Studies of Cs Dynamics in Large Ion Sources Using the CsFlow3D Code

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Abstract. Large negative ion sources for neutral beam injection rely on surface production of negative ions on a converter surface (plasma grid) in a low temperature plasma environment. To increase the negative ion production efficiency and reduce the amount of co-extracted electrons, the work function of the plasma grid is reduced by using Cs, which is evaporated in the source and redistributed by the plasma on the inner surfaces. In order to avoid a degradation of the plasma grid work function during beam pulses a sufficient flux of Cs onto the plasma grid needs to be maintained, especially for long pulses (several hundred seconds). The Cs flux is influenced by the plasma distribution in the source, which can be affected by a vertical drift due to the magnetic filter field. Simulations of Cs transport performed with the Monte Carlo code CsFlow3D have shown that the plasma drift in ELISE does not lead to an asymmetric distribution of neutral Cs density, as shown also by experimental data from TDLAS (Tunable Diode Laser Absorption Spectroscopy). Different results were obtained for the transport of Cs^+ ions, which are affected by the presence of the plasma grid bias potential with the conclusions that Cs^+ ions might not have enough energy to overcome the plasma grid bias potential. An alternative configuration of Cs ovens relies on the direct evaporation close to the plasma grid and can help in delivering the required Cs flux for long pulses at ELISE is suggested. Furthermore, CsFlow3D was extended to the full size ITER-NBI source at SPIDER and simulations for long pulses have indicated the evaporation rate needed in this large source and show a strong temporal dynamics of the Cs flux.

INTRODUCTION

Neutral Beam Injection (NBI) systems will be used in ITER to provide heating and current drive with a total power of 33 MW at 1 MeV energy in deuterium (0.87 MeV in hydrogen) [1]. These systems rely on large negative ion sources with 0.2 m^2 extraction area which need to deliver 40 A of accelerated D^- current for up to one hour, with a co-extracted electron current below that of the extracted negative ions [1]. The RF prototype source (1/8 of the ITER-NBI source size) in operation at IPP Garching has been chosen as the reference design for the ITER-NBI source [2]. An intermediate step towards the full-size source is represented by the ELISE ion source [3], half the size of the ITER-NBI source, also in operation at IPP. The prototype of the full ITER-NBI source has just started the operation at the SPIDER test facility (Consorzio RFX, Padova, Italy) [4].

In these sources negative ions are mostly produced by the surface conversion of H/D atoms onto a metallic converter surface. The conversion efficiency can be increased by reducing the converter surface work function, which is achieved by evaporating Cs inside source [5]. The evaporated Cs can deposit onto the source inner surfaces and be redistributed inside the source by the plasma. During source operation there are in fact mechanisms that can lead to a degradation of the surface work function [6], due to the high reactivity of Cs with the impurities present in the source (the background gas pressure is ~ 10^{-4} Pa, which is far from the ultra-high vacuum condition) and the plasma induced removal of the Cs layers deposited on the converter surface. In order to achieve the required extracted negative ion current and to limit the amount of co-extracted electrons for the one hour pulse required by ITER, it is mandatory to maintain the low work function of the converter surface by having a sufficient Cs flux onto the surface [6].

The study of the Cs transport inside the source and the understanding of the mechanism driving the Cs dynamics are therefore of fundamental importance to achieve the high performances required by ITER. These investigations can be carried out by combining the experimental results from the test facilities with the modelling of Cs transport performed with the Monte Carlo Transport Code CsFlow3D [7]. The model uses as input the ion source geometry, plasma parameter maps (plasma density, electron temperature, plasma potential) and the sticking probability of Cs onto the inner surfaces in order to determine the Cs transport probability between surface elements in the source by considering different collisional processes with the background gas and the plasma particles. The plasma parameter map used in the simulations where obtained from experimental measurements: a more detailed description of the code with the list of the collisions taken into account is given in [7]. The simulation domain is three dimensional and corresponds to the entire volume of the modelled negative ion source. The boundary conditions are represented by the source inner walls, where Cs can either be adsorbed or desorbed and the apertures of the plasma grid (PG) surface, through which Cs particles can be lost. The output values that can be calculated are the Cs fluxes onto the surface (both for neutral and positive Cs ions), the Cs coverage on the surfaces and the line averaged neutral Cs density which can be directly compared with the experimental measurements performed with Tunable Diode Absorption Spectroscopy (TDLAS) [8].

The CsFlow3D code results were compared and benchmarked with experimental data from the prototype source at the BATMAN test facility as well as from the ELISE source [9,10]. The application of the code to the prototype source allowed to identify the principal mechanisms which are relevant for the Cs dynamics, such as the influence of the plasma parameters on Cs redistribution, the role of Cs reservoirs deposited on the walls and the Cs release due to the back-streaming positive ions sputtering the Cs at the backplate of the ion source [9,10].

This work focuses on the application of the code to the ELISE test facility in order to study up to which extent the Cs distribution and the Cs flux impinging onto the converter surface (plasma grid) can be influenced by the plasma distribution and the electrostatic potential inside the source. For the first time the code has been used to evaluate the Cs consumption at the SPIDER test facility with the premises to obtain similar fluxes observed at ELISE and to investigate the temporal evolution of the Cs flux during long pulses with continuous extraction.

DESCRIPTION OF THE SOURCE AT THE ELISE TEST FACILITY

Figure 1 shows a schematic of the source at the ELISE test facility with the main parts. The plasma is inductively generated in four cylindrical drivers and expands into the large expansion chamber. The maximum available RF power is 75 kW/driver. The main converter surface where negative ions are produced is the plasma grid, the first grid of a three grid system which is used to extract and accelerate the negative ions to a maximum energy of 60 kV.

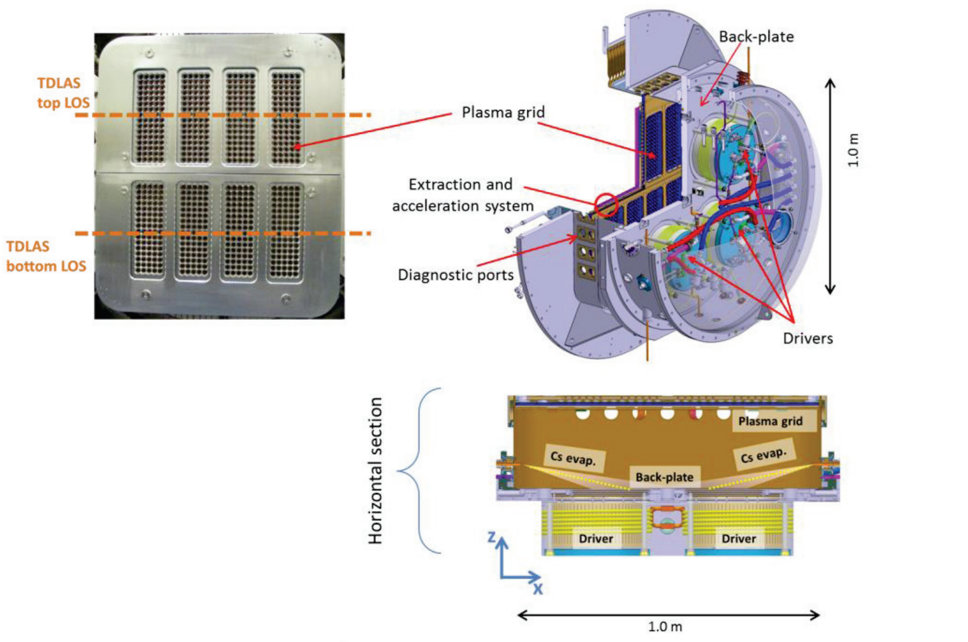


FIGURE 1. Schematic view of the source at the ELISE test facility**.** The horizontal cross section shows the positions of two Cs ovens. The front view of the plasma grid shows the two horizontal lines of sight used for monitoring the neutral Cs density by means of TDLAS.

The operation of the source is pulsed, i.e. it operates in cycles of a vacuum phase (with a background pressure of 10^{-4} Pa) followed by a plasma phase, in which the RF power supply is turned on and the hydrogen/deuterium filling pressure is set to 0.3 Pa. The plasma phase is unlimited, whereas beam extraction is possible only for 10 s every 150 s (pulsed extraction) due to restriction of the HV power supply.

Caesium is continuously evaporated inside the source during the source operation (both during the vacuum and plasma phases) by means of two nozzles located in the side of the source expansion chamber. The nozzles are oriented in order to evaporate Cs towards the back-plate of the source expansion chamber.

In order to monitor the amount of Caesium in the source, Tunable Diode Laser Absorption Spectroscopy (TDLAS) [8] is used and the two lines of sight in front of the plasma grid as indicated in Fig. 1.

A magnetic filter field is needed to reduce the electron density and temperature in front of the plasma grid. This reduces also the amount of co-extracted electrons. The horizontal magnetic field is generated by driving a current on the order of kA through the PG (1 kA of current is equivalent to a magnetic field close to the PG of ~ 1 mT). The filter field causes of vertical asymmetry of plasma profiles, such as plasma density and temperature, due to $\vec{F} \times \vec{B}$ drift as well as diamagnetic drifts [11]. Since the current flows from the bottom to the top of the plasma grid, the generated magnetic field induces an upward plasma drift.

An additional parameter that can be adjusted to reduce the amount of the co-extracted electrons is represented by the bias voltage: the PG is typically positively biased with respect to the source walls. Due to the plasma drift, the plasma potential might locally different: if the PG potential is higher than the plasma potential, an electron attracting sheath can be created, i.e. the electrons are accelerated towards the PG surface thus reducing the amount of co-extracted electrons; in the other case, if the PG is instead at a lower potential w.r.t. the plasma potential, an electron repelling sheath is formed.

INFLUENCE OF THE PLASMA DRIFT ON CAESIUM DISTIRBUTION

Simulations performed with CsFlow3D and experimental measurements at the prototype source have shown that an asymmetry of the Cs distribution inside the source can be connected to the vertical plasma drift induced by the magnetic filter field: it has in fact been proven that the plasma transport is mostly determined by the distribution of the plasma inside the source [9].

In the case of ELISE, the plasma drift is far less pronounced w.r.t. the prototype source, as observed experimentally [12, 13]. In order to investigate the effect of the drift on the Cs distribution, twenty consecutive pulses consisting of a 400 s vacuum phase and 20 s plasma pulses starting with a Cs free source (clean source) have been simulated by using CsFlow3D. The neutral Cs density along the two horizontal lines of sight used by TDLAS in the experiment (fig. 1), averaged during the 20 s plasma pulse, was calculated. These simulations have been performed for two different plasma parameter maps (plasma density, electron temperature, plasma potential): first by neglecting any plasma drift, i.e. with vertically symmetric plasma parameter maps, secondly by considering a vertical upward shift of the plasma parameter maps in order to reproduce the plasma drift which occurs experimentally. Langmuir probes measurements have shown a plasma density in the top probe almost twice as high as in the bottom for a magnetic filter field of ~ 2 mT (i.e. 2 kA of PG current) [13].

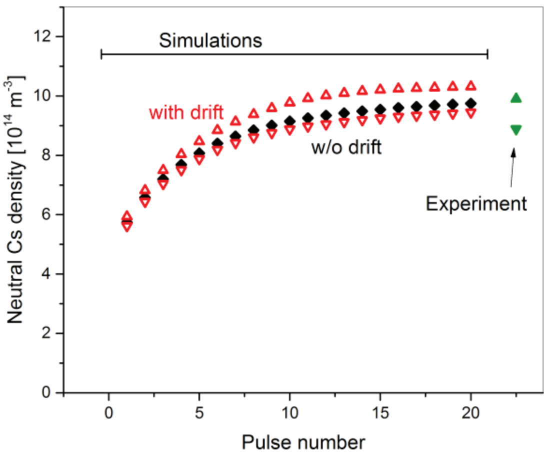


FIGURE 2. Simulated neutral Cs density in the two horizontal lines of sight shown in Fig. 1, for the 20 consecutive conditioning pulses: empty symbols show the case considering the plasma drift, full symbols the case without drift. Additionally labeled on the right the experimental values from TDLAS.

Figure 2 shows the plots of the Cs density as function of the consecutive pulse number for the two horizontal lines of sight and for the two cases with and without plasma drift. When the plasma drift is neglected (full symbol in the plot), the neutral Cs densities on the two lines of sight are identical: in this condition there is nothing that can perturb the symmetry of Cs redistribution, due to the vertical symmetry of the source geometry, the plasma parameters and of the nozzle position. When considering the plasma drift (empty triangles in the plot), the neutral Cs density in the top (n_{top}) is higher than in the bottom (n_{btm}), confirming that the Cs distribution follows the plasma distribution. The difference between the two lines of sight is however very small: the ratio n_{top}/n_{btm} for the 20th pulse is ~ 1.1, while for the prototype source investigations, with a higher plasma drift, this ratio was up to 2.5 [9]. These simulation results are in agreement with the absolute value of the experimental observations from TDLAS, which are also shown on the right side of the plot of Fig. 2.

It can therefore be stated that in the larger source at the ELISE test facility due to the low vertical plasma drift, there is no relevant vertical asymmetry of the neutral Cs distribution in front of the plasma grid. However the Cs^+ ion transport is differently affected, since it depends also on the presence of the PG bias voltage.

INFLUENCE OF THE PG BIAS VOLTAGE ON THE CAESIUM FLUX

The numerical simulations of Cs transport performed with CsFlow3D are particularly interesting also because they allow to access information which cannot be easily measured experimentally, i.e. to calculate the value of the caesium flux impinging onto the PG and to distinguish between neutral Cs and Cs^+ ions (while the TDLAS used experimentally is only sensitive to neutral Cs) as well as the spatial distribution over large area of the PG.

Most of the Cs particles undergo ionization due to collisions with the plasma electrons. When the PG positive bias voltage is not taken into account in the code (i.e. the difference between the PG and the plasma potential is set to zero: $\Delta\varphi = \varphi_{PG} - \varphi_{plasma} = 0$ over all the surface of the plasma grid) up to 70% of the Cs flux onto the PG consists of Cs^+ ions [10]. In the experiment however the PG is always positively biased w.r.t. the source walls: there might be conditions for which $\varphi_{plasma} > \varphi_{PG}$ and therefore $\Delta\varphi < 0$, i.e. for which the positive Cs^+ ions can be repelled by the plasma grid. In addition the value of φ_{plasma} is not necessarily uniform over the large area of the plasma grid, leading to non-uniformities in the value of $\Delta\varphi$ [13]. In these conditions the flux of Cs^+ is strongly dependent on the value of $\Delta\varphi$ and on the energy of the particles.

The energy of the Cs^+ ions is influenced by the presence of the electric field in the source, due to the gradient of the plasma potential inside the source volume (e.g. from 40 V inside the driver and down to 30 V inside the expansion chamber) and due to the energy exchanged during collisions, e.g. with the H atoms and H^+ particles, whose energy in the code is set to 0.8 eV. Figure 3 shows the calculated energy probability density function $f_{Cs^+}(E)$ of the Cs^+ ions impinging onto the PG for $\Delta\varphi = 0$. The PDF $f_{Cs^+}(E)$ is normalized so that $\int f_{Cs^+}(E)dE = 1$.

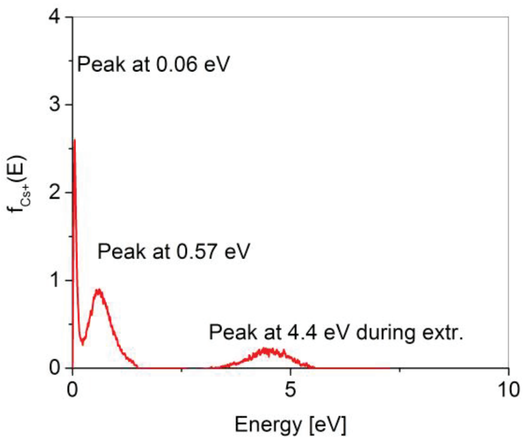


FIGURE 3. Energy distribution of the Cs^+ ions impinging the PG at ELISE during beam extraction phase. Simulations performed for $\boldsymbol{\varphi = \varphi_{plasma} - \varphi_{PG} = 0\ V}$.

Three peaks are visible at the energy 0.06 eV, 0.57 eV and 4.4 eV. The lowest energy peak corresponds to Cs^+ ions that are ionized close to PG and they have the same energy of the neutral Cs, which in the simulations resulted exactly to be peaked at 0.06 eV; the peak at 0.57 eV is due to Cs particles ionized further from the plasma grid. A better understanding of the mechanisms that transfer energy to the Cs^+ ions will be achieved by investigating the most relevant influencing parameters, i.e. by varying the electric field in the source volume (i.e. the plasma potential map used as input by the code) and the temperature of the collision partners (such as the H and H^+ particles).

The highest energy peak around 4.4 eV occurs only during the extraction phase. This energy corresponds to that of the ionized Cs particles released by sputtering from the source back-plate. This is sputtering is produced by the back-streaming ions, i.e. the positive H^+, H_2^+ ions created inside the extraction and acceleration systems, which after being accelerated back inside the source hit the back-plate. The sputtering yield was calculated by TRIM simulations: more detail on the treatment of back-streaming ions with CsFlow3D simulations can be retrieved in [9].

Figure 4 (a) shows the temporal behavior of the Cs flux onto the area of a group of 5 x 16 apertures (beamlet group) highlighted in red. The simulations were performed for a long pulse of 400 s with pulsed extraction and $\Delta\varphi = 0$ (over all the surface of the PG). In this condition the Cs flux mostly consists of ions, which can reach the PG for any kinetic energy.

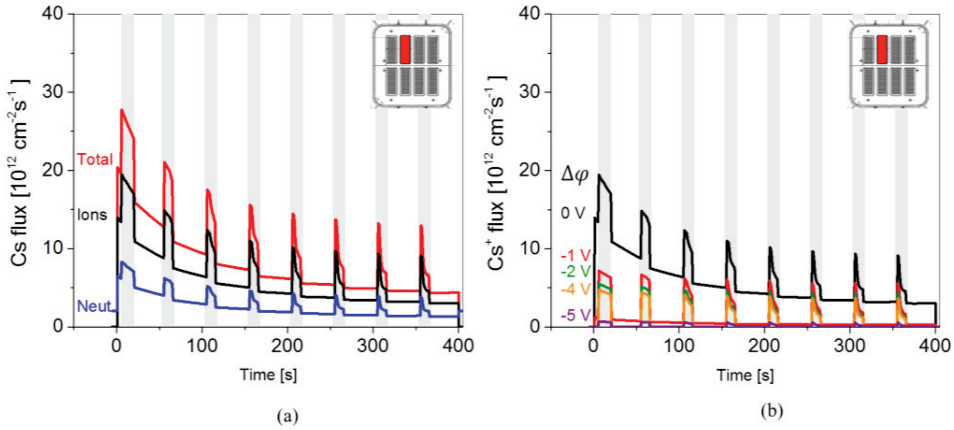


FIGURE 4. (a) Time trace of the Cs flux averaged onto the highlighted beamlet group for 400 s plasma with pulsed extraction: the total Cs flux as well as its neutral and ion components is shown $\boldsymbol{\Delta\varphi = \varphi_{plasma} - \varphi_{PG} = 0\ V}$; (b) Time traces of the Cs+ flux onto the highlighted beamlet group for different values $\boldsymbol{\Delta\varphi = \varphi_{plasma} - \varphi_{PG}}$.

The overall decrease of the Cs flux in time is due to the depletion of the Cs reservoirs on the source walls, while the increased values during beam extraction is due to the Cs released from the source back-plate by the back-streaming ion sputtering [10]. Figure 4 (b) shows a comparison of the Cs^+ ion flux time trace of the same 400 s pulse but for different values of $\Delta\varphi = 0, -1, -2, -4, -5\ V$, i.e. the plasma sheath at the PG repels the impinging Cs^+ ions stronger with each voltage step. Consequently, the flux decreases: at $\Delta\varphi = -2V$ the flux is greater than zero only during the beam extraction phases, while it is strongly reduced and almost negligible at $\Delta\varphi = -5V$.

Although the Cs neutrals are uniform as shown in the previous paragraph, such interaction between the Cs^+ ions and the potential can lead to a non-uniform Cs^+ ion flux on the grid due to the non-uniformity in the $\Delta\varphi$ over the large area of the plasma grid and to asymmetries on the caesiation of the PG. This needs to be considered, especially because it cannot be detected by the TDLAS that sensitive only to the neutral Cs. A non-uniform caesiation of the plasma grid could lead to non-uniformity of the co-extracted electrons, which is the limiting factor for long pulse extraction. In addition, this non-uniformity of the Cs can be the reason for non-homogeneities on the extracted and accelerate negative ion current observed during the conditioning process [14].

Alternative Cs Evaporation Close to the PG

A better control of the PG caesiation, e.g. the achievement of a sufficient, stable and uniform Cs flux, could be achieved by using an alternative Cs evaporation method, namely by evaporating Cs close to the plasma grid in a configuration as that one shown in Fig. 5 (a). By evaporating Cs at a short distance d between 1 to 5 cm from the plasma grid, it is possible to accomplish two targets:

1. Reducing the ionization probability of Cs while it is transported between the Cs evaporators and the PG surface, due to the lower temperature and density of electrons close to the plasma grid;
2. Avoid relying on the plasma redistribution of Cs, which can be influenced by many factors, such as the plasma parameters and the amount and distribution of Cs on the inner surfaces.
3. Provide sufficient flux directly to the grid.

The first point is of importance when considering the effect of the PG bias potential: since the Cs^+ flux is strongly affected by the value of $\Delta\varphi$ and its spatial homogeneity over the PG, reducing Cs ionization degree allows to achieve a flux which is less dependent on this parameter. Figure 5 (b) shows the amount of Cs^+ flux normalized on the total Cs flux onto the PG which is delivered by this alternative Cs evaporation system as a function of the distance between the Cs evaporators and the PG. These simulations were performed at $\Delta\varphi = 0\ V$. The evaporation rate was set to 10 mg/h as in the standard case. For distances very close to the PG, i.e. between 10 mm and 20 mm the Cs^+ flux onto the PG can be reduced down to only 20% of the total Cs flux: this means that most of the Cs reaching the grid is neutral, thus ensuring that an eventual spatial or temporal variation of $\Delta\varphi$ in the source will not affect the Cs flux.

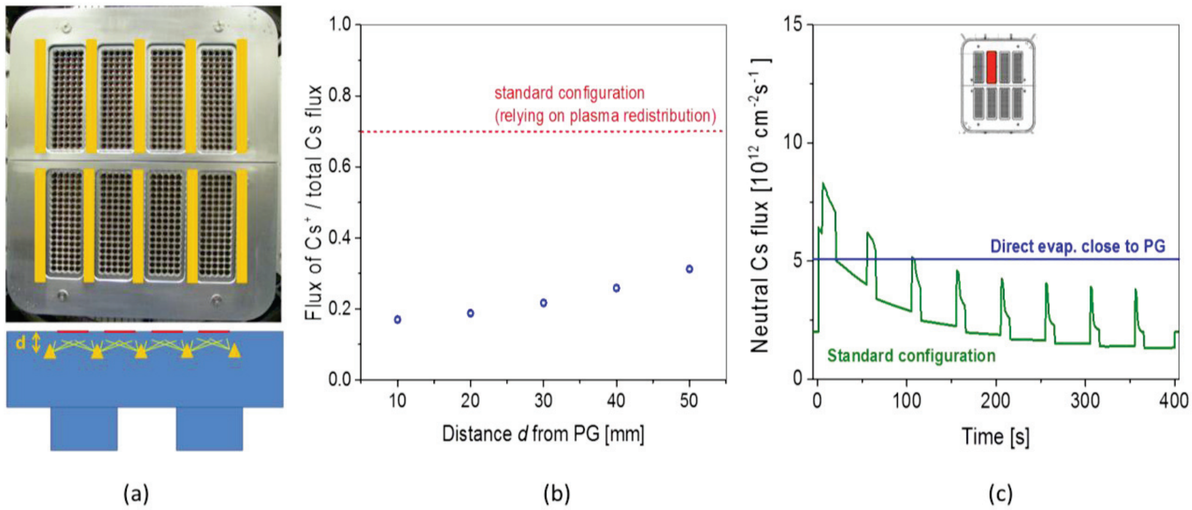


FIGURE 5. (a) Schematic view of the alternative Cs evaporation concept, by means of Cs evaporators located close to the PG on the sides of the beamlet groups; (b) Simulated ratio between Cs^+ ion flux and total Cs flux onto the PG as function of the distance from the PG; (c) Simulated time trace of the neutral Cs flux onto the highlighted beamlet group during a 400 s plasma phase with pulsed extraction, the straight horizontal line shows the simulated flux provided by the direct evaporation.

The second point, i.e. avoid relying on the plasma to redistribute the Cs, is of particular importance in long pulses, since it allows limiting the problem of Cs depletion from the source walls. Figure 5 (c) shows the time trace of the neutral Cs flux onto one beamlet group surface in the case of the standard configuration (relying on plasma redistribution), for a 400 s pulse at ELISE with pulsed extraction; the straight horizontal line shows the Cs flux provided by direct evaporation close to the grid. Only the neutral fluxes have been compared, since as shown previously, in the worst-case scenario, i.e. $\Delta\varphi < -5\,V$, no Cs^+ can reach the plasma grid. After ≈ 70 s the neutral Cs flux provided from direct evaporation is constantly higher than the one achieved by plasma redistribution with the standard oven configuration, avoiding the depletion problem.

In addition to these advantages, direct Cs evaporation close to the PG allows also to have a sort of feedback control of the caesiation during long pulses, since the Cs evaporation rate could be adjusted runtime, according to the performances. On the other side, the disadvantage of an evaporation so close to the PG can lead to an increased Cs leakage throughout the aperture into the extraction system. An increased amount of Cs in the extraction system might be harmful for the high voltage holding [15]. This eventual limitation could only be tested experimentally.

SIMULATION OF CAESIUM CONDITIONING AND LONG PULSE AT SPIDER

The full size ITER-NBI source at the SPIDER test facility will be equipped with three Cs ovens, which will be positioned on the back-plate of the expansion chamber [4, 16]. Figure 6 shows the ports for the three Cs ovens as well as the geometry of the nozzles, which consist of a horizontal cylindrical injection pipe of 12 mm of diameter with 6 equidistant orifices along the circumference on the later surface of the pipe.

The CsFlow3D code was extended to the source geometry of SPIDER (twice the size of the ELISE source in the vertical direction) and it has been used to determine what the required evaporation rate from the oven is, to reach the same Cs flux onto the PG calculated for ELISE. There is in fact not a simple rule to perform this scaling for different source sizes, since also the Cs oven configuration changes. For example, when considering the scaling between the prototype source and ELISE it was observed, both with the code and with the experiments that similar fluxes and performances can be achieved with the same or lower total evaporation rate, despite the different source volumes [9].

The conditioning phase for SPIDER was simulated in the same way as for ELISE, i.e. with 20 consecutive cycles of 200 s vacuum phase and 20 s plasma phase. The simulation was repeated for different values of the total evaporation rate, namely 10, 15, 20, 25 and 30 mg/h, equally divided among the three oven nozzles (i.e. for the 18 orifices in total).

Figure 7 (a) shows the total Cs flux averaged on the area of one beamlet group and over the time of the plasma phase, as a function of the consecutive pulse number. The Cs flux increases pulse by pulse due to the increased amount of Cs available in the reservoirs on the source walls for the plasma redistribution. The saturation value of the total Cs flux increases with increasing evaporation rate. The same simulations performed for the standard evaporation rate used at ELISE (10 mg/h) lead to a saturation value of $17 \cdot 10^{12}$ $cm^{-2}s^{-1}$, which is indicated in the Fig. by the dashed lines. In order to reach the reference Cs flux calculated for ELISE, a total evaporation rate of 20 mg/h is needed for SPIDER, which corresponds to 7 mg/h/oven. There might be still margin for an optimization, i.e. a reduction of the evaporation rate, by investigating also the effect of the duty cycle on the conditioning process.

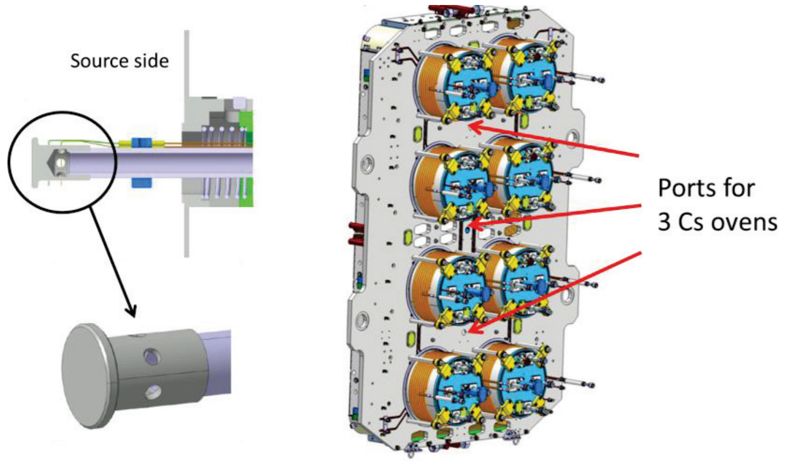
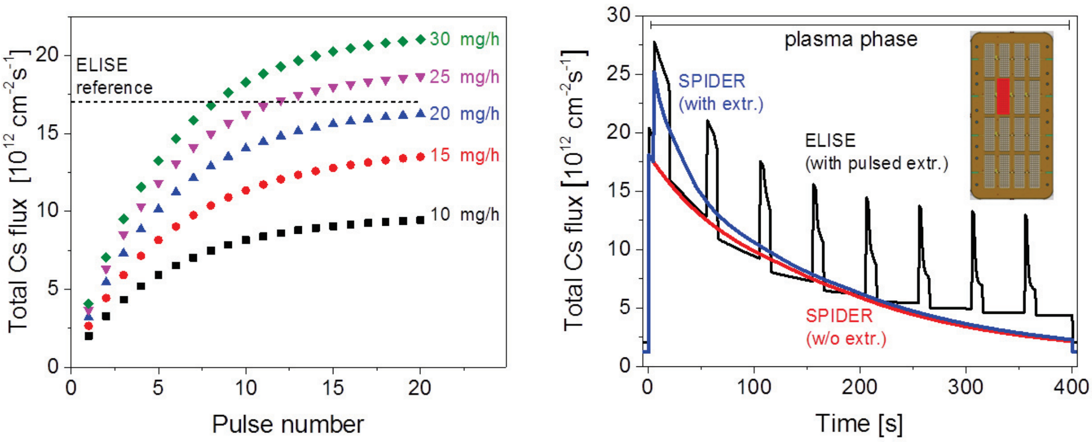


FIGURE 6. Schematic view of the Cs oven nozzle designed for the SPIDER test facility. The ports on the source back-plate for the positioning of the three Cs ovens are indicated.



(a) (b)

FIGURE 7. (a) Total Cs flux averaged on the area of a beamlet group as function of the consecutive pulse number for different total Cs evaporation rate at SPIDER. The reference value for the flux achieved at ELISE is indicated by the dashed line; (b) Time traces of the total Cs flux onto the highlighted beamlet group for three cases: the reference case at ELISE with pulsed beam extraction, the cases for SPIDER without beam extraction and with continuous beam extraction.

With this scaled value of evaporation rate is then possible to compare simulations between ELISE and SPIDER in the case of long pulses. Figure 7 (b) shows simulated time traces of the total Cs flux averaged on the area of a beamlet group during a 400 s pulse: the case of SPIDER without beam extraction, with continuous beam extraction and the reference case for ELISE with pulsed beam extraction are shown.

In the case of SPIDER without extraction, a strong decrease of the Cs flux in time can be observed, which is even more pronounced w.r.t. ELISE: a reduction of the flux of a factor of 6 in 400 s occurs. This can have negative effect in the surface condition of the PG, eventually leading to a degradation of the work function and therefore a reduction of the source performance during long pulses. When including the effect of the Cs release due to back-streaming ion sputtering in SPIDER (i.e. modelling the continuous extraction), an increased value of flux is observed especially at the beginning of the pulse: the additional released Cs is however not enough to compensate the flux reduction in time.

After ≈ 100 s there is no more relevant differences between the continuous extraction case and the case without extraction.

These simulations show that for the larger source at SPIDER with different Cs evaporation configurations than in ELISE, similar problems of Cs depletion during long pulses arise, which could affect the source performance. Investigations to identify if different conditioning processes, especially concerning the duty cycle, could improve the stability of the Cs flux are ongoing. Experimental measurements of Cs density for large sources with continuous extraction will be mandatory to gain a deeper insight on this phenomenon.

SUMMARY AND CONCLUSIONS

Cs dynamics in the large negative ion sources at the ELISE and SPIDER test facilities have been investigated by means of the Monte Carlo transport code CsFlow3D. The simulations for the source at ELISE have shown that a vertical plasma drift caused by the $\vec{F} \times \vec{B}$ does not lead to relevant asymmetry in the vertical distribution of neutral Cs, as confirmed also by the experimental data from absorption spectroscopy. However, the flux of the Cs^+ ions (which represents up to 70% of the total Cs flux) resulted to be strongly affected by the shape of the plasma sheath in front of the plasma grid, i.e. the difference $\Delta\varphi$ between the plasma potential and PG potential: already with a $\Delta\varphi$ below -1 V there is a strong reduction of Cs^+ flux onto the grid. This lead to the fact that spatial non-uniformity of $\Delta\varphi$ could lead to spatial non-uniformity of the Cs^+ flux onto the grid.

These spatial differences cannot be experimentally detected by the laser absorption spectroscopy, since it is only sensitive to neutral Cs. Therefore an observed symmetric distribution of Cs by means of laser absorption spectroscopy does not necessarily mean that also the Cs^+ flux onto the grid is symmetrically distributed. Hence, the CsFlow3D code gives valuable information which cannot be gained by experimental diagnostics.

A possible solution to achieve a more controllable caesiation of the PG is to evaporate Cs close to the PG: simulations have shown that with this configuration the ionization of Cs can be strongly reduced, thus avoiding this dependence of the Cs flux on the shape of the potential. In addition the direct evaporation method is independent on the plasma redistribution and therefore is not affected by the depletion of Cs reservoir on the surface of the source.

The extension of the CsFlow3D simulations to the full size ITER-NBI sources has shown that in long pulses a strong decrease of the Cs flux onto the PG occurs, even more than what has been observed for ELISE. The back-streaming ions provide additional Cs through sputtering, but this contribution is however not enough to compensate for the reduction of the Cs flux. Further possibilities to reduce this instability in long pulses will be investigated, for example by optimizing the duty cycle between vacuum and plasma phase.

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