

PAPER • OPEN ACCESS

Operation of a lithium beam diagnostic in tritium and deuterium–tritium experiments at JET




To cite this article: M Brix *et al* 2025 *Plasma Phys. Control. Fusion* **67** 015022

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

You may also like

- [Characterization and controllability of radiated power via extrinsic impurity seeding in strongly negative triangularity plasmas in DIII-D](#)
D Eldon, L Casali, I Bykov *et al*.
- [Investigation of triangularity effects on tokamak edge turbulence through multi-fidelity gyrokinetic simulations](#)
A C D Hoffmann, A Balestri and P Ricci
- [JET Active Gas Handling System—operating experience and lessons learned from recent D-T campaigns](#)
Robert George, Sarah Bickerton, Peter Cahill *et al*.

Operation of a lithium beam diagnostic in tritium and deuterium–tritium experiments at JET

M Brix^{1,*} , R Gomes^{1,2}, T Pereira^{1,2}, G Anda³, D Dunai³, I Nedzelksi², G Petravich³, D Refy³ , K Riddle¹, S Scully¹ , B Tal³, M Vécsei³, S Zoletnik³ 
and the JET Operations Team⁴

¹ UKAEA United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxon OX14 3DB, United Kingdom

² Instituto de Plasma e Fusão Nuclear, Instituto Superior Técnico, Associação EURATOM/IST, Universidade de Lisboa, 1049-001 Lisboa, Portugal

³ HUN-REN Centre for Energy Research, Budapest, Hungary Centre for Energy Research, POB 49, H-1525 Budapest, Hungary

E-mail: mathias.brix@ukaea.uk

Received 26 March 2024, revised 27 November 2024

Accepted for publication 12 December 2024

Published 24 December 2024



CrossMark

Abstract

A fast neutral lithium beam has been used at JET for more than 30 years to measure profiles of electron density in the pedestal and scrape off layer. The diagnostic was not designed for tritium operation. In this paper, we describe the modifications which were required to allow operation in tritium (T) and deuterium–tritium (D-T) fuelled pulses at JET in 2021 and 2023. Methods to allow remote startup and remote control of the beam were implemented. The vacuum pump and exhaust system had to be made tritium compatible. Radiation vulnerable electronics had to be removed from the torus hall. The observation system relied on regular in vessel mirror exchange. An in-vessel protection shield was installed close to the observation mirror to protect the mirror surface. Operation in T and D-T discharges, maintenance post tritium exposure, commissioning and the calibration of the diagnostic are discussed.

Keywords: lithium beam diagnostic, JET, tritium, deuterium–tritium plasmas, tritiated sodium

1. Introduction

Fast lithium beams have been used for plasma edge electron density diagnostics in tokamak fusion experiments for several

decades [1–7]. A lithium beam diagnostic was installed at JET more than 30 years ago [2, 3] and has been continuously upgraded and improved. Due to port restrictions on the JET tokamak, the beam source is located on top of JET, the lithium beam is injected vertically from the top into the boundary plasma (figure 1 in [2]). A periscope with an in-vessel mirror was installed in close vicinity, the measured beam emission profiles allow a reconstruction of the electron density profile in the scrape off layer and pedestal region [2–7]. Depending on the plasma shape, the location of the last closed flux surface along the Li beam can change by about 30 cm. The angle of the periscope mirror can be adjusted to match the desired observation range. Adjusting the mirror, monitoring and fine tuning of the beam properties requires an operator to supervise the diagnostic operation.

⁴ See the author list of *JET machine operations in tritium & D-T* by D B King *et al.*, to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16–21 October 2023).

* Author to whom any correspondence should be addressed.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

The observation system has in-vessel actuators and was designed to be tritium compatible. The JET lithium ion gun was not designed for tritium operation. An early exposure of the ion gun and neutralisation cell to tritium would have caused contamination on a level which would have made maintenance very hard if not impossible.

When JET was approaching the final years of operation, we investigated how we could use the diagnostic in the tritium experiments. One crucial requirement for tritium compatibility is a double-wall vacuum boundary for systems which connect to the torus vacuum. The ion gun and neutralisation cell are built from single wall vacuum components. However, the double wall rule is fulfilled because the torus isolation valve in the lithium beam line (see figure 1) can be considered as a first wall and the single wall of the vacuum components behind the torus isolation valve as the second vacuum boundary. We could therefore use the lithium beam in tritium experiments with a reasonable amount of modifications. The main modifications were:

- making the operation remote-controlled
- replacing the existing turbo pump (TP) with a tritium compatible turbo molecular pump
- connecting the TP exhaust to a tritium compatible exhaust
- removing radiation sensitive electronics from the torus hall.

2. Remote operation of the diagnostic

Diagnostic operation required frequent access to the JET diagnostic hall, where the diagnostic control cubicles are located. During T or deuterium–tritium (D-T) operation, access to the diagnostic hall was restricted hence we had to make the controls remote controllable.

We replaced in 2013 the thermionic heating element (Heatwave) with a SiC based emitter heating system (check ion source section in [8]). The new heating element offered longer lifetime of the heating element and better beam performance. The non-linear heating characteristics of the heating element required computer-controlled heating, which was implemented with a Siemens S7 programmable logic controller (PLC). The PLC controlled not only the heating of the emitter but also the heating of the sodium neutralisation cell. Furthermore, the control of the vacuum components was implemented on the PLC. The touch panel of this system was easily connected via the Siemens smart client software to a diagnostic PC, which could be reached via ethernet connections from the JET control room. A weekly timer program was included in the PLC control software to pre-program the heating waveforms. To reduce thermal stress, we ramped the emitter heating currents slowly within 30–60 min from standby or cold conditions to operation conditions (and vice versa).

The high voltage power supply settings and the voltages for the deflection plates are remote controlled via the JET control software and CAMAC modules.

Source performance and beam alignment are monitored with a beam profile monitor BPM. Details on the BPM setup

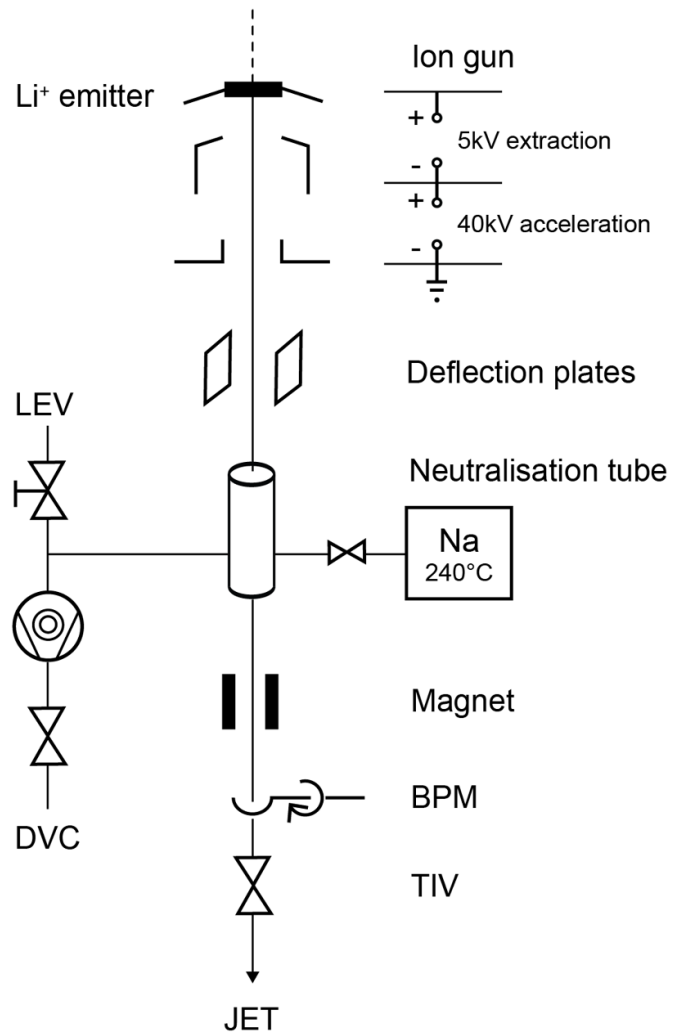


Figure 1. Schematic of the lithium beam source at JET with the ion gun, ion optics and deflection plates, the neutralisation cell with the heated sodium reservoir and heated tube, beam profile monitor BPM and torus isolation valve TIV, the tritium compatible exhaust with turbo pump and connection to the diagnostic vacuum crown DVC. Local extraction ventilation LEV has been used on the venting valve during ion gun exchange after exposure to tritium.

and measurements can be found in [9] (National Electrostatics Cooperation NEC BPM92). The BPM detector is located just above the torus isolation valve in the torus hall, a current amplifier is installed in close vicinity and the signals are relayed to the BPM control unit in the diagnostic hall. The BPM data can be displayed with an oscilloscope in the diagnostic hall. For remote access, we installed a USB oscilloscope (type Picoscope 2205 MSO) and connected it to a diagnostic PC, which could be reached via ethernet from the JET control room. Hence, ion gun operation, monitoring and optimisation could be performed from the JET control room.

3. Tritium compatible vacuum system

The vacuum system of the lithium beam diagnostic is pumped by a TP. During normal operation the pressure in the system

was typically below 10^{-6} mbar. Note that it is crucial that the pressure inside the system is below 10^{-2} mbar when the gun is heated to standby or operation conditions. Exposure to higher pressures in heated condition can destroy the ion source coating, it can create insulating coatings on the ion optics, which can impact lithium extraction, beam focussing and beam geometry. Maintenance and cleaning of contaminated components requires dismantling components, which is very restricted following exposure to tritium.

Pre tritium operation, the TP was connected to an oil sealed rotatory pump and connected to a vacuum crown, an exhaust system operating just below atmospheric pressures. For tritium operation, we had to install a tritium compatible TP (Agilent Varian TV 551 Navigator with modified control electronics for 120 m long cables between pump and control electronics and metal seal on the exhaust flange).

The TP exhaust needed to be connected to the tritium reprocessing facilities via the diagnostic vacuum crown DVC. The DVC was shared with other vacuum diagnostics, the DVC pressure was usually below 10^{-2} mbar, but can rise in planned scenarios (for maintenance) and unplanned situations (vacuum incidents) above these values. In these situations, in particular when the DVC pressure exceeds several mbar, pressure rises can occur in the high vacuum part of the lithium beam vacuum chamber—and can compromise a heated ion gun. The control software of the DVC monitored the heating status of the Li ion source and prevented disconnection of the lithium beam vacuum system from the DVC whilst the ion gun was heated. In case of a pressure surge in the torus or DVC beyond certain threshold values, the torus isolation valve and the DVC valve were automatically closed.

During the four years of operation with the DVC we observed several incidents where the DVC pressure exceeded pressures above several mbar. Fortunately, the gun was always cold during these events. To extend the lifetime of the thermionic emitter, it would have been advantageous to keep it always heated either at operation conditions or in non-operation hours at standby conditions (at less than half of the operation heating power). However, to avoid exposure to unplanned pressure surges the diagnostic was turned off when operation was not required for more than a day. A backup pumping system in case of a DVC failure would have been highly desirable for protection of the ion gun.

4. In vessel mirror

Figure 2 shows the in-vessel periscope head and observation mirror. These components are protected by limiters during normal plasma operation, nevertheless the mirror coating gets damaged [10, 11] and the mirror requires regular replacement. We reported in [11] the installation of a new periscope head. The improved design offered mainly two advantages: the drive mechanism is optimised to reduce mechanical vibration of the mirror and the mirror holder was designed to allow a replacement of the mirror via in vessel remote handling. A mirror exchange with the old periscope head required dismantling the

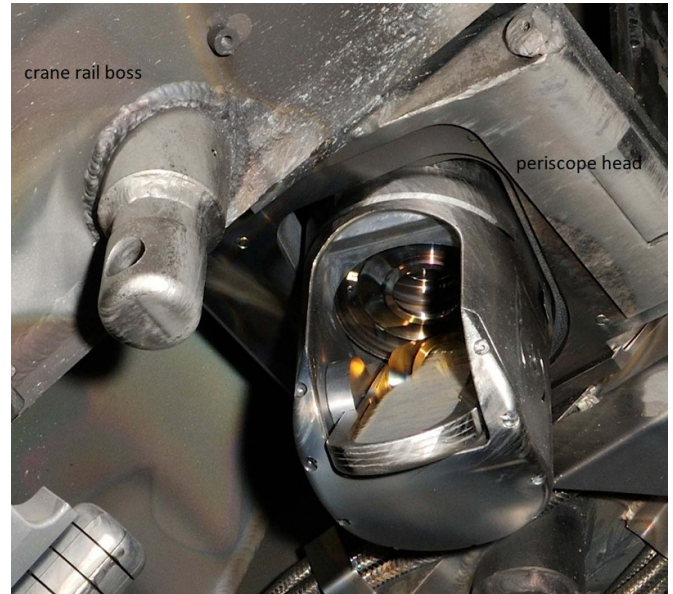


Figure 2. Periscope head with gold coated mirror and crane rail boss (on the left) in 2015 after plasma operation. The bottom right area of the gold coated mirror is grey, the coating is eroded. The top left part is undamaged, indicating that the crane rail boss created a protective shadow.

whole periscope, a major effort which required isolators for beryllium and tritium protection and the removal of the interferometer tower. With the new periscope head, we exchanged the mirror with less effort whenever we had remote access for in vessel work.

A closer look at the mirror in figure 2 suggested that a crane rail boss protected a part of the gold coating. We designed a clamp to increase the protected area on the mirror and installed this protection clamp by remote handling on the crane rail boss in 2015 (figure 3). After one year of plasma operation, the gold coating did not show any damage. This is a huge improvement, in particular, because there were no more opportunities to replace the mirror via remote handling after 2018. The pictures in figures 2 and 3 were taken by remote handling with a high-resolution camera. We hope we can inspect the mirror later this year via remote handling.

5. Removal of radiation sensitive electronics from the torus hall

The lithium beam emission is transferred via optical fibres to the diagnostic hall [2, 6, 7]. The signal is shared by a spectrometer observation system and a fast detector [7, 12]. The fast camera is based on an APD diode sensor array (Hamamatsu 4×8 element silicon diode array S8550, details are in [12], chapter IV). To improve the signal to noise level of the measurements, we replaced in 2019 the sensor array by a Multi Pixel Photo Counter MPPC array detector (Hamamatsu S13361-2050).

The fast measurement relies on fast modulation of the active beam emission signal to distinguish between beam emission



Figure 3. Mirror protection clamp installed on the crane rail boss (top left), the gold coated periscope mirror is undamaged after a year of plasma operation (picture was taken in February 2017).

and background light. The beam can be deflected out of the observation volume by changing the voltage on the deflection plates. To achieve fast modulation, a modulation box was installed in 2012 next to the ion gun in the torus hall. The box switches between typical values of 100 V in aligned and 800 V in deflection state at frequencies up to 100 kHz. The solid state fast high voltage switch (Behlke) and the control electronics were not expected to survive the radiation during D-T experiments. Therefore, prior to D-T operation, the modulation box had to be removed from the torus hall.

The old modulation box could not provide enough current to drive the capacity of the 120 m long BNC cables from the diagnostic hall towards the ion gun in the torus hall. A new modulation setup used stronger power supplies providing 120 mA current whereas the old modulation box used 10 mA power supplies. Furthermore, the new box modulated the voltages of both deflection plates whereas the old switch acted only one plate. Still, the maximum modulation frequency of the new setup with the long cables was restricted to 10 kHz. The design principle of the fast switch electronics was discussed in [13].

During D-T operation we kept the BPM current amplifier in the torus hall. The current amplifier had to remain close to the rotating wire detector because the raw signals are too weak for direct transfer to the diagnostic hall. Fortunately, the current amplifier survived the D-T experiments, and the BPM could be used until the end of the JET experiments in December 2023. Modelling of the neutron flux at the current amplifier

location with the radiation transport code MCNP [14] were performed. They indicate that the total neutron fluence during the DTE2 and DTE3 experiments is comparable to the numbers during the non D-T experiments since 2008 (when the BPM was installed).

6. Ion gun replacement post tritium

Whereas the ion gun was usually replaced every 3–6 month during operation periods, the ion optics, deflection plates and the sodium neutralisation cell required less frequent maintenance/cleaning. During the T and D-T experiments, the ion gun and neutralisation cell were operated conservatively at lower temperatures to allow a maximum of operation time without maintenance. We extracted typically 1 mA ion current and achieved about 0.7 mA of neutral current.

The lithium beam diagnostic was managed as a scarce resource to assure availability for all high priority experiments. We ran the diagnostic in both, the DTE2 experiments in 2021 and in the 2023 DTE3 experiments. Post DTE2, the ion gun performance had significantly deteriorated, hence we needed to find a safe procedure for an exchange of a tritium contaminated ion gun. Several months after the DTE2 experiments, radiation levels in the torus hall close to the ion gun were not posing any restrictions for the work, but once the diagnostic vacuum was breached, we could be exposed to tritium contaminated components and would expect a release of tritium to ambient air.

The ion gun is mounted on a small CF63 flange. With optimised planning and preparation, the vacuum breach to air did not have to last longer than a few minutes. To reduce the exposure of staff to tritium to a minimum, we pumped air through the ion gun flange into the diagnostic chamber via the venting flange, which is located close to the TP intake (figure 1). This procedure was successful. A significant amount of tritium was recorded on the exhaust system during the breach to air, but no tritium was found in the operator's breathing zone (as monitored with a real time Overhoff tritium monitor). A total of 3.5 GBq was detected on the extraction system which relates to 10% of the daily allowance on this exhaust system (1 GBq is the maximum annual allowance for a radiation worker at JET). The ion gun exchange was successful, but also demonstrated that a longer breach to air for cleaning of ion optics surfaces or replenishing the neutralisation cell with sodium would not be possible because we would have released much more tritium.

7. Commissioning the new ion gun

We are now describing pump down and commissioning following the ion gun exchange. The ion gun flange was tightened, and the system was pumped down with a leak detector through the turbopump. Leak tests were performed, no leaks were found and the turbopump exhaust was reconnected to the DVC. The TP was started, the pressure dropped

within several hours below 10^{-6} mbar. On the next day, we started baking of the ion gun and the neutralisation cell, adjusting heating currents slowly avoiding pressure rises above several 10^{-4} mbar. Then we started high voltage commissioning by testing first the HV stability of the setup with a cold ion gun (not exceeding extraction voltages of 5.5 kV and acceleration voltages of 45 kV). The HV tests were repeated with the heated ion gun, starting at lower voltages, then increasing the extraction and acceleration voltages until we extracted an ion current of about 1 mA. The ratio of extraction to acceleration voltage was adjusted to provide a narrow beam profile on the BPM, the alignment on the observation volume was done by adjusting the voltages on two pairs of deflection capacitor plates (oriented in radial and toroidal direction). With a bending magnet in the beam line below the neutralisation cell (compare with [9]), we confirmed a neutralisation efficiency of about 70%.

Both ion guns were heated to operation conditions for about 500 h. Whereas the first gun reached the end of its useful lifetime post DTE2, the second ion gun was not yet exhausted at the end of the DTE3 experiments, so operation could continue until the end of JET operations in December 2023.

8. Intensity calibration of the observation system and restrictions of lithium beam operations

The spatial calibration of the observation system is calculated from the measured Doppler shift of the beam emission [6]. Fortunately, the electron density profile reconstruction does not require an absolute calibration of the system, only a relative channel to channel intensity is required [4, 5]. The relative intensity calibration can change for many reasons:

- The mirror can take damage as shown in figure 2.
- the transmission of the fibres can change because of neutron damage.
- the alignment of beam and observation system can change for mechanical reasons (e.g. the mirror position can change during violent disruptions).
- the beam position can change. Thermal expansion of the ion gun components can change the beam position (it takes up to two hours to reach thermal equilibrium after starting heating); the extracted current and the resistance of the heating element can change during an operation day (we control the heating current only, the resistance of the heating elements can change in particular at the end of the useful lifetime of an ion gun).

It would be highly desirable to calibrate the system after each pulse by injecting the beam into a well-defined gas target. Collisions of the fast lithium beam atoms with the gas will

excite the beam, the resulting beam emission profile is providing the channel-to-channel intensity calibration for the observation system. Unfortunately, the JET plasma control and protection system prevented gas injection after pulse termination. Fortunately, the outgassing wall can provide a useful gas target after pulse termination [11]. Therefore, we injected the beam a second time for calibration purposes at the pre-programmed pulse termination time. If the pulse behaves as expected, good calibration information was found. This method can fail for several reasons:

- if the pulse is terminated too early, the torus pressure can be too low at the time of the calibration measurement and the beam emission signal will be too weak.
- rarely, the discharges were longer than the pre-programmed time. Residual electron density will dominate beam excitation and therefore void the beam into gas calibration measurement.
- In cases of disruptions with disruption mitigation valve DMV [15], the ion gun extraction voltage was turned off within milliseconds after disruption detection by the real time protection network. The plasma protection control software re-enabled lithium beam extraction only several minutes later. More importantly, the beam extraction can be impacted by the massive gas puff, for a short period the Li ion extraction was weakened, the ion gun usually recovered within one minute to normal behaviour.

Depending on the complexity of the plasma scenario, we usually got reasonable calibration information on every operation day. If this was not the case, we could perform beam into gas dry-run pulses. These were pulses without plasma which injected gas for lithium beam calibration and triggered the lithium beam injection and observation system. The disadvantage of these pulses was that they usually required 20–30 min of JET operation time, so they delayed the progress of the plasma experiments.

We restricted lithium beam operation to experiments with a reasonable chance of getting calibration information during the session. Therefore, we rarely measured in disruption mitigation, density limit or shattered pellet injection experiments SPI [16]. We always closed the observation mirror in runaway electron experiments [17] to avoid damage of the observation mirror.

9. Summary

The lithium beam diagnostic was modified to allow operation in tritium and D-T experiments. We made diagnostic operation remotely controllable, made the vacuum pump and exhaust tritium compatible and removed radiation sensitive components from the torus hall. We operated the diagnostic in tritium and D-T fuelled discharges. Maintenance of ion gun and neutralisation cell was severely restricted post tritium exposure. We

exchanged an ion gun after the first tritium operation phase in 2021 and found, as expected, very high levels of tritium. The commissioning of the new ion gun and the calibration in tritium and D-T plasmas is discussed. The mirror of the in-vessel observation periscope was successfully protected by an in-vessel protection shield allowing years of operation without exchange of the mirror. Results of the diagnostic are not reported here but in various scientific publications on the JET tritium and D-T experiments [18].

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).





Acknowledgments

The lead author acknowledges the support by many members of the JET team including Phil Morgan, David Croft, Garry Kaveney, Paddy Doyle, Joe Banks and the vacuum team, Etienne Letelliere and the Health Physics team, Colin Hogben, Alan Horton and Martin Fortune, Mikhail Maslov and Tony Turner. Rui Gomes and Tiago Pereira were supporting the lithium beam operation, maintenance and analysis as long-term secondees on site.

JET, which was previously a European facility, is now a UK facility collectively used by all European fusion laboratories under the EUROfusion consortium. It is operated by the United Kingdom Atomic Energy Authority, supported by BEIS and its European partners.

This work, which has been carried out within the framework of the Contract for the Operation of the JET Facilities up to 31 October 2021, has been funded by the Euratom Research and Training Programme. Since 31 October 2021, UKAEA has continued to work with the EUROfusion Consortium as an Associated Partner of Max-Planck-Gesellschaft zur Förderung der Wissenschaft e.V represented by Max-Planck-Institut für Plasmaphysik ('IPP') pursuant to Article 9.1 of the EUROfusion Grant Agreement for Project No. 101052200. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ORCID iDs

M Brix  <https://orcid.org/0000-0001-8219-7916>
 D Refy  <https://orcid.org/0000-0002-0846-8236>
 S Scully  <https://orcid.org/0000-0002-4060-4621>
 S Zoletnik  <https://orcid.org/0000-0002-7324-2647>

References

- [1] Zoletnik S et al 2018 *Rev. Sci. Instrum.* **89** 10D107
- [2] Pietrzyk A, Breger P and Summers D D R 1993 *Plasma Phys. Control. Fusion* **35** 1725
- [3] Breger P, Flewin C, Zastrow K-D, Davies S J, Hawkes N C, König R W T, Pietrzyk Z A, Porte L, Summers D D R and Hellermann M G V 1998 *Plasma Phys. Control. Fusion* **40** 347–59
- [4] Schweinzer J, Wolfrum E, Aumayr F, Pockl M, Winter H, Schorn R P, Hintz E and Unterreiter A 1992 *Plasma Phys. Control. Fusion* **34** 1173
- [5] Brix M et al 28th *EPS Conf. on Controlled Fusion and Plasma Physics (Madeira, Portugal, 18–22 June 2001)*
- [6] Brix M et al 2010 *Rev. Sci. Instrum.* **81** 10D733
- [7] Refy D, Brix M, Gomes R, Tál B, Zoletnik S, Dunai D, Kocsis G, Kálvin S and Szabolics T 2018 *Rev. Sci. Instrum.* **89** 043509
- [8] Anda G, Dunai D, Lampert M, Krizsanóczy T, Németh J, Bató S, Nam Y U, Hu G H and Zoletnik S 2018 *Rev. Sci. Instrum.* **89** 013503
- [9] Nedzelski I, Korotkov A, Brix M, Morgan P and Vince J 2010 *Rev. Sci. Instrum.* **81** 10D734
- [10] Garcia-Carrasco A, Petersson P, Rubel M, Widdowson A, Fortuna-Zalesna E, Jachmich S, Brix M and Marot L 2017 *Nucl. Mater. Energy* **12** 506–12
- [11] Brix M et al 2012 *Rev. Sci. Instrum.* **83** 10D533
- [12] Field A R, Dunai D, Gaffka R, Ghim Y-C, Kiss I, Mészáros B, Krizsanóczy T, Shibaev S and Zoletnik S 2012 *Rev. Sci. Instrum.* **83** 013508
- [13] Zoletnik S, Petravich G, Bencze A, Berta M, Fiedler S, McCormick K and Schweinzer J 2005 *Rev. Sci. Instrum.* **76** 073504
- [14] Werner C J et al 2017 *LANL Technical Report Request MCNP 6.2 radiation transport code user manual* (available at: <https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-17-29981>)
- [15] Reux C et al 2013 *Fusion Eng. Des.* **88** 1101–4
- [16] Jachmich S et al 2022 *Nucl. Fusion* **62** 026012
- [17] Reux C et al 2015 *Nucl. Fusion* **55** 093013
- [18] Maggi C F Overview of T and D-T results in JET with ITER-like wall *Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conf. (London, UK, 16–21 October 2023)*