Optical Emission Spectroscopy at the Large RF Driven Negative Ion Test Facility ELISE: Instrumental Setup and First Results

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One of the main topics to be investigated at the recently launched large ($A_{\mathrm{source}} = 1.0 \times 0.9\,\mathrm{m}^2$) ITER relevant RF driven negative ion test facility ELISE (Extraction from a Large Ion Source Experiment) is the connection between the homogeneity of the plasma parameters close to the extraction system and the homogeneity of the extracted negative hydrogen ion beam. While several diagnostics techniques are available for measuring the beam homogeneity, the plasma parameters are determined by optical emission spectroscopy (OES) solely.

First OES measurements close to the extraction system show that without magnetic filter field the vertical profile of the plasma emission is more or less symmetric, with maxima of the emission representing the projection of the plasma generation volumes, and a distinct minimum in between. The profile changes with the strength of the magnetic filter field but under all circumstances the plasma emission in ELISE is much more homogeneous compared to the smaller IPP prototype sources.

Planned after this successful demonstration of the ELISE OES system is to combine OES with tomography in order to determine locally resolved values for the plasma parameters.

I. INTRODUCTION

The neutral beam injection (NBI) system of the international fusion experiment ITER[1,2] is based on the production, extraction and acceleration of negative hydrogen or deuterium ions[3]. These negative ions will be produced in a large ($A_{\mathrm{source}} = 1.9 \times 0.9\,\mathrm{m}^2$, 1280 extraction apertures, $A_{\mathrm{extr}} = 0.2\,\mathrm{m}^2$) RF driven ion source. The ITER baseline design for this ion source is based since 2007 on the RF driven prototype source developed at the Max-Planck-Institut für Plasmaphysik (IPP), Garching[4].

The IPP test facility ELISE[5,6] ($\frac{1}{2}$ area of the ITER source) went into operation in December 2012[7,8]. ELISE is part of the R&D roadmap for the construction of the neutral beam heating systems[9,10] defined by the European ITER domestic agency F4E and represents an important intermediate step between the prototype source[11,12] ($\frac{1}{8}$ area of the ITER source) developed at IPP and the full ion source for ITER NBI[13]. Figure 1 shows a schematic view of the ion source of ELISE: the plasma is generated in four cylindrical drivers by inductive RF coupling. The RF power is provided by two generators ($P_{\mathrm{RF,max}} = 180\,\mathrm{kW}$ each), the first being connected to the upper pair of drivers and the second to the lower pair. The plasma generated in the drivers expands into the expansion region where it is cooled (from $T_{\mathrm{e}} \gtrsim 10\,\mathrm{eV}$ to $\approx 1\,\mathrm{eV}$ at $n_{\mathrm{e}} \approx 10^{17}\,\mathrm{m}^{-3}$, measured in the prototype sources[14]) by means of a magnetic filter field. This filter field is generated by a current ($I_{\mathrm{PG}} \leq 5\,\mathrm{kA}$) flowing through the plasma grid (PG), the first grid of a multi aperture extraction system[5] (consisting of the PG, the extraction grid and the grounded grid). Due to limitations of the IPP high voltage system only pulsed beam operation is possible (one beam pulse with a duration of 10 s every 180 s) during long plasma pulses (up to 3600 s).

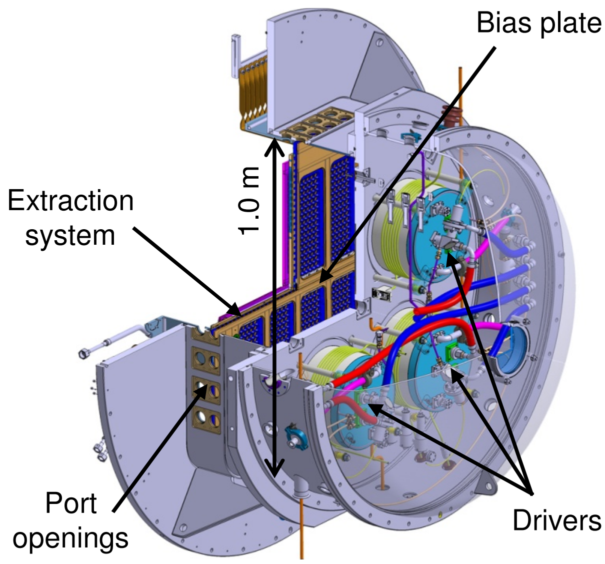

FIG. 1. Schematic view of the ELISE ion source.

Negative hydrogen ions are produced in ITER relevant ion sources predominately on the caesiated surface of the PG[11] by conversion of impinging hydrogen atoms and positive hydrogen ions. The conversion of neutral atoms is the dominant channel[15], but it is known from calculations with a 1d PIC code that a certain plasma density is needed close to the PG in order to enable the space charge limited transport of the surface produced ions to the extraction apertures[16]. It was shown in the prototype sources that the co-extracted electron current is reduced significantly by the filter field. A bias potential, applied to the PG with respect to the source walls and a bias plate, is utilized for a further reduction of the amount of co-extracted electrons[17]. The magnetic filter field can induce – in interplay with potential gradients in the plasma, for example generated by the bias potential – a plasma drift that strongly affects the homogeneity of the charged plasma particles[18]. This drift results mainly in an upward or downward (depending on the polarity of the magnetic field and the potential gradients) shift of the plasma. However, it was demonstrated in the prototype sources by means of beam emission spectroscopy that the negative hydrogen ion beam is much more homogeneous compared with the plasma non-uniformity[19].

In order to obtain a good transmission of the ITER heating beam, temporal and spatial variations of the negative ion beam have to be kept below $10\,\%$[20]. As described above, a lot of experience exists on the interplay of neutral particle, plasma and beam homogeneity in the prototype sources. But up to now neither theoretical nor experimental investigations on this topic in an experiment of the size of ELISE have been performed and one of the main topics of ELISE is to close this knowledge gap. As a first step towards fulfilling this task, prior to optimizing the source for a high extracted negative hydrogen ion current (by injecting caesium), a dedicated campaign is performed during which the influence of different parameters (e.g. the strength of the magnetic filter field) on the plasma in the volume close to the PG – the so-called boundary layer – is investigated.

After dealing with different measurement methods for the beam and plasma homogeneity this paper describes the setup used in ELISE for measuring the plasma properties by means of optical emission spectroscopy (OES). The results of OES measurements taken during a scan of the magnetic filter field strength in the caesium-free source are shown and discussed.

II. MEASURING THE BEAM AND PLASMA HOMOGENEITY

At ELISE the beam homogeneity will be determined mainly by means of calorimetric and spectroscopic measurements. Installed, in 3.5 m distance to the extraction system, is a beam dump calorimeter (only capable of determining a rough estimate of the homogeneity: the beam dump is divided into four quadrants, each containing four thermocouples and one circuit for water calorimetry) and additionally – in 1.8 m distance to the extraction system – a tungsten wire calorimeter. The beam dump will be replaced within the year 2013 by a diagnostic calorimeter[21]. Additionally available are current measurements in the extraction system and a beam emission spectroscopy (BES) system, consisting of 20 lines of sight (16 aligned horizontally and 4 aligned vertically) connected via optical fibers to a high resolution spectrometer[21] (ACTON SpectraPro-750i). Detected by this spectrometer is the spectral range around 656 nm. From the measured Doppler shifted H_α line (the wavelength shift corresponds to the sum of extraction and acceleration voltage), the non-shifted H_α line and the so-called stripping peak (between the Doppler shifted and the non-shifted H_α lines) all relevant beam properties (e.g. beam divergence and amount of negative ion destruction by collisions in the extraction system) can be determined[22].

For diagnosing the plasma and neutral particle homogeneities in the boundary layer a diagnostic method is necessary capable of measuring a two dimensional distribution of T_e, n_e and the densities of all other relevant particle species (hydrogen atoms and molecules, positive and negative hydrogen ions). This task is fulfilled by means of OES, a non-invasive technique used as standard diagnostics method at the prototype sources[22]. The measured absolute radiation is evaluated using collisional radiative (CR) models[23]. At IPP several CR models have been developed for different particle species – amongst others also the models for atomic and molecular hydrogen[24–26] that will be applied for evaluating the ELISE results.

At the prototype sources several lines of sight (LOS) are used for OES[27] – resulting in LOS averaged information on the plasma emission. If strong gradients exist in the profile of the plasma parameters, such an approach can result in drastically increased error bars of the results. The character of the gradients in the plasma parameter profiles in the boundary layer of ELISE is not known yet. However, at ELISE – compared to the prototype sources – a significantly larger number of LOS is available in a crossed layout. It has been demonstrated that this number of LOS is sufficient to determine the 2d distribution of the plasma emission close to the PG by means of tomography[28]. Since the dimension of the pixels foreseen for the tomographic reconstruction is small compared to the length of the LOS, a smaller influence of gradients in the plasma parameter profiles and thus a significantly decreased error bar is expected when the plasma parameters are determined by OES in combination with tomography.

Within the scope of the first operational phase of ELISE (and also of this paper) the operation of the ELISE OES system is demonstrated by measuring profiles of the plasma emission. Tomographic investigations and an absolute evaluation of the plasma emission will be performed in the near future.

III. INSTRUMENTAL SETUP

A. Geometry of the used lines of sight

Figure 2 consists of two schematic drawings depicting the ELISE ion source together with the port openings enabling diagnostics access parallel and close to the PG as well as the respective LOS. In order to illustrate the course of the different LOS as accurate as possible, figure 2 a) gives an axial view onto the ion source and the port openings and figure 2 b) a horizontal view from the left side. Additionally indicated in figure 2 b) is the axial

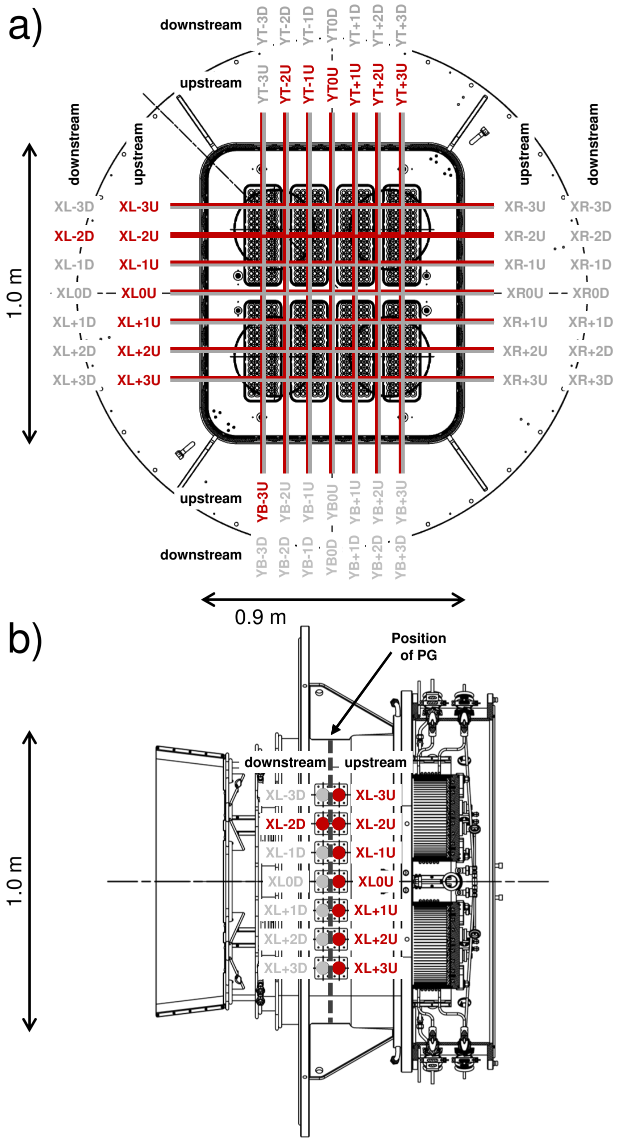

FIG. 2. Port openings enabling horizontal access to the ELISE ion source and the respective LOS. Ports to that in the current setup a lens head mounting is attached are marked in red, all others in grey. a) axial view b) horizontal view (from the left side).

position of the PG.

The naming of the ports providing horizontal access to the source volume starts with an uppercase "X", for the vertical ports with a "Y". The second letter of the naming represents the position of the port opening: for horizontal ports either the left ("L") or right ("R") side of the source; for the vertical ports the top ("T") or bottom ("B") side. The following number represents the position of the port in a relative coordinate system. The zero point of this coordinate system is the center of the PG, with positive directions towards the bottom right side of the ion source. Additionally, the ports are arranged in two levels with different axial position:

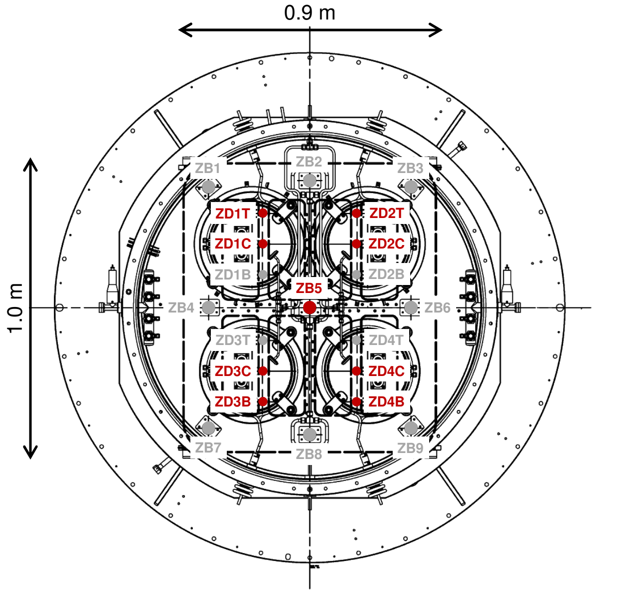

FIG. 3. Port openings enabling axial access to the ELISE ion source and the respective LOS. Additionally indicated is the position of the PG. Ports to that in the current setup a lens head mounting is attached are marked in red, all others in grey.

The 28 ports of the first level are denoted as "upstream" (the naming of the ports ends with a capital "U") and allow (in the current configuration) access to the plasma of the boundary layer in 2.0 cm (center of the ports) axial distance to the PG surface.

The 28 ports of the second – the "downstream" (the naming of the ports ends with a capital "D") – level correspond to the gap between the extraction grid and the grounded grid. The axial position of the three grids relative to the source body is defined by flexible spacers. By modifying the length of these spacers the relative position of the grids with respect to the "upstream" and "downstream" ports can be adjusted. Changing the spacers is possible only after a complete disassembly of the ion source and the grid stack.

Shown in figure 3 are the 21 port openings and the respective LOS in the source back plate and the driver back plates of ELISE, providing axial LOS perpendicular to the PG surface.

The naming of the axial ports starts with an uppercase "Z", followed by a uppercase letter depicting the position of the port: in the source source back plate ("B") or the driver back plates ("D"). The ports in the back plate are numbered consecutively from "ZB1" to "ZB9" (see figure 3). The ports in the driver back plates are distinguished by the number of the respective driver (1 to 4) and the position of the port in the driver: the three different available port positions in the driver back plates are in the top ("T"), center ("C") or bottom ("B").

Mounted to all port openings of ELISE can be quartz windows (diameter=4 cm for most of the ports, 2.5 cm for

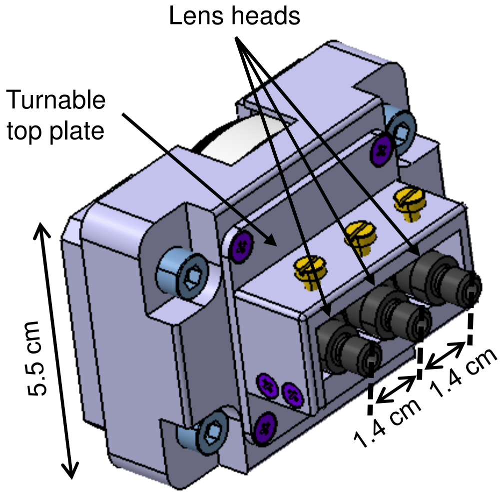

FIG. 4. ELISE lens head mounting equipped with three lens heads (distance = 1.4 cm). By turning the top plate (by 90 degree) the alignment of the lens heads can be changed.

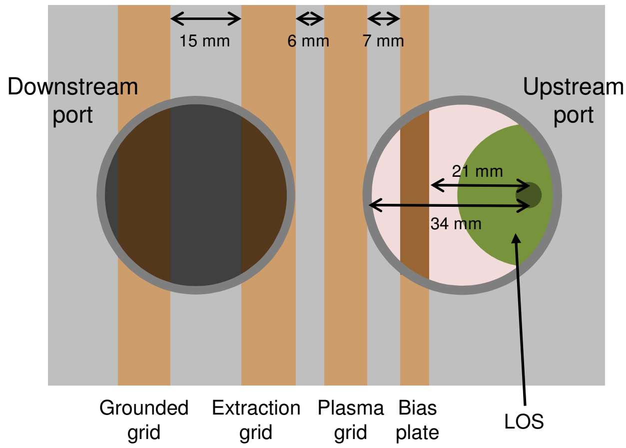

FIG. 5. Schematic drawing of an upstream and a downstream port opening, together with the position of the bias plate, the grids of the extraction system and the size and position of a LOS (at the lens head aperture as well as at the opposing wall of the ion source).

the ports in the driver back plates) in combination with lens head mountings as the one shown in figure 4. The lens head mountings provide space for three lens heads (distance between the three possible positions for the lens heads: 1.4 cm), each consisting of a casing equipped with a SMA connector and a collimator lens (f = 12.5 mm). By turning the top plate, the alignment of the three lens heads can quickly be turned by 90 degrees, resulting in five different possible positions for a LOS attached to one of the port openings. These five possible LOS are labeled with the name of the respective port opening, followed by a lowercase letter indicating the precise position, for example "c" for the center position or (for the horizontal and vertical LOS) "u" and "d" for the LOS shifted 1.4 cm in the upstream or downstream position, respectively. For example, the full name of the horizontal LOS attached to the uppermost port on the left side of the ion source and shifted axially 1.4 cm towards the drivers is XL-3Uu.

The port openings and the corresponding LOS to which in the current setup of ELISE lens head mountings are attached are marked in red in the figures 2 and 3: the seven "upstream" port openings on the left side of the ion source, the port YB-3U and all "upstream" ports on the upper side of the source except of YT-3U. The latter port opening is not available for OES since it is equipped with a quadrupol mass spectrometer. Additionally equipped with lens head mountings are the four central ports in the driver back plates (ZD1C to ZD4C), four of the ports in the driver back plates close to the driver wall (ZD1T, ZD2T, ZD3B and ZD4B) and the central port in the source back plate (ZB5). An additional lens head mounting at the port XL-2D is intended for investigating the gas temperature in the extraction system (based on the evaluation of the molecular Fulcher band emission), which is an important parameter for characterizing the destruction of extracted negative ions by collision with the background gas.

Mounted to each of the lens head mountings is at least one lens head – the four central ports in the driver back plates are equipped with two lens heads each. For the horizontal and vertical LOS it was determined by means of a calibration laser that the cone from which light is collected spreads up from 5.5 mm (the aperture size of the lens heads) to approximately 3 cm along the path from the lens head to the port opening at the opposite source wall. This result is in good agreement with simple geometrical optics, taking into account the focal length of the lenses and the width of the source body (87.5 cm horizontally and 100.2 cm vertically).

Although the described geometry of the light collection cone is considered intrinsically during the calibration of the OES system (described below), the broadening of the LOS results in a decrease of the spatial resolution along the LOS from the port opening to the plasma close to the opposite source wall. Additionally, the position of the axis of the LOS have to be chosen carefully: figure 5 shows a schematic drawing of an upstream and a downstream port opening, together with the position of the bias plate and the grids of the extraction system. Due to the position of the bias plate (parallel and upstream the PG, gap between the PG and the bias plate: 7 mm; thickness of the bias plate: 6 mm), the LOS shifted by 1.4 cm in the upstream directions are used. Shown in figure 5 is the size and position of such a LOS at the lens head aperture as well as at the opposing wall of the ion source. It can be seen that using the slightly shifted upstream LOS results in a distance between the center of the LOS and the surface of the bias plate of 2.1 cm (distance between the center of the LOS and the PG surface: 3.4 cm). This distance ensures that the amount of light originating from other sections of the plasma (e.g. the bright driver plasma) and being reflected into the collection cone of the LOS is low since the cone connects at no position with the bias plate.

B. Spectrometers used at ELISE

24 optical fibres (length: 45 m each) for the UV-VIS wavelength range connect the source area of ELISE with a switchboard in the control room. This switchboard allows to flexibly reconfigure the combination of the different spectrometers to the available LOS. Additionally, it is possible to use the switchboard in order to introduce filters into the different optical paths. Usually, neutral density filters (Kodak Wratten gelatin filters) are used in order to specifically decrease the amount of light and hence optimally utilize the dynamics of the spectrometers.

Presently available at ELISE are 13 survey spectrometers (PLASUS EMICON MC system, $\lambda = 180 \ldots 880$ nm, sampling rate < 15 Hz) and one high resolution Echelle survey spectrometer (LLA Instruments ESA 3000, $\lambda = 200 \ldots 780$ nm, sampling rate ≈ 0.2 Hz). These spectrometers are applied to monitor the emission of different atomic emission lines and molecular bands, needed for investigating the homogeneity of the plasma emission or the plasma parameters. Additionally, four fast photo diodes (UDT-020D, sampling rate ≈ 1 kHz) are connected to four of the axial LOS and used to monitor the total plasma emission in the drivers. These diodes are connected to a safety system that shuts down the RF generators if during source operation no plasma light is detected in the four drivers. Aim of this safety system is to prevent possible damages on the one hand in the drivers, caused by a too high amount of RF power coupled directly into the structure and on the other hand in the RF generators itself.

During the startup phase of ELISE five of the other available axial LOS are used together with four of the survey spectrometers and the Echelle spectrometer for impurity detection in the drivers. Aim is to discover possible damages during the pulses as quick as possible. For investigating the plasma radiation in the boundary layer, the remaining nine survey spectrometers are available. In the current setup of the magnetic filter field an upward shift of the plasma caused by the plasma drift is expected. Hence, the seven available horizontal LOS parallel to the PG have been chosen in combination with two of the vertical LOS. This configuration enables a full vertical scan of the plasma and to roughly determine the horizontal symmetry.

C. Calibration and data acquisition

The nine survey spectrometers monitoring the boundary layer are absolutely calibrated. The calibration have been performed by means of an Ulbricht sphere (Labsphere USS-800C-100R in combination with a LPS-100 power supply) and considers the complete path of the collected light – including the lens head, the optical fiber between the ion source and the switchboard, the neutral density filters available for the switchboard, the fiber between the switchboard and the spectrometers and finally the spectrometer itself.

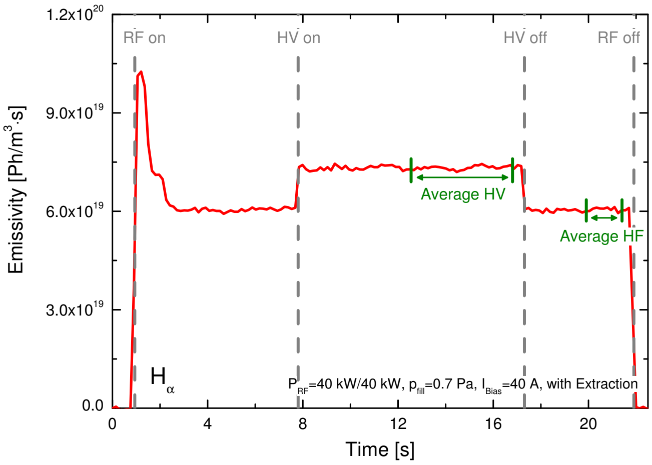

FIG. 6. Time trace of the H_α emission during a pulse at ELISE. Indicated are the time intervals over that average emission values are determined representing the emission during the beam pulse and the RF phase.

The raw spectra measured by the different spectrometers during source operation are processed and calibrated by means of a dedicated software tool installed on all control PCs. During this process also time traces of the emission of several lines and bands during the pulse are saved, namely: the Balmer lines H_α, H_β, H_γ, the Fulcher band of molecular hydrogen, the caesium line at 852 nm, the atomic oxygen line at 777 nm and three copper lines around 515 nm. Figure 6 shows – as example – the temporal evolution of the H_α emission during a beam pulse of 9.5 s length, surrounded by a plasma pulse of 21.9 s length. For the first second of the plasma pulse a peak in the emission is observed, caused by a gas puff ($p_{\rm fill} \approx 1.2$ Pa) which is necessary for plasma ignition (in combination with two tungsten filaments). During the beam pulse a pronounced influence of the extraction voltage on the plasma radiation can be seen. It is known from the prototype sources that the strength and even the direction of this influence strongly depends on the plasma parameters along the LOS and how these plasma parameters are affected by the extraction: depending on the extraction voltage, the bias voltage, the caesiation of the source and position of the LOS either an increased, decreased or constant plasma emission during the extraction was observed.

In order to simplify the comparison of the plasma emission measured for different pulses – for example during a parameter scan – two averaged values of the emission are calculated: for the beam pulse and for the RF phase. The respective time intervals used for determining these

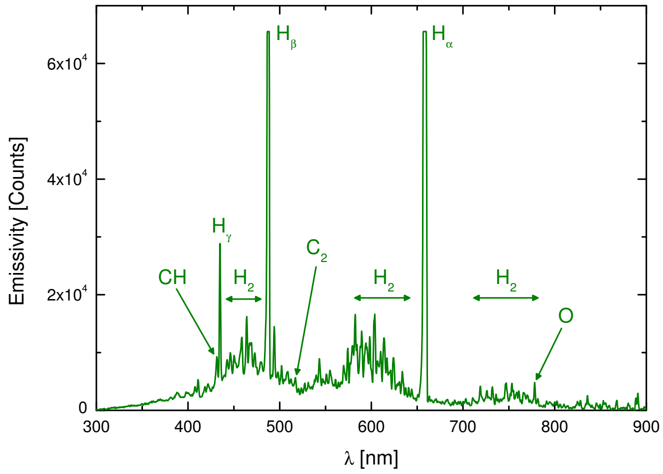

FIG. 7. Spectrum taken during one of the first pulses in ELISE showing – besides atomic and molecular hydrogen emission – only small amounts of impurities being present in the plasma.

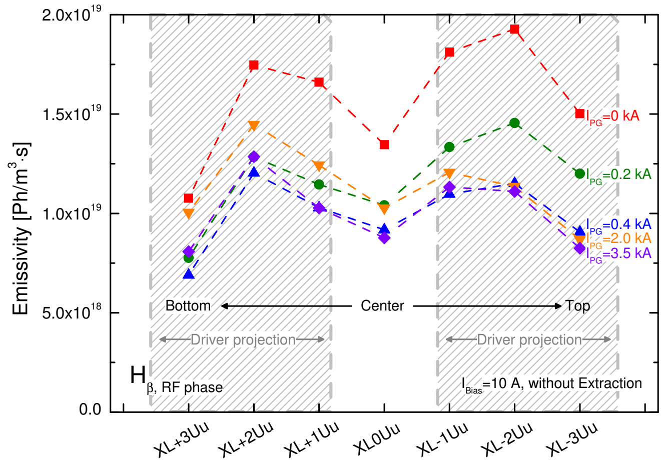

FIG. 8. Vertical profile of the LOS averaged H_β emission measured in ELISE for a scan of the magnetic filter field strength. Indicated by the shaded areas are the downstream projections of the drivers.

average values (the second half of the beam pulse and 1.5 s at the end of the RF phase, respectively) are indicated in figure 6. In case of several beam pulses during a long plasma pulse at ELISE, the two averaged values of the emission (one for the beam pulse itself and one for the RF phase directly after the end of the extraction) are determined for each of the beam pulses.

Finally, the calibrated data and the averaged values for the emission are integrated into the data base containing the results of all available diagnostics of ELISE.

IV. RESULTS

The commissioning phase of ELISE was accompanied by OES from the very first plasma pulses (pulse length: a few milliseconds) on[7]. In the spectra of these first low power hydrogen pulses besides the much stronger radiation of atomic and molecular hydrogen, radiation emitted by impurities – mainly molecular carbon, CH and oxygen – could be seen. An example spectrum is shown in figure 7. Due to a thorough bake-out process of the inner surfaces of the ion source (up to 400 K) prior to the first plasma pulses, the amount of impurities was much smaller than observed in the prototype sources (The spectrum shown in figure 7 is strongly overexposed by purpose in order to clearly distinct the impurities from the surrounding hydrogen radiation). During subsequent pulses a rapid decrease of the amount of impurities was monitored from pulse to pulse. Up to now the length of the plasma pulses was extended up to several minutes ($P_{\mathrm{RF}} = 40$ kW per generator, $p_{\mathrm{fill}} = 0.6$ Pa).

After this successful startup of ELISE, first investigations on the physics in the caesium-free source have been performed. As mentioned earlier, the magnetic filter field in ELISE is generated by a electric current through the PG and thus the field strength can easily be varied. Compared to the prototype sources – in which the magnetic filter is generated by means of permanent magnets attached to the side walls of the source – this possibility enables a great experimental flexibility. As first physical investigation at ELISE a scan of the magnetic filter field was performed (I_{PG} was varied from 0 kA to 3.5 kA. For $I_{\mathrm{PG}} = 3.5$ kA a maximum field strength of approximately 3.3 mT is reached[29]. For the sake of simplicity, subsequently the current through the PG is used as measure for the strength of the filter field). The RF power was set to 40 kW for both generators at a filling pressure of 0.7 Pa. The temporal stability of the plasma radiation during the pulses is very good; the observed variations are well below the error bars of the OES system (≈ 10 %). In negative hydrogen ion sources usually the radiation of the Balmer lines H_β, H_γ, ... is used for determining the plasma parameters since the more intense line H_α can be strongly influenced by the presence of even a low density of negative ions[24]. Figure 8 a) shows the vertical profile of the H_β emission – averaged as described above – measured during the magnetic field scan at ELISE. The measurements have been performed in a hydrogen plasma and without extraction.

The profile of the H_β emission consists of two maxima, corresponding to the LOS positioned directly in the downstream projections of the plasma generation volumes in the drivers. Without magnetic field for the upper pair of drivers (LOS XL-2Uu) only a slightly higher plasma emission is observed than for the lower pair (LOS XL+2Uu), $F_{\mathrm{symm.}} = \varepsilon_{\mathrm{XL-2Uu}}/\varepsilon_{\mathrm{XL+2Uu}} = 1.10$. This asymmetry is comparable to the error bars of the OES system and thus the emission profiles can be considered as symmetric. Minima occur in the center and close to the side walls of the ion source. From the shape of the profile it can be deduced that the plasma expansion out of the drivers into the expansion region is very localized.

However, the path of the central LOS, XL0Uu, traverses on its complete path the surface of the bias plate (see figure 2). All other LOS traverse partially the bias plate and partially – along the groups of the extraction apertures – the PG. This closer distance of the LOS XL0Uu to a surface can result in slightly different plasma parameters and consequently also a different plasma radiation along the LOS. Additionally, the influence of the bias voltage on the electrostatic potential distribution in the ion source and consequently also on the fluxes and densities of charged plasma particles is expected to be high. Since the bias is applied to the PG only (i.e. the bias plate is a non-biased surface), slightly different plasma parameters seen by the LOS XL0Uu – resulting in the observed central minimum – fit into the picture.

With increasing strength of the filter field the plasma emission close to the PG is reduced on the whole – as can be seen also in figure 8 a). Additionally, the shape of the profile is modified by the magnetic field: up to $I_{\mathrm{PG}} = 0.4\,\mathrm{kA}$ the slight enhancement of the radiation in the upper part of the ion source compared to the lower part almost vanishes and the profile is symmetric. For $I_{\mathrm{PG}} = 2.0\,\mathrm{kA}$ a more intense emission is observed in the lower part ($F_{\mathrm{symm.}} = 0.78$) and for $I_{\mathrm{PG}} = 3.5\,\mathrm{kA}$ the radiation profile again is significantly more symmetric ($F_{\mathrm{symm.}} = 0.86$).

In order to investigate in more detail the influence of the magnetic field on the plasma radiation, plotted in figure 9 is the dependence of the plasma emission measured along the seven horizontal LOS against the strength of the magnetic filter field. In principle, the data shown in this figure is identical to the one in figure 8, but a larger number of values over the magnetic field variation is used. The most pronounced asymmetry ($F_{\mathrm{symm.}} = 0.73$, corresponding to an asymmetry of about 36 %) occurs at $I_{\mathrm{PG}} = 1.4\,\mathrm{kA}$ – this means that the plasma emission in ELISE is much more homogeneous compared to the prototype sources[19]. For source operation with caesium an even more homogeneous plasma emission is expected: in the prototype sources the plasma is getting more symmetric with increasing source performance[30] – the latter being correlated with an increasing amount of caesium in the plasma.

Considering experience gained at the prototype sources, it is expected that the magnetic filter field influences the plasma in several ways: first, it is expected that the field cools down the plasma. Without magnetic filter ($I_{\mathrm{PG}} = 0\,\mathrm{kA}$) the plasma is assumed to be ionizing, i.e. the intensity of H_β correlates mainly with the electron density, the electron temperature and the density of atomic hydrogen[31]. For purely ionizing plasmas decreasing the electron temperature leads to a lower plasma emission due to reduced probabilities for direct excitation of the hydrogen atom by electron collision and dissociative excitation of H_2 into the excited states of the atom. However, if a plasma gets cold (T_{e} below a few eV, also depending on the ionization degree and the electron density) the influence of recombining excitation processes

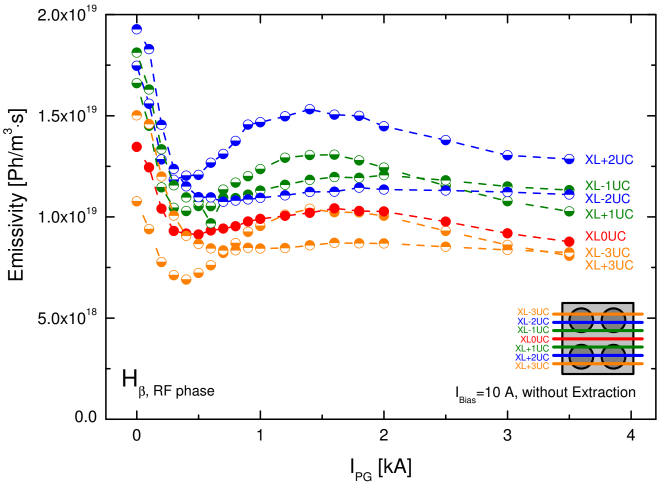

FIG. 9. Dependence of the magnetic filter field strength on the H_β emission measured along the horizontal LOS of ELISE.

(recombination of atomic ions and dissociative recombination of molecular ions) increases. Below $T_{\mathrm{e}} = 1\,\mathrm{eV}$ in most cases a plasma is purely recombining, i.e. the influence of direct and dissociative excitation on the population density of excited states is negligible. The excitation probabilities for recombining processes can be very large compared to the probabilities for direct or dissociative excitation[24]. Additionally, the electron temperature dependence of excitation by recombination usually is very weak. Taken the described effects together, a reduction of electron temperature can result in an increased plasma radiation.

The second expected effect of the magnetic field on the plasma is the previously mentioned plasma drift, strongly influencing the vertical distribution of plasma density and temperature - and consequently also of the plasma emission.

Taking into account the effect of both the expected plasma cooling and the plasma drift, the results shown in figure 9 can be explained at least qualitatively (assuming that the reaction of the plasma on the filter field in ELISE in general is comparable to the prototype sources): with increasing field strength the plasma as whole is shifted upwards by the plasma drift. Up to $I_{\mathrm{PG}} = 0.4\,\mathrm{kA}$ the effect of this shift is strongly overlapped by an overall decrease in the emission, caused by the decreased electron temperature. For increased filter field strength, $I_{\mathrm{PG}} < 1.5\,\mathrm{kA}$, the reduced electron temperature and the plasma shift result in a strong increase of the role of recombining processes in the lower part of ELISE. Result is an increased Balmer emission mainly in the lower LOS XL+3Uu, XL+2Uu and XL+1Uu. In the upper half of the ion source, the effects of plasma cooling and the drift (the latter increases the plasma density in the plasma volume observed by the LOS) mostly compensate mutually and the Balmer emission is more or less constant. For further increased filter field strengths (up to $I_{\mathrm{PG}} = 3.5\,\mathrm{kA}$), finally the plasma radiation in the complete boundary layer is determined by recombining processes. The excitation in the hydrogen atom no longer depends to a large extend on the electron temperature. The decrease of the plasma emission observed in the lower part of the ion source for these strengths of the filter field is mainly caused by the plasma drift.

The described qualitative explanation of the influence of the magnetic filter on the plasma radiation is in principle agreement with first preliminary quantitative evaluations of the measured plasma radiation – indicating a distinct plasma cooling caused by the filter field (from $T_{\mathrm{e}} \approx 4.5\,\mathrm{eV}$ at $I_{\mathrm{PG}} = 0\,\mathrm{kA}$ to $T_{\mathrm{e}} \approx 1.0\,\mathrm{eV}$ at $I_{\mathrm{PG}} = 3.5\,\mathrm{kA}$, n_{e} around $10^{17}\,\mathrm{m}^{-3}$).

The present results demonstrate that the OES system of ELISE has gone successfully into operation and first physical investigations have been performed in a caesium-free source. More quantitative evaluations will be performed in the next future; such evaluations will be based on locally (and not LOS averaged) resolved values of the Balmer radiation determined by applying tomography to OES results. The existing CR model for atomic hydrogen can then be applied in order to determine locally resolved values for the electron density, electron temperature and particle densities. As soon as a sufficient amount of caesium will be present in ELISE to create a powerful negative hydrogen ion beam, this setup enables to investigate the correlation between plasma and neutral particle homogeneity with the beam homogeneity.

V. CONCLUSIONS

The OES system at the large RF driven negative ion test facility ELISE has gone successfully into operation. Available for OES are 77 port openings, of which presently 24 are equipped with lens head mountings. 24 optical fibers between the ion source, a switchboard as well as 13 survey spectrometers and a high resolution survey spectrometer allow to customize the setup very flexibly.

First results prove a more or less symmetric vertical profile of the plasma radiation in caesium-free operation without magnetic filter field. The profile depends on the strength of the magnetic filter field. During a magnetic field scan the maximum vertical asymmetry of the plasma emission was around 36 % which means it is much more homogeneous compared to the smaller IPP prototype sources. An even more homogeneous plasma emission is expected for source operation with caesium.

For high field strengths – i.e. for the filter field that will later be used in the caesiated source in order to suppress the co-extracted electron current as much as possible – the determined emission asymmetry (around 14 %) lies only slightly above the error bars of the OES system.

The successful startup of the ELISE OES system is a very important step towards full investigations of the correlation between plasma homogeneity and beam homogeneity: such investigations require (besides precise measurements of the beam homogeneity) locally resolved knowledge of the plasma parameters in the boundary layer, determined by applying tomography to OES results.

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REFERENCES

[1] R. Aymar, Fusion Eng. Des. **62**, 5 (2002).
[2] N. Holtkamp, Fusion Eng. Des. **82**, 427 (2007).
[3] R. S. Hemsworth, J.-H. Feist, M. Hanada, B. Heinemann, T. Inoue, E. Kussel, A. Krylov, P. Lotte, K. Miyamoto, N. Miyamoto, D. Murdoch, A. Nagase, Y. Ohara, Y. Okumura, J. Pamela, A. Panasenkov, K. Shibata, M. Tanii, and M. Watson, Rev. Sci. Instrum. **67**, 1120 (1996).
[4] R. Hemsworth, A. Tanga, and V. Antoni, Rev. Sci. Instrum. **79**, 02C109 (2008).
[5] B. Heinemann, H. Falter, U. Fantz, P. Franzen, M. Fröschle, R. Gutser, W. Kraus, R. Nocentini, R. Riedl, E. Speth, A. Stäbler, D. Wünderlich, P. Agostinetti, and T. Jiang, Fusion Eng. Des. **84**, 915 (2009).
[6] B. Heinemann, U. Fantz, P. Franzen, M. Fröschle, M. Kircher, W. Kraus, C. Martens, R. Nocentini, R. Riedl, B. Ruf, L. Schiesko, C. Wimmer, D. Wünderlich, and the NNBI-Team, "Negative ion test facility ELISE - Status and first results," Fusion Eng. Des. (in press).
[7] P. Franzen, B. Heinemann, U. Fantz, D. Wünderlich, W. Kraus, M. Fröschle, C. Martens, R. Riedl, A. Masiello, B. Ruf, L. Schiesko, C. Wimmer, and the NNBI-Team, "Commissioning and First Results of the ITER-Relevant Negative Ion Beam Test Facility ELISE," Fusion Eng. Des. (submitted).
[8] R. Nocentini, U. Fantz, P. Franzen, M. Fröschle, B. Heinemann, R. Riedl, and the NNBI-Team, "Towards a large RF ion source for the ITER neutral beam injector: overview of the ELISE test facility and first results," (), IEEE Trans. Plasma Sci. (submitted).
[9] A. Masiello, G. Agarici, T. Bonicelli, M. Simon, V. Antoni, H. D. Esch, A. D. Lorenzi, M. Dremel, P. Franzen, R. Hemsworth, M. Liniers, D. Marcuzzi, D. Martin, R. Piovan, A. Simonin, P. Sonato, E. Surrey, L. Svensson, A. Tanga, V. Toigo, C.Waldon, and P. Zaccaria, Fusion Eng. Des. **84**, 1276 (2009).
[10] A. Masiello, G. Agarici, T. Bonicelli, F. Paolucci, M. Simon, D. Boilson, H. Decamps, J. Graceffa, B. Heinemann, R. Hemsworth, M. Kuriyama, B. Schunke, L. Svensson, A. Luchetta, P. Sonato, V. Toigo, and P. Zaccaria, in *Proc. 24th IAEA Fusion Energy Conference* (2012).
[11] E. Speth, H. D. Falter, P. Franzen, U. Fantz, M. Bandyopadhyay, S. Christ, A. Encheva, M. Fröschle, D. Holtum, B. Heinemann, W. Kraus, A. Lorenz, C. Martens, P. McNeely, S. Obermayer, R. Riedl, R. Süss, R. W. A. Tanga, and D. Wünderlich, Nucl. Fusion **46**, S220 (2006).
[12] U. Fantz, P. Franzen, W. Kraus, H. D. Falter, M. Berger, S. Christ-Koch, M. Fröschle, R. Gutser, B. Heinemann, C. Martens, P. McNeely, R. Riedl, E. Speth, and D. Wünderlich, Rev. Sci. Instrum. **79**, 02A511 (2008).

[13] D. Marcuzzi, M. D. Palma, M.Pavei, B. Heinemann, W. Kraus, and R. Riedl, Fusion Eng. Des. **84**, 1253 (2009).
[14] L. Schiesko, P. Franzen, and U. Fantz, Plasma Sources Sci. Technol. **21**, 065007 (2012).
[15] D. Wünderlich, L. Schiesko, P. McNeely, U. Fantz, P. Franzen, and the NNBI-Team, Plasma Phys. Control. Fusion **54**, 125002 (2012).
[16] D. Wünderlich, R. Gutser, and U. Fantz, Plasma Sources Sci. Technol. **18**, 045031 (2009).
[17] P. Franzen, L. Schiesko, M. Fröschle, D. Wünderlich, U. Fantz, and the NNBI-Team, Plasma Phys. Control. Fusion **53**, 115006 (2011).
[18] U. Fantz, P. Franzen, W. Kraus, M. Berger, S. Christ-Koch, M. Fröschle, R. Gutser, B. Heinemann, C. Martens, P. McNeely, R. Riedl, E. Speth, and D. Wünderlich, Plasma Phys. Control. Fusion **49**, B563 (2007).
[19] P. Franzen, U. Fantz, and the NNBI-Team, AIP Conf. Proc. **1390**, 310 (2011).
[20] P. Sonato, P. Agostinetti, G. Anaclerio, V. Antoni, O. Barana, M. Bigi, M. Boldrin, M. Cavenago, S. D. Bello, M. D. Palma, A. Daniele, M. DArienzo, A. D. Lorenzi, A. Ferro, A. Fiorentin, E. Gaio, E. Gazza, L. Grando, F. Fantini, F. Fellin, A. Luchetta, G. Manduchi, F. Milani, D. Marcuzzi, L. Novello, R. Pasqualotto, M. Pavei, R. Pengo, S. Peruzzo, A. Pesce, N. Pilan, R. Piovan, N. Pomaro, M. Recchia, W. Rigato, A. Rizzolo, G. Serianni, M. Spolaore, P. Spolaore, S. Sandri, C. Taliercio, V. Toigo, M. Valisa, P. Veltri, P. Zaccaria, A. Zamengo, and L. Zanotto, Fusion Eng. Des. **84**, 269 (2009).
[21] R. Nocentini, U. Fantz, P. Franzen, M. Fröschle, B. Heinemann, R. Riedl, B. Ruf, D. Wünderlich, and the NNBI-Team, "Beam diagnostic tools for the negative hydrogen ion source test facility ELISE," (), Fusion Eng. Des. (in press).
[22] U. Fantz, H. Falter, P. Franzen, D. Wünderlich, M. Berger, A. Lorenz, W. Kraus, P. McNeely, R. Riedl, and E. Speth, Nucl. Fusion **46**, S297 (2006).
[23] D. R. Bates, A. E. Kingston, and R. W. P. McWirter, Proc. R. Soc. Lond. A **267**, 297 (1962).
[24] U. Fantz and D. Wünderlich, New J. Phys. **8**, 301 (2006).
[25] D. Wünderlich, S. Dietrich, and U. Fantz, J. Quant. Spectrosc. Radiat. Transfer **110**, 62 (2009).
[26] D. Wünderlich and the NNBI-Team, in *Proc. 30th International Conference on Phenomena in Ionized Gases* (2011).
[27] U. Fantz, P. Franzen, W. Kraus, M. Berger, S. Christ-Koch, H. Falter, M. Fröschle, R. Gutser, B. Heinemann, C. Martens, P. McNeely, R. Riedl, E. Speth, A. Stäbler, and D. Wünderlich, Nucl. Fusion **49**, 125007 (2009).
[28] F. Bonomo, M. Agostini, M. Brombin, U. Fantz, P. Franzen, R. Pasqualotto, D. Wünderlich, and the NNBI-Team, "Tomography Feasibility Study on the Optical Emission Spectroscoy Diagnostic for the Negative Ion Source ELISE," Plasma Phys. Control. Fusion (submitted).
[29] M. Fröschle, U. Fantz, P. Franzen, W. Kraus, R. Nocentini, L. Schiesko, D. Wünderlich, and NNBI-Team, "Magnetic filter field for ELISE - Concepts and design," Fusion Eng. Des. (in press).
[30] U. Fantz, P. Franzen, W. Kraus, D. Wünderlich, R. Gutser, M. Berger, and the NNBI-Team, AIP Conf. Proc. **1097**, 265 (2009).
[31] U. Fantz, Plasma Sources Sci. Technol. **15**, S137 (2006).