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Induced polarization effects in high density plasma with coherent x-ray

コヒーレントX線による高密度プラズマ中の誘導分極について

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In this paper induced polarization effects in high density plasma is discussed. Recent XFEL technology make it possible to achieve high gain medium in initially solid target. By converting XFEL pulse to atomic x-ray laser inside this medium, coherence of x-ray laser drastically increases. In this condition, strong interaction between hard x-ray and atom system is expected. Those include several polarization effect inside high energy density plasmas. Using these process, various type of new photonic phenomena will be observed in hard x-ray region.

1. Introduction

Recent X-ray free electron laser(XFEL) can deliver GW-level hard x-ray laser with sub 10fs pulse duration[1, 2]. In addition this XFEL has single spatial mode so that we can focus it into almost diffractive limit size. In Japanese XFEL facility, SACLA, a 100μJ hard x-ray pulse can be focused down to 50nm diameter spot. Therefore, achievable intensity exceeds 10^{20}W/cm^2. This is enough high to generate high density inner shell ionization plasma. In this study, we will discuss the nonlinear phenomena and quantum photonic phenomena in such high intensity x-ray generated plasmas.

2. High density K-shell vacancy plasma

Speed of photoionization is determined with the following equation,

$$\frac{1}{\tau_{ionization}} = \frac{\sigma I}{h\nu} \qquad (1)$$

,where $\tau_{\mathrm{ionization}}$ is the photo ionization time, σ is photo-absorption cross section, I is intensity of x-ray, and $h\nu$ is the photon energy. After ionization of a K-shell electron, single vacancy of K-shell orbit is created. This vacancy is rapidly reoccupied with outer orbital electrons(L shell or M shell) within one femtosecond at middle Z atoms(Ti ~ Zn).. This process includes Auger effects(KLL, KLM, KMM..), and fluorescence emissions(Kα, Kβ, …). If the speed of eq. (1) is faster than sum of these rates, density of single K-shell vacancy's ions increase at the early part of XFEL laser pulse. This threshold is about 2×10^{19}W/cm^2 for Fe ~ Cu atoms.

Next, we estimate the ratio R_{i} of the ionized atoms to the total atoms in solid, which is given by

$$Ri = \frac{\alpha I_p \, \tau_{decay}}{h\nu \, N_{solid}}, \qquad (3)$$

where τ_{decay} is decay time of the single vacancy state, and N_{solid} is the initial density of the target, a is absorption coefficient for photo-ionizing beam. At the previous threshold intensity, this R_{i} is estimated to be about 10%. Those estimations denote that we can produce high density single K-shell vacancy's ions inside the solid density medium.

3. Hard x-ray radiation dominated plasmas

In such extreme condition, we can expect large x-ray gain of Kα emission[3]. By using simple gain estimation with above mentioned parameters, the small signal gain coefficient of Kα1 is calculated and that is larger than 4×10^4cm^{-1}. Typical length of this gain medium is assumed to be the absorption length of the pump laser. Finally, we reach the gain-length product of this radiation is larger than ten. That means the gain saturation will occur. Once the saturation is occurred, the effective rates of the other transitions could be modified. The branching ratio of these transition is also different from natural condition.

In the SACLA experiments we observed the spectrum of Kα emissions which shows this modification of the transitions. As well-known, the emission of the K shell fluorescence have two components. Namely, these are Kα1($2p^{3/2}$-1s) and Kα2($2p^{1/2}$-1s). The intensity ratio of these emissions is determined with statistical weight and that is 2:1 in the normal condition. Normally, both of Kα1 and Kα2 are observed simultaneously with this intensity ratio. However, at the condition mentioned above, only Kα1 emission is appeared. This means the transition from the upper state(single vacancy of K shell orbit) is mainly induced into only Kα1. That is also denotes that branching ratio of Auger effect decreases.

4. Coupling plasma between radiation and resonant quasi-two levels

In the above condition, the transition of one of the Kα radiations dominated and the other transition processes are restrained. In other words, this system looks quasi-two level's system. These two levels also contribute amplification and absorption of Kα radiation. In the optical quantum photonics, such system results in superposition of these states with a photonic wave. Up to now, there is no evidence to observe such phenomena in hard x-ray region. But recently, we observed some evidence. That is the splitting of Kα spectrum. Splitting in frequency space means oscillation in time. Therefore, it is some possibility to achieve Rabi-oscillation, which is one of the evidence of the superposition.

The 1D simulation for calculating x-ray intensity and population of each states also denotes this phenomena. Figure 1 shows typical calculation result for spatial distribution of number density of each states and intensity of the pump laser and the Kα atomic laser. After 5micron, the number density of the upper and the lower states of the Kα laser are almost equal each other(N1 and N2 in this figure). That means balance between existing radiation and states of the two levels is occurred and those are coupled strongly.

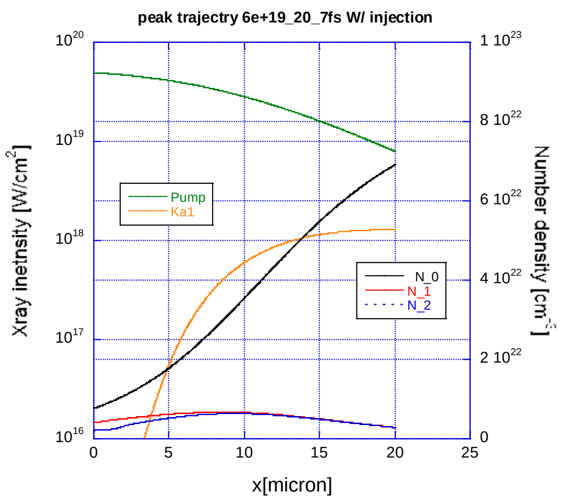

Fig.1 Spatial dependence of radiation intensity and number density of each states

3. Conclusion

In this paper, we discuss the interaction physics between ultra-high intense hard x-ray radiation and inner-shell vacancy condition of ions. In Japanese SACLA facility, there is many type of high intensity experiments which connects to these physical phenomena.

References

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