Transferring knowledge gained for pulsed extraction at the ELISE test facility to ITER-relevant CW extraction

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Abstract. Beam extraction at the large ELISE test facility is currently possible only pulsed, with short extraction phases, so-called extraction blips, of up to 10 s each ≈150 s. During the past years, a good insight in the physics of this operational mode was gained in both hydrogen and deuterium operation. The uniformity of the co-extracted electrons was identified as a key issue and it was possible to achieve 1000 s plasma pulses in hydrogen with repetitive extraction blips and an extracted current density of over 90 % of the ITER target value by improving the co-extracted electron symmetry. In deuterium roughly 67 % of the ITER target for the extracted current density has been achieved for long pulses. During such pulses an overall increase of the co-extracted electron current is typically observed between one blip and the next one, even though the electron current is observed to actually decrease during each blip. These opposing effects are explained by different caesium dynamics during the source plasma phase when compared to the beam phase and they were one motivation behind the currently ongoing upgrade of ELISE to a CW extraction system. This update consists of two main hardware changes: i) installation of a new CW high voltage power supply and ii) installation of a CW beam calorimeter. Being able to achieve beam pulses of up to 1 hour will allow knowledge to be gained on the physics of caesium redistribution and conditioning over the long timescales needed for ITER operation.

INTRODUCTION

Essential part of the two ITER NBI beam lines is a negative hydrogen ion source, capable of delivering over one hour a current density of 200 A/m^2 of negative deuterium ions, accelerated to 1 MeV, or over 1000 s a current density of 230 A/m^2 of negative hydrogen ions, accelerated to 870 keV [1]. Assuming for both isotopes a stripping fraction of 30 %, as calculated for deuterium in [2], the extracted ion current density should be 286 A/m^2 for deuterium and 329 A/m^2 for hydrogen.

In order to minimize the destruction rate of negative ions in the accelerator, the source has to be operated at a filling pressure of p_{fill}=0.3 Pa. Additionally, to limit the power loads in the extraction system, the current of co-extracted electrons has to be less than or equal to the extracted negative ion current. In order to ensure a good beam transmission, the uniformity of the extracted beam is required to be better than 90 %.

ELISE (Extraction from a Large Ion Source Experiment) [3] is part of a R&D roadmap defined by the European domestic agency F4E for the construction of the neutral beam heating systems [4]. The half-ITER-size ion source of the ELISE test facility (0.9×1.0 m^2 with an extraction area of 0.1 m^2) is an intermediate step between the RF driven ITER prototype source (0.3×0.6 m^2 with an extraction area of typically $1\cdot10^{-2}$ m^2), used at the BATMAN Upgrade test facility [3], and the ion source for the ITER NBI system (1.0×2.0 m^2 with an extraction area of 0.2 m^2) [1]. The latter ion source is tested at the SPIDER test bed at the Neutral Beam Test Facility PRIMA in Padova [5].

Up to now, ELISE is operated in pulsed extraction mode: plasma pulses are possible up to one hour, with short extraction phases, so-called extraction blips (length: up to 10 s; the shortest time between two blips is ≈150 s, defined mainly by the available HV power supply). During the last years important lessons have been learned in this operational mode, making it possible to achieve series of reproducible long (1000 s) pulses in hydrogen at 0.3 Pa and with about 90 % of the ITER target for the extracted negative ion current density [6]. Due to a pronounced isotope effect, affecting strongly the amount of co-extracted electrons as well as their increase in time, similar pulses have not yet been achieved in deuterium [7] and up to now only 67 % of the ITER target for the extracted current density was achieved during long pulses with this isotope (results for the best D_2 pulse up to now are shown in Figure 3).

Currently ongoing is an upgrade of ELISE to CW extraction. This paper describes the latest results obtained in deuterium for short extraction phases, the physics motivation behind the CW upgrade and its current status.

THE ELISE TEST FACILITY

Figure 1 shows a schematic view of the ELISE ion source. The plasma is generated by inductive RF coupling into four cylindrical RF drivers (P_{RF}<75 kW/driver, delivered by two RF generators, f=1 MHz) and then expands toward the plasma grid (PG), first grid of the multi-grid multi-aperture extraction system.

Negative hydrogen (or deuterium) ions are produced predominately by surface conversion of hydrogen atoms impinging onto a low work function metallic surface. The most relevant converter surface is the PG, whose work function is effectively reduced by coverage with a thin (several monolayers) layer of caesium. Caesium is evaporated into the source by means of two ovens, attached to the sidewalls of the ion source. The horizontal magnetic filter field with a strength of a few mT (sufficient for magnetizing electrons but not the ions) plays a crucial role for the reduction of the negative ion destruction by electron collisions and the co-extracted electron current, as well as for the transport of negative hydrogen ions to the extraction apertures [8]. A strong electrical current, I_{PG}, flowing through the PG in vertical direction generates this filter field [9] which is strengthened by external permanent magnets attached to the vertical sidewalls of the source [10]. By varying I_{PG}, the strength of the filter field can be adjusted (up to 5.3 kA at maximum, equivalent to a field strength of ≈5.4 mT close to the PG). The horizontal component of the filter field in front of the PG creates vertical plasma asymmetries, caused by cross **B** drifts [11,12]. The co-extracted electron current is reduced by a factor of up to ten (depending on the source parameters) by the magnetic filter because of the low probability for cross-field transport of magnetized electrons.

An additional reduction of the co-extracted electrons is obtained by a positive bias potential applied to the PG with respect to the source body and the so-called bias plate [3] (see Figure 1). Usually, not the bias potential but the bias current I_{bias}, i.e. the current flowing onto the plasma grid is defined and kept constant during the pulses. It was demonstrated at the prototype source that keeping I_{bias} constant is beneficial for obtaining stable operation [13].

The co-extracted electrons are magnetically deflected onto the surface of the extraction grid (EG), the second grid of the extraction system, acting as an electron dump. If the power deposited onto this grid is too high, beam extraction is stopped by a safety interlock. A unique feature of ELISE is that separate current measurements are available for the top and bottom segment of the EG, allowing to detect top-bottom asymmetry of the co-extracted electron current. The design limit of the power deposited onto the EG is 200 kW per segment [14]; the safety interlock is set to 125 kW/segment, accounting for possible local non-homogeneities of the deposited power. Thus, a high co-extracted electron current can prevent the use of a higher extraction potential or RF power, limiting the extracted negative ion current. Moreover, the length of long pulses can be strongly restricted by an increasing co-extracted electron current during the pulses and consequently an increasing power deposited on the PG.

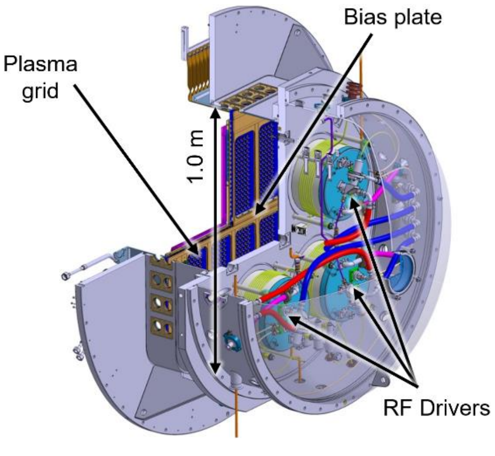

FIGURE 1. Schematic view of the ELISE ion source.

LATEST RESULTS IN DEUTERIUM

Vertical non-uniformities in the co-extracted electron current, mainly caused by the cross-**B** drifts, result in an asymmetric power load of the EG and thus are of high relevance during long pulses at high performance. Strongly non-uniform co-extracted electron currents can trigger early the EG safety interlock in one of the two segments and are thus not desired during long pulses. The installation of the so-called potential rods [15] close to the plasma grid was decisive for achieving the best long pulses mentioned above: the rods shift the ratio of co-extracted electrons impinging onto the top and bottom segment of the EG, $j_{e,top}/j_{e,bot}$, towards smaller values, resulting in a symmetrization, accompanied by a slight reduction (a few percent) of the extracted negative ion current.

The effect of the potential rods on the symmetry of the co-extracted electron is most probably caused by a modified topology of the electrostatic potentials in the source volume, affecting the plasma drifts. In general, the vertical asymmetry of the co-extracted electron current strongly increases with the RF power, with reduction of p_{fill} or changing the working gas from hydrogen to deuterium. It additionally depends on the filter field strength. When using the potential rods, a value of $j_{e,top}/j_{e,bot}$ about one is achieved in hydrogen operation at the source parameters needed for high-performance pulses. Though, in deuterium at a filling pressure of 0.3 Pa typically the power load of the co-extracted electrons onto the top EG segment is higher than the one onto the bottom segment (see Figure 3), even with the potential rods, and it increases much stronger in time.

The results shown in Figure 2 illustrate the high relevance of the co-extracted electron uniformity. The extracted negative ion current density j_{ex} and the power deposited by the co-extracted electrons onto the two EG segments are shown for a series of short pulses (t_{plasma}=20 s, one extraction blip) in deuterium with the maximum available RF power (75 kW/driver), a small bias current (10 A) and an extraction voltage of 10.5 kV. These pulses have been done with an increased and not ITER-relevant filling pressure of 0.6 Pa to check if for this pressure the ITER requirement regarding the extracted current density can be fulfilled. Motivation is the well-known positive effect of increasing the pressure on the amount and stability of the co-extracted electrons [16].

For the first pulse (#38122) the total electron-ion ratio is 0.39, i.e. quite low, but the power load on the top grid segment is about a factor of two higher than the one on the bottom segment. During the following pulses (#38123 to #38126) the strength of the filter field is reduced stepwise from ≈3.4 mT to ≈2.3 mT close to the PG. The extracted current density increases, as well as the power load on the EG bottom segment, while the power load on the top segment first decreases and then increases. The results can be explained by the superposition of two physical effects: first, reducing the filter strength increases the total amount of extracted negative ions and co-extracted electrons. And second, the beneficial reduction of $P_{EG,top}$ is caused by the already mentioned dependence of $j_{e,top}/j_{e,bot}$ on the field strength. For a filter strength of 2.6 mT (#38125) the maximum power load on both EG segments is comparable to the first pulse of the series, however about 7 % more negative ions are extracted. Finally, for the pulse #38126 (B=2.3 mT) the co-extracted electron uniformity is flipped vertically. The bottom segment of the EG is close to the power limit set in the control system but a negative ion current density of 277 A/m^2 is achieved, i.e. 97 % of the ITER target.

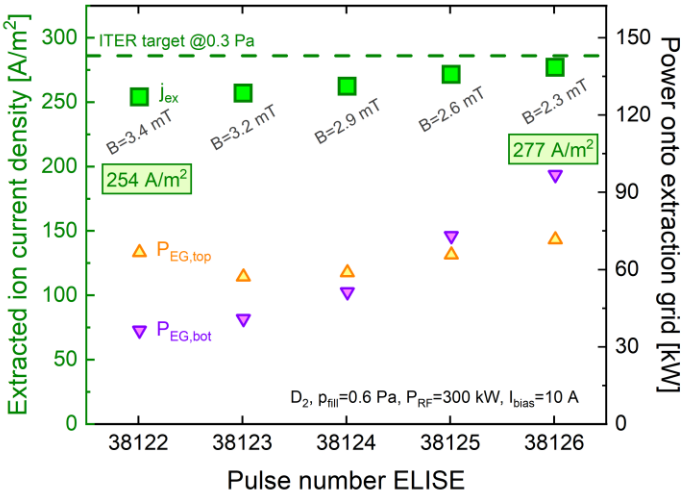

FIGURE 2. Current density of extracted negative ions and co-extracted electrons (top and bottom segment) for a series of short pulses in D_2 at p_{fill}=0.6 Pa with identical RF power, extraction potential and bias current but varying the magnetic filter strength.

Similar pulses are not possible up to now at 0.3 Pa due to much more pronounced co-extracted electron instabilities and non-uniformities. A key topic for the future is finding measures for not only further reducing in deuterium the amount of co-extracted electrons but also increasing the uniformity of the power load onto the EG.

DIFFERENCES PULSED EXTRACTION AND CW EXTRACTION

A key issue for stable high-performance pulses is a low and stable work function of the PG surface. Starting from an ion source containing no caesium at all, a dedicated caesium conditioning phase is necessary that can take up to several days. Conditioning pulses are repeated until a good and stable source performance is reached. Caesium is re-distributed to create suitable reservoirs inside the source, resulting in an improved subsequent source performance, i.e. an increased stability and/or higher extracted ion current and/or lower co-extracted electron currents. After finishing the conditioning phase, neutral caesium densities measured by Tunable Diode Laser Absorption Spectroscopy [17] can reach values of up to about 2×10^{14} m^{-3} in hydrogen and 10^{15} m^{-3} in deuterium in the vacuum phases in-between the plasma pulses.

The so-called caesium overconditioning, developed and applied at ELISE [18], namely conditioning to a status where the caesium density in the source is too high for short pulses (and results in a reduction of the extracted negative ion current during such pulses) enables effectively stabilizing the co-extracted electrons during long pulses. Other effective measures for improving the caesium conditioning include a prolonged pause time between two consecutive pulses in order to increase the caesium fluence evaporated from the oven into the source and performing pure plasma pulses (i.e. without extraction) in-between pulses with extraction.

All these measures have been developed and tested for pulsed extraction. Figure 3 shows the extracted negative ion current density and the power deposited by the co-extracted electrons onto the two segments of the EG for the best long ELISE pulse up to now in deuterium at p_{fill}=0.3 Pa. In Figure 3a the shown values are averaged over the second half of the extraction blips, thus showing one data point each blip. The extracted negative ion current decreases slightly between one blip and the next one, while the increase in the co-extracted electron current (proportional to P_{EG}) is more pronounced. The co-extracted electrons exhibit a totally different behavior over time during the individual extraction blips, as it can be seen in Figure 3b, showing for the very last extraction blip a zoom into the time traces of the same three signals of Figure 3a. The amount of co-extracted electrons is significantly higher at the beginning of the extraction blip and decreases subsequently by 30 to 40 %. This decrease is caused by the release of caesium from reservoirs at the source backplate by back-streaming positive ions from the extraction system.

A similar opposing effect in the temporal behavior of the co-extracted electrons was observed at the MANITU test facility by directly comparing CW extraction with probing long plasma pulses by extraction blips [3]. At MANITU the effect was much less pronounced than now at ELISE which can be explained by the fact that the MANITU experiments were done at a non-ITER relevant filling pressure of 0.45 Pa. Simulations using the particle tracking code CsFlow3D [19] confirm a strong impact of back-streaming ions on the caesium re-distribution, but also that modified

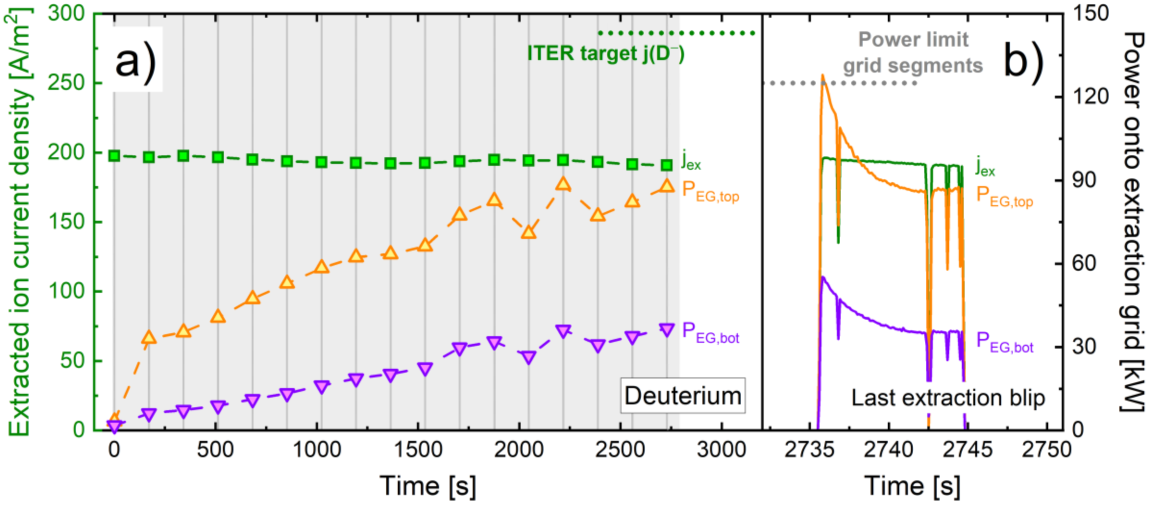

FIGURE 3. Extracted negative ion current density and power onto the two EG segments for the best long D_2 pulse up to now. a): one averaged data point per extraction blip. b): zoom into the time traces for the last blip.

caesium evaporation and re-distribution techniques may help stabilizing the co-extracted electron currents during CW extraction. One of the main aims of ELISE in the future will be to develop such modified caesium handling methods.

CURRENT STATUS OF THE UPGRADE TO CW EXTRACTION

The upgrade of ELISE to CW extraction consists of two main hardware changes: i) installation of a new CW high voltage power supply and ii) installation of a CW beam calorimeter.

The HV power supply is being built by the OCEM company. It consists of two separate power supplies: the first for 12 kV and 70 A maximum (i.e. the extraction step) and the second for 50 kV and 35 A maximum (i.e. the acceleration step). Both power supplies consist of a number of power modules connected in series (24 with a nominal voltage of 600 V each for the 12 kV power supply, 62 with a nominal voltage of 900 V each for the 50 kV power supply). The voltage delivered by the power supplies is regulated by modifying the power output of the single power modules. The maximum allowed voltage ripple is ±100 V and ±200 V for the two power supplies, respectively, and the tube based HV modulators used up to now at ELISE for regulating and smoothing the high voltage will be no longer needed. Preparatory work for the commissioning of the power supplies are currently finished and the delivery is ongoing. Commissioning as well as first tests using a dummy load are planned for autumn 2020.

The design of the CW calorimeter is driven by the following requirements: i) the calorimeter should withstand one-hour pulses with the ITER value for the negative ion current density and the maximum voltages of the new power supply, resulting in a total maximum beam power of 1.8 MW and peak power density of 5 MW/m^2. ii) The diagnostic capabilities should be similar to the existing short pulse inertial calorimeter [20], i.e. mainly water calorimetry for the total deposited power (and a rough estimation of the power distribution) and IR calorimetry for the beam topology [21], possibly with a better spatial resolution with respect to the inertial calorimeter (with a resolution of ≈4 cm×4 cm); iii) fast time resolution of the beam power measurement, in the order of a few seconds, is highly desirable to be able to characterize also short beam pulses; iv) the size of the measuring surface should not be smaller than for the existing inertial calorimeter.

The main design principle of the calorimeter is shown in Figure 4. It consists of three water-cooled copper plates (size: 1330×401 mm each, thickness: 25.5 mm) vertically stacked on top of each other (see Figure 4a). Two independent cooling circuits embedded in each copper plate (total water flow of 11 kg/s) ensure long pulse capability. The water temperature is measured independently for each cooling circuit, enabling a rough estimation of the vertical beam power uniformity.

At the existing calorimeter [20] a distinct and non-uniform degradation of the surface blackening (made of MoS_2), that is needed at the beam facing side for IR calorimetry, is observed and attributed to the sputtering by the beam. Thermocouples integrated into some of the calorimeter blocks (for details see [20]) are used to determine the surface emissivity ε for these blocks and an average ε is used for the rest of the blocks. However, a strong inhomogeneity of the local ε due to the degradation of the black layer can decrease the accuracy of the IR calorimetry results [21]. Additionally, sputtered material deposited onto the ZnSe viewport used for the IR camera can considerably reduce its transmissivity. These problems are solved in the new calorimeter by placing the IR camera downstream of the calorimeter and attaching the blackening layer (soot or MoS_2) to the downstream surface.

In the three plates of the CW calorimeter, 2400 holes (diameter: 2 mm) are placed with a spacing of 30 mm (H) × 20 mm (V). These holes act as stencils: through each of them a small fraction of the beam can traverse the calorimeter

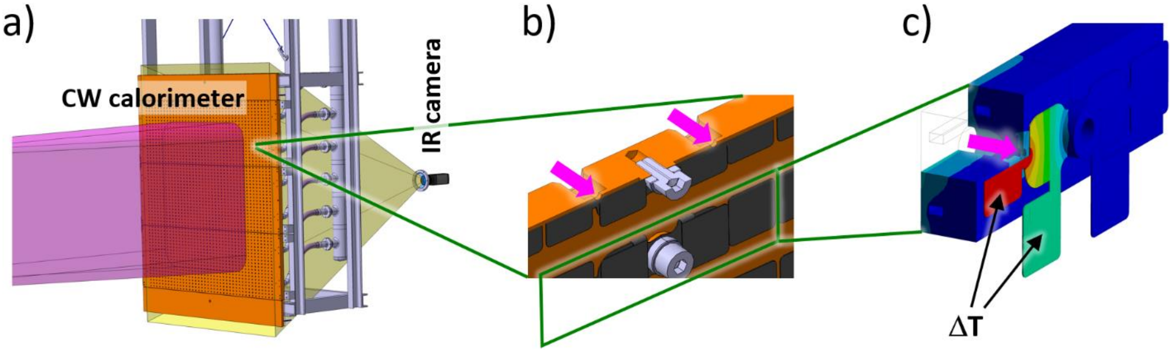

FIGURE 4. a) Overview of the new CW calorimeter. b) Zoom onto a part of the calorimeter back side. The green rectangle indicates one of the copper foils. Two of the four square surfaces are folded in order to save space. c) Thermal distribution on one half of one of the foils during a pulse. In order to have a better overview, the surface of the folded squares is folded out.

plate and hit a thin copper foil attached to the back side of the calorimeter. Figure 4b shows a zoom onto the back side of the calorimeter and the green rectangle indicates one of the foils. The central strip of each copper foil is in thermal contact with the cooled calorimeter plate by a screw coupling and it is surrounded by four quadratic segments that are thermally linked to the central strip by means of a connection with reduced cross section. In order to save space, each second of these quadratic foils is folded. After a few seconds under the heat load of the beam, a temperature difference is established between the two square surfaces on one side of the foil (see Figure 4c), which is directly proportional to the beam power at the position of the through-hole.

A similar calorimeter system (using one plate instead of three and with a slightly different design) is operational at BATMAN Upgrade since May 2020 [22] and thus acts as a prototype for the ELISE CW calorimeter. A MATLAB-based data evaluation system is used to automatically detect the position of the copper foils and the corresponding quadratic segments in the raw image from the IR camera (resolution: 640×480 pixels).

The ELISE CW calorimeter currently is in fabrication, and commissioning is envisaged for the first half of 2021.

CONCLUSIONS

ELISE is currently being upgraded to CW extraction in order to bring its operational scenario even closer to the one of the ITER NBI system. The new HV power supply will go in operation in the end of 2020, while the new CW beam calorimeter is envisaged for the first half of 2021. The so far used pulsed extraction demonstrated that caesium re-distribution during extraction blips significantly differs from pure plasma phases due to the back streaming positive ions. Consequently, using extraction blips for probing long plasma pulses with high RF power and ITER-relevant filling pressure does not yield identical results as performing CW extraction. The caesium conditioning techniques developed up to now at ELISE enabled demonstrating that the ITER requirements can be achieved in long hydrogen pulses. Now, these conditioning techniques will be checked for applicability to CW operation. Where necessary they will be re-defined or new techniques will be developed. In either way, one of the key points is the vertical uniformity of the co-extracted electrons, especially in deuterium operation. This point is crucial in particular for the ITER NBI system, where the co-extracted electrons are measured only globally and strong asymmetries that could locally damage the second grid cannot be detected.

REFERENCES

1. R. Hemsworth, D. Boilson, P. Blatchford et al, New J. Phys. 19, 025005, (2017).
2. A. Krylov and R. Hemsworth, Fusion Eng. Des. **81**, 2239, (2006).
3. B. Heinemann, U. Fantz, W. Kraus et al, New J. Phys. **19**, 015001, (2017).
4. A. Masiello, G. Agarici, T. Bonicelli et al, Fusion Eng. Des. **84**, 1276, (2009).
5. V. Toigo, R. Piovan, S. Dal Bello et al, New J. Phys. **19**, 085004, (2017).
6. D. Wünderlich, R. Riedl, F. Bonomo et al, Nucl. Fusion **59**, 084001, (2019).
7. D. Wünderlich, R. Riedl, I. Mario et al, Rev. Sci. Instrum. **90**, 113304, (2019).
8. P. Franzen, L. Schiesko, M. Fröschle et al, Plasma Phys. Control. Fusion **53**, 115006, (2011).
9. M. Fröschle, U. Fantz, P. Franzen et al, Fusion Eng. Des. **88**, 1015, (2013).
10. D. Wünderlich, W. Kraus, M. Fröschle et al, Plasma Phys. Control. Fusion **58**, 125005, (2016).
11. U. Fantz, L. Schiesko and D. Wünderlich, Plasma Sources Sci Technol. **23**, 044002, (2014).
12. S. Lishev, L. Schiesko, D. Wünderlich et al,AIP Conf. Proc. **1655**, 040010, (2015).
13. E. Speth, H. D. Falter, P. Franzen et al, Nucl. Fusion **46**, S220, (2006).
14. B. Heinemann, H. D. Falter, U. Fantz et al, Fusion Eng. Des. **84**, 915, (2009).
15. W. Kraus, D. Wünderlich, U. Fantz et al, Rev. Sci. Instrum. **89**, 052102, (2018).
16. P. Franzen, U. Fantz, D. Wünderlich et al, Nucl. Fusion **55**, 053005, (2015).
17. C. Wimmer, A. Mimo, M. Lindauer et al, AIP Conf. Proc. **2011**, 060001, (2018).
18. D. Wünderlich, R. Riedl, F. Bonomo et al, AIP Conf. Proc. **2052**, 040001, (2018).
19. A. Mimo, C. Wimmer, D. Wünderlich et al, AIP Conf. Proc. **2052**, 040009, (2018).
20. R. Nocentini, F. Bonomo, A. Pimazzoni et al, AIP Conf. Proc. **1655**, 060006, (2015).
21. I. Mario, F. Bonomo, D. Wünderlich et al, Nucl. Fusion **60**, 066025, (2020).
22. R. Nocentini, F. Bonomo, B. Heinemann et al, *"Long-Pulse Diagnostic Calorimeter for the Negative Ion Source Testbed BATMAN Upgrade"*, submitted to Rev. Sci. Instrum.