様式Ｃ－１９

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研究課題名（和文）　**レーザープラズマと電子加速における船首波**

研究課題名（英文）　Bow wave in laser plasma and electron acceleration

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研究成果の概要（和文）：船首波による高次高調波生成の機構をシミュレーション及びカタストロフィー理論によって発見した。この機構の妥当性は 2D PIC 計算と 3D PIC 計算によって確かめられた。機構とシミュレーションによって、テラワットレーザーの最近の実験で見られた XUV の領域の高次高調波について説明することができた。これにより、この高次高調波生成機構に基づいた、新しい XUV 光および X 線源の開発を提案した。

研究成果の概要（英文）：The bow wave induced mechanism of high-order harmonics generation was discovered using simulations and catastrophe theory. This mechanism feasibility was successfully demonstrated in 3D and 2D PIC simulations. The mechanism and the simulations explained high-order harmonics in the XUV spectral region seen in recent experiments with terawatt lasers. Development of new XUV light and X-ray source based on the high-order harmonics generation mechanism is proposed.

交付決定額

（金額単位：円）

	直接経費	間接経費	合　計
2009 年度	1,800,000	540,000	2,340,000
2010 年度	800,000	240,000	1,040,000
2011 年度	500,000	150,000	650,000
総　計	3,100,000	930,000	4,030,000

研究分野：数物系科学
科研費の分科・細目：物理学・原子・分子・量子エレクトロニクス
キーワード：ビーム物理

１．研究開始当初の背景

(1) The interaction of electromagnetic radiation with matter exhibits plenty of nonlinear phenomena such as plasma formation, change of electromagnetic radiation frequency, beam divergence and intensity, charged particle acceleration, etc. A nonlinearity caused by relativistic effects came into play with the progress of laser technology which resulted in the laser focused intensity increase above 10^{18} W/cm^2 and the laser pulse shortening below 100 fs. The corresponding regimes of laser-matter interaction attract interest owing to many important applications.

(2) In underdense plasma (whose density, n_e, is well below the critical density, $n_{cr} \approx 10^{21}\mathrm{cm}^{-3}\times(\lambda\ [\mu\mathrm{m}])^{-2}$ where λ is a laser wavelength), a femtosecond laser pulse undergoes relativistic self-focusing when its power exceeds the threshold of $P_{sf} \approx 17$ GW×(n_{cr}/n_e). As a result its dimensionless amplitude $a_0=eE/m_e\omega c$ can exceed unity,

which corresponds to the laser intensity of $I_{0L}=1.37\times10^{18}$ W/cm$^2\times a_0^2\times(\lambda\ [\mu m])^{-2}$ for linear and $I_{0C}=2I_{0L}$ for circular polarization. Here $\omega=2\pi c/\lambda$ and E are the laser frequency and electric field amplitude, e and m_e are the electron charge and mass, c is the light speed in vacuum, respectively. For $a_0\geq1$, electron motion is essentially relativistic. Such the laser pulse pushes electron component of plasma in longitudinal direction (along the laser pulse propagation) exciting Langmuir waves (wake waves). Due to tight focusing, electrons are pushed also in transverse direction, forming the bow wave.

(3) Wake and bow waves are coherent nonlinear structures of the electron 4-current density moving with the laser pulse with its group velocity, $v_g\approx c(1-\omega_{pe}^2/2\omega^2)$, where $\omega_{pe}=(4\pi n_e e^2/m_e)^{1/2}$ is the Langmuir frequency. Electrons injected into the wake via longitudinal or transverse wave-breaking can be accelerated up to the energy of $a_0^2\gamma_{ph}^2 m_e c^2$ on a distance of the order of $2c\gamma_{ph}^2/\omega_{pe}$, where $\gamma_{ph}=(1-v_g^2/c^2)^{-1/2}\approx\omega/\omega_{pe}$ is the Lorentz factor. This makes the wake field the basis of a compact laser driven accelerator.

(4) Electrons accelerated by the laser and collective plasma fields emit electromagnetic radiation with frequency which differs from that of laser. Higher frequencies produced due to relativistic effects via various mechanisms (nonlinear Thomson scattering, betatron radiation, transient radiation, reflection from plasma wake wave density modulations, etc.) underlie an idea of a laser driven source of XUV and x-ray radiation.

(5) Coherent structures emerged in laser-matter interactions, in particular the bow wave, provide examples of a deep analogy between processes in gases, fluids and plasma, facilitating fruitful exchange of ideas between different branches of physics - hydrodynamics, plasma and space physics.

２．研究の目的

(1) To investigate the long-term evolution of a relativistically strong laser pulse in underdense plasma.

(2) To find the conditions of the bow wave excitation by a relativistically strong laser pulse in underdense plasma.

(3) To determine the structure of the collisionless bow wave.

(4) To investigate the influence of the bow wave excitation on the wake field and electron acceleration.

(5) To investigate high frequency electromagnetic radiation emission of electrons under the action of a laser pulse and collective plasma fields.

３．研究の方法

(1) The research was done using analytical methods and numerical simulations.

①The region of parameters for simulations was chosen using the theory of a laser pulse relativistic self-focusing and a wake wave excitation in tenuous plasma.

②The structures forming in multi-stream flow plasma driven by the laser pulse were described by mathematical catastrophe theory.

(2) The simulations were carried out with the 2D & 3D Relativistic Electro-Magnetic Particle-mesh (REMP) code based on the particle-in-cell method.

①In simulations, processor subsets of a multi-processor computer simultaneously performed similar tasks with different sets of initial parameters, producing multi-parametric data.

② Moving window technique was used to follow the laser pulse in plasma.

③The following region of parameters was sought: the laser intensity is from 10^{19} to 10^{22} W/cm^2, focal spot from 2 to 30 μm, duration from 15 to 50 fs, plasma density is from 10^{17} to 10^{19} cm^{-3}.

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

①An intermediate software for the cluster management was developed.

②The cluster performance was tuned with Intel Cluster Toolkit and measured with LINPACK package.

４．研究成果

(1) A computer cluster of 12 nodes was assembled and named “Skaf”, 図 1. Each node is a personal computer (PC) made of the GA-EX58-UD3R motherboard, CPU Intel Core i7 950 (4 cores, 3.06GHz, nominal performance 48.96 GFlops), RAM of type DDR3 PC3-10600 (8 GB), HDD SATA 3Gb/s 1 TB + 2 TB, LAN 10/100/1000 base-T (on-board, MTU set to 7.2 KB). Each node can be

individually accessed via 4 KVM (keyboard-video-mouse) switches. The nodes are connected by a switch DELL PowerConnect 6224 (core type, 96 Mpps). Linux Debian (currently version 6.0.3 "squeeze") and Intel Cluster Toolkit 3.2 were installed on each node; Intel Fortran Compiler 11.1 was installed on one node (master). The cluster is equipped with 5 uninterruptable power supply units (UPS) controlled by an additional low-end PC under Windows XP (Front end). The parameters of the "Skaf" cluster are shown in Table 1.

Table 1. Computer cluster "Shkaf" (12 nodes, 48 cores)

Performance	411.2 GFlops (LINPACK), 587.52 GFlops (nominal)
Memory	96 GB
Disk	24.4 TB
Network	Gigabit Ethernet
Power	1.2 kW (idle), 2.4 kW (load)
Software	Linux Debian Intel Cluster Toolkit 3.2 Intel Fortran Compiler 11.1

図 1. Computer cluster "Shkaf".

(2) A long-term evolution of a relativistically strong laser pulse in underdense plasma was investigated using PIC simulations in the above mentioned region of laser and plasma parameters. A typical scenario where a bow wave is excited and which is interesting for laser-plasma experiments (see section (7) below) is illustrated in 図 2. Wake wave generation, self-focusing of the laser pulse, formation of the electron density cavity, longitudinal and transverse wake wave breaking, bow wave excitation and electron injection into the wake wave can be seen.

(3) A bow wave was found to be excited when the focal spot of a relativistically strong ($a_0 \geq 1$) laser pulse becomes less than $D_{las} \leq 4ca_0^{1/2}/\omega_{pe}$.

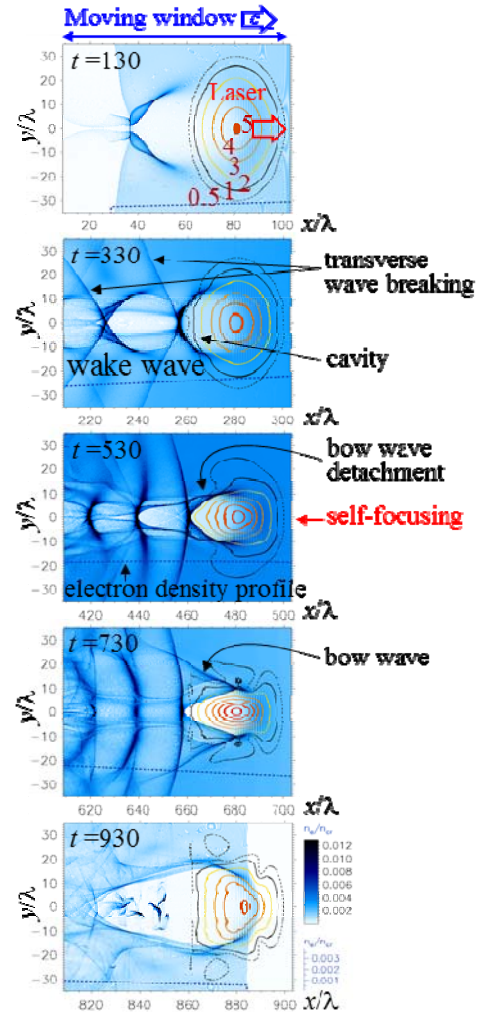

図 2. 2D PIC simulation of a propagation of a relativistically strong laser pulse (denoted by curves, for the laser dimensionless amplitude) in underdense plasma (denoted by colorscale, for the electron density). The time and spatial units are the laser cycle period and wavelength, respectively. Plasma density profile is shown by the blue dotted line at the bottom of each frame.

(4) The microstructure of the bow wave excited in laser plasma was revealed with the help of 2D and 3D high resolution PIC simulations. Pushing electrons in longitudinal and transverse directions, the laser pulse creates a cavity and bow wave in plasma, 図 3. The electron density has maximum at the cavity walls and at the bow wave outer boundary. At the joint of these structures, appears the electron density spike which is approximated by the singularity of $\Delta y^{-2/3}$, 図 3 (c). This can be explained by catastrophe theory.

The laser pulse creates a multi-stream electron flow, stretching and folding an initially flat surface formed by electrons in their phase space, 図 4 and 図 6 (b). The surface projection onto the (x,y) plane gives the electron density where outer and inner folds are mapped into singular curves outlining the bow wave and cavity boundaries, respectively. Catastrophe theory here establishes universal structurally stable singularities, insensitive to perturbations. The bow wave and cavity boundaries produce the fold type singularity, where the density grows as $\Delta r^{-1/2}$ with decreasing distance to the boundary, r. At the joint of the two folds, the density grows as $\Delta r^{-2/3}$, forming a higher order singularity, the cusp, 図 3 (c) and 図 6 (b). Stronger singularities exist; however, they are not stable against perturbations.

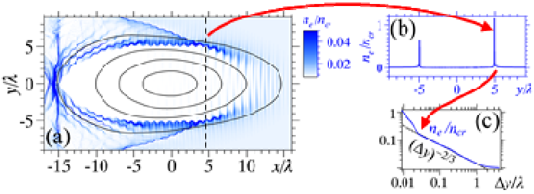

図 3. 2D PIC simulation. (a) The laser pulse (curves for a_0=1, 4, 7, 10), moving from left to right, creates a cavity and bow wave in plasma (colorscale, for the electron density). The transverse cross-section (b) reveals density spikes at the joints of the cavity walls and bow wave outer boundaries. The spikes are approximated by the singularity of $\Delta y^{-2/3}$ (c).

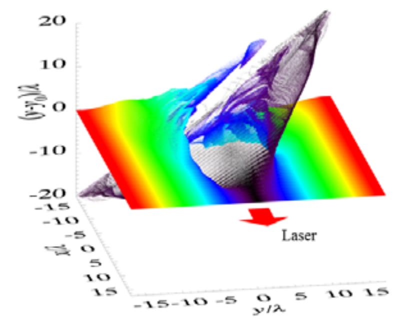

図 4. Multi-stream motion of the electron fluid corresponding to 図 3. Each color point represents one out of 10 quasi-particles with the coordinates $(x,y,y-y_0)$, where y_0 is the quasiparticle displacement along y-axis from the initial coordinate y_0. The color encodes the initial distance, $|y_0|$, of quasi-particles from the axis of the laser pulse propagation.

(5) The influence of the bow wave excitation on the wake field and electron acceleration was investigated. Due to spreading of the laser pulse energy in transverse direction during the bow wave excitation, the longitudinal electric field (E_x) is formed in a region which is much greater in transverse direction than the cavity width corresponding to the first period of the wake wave, 図 5 (d). The electric potential is not limited by the size of the cavity, in contrast to the regimes not favorable for the bow wave formation, e. g. when the bow wave does not detach from the cavity and the electric potential in the cavity is determined by the smallest dimension of the cavity, either longitudinal or transverse.

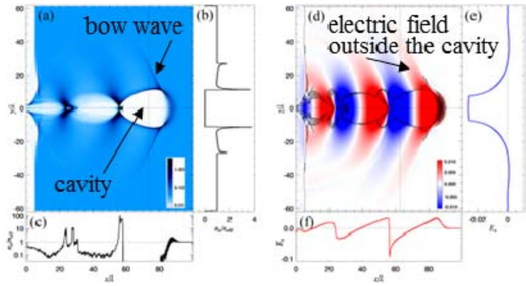

図 5. 3D PIC simulation. 2D cross-sections of the electron density (a) and the electric field component E_x (b). Vertical (b, e) and horizontal (c, f) 1D cross-sections of the density and E_x component correspond to the positions shown by the dashed lines. In (d) the electron density curves are drawn by the black curves for n_e/n_{e0} = 0.75, 1.5.

(6) A new mechanism of high order harmonics generation in laser-driven relativistic plasma was discovered. The electron density spike formed in a ring surrounding the cavity head and moving together with the laser pulse emits high-order harmonics, 図 6 (a) and 図 7 (b). For linear polarization, this harmonic emitting ring breaks up into two segments, 図 6 (a). The high-order harmonics are generated due to the spike oscillations imposed by the laser field. The cusp singularity ensures a robust and tight concentration of electric charge, making the emission coherent, i. e., its intensity is proportional to the particle number squared N_e^2, similarly to the coherent nonlinear Thomson scattering. However, the cusp consists of different particles at every moment of time, in contrast to a synchronous motion of the same particles. In addition, for constructive interference, it is sufficient that the emission source size is smaller than the emitted wavelength only in the direction of observation.

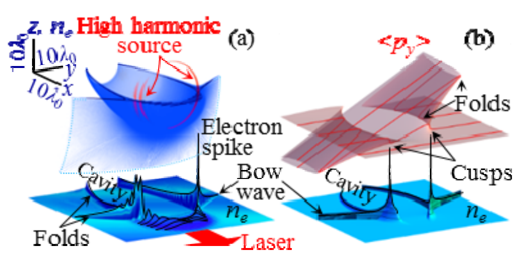

図 6. (a) 3D PIC simulation (the same as in 図 5). Electron density n_e (top, upper half removed) and its cross-section at z=0 (bottom). The electromagnetic energy density for frequencies ≥4ω is represented by red arcs. (b) Catastrophe theory model. Singularities in the electron density are created by foldings of the electron phase space ($x,y,<p_y>$), where $<p_y>$ is averaged over the laser period.

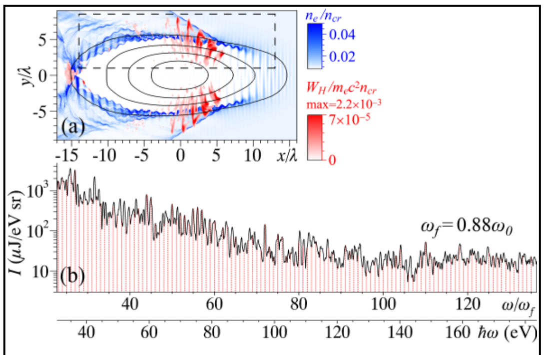

図 7. 2D PIC simulation, 10 cycles later than 図 3. (a) The electron density (colorscale), laser pulse (curves for a_0=1, 4, 7, 10), and electromagnetic energy density, W_H, for frequencies from 60 to 100ω (red). (b) The upper spike emission spectrum for the dashed rectangle in (a).

(7) The described mechanism and PIC simulations explained recent experiments with terawatt lasers J-Karen (JAEA) and Astra-Gemini (RAL, UK), where high-order harmonics in the XUV spectral region with a brilliance reaching that of a synchrotron where detected. This result opens the way to a compact coherent x-ray source built on a university laboratory scale repetitive laser and an accessible, replenishable, and debris-free gas jet target. This will impact many areas requiring a bright x-ray or extreme ultraviolet source for pumping, probing, imaging, or attosecond science.

(8) Bow waves excited by tightly focused relativistically strong laser pulses were suggested for laboratory astrophysics, where their investigation can be used for modeling collisionles bow shocks in space plasma, basing on similarity principles.

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）

〔雑誌論文〕（計 2 件）

① A. S. Pirozhkov, M. Kando, T. Zh. Esirkepov, P. Gallegos, H. Ahmed, E. N. Ragozin, A. Ya. Faenov, T. A. Pikuz, T. Kawachi, A. Sagisaka, J. K. Koga, M. Coury, J. Green, P. Foster, C. Brenner, B. Dromey, D. R. Symes, M. Mori, K. Kawase, T. Kameshima, Y. Fukuda, L. Chen, I. Daito, K. Ogura, Y. Hayashi, H. Kotaki, H. Kiriyama, H. Okada, N. Nishimori, T. Imazono, K. Kondo, T. Kimura, T. Tajima, H. Daido, P. Rajeev, P. McKenna, M. Borghesi, D. Neely, Y. Kato, S. V. Bulanov. "Soft-X-Ray Harmonic Comb from Relativistic Electron Spikes", Physical Review Letters, Vol. 108, 2012, pp. 135004-1 – 135004-5.

② A. S. Pirozhkov, M. Kando, T. Zh. Esirkepov, J. K. Koga, H. Kiriyama, K. Kondo, H. Daido, P. Gallegos, D. Neely, H. Ahmed, M. Borghesi, E. N. Ragozin, A. Ya. Faenov, T. A. Pikuz, P. McKenna, Y. Kato, S. V. Bulanov. "Coherent x-ray generation in relativistic laser/gas jet interactions", Proceedings of SPIE, Vol. 8140, 2011, pp. 81400A-1 - 81400A-16.

〔学会発表〕（計３件）

① T. Esirkepov, "Proposed experiments for the study of extreme field limits in the ultra-relativistic laser-plasma interaction", SPIE Optics + Optoelectronics, 平成23年4月20日, Prague Congress Centre, Prague, Czech Republic.

② T. Esirkepov, "Proposed experiments for the study of extreme field limits in the ultra-relativistic laser-plasma interaction", 3rd International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Energy, Industry, and Medicine, 平成23年6月2日, KPSI, Kizugawa, Japan.

③ T. Esirkepov, "Fundamental Physics and Relativistic Laboratory Astrophysics with Extreme Power Lasers", European Conference on Laboratory Astrophysics (ECLA), 平成23年9月30日, Eurosites-République, Paris, France.

〔図書〕（計０件）

〔産業財産権〕
○出願状況（計０件）
○取得状況（計０件）

〔その他〕
ホームページ等
① http://www.jaea.go.jp/02/press2011/p12030201/index.html
② http://prl.aps.org/supplemental/PRL/v108/i13/e135004

６．研究組織

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