

The revised calorimetry of the ASDEX Upgrade tokamak

T. Hohmann^{a,*}, A. Redl^b, V. Rohde^a, G. Schall^a, M. Schandrlul^a,
and the ASDEX Upgrade Team^{a,1}

^a Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

^b Università degli Studi della Tuscia, DEIM, 01100 Viterbo, Italy

ARTICLE INFO

Keywords:

ASDEX Upgrade
Calorimetry
Energy balance
Plasma facing components
Python

ABSTRACT

With the construction of the ASDEX Upgrade tokamak (AUG) in the early 1990s, an extensive calorimetry was installed. This setup is described in the publication Richter and Vernickel (1994). However, the data acquisition was limited in resolution and recording length. In addition, the outdated system setup caused high space, maintenance and energy requirements. This paper first describes the overall setup and then presents the technical modifications for the revised calorimetry on ASDEX Upgrade. The revision was intended to achieve a dynamic recording time for the calorimetric data and to improve the evaluation capabilities. Furthermore, the aim was to downsize and simplify the overall setup with industry standard components in the challenging environment of a tokamak. The revised calorimetry of AUG was put back into operation as a standard diagnostic with the start of the experimental campaign 2021/2022 and provides data in order to establish the global energy balance as well as the investigation of heat loads of individual components.

1. Introduction

It is essential to know the energy loading on the plasma facing components (PFCs) for future nuclear fusion power plants. In experiments of the scale of ITER or DEMO, these heat loads can reach critical levels and limit lifetime or can even cause permanent damage to the PFCs. Therefore, a reliable measurement of the energy distribution in the relevant components is required. The energy input to the PFCs is normally measured with infrared (IR) cameras. However, these measurements are hampered by a variety of factors (IR emission of the plasma, the surface emissivity, the reflected radiation of the tile surface) [1,2] and cover only parts of the vessel. Calorimetric diagnostics cover the whole vessel and can provide absolute measurements. Furthermore, such diagnostics are easy to implement, evaluate, and have already been proven at many fusion devices such as JET [1], Tore Supra [3], EAST [4], QUEST [5], and TRIAM-1M [6]. Thus, they might be an important contribution to heat load studies for future fusion devices.

2. Cooling water calorimetry

At AUG, the in-vessel components and the supporting structures are connected to a cooling water system. The cooling system consists of heat exchangers cooled by a primary circuit. The flow in the primary circuit is regulated by a control valve via a PID controller to keep the

temperature in the secondary circuit as constant as possible at 20 °C. This secondary circuit supplies the in-vessel components, auxiliary limiters and ion cyclotron resonance heating (ICRH) antennas. The remaining heating systems (neutral beam injection (NBI) and electron cyclotron resonance heating (ECRH)) are operating independent setups and providing their energy input in a database.

AUG is divided into 16 segments. Two segments always build an octant. All in-vessel PFCs are mounted to a cooling unit, which is supplied by separate water channels for each unit. The cooling water calorimetry utilizes the relative increase between the cooling water inlet and outlet to determine the heat loads in 80 cooling units [7]. In addition to the cooling units for the divertor plates and the central column, a total of eight cooling circuits for the ICRH antennas and the auxiliary limiters are installed in certain segments. Thus, a total of 88 cooling units are installed at AUG. This allows a nearly perfect toroidal and poloidal coverage of the AUG vessel [8].

First, the inlet cooling water temperature is measured in each octant. Afterwards, the supply pipe is divided into the two segments. In the respective segments, the pipe is divided to the individual in-vessel components (see Fig. 1).

The flow rate through the individual units is determined by orifice plates. After the cooling water has passed the individual components, the water temperature is measured again in the outlet pipe. Later, the

* Corresponding author.

E-mail address: tim-oliver.hohmann@ipp.mpg.de (T. Hohmann).

¹ See author list of U. Stroth et al. 2022 Nucl. Fusion 62 042006.

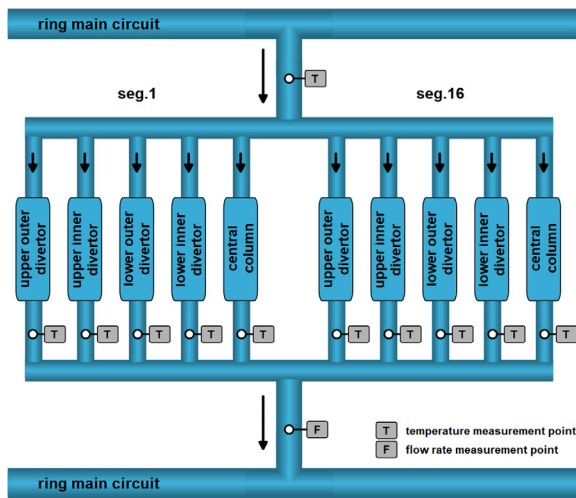


Fig. 1. Simplified illustration of the cooling circuit of an octant [8]. The positions of the individual in-vessel components in AUG are shown in Fig. 5b.

pipes are merged together again and the flow of an octant is recorded by differential pressure sensors.

The measurement of the water temperatures is realized with PT-100 sheathed resistance thermometers (PHG-1B304CLLM31) from Schweitzer Messtechnik. These temperature sensors are installed in a pipe angle by means of a compression fitting (see Fig. 2). They comply with the 1/3 DIN EN 60751 Class AA standard and are installed in four-wire technology from the measuring sensor to the Simatic input card.

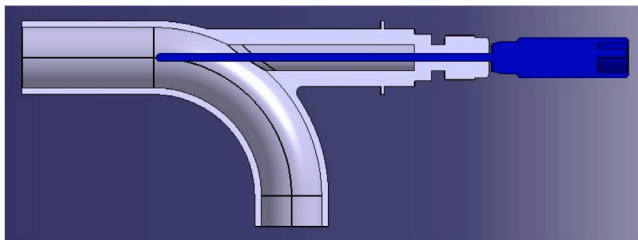


Fig. 2. CAD drawing of a measuring point with PT100.

Differential pressure cells (STD624/ST3000) from Honeywell measure the flows through each octant. The pressure transmitter provides a 4–20 mA signal that is also acquired by Simatic input cards. In addition to the flow measurements on the return lines of the octants, it is also necessary to determine the flows of the individual cooling units. Since these measurements are mandatory for the evaluation of the calorimetric data, the flow rate was determined for each cooling unit using a portable ultrasonic flowmeter (KATflow 200). A permanently installed measurement is not necessary, because all flows in the secondary circuit are kept constant during the operation of AUG.

3. Thermometry of PFCs

In addition to the cooling water calorimeter, AUG has been equipped with thermocouples mounted in certain tiles of the PFCs. The thermocouples in the individual tiles make it possible to calculate the energy input into the respective tile using the temperature rise, the weight and the temperature-dependent heat capacity of the tile. Based on this data, it is possible to extrapolate the results of the thermocouples to specific components (e.g. divertor assemblies (see Fig. 10)) or to the entire machine [1]. Thus, they provide important comparative data for other diagnostics (e.g. cooling water calorimetry

or IR cameras). Furthermore, these data can be used to determine the radiation in certain areas of the machine, such as the cover passive stabilization loop (PSL), more precisely.

Type K thermocouples are installed at AUG as standard. Some of these thermocouples are still of the original design (welded thermocouple heads in an alumina ceramic which is bonded into the PFCs) as described by Richter and Vernickel [7]. Sheath thermocouples (MTE207) from SAB Bröckskes with an outer diameter of 1 mm are used for modernized assemblies. The thermocouples are pressed against the measuring point by means of a spring, creating a detachable connection and avoiding the need for bonding (see Fig. 3).

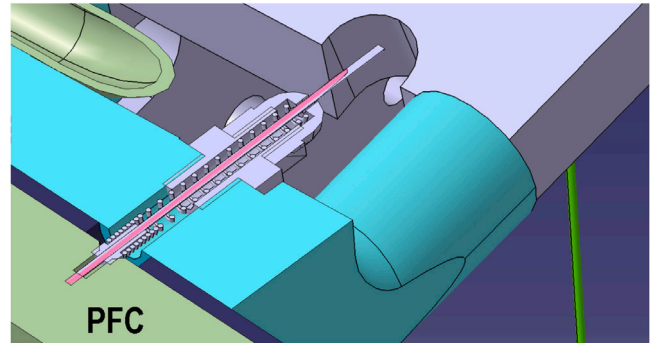


Fig. 3. CAD view of a thermocouple at the central column.

In segments 8 and 10, certain tiles of the lower divertor are equipped with thermocouples. In segments 4 and 13, in addition to the lower divertor, the upper divertor is also equipped with thermocouples to cover the entire divertor in the poloidal direction. Further thermocouples are installed in the central column, the ICRH antennas and the auxiliary limiters. (see Fig. 4).

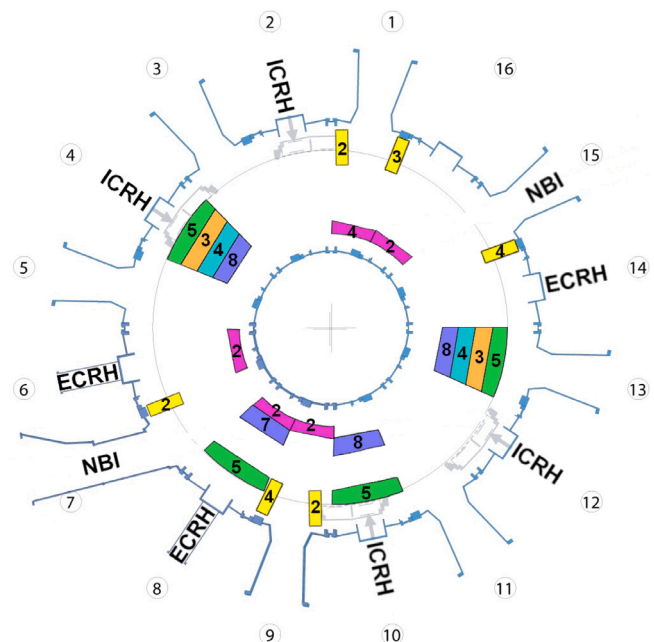


Fig. 4. Toroidal cross section of AUG showing of the positions of the thermocouples in AUG. The colors are assigned to the individual cooling units as follows: Lower outer divertor (green); upper outer divertor (orange); upper inner divertor (blue); lower inner divertor (purple); central column (pink) and ICRH antennas + auxiliary limiters (yellow). The number in each field indicates the number of installed thermocouples.

A total of 94 thermocouples are installed at AUG for calorimetry measurement and machine monitoring, allowing the thermal load to be displayed in a high spatial resolution (see Fig. 5a).

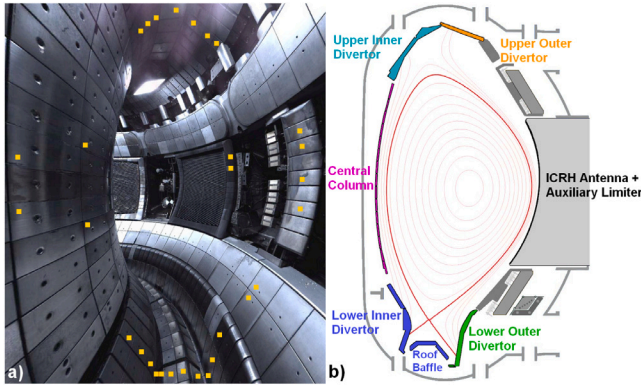


Fig. 5. The left picture gives an exemplary overview of the position of the most important thermocouples at AUG. The right picture displays a poloidal cross section of AUG showing the installed cooling water units. It must be mentioned that the roof baffle is aligned to the cooling unit 'lower inner divertor'. The black indicated cooling units are installed in certain segments. The cooling units marked in color cover the vessel in the entire toroidal direction.

The thermocouple compensation cable runs on the inside of AUG to a vacuum feedthrough. The temperature of the vacuum feedthrough corresponds to the known temperature of the vessel shell and serves as reference junction. Copper wires are installed from the atmosphere side to the Simatic input card.

4. Signal acquisition and conditioning

Operation of temperature measurements in the harsh environment of a tokamak requires robust amplifiers and especially an electrical isolation of the individual devices. Potential differences may occur between different measuring points, which is the reason why special amplifiers had been built in the 1990s. Since both the cooling water temperatures and the thermocouple data are used in parallel for machine monitoring purposes and for the evaluation of the calorimetric data, a high number of isolation amplifiers and signal acquisition cards were necessary in the first setup. The consequence was a high space, maintenance and energy requirement (approx. 200 amplifiers and 400 input channels) (see Fig. 6a).

In order to simplify the setup, the system was modified to connect only measuring points within an octant to a signal acquisition module (distributed i/o device). The individual signal acquisition modules (one module per octant) are installed floating and have no galvanic connection to each other. Disruptions or other events can cause potential differences between different octants, but the differences within an octant are smaller. Since the sensors have no galvanic connection to the measuring point and only measurements within an octant are connected to the respective signal acquisition module, the isolation voltage (500 V) of the individual input channels is sufficient. Simatic ET200M (IM153-2) [9] modules are used in connection with analog input cards (SM331) [10] for signal acquisition.

AUG diagnostics have a limited recording time of 600 s. This is often not sufficient to record the entire cooling process of the individual assemblies. This led to uncertainties in the later data analysis (see Fig. 7, red curve). In order to be able to use the signals for other purposes in addition to machine monitoring and to increase the recording time of the diagnostics, a software access method was chosen that allows the

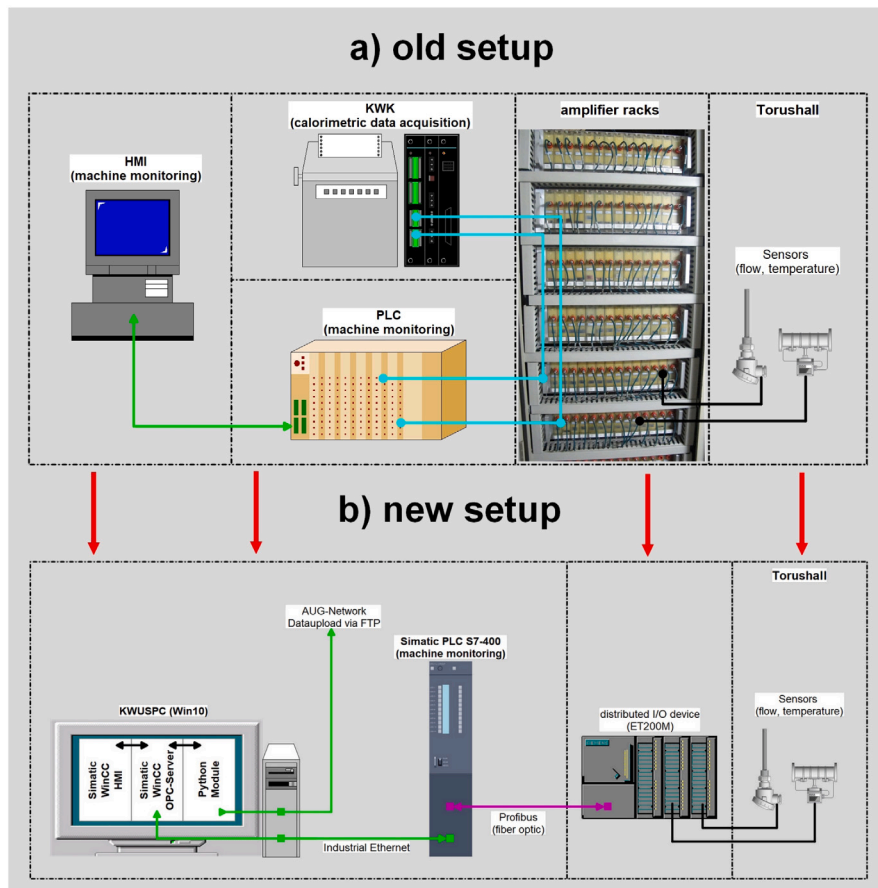


Fig. 6. Schematic comparison of the old and new system setup.

measured data to be acquired with a simple Python code and made available for further data evaluation.

5. Data acquisition and evaluation

At AUG, Simatic WinCC [11] is used in wide areas as a human-machine interface (HMI). This is also the case for monitoring vessel temperatures. All previously described measurements are acquired with Simatic input cards, monitored by a Simatic S7-400 [12] programmable logic controller (PLC) and visualized by using Simatic WinCC (see Fig. 6b). By starting the Simatic WinCC software, a local open platform communication (OPC) server is launched to provide the process values for the runtime. This OPC server can also be accessed by other applications. The only requirement is an OPC client that runs on the same PC as the WinCC visualization software. In order to cyclically read and archive the measured values, a Python routine is used that acts as an OPC client. This OPC client connects to the WinCC OPC server if required and is supplied with process data by it. The proper function of the routine is checked with a watchdog timer. If the watchdog timer fails, the PLC detects this and displays a message to the AUG operators. All other processes are fully automated and do not require any manual intervention by the operator. The Python routine is started automatically as soon as the AUG shot operation is active and connects to the WinCC OPC server in the first step. Data acquisition and archiving is started with a trigger signal 10 s before a plasma discharge. From this point on, the Python module polls the process values from the WinCC OPC server every second. The data aggregation runs until another trigger (30 s before the next plasma discharge) arises with a restriction to the maximum length of 3600 s. Thus, the routine is able to record the maximum possible duration of the cooling process. The collected data is first stored locally in a pickle file and in the next step made available on the AUG network. Finally, another Python routine processes the measured calorimetric profiles and creates AUG standardized shot files of the raw profiles and the evaluated profiles. The maximum sampling rate of the used WinCC system is 4 Hz. Since calorimetry at AUG is a relatively slow process, a sampling rate of 1 Hz was selected, which proved to be sufficient.

6. Results

The previously described measures have improved the signal resolution from 0.2 K to 0.03 K for PT-100s (see Fig. 7) and from 1 K to 0.5 K for thermocouples.

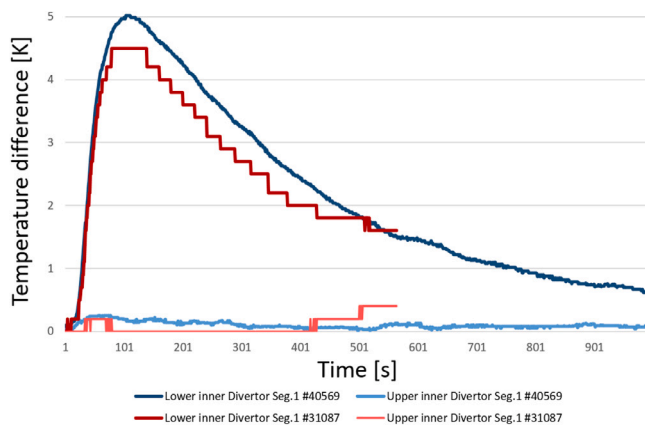


Fig. 7. Curve comparison from lower and upper inner divertor in seg. 1. The red curve shows the trace with the old data acquisition and the blue curve shows the new one. Plasma discharges with similar parameters were chosen.

In addition, the longer recording time allows more robust fitting routines in the later data analysis. Up to now, about 1700 shot files have been generated using the described method. A selection of first scientific results from these discharges are briefly presented in Figs. 8, 9, and 10. Detailed information can be found in articles [8,13] and were presented at the 25th PSI conference [14]. Fig. 8 shows a database of 500 plasma discharges with a large range of different scenarios.

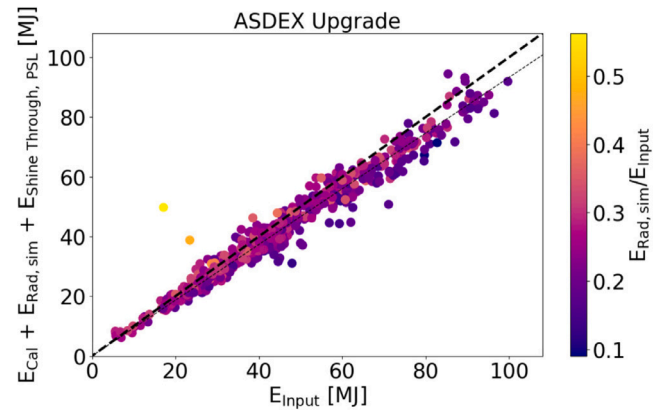


Fig. 8. Visualization of the global energy balance obtained with the optimized cooling water calorimetry at AUG. The color map visualizes the simulated radiation energy, normalized to the injected energy [8].

For these discharges up to 93% of the injected energy has been found on average. Fig. 9 shows the energy distribution of the individual in-vessel components between the segments.

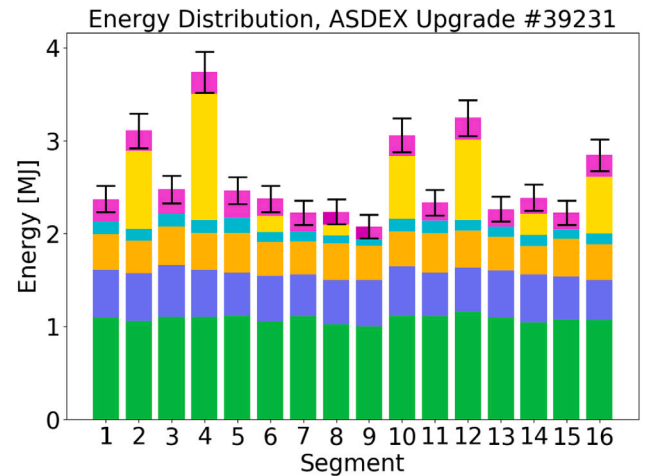


Fig. 9. Energy distribution in AUG calculated with the cooling water calorimetry for a QCE [15] discharge (input energy: 7.5 MW at 6 s flattop time). The colors are assigned to the individual cooling units as follows: Lower outer divertor (green); lower inner divertor (blue); upper outer divertor (orange); upper inner divertor (red); central column (cyan) and ICRH antennas + auxiliary limiters (yellow). The displayed error bars show the known uncertainties [8].

Fig. 10 shows an example of calorimetry using thermocouples. Possible reasons for the deviation between thermocouple and cooling water calorimetry can be found in [16].

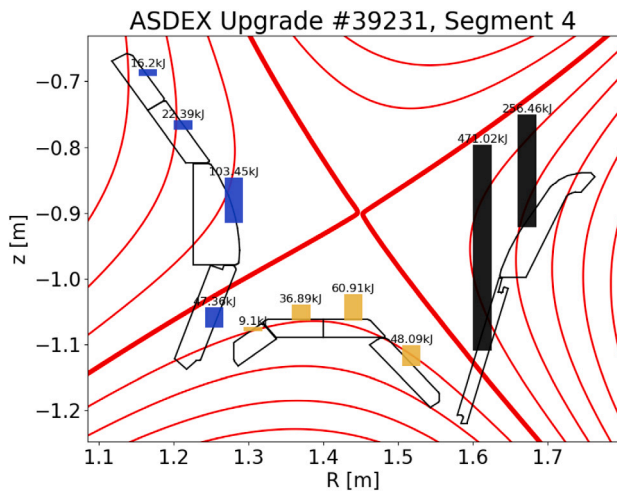


Fig. 10. Tile resolved energy distribution of the lower divertor in segment 4. The energy was measured in the tiles equipped with thermocouples, evaluated using the approach in [1], and extrapolated to an entire segment.

7. Final remarks

The use of the internal WinCC OPC server is a very simple and cost-effective solution to process PLC data in an external module and does not require proprietary hardware such as isolation amplifiers or measuring systems. The modified galvanic isolation, the software-based access to the calorimetric data and the use of industry standard components significantly reduced the space, maintenance and energy requirements of the overall system (see Fig. 6). The increased resolution and longer recording time greatly improved the evaluation capabilities and thus the results. Standardized shot files created by using Python routines allow reasonable and robust calorimetric values required to study the PFCs heat load distribution at AUG.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to acknowledge the support of colleagues, without whom this work would not have been possible: A. Dollenbacher, N. Berger, S. Vorbrugg, D. Grossmann and R. Merkel. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

- [1] G. Matthews, Energy balance in JET, *J. Nucl. Mater.* 12 (2017) 227–233.
- [2] B. Sieglin, Experimental Investigation of Heat Transport and Divertor Loads of Fusion Plasma in All Metal ASDEX Upgrade and JET (Ph.D. thesis), TUM, 2014.
- [3] J.-C. Vallet, Calorimetry in tore Supra: An accurate tool and a benchmark for ITER, *J. Nucl. Mater.* 313–316 (2003) 706–710.
- [4] T. Ming, Calorimetry system for heat load in long-pulse discharges on EAST tokamak, *Phys. Scr.* (2022) 97 095602.
- [5] K. Hanada, Power balance estimation in long duration discharges on QUEST, *Plasma Sci. Technol.* 18 (2016) 1069.
- [6] K. Hanada, Power balance investigation in steady-state LHCD discharges on TRIAM-1M, *Fusion Eng. Des.* 81 (2006) 2257–2265.
- [7] T. Richter, H. Vernickel, The cooling water calorimetry system at ASDEX Upgrade tokamak, *Rev. Sci. Instrum.* (1994) 65.
- [8] A. Redl, The global energy balance of the ASDEX Upgrade tokamak determined with the revised cooling water calorimetry, 2022, submitted for publication.
- [9] Siemens, ET 200M operating instructions, 2022, EWA-4NEB7806006-09.
- [10] Siemens, S7-300 module data, 2022, A5E00105505-AK.
- [11] Siemens, SIMATIC HMI, WinCC V7.5 system manual, 2018, A5E45518509-AA.
- [12] Siemens, Automation system S7-400, 2002, A5E00165965-01.
- [13] T. Lunt, Compact radiative divertor experiments at ASDEX Upgrade and their consequences for a reactor, PRL (2022) submitted for publication.
- [14] A. Redl, Energy load on first wall components in high density, small ELM regimes in ASDEX Upgrade, NME (2022) submitted for publication.
- [15] M. Faitsch, Broadening of the power fall-off length in a high density, high confinement H-mode regime in ASDEX Upgrade, *Nucl. Mater. Energy* 26 (2021).
- [16] V. Rohde, Surface features of strongly heated bulk tungsten divertor plates at ASDEX Upgrade, NME (2022) submitted for publication.