INTRODUCTION

The soft x-rays, coherent or not, have many important applications, and there are increasing needs for powerful and short x-ray source in the spectroscopy or the semiconductor lithography\(^1\)\(^-\)\(^7\)\) and many others. Most of those applications have not been realized, as the current light sources need to be improved significantly in the efficiency, the power and the intensity.

One emerging way to generate intense x-ray is to utilize the scattering between an intense laser and a relativistic electron beam, potentially surpassing the conventional free electron laser (FEL), the most powerful soft x-ray light so far. The great advances in intense visible-light lasers\(^8\)\(^-\)\(^10\)\) and dense relativistic electron beams\(^11\)\(^-\)\(^12\)\) make the technology based on these advances promising: The laser-based FEL\(^13\)\(^,\)\(^14\)\) and non-linear Thomson scattering\(^15\)\) are among them.

In this paper, the authors discuss a new approach of soft x-ray generation along this line of thought. The relevant physics, that the authors take advantage of, are the two-plasmon decay and the backward Raman scattering (BRS). An intense laser, which we call the plasmon pump laser, passes through an electron beam and renders the two-plasmon decay unstable if the wave frequency of the laser is twice of the plasmon frequency in the co-moving frame. Among the plasmons excited, our interest is in the ones whose wave vector is parallel to the electron beam direction. The second laser (the BRS pump laser) encounters the electron beam in the opposite direction and emits soft x-rays via the backward Raman scattering.

In Sec. II, we analyze the two-plasmon decay in a moderately relativistic electron beam. As the second laser encounters the electron beam in the opposite direction, it emits soft x-rays via the backward Raman Scattering. Our analysis suggests that the effective cross-section of this scattering is higher than the Thomson scattering and that the conversion efficiency from the pump laser to the soft x-ray could be as high as 100% in the optimal scenario. Using the plasmon pump with duration of 1-100 pico-second and the electron beam with density of \(10^{18}/cc\) to \(10^{12}/cc\) and energy of 1-10 MeV, soft x-ray of 5 nm to 300 nm with the duration of 10 femto seconds to 1 pico-second can be emitted in the direction of the electron beam. Advantages (disadvantages) of the scheme over other schemes are discussed.

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TWO-PLASMON DECAY IN A MODERATELY RELATIVISTIC ELECTRON BEAM

Let us consider a plasmon pump laser propagating in the same direction with the electron beam (density \(n_0\) and relativistic factor \(\gamma_0\)) and denote the plasmon pump as

\[
S = \left( \frac{\omega_{p0}}{\gamma_0^{1/2} \omega_{pe}} - \frac{\gamma_0^{1/2}}{\omega_{p0}} \right) / 2\sqrt{3},
\]

where \(\omega_{pe}^2 = 4\pi n_0 e^2/m_e\) is the plasmon frequency. Eqs. (1) and (2) will be derived later in this paper.

According to our analysis, the laser with intensity of \(I = 10^{11} W/cm\) to \(I = 10^{13} W/cm\) excites strong plasmons to the level of \(0.01 < \delta n/n_1 < 0.5\) in the electron beam with the density of \(10^{18}/cc\) to \(10^{22}/cc\). The BRS pump with the duration of 1 to 100 pico-seconds could emit the soft x-ray of 5 nm to 300 nm in the duration of 10 femto-seconds to 1 pico-second when \(2 < \gamma_0 < 10\) and \(1 < S < 5\). The effective cross-section of the BRS is much larger than the Thomson scattering and the conversion efficiency of the BRS pump laser to the seed pulse could be as high as 100%. Contrary to the usual BRS, the most of the soft x-ray energy comes not from the BRS pump laser but from the plasmon energy; In this context, the conversion efficiency larger than 100 % is not contradictory.

This paper is organized as follows. In Sec. II, we analyze the two-plasmon decay in a moderately relativistic electron beam. In Sec. III, we discuss the BRS scattering and soft x-ray generation deriving Eqs. (1) and (2). In Sec. IV, we estimate the mean-free path of the BRS and the conversion efficiency. We also suggests the physical parameter regime for practical interest. In Sec.V, we summarize and discuss various aspects of the current scheme.
laser frequency (the wave vector) as $\omega_{pp0}$ ($k_{pp0}$). It is most convenient to analyze the two-plasmon decay in the co-moving frame where the electron beam is stationary. We denote the co-moving frame (the laboratory frame) as 1 (0). For an example, the wave frequency and the wave vector in the laboratory frame (the co-moving frame) are denoted as $\omega_{pp0}$ and $k_{pp0}$ ($\omega_{pp1}$ and $k_{pp1}$). In the co-moving frame, the electron density is given as $n_1 = n_0 / \gamma_0$ due to the length dilatation and the plasmon frequency is given as $\omega^2_{pp0} \approx 4 \pi n_0 e^2 / m_0 \gamma_0$. A photon in the co-moving frame satisfies the dispersion relationship, $\omega^2 = \omega^2_{pe} / \gamma_0 + c^2 k^2$, where $k$ ($\omega$) is the wave vector (frequency) of the photon. The two plasmon decay occurs when $\omega \approx 2 \omega_{pe} / \gamma_0$ or $ck \approx \sqrt{3} \omega_{pe} / \gamma_0$.

Consider the case when the wave vector of the plasmon pump laser is parallel (the same or opposite direction) to the electron beam direction. The wave vectors (wave frequency) of the plasmon pump laser between the laboratory frame and the co-moving frame are related as

$$\omega_{pp0} = \gamma_0 \left[ \sqrt{\omega^2_{pe} / \gamma_0 + c^2 k^2_{pp0} \pm v k_{pp1}} \right], \quad (3)$$

$$k_{pp0} = \gamma_0 \left[ k_{pp1} \pm \omega_{pp1} v_0 / c \right], \quad (4)$$

where $\omega_{pp0}$ and $k_{pp0}$ ($\omega_{pp1}$ and $k_{pp1}$) are the wave frequency and the vector of the laser in the laboratory frame (the co-moving frame), and the upper case (the lower case) is when the photon wave vector is the same (opposite direction) to the electron beam in the co-moving frame. From Eq. 3 and the condition of the two-plasmon decay ($ck_{pp1} \approx \sqrt{3} \omega_{pe} / \gamma_0 c$, $\omega_{pp1} \approx 2 \omega_{pe} / \gamma_0$), we obtain

$$\omega_{pp0} \approx (1 \pm \sqrt{3} / 2 \beta) \omega_{pp1},$$

$$k_{pp0} \approx \left(1 \pm \frac{2}{\sqrt{3}} \right) k_{pp1}. \quad (5)$$

For the upper case (the lower case), the signs of $k_{pp1}$ and $k_{pp0}$ are the same (opposite) and the laser propagates with the same direction (opposite direction) to the beam in the laboratory frame. However, for both cases, the laser propagates in the same direction with the beam in the laboratory frame. For the upper case (lower case), the frequency down-shift of the plasmon pump laser from the laboratory frame $\omega_{pp0}$ to the co-moving frame $\omega_{pp1}$ is given by the factor $F = (1 + \sqrt{3} \beta / 2) / \gamma_0 > 1$ ($F = (1 - \sqrt{3} \beta / 2) / \gamma_0$). For the lower case, assuming $\beta \approx 1$, $F > 1$ ($F < 1$) when $\gamma_0 > 7$ ($\gamma_0 < 7$) so that the frequency can be both down-shifted and up-shifted.

When the electron beam density is low, it is better to have a down-shifted laser in the co-moving frame for the two-plasmon frequency condition. On the other hand, if the electron beam density as high as $10^{20}$/cc or higher, the down-shifting of the plasmon pump laser renders the two-plasmon decay condition not feasible. In this case, the lower case, which does not down-shift as much as the upper case or even up-shift, is advantageous. This is especially the case for the co2 laser.

Lastly, consider a situation when the plasmon pump laser in the co-moving frame is propagating to the $\pi / 4$ angle to the beam direction. This is particular useful since the most unstable plasmon would be in the parallel direction to the beam. Denote the wave vector $k_{pp0} = (k_{pp0x}, 0, k_{pp0z})$ in the laboratory frame. From the Lorentz transform, we obtain $k_{pp1x} \approx k_{pp0x}$ and $k_{pp1z} \approx \gamma_0 (1 + 2 \sqrt{2} \beta) k_{pp0z}$ and then $k_{pp0z} / k_{pp0z} \approx \gamma_0 (1 + \sqrt{8} \beta)$ from the condition $k_{pp1x} \approx k_{pp1z}$. For a given electron beam, the laser should be injected into the beam with the angle given by $k_{pp0x} / k_{pp0z} \approx \gamma_0 (1 + \sqrt{8} \beta)$ and $c k_{pp0x} / \omega_{pe} / \sqrt{\gamma_1}$, where the laser direction is almost at the right angle to the beam direction and thus the interaction time between the beam and the laser will be limited by the spot size of the laser.

The density fluctuation due to the plasmon pump laser from the two-plasmon decay is well-analyzed and given as [16]

$$\left( \frac{\delta n}{n_1} \right)^2 \approx \frac{3}{8 \pi} \frac{c}{v_{te}} \left( \frac{c^2 k^2_{pp1} \gamma_0}{\omega^2_{pe}} \right) \left( \frac{\epsilon^2 E^2_{pp1} \gamma_0}{m^2 e^2 \omega^2_{pe} c^2} \right) \approx \frac{9 \gamma_0^2}{2 \pi} \frac{c}{v_{te}} \left( \frac{c^2}{\gamma_0^2} \right) \left( \frac{k^2}{k_{pp1}} \right), \quad (6)$$

where $E_{pp1}$ is the electric field strength of the plasmon pump laser in the co-moving frame, $v_q = e E_{pp1} / m_0 \omega_{pp1}$ is the quiver velocity, $k_3$ is the wave vector of the Langmuir wave, $v_{te}$ is the electron thermal velocity in the same frame, and we use $ck_{pp1} \approx \sqrt{3} \omega_{pe} / \gamma_0$ and $\omega_{pp1} = 2 c k_{pp1} / \sqrt{3}$. The threshold condition for the two-plasmon decay is given as $1 / 3 (v_q / v_{te})^2 k_{pp1} L > 1$ [16], where $L$ is the length scale of the density variation. For an example, for the co2 laser with $k_{pp1} L \approx 100$ and the electron beam with the temperature of 1 keV in the co-moving frame, the threshold intensity is given as $I \approx 10^{10}$ W/cm² for $k_3 / k_{pp1} \approx 3$. One useful fact is that the quiver velocity $v_q$ is invariant under the Lorentz transform if $E_{pp0} \approx B_{pp0}$ and $E_{pp1} \approx B_{pp1}$, where $E_{pp0}$ ($B_{pp0}$) is the electric (magnetic) field strength of the plasmon pump laser. Also note that the kinetic energy spread $\delta E / E$ of the electron beam in the laboratory frame is the same order with the velocity spread of the beam in the co-moving frame: $\delta E / E \approx \delta v / v$. Assuming the beam energy spread in the laboratory frame is between 1 % and 10 %, the electron temperature in the co-moving frame is between 50 eV and 5 keV.
SOFT X-RAY GENERATION VIA THE BRS

Consider the BRS pump laser propagating in the opposite direction to the beam. Denote \( \omega_{p0} \) and \( k_{p0} \) (\( \omega_{p1} \) and \( k_{p1} \)) as the wave frequency and vector of the laser in the laboratory frame (co-moving frame). It is usually the case that \( k_{p1} > k_{p0} \) and define \( S = k_{p1}/k_{p0} > 1 \). Then, using Eq. (3), we obtain the relationship of the laser frequencies (vectors) between the laboratory frame and co-moving frame;

\[
\frac{\omega_{p0}}{\sqrt{\gamma_0 \omega_{pc}}} = \left( \sqrt{1 + 3S^2} - \sqrt{3\beta S} \right) = \Delta_s,
\]

\[
\omega_{p1} = \sqrt{1 + 3S^2} \left( \frac{\omega_{pc}}{\sqrt{\gamma_0}} \right).
\]

From Eq. (7), Eq. (2) can be derived assuming \( \beta \approx 1 \). The BRS scattering of the laser and the plasmons excited by the first laser is given in the co-moving frame by [18]:

\[
\left( \frac{\partial}{\partial t} + v_s \frac{\partial}{\partial x} + v_2 \right) A_s = -ic_s A_p A_3^*,
\]

where \( A_i = e E_{i1}/m_\epsilon \omega_{i1} c \) is the ratio of the electron quiver velocity of the pump pulse (\( i = p \)) and seed pulse (\( i = s \)) relative to the velocity of the light \( c \), \( A_3 = \tilde{n}/n_1 \) is the the Langmuir wave amplitude, \( v_2 \) is the rate of the inverse bremsstrahlung of the seed, \( c_2 = \omega_3^2/2\omega_{p1} \), and \( \omega_3 \approx \omega_{pc}/\sqrt{\gamma_0} \) is the plasmon frequency in the co-moving frame. The energy and momentum conservation of the BRS is given as

\[
\omega_{p1} = \omega_{s1} + \omega_3,
\]

\[
k_{p1} = k_{s1} + k_3,
\]

where \( k_3 \) is the wave vector of the plasmon. Define \( P = k_{s1}/k_{pp1} \) and we obtain \( P \approx S - 1/\sqrt{3} \) from the energy conservation of Eq. (9), \( \sqrt{1 + 3S^2} = \sqrt{1 + 3P^2} + 1 \). The frequency of the seed pulse is given from the Lorentz transform as

\[
\frac{\omega_{s0}}{\sqrt{\gamma_0 \omega_{pc}}} = \left( \sqrt{1 + P^2} + \sqrt{3\beta P} \right) = \Delta_p.
\]

Using Eqs. (7) and (10), the ratio between the plasmon pump frequency and the seed pulse (soft x-ray) in Eq. (11) can be derived.

MEAN-FREE PATH OF THE BRS AND CONVERSION EFFICIENCY

From Eq. (8), the considerable part of the pump energy will be transferred to the seed pulse when \( c_s A_3 \delta t_b \approx 1 \), where \( t_b \) is the BRS interaction time in the co-moving frame and we obtain the mean-free path

\[
l_b = \delta t_b c \approx c(2\omega_{s1}/\omega_3^2)(1/A_3).
\]

On the other hand, the Thomson scattering suggests that \( l_t \approx 1/n\sigma_t \) with \( \sigma_t = (mc^2/e^2)^2 \). For an example, when \( n_1 \approx 10^{20}/cc \), we estimate \( l_t \approx 10^3 \) cm and \( l_b \approx (10^{-4}/A_3)S \) cm. Even for \( A_3 \approx 0.001 \), the soft x-ray radiation by the BRS is considerably stronger than the Thomson scattering or \( l_t \gg l_b \).

The maximum conversion efficiency from the pump energy to the seed energy can be estimated as follows. Denote the total energy of the pump laser (the seed laser) in the laboratory frame as \( E_{p0} = E_{s0} \). In the co-moving frame, the pump energy is seen to be as \( E_{p1} \approx (\sqrt{3SE_{p0}}/\Delta_s\gamma_0) \) from Eq. (7). Considering the conversion efficiency in this co-moving as \( \epsilon_1 \), the energy of the seed pulse is given as \( E_{s1} = \epsilon_1(\sqrt{3SE_{p0}}/\Delta_s\gamma_0) \). This energy of the seed pulse is seen in the laboratory frame to be \( E_{s0} = \Delta_s\gamma_0 E_{s1}/\sqrt{3}S = \epsilon_1(\Delta_p/\Delta_s)E_{p0} \). Then, the conversion efficiency in the laboratory frame is given as

\[
\epsilon_0 = \left( \frac{\Delta_p}{\Delta_s} \right) \epsilon_1 \approx \left( \frac{\sqrt{(1 + 3P^2)} + \sqrt{3\beta P}}{\sqrt{(1 - 3S^2)} - \sqrt{3\beta S}} \right) \epsilon_1.
\]

The estimation of \( \epsilon_1 \) in the co-moving frame follows. We consider two cases: when the Langmuir waves are rather excited isotropically and when they are excited preferentially in the beam direction. If the plasmons are excited isotropically, the BRS would be radiated isotropically. However, only the radiations in the direction of the beam are relevant for the soft-x ray since only those radiations would be up-shifted by the Doppler effect in the laboratory frame; The angular width relevant for the soft x-ray would be given as \( d\theta \approx S/\gamma_0 \Delta_p \) and the relevant portion of the radiation is then \( (d\theta)^2 \) or \( \epsilon_1 \approx (S/\gamma_0 \Delta_p)^2 \). In the case when the plasmon distribution is sharply peaked at \( \theta \equiv 0 \), the most of the radiation would be in the direction of the beam and \( \epsilon_1 \approx 1 \). From the above consideration, we could estimate the optimal conversion efficiency as

\[
\left( \frac{S^2}{\Delta_p^2} \right) \left( \frac{\Delta_p}{\Delta_s} \right) < \epsilon_0 < \frac{\Delta_p}{\Delta_s}.
\]

Eq. (13) is the maximum possible efficiency since we assume that most of the BRS pump energy will be radiated via the BRS. Given the fact that \( \epsilon_1 \) could be a few tens of percent in an optimistically envisioned scenario, it is possible that \( \epsilon_0 > 1 \) or the conversion efficiency could be larger than 100%. This apparent contradiction can be understood by estimating the energy and momentum conservation of the BRS in the laboratory frame. In the co-moving frame, the BRS pump laser and plasmons will be scattered into a seed photon. In this process, the laser photon and plasmon gives the energy and momentum to the seed photon; the plasmon (the BRS pump laser) gives the momentum \( -k_{s1} - k_{p1} \) (\( k_{p1} \)) and the seed photon acquires \( -k_{s1} \) momentum. In the laboratory frame, the momentum (energy) of the plasmon is much larger than
the BRS pump photon due to the Doppler effect and the seed pulse obtains most of its energy not from the pump pulse but from the plasmon decay. This is not contradictory since the energy for the soft x-ray is mostly not from the BRS pump laser but from the plasmon energy. Using the plasmon pump and BRS pump with the wave length of 1 µm and intensity of $I \approx 10^{12}$ W/cm$^2$ and the electron beam with density of $10^{18}$/cc and relativistic factor $\approx 10$, the scheme can generate the soft x-ray from 10 nm to 300 nm with the duration of 10 femto seconds to 1 pico-second.

This scheme has a few drawbacks. First, it needs dense and uniform electron beam for efficient two-plasmon decay. Second, once the electron beam density and the relativistic factor are fixed, there is no freedom in the frequency for the plasmon pump laser as given in Eq. (5); the auto tuning is harder than other schemes. Third, two lasers instead of one are needed. Fourth, because the electron beam density is high, it needs to propagate inside the plasma of comparable density in order to avoid the space charge expansion. However, with all these drawbacks, given the low intensity threshold of the plasmon pump laser and the possible high conversion efficiency, this scheme is very attractive as an alternative soft x-ray source. In the two-plasmon decay, the saturation mechanism is the ion-dynamics [17]. But in the current scheme, the ion might have relativistic velocity in the co-moving frame and its effective mass could be higher. Then, the non-linear saturation mechanism in the conventional two-plasmon decay [17] might be further mitigated leading to the stronger BRS.

**SUMMARY**

In summary, we propose a scheme for soft x-ray radiations. The scheme is based on the laser-plasm interaction in a moderately relativistic electron beam; namely the two-plasmon decay and the backward Raman scattering. In the scheme, the first laser (the plasmon pump) excites the plasmons inside the electron beam via the two-plasmon decay [16,17]. There are three possibilities for the two-plasmon decay and those three cases are compared. The most prominent one is to excite the plasmons in the same direction to the beam. The second laser (the BRS pump) emits the soft x-ray via the BRS with the excited plasmon. The ratio of the seed pulse frequency to the BRS pump frequency is given in Eq. (10). We estimate the conversion efficiency from the BRS pump to the soft x-ray and conclude that it is sometimes larger than the unit. This scheme has a few drawbacks. First, it needs dense and uniform electron beam for efficient two-plasmon decay. Second, once the electron beam density and the relativistic factor are fixed, there is no freedom in the frequency for the plasmon pump laser as given in Eq. (5); the auto tuning is harder than other schemes. Third, two lasers instead of one are needed. Fourth, because the electron beam density is high, it needs to propagate inside the plasma of comparable density in order to avoid the space charge expansion. However, with all these drawbacks, given the low intensity threshold of the plasmon pump laser and the possible high conversion efficiency, this scheme is very attractive as an alternative soft x-ray source. In the two-plasmon decay, the saturation mechanism is the ion-dynamics [17]. But in the current scheme, the ion might have relativistic velocity in the co-moving frame and its effective mass could be higher. Then, the non-linear saturation mechanism in the conventional two-plasmon decay [17] might be further mitigated leading to the stronger BRS.

**TABLE I:**

| $n_{16}$ | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
|----------|-----|-----|-----|-----|-----|-----|
| $\gamma_0$ | 3.0 | 3.0 | 3.0 | 10.0 | 15.0 | 7.0 |
| $S$ | 4.0 | 10.0 | 3.0 | 15.0 | 5.0 |
| $\lambda_{pp}$ | 1.15 | 2.7 | 9.8 | 5.1 | 1.0 | 1.0 |
| $\lambda_{p0}$ | 1.0 | 1.0 | 10.0 | 10.0 | 3.6 | 2.0 |
| $\lambda_{00}$ | 31.4 | 29.4 | 535.7 | 133.5 | 5.2 | 16.6 |
| $\Delta \rho/\Delta s$ | 0.022 | 0.128 | 0.14 | 0.07 | 0.2 | 0.076 |
| $t_e$ | 436 | 2380 | 31399 | 52426 | 4483 | 1089 |
| $l_b$ | 0.005 | 0.005 | 0.005 | 0.013 | 0.006 | 0.003 |
| $\Delta \rho/\Delta s$ | 0.098 | 0.09 | 0.09 | 0.029 | 0.02 | 0.04 |

The laser and electron beam parameter and the characteristic of the THz radiation. $n_{16}$ is the electron density $n_0$ normalized by $10^{20}$/cc, $S$ is defined in Eq. (2), $\lambda_{pp}$ and $\lambda_{00}$ is the plasmon and BRS pump laser normalized by 1 µm, $\lambda_{p0} = 2\pi c/\omega_{p0}$ is the wave length of the seed pulse in the unit of nm from Eq. (1). $A_3 = \delta n/n_0$ is the plasmon intensity given in Eq. (10), $t_e$ ($l_b$) is the mean-free path of the Thomson scattering (BRS) in the unit of cm from Eq. (11), $\Delta \rho/\Delta s$ is the ratio of the seed pulse frequency to the BRS pump pulse frequency as given in Eq. (10), and $d\theta = S/\Delta \rho\gamma_0$ is the angular width in the conversion efficiency estimation.

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