

# Investigation of the boundary layer during the transition from volume to surface dominated $H^-$ production at the BATMAN test facility<sup>a)</sup>

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BATMAN is a test facility equipped with a  $1/8$  scale  $H^-$  source for the ITER heating Neutral Beam Injection (NBI). Several diagnostics in the boundary layer close to the plasma grid (first grid of the accelerator system) followed the transition from volume to surface dominated  $H^-$  production starting with a Cs-free, cleaned source and subsequent evaporation of caesium, while the source has been operated at ITER relevant pressure of 0.3 Pa: Langmuir probes are used to determine the plasma potential, Optical Emission Spectroscopy (OES) is used to follow the caesiation process and Cavity Ring-Down Spectroscopy allows for the measurement of the  $H^-$  density. The influence on the plasma during the transition from an electron-ion plasma towards an ion-ion plasma, in which negative hydrogen ions become the dominant negatively charged particle species, is seen in a strong increase of the  $H^-$  density combined with a reduction of the plasma potential. A clear correlation of the extracted current densities ( $j_{H^-}$ ,  $j_e$ ) exists with the Cs emission.

## I. INTRODUCTION

The heating Neutral Beam Injection (NBI) system at ITER will be based on large-scale sources for negative hydrogen ions. A filling pressure of  $p \leq 0.3$  Pa is required in order to minimize  $H^-$  losses by background gas stripping in the accelerator system.<sup>1</sup> The RF-driven prototype source had become the reference design for the ITER heating neutral beam facility in 2007.<sup>2</sup> In this source, negative hydrogen ions are mainly generated by surface production. For this purpose, Cs is evaporated into the source, lowering the work function on the plasma grid (PG, first grid of the accelerator system) and thus strongly enhancing the surface production rate of  $H^-$ .<sup>3</sup>

BATMAN is a short pulse test facility equipped with the prototype source, i.e. a  $1/8$  scale  $H^-$  source for the ITER NNBI.<sup>4</sup> BATMAN is dedicated to physical investigations including the understanding of the processes involved in the surface negative ion generation and extraction. As most of the extracted negative ions are generated on the caesiated plasma grid, understanding the physics occurring in the vicinity of the plasma grid, called the boundary layer, is in the focus of the investigations.

The transition from volume<sup>3</sup> to surface dominated  $H^-$  production can be observed during the Cs conditioning phase, only if the source had been carefully cleaned from remaining caesium and its compounds. During this phase, Cs is continuously evaporated into the source while a stepwise improvement of the source performance (high  $j_{H^-}$ , low  $j_e$ ) takes place shot by shot until high performance is

reached. For the first time, BATMAN has been operated at 0.3 Pa during the whole Cs conditioning phase as well as with constant RF power and extraction voltage in order to investigate only the influence of Cs. The process has been followed by several diagnostics in the boundary layer, which is the plasma volume close to the PG. A rather low evaporation rate of Cs into the source had been chosen in order to follow more accurately the transition.

## II. EXPERIMENTAL SETUP

BATMAN is a pulsed test facility allowing for plasma pulses of up to 10 s length (including 4.5 s of beam extraction) and a vacuum phase of typically 200 s between two pulses. A sketch of the ion source at BATMAN is shown in Figure 1 (a). BATMAN is equipped with one driver, in which a hydrogen plasma is created by inductive RF coupling of up to 75 kW of power, using the current solid state RF generator.<sup>5</sup> A horizontal magnetic filter field in an expansion chamber reduces the electron temperature and lowers the plasma density. For the present investigations the standard configuration with permanent magnets in internal boxes is applied. The horizontal magnetic filter field leads to vertical plasma drifts and thus to a vertical plasma asymmetry in the expansion chamber.<sup>6</sup> In order to suppress the amount of co-extracted electrons, the plasma grid is positively biased with respect to the source body by several tens of Volt. A bias plate covering most part of the PG without extraction apertures increases the surface area on source potential. Caesium is carefully evaporated into the source by usage of a Cs oven, whose nozzle is bent directly onto the PG in the current setup. The extraction system consists of three grids. Co-extracted electrons are removed out of the extracted particle beam by

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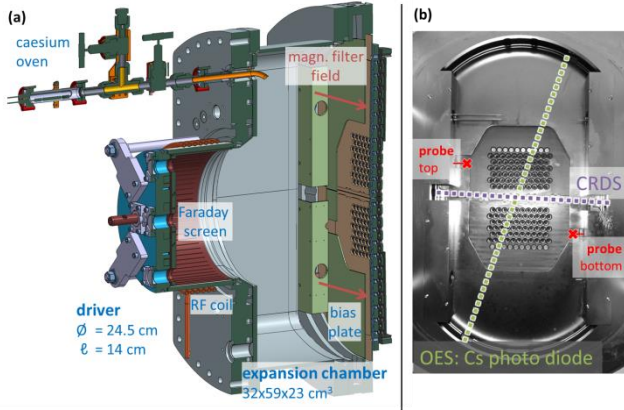


FIG. 1. (Color online). (a): sketch of the ion source at BATMAN. (b): view onto the plasma grid showing the measurement positions of the Langmuir probes as well as the lines of sight of the Optical Emission Spectroscopy (OES) and Cavity Ring-Down Spectroscopy (CRDS).

magnets in the extraction grid (EG, second grid), bending electrons directly onto the EG. The tolerable heat load limits the maximum amount of co-extracted electrons ( $j_e/j_{H^-} < 1$  for the ITER source). The amount of co-extracted electrons often limits the operational parameters of the source.

The diagnostic setup is shown in Figure 1 (b). Two Langmuir probes are used for the determination of the plasma potential in the top and bottom part of the source (axial distance of 7 mm to the PG). The Cs emission at 852 nm is recorded by a photodiode using an interference filter at a vertical line of sight (22 mm distance to PG). A vertically centered, horizontal LOS (22 mm distance to PG) is used by the Cavity Ring-Down Spectroscopy for determining the  $H^-$  density.<sup>7</sup>

### III. EXPERIMENTAL RESULTS

The evolution of the extracted  $H^-$  current density as well as the co-extracted electron current density during the first day of caesiation is shown in Figure 2 (a), in which the start of Cs evaporation is indicated. Operational parameters have been kept constant at  $P_{RF} = 60$  kW,  $p = 0.3$  Pa and an extraction voltage of  $U_{ex} = 5$  kV in  $H_2$  operation. In volume operation before evaporating Cs the extracted current densities of  $j_{H^-} = 1.6$  mA/cm<sup>2</sup> and  $j_e = 43.1$  mA/cm<sup>2</sup> result in  $j_e/j_{H^-} = 27$ . Already during the shown first hours of caesiation,  $j_{H^-}$  is increased by a factor of 9.7 to 14.8 mA/cm<sup>2</sup>, whereas  $j_e$  is decreased by a factor of 1.8 to 24.3 mA/cm<sup>2</sup> ( $j_e/j_{H^-} = 1.6$ ), thus  $H^-$  reacts stronger to changes of the Cs conditions in the badly conditioned source. In contrary, in a well-conditioned source it is usually observed that electrons react more sensitive to changes of the conditioning.<sup>8</sup> During the plotted conditioning phase, the Langmuir probe characteristics of both probes change from a classical electron – positive ion shape towards a symmetric ion-ion curve, meaning that  $H^-$  becomes the dominant negatively charged particle species. So it is obviously the minority species ( $H^-$  in a badly conditioned source as shown here, electrons in a well-

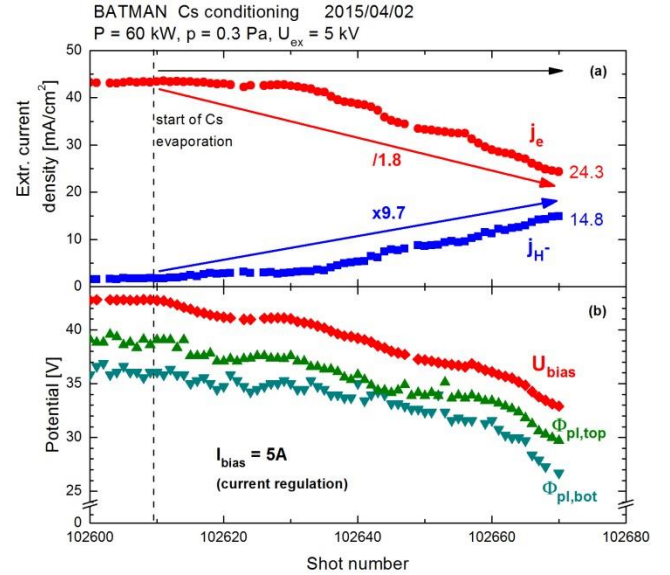


FIG. 2. (Color online). (a): extracted  $H^-$  and co-extracted electron current density for the first hours of Cs conditioning at BATMAN, starting in volume production. (b): plasma potentials (top and bottom) and applied bias voltage (const.  $I_{bias} = 5$  A) for the same pulses.

conditioned source) that reacts stronger to changes of the Cs conditions in the source.

The source is operated at a constant bias current of 5 A, thus the bias voltage  $U_{bias}$  is adjusting itself with respect to the local plasma parameters. The influence of the caesiation process on the bias voltage as well as on the plasma potentials at the top and bottom probe position is shown in Figure 2 (b). Due to changing fluxes of charged particles from and towards the wall (less electrons onto the source walls in combination with surface-produced  $H^-$  from the walls into the plasma) the plasma potential is reduced during the Cs conditioning by about 10 V at both positions. As a consequence, the required bias voltage for drawing the 5 A bias current is also reduced. Since  $U_{bias}$  is lowered by the same level as the plasma potential, the potential difference close to the PG stays almost constant during the shown conditioning process. The reduction of the plasma potential during the beginning of the Cs conditioning phase has regularly been observed for different operational parameters as well.<sup>9</sup>

The dependence of the source performance ( $j_{H^-}$  and  $j_e$ ) on the Cs emission is shown in Figure 3. Since the wavelength range of the interference filter ( $\lambda_c = 852$  nm,  $\Delta\lambda_{FWHM} = 10$  nm) does not only contain the emission line of Cs at 852 nm but also molecular hydrogen emission, the signal contains an offset clearly visible in the volume production case without any Cs evaporation. However, a comparison of the diode signal with a spectrometer showed that the additional signal is mainly linked to the Cs emission. The source performance shows an almost linear dependence on the Cs emission signal:  $j_{H^-}$  is increased and  $j_e$  decreased at higher Cs emission and thus higher Cs amount in the source volume close to the PG. Thus, it seems that the work function of the plasma grid is linked to the Cs density close to the PG and in this way to the incoming flux of Cs onto the PG. These clear trends are

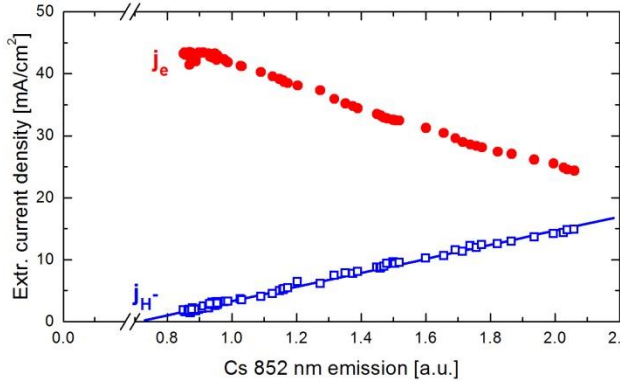


FIG. 3. (Color online). Extracted  $H^-$  current density and co-extracted electron current density as a function of the Cs 852 nm emission during the caesiation process.

regularly seen at BATMAN during the first stage of caesiation<sup>9,10</sup>; however, this correlation does no longer hold in a well-conditioned stage of the source.

The evolution of the  $H^-$  density in the volume as a function of the extracted  $H^-$  current density during the first day of the caesiation is shown in Figure 4. A linear correlation exists in the case of a more conditioned source ( $j_{H^-} > 6 \text{ mA/cm}^2$ ), which has been regularly seen in the past as long as the operational parameters of the source have been kept constant.<sup>10</sup> Deviations from this linear dependence take place towards volume dominated production of  $H^-$  at low extracted current densities ( $j_{H^-} < 6 \text{ mA/cm}^2$ ). This deviation can be either attributed to the different measurement area of  $H^-$ : whereas  $j_{H^-}$  is averaged over the full extraction area of the plasma grid (126 apertures, total area of  $63.3 \text{ cm}^2$ ),  $n_{H^-}$  is averaged along a vertically centered, horizontal LOS (diameter of several mm). Possible vertical gradients of  $H^-$  production would lead to variations of the ratio  $n_{H^-}/j_{H^-}$ . A further possibility for this varying ratio during the beginning of the conditioning is a change in the transport of  $H^-$  from the PG surface into the plasma volume of the CRDS LOS, which can take place due to the large change of plasma parameters (in particular reduction of  $n_e$  and increase of  $n_{H^-}$ ).

#### IV. CONCLUSIONS

The caesiation process at BATMAN starting with a cleaned source has been followed by several diagnostics in the boundary layer close to the plasma grid. Careful evaporation of Cs in combination with operation of the source at constant parameters (in particular at a pressure of 0.3 Pa) resulted in clear trends of the measured quantities. The source performance is directly linked to the Cs emission in the early stage of the Cs conditioning phase. Due to change of charged particle fluxes towards and from the wall while increasing the surface production rate of  $H^-$ , the plasma potential in front of the PG is lowered and in the same way the required bias voltage for drawing the set value of 5 A bias current decreases. Comparison of  $n_{H^-}$

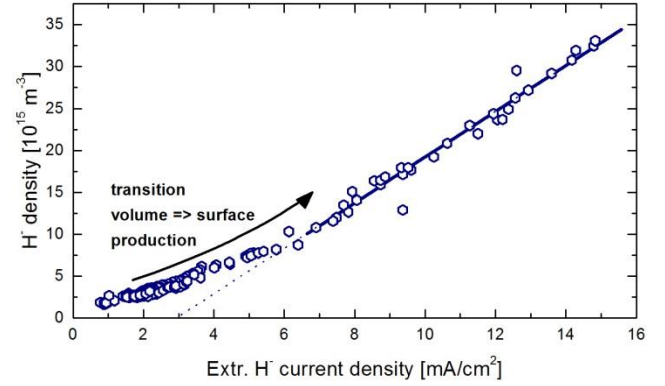


FIG. 4. (Color online).  $H^-$  density as a function of the extracted  $H^-$  current density during the caesiation process.

with  $j_{H^-}$  shows a linear correlation when the source reaches a certain stage of conditioning, whereas deviations take place towards volume dominated  $H^-$  production, which is attributed to either different measurement areas in combination with possible vertical gradients of  $H^-$  or to a change in the transport of  $H^-$  from the surface into the plasma volume.

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