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Emitting large dust grains: Floating potential and potential wells

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In this paper we present a new theory, Modified Orbital Motion Limited - EMission, which examines the effect of electron emission on the charging of large dust grains. One of the most important aspects is the calculation of the particle's floating potential, which is the potential that the dust acquires when it is in contact with the plasma. Our theory determines the floating potential on the surface of the dust grain and predicts the formation of a potential well. Our model is applied in the Dust in TOKamakS (DTOKS) dust transport code and it is compared with DTOKS' pre-existing model. *Published by AIP Publishing.* https://doi.org/10.1063/1.5010042

I. INTRODUCTION

The behaviour of solid particles in a plasma environment is an important issue that has applications both in artificial plasmas, e.g., low temperature plasma discharges or tokamaks, and naturally occurring plasma systems, e.g., the spokes in Saturn's rings or Enceladus' ice plumes. An important aspect of the physics of the interaction of these particles with the plasma is the model determining their charge. Specifically, in the modelling of dust transport in tokamaks, it was shown that in the Scrape-Off Layer (SOL) relevant conditions, the dust's floating potential was found to be the most important factor determining the dynamical behavior of the particle in the reactor,[1,2] as they were found to have the largest impact on the particle's trajectory.

In applications where the charging of the solid particles is due to the ion and electron fluxes from the plasma and where the size of the particles is smaller than the electron Debye length, the Orbital Motion Limited (OML) approach can be applied. In cases where the size of the particles is larger than the electron Debye length, there are alternative approaches to OML, like the orbital motion (OM[3]) theory and the Modified Orbital Motion Limited (MOML)[4] approach. However, in many plasma environments, e.g., in space physics and in tokamaks, there are additional charging mechanisms that need to be taken into account and add complications to the modelling of dust charging. These challenges include the effect of magnetic fields, thermionic emission,[5,6] photoelectric effects,[5] radioactivity,[7] secondary effects,[5,6] and in some cases combinations of all the above factors. Specifically for tokamaks and the case of electron emission versions of OML have been initially introduced.[6,8] It was shown that in cases where the emitted electron flux is high compared to the plasma electron flux to the grain we have a formation of a potential well and this must be taken into account[5] as it plays an important role in the charging of emitting dust grains. The aforementioned approaches do not adequately predict the formation of the potential well. Some recent approaches address this but they are based on OML focusing on the grains with radius smaller than the electron Debye length.[5,9] However, as it was shown in Kennedy and Allen,[3] OML does not fully resolve the physics of large dust grains. Our approach takes into account the effect of a formed sheath around the dust grain and it accurately addresses the charging in the case of emitting large dust grains.

In this work, we will focus on the effect of electron emission to the charging of dust grains larger than the Debye length and explore how to incorporate the formation of a potential well structure when the ratio of emitted electron flux to the electron flux from the plasma is close or larger than one. We will start by giving a brief account of the source-collector sheath system in planar geometry upon which our theory stems from and we will present the new theory, MOML-EM (Modified Orbital Motion Limited - EMission), which calculates the floating potential for all values of δ, where δ is the ratio the flux of the emitted electrons over the flux of electrons coming from the plasma. The new theory addresses the previous limitations and also predicts the formation of a potential well. Finally, we will apply its results to the Dust in TOKamakS (DTOKS) dust transport modeling code, developed at Imperial College[6] and discuss an example of the model's application.

II. THE MOML-EM THEORY

MOML with electron emission[10] takes into account the fact that large dust grains have a developed sheath structure around them. In the sheath, we have a large percentage of the potential drop between the dust grain and the plasma. We also assume that the spatial dimensions of the sheath are much smaller than the size of the dust grain, $\rho = \frac{r_d}{\lambda_{De}} \gg 1$. We also assume that all the ions that reach the sheath will also reach the grain's surface. Taking these two points into account, in MOML, the ion current is not calculated at the grain's surface but at the sheath's edge. In this case, the current balance, including electron emission from the dust grain, is given by

$$(1-\delta)\exp(\psi_f) = (\tau\mu)^{1/2}\left(1 - \frac{\psi_f - \Delta\psi_{em}}{\tau}\right), \qquad (1)$$

where $\psi_f = (e\phi)/(kT_e)$ is the normalised dust floating potential, $\Delta\psi_{em}$ is the potential drop in the sheath, τ is the ratio of the ion temperature to the electron temperature, and μ is the

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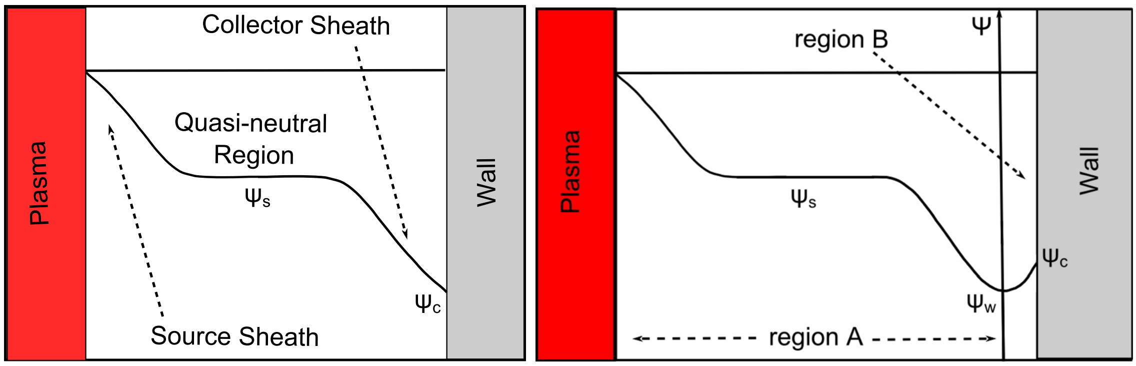

FIG. 1. Graphic representation[11] of the source collector sheath system with electron emission for the cases with no potential well (left) and with potential well (right). In the case with potential well, the figure also depicts the two regions A and B. Also, in the figures, we have the depiction of the source potential, ψ_s, the collector potential, ψ_c, at the wall and the well potential, ψ_w.

ratio of the electron mass to ion mass. In the case of MOML with electron emission,[10] this is calculated using

$$\Delta\psi_{em} = \frac{1}{2}\ln\left(2\pi\mu\cdot\frac{1+\gamma\tau}{(1-\delta)^2}\right), \tag{2}$$

where γ is assumed[4] to be 5/3. In this case, the potential of the surface is assumed to be negative compared to the plasma and the potential in the sheath to be monotonic. From combining these with Eq. (1), we can find that these conditions break down for δ in the range of 0.91 to 0.97, depending on the value of τ.

However, by looking back at theoretical and simulation results of the sheath of electron emitting surfaces in the source collector sheath system,[11] it was shown that even before the break down of the above equations we have a transition to a non-monotonic potential in the sheath region, namely, the formation of a potential well. This can be seen also in Fig. 3 where the formation of the potential well starts for $\delta \approx 0.85$. Our approach in this paper will incorporate the formation of the potential well to the MOML theory. We will refer to this new theory as MOML-EM.

In the source collector sheath model with thermionic emission,[11] we have two distinct cases. In the first case, where there is no potential well formed (see Fig. 1), we have the formation of a source sheath near the boundary and a collector sheath near the wall. Between the two, we have the formation of a quasi-neutral region. In this case, the ions are being accelerated towards the emitting boundary and every ion is absorbed by the wall and none of them returns to the source. In this case,[11] the electron flux and the emitted electron flux are given by

$$F_e(\psi) = A_e v_{BC}^2 \frac{\exp\psi_c}{\mu}, \tag{3}$$

$$F_{em}(\psi) = A_e v_{BC}^2 \frac{\Xi\sqrt{\Delta}}{\mu}, \tag{4}$$

where $A_e = N_{se}\left(\frac{m}{2\pi k T_e}\right)^{1/2}$, m is the electron mass, T_e is the plasma's electron temperature, N_{se} is the electron density of the full Maxwellian source, and v_{BC} is the Bohm velocity for cold ions. We also denote Δ as the ratio of emitted electron temperature over the electron temperature, $\Delta = T_{em}/T_e$, where T_{em} is the emitted electron temperature, and we set $\Xi = N_{em}/N_{se}$ where N_{em} is the number density of the emitted electrons at the wall and N_{se} is the number density of the electrons at the bulk plasma.

The ratio of the emitted electron current over the electron current, δ, is given by dividing the two above equations

$$\delta = \frac{\Xi\sqrt{\Delta}}{\exp\psi_c}. \tag{5}$$

The above δ is used in Eq. (1) combined with $\Delta\psi = \psi_c - \psi_s$ (see Fig. 2), as calculated in Ref. 11, where ψ_c is the collector potential and ψ_s is the source sheath potential. $\Delta\psi$ is used instead of $\Delta\psi_{em}$. From Eq. (1) and as described above, we calculate the floating potential (see Fig. 3 for values of $\delta = 0$ to $\delta \approx 0.85$). The floating potential for $\delta = 0$ can be seen in Fig. 4 where it is compared with the potential drop used in MOML, as detailed in Eq. (2).

The value of δ where the transition between the case, where the potential is monotonic to the formation of the potential well, is predicted using the model developed by Rizopoulou *et al.*[11]

For the second case, we have a formation of a potential well and the area between the source and the collector can be divided in two distinct regions (see Fig. 1); the first is from

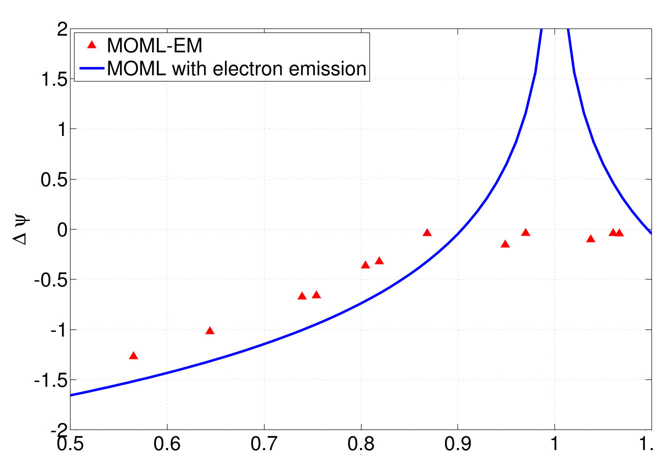

FIG. 2. The potential drop $\Delta\psi$ for MOML with electron emission[10] versus the one calculated from the source-collector sheath system with electron emission[11] as a function of δ, with $\tau = 1$.

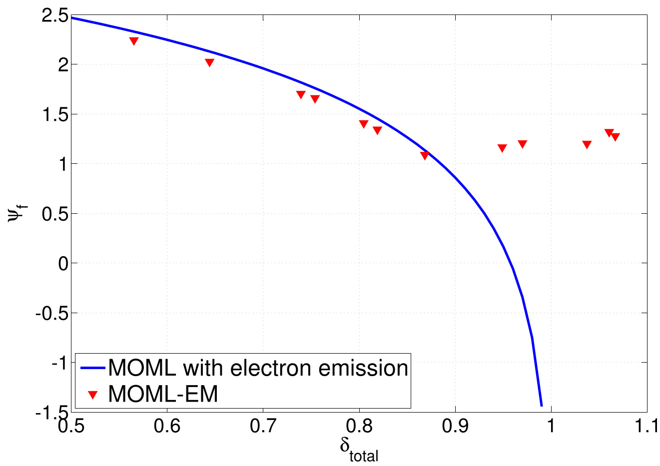

FIG. 3. The floating potential calculated from MOML with electron emission and with the MOML-EM as a function of δ_{total}, $\tau = 1$.

the plasma source to the potential well (region A) and the second from the potential well to the collector (region B). In region A, the situation is similar to the no well case. In region B, the ions are moving into a retarding potential, whereas the plasma electrons are moving into an accelerating potential. The emitted electrons move into a retarding potential between the wall and the minimum of the potential well. Because of this, a fraction of the emitted electrons returns to the surface.

In this case,[11] the electron flux is given by the following equation:

$$F_e(\psi) = A_e v_{BC}^2 \frac{\exp \psi_w}{\mu}, \tag{6}$$

and it represents the electrons that reach the collector, where ψ_w is the potential at the bottom of the well. The flux of the emitted electrons from the surface of the dust grain is given by the following equation:

$$F_{em,surface}(\psi) = A_e v_{BC}^2 \frac{\Xi\sqrt{\Delta}}{\mu}. \tag{7}$$

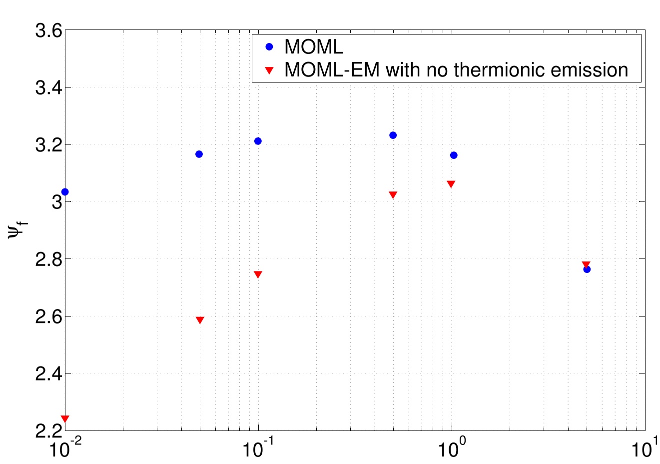

FIG. 4. The floating potential for MOML[4] and MOML-EM, with no electron emission, as a function of τ.

From these electrons, the fraction which manages to escape from the potential well is given by

$$F_{em,well}(\psi) = A_e v_{BC}^2 \frac{\Xi\sqrt{\Delta}}{\mu} \exp \frac{\psi_w - \psi_c}{\Delta}, \tag{8}$$

while the rest returns to the grain's surface.

In this case, δ is calculated by dividing Eq. (8) by Eq. (6) and it is given by the equation

$$\delta = \frac{\Xi\sqrt{\Delta}\exp((\psi_w - \psi_c)/\Delta)}{\exp(\psi_w)}. \tag{9}$$

The above δ is used in Eq. (1) combined with $\Delta\psi = \psi_w - \psi_s$ (see Fig. 2), as calculated in Ref. 11, where $\Delta\psi$ is used instead of $\Delta\psi_{em}$. Using this, we calculate the floating potential. More specifically, in Fig. 2, we can see the potential drop $\Delta\psi$ calculated from the MOML with electron emission and the new theory MOML-EM as a function of δ. We can see that in the previous model around the value $\delta = 1$ there is a discontinuity, whereas in the new theory, this is successfully addressed. In Fig. 3, we compare MOML-EM to MOML with electron emission, and we plot both theories against δ_{total}, defined as the ratio of the flux of the total emitted electrons from the surface over the flux of the ones coming from the plasma, not taking into account emitted electrons returning to the surface. It can be seen that in the previous model the floating potential tends to zero and changes sigh, whereas in the new theory it is stabilized predicting also the formation of a potential well.

In order to find the floating potential at the surface of the dust grain, we add to this value the $\Delta\psi = \psi_c - \psi_w$, which is calculated by the source collector sheath system.[11] So, for the potential well case, the floating potential is calculated by

$$\psi_{f,dust} = \psi_{w,MOML-EM} + (\psi_c - \psi_w). \tag{10}$$

III. MOML-EM THEORY IN DTOKS

In this section, we apply our charging theory, MOML-EM, in the dust transport code DTOKS[6] for Hydrogen ions. DTOKS simulates the dynamical behavior of solid particles in a plasma environment by calculating their charge, the forces acting on them, and the energy fluxes on the grains. DTOKS' charging model employs OML for electron emission for cases where $\delta < 1$ and the calculated potential is negative. When the second condition fails, DTOKS assumes the formation of a potential well. This potential at the bottom of the potential well is given by OML without electron emission. This is because it is assumed that the emitted electrons are trapped in the potential well and return to the grain. Furthermore, it is assumed that the potential difference between the bottom of the potential well and the grain's surface is of the order the temperature of the dust grain, T_d. One of the problems of this approach is that as δ and the corresponding electron emitted flux increase, the potential of the dust grain tends to zero. However, when DTOKS assumes the formation of a potential well the predicted grain's potential becomes much more negative creating a discontinuity (see Fig. 5).

In this work, we compare two modifications of the DTOKS charging model for electron emitting large dust grains. First, we apply for the first time the MOML with electron emission theory to the DTOKS code and examining for the first time the case of large dust grains. This previously published approach, MOML with electron emission theory, provides a much better estimate to the grain's potential for large particles but exhibits the same discontinuity discussed above (see Fig. 5). The second approach is using our new model, the MOML-EM theory, developed in this paper which treats the formation of the potential well self-consistently. As a result, as we can also see in Fig. 5, MOML-EM predicts a continuous transition to the potential well regime. In Fig. 5, the floating potential of the dust grain in DTOKS as a function of time is plotted, predicted by the previous theory and our new theory, MOML-EM. At the initial charging phase, secondary electron emission dominates, whereas as the temperature of the grain increases, thermionic emission becomes dominant.

The result of self-consistently calculating the formation of the potential well has an important impact on the dynamical behavior of the dust grains in the plasma environment. The use of the MOML-EM has two main effects. The first is the prediction of a smaller magnitude for the potential and thus larger plasma currents. This leads to comparatively higher ion drag on the dust grain (see Fig. 6). Furthermore, the observed discontinuity in the previous model is due to the sudden change in the floating potential predicted by DTOKS previous model. The second effect is that MOML-EM allows for emitted electrons escaping the potential well, acting as an additional cooling mechanism for the dust grain. The result of this can be seen in Fig. 7 where this outward energy flux, in higher temperatures, leads to a lower equilibrium dust temperature and thus to a larger survival time.

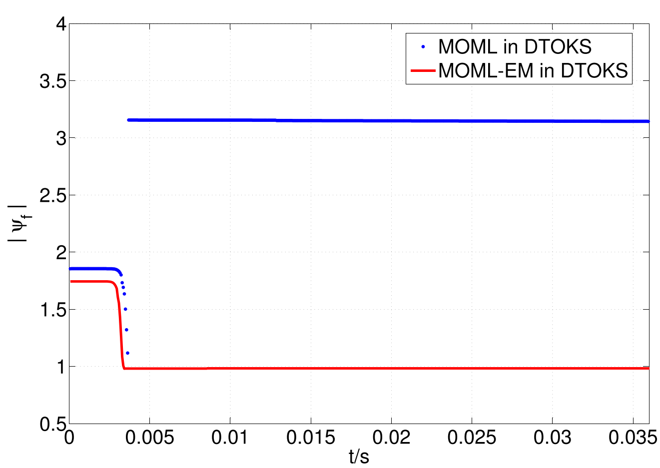

FIG. 5. The floating potential of the dust grain in DTOKS as a function of time, for the previous theory MOML (blue line) and the new MOML-EM theory (red line). At the initial charging phase, secondary electron emission dominates. As the temperature of the grain increases, thermionic emission becomes dominant. The DTOKS simulations were carried out for a tungsten dust grain with a radius of $r_d = 400\,\mu$m, an initial velocity of $v_d = 75\,\mathrm{ms}^{-1}$, and a plasma with $T_i = T_e = 60\,$eV, $n = 5\times10^{19}\ \mathrm{m}^{-3}$, and a plasma flow velocity $v_p = u_{th,i}$, where $u_{th,i}$ is the ion thermal velocity.

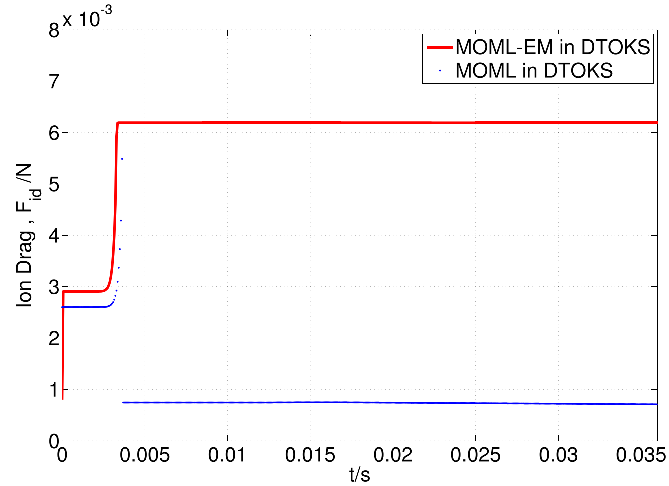

FIG. 6. The ion drag force on the dust grain in DTOKS as a function of time, for the MOML and MOML-EM theories. The DTOKS simulations were carried out for a tungsten dust grain with a radius of $r_d = 400\,\mu$m, an initial velocity of $v_d = 75\,\mathrm{ms}^{-1}$, and a plasma with $T_i = T_e = 60\,$eV, $n = 5\times10^{19}\ \mathrm{m}^{-3}$, and a plasma flow velocity $v_p = u_{th,i}$, where $u_{th,i}$ is the ion thermal velocity.

IV. CONCLUSIONS

In conclusion, we have introduced a new theory MOML-EM focusing on electron emitting large dust grains. Our theory addresses the behavior of the dust grain in the regime where the emitted electron flux dominates the charging mechanism of the dust grain and leads to the creation of a potential well. We have also applied our theory in the dust transport code DTOKS and compared our results with DTOKS initial charging model, which we modified for large dust grains. We verified that the application of MOML-EM in DTOKS addresses the code's previous limitations in this regime including the discontinuity from the no-well to the well regime. Furthermore, we have observed the important effect that MOML-EM has on the dynamic behavior of the dust grain. The potential impact of our findings spans a wide region of physics where plasma-dust interactions are

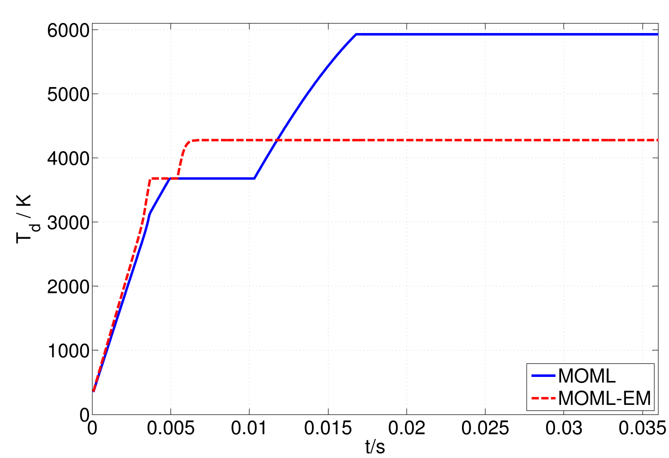

FIG. 7. The dust grain temperature in DTOKS as a function of time, for the MOML and MOML-EM theories. The DTOKS simulations were carried out for a tungsten dust grain with a radius of $r_d = 400\,\mu$m, an initial velocity of $v_d = 75\,\mathrm{ms}^{-1}$, and a plasma with $T_i = T_e = 60\,$eV, $n = 5\times10^{19}\ \mathrm{m}^{-3}$, and a plasma flow velocity $v_p = u_{th,i}$, where $u_{th,i}$ is the ion thermal velocity.

involved, such as space physics, astrophysics, plasma processing and diagnostics, and magnetic confinement fusion.

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[1]M. Bacharis, M. Coppins, and J. E. Allen, Phys. Rev. E **82**, 026403 (2010).
[2]M. Bacharis, *Theoretical Study of Dust in RF Discharges and Tokamak Plasmas* (Imperial College London, 2009).
[3]R. V. Kennedy and J. E. Allen, J. Plasma Phys. **69**(6), 485–506 (2003).
[4]C. T. N. Willis, M. Coppins, M. Bacharis, and J. E. Allen, Phys. Rev. E **85**(3), 036403 (2012).
[5]G. L. Delzanno, A. Bruno, G. Sorasio, and G. Lapenta, Phys. Plasmas **12**, 062102 (2005).
[6]M. Bacharis, M. Coppins, and J. E. Allen, Phys. Plasmas **17**, 042505 (2010).
[7]J. Winter, V. E. Fortov, and A. P. Nefedov, J. Nucl. Mater. **290-293**, 509–512 (2001).
[8]R. D. Smirnov, A. Yu Pigarov, M. Rosenberg, S. I. Krasheninnikov, and D. A. Mendis, Plasma Phys. Controlled Fusion **49**(4), 347 (2007).
[9]G. L. Delzanno and X. Z. Tang, Phys. Rev. Lett. **113**, 035002 (2014).
[10]M. Bacharis, Phys. Plasmas **21**, 074501 (2014).
[11]N. Rizopoulou, A. P. L. Robinson, M. Coppins, and M. Bacharis, Phys. Plasmas **21**, 103507 (2014).