SUPERSONIC GAS JET TARGET FOR GENERATION OF RELATIVISTIC ELECTRONS WITH 12TW-50fs LASER PULSE

T. Hosokai, K. Kinoshita, T. Watanabe, K. Yoshii, T. Ueda, A. Zhidokov, M. Uesaka,
NERL, University of Tokyo, Tokai, Naka, Ibaraki, 319-1106 Japan
K. Nakajima, KEK, Tsukuba, Ibaraki, 305-0801 Japan
M. Kando, H. Kotaki, JAERI Kansai, 8-1Umemidai Kizu, Souraku, Kyoto, 619-0215 Japan

Abstract

We have generated relativistic electrons by interaction between a high intensity ultra-short laser pulse (Ti:Sapphire, max 12TW, λ = 800nm , 50fs, 10Hz) and gas jet. Using the method of characteristics, we designed a supersonic, rapidly expanding conical *Laval* nozzle to form a well-defined, localized gas target column with the sharp boundary. The experiment was performed with the nozzle, and the energetic electron beam (up to 40MeV) was observed under the condition of the relativistic laser intensity of 1.5 $\times$ 10^{19} W/cm^2 and the helium gas jet density range of 1 .4 - 3 $\times 10^{19}$ cm^{-3}.

1 INTRODUCTION

Recent rapid progress in intense ultra-short pulse lasers has opened high-field sciences such as particle acceleration via laser-plasma interactions, which seem to be quite promising [1]. The laser-plasma accelerators [2], and electron beam generation [3, 4] have been studied in underdense plasma region. We have been investigating relativistic electron generation in a plasma wake wave breaking scheme [5] aiming at a compact ultra-short pulse relativistic electron accelerator / injector which we called laser-plasma cathode [6].

In these experiments a laser pulse is focused on a gas medium with required high power density. Until recently the gas injection into vacuum have been often used as a target owing to its easy handling and high repetition rate [7, 8]. However, production of a high-density, low-vacuum contaminative and spatially well-defined gas jet is a crucial issue for the studies. A supersonic gas jet produced by well-designed nozzle is supposed to provide a high density shock-free flow. We have designed a conical *Laval* supersonic nozzle which can produce gas jet in the density range of 10^{18} - 10^{20} cm^{-3} to perform well-defined laser-plasma interaction studies for energetic electron generation. In this paper we show the design concept of our supersonic nozzle for well-defined gas jet target, and recent results of the electron generation experiment with this nozzle.

2 SUPERSONIC GAS JET TARGET

In order to form a well-defined, localized gas column with sharp boundary, *ie*, to suppress the transverse expansion due to the thermal and fluid motion of the injected gas, the temperature and pressure of the nozzle exit flow should be as low as possible. On the other hand, the number density of the gas must be higher than a certain value for the laser plasma interaction. Therefore we use a conical *Laval* supersonic nozzle to produce a gas target [9]. Assuming the isentropic flow, the figure-of-merits of the localized gas injection are shown as,

$$V_e/V_m = (\gamma/2)^{1/2}\, M_e \qquad (1)$$

for velocity ratio and

$$\frac{N_e/N_0}{P_e/P_0} = 1 + \frac{\gamma-1}{2} M_e^2 \qquad (2)$$

for number density at nozzle exit [10], where V_e is the flow speed at nozzle exit, V_m is the most probable thermal speed, which can be written as $V_m = (2kT/m)^{1/2}$ here, k is the Boltzmann constant, T is the temperature, m is the molecular mass, M is the Mach number, γ is the ratio of specific heat, N is the number density, P is the pressure and subscript e , 0 denote the nozzle exit condition and the stagnation state. The left-hand side of Eq. (1) and (2) is plotted in Fig.1 as a function of Mach number at the exit of nozzle. These equations say that Mach number is a critical parameter and the nozzle with higher Mach number, *ie*, larger expansion ratio, are desirable for the localized gas injection. On the other hand, we have to suppress nozzle length at minimum value to avoid the development of boundary layer.

We have designed wave-free nozzle contours with minimum length [9] and M_e = 4.2, for He (γ = 1.660) by a method of characteristics [11]. Fig.2 shows the calculated density distribution near the exit of the nozzle. Fig.3 shows a gas density at the exit of the nozzle as a function of stagnation pressure at the reservoir. As shown in the figures, the nozzle exit condition is maintained until the arrival of expansion waves and profiles are fairly flat with sharp boundary compared with a case of sonic injection. The gas density at nozzle exit are expected 1.1 $\times$ 10^{20} cm^{-3} for He, at P_0 = 80 atm and M_e = 4.2. The desired gas density and its distribution are reached by choosing the stagnation pressure, Mach number at the exit, and the radius of the nozzle exit.

Thepulsed supersonic gas injection device consist of a nozzle block designed by us and a solenoid fast pulse valve. The high pressure gas is regulated into a reservoir of the

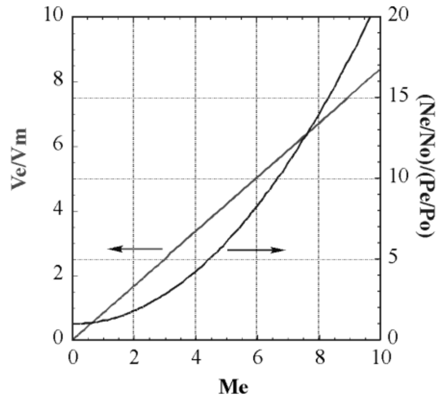

Figure 1: Figure of merit of supersonic gas injection.

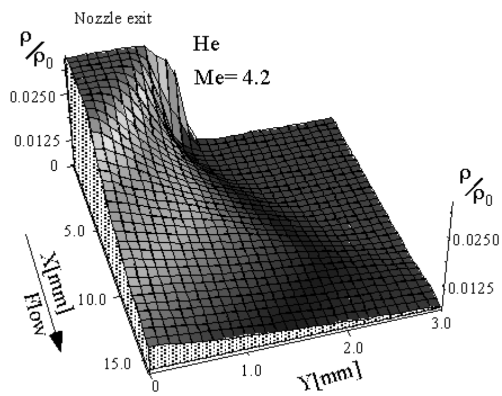

Figure 2: The density profiles of the supersonic jet near the exit of the nozzle for Me=4.2 and helium obtained by the method of characteristics. Density is normalized by stagnation density at the reservoir.

nozzle block through an aperture of the valve, which can control the pulsed supersonic injection. In case of the pulsed supersonic injection, area ratio of an aperture of the valve to a throat of the nozzle (A_a/A^*) must be greater than 1, where area of the aperture and the throat are given as A_a and A^*, respectively. In our nozzle the A^* is 0.5 mm^{-2}, while the A_a is supposed to vary from 0 to π mm^{-2} as a function of the valve motion. The temporal and spatial density distributions of the gas jet from the nozzle were experimentally measured by interferograms with a fast gate CCD camera and they were corroborated with results of the calculation. The temporal density structure of the jet due to slow response of the valve was observed. The required high pressure gas was regulated into the reservoir of the nozzle for only 50 μs, though the valve was driven for more than 5 ms. According to experimental results, the pulse valve with larger effective aperture area and fast opening and closing motion is essential for production of low vacuum contaminative supersonic gas injection. Therefore, we have started development of fast pulse valves with a larger effective aperture, and would like to present it in the next article.

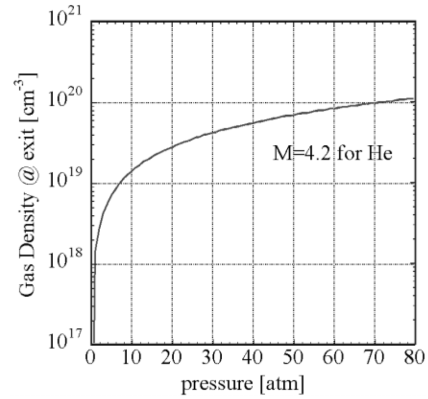

Figure 3: Gas density at the exit of the nozzle as a function of stagnation pressure at the reservoir for Me=4.2 and helium.

3 GENERATION OF RELATIVISTIC ELECTRONS FROM SUPERSONIC GAS JET WITH ULTRA-SHORT LASER PULSE

The typical experimental setup is shown in Fig.4. The nozzle with the pulse valve mentioned in the previous section was fixed inside the vacuum chamber. The pulse valve was driven for 5 ms a shot at a repetition rate of 0.2 Hz. The stagnation pressure of the valve is varied from 5.0 to 20.0 atmosphere. With these pressures the density at the exit of the nozzle ranged from 7×10^{18} to $3{\times}10^{19}$ cm^{-3}. The background pressure of the vacuum chamber was kept lower than 1.0×10^{-4} Torr.

The 12 TW Ti:Sapphire laser system based on CPA technique gives up to 600 mJ, 50 fs laser pulses at a wavelength of 800 nm at the repetition rate of 10 Hz. In this study, available laser power at the target in the vacuum chamber was up to 5 TW. As shown in Fig.4 the *p*-polarized laser pulse with diameter of 50mm was delivered into the vacuum chamber and focused on the front edge of a helium gas jet column at the height of 1.3 mm from nozzle exit with an $f/3.5$ off-axis parabolic mirror. The focal spot size was approximately 5 μm full width at half maximum (FWHM) in diameter. The maximum laser intensity on the target was estimated to be approximately 1.5×10^{19} W/cm^2.

The electron emission from the gas jet was directly measured by a cup-shaped detector consist of imaging plates (I.P.) (FUJI FILM BAS-SR). They were laminated with an aluminum foil in 15 μm thickness on the surface to avoid exposure to X-rays or laser pulses. The electron signals were accumulated for 300 shots. Typical image of electron signals on I.P. s, the side and bottom plates of the cup, were shown in Fig.5.

As shown in the bottom plate in Fig.5, energetic electrons were observed in the forward direction with a narrow cone angle of less than 2.0 degree. They were clearly observed in gas-density range of more than 1.4×10^{19} cm^{-3}, and the beam profiles depended strongly on the density.

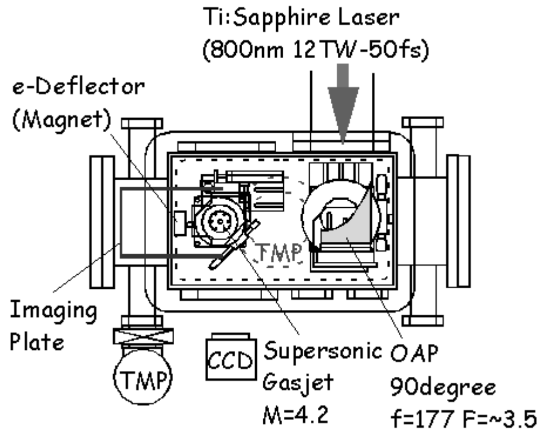

Figure 4: Experimental setup for electron generation with the supersonic gas jet and ultra-short laser pulse.

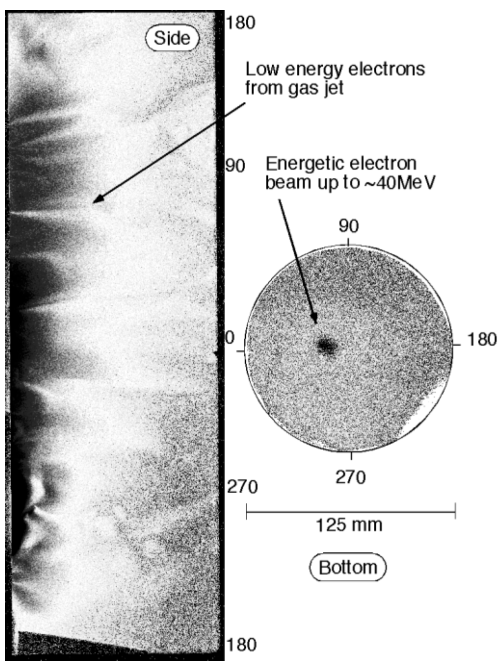

Figure 5: Typical I.P. images of electron emission at a helium gas density of 2.1×10^{19} cm^{-3} and laser power of 2.9 TW.

The electron energy spectra of the generated beam were obtained by a compact magnetic electron spectrometer set on the laser axis behind the jet. With this setup energetic electrons up to 40MeV, which was the spectrometer limit, were observed. In addition, the lower energy electrons less than 500 keV with a wide cone angle of larger than 30 degree from the laser axis were observed on the side-plate. Furthermore, relativistic self-channeling of the laser pulse in a jet, or strong correlations between the energetic electron beam generation and pre-formed plasma by irradiation of laser pre-pulse were observed. The results of the relativistic electron generation experiment will be reported in the next article in details.

4 SUMMARY

We have designed the supersonic, rapidly expanding conical *Laval* nozzle using the method of characteristics to make a well-defined gas jet target for the relativistic electron generation experiment. The ultra-short laser pulse was focused on the supersonic helium jet in the gas density range from 7×10^{18} to 3×10^{19} cm^{-3} with the relativistic intensity of approximately 1.5×10^{19} W/cm^2. The energetic electron beams (up to 40MeV) were observed in the forward direction.

We gratefully acknowledge Prof. K.Horioka of Tokyo Institute of Technology for his encouragement and helpful discussions.

5 REFERENCES

[1] D.Umstadter, “Review of physics and applications of relativistic plasmas driven by ultra-intense lasers”, Phys. Plasmas.**8**, 1774 (2001)

[2] K. Nakajima, Phys. Plasmas., “Challenge to tabletop high-energy laser wake-field accelerator”, **3**, 2169 (1996)

[3] C. Gahn, G. D. Tsakiris, A. Pukov, J. Meyer-ter-Vehen, G. Pretzler, P. Thirolf, D. Habs, and K. J. Witte, ”Multi-MeV electron beam generation by direct laser acceleration in high density plasma channels”, Phys. Rev. Lett.**83**, 4772 (1999)

[4] V. Malka, J. Faure, J. R. Marques, F. Amiranoff, J. P. Rousseau, S.Ranc, J. P. Chambaret, Z. Najmudin, B. Walton, P. Mora, and A. Solodov, ”Characterization of electron beams produced by ultrashort (30fs) laser pulses”, Phys. Plasmas.**8**, 2605 (2001)

[5] S. Bulanov, N. Naumova, F. Pegoraro, and J.Sakai, ”Particle injection into the wave acceleration phase due to nonlinear wake wave breaking”, Phys. Rev. E, **58**, R5257 (1998)

[6] N. Hafz, M. Uesaka, J. Koga, and K. Nakajima, ”Numerical analysis of 10’s femtosecond relativistic electron beam generation using single 12 TW 50fs laser pulse”, NIM. A, **455**, 148 (2000)

[7] V. Malka, C. Couland, J. P. Geindre, V. Lopez, Z. Najmudin, D. Neely, and F. Amiranoff, “Characterization of neutral density profile in wide range of pressure of cylindrical pulsed gas jet”, Rev. Sci. Instrum. **71**, 2329(2000)

[8] S. Semushin and V. Malka, “High density gas jet nozzle design for laser target production”, Rev. Sci. Instrum. **72**, 2961 (2001)

[9] J. D. Anderson, Jr,*Modrrn Compressible Flow with Histrical Perspective 2nd Edition*, (Mc Graw Hill,1989), Chap.5, Chap.11

[10] K. Horioka, K.Ohbayashi, H.Yoneda, and K.Kasuya, “Supersonic gas injection valve for beam neutralization from Applied-B pulsed ion diodes”, Appl. Phys. Lett. **47**, 792 (1985)

[11] R. A. Greenberg, A. M. Schneiderman, D. R. Ahouse and E. M. Paramentier,AIAAJ.,”Rapid Expansion Nozzles for gasdynamic lasers” **10**, 1494 (1972)