



# Disruption prediction with artificial intelligence techniques in tokamak plasmas

J. Vega<sup>1</sup>✉, A. Murari<sup>2</sup>, S. Dormido-Canto<sup>3</sup>, G. A. Rattá<sup>1</sup>, M. Gelfusa<sup>4</sup> and JET Contributors\*

**In nuclear fusion reactors, plasmas are heated to very high temperatures of more than 100 million kelvin and, in so-called tokamaks, they are confined by magnetic fields in the shape of a torus. Light nuclei, such as deuterium and tritium, undergo a fusion reaction that releases energy, making fusion a promising option for a sustainable and clean energy source. Tokamak plasmas, however, are prone to disruptions as a result of a sudden collapse of the system terminating the fusion reactions. As disruptions lead to an abrupt loss of confinement, they can cause irreversible damage to present-day fusion devices and are expected to have a more devastating effect in future devices. Disruptions expected in the next-generation tokamak, ITER, for example, could cause electromagnetic forces larger than the weight of an Airbus A380. Furthermore, the thermal loads in such an event could exceed the melting threshold of the most resistant state-of-the-art materials by more than an order of magnitude. To prevent disruptions or at least mitigate their detrimental effects, empirical models obtained with artificial intelligence methods, of which an overview is given here, are commonly employed to predict their occurrence—and ideally give enough time to introduce counteracting measures.**

Tokamaks are currently the most promising configuration for a commercial fusion reactor but—contrary to stellarators—they are prone to disruptions. Because they are also very complex devices, disruptions depend on many effects as well as on nonlinear interactions between them. Pulsed tokamak experiments consist of discharges of currents of the order of millions of amperes. The normal evolution of these discharges can be suddenly interrupted by various types of instability<sup>1</sup>. Particularly frequent and dangerous are instabilities related to excessive radiation (from the visible to the X-ray region of the spectrum), too high plasma density or anomalous current profiles.

Disruptions occur in two stages, namely the thermal quench and the current quench. During the thermal quench, most of the plasma's internal energy is lost on timescales of the order of 1 ms. This thermal quench is immediately followed by the current quench, during which the plasma current is extinguished in time intervals that can last from a few to hundreds of milliseconds in present-day tokamaks. The lead-up to a disruption is typically characterized by anomalies in several diagnostic signals, such as in the electron temperature (Fig. 1). These so-called precursor signals, however, can also be present in non-disruptive plasmas, making the prediction of disruptions a complex multi-objective problem. Because the mitigation of disruptions requires immediate termination of the discharge, false alarms are costly in terms of resources, as well as risking damage to the devices. For this reason, both false positives and false negatives need to be kept to a minimum.

The accurate prediction of disruptions will be even more important for next-generation tokamaks, which will operate with metallic plasma-facing components. Metal offers several advantages. First, it can stand the loads with acceptable erosion, meaning that it has a smaller impact on the lifetime of the components facing the plasma and thus on the efficiency of the tokamak. Second, retention of plasma fuel is comparatively low. High retention, that is, the accumulation of radioactive fuel within the wall, is a safety threat

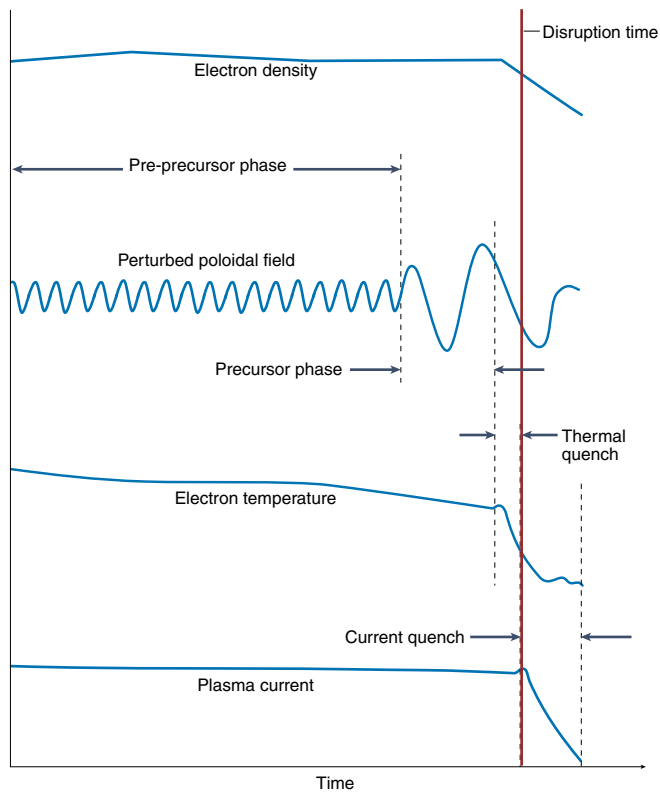
and would also affect the availability of the tokamak. However, recent experiments with metallic walls have shown that the challenge posed by disruptions is more severe for devices with metallic plasma-facing components than expected. ITER ('The Way' in Latin) requires there be less than 5% of pulses with disruptions at a maximum current of 15 MA (ref. <sup>2</sup>). Experiments on the Joint European Torus (JET) with the ITER-like wall (ILW) made of tungsten and beryllium have demonstrated that the rate of disruptions can be unacceptably high<sup>3</sup>. The rate in the so-called baseline reference scenario for ITER reached 80% on JET<sup>4</sup>, but was excessive in all devices on which the scenario was tested under reactor relevant conditions. In the hybrid reference scenario that has been developed on JET, the rate of disruptions was ~20%, which also does not meet the requirements for ITER.

In light of these recent findings, abrupt termination of discharges is a major issue for current tokamaks and disruption prediction will be a crucial real-time requirement in even larger ones. Because theoretical models are often insufficient to reliably describe disruptions, empirical models based on machine learning are a common approach for understanding and predicting disruptions.

## Models based on traditional machine learning

Disruption predictors based on machine learning are usually conceptualized as binary classifiers: the training process splits the operational space into two regions—disruptive and non-disruptive regions—and determines the boundary between. Ideally, classifications are meant to be carried out during discharges with a typical time resolution on the order of milliseconds. The signals are typically available in the form of time series, which are sequences of data points indexed in time (usually equally spaced). For disruption prediction, the signals have to be processed and then suitable predictors have to be developed. So far, the variety of existing real-time signal-processing methods implemented have explored practically all known data analysis techniques for time series in the time

<sup>1</sup>Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain. <sup>2</sup>Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Padova, Italy. <sup>3</sup>Depto. de Informática y Automática, UNED, Madrid, Spain. <sup>4</sup>Department of Industrial Engineering, University of Rome "Tor Vergata", Rome, Italy. \*A list of authors and their affiliations appears at the end of the paper. ✉e-mail: [jesus.vega@ciemat.es](mailto:jesus.vega@ciemat.es)



**Fig. 1 | Disruption precursors.** Time evolution of typical disruption precursors during normal operation and in the lead-up to a disruption. In agreement with the literature, the beginning of the current quench is considered the disruption time.

domain<sup>5–15</sup>. These techniques have been complemented with tools in the frequency domain<sup>16</sup>, based on Fourier transforms. Approaches relying on a mixture of time/frequency domains, including wavelet decompositions, have also been pursued<sup>17–19</sup>. With regard to classifier technologies, real-time compatible predictors have typically been based on artificial neural networks, support vector machines, fuzzy logic, generative topographic mapping and deep learning and have been studied on a broad range of tokamaks, including ADITYA (India)<sup>20</sup>, ASDEX Upgrade (Germany)<sup>21</sup>, DIII-D (United States)<sup>22–24</sup>, J-TEXT (China)<sup>25</sup>, NSTX (United States)<sup>26</sup>, ALCATOR C-MOD (United States)<sup>27</sup>, JT-60U (Japan)<sup>28</sup>, EAST (China)<sup>29–31</sup>, HL-2A (China)<sup>32</sup> and JET (United Kingdom)<sup>33–35</sup>.

Of the three machine-learning-based predictors that were implemented in JET's real-time network, APODIS<sup>17</sup>, SPAD<sup>36</sup> and Centroid<sup>37</sup>, the former correctly identified disruptions in more than 98% of cases and had a false alarm rate (that is, wrongly classified non-disruptive data) in fewer than 2% of cases, with an average warning time of hundreds of milliseconds.

Despite encouraging results, this disruption predictor and others based on traditional machine-learning technologies suffer from inherent fundamental limitations. First, they are not derived from first principles but are empirical. This means that their results are difficult to interpret in terms of plasma dynamics, and whether they can be extrapolated to future, larger devices<sup>38,39</sup> remains unclear. Second, traditional machine-learning predictors require very large amounts of data for the training. Given the potential damage caused by disruptions, collecting many examples is not a viable option for large-scale devices such as ITER. Finally, the predictors lack generality. Even when large datasets are available, the performance of these predictors degrades quickly when a discharge presents



**Fig. 2 | Performance of adaptive disruption predictors on JET with the ILW.** The rate of correctly identified disruptions, the so-called true positive rate, is shown in red on the left vertical axis. The right vertical axis displays the false alarms rate. The x axis reports the sequential discharge number (the database consists of ~2,500 shots). The results are based on a purely adaptive approach, where the discharges in the figure had not been used in the training of the classifier, which was retrained only when errors occurred in the predictions.

characteristics different from those in the training data. Moreover, the use of predictors is typically restricted to the specific tokamak for which they were derived and it has proven challenging to transfer machine-learning classifiers from one device to another.

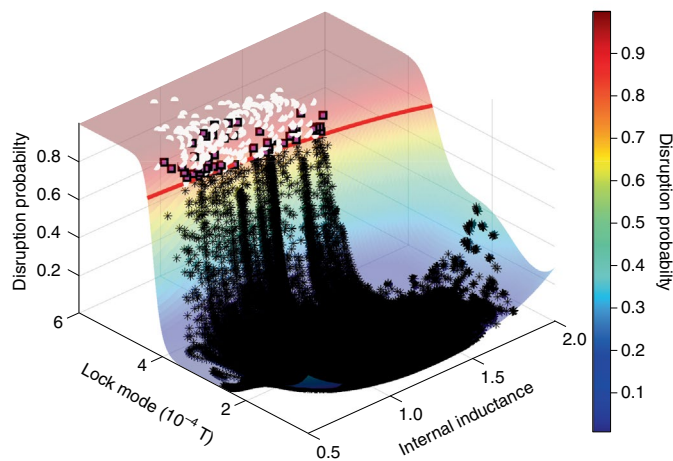
The classifiers employed in the studies on tokamaks mentioned above<sup>20–35</sup> were developed using real-time valid solutions, which guarantee response times within a specified time window. The predictors discussed in the remainder of this work have been tested offline with real-time compatible technologies and using only real-time available signals. After having been trained, these predictors can provide their output on a millisecond timescale, which is sufficiently fast not to affect the overall reaction time of the actuators for disruption mitigation and avoidance in tokamaks.

### From closed- to open-world learning

The main drawbacks of traditional machine-learning predictors can be attributed to the assumptions adopted for their training. Most examples discussed above followed a closed-world approach to learning. This means that the information required for training the classifier has to be available before the first prediction. Moreover, the performance of traditional classifiers hinges on the assumption that the data are sampled independently from an identical distribution function. This assumption, however, implies that the plasmas are stationary in the sense that their data distribution function does not change substantially because the predictors have no capability of adapting to new regimes or new physics. In practice, these assumptions are systematically violated due to the rapid evolution of experimental programmes.

This situation is particularly unsatisfactory because humans can learn from few examples, can adapt to changing situations and can also transfer knowledge from one problem to similar ones.

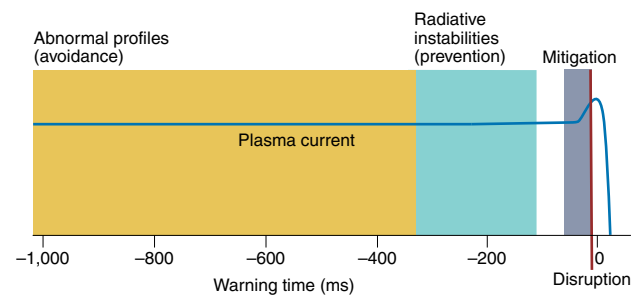
In recent years, more attention has been devoted to providing deep learning and interpretable solutions for disruption prediction across tokamaks and in particular for the next generation of devices such as ITER<sup>40</sup>. Efforts towards implementing an open-world approach to learning have also become more popular, as evidenced by a series of adaptive strategies that have been developed to maximize the performance of disruption predictors in non-stationary conditions. The



**Fig. 3 | Non-disruptive and disruptive regions of the operational space in JET.** In discharges with the ITER-like wall, non-disruptive and disruptive regions are identified. The vertical axis and the surface, depicted according to the colour code on the right, represent the posterior probability of disruption. The black asterisks show all the non-disruptive shots (ten random time slices for each shot). The white dots are the data of the disruptive shots, at the time when the predictor triggers the alarm. The black squares are the false alarms. The line separating the disruptive from the safe region of the operational space, whose equation was obtained from symbolic regression, is displayed in red. The lock mode measures the amplitude of macroscopic magnetic perturbations when they become stationary in the reference frame of the laboratory. The internal inductance refers to the plasma internal inductance as the plasma is a conductor. Figure adapted from ref. <sup>49</sup> under a Creative Commons license [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/).

training of adaptive predictors is done from scratch, meaning that only a single example of each class (discharge with or without a disruption) is needed for a prediction<sup>18,19,21,34</sup>. The predictors are updated between discharges by refining the training sets and by implementing trajectory learning during the shots. The cases causing the predictors to err still contain a lot of useful information. Retraining them with these failed examples is an effective form of adaptive learning. Because fusion plasmas exhibit memory effects, taking into account the evolution of their properties (their trajectories as opposed to values at specific times) is beneficial for improvement of the predictor performance. The most advanced versions of open-world strategies also include various forms of de-learning that allow predictors to discard or reduce the effects of training data that no longer apply.

For the JET tokamak, fully general and automatic adaptive predictors have been developed. These are based on ensemble classifiers, which consist of a high number of specific predictors, each trained on slightly different datasets<sup>41</sup>. The outputs of the individual classifiers are then evaluated with a suitable decision function to determine whether a disruption is likely to occur. The overall performance of these adaptive predictors is promising: the rate of false alarms is less than 1% and the rate of correctly identified disruptions is higher than 99%. This is shown in Fig. 2, which reports the results for thousands of discharges at the beginning of the operation of JET with the ITER-like wall to simulate the initial operation of a new device<sup>41</sup>. In this case, the first prediction of the ensemble classifier was based on a single disruptive and four non-disruptive discharges<sup>34,41</sup>. Because adaptive predictors based on open-world learning have been successfully transferred from one device to another<sup>42,43</sup>, they provide much better flexibility and generality than more traditional machine-learning techniques. Therefore, open-world learning is a very promising approach for implementation in next-generation tokamaks.



**Fig. 4 | Warning time intervals for predictors.** The predictors were optimized for avoidance, prevention and mitigation of disruptions. Avoidance actions keep the plasma within stability boundaries, prevention methods terminate the discharge in a controlled way, and mitigation techniques alleviate the consequences of unavoidable disruptions. More than 1,000 discharges of JET with the ILW were analysed. The warning times present negligible overlap, providing a clear estimate of the minimum intervals remaining to introduce remedial actions—from a minimum of 400 ms in the case of the avoidance predictor to tens of milliseconds in the case of the one for mitigation. The vertical red line indicates the disruption time, that is the beginning of the current quench, and the blue solid line represents the plasma current.

### Interpretable models with symbolic regression

The classifiers discussed above provide mathematical models, which have no relation to the actual plasma dynamics and are difficult to interpret in terms of our understanding of plasma physics. For this reason, methodologies for steering the machine-learning process toward interpretable models, reflecting the actual physics and dynamics of the phenomena involved, are under development. This is more ambitious than ‘traditional’ explainable artificial intelligence<sup>44</sup>, because the goal is to obtain mathematical equations describing the underlying physics<sup>26,45,46</sup>.

Physics interpretability of models obtained with support vector machines was achieved by applying symbolic regression methods<sup>47</sup>, which make use of genetic algorithms<sup>48</sup>. The deployment of symbolic regression allows the exploration of a large set of mathematical equations—hundreds of thousands of models—describing the boundary between non-disruptive and disruptive regions of the operational space. Each generation of models is evaluated based on a fitness function and those demonstrating better performance in terms of this metric are retained and used as starting point for the next iteration, from which new models are derived by using traditional genetic operators such as mutation, copy and cross-over.

The equation of the boundary between disruptive and non-disruptive regions in JET’s operational space, with an ITER-like wall as displayed in Fig. 3, was obtained with symbolic regression and revealed information on factors that are likely to trigger disruptions<sup>49</sup>.

### Warning time prediction

Even predictors with a good performance in terms of success and false alarm rates suffer from a major limitation: on JET, the range of their warning times can be of the order of 1 s. Thus, the control system lacks the information about the time remaining before the beginning of the current quench—it could be in a few milliseconds or in a second. Given the importance of predicting the time remaining before the occurrence of a disruption<sup>37</sup> or at least providing a robust estimate of the minimum time still available to introduce remedial actions<sup>50,51</sup>, accurate estimates of the warning time are indispensable. A recent study on JET combining support vector machines and genetic programming<sup>52</sup> allowed the integration of three classes of predictor, for the avoidance, prevention and

mitigation of disruptions. As shown in Fig. 4, the warning times of the overall system obtained with the three predictors present negligible overlap, providing a clear lower bound of the time intervals available to introduce remedial actions.

## Outlook

For the prediction of disruptions on next-generation tokamaks like ITER, these results need to be transferred to these devices. Achieving the same performance after adequate modifications of the algorithms would be a major breakthrough—even if the overall system requires large amounts of data for the training. In this regard, a coherent strategy is emerging for ITER, suggesting the deployment of adaptive predictors in the first operational stages, providing inputs to the genetic programming for the training of the integrated system that would provide accurate warning times for avoidance, prevention and mitigation of disruptions.

Apart from the prediction of disruptions in tokamaks, most of the discussed data-driven techniques are fully general and could be adapted for forecasting and understanding any form of collapse, crash and catastrophe in other fields of science. Indeed, some of these techniques are already being deployed in various disciplines ranging from earth science to epidemiology<sup>53–55</sup>.

Received: 2 June 2021; Accepted: 30 March 2022;  
Published online: 6 June 2022

## References

- Boozer, A. H. Theory of tokamak disruptions. *Phys. Plasmas* **19**, 058101 (2012).
- de Vries, P. C. et al. Requirements for triggering the ITER disruption mitigation system. *Fusion Sci. Technol.* **69**, 471–484 (2016).
- Wenninger, R. et al. Power handling and plasma protection aspects that affect the design of the DEMO divertor and first wall. In *Proc. 26th IAEA Fusion Energy Conference (FEC, 2018)*; <https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/FEC%202016/fec2016-preprints/preprint0322.pdf>
- Sozzi, C. et al. Termination of discharges in high performance scenarios in JET. In *Proc. 28th IAEA Fusion Energy Conference (FEC, 2020)*; <https://conferences.iaea.org/event/214/contributions/17328/>
- Strait, E. J. et al. Progress in disruption prevention for ITER. *Nucl. Fusion* **59**, 112012 (2019).
- Hollmann, E. M. et al. Status of research toward the ITER disruption mitigation system. *Phys. Plasmas* **22**, 021802 (2015).
- Esposito, B. et al. Disruption avoidance in the Frascati tokamak upgrade by means of magnetohydrodynamic mode stabilization using electron-cyclotron-resonance heating. *Phys. Rev. Lett.* **100**, 045006 (2008).
- Maraschek, M. et al. Path-oriented early reaction to approaching disruptions in ASDEX upgrade and TCV in view of the future needs for ITER and DEMO. *Plasma Phys. Control. Fusion* **60**, 014047 (2017).
- Baylor, L. R. et al. Disruption mitigation system developments and design for ITER. *Fusion Sci. Technol.* **68**, 211–215 (2015).
- Pautasso, G. et al. On-line prediction and mitigation of disruptions in ASDEX upgrade. *Nucl. Fusion* **42**, 100–109 (2002).
- Cannas, B., Fanni, A., Pautasso, G., Sias, G. & Sonato, P. An adaptive real-time disruption predictor for ASDEX Upgrade. *Nucl. Fusion* **50**, 075004 (2010).
- Kates-Harbeck, J., Svyatkovskiy, A. & Tang, W. Predicting disruptive instabilities in controlled fusion plasmas through deep learning. *Nature* **568**, 526–531 (2019).
- Churchill, R. M. et al. Deep convolutional neural networks for multi-scale time-series classification and application to tokamak disruption prediction using raw, high temporal resolution diagnostic data. *Phys. Plasmas* **27**, 062510 (2020).
- Akçay, Cihan et al. Machine learning methods for probabilistic locked-mode predictors in tokamak plasmas. *Phys. Plasmas* **28**, 082106 (2021).
- Ferreira, D. R., Carvalho, P. J. & Fernandes, H. Deep learning for plasma tomography and disruption prediction from bolometer data. *IEEE Trans. Plasma Sci.* **48**, 36–45 (2019).
- Rattá, G. A. et al. An advanced disruption predictor for JET tested in a simulated real-time environment. *Nucl. Fusion* **50**, 025005 (2010).
- Vega, J. et al. Results of the JET real-time disruption predictor in the ITER-like wall campaigns. *Fusion Eng. Des.* **88**, 1228–1231 (2013).
- Dormido-Canto, S. et al. Development of an efficient real-time disruption predictor from scratch on JET and implications for ITER. *Nucl. Fusion* **53**, 113001 (2013).
- Vega, J. et al. Adaptive high learning rate probabilistic disruption predictors from scratch for the next generation of tokamaks. *Nucl. Fusion* **54**, 123001 (2014).
- Agarwal, A. et al. Deep sequence to sequence learning-based prediction of major disruptions in ADITYA tokamak. *Plasma Phys. Control. Fusion* **63**, 115004 (2021).
- Zhang, Y., Pautasso, G., Kardaun, O., Tardini, G. & Zhang, X. D. Prediction of disruptions on ASDEX Upgrade using discriminant analysis. *Nucl. Fusion* **51**, 063039 (2011).
- Rea, C. et al. Disruption prediction investigations using machine learning tools on DIII-D and Alcator C-Mod. *Plasma Phys. Control. Fusion* **60**, 084004 (2018).
- Rea, C., Montes, K. J., Erickson, K. G., Granetz, R. S. & Tinguely, R. A. A real-time machine learning-based disruption predictor in DIII-D. *Nucl. Fusion* **59**, 096016 (2019).
- Rea, C. & Granetz, R. S. Exploratory machine learning studies for disruption prediction using large databases on DIII-D. *Fusion Sci. Technol.* **74**, 89–100 (2018).
- Zheng, W. et al. Disruption predictor based on neural network and anomaly detection on J-TEXT. *Plasma Phys. Control. Fusion* **62**, 045012 (2020).
- Gerhardt, S. P. et al. Detection of disruptions in the high- $\beta$  spherical torus NSTX. *Nucl. Fusion* **53**, 063021 (2013).
- Montes, K. J. et al. Machine learning for disruption warnings on Alcator C-Mod, DIII-D and EAST. *Nucl. Fusion* **59**, 096015 (2019).
- Yokoyama, T. et al. Likelihood identification of high- $\beta$  disruption in JT-60U. *Plasma Fusion Res.* **16**, 1402073 (2021).
- Guo, B. H. et al. Disruption prediction on EAST tokamak using a deep learning algorithm. *Plasma Phys. Control. Fusion* **63**, 115007 (2021).
- Guo, B. H. et al. Disruption prediction using a full convolutional neural network on EAST. *Plasma Phys. Control. Fusion* **63**, 025008 (2020).
- Hu, W. H. et al. Real-time prediction of high-density EAST disruptions using random forest. *Nucl. Fusion* **61**, 066034 (2021).
- Zhong, Y. et al. Disruption prediction and model analysis using LightGBM on J-TEXT and HL-2A. *Plasma Phys. Control. Fusion* **63**, 075008 (2021).
- Moreno, R. et al. Robustness and increased time resolution of JET Advanced Predictor of Disruptions. *Plasma Phys. Control. Fusion* **56**, 114003 (2014).
- Murari, A. et al. Adaptive predictors based on probabilistic SVM for real-time disruption mitigation on JET. *Nucl. Fusion* **58**, 056002 (2018).
- López, J. M. et al. Implementation of the disruption predictor APODIS in JET's real-time network using the MARTe framework. *IEEE Trans. Nucl. Sci.* **61**, 741–744 (2014).
- Esquembrí, S. et al. Real-time implementation in JET of the SPAD disruption predictor using MARTe. *IEEE Trans. Nucl. Sci.* **65**, 836–842 (2018).
- Vega, J. et al. A linear equation based on signal increments to predict disruptive behaviours and the time to disruption on JET. *Nucl. Fusion* **60**, 026001 (2019).
- Rea, C. et al. Progress toward interpretable machine learning-based disruption predictors across tokamaks. *Fusion Sci. Technol.* **76**, 912–924 (2020).
- Zhu, J. X. et al. Hybrid deep-learning architecture for general disruption prediction across multiple tokamaks. *Nucl. Fusion* **61**, 026007 (2020).
- Zhu, J. et al. Scenario adaptive disruption prediction study for next generation burning-plasma tokamaks. *Nucl. Fusion* **61**, 114005 (2021).
- Murari, A., Lungaroni, M., Gelfusa, M., Peluso, E. & Vega, J. JET Contributors Adaptive learning for disruption prediction in non-stationary conditions. *Nucl. Fusion* **59**, 086037 (2019).
- Murari, A. et al. On the transfer of adaptive predictors between different devices for both mitigation and prevention of disruptions. *Nucl. Fusion* **60**, 056003 (2020).
- Murari, A., Rossi, R., Lungaroni, M., Baruzzo, M. & Gelfusa, M. Stacking of predictors for the automatic classification of disruption types to optimize the control logic. *Nucl. Fusion* **61**, 036027 (2021).
- Gunning, D. et al. XAI-explainable artificial intelligence. *Sci. Robot.* **4**, eaay7120 (2019).
- Yokoyama, T. et al. Prediction of high-beta disruptions in JT-60U based on sparse modeling using exhaustive search. *Fusion Eng. Des.* **140**, 67–80 (2019).
- Piccione, A. et al. Physics-guided machine learning approaches to predict the ideal stability properties of fusion plasmas. *Nucl. Fusion* **60**, 046033 (2020).
- Li, H. X., Yang, J. L., Zhang, G. & Fan, B. Probabilistic support vector machines for classification of noise affected data. *Inf. Sci.* **221**, 60–71 (2013).
- Rattá, G. A., Vega, J. & Murari, A., JET-EFDA Contributors. Improved feature selection based on genetic algorithms for real-time disruption prediction on JET. *Fusion Eng. Des.* **87**, 1670–1678 (2012).
- Murari, A. et al. Investigating the physics of tokamak global stability with interpretable machine learning tools. *Appl. Sci.* **10**, 6683 (2020).
- Fu, Y. et al. Machine learning control for disruption and tearing mode avoidance. *Phys. Plasmas* **27**, 022501 (2020).
- Boyer, M. D., Rea, C. & Clement, M. D. Toward active disruption avoidance via real-time estimation of the safe operating region and disruption proximity in tokamaks. *Nucl. Fusion* **62**, 026005 (2021).

52. Rattá, G. A., Vega, J., Murari, A. & Gadariya, D., JET Contributors. PHAD: a phase-oriented disruption prediction strategy for avoidance, prevention and mitigation in JET. *Nucl. Fusion* **61**, 116055 (2021).
53. Rossi, R., Gelfusa, M., Malizia, A. & Gaudio, P. Adaptive quasi-unsupervised detection of smoke plume by LIDAR. *Sensors* **20**, 6602 (2020).
54. Murari, A., Peluso, E., Gelfusa, M., Lungaroni, M. & Gaudio, P. How to handle error bars in symbolic regression for data mining in scientific applications. In *Proc. Third International Symposium on Statistical Learning and Data Sciences, Statistical Learning and Data Sciences. SLDS 2015. Lecture Notes in Computer Science* Vol. 9047 (eds Gammerman, A. et al.) 347–355 (Springer, 2015).
55. Gelfusa, M. et al. UMEL: a new regression tool to identify measurement peaks in LIDAR/DIAL systems for environmental physics applications. *Rev. Sci. Instrum.* **85**, 063112 (2014).

### Acknowledgements

This work was partially funded by the Spanish Ministry of Science and Innovation under projects nos. PID2019-108377RB-C31 and PID2019-108377RB-C32. 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 authors 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.

### Competing interests

The authors declare no competing interests.

### Additional information

Correspondence should be addressed to J. Vega.

Peer review information *Nature Physics* thanks Cristina Rea and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© Springer Nature Limited 2022

### JET Contributors

J. Mailloux<sup>5</sup>, N. Abid<sup>5</sup>, K. Abraham<sup>5</sup>, P. Abreu<sup>6</sup>, O. Adabonyan<sup>5</sup>, P. Adrich<sup>7</sup>, V. Afanasev<sup>8</sup>, M. Afzal<sup>5</sup>, T. Ahlgren<sup>9</sup>, L. Aho-Mantila<sup>10</sup>, N. Aiba<sup>11</sup>, M. Airila<sup>10</sup>, M. Akhtar<sup>5</sup>, R. Albanese<sup>12</sup>, M. Alderson-Martin<sup>5</sup>, D. Alegre<sup>13</sup>, S. Aleiferis<sup>14</sup>, A. Aleksa<sup>5</sup>, A. G. Alekseev<sup>15</sup>, E. Alessi<sup>16</sup>, P. Aleynikov<sup>17</sup>, J. Alguacil<sup>18</sup>, M. Ali<sup>5</sup>, M. Allinson<sup>5</sup>, B. Alper<sup>5</sup>, E. Alves<sup>6</sup>, G. Ambrosino<sup>12</sup>, R. Ambrosino<sup>12</sup>, V. Amosov<sup>19</sup>, E. Andersson Sundén<sup>20</sup>, P. Andrew<sup>17</sup>, B. M. Angelini<sup>21</sup>, C. Angioni<sup>22</sup>, I. Antoniou<sup>5</sup>, L. C. Appel<sup>5</sup>, C. Appelbee<sup>5</sup>, S. Aria<sup>5</sup>, M. Ariola<sup>12</sup>, G. Artaserse<sup>21</sup>, W. Arter<sup>5</sup>, V. Artigues<sup>22</sup>, N. Asakura<sup>11</sup>, A. Ash<sup>5</sup>, N. Ashikawa<sup>23</sup>, V. Aslanyan<sup>24</sup>, M. Astrain<sup>25</sup>, O. Asztalos<sup>26</sup>, D. Auld<sup>5</sup>, F. Auremma<sup>27</sup>, Y. Austin<sup>5</sup>, L. Avotina<sup>28</sup>, E. Aymerich<sup>29</sup>, A. Baciero<sup>13</sup>, F. Bairaktaris<sup>30</sup>, J. Balbin<sup>31</sup>, L. Balbinot<sup>27</sup>, I. Balboa<sup>5</sup>, M. Balden<sup>32</sup>, C. Balshaw<sup>5</sup>, N. Balshaw<sup>5</sup>, V. K. Bandaru<sup>22</sup>, J. Banks<sup>5</sup>, Yu. F. Baranov<sup>5</sup>, C. Barcellona<sup>33</sup>, A. Barnard<sup>5</sup>, M. Barnard<sup>5</sup>, R. Barnsley<sup>17</sup>, A. Barth<sup>5</sup>, M. Baruzzo<sup>21</sup>, S. Barwell<sup>5</sup>, M. Bassan<sup>17</sup>, A. Batista<sup>6</sup>, P. Batistoni<sup>21</sup>, L. Baumane<sup>28</sup>, B. Bauvir<sup>17</sup>, L. Baylor<sup>34</sup>, P. S. Beaumont<sup>5</sup>, D. Beckett<sup>5</sup>, A. Begolli<sup>5</sup>, M. Beidler<sup>34</sup>, N. Bekris<sup>35,36</sup>, M. Beldishevski<sup>5</sup>, E. Belli<sup>37</sup>, F. Belli<sup>21</sup>, É. Belonohy<sup>5</sup>, M. Ben Yaala<sup>38</sup>, J. Benayas<sup>5</sup>, J. Bentley<sup>5</sup>, H. Bergsaker<sup>39</sup>, J. Bernardo<sup>6</sup>, M. Bernert<sup>22</sup>, M. Berry<sup>5</sup>, L. Bertalot<sup>17</sup>, H. Betar<sup>40</sup>, M. Beurskens<sup>41</sup>, S. Bickerton<sup>5</sup>, B. Bieg<sup>42</sup>, J. Bielecki<sup>43</sup>, A. Bierwage<sup>11</sup>, T. Biewer<sup>34</sup>, R. Bilato<sup>22</sup>, P. Bílková<sup>44</sup>, G. Birkenmeier<sup>22</sup>, H. Bishop<sup>5</sup>, J. P. S. Bizarro<sup>6</sup>, J. Blackburn<sup>5</sup>, P. Blanchard<sup>45</sup>, P. Blatchford<sup>5</sup>, V. Bobkov<sup>22</sup>, A. Boboc<sup>5</sup>, P. Bohm<sup>44</sup>, T. Bohm<sup>46</sup>, I. Bolshakova<sup>47</sup>, T. Bolzonella<sup>27</sup>, N. Bonanomi<sup>22</sup>, D. Bonfiglio<sup>27</sup>, X. Bonnin<sup>17</sup>, P. Bonfiglio<sup>48</sup>, S. Boocock<sup>5</sup>, A. Booth<sup>5</sup>, J. Booth<sup>5</sup>, D. Borba<sup>6,35</sup>, D. Borodin<sup>49</sup>, I. Borodkina<sup>44,49</sup>, C. Boulbe<sup>50</sup>, C. Bourdelle<sup>31</sup>, M. Bowden<sup>5</sup>, K. Boyd<sup>5</sup>, I. Božičević Mihalić<sup>51</sup>, S. C. Bradnam<sup>5</sup>, V. Braic<sup>52</sup>, L. Brandt<sup>53</sup>, R. Bravanec<sup>54</sup>, B. Breizman<sup>55</sup>, A. Brett<sup>5</sup>, S. Brezinsek<sup>49</sup>, M. Brix<sup>5</sup>, K. Bromley<sup>5</sup>, B. Brown<sup>5</sup>, D. Brunetti<sup>5,16</sup>, R. Buckingham<sup>5</sup>, M. Buckley<sup>5</sup>, R. Budny, J. Buermans<sup>32</sup>, H. Bufferand<sup>31</sup>, P. Buratti<sup>21</sup>, A. Burgess<sup>5</sup>, A. Buscarino<sup>33</sup>, A. Busse<sup>5</sup>, D. Butcher<sup>5</sup>, E. de la Cal<sup>13</sup>, G. Calabro<sup>56</sup>, L. Calacci<sup>57</sup>, R. Calado<sup>6</sup>, Y. Camenen<sup>31</sup>, G. Canal<sup>58</sup>, B. Cannas<sup>29</sup>, M. Cappelli<sup>21</sup>, S. Carcangiu<sup>29</sup>, P. Card<sup>5</sup>, A. Cardinali<sup>21</sup>, P. Carman<sup>5</sup>, D. Carnevale<sup>57</sup>, M. Carr<sup>5</sup>, D. Carralero<sup>13</sup>, L. Carraro<sup>27</sup>, I. S. Carvalho<sup>6</sup>, P. Carvalho<sup>6</sup>, I. Casiraghi<sup>59</sup>, F. J. Casson<sup>5</sup>, C. Castaldo<sup>21</sup>, J. P. Catalan<sup>18</sup>, N. Catarino<sup>6</sup>, F. Causa<sup>16</sup>, M. Cavedon<sup>22</sup>, M. Cecconello<sup>20</sup>, C. D. Challis<sup>5</sup>, B. Chamberlain<sup>5</sup>, C. S. Chang<sup>48</sup>, A. Chankin<sup>22</sup>, B. Chapman<sup>5,60</sup>, M. Chernyshova<sup>61</sup>, A. Chiariello<sup>12</sup>, P. Chmielewski<sup>61</sup>, A. Chomiczewska<sup>61</sup>, L. Chone<sup>62</sup>, G. Ciraolo<sup>31</sup>, D. Ciric<sup>5</sup>, J. Citrin<sup>63</sup>, t. Ciupinski<sup>64</sup>, M. Clark<sup>5</sup>, R. Clarkson<sup>5</sup>, C. Clements<sup>5</sup>, M. Cleverly<sup>5</sup>, J. P. Coad<sup>5</sup>, P. Coates<sup>5</sup>, A. Cobalt<sup>5</sup>, V. Coccoresse<sup>12</sup>, R. Coelho<sup>6</sup>, J. W. Coenen<sup>49</sup>, I. H. Coffey<sup>65</sup>, A. Colangeli<sup>21</sup>,

L. Colas<sup>31</sup>, C. Collins<sup>34</sup>, J. Collins<sup>5</sup>, S. Collins<sup>5</sup>, D. Conka<sup>28</sup>, S. Conroy<sup>20</sup>, B. Conway<sup>5</sup>, N. J. Conway<sup>5</sup>, D. Coombs<sup>5</sup>, P. Cooper<sup>5</sup>, S. Cooper<sup>5</sup>, C. Corradino<sup>33</sup>, G. Corrigan<sup>5</sup>, D. Coster<sup>22</sup>, P. Cox<sup>5</sup>, T. Craciunescu<sup>66</sup>, S. Cramp<sup>5</sup>, C. Crapper<sup>5</sup>, D. Craven<sup>5</sup>, R. Craven<sup>5</sup>, M. Crialesi Esposito<sup>53</sup>, G. Croci<sup>59</sup>, D. Croft<sup>5</sup>, A. Croitoru<sup>66</sup>, K. Cromb <sup>32,67</sup>, T. Cronin<sup>5</sup>, N. Cruz<sup>6</sup>, C. Crystal<sup>37</sup>, G. Cseh<sup>26</sup>, A. Cufar<sup>68</sup>, A. Cullen<sup>5</sup>, M. Curuia<sup>69</sup>, T. Czarski<sup>61</sup>, H. Dabirikhah<sup>5</sup>, A. Dal Molin<sup>59</sup>, E. Dale<sup>5</sup>, P. Dalglish<sup>5</sup>, S. Dalley<sup>5</sup>, J. Dankowski<sup>36</sup>, P. David<sup>22</sup>, A. Davies<sup>5</sup>, S. Davies<sup>5</sup>, G. Davis<sup>5</sup>, K. Dawson<sup>5</sup>, S. Dawson<sup>5</sup>, I. E. Day<sup>5</sup>, M. De Bock<sup>17</sup>, G. De Temmerman<sup>17</sup>, G. De Tommasi<sup>12</sup>, K. Deakin<sup>5</sup>, J. Deane<sup>5</sup>, R. Dejarnac<sup>44</sup>, D. Del Sarto<sup>40</sup>, E. Delabie<sup>34</sup>, D. Del-Castillo-Negrete<sup>34</sup>, A. Dempsey<sup>70</sup>, R. O. Dendy<sup>5,60</sup>, P. Devynck<sup>31</sup>, A. Di Siena<sup>22</sup>, C. Di Troia<sup>21</sup>, T. Dickson<sup>5</sup>, P. Dinca<sup>66</sup>, T. Dittmar<sup>49</sup>, J. Dobrashian<sup>5</sup>, R. P. Doerner<sup>71</sup>, A. J. H. Donn <sup>72</sup>, S. Dorling<sup>5</sup>, S. Dormido-Canto<sup>73</sup>, D. Douai<sup>31</sup>, S. Dowson<sup>5</sup>, R. Doyle<sup>70</sup>, M. Dreval<sup>74</sup>, P. Drewelow<sup>41</sup>, P. Drews<sup>49</sup>, G. Drummond<sup>5</sup>, Ph. Duckworth<sup>17</sup>, H. Dudding<sup>5,75</sup>, R. Dumont<sup>31</sup>, P. Dumortier<sup>32</sup>, D. Dunai<sup>26</sup>, T. Dunatov<sup>51</sup>, M. Dunne<sup>22</sup>, I. Duran<sup>44</sup>, F. Durodi <sup>32</sup>, R. Dux<sup>22</sup>, A. Dvornova<sup>31</sup>, R. Eastham<sup>5</sup>, J. Edwards<sup>5</sup>, Th. Eich<sup>22</sup>, A. Eichorn<sup>5</sup>, N. Eidietis<sup>37</sup>, A. Eksaeva<sup>49</sup>, H. El Haroun<sup>5</sup>, G. Ellwood<sup>17</sup>, C. Elsmore<sup>5</sup>, O. Embres<sup>76</sup>, S. Emery<sup>5</sup>, G. Ericsson<sup>20</sup>, B. Eriksson<sup>20</sup>, F. Eriksson<sup>77</sup>, J. Eriksson<sup>20</sup>, L. G. Eriksson<sup>78</sup>, S. Ertmer<sup>49</sup>, S. Esquembr <sup>25</sup>, A. L. Esquisabel<sup>79</sup>, T. Estrada<sup>13</sup>, G. Evans<sup>5</sup>, S. Evans<sup>5</sup>, E. Fable<sup>22</sup>, D. Fagan<sup>5</sup>, M. Faitsch<sup>22</sup>, M. Falessi<sup>21</sup>, A. Fanni<sup>29</sup>, A. Farahani<sup>5</sup>, I. Farquhar<sup>5</sup>, A. Fasoli<sup>45</sup>, B. Faugeras<sup>50</sup>, S. Fazini <sup>51</sup>, F. Felici<sup>45</sup>, R. Felton<sup>5</sup>, A. Fernandes<sup>6</sup>, H. Fernandes<sup>6</sup>, J. Ferrand<sup>5</sup>, D. R. Ferreira<sup>6</sup>, J. Ferreira<sup>6</sup>, G. Ferro<sup>57</sup>, J. Fessey<sup>5</sup>, O. Ficker<sup>44</sup>, A. R. Field<sup>5</sup>, A. Figueiredo<sup>6</sup>, J. Figueiredo<sup>6,35</sup>, A. Fil<sup>5</sup>, N. Fil<sup>5,24</sup>, P. Finburg<sup>5</sup>, D. Fiorucci<sup>27</sup>, U. Fischer<sup>36</sup>, G. Fishpool<sup>5</sup>, L. Fittill<sup>5</sup>, M. Fitzgerald<sup>5</sup>, D. Flammini<sup>21</sup>, J. Flanagan<sup>5</sup>, K. Flinders<sup>5</sup>, S. Foley<sup>5</sup>, N. Fomesu<sup>21</sup>, M. Fontana<sup>45</sup>, J. M. Fontdecaba<sup>13</sup>, S. Forbes<sup>5</sup>, A. Formisano<sup>12</sup>, T. Fornal<sup>61</sup>, L. Fortuna<sup>33</sup>, E. Fortuna-Zalesna<sup>64</sup>, M. Fortune<sup>5</sup>, C. Fowler<sup>5</sup>, E. Fransson<sup>77</sup>, L. Frassinetti<sup>39</sup>, M. Freisinger<sup>49</sup>, R. Fresa<sup>12</sup>, R. Fridstrom<sup>39</sup>, D. Frigione<sup>57</sup>, T. F <sup>76</sup>, M. Furseman<sup>5</sup>, V. Fusco<sup>21</sup>, S. Futatani<sup>80</sup>, D. Gadariya<sup>13</sup>, K. G <sup>72</sup>, D. Galassi<sup>45</sup>, K. Gaf zka<sup>61</sup>, S. Galeani<sup>57</sup>, D. Gallart<sup>81</sup>, R. Galvao<sup>58</sup>, Y. Gao<sup>49</sup>, J. Garcia<sup>31</sup>, M. Garc a-Mu oz<sup>82</sup>, M. Gardener<sup>5</sup>, L. Garzotti<sup>5</sup>, J. Gaspar<sup>83</sup>, R. Gatto<sup>84</sup>, P. Gaudio<sup>57</sup>, D. Gear<sup>5</sup>, T. Gebhart<sup>34</sup>, S. Gee<sup>5</sup>, M. Gelfusa<sup>57</sup>, R. George<sup>5</sup>, S. N. Gerasimov<sup>5</sup>, G. Gervasini<sup>16</sup>, M. Gethins<sup>5</sup>, Z. Ghani<sup>5</sup>, M. Gherendi<sup>66</sup>, F. Ghezzi<sup>16</sup>, J. C. Giacalone<sup>31</sup>, L. Giacomelli<sup>16</sup>, G. Giacometti<sup>85</sup>, C. Gibson<sup>5</sup>, K. J. Gibson<sup>75</sup>, L. Gil<sup>6</sup>, A. Gillgren<sup>77</sup>, D. Gin<sup>8</sup>, E. Giovannozzi<sup>21</sup>, C. Giroud<sup>5</sup>, R. Glen<sup>5</sup>, S. Gloggl <sup>22</sup>, J. Goff<sup>5</sup>, P. Gohil<sup>37</sup>, V. Goloborodko<sup>86</sup>, R. Gomes<sup>6</sup>, B. Gon alves<sup>6</sup>, M. Goniche<sup>31</sup>, A. Goodyear<sup>5</sup>, S. Gore<sup>5</sup>, G. Gorini<sup>59</sup>, T. Gorler<sup>22</sup>, N. Gotts<sup>5</sup>, R. Goulding<sup>48</sup>, E. Gow<sup>5</sup>, B. Graham<sup>5</sup>, J. P. Graves<sup>45</sup>, H. Greuner<sup>22</sup>, B. Grierson<sup>48</sup>, J. Griffiths<sup>5</sup>, S. Griph<sup>5</sup>, D. Grist<sup>5</sup>, W. Gromelski<sup>61</sup>, M. Groth<sup>62</sup>, R. Grove<sup>34</sup>, M. Gruca<sup>61</sup>, D. Guard<sup>5</sup>, N. Gupta<sup>5</sup>, C. Gurl<sup>5</sup>, A. Gusarov<sup>87</sup>, L. Hackett<sup>5</sup>, S. Hacquin<sup>31,35</sup>, R. Hager<sup>48</sup>, L. Hagg<sup>20</sup>, A. Hakola<sup>10</sup>, M. Halitovs<sup>28</sup>, S. Hall<sup>5</sup>, S. A. Hall<sup>5</sup>, S. Hallworth-Cook<sup>5</sup>, C. J. Ham<sup>5</sup>, D. Hamaguchi<sup>11</sup>, M. Hamed<sup>31</sup>, C. Hamlyn-Harris<sup>5</sup>, K. Hammond<sup>5</sup>, E. Harford<sup>5</sup>, J. R. Harrison<sup>5</sup>, D. Harting<sup>5</sup>, Y. Hatano<sup>88</sup>, D. R. Hatch<sup>55</sup>, T. Haupt<sup>5</sup>, J. Hawes<sup>5</sup>, N. C. Hawkes<sup>5</sup>, J. Hawkins<sup>5</sup>, T. Hayashi<sup>11</sup>, S. Hazael<sup>5</sup>, S. Hazel<sup>5</sup>, P. Heesterman<sup>5</sup>, B. Heidbrink<sup>89</sup>, W. Helou<sup>17</sup>, O. Hemming<sup>5</sup>, S. S. Henderson<sup>5</sup>, R. B. Henriques<sup>6</sup>, D. Hepple<sup>5</sup>, J. Herfindal<sup>34</sup>, G. Hermon<sup>5</sup>, J. Hill<sup>5</sup>, J. C. Hillesheim<sup>5</sup>, K. Hizanidis<sup>30</sup>, A. Hjalmarsson<sup>20</sup>, A. Ho<sup>63</sup>, J. Hobirk<sup>22</sup>, O. Hoenen<sup>17</sup>, C. Hogben<sup>5</sup>, A. Hollingsworth<sup>5</sup>, S. Hollis<sup>5</sup>, E. Hollmann<sup>71</sup>, M. Holz<sup>22</sup>, B. Homan<sup>50</sup>, M. Hook<sup>5</sup>, D. Hopley<sup>5</sup>, J. Hor ek<sup>44</sup>, D. Horsley<sup>5</sup>, N. Horsten<sup>62</sup>, A. Horton<sup>5</sup>, L. D. Horton<sup>35,45</sup>, L. Horvath<sup>5,75</sup>, S. Hotchin<sup>5</sup>, R. Howell<sup>5</sup>, Z. Hu<sup>59</sup>, A. Huber<sup>49</sup>, V. Huber<sup>49</sup>, T. Huddleston<sup>5</sup>, G. T. A. Huijsmans<sup>17</sup>, P. Huynh<sup>31</sup>, A. Hynes<sup>5</sup>, M. Iliasova<sup>8</sup>, D. Imrie<sup>5</sup>, M. Imr sek<sup>44</sup>, J. Ingleby<sup>5</sup>, P. Innocente<sup>27</sup>, K. Insulander Bj rk<sup>76</sup>, N. Isernia<sup>12</sup>, I. Ivanova-Stanik<sup>61</sup>, E. Ivings<sup>5</sup>, S. Jablonski<sup>61</sup>, S. Jachmich<sup>17,32,35</sup>, T. Jackson<sup>5</sup>, P. Jacquet<sup>5</sup>, H. J rleblad<sup>90</sup>, F. Jaulmes<sup>44</sup>, J. Jenaro Rodriguez<sup>5</sup>, I. Jepu<sup>66</sup>,

E. Joffrin<sup>31</sup>, R. Johnson<sup>5</sup>, T. Johnson<sup>39</sup>, J. Johnston<sup>5</sup>, C. Jones<sup>5</sup>, G. Jones<sup>5</sup>, L. Jones<sup>5</sup>, N. Jones<sup>5</sup>, T. Jones<sup>5</sup>, A. Joyce<sup>5</sup>, R. Juarez<sup>18</sup>, M. Juvonen<sup>5</sup>, P. Kalnina<sup>28</sup>, T. Kaltiaisenaho<sup>10</sup>, J. Kaniewski<sup>5</sup>, A. Kantor<sup>5</sup>, A. Kappatou<sup>22</sup>, J. Karhunen<sup>9</sup>, D. Karkinsky<sup>5</sup>, Yu Kashchuk<sup>91</sup>, M. Kaufman<sup>34</sup>, G. Kaveney<sup>5</sup>, Y. E. O. Kazakov<sup>32</sup>, V. Kazantzidis<sup>30</sup>, D. L. Keeling<sup>5</sup>, R. Kelly<sup>5</sup>, M. Kempenaars<sup>17</sup>, C. Kennedy<sup>5</sup>, D. Kennedy<sup>5</sup>, J. Kent<sup>5</sup>, K. Khan<sup>5</sup>, E. Khilkevich<sup>8</sup>, C. Kiefer<sup>22</sup>, J. Kilpeläinen<sup>62</sup>, C. Kim<sup>37</sup>, Hyun-Tae Kim<sup>5,35</sup>, S. H. Kim<sup>17</sup>, D. B. King<sup>5</sup>, R. King<sup>5</sup>, D. Kinna<sup>5</sup>, V. G. Kiptily<sup>5</sup>, A. Kirjasuo<sup>10</sup>, K. K. Kirov<sup>5</sup>, A. Kirschner<sup>49</sup>, T. Kiviniemi<sup>62</sup>, G. Kizane<sup>28</sup>, M. Klas<sup>92</sup>, C. Klepper<sup>34</sup>, A. Klix<sup>36</sup>, G. Kneale<sup>5</sup>, M. Knight<sup>5</sup>, P. Knight<sup>5</sup>, R. Knights<sup>5</sup>, S. Knipe<sup>5</sup>, M. Knolker<sup>37</sup>, S. Knott<sup>93</sup>, M. Kocan<sup>17</sup>, F. Kochl<sup>5</sup>, I. Kodeli<sup>68</sup>, Y. Kolesnichenko<sup>86</sup>, Y. Kominis<sup>94</sup>, M. Kong<sup>5</sup>, V. Korovin<sup>74</sup>, B. Kos<sup>68</sup>, D. Kos<sup>5</sup>, H. R. Koslowski<sup>49</sup>, M. Kotschenreuther<sup>55</sup>, M. Koubiti<sup>85</sup>, E. Kowalska-Strzęciwilk<sup>61</sup>, K. Koziol<sup>7</sup>, A. Krasilnikov<sup>91</sup>, V. Krasilnikov<sup>17,19</sup>, M. Kresina<sup>5,31</sup>, K. Krieger<sup>22</sup>, N. Krishnan<sup>5</sup>, A. Krivska<sup>32</sup>, U. Kruezi<sup>17</sup>, I. Księżek<sup>95</sup>, A. B. Kukushkin<sup>15</sup>, H. Kumpulainen<sup>62</sup>, T. Kurki-Suonio<sup>62</sup>, H. Kurotaki<sup>11</sup>, S. Kwak<sup>41</sup>, O. J. Kwon<sup>96</sup>, L. Laguardia<sup>16</sup>, E. Lagzdina<sup>28</sup>, A. Lahtinen<sup>9</sup>, A. Laing<sup>5</sup>, N. Lam<sup>5</sup>, H. T. Lambertz<sup>49</sup>, B. Lane<sup>5</sup>, C. Lane<sup>5</sup>, E. Lascas Neto<sup>45</sup>, E. Łaszcyńska<sup>61</sup>, K. D. Lawson<sup>5</sup>, A. Lazaros<sup>30</sup>, E. Lazzaro<sup>16</sup>, G. Learoyd<sup>5</sup>, Chanyoung Lee<sup>97</sup>, S. E. Lee<sup>88</sup>, S. Leerink<sup>62</sup>, T. Leeson<sup>5</sup>, X. Lefebvre<sup>5</sup>, H. J. Leggate<sup>70</sup>, J. Lehmann<sup>5</sup>, M. Lehnen<sup>17</sup>, D. Leichtle<sup>36,98</sup>, F. Leipold<sup>17</sup>, I. Lengar<sup>68</sup>, M. Lennholm<sup>5,78</sup>, E. Leon Gutierrez<sup>13</sup>, B. Lepiavko<sup>86</sup>, J. Leppanen<sup>10</sup>, E. Lerche<sup>32</sup>, A. Lescinskis<sup>28</sup>, J. Lewis<sup>5</sup>, W. Leysen<sup>87</sup>, L. Li<sup>49</sup>, Y. Li<sup>49</sup>, J. Likonen<sup>10</sup>, Ch. Linsmeier<sup>49</sup>, B. Lipschultz<sup>75</sup>, X. Litaudon<sup>31,35</sup>, E. Litherland-Smith<sup>5</sup>, F. Liu<sup>31,35</sup>, T. Loarer<sup>31</sup>, A. Loarte<sup>17</sup>, R. Lobel<sup>5</sup>, B. Lomanowski<sup>34</sup>, P. J. Lomas<sup>5</sup>, J. M. López<sup>25</sup>, R. Lorenzini<sup>27</sup>, S. Loreti<sup>21</sup>, U. Losada<sup>13</sup>, V. P. Loschiavo<sup>12</sup>, M. Loughlin<sup>17</sup>, Z. Louka<sup>5</sup>, J. Lovell<sup>34</sup>, T. Lowe<sup>5</sup>, C. Lowry<sup>5,78</sup>, S. Lubbad<sup>5</sup>, T. Luce<sup>17</sup>, R. Lucock<sup>5</sup>, A. Lukin<sup>94</sup>, C. Luna<sup>99</sup>, E. de la Luna<sup>13</sup>, M. Lungaroni<sup>57</sup>, C. P. Lungu<sup>66</sup>, T. Lunt<sup>22</sup>, V. Lutsenko<sup>86</sup>, B. Lyons<sup>37</sup>, A. Lysoivan<sup>32</sup>, M. Machielsen<sup>45</sup>, E. Macusova<sup>44</sup>, R. Mäenpää<sup>62</sup>, C. F. Maggi<sup>5</sup>, R. Maggiora<sup>100</sup>, M. Magness<sup>5</sup>, S. Mahesan<sup>5</sup>, H. Maier<sup>22</sup>, R. Maingi<sup>48</sup>, K. Malinowski<sup>61</sup>, P. Manas<sup>22,85</sup>, P. Mantica<sup>16</sup>, M. J. Mantsinen<sup>101</sup>, J. Manyer<sup>81</sup>, A. Manzanares<sup>102</sup>, Ph. Maquet<sup>17</sup>, G. Marceca<sup>45</sup>, N. Marcenko<sup>91</sup>, C. Marchetto<sup>103</sup>, O. Marchuk<sup>49</sup>, A. Mariani<sup>16</sup>, G. Mariano<sup>21</sup>, M. Marin<sup>63</sup>, M. Marinelli<sup>57</sup>, T. Markovič<sup>44</sup>, D. Marocco<sup>21</sup>, L. Marot<sup>38</sup>, S. Marsden<sup>5</sup>, J. Marsh<sup>5</sup>, R. Marshall<sup>5</sup>, L. Martellucci<sup>57</sup>, A. Martin<sup>5</sup>, A. J. Martin<sup>5</sup>, R. Martone<sup>12</sup>, S. Maruyama<sup>17</sup>, M. Maslov<sup>5</sup>, S. Masuzaki<sup>23</sup>, S. Matejčik<sup>92</sup>, M. Mattei<sup>12</sup>, G. F. Matthews<sup>5</sup>, D. Matveev<sup>49</sup>, E. Matveeva<sup>44</sup>, A. Mauriya<sup>6</sup>, F. Maviglia<sup>12</sup>, M. Mayer<sup>22</sup>, M-L. Mayoral<sup>5,72</sup>, S. Mazzi<sup>85</sup>, C. Mazzotta<sup>21</sup>, R. McAdams<sup>5</sup>, P. J. McCarthy<sup>93</sup>, K. G. McClements<sup>5</sup>, J. McClenaghan<sup>37</sup>, P. McCullen<sup>5</sup>, D. C. McDonald<sup>5</sup>, D. McGuckin<sup>5</sup>, D. McHugh<sup>5</sup>, G. McIntyre<sup>5</sup>, R. McKean<sup>5</sup>, J. McKehon<sup>5</sup>, B. McMillan<sup>60</sup>, L. McNamee<sup>5</sup>, A. McShee<sup>5</sup>, A. Meakins<sup>5</sup>, S. Medley<sup>5</sup>, C. J. Meekes<sup>63,104</sup>, K. Meghani<sup>5</sup>, A. G. Meigs<sup>5</sup>, G. Meisl<sup>22</sup>, S. Meitner<sup>34</sup>, S. Menmuir<sup>5</sup>, K. Mergia<sup>14</sup>, S. Merriman<sup>5</sup>, Ph. Mertens<sup>49</sup>, S. Meshchaninov<sup>19</sup>, A. Messiaen<sup>32</sup>, R. Michling<sup>17</sup>, P. Middleton<sup>5</sup>, D. Middleton-Gear<sup>5</sup>, J. Mietelski<sup>43</sup>, D. Milanese<sup>100</sup>, E. Milani<sup>57</sup>, F. Militello<sup>5</sup>, A. Militello Asp<sup>5</sup>, J. Milnes<sup>5</sup>, A. Milocco<sup>59</sup>, G. Miloshevsky<sup>105</sup>, C. Minghao<sup>5</sup>, S. Minucci<sup>56</sup>, I. Miron<sup>66</sup>, M. Miyamoto<sup>106</sup>, J. Mlynář<sup>44,107</sup>, V. Moiseenko<sup>74</sup>, P. Monaghan<sup>5</sup>, I. Monakhov<sup>5</sup>, T. Moody<sup>5</sup>, S. Moon<sup>39</sup>, R. Mooney<sup>5</sup>, S. Moradi<sup>32</sup>, J. Morales<sup>31</sup>, R. B. Morales<sup>5</sup>, S. Mordijck<sup>108</sup>, L. Moreira<sup>5</sup>, L. Morgan<sup>5</sup>, F. Moro<sup>21</sup>, J. Morris<sup>5</sup>, K-M. Morrison<sup>5</sup>, L. Moser<sup>17,38</sup>, D. Moulton<sup>5</sup>, T. Mrowetz<sup>5</sup>, T. Mundy<sup>5</sup>, M. Muraglia<sup>85</sup>, A. Murari<sup>27,35</sup>, A. Muraro<sup>16</sup>, N. Muthusonai<sup>5</sup>, B. N'Konga<sup>50</sup>, Yong-Su Na<sup>97</sup>, F. Nabais<sup>6</sup>, M. Naden<sup>5</sup>, J. Naish<sup>5</sup>, R. Naish<sup>5</sup>, F. Napoli<sup>21</sup>, E. Nardon<sup>31</sup>, V. Naulin<sup>90</sup>, M. F. F. Nave<sup>6</sup>, I. Nedzelskiy<sup>6</sup>, G. Nemtsev<sup>19</sup>, V. Nesenevich<sup>8</sup>, I. Nestoras<sup>5</sup>, R. Neu<sup>22</sup>, V. S. Neverov<sup>15</sup>, S. Ng<sup>5</sup>, M. Nicassio<sup>5</sup>, A. H. Nielsen<sup>90</sup>, D. Nina<sup>6</sup>, D. Nishijima<sup>109</sup>, C. Noble<sup>5</sup>, C. R. Nobs<sup>5</sup>, M. Nocente<sup>59</sup>, D. Nodwell<sup>5</sup>, K. Nordlund<sup>9</sup>, H. Nordman<sup>77</sup>, R. Normanton<sup>5</sup>, J. M. Noterdaeme<sup>22</sup>, S. Nowak<sup>16</sup>, E. Nunn<sup>5</sup>, H. Nystrom<sup>39</sup>, M. Oberparleiter<sup>77</sup>, B. Obryk<sup>43</sup>, J. O'Callaghan<sup>5</sup>, T. Odupitan<sup>5</sup>, H. J. C. Oliver<sup>55,102</sup>, R. Olney<sup>5</sup>,

M. O'Mullane<sup>110</sup>, J. Ongena<sup>32</sup>, E. Organ<sup>5</sup>, F. Orsitto<sup>12</sup>, J. Orszagh<sup>92</sup>, T. Osborne<sup>37</sup>, R. Otin<sup>5</sup>, T. Otsuka<sup>111</sup>, A. Owen<sup>5</sup>, Y. Oya<sup>112</sup>, M. Oyaizu<sup>11</sup>, R. Paccagnella<sup>27</sup>, N. Pace<sup>5</sup>, L. W. Packer<sup>5</sup>, S. Paige<sup>5</sup>, E. Pajuste<sup>28</sup>, D. Palade<sup>66</sup>, S. J. P. Pamela<sup>5</sup>, N. Panadero<sup>13</sup>, E. Panontin<sup>59</sup>, A. Papadopoulos<sup>30</sup>, G. Papp<sup>22</sup>, P. Papp<sup>92</sup>, V. V. Parail<sup>5</sup>, C. Pardanaud<sup>85</sup>, J. Parisi<sup>5,113</sup>, F. Parra Diaz<sup>113</sup>, A. Parsloe<sup>5</sup>, M. Parsons<sup>34</sup>, N. Parsons<sup>5</sup>, M. Passeri<sup>57</sup>, A. Patel<sup>5</sup>, A. Pau<sup>45</sup>, G. Pautasso<sup>22</sup>, R. Pavlichenko<sup>74</sup>, A. Pavone<sup>41</sup>, E. Pawelec<sup>95</sup>, C. Paz Soldan<sup>114</sup>, A. Peacock<sup>5,78</sup>, M. Pearce<sup>5</sup>, E. Peluso<sup>57</sup>, C. Penot<sup>17</sup>, K. Pepperell<sup>5</sup>, R. Pereira<sup>6</sup>, T. Pereira<sup>6</sup>, E. Perelli Cippo<sup>16</sup>, P. Pereslavtsev<sup>36</sup>, C. Perez von Thun<sup>61</sup>, V. Pericoli<sup>61</sup>, D. Perry<sup>5</sup>, M. Peterka<sup>44</sup>, P. Petersson<sup>39</sup>, G. Petravich<sup>26</sup>, N. Petrella<sup>5</sup>, M. Peyman<sup>5</sup>, M. Pillon<sup>21</sup>, S. Pinches<sup>17</sup>, G. Pintsuk<sup>49</sup>, W. Pires de Sá<sup>58</sup>, A. Pires dos Reis<sup>58</sup>, C. Piron<sup>21</sup>, L. Piron<sup>27,115</sup>, A. Pironti<sup>12</sup>, R. Pitts<sup>17</sup>, K. L. van de Plassche<sup>63</sup>, N. Platt<sup>5</sup>, V. Plyusnin<sup>6</sup>, M. Podesta<sup>48</sup>, G. Pokol<sup>26</sup>, F. M. Poli<sup>48</sup>, O. G. Pompilian<sup>66</sup>, S. Popovichev<sup>5</sup>, M. Poradziński<sup>61</sup>, M. T. Porfiri<sup>21</sup>, M. Porkolab<sup>24</sup>, C. Porosnicu<sup>66</sup>, M. Porton<sup>5</sup>, G. Poulipoulis<sup>116</sup>, I. Predebon<sup>27</sup>, G. Prestopino<sup>57</sup>, C. Price<sup>5</sup>, D. Price<sup>5</sup>, M. Price<sup>5</sup>, D. Primetzhofer<sup>20</sup>, P. Prior<sup>5</sup>, G. Provas<sup>51</sup>, G. Pucella<sup>21</sup>, P. Puglia<sup>45</sup>, K. Purahoo<sup>5</sup>, I. Pusztai<sup>76</sup>, O. Putignano<sup>59</sup>, T. Pütterich<sup>22</sup>, A. Quercia<sup>12</sup>, E. Rachlew<sup>76</sup>, G. Radulescu<sup>34</sup>, V. Radulovic<sup>68</sup>, M. Rainford<sup>5</sup>, P. Raj<sup>36</sup>, G. Ralph<sup>5</sup>, G. Ramogida<sup>21</sup>, D. Rasmussen<sup>34</sup>, J. J. Rasmussen<sup>90</sup>, G. Rattá<sup>13</sup>, S. Ratynskaia<sup>117</sup>, M. Rebai<sup>16</sup>, D. Réfy<sup>26</sup>, R. Reichle<sup>17</sup>, M. Reinke<sup>34</sup>, D. Reiser<sup>49</sup>, C. Reux<sup>31</sup>, S. Reynolds<sup>5</sup>, M. L. Richiusa<sup>5</sup>, S. Richyal<sup>5</sup>, D. Rigamonti<sup>16</sup>, F. G. Rimini<sup>5</sup>, J. Risner<sup>34</sup>, M. Riva<sup>21</sup>, J. Rivero-Rodriguez<sup>82</sup>, C. M. Roach<sup>5</sup>, R. Robins<sup>5</sup>, S. Robinson<sup>5</sup>, D. Robson<sup>5</sup>, R. Rodionov<sup>91</sup>, P. Rodrigues<sup>6</sup>, M. Rodriguez Ramos<sup>51</sup>, P. Rodriguez-Fernandez<sup>24</sup>, F. Romanelli<sup>21</sup>, M. Romanelli<sup>5</sup>, S. Romanelli<sup>5</sup>, J. Romazanov<sup>49</sup>, R. Rossi<sup>57</sup>, S. Rowe<sup>5</sup>, D. Rowlands<sup>5,35</sup>, M. Rubel<sup>39</sup>, G. Rubinacci<sup>12</sup>, G. Rubino<sup>56</sup>, L. Ruchko<sup>47</sup>, M. Ruiz<sup>25</sup>, J. Ruiz Ruiz<sup>113</sup>, C. Ruset<sup>66</sup>, J. Rzakiewicz<sup>7</sup>, S. Saarelma<sup>5</sup>, E. Safi<sup>9</sup>, A. Sahlberg<sup>20</sup>, M. Salewski<sup>90</sup>, A. Salmi<sup>10</sup>, R. Salmon<sup>5</sup>, F. Salzedas<sup>6,118</sup>, I. Sanders<sup>5</sup>, D. Sandiford<sup>5</sup>, B. Santos<sup>6</sup>, A. Santucci<sup>21</sup>, K. Sarkimaki<sup>76</sup>, R. Sarwar<sup>5</sup>, I. Sarychev<sup>5</sup>, O. Sauter<sup>45</sup>, P. Sauwan<sup>18</sup>, N. Scapin<sup>53</sup>, F. Schluck<sup>49</sup>, K. Schmid<sup>22</sup>, S. Schmuck<sup>16</sup>, M. Schneider<sup>17</sup>, P. A. Schneider<sup>22</sup>, D. Schworer<sup>70</sup>, G. Scott<sup>5</sup>, M. Scott<sup>5</sup>, D. Scraggs<sup>5</sup>, S. Scully<sup>5</sup>, M. Segato<sup>5</sup>, Jaemin Seo<sup>97</sup>, G. Sergienko<sup>49</sup>, M. Sertoli<sup>5</sup>, S. E. Sharapov<sup>5</sup>, A. Shaw<sup>5</sup>, H. Sheikh<sup>5</sup>, U. Sheikh<sup>45</sup>, A. Shepherd<sup>5</sup>, A. Shevelev<sup>8</sup>, P. Shigin<sup>17</sup>, K. Shinohara<sup>119</sup>, S. Shiraiwa<sup>48</sup>, D. Shiraki<sup>34</sup>, M. Short<sup>5</sup>, G. Sias<sup>29</sup>, S. A. Silburn<sup>5</sup>, A. Silva<sup>6</sup>, C. Silva<sup>6</sup>, J. Silva<sup>5</sup>, D. Silvagni<sup>22</sup>, D. Simfukwe<sup>5</sup>, J. Simpson<sup>5,62</sup>, D. Sinclair<sup>5</sup>, S. K. Sipilä<sup>62</sup>, A. C. C. Sips<sup>78</sup>, P. Sirén<sup>9</sup>, A. Sirinelli<sup>17</sup>, H. Sjöstrand<sup>20</sup>, N. Skinner<sup>5</sup>, J. Slater<sup>5</sup>, N. Smith<sup>5</sup>, P. Smith<sup>5</sup>, J. Snell<sup>5</sup>, G. Snoep<sup>63</sup>, L. Snoj<sup>68</sup>, P. Snyder<sup>37</sup>, S. Soare<sup>120</sup>, E. R. Solano<sup>13</sup>, V. Solokha<sup>62</sup>, A. Somers<sup>70</sup>, C. Sommariva<sup>45</sup>, K. Soni<sup>38</sup>, E. Sorokovoy<sup>74</sup>, M. Sos<sup>44</sup>, J. Sousa<sup>6</sup>, C. Sozzi<sup>16</sup>, S. Spagnolo<sup>27</sup>, T. Spelzini<sup>5</sup>, F. Spineanu<sup>66</sup>, D. Spong<sup>34</sup>, D. Sprada<sup>5</sup>, S. Sridhar<sup>31</sup>, C. Srinivasan<sup>5</sup>, G. Stables<sup>5</sup>, G. Staebler<sup>37</sup>, I. Stamatelatos<sup>14</sup>, Z. Stancar<sup>68</sup>, P. Staniec<sup>5</sup>, G. Stankūnas<sup>121</sup>, M. Stead<sup>5</sup>, E. Stefanikova<sup>39</sup>, A. Stephen<sup>5</sup>, J. Stephens<sup>5</sup>, P. Stevenson<sup>5</sup>, M. Stojanov<sup>5</sup>, P. Strand<sup>77</sup>, H. R. Strauss<sup>122</sup>, S. Strikwerda<sup>5</sup>, P. Ström<sup>39</sup>, C. I. Stuart<sup>5</sup>, W. Studholme<sup>5</sup>, M. Subramani<sup>5</sup>, E. Suchkov<sup>35</sup>, S. Sumida<sup>11</sup>, H. J. Sun<sup>5</sup>, T. E. Systs<sup>28</sup>, J. Svensson<sup>41</sup>, J. Svoboda<sup>44</sup>, R. Sweeney<sup>24</sup>, D. Sytnykov<sup>74</sup>, T. Szabolics<sup>26</sup>, G. Szepesi<sup>5</sup>, B. Tabia<sup>5</sup>, T. Tadić<sup>51</sup>, B. Tál<sup>22</sup>, T. Tala<sup>10</sup>, A. Tallargio<sup>5</sup>, P. Tamain<sup>31</sup>, H. Tan<sup>5</sup>, K. Tanaka<sup>23</sup>, W. Tang<sup>48</sup>, M. Tardocchi<sup>16</sup>, D. Taylor<sup>5</sup>, A. S. Teimane<sup>28</sup>, G. Telesca<sup>61</sup>, N. Teplova<sup>8</sup>, A. Teplukhina<sup>48</sup>, D. Terentyev<sup>87</sup>, A. Terra<sup>49</sup>, D. Terranova<sup>27</sup>, N. Terranova<sup>21</sup>, D. Testa<sup>45</sup>, E. Tholerus<sup>5,39</sup>, J. Thomas<sup>5</sup>, E. Thoren<sup>117</sup>, A. Thorman<sup>5</sup>, W. Tierens<sup>22</sup>, R. A. Tinguely<sup>24</sup>, A. Tipton<sup>5</sup>, H. Todd<sup>5</sup>, M. Tokitani<sup>23</sup>, P. Tolias<sup>117</sup>, M. Tomes<sup>44</sup>, A. Tookey<sup>5</sup>, Y. Torikai<sup>123</sup>, U. von Toussaint<sup>22</sup>, P. Tsavalas<sup>14</sup>, D. Tskhakaya<sup>44,120</sup>, I. Turner<sup>5</sup>, M. Turner<sup>5</sup>, M. M. Turner<sup>70</sup>, M. Turnyanskiy<sup>5,72</sup>, G. Tvalashvili<sup>5</sup>, S. Tyrrell<sup>5</sup>, M. Tyshchenko<sup>86</sup>, A. Uccello<sup>16</sup>, V. Udintsev<sup>17</sup>, G. Urbanczyk<sup>31</sup>, A. Vadgama<sup>5</sup>, D. Valcarcel<sup>5</sup>, M. Valisa<sup>27</sup>, P. Vallejos Olivares<sup>39</sup>, O. Vallhagen<sup>76</sup>, M. Valovič<sup>5</sup>, D. Van Eester<sup>32</sup>, J. Varje<sup>62</sup>, S. Vartanian<sup>31</sup>,

T. Vasilopoulou<sup>14</sup>, G. Vayakis<sup>17</sup>, M. Vecsei<sup>26</sup>, J. Vega<sup>13</sup>, S. Ventre<sup>12</sup>, G. Verdoolaege<sup>67</sup>, C. Verona<sup>57</sup>, G. Verona Rinati<sup>57</sup>, E. Veshchev<sup>17</sup>, N. Vianello<sup>27</sup>, E. Viezzer<sup>82</sup>, L. Vignitchouk<sup>117</sup>, R. Vila<sup>13</sup>, R. Villari<sup>21</sup>, F. Villone<sup>12</sup>, P. Vincenzi<sup>27</sup>, I. Vinyar<sup>94</sup>, B. Viola<sup>21</sup>, A. J. Virtanen<sup>62</sup>, A. Vitins<sup>28</sup>, Z. Vizvary<sup>5</sup>, G. Vlad<sup>21</sup>, M. Vlad<sup>66</sup>, P. Vondráček<sup>44</sup>, P. de Vries<sup>17</sup>, B. Wakeling<sup>5</sup>, N. R. Walkden<sup>5</sup>, M. Walker<sup>5</sup>, R. Walker<sup>5</sup>, M. Walsh<sup>17</sup>, E. Wang<sup>49</sup>, N. Wang<sup>5</sup>, S. Warder<sup>5</sup>, R. Warren<sup>5</sup>, J. Waterhouse<sup>5</sup>, C. Watts<sup>17</sup>, T. Wauters<sup>32</sup>, A. Weckmann<sup>39</sup>, H. Wedderburn Maxwell<sup>5</sup>, M. Weiland<sup>22</sup>, H. Weisen<sup>45</sup>, M. Weiszflog<sup>20</sup>, P. Welch<sup>5</sup>, N. Wendler<sup>61</sup>, A. West<sup>5</sup>, M. Wheatley<sup>5</sup>, S. Wheeler<sup>5</sup>, A. Whitehead<sup>5</sup>, D. Whittaker<sup>5</sup>, A. Widdowson<sup>5</sup>, S. Wiesen<sup>49</sup>, J. Wilkinson<sup>5</sup>, J. C. Williams<sup>5</sup>, D. Willoughby<sup>5</sup>, I. Wilson<sup>5</sup>, J. Wilson<sup>5</sup>, T. Wilson<sup>5</sup>, M. Wischmeier<sup>22</sup>, P. Wise<sup>5</sup>, G. Withenshaw<sup>5</sup>, A. Withycombe<sup>5</sup>, D. Witts<sup>5</sup>, A. Wojcik-Gargula<sup>43</sup>, E. Wolfrum<sup>22</sup>, R. Wood<sup>5</sup>, C. Woodley<sup>5</sup>, R. Woodley<sup>5</sup>, B. Woods<sup>5</sup>, J. Wright<sup>5</sup>, J. C. Wright<sup>24</sup>, T. Xu<sup>5</sup>, D. Yadikin<sup>77</sup>, M. Yajima<sup>23</sup>, Y. Yakovenko<sup>86</sup>, Y. Yang<sup>17</sup>, W. Yanling<sup>49</sup>, V. Yanovskiy<sup>44</sup>, I. Young<sup>5</sup>, R. Young<sup>5</sup>, R. J. Zabolockis<sup>28</sup>, J. Zacks<sup>5</sup>, R. Zagorski<sup>7</sup>, F. S. Zaitsev<sup>92</sup>, L. Zakharov<sup>9</sup>, A. Zarins<sup>28</sup>, D. Zarzoso Fernandez<sup>85</sup>, K.-D. Zastrow<sup>5</sup>, Y. Zayachuk<sup>5</sup>, M. Zerbini<sup>21</sup>, W. Zhang<sup>22</sup>, Y. Zhou<sup>39</sup>, M. Zlobinski<sup>49</sup>, A. Zocco<sup>41</sup>, A. Zohar<sup>68</sup>, V. Zoita<sup>66</sup>, S. Zoletnik<sup>26</sup>, V. K. Zotta<sup>84</sup>, I. Zoulias<sup>5</sup>, W. Zwingmann<sup>6</sup> and I. Zychor<sup>7</sup>

<sup>5</sup>United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, UK. <sup>6</sup>Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal. <sup>7</sup>National Centre for Nuclear Research (NCBJ), Otwock-Swierk, Poland. <sup>8</sup>Ioffe Physico-Technical Institute, St Petersburg, Russian Federation. <sup>9</sup>University of Helsinki, Helsinki, Finland. <sup>10</sup>VTT Technical Research Centre of Finland, Espoo, Finland. <sup>11</sup>National Institutes for Quantum and Radiological Science and Technology, Naka, Ibaraki, Japan. <sup>12</sup>Consorzio CREATE, Napoli, Italy. <sup>13</sup>Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain. <sup>14</sup>NCSR 'Demokritos' 153 10, Agia Paraskevi Attikis, Greece. <sup>15</sup>NRC Kurchatov Institute, Moscow, Russian Federation. <sup>16</sup>Institute for Plasma Science and Technology, CNR, Milan, Italy. <sup>17</sup>ITER Organization, Saint Paul Lez Durance, France. <sup>18</sup>Dept Ingn Energet, Universidad Nacional de Educacion a Distancia, Madrid, Spain. <sup>19</sup>Troitsk Insitute of Innovating and Thermonuclear Research (TRINITI), Troitsk, Moscow, Russian Federation. <sup>20</sup>Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden. <sup>21</sup>Dipto Fusione e Tecnologie per la Sicurezza Nucleare, ENEA C. R. Frascati, Frascati, Roma, Italy. <sup>22</sup>Max-Planck-Institut für Plasmaphysik, Garching, Germany. <sup>23</sup>National Institute for Fusion Science, Oroshi, Toki, Gifu, Japan. <sup>24</sup>MIT Plasma Science and Fusion Center, Cambridge, MA, USA. <sup>25</sup>Universidad Politécnica de Madrid, Grupo I2A2, Madrid, Spain. <sup>26</sup>Centre for Energy Research, Budapest, Hungary. <sup>27</sup>Consorzio RFX, Corso Stati Uniti 4, Padova, Italy. <sup>28</sup>University of Latvia, Riga, Latvia. <sup>29</sup>Department of Electrical and Electronic Engineering, University of Cagliari, Cagliari, Italy. <sup>30</sup>National Technical University of Athens, Iroon Politechniou 9, Athens, Greece. <sup>31</sup>CEA, IRFM, Saint Paul Lez Durance, France. <sup>32</sup>Laboratory for Plasma Physics LPP-ERM/KMS, Brussels, Belgium. <sup>33</sup>Dipartimento di Ingegneria Elettrica Elettronica e Informatica, Università degli Studi di Catania, Catania, Italy. <sup>34</sup>Oak Ridge National Laboratory, Oak Ridge, TN, USA. <sup>35</sup>EUROfusion Programme Management Unit, Culham Science Centre, Culham, UK. <sup>36</sup>Karlsruhe Institute of Technology, Karlsruhe, Germany. <sup>37</sup>General Atomics, San Diego, CA, USA. <sup>38</sup>Department of Physics, University of Basel, Basel, Switzerland. <sup>39</sup>Fusion Plasma Physics, EECS, KTH Royal Institute of Technology, Stockholm, Sweden. <sup>40</sup>Institut Jean Lamour, UMR 7198, CNRS-Université de Lorraine, Vandoeuvre-les-Nancy, France. <sup>41</sup>Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Greifswald, Germany. <sup>42</sup>Faculty of Marine Engineering, Maritime University of Szczecin, Szczecin, Poland. <sup>43</sup>Institute of Nuclear Physics, Radzikowskiego, Krakow, Poland. <sup>44</sup>Institute of Plasma Physics of the CAS, Prague, Czech Republic. <sup>45</sup>Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland. <sup>46</sup>University of Wisconsin-Madison, Madison, WI, USA. <sup>47</sup>Magnetic Sensor Laboratory, Lviv Polytechnic National University, Lviv, Ukraine. <sup>48</sup>Princeton Plasma Physics Laboratory, James Forrestal Campus, Princeton, NJ, USA. <sup>49</sup>Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung, Plasmaphysik, Jülich, Germany. <sup>50</sup>Université Cote d'Azur, CNRS, Inria, LJAD, Parc Valrose, Nice, France. <sup>51</sup>Ruder Bošković Institute, Zagreb, Croatia. <sup>52</sup>The National Institute for Optoelectronics, Magurele-Bucharest, Romania. <sup>53</sup>Mechanics, SCI, KTH SE-100 44, Stockholm, Sweden. <sup>54</sup>Fourth State Research, Austin, TX, USA. <sup>55</sup>Institute for Fusion Studies, University of Texas at Austin, Austin, TX, USA. <sup>56</sup>University of Tuscia, DEIM, Viterbo, Italy. <sup>57</sup>Università di Roma Tor Vergata, Rome, Italy. <sup>58</sup>Instituto de Física, Universidade de São Paulo, CEP 05508-090 Cidade Universitária, São Paulo, Brasil. <sup>59</sup>University of Milano-Bicocca, Milan, Italy. <sup>60</sup>Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry, UK. <sup>61</sup>Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland. <sup>62</sup>Aalto University, Aalto, Finland. <sup>63</sup>FOM Institute DIFFER, Eindhoven, Netherlands. <sup>64</sup>Warsaw University of Technology, Warsaw, Poland. <sup>65</sup>Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, Belfast, UK. <sup>66</sup>The National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania. <sup>67</sup>Department of Applied Physics, Ghent University, Ghent, Belgium. <sup>68</sup>Slovenian Fusion Association (SFA), Jozef Stefan Institute, Ljubljana, Slovenia. <sup>69</sup>The National Institute for Cryogenics and Isotopic Technology, Ramnicu Valcea, Romania. <sup>70</sup>Dublin City University (DCU), Dublin, Ireland. <sup>71</sup>University of California at San Diego, La Jolla, CA, USA. <sup>72</sup>EUROfusion Programme Management Unit, Garching, Germany. <sup>73</sup>UNED, Dpto. Informática y Automática, Madrid, Spain. <sup>74</sup>National Science Center "Kharkov Institute of Physics and Technology", Akademichna 1, Kharkiv, Ukraine. <sup>75</sup>York Plasma Institute, Department of Physics, University of York, York, UK. <sup>76</sup>Department of Physics, Chalmers University of Technology, Gothenburg, Sweden. <sup>77</sup>Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden. <sup>78</sup>European Commission, Brussels, Belgium. <sup>79</sup>University of Tennessee, Knoxville, TN, USA. <sup>80</sup>Universitat Politècnica de Catalunya, Barcelona, Spain. <sup>81</sup>Barcelona Supercomputing Center, Barcelona, Spain. <sup>82</sup>Universidad de Sevilla, Sevilla, Spain. <sup>83</sup>Aix-Marseille University, CNRS, IUSTI, UMR 7343, Marseille, France. <sup>84</sup>Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica, SAPIENZA Università di Roma, Rome, Italy. <sup>85</sup>Aix-Marseille University, CNRS, PIIM, UMR 7345, Marseille, France. <sup>86</sup>Institute for Nuclear Research, Prospekt Nauky 47, Kyiv, Ukraine. <sup>87</sup>Studiecentrum voor Kernenergie - Centre d'Etude de l'Energie Nucléaire, Mol, Belgium. <sup>88</sup>University of Toyama, Toyama, Japan. <sup>89</sup>University of California, Irvine, Irvine, CA, USA. <sup>90</sup>Department of Physics, Technical University of Denmark, Kgs Lyngby, Denmark. <sup>91</sup>Institution "Project Center ITER", Moscow, Russian Federation. <sup>92</sup>Faculty of Mathematics, Department of Experimental Physics, Physics and Informatics Comenius University Mlynska dolina F2, Bratislava, Slovakia. <sup>93</sup>University College Cork (UCC), Cork, Ireland. <sup>94</sup>PELIN LLC, 27a, Gzhatskaya Ulitsa, Saint Petersburg, Russian Federation. <sup>95</sup>Institute of Physics, Opole University, Opole, Poland. <sup>96</sup>Daegu University, Jillyang, Gyeongsan, Gyeongbuk, Republic of Korea. <sup>97</sup>Department of Nuclear Engineering, Seoul National

University, Seoul, South Korea. <sup>98</sup>Fusion for Energy Joint Undertaking, Josep Pl. 2, Torres Diagonal Litoral B3, Barcelona, Spain. <sup>99</sup>Arizona State University, Tempe, AZ, USA. <sup>100</sup>Politecnico di Torino, Torino, Italy. <sup>101</sup>ICREA and Barcelona Supercomputing Center, Barcelona, Spain. <sup>102</sup>Universidad Complutense de Madrid, Madrid, Spain. <sup>103</sup>Istituto dei Sistemi Complessi - CNR and Dipartimento di Energia - Politecnico di Torino, Torino, Italy. <sup>104</sup>Eindhoven University of Technology, Eindhoven, Netherlands. <sup>105</sup>Purdue University, West Lafayette, IN, USA. <sup>106</sup>Department of Material Science, Shimane University, Matsue, Japan. <sup>107</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic. <sup>108</sup>College of William and Mary, Williamsburg, VA, USA. <sup>109</sup>University of California, Oakland, CA, USA. <sup>110</sup>University of Strathclyde, Glasgow, UK. <sup>111</sup>Kindai University, Higashi-Osaka, Japan. <sup>112</sup>Shizuoka University, Shizuoka, Japan. <sup>113</sup>Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK. <sup>114</sup>Columbia University, New York, NY, USA. <sup>115</sup>Dipartimento di Fisica "G. Galilei", Università degli Studi di Padova, Padova, Italy. <sup>116</sup>University of Ioannina, Ioannina, Greece. <sup>117</sup>Space and Plasma Physics, EECS, KTH SE-100 44, Stockholm, Sweden. <sup>118</sup>Universidade do Porto, Faculdade de Engenharia, Porto, Portugal. <sup>119</sup>The University of Tokyo, Kashiwa, Chiba, Japan. <sup>120</sup>Technische Universität Wien, Fusion@ÖAW Österreichische Akademie der Wissenschaften (ÖAW), Vienna, Austria. <sup>121</sup>Lithuanian Energy Institute, Kaunas, Lithuania. <sup>122</sup>HRS Fusion, West Orange, NJ, USA. <sup>123</sup>Ibaraki University Graduate School of Science and Engineering, Mito, Ibaraki, Japan.