Mitigation of the tracer impurity accumulation by EC heating in the LHD

N Tamura 1, S Sudo 2, C Suzuki 1, H Funaba 1, Y Nakamura 1,3, K Tanaka 1, M Yoshinuma 1,3, K Ida 1,3 and The LHD Experiment Group 1

1 National Institute for Fusion Science, National Institutes of Natural Sciences, 322-6, Oroshi-cho, Toki-shi, Gifu 509-5292, Japan
2 Chubu University, 1200 Matsumoto-cho, Kasugai-shi, Aichi 487-8501, Japan
3 The Graduate University for Advanced Studies, 322-6, Oroshi-cho, Toki-shi, Gifu 509-5292, Japan

E-mail: ntamura@LHD.nifs.ac.jp

Received 5 February 2016, revised 9 August 2016
Accepted for publication 18 August 2016
Published 20 September 2016

Abstract
The mitigation of a tracer impurity accumulation in the core region of high-temperature helical plasma was clearly observed by applying electron cyclotron heating (ECH) in the large helical device (LHD). In the LHD, the accumulation of impurities toward the centre of the plasma has been observed in a high-density regime. In this study, for observing clearly the behaviour of impurity ions in the plasma core, the extrinsic ‘tracer’ impurity was injected into that region by means of a tracer-encapsulated solid pellet (TESPEL). The high-density LHD plasma without ECH definitely shows the strong impurity accumulation, and then it causes the reduction in electron and ion temperatures in the core region. When ECH was applied just after the TESPEL injection, the accumulation of the tracer impurity ions was mitigated. Even after ECH was switched-off, the intensities of the line emissions from the highly-ionized tracer impurity were increased very slightly. The micro-turbulence measurement with a 2-dimensional phase contrast imaging diagnostic during ECH does not support the view that the change in the micro-turbulence would enhance the outward flow (an increase in a diffusive flux, a decrease in an inward convective flux and/or a change the direction of the convective flux from inward to outward) of the impurity ions. Moreover, at this moment, there is no conclusive data regarding a radial electric field measured with a charge exchange spectroscopy diagnostic to support the view that the change in the radial electric field would be attributed to the increment in the outward flow of the impurity ions from the core region of the LHD plasma.

Keywords: impurity transport, impurity accumulation, mitigation, ECH, tracer-encapsulated solid pellet (TESPEL), large helical device (LHD)

(Some figures may appear in colour only in the online journal)

1. Introduction
In a magnetic confinement fusion device, various impurities from low-Z material, e.g. a helium ash, which is a by-product of the fusion reaction, to high-Z material, e.g. a tungsten, which is derived from a possible plasma facing component, will exist inside a high-temperature plasma. When the amount of impurities exceeds an acceptable level for some reason, e.g. possibly due to an accumulation of the impurities towards the plasma core, it can cause radiation losses and plasma dilution resulting in lower fusion power, which leads to a significant fusion reactor performance degradation. Therefore, the impurity accumulation is a potential show-stopper for the realization of the fusion reactor, and it is crucially important to develop an effective scheme for avoiding and/or controlling the impurity accumulation towards the plasma core. In helical
plasmas, a global impurity confinement time has been found to generally increase with a line-averaged electron density [1]. Unfortunately, a so-called ‘ion temperature screening effect’ due to an ion temperature gradient, which is predicted by the neoclassical transport theory and creates a convective flow directed outward [2], is not expected in the helical plasmas unlike in tokamaks [3]. This means that the helical-type fusion reactor based on a scenario with a high-density seems to be unfeasible. However, a so-called confinement mode (high-density and high-confinement mode, HDH-mode), which has a good particle confinement with a low impurity confinement, has been found in the W7-AS stellarator [4]. And moreover, an extremely hollow impurity profile, which is a so-called ‘impurity hole’, has been observed in the plasma with a large ion temperature gradient in the LHD [5]. These findings could shed light on the path to the helical-type fusion reactor. Meanwhile, in order to enhance the economic rationality of the possible helical-type fusion reactor, it is highly important to develop several methods to achieve actively the low impurity confinement state. The additional heating, such as electron cyclotron heating (ECH) and ion cyclotron heating (ICH), is one of several such method to control the impurity inside the plasma. Even now, many experiments with the additional heating have been performed to demonstrate and investigate the suppression or mitigation of the core impurity accumulation in tokamaks (among others, see, for example, [6–9]) and stellarators [1, 10]. In both devices, the clear effects of the additional heating on the impurity accumulation have been observed. However, the physical mechanisms of such effects still are not yet cleared.

In this paper, we show observational results on the mitigation of the impurity accumulation by applying ECH in a plasma of the Large Helical Device. This paper is structured as follows. In section 2, the experimental set-up including important diagnostics for this work is explained. In section 3, we show the experimental results. In section 4, we discuss the results obtained to investigate the cause of the mitigation. In section 5, we draw some conclusions.

2. Experimental set-up

In this study, we investigate high-density discharges in the LHD [11]. The LHD with a heliotron-type magnetic configuration has superconducting \( l/m = 2/10 \) helical coils and three pairs of superconducting poloidal coils. Here, \( l \) and \( m \) are a pole number of the helical coil winding and a toroidal field period, respectively. In this work, the magnetic axis is set at \( R_{ax} = 3.6 \) m, and then the resulting averaged minor radius \( a \) is \( \sim 0.62 \) m. The magnetic field at the axis \( B_{ax} \) is set at 2.75 T. The plasma was initiated by ECH (injected power: about 1.2 MW) and heated additionally by negative-ion and positive-ion based neutral beam injections (NBIs, total injected power: about 7 MW). In the LHD, an impurity hole, which is characterized by the extremely hollow profile of the impurity density, is observed associated with an increase of ion temperature gradient in the plasma with an ion thermal internal transport barrier [5]. Here, as will be shown later in figure 4, the plasma of interest have no impurity hole, because there is no large ion temperature gradient. No impurity hole is also inferred from the shape of radiated power profile measured with an absolute extreme ultra violet silicon photodiode (AXUVD) array, as will be shown later in figure 3. And moreover, no significant magnetohydrodynamics (MHD) activities are also observed.

In order to inject the impurities into the core plasma of LHD, a tracer-encapsulated solid pellet (TESPEL [12–14]) is used. In this work, the TESPEL contained two extrinsic impurities, vanadium (V) and chlorine (Cl). The vanadium is in the core of the TESPEL. And the chlorine is in the shell of the TESPEL in the form of an organic compound, poly-2,6-dichlorostyrene \((\text{C}_8\text{H}_6\text{Cl}_2)_n\). The light emission from the ablation cloud of the TESPEL injected into the LHD plasma is measured with an optical-fibre-based diagnostic system [15]. The ablation lights from the shell and core are measured separately with the corresponding optical filters; one has \( \lambda_{centre} = 657.2 \) nm and FWHM = 1.2 nm for H\( \alpha \) emission from the shell ablation and the other has \( \lambda_{centre} = 412.3 \) nm and FWHM = 1.1 nm for V I emission from the vanadium ablation. The most important diagnostics in this work is a spectrometer for detecting the behaviour of the impurity ions in the core region of the LHD plasma. When the electron temperature of the LHD plasma of interest is basically above 1 keV, the line emissions from the impurity ions in the core LHD plasma will appear in a vacuum ultraviolet (VUV) domain. A 2 m Schott–Frenkel soft x-ray multi-channel spectrometer (SOXMOs) [16, 17], which is installed at Port 7-O of LHD, is used, although not calibrated, for measuring the temporal behaviour of the line emissions in the VUV domain. The temporal resolution of the SOXMOs is set at 50 ms. A wide-angle (\( \pi \)) metal foil bolometer, which is installed at the same port (Port 3-O of LHD) as the TESPEL injector is used for measuring the total radiated power \( P_{rad} \) with a 5 ms temporal resolution [18]. Unfiltered 20-channel AXUVD arrays [19], which are installed at the upper side of Port 8-O of LHD, can also measure the plasma radiation, whose energy ranges from 1.1 eV (visible) to \( \sim 6000 \) eV (x-ray) [20]. The temporal resolution of the AXUVD array is set at 0.1 ms. A YAG Thomson scattering system, which is installed at Port 4-O of LHD, is used for measuring detailed radial profiles of electron density \( n_e \) and temperature \( T_e \) along the LHD major radius at a horizontally-elongated cross-section [21, 22]. The typical temporal resolution of the LHD YAG Thomson scattering system is 100 ms. A charge exchange spectroscopy diagnostic (CXS), which utilizes the positive-ion-based NBI at Port 5-O of LHD, is used for measuring the temporal and spatial evolutions of ion temperature \( T_i \), plasma poloidal and toroidal rotation velocities by using a charge exchange reaction between fully-ionized carbon impurity and atomic hydrogen from the neutral beam [23]. Consequently, the CXS can estimate a radial electric field. A 2-dimensional phase contrast imaging diagnostic employing a CO\(_2\) laser [24–26], which is installed at Port 8.5-U of LHD, is utilized for estimating the turbulence properties in the LHD plasma.

3. Experimental results

Figure 1 shows a typical example of the spectrum in the vacuum ultraviolet (VUV) domain measured with the SOXMOs before \( (t = 3.825 \) s) and just after \( (t = 4.025 \) s) the TESPEL injection
From the shell

from the plasma with the high-density (here, the line-averaged electron density is $4.0 \sim 5.0 \times 10^{19} \text{ m}^{-3}$). The TESPEL was injected at the time of $t = 3.941 \text{s}$. As can be seen from figure 1, just after the TESPEL injection, many emission lines from the highly-ionized vanadium and chlorine appeared clearly. Here, we study the vanadium Be-like emission ($\text{V XX} 15.936 \text{nm}$ ($1s^22s^21S_{1/2} - 1s^21s2p^23P_{1/2}$)) and the vanadium Li-like emission ($\text{V XXI} 24.04\text{nm}$ ($1s^22s^22p^21S_{1/2} - 1s2s2p^21S_{1/2}$)) and 29.37 nm ($1s^22p^23S_{1/2} - 1s^22p^21S_{1/2}$) (not shown in figure 1) from the highly-ionized vanadium.

In order to investigate precisely the transport of the impurities injected into the core plasma, the impurity injection should be performed with minimal disturbance of the plasma. In this regard, the impurity injection by using the impurity pellet injection technique is not the most suitable. Therefore, it is important to assess the impact of the TESPEL injection on the LHD plasma. In this study, we investigate three LHD discharges: the discharge without additional ECH ($\#128070$), the discharge with additional 0.7 MW, 154 GHz ECH ($\#128087$) and the discharge with additional 1.5 MW, 154 GHz ECH ($\#128081$). All the discharges have the TESPEL injection at the time of around 3.95 s. The diameter of the TESPEL used is $128081 \text{ and } 128082$). As can be seen from figure 2, there are no significant changes in the electron density and temperature just after the TESPEL injection. As already described in the Introduction, the global impurity confinement time in helical plasmas increases with the line-averaged electron density. We have tried unsuccessfully to make the steady-state line-averaged electron density in the discharges without the additional injection of ECH, and the line-averaged electron density continued to increase even without a gas fueling. This could be attributed to a recycled hydrogen gas from a first wall of the LHD vacuum vessel and the accumulation of impurity toward the plasma centre. In order to establish the steady-state line-averaged electron density, around $4 \sim 5 \times 10^{19} \text{ m}^{-3}$, we have finally applied a hydrogen gas puff for 120 ms from $t = 3.3 \text{s}$ in the discharges with the additional injection of ECH. Then, unfortunately, there are no hydrogen-gas-puffed reference discharges without ECH during the discharge. However, since the values of the line-averaged electron density from $t = 4.8 \text{s}$ to $t = 6.0 \text{s}$ (about half of the duration of interest) in the discharges without the additional injection of ECH are close to those of the line-averaged electron density in the discharges with ECH, the discharges without ECH ($\#128069$ and $\#128070$) are, although not the best, used as references. When ECH is applied during the discharge, the line-averaged electron density decreases slightly with time. The effect of ECH on the line-averaged electron density, which is well known as a density pump-out effect [27], is strengthened by the higher-power ECH. In the case without ECH during the discharge ($\#128070$), the electron temperature at the plasma centre decreased gradually, and then it dropped to below half, compared to that around the time of $4.0 \text{s}$. Such a decrease in the electron temperature is also observed in the case without the TESPEL ($\#128069$), although it is a bit behind the case with the TESPEL. Thus the impurities injected by the TESPEL might hasten the decrease in the electron temperature in the plasma centre. When the total radiated power is compared under the same electron temperature level in the plasma centre, the total radiated power (at $t = 6.7 \text{s}$) in the case without the TESPEL is higher than that (at $t = 5.5 \text{s}$) in the case with the TESPEL. Therefore the contribution to the total radiated power by the impurities injected by the TESPEL is found to be very small. The small contribution to the total radiated power by the impurities injected by the TESPEL is also confirmed by the comparison between the discharges having the additional injection of ECH with ($\#128081$) and without TESPEL ($\#128082$). However, the measurement with the AXUVD array, even though it is the sightline-integrated, indicates a pronounced increase of the local radiated power from the plasma centre in the case with the TESPEL, but without ECH ($\#128070$), as shown in figure 2(g). As can be

### Table 1. Particle number of the impurities injected by the TESPEL for three LHD discharges ($\#128070$, $\#128081$, $\#128087$) that are being studied.

| Impurity   | Without TESPEL | With TESPEL | Note        |
|------------|----------------|-------------|-------------|
| Vanadium (V) | $3.1 \times 10^{17}$ | $5.4 \times 10^{17}$ | From the core |
| Carbon (C)  | $1.5 \times 10^{18}$ | $2.2 \times 10^{18}$ | From the shell |
| Chlorine (Cl) | $3.6 \times 10^{17}$ | $5.5 \times 10^{17}$ | From the shell |
| Hydrogen (H) | $1.1 \times 10^{18}$ | $1.6 \times 10^{18}$ | From the shell |
seen from the two bottom frames of figure 2, just after the TESPEL injection, V XXI (29.37 nm) is quickly increased, and then it maintains the elevated level up to the time of $t \sim 5.5$ s. And V XX (15.936 nm) is also quickly increased, and then it starts to decrease shortly thereafter. However, V XX is increased again, gradually up to the time of $t \sim 5.7$ s. These experimental results suggest that the impurities injected is accumulated towards the plasma core. When 0.7 MW, 154 GHz ECH is applied ($#128087$), the behaviour of impurity injected is certainly changed. Just after the TESPEL injection, V XXI (24.04 nm) is quickly increased, and then gradually decreased. However, the decrease of V XXI seems to be stagnated around $t = 5.0$ s. And the temporal behaviour of V XX is almost the same as that of V XXI. These behaviours strongly suggest that applying 0.7 MW, 154 GHz ECH certainly affects the impurity accumulation, but it is not sufficient for mitigating that. This is also proven by the temporal behaviour of the line emissions from the vanadium ions after ECH switch-off. After ECH (after the time of $t = 6.0$ s), both the V Li-like and Be-like emissions start to increase again. When 1.5 MW, 154 GHz ECH is applied ($#128081$), the behaviour of impurity injected are dramatically changed. V XXI is decreased to 20% of its peak, and then, even after ECH switch-off, it maintains the suppressed level. The temporal evolution of V XX is almost the same as that of V XXI. These behaviours strongly suggest that applying
1.5 MW, 154 GHz ECH definitely mitigates the impurity accumulation. After ECH, in almost all cases, the electron density increased and the electron and ion temperatures decreased. Taking into account the temporal response of the total radiated power, the revival of the impurity accumulation could contribute to the plasma response. The change in plasma radiation profile would be a better indicator for the appearance of impurity accumulation. As can be recognized easily from figure 3(b), the plasma radiation measured with the AXUVD array shows a very peaked profile in the case without ECH (#128070). And the very peaked radiation profile almost disappears with 1.5 MW ECH, which is close to that before the TESPEL injection.

Figure 4 shows the normalised radial profiles of the electron density and temperature, and the ion temperature ((a), (c), (e)) before and ((b), (d), (f)) after the TESPEL injection for the three LHD discharges (#128070 (black), #128087 (blue) and #128081 (red)). The deposited region of the vanadium impurity injected by the TESPEL is indicated in figure 4(a). And the normalised radial profile of the absorbed power density of the additional ECH is depicted in figure 4(d).

Figure 4. Normalised radial profiles of the electron density, the electron temperature and the ion temperature ((a), (c), (e)) before and ((b), (d), (f)) after the TESPEL injection for the three LHD discharges (#128070 (black), #128087 (blue) and #128081 (red)). The deposited region of the vanadium impurity injected by the TESPEL is indicated in figure 4(a). And the normalised radial profile of the absorbed power density of the additional ECH is depicted in figure 4(d).
electron density and temperature, and the ion temperature. The electron temperature profile is changed from peaked to slightly hollow, which is one of the most significant features of the impurity accumulation towards the plasma core. In the case with 1.5 MW ECH, both the electron and ion temperatures increase strongly in comparison to the values before ECH. On the other hand, the overall electron density is decreased slightly. In the case with 0.7 MW ECH, the electron and ion temperatures over the whole region are still higher than that before ECH. However, the electron density inside the $r_{\text{eff}}/a_{99}$ of 0.4 is higher than that before ECH. This increment of the electron density in the plasma core suggests that the impurities continue to be accumulated even after ECH switch-on. The erosion of the electron temperature could be appeared when the radiative losses exceed the deposited power. However, as already shown in figure 2, the total radiated power is increased a little, when the erosion of the electron temperature due to the impurity accumulation is appeared. This is because the absorbed power in the central region of that plasma is very low, as shown in figure 5. The very low and rather flat absorbed power density is attributed to the high-density discharges. As shown in figure 4, the profiles of the electron density as well as that of the electron temperature are certainly modified by the injection of ECH. And then, the first thing to check is whether a mean charge state of vanadium ion is also changed or not by the changes in the electron density and temperature. It is important to judge whether the temporal variation of the line emissions from the highly ionized vanadium is that of the vanadium ion density or the change in the charge state distribution of vanadium ion. As shown in figure 6(a), the mean charge state $\langle Z \rangle$ of vanadium ion, which is calculated with the atomic code, FLYCHK [28], depends on the electron temperature, does not on the electron density in the parameter range of interest. Figures 6(b) and (c) show mean charge state profiles just before and after the TESPEL injection, which are calculated by using the data shown in figure 6(a). It should be noted here that the mean charge state profiles calculated do not include the transport effect. In the case with 1.5 MW ECH ($\#128081$), the region where the mean charge state is above $\langle Z \rangle = 19$, the Be-like ion, could exist in the wide region, inside the $r_{\text{eff}}/a_{99}$ of 0.7 at $t = 3.933$ s (before the TESPEL injection), and inside the $r_{\text{eff}}/a_{99}$ of 0.85 at $t = 5.700$ s (during ECH). Taking into account the fact that the V Li-like and Be-like emissions increase very little after ECH switch-off, the temporal behaviour of the line emissions from the highly-ionized vanadium would reflect that
of the vanadium ion density. In the case with 0.7 MW ECH (#128070), the region with the mean charge state of \( Z \geq 19 \) could also exit in the almost same region as the case with 1.5 MW ECH at \( t = 3.933 \) s, and inside the \( r_{eff}/a_{99} \) of 0.75 at \( t = 5.700 \) s. In this case, considering that the V Li-like and Be-like emissions increase after ECH switch-off, the vanadium ions could move in the region outside the \( r_{eff}/a_{99} \) of around 0.75 from the plasma centre during ECH, and the vanadium ions could get back to the plasma core from there after ECH switch-off. In the case without ECH (#128070), as shown in figure 6(c), the mean charge state profile of vanadium at \( t = 5.700 \) s is totally below \( Z = 19 \). This can be the reason why the V Li-like and Be-like emissions decreased after the time of 5.5 s - 5.7 s for that case.
4. Discussion

There are several possibilities for the mitigation of the impurity accumulation by applying ECH. One possible cause is the enhancement of the outward flow, i.e., an increase in a diffusive flux, a decrease in an inward convective flux and/or a change in the direction of the convective flux from inward to outward, due to the enhancement of the turbulence by the increase in the electron temperature gradient, such as trapped electron mode [29] and electron temperature gradient mode [30]. Thus, it is important to check the variation in such driving terms, including the gradients of electron density and ion temperature for three LHD discharges of interest. As shown in figure 7, the inverse electron density scale lengths for the plasmas with ECH of 0.7 MW and 1.5 MW is similar to that for the initial state ($t = 3.933$ s) of the plasma without ECH. The inverse electron temperature scale length with 1.5 MW ECH is slightly larger than the others in the region outside $r_{\text{eff}}/a_{99} \sim 0.6$. The inverse ion temperature scale length with 1.5 MW ECH is certainly very slightly larger than the other inverse ion temperature scale length in the region inside $r_{\text{eff}}/a_{99} \sim 0.5$. In either case, the inverse gradient scale lengths with 1.5 MW ECH are found not to be so different from those in the other cases. As can be seen in figure 8, the electron density fluctuations measured with the 2D PCI are found to exist largely outside $r_{\text{eff}}/a_{99} \sim 0.7$. In such a high-density regime, the electron density fluctuations inside $r_{\text{eff}}/a_{99} \sim 0.7$ is considered to be stabilized due to the collisions. Therefore, the expelling of the impurity ions from the plasma core (inside $r_{\text{eff}}/a_{99} \sim 0.7$) is not attributed to the change in the micro-turbulences. The maximum amplitude of the density fluctuations measured in the case with 0.7 MW ECH is larger than that in the case with 1.5 MW ECH in the first place.

The other possible cause for the mitigation of the impurity accumulation is the change of the radial electric field from the positive to the negative. In helical plasmas, the radial electric field has a significant impact on the plasma confinement and impurity transport [31, 32]. The transition of the radial electric field from the ion root (negative) to the electron root (positive) triggered by enhancing the electron particle flux due to ECH has been already demonstrated in low-density CHS heliotron plasmas [33]. However, the radial electric field evaluated with the CXS during 1.5 MW ECH was applied seems to be almost unchanged compared to that before ECH within the errors, as shown in figures 9(e) and (f). Therefore, at present, there is no conclusive data to rationalize the mitigation of the impurity accumulation due to ECH.

In order to determine the cause for why the impurity accumulation was mitigated by applying ECH, further investigation using the theoretical and simulation studies would be useful. As can be seen in figures 9(c) and (d), there is a large uncertainty in the measurement of the toroidal rotation velocity in the plasma core, inside the $r_{\text{eff}}/a_{99}$ of around 0.5. The calculation including momentum conservation [34] could provide us a more precise picture on that. Currently, the evaluations of the neoclassical radial electric field taking into account momentum conservation and turbulent flux of the impurities are underway, which will be published elsewhere.

From a pragmatic point of view, the optimum conditions (injected power, power absorbed location and ECH duration) of the additionally applied ECH should be also clarified for achieving the mitigation of impurity accumulation in the fusion-reactor relevance conditions.

5. Summary

We assessed the effect of ECH on the impurity accumulation toward the plasma core in the LHD. When 1.5 MW, 154 GHz ECH was applied just after the injection of the impurity by using the TESPEL, the mitigation of the impurity accumulation toward the core region of the LHD plasma was observed. On the other hand, when 0.7 MW, 154 GHz ECH was applied just after the TESPEL injection, the mitigation of the impurity accumulation was incomplete. During ECH, the change in both the inverse gradient scale lengths of electron density, electron temperature and ion temperature and the properties of micro-turbulence measured with the 2D-PCI does not support the view that the change in the micro-turbulence would enhance the outward flow of the impurity ions. In addition, there is no conclusive data regarding the radial electric field evaluated with the CXS to support the view that the change in the radial electric field would be attributed to increment in the outward flow of the impurity ions from the core region of the LHD plasma.
Acknowledgments

The authors acknowledge all of the technical staff of NIFS for their excellent support in performing the experiments for this work. They also would like to thank Prof Y Takeiri (Director of NIFS) for his continuous encouragement. This work is supported by JSPS KAKENHI Grant Numbers 23360415, 15H03759, 15H04234 and a budgetary Grant-in-Aid (Nos. ULHH012 and ULHH017) of the National Institute for Fusion Science.

References

[1] Burhenn R et al 2009 Nucl. Fusion 49 065005
[2] Hirshman S P and Sigmar D J 1981 Nucl. Fusion 21 1079
[3] Maassberg H et al 1999 Plasma Phys. Control. Fusion 41 1135
[4] McCormick K et al 2002 Phys. Rev. Lett. 89 015001
[5] Ida K et al 2009 Phys. Plasma 16 056111
[6] Cui Z Y et al 2013 Nucl. Fusion 53 093001
[7] Hong J et al 2015 Nucl. Fusion 55 063016

Figure 9. Normalised radial profiles of the poloidal rotation velocity, the toroidal rotation velocity and the radial electric field ((a), (c), (e)) before and ((b), (d), (f)) after the TESPEL injection for the three LHD discharges (#128070 (black circle), #128087 (blue square) and #128081 (red diamond)).
[8] Sertoli M et al 2015 Nucl. Fusion. 55 113029
[9] Lecce E et al 2016 Nucl. Fusion. 56 036022
[10] Kaneko H et al 1987 Nucl. Fusion. 27 1075
[11] Motojima O et al 1999 Phys. Plasma 65 1843
[12] Sudo S 1993 J. Plasma Fusion Res. 69 1349
[13] Khlopenkov K et al 1998 Rev. Sci. Instrum. 69 3194
[14] Sudo S and Tamura N 2012 Rev. Sci. Instrum. 83 023503
[15] Tamura N et al 2008 Rev. Sci. Instrum. 79 10F541
[16] Schwob J L et al 1987 Rev. Sci. Instrum. 58 1601
[17] Suzuki C et al 2012 J. Phys. B: At. Mol. Opt. Phys. 45 135002
[18] Peterson B J et al 2010 Fusion Sci. Technol. 58 412
[19] Peterson B J et al 2003 Plasma Phys. Control. Fusion 45 1167
[20] Datasheet of a 20 ch. AXUV photodiode array http://optodiode.com/pdf/AXUV20ELG.pdf
[21] Narihara K et al 2001 Rev. Sci. Instrum. 72 1122
[22] Yamada I et al 2010 Fusion Sci. Technol. 58 345
[23] Yoshinuma M et al 2010 Fusion Sci. Technol. 58 375
[24] Sanin A et al 2004 Rev. Sci. Instrum. 75 3439
[25] Michael C A et al 2006 Rev. Sci. Instrum. 77 10E923
[26] Tanaka K et al 2008 Rev. Sci. Instrum. 79 10E702
[27] Makino R et al 2013 Plasma Fusion Res. 8 2402115
[28] Chung H K et al 2005 High Energy Density Phys. 1 3
[29] Mollen A et al 2013 Phys. Plasmas 20 032310
[30] Howard N T et al 2014 Phys. Plasmas 21 112510
[31] Ida K et al 2004 Phys. Plasmas 11 2551
[32] Ida K et al 2005 Nucl. Fusion 45 391
[33] Idei H et al 1993 Phys. Rev. Lett. 71 2220
[34] Briesemeister A et al 2012 Plasma Phys. Control. Fusion 55 014002