



## High resolution gamma-ray spectrometer with MHz capabilities for runaway electron studies at ASDEX Upgrade

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# High resolution gamma-ray spectrometer with MHz capabilities for runaway electron studies at ASDEX Upgrade

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A new gamma-ray spectrometer with MHz capabilities has been developed to measure the bremsstrahlung emission spectrum in the gamma-ray energy band generated by MeV range runaway electrons in disruption experiments at ASDEX Upgrade. Properties of the runaway electrons are inferred from the measured bremsstrahlung spectrum by a deconvolution technique, particularly with regard to their maximum energy. Changes induced to the runaway electron velocity space are unambiguously observed both in massive gas injection and resonant magnetic perturbation experiments with the detector. <https://doi.org/10.1063/1.5036658>

## I. INTRODUCTION

Understanding and controlling runaway electrons (REs) is among the grand challenges that must be faced to ensure safe operations at ITER. In this device, up to 70% of the plasma current in a disruption may be converted to a RE beam which, if left untamed, could cause a major damage to the machine first wall.<sup>1,2</sup> In order to limit the risks for ITER operations, different mitigation techniques have been developed and experiments are presently ongoing to study their impact on the REs. Since 2015, an experimental scenario to generate REs in a reproducible way has also been developed at the ASDEX Upgrade tokamak and studies of RE mitigation by means of massive gas injection (MGI)<sup>3</sup> or resonant magnetic perturbations (RMP)<sup>4</sup> are being conducted. An important goal of these experiments is to validate theoretical models with data from existing machines in order to increase the confidence on their predictions for ITER. A crucial parameter for model validation is the RE distribution function, which can be probed by measurements of the bremsstrahlung emission spectrum in the gamma-ray energy band (also called hard X-ray, HXR) induced by MeV range electrons.<sup>5</sup> Recently, measurements of this type have been demonstrated at the DIII-D tokamak in flat top experiments,<sup>6</sup> but their application to disruptions is significantly more challenging. There is a need to accumulate enough statistics in the spectrum within a fraction of the short (say,

some 10 ms) duration of the current quench, which requires to reliably operate the detector at counting rates often exceeding 1 MHz. By combining recent developments for MHz counting rate gamma-ray spectroscopy of fusion plasmas,<sup>7,8</sup> mostly in the field of fast ion measurements at the JET tokamak,<sup>9</sup> with proof of principle results obtained at the FT-2 tokamak,<sup>10,11</sup> we have developed a gamma-ray spectrometer with MHz capabilities for RE studies at ASDEX Upgrade. In this paper, we present the main features of the detector, a technique adopted to retrieve the RE distribution function from the measured HXR spectrum and an example of results from experiments on RE mitigation during disruptions. Limitations of the present system and prospects for improvements are finally addressed.

## II. INSTRUMENTATION

The detector developed for ASDEX Upgrade is made of a 25 mm × 17 mm (diameter × height) cylindrical LaBr<sub>3</sub> crystal coupled to a RS6231 Hamamatsu photomultiplier tube (PMT) and is placed inside a soft iron shielding which minimises possible drifts of the PMT gain due to the tokamak magnetic field down to a level of <1%. The crystal is a spare of those used in the upgraded JET gamma-ray camera,<sup>12</sup> for which the dimensions were chosen based on needs dictated by space requirements. The system is located on a shelf in the ASDEX Upgrade Bragg bunker, about 1 m behind the Bragg spectrometer and at a distance of approximately 7 m from the machine first wall. It views the plasma along a radial line of sight which makes an angle of 98° with respect to the toroidal magnetic field in the plasma core (see Fig. 1). The collimation of soft

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<sup>c)</sup>See the author list of H. Meyer *et al.*, Nucl. Fusion **57**, 102014 (2017).

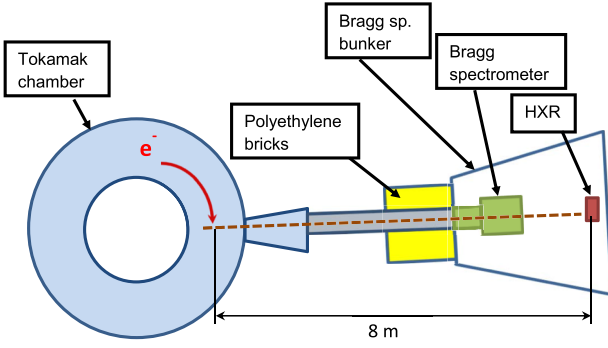


FIG. 1. Arrangement of the gamma-ray spectrometer developed at ASDEX Upgrade. The instrument (HXR) is placed in vicinity of a wall in the ASDEX Upgrade Bragg bunker and observes the plasma through the collimator of the Bragg spectrometer (gray) with a radial view. A wall made of polyethylene bricks (yellow) provides some additional collimation.

X-rays with energies up to about 100 keV is provided by the set of pipelines of the Bragg spectrometer. A few blocks of polyethylene with a thickness of about 1 m and a 20 cm concrete wall provide further collimation of the line of sight to gamma-rays of higher energy, even though with some limitations (see Sec. V). Additional blocks of lead with a thickness of 10 cm are then placed around the detector to shield it from the background radiation coming from the wall at the back of the detector.

The PMT is operated at a voltage of 650 V, which corresponds to a gamma-ray energy dynamic range up to about 20 MeV. Correspondingly, the energy resolution (full width at half maximum divided by peak position) is 4% at the 662 keV  $^{137}\text{Cs}$  line. A fast data acquisition system (400 MHz, 14 bit) based on the Advanced Telecommunication Computing Architecture (ATCA)<sup>13</sup> framework is used to acquire data from the detector in the so-called “segmented” mode. A free running digitizer stores a segment of data whenever the input signal exceeds a predefined threshold. Each segment consists of 128 consecutive points and a time stamp that indicates when the threshold has been exceeded for time-resolved analysis of the data. A similar data acquisition mode has been used earlier

for gamma-ray measurements at the JET tokamak at MHz counting rates.<sup>7,8</sup>

### III. DATA PROCESSING

The HXR energy spectrum, as well as the counting rate as a function of time, is reconstructed off-line by the pulse fitting algorithm described in Ref. 8. As pile up is of relevance particularly when the counting rate exceeds 1 MHz, we have further implemented a pile up recognition algorithm,<sup>14</sup> whereby superimposed pulses are separated and individually fitted in order to avoid the distortion of the pulse height spectrum at higher energies.

The RE distribution function  $f(E_{RE})$  is related to the reconstructed gamma-ray energy spectrum  $s(E_\gamma)$  by the equation

$$s(E_\gamma) = \int_0^\infty dE'_\gamma d(E_\gamma, E'_\gamma) \times \int_0^\infty dE_{RE} g(E'_\gamma, E_{RE}) f(E_{RE}) + n(E_\gamma). \quad (1)$$

Here  $E_{RE}$  and  $E_\gamma$  are the RE and measured gamma-ray energies, respectively;  $n(E_\gamma)$  indicates the Poisson noise.  $g(E'_\gamma, E_{RE})$  is a function that describes the bremsstrahlung gamma-ray spectrum produced by a RE at the given energy  $E_{RE}$ .  $d(E_\gamma, E'_\gamma)$  is the detector response function that evaluates the pulse height spectrum expected at the detector when a gamma-ray at the energy  $E'_\gamma$  impinges on it. In our application, we have used the MCNP<sup>15</sup> code to calculate both  $d(E_\gamma, E'_\gamma)$  and  $g(E'_\gamma, E_{RE})$ , with the results shown in Fig. 2 for REs and impinging gamma-rays at a few selected energies  $E_{RE}$  and  $E'_\gamma$ , respectively.

If  $f(E_{RE})$  were known, Eq. (1) would provide a way to calculate the corresponding, synthetic HXR spectrum for a direct comparison with measurements. Practically, due to the fast (a few ms) time scales involved in a disruption, where the background parameters change by orders of magnitude, simulations of the plasma dynamics are particularly challenging and a calculation of  $f(E_{RE})$  is not available most of the times. In this

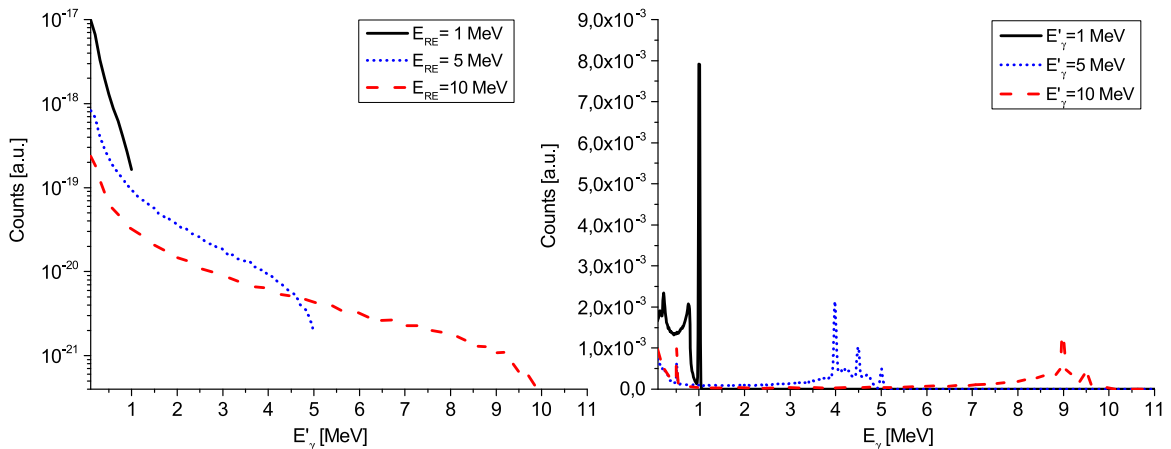


FIG. 2. (Left) HXR bremsstrahlung spectrum  $g(E'_\gamma, E_{RE})$  generated by monoenergetic runaway electrons at energies  $E_{RE} = 1, 5,$  and  $10$  MeV. (Right) Response function of the  $\text{LaBr}_3$  detector used at ASDEX Upgrade:  $d(E_\gamma, E'_\gamma)$  to monoenergetic gamma-rays at energies  $E'_\gamma = 1, 5,$  and  $10$  MeV.

case, we can still attempt to retrieve  $f(E_{RE})$  by direct inversion of Eq. (1). In this work, we have implemented the recipe previously adopted for similar measurements at the JET<sup>16</sup> and FT-2 tokamaks,<sup>10,11</sup> where the Richardson-Lucy<sup>17,18</sup> algorithm has been used to infer  $f(E_{RE})$  from the measured  $s(E_\gamma)$ . This gives the average distribution function in the observed plasma volume, which can be used to determine especially the evolution of the maximum RE energy and current in different time windows of the discharge. In our application, we have focused only on these two parameters, as additional uncertainties due to some unshielded background radiation made the inference of the whole distribution function more difficult at ASDEX Upgrade (see also below).

#### IV. EXPERIMENTAL RESULTS

The gamma-ray spectrometer developed for ASDEX Upgrade has been used to measure the HXR spectrum from REs in experiments on mitigation both by MGI<sup>3</sup> and by the application of RMPs.<sup>4</sup> Here we do not present a complete summary of these experiments, but we rather limit ourselves to show an example of results for discharge #34084 on RE mitigation by MGI with single argon injection.

Figure 3 shows an overview of the plasma parameters in the discharge. The disruption is triggered by argon injection and occurs at 1 s. Correspondingly, we observe the current quench followed by the runaway plateau. Overall, the plasma current decays from 0.8 MA down to 0 in about 400 ms and

the loop voltage experiences a sudden rise from 2 V up to about 100 V in less than 50 ms. The production of REs is indicated by the HXR counting rate as a function of time. There is an initial spike, which can be ascribed to the loss of a fraction of the electrons to the chamber wall right after the interaction with the Ar gas. As the loop voltage increases, the counting rate then ramps up to about 3 MHz, a high value but still within the capabilities of the detector. The drop of the plasma current is associated with a decay of the HXR counting rate with three distinctive slopes: about 27 MHz/s between 1 s and 1.15 s, an almost constant counting rate of  $\approx 400$  kHz up to 1.29 s, and a further drop down to 0 within the following 100 ms.

Figure 4 (top) shows the measured HXR energy spectrum in two time windows, 1 s–1.13 s and 1.13–1.45 s, corresponding to the first two phases of the counting rate evolution. Besides a difference in terms of the number of events, which is about twice at  $t = 1$ –1.13 s compared with  $t = 1.13$ –1.45 s, there is a clear change of the shape of the two spectra, with an overall steeper slope for data at  $t = 1.13$ –1.45 s. The Richardson-Lucy deconvolution algorithm has been applied to reflect this difference back to the RE velocity space, with the results shown in the bottom panel of Fig. 4. We find a change in the maximum RE electron energy, which is reduced from about  $E_{RE} = 24$  MeV at  $t = 1$ –1.13 s down to about  $E_{RE} = 17$  MeV at  $t = 1.13$ –1.45 s. The inferred distribution function also shows an oscillatory pattern, with an amplitude that exceeds the error bars derived from the statistical uncertainty of the input data.

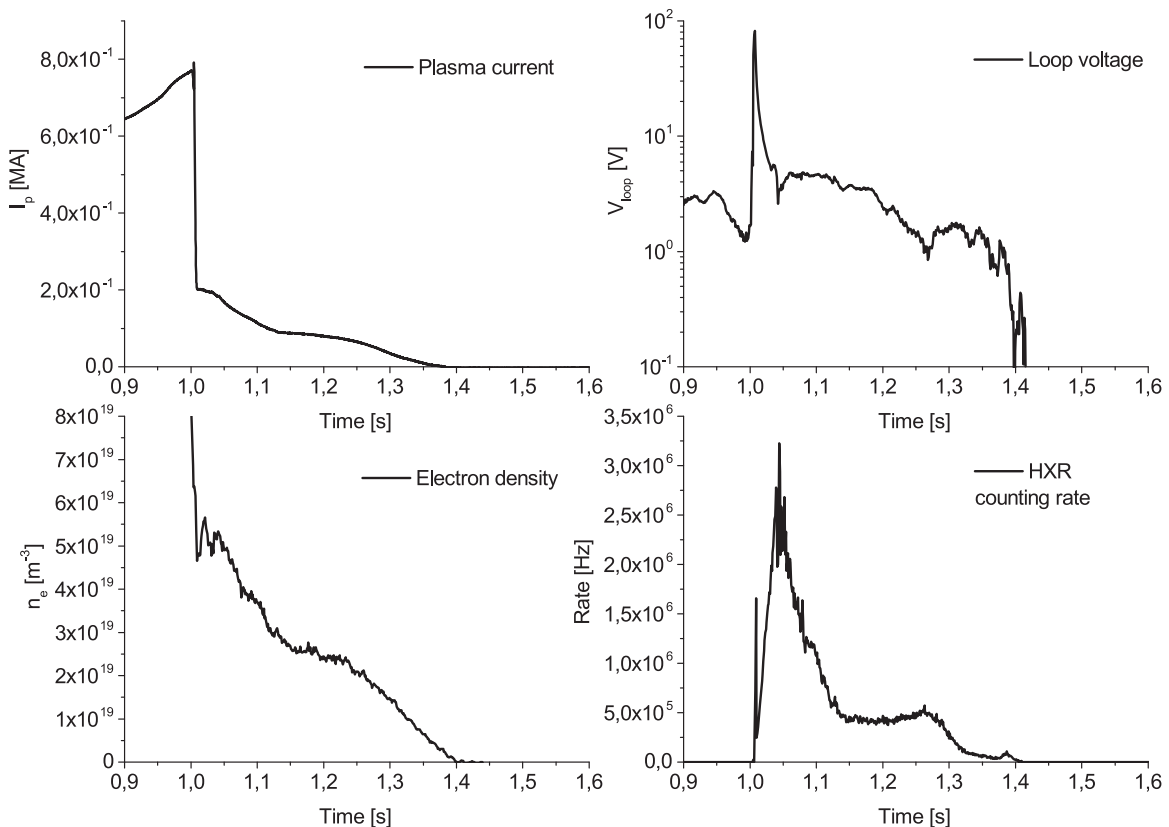


FIG. 3. Plasma parameters for discharge #34084 with massive gas injection. From top left to bottom right in clockwise order: plasma current, loop voltage, core electron density, and counting rate measured by the gamma-ray spectrometer.

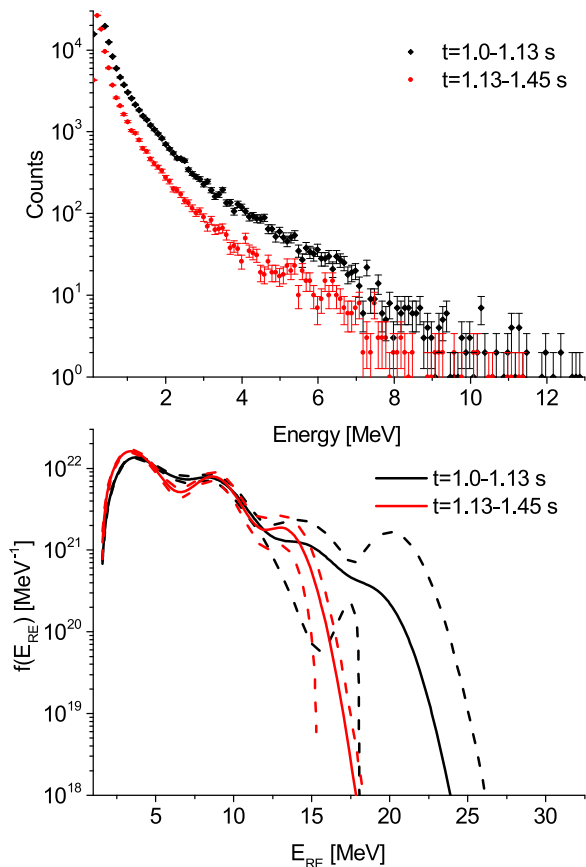


FIG. 4. (Top) Hard x-ray bremsstrahlung spectrum measured for discharge #34084 with MGI in the time windows  $t = 1.0\text{-}1.13$  s and  $t = 1.13\text{-}1.45$  s. (Bottom) Runaway electron distribution functions obtained by the deconvolution of the data shown in the top figure. The dashed lines indicate the statistical uncertainty level.

However, whether this actually points to the development of local maxima in the RE distribution function or is simply an artifact of the deconvolution process is still under investigation (see also the discussion below). Still, the observed change in the maximum energy of the RE on the order of a few MeV seems unambiguous.

Besides MGI experiments, HXR measurements have been performed also in experiments on the use of RMPs as a mitigation technique.<sup>4,19</sup> As for the MGI case, we have observed changes in the maximum RE energy, particularly when the RMP had the largest effect on the RE beam. An additional difficulty in these types of experiments was due to the pronounced counting rate which, in some cases, approached 10 MHz, at the limit of the gain stability of the instrument. A study of the correlation between the phasing of the RMP and the corresponding change in the RE end point energy is presently ongoing and will be presented in a forthcoming paper.

## V. DISCUSSION AND OUTLOOK

The principal value of the gamma-ray spectrometer developed for ASDEX Upgrade consists in making it possible to track the effect of different mitigation techniques on the RE velocity space in disruption experiments, as shown in Fig. 4 with reference to a MGI experiment. There are however

also some drawbacks in the present setup. A first limitation comes from the imperfect collimation to the background radiation at high energies (say,  $E_\gamma > 5$  MeV) due to the limited attenuation offered by the polyethylene shielding of the ASDEX Upgrade Bragg bunker. An ideal collimation should provide no signal at the detector when this is placed out of the line of sight (off-LOS). By repeating the same discharge and performing HXR measurements with the detector in and off LOS, we have observed instead that there is still a counting rate at the 30% level in the off-LOS position compared to the in-LOS position. When this is analyzed spectrally, we find that the attenuation of the background radiation is poor for  $E_\gamma > 5$  MeV, pointing to an insufficient collimation of the polyethylene wall at high energies. While the measured signal in the off-LOS position can be used for subtraction during RE experiments, we have estimated that this may imply an uncertainty of a factor 2-3 in the ratio between  $E_{RE} < 5$  MeV and  $E_{RE} > 5$  MeV REs of the reconstructed distribution function, while no effect has been observed on the maximum energy of the distribution, which remains a robust parameter. A further limitation is then intrinsic to the Richardson-Lucy method itself, particularly with regard to establishing whether the oscillations that are often found in the solution are physical or not.<sup>10,16</sup>

In order to improve the reliability of the overall inferred RE distribution function, we are presently developing a new detector that observes the plasma through a hole drilled in a 2 m thick concrete wall, which is expected to provide sufficient shielding from the background radiation (i.e., virtually no signal in the off-LOS position) and to be placed at a different toroidal location. Concerning the need to establish whether the oscillations in the RE distribution function are real, in the absence of a model, a possibility is here to invert the measurements by a different method and compare the results with those presented in Fig. 4. Recently, first order Tikhonov regularization has been successfully employed to infer the fast ion distribution function from neutron and gamma-ray measurements at the Joint European Torus by the development of the so-called “velocity space tomography” method,<sup>20</sup> which makes use of weight functions<sup>21–23</sup> in the velocity space to connect actual measurements with the energy distribution of the energetic ions. A similar approach might also be tested to invert HXR measurements from RE experiments and is presently under study.

## VI. CONCLUSIONS

A new gamma-ray detector has been developed for RE experiments at ASDEX Upgrade. The instrument has MHz capabilities and measures the HXR bremsstrahlung spectrum in the MeV range as a way to infer information on the RE energy distribution during disruptions and its changes in experiments on mitigation by massive gas injection or resonant magnetic perturbations. The experimental results unambiguously indicate a change of the shape of the bremsstrahlung spectrum in both types of experiments. The energy distribution of the REs can be inferred from the HXR data, albeit with some limitations. We find that the main difference is a modification of the maximum RE energy, which is reduced

by a few MeVs. Correspondingly, the slope of the gamma-ray spectrum is observed to become steeper. Future applications of the diagnostics concern the possibility to systematically study the impact of different mitigation techniques on the RE distribution function at ASDEX Upgrade, as a way to complement more conventional measurements on the post-disruption plasma current dynamics and to provide an additional parameter for a stringent validation of first principle modeling (when available) by means of synthetic diagnostics and data inversion.

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- <sup>1</sup>E. Hollmann, P. Aleynikov, T. Fülöp, D. Humphreys, V. Izzo, M. Lehnen, V. Lukash, G. Papp, G. Pautasso, F. Saint-Laurent *et al.*, *Phys. Plasmas* **22**, 021802 (2015).
- <sup>2</sup>M. Lehnen, K. Aleynikova, P. Aleynikov, D. Campbell, P. Drewelow, N. Eidietis, Y. Gasparyan, R. Granetz, Y. Gribov, N. Hartmann *et al.*, *J. Nucl. Mater.* **463**, 39 (2015).
- <sup>3</sup>G. Pautasso, M. Bernert, M. Dibon, B. Duval, R. Dux, E. Fable, J. Fuchs, G. Conway, L. Giannone, A. Gude, A. Herrmann, M. Hoelzl, P. McCarthy, A. Mlynek, M. Maraschek, E. Nardon, G. Papp, S. Potzel, C. Rapson, B. Sieglin, W. Suttrop, and W. Treutterer, *Plasma Phys. Controlled Fusion* **59**, 014046 (2016).
- <sup>4</sup>M. Gobbin, L. Li, L. Liu, L. Marrelli, M. Nocente, G. Papp, G. Pautasso, P. Piovesan, M. Valisa, D. Carnevale, B. Esposito, L. Giacomelli, M. Gospodarczyk, P. J. McCarthy, P. Martin, W. Suttrop, M. Tardocchi, M. Teschke, ASDEX Upgrade Team, and EUROfusion MST1 Team, *Plasma Phys. Controlled Fusion* **60**, 014036 (2018).
- <sup>5</sup>M. Nocente, M. Tardocchi, R. Barnsley, L. Bertalot, B. Brichard, G. Croci, G. Brolatti, L. Di Pace, A. Fernandes, L. Giacomelli, I. Lengar, M. Moszynski, V. Krasilnikov, A. Muraro, R. Pereira, E. Perelli Cippo, D. Rigamonti, M. Rebai, J. Rzakiewicz, M. Salewski, P. Santosh, J. Sousa, I. Zychor, and G. Gorini, *Nucl. Fusion* **57**, 076016 (2017).
- <sup>6</sup>C. Paz-Soldan, C. M. Cooper, P. Aleynikov, D. C. Pace, N. W. Eidietis, D. P. Brennan, R. Granetz, E. M. Hollmann, C. Liu, A. Lvovskiy, R. Moyer, and D. Shiraki, *Phys. Rev. Lett.* **118**, 255002 (2017).
- <sup>7</sup>M. Nocente, M. Tardocchi, A. Olariu, S. Olariu, R. Pereira, I. N. Chugunov, A. Fernandes, D. B. Gin, G. Grosso, V. Kiptily, A. Neto, A. Shevelev, M. Silva, S. Sousa, and G. Gorini, *IEEE Trans. Nucl. Sci.* **60**, 1408 (2013).
- <sup>8</sup>M. Nocente, M. Tardocchi, I. Chugunov, R. Pereira, T. Edlington, A. M. Fernandes, D. Gin, G. Grosso, V. Kiptily, A. Murari, A. Neto, E. Perelli Cippo, A. Pietropaolo, I. Proverbio, A. Shevelev, J. Sousa, B. Syme, G. Gorini, and JET-EFDA Contributors, *Rev. Sci. Instrum.* **81**, 10D321 (2010).
- <sup>9</sup>Y. O. Kazakov, J. Ongena, J. Wright, S. Wukitch, E. Lerche, M. Mantsinen, D. Van Eester, T. Craciunescu, V. Kiptily, Y. Lin *et al.*, *Nat. Phys.* **13**, 973 (2017).
- <sup>10</sup>A. Shevelev, E. M. Khilkevitch, S. I. Lashkul, V. Rozhdestvensky, A. Altukhov, I. Chugunov, D. Doinikov, L. Esipov, D. Gin, M. V. Iliasova, V. Naidenov, N. Nersesyan, I. Polunovsky, A. Sidorov, and V. Kiptily, *Nucl. Instrum. Methods Phys. Res., Sect. A* **830**, 102 (2016).
- <sup>11</sup>A. Shevelev, E. Khilkevitch, S. Lashkul, V. Rozhdestvensky, S. Pandya, V. Plyusnin, A. Altukhov, D. Kouprienko, I. Chugunov, D. Doinikov *et al.*, *Nucl. Fusion* **58**, 016034 (2018).
- <sup>12</sup>D. Rigamonti *et al.*, *Rev. Sci. Instrum.* **89**, 10I116 (2018).
- <sup>13</sup>R. Pereira, J. Sousa, A. Fernandes, F. Patrício, B. Carvalho, A. Neto, C. Varandas, G. Gorini, M. Tardocchi, D. Gin, and A. Shevelev, *Fusion Eng. Des.* **83**, 341 (2008).
- <sup>14</sup>D. Gin, I. N. Chugunov, and A. Shevelev, *Instrum. Exp. Tech.* **51**, 240 (2008).
- <sup>15</sup>See <https://mcnp.lanl.gov/> for Monte Carlo N-particle.
- <sup>16</sup>A. Shevelev, E. Khilkevitch, V. Kiptily, I. Chugunov, D. Gin, D. Doinikov, V. Naidenov, A. Litvinov, I. Polunovskii, and JET-EFDA Contributors, *Nucl. Fusion* **53**, 123004 (2013).
- <sup>17</sup>W. H. Richardson, *J. Opt. Soc. Am.* **62**, 55 (1972).
- <sup>18</sup>L. B. Lucy, *Astron. J.* **79**, 745 (1974).
- <sup>19</sup>M. Gobbin, M. Valisa, R. White, D. Cester, L. Marrelli, M. Nocente, P. Piovesan, L. Stevanato, M. Puiatti, and M. Zuin, *Nucl. Fusion* **57**, 016014 (2017).
- <sup>20</sup>M. Salewski, M. Nocente, A. Jacobsen, F. Binda, C. Cazzaniga, G. Ericsson, J. Eriksson, G. Gorini, C. Hellesen, A. Hjalmarsson, V. Kiptily, T. Koskela, S. Korsholm, T. Kurki-Suonio, F. Leipold, J. Madsen, D. Moseev, S. Nielsen, J. Rasmussen, M. Schneider, S. Sharapov, M. Stejner, M. Tardocchi, and JET Contributors, *Nucl. Fusion* **57**, 056001 (2017).
- <sup>21</sup>M. Salewski, M. Nocente, G. Gorini, A. Jacobsen, V. Kiptily, S. Korsholm, F. Leipold, J. Madsen, D. Moseev, S. Nielsen, J. Rasmussen, M. Stejner, M. Tardocchi, and JET Contributors, *Nucl. Fusion* **55**, 093029 (2015).
- <sup>22</sup>M. Salewski, M. Nocente, G. Gorini, A. Jacobsen, V. Kiptily, S. Korsholm, F. Leipold, J. Madsen, D. Moseev, S. Nielsen, J. Rasmussen, M. Stejner, M. Tardocchi, and JET Contributors, *Nucl. Fusion* **56**, 046009 (2016).
- <sup>23</sup>A. Jacobsen, F. Binda, C. Cazzaniga, J. Eriksson, A. Hjalmarsson, M. Nocente, M. Salewski, G. Tardini, JET Contributors, and ASDEX Upgrade Team, *Rev. Sci. Instrum.* **88**, 073506 (2017).