X-Ray Polarization Spectroscopy of Heα Line Emission for Diagnosis of the Anisotropy of Hot Electrons

Yuichi INUBUSHI, Takeshi KAI, Tohru KAWAMURA[1)], Shinsuke FUJIOKA, Hiroaki NISHIMURA and Kunioki MIMA

Institute of Laser Engineering, Osaka University, Suita 565-0871, Japan

[1)]*Tokyo Institute of Technology, Interdisciplinary Graduate School of Science and Engineering, Yokohama 226-8502, Japan*

(Received 6 December 2006 / Accepted 22 March 2007)

X-ray polarization spectroscopy is proposed as an advanced diagnostic tool to measure the anisotropic velocity distribution of hot electrons generated by an ultra-high intensity laser pulse. The relationship between the anisotropy of the hot electron velocity distribution and the polarization degree was investigated for various tracer materials. It is shown that the polarization degrees of Heα lines are a function of electron energy normalized by the excitation threshold. Depolarization is caused by isotropic bulk electrons in high temperature plasma. To diagnose the anisotropy of the hot electron velocity distribution without depolarization, it is essential to select a tracer material whose energy of Heα line is 10 times higher than the bulk electron temperature.

Keywords: laser-produced plasma, polarization spectroscopy, hot electron, velocity distribution function, energy transport

DOI: 10.1585/pfr.2.013

1. Introduction

Recent advances in ultra-short pulse, high-intensity lasers have opened the possibility of novel experiments in fields such as fast ignition [1, 2], particle acceleration [3–6], and short x-ray pulse generation [7]. Efficient energy transport from ultra-high intensity laser pulses to dense plasma is a critical issue in all of these research areas. Plasmas generated by ultra-high intensity laser pulses include two major electron components. The hot electrons, which transfer the absorbed energy to the plasma's high-density region, are generated predominantly by collective processes in the laser-plasma interaction region [8]. Consequently, an initial velocity distribution of hot electrons is highly anisotropic. The other one is cold bulk electrons. These form a return current as a counter-stream of hot electrons, and are mostly affected by the Ohmic process [9]. Thus, a velocity distribution of cold electrons is substantially isotropic. To clarify the energy transport by hot electrons in ultra-high intensity laser-produced plasmas, investigation of the anisotropy of the velocity distribution function (VDF) of hot electrons is very important. An electron spectrometer is widely used to measure the electron spectrum of ultra-high intensity laser produced plasma [10]. However, the electron spectrum measured using an electron spectrometer is affected by the sheath potential of the target and does not correspond with the VDF of electrons inside plasma.

X-ray polarization spectroscopy is a useful diagnostic tool for measuring the anisotropy of the VDF of electrons inside plasma. In general, polarized radiation is emitted due to the anisotropy of the electron velocity distribution or the surrounding electromagnetic field [11–13]. By utilizing this principle, the anisotropy of a hot electron VDF can be determined by observing the polarization degree P of a specific x ray [14, 15]. In the case of a planar target irradiated by a high intensity laser beam of 10^{16}-10^{17} W/cm^2, hot electrons are generated predominantly by resonance absorption and/or parametric processes so that hot electrons initially propagate parallel to the direction of the density gradient, that is, perpendicular to the target surface. This direction is referred to hereafter as the quantization axis. The polarization degree P is defined by

$$P = \frac{I_{//} - I_{\perp}}{I_{//} + I_{\perp}}, \tag{1}$$

where $I_{//}$ and $I_{\perp}$ are, respectively, the intensities of the x-ray radiation whose electric field is parallel and perpendicular to the quantization axis for an observer. This definition accords with that employed in polarization spectroscopy using an electron beam ion trap (EBIT) [16].

Some experiments of x-ray polarization spectroscopy have been performed [14, 15, 17–19]. Although Heα line emissions from various He-like ions, such as Al [14, 15], F [17] and Cl [18, 19], have been measured, there are no reports on the relationship between the material emitting polarized x rays and plasma conditions. To use polarization spectroscopy as a diagnostic tool for the anisotropy of hot electron VDF, it is important to investigate this relationship. In this paper, we propose the selection of a suitable tracer material for the plasma condition of x-ray polarization spectroscopy.

author's e-mail: yinubusi@ile.osaka-u.ac.jp

2. Polarization Caused by Electron-Ion Impact

In this study, observation of Heα line ($1s^2\ ^1S_0$-$1s2p\ ^1P_1$) is proposed. Emissions of the polarized x rays are caused by electron-ion impacts. The π-component of the radiation, whose electric field is parallel to the electron beam, is emitted by transitions with no change in the magnetic quantum number, namely $\Delta M = 0$, while the σ-component of the radiation, whose electric fields is perpendicular to the electron beam, is emitted by transitions with $\Delta M = \pm 1$. The polarization degree of the Heα line can be calculated using the following equation [20]:

$$P_0(E) = \frac{\sigma_0(E) - \sigma_1(E)}{\sigma_0(E) + \sigma_1(E)}, \quad (2)$$

where σ_i are the integral cross-sections of the $1s^2\ ^1S_0$-$1s2p\ ^1P_1$ transition, and the subscript i denotes the magnetic quantum number of the $1s2p\ ^1P_1$ level, and E is the energy of the impact electrons.

The polarizations of the Heα line of carbon, chlorine, and copper are discussed in the following. The polarization degree can be adequately calculated by means of a semi-relativistic calculation with close-coupling expansion for the ions under consideration [21]; however, a fully relativistic calculation is preferable for the case of highly charged ions [22]. Therefore, the integral cross-sections with sublevels were calculated using the semi-relativistic Breit-Pauli R-matrix method [23] for the 17 lowest excited levels.

Figures 1 (a)-(c) show the calculated polarization degrees as a function of the energy of the electrons colliding with He-like (a) carbon, (b) chlorine, and (c) copper ions. The electron energy is normalized by the transition energy of $1s^2\ ^1S_0$-$1s2p\ ^1P_1$ (the threshold energy): (a) 0.308 keV, (b) 2.79 keV, and (c) 8.39 keV, respectively. All polarization degrees decrease monotonically with an increase of the incident electron energy, except in the region close to the threshold energies due to resonance phenomena [24]. These results indicate that the polarization degrees normalized by the threshold energies of various ions are almost the same. The reason for this is that the Heα line is not affected by intermediate coupling, because the integral cross-sections of the $1s^2\ ^1S_0$-$1s2p\ ^1P_1$ transition is much larger than that of the $1s^2\ ^1S_0$-$1s2p\ ^3P_1$ transition [25].

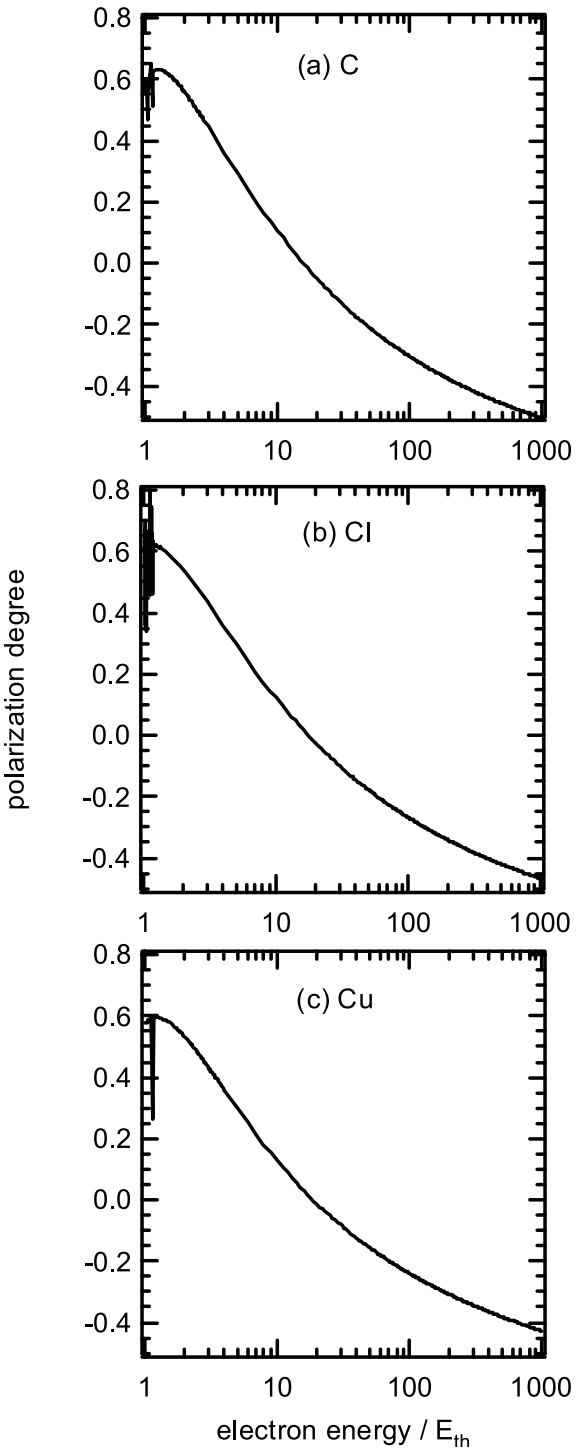

Fig. 1 Polarization degree as a function of electron energy normalized by the threshold energies of $1s^2\ ^1S_0$-$1s2p\ ^1P_1$ transition of (a) carbon, (b) chlorine, and (c) copper. The threshold energies are (a) 0.308 keV, (b) 2.79 keV, and (c) 8.39 keV, respectively.

3. Polarization Model and Calculations

In a plasma, the radiation of polarized x rays is emitted due to the creation of an alignment by electron-ion impacts. This alignment is influenced by various atomic processes such as elastic collision, recombination, and cascade processes. This model treats only the transition between two energy levels ($1s^2\ ^1S_0$-$1s2p\ ^1P_1$). Therefore, this model is valid for low density plasmas such as plasmas expanding from solid target surfaces. In the case of dense plasmas, such as laser-driven implosion cores, it is necessary to use a detailed atomic kinetic code associated with the above processes.

The polarization degree of an x-ray line from laser-

produced plasma can be calculated using the following equation:

$$P(\theta) = \frac{\int_{E_{\rm th}}^{\infty} Q(\theta, E)\mathrm{d}E}{\int_{E_{\rm th}}^{\infty} I(\theta, E)\mathrm{d}E}, \quad (3)$$

where θ is the angle between a quantization axis and a direction of sight and $E_{\rm th}$ is a threshold energy of the $1s^2\ {}^1S_0$-$1s2p\ {}^1P_1$ transition. $I(\theta, E)$ and $Q(\theta, E)$ are Stokes parameters weighted by the electron energy distribution function, and are given by

$$I(\theta, E) = I_0(E)\left[f_0(\theta) + \frac{P_0(E)f_2(E)}{5(3 - P_0(E))}\left(1 - 3\cos^2\theta\right)\right], \quad (4)$$

$$Q(\theta, E) = \frac{3I_0(E)P_0(E)f_2(E)}{5(3 - P_0(E))}\sin^2\theta, \quad (5)$$

where $I_0(E)$ is the intensity of the x ray and $P_0(E)$ is the polarization degree shown in Fig. 1. $f_0(E)$ and $f_2(E)$ are, respectively, the isotropic components and the anisotropic components of the Legendre polynomials of electron distribution function $f(\alpha, E)$, and are given as

$$f_0(E) = \frac{1}{2}\int_0^{\pi} f(\alpha, E)\sin\alpha\mathrm{d}\alpha, \quad (6)$$

$$f_2(E) = \frac{5}{4}\int_0^{\pi} f(\alpha, E)\frac{1}{2}\left(3\cos^2\alpha - 1\right)\sin\alpha\mathrm{d}\alpha, \quad (7)$$

where α is the angle between the quantization axis and the direction of electron motion.

We assume that the hot electron VDF is axially symmetric with respect to the quantization axis and can be represented by a 2-dimensional (2-D) distribution function for hot electrons (illustrated schematically in Fig. 2):

$$f_{\rm h}(E, \alpha) \propto \exp\left(-\frac{E\sin^2\alpha}{T_r} - \frac{E\cos^2\alpha}{T_z}\right). \quad (8)$$

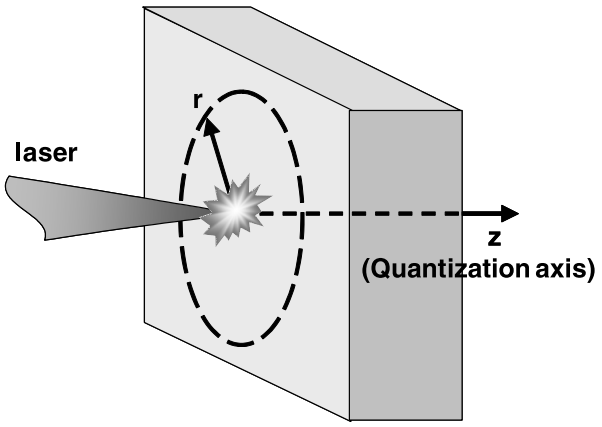

Fig. 2 Axes used to describe a 2-D electron energy distribution. The z-axis corresponds to the target normal direction. The r-direction is perpendicular to the z-axis.

Here, T_z and T_r are the slope temperatures of hot electrons traveling parallel and perpendicular to the quantization axis z, respectively. An isotropic bulk electron distribution can be described as a Maxwellian distribution, namely

$$f_{\rm b}(E, \alpha) = N\sqrt{E}\exp\left(-\frac{E}{T_{\rm b}}\right), \quad (9)$$

where $T_{\rm b}$ is the bulk electron temperature. The distribution

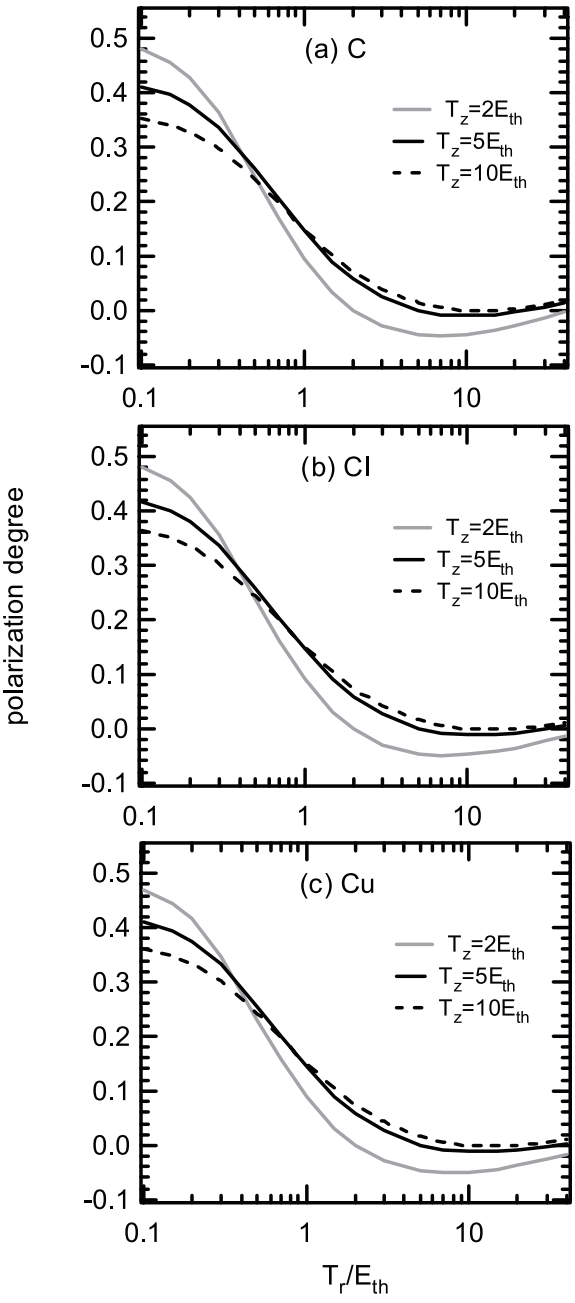

Fig. 3 Polarization degrees given as a function of $T_r/E_{\rm th}$ for various T_z and (a) C-Heα, (b) Cl-Heα, and (c) Cu-Heα lines. The contribution of the bulk electron component is neglected.

of all electrons can be represented by

$$f(E,\alpha) = f_{\rm h}(E,\alpha) + k \cdot f_{\rm b}(E,\alpha). \quad (10)$$

Here, k is the coefficient determining the ratio of the number of hot electrons to the total number of free electrons.

Initially, the calculation was done by neglecting the contribution of the bulk electron component (i.e., with $k = 0$ in Eq. (10)). Figures 3 (a)-(c) show polarization degrees as a function of $T_r/E_{\rm th}$ for various T_z of (a) C-Heα, (b) Cl-Heα, and (c) Cu-Heα lines. It can be seen that the polarization degrees for these ions are almost the same.

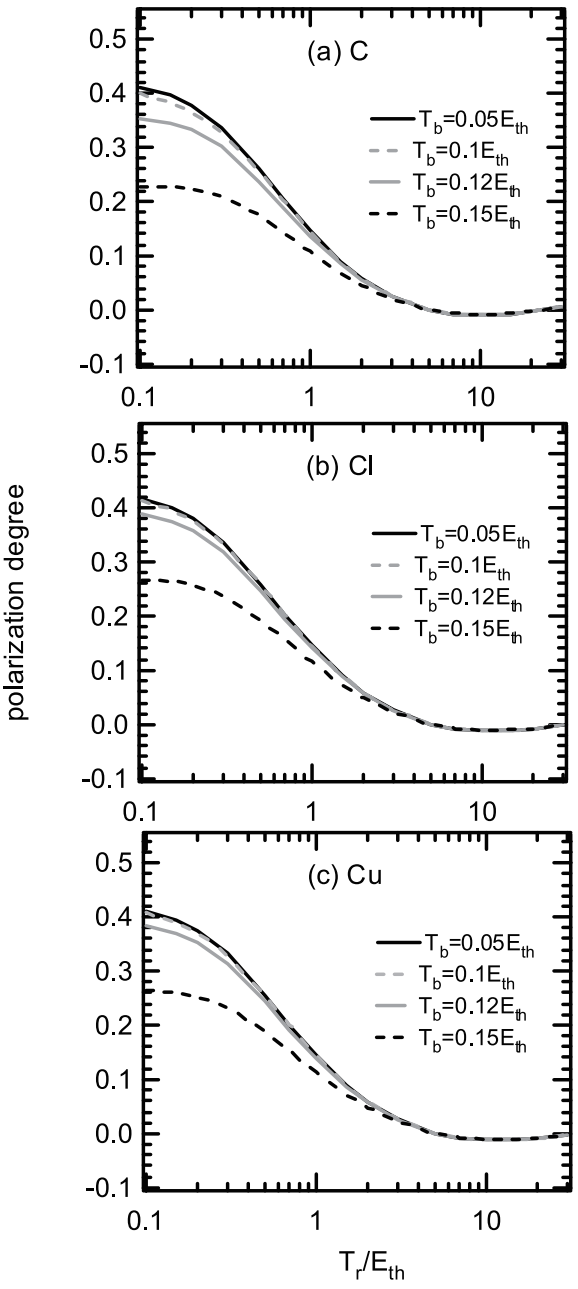

Fig. 4 Polarization degrees of (a) C-Heα, (b) Cl-Heα, and (c) Cu-Heα lines including the contribution of bulk electron components with an assumption of $T_z = 5E_{\rm th}$. $T_{\rm b}$ is normalized by the threshold energy.

A depolarization can be seen with an increase in T_z due to the reduction of the fractional number of free electrons with near threshold energy which induces a high polarization degree. When the polarization degree is positive, T_z is higher than T_r, indicating that a VDF has a cigar-like shape, that is, an elongated shape along the direction parallel to a target normal. In contrast, when the polarization degree is negative, T_z is lower than T_r, indicating that a VDF has a pancake-like shape, that is, elongated in a direction parallel to the target surface. It is possible to derive T_r by comparing these curves with experimentally measured polarization degrees and T_z.

Figures 4 (a)-(c) show an influence of the bulk electron components on polarization degree. In this case, the fractional number of hot electrons is 1%, and $T_z = 5E_{\rm th}$. When $T_{\rm b}$ is lower than $0.1E_{\rm th}$, the polarization degrees are almost equal to the results shown in Fig. 3. In contrast, when $T_{\rm b}$ is higher than $0.1E_{\rm th}$, depolarization can clearly be seen. This is because the high-energy tail component of the bulk electrons overlaps with the hot electron component, and isotropic excitation leading to Heα line emission is enhanced. These results indicate that it is essential to select a tracer material whose Heα line energy is 10 times higher than the bulk electron temperature for hot electron VDF diagnostics.

4. Conclusion

In this paper, polarization spectroscopy is proposed as a promising diagnostic tool for the anisotropy of hot electron VDF in ultra-high intensity laser-produced plasmas. The polarization degrees can be described by a function of threshold energy. It is also shown that depolarization of the Heα line is induced by excitation with the high energy tail of bulk electrons. To avoid depolarization, suitable tracers must be carefully selected. With such selection, x-ray polarization spectroscopy can provide an effective tool for the diagnosis of ultra-high intensity laser-produced plasma.

Acknowledgment

This work was partly supported by MEXT, Grant-in Aid for Creative Scientific Research (15GS0214).

[1] M. Tabak, J. Hammer, M.E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Cambell, M.D. Perry and R.J. Mason, Phys. Plasmas **1**, 1624 (1994).

[2] R. Kodama, H. Shiraga, K. Shigemori, Y. Tohyama, S. Fujioka, H. Azechi, H. Fujita, H. Habara, T. Hall, Y. Izawa, T. Jitsuno, Y. Kitagawa, K.M. Krushelnick, K.L. Lancaster, K. Mima, K. Nagai, M. Nakai, H. Nishimura, T. Norimatsu, P.A. Norreys, S. Sakabe, K.A. Tanaka, A. Youssef, M. Zept and T. Yamanaka, Nature **418**, 933 (2002).

[3] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[4] S.P.D. Mangles, C.D. Murphy, Z. Najmudin, A.G.R. Thomas, J.L. Collier, A.E. Dangor, E.J. Divall, P.S. Foster, J.G. Gallacher, C.J. Hooker, D.A. Jaroszynski, A.J.

Langley, W.B. Mori, P.A. Norreys, F.S. Tsung, R. Viskup, B.R. Waltonand and K. Krushelnick, Nature **431**, 535 (2004).
[5] C.G.R. Geddes, C.S. Toth, J. Van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary and W.P. Leemans, Nature **431**, 538 (2004).
[6] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.P. Rousseau, F. Burgy and V. Malka, Nature **431**, 541 (2004).
[7] A. Rousse, C. Rischel, S. Fourmaux, I. Uschmann, S. Sebban, G. Grillon, Ph. Balcou, E. Forster, J.P. Geindre, P. Audebert, J.C. Gautheir and D. Hulin, Nature **410**, 65 (2001).
[8] S.C. Wilks and W.L. Kruer, IEEE J. Quantum Electron **33**, 1954 (1997), and references therein.
[9] Y. Sentoku, K. Mima, P. Kaw and K. Nishikawa, Phys. Rev. Lett. **90**, 155001 (2003).
[10] P.A. Norreys, K.L. Lancaster, C.D. Murphy, H. Habara, S. Karsch, R.J. Clarke, J. Collier, R. Heathcote, C. Hemandes-Gomez, S. Hawkes, D. Neely, M.H.R. Hutchinson, R.G. Evans, M. Borghesi, L. Romagnani, M. Zepf, K. Akli, J.A. King, B. Zhang, R.R. Freeman, A.J. Mackinnon, S.P. Hatchett, P. Patel, R. Snavely, M.H. Key, A. Nikroo, R. Stephens, C. Stoeckl, K.A. Tanaka, T. Norimatsu, Y. Toyama and R. Kodama, Phys. Plasmas **11**, 2746 (2004).
[11] M. Lombardi and J.C. Pebay-peyroula, C.R. Acad. Sc. Paris **261**, 1485 (1965).
[12] Kh. Kallas and M. Chaika, Opt. Spectrosc. **27**, 376 (1969).
[13] C.G. Carrington and A. Corney, Opt. Commun. **1**, 115 (1969).
[14] J.C. Kieffer, J.P. Matte, H. Pepin, M. Chaker, Y. Beaudoin, T.W. Johnston, C.Y. Chien, S. Coe, G. Mourou and J. Dubau, Phys. Rev. Lett. **68**, 480 (1992).
[15] J.C. Kieffer, J.P. Matte, H. Pepin, M. Chaker, Y. Beaudoin, C.Y. Chien, S. Coe, G. Mourou, J. Dubau and M.K. Inal, Phys. Rev. E **48**, 4648 (1993).
[16] P. Beiersdorfer and M. Slater, Phys. Rev. E **64**, 066408 (2001).
[17] H. Yoneda, N. Hasegawa, S. Kawana and K. Ueda, Phys. Rev. E **56**, 988 (1997).
[18] Y. Inubushi, H. Nishimura, M. Ochiai, S. Fujioka, Y. Izawa, T. Kawamura, S. Shimizu, M. Hashida and S. Sakabe, Rev. Sci. Instrum. **75**, 3699 (2004).
[19] Y. Inubushi, H. Nishimura, M. Ochiai, S. Fujioka, T. Johzaki, K. Mima, T. Kawamura, S. Nakazaki, T. Kai, S. Sakabe and Y. Izawa, J. Quant. Spectrosc. Radiat. Transf. **99**, 305 (2006); Erratum, **101** 191 (2006).
[20] I.C. Percival and M.J. Seaton, Philos. Trans. R. Soc. London, Ser. A **251**, 113 (1958).
[21] T. Kai, S. Nakazaki and K.A. Berrington, Nucl. Instum. Methods Phys. Res. B **235**, 249 (2005).
[22] K.J. Reed and M.H. Chen, Phys. Rev. A **48**, 3644 (1993).
[23] K.A. Berrington, W.B. Eissner and P.H. Norrington, Comput. Phys. Commum. **92**, 290 (1995).
[24] H. Feshbach, Ann. Phys. (N. Y.) **5**, 357 (1958).
[25] T. Kai, S. Nakazaki, T. Kawamura, H. Nishimura and K. Mima, Phys. Rev. A **75**, 012703 (2007).