J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 295–298

On Potentiality of Ion Temperature and Fuel Density Ratio Measurements in D-T Plasma Using ^{6}Li+D and ^{6}Li+T Nuclear Reactions

NAKAMURA Makoto, VORONCHEV Victor T.[1] and NAKAO Yasuyuki

Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Hakozaki 812-8581, Japan

[1]Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia

(Received: 9 December 2003 / Accepted: 6 July 2004)

Abstract

Abstract The use of ^{6}Li isotope as a low Z (which denotes atomic number) diagnostic admixture in a D-T fusion plasma has been investigated. We show that monochromatic γ rays generated in ^{6}Li+T and ^{6}Li+D nuclear reactions might be used for measurements of two important plasma parameters, bulk ion temperature T_i and the fuel density ratio n_T/n_D. Results presented in the report are restricted to the case of Maxwellian plasma. A possibility of detection of diagnostic γ rays in the presence of γ-ray background is discussed.

Keywords:

D-T plasma diagnostic, ion temperature, fuel density ratio, ^{6}Li+T and ^{6}Li+D nuclear reaction, γ rays

1. Introduction

Control of burning dynamics of fusion fuels has been an essential part of hot plasma diagnostics. An important parameter, which determines reactivity of any plasma at thermal equilibrium, is temperature of bulk fuel ions. When a many-component plasma is considered, other essential parameters capable of reflecting burning history also appear. These are relative concentrations (density ratios) of fuel species composing the plasma.

The problem of fuel density ratio measurements is comparatively new. At early stages of nuclear fusion research experimental studies were mainly focused on one-component (hydrogen or deuterium) plasmas, so density ratio diagnostics was considered to be rather of academic interest. At present, however, this problem has become urgent because modern hot plasma devices can operate with deuterium-tritium mixture. Density ratio diagnostics is of particular importance for the International Thermonuclear Experimental Reactor (ITER) project, which has recently been entered in a new phase aiming at the construction of an experimental D-T reactor. However, the question whether the n_T/n_D fuel ratio can be measured with satisfactory accuracy has not been clear yet.

Neutron spectroscopy is the most natural way of diagnosing fuel ions in D-T or D-D plasmas. The status of this diagnostics for magnetic confinement fusion devices is described in a recent review [1]. Such methods, however, do not give an exhaustive prescription for both ion temperature and density ratio measurements. It is known that neutron spectroscopy allows controlling the variation of plasma temperature, but it is incapable of providing reliable values of ion temperature T_i. The situation with fuel density ratio measurements seems to be also intricate. In the D-T plasma, the determination of the n_T/n_D ratio [2] requires a simultaneous detection of 14.06- and 2.45-MeV neutrons produced in $D(t,n)\alpha$ and $D(d,n)^3$He reactions. Unfortunately, the strong background [3] arising from collisions of fusion neutrons with a plasma-facing wall makes it rather difficult counting the flux of DD neutrons.

Apart from neutron measurements, nuclear-physics activation methods have been used for plasma diagnostics. These methods are based on seeding plasmas with light isotopes to induce nuclear reactions most appropriate for solving a particular problem. Convenient diagnostic reactions are those generating γ rays which freely escape from laboratory plasmas. In Joint European Torus (JET), for example, reaction-produced γ rays have already been used for diagnosing fast particles (fusion products and ions heated by radio frequency (RF) or neutral beam injection (NBI)) [4].

Recently, a new method of ion temperature measurements has been reported by our group [5]. The method is based on seeding the D-T plasma with a small amount of ^{6}Li and detecting subsequently three narrow γ lines associated with ^{6}Li+D and ^{6}Li+T nuclear reactions. It was shown that in the Maxwellian plasma ion temperature might be determined by comparing the respective γ-ray yields. However, there has remained a drawback that the value of T_i

Corresponding author's e-mail: nakamura@nucl.kyushu-u.ac.jp

derived in such a scenario depends on an unknown plasma parameter, the ion density ratio $\eta = n_T/n_D$.

In this report we resolve the above drawback and discuss a potentiality of absolute ion temperature and fuel density ratio measurements. The results presented below correspond to the case of Maxwellian plasma, but an important kinetic issue relevant to the problem is also discussed. A possibility of counting diagnostic γ quanta in the presence of γ-ray background is examined.

2. Diagnostic reactions and γ-ray yields

We consider the following specific modes of nuclear reactions between ^{6}Li and fuel ions D and T:

$$^6\text{Li} + d \rightarrow {}^7\text{Be}^*[0.429] + n + 2.95\text{MeV} \qquad (1a)$$

$$^6\text{Li} + d \rightarrow {}^7\text{Li}^*[0.478] + p + 4.55\text{MeV} \qquad (1b)$$

$$^6\text{Li} + t \rightarrow {}^7\text{Li}^*[0.478] + d + 0.15\text{MeV} \qquad (2a)$$

$$^6\text{Li} + t \rightarrow {}^8\text{Li}^*[0.981] + p - 0.18\text{MeV} \qquad (2b)$$

The modes lead to a formation of excited daughter nuclei ^{7}Li*, ^{8}Li* and ^{7}Be* which further generate electromagnetic radiation in their decay to ground states. The yields of these monochromatic γ rays with energies of 0.429-, 0.478- and 0.981-MeV are given by, respectively,

$$Y_\gamma(0.429) = n_{^6Li} n_D \langle\sigma v\rangle_{^6Li(d,n)} \qquad (3)$$

$$Y_\gamma(0.478) = n_{^6Li} n_D \langle\sigma v\rangle_{^6Li(d,p)} + n_{^6Li} n_T \langle\sigma v\rangle_{^6Li(t,d)} \qquad (4)$$

$$Y_\gamma(0.981) = n_{^6Li} n_T \langle\sigma v\rangle_{^6Li(t,p)}\,, \qquad (5)$$

where n_a represents the density of ion species a (a = D,T or ^{6}Li) and $\langle\sigma v\rangle$ is the reaction rate parameter. For Maxwellian ion velocity distribution functions, the rate parameter is of the form:

$$\langle\sigma v\rangle = \left(\frac{8}{\mu\pi}\right)^{1/2} (kT_i)^{-3/2} \int_0^\infty E\sigma(E) e^{-E/kT_i}\,\mathrm{d}E\,, \qquad (6)$$

where μ and E are, respectively, the reduced mass and the relative energy of reacting particles, σ is cross section of nuclear reacrion, and kT_i is plasma ion temperature.

3. Scenario of ion temperature and density ratio measurements

In the previous work [5] we calculated cross sections of the ^{6}Li-induced reactions and examined the production of diagnostic γ rays in the Maxwellian D-T plasma. It was found that ion temperature might be found by comparative measurements of any pair of 0.429-, 0.478- and 0.981-MeV γ rays. This concept, however, implies that the fuel density ratio $\eta = n_T/n_D$ should be known with sufficient accuracy.

In the present report we modify our approach and analyze a possibility of absolute ion temperature T_i and the density ratio η measurements. The following relations appropriate for such diagnostics can be derived from Eqs. (3)-(5):

$$C_1 \equiv \frac{Y_\gamma(0.478)}{Y_\gamma(0.981)} - f_1(T_i)\frac{Y_\gamma(0.429)}{Y_\gamma(0.981)} = f_2(T_i) \qquad (7)$$

$$C_2 \equiv \frac{Y_\gamma(0.478)}{Y_\gamma(0.429)} = f_1(T_i) + \eta f_3(T_i)\,, \qquad (8)$$

where

$$f_1(T_i) = \frac{\langle\sigma v\rangle_{^6Li(d,p)}}{\langle\sigma v\rangle_{^6Li(d,n)}}\,,\quad f_2(T_i) = \frac{\langle\sigma v\rangle_{^6Li(t,d)}}{\langle\sigma v\rangle_{^6Li(t,p)}}\,,$$

$$f_3(T_i) = \frac{\langle\sigma v\rangle_{^6Li(t,d)}}{\langle\sigma v\rangle_{^6Li(d,n)}}\,. \qquad (9)$$

Equation (7) is fully independent of plasma density. The ratio f_1 of the ^{6}Li+D rate parameters can be assumed to be constant, because cross sections of the respective reactions show similar energy behavior in the range of thermonuclear interest. In the Maxwellian plasma $f_1 \approx 0.84$, while f_2 is essentially dependent on T_i. Therefore, the value of C_1 is tightly interrelated with ion temperature and, at the same time, is not affected by fluctuations of other plasma parameters. The temperature behavior of $C_1(T_i)$ is shown in Fig. 1, which suggests that a detection of the three γ lines would be sufficient for absolute measurements of bulk ion temperature, i.e. an average ion temperature of core plasma.

Once ion temperature T_i is found (either by the above method or from independent measurements), then the density ratio $\eta = n_T/n_D$ could be determined from Eq. (8). Several curves of $C_2(\eta)$ corresponding to various plasma temperatures within the 0–50 keV range are plotted in Fig. 2. At low ion

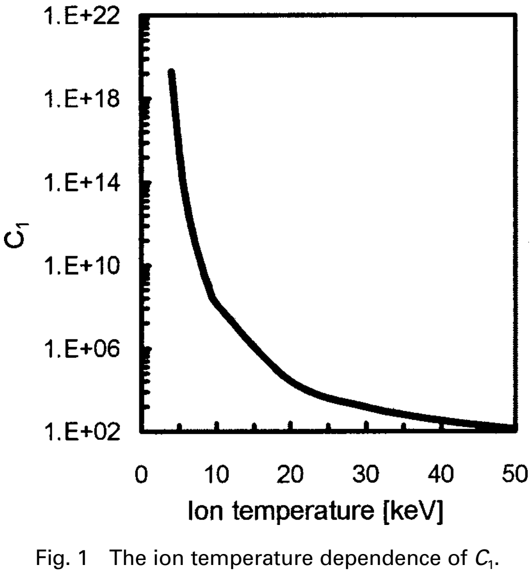

Fig. 1 The ion temperature dependence of C_1.

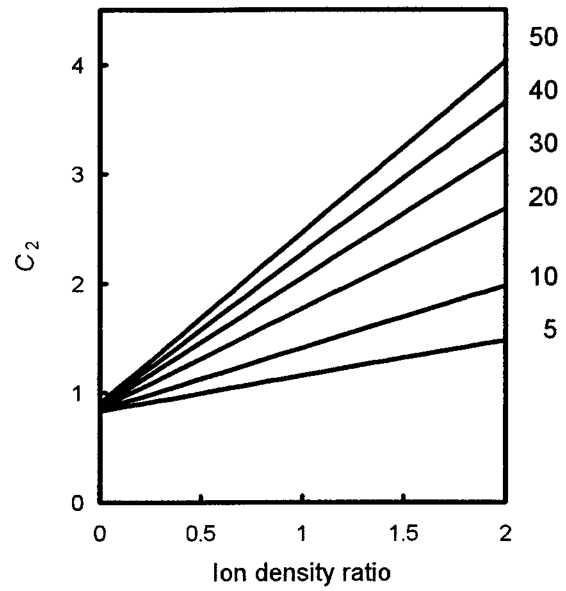

Fig. 2 The dependence of C_2 on the ion density ratio $\eta = n_T/n_D$. The values of ion temperature (in keV) are given on the right.

temperature (below the D-T ignition point) the dependence of C_2 on η is rather weak, so the density ratio could not be measured with satisfactory accuracy. However, in the 10–50 keV temperature range, which corresponds to the important phase of plasma burning, the measurements of the n_T/n_D ratio might become possible.

The above conclusions have been derived under two model assumptions. First, velocity distributions of plasma ions were taken to be Maxwellian and, second, it was assumed that the γ rays could be resolved and distinguished from γ-ray background. These points are worth discussing below:

1. It is known that in the D-T plasma ion distributions are not described by the purely Maxwellian form. A possible source of the distortion results from nuclear elastic scattering of 3.5-MeV α-particles by fuel ions. This scattering is accompanied by large momentum transfer and produces fast (knock-on) deuterons and tritons that perturb high-energy tails of the distributions. Such fast ions of MeV energies were both predicted theoretically [6-8] and recently observed in JET experiments [9]. Apparently, the distortion of distribution functions can affect rate parameters of the diagnostic reactions, especially, the endothermic mode (2*b*). The latter is suppressed in the deep sub-barrier range and proceeds with sizable probability at energies only well above the reaction threshold. This means that the yield of 0.981-MeV γ rays should be sensitive to the shape of triton distribution at high energy and then a small deviation from the Maxwellian form might change significantly the γ-ray flux. Therefore, the model temperature profile of C_1 in Fig. 1 might be changed crucially for realistic distributions, so the above method would not be able of providing high accuracy of temperature diagnostics. It is important, however, that the non-Maxwellian deviation is unlikely to affect significantly yields of other exothermic reactions in Eq. (8). Therefore, the 0.429- and 0.478-MeV γ-ray signals could be used for n_T/n_D ratio measurements, even if some distortion of ion distributions exists.
2. The γ lines can be resolved experimentally. Doppler broadening is estimated to be less than 15 keV, so it does not cause γ-line overlapping. A more serious problem is detection of the diagnostic signals in the presence of γ-ray background. In the present report we analyze a possibility of counting the 0.429- and 0.478-MeV γ rays in the Compact Ignition Tokamak (CIT) and the Tokamak Fusion Test Reactor (TFTR). In the both cases the concentration of ^{6}Li is assumed to be 1% of plasma density. In CIT, the flux of background quanta [10] with energy around 0.5 MeV within the 10-keV spectral range (corresponding to widths of the diagnostic γ rays) is estimated to be ~ 10^{12} cm^{-2} s^{-1}. Yields of the 0.429- and 0.478-MeV signals in CIT plasma (T_i = 40 keV, $n_T = n_D$ = 10^{15} cm^{-3}) is estimated by us to be at the level of (2–4) $\times$ 10^9 cm^{-3} s^{-1}. These values are very similar to those used in a previous analysis [11] of γ-ray detection in CIT. By analogy with results of Ref. [11] we find that the signal to noise ratio R is close to unity, i.e., marginal for the measurements. However, even when the signal to noise ratio is less than 1 ($R < 1$), measurement is possible using the long exposure time of the detector. The exposure time t_c required for counting a signal with a fractional error f equals $(B + S)/(Sf)^2$ where B and S are, respectively, background and signal count rates [12]. For TFTR plasma (T_i = 20 keV, $n_T = n_D = 10^{14}$ cm^{-3}) with B = 3,900 counts s^{-1} and a detector adjustment adopted in Ref. [12] we find:

$S(0.478)$ = 1,645 counts s^{-1} t_c (0.478) = 33 ms
$S(0.429)$ = 929 counts s^{-1} t_c (0.429) = 89 ms

The values of t_c correspond to measuring the signals with accuracy of 25% by a single NaI detector. When a 10 $\times$ 10 array of detectors is used, the exposure time t_c can be further reduced by two orders of magnitude [12]. Moreover, since the diagnostic γ rays are monochromatic, the background B and the exposure time t_c could be also reduced by counting the signals within a narrow spectral range not exceeding ~ 10 keV. Such measurements could be performed using Ge(Li) detectors, which have high resolution of only few keV. The above estimations are very likely to be also valid for ITER plasma.

4. Conclusions

In the present report we have investigated the use of ^{6}Li isotope as a low-Z diagnostic admixture in the D-T fusion plasma. Our main goal was to understand whether γ rays generated in ^{6}Li+T and ^{6}Li+D nuclear reactions could be employed for measuring two important plasma parameters - ion temperature T_i and the fuel density ratio $\eta = n_T/n_D$.

In the Maxwellian plasma, T_i could be determined by measuring comparative yields of three reaction-produced γ rays. The method, however, may turn out to be useless if a deviation of ion distributions from the Maxwellian form appears. To make a final conclusion one should know realistic distributions of fuel ions in experimental devices.

We have shown that in the plasma burning phase at $T_i >$ 10 keV the n_T/n_D density ratio could be measured by means of γ-ray spectroscopy. This technique requires a simultaneous detection of two 0.429- and 0.478-MeV γ rays and may be applicable even if some distortion of ion distributions exists. The γ-ray signals can be resolved and counted in the presence of background typical of CIT and TFTR. This conclusion is very likely to be also valid for ITER.

Acknowledgments

The authors would like to thank the referee for valuable comments and suggestions.

References

[1] B. Wolle, Phys. Rep. **312**, 1 (1999).

[2] J. Kallne *et al.*, *Diagnostics for Experimental Thermonuclear Fusion Reactors*, Edited by P.E. Stott (Plenum Press, 1996), p397.

[3] P. Antozzi *et al.*, Rev. Sci. Instrum. **66**, 939 (1995).

[4] V.G. Kiptily *et al.*, Nucl. Fusion **42**, 999 (2002).

[5] V.T. Voronchev *et al.*, Phys. Rev. **E63**, 026413 (2001).

[6] R.K. Fisher *et al.*, Nucl. Fusion **34**, 1291 (1994).

[7] L. Ballabio *et al.*, Phys. Rev. **E55**, 3358 (1997).

[8] F.S. Zaitsev *et al.* Nucl. Fusion **42**, 1340 (2002).

[9] A.A. Korotkov *et al.*, Phys. Plasmas **7**, 957 (2000).

[10] S.L. Liew and L.P. Ku, "Preliminary Radiation Damage Assessment for the CIT", A-870427-PPL-04/EAD-1819, Princeton University.

[11] V.G. Kiptilyj, Fusion Technol. **18**, 583 (1990).

[12] F.E. Cecil *et al.*, Nucl. Instr. Meth. Phys. Research, **A245**, 547 (1986).