

Cesium Dynamics and H^- Density in the Extended Boundary Layer of Negative Hydrogen Ion Sources for Fusion

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Abstract. The cesium dynamics of the IPP prototype source for negative hydrogen ions is investigated using the Cs laser absorption spectroscopy spatially resolved at two lines of sight during vacuum and plasma phases. The spatially resolved measurement is of particular interest since the source has an intrinsic asymmetry due to the Cs oven position. Comparisons of the Cs homogeneity show an inhomogeneous distribution during vacuum phases and a more uniform distribution of neutral Cs during plasma phases. The Cs densities are compared to the extracted negative hydrogen ion and co-extracted electron current densities, and correlations are shown for different timescales. In addition, the cavity ring-down spectroscopy has been reinstalled for the measurement of the negative hydrogen ion density with a line of sight in the center of the ion source. A comparison of the extracted ion current density with the negative hydrogen ion density in the source shows a clearly linear correlation.

Keywords: negative hydrogen ion source, cesium absorption, cesium dynamics, cavity ring-down spectroscopy

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INTRODUCTION

High power, large scale negative deuterium (or hydrogen) ion sources with stable ion currents for up to 1 h operating time at a pressure of 0.3 Pa are required for the neutral beam heating and current drive of the upcoming ITER fusion experiment [1]. Negative hydrogen ions are produced by surface conversion of hydrogen atoms and ions on a surface with low work function [2]. To achieve a low work function, cesium (work function of bulk material 2.14 eV [3]) is evaporated onto the convertor surface (plasma grid, the first grid of the extraction system). In order to obtain a stable extracted negative hydrogen ion current, a stable production of H^- and for that a stable work function of the convertor surface is mandatory. Due to the high chemical reactivity of Cs the Cs layer can be degenerated by background gas components or hydrogen gas. For that reason continuous fluxes of pure Cs onto the convertor surface are required for the build-up of a stable Cs layer. Cs fluxes are provided by a continuous flow out of a Cs oven and by plasma induced distribution and redistribution processes resulting in a complex Cs dynamics. Thus, diagnostics for cesium are necessary for a better understanding of this Cs dynamics.

During plasma phases monitoring the Cs D₂ emission line (852 nm) is usually done by using spectrometers or a simple photodiode with an interference filter [4]. Since the prototype ion sources are operated in pulsed mode, a measurement of Cs in the vacuum phases (usually 200 s) between the plasma pulses is also desirable. For that reason a laser absorption spectroscopy at the same Cs D₂ transition (resonance line) has been installed in the past at one line of sight (LOS) at both, the BATMAN short pulse testbed [5] (6 s plasma time including 4 s extraction, 200 s vacuum phase between) and the MANITU long pulse testbed [6] (plasma and extraction time up to one hour). The benefits of the absorption diagnostics are the possibility to monitor the neutral Cs density in the vacuum phase as well as in the plasma phase. The analysis is straightforward and is independent from plasma parameters. However, due to its low ionization energy a large fraction of Cs is ionized during the plasma phase, which is not detected by the Cs absorption spectroscopy but also contributes to the total amount of Cs in the ion source.

Recently, the setup has been expanded to two lines of sight at BATMAN, enabling a better insight into the spatial resolved Cs dynamics. In addition correlations of the Cs density with the performance of the ion source may help to use the Cs density as a monitor signal during the conditioning phase of the ion source.

Beside the Cs absorption the previously installed cavity ring-down spectroscopy (CRDS) [7] has been reinstalled for measurements of the H⁻ density in the plasma volume. Comparisons of the extracted H⁻ current to the H⁻ density in the volume and with the Cs density can deliver interesting insights to the production, destruction and transport processes in the extended boundary layer close to the convertor surface.

ION SOURCE AND DIAGNOSTICS

A sketch of the prototype ion source at the Max-Planck-Institut für Plasmaphysik (IPP, Garching) with the lines of sight of the diagnostics is shown in Figure 1. During the campaign, the magnetic filter field was not created by the internal magnets but by a magnetic frame outside the expansion chamber [8]. The walls are kept at a temperature of 35 °C and the plasma grid at 150 °C. These temperatures are based on experimental experience and help for the conditioning of the source. At these temperatures a strong accumulation of Cs is avoided by also enhancing Cs redistribution processes.

The LOS of the Cs absorption are located in the top and bottom part of the source (distance of 2 cm to the plasma grid, diameter of approx. 1 cm). The spatially resolved monitoring is of particular interest since the Cs oven is mounted in the top part. A fiber coupled distributed feedback tunable diode laser is used as the light source for the Cs absorption and a photodiode with an interference filter for the Cs 852 nm line ($\Delta\lambda_{\text{FWHM}} = 10$ nm) is used as the detector. The temporal resolution of the system is up to 25 spectra per second. A more detailed description of the Cs laser absorption diagnostic can be found in [9].

The horizontal line of sight of the CRDS is now located in the vertically center of the ion source with the same distance (2 cm) to the plasma grid. It is expected that this position gives a direct correlation of the H⁻ density with the source performance, i. e. the extracted current density of negative hydrogen ions. A Q-switched Nd:YAG laser

with a pulse energy of up to 50 mJ, cavity mirrors with a radius of curvature of 1 m and a reflectivity of nominal 99.995% at the used fundamental harmonic wavelength (1064 nm), a cavity length of 1.2 m and a photodiode with a fast amplifier is used, as described in detail in [7]. Due to aging of the CRDS mirrors the intrinsic decay time of the cavity is decreased to about 15 μ s from the nominal value of 80 μ s. The temporal resolution of the CRDS has been increased from 4 Hz to up to 8 Hz.

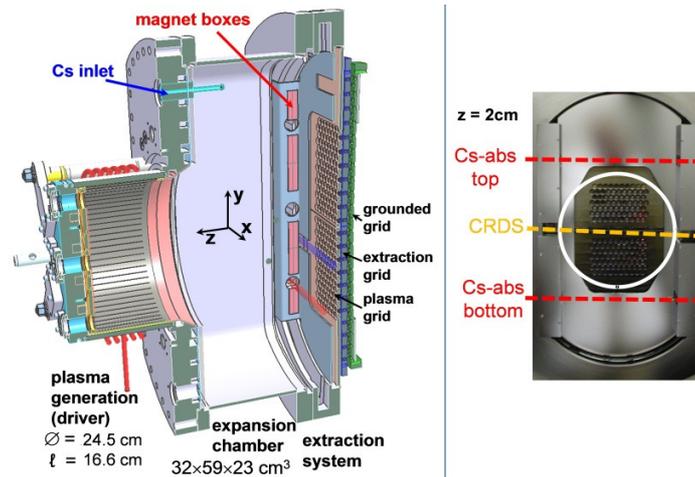


FIGURE 1. Sketch of the IPP prototype source for negative hydrogen ions and a view on the plasma grid of the BATMAN source with the lines of sight of the diagnostics.

The measured H^- density of two consecutive pulses with different pulse lengths is shown in Figure 2. A peak at the beginning of the plasma phase is followed by a stable H^- density during the pulses. The peak occurs during the gas puff at the start of a pulse: for the plasma ignition a higher flux of H_2 gas is injected into the source, followed by a stable source pressure. After the end of the pulses, both time traces show a higher absorption value inside the cavity that cannot be explained by absorption of H^- . Since this afterglow in the absorption does only appear after evaporating Cs into the ion source and not in a clean source, it is most likely caused by absorption of molecules containing Cs, which can be built in plasma (e. g. CsH / Cs_2) [7]. The height of the absorption after the end of the pulse is equal for both pulses, which means that an equal amount of the Cs compound is created in both pulses on a short timescale (second).

For a comparison of the measured H^- density with the extracted ion current the values are usually averaged during the extraction phase, which begins 1.5 s after the start of the plasma pulse. For that reason it is possible to subtract the additional absorption of the Cs compound from the total absorption signal, which is done by simply using the decay time of the first laser shot after the end of a pulse as the intrinsic decay time of the cavity.

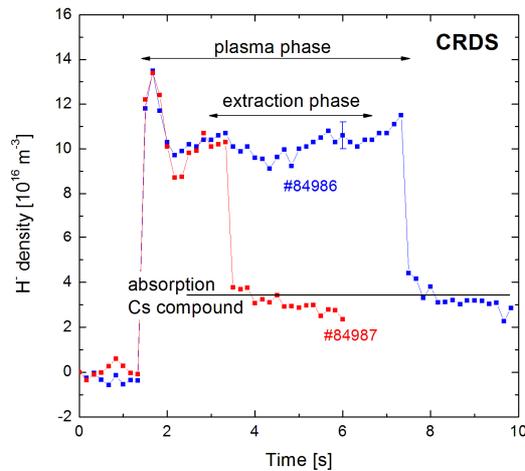


FIGURE 2. H^- density of two consecutive pulses with different pulse lengths measured by CRDS.

RESULTS

The Cs dynamics of a typical BATMAN pulse is plotted in Figure 3, which shows the measured neutral Cs density at both LOS and the ratio between them, indicating the Cs homogeneity. During the vacuum phase, before the pulse, the Cs density is higher in the upper part of the source due to the oven position. The Cs volume density during vacuum phases depends on the evaporation rate of the Cs oven and can vary from a value below the detection limit (roughly 10^{14} m^{-3}) up to values in the order of 10^{15} m^{-3} . During the plasma phase the density of neutral Cs is increased at both LOS. Taking into account the large ionization rate of Cs in the source ($> 90\%$) [4], the total amount of Cs (neutral and ions) is instantaneously highly increased due to a release of Cs from the source walls interacting with plasma. The Cs density rises further in the first second of a plasma discharge, when the source pressure is still raised due to the gas puff. The start and stop of the extraction phase is also to be seen in the Cs signal: a small increase and decrease appears, respectively. The neutral Cs density during plasma phases is in the order of 10^{15} m^{-3} with a more homogeneous distribution of Cs during the plasma phase. However, there is still more Cs at the top part of the source ($\approx 20 - 30 \%$). This behavior can vary slightly by changing the drift of the plasma (a vertical drift is created by the magnetic filter field with the direction changing by turning the direction of the magnetic field [10]). At the pulse shown in Figure 3 the polarization of the magnets was set such that the plasma drifts to the top part of the source. As a consequence more Cs can be released from the source walls in the top part. When changing the drift to the bottom part, the homogeneity of Cs can increase further or even change to the other direction during plasma pulses. In any case the asymmetry of the Cs distribution inside the source due to the oven position is almost compensated during plasma discharges.

After the end of the plasma pulse a peak of neutral Cs usually appears at the top part of the source with decay to the initial value within some seconds. In contrast, usually no peak appears at the bottom LOS, where the decay to the initial Cs density

happens much faster. The peak is created due to the lack of Cs ionization after switching off the RF: neutral Cs fluxes from the walls are no longer ionized and contribute to the measured density as well as recombined Cs atoms. The different dynamics between the top and bottom LOS indicates that the properties of Cs fluxes at the wall (adsorption, desorption and reflection) differ inside the source with a higher adsorption or lower desorption rate at the bottom part, the contrary part regarding the position of the Cs oven.

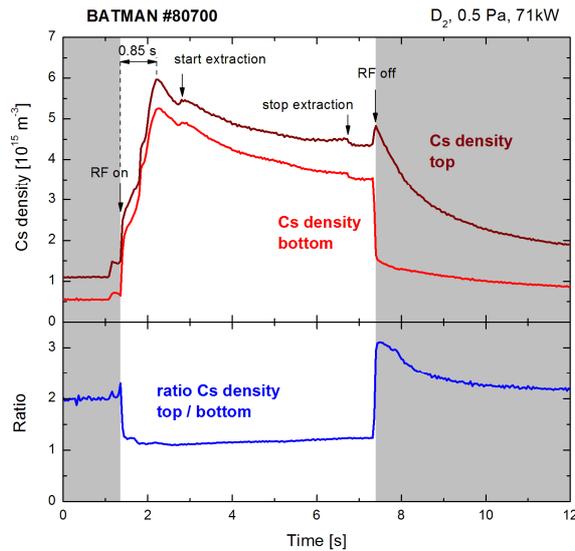


FIGURE 3. Dynamics of neutral Cs at two lines of sight for a typical BATMAN pulse (plasma drift up).

Figure 4 shows the ratio of the Cs density between the top and the bottom line of sight during vacuum and plasma phases (averaged during the time of extraction) for seven consecutive days of operation. The Cs oven was turned on at all pulses shown. Without evaporating Cs the Cs density is usually below the detection limit (roughly 10^{14} m^{-3}) in the vacuum phase. The plot shows again that Cs is distributed more homogeneously in plasma phases compared to vacuum phases.

As can be seen, during one day the homogeneity is usually increased continuously in the vacuum phase, starting with a ratio of the Cs density between the two LOS of roughly 4. This behavior can be explained as follows: within a day of operation the Cs layers on the walls of the ion source are cleaned by plasma pulses. Due to changing adsorption and desorption fluxes of Cs this can lead to a better distribution of Cs inside the ion source. In contrary, during plasma phases the ratio rarely changes during one operation day. This shows again that the redistribution processes due to plasma induced desorption fluxes of Cs from the walls dominate during plasma phases, ensuring a reproducibility of the source performance.

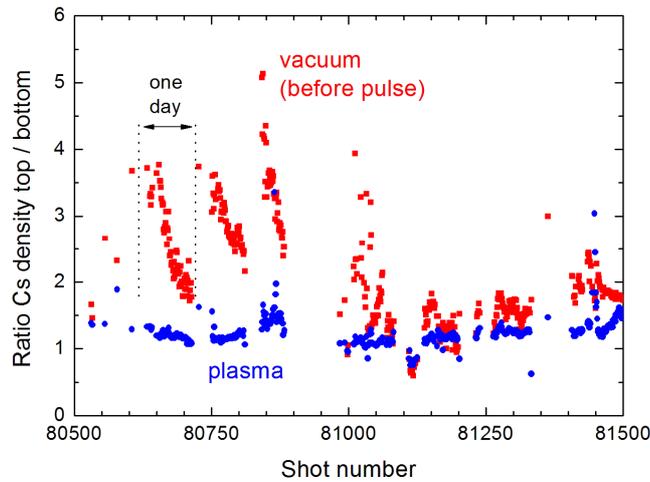


FIGURE 4. Ratio between Cs density top and bottom in the vacuum and plasma phase (averaged during extraction time) for seven consecutive days of operation.

The upcoming more ITER-like ion sources contain multiple Cs ovens and have a larger size of the source [11, 12]. For that reason, the results of the Cs dynamics observed at the BATMAN prototype source cannot be directly transferred. Nevertheless, asymmetries of the Cs evaporation are expected to be compensated due to plasma induced redistribution processes, and for that are not expected to be an issue.

A driving question is whether the neutral Cs density measured by the absorption spectroscopy or even by the much simpler technique of OES can be used as a monitor signal for an optimal Cs evaporation rate of the oven. Thus the Cs density is compared with the extracted H^- current density and the ratio between co-extracted electron current density and extracted H^- current density for three days out of an operational campaign in Figure 5. The first example (04/24) shows the Cs conditioning phase of the ion source. This means that no stable and pure Cs layer was built on the plasma grid yet since only a small amount of pure Cs has been evaporated into the ion source during this campaign. The second exemplary day (06/26) also shows the Cs conditioning phase, however two months later. The third example (07/25) shows a completely conditioned source, when a stable and high performance (large amount of extracted H^- and low co-extracted e^- current density) of the source is achieved.

The first two exemplary days show an influence of the measured Cs amount on the source performance, with the ratio j_e/j_{H^-} reacting more sensitive especially at low Cs densities. Although there is a correlation between the Cs density and the source performance at each day, the amount of Cs differs for the same values of the source performance between these days. In contrast, at the well-conditioned source there is almost no dependence of the performance on the Cs density.

The different amount of Cs density required for the Cs conditioning of the source is explained as follows: the production rate of H^- is determined by the work function of the plasma grid during the Cs conditioning phase. The work function of the plasma grid, however, changes depending on the incoming fluxes of Cs. Although not only Cs fluxes onto the PG contribute to the volume averaged Cs density measured by the Cs

absorption, it can obviously reflect changes of Cs fluxes onto the PG on a short timescale. On a long timescale the adsorption or desorption fluxes of Cs from the walls can change, for instance due to a different amount of Cs inside the source. This means that on a long term changes of the volume averaged Cs density does not reflect changes of Cs fluxes onto the plasma grid anymore. The optimal flux of Cs onto the plasma grid cannot be adjusted by simply measuring the LOS-integrated Cs density in front of the plasma grid on a long term. Nevertheless, the neutral Cs density at optimal performance is always in the range of 10^{15} m^{-3} .

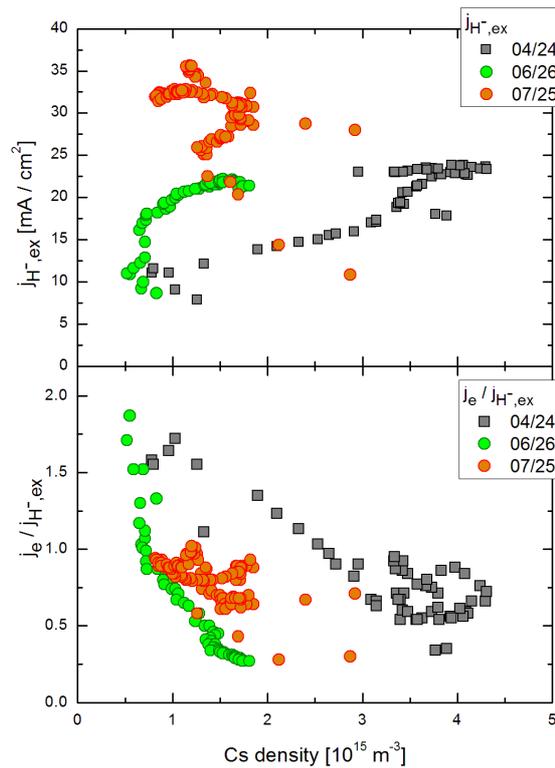


FIGURE 5. Comparison of the source performance with the Cs density at three different days of operation (hydrogen, 40 – 75 kW RF power, pressure 0.5 – 0.6 Pa).

A comparison of the extracted H^- current density with the H^- density is shown in Figure 6 for the same days as in Figure 5. A clearly linear correlation of both values is obtained. This behavior is a consequence of the present position of the LOS of the CRDS, which is located in the vertically center of the ion source. However, the individual days differ slightly from the straight line. This is caused by a pressure dependence of the measured density: a higher H^- density is obtained at higher source pressures, whereas the extracted H^- current density reacts only weakly on changes of the source pressure. A different source pressure has an influence on the transport of negative hydrogen ions to the observed volume.

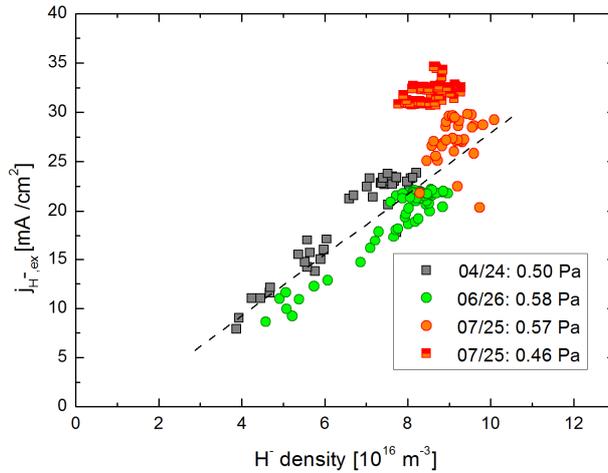


FIGURE 6. Comparison of the H⁺ density measured by CRDS with the extracted H⁺ current density.

CONCLUSION

The Cs laser absorption spectroscopy at the IPP prototype source for negative hydrogen ions has been equipped with an additional line of sight now allowing for spatial resolved measurements. This gives a closer insight into the Cs dynamics in the ion source, in particular the uniformity of the Cs distribution: a higher Cs density at the LOS in the upper part, where the Cs oven is located, appears during vacuum phases. Due to plasma induced redistribution processes a much better homogeneity is observed for the duration of plasma pulses. During the Cs conditioning phase of the ion source a dependence of the measured neutral Cs density on the source performance on a short timescale (one day) occurs, but due to the change of complex Cs fluxes there is no long-term dependence. Nevertheless, a neutral Cs density in the order of magnitude of 10^{15} m^{-3} is detected during plasma phases when achieving a high source performance.

For comparison of the H⁺ density inside the source with the extracted ion current density, the CRDS spectroscopy has been reinstalled with a LOS in the vertical center of the ion source. A Cs compound (possibly Cs₂ or CsH) is created in plasma and contributes to the absorption signal. Since its build-up happens during the first two seconds of a pulse, the additional absorption is subtracted to allow for comparison of averaged values during the extraction phase. The H⁺ density correlates well with the extracted H⁺ current density, taking the source pressure dependence into account.

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