3. Recent Research Work on Ultra-High-Power Laser Plasma Aiming at Nuclear Physics

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Abstract

This paper reviews recent experimental research using ultra-high-power laser. The intensity achievable with PW-level lasers now reaches $10^{21}$ W/cm². At that intensity, the quiver velocity of electrons increases to be fully relativistic. The hopes for application of these laser-plasmas to nuclear physics experiments become larger and larger. Although the intensity is still lower than required for direct excitation of the nucleus, the recent nuclear reaction experiments with PW-lasers and the trend of this field will be described. The plan of future investigations will be also introduced.

Keywords:
relativistic laser plasma, ultra-high-power laser, QED, photo-nuclear reaction, peta watt laser, intense charged particle beam, electron-positron pair creation, Bremsstrahlung

3.1 Present Status of Ultra-High Power Laser and their Limitation Factor

3.1.1 History of laser power development

Since application of chirped pulse amplification to large-scale laser systems [1], ultra-high power intensity experiments can be performed. The basic idea of this amplification is expanding the pulse duration during the amplification stage for avoiding optical damage to the amplifier and preventing undesirable nonlinear effects (such as self focusing and phase distortion due to increasing B-integral). In 1996, Lawrence Livermore National Laboratory (LLNL) succeeded in the development of a Petawatt Laser [2]. They constructed it with one arm of the NOVA Nd:glass laser chain, which was used as a driver laser for inertial confinement fusion research. The frequency chirped pulses were amplified to kJ energies and were compressed with very large gratings (940 mmφ) to 0.45 ps. The peak power of the pulses was as large as 1,000 TW and the focused intensity (with F/3 on-axis parabola to a <20 μm spot size) exceeded $10^{20}$ W/cm². After this development, Rutherford Appleton Laboratory in UK and Institute of Laser Engineering in Japan built or plan to build PW-level laser systems.

At those intensities, quiver energy of electrons reaches a fully relativistic condition. Various mechanisms or approaches were proposed and discussed. Specially, high energy electrons having the energy of tens-MeV were obtained with several plasma acceleration mechanisms so that some laser driven nuclear physics phenomena were expected and investigated from that time.

3.1.2 Limitation factor for ultra-high-power laser

The output fluence of a laser amplifier is limited by many factors. For example, the saturation mechanism of amplification, nonlinear optical effects, and damage of optics, and so on. In CPA high power laser system, a pair of compression gratings are used for final pulse compression. The laser intensity at the second grating causes most severe limitation due to the large and
complex electric field at the grating surface. Therefore, improvement of the damage characteristics of gratings is most important problem in PW laser systems. Figure 1 [3] shows the damage threshold of optical components (fused silica transmission grating, multilayer dielectric coating polarizer and the grating) [4-6]. Recently, a multilayer-coated grating was developed [6]. To compare to the normal metal gold grating, the surface absorption was reduced and a higher damage threshold was obtained. However, from Fig. 1, even for these new optical devices the damage threshold is 0.8 J/cm² for a 0.5 ps pulse. If we consider the 1 PW laser with 1 kJ/1 ps and using the grating at 75% damage threshold, the effective grating size has to be larger than 1,700 cm².

Because of the cost and technical difficulty of production of large multilayer coated grating, the gold coating was still used at the PW laser system of LLNL. In this case, the grating size has to be larger than above estimation. Since the present typical manufacturing error of large grating is 0.01-0.03 μm/cm, research and development for new manufacturing methods for large size of gratings are strongly required. In addition, new ideas will be needed such as coherent adding of multi-beam laser, phase-front alignment with multi-grating optics, and so on.

### 3.1.3 Electric field at laser focal point

The focusing diameter of any laser is limited by diffraction. Practically, the F-number will be larger than 1 so that minimum diameter of high power focusing will be larger than wavelength even if perfect collection of phase front is achieved. Therefore, present ideal maximum intensity will be $10^{21}$ W/cm² (Actually, the present record value is $10^{21}$ W/cm² [7]). That is because focusability is not so ideal due to imperfection of wave front.). The corresponding electric field for this intensity was $5 \times 10^{12}$ V/cm = 50 kV/Å. Considering typical size of atom, this field is larger than binding energy of electrons. (Actually, in the case of $I > 10^{18}$ W/cm², the electric field of laser can exceed 1s-electron binding energy of hydrogen and there were several studies such as field ionization of atoms.) After achieving this intensity, there are a lot of interesting research work because the energy of electron quiver motion exceeds its rest mass energy. However, even with this extremely large intensity, if we consider the nuclear size ($R_N = 2-10 \times 10^{-13}$ cm), corresponding potential energy is only 1-5 eV. That is present status of available laser focusing intensity and we will need more intense lasers to directly excite nucleus.

### 3.2 Interaction of Laser Light and Nucleus

#### 3.2.1 Normalized numbers for understanding the interaction of photon and nucleus

It is easy to understand the interaction phenomena with dimensional arguments [8]. At first, we summarize three characteristic lengths:

- Classical radius of the electron
  \[ r_0 = \frac{e^2}{mc^2} = 2.8 \times 10^{-13} \text{ cm} \]

- Wavelength of laser
  \[ \lambda_{\text{laser}} = 10^{-5} \text{ cm} \]

- Electron Compton wavelength
  \[ \lambda_{\text{c}} = \frac{h}{mc} = 2.4 \times 10^{-10} \text{ cm} \]

In addition, a photon density $\rho = I / h\omega_{\text{c}}$ is considered. With the above parameters, the following dimensionless numbers can be extracted to estimate the number of photons inside a particular volume.

\[
C_1 = \rho \lambda_{\text{c}} r_0^2 \\
C_2 = \rho \lambda_{\text{c}} r_0 \lambda_{\text{laser}} \\
= \rho r_0 \lambda_{\text{laser}}^2 / mc^3 = 10^{-10} \lambda_{\text{laser}}^2 I \\
C_3 = \rho \lambda_{\text{laser}}^2 r_0 = 1 \lambda_{\text{laser}}^2 / c \cdot 1 / \hbar \omega_{\text{c}}
\]

Because $r_0 \ll \lambda_{\text{c}} \ll \lambda_{\text{laser}}$, the value of these parameters are going to smaller from $C_3$ to $C_1$. For example, $C_1$ at $I = 10^{21}$ W/cm² is $5.1 \times 10^{-2}$. This extremely small value means that present intensities are far from that required for the direct interaction with the nucleus. The parameter of $C_2$ means the ratio of electromagnetic wave energy within volume of $r_0 \lambda_{\text{c}}^2$ and electron rest mass. In other word, this number denotes relativistic factor of electron quiver motion. The
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Parameter $C_3$ means the ratio of the energy of laser electromagnetic wave within volume of $r_0\lambda^2$ to the photon energy. This value denotes capability of multi-photon interaction with free electrons. This value becomes unity at $I\sim 10^{12}$ W/cm$^2$. We have already passed this criterion with smaller commercial laser systems so that we have observed a lot of nonlinear multi-photon interaction phenomena.

3.2.2 Three roads for laser driven (assisted) nuclear reaction

In this section, I summarize the laser driven or assisted nuclear reaction route. There are three routes to consider.

(1) Direct interaction of nucleus

People believe, someday, we will reach the direct interaction intensity ($C_1\sim 1$). After achieving this intensity, high precision test of quantum electrodynamics will be started. These effects include scattering of light by light, production of electron-positron pairs out of the vacuum in the present of intense external field, photon decay in intense field, and nonlinear dispersion of vacuum such as field dependent refractive index and birefringence. The critical field of this phenomenon is

$$E_c = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm}.$$  (4)

The corresponding intensity is $I_c = \frac{cE_c^2}{4\pi} = 4.7 \times 10^{29} \text{ W/cm}^2$ so that we have to increase 5-7 orders of magnitude larger power for laser pulse.

(2) Laser assisted or laser induced effect in nuclear physics process [8]

It was considered there are some possibilities to interact directly low-lying nuclear levels with laser photon. The theoretical studies of these phenomena have long history. However the direct use of laser radiation remains hopeless even with very small energy difference in nucleus system (For example, the Hamiltonian of interaction with laser wave is $H_{LA} = -e \sum_{p=1}^{N} r_p \cdot E_p(t)$ and the matrix element of this process can be derived to $M = (10^{13} \sim 10^{15}) I_4 [\text{W/cm}^2]^{1/2} [\text{eV}]$. Therefore, if we can assume the energy difference of only a few eV energy (for example, $^{229}$Th etc.), $M/\Delta E$ is estimated to order of $10^{3}$ even for $I = 10^{21} \text{ W/cm}^2$.)

Although there is small possibility for these direct interactions, several other methods was proposed to promote nuclear reaction with laser photons (Fig. 2). For example, use of atomic shells in the Compton excitation of nuclei [9], laser assisted nuclear anti-Stokes transitions [10], laser-assisted internal conversion of nuclei [11], and electron bridge mechanism as a source of de-excitation of nuclei [12]. All of these processes have common property because electronic shells of atoms are used as mediators between laser and nuclei. Specially, anti-Stokes $\beta$-transition on the nucleus will be important at ultra-high intensity laser field. In this process, de-excited transitions of nuclear levels located close to the ground state are occurred. Since this process has different selection rule, it is expected to apply the investigation of specific nuclear levels which are inaccessible by the other method. Recent theoretical investigation denoted there was no intensity dependence of laser for the total $\beta$-decay in longer wavelength limit. However, the strong intensity dependence is still expected because the capture of the orbital electrons by a nucleus is naturally influenced by external electromagnetic field. For more quantitative estimation of this process under the stronger laser field condition, theoretical investigation including the ponderomotive potentials will be required.

(3) Use of laser produced high energy particles or high energy photons

As compared with use of bounded electrons, there are a lot of experiments with "external source" of electrons or photons for nuclear reactions. They had some advantages because target condition can be chosen for efficient generation of "reactive" particles or photons.
to separate from that of nuclear reaction target. For example, temperature in the target of nuclear reaction will remain to be low and ionization of other process (such as thermal collisional one) will be minimized. It is often important for investigation of the minor reaction to keep a 'silent' condition. High-energy photons were also produced by these accelerated electrons. In this case, the accelerator like experiments can be done.

Among these three routes for laser started/assisted/driver driven nuclear reactions, almost all the present experiments belong to this third route. That is because it is difficult to achieve (1) scheme and there are small attractive points in (2) without more accurate theoretical supports. So, in the following section, I will concentrate to the recent experimental results related to the third route.

3.3 Trend of Recent Investigation with Ultra-High Power Laser Toward Nuclear Physics

3.3.1 Production of high energy electrons

There was no doubt of generation of energetic electrons because the quiver velocity exceeds relativistic. The model included $J \times B$ ponderomotive force also predicted hot electron temperature would be larger than MeV [13]. Present interest was concentrated to improvement of efficiency and the detail physics for the generation. Figure 3 shows that measured energy distribution functions of electrons ejected from solid state targets at $I = 10^{20}$ W/cm$^2$ ($\lambda = 1.06$ $\mu$m) [14]. There were two components in the observed electron velocity. The lower energy part was generated with direct ponderomotive scattering of electrons. The electron temperature with this process can be estimated with following formula of cycle-averaged energy $\bar{E}$ of the quiver electrons.

$$\bar{E} = mc^2 (1 + 2U_p / mc^2)^{1/2}$$  \hspace{1cm} (5)

$$U_p = 9.33 \times 10^{-14} I [W/cm^2] \lambda [\mu m]^2$$  \hspace{1cm} (6)

For intensity of $I = 10^{20}$ W/cm$^2$ $\bar{E}$ is ~3 MeV. This value consisted with the experimental results of Fig. 3. It was considered the higher energy component of electrons was produced by some acceleration mechanisms in the underdense plasma. These mechanisms included stimulated forward Raman scattering, self-modulated wakefield acceleration, 3D magnetic field effect. The presence of the higher energy component was also confirmed by yield of photo-

![Fig. 3 Measured energy distributions for electrons emitted at 30 and 98 with respected to the incident laser direction for 300 J, 0.5 ps shot on thick gold targets [14].](image3)

![Fig. 4 Angular distribution of suprathermal electrons without prepulse [15].](image4)

![Fig. 5 Spectral distribution of electrons in one filament, showing narrow, mono-energetic electron beam [14].](image5)
nuclear reactions [14], which had some threshold energy. The highest observed energy of electron reached to 100 MeV.

This energetic electron can be used for the sequential nuclear reaction. For this purpose, the electron beam having lower divergence and narrow energy spread was desirable. In contrast with longer pulse laser experiments, the angular collimated jets of electron could be generated from planer solid state target (Fig. 4) with ultra-short-pulse laser [15]. In addition, there was some result to achieve narrower energy spread of electrons with choosing the experimental conditions (Fig. 5) [14]. The key point for these monoenergetic-like electron beams was controlling the plasma scale length, which was decided with intensity ratio of the prepulse and the main pulse laser and the duration of them. For example, to achieve energy spectrum shown in Fig. 5, the pulse duration increased to 5 ps. It would remain to determine the precise acceleration mechanism, but these results were the first step to control directional monoenergetic electron beams from the PW-class laser produced plasma.

3.3.2 Generation of positron

There was strong Bremsstrahlung radiation in PW-class laser produced plasma because even with quiver motion, the electron energy exceeds the relativistic criteria. The positron-electron pair production was occurred with these high-energy photons. In 1999, the LLNL group succeeded the observation of positrons from laser produced plasma [16]. Figure 6 denoted the observed energy spectrum of the positrons and the electrons. They measured target thickness dependence on the positron energy spectrum. In the case of thick targets, the positron yield was consistent with the value estimated from pair production process due to the Bremsstrahlung photons. However, in the case of the thinner target shown in Fig. 6, the number of positrons clearly exceeds the expected yield calculated with the external Bremsstrahlung photons. This discrepancy means there were additional mechanisms such as “trident” production, which is direct positron-electron pair production due to electron-ion collisions.

Before this positron experiment, the positron production in light-by-light scattering was already observed in an experiment at the Final Focus Test Beam of SLAC [17]. In this experiment, 46.6 GeV electron beam from SLAC collided with TW laser pulses to generate 29.2 GeV photon. Interact with this high-energy photon and original laser photon, they achieved the multi-photon Breit-Wheeler reaction.

\[ \omega + n \omega_0 \rightarrow e^+e^- \]

Actually, it was the first laboratory evidence for inelastic light-by-light scattering involving only real photon. It is important to consider the position of the PW-class plasma positron experiment among various experiments of positron generation. Of course, it was not surprising that the positron production occurred in solid state material with γ-ray. For the sense of the fundamental investigation toward QED physics, the SLAC experiment will be more attractive. The

![Fig. 6 Spectra of electrons and positrons measured in 600 J / 0.5 ps shot on 125 µm Au target. Histograms show PIC simulation of electrons, and corresponding prediction for positron creation by Bremsstrahlung in the Au target [16].](image)

![Fig. 7 Experimental setup for positron generation with high repetitive TW-class laser [18].](image)
sophisticated point of the PW-laser experiment was that only low energy photons was used for positron generation. However, it may be clear that this PW experiments was the first step for future laser-driven nuclear experiments.

Recently, Max Plank Institute (MPQ) succeeded $2 \times 10^8$ Bq positrons with a high repetitive femtosecond table-top TW laser [18]. Figure 7 shows schematic drawing of their experimental setup. They created a relativistic plasma channel and accelerated electrons to multi-MeV energies in it. These electrons was well collimated and collided with a high-Z solid target. There were several investigations about the formation of relativistic self-focusing channels and the mechanism of electron acceleration in it [19-23]. According to these studies, for creating the channel laser power has to be exceeding $17(n_e/n_c)$ GW. As the plasma density increases, the required power decreases. Because loss rate of the laser intensity inside the channel (ex. absorption with ionization and defocusing with ionization phase change) is larger in higher density plasmas, there is some optimum condition for density. In TW level experiments, the total accelerated energy of electrons also had a maximum value at above optimum condition for the channel [19]. The mechanism of positron generation was again considered to be two possibilities, such as (a) via Bremsstrahlung photon or (b) direct electron-nucleus collision (trident process). To contrast with the PW-level laser experiment, indirect process (a) is dominant in this energy range of electrons. The number of generated positron was $-2 \times 10^7$ shot. Since the laser can be operated with more than 10 Hz repetition rates, these positron sources will be applicable for the fundamental physics research and material science.

### 3.3.3 Photo-nuclear fission experiments

In 1988, Boyer, Luc, and Rhodes predicted optically induced nuclear fission [24]. They considered that there were two possible processes to achieve laser-started nuclear fission reaction.

\[
\gamma + A \rightarrow f_1 + f_2 + \tilde{n} \tag{7}
\]

\[
e^- + A \rightarrow f_1 + f_2 + \tilde{n} + e^- \tag{8}
\]

The process (7) denoted fission via Bremsstrahlung $\gamma$-ray and (8) means direct nuclear fission started with quivering electrons. For the latter process, the energy of electrons had to be as large as $\gamma = 24$. They predicted that the fission events of heavy elements like $^{238}$U would be observed at $I \sim 10^{23}$ W/cm² with $\lambda = 0.248$ µm laser. The fission probability was also calculated and would be $10^{-3}$ for $^{238}$U with 100 fs laser pulse. They also considered that the observation of fission fragment would become the sensitive diagnostics because they could be detected even with single event. Therefore, they said it would be good test for intensity of coherent fields at interaction region.

After ten years from Boyer’s work, the laser started photo-nuclear experiment was succeeded. The high-energy Bremsstrahlung photon was used for this experiment. The energy of this photon was less than 60 MeV (see Sec. 3.3.1) so that the photons can excite nucleus directly. Figure 8 shows energy

![Fig. 8 Calculated Bremsstrahlung spectrum compared to yield of high-energy photons determined from $^{197}$Au ($\gamma$, xn) activation yields [14].](image)

![Fig. 9 Mass distribution of fission fragments detected curves show mass yield versus Bremsstrahlung end-point energy for accelerator-based measurements.](image)
distribution of γ-rays emitted from the target in the LLNL PW-laser experiment [14]. They identified \(^{87,88}\text{Kr},^{92,93}\text{Sr},^{93,94,95}\text{Y},^{101,104}\text{Tc},^{105}\text{Ru},^{107}\text{Rh},^{128}\text{Sb},^{128}\text{Sn},^{135}\text{Te},^{137}\text{I},^{138}\text{Xe},^{139}\text{Cs},^{141}\text{Ba},\) and \(^{146}\text{Ce}\) spectrum. These products were obtained with photon-fission process of \(^{238}\text{U}\). The mass distribution of these fission fragments was plotted in Fig. 9. It was found that these yields were in good agreement with those estimated from ordinal cross-section data obtained in conventional accelerator experiments. This agreement means the measured γ-ray spectrums can be used as diagnostics for high energetic electrons in ultra-high-peak power laser plasma interaction.

In Rutherford Appleton Laboratory (RAL), photonuclear reaction experiments were also done [25]. Because they concentrated into the simplest photonuclear reactions with γ-ray beam, a high-Z Bremsstrahlung target was located separately from photonuclear reaction materials (Fig. 10). A 50 TW of Nd:glass VULCAN laser pulse was focused with f/1.7 parabolic mirror and achieved \(I = 10^{19}\) W/cm\(^2\). Firstly, they investigated the angular distribution of the high-energy γ-rays from Bremsstrahlung targets. The dependence of plasma scale length was also studied experimentally. The scale length was controlled with changing the temporal duration of the pedestal pulse preceding the main pulse (Fig. 11) [26]. For shorter scale length plasma interaction, Brunel-type resonance absorption [27] was dominant, while for longer one, \(J \times B\) type acceleration dominated in production of hot electrons. These different absorption mechanisms resulted in different properties of electron trajectory so that profile of γ-ray was changed. In both scale length cases, γ-ray beams had 35–40 angular spread.

Using this γ-ray beam, they succeeded to activate \(^{11}\text{C},^{38}\text{Kr},^{62}\text{Zn},^{106}\text{Ag},^{140}\text{Pr}\) and \(^{180}\text{Ta}\) with \(^{60}\text{Cu}\). They proposed to use the activation ratio between \(^{11}\text{C}\) and \(^{60}\text{Cu}\) as a temperature diagnostic of hot electrons. In Fig. 12, there are three data of this ratio for similar shots at intensities around \(10^{19}\) W/cm\(^2\). Although difference of laser intensity and temperature of hot electron seemed to be small, relatively large variety of the ratio was observed. They estimated the temperature of 1.43, 1.63, and 2.06 MeV, respectively.

To look back upon 1988-paper [24], these photo-

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![Target normal](image1)

**Fig. 10** The arrangement for irradiating a number of different targets simultaneously. All samples had dimensions \(10 \times 10 \times 3\) mm. The copper target was used for normalization of activities [26].

![Target normal](image2)

**Fig. 11** Four normalized angular distributions fitted with Gaussian distributions, offset for clarity. (a) Large scale length (\(L = 5.9\) \(\mu\)m) and (b) small scale length (2.6 \(\mu\)m) cases. (c) and (d) show evidence of two different beams as a very wide single peak (c) and as a double-peaked distribution (d) [26].

![Target normal](image3)

**Fig. 12** The calculated \(^{11}\text{C}/^{60}\text{Cu}\) ratio as a function of \(kT\). Three typical experimental ratios are shown for three shots at laser intensities \(I = 10^{19}\) W/cm\(^2\) [25].
fission experiments were proposed at that time. Today, this proposal materialized with the PW-class high power lasers.

3.3.4 Collimated proton beam generation

Even with lower intensity experiments, high energy ions were observed. Before PW-class laser, the following mechanisms were proposed for ion acceleration in laser-plasma interaction.
(A) Radial acceleration with ponderomotive pressure at focusing columns in low density plasma [28].
(B) Axial acceleration with ponderomotive force in solid state target [29].
(C) Coulomb explosion of molecules [30] and clusters [31].

The ion energy with these mechanisms was limited at ~1 MeV/nucleon. However, much more high-energy proton beam was generated from a simple plane CH target [32] in the PW-class laser experiments. In this experiment, there were several interesting features observed.
(i) The collimated proton beam were generated only from rear surface of the target. The direction of this beam was perpendicular to the surface.
(ii) The maximum energy was twice higher than previous scaling law \( E \sim n^{2/3} \) [33].
(iii) The conversion efficiency was estimated to be 12% from incident laser one. This value was higher than those for lower intensity.
(iv) The current of the proton beam was estimated to be of order of MA.
(v) The energy spectrum of the proton had a sharp cut-off at \( E = 58 \) MeV.

Wilks et al. proposed the model of this acceleration [34]. A physical picture of the ion acceleration is shown in Fig. 13. According to their explanation, this scheme is;
(i) The prepulse creates large plasma in front of a solid target.
(ii) Once the main pulse hits the target, a cloud of energetic electrons is generated.
(iii) Those electrons extend past the ions on both of the front side and backside.
(iv) Proton density profile on the back surface is kept to be sharp because there are no laser light and low density preplasma.
(v) Protons are quickly accelerated from back surface in the forward direction with the sheath potential, which is created with high energy electrons.
(vi) On the contrary, the plasma of the front surface has sphere-like geometry and longer scale length. Therefore, the acceleration energy is lower and the protons scatter into \( 2\pi \) direction.

This acceleration mechanism is similar to the reflection ion diode scheme of pulsed ion beam generators. They checked this model with 2D PIC code and confirmed the creation of high gradient electric field at the back surface. The electric field acting on the ions in these scheme is given by \( E = T_{hot}/eL \) [35]. Ideally, the temperature of hot electrons \( T_{hot} \) is deduced from eq. (5) and \( L \) may be decided by orbital radius of quiver motion of electrons. This simple estimation concluded that more than MeV/\( \mu \)m gradient of electric field can be generated in this scheme.

These ion beams could be of interest for medical cancer therapy, the production of short-lived radionuclides, and a driver of fast igniter fusion.

3.4 Future and Attractive Plans
3.4.1 Modification of laser system suitable for high energy particle acceleration

To date, people have concentrated to increase the focusing laser intensity. This trend is still important and won’t be changed. However, for some applications other parameters are also important. As mentioned before, using the plasma channel, more efficient and lower divergence particle acceleration was achieved. The optimization of scale length of pre-plasma also became key points to control the energy spectrum of electrons. This trend can produce more attractive results with present PW-laser system. Recently, RAL proposed CPA
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Fig. 14 Graph showing the beat wavelength (solid line) and the required electron density (dashed line) as a function of the wavelength separation of the two drive wavelengths centered on 1,054 nm [36].

beat-wave configuration on their VULCAN based laser [36]. This scheme uses two laser pulses, which are separated everywhere in time in amplification system and are temporally overlapped only in the interaction region. These pulses have slightly different wavelength and will make a strong beat wave in focusing point. The beat wavelength $\lambda_b$ as a function of wavelength separation $\Delta \lambda = \lambda_0 - \lambda_1$ of two laser pulses was plotted in Fig. 14. The required electron density for resonance excitation is also shown in the same figure. It is considered that the plasma wave can be driven to the relativistic saturation level before modulation instability grows. This kind of modification or the control of laser pulse waveform will be strong tool for improving the laser-plasma interaction in the present PW-class laser.

3.4.2 Increasing intensity for increasing electron energy

If 1 PW laser pulse can be focused more tightly and the intensity become larger than $10^{21}$ W/cm², the hot electron temperature will reach $T_{\text{hot}} \sim 50$ MeV. In this situation, Bremsstrahlung energy spectrum shifts to higher energy and matched to the giant resonance of nuclei (oscillating between the proton sphere and neutron one: The resonant energy is located in 15–25 MeV and the width is 4–10 MeV for almost all the nucleus). This mechanism produces neutrons via a $(\gamma, n)$ reaction. The GSI group (Gesellschaft für Schwerionenforschung) proposed to use the neutron yield of this reaction as diagnostics of intensity [37] (They calculated yield of $10^{10}$ per shot at $I = 10^{21}$ W/cm²). Since this intensity will be achievable with the table-top high repetitive laser system, use of this resonant process may open new applications.

3.5 Summary

The LLNL results of the laser started nuclear experiments denoted that those reactions could be explained by “normal reaction rate of nuclear physics” [14]. That means there are no new physical interesting or uncertain in this nuclear reaction. What is the sophisticated point of laser starting nuclear reaction phenomena? There seems to be no doubt that the other-field physicists will be interested in these investigations after the laser intensity reaches the QED criteria. However, this intensity is five or six orders of magnitude larger than present status. Therefore, it is important to discuss and find the answer of this question with present achievable intensity region.

One of the interesting physics before reaching QED is whole system interaction of atom, which include bounded electron and nucleus. The laser electromagnetic field easily drives the bounded electrons of atom and some of them have large possibility around nucleus. Because the quiver velocity of them reaches fully relativistic one, the rate of the nuclear reaction will be strongly affected with existence of them. The detailed theoretical modeling of these “transit state atom” will be expected in near future.

If we turn our eyes on the application for this field, there are several advantage points. The volume of the source of the high-energy particles and photons are smaller than the other type of sources. The whole system size seems to be smaller. The flux of these particles and radiation will be extremely high, though the energy spread of them is wider than conventional one. Maximum current density of charged particles in the PW-level experiments was about $10^{13}$ A/cm². Although this value is still smaller possibility to occur the higher order nuclear physical effects, if we can find and add some pinching (self focusing) process, the field of this investigation will be very attractive. Anyway, this ultra-high-power laser plasma investigation is just starting program. We need to discuss about possible experiments with laser scientists, plasma physicists, and nuclear physicists, together.

References