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L Giacomelli et al.

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L. Giacomelli[a*], D. Rigamonti[b], M. Nocente[b], M. Rebai[b], M. Tardocchi[a],
W. Biel[c], M. Cecconello[d], S. Conroy[d], H. Hjalmarsson[d], T. Franke[e]

[a]*Istituto di Fisica del Plasma "P. Caldirola", CNR, Milano, Italy*
[b]*Dipartimento di Fisica "G. Occhialini", Università degli Studi di Milano-Bicocca, Milano, Italy*
[c]*Institute of Energy- and Climate Research, Forschungszentrum Jülich GmbH, Germany*
and Department of Applied Physics, Ghent University, Belgium
[d]*Department of Physics and Astronomy, Uppsala University, Sweden*
[e]*Max-Planck-Institut für Plasmaphysik and EUROfusion Power Plant Physics*
and Technology (PPPT) department, Garching, Germany
**Corresponding author: giacomelli@ifp.cnr.it*

The future tokamak demonstration fusion reactor (DEMO) will operate at unprecedented physical and technological conditions where high reliability of the system components is required. The conceptual study of a suite of DEMO diagnostics is on-going. Among these, a Gamma-Ray Spectrometric Instrument (GRSI) is being investigated to assess its performance and information quality in view of DEMO control. The GRSI foresees radial-orthogonal multi-lines of sight viewing DEMO plasma across its poloidal section as a further development of the Gamma-Ray Camera of JET and of the Radial Gamma-Ray Spectrometers proposed for ITER but with stricter technological constraints. These include surface availability in the Tritium Breeding Blankets of DEMO vessel inner wall for diagnostics collimators openings, diagnostics distance from the plasma, neutron irradiation and activation of the reactor structures. On DEMO the gamma-ray (γ) emission from DT plasmas consists of $D(T,\gamma)^5He$ (E_γ = 16.63 MeV) and $T(p,\gamma)^4He$ (E_γ = 19.81 MeV) reactions which for their high E_γ would allow in principle for background-free measurements. This work reports the assessment on the GRSI diagnostic capability. Reactions cross sections are assessed and used for the calculations of the reactions γ emission energy spectrum under DEMO DT plasma conditions and compared with 14 MeV neutron emissions before and after the GRSI collimator. Investigation of the GRSI γ spectrometers performance is also presented. Measurement of the γ emission intensity of $D(T,\gamma)^5He$ can be in principle used as an independent assessment of DEMO DT plasmas neutron yield.

Keywords: DEMO plasma control, Gamma-Ray diagnostics, Gamma-Ray spectroscopy, DT fusion gamma-ray emission energy spectra, DEMO DT plasma neutron yield.

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author's email: firstname.lastname@some.mail.server

1. Introduction

Gamma-ray (γ) spectrometry is a diagnostic method which consists in measuring the γ energy from nuclear reactions. From the measured γ emission energy spectra (GES) is possible to attain information upon the reactants kinematics, qualify their reaction process and extract information on the plasma conditions. With this aim, instruments which are well characterized in terms of their response function to γ detection and perform with good efficiency, resolution and energy bite, namely spectrometers, can be used to measure the specific γ emission and study the reaction. Since few years, γ diagnostics have been used in nuclear fusion as plasma diagnostics [1][2][3][4][5]. Depending on γ energy, information on the temperature and purity of the plasma can be obtained as well as the quality of the adopted auxiliary heating schemes verified [6][7][8][9].

For DEMO, γ spectroscopy is relevant in view of the extreme conditions of DT plasma itself and of the tokamak (magnetic field, temperature, radiation) which will be maintained for long time. Various neutron and γ reactions can be considered for DEMO DT plasmas [10]:

$D + T \rightarrow n(14.03\ \mathrm{MeV}) + {}^{4}He(3.54\ \mathrm{MeV})$

$D + T \rightarrow \gamma(16.63\ \mathrm{MeV}) + {}^{5}He$

$D + D \rightarrow n(2.45\ \mathrm{MeV}) + {}^{3}He(0.82\ \mathrm{MeV})$

$D + D \rightarrow p(3.02\ \mathrm{MeV}) + T(1.01\ \mathrm{MeV})$

$D + D \rightarrow \gamma(23.84\ \mathrm{MeV}) + {}^{4}He$

$D + {}^{3}He \rightarrow p(14.64\ \mathrm{MeV}) + {}^{4}He(3.71\ \mathrm{MeV})$

$D + {}^{3}He \rightarrow \gamma(16.38\ \mathrm{MeV}) + {}^{5}Li.$

The γ diagnostics have some significant advantages on DEMO: γ spectrometry of the plasma does not require direct access to the vessel; several centimeters of thickness of the vessel first wall reduces the strong flux of the undesirable low energy γ and neutrons; viewing the plasma through a long collimator, the spectrometer can be placed far away from the machine; the collimator should be filled with Lithium Hydride (LiH) [11] to suppress the neutron flux and thus neutron induced γ background meeting the required radiation conditions behind the biological shield; γ detectors are compact with well-known and simple response function; γ detectors can be easily replaced in the case of any damage.

In principle, a γ diagnostic for DEMO could be placed behind the neutron multi lines of sight diagnostic (Neutron Camera) similarly to the Radial Gamma-Ray Spectrometers (RGRS) being studied for ITER [12]. γ spectrometers can share the same line of sight of the neutron spectrometers provided the neutron detectors/spectrometers are neither bulky nor contain high-Z materials (Z atomic number) and attenuators are placed in the neutron beam dumps to strongly diminish the direct neutron flux to the γ spectrometers. Neutron attenuators can be made of Lithium Hydrade (LiH) capsules. If possible, dedicated viewing lines would be a preferable choice for a γ diagnostic in order to avoid modifications and/ or depression of the GES to be measured. Based on the actual experience at JET [2][3][4] and the RGRS for ITER, the assessment for DEMO γ diagnostic for will be based on Lanthanum Bromide doped with Cerium ($LaBr_3$:Ce), Cerium Bromide ($CeBr_3$) and High Purity Germanium (HPGe). Each detector ($LaBr_3$ and $CeBr_3$ both of about 7.62 cm diameter and 15.24 cm long, and HPGe) consists in a cylinder of dimensions 30 cm diameter and 50 cm length including the μ-metal shielding of the magnetic field. The scintillators $LaBr_3$ and $CeBr_3$ will implement a Light Emitting Diode (LED) to provide a reference signal in high rate measurements to monitor and correct for possible gain drifts of the photomultiplier tubes coupled to the detector crystals. Compact magnetic field insensitive Silicon photomultiplier (SiPM) can be also be considered [13].

Each spectrometer is facing the collimated line of sight, and possibly, a pneumatic/mechanical system can be designed to exchange two different types of γ spectrometers on the same line of sight such that, for instance, high rate or high resolution γ measurements can be performed alternately depending on the DEMO phase and plasma scenario. These measurements provide different insights and details on ion kinematics and plasma conditions by means of a similar but more complex analysis with respect to the neutrons [14][15][16][17], of the measured γ peak of the reactions. The analysis of the Doppler broadened γ peak at a specific energy with proper plasma modelling provides information on the energy distributions of the fusing ions as well as on their gyro-motion and trajectories with respect to the collimated lines of sight of the instrument [2]. Moreover, depending on the measurement count rate, being the GRSI a multi lines of sight instrument, it allows for plasma positioning and control measurements and, possibly, for tomographic reconstruction of the plasma γ emission during the evolution of DEMO DT plasmas.

Particular attention has to be devoted to the shielding of the spectrometers to avoid contamination of the direct γ signals in the collimators with background caused by downgraded scattered γ's, Compton electrons and γ's generated by neutron activation of the structures around the instrument. However, being $E_\gamma > 15$ MeV for the reactions of interest, a good signal/background ratio should be obtained. Still, detailed studies are needed as part of the design to better assess the impact of the thickness of DEMO vessel wall on GES and of the neutron and γ background effects on GRSI spectrometers.

2. Description

Two γ reactions were selected for this study: D + T → γ(16.63 MeV) + ^{5}He and T + p → γ(19.81 MeV) + ^{4}He. The databases ENDF [18] and EXFOR [19] were consulted to find the cross sections of these reactions and use them to simulate GES of these reactions with the simulation code GENESIS [20]. Unfortunately, the information on these cross sections is either partial or not reliable and then not directly usable for this investigation. A thorough investigation of [21][22][23] [24][25][26] [27] was thus carried out and the cross sections estimated.

For d(T,γ)^{5}He following what discussed in [25][27], the cross section was obtained, firstly, evaluating the reaction branching ratio which results $2.068\cdot 10^{-6}$ and, secondly, the cross section of d(T,n)^{4}He in ENDF/B-VI library which is highly reliable and accurate [28].

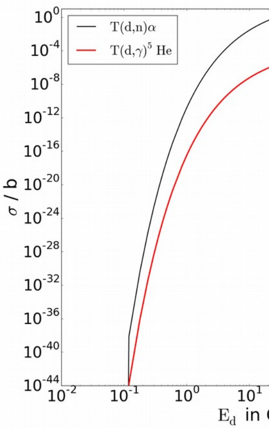


Figure 1: Log scale comparison of d(T,n)^{4}He and d(T,γ)^{5}He cross sections for D energies E_d in the centre of mass (CM) system with $2.068\cdot 10^{-6}$ branching ratio.

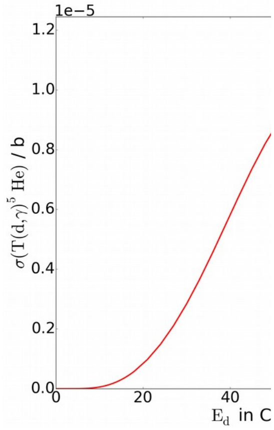
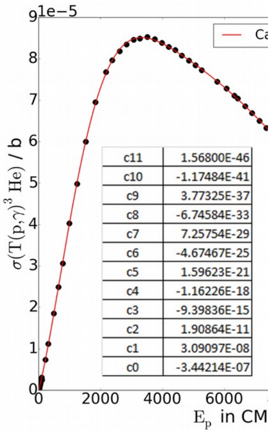


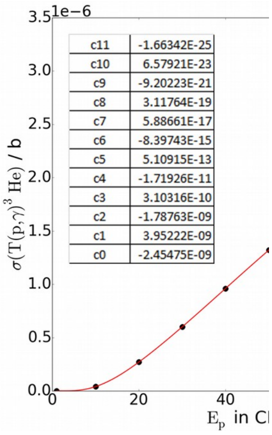
Figure 2: d(T,γ)^{5}He cross section for D energies $E_d \leq 100$ keV in CM system in linear scale.

Figure 1 shows the comparison of d(T,γ)^{5}He and d(T,n)^{4}He cross sections [28] while Figure 2 displays a magnification of the one for d(T,γ)^{5}He for DT ion temperatures below 100 keV of interest for DEMO. To be noted is that ^{5}He nucleus features numerous possible final excited states which give rise to uncertainties and broadening in its measured GES. In this work only ^{5}He ground (GS) and first excited (1L) states are considered, respectively with 50 % branching ratio, in GES simulation with GENESIS. For the reaction and p(T,γ)^{4}He references [29][30] were considered and comparison carried out with the experimental measurements presented in [23]. Figure 3 shows the experimental data of the cross section p(T,γ)^{4}He indicated in [23][29][30] and the fit analysis with a 11th order polynomial function. The interpretation of the data is very good and Figure 4 highlights the behavior of the cross section for proton energies $E_p \leq 100$ keV in the centre of mass (CM) system of interest for the simulation of DEMO DT plasma conditions with a specific fit.



c11	1.56800E-46
c10	-1.17484E-41
c9	3.77325E-37
c8	-6.74584E-33
c7	7.25754E-29
c6	-4.67467E-25
c5	1.59623E-21
c4	-1.16226E-18
c3	-9.39836E-15
c2	1.90864E-11
c1	3.09097E-08
c0	-3.44214E-07

Figure 3: Comparison of p(T,γ)^{4}He cross section data with a polynomial fit analysis for $E_p < 14$ MeV in CM system.



c11	-1.66342E-25
c10	6.57921E-23
c9	-9.20223E-21
c8	3.11764E-19
c7	5.88661E-17
c6	-8.39743E-15
c5	5.10915E-13
c4	-1.71926E-11
c3	3.10316E-10
c2	-1.78763E-09
c1	3.95222E-09
c0	-2.45475E-09

Figure 4: As Figure 3 but for $E_p \leq 100$ keV in CM system.

Both d(T,γ)^{5}He and p(T,γ)^{4}He cross sections were then implemented in the simulation code GENESIS. Calculations were carried out to determine GES for the two reactions for plasmas in thermal equilibrium at D, T and p temperatures of 10 keV, 20 keV and 50 keV. Figure 5 shows the d(T,γ)^{5}He GES for 20 keV temperature.

Comparison of neutron and γ emission energy spectra of d(T,n)^{4}He, d(T,γ)^{5}He and p(T,γ)^{4}He for DEMO plasma equilibrium with D, T and p ions temperatures of 10 keV, 20 keV and 50 keV is carried out in order to assess shapes, magnitude and extension (energy bite) of neutron and γ emission energy spectra (Figure 6). Up to plasmas of 20 keV temperature, the d(T,γ)^{5}He γ peak is clearly visible at the source. If temperatures grew up to 50 keV, the high energy neutron tail of d(T,n)^{4}He would be superimposed to the d(T,γ)^{5}He peak at 16.63 MeV. Concerning p(T,γ)^{4}He instead, the magnitude of the γ peak emissions at 19.81 MeV is always comparable with the high energy tails of d(T,γ)^{5}He reaction. Evidence of the p(T,γ)^{4}He peak can be recognizable as a bump on the high energy tail of the GES obtained as summation of the γ emissions from the two reactions in the source DT plasma.

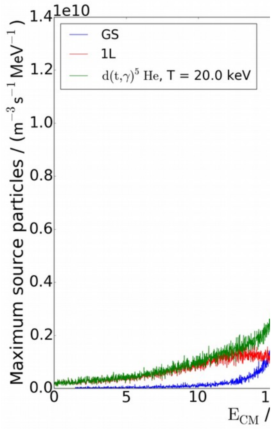


Figure 5: $d(T,\gamma)^5He$ GES for D and T ions at 20 keV temperature as sum (green line) of the contributions of γ's relative to ^5He born in either its GS (blue line) or 1L state (red line) with 50 % branching ratio.

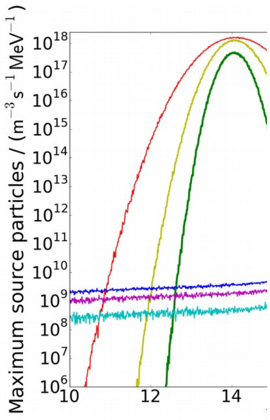


Figure 6: DT plasma source neutron and γ emission energy spectra in log scale of $d(T,n)^4He$, $d(T,\gamma)^5He$ and $p(T,\gamma)^4He$ reactions for D, T and p temperatures of 10 keV, 20 keV and 50 keV calculated with GENESIS.

A further step in the analysis was carried out considering the line of sight of the γ spectrometers as a long collimator which contains a neutron attenuator made of LiH. This to verify the characteristics of neutron and γ spectra which GRSI spectrometers would be exposed to. Calculation in MCNPX [31] were performed to study the problem and modelling the geometry of the cylindrical 900 cm long and 2.2 cm diameter collimator including the cylindrical LiH neutron attenuator (120 cm long and 2.2 cm diameter with LiH pellets encapsulated into 1 mm thick Aluminum casing). The theoretical source energy spectra shown in Figure 6 were used individually as input source to the MCPNX calculations to determine the correspondent neutron and γ energy spectra at the end of the collimator which will be facing the GRSI detector front, i.e., the $LaBr_3$ crystal (Figure 7).

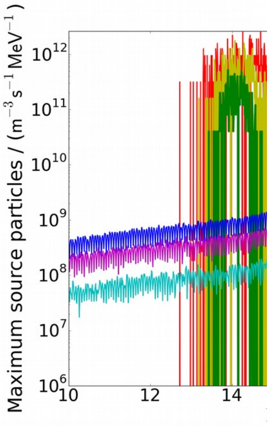


Figure 7: Neutron and γ energy spectra in log scale for 10 keV, 20 keV and 50 keV plasma temperatures at the end of the 900 cm long collimator with 120 cm long LiH neutron attenuator embedded. The diameter of collimator and neutron attenuator measures 2.2 cm.

The attenuation coefficients due to LiH are about $4.20\cdot10^{-7}$ for 14.03 MeV neutrons, 0.24 for 16.63 MeV γ's and 0.29 for 19.81 MeV γ's. As can be seen in figure, the $d(T,\gamma)^5He$ γ's are now clearly detectable also for plasma temperatures of about 50 keV. This is a good results which make it possible to clearly make use of $d(T,\gamma)^5He$ γ's as diagnostic tool in DEMO in terms of spectroscopic measurements to determine plasma temperature and to control the burning plasma conditions. Still, the high energy tail of these γ's is of the same magnitude of the peak amplitude of $p(T,\gamma)^4He$ γ's. Further calculations will be done in order to consider the effects of DEMO vessel material and thicknesses on the summation GES of the two γ reactions.

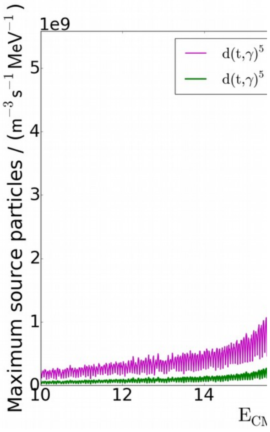


Figure 8: Comparison of $d(T,\gamma)^5He$ GES at 20 keV temperature for collimators of 2.2 cm (purple line as in Figure 7) and 1.1 cm (green line) diameters after 120 cm long LiH neutron attenuator.

MCNPX calculations were then performed considering only $d(T,\gamma)^5He$ reaction at 20 keV temperature and a collimator of 1.1 cm diameter instead. Figure 8 displays the correspondent downgraded GES by a factor 0.25 with respect to the one relative to 2.2 cm diameter collimator of Figure 7.

MCNPX calculations were carried out also to assess GES a $LaBr_3$ crystal would measure from 20 keV DT plasma and determining its measurement sensisivity and efficiency. To the collimator model a $LaBr_3$ crystal, 7.62 cm diameter 15.24 cm long, was included. The collimator is 2.2 cm diameter and the crystal is facing it. Figure 9 displays the $d(T,\gamma)^5He$ GES featuring a broaden peak and overshadowing the one relative to the $p(T,\gamma)^4He$ reaction which features full, single and double escape peaks in view of the crystal dimensions compared to the incoming γ's of $E_\gamma = 19.81$ MeV. The crystal efficiency to $d(T,\gamma)^5He$ γ's is 0.93 for 16.63 MeV γ count rates in the range of 40-300 Counts/s depending on the line of sight.

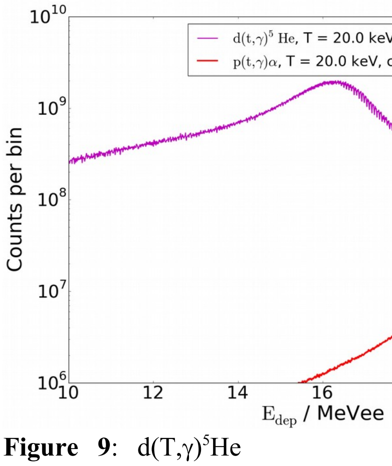


Figure 9: $d(T,\gamma)^5He$ and $p(T,\gamma)^4He$ GES measured by a 7.62 cm diameter and 15.24 cm long $LaBr_3$ crystal facing the collimator with its LiH neutron attenuator.

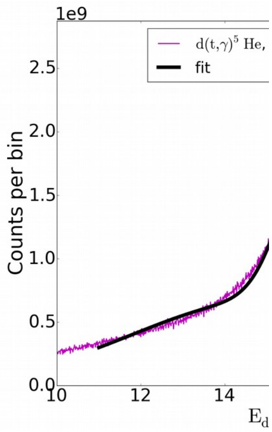


Figure 10: Fit (black line) of the peak about 16.63 MeV of the $d(T,\gamma)^5He$ GES measured by a 7.62 cm diameter and 15.24 cm long $LaBr_3$ crystal with an analytic function.

The shape and broadening of the peak of the $d(T,\gamma)^5He$ GES contains the diagnostic information of the plasma conditions. Figure 10 shows a fit analysis of the peak using a tentative analytic function. Making use instead of an accurate model of the distributions functions of the reactants in the plasmas, of the background radiation and considering the spectrometer response function, a good representation of the GRSI measured GES can be achieved such that plasma temperature, reactant ions kinematics, the fuel ratio I_D/I_T as, possibly, the thermal/non-thermal ratio can be obtained together with DEMO plasma position control from the comparison of the GRSI spectrometers γ measurement rates. Furthermore, considering the area under the peak within $10 \leq E_\gamma \leq 22$ MeV, the $d(T,\gamma)^5He$ γ events are $7.46 \cdot 10^{11}$ which, considering the branching ratio, correspond to a neutron yield of $3.61 \cdot 10^{17}$. This allows for an independent assessment of the nuclear fusion power.

3. Conclusions

The main purpose of the Gamma-Ray Spectrometric Instrument (GRSI) for DEMO is the control of its plasma. The GRSI is thought to be a multi-line of sight instrument implementing in each position one or, possibly, two γ spectrometers for exclusive high rate or high resolution γ measurements from which the plasma positioning and the kinematics of the fusing ions can be obtained. In view of the γ emission energy spectra (GES) of interest, this diagnostic can be placed behind the neutron diagnostic opportunely shielded provided the neutron spectrometers are not bulky and/or there is not high/Z material interposed. Based on the results of the calculation presented here, the neutron contribution to the γ measurements can be effectively suppressed by the implementation of LiH neutron attenuators in the collimator design. A 120 cm long 2.2 cm diameter LiH neutron attenuator features attenuation factors of $4.20 \cdot 10^{-7}$ for DT 14 MeV neutrons and lower than 0.30 for the γ energies of interest. Further reduction of the neutron flux (and of possible γ background at much lower energies) is possible by increasing the length of the LiH attenuator which would also affect the direct γ's of interest. The reduction of the collimator diameter impacts on the GES peak amplitude (factor 0.25). Depending on the number and positions of GRSI sight lines, a trade off analysis needs to be carried out in order to assess the γ diagnostic capabilities useful for DEMO plasma control and spectroscopy. For the former, the comparison/variation of the γ fluxes measured by the spectrometers along different lines of sight (50-300 Counts/s) allows for the definition of the DEMO plasma shape and position and for the detection of variations with respect to its nominal operational configuration.

Considering wider 4.2 cm diameter collimators and larger 8.7 cm x 24.6 cm $LaBr_3$ (0.99 efficiency) GRSI would be capable of 180-1400 Counts/s. Concerning GES spectroscopy, a good model interpretation provides information on plasma temperature, on the reactants kinematic, on the fuel ratio I_D/I_T and on thermal/non-thermal ion ratio which can be obtained based on the observations and the analysis of asymmetries and energetic tails featuring the measured Doppler broadened γ peak in the spectrum as well as an independent estimate of the neutron yield that is the produced nuclear fusion power.

Acknowledgments

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