Modelling of Caesium Dynamics in the Negative Ion Sources at BATMAN and ELISE

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Abstract. The knowledge of Cs dynamics in negative hydrogen ion sources is a primary issue to achieve the ITER requirements for the Neutral Beam Injection (NBI) systems, i.e. one hour operation with an accelerated ion current of 40 A of D^- and a ratio between negative ions and co-extracted electrons below one.

Production of negative ions is mostly achieved by conversion of hydrogen/deuterium atoms on a converter surface, which is caesiated in order to reduce the work function and increase the conversion efficiency. The understanding of the Cs transport and redistribution mechanism inside the source is necessary for the achievement of high performances. Cs dynamics was therefore investigated by means of numerical simulations performed with the Monte Carlo transport code CsFlow3D.

Simulations for the prototype source (1/8 of the ITER NBI source size) have shown that the plasma distribution inside the source has the major effect on Cs dynamics during the pulse: asymmetry of the plasma parameters leads to asymmetry in Cs distribution in front of the plasma grid. The simulated time traces and the general simulation results are in agreement with the experimental measurements.

Simulations performed for the ELISE testbed (half of the ITER NBI source size) have shown an effect of the vacuum phase time on the amount and stability of Cs during the pulse. The sputtering of Cs due to back-streaming ions was reproduced by the simulations and it is in agreement with the experimental observation: this can become a critical issue during long pulses, especially in case of continuous extraction as foreseen for ITER. These results and the acquired knowledge of Cs dynamics will be useful to have a better management of Cs and thus to reduce its consumption, in the direction of the demonstration fusion power plant DEMO.

INTRODUCTION

The heating and current drive in ITER will rely on two Neutral Beam Injection (NBI) systems, with a total power of 33 MW [1]. These systems are based on negative hydrogen/deuterium ions and the requirement for the NBI ion source is to deliver 40 A accelerated current of D^- for one hour, with a ratio between co-extracted electrons and negative ions lower than one [1] at a pressure of 0.3 Pa [2]. The RF prototype source [3] (1/8 of the ITER source size) currently operating at the BATMAN test facility has been chosen as the ITER reference design. Beside the prototype source a larger source (1/2 of the ITER source size) at the ELISE test facility [5] is also in operation.

In these sources negative ions are mostly produced by surface conversion of hydrogen/deuterium atoms. The conversion efficiency increase by decreasing the surface work function and this is achieved by evaporating Cs inside the source [6, 7]. Cs transport onto the converter surface can be influenced by many factors, such the position where Cs evaporation occurs and the plasma parameter profiles, i.e. plasma density and electron temperature.

In order to investigate Cs dynamics in negative ion sources the Monte Carlo test particle `CsFlow3D` code [8] was developed. This code calculates the fluxes of Cs onto the inner source surfaces as well as the Cs coverage. Preliminary simulations of the prototype source at the test facility BATMAN and MANITU were performed [9], in which the homogeneity of Cs redistribution in the prototype source have been investigated in dependence on the adhesion probability of Cs onto the source surfaces.

The following step, which will be presented in this work, is to reproduce with the simulations the conditioning process which takes place in the negative ion sources for the achievement of high performances and to investigate the role of the plasma parameter on the Cs distribution. The calculation of neutral Cs density was also implemented in the code, so that a direct comparison with the prototype source data is possible. In addition, in order to investigate Cs dynamics also in larger ion sources, the geometry of the ELISE source was implemented in the code and simulations were performed for the first time.

THE TEST FACILITIES BATMAN AND ELISE

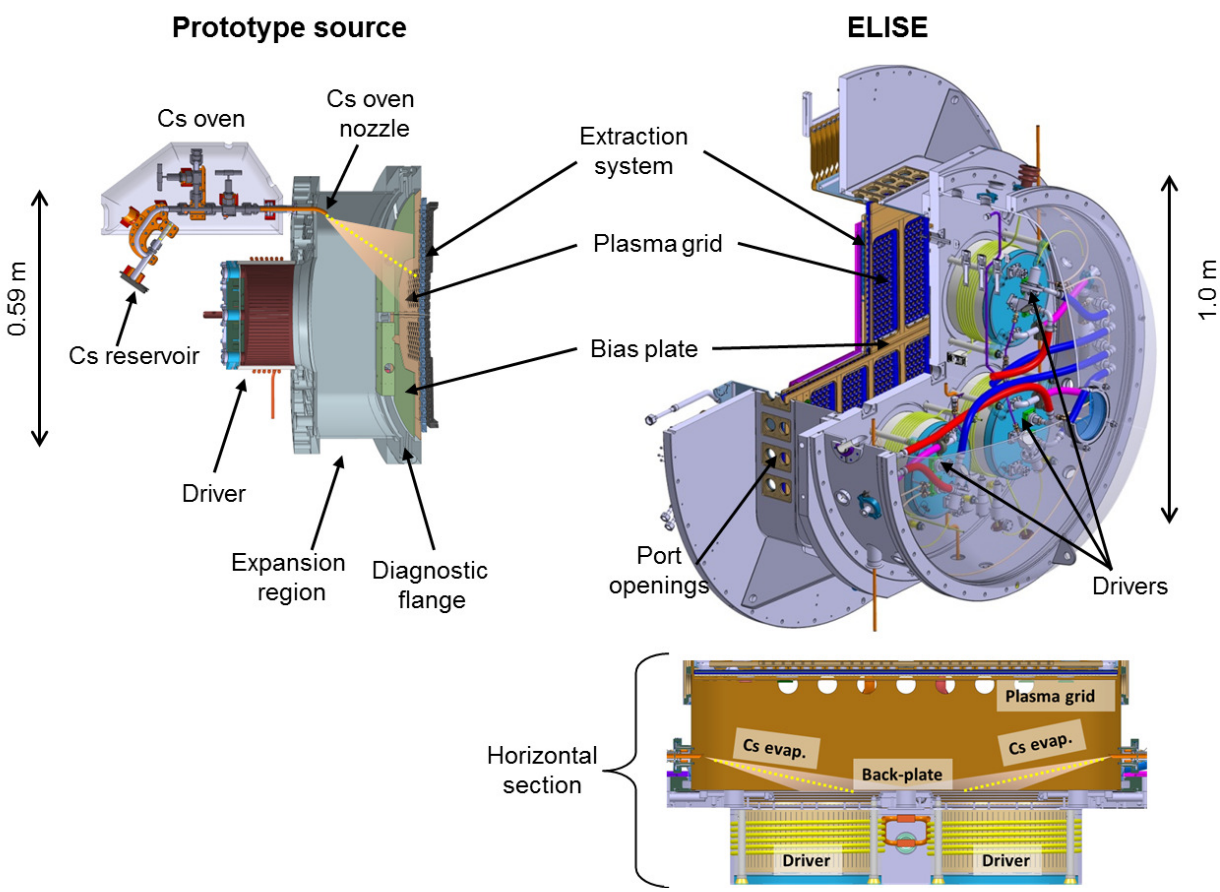


FIGURE 1: Left: prototype source at BATMAN test facility, with the Cs oven in the top, evaporating towards the plasma grid. Right: source at ELISE test facility. The horizontal section show the two Cs oven nozzle on the side, evaporating towards the back-plate.

TABLE 1: Typical operative parameters of BATMAN and ELISE test facilities.

	BATMAN	**ELISE**
Maximum RF power	100 kW	360 kW
Total acceleration voltage	22 kV	60 kV
Plasma pulse duration	~ 7 s	up to 3600 s
Beam pulse duration	~ 4.5 s	10 s every ~ 150 s

Figure 1 shows a scheme of the prototype source at BATMAN and of the larger source at ELISE, where the main parts are highlighted. In these sources the plasma is inductively generated in the driver and expands in the expansion chamber. Negative ions are mostly produced by surface conversion of hydrogen/deuterium atoms at the surface of the plasma grid (PG). In order to reduce the destruction of negative ions due to electron stripping, the electron temperature is reduced by using a magnetic filter field: in the driver region the electron temperature T_e is ~ 10 eV and the plasma density ~ 10^{18} m^{-3}, while in front of the plasma grid T_e ~ 1 eV and the plasma density ~ 10^{17} m^{-3} [10]. Negative ions are extracted and accelerated by means of a three grid extraction system.

The operation of these sources is pulsed and consists in two main phases: the vacuum phase, with a background pressure of the order of 10^{-4} Pa, and the plasma pulse, in which the RF is turned on and the gas pressure can be set in the range 0.3 Pa - 0.8 Pa. The phase during the plasma pulse in which the high voltage is applied to the extraction system, thus generating the negative ion beam, will be indicated in the following as "beam pulse". The available RF power, extraction and acceleration voltage as well as the duration of the plasma and beam pulse is different for the two test facilities BATMAN and ELISE: the values are summarized in table 1.

In the following sections the principle of Cs seeding inside the source and the available diagnostics for monitoring the amount and the temporal evolution of Cs in BATMAN and ELISE will be presented.

Caesium seeding

Cs seeding is performed by means of a Cs oven where a liquid reservoir of Cs is heated up in order to increase its vapour pressure and then the flux of Cs, which is evaporated inside the source through a nozzle. The Cs evaporation can be adjusted by setting the temperature of the liquid reservoir (which in standard condition is between 90 °C and 150 °C). The temperature of the Cs reservoir can be changed during the conditioning process in order to reach the optimal source performance, i.e. maximum extracted current and lowest co-extracted electron current. Standard evaporation rate has been estimated to be 10 mg/h [11]. The temperature of the conduction pipe and of the nozzle has to be kept above 250 °C in order to avoid the presence of cold spot in the pipes where the evaporated Cs can accumulate.

The position and orientation of the Cs nozzles are different for the two test facilities, as can be seen in figure 1. In the standard operation of the prototype source the Cs oven is located in the top of the back-plate of the expansion chamber and the nozzle is bent downwards, so that the evaporation occurs toward the plasma grid. In ELISE two Cs ovens are in use, which are positioned on the sides of the expansion chamber. The edge of each nozzle is cut at 45° and the evaporation occurs towards the back-plate of the expansion chamber.

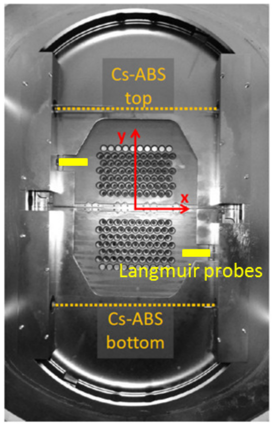
The efficiency of negative ion production depends on the work function of the main converter surface (PG) and this is affected by the caesiation condition of the source. The Cs evaporation from the oven is continuous during the source operation: it has in fact been observed that a sufficient flux of Cs onto the plasma grid is needed in order to counteract the degradation of the work function [12], which can take place due to the high reactivity of pure Cs with the impurities during the vacuum phase and due to the removal of the Cs layers deposited onto the PG during the plasma pulse.

Cs transport in the source can be affected by many factors: the position of the Cs oven nozzle, the plasma parameter profiles (such as electron temperature and plasma density) and the duty cycle of the source, i.e. the ratio between the vacuum phase duration and the plasma pulse length.

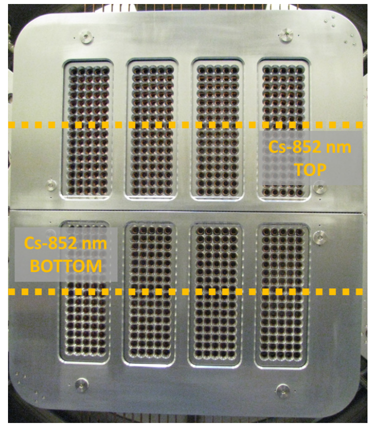
Caesium diagnostics

In the prototype source at BATMAN the main diagnostic for monitoring Cs is the laser absorption spectroscopy [13], which measures the neutral Cs density, averaged along a line of sight, both during the vacuum phase and the plasma pulse. Figure 2 (a) shows the two horizontal top and bottom lines of sight, used for the Cs absorption in front of the PG of the prototype source. Also the top and bottom Langmuir probes, for the determination of plasma parameter in front of the PG are shown. In particular the usage of a top and a bottom lines of sight is useful to study the effect of the plasma drift in the source on the asymmetry of Cs redistribution.

In ELISE the Cs dynamics is monitored with the detection of the Cs emission at 852 nm during the plasma pulse by means of a photodiode with an interference filter. Figure 2 (b) shows two horizontal lines of sight in front of the PG for ELISE dedicated to the Cs emission detection. Cs emission is proportional to Cs density but it depends also on the plasma parameters, so the experimental data cannot be directly compared with the simulation results and only relative trends have to be considered. In order to have a measure of neutral Cs density independent from the plasma parameters, the laser absorption spectroscopy will be installed also in ELISE for the next experimental campaign.



(a)



(b)

FIGURE 2: (a) Horizontal lines of sight (LOS) in front of the PG of the prototype source for the determination of Cs density by laser absorption spectroscopy and the two Langmuir probes; (b) LOS in front of the PG in ELISE for the monitoring of Cs emission.

INVESTIGATION OF CAESIUM DYNAMICS BY NUMERICAL SIMULATIONS

In this section the study of Cs redistribution by means of the code `CsFlow3D` will be presented. A description of the parameters that influence Cs dynamics in the different operative phases and which have been taken into account by the code will be described. Successively the simulations results will be discussed in comparison with the experimental data.

Parameter influence on Cs dynamics

During the vacuum phase, Cs is evaporated into the source through the Cs oven nozzle: due to the low background pressure, the mean free path of the Cs particles is long enough to neglect collisions with the background gas and the modelled Cs transport is ballistic. Cs that hit the source wall can either stick to the surface or be reflected: the sticking probability depends on the source wall temperature and on the amount of impurities, due to the high reactivity of Cs. The sticking probability used in the code depends only on the temperature of the surface and it is based on measurements [14] performed in similar conditions to the ion source ones.

During the plasma pulse, the Cs accumulated on the source walls can be sputtered and then redistributed by the plasma. In this condition the ionization of Cs atoms and the collisions with the plasma are modeled, as well as the effect of the magnetic filter field on the transport of Cs ions. Due to this interaction between Cs and plasma, the Cs transport have a dependence on the plasma parameter profiles, i.e. plasma temperature and density. A homogeneous and axi-symmetric profile [8], which is based on Langmuir probe measurements performed at the BATMAN test facility [15, 16], has been used in the code. The vertical profile of the plasma density and electron temperature in front of the plasma grid of the prototype source is plotted in figure 3. However the presence of $\vec{F} \times \vec{B}$ plasma drifts due to the magnetic filter field and diamagnetic drifts [17], which have been experimentally observed, can determine an asymmetry in the plasma profiles, thus affecting the Cs redistribution.

During the beam pulse, the Cs accumulated on the back-plate can be sputtered by the back-streaming ions, which are positive ions created inside the extraction and acceleration region due to collision of the fast negative ions with the background gas. The high voltage difference between the grids accelerates them back inside the source through the grid apertures. Calculations and measurements [18] carried on for the prototype source have shown that the back-streaming ions consist of $\sim 36\%$ H^+ and $\sim 64\%$ H_2^+, with a total flux at the back-plate of $2.5 \cdot 10^{15}$ $cm^{-2}s^{-1}$ and that the energy distribution function for the H^+ has a peak at 15 keV and for the H_2^+ has two peaks at 7.5 keV and 20 keV. The sputtering yield has been calculated by means of TRIM simulations and the values assumed in the code were 0.01 for H^+ ions at 15 keV, 0.025 for H_2^+ ions at 20 keV and 0.034 for H_2^+ ions at 7.5 keV.

Three main factors that influences the Cs dynamics can be identified: (i) the time of the vacuum phase, since

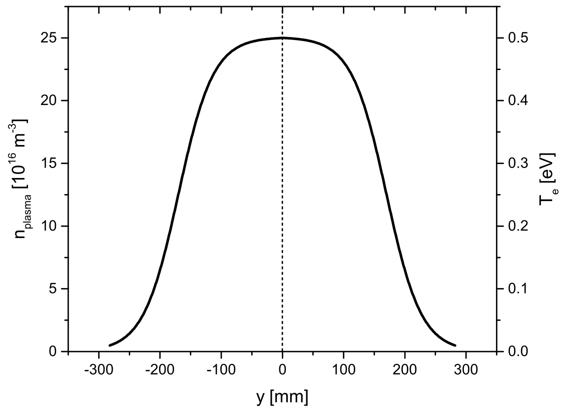


FIGURE 3: (a) Assumed vertical profile of plasma density and electron temperature in front of the plasma grid of the prototype source.

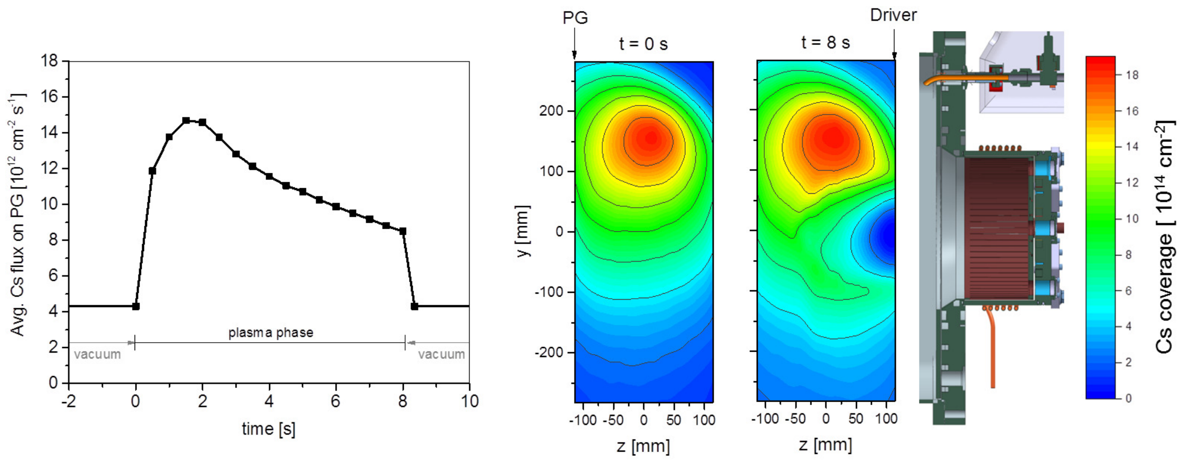
by evaporating for a longer time in vacuum, the amount of deposited Cs which can be redistributed by the plasma increases; (ii) the position and orientation of the oven nozzle, since this change the spatial distribution of the Cs deposited on the walls; (iii) the plasma parameters and the presence of plasma drifts, that can change the Cs redistribution during the plasma pulse.

Results for the prototype source

For the simulation of the prototype source the Cs nozzle configuration used in the code is the one already described in (figure 1, with the nozzle in the top of the back-plate and directed towards the plasma grid. The temperature of the source walls is set to 35 °C and the PG temperature is 150 °, which are the typical values used in the experiment. The simulated pulse length is 8 s, with a vacuum phase before the pulse of 240 s, in order to reproduce the experimental operations. At the beginning of the simulation no Cs is deposited onto the source walls. To a first approximation the effect of the back-streaming ions can be neglected: due to the geometry of the grid apertures, the back-streaming ions doesn't hit the back-plate of the expansion chamber, but only the back-plate of the driver. In this area the amount of deposited Cs is much lower, due to the position and orientation of the Cs oven nozzle.

Figure 4 (a) shows the average Cs flux onto the plasma grid area as a function of time. Before the pulse (time $<$ 0 s) the flux is $4{\cdot}10^{12}\,cm^{-2}\,s^{-1}$, due to evaporation from the oven. At the beginning of the plasma phase the Cs flux increases with respect to the vacuum phase, due to the plasma sputtering. The peak value of $15{\cdot}10^{12}\,cm^{-2}\,s^{-1}$ was reached after 1.5 s and afterwards the Cs flux decreases in time. Once the plasma is turned off, the Cs flux restores to the previous vacuum phase value. The decrease of the Cs flux after 2 s is caused by the depletion of the accumulated Cs on the walls, which is sputtered and redistributed by the plasma. This can be observed in figure 4 (b), which shows the coverage of Cs on the side wall of the prototype source at the very beginning of the plasma phase (t = 0 s) and immediately after the pulse (t = 8 s). An area with greater Cs coverage (up to $18{\cdot}10^{14}$ atoms per square centimeter, i.e. ~ 4 monolayers) is visible in the top part, due to the position of oven in the top of the source back-plate. After the pulse, an erosion zone due to plasma sputtering is evident, and it is located close to the driver exit, where the plasma density is higher. This result is obtained by simulating only the first pulse after one vacuum phase: it is an experimental evidence that in order to have sufficient Cs in the source to achieve good performance a procedure called conditioning have to be performed, i.e. the repetition of many consecutive pulses with constant Cs evaporation. The amount of Cs in the source increases at each vacuum phase and the Cs accumulated on the walls is available for redistribution during plasma. In order to compare the simulations with experiment it is necessary to reproduce this conditioning process by simulating many consecutive identical pulses.

Simulations have been performed by repeating 20 times the standard pulse consecutively (i.e. 240 s vacuum phase and 8 s plasma). Figure 5 (a) shows the results for the 20th pulse: the experimental values of neutral Cs density are plotted with full line, the simulations with dashed lines, for both the top and bottom lines of sight. By observing the experimental data, it is possible to see some peaks of the absorption signal at the beginning of the pulse which are



(a) (b)

FIGURE 4: (a) Cs flux averaged onto the PG area of the prototype source vs. time. Plasma pulse start at t = 0 s ; (b) Cs coverage of the side wall of the prototype source before the pulse (t = 0 s) and immediately after (t = 8 s).

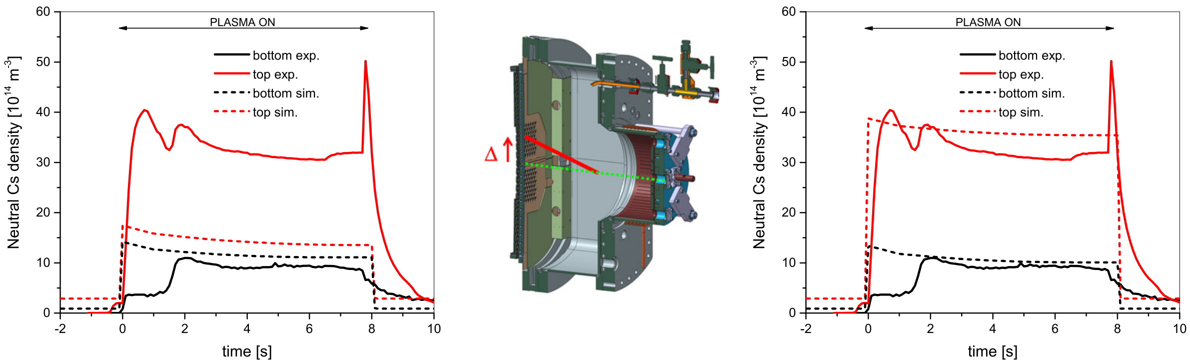
not reproduced by the simulations: these are caused by the change of the discharge parameter during and immediately after the ignition (such as the change of pressure due to the gas puff and the increase of RF up to the nominal value). Another peak in neutral Cs density on the top line of sight after the plasma grid is present. The laser absorption spectroscopy is sensitive only to neutral Cs: during the pulse a large fraction of Cs is ionized and cannot be detected. Immediately after switching off the RF, there is no more ionization but still neutral Cs coming from the walls, that can be detected by laser absorption and produce the peak in the signal. During the vacuum phase before the pulse no absorption signal is evident: this is most probably due to the fact that the value of Cs density is below or very close to the detection limit, which in the current setup is around $2{\cdot}10^{14}\,\mathrm{m}^{-3}$.

Both the simulated and experimental values are in the orders of magnitude 10^{14} - $10^{15}\,\mathrm{m}^{-3}$, but the experiment shows a much higher asymmetry of Cs density between top and bottom than the simulations. The reason for the experimental asymmetry of Cs density can be the presence of the plasma drift, which in the considered magnetic configuration is upward. In the previous simulation the plasma drift was in fact not taken into account.

In order to see if the asymmetry in plasma profile can affect the redistribution of Cs, further simulations were performed by considering an upward drift of the plasma parameters. After defining z as the axial coordinate, the plasma density and temperature profiles have been shifted upward by a quantity $\Delta(z)$. $\Delta(z)$ is zero at the driver exit, where the effect of the filter field is lower and the plasma is assumed to be symmetric, and linearly increases towards the plasma grid up to $\Delta(z_{PG})$. Figure 5 (b) shows a sketch of the simulated upward plasma displacement Δ. Figure 5 (c) shows again the experimental value of the top and bottom Cs density and the results of the simulations, in which the plasma asymmetric profile is modelled with $\Delta z_{PG} = 10\,\mathrm{cm}$. This value was chosen in accordance with the Langmuir probe measurements. The simulated bottom Cs density is very close to the simulations performed without considering the plasma drift, but the measured top density is higher.

By inserting an asymmetry in the plasma profiles, the code can reproduce the experimental asymmetry between top and bottom neutral Cs density. The behaviour of the plasma inside the ion source due to the drifts is probably more complex than the simple implementation of plasma parameter asymmetry used in the code: these results suggest anyhow that the Cs redistribution strongly reacts to a variation of the plasma profiles. Further simulations assuming different plasma profiles are also foreseen in the future.

Beside the effects of the plasma asymmetry, also the position of Cs accumulation areas on the source walls, which depends on the Cs nozzle position and direction, can play a role. Further simulations have been performed to investigate this effect, by positioning the oven nozzle on the bottom of the back-plate. The two previous cases were simulated, i.e. without any plasma drift and by implementing a plasma drift with $\Delta z_{PG} = 10\,\mathrm{cm}$. The results are summarized in table 2, where the average value of neutral Cs density during the pulse along the two lines of sight is given for the two oven configurations. In order to compare the different cases, an asymmetry index ξ of Cs density is



(a) (b) (c)

FIGURE 5: (a) Experimental data and simulation of neutral Cs density in the prototype source. No plasma drift considered in the simulation; (b) Sketch of the plasma displacement implemented in the code to model the plasma drift; (c) Results of simulations by implementing a plasma profile asymmetry and experimental laser absorption data.

defined as $\xi = (n_{\mathrm{Cs,TOP}} - n_{\mathrm{Cs,BTM}}) / min(n_{\mathrm{Cs,TOP}}; n_{\mathrm{Cs,BTM}})$. Without taking into account the plasma drift, an asymmetry in Cs density between top and bottom lines of sight is present due to the position of the oven: the absolute value of the asymmetry is the same, but opposite for the top oven with respect to the bottom oven. The plasma drift drastically changes the Cs redistribution with an increase of Cs density in the top and a decrease in the bottom Cs density. The magnitude of the effect is however different between the two nozzle configurations: with the nozzle positioned in the top the asymmetry is higher with respect to the oven in the bottom.

These results show that the leading factor is the plasma drift, which can determine such a large difference between top and bottom density, with the second order effect due to the position of the oven. Further investigations on these effects are ongoing, in particular a systematic set of simulations performed with the usage of only the top oven, only the bottom oven and both ovens: the results will be interesting for the comparisons with the available experimental data for these three Cs evaporation configurations [19].

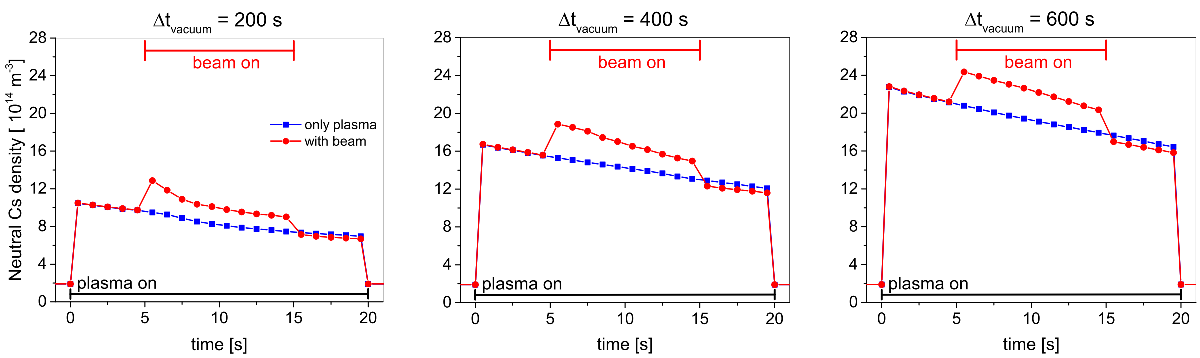
TABLE 2: Simulation results for neutral Cs density in the top and bottom lines of sight of the prototype source and Cs density asymmetry factor for different oven positions (top and bottom). The two cases without plasma drift and with are showed.

	No plasma drift			**With plasma drift upward**		
	n_{Cs} top	n_{Cs} bottom	ξ	n_{Cs} top	n_{Cs} bottom	ξ
Top oven	$1.38{\cdot}10^{15}$ m^{-3}	$1.12{\cdot}10^{15}$ m^{-3}	+0.23	$3.56{\cdot}10^{15}$ m^{-3}	$1.02{\cdot}10^{15}$ m^{-3}	+2.5
Bottom oven	$1.13{\cdot}10^{15}$ m^{-3}	$1.36{\cdot}10^{15}$ m^{-3}	-0.20	$2.02{\cdot}10^{15}$ m^{-3}	$0.88{\cdot}10^{15}$ m^{-3}	+1.3

Results for the ELISE test facility

As shown before in figure 1, the Cs seeding in ELISE is performed by means of two ovens positioned in the sidewalls of the source and the evaporation occurs towards the back-plate. The total Cs evaporation rate has been set to 10 mg/h, i.e. 5 mg/h for each oven, since during the experiment at ELISE the best performances have been reached with a Cs reservoir temperature set to a lower value (90°C - 100°C) than the prototype source. In the code the temperature of the source wall was set at 40°C and the one of the PG to 125°C: these are the values used in the experiment. The plasma drift was neglected in the model and vertical symmetric plasma profiles were assumed: no pronounced drift was in fact experimentally observed in ELISE [20]. For the ELISE case, the effect of back-streaming ions has to be taken into account; the geometry of the grid apertures allows the back-streaming ions to hit the back-plate of the expansion chamber, which during a vacuum phase is highly covered by Cs due to the orientation of the Cs oven nozzles.

The source at ELISE is designed for achieving long pulses: in this condition the maintenance of a sufficient Cs flux onto the plasma grid during the plasma pulse is a critical factor to reach good performances. The duration of the vacuum phase in which Cs reservoirs are built up on the wall, and which provide fresh Cs onto the PG during the pulse, can be an important parameter which influences the amount and stability of Cs flux. For this reason simulations of 20 s plasma pulses were performed, by setting different vacuum phase times between the pulses, i.e. 200 s, 400 s and 600 s. For every duty cycle, 20 consecutive pulses were simulated, in order to reproduce the conditioning procedure (which occurs experimentally).



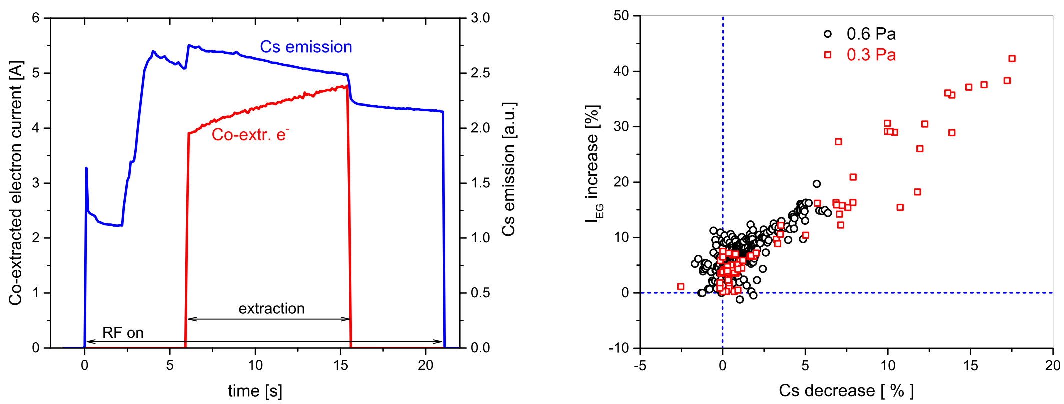
(a) (b) (c)

FIGURE 6: Simulation of neutral Cs density in the top lines of sight for ELISE for the no extraction case (squares) and with extraction (circles). Vacuum phase time set to 200 s (a), 400 s (b) and 600 s (c).

The simulated neutral Cs density on the top line of sight for the twentieth shot are presented in fig. 6 (a), (b) and (c) with a vacuum phase respectively of 200 s, 400 s and 600 s. Since the position of the oven nozzles is vertically symmetric and no plasma drift is assumed, the results of the two horizontal lines of sight are identical, and for this reason only the top one is plotted. Two different cases have been considered for this pulse: the squares refers to a plasma pulse without beam (i.e. without high voltage extraction); the circles refers to a pulse with 10 s extraction time in the middle, as indicated by the label "beam on". By observing the results, it appears that an increase of the vacuum phase duration has an effect on the total amount of the Cs density in front of the plasma grid, due to the increase of the Cs deposited on the surfaces of the source. It is also evident that the Cs density decreases during the pulse in all the three cases. By observing the pulses with the 10 s extraction, the release of Cs due to the sputtering of the back-streaming ions on the back-plate is evident: when extraction starts, there is an increase in Cs density between $\sim 30\%$ in the 200 s case and $\sim 15\%$ in the 600 s case. When the extraction stops, Cs density reduces back to values slightly below the density simulated for the pulse without beam, due the depletion of the accumulated Cs on the back-plate by means of the back-streaming ion sputtering. By changing the vacuum phase time, also the stability of Cs density is affected. By defining the Cs instability as $i = (Cs_{\mathrm{START}} - Cs_{\mathrm{AVERAGE}})/Cs_{\mathrm{START}}$, i.e. the relative difference between the Cs density at the beginning of the pulse and the average value during the pulse, in the case of 200 s vacuum phase the instability is $\sim 20\%$, while for the other cases it is reduced to $\sim 15\%$.

The decrease of Cs density can indicate a reduction of the Cs flux onto the PG below the minimum level which is needed to achieve good performances. It has been observed during the experiment that a reduction of Cs emission in front of the plasma grid frequently associates with an increase of the undesired co-extracted electrons, in particular for lower pressure; figure 7 (a) shows the Cs emission at 852 nm measured by a photodiode on the top line of sight, together with the amount of co-extracted electrons (RF power = 30 kW / driver, extraction voltage = 8 kV, acceleration voltage =25 kV, pressure = 0.3 Pa), (b) shows a statistical analysis of the correlation between the decrease of Cs emission during the pulse and the increase of co-extracted electrons. By assuming no relevant change of the plasma parameters during the pulse, the Cs emission can be considered proportional to the neutral Cs density. The experimental time trace of Cs emission shows an increment during the beam pulse which is in the same order of magnitude of the one observed in the simulations (figure 6). The increase of Cs emission is most probably caused by the release of Cs from the back-plate due to the back-streaming ions, and this will be quantitatively investigated with the future measurements of laser absorption spectroscopy, which in contrast to Cs emission is not influenced by a change of plasma parameters during beam extraction.

The benchmark of the simulation results taking into account the effect of back-streaming ions with the laser absorption experimental data of ELISE will be necessary to provide a reliable simulation tool, which is capable to optimize the Cs evaporation and thus to reduce the Cs consumption also in the larger sources, which will eventually be used in the future industrial scale power plants, such as DEMO. Cs redistribution in longer pulses (up to 1 hour) will also be investigated both with experiments and simulations, as well as the dynamics during the extraction phase. These investigation will be helpful in identifying the best condition of the source, such as temperatures, duty cycle, Cs nozzle configuration, in order to have a sufficient Cs flux during long pulses onto the plasma grid.



(a)

(b)

FIGURE 7: (a) Time trace of Cs emission on the top line of sight of the source at ELISE and co-extracted electron current; (b) Statistical correlation between decrease of Cs and increase of co-extracted electron for the two pressure 0.3 Pa and 0.6 Pa.

SUMMARY

In order to investigate the Cs dynamics in negative ion sources for ITER NBI, simulations with the Monte Carlo test particle code `CsFlow3D` were performed. The operation of the prototype source were modelled: the time traces of the flux onto the plasma grid and the neutral Cs density along two horizontal lines of sight in front of the PG were calculated, as well as the coverage onto the walls. It has been experimentally observed that during the plasma phase there is an increase of Cs fluxes onto the plasma grid, due to the sputtering and redistribution of Cs which is deposited on the source walls.

When symmetric plasma parameter profiles (i.e. density and temperature) are assumed, the position of the oven has only a slight effect on the Cs dynamics and the Cs redistribution appears to be symmetric. A much more relevant effect is determined by the plasma parameter profiles: when a plasma asymmetry is introduced in the model, as observed experimentally, the asymmetry of Cs redistribution increases. In particular, by assuming an upward plasma drift, the Cs density at the top results was 3 times larger than the Cs density at bottom. These results are in agreement with the experimental measurements performed in the prototype source [19].

The code was also applied to the larger source at ELISE test facility. Simulations have shown that the length of the vacuum phase, i.e. the time between two pulses, have an effect on the amount and on the temporal evolution of Cs density in front of the plasma grid: the longer the vacuum phase, the higher the Cs density in front of plasma grid. The simulated Cs density values for ELISE are generally lower compared with the ones calculated for the prototype source, with the assumption of the same total Cs evaporation rate. The increase of Cs density during the beam pulse due to the sputtering of Cs by the back-streaming ions was observed in the simulations and the results are agreement with the experimental time traces of Cs emission. A correlation between Cs stability and source performance, i.e. the amount of co-extracted electrons, has also been shown: more investigations of Cs dynamics in long pulses are therefore needed.

Further simulations will be performed for one hour pulse at ELISE, both considering 10 s extraction every 180 s and with extraction during all the pulse (as it is foreseen for ITER): the effect of the back-streaming ions can in fact change Cs dynamics in the case of continuous extraction. In order to have quantitative data to compare the simulation results also for ELISE, the laser absorption spectroscopy diagnostic will be installed in the next experimental campaign. The knowledge obtained by the comparisons between simulations and the ELISE measurements will be used for the optimization of Cs dynamics in negative ion sources, towards a reduction of the Cs consumption, which is one of the key issues for the development of the demonstration power plant DEMO.

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