

PAPER • OPEN ACCESS

Analytical and MonteCarlo approaches to infer the total gamma ray emission from the JET tokamak

To cite this article: G. Marcer *et al* 2023 *JINST* **18** C05020

View the [article online](#) for updates and enhancements.

You may also like

- [THE EFFECT OF INTERMITTENT GYRO-SCALE SLAB TURBULENCE ON PARALLEL AND PERPENDICULAR COSMIC-RAY TRANSPORT](#)
J. A. le Roux
- [Impact of Cosmic-Ray Transport on Galactic Winds](#)
R. Farber, M. Ruszkowski, H.-Y. K. Yang et al.
- [-cascade: a simple program to compute cosmological gamma-ray propagation](#)
Carlos Blanco



PRIME
PACIFIC RIM MEETING
ON ELECTROCHEMICAL
AND SOLID STATE SCIENCE

HONOLULU, HI
Oct 6–11, 2024

Abstract submission deadline:
April 12, 2024

Learn more and submit!

Joint Meeting of
The Electrochemical Society
•
The Electrochemical Society of Japan
•
Korea Electrochemical Society

6TH INTERNATIONAL CONFERENCE FRONTIERS IN DIAGNOSTICS TECHNOLOGIES
ENEA FRASCATI RESEARCH CENTRE, FRASCATI, ITALY
19–21 OCTOBER 2022

Analytical and MonteCarlo approaches to infer the total gamma ray emission from the JET tokamak

G. Marcer,^{a,*} A. Zohar,^b A. Dal Molin,^d D. Rigamonti,^d M. Rebai,^d M. Nocente,^{a,d}
E. Panontin,^a G. Croci,^a G. Gorini,^{a,d} G. Grosso,^d A. Muraro,^d E. Perelli Cippo,^d
O. Putignano,^a E. de la Luna,^e Z. Ghani,^h S. Conroy,^c J. Garcia,^f Y. Kazakov,^g V. Kiptily,^h
M. Maslov,^h M.F.F. Nave,ⁱ J. Ongena,^g M. Tardocchi^d and the JET contributors

^aDepartment of Physics, University of Milan-Bicocca, Piazza dell'Ateneo Nuovo, Milan, Italy

^bReactor physics department, Jozef Stefan Institute, Jamova Cesta, Ljubljana, Slovenia

^cEURATOM-VR Fusion Association, Uppsala University, Uppsala, Sweden

^dInstitute for Plasma Science and Technology, CNR, Via Roberto Cozzi, Milan, Italy

^eLaboratorio Nacional de Fusion, CIEMAT, Complutense, Madrid, Spain

^fCEA, IRFM, Bât, Saint-Paul-lez-Durance, France

^gLaboratory for Plasma Physics, ERM/KMS, Avenue de la Renaissancelaan, Brussels, Belgium

^hCulham Centre for Fusion Energy, United Kingdom Atomic Energy Authority, Abingdon, United Kingdom

ⁱAssociação EURATOM/IST, Universidade Tecnica de Lisboa, Av. Rovisco Pais, Lisbon, Portugal

E-mail: g.marcer@campus.unimib.it

ABSTRACT: A single gamma-ray spectrometer installed at the end of a collimator can be used to infer the total emission from a tokamak plasma if the transport of gamma-rays from the plasma to the detector is known. In such analysis, the plasma emission profile plays a fundamental role, since it impacts the fraction of plasma volume intercepted by the detector line of sight.

In this work, the DT 17 MeV fusion gamma-rays emission profile of the JET discharge #99608 from second 46 to 48 has been estimated both with the TRANSP code and reconstructed through tomographic inversion based on the neutron camera data, assuming that fusion gamma-rays have the same profile as the 14 MeV fusion neutrons. The gamma-ray transport has been evaluated both by MonteCarlo simulations and analytical calculations.

By combining MonteCarlo and analytical evaluations of the gamma-ray transport in different ways with the estimated radiation emission profile, we provide four different routes to determine the total gamma-ray yield from measurements whose results agree within better than 10%.

KEYWORDS: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Gamma detectors (scintillators, CZT, HPGe, HgI etc); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

*Corresponding author.

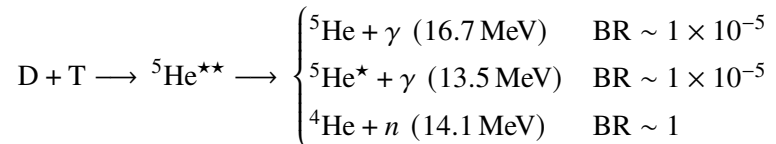
Contents

1	Introduction	1
2	Plasma emission profile	2
3	Emission transport coefficients	3
3.1	Analytical approach	3
3.2	MonteCarlo simulations	4
4	Results	4
5	Conclusions	5

1 Introduction

Nowadays, the fusion power emitted at JET is measured with the fission chambers diagnostics, which constitute the reference absolute neutron counter of the tokamak. Though, counting neutrons absolutely requires laborious simulations and the cross-calibration with activation foils [17]. The purpose of this study is that of developing a simpler technique for the estimation of the fusion power of a DT plasma independent from the reference method.

During the last deuterium-tritium campaign at JET [1], the tangential gamma-ray spectrometer was employed for inferring the absolute number of emitted fusion gamma-rays starting from those detected [2–5]. According to literature, fusion gamma-rays have a very tiny probability of being produced in a DT fusion reaction [6, 18]:



The employed spectrometer is based on a lanthanum bromide scintillator which views the plasma along a collimated horizontal line of sight (LoS), tangent to the inner vessel walls. The procedure for obtaining the number of detected fusion gamma-rays from the measured spectra will not be described in this paper [19], in which the exact number N_{LoS} of gamma-rays travelling toward the detector surface will be assumed as known.

Instead, the paper focuses on the determination of a transport coefficient α_T which allows converting the number of gamma-rays that deposit their full energy in the crystal to the total number N_{tot} of those emitted by the plasma: $N_{\text{tot}} = \alpha_T \cdot N_{\text{LoS}}$. Gamma rays which deposit their full energy have not collided against any material in their path from the plasma to the detector, hence this makes it possible to avoid the calculation of any attenuation that the gamma-ray beam may experience and follow an approach based solely on geometrical considerations [3, 5].

In such analysis, the plasma emission profile plays a fundamental role, since it impacts the fraction of plasma volume intercepted by the detector LoS. For the sake of consistency, the gamma-camera diagnostic should have been used in order to infer the emission profile but, because of the very high neutron yield expected during the DT JET campaign, the gamma camera diagnostic would have been completely impaired and therefore it was not even set to operability. The neutron camera was used in its stead.

The following sections describe the two techniques adopted to determine the profile of the nuclear radiation emitted by the plasma (section 2), the analytical and MonteCarlo approaches used for estimating the transport coefficient (section 3) and a comparison of the results (section 4). Conclusions follow in (section 5).

2 Plasma emission profile

One of the most challenging aspects of operating with a single LoS spectrometer is that each plasma discharge has its own time dependent radiation emission profile. For this work, the neutron emission profile was both measured with the neutron camera diagnostics [7] and, in order to benchmark the reconstructed profile, estimated numerically based on the plasma heating configuration and a number of measured plasma parameters given as input to the TRANSP [8] code. In this second case, a prediction of the neutron emission profile in the 3D space is obtained as output [9, 10], whose projection in the poloidal plane for deuterium-tritium JET pulse #99608 at time $t = 47$ s is shown on the right in figure 1. Discharge #99608 was a deuterium-tritium pulse part of the 3-ion scenario experiment [11, 12] with a neutron yield of about 10^{17} neutrons per second whose most significant plasma parameters are given in [5].

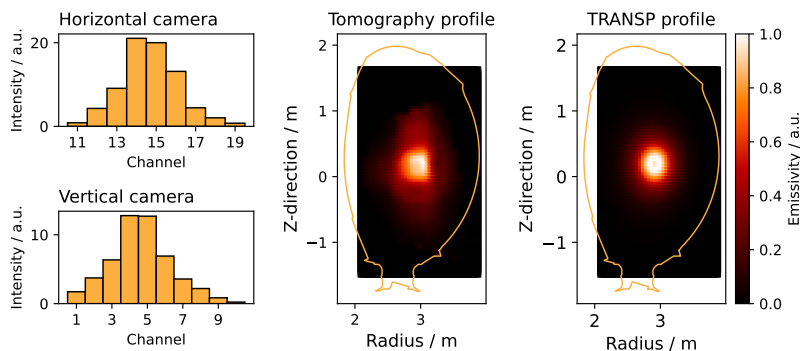


Figure 1. Neutron emission profile in the poloidal plane of discharge #99608 reconstructed through tomography (center) and from TRANSP (right). See the text for further descriptions. Neutron camera data are shown to the left; the channels on the x-axis refer to the detectors which compose the camera itself, which are 9 in the horizontal and 10 in the vertical camera.

When starting from the neutron camera data, the profile was inferred by tomographic inversion [13–15] of the data collected between seconds 46 and 48, during which timelapse the magnetic equilibrium was considerably stable. The output is the neutron emission represented by a matrix of points in the poloidal plane (see the middle plane in figure 1).

When the full toroidal geometry is considered, each pixel in the poloidal plane (see figure 1) corresponds to a ring that extends along the toroidal direction. If the total neutron yield from the discharge is known, from these results of the profile obtained with either method, we can finally determine the number of neutrons that were generated in each toroidal ring.

3 Emission transport coefficients

3.1 Analytical approach

The analytical approach for determining the transport coefficient relies on the description of the detector field of view (FoV) inside the vessel. For this purpose, both Euclidean (x, y, z) and cylindrical (R, z, ϕ) coordinates were employed, as shown in figure 2. The JET torus is centered at the origin, coaxial with the z axis, with the equator lying on the $z = 0$ plane. The detector LoS lies on the same plane and starts about 22 m outside the vessel, at the end of a cylindrical beamline with a 10.05 cm radius.

The procedure is divided into two logical steps: 1) characterisation of the FoV from the detector and collimator positions; and 2) estimation of the probability for each gamma-ray generated inside the FoV to reach the detector.

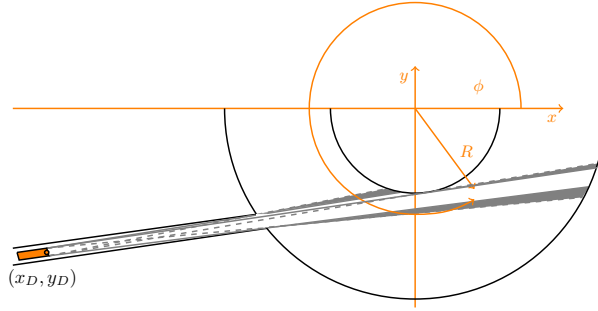


Figure 2. Scheme of the coordinate system used in the analytical evaluation of the transport coefficient and the detector field of view inside the vessel in the $z = 0$ equatorial plane. The detector is on the lower left corner.

The FoV can be divided into light and penumbra depending on the possibility for a gamma-ray born in that region to illuminate all of the detector surface or just part of it, respectively. For the sake of simplicity, we considered two cases, where the penumbra was either approximated to light (upper limit for the coefficient α_T) or considered just dark (lower limit for the coefficient α_T). Our best estimate of α_T was taken by the average of its lower and upper limits.

Fixed the z -plane, for each possible gamma-ray source in the FoV, isotropic emission was assumed, so that the probability $p(R, \phi)$ for an emitted gamma-ray to reach the detector was simply given by the solid angle determined by the detector and the point itself, leading to eq. (3.1), where (x_D, y_D) and A_D are the detector position and area respectively.

$$p(R, \phi) = \frac{A_D}{4\pi [(R \cos(\phi) - x_D)^2 + (R \sin(\phi) - y_D)^2]} \quad (3.1)$$

The aim of this step was to estimate the probability ε_i that a particle generated in each tomography ring $\{R_i, z_i\}$ has to reach the detector. For each pixel, ε_i can be obtained by integrating

the probability along the torus ring, spanning over the angle ϕ , inside the light region:

$$\varepsilon_i = \langle P(R_i) \rangle_\phi = \frac{1}{2\pi} \int_0^{2\pi} d\phi p(R_i, \phi)$$

ε_i can be computed analytically, since:

$$\int d\phi p(R_i, \phi) = -\frac{A_D}{4\pi^2 (x_D^2 + y_D^2 - R^2)} \cdot \text{atan} \left(\frac{y_D \cos\left(\frac{\phi}{2}\right) - (R + x_d) \sin\left(\frac{\phi}{2}\right)}{y_d \sin\left(\frac{\phi}{2}\right) - (R - x_d) \cos\left(\frac{\phi}{2}\right)} \right)$$

If N_{LoS} is the number of measured gamma-rays travelling toward the detector, knowledge of ε_i allows inferring the total number of emitted gamma-rays N_{tot} through the formulas:

$$N_{\text{tot}} = \sum_i N_i, \quad N_i = n_i \cdot \text{BR}, \quad N_{\text{LoS}} = \sum_i N_i \varepsilon_i$$

where i runs over the pixels and N_i is the number of gamma-rays emitted in each ring, which is directly proportional to the emitted neutrons n_i based on the reaction branching ratio BR. The latter is still not known [6] and could be computed by this analysis starting from the measured fusion gamma-rays and the total neutron yield.

Once all the ε_i have been evaluated, the transport coefficient is given by $\alpha_T = N_{\text{tot}}/N_{\text{LoS}}$.

3.2 MonteCarlo simulations

For comparison, a MonteCarlo simulation was run with the MCNP model of JET [10, 20] using monoenergetic 16.7 MeV gamma sources. The simulation used as input the spatial emission profile of the radiation and simulated the source as a set of toroidal rings with constant emissivity. It gave as output the number of gamma-rays that travel towards the detector, allowing for a direct comparison with the analytical result.

A simulation was also used to determine the attenuation effects of the material along the detector beamline and the detector detection efficiency, obtaining a rescaling factor 0.192 which included both. They were both performed in Geant4 [16] and MCNP, which gave the same result within statistic fluctuations. At last, this coefficient was included in both the analytical and MonteCarlo approaches.

4 Results

Four routs could hence be followed to obtain α_T and the results are summarized in table 1.

For each gamma-ray transport approach, variations of α_T using the same emission profile are similar, bot less than 5%, with the MonteCarlo simulations output varying a bit more than the analytic computations results.

For each evaluated radiation emission profile, instead, the discrepancy between the factors obtained with the two gamma-ray transport approaches are quite different, with less than 1% with the analytical and within 10% with the MonteCarlo simulations.

Table 1. Transport coefficient obtained by combining the four procedures described so far. For each line/column, the percentage variation is given in the last column/line.

	tomography profile	TRANSP profile	difference / %
analytic transport	3.180×10^{-10}	3.194×10^{-10}	0.44
MonteCarlo transpo	3.043×10^{-10}	3.353×10^{-10}	9.24
difference / %	4.30	4.74	

5 Conclusions

JET pulse number 99608 between seconds 46 and 48 was selected to validate the method. The starting point is the determination of the radiation emission profile which can be inferred by tomographic inversion of the neutron camera data or be the result of a TRANSP routine. For either choice, the transport factor α_T can be evaluated analytically or by a full transport simulation with the MCNP code. α_T obtained values are summarized in table 1.

We found that values differ by 10% at most. As the analytical approach applied to the tomographic inversion of the neutron camera data is the least computationally expensive, we conclude that we can rely on this approach to obtain α_T for other discharges with an expected accuracy better than 10%.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

- [1] J. Mailloux, *Deuterium-tritium experiments in JET with the ITER-like wall*, plenary talk at *The 48th European Conference on Plasma Physics*, 27 June – 1 July 2022.
- [2] M. Nocente et al., *A new tangential gamma-ray spectrometer for fast ion measurements in deuterium and deuterium-tritium plasmas of the joint european torus*, *Rev. Sci. Instrum.* **92** (2021) 043537.
- [3] M. Nocente et al., *Fusion product measurements by nuclear diagnostics in the Joint European Torus deuterium-tritium 2 campaign*, *Rev. Sci. Instrum.* **93** (2022) 093520.
- [4] G. Marcer et al., *Study of a single line of sight gamma ray diagnostics for measurements of the absolute gamma ray emission from JET*, *2021 JINST* **16** C12019.
- [5] G. Marcer et al., *A new dedicated signal processing system for gamma-ray spectrometers in high power deuterium-tritium plasma scenarios in tokamaks*, *Rev. Sci. Instrum.* **93** (2022) 093525.
- [6] J. Jeet et al., *Inertial-confinement fusion-plasma-based cross-calibration of the deuterium-tritium γ -to-neutron branching ratio*, *Phys. Rev. C* **104** (2021) 054611.

- [7] J. Adams, O. Jarvis, G. Sadler, D. Syme and N. Watkins, *The JET neutron emission profile monitor*, *Nucl. Instrum. Meth. A* **329** (1993) 277.
- [8] J. Breslau et al., *TRANSP*, Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ, U.S.A. (2018).
- [9] Ž. Štancar et al., *Multiphysics approach to plasma neutron source modelling at the JET tokamak*, *Nucl. Fusion* **59** (2019) 096020.
- [10] A. Žohar et al., *Validation of realistic Monte Carlo plasma gamma-ray source on JET discharges*, *Nucl. Fusion* **62** (2022) 066004.
- [11] M. Nocente et al., *Generation and observation of fast deuterium ions and fusion-born alpha particles in JET D – ^3He plasmas with the 3-ion radio-frequency heating scenario*, *Nucl. Fusion* **60** (2020) 124006.
- [12] Y.O. Kazakov et al., *Plasma heating and generation of energetic D ions with the 3-ion ICRF + NBI scenario in mixed H-D plasmas at JET-ILW*, *Nucl. Fusion* **60** (2020) 112013.
- [13] T. Craciunescu et al., *The maximum likelihood reconstruction method for JET neutron tomography*, *Nucl. Instrum. Meth. A* **595** (2008) 623.
- [14] E. Panontin et al., *First spatially resolved measurements of the D- ^3He α -particle source with the upgraded JET gamma-ray camera*, *Rev. Sci. Instrum.* **92** (2021) 053529.
- [15] E. Panontin, *Development of Nuclear Radiation Based Tomography Methods for Runaway Electrons and Fast Ions in Fusion Plasmas*, Department of Physics, Università degli Studi di Milano-Bicocca (2021) [<https://hdl.handle.net/10281/383194>].
- [16] GEANT4 collaboration, *Geant4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.
- [17] L. Bertalot, A.L. Roquemore, M. Loughlin and B. Esposito, *Calibration of the JET neutron activation system for DT operation*, *Rev. Sci. Instrum.* **70** (1999) 1137.
- [18] Y. Kim et al., *Determination of the deuterium-tritium branching ratio based on inertial confinement fusion implosions*, *Phys. Rev. C* **85** (2012) 061601.
- [19] A. Dal Molin et al., *Measurement of the deuterium-tritium branching ratio from magnetic confinement fusion experiments at the Joint European Torus*, to be published.
- [20] A. Žohar, *Analysis and modelling of gamma ray emission in large tokamaks plasmas*, Department of Physics, Faculty of Mathematics and physics, University of Ljubljana (2022) [<https://repozitorij.uni-lj.si/IzpisGradiva.php?id=137336>].