Improved Understanding of the Cs Dynamics in Large H^- Sources by Combining TDLAS Measurements and Modeling

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Abstract. The ITER Neutral Beam Injection (NBI) relies on sources of negative hydrogen and deuterium ions which deliver a homogeneous and temporally stable extracted negative hydrogen ion beam for up to one hour (57 A extracted D^- current from an extraction area of 2000 cm^2), at which the co-extracted electron current has to be lower than the extracted negative ion current. The ELISE (Extraction from a Large Ion Source Experiment) test facility is equipped with a 1/2 ITER-NBI scale H^- source. Negative hydrogen ions are mainly created by conversion of hydrogen atoms on a surface with low work function. In order to reach the ITER requirements, a stable and homogeneous coverage of caesium has to be maintained on the plasma grid, which is the first grid of the extraction system. The dynamics of the highly-reactive Cs in the source is complex due to the non-ultra-high-vacuum conditions (10^{-7} mbar), the plasma-enabled redistribution of Cs and the continuous evaporation of Cs from two ovens.

The Monte-Carlo test particle transport code CsFlow3D has been developed in order to simulate fluxes of Cs and Cs^+ as well as the Cs coverage on the surfaces of the ion source during vacuum and plasma phases of the pulsed-driven sources. A successfully applied benchmark of the code at the small prototype ion source (1/8 ITER source size) allows now for giving predictions also for the larger ion sources. With the newly installed Tunable Diode Laser Absorption Spectroscopy (TDLAS) diagnostic at the Cs 852 nm resonance line the neutral Cs density averaged along two horizontal lines-of-sight close to the plasma grid is determined. No significant vertical asymmetry of neutral Cs is found. As a new feature, the temperature of Cs is evaluated from the Doppler broadening, resulting in 350 ± 50 K during vacuum phase and 960 ± 100 K during plasma phases. Both, measurements and simulations, reveal the high relevance of back-streaming positive ions created in the extraction system, leading to an additional source term of Cs. The simulation clearly shows a different regime in the Cs dynamics between continuous extraction and pulsed extraction, which is of particular interest since due to the available HV power supply ELISE is presently only able to extract a beam for 10 s each three minutes in long (up to one hour) plasma pulses.

INTRODUCTION

Large and powerful sources for negative hydrogen ions (D^- and H^-) are required for the Neutral Beam Injection (NBI) system of ITER. These must be capable to deliver a current of 57 A D^- and 66 A H^- for a duration of 3600 s and 1000 s, respectively [1]. ELISE (Extraction from a Large Ion Source Experiment) is a 1/2-ITER source size test facility at IPP (Max-Planck-Institut f. Plasmaphysik) Garching, which shall demonstrate the reachability of the ITER parameters for the ion source. Negative ions are produced by surface conversion [2] of mainly hydrogen atoms (created in a low-pressure, low-temperature plasma) on the Plasma Grid (PG), which is the first grid of a three grid extraction and acceleration system. Caesium is evaporated into the ion source in order to lower the work function of the PG, made of molybdenum-coated copper. An expansion chamber with a magnetic filter field divides the source between the plasma generation region in the driver ($T_e \approx 10$ eV) and the H^- production and extraction region ($T_e \approx 1$ eV). The low electron temperature in the latter region is required to minimize H^- destruction by electron collisions.

A critical parameter is the amount of co-extracted electrons: these are removed out of the extracted ion beam by magnets in the Extraction Grid (EG, second grid of the extraction system), bending them directly onto the grid. The created heat load on the EG limits technologically the tolerable amount of co-ectracted electron current, which must be lower than the extracted ion current for the ITER source parameters. Since electrons form the minority species in the ion-ion-plasma close to the extraction area in a well-conditioned source [3], they react very sensitive on the production rate of negative ions and thus on the work function of the plasma grid. The strong increase of the electron current in long (> 100 s) pulses usually limits the achievable source performance (i.e. large amount of ion current combined with a low amount of electron current) at present, whereas the slight decrease of the extracted ion current is less critical [3, 4].

In order to achieve the full ITER requirements in long pulses, the stability of the co-extracted electrons needs to be controlled better. Thus, a sufficiently low and stable work function of the plasma grid is required. The high chemical reactivity of caesium, the fact that the ion sources are not operated in ultra-high-vacuum conditions (background pressure in the order of 10^{-7} mbar) and plasma-enabled redistribution processes of caesium make the caesium dynamics complex. Two methods are used in order to gain a better insight into the caesium dynamics at ELISE: on the one hand, a transport code for Cs is used to model the Cs distribution in the source as well as the fluxes of Cs onto the plasma grid. The latter is expected to correlate with the work function of the PG. On the other hand, the neutral Cs density in front of the plasma grid is measured experimentally by a Tunable Diode Laser Absorption Spectroscopy (TDLAS) diagnostic. New insights into the Cs dynamics, as e.g. the role of back-streaming positive ions created in the extraction system by collision of negative ions with background gas particles on the Cs dynamics and thus the source performance, are expected by combining these two tools, which is done for the first time at the large ion source of ELISE.

CAESIUM DYNAMICS AND MODELING

The CsFlow3D code [5] is a 3D Monte Carlo transport code for caesium that has been developed in order to study the Cs dynamics in the source (i.e. fluxes of Cs and Cs^+ as well as the coverage of Cs on surfaces). The real geometry of the ion source is taken into account. Three phases need to be distinguished:

- Vacuum phase: the transport of Cs is modeled as a ballistic transport. Cs is evaporated out of the oven. A fraction of Cs is adsorbed at the wall during contact. The sticking coefficient has been experimentally determined for the vacuum conditions of the ion source [6]. Outgoing fluxes from the walls are created by reflection or thermal desorption.
- Plasma phase: neutral Cs and Cs ions are taken into account as well as collisions of Cs with gas and plasma particles. Erosion of adsorbed Cs layers by plasma particles lead to a redistribution of Cs.
- Extraction phase: in addition to the plasma phase, physical sputtering of Cs from the back plate by back-streaming positive ions leads to an additional source term of Cs.

For benchmarking, CsFlow3D can determine the Cs density along a line of sight. CsFlow3D has been succesfully benchmarked at the small prototype ion source [7] and is now, after implementing the geometry of ELISE, able to give predictive results for ELISE, which can be partially compared with experimental measurements of the Cs density.

ELISE SOURCE AND TDLAS DIAGNOSTIC

Figure 1 shows a sketch of the ELISE ion source. A hydrogen plasma is created in four drivers by inductive RF coupling with a total RF power up to 300 kW. The magnetic filter field (several mT), needed to reduce the electron temperature and density in front of the PG, is mainly created by a vertical current through the PG (several kA). The field topology and field strength (in particular close to the side walls) can be modified by mounting bars of permanent magnets at the side wall of the source. The particle beam is extracted through 640 apertures of 14 mm diameter, which are arranged in eight beamlet groups of 80 apertures each. For extraction and acceleration of the beam, high voltage of up to 60 kV is applied to the source using a typical extraction voltage of 10 kV between PG and EG. ELISE is capable to demonstrate plasma pulses with the full length of the ITER requirements (up to one hour); however, due to technical limitations of the HV supply, a particle beam can only be extracted for 10 s each three minutes within a plasma pulse (resulting in several individual beam blips in long pulses). Plasma pulses are divided by a vacuum phase of several minutes. For the evaporation of Cs, two Cs ovens are mounted at the side wall of the expansion chamber. During operation, Cs is continuously evaporated through two nozzles, which direct the Cs flow towards the back plate of the expansion chamber. In order to avoid a strong, local adsorption of Cs, all walls of the ion source are controlled to a temperature of 45 °C. The PG is temperature-controlled to 125 °C, which is a experimentally determined value allowing for achieving a high source performance. A more detailed description of ELISE can be found elsewhere [8].

For the measurement of the Cs density, a TDLAS diagnostic at the Cs-D_2 852 nm resonance line of neutral caesium [9], which is regularly operated at the prototype source [3], is newly applied at ELISE. It is installed at two horizontal lines of sight (LOS) in the top and bottom part of the source (vertically in the center of the driver

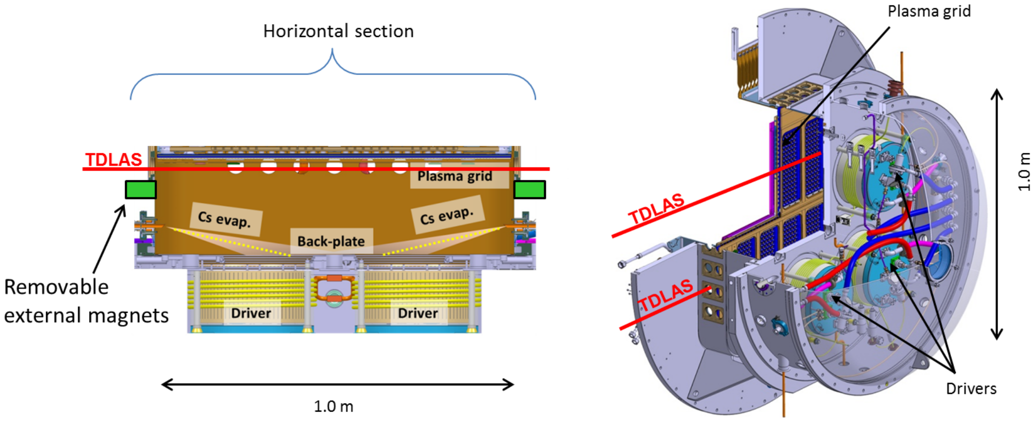

FIGURE 1. Left: horizontal cut through the ion source of ELISE. The positions of the Cs ovens as well as the axial position of the TDLAS measurement are indicated. Right: view of the ELISE ion source from the back with the two LOS for TDLAS.

projection) at an axial distance of 3 cm to the plasma grid. It allows for the measurement of the LOS-averaged neutral Cs density (length of LOS: 0.875 m). For the first time at a negative ion source, also the profile of the absorption peaks is evaluated in order to estimate the gas temperature out of the Doppler broadening of the six hyperfine lines.

RESULTS

All measurements presented in this paper have been carried out in deuterium operation of ELISE. In deuterium operation, the amount of Cs (a higher Cs evaporation rate from the ovens is required) as well as the co-extracted electron current is a very critical issue, since the latter is known to be higher in deuterium operation compared to hydrogen [3]. The measured neutral Cs density during a plasma pulse as function of the applied RF power is shown in Figure 2 (a) for two source filling pressures (0.3 Pa and 0.6 Pa). As known from the prototype source, the Cs density is increased at higher RF power and at lower filling pressure. The absolute value is somewhat lower than in the prototype source (in the order of 10^{15} m^{-3} in deuterium operation), which is attributed to a slightly lower evaporation rate of Cs in ELISE for short pulses. The vertically symmetric evaporation of Cs into the ion source results in an almost vertically symmetric distributed neutral Cs density (indicated by no significant difference of the Cs density between the top and bottom LOS).

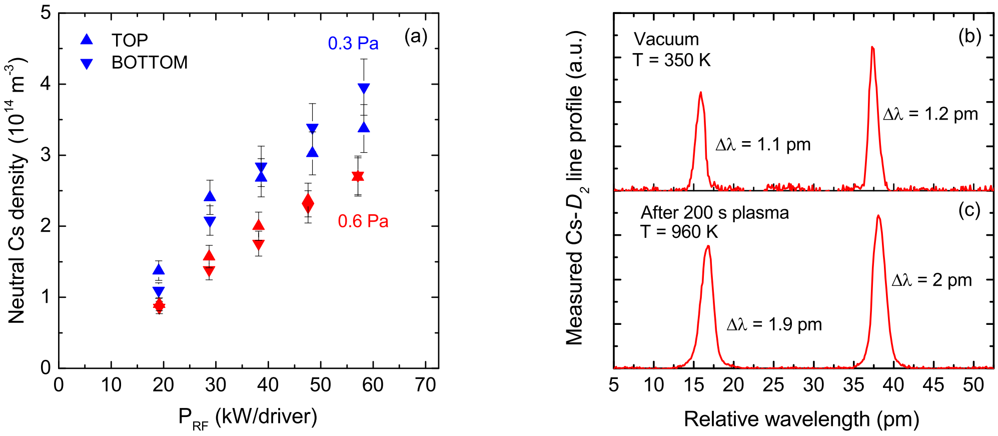

FIGURE 2. (a): neutral Cs density at the top and bottom LOS as function of the applied RF power in case of 0.3 Pa and 0.6 Pa filling pressure (deuterium operation). (b): absorption line profile in the vacuum phase. (c): absorption line profile in the plasma phase (200 s plasma).

The measured absorption line profiles of the Cs-D$_2$ line (852 nm) in the vacuum and plasma phase are shown in the Figures 2 (b) and (c), respectively. For this measurement, a low magnetic filter field strength has been used ($\approx$ 1.5 mT, no external magnets) in order to keep an influence of the Zeeman splitting of the individual levels insignificant. The measured spectrum consists of six Doppler-broadened hyperfine lines, in which each three overlap to form only two distinguishable peaks. However, in order to determine the correct gas temperature, the hyperfine structure needs to be taken into account. When doing so, the resulting Cs gas temperature is 350 ± 50 K in the vacuum phase and 960 ± 100 K in the plasma phase. The temperature of Cs atoms in vacuum is thus between the temperature of the source walls ($\approx$ 320 K) and the body temperature of the Cs oven ($\approx$ 550 K). During plasma phases, the Cs gas temperature is in the range of the gas temperature of hydrogen molecules ($\approx$ 0.1 eV [10]).

The measured timetrace of two following short (20 s) pulses with and without extraction at stable Cs conditions as well as the simulated Cs density for the same cases is shown in Figure 3. A reasonable evaporation rate of 5 mg/h has been used for each of the two ovens in the simulation. The simulation reflects all significant details of the experimentally measured timetrace: a strong increase of the neutral Cs density from vacuum ($2–3\times10^{14}$ m^{-3}) to plasma phase ($8–14\times10^{14}$ m^{-3}), a decrease of the Cs density during the plasma phase as well as an increase of the Cs density during the extraction phase. The latter is generated by the release of adsorbed Cs by back-streaming ions. The different behavior at the beginning of the plasma pulse is attributed to changes in the plasma discharge parameters (RF power and pressure), which are not taken into account in the simulation.

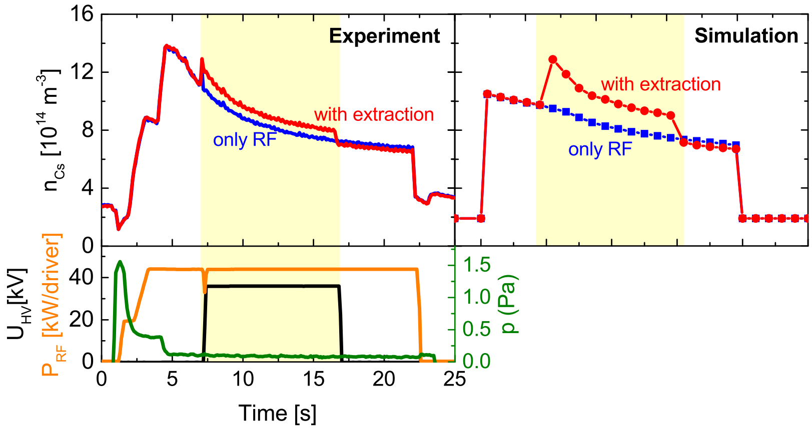

FIGURE 3. Top left: measured neutral Cs density n_{Cs} in two similar short pulses with and without extraction at the top LOS (deuterium operation). Bottom left: timetraces of the source pressure p, applied RF power per driver P_{RF} and total applied high voltage U_{HV}. Top right: simulated neutral Cs density n_{Cs} for two pulses with and without extraction.

The release of Cs by back-streaming ions is often linked with a temporary increase of the source performance during an individual beam blip in long pulses: whereas the co-extracted electron current generally increases from beam blip to beam blip, it usually decreases within one beam blip [3]. The extracted ion current is more stable within usually 10% variation. In total, the Cs release by back-streaming ions seems to play a major role in the Cs dynamics at ELISE. For this reason, the flux of Cs onto the PG has been simulated for 400 s pulses using different conditions (Figure 4). It should be noted that a higher duty cycle between extraction phase and plasma only phase has been used in order to reach eight beam blips within the pulse while saving computational time.

The total flux of Cs (neutrals and ions) onto the PG averaged on the area of one beamlet aperture group (indicated in the figure) is shown in red for the standard case (pulsed extraction). Generally, the Cs flux is reduced within the first 200 s of plasma time by a factor of approximately 2, afterward an almost stable level is reached. During all extraction phases, the flux is increased due to the release of Cs by back-streaming ions. The dashed lines indicate the fraction of ions (blue) and neutrals (green) of the total flux. The contribution of the ions is roughly 2/3, and 1/3 of the neutrals. It should be noted that depending on the potential structure of the PG sheath, which is influenced by a positive bias voltage applied between the PG and the source body, ions might not be able to reach the PG surface [11]. Additionally, the case of a – at present experimentally not possible – continuous extraction is shown with the black curve (total Cs flux). From the second beam blip onwards, the flux is lower than in case of the pulsed extraction. This behavior is attributed to a depletion of Cs reservoirs at the back plate by back-streaming ions. In case of an unlimited Cs reservoir at the back plate (orange curve, continuous extraction), the total Cs flux is much higher and in particular saturates

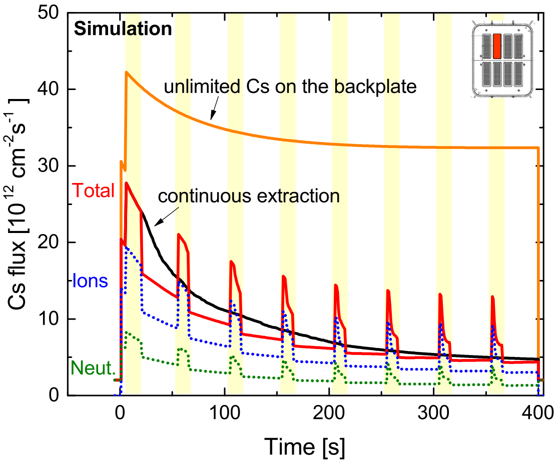

FIGURE 4. Simulated caesium flux during a 400 s pulse onto one beamlet aperture group. Red: total flux (Cs^0 and Cs^+) in case of a pulsed extraction. The individual contributions of Cs ions are plotted in blue and of neutral Cs in green. Black: total flux of Cs in case of a continuous extraction. Orange: total Cs flux in case of a unlimited reservoir of Cs on the back plate and continuous extraction.

earlier and at a much higher value (approximately seven times higher).

This simulation shows the high relevance of back-streaming ions in combination with the available Cs reservoirs at the back plate for the Cs dynamics in the ELISE source. In particular the pulsed extraction leads to a regime, which is unfortunately less relevant for sources with continuous extraction. Nevertheless, achieving a higher Cs reservoir at the back plate of the ion source would lead to a better Cs regime in both cases, pulsed and continuous extraction.

SUMMARY

The combination of TDLAS measurements and simulations using the CsFlow3D code crystallized to be the most promising tool in order to gain an improved understanding of the Cs dynamics at the ELISE ion source: measurements revealed no significant vertical asymmetry of neutral Cs in the source. The temperature of Cs atoms has been determined to reasonable values of 350±50 K in the vacuum phase and 960±100 K in the plasma phase. The timetrace of neutral Cs in a short (20 s) pulse can be almost perfectly reproduced by the simulation using CsFlow3D, revealing the importance of back-streaming positive ions created in the extraction system that lead to a relevant source term of Cs. Simulations of longer pulses showed a change in the dynamics between the at present only available pulsed extraction and continuous extraction, as well as the high importance of Cs reservoirs at the back plate of the ion source. Thus, CsFlow3D can be used as a predictive tool for the optimization of the Cs dynamics in large negative ion sources.

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