Nonlinear dependence of plasma potential and ion impinging energy on energy loss of edge localized modes

S.Y. Dai and D.Z. Wang

Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People’s Republic of China

E-mail: daishuyu@dlut.edu.cn

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Abstract

Particle-in-cell (PIC) modelling has been performed to investigate the impact of energy loss during edge localized modes (ELMs) on the plasma potential and ion impinging energy on the divertor target. A double-peak structure of the ion impinging energy has been identified under JET-relevant ELM conditions. The ELM burst leads to a strong increase in the potential drop in front of the target plate, which accelerates the cold ions from the downstream divertor and accordingly causes a peak value of ion impinging energy. Moreover, the great potential drop helps confine the fast electrons and leads to a reduction in the potential drop and ion impinging energy. The arrival of the upstream hot ions results in the second peak value of ion impinging energy. The maximum potential drop and ion impact energy show a linear dependence on the pedestal temperature. Further, a nonlinear dependence of the peak potential drop and ion impact energy on the ELM energy loss can be ascertained based on the PIC simulations.

Keywords: particle-in-cell, edge localized modes, plasma sheath

(Some figures may appear in colour only in the online journal)
can provide the incident particles information and sputtering related data for other codes to mimic erosion process [27] and subsequent impurity transport [13]. Further, we study the influence of the plasma sheath evolution on the ion impact energy and the contribution of the potential drop to the ion impact energy during ELMs for EAST tokamak [14]. However, an important unresolved issue concerns that the role of the upstream ELM energy loss \( \Delta W_{\text{ELM}} \) affects the downstream sheath potential and ion impinging energy. The amplitude of \( \Delta W_{\text{ELM}} \) is strongly associated with the pedestal plasma temperature \( T_{\text{ped}} \) and the particle source \( S_p \). The measurements of the ion target impact energy on the JET experiments have been conducted by Langmuir probe and coupled infrared thermography, which indicates that the peak ion impact energy during ELMs has a linear dependence on \( T_{\text{ped}} \) [28]. Further, ELM-induced sudden increase in \( S_p \) can change the space charge distribution, which leads to a remarkable response of the plasma potential and ion impinging energy [14]. Hence, understanding the dependence of the potential drop and ion impact energy on \( \Delta W_{\text{ELM}} \) has a more general implication for estimating the ion impinging energy and the material sputtering yield.

In this work, the correlation of the plasma potential and ion impact energy with \( \Delta W_{\text{ELM}} \) is investigated by one-dimension-in-space and three-dimension-in-velocity (1d3v) PIC code SDPIC [13, 14]. The numerical algorithms of the SDPIC code and the comparison with the Type I ELM My H-mode experiments on EAST are introduced in [13]. In this study, the evolutions of potential drop and ion impinging energy are studied under the JET-relevant H-mode plasma conditions. The detailed analysis of dependence of maximum potential drop and ion impinging energy on \( T_{\text{ped}} \) and \( \Delta W_{\text{ELM}} \) has been conducted based on the SDPIC modelling results. Moreover, the same survey has been attempted for EAST case in order to make a comparative study for different size tokamaks. It is found that the amplitudes of the potential drop and ion impact energy are associated with the device size.

### 2. Methods and simulation setup

The ELMs modelling in SDPIC code is treated as before-ELM SOL source, ELM source and after-ELM SOL source (same as before-ELM). For the pre-ELM phase, the ions and electrons with a Maxwellian velocity distribution are injected into the simulation volume and tracked until a steady-state solution is obtained. The ELM burst is modelled as a transient source of plasma releasing the ELM energy loss \( \Delta W_{\text{ELM}} \sim T_{\text{ped}} S_p V_{\text{ac}} \) into the source volume \( V_{\text{ac}} \) in the SOL for a period of the ELM crash duration \( t_{\text{ELM}} \). The spatial grid-cell size and the time step should be of the order of Debye length and the plasma oscillation period in the PIC simulation, respectively [29]. This indicates that an unrealistically large number of spatial grid cells is required for a real size tokamak SOL. In order to resolve this issue, the shortening technique commonly implemented into the PIC modes [13, 14, 19–21] for SOL modelling is employed to reduce the computational size and simulation time, which is achieved by increasing the collision frequency by a shortening factor \( \alpha \) in the upstream plasma while the sheath remains unchanged. Increase in the collisionality results in a reduction in the mean free path length as well as time and size of the PIC model according to [19–21]. In order to discuss the simulation results in a real SOL size, it is necessary to rescale the simulation data by the shortening factor \( k \) for the shortened size and time. Here, it is noted that the domain length and transit times discussed in later text and figures have been converted to the situation with a real SOL size.

In this work, the geometric and plasma parameters are specified according to the typical H-mode discharge with ELMs on JET [5, 21, 25]. Table 1 presents the summary of parameters used in SDPIC modelling. The major radius of JET \( R = 3.0 \) m, the connection length \( L_c = 40 \) m and the shortening factor \( k = 70 \) are used for JET modelling. The magnetic field strength \( B = 2.4 \) T and pitch angle \( \alpha = 6^\circ \) are employed. One half of the target-to-target poloidal length \( L_{\text{pol}} = L_c \sin \alpha \) is about 4.181 m. The parallel length of the upstream source \( L_c = 25 \) m is used where hot particles are released. The pedestal plasma density \( n_{\text{ped}} = 1.0 \times 10^{19} \) m\(^{-3}\), electron temperature \( T_e = 100 \) eV and ion temperature \( T_i = 200 \) eV are applied for the upstream source before ELM burst. The ELM is triggered at 28 \( \mu \)s in the SDPIC simulation when ELM-free plasma is in the steady-state. The transient burst of ELM releases an ELM energy loss.

### Table 1. Summary of parameters used in SDPIC modelling.

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Magnetic field strength (T)            | 2.4                    |
| Pitch angle (°)                        | 6                      |
| Connection length \( L_c \) (m)        | 40                     |
| One half target-to-target poloidal length \( L_{\text{pol}} \) (m) | 4.181                 |
| Parallel length of upstream source \( L_c \) (m) | 25                    |
| Major radius \( R \) (m)              | 3                      |
| Pedestal plasma density before ELM (m\(^{-3}\)) | \( 1.0 \times 10^{19} \) |
| Pedestal temperature before ELM (keV)  | \( T_{\text{ped}} = 0.1 \) |
| Pedestal temperature during ELM (keV)  | \( T_{\text{ped}} = 0.5 \) |
| Particle source during ELM \( S_p \) (10\(^{26}\) m\(^{-3}\) s\(^{-1}\)) | 0.7                    |

For EAST simulations, the same survey has been attempted for EAST case in order to make a comparative study for different size tokamaks. It is found that the amplitudes of the potential drop and ion impact energy are associated with the device size.
\[ \Delta W_{\text{ELMs}} = 119 \, \text{KJ} \]
into the upstream source region with an ELM crash duration \( t_{\text{ELM}} = 200 \, \mu\text{s} \), which is referred to as the default case in this study. The pedestal plasma temperature \( T_{\text{ped}} = T_{\text{ped}} = 0.5 \, \text{keV} \) and particle source \( S_p = 0.7 \times 10^{26} \, \text{m}^{-3} \, \text{s}^{-1} \) are employed for the upstream source during ELM. In addition, the simulation parameters for EAST reference case are also shown in table 1.

### 3. Results and discussion

Figure 1(a) displays the spatial and temporal evolutions of the plasma potential during ELM for JET case. The spatial dimension of the simulation domain for ELM modelling is described as the poloidal length \( L_{\text{pol}} \) in figure 1(a), which is non-uniform due to the use of the shortening technique as mentioned above. The positions of the downstream divertor and upstream SOL are indicated to clearly mark the spatial evolution of the potential drop. The transit time scale for the upstream ELM electrons is evaluated as \( \tau_e \approx L_v/\nu_{th} \approx 4 \, \mu\text{s} \), where \( \nu_{th} \) is the electron thermal velocity at the pedestal. The propagation time scale \( \tau_i \) for the upstream ELM ions is about 183 \( \mu\text{s} \) (\( \tau_i \approx L_v/c_s \), \( c_s \) is the ion sound speed at the pedestal). Hence, the fast transit of electrons can lead to a strong space charge separation after triggering the ELM and accordingly a great evolution of plasma potential as shown in figure 1(a).

The peak value of the space potential is about 1.47 keV for the default case. The spatial evolutions of the plasma potential and ion velocity along the normal to the wall for the pre-ELM (14 \( \mu\text{s} \)) and during-ELM (98 and 196 \( \mu\text{s} \)) phases are presented in figures 1(b) and (c), respectively. For the case of 98 \( \mu\text{s} \), it can be calculated that the upstream ELM ions arrive at the location of \( L_{\text{pol}} \approx 2.6 \, \text{m} \). The increased ion velocity around \( L_{\text{pol}} = 2.6 \, \text{m} \) can also be seen for 98 \( \mu\text{s} \) in figure 3(c). While for 196 \( \mu\text{s} \), the main ELM ions are delivered to the position of \( L_{\text{pol}} \approx 0.3 \, \text{m} \). Hence, the ion velocity between \( L_{\text{pol}} = 0.3 \) and 2.6 \( \mu\text{m} \) for 196 \( \mu\text{s} \) is higher than that for the cases of 14 and 98 \( \mu\text{s} \) in figure 1(c). The significant potential drops during ELMs near the wall (\( L_{\text{pol}} \approx 10 \, \text{cm} \)) in figure 1(b) lead to an intense acceleration of the ion velocity in figure 1(c). The higher potential drop (~1.1 keV) for 98 \( \mu\text{s} \) results in a larger ion velocity on the wall compared to the cases of 14 and 196 \( \mu\text{s} \).

Based on the above simulation results, the detailed analysis of the influence of ELM-induced potential evolution on the ion impact energy has been performed in the current work, which is presented in figures 1(d)–(f) below. In addition, the potential evolution and the associated ion acceleration during ELMs were also studied by the BIT1 modelling in [5, 20, 21].

The impact of the strong evolution of the plasma potential on the ion impinging energy is studied by comparing the ion initial energy \( E_{\text{initial}} \) and ion impinging energy \( E_{\text{wall}} \). Since \( E_{\text{initial}} \) is recorded for each simulated particle in SDPIC, the distribution of \( E_{\text{wall}} \) can be obtained after the bombardment of the incident ions on the wall. In principle, the influence of the potential drop on the ion impact energy during ELM can be analysed by the energy difference \( (E_{\text{wall}} - E_{\text{initial}}) \). An interesting double-peak structure (labelled as EP1 and EP2) of the ion impinging energy can be seen in figure 1(d). At the beginning phase of ELM, the great potential drop induced by the fast electrons leads to a steep increase in the ion impinging energy, which are mainly from the cold ions with a very low initial energy near the target plate. However, the energy difference and the ion impinging energy decrease after around...
50 μs as shown in figure 1(e). The potential drop in figure 1(a) causing the energy difference in figure 1(e) reduces gradually in front of the divertor target. The great potential hill (>1 kV) near the target prevents the fast electrons ($T_{ped, e,i} = 0.5$ keV) from surmounting the repulsive sheath and reaching the wall surface. The deceleration of the upstream electrons leads to a suppression of the space charge separation and a resulting pullback of the potential drop, which results in a decrease of the ion impinging energy in figure 1(e). This pullback of the potential drop was not discovered in the previous study of EAST case [14] because the potential hill near the target is too low to obstruct upstream fast electrons. The upstream high energy ions lead to an increase of the ion impact energy after about 125 μs. The second peak value of the ion impact energy is obtained around 200 μs along with the arrival of the upstream bulk plasma to the downstream divertor. The peak ion impact energy (~2 keV) is about four times larger than $T_{ped} = 0.5$ keV, which has a good agreement with the experimental result on JET [28]. In addition, the second peak value of the energy difference is also obtained because the upstream ions can be accelerated by the space potential. Finally, the ion impact energy decreases gradually after the termination of ELM burst.

The effect of the ELM energy loss on the ion impinging energy and potential drop for JET is studied in figure 1(f). The larger $S_p$ can lead to a higher fast electron flux and an increased space charge separation on JET, which results in a higher potential drop and ion impact energy compared to EAST. Furthermore, the extent to which the ELM energy loss and the plasma potential affect the ion impinging energy for JET is investigated. The ratios of the corresponding energy difference to the maximum ion impact energy maintain about 0.46 for different ELM powers. The similar phenomena are also observed for the modelling of EAST, which shows that the contribution of the potential drop to the maximum ion impact energy is stronger for EAST [14]. For the same $T_{ped} = 0.5$ keV, the time interval between the maximum potential drop (EP1) and ion impact energy (EP2) is about 140 μs for JET ($\Delta W_{ELMs} = 119$ KJ), while the time interval is around 80 μs for EAST ($\Delta W_{ELMs} = 10.6$ KJ) [14]. The larger $L_e$ for JET results in a longer transit time for the upstream ions which are unable to replenish the downstream plasma in time as well as EAST for the same $T_{ped}$, which leads to a slower recovery of the potential drop for JET. Hence, the contribution of the potential drop to the maximum ion impact energy is stronger for JET.

Further, the impacts of pedestal temperature ($T_{ped}$) on the peak potential drop and ion impact energy have been ascertained in figure 2. The upstream particle source $S_p$ is governed by the parallel flux loss ($n_{ped} \times T_{0,ped}^0$) along the open field line according to the [25, 30]. Hence, the change in $T_{ped}$ would affect $S_p$ as well. Moreover, it can be derived $\Delta W_{ELMs} \sim (n_{ped}V_{src}^{ELMs}) \times T_{ped}^{1.5}$ according to the above-mentioned relation ($\Delta W_{ELMs} \sim T_{ped}^0S_pV_{src}^{ELMs}$). Table 2 shows the simulation parameters of pedestal temperature and particle source for different ELM energy losses during ELMs for JET and EAST cases.

Table 2. Simulation parameters for EAST.

| Parameter       | EAST 110 | EAST 119 | EAST 122 | EAST 111 | EAST 111 | EAST 111 | EAST 111 | EAST 111 | EAST 111 | EAST 111 |
|-----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $T_{ped, el}$   | 50       | 50       | 50       | 50       | 50       | 50       | 50       | 50       | 50       | 50       |
| $S_p$ (10^{26} m^{-3} s^{-1}) | 10.6     | 1.92     | 0.222    | 0.248    | 0.272    |         |         |         |         |         |
| $\Delta W_{ELMs}$ (KJ) | 10.6     | 1.92     | 0.222    | 0.248    | 0.272    |         |         |         |         |         |

The larger $S_p$ as well.

Figure 2. Profiles of the maximum potential drop ($\Delta \phi_{peak}$) and the ratio $\Delta \phi_{peak}/T_{ped}$ (a) and the peak value of ion impact energy ($E_{wall}^{max}$) and the ratio $E_{wall}^{max}/T_{ped}$ (b) against the pedestal temperature $T_{ped}$ for JET case.
parameters of pedestal temperature and particle source for different ELM energy losses during ELMs for JET and EAST cases. As the $T_{\text{ped}}$ rises, the increased fast electron flux makes a stronger space charge separation and a larger peak value of the potential drop in figure 2(a). It is found that the ratio $\Delta \phi_{\text{peak}}/T_{\text{ped}}$ maintains in the range from 2.7 to 3.0 for different $T_{\text{ped}}$. Moreover, the peak value of the ion impact energy, which emerges behind the maximum potential drop, also increases with $T_{\text{ped}}$. In particular, the simulated $E_{\text{wall}}$ has a four-fold linear relationship with $T_{\text{ped}}$, which is in reasonable agreement with the JET experimental measurements [28]. In addition, the same calculations of $\Delta \phi_{\text{peak}}/T_{\text{ped}}$ and $E_{\text{wall}}/T_{\text{ped}}$ have been carried out for EAST, which also shows the linear relations $\Delta \phi_{\text{peak}}/T_{\text{ped}} \approx 1$ and $E_{\text{wall}}/T_{\text{ped}} \approx 2$, respectively. The different ratios in $\Delta \phi_{\text{peak}}/T_{\text{ped}}$ and $E_{\text{wall}}/T_{\text{ped}}$ between JET and EAST are mainly due to different geometrical sizes and ELM powers for both devices. The larger $L_{c}$ and higher $S_{p}$ for JET lead to a stronger potential drop and a bigger ion impinging energy compared to EAST as mentioned above.

A further analysis of the relation of the peak potential drop and ion impact energy with the ELM energy loss is performed in figure 3, which can include both information of $T_{\text{ped}}$ and $S_{p}$. Since $\Delta \phi_{\text{peak}}$ and $E_{\text{wall}}$ have a linear dependence on $T_{\text{ped}}$, as shown in figure 2, $\Delta \phi_{\text{peak}}$ and $E_{\text{wall}}$ can be expressed as the empirical formula of $\Delta \phi_{\text{peak}} = f_{\phi} \cdot (\Delta W_{\text{ELMs}})^{2/3}$ and $E_{\text{wall}} = f_{E} \cdot (\Delta W_{\text{ELMs}})^{2/3}$ in combination with the above-mentioned relation $(\Delta W_{\text{ELMs}} \approx T_{\text{ped}}^{1.5})$, respectively. Here, the coefficients $f_{\phi}$ and $f_{E}$ can be estimated according to the results in figure 2. Figure 3 shows the maximum potential drop and ion impact energy against $\Delta W_{\text{ELMs}}$ by SDPIC simulations. The use of $f_{\phi} = 57$ and $f_{E} = 81$ in the empirical formula for $\Delta \phi_{\text{peak}}$ and $E_{\text{wall}}$ gives a good agreement with the simulated data set by SDPIC, as shown in figure 3. The same attempt has been conducted for the EAST tokamak, which also shows the nonlinear dependence of $\Delta \phi_{\text{peak}}$ and $E_{\text{wall}}$ on $\Delta W_{\text{ELMs}}$ with $f_{\phi} = 110$ and $f_{E} = 218$, respectively. The different coefficients are mainly associated with the dimensional difference between JET and EAST. The larger size of JET possesses a stronger $S_{p}$ and also a bigger $V_{\text{ac}}$ and $L_{c}$, which leads to a different ELM transport behaviour as mentioned above and resulting different coefficients between JET and EAST. The ELM energy loss for JET is around ten times higher than that for EAST for the same $T_{\text{ped}}$. The respective maximum potential drop and ion impact energy for JET are enhanced by a factor of about 2.6 and 1.8 compared to EAST according to the above empirical formulae.

4. Conclusions

This study, for the first time, identifies that the maximum potential drop and ion impact energy during ELMs have a nonlinear dependence on the ELM energy loss. The empirical formulae derived from the numerical modelling can be used to make an analytic scaling of the peak potential drop and ion impact energy, which has a strong implication for estimating the sputtering yield induced by ELMs for tokamak devices. For JET-relevant ELM conditions, a double-peak structure of the ion impinging energy has been observed. The first peak value of the ion impact energy is due to the strong ELM-induced potential drop causing a significant increase in the impinging energy of the cold ions from the downstream divertor; and then the great potential hill near the target can help confine the fast electrons, which leads to a potential pullback; finally the second peak value is obtained by the upstream hot ions which can be adequately accelerated by the space potential. The peak potential drop and ion impact energy show a linear dependence on the pedestal temperature for both JET and EAST. The simulated maximum ion impact energy has a four-fold linear relationship with the pedestal temperature on JET, which is in reasonable agreement with the experimental measurements.

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ORCID iDs
S.Y. Dai https://orcid.org/0000-0001-6384-8437
D.Z. Wang https://orcid.org/0000-0003-0517-7318

References

[1] Loarte A. et al 2007 Nucl. Fusion 47 S203
[2] Zohm H. 1996 Plasma Phys. Control. Fusion 38 105
[3] Loarte A. et al 2003 Plasma Phys. Control. Fusion 45 1549
[4] Pitts R.A. et al 2006 Nucl. Fusion 46 82
[5] Pitts R.A. et al 2007 Nucl. Fusion 46 1437
[6] Eich T. et al 2003 Phys. Rev. Lett. 91 195003
[7] Eich T. et al 2011 Phys. Rev. Lett. 107 215001
[8] Federici G. et al 2003 Plasma Phys. Control. Fusion 45 1523
[9] Kreter A. et al 2009 Phys. Rev. Lett. 102 045007
[10] Eckstein W. 2008 Vacuum 82 930
[11] Pitts R.A. et al 2013 J. Nucl. Mater. 438 S48–56
[12] Doerner R.P. et al 2009 Nucl. Fusion 49 033002
[13] Dai S.Y. et al 2015 Nucl. Fusion 55 043003
[14] Dai S.Y. et al 2018 Nucl. Fusion 58 014006
[15] Federici G. et al 2001 Nucl. Fusion 41 1967
[16] Manfredi G. et al 2011 Plasma Phys. Control. Fusion 53 015012
[17] Moulton D. et al 2013 Plasma Phys. Control. Fusion 55 085003
[18] Coulette D. et al 2016 Plasma Phys. Control. Fusion 58 085004
[19] Bergmann A. 2002 Nucl. Fusion 42 1162
[20] Tskhakaya D. 2017 Plasma Phys. Control. Fusion 59 114001
[21] Tskhakaya D. et al 2004 Proc. ‘Theory of Fusion Plasmas’ (Bologna, Italy) p 97
[22] Hosokawa M. 2016 Plasma Fusion Res. 11 1403104
[23] Hosokawa M. et al 2018 Proc. 45th EPS Conf. on Plasma Physics (Prague, Czech Republic, 2–6 July 2018) p O2.110 (http://ocs.ciemat.es/EPS2018PAP/pdf/O2.110.pdf)
[24] Havlíčková E. et al 2011 Plasma Phys. Control. Fusion 53 065004
[25] Havlíčková E. et al 2012 Plasma Phys. Control. Fusion 54 045002
[26] Dai S.Y. et al 2014 Nucl. Fusion 54 123015
[27] Dai S.Y. et al 2015 J. Nucl. Mater. 463 372
[28] Guillemaut C. et al 2015 Plasma Phys. Control. Fusion 57 085006
[29] Birdsall C.K. et al 1985 Plasma Physics via Computer Simulation (New York : McGraw-Hill)
[30] Loarte A. et al 2002 Plasma Phys. Control. Fusion 44 1815