Development of TOF Neutron Spectrometer for the measurement of degenerated plasma in Fast Ignition experiment

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Abstract. There are two essential requirements to achieve the Fast Ignition. One is high density compression of main fuel and the other one is additional heating of main fuel by ultra intense laser. Then the experimental determination of both the density of the main fuel before heating laser irradiation and ion temperature after heating laser irradiation is necessary. In the experiment of the Central Ignition, we developed both ion temperature measurement and density measurement, which is based on theoretical degenerated plasma model, by using Time-Of-Flight neutron spectrometer. The main problem in applying this measurement in Fast Ignition experiment is huge amount of high energy x ray, which is generated as a result of heating laser irradiation. Then we installed a total 15-cm thick lead shield as a measure against it. It was confirmed that the newly installed shield achieves x ray attenuation to $5.7\pm2.0\times10^{-4}$ of previous level by Geant4 MC simulation. And the error for ion temperature measurement was confirmed to be smaller than 0.3 keV in an experiment whose neutron yield was $1.7\pm0.2\times10^6$.

1. Density measurement of degenerated core plasma

In the Inertial Confinement Fusion, it is necessary to compress the main fuel for effective self-heating by alpha particles generated in D(t,n)α reactions. The self-heating appears as a result of deceleration of alpha particles in plasma. The stopping power of the plasma is depends on the density and temperature of the plasma. The stopping power increases and the range of alpha particles become shorter in the strongly coupled plasma. In high density and degenerated plasma, the stopping power is decreased because of the decrease in the number of electron which can receive the kinetic energy from alpha particles due to the Pauli Exclusion Principle. The extension of alpha range remarkable in high density and low temperature plasma, or degenerated plasmas, is clearly shown in Fig.1. The range extension of alpha particles affects the physics of ignition and burning. Therefore we need to measure the extension of alpha range in degenerated plasma and confirm the validity of the theoretical model. However the measurement is difficult because most alpha particles are confined in the plasmas. Since the extension of range is also occurs for tritons as shown in Fig.2 (a), we may use the triton as an alternative test particle to the alpha particle. Although most tritons are also confined in the plasma the same as alpha particles, the number of tritons which react with deuterons in T(d,α)n reactions can be
measured as the neutron yield. As the opportunity for the reaction increases with the extension of triton range, the reaction ratio of triton increases in degenerated plasma (Fig.2 (b)).

We use tritons generated in D(d,p)T reactions, because the monochromaticity of the 1.01 MeV triton is of great advantage in the viewpoint that we can assume the same initial energy for all tritons. In addition, since the Branching Ratio for two DD reactions, D(d,p)T and D(d,3He)n, is almost unity, the normalized DT neutron yield (Y_{DT}) by DD neutron yield (Y_{DD}) becomes an absolute value for DT reactions ratio. Here we called the neutrons generated in T(d,α)n reactions as DT neutrons and the neutrons generated in D(d,3He)n reactions as DD neutrons. Since the reaction ratio of the tritons is given as a function of both density and temperature, conversely we can determine the density by solving the function in density assigning the temperature and reaction ratio which was measured by Time-of-Flight (TOF) neutron spectrometer, MANDALA [1].

![Figure 1. Alpha particle range extension calculated by using the degenerated plasma model.](image)

![Figure 2 (a) Triton range also extends along with the increase of density. (b) The reaction ratio increases with the extension of triton range.](image)

2. Degenerated plasma measurement applied in fast ignition experiment

In the Fast Ignition experiment, MANDALA is expected to measure the density of compressed main fuel and ion temperature of heated core plasma. The compressed fuel is a degenerated plasma, so that we would apply the above mentioned density measurement method for degenerated plasma to fast ignition experiment. In fact, MANDALA could measure neutrons in some basic experiments for fast ignition which was performed as an implosion experiment without heating laser irradiation. In the previous integration experiments which contained heating laser irradiation to gold cone, no neutron signal was measured or distinguished in MANDALA. It is because the saturation of MANDALA detectors by huge amount of high energy x rays, which is emitted from energetic electrons in the gold cone. Since those electrons are generated to heat cold main fuel and lead to ignition, the emission of high energy x ray is unavoidable in fast ignition experiment. Then we must take some measures for ion temperature measurement under such high energy x-ray environment, because the ion temperature is necessary to estimate the heating efficiency experimentally.

This high energy x ray was not attenuated enough by the initial lead shield with 4 cm thickness which is designed and installed for the central ignition experiment as a measure to attenuate hard x ray from core plasma and γ-ray generated in (n,γ) reaction. When we monitored a detector of MANDALA in current mode on previous fast ignition experiments, we observed x-ray signal with more than 10-V pulse height and long decay time. The x-ray signal was extremely huge compared with the threshold of neutron measurement (50 mV) or the pulse height for a head-on proton generated by a DD neutron (616 mV). Thus we estimated that the x ray signal need to be attenuated to 1/30 of that in the central ignition experiment to measure both DT and DD neutrons. We also estimated that the difference in the laser energy of the “PW laser” and newly constructing “LFEX laser” will appear not in change of the spectrum but in increase of the dose by 30 times at maximum. Finally, we concluded that an x-ray shield which attenuates x-ray signal to 10^{-3} of the previous experiment is necessary for ion temperature measurement in fast ignition experiment.
3. Designing for new x-ray shield

We assumed the continuous x-ray spectrum in the range of 1-20 MeV as Bremsstrahlung from plasma with 5-MeV electron temperature which was measured by an electron spectrometer [2]. A calculation was performed to estimate minimal thickness necessary to achieve desired performance by using photon cross-section in lead. Then we confirmed that 15-cm thick lead shield satisfies the requirement.

Next we considered two installation plans for the new shield in the aspect of both x-ray shielding and neutron measurement. An installation plan is that a new shield is installed just in front of current system. This installation has advantages in shield performance and geometrical detection efficiency, but it has a disadvantage in neutron spectroscopy. The other installation plan is that a new shield is installed close by the vacuum target chamber for laser irradiation of the GEKKO-XII system. This installation has an advantage in neutron spectroscopy, but it has disadvantages in shield performance and geometrical detection efficiency. Simulations for several distributions of 15-cm thick lead shield were performed by using a Monte Carlo simulation tool, Geant4 [3], to optimize the distribution of shield thickness for two installation plans. The result of the simulations showed that more than 10 cm of total thickness had to be installed just in front of present system. The geometrical detection efficiency changed only 20% between 10 cm and 15 cm shield installation in front of the current system, so that we decided to install 10-cm thick shield just in front of the present system from the viewpoint that the distribution achieves better energy resolution. And rest 5-cm shield was installed close by the target chamber.

When the distribution of shield thickness was determined, a simulation was performed to confirm x-ray attenuation and the energy resolution for DD neutrons. In the simulation, the geometry of the MANDALA system and new shields were constructed based on blueprints of them. In a simulation result which assumed Bremsstrahlung x-ray from a 5-MeV plasma, total deposit energies for all the detectors were compared with and without new shields to show the attenuation factor of 5.7±2.0×10^{-4}. The energy resolution for DD neutrons was evaluated from the probability distribution for detection timing of mono-energetic 2.453 MeV neutrons. The energy resolution for DD neutrons was evaluated to be 92 keV. The derivation of the probability distribution is shown in the next section.

4. Analytical method for ion temperature measurement

4.1. Probability distribution for detection timing

A simulation for 2.453 MeV mono-energetic neutron transport was performed using realistic shields and the detector geometry. In the simulation, 5×10^{7} neutrons were spherically injected from the center of vacuum chamber. Their traveling time and kinetic energy were accumulated at the timing of incidence to scintillator volume of MANDALA detectors. The detection timing distribution was given by weighting each event by detection efficiency. Finally, the probability distribution for detection timing was obtained by normalizing the integration of the distribution to 1 (Fig.3).

The detection efficiency of neutron was calculated in following way. A relationship between proton energy (E_p) and pulse height (H) is given in $H \propto E_p^{2/3}$ [4]. And the response of MANDALA detectors for electron is assured by the calibration which is performed by using the Compton scattering of 60Co γ-rays. The relative scintillation efficiency (light output) for an electron and a proton is given by Premium Scintillator Datasheet provided by Bicron. Then we can evaluate the corresponding energy of a recoiled proton by an incident neutron to the threshold of our measurement as 0.394 MeV. A calculation was performed to determine detection efficiency for a neutron taking account of a little contribution of recoiled carbons. In the calculation, we assumed normal incidence of a neutron to the center of scintillator front surface, multiple scattering of a neutron in the scintillator is allowed 2 times at maximum and recoiled particles deposit their all kinetic energy in the scintillator. I calculated the energy transfer from an incident neutron to recoiled particles and the light output which is converted from their deposit energies with appropriate scintillation efficiencies depending on the species of the particles. Finally, the detection efficiency for a neutron with a kinetic energy was defined as the probability that the neutron generates light output greater than threshold.
4.2. Ion temperature analysis
The probability distribution for detection timing enables us to evaluate the energy of neutrons from the peak timing of the distribution for statistically enough mono-energetic neutrons. Furthermore, an appropriate assumption that the cross-section for elastic and inelastic scattering of neutrons by \(^1\text{H}\), \(^{12}\text{C}\), \(^{206}\text{Pb}\), \(^{207}\text{Pb}\) and \(^{208}\text{Pb}\) do not change remarkably near 2.453 MeV, the typical energy of DD neutron, enables us to calculate the expected ideal TOF spectrum of neutrons generated in plasma with finite ion temperature.

The experimentally obtained TOF spectrum is ideally the convolution of the probability distribution for detection timing and original TOF spectrum. The original TOF spectrum of neutrons generated in thermonuclear fusion reaction is approximated by Gaussian. In addition this, the realistic detector has finite temporal resolution and dead time. The measured TOF spectrum is a TOF spectrum convoluted by a temporal response. Since a count mode detector can not detect one more neutron during the dead time, it causes the decrease in the number of effective detector. The effect is taken account in first-hit analysis [5]. Eventually we can evaluate ion temperature by fitting the experimental TOF spectrum data by the convolution function with the first-hit analysis applied.

We used the most likelihood method as the fitting method. And the error of ion temperature measurement is evaluated from the deviation of ion temperature around the most likely value. The experimental data was well fitted by the function and we obtained the ion temperature 1.56±0.29 keV and neutron yield 1.7±0.2×10⁶ for an implosion experiment (shown in Fig.4).

![Figure 3](image1.png)  
**Figure 3.** The probability distribution for detection timing is consisted of 2 components, one is elastically scattered neutrons and the other is inelastically scattered neutrons.

![Figure 4](image2.png)  
**Figure 4.** An experimental data was fitted by the convolution function in first-hit analysis and we obtained the ion temperature 1.56±0.29 keV.

5. Conclusion
We developed the density measurement based on theoretical degenerated plasma model. In order to apply the measurement to fast ignition experiments, measures for high energy x-ray are necessary. So we designed and installed new lead shields with the 15-cm thickness in total. The set of new shields attenuates x-ray to 5.7±2.0×10⁻⁴ of that in the previous experiment. The energy resolution of the new MANDALA system for DD neutrons was estimated to be 92 keV. The ion temperature was obtained by fitting experimental data by a response function in first-hit analysis. And the error for ion temperature measurement was confirmed to be smaller than 0.3 keV in the experiment whose DD neutron yield was 1.7±0.2×10⁶. It enables us to determine the density in the accuracy of 150 g/cc, when we observe 0.7 keV and 200 g/cc plasmas and measure the \(Y_{DT}/Y_{DD}\) with 10 % error.

References
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