Reconstructions of the fast-ion deuterium distribution in a tritium-rich plasma in the JET DTE2 campaign

H. Järleblad[1], B.C.G. Reman[2,3,4], Y. Dong[1], M. Nocente[5], J. Eriksson[6], A. Valentini[2], M. Rud[2], A. Dal Molin[7], J. Garcia[8], Ye.O. Kazakov[4], D. Keeling[9], D. King[9], E.A. Lerche[4], R. Lorenzini[10], C. Maggi[9], M. Maslov[11], D. Moseev[12], D. Rigatoni[7], B. Schmidt[13], Ž. Štancar[11, 14], M. Tardocchi[7], M. Salewski[2] and JET Contributors[*]

[1] *Department of Applied Mathematics and Computer Science, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

[2] *Department of Physics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

[3] *Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, United Kingdom*

[4] *Laboratory for Plasma Physics LPP-ERM/KMS, B-1000 Brussels, Belgium*

[5] *Department of Physics, University of Milano-Bicocca, 20126 Milano, Italy*

[6] *Department of Physics and Astronomy, Uppsala University, 751 20 Uppsala, Sweden*

[7] *Institute for Plasma Science and Technology, National Research Council, 20125, Milan, Italy*

[8] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

[9] *CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom of Great Britain and Northern Ireland*

[10] *Consorzio RFX, CNR Research Area, Corso Stati Uniti, 4-35127 Padua, Italy*

[11] *UKAEA, Culham Centre for Fusion Energy, Abingdon, Oxfordshire OX14 3DB, United Kingdom of Great Britain and Northern Ireland*

[12] *Max-Planck-Institut für Plasmaphysik Teilinstitut Greifswald, Greifswald, Mecklenburg-Vorpommern, Germany*

[13] *University of California, Irvine, CA, United States of America*

[14] *Jožef Stefan Institute, 1000 Ljubljana, Slovenia*

Introduction

The Joint European Torus[1] (JET) carried out its second deuterium-tritium (DT) campaign (DTE2) in 2021. It was an important step on the way to develop future viable fusion reactors[2] in which the majority of the plasma heating will be due to so-called fast ions being born in fusion reactions in the plasma, a process known as plasma self-heating[3,4]. Understanding how fast ions behave and interact with the bulk plasma is therefore

---

[*] Please see the author list of [1]

paramount[5,6]. The behaviour of fast ions is governed by the fast-ion distribution. In this work, we have used neutron emission spectroscopy (NES)[7,8] measurements to tomographically reconstruct the fast-ion deuterium distribution in JET discharge 99971[9]. Deuterium neutral beam injection (NBI)[10] was injected at ~110 keV, forming a significant minority population in the plasma (~5%). The bulk plasma is tritium-rich, with a ~15% D population, as Figure 1 shows. Both the NBI and bulk D populations were accelerated by ICRF heating tuned to the fundamental D cyclotron frequency. This was on purpose to maximize fusion reactions (DT cross-section peak at ~110 keV).

This work is the first time that the fast-ion distribution has been reconstructed from experimental data in a DT discharge. It was achieved by using so-called weight functions[11-16] which can be used to linearly relate the fast-ion distribution F to the diagnostic signal S. The heating of the plasma in JET pulse 99971 is beam-target dominated[17], making analysis via weight functions suitable[12]. Furthermore, the fast-ion distribution was assumed to be spanned by a set of expansion functions based on slowing-down physics[18,19]. This has been shown to result in improved reconstructions[20,21]. The inverse problem solved in this work can be written as (a 0^{th} order Tikhonov problem)

$$A^* = \underset{A}{arg\,min} \left\| \begin{pmatrix} W\Psi \\ \lambda L_0 \end{pmatrix} A - \begin{pmatrix} S \\ 0 \end{pmatrix} \right\|_2^2$$

where A are the expansion coefficients of the slowing-down functions, W is the weight matrix[22], Ψ is a matrix with the slowing-down functions, λ is the regularization parameter and L_0 is the identity matrix. From the optimal set of expansion coefficients A^* the optimal fast-ion distribution is computed as $F^* = \Psi A^*$.

Experimental setup

In this work, experimental data was collected for 1 s between the 8.5 s and 9.5 s timepoints, as Figure 1 shows. In this work we are using neutron measurements from one diagnostic with a perpendicular LOS (KM14[23,24]) and two diagnostics with oblique LOS (KM15[23,25] and the MPRu[26]).

Results

As can be observed in Figure 2, the fast-ion distribution in JET pulse 99971 is found to be anisotropic with a bias towards positive pitches (co-going ions). This bias is by construction, since co-current NBI was used. The fast-ion distribution likely peaks in energy around $E \sim 60-70$ keV.

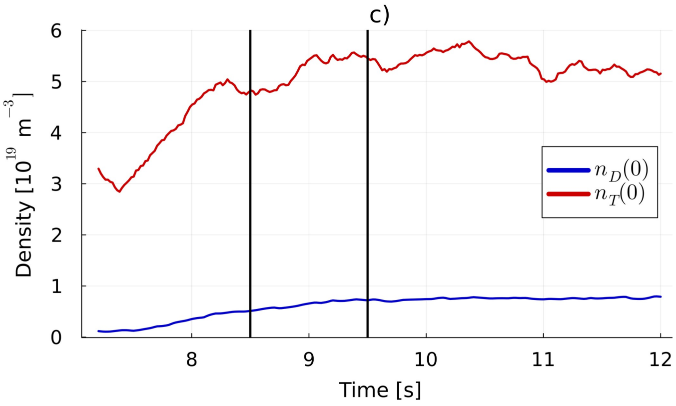

Figure 1. A plot showing the evolution of the bulk deuterium and tritium plasma densities for JET pulse 99971. The black vertical lines indicate the time window of interest for this study. The diagnostic measurements used in the reconstruction of the fast-ion distribution were collected during this time window.

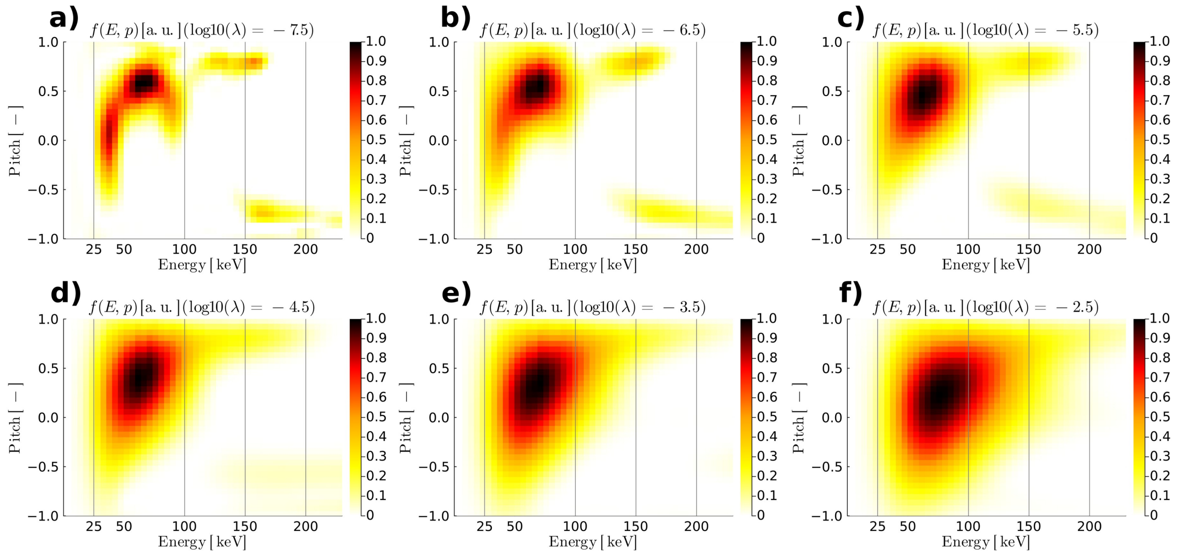

Figure 2. The reconstructed fast-ion distribution in JET pulse 99971, with varying regularization (λ).

At low levels of regularization (Figure 2a), the fast-ion distribution is plagued by artefacts and fractured. At high levels of regularization (Figure 2f), the fast-ion distribution is more coherent and the peak is predicted to be located at slightly higher energies. In addition, the bias towards positive pitches is less pronounced. At most levels of regularization, we can also observe how the fast-ion distribution seems to have a tail close to pitch values of 1.0, that goes up to energies higher than the NBI injection energy. With ICRF heating, a fast-ion population above the NBI injection energy is possible. However, the tail in the reconstructions in Figure 2 is prominent and close to pitch values of 1, characteristics not expected for a tail as a result of the employed heating scheme. This suggests the tail above the NBI injection energy in this work is more likely to be an artefact appearing due to few measurements, rather than physics.

Acknowledgements

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 *et al* 2022 Nucl. Fusion **63** 042026

[2] M Costanza *et al* 2023 Nucl. Fusion **63** 110201

[3] M Salewski *et al* 2018 Nucl. Fusion **58** 096019

[4] M Salewski *et al* 2011 Nuclear Fusion **51** 083014

[5] B Madsen *et al* 2020 Nucl. Fusion **60** 066024

[6] M Salewski *et al* 2012 Nucl. Fusion **52** 103008

[7] D Rigamonti *et al* 2024 Nucl. Fusion **63** 016016

[8] J Eriksson *et al* 2018 Plasma Phys. Control. Fusion **61** 014027

[9] M Maslov *et al* 2023 Nucl. Fusion **63** 112002

[10] D.B. King et al 2023 Nucl. Fusion **63** 112005

[11] M Salewski *et al* 2014 Plasma Phys. Control. Fusion **56** 105005

[12] E. Lerche *et al* 2023 AIP Conf. Proc. **2984** 030005

[13] M Salewski *et al* 2015 Nucl. Fusion **55** 093029

[14] A S Jacobsen *et al* 2015 Nucl. Fusion **55** 053013

[15] A S Jacobsen *et al* 2017 Rev. Sci. Instrum. **88** 073506

[16] H Järleblad *et al* 2021 Rev. Sci. Instrum. **92** 043526

[17] B Schmidt *et al* 2023 Phys. Plasmas **30** 092109

[18] J D Gaffey 1976 Journal of Plasma Physics **16** 149–169

[19] W Core 1993 Nuclear fusion **33** 829

[20] B Madsen *et al* 2020 Plasma Phys. Control. Fusion **62** 115019

[21] B Schmidt *et al* 2023 Nuclear Fusion **63** 076016

[22] H Järleblad *et al* 2022 Nucl. Fusion **62** 112005

[23] D Rigamonti *et al* 2024 Nucl. Fusion **63** 016016

[24] A Muraro *et al* 2016 Rev. Sci. Instrum. **87** 11D833

[25] C Cazzaniga *et al* 2014 Rev. Sci. Instrum. **85** 043506

[26] E Andersson Sundén *et al* 2009 Nucl. Instrum. Meth. Phys. Res. A **610** 682–699