Limitation of the plasma channel due to the frequency blueshift

Hideyuki Kotaki[1], Yukio Hayashi[1], Michiaki Mori[1], Masaki Kando[1], James K. Koga[1], and Sergei V. Bulanov[1,2]

[1]Japan Atomic Energy Agency, Kizugawa, Kyoto 619-0215, Japan
[2]A. M. Prokhorov Institute of General Physics RAS, Moscow, Russia

E-mail: `kotaki.hideyuki@jaea.go.jp`

Abstract. In laser-plasma interaction, there are physical mechanisms, such as quantum beam generation, relativistic self-focusing of laser pulses, frequency blueshift of laser pulses, etc. Long plasma channel formation via self-focusing is an important mechanism for generating a stable electron beam. The frequency blueshift changes the critical power of the self-focusing. The plasma channel is limited by the change of the power. The limit of the channel causes a fixed blueshift of the laser pulse.

1. Introduction

Laser-plasma interaction includes a lot of physics, such as quantum beam generation, laser self-focusing, frequency shift, etc. Laser WakeField Acceleration (LWFA) [1], which is based on the effect of plasma wave excitation in the wake of an intense laser pulse, is now regarded as a basis for the next-generation of charged particle accelerators. Electron bunches have been accelerated up to 1 GeV by LWFA [2, 3]. In experiments, it has been demonstrated that LWFA is capable of generating electron bunches with high quality [4, 5, 6, 7, 8].

In order to generate a bunch with high quality, required for applications, the electrons should be duly injected into the wakefield and this injection should be controllable. The injection can happen spontaneously, due to a longitudinal or transverse break of the wake wave, caused by its strong nonlinearity [9, 10, 11] and with cluster-gas targets [12]. This regime leads to the acceleration of fast particles, although in an uncontrolled way. Recently we generated a stable electron beam by using an Argon and Nitrogen gas target in the self-injection scheme [15, 16]. In the scheme of self-injection, the long channel improves the stability of the electron beam energy, pointing, and divergence.

On the other hand, in laser-plasma interactions, there is a phenomenon of blueshifting of the laser pulse. The frequency blueshift has two mechanisms, which are ionization blueshift [17, 18, 19] and photon acceleration [20, 21]. The ionization blueshift occurs due to a frequency shift at the boundary between neutral gas and plasma. It occurs in an ionization front. The ionization blueshift is independent of the interaction length and the laser intensity. Photon acceleration is a frequency blueshift in a plasma wake wave. The shift depends on the interaction length, the plasma density, and the laser intensity. From experimental results, a fixed blueshift has been observed [17]. When the target gas is changed, the parameters of ionization should
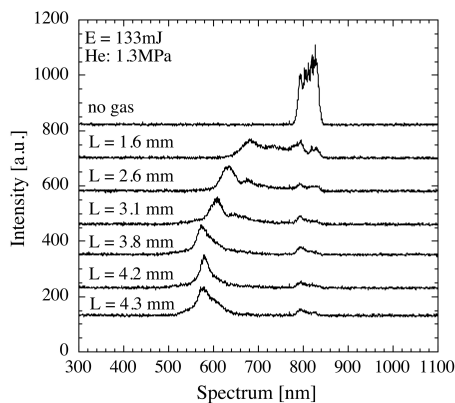
change. Nevertheless, the spectrum of the transmitted laser light was the same, even though the target gases were different.

In addition, relativistic self-focusing is one of the important physics for laser-plasma interaction [22]. When the laser power is high enough, the laser pulse self-focuses. The critical power, P_{cr}, is $P_{cr} = 16.2(\omega_0/\omega_p)^2$ [GW], where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the plasma frequency, ω_0 is the laser frequency, and n_e is the plasma density. The self-focusing is related to n_e and ω_0. The plasma channel is produced in a balance between focusing and de-focusing.

In plasma, the laser pulse is self-focused with frequency blueshift, which includes both the ionization blueshift and the photon acceleration. The plasma channel ends when the laser power becomes smaller than the critical power for self-focusing. In this letter, the effect of the frequency blueshift of the laser pulse in the plasma channel is studied in order to elucidate the fixed blueshift and the plasma channel length limitation.

2. Experimental setup and condition

The experiments have been performed with a Ti:sapphire laser system at the Japan Atomic Energy Agency (JAEA) - Advanced Photon Research Center (APRC) named JLITE-X [23]. The laser contrast ratio within picosecond timescales is 10^6. The contrast ratio within nanosecond timescales is significantly suppressed to the order of 10^8. The laser pulses, which are linearly polarized, with 200 and 133 mJ energy are focused onto a 3-mm-diameter helium gas-jet by an off-axis parabolic mirror (OAP) with the focal length of 646 mm (f/22). The $1/e^2$ diameter of the focal spot is 32 μm. The energy concentration within this region is 60%. The pulse width of the laser pulse, τ, is 40 fs. The estimated peak irradiances from the measurement data, I_0, are 7.5×10^{17} and 5.0×10^{17} W/cm^2 in vacuum corresponding to a dimensionless amplitude of the driver laser fields $a_0 = 8.5 \times 10^{-10}\lambda_0[\mu\text{m}]\sqrt{I_0[\text{W/cm}^2]} = 0.6$ and 0.5, where λ_0 is the laser light wavelength of 800 nm. The spectrum of the transmitted laser pulse is measured with a spectrometer. Figure 1 shows the spectrum of the transmitted laser light. The spectrum shifts with the interaction length, L. The transmitted laser power is measured with a power meter on a linear stage.
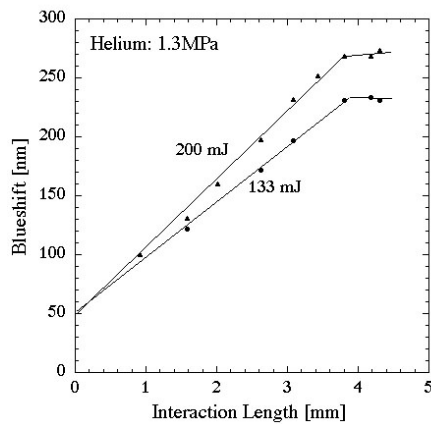

Figure 1. Spectrum of the transmitted laser light. The spectrum shift increased with increasing interaction length, L.

3. Experimental results and discussion

3.1. Gas-length vs shift

The frequency blueshift has two mechanisms, ionization blueshift and photon acceleration. The ionization blueshift is independent of the interaction length and the laser intensity. The photon acceleration depends on the interaction length, the plasma density, and the laser intensity. Figure 2 shows the peak value of the spectrum of the transmitted laser light. The first shift of 50 nm at $L = 0$ is the ionization blueshift. It is independent of the interaction length. The
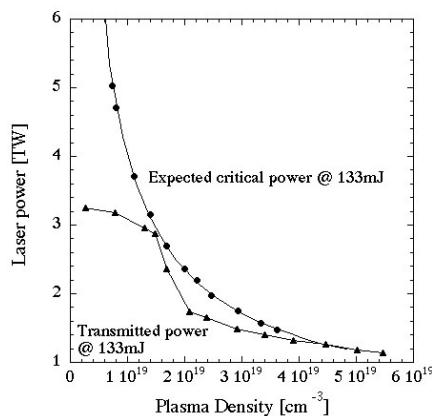
spectrum shift is increasing with L. The shifts are proportional to L and depend on the laser intensity. These should be caused by the photon acceleration. The shifts are saturated when $L > 3.8$ mm. The shifts may finish due to the ending of the plasma channel.

Figure 2. The peak value of the transmitted laser spectrum. The first shift of 70 nm at $L = 0$ is the ionization blueshift. The spectrum shift, which is increasing with L, is the photon acceleration.

4. Comparison of P vs P_{cr}

In the interaction, the laser power decreases due to the plasma generation by the laser pulse. The laser spectrum blueshifts are due to (i) ionization blueshift and (ii) photon acceleration. These effects change P_{cr} and the transmitted laser power, P. The plasma channel ends when $P < P_{cr}$ due to the end of the relativistic self-focusing. Figure 3 shows the relationship between the transmitted laser power, P, and the critical power, P_{cr}. P_{cr} is calculated from the plasma density and the measured transmitted laser spectrum. When n_e is less than 1.5×10^{19} cm^{-3}, the laser pulse has no self-focusing due to low plasma density. When n_e is between 2.0×10^{19} cm^{-3} and 4.0×10^{19} cm^{-3}, the difference of P and P_{cr} is caused by the scattering of the laser pulse by gas after the plasma channel ends. When the plasma density is high enough, the plasma channel continues to the end of the gas-jet. When n_e is higher than 4.0×10^{19} cm^{-3}, P is in good agreement with P_{cr}, because the plasma channel continues to the end of the gas-jet. These results show that the laser pulse in plasma is blueshifted and the plasma channel length is limited due to the spectrum shift. In addition, the blueshift stops when $P < P_{cr}$. The blueshift is also limited due to the stop of self-focusing, and the spectrum of the transmitted laser light is fixed.

Figure 3. Relationship between the transmitted laser power, P, and the critical power, P_{cr}. P_{cr} is calculated from the plasma density and the measured transmitted laser spectrum.

5. Conclusions

In conclusion, we observe two types of the blueshift, (a) ionization blueshift and (b) photon acceleration. The intense laser pulse produces a plasma channel due to the self-focusing. The plasma channel corresponds to a balance between self-focusing and defocusing. In the channel, the laser power decreases and the frequency is blueshifting. When $P < P_{cr}$, the balance is broken and the plasma channel disappears. The end of self-focusing limits the length of the plasma channel and fixes the spectrum of the transmitted laser light.

6. Acknowledgments

References

[1] Tajima T and Dawson J M 1979 *Phys. Rev. Lett.* **43** 267
[2] Leemans W P, Nagler B, Gonsalves A J, Tth Cs, Nakamura K, Geddes C G R, Esarey E, Schroeder C B and Hooker S M 2006 *Nat. Phys.* **2** 696
[3] Hafz N A M, Jeong T M, Choi I W, Lee S K, Pae K H, Kulagin V V, Sung J H, Yu T J, Hong K-H, Hosokai T, Cary J R, Ko D-K and Lee J-M 2008 *Nat. Photonics* **2** 571
[4] Miura E, Koyama K, Kato S, Saito N, Adachi M, Kawada Y, Nakamura T and Tanimoto M 2005 *Appl. Phys. Lett.* **86** 251501
[5] Mangles S P D, Murphy C D, Najmudin Z, Thomas A G R, Collier J L, Dangor A E, Divall E J, Foster P S, Gallacher J G, Hooker C J, Jaroszynski D A, Langley A J, Mori W B, Norreys P A, Tsung F S, Viskup R, Walton B R and Krushelnick K 2004 *Nature* **431** 535
[6] Geddes C G R, Toth Cs, Tilborg J van, Esarey E, Schroeder C B, Bruhwiler D, Nieter C, Cary J and Leemans W P 2004 *Nature* **431** 538
[7] Faure J, Glinec Y, Pukhov A, Kiselev S, Gordienko S, Lefebvre E, Rousseau J-P, Burgy F and Malka V 2004 *Nature* **431** 541
[8] Yamazaki A, Kotaki H, Daito I, Kando M, Bulanov S V, Esirkepov T Zh, Kondo S, Kanazawa S, Homma T, Nakajima K, Oishi Y, Nayuki T, Fujii T and Nemoto K 2005 *Phys. Plasmas* **12** 093101
[9] Bulanov S V, Pegoraro F, Pukhov A M and Sakharov A S 1997 *Phys. Rev. Lett.* **78** 4205
[10] Pukhov A and Meyer-ter-Vehn J 2002 *Appl. Phys.* B **74** 355
[11] Zhidkov A, Koga J, Hosokai T, Kinoshita K and Uesaka M 2004 *Phys. Plasmas* **11** 5379
[12] Fukuda Y, Akahane Y, Aoyama M, Hayashi Y, Homma T, Inoue N, Kando M, Kanazawa S, Kiriyama H, Kondo S, Kotaki H, Masuda S, Mori M, Yamazaki A, Yamakawa K, Echkina E Yu, Inovenkov I N, Koga J and Bulanov S V 2007 *Phys. Lett.* A **363** 130
[13] Bulanov S V, Naumova N, Pegoraro F and Sakai J 1998 *Phys. Rev.* E **58** R5257
[14] Geddes C G R, Nakamura K, Plateau G R, Toth Cs, Cormier-Michel E, Esarey E, Schroeder C B, Cary J R and Leemans W P 2008 *Phys. Rev. Lett.* **100** 215004
[15] Mori M, Kondo K, Mizuta Y, Kando M, Kotaki H, Nishiuchi M, Kado M, Pirozhkov A S, Ogura K, Sugiyama H, Bulanov S V, Tanaka K A, Nishimura H and Daido H 2009 *Phys. Rev. ST Accel. Beams* **12** 082801
[16] Mori M, Kando M, Kotaki H, Hayashi Y, Bulanov S V, Koga J K, Kondo K, Pirozhkov A S, Nishimura H and Nagashima K 2011 *J. Phys. Soc. Jpn.* **80** 105001
[17] Koga J K, Naumova N, Kando M, Tsintsadze L N, Nakajima K, Bulanov S V, Dewa H, Kotaki H and Tajima T 2000 *Phys. Plasmas* **7** 5223
[18] Koga J K 2009 *J. Opt. Soc. Am.* **26** 930
[19] Savage R L Jr, Joshi C and Mori W B 1992 *Phys. Rev. Lett.* **68** 946
[20] Wilks S C, Dawson J M, Mori W B, Katsouleas T and Jones M E 1989 *Phys. Rev. Lett.* **62** 2600
[21] Murphy C D, Trines R, Vieira J, Reitsma A J W, Bingham R, Collier J L, Divall E J, Foster P S, Hooker C J, Langley A J, Norreys P A, Fonseca R A, Fiuza F, Silva L O, Mendona J T, Mori W B, Gallacher J G, Viskup R, Jaroszynski D A, Mangles S P D, Thomas A G R, Krushelnick K and Najmudin Z 2006 *Phys. Plasmas* **13** 033108
[22] Sun G Z, Ott E, Lee Y C and Guzdar P 1987 *Phys. Fluids* **30** 526
[23] Mori M, Pirozhkov A, Nishiuchi M, Ogura K, Sagisaka A, Hayashi Y, Orimo S, Fukumi A, Li Z, Kado M and Daido H 2006 *Laser Phys.* **16** 1092