Demonstration of light reflection from the relativistic mirror

A S Pirozhkov1,2, T Zh Esirkepov1,3, M Kando1, Y Fukuda1, J Ma1, L-M Chen1, I Daito1, K Ogura1, T Homma1, Y Hayashi1, H Kotaki1, A Sagisaka1, M Mori1, J K Koga1, T Kawachi1, H Daido1, S V Bulanov1,3,4, T Kimura1, Y Kato1 and T Tajima1

1 Advanced Photon Research Center, Japan Atomic Energy Agency, 8-1 Umemidai, Kizugawa, Kyoto 619-0215, Japan
2 P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky prospekt 53, 119991 Moscow, Russia
3 Moscow Institute of Physics and Technology, Institutskij pereulok 9, Dolgoprudny, 141700 Moscow region, Russia
4 A. M. Prokhorov Institute of General Physics of the Russian Academy of Sciences, Vavilov Street 38, 119991 Moscow, Russia

E-mail: pirozhkov.alexander@jaea.go.jp

Abstract. Electromagnetic wave frequency upshifting upon reflection from a relativistic mirror (the double Doppler effect) can be used for the generation of coherent high-frequency radiation. The reflected high-frequency pulse inherits the coherence, polarization, and temporal shape from the original laser pulse. A partly reflecting relativistic mirror (flying mirror) can be formed by a breaking wake wave created by a strong laser pulse propagating in underdense plasma [Bulanov S V et al. 2003 Phys. Rev. Lett. 91, 085001]. We present the results of the proof-of-principle experiment for frequency upshifting of the laser pulse reflected from the flying mirror. In the experiment, the breaking wake wave is created by a Ti:S laser pulse (2 TW, 76 fs) in helium plasma with the electron density of ~5x10^{19} cm^{-3}. The incidence angle of the second laser pulse on the flying mirror is 45°. The reflected signal is observed in 24 shots, with the wavelength from 7 to 14 nm, which corresponds to the frequency upshifting factors from 55 to 114 and the relativistic gamma-factors from 4 to 6. The reflected signal contains at least 3x10^7 photons/sr. The new source promises the generation of coherent ultrashort XUV and x-ray pulses with tunable wavelength and duration, with the possibility of focusing to record intensities.

1. Introduction
Electromagnetic wave frequency upshifting upon reflection from a mirror moving with relativistic velocity [1] can be used for the generation of coherent high-frequency radiation. The frequency of the reflected laser pulse is upshifted and the duration is reduced by the factor \( \approx 4\gamma^2 \cos^2(\theta/2) \), where \( \gamma \) is the relativistic gamma-factor of the mirror and \( \theta \) is the incidence angle. Furthermore, the reflected high-frequency pulse inherits the coherence, polarization, and temporal shape from the original laser.
pulse. A partly reflecting relativistic mirror (flying mirror) can be formed by a breaking wake wave created by a strong laser pulse propagating in underdense plasma [2, 3]. In this case, due to a paraboloidal shape of the mirror surface, the reflected pulse can be focused to record intensities. It is worth noting that the reflection from the flying mirror is a collective effect, arising due to formation of sharp electron density spikes near the wave breaking threshold.

2. Experimental setup
In the experiment [4] (figure 1), the breaking wake wave is created by a Ti:S driver pulse (2 TW, 76 fs) in helium plasma with the peak electron density of $n_e \approx 5 \times 10^{19}$ cm$^{-3}$; the slit nozzle has the dimensions of 1.26 mm (along the driver propagation direction) by 10 mm. To avoid possible laser system damage, the incidence angle of the source laser pulse (6% of the laser energy) on the flying mirror is $\theta = 45^\circ$, so the frequency upshifting factor is $\approx 3.4\gamma^2$. (Here and further $\gamma$ denotes the gamma-factor associated with the phase velocity of the wake wave.) The third laser pulse (probe) is used for alignment (shadowgraph and interferometry). The reflected radiation (signal) is measured with a flat-field grazing-incidence imaging spectrograph consisting of a toroidal mirror, slit, multilayer Mo/C optical blocking filters transmitting radiation within the 5-15 nm spectral region, spherical varied-line-space grating, and back-illuminated CCD. The spectral resolution of the spectrograph $\delta\lambda / \lambda$ changes from $\approx 100$ at 5 nm to $>200$ at $\lambda > 12$ nm. The acceptance angle is $10^{-4}$ sr.

The intensity of the driver pulse in vacuum is estimated to be $5 \times 10^{17}$ W/cm$^2$. However, its power is several times larger than the self-focusing threshold for our electron density ($P_{cr} \approx 0.6$ TW), and the pulse length is several times longer than the plasma wave wavelength $\lambda_{pe} \approx 5$ μm. Under these conditions, the driver pulse becomes self-modulated and self focused during the propagation in the plasma; its intensity increases several times. At the same time, a strongly nonlinear wake wave is generated that eventually breaks, which leads to the acceleration of electrons up to 20-40 MeV. These electrons are monitored by an electron spectrometer consisting of a permanent magnet, phosphor screen, and intensified CCD. The electron acceleration in the self-modulated regime using the same laser system and the gas jet target is described in [5].

3. Particle-In-Cell simulations
According to the 2D Particle-In-Cell (PIC) simulations using the REMP code [6], the self-focusing leads to the driver pulse intensity increase more than 10 times. A good-quality wake wave close to the wave breaking is generated at $\approx 300$ μm before the gas jet center. This region is appropriate for crossing the driver and source laser pulses in order to obtain efficient reflection. Further propagation leads to strong driver pulse depletion accompanied by the soliton formation and intense stimulated Raman scattering. This turns out to be in good agreement with the experimental findings (section 4).

The simulation results of the two pulse crossing are shown in figure 2. The parameters are set according to the experimental conditions. Figure 2 (a) shows the electron density, $n_e$, in the wake of the driver pulse and contours of the source pulse dimensionless amplitude $a_s = eE_0/(m_e c \omega_s)$ (dashed curves) at the source delay $\tau = 0$ (crossing time). Here $e$ and $m_e$ are the electron charge and mass, $E_0$...
and \( \omega_s \) are the source pulse electric field and frequency, and \( c \) is the velocity of light in vacuum. A strongly nonlinear wake wave with thin dense concave reflecting surfaces is clearly visible. Figures 2 (b) and (c) show the electric field of the reflected radiation at the source delays \( \tau = 0 \) and 26.8 fs. (Frequency components near the original source's frequency \( \omega_s \) are filtered out.) The frequency of the reflected radiation depends on the observation angle; the maximum frequency \( \approx 57 \omega_s \) is in the forward direction. This frequency corresponds to the gamma-factor \( \gamma = 4.17 \), in good agreement with gamma-factor values observed in the experiment (see section 4).

### 4. Experimental results

According to the PIC simulations, the crossing point needs to be set just before the soliton formation region. In the spatial region \( \sim 200 \mu \text{m} \) before to \( \sim 100 \mu \text{m} \) after the gas jet center, \( \sim 4 \) to 8 \( \mu \text{m} \) bright spots attributed to the soliton formation have been observed on high-resolution optical plasma images, and intense stimulated Raman scattering cascade has been observed using the imaging spectrograph in the 600 – 1000 nm spectral region. Thus, in most of the shots, the crossing point is set to be within the spatial region from 200 to 400 \( \mu \text{m} \) before the gas jet center. In some shots the crossing point is set outside this region, but no reflected signal has been observed in this case.

The reflected signal is observed in 24 shots. The wavelength of the reflected radiation changes from 7 to 14 nm, which corresponds to the frequency upshifting factors from 55 to 114 and the gamma-factors from \( \gamma = 4 \) to 6. The reflected signal contains at least \( 3 \times 10^7 \) photons/sr in some shots (conservative estimation).

An example of the reflected spectrum is shown in figure 3 (thick solid line). The wavelength of the reflected radiation is \( \lambda_x = 13.5 \text{ nm} \), which corresponds to the frequency upshifting factor of 59, and the wake wave gamma-factor of \( \gamma = 4.2 \). The spectral peak exceeds background by \( 5.4 \sigma \), where \( \sigma \) is the noise standard deviation. Also shown for comparison the spectrum obtained with the blocked source pulse (dashed line, below). The spectrum which can be expected from the Thomson scattering calculated under the most favourable conditions is shown by the filled area; it is very broadband and is well within the noise level.

![Figure 3. Reflected spectrum example.](image)

Dependence of the CCD counts in the highest spectral peak on the source delay in one series of measurements is shown is figure 4. Right part of the figure shows shots with the source pulse blocked. All shots, both containing the signal and not, are shown. The separated point (open circle) is most probably due to the noise. As we can see, the reflected spectra have a pronounced peak near zero source delay. When the source delay \( |\tau| \) reaches 200 fs, the detected spectra are nearly same as those obtained with the blocked source pulse. Figure 5 shows the dependence of the reflected photon number on the source delay and the vertical misalignment; shots from all experimental series containing all 24 detected signals are shown. The gray scale denotes the normalized reflected photon
density (sr^{-1} \mu m^{-1} ps^{-1}) obtained as a sum of Gaussian distributions centred on each signal point with the widths equal to the monitor accuracies. The width of the signal distribution is about 180 fs with respect to the source delay, which is somewhat longer than the source pulse duration, and 12 \mu m with respect to the vertical displacement from the crossing point, which is approximately equal to the source spot size. This means that the reflecting surface size is smaller than the focal spot of the source pulse. The 24 signals detected in the experiment constitute 15\% of shots, in which the crossing point is within the above-specified spatial region, and the alignment accuracy satisfies requirements |\Delta z| \leq 12 \mu m and |\tau| \leq 200 fs.

![Figure 4](image1.png)  
**Figure 4.** Dependence of the CCD counts in the highest spectral peak on the source delay.

![Figure 5](image2.png)  
**Figure 5.** Signal dependence on the alignment accuracy in space (\Delta z) and time (\tau).

5. Conclusion

We experimentally demonstrate the reflection of laser pulses from wake waves generated by ultrashort high-irradiance laser pulses propagating in underdense plasma. The new source promises the generation of coherent ultrashort XUV and x-ray pulses with tunable wavelength and duration, with the possibility of focusing to record intensities. The reflected radiation can also be used to measure parameters of the strongly nonlinear wake waves, such as phase velocity, length, breaking point location, etc.

Acknowledgments

The work was supported by the Japanese Ministry of Education, Culture, Sports, Science, and Technology grant No. 15002013.

References

[1] Einstein A 1905 *Ann. Phys.* 17 891
[2] Bulanov S V, Inovenkov I N, Kirsanov V I, Naumova N M, Sakharov A S 1991 *K Pratt. Soobshch. Fiz.* No. 6 9-11
[3] Bulanov S V, Esirkepov T Zh Tajima T 2003 *Phys. Rev. Lett.* 91 085001
[4] Kando M et al. 2007 Demonstration of laser-frequency upshift by electron-density modulations in a plasma wakefield *Phys. Rev. Lett.* (accepted)
[5] Morí M et al. 2006 Transverse Dynamics and Energy Tuning of Fast Electrons Generated in Sub-Relativistic Intensity Laser Pulse Interaction with Plasmas *Phys. Lett. A* 356 146-51
[6] Esirkepov T Zh 2001 Exact charge conservation scheme for Particle-in-Cell simulation with an arbitrary form-factor *Comput. Phys. Commun.* 135, 144-53