental finding of point-like x-ray sources of high-order harmonics in plasma irradiated by the J-KAREN laser, Fig. 5.

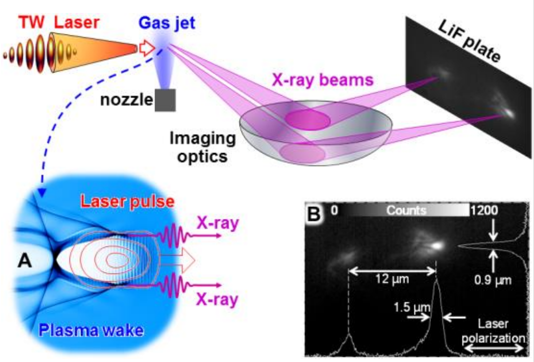

図 5. Top: experimental observation of point-like x-ray sources by imaging with LiF plate. Bottom: the model (A) and the image of point-like x-ray sources (B).

The simulation results are shown in Fig. 6. The electron density spikes move along the cavity walls when the laser pulse propagates in inhomogeneous plasma and undergoes relativistic self-focusing. Correspondingly, the emission from spikes is analogous to that of a search light moving along a curved trajectory. At certain moment of time it covers some solid angle being off axis, as seen in the experiments. Fig. 6, bottom raw, presents only the emission going into the angle between 8° and 18°, which corresponds to the experimental observation. The applied spectral filter retains only the range from 60 to 90 eV, which is “seen” by the LiF plate. The resulting distribution of electromagnetic energy density (irradiance) reveals two trains of short pulses emitted from two point-like sources. This result is in excellent agreement with the experiment. These results will be soon submitted for publication.

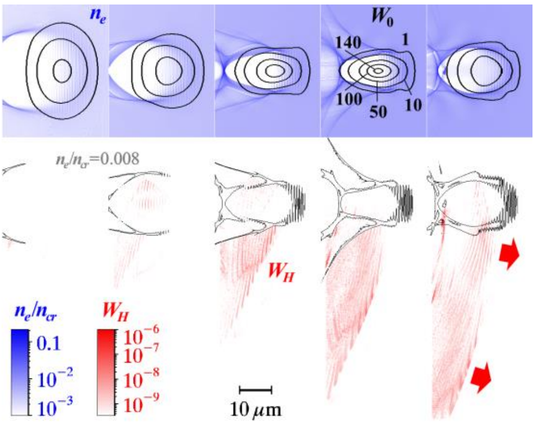

図 6. PIC simulation for the experiment in 図 5. Top: the laser pulse (curves of irradiance W_0 in units of I_R) propagates in plasma (blue colorscale for the electron density n_e). Bottom: the irradiance W_H of electromagnetic field with photon energy from 60 to 90 eV emitted between angles 8° and 18° with superimposed electron density curve of n_e/n_{cr}=0.008. The time between frames is 270 fs. The rightmost frame corresponds to the center of the jet.

(5) Using the computer cluster “Shkaf-2”, I investigated the high-order harmonic generation in preplasma created by a prepulse of the laser interacting with a solid density target. Simulations revealed that the harmonic quality indicates the laser-target interaction properties, which is crucial for diagnostics.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

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６．研究組織

(1)研究代表者
エシユールケポフ テイムール
（ESIRKEPOV TIMUR）
国立研究開発法人日本原子力研究開発機構・原子力科学研究部門 量子ビーム応用研究センター・研究副主幹
研究者番号：10370363