PAPER

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On the core deuterium–tritium fuel ratio and temperature measurements in DEMO

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Abstract

Comparing with ITER, the experimental fusion machine under construction, the next-step test fusion power plant, DEMO will be characterized by a very long pulse/steady-state operation and much higher plasma volume and fusion power. The substantially increased level of neutron and gamma fluxes will require reducing the physical access to the plant. It means some conventional diagnostics for the fusion plasma control will not be suitable in DEMO. Development of diagnostics along with the machine design is a primary task for the test plant. The deuterium–tritium fuel ratio and temperature are among important parameters, which should be under control. In this paper, a novel technique for the core fuel ratio and temperature diagnostics is proposed. It is based on measurements and comparison of the rates T (p, γ)^4 He and D (T, γ)^5 He nuclear reactions that take place in the hot deuterium–tritium plasma. Based on detection of high-energy gamma-rays, this diagnostic is robust, efficient and does not require direct access to the plasma. It could be included in the loop of the burning plasma control system. A feasibility of the diagnostic in experiments on JET and ITER is also discussed.

Keywords: fuel ratio, temperature, deuterium, tritium, gamma-rays, fusion reaction

(Some figures may appear in colour only in the online journal)

1. Introduction

A goal of the DEMO fusion power plant is to demonstrate that the major scientific and technological obstacles on the way to the commercial power plant are overcome, and one of the real challenges is development of the unprecedented robust and reliable diagnostic system [1, 2]. A harsh DEMO environment with a very high level of neutron and gamma-ray fluxes will make some conventional ITER diagnostics unfeasible. Among the restricted set of instruments, which are available for the machine protection and plasma control in DEMO, neutrons and gamma-ray measurements will be useful as the neutron and gamma-ray detectors can be placed far away from the plasma and they do not require a direct access to the vessel.

The main roles of neutron diagnostics in DEMO will be fusion power and core ion temperature measurements [3, 4]. Gamma-ray diagnostics [5], which are routinely used for fast ion studies on JET [6], can provide information on the confined alpha-particle distribution in the energy range $E_\alpha > 1.7$ MeV, impurities and fusion power in ITER. In this paper, a novel gamma-ray technique is proposed, which can allow measurement of the core fuel ratio and temperature in DEMO.

A conventional diagnostic for the direct measurement of the plasma composition is a neutral particle analyser (NPA). A prototype of the NPA system developed for the ITER operation [7] has been tested and successfully used on JET [8]. A feasibility study of the method for the fuel ratio measurements in DEMO is still required. The NPA detectors should be placed far away from the reactor and shielded from neutrons. In DEMO, the detected neutral particles will be strongly weighted to those from the plasma periphery, where the neutral gas pressure is highest, and it may be difficult to de-convolve the spectra to yield the core fuel composition reliably.

Neutron spectrometry is another tool for the fuel ratio measurement [9]. Indeed, the ratio of neutron rates generated in the D (D, n)^3 He and D (T, n)^4 He reactions is proportional to the fuel ratio, $n_\mathrm{D}/n_\mathrm{T}$ (DTR). For the steady-state (SS) plasma this relation is rather simple

$$\frac{R_{\mathrm{DD}n}}{R_{\mathrm{DT}n}} = \frac{1}{2}\frac{n_\mathrm{D}}{n_\mathrm{T}}\frac{\langle\sigma v\rangle_\mathrm{DD}}{\langle\sigma v\rangle_\mathrm{DT}}, \qquad (1)$$

where $\langle\sigma v\rangle_\mathrm{DD}$ and $\langle\sigma v\rangle_\mathrm{DT}$ are reactivities in the case of the Maxwellian distribution function of the plasma components (figure 1). The neutron spectrum of DT plasmas consists of several main components: two peaks, one at 2.5 MeV due to the DD-reaction and another at 14 MeV due to the DT-reaction, and three components with continuous neutron spectra, at $E_\mathrm{n} < 11.5$ MeV from the three-body reaction T (T, 2n)^4 He, at $E_n < 2.5$ MeV from endothermic secondary reaction T (p, n)^3 He and a continuous spectrum of the scattered neutrons. Cross-sections of the above mentioned reactions are shown in figure 2.

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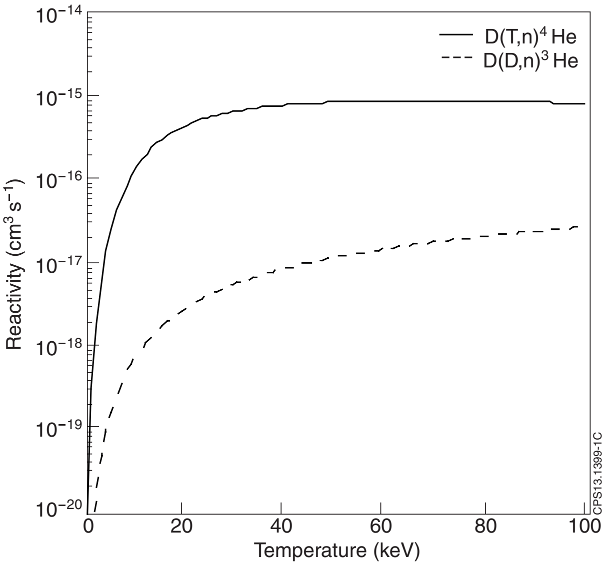

Figure 1. Reactivities of the D (D, n)^3 He and D (T, n)^4 He reactions calculated with parameters for Maxwellian plasmas from [10].

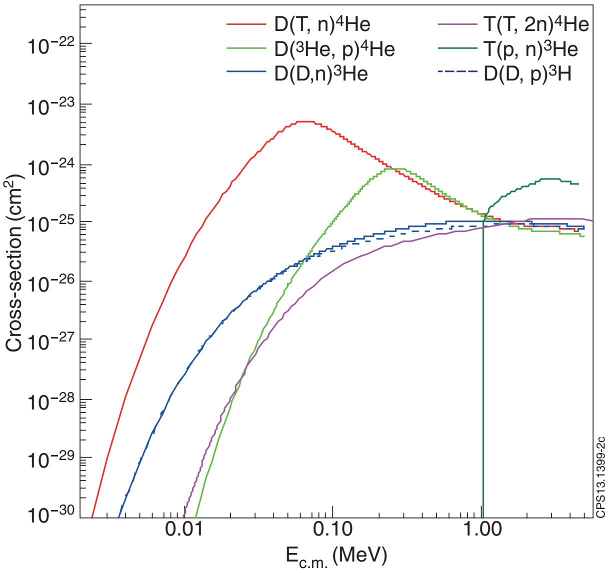

Figure 2. Cross-sections of main fusion reactions calculated with parameters from [10] in comparison with T (T, 2n)^4 He [11] and T (p, n)^3 He [12].

A main applicability criterion of this diagnostic approach is the signal-to-background ratio (S/B) for the 2.5 MeV peak. In the feasibility study of the diagnostic proposed for the ITER application [13] it has been found that the main feasibility concern is scattered neutrons. It was shown that for the DTR $= 1$ the total S/B ratio for the 2.5 MeV peak is around 0.4 in the case of the tangential line-of-sight. The radial plasma observation gives much worse S/B value. Neutrons from TT-reaction play a role in the case of $n_{\mathrm{D}}/n_{\mathrm{T}} \equiv \mathrm{DTR} < 1$. However, influence of the continuous neutron spectra from the secondary reactions of bulk tritium with fusion protons and tritons, for example T (p, n)^3 He reaction need to be assessed.

There are also two microwave diagnostics, which could be used for the fuel ratio measurements. If in the fast wave reflectometry [14] used Alfvén waves or waves in the ion cyclotron range, the propagation properties will depend on ion density and the ion charge and mass. Measurements of the phase delay in that range will therefore be a way to obtain information on those quantities. The second method is collective Thomson scattering. A diagnostic system developed for ITER [15] is capable of measuring the fusion alpha-particle distribution parallel and perpendicular to the magnetic field. It can be redesigned to provide temporally and spatially resolved measurements of the fuel ion ratio. For both two methods, practical implementation issues are associated with integration of in-vessel components such as antennas and mirrors.

The gamma-ray diagnostics has some significant advantages to be used on DEMO. First, gamma-ray spectrometry of the plasma does not require a direct access to the vessel. Furthermore, several centimetres of the first wall could play a positive role as it reduces the strong flux of the undesirable low energy gamma-rays. Gamma-ray detectors are compact and the response function is well known and simple. Viewing the plasma through a long collimator, the spectrometer can be placed far away from the machine. The collimator should be filled with material, which suppress the neutron flux and thus neutron induced gamma-ray background. In this case, the required radiation conditions behind the biological shield of DEMO will be assured. Gamma-ray detectors can be easily replaced in the case of any damage.

2. Physics basics of the proposed technique

Several nuclear reactions could be useful for the fuel ratio measurements. A list of these reactions $A(B,\gamma)C$ is given in the table 1. The nuclear reaction energies, the Q-values, which characterize the mass balance of the reactions $Q = (M_A + M_B - M_C)c^2$, are also presented there and can be used for an assessment of the excitation energy of the residual nuclei. In the centre-of-mass frame, the energy of gamma-rays de-excited the final nuclei to the ground state is given by $E_\gamma = Q + E_A + E_B - E_C$. For some reactions, a ratio of the radiation capture to the cross-section of a main fusion reaction (branching ratio or BR) is available and presented in the table 1.

One can see, by analogy with the above mentioned neutron diagnostic, D (D, γ)^4 He and D (T, γ)^5 He radiation capture reactions could be useful for the fuel ratio diagnostic, but the cross-section of the D (D, γ)^4 He reaction is very low as the branching ratio of two orders of magnitude less than the D (T, γ)^5 He.

There is another group of the radiation capture reactions, which are suitable for this purpose. Indeed, secondary reactions of fuel with energetic charged products from the fusion reactions D + D $\rightarrow$ ^{3}He(0.82 MeV) + n(2.45 MeV) and D + D $\rightarrow$ t(1.01 MeV) + p(3.02 MeV) can be used. The rate of these fusion reactions is proportional to n_{D}^2, and secondary reactions D (p, γ)^3 He, D (T, γ)^5 He, D(^{3}He, γ)^{5}Li and T (p, γ)^4 He are also proportional to n_{D} and n_{T}. However, not all of these reactions are feasible for the fuel ratio measurements.

The first reaction in the table 1 has relatively large cross-section and has been exploited for the effective temperature assessments of hydrogen ions injected for the plasma heating (NBI) [20] and accelerated during the minority ion cyclotron resonance heating (ICRH) [6]. In the case of Maxwellian

Table 1. Summary of the radiation capture reactions potential for the fuel ratio measurements.

Reaction	Q (MeV)	Branching ratio^{a}
$\mathrm{D\,(p,\gamma)^3\,He}$	5.5	—
$\mathrm{D\,(D,\gamma)^4\,He^b}$	23.84	10^{-7}–10^{-6}
$\mathrm{D\,(T,\gamma)^5\,He^c}$	16.63	5×10^{-5}–5×10^{-4}
$\mathrm{D(^3He,\gamma)^5Li^d}$	16.38	5×10^{-5}–$5\times10^{-4\ e}$
$\mathrm{T\,(p,\gamma)^4\,He^f}$	19.814	—

[a] In the energy range 0.02–3 MeV.

[b,c,d] Branch reactions: $\mathrm{D\,(D,n)^3\,He}$ and $\mathrm{D\,(D,p)^3\,H}$ [16], $\mathrm{D\,(T,n)^4\,He}$ [17, 18], $\mathrm{D(^3He,p)^4He}$ [19];

[e] for the ground state branch.

[f] Branch reaction: $\mathrm{T\,(p,n)^3\,He}$ with $Q = -0.764$ MeV (threshold reaction).

distribution function of the interacted ions, the gamma-ray peak position $E_\gamma = Q + E_\mathrm{G}$, depends on the Gamov's peak energy, for example for the $\mathrm{D\,(p,\gamma)^3\,He}$ reaction $E_\mathrm{G} \approx 0.74\langle T_\mathrm{Dp}\rangle^{2/3}$ (MeV). The peak width also depends on E_G and the Doppler broadening due to the reaction kinematics. The experiments with the H-minority ICRH have shown that this diagnostic tool is useful for the ion tail temperatures below 400 keV. The broadening at high temperatures makes the peak unrecognizable since the background, which continues up to 9 MeV. In the DEMO case, the fusion protons, with a broad energy distribution below 3 MeV, will give rise to excessively broad spectrum of gammas from the $\mathrm{D\,(p,\gamma)^3\,He}$ reaction and intensity of the peak cannot be convincingly obtained.

The $\mathrm{D(^3He,\gamma)^5Li}$ reaction has been used for the assessments of the fusion power generated in the plasma with $\mathrm{D(^3He,p)^4He}$ reaction [21] and the efficiency of the ^{3}He minority ICRF heating in D^{3}He plasmas [6], but it is inappropriate for the DT fuel ratio measurements in DEMO. There is an advantage that gamma-ray energy spectrum generated by ^{3}He ions lies outside of the energy range with a strong background, however spectra of the $\mathrm{D(^3He,\gamma)^5Li}$ and $\mathrm{D\,(T,\gamma)^5\,He}$ reactions are overlapped as Q values are roughly the same. Furthermore, because of the large width of the ^{5}Li ground state ($\Gamma_\mathrm{g.s.} = 2.6 \pm 0.4$ MeV) and the first excited one ($E_x = 7.5 \pm 1.0$ MeV, $\Gamma_x = 6.6 \pm 1.2$ MeV), the peaks cannot be separated. Although both $\mathrm{D(^3He,p)^4He}$ and $\mathrm{D\,(T,n)^4\,He}$ reaction cross-sections are nearly the same in the range above 0.2 MeV (figure 2), the yield of the secondary reactions is much lower and the $\mathrm{D(^3He,\gamma)^5Li}$ gamma-rays will be a background for the intensive gamma-ray peak from the $\mathrm{D\,(T,\gamma)^5\,He}$ reaction.

To measure the fuel ratio in DEMO with the gamma-ray diagnostic, utilizing of the $\mathrm{T\,(p,\gamma)^4\,He}$ and $\mathrm{D\,(T,\gamma)^5\,He}$ reactions would appear to be the only practical possibility, deriving the $n_\mathrm{D}/n_\mathrm{T}$ value from the ratio of gamma-ray reaction rates $R_{\mathrm{Tp}\gamma}/R_{\mathrm{DT}\gamma}$. The $\mathrm{T\,(p,\gamma)^4\,He}$ reaction has been proposed for use in ITER but for other applications [22].

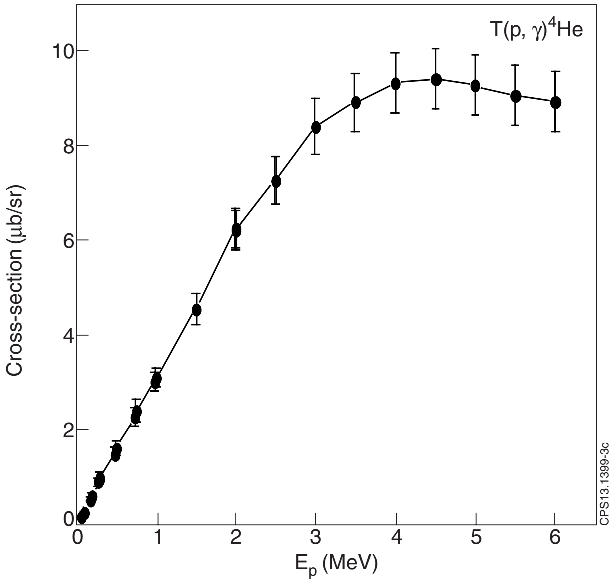

Figure 3. The experimental differential cross-section of the $\mathrm{T\,(p,\gamma)^4\,He}$ reaction [21, 22].

Indeed, the gamma-ray peaks related to these reactions are well separated and both lie far away from the strong background energy range. The main gamma-ray background is build up by the neutron capture (n,γ) and inelastic scattering $(n,n'\gamma)$ reactions in the range $E_\gamma < 9$ MeV. In the range $E_\gamma < 14$ MeV background mainly produced in the $(n,n'\gamma)$ reactions. However, density of nuclear levels at high excitation energies is very low that is why background gamma-ray emission in the range 9–14 MeV is rather weak. Gamma-rays with energies $E_\gamma > 14$ MeV can be produced in radiation capture nuclear reactions between the possible low-Z plasma impurities and confined charged particles in the plasma, e.g. $\mathrm{^7Li\,(p,\gamma)^8\,Be}(Q = 17.35\,\mathrm{MeV})$, $\mathrm{^{11}B\,(d,\gamma)^{13}\,C}(Q = 18.7\,\mathrm{MeV})$, $\mathrm{^{14}N(d,\gamma)^{16}\,O}(Q = 20.7\,\mathrm{MeV})$. However, both concentration of impurities in plasmas and cross-sections of these reactions are very low. The $\mathrm{D(^3He,\gamma)^5Li}$ gamma-rays which are a weak background for the $\mathrm{D\,(T,\gamma)^5\,He}$ can be taken into account for the fuel composition measurements.

Experimental studies of the $\mathrm{T\,(p,\gamma)^4\,He}$ reaction [23, 24] shows that its cross-section (figure 3) is high enough and exceeds the cross-section of the $\mathrm{D(^3He,\gamma)^5Li}$ reaction by factor of 10 in the MeV range. It has been demonstrated that the $\mathrm{T\,(p,\gamma)^4\,He}$ reaction can be used for characterization of the fast H-ion tail during the ICRF heating of tritium plasmas in JET [25] as the produced gamma-ray spectrum depends on the proton distribution function. The Compton part of the $\mathrm{T\,(p,\gamma)^4\,He}$ gamma-ray spectrum was already recorded in the JET experiments with fully tritium plasmas during H-minority heating [26].

3. Implementation

To assess this technique as a possible DEMO diagnostic one need to consider several issues: plasma scenarios, diagnostic field of view, an experimental setup and uncertainties of the measured parameters.

For the feasibility study of the fuel ratio measurements in the DEMO plasma core by means of the gamma-ray diagnostic, two possible reactor designs: one for the SS operation, with the major radius $R = 8.5$ m and the minor radius $a = 2.83$ m and one for the long pulse operation (LP) with $R = 9.6$ m and $a = 2.4$ m, are chosen [27]. Parameters for SS and LP operations considered in this paper with two values for plasma current, central electron density and central electron

Table 2. DEMO parameters [27] used for the feasibility study of the fuel ratio diagnostic.

DEMO plasma scenarios		n_{e0} ($10^{19}\,m^{-3}$)	T_{e0} (keV)
Steady-state	n_e-flat	9.3	64
	n_e-peaked	15.0	53
Long Pulse	n_e-flat	10.4	54
	n_e-peaked	16.8	57

temperature related to the peaked density and flat density scenarios [27] presented in the table 2 and used for a consistent sensitivity calculations of the method.

The effective charges $Z_{eff} = 2.57$ and 1.95 for SS and LP operations respectively, were used for the fuel density calculations, assuming the average impurity charge $Z_{imp} = 6$. The parameter Z_{imp} is an important one for the fusion reactor design as it defines the fuel density and by that the fusion power. Indeed, the fuel density n_{DT} depends on both Z_{eff} and Z_{imp} as follow

$$\frac{n_{DT}}{n_e} = \frac{Z_{imp} - Z_{eff}}{Z_{imp} - 1}, \tag{2}$$

where

$$Z_{eff} = \frac{\sum_{i=1} n_i Z_i^2}{\sum_{i=1} n_i Z_i} \equiv \frac{n_{DT} + \sum_{i=2} Z_i^2}{n_e} \tag{3}$$

and

$$Z_{imp} = \frac{\sum_{i=2} n_i Z_i^2}{\sum_{i=2} n_i Z_i} \equiv \frac{\sum_{i=2} n_i Z_i^2}{n_e - n_{DT}}. \tag{4}$$

One can see that an increase of Z_{imp}, including contribution of the thermalized alpha-particles, at the fixed Z_{eff} leads to increase of n_{DT}/n_e and, consequently fusion reaction rates.

In this paper, a realistic value Z_{imp}, which is expected in DEMO plasmas, has been chosen, though there is no an established model yet. For the assessment purpose, in the SS case with $Z_{eff} = 2.57$, assuming that main impurities are He, Ar and W and their relative concentrations 8%, 0.3% and 0.0005%, the parameter $Z_{imp} \approx 6.2$. If the plasma contains He, Li, Ar and W with relative concentrations 6%, 2%, 0.28% and 0.0005%, the parameter will be around 5.9. In this case, rates of the D (T, γ)^5 He and T (p, γ)^4 He reactions will be 5% and 7% less, correspondingly. Here, lithium is a proxy for some seeding by as yet unspecified low atomic number impurities to control radiated power fraction, and not critical to the main topic of the paper. However, these two examples just demonstrate a sensitivity of the reaction rates to the parameter Z_{imp}.

Studying sensitivity of the gamma-ray diagnostic to the n_D/n_T value, the reaction rate ratio of the T (p, γ)^4 He and D (T, γ)^5 He reactions was examined for different steady Maxwellian plasmas. In the figure 4 rates of these reactions calculated for the SS scenario with flat n_e-profile (see table 2) are presented against the n_D/n_T value. It was assumed that n_D-, n_T- and Z_{eff}-profiles have the same shape as n_e-profile.

For the T (p, γ)^4 He reaction rate the DD fusion proton energy distribution function was calculated in the simple classical approximation [28], i.e.

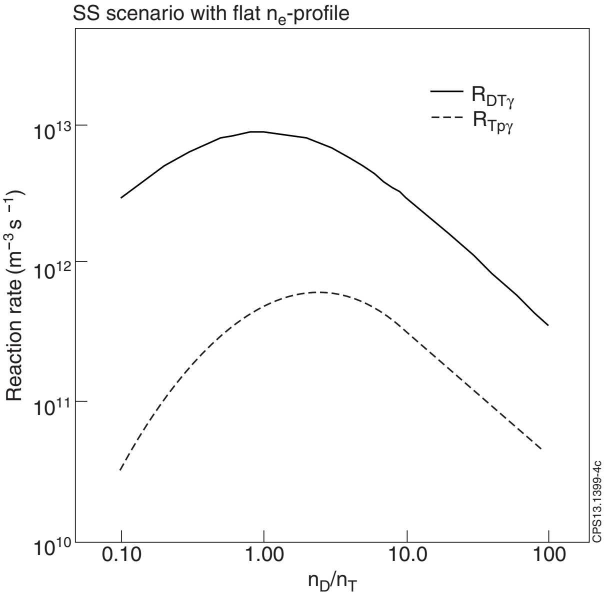

Figure 4. Rates of the T (p, γ)^4 He and D (T, γ)^5 He reactions versus n_D/n_T calculated for the SS scenario with a flat n_e-profile (see table 2).

$$f_p(E) \propto \frac{1}{E_0}\sqrt{\frac{E_0}{E}}\,\frac{E_0^{\frac{3}{2}} + E_c^{\frac{3}{2}}}{E^{\frac{3}{2}} + E_c^{\frac{3}{2}}}, \tag{5}$$

with the critical proton energy $E_c \propto T_e$ and the Spitzer slowing-down time $\tau_e \propto T_e^{3/2}/n_e$.

In reality, the proton energy distribution function in DEMO can differ from this one, especially in the energy range below the critical energy at around of 0.9 MeV, where the transport effects and losses may play a role. However, the proton energy distribution function can be derived from the recorded T (p, γ)^4 He gamma-ray spectrum. Since the distribution function depends on temperature the T (p, γ)^4 He reaction gamma-rays could be used to infer this important plasma parameter. An example of how the spectrum depends on the T_e with the classical slowing down demonstrated in figure 5(*a*). The temperature dependence of the reaction rate is shown in figure 5(*b*). One can see that with increasing electron temperature, the maximum of the T (p, γ)^4 He reaction emission is shifted to the higher energy at about 1 MeV and also, the gamma-ray peak became much broader. These changes are due to the changes of the fusion protons energy distribution. It is important to emphasize that the n_e-dependence of the gamma-ray spectrum is negligible.

The evolution of the spectrum is big enough for obtaining information about $\langle T_e \rangle$. To get a reasonable temperature accuracy, the continuously recorded T (p, γ)^4 He spectrum can be averaged over required period. So, in DEMO the $\langle T_e \rangle$ could be monitored in the real time mode with a resolution time defined by the T (p, γ)^4 He gamma-ray count-rate. Indeed, this task needs a comprehensive study of the proton distribution function, which should account for the alpha-particle knock effect and the proton transport, including toroidal field ripple effects. This special study should be addressed in ITER experiments for a validation of the model.

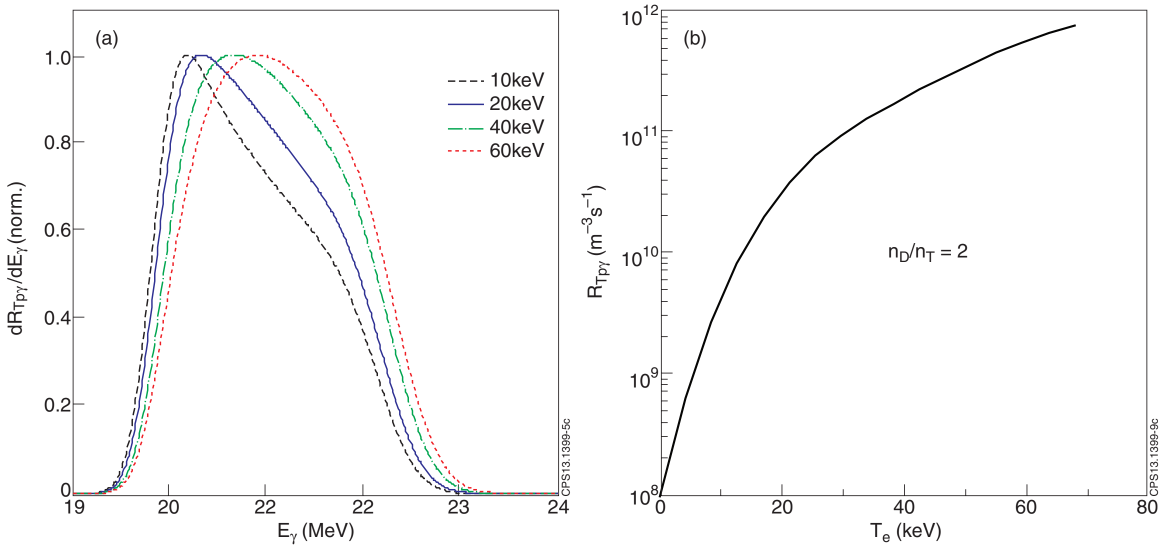

Figure 5. (*a*) T (p, γ)^4 He gamma-ray spectra calculated at different $T_e(0)$; (*b*) T (p, γ)^4 He reaction rates versus $T_e(0)$ for the case $n_D/n_T = 2$. The calculations have been done for the SS scenario with a flat n_e-profile (see table 2); T_e-profiles were assumed to be the same.

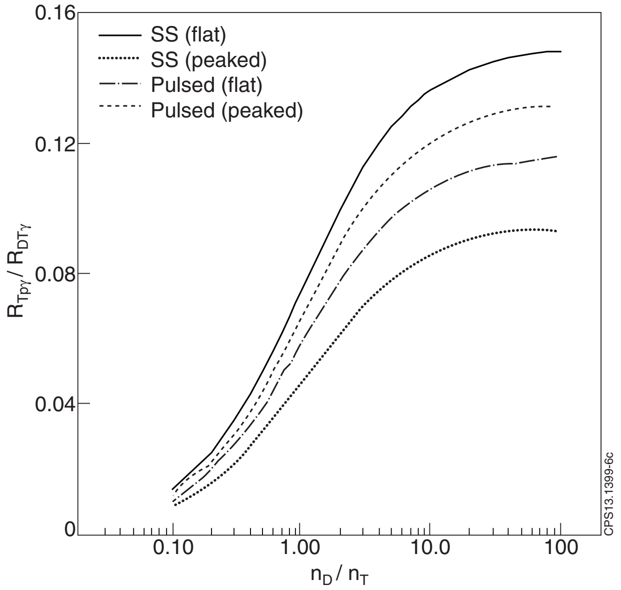

Figure 6. Ratio of the T (p, γ)^4 He and D (T, γ)^5 He reaction rates (like on figure 4) versus n_D/n_T calculated for the DEMO scenarios (see table 2) used for the feasibility study.

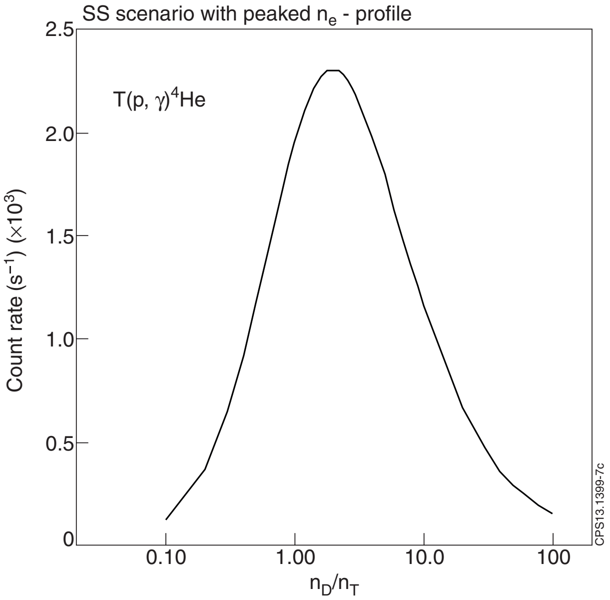

Figure 7. Count rate of the T (p, γ)^4 He gammas versus n_D/n_T calculated for the SS scenario with a peaked n_e-profile (see table 2).

The $R_{Tp\gamma}/R_{DT\gamma}$ ratios for the plasma core calculated for all DEMO scenarios presented in table 2 are shown in figure 6. In this paper, the plasma core defined as a volume, in which 50% of DT neutron rate is generated.

One can see that sensitivity of this diagnostic lies in the n_D/n_T range of 0.1–10, with a particularly strong sensitivity around the expected reactor operating point at or near $n_D/n_T = 1.0$.

One of the important issues of the feasibility assessment is the experimental setup. For the proposed measurements in DEMO a well-collimated gamma-ray spectrometer is needed. It should be fast, providing a MHz count-rate and its energy resolution should be sufficient to deliver the proton energy distribution reconstruction and ion temperature with a required accuracy. To illustrate the application of this technique as a realistic DEMO diagnostics, and assess the diagnostic time resolution and measurement accuracy, it is assumed that the spectrometer is placed 20 m from the plasma centre and it has tangential line-of-sight viewing the plasma through the 2 m long collimator. The collimator with diameter of 4 cm is filled with a material, which can effectively attenuate neutrons and has a high transparency for MeV gamma-rays. The best material is lithium hydride (LiH), which is already used on JET [29]. A 30 cm sample of the ^{6}LiH-filter reduces 2.5 MeV neutron flux by factor of 900 and the 15 MeV neutron flux by factor of 30 [30]. The 2 m long collimator plugged with LiH will attenuate 14 MeV neutrons by factor of 2×10^{10} and gamma-rays in the energy range 15–25 MeV by factor of 100.

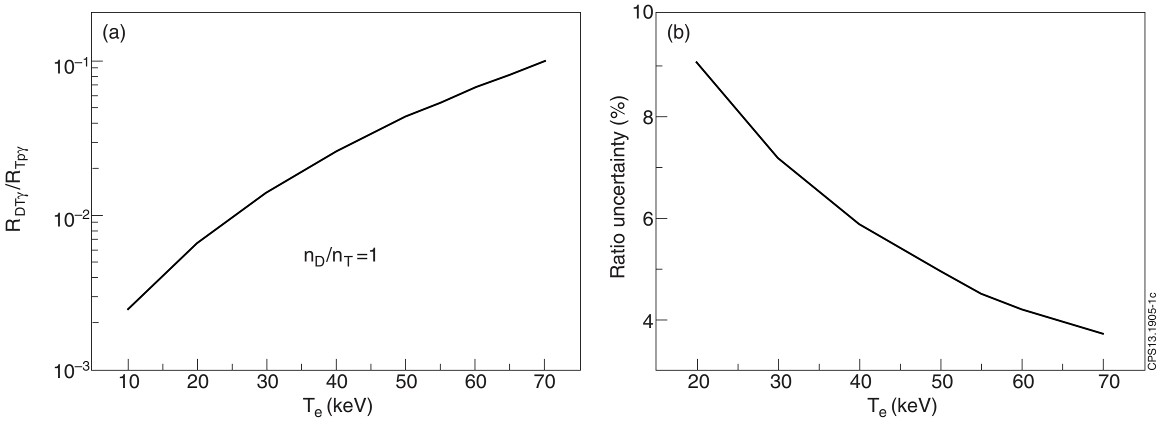

Figure 8. (*a*) Rate ratio for T (p, γ)^4 He and D (T, γ)^5 He gammas calculated versus $T_e(0)$ in the case $n_D/n_T = 1$; (*b*) uncertainties of the reaction ratio versus $T_e(0)$. The calculations have been done for the SS scenario with a flat n_e-profile (see table 2); T_e-profiles were assumed to be the same.

To provide high detection efficiency for the T (p, γ)^4 He and D (T, γ)^5 He gammas, a full energy peak spectrometer [5] should be used with efficiency up to 60%. Nowadays the best detector for this diagnostic is a heavy high-Z scintillator LaBr$_3$(Ce). It has short decay time (~20 ns), high photons yield and low sensitivity to neutrons. The high rate capability could be enabled by a dedicated data acquisition system with a sampling frequency of 400 MHz or higher and 14-bit resolution [31]. These outstanding properties of the system open a possibility to extend the pulse height analysis limit beyond 5 MHz [32] with energy resolution ~1% in the energy range 15–25 MeV.

Using this diagnostic scheme, the T (p, γ)^4 He gamma-ray count rate will depend on the n_D/n_T ratio as shown in figure 7. These results reveal that proposed method is feasible for measurements of the fuel ratio in the range 0.5–10.

The proposed scheme of the diagnostic setup allows assessing the accuracy of the fuel ratio measurements. The temperature dependence of the $R_{Tp\gamma}/R_{DT\gamma}$ ratio and the relevant spectrum measurement uncertainties are shown in figure 8. The figure demonstrates an impact of temperature changes and the sensitivity of the proposed technique in the case for the SS scenario with flat n_e-profile (see table 2).

Since the D (T, γ)^5 He gamma-ray rate will be higher by factor of 7–70 in the n_D/n_T value range 0.1–100, the main contribution to the statistical uncertainty of these measurements will give count-rate of the T (p, γ)^4 He gamma-rays. Note that only the DD fusion source of fast protons is taken into account. There are some other channels that can increase the rate of this reaction, e.g. interaction of 1 MeV DD fusion tritons with bulk hydrogen, H (t, γ)^4 He. However, relative hydrogen concentration will be low; hence, this additional contribution to the reaction rate is small. Also, an alpha-particle knock-on effect increases rates of the D (d, p) T and D (T, n)^4 He reactions, enhancing gamma-ray yields of T (p, γ)^4 He and H (t, γ)^4 He and D (T, γ)^5 He reactions. In the JET deuterium–tritium experiments the knock-on effects on the tail of the neutron spectrum have been found [33], but the relative contribution of the affected neutrons was rather small. Indeed, during the implementation of the diagnostic for the core fuel ratio control, all useful reactions and effects should be taken into account for the comprehensive modelling of the proton distribution function. In this paper a simplified approach is used for the assessment of the technique feasibility.

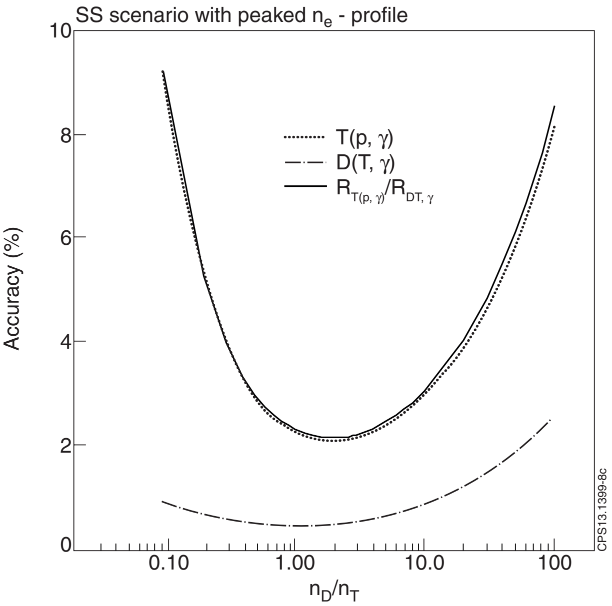

Figure 9. Statistical uncertainty of the T (p, γ)^4 He and D (T, γ)^5 He gamma-ray measurements and its ratio versus n_D/n_T calculated for the acquisition time of 1 s in the SS scenario with a peaked n_e-profile.

Figure 9 demonstrates the relative uncertainties of measurements for the acquisition time $\Delta t = 1.0$ s. In the DEMO with the SS operation and slowing-down time $\tau_e \sim 5$–7 s, the fuel composition variations in the core is expected to be rather slow. In this case, the measurement accuracy, ε could be improved by means of increasing the integration time, so that $\varepsilon \propto 1/\sqrt{\Delta t}$. A continued recording of the T (p, γ)^4 He and D (T, γ)^5 He gamma-ray spectra will allow monitoring of the core fuel ratio and temperature as well as making corrections of the fusion proton energy distribution function derived from the shape of the T (p, γ)^4 He spectra.

The accuracy of the $R_{Tp\gamma}/R_{DT\gamma}$ ratio diagnostic presented in figure 9 shows just expected gamma-ray measurement uncertainties. The overall uncertainty of the n_D/n_T ratio inference will be higher as it includes systematic uncertainties connected to reconstruction of the fusion protons distribution function, n_e profile, nuclear cross-sections, spectrometer calibration etc. The nuclear cross-section knowledge could be improved as the branching ratio of the D (T, γ)^5 He reaction is known with accuracy ~25% and the T (p, γ)^4 He reaction cross-section ~10% (see figure 3). Most significant difficulties for these measurements can be caused by interaction of charged fusion products with plasma instabilities. However, it should be emphasized that monitoring of relative changes of the fuel ratio in core during the continuous plasma control reduces these systematic errors substantially.

As was shown in [25], the proposed technique for temperature measurements can be tested in experiments on the H-minority heating of the tritium plasma on JET, where the effective tail temperature of accelerated H-ions can be inferred from the T (p, γ)^4 He spectra. For the application of the proposed fuel composition measurements in the high performance DT discharges, a well-shielded gamma-ray spectrometer with the high count-rate capabilities [32] is needed. As a preparation for the full-scale DT campaign, during the next few years an upgrade of the gamma-ray spectrometry system, viewing the plasma quasi-tangentially will be implemented. It could be a first prototype of the diagnostic setup described in this paper.

According to the ITER requirements on the fuel ratio measurements in the plasma core, accuracy of 20% should be provided during of 100 ms acquisition time. For the ITER SS scenario [34] with $R = 6.35\,\text{m}$, $a = 1.85\,\text{m}$, $n_e = 8.5 \times 10^{19}\,\text{m}^{-3}$, $Z_{\text{eff}} = 2.6$, $T_e = 25\,\text{keV}$ and $n_D/n_T = 1$, the required accuracy will be obtained recording gamma-ray spectrum with an integration time of 150 ms. For the assessments the diagnostic setup was taken the same as in the DEMO case, but the length of the LiH-plug in the collimator has been reduced by factor of 2. This diagnostic will be feasible in ITER, but an optimization of the gamma-ray spectrometry system based on the JET experience is needed to meet the requirements.

4. Conclusions

The deuterium–tritium fuel ratio and temperature measurements in the plasma core will be among important diagnostics in DEMO. A novel technique based on measurements and comparison of rates of the T (p, γ)^4 He and D (T, γ)^5 He nuclear reactions that take place in the hot deuterium–tritium plasma has been examined in the paper. The assessments reveal that proposed method is feasible for measurements of the core temperature and fuel ratio n_D/n_T in the range 0.5–10. It was shown that this diagnostic based on detection of high-energy gamma-rays is robust, efficient and does not require direct access to the plasma. The proposed measurements could be included in the loop of the DEMO plasma control system. The diagnostic will be tested in experiments on JET and can be considered for use in ITER.

Concluding the paper, one can say that JET, together with ITER experiments, operating with DT plasmas will provide the opportunity to obtain full information on the feasibility and capability of the proposed technique for the temperature measurements and control of the fuel composition in the DEMO plasma core with time resolution smaller than the energy and particle confinement times.

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References

[1] Costley A.E. 2010 *IEEE Trans. Plasma Sci.* **38** 2934–43
[2] Donné A.J.H., Costley A.E. and Morris A.W. 2012 *Nucl. Fusion* **52** 074015
[3] Jarvis O.N. *et al* 1994 *Plasma Phys. Control. Fusion* **36** 209–44
[4] Sasao M. *et al* 2004 *Plasma Phys. Control. Fusion* **46** S107–18
[5] Kiptily V.G., Cecil F.E. and Medley S.S. 2006 *Plasma Phys. Control. Fusion* **48** R59–82
[6] Kiptily V.G. *et al* 2002 *Nucl. Fusion* **42** 999
[7] Afanasyev V.I. *et al* 2010 *Nucl. Instrum. Methods Phys. Res.* A **621** 456–67
[8] Afanasyev V.I. *et al* 2003 *Rev. Sci. Instrum.* **74** 2388–52
[9] Kallne J., Batistoni P. and Gorini G. 1991 *Rev. Sci. Instrum.* **62** 2871–4
[10] Bosch H.-S. and Hale G.M. 1992 *Nucl. Fusion* **32** 611–31
[11] Nuclear database ENDF/B VII.1, www.nndc.bnl.gov
[12] Brune C.R. *et al* 1999 *Phys. Rev.* C **60** 015801
[13] Kallne J., Gorini G. and Ballabio L. 1997 *Rev. Sci. Instrum.* **68** 581–4
[14] Luhmann N.C. *et al* 2008 *Fusion Sci. Technol.* **53** 335–96
[15] Meo F. *et al* 2004 *Rev. Sci. Instrum.* **75** 3585–8
[16] Wilkinson F.J. and Cecil F.E. 1985 *Phys. Rev.* C **31** 2036
[17] Cecil F.E. and Wilkinson F.J. 1984 *Phys. Rev. Lett.* **53** 767–70
[18] Kammeraad J.E. *et al* 1993 *Phys. Rev.* C **47** 29–35
[19] Cecil F.E. *et al* 1985 *Phys. Rev.* C **32** 690
[20] Newman D.E. and Cecil F.E. 1984 *Nucl. Instrum. Methods* **227** 339–41
[21] Jacquinot J. and Sadler G.J. 1992 *Fusion Technol.* **21** 2254–64
[22] Kiptily V.G. *et al* 1998 Gamma ray spectrometry in ITER: conceptual design *Diagnostics for Experimental Thermonuclear Fusion Reactors 2* ed P.E. Stott *et al* (New York: Plenum)
[23] Hahn K.I., Brune C.R. and Kavanagh R.W. 1995 *Phys. Rev.* C **51** 1624–32
[24] Canon R.S. *et al* 2002 *Phys. Rev.* C **65** 044008
[25] Kiptily V.G. *et al* 2010 *Nucl. Fusion* **50** 084001
[26] Mantsinen M.J. *et al* 2001 *Nucl. Fusion* **41** 1815–22
[27] Poli E. *et al* 2013 *Nucl. Fusion* **53** 013011
[28] Post D.E. *et al* 1981 *J. Fusion Energy* **1** 129
[29] Chugunov I.N. *et al* 2008 *Instrum. Exp. Tech.* **51** 166–70
[30] Kiptily V.G. *et al* 1998 *Tech. Phys.* **43** 471
[31] Nocente M. *et al.* 2010 *Rev. Sci. Instrum.* **81** 10D321
[32] Nocente M. *et al* 2013 *IEEE Trans. Nucl. Sci.* **60** 1408–15
[33] Kallne J. *et al* 2000 *Phys. Rev. Lett.* **85** 1246
[34] Mukhovatov V. *et al* 2007 *Nucl. Fusion* **47** S404–13