Development of a multi-channel retarding field analyzer for the SOL physics on EAST and W7-X

M. Henkel[1], D. Höschen[1], Y. Li[2], Y. Liang[1], D. Nicolai[1], N. Sandri[1], the EAST Team[2], and the W7-X Team[1]

[1]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[2]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

Steady-state operation of ITER and future power plants needs a detailed understanding of plasma-wall interaction (PWI) physics. Previous experiments in tokamaks as well as in stellarators have shown that the magnetic topology plays an essential role in the particle and heat transport in the scrape-off layer (SOL), which is one of important PWI issues. To investigate this interplay, a multi-channel retarding field analyzer was developed for the W7-X stellarator and tested on the EAST tokamak. The multi-channel retarding field analyzer was designed for simultaneous measurements of ion and as well electron parameters in the scrape-off layer (SOL). First results will be shown in this paper.

With operation commencing in 2015 [1], Wendelstein 7X (W7-X) aims to demonstrate a high performance steady-state plasma operation with a natural 3-dimensional (3D) island divertor configuration. To investigate the interplay between magnetic topology and particle and heat transport in the SOL, a multi-channel retarding field analyzer (MC-RFA) has been developed for measurements of the edge plasma ion and electron temperature and density profiles, as well as fast particles, in the upcoming W7-X experimental campaign. The basic design of the MC-RFA was tested on the linear device PSI-2 and the commissioning of the developed MC-RFA was done in the 2016B and 2017 campaigns of the Experimental Advanced Superconducting Tokamak (EAST) [2] at the Institute of Plasma Physics of the Chinese Academy of Sciences in Hefei (China).

The manipulator is located in the outer midplane. The MC-RFA probe includes two RFA modules back-to-back oriented, each with 3 independent channels at different radial positions and two Langmuir probe pins, one used for floating potential and one for electron temperature and density. This set of diagnostics allows simultaneous measurements of the radial profiles of the ion temperature, the electron temperature and density, floating potential and Mach number.

Furthermore, in the fast particle mode fast ion and electron transport, e.g. driven by ELM events, can be investigated. Due to capacity effects between the different grids inside the probe head, the temperature-sampling rate is limited to 1 kHz. However, the sampling rate of fast particles is mostly limited by the data acquisition, which had a sampling rate of 1 MHz.

To shield the RFA modules from plasma effects, the slits of the front plate have to be in the order of the debye length [3]. Based on the observed densities in the first campaign of W7-X in the order of $10^{18} - 10^{19}$ m^{-3} and temperatures up to 50 eV, slits with a width of 100 μm were used. To ensure that the plasma density inside the probe head is below the space charge limit, a distance of 4mm for the different channels and 1 mm for the low transmission grid and therefore a transmission factor of 0.25% is used.

The first grids of the RFA modules are biased negatively U_0 to repel the electrons from plasma. The second grid will be biased sweeping positivly U_G to measure an energy distribution of the ions, because only particles with energy higher than eU_G can overcome these grids. The ion temperatures $T_i^{a,b}$ therefore can be calculated using the measured I-U-characteristics [3]:

$$j^{a,b} = \frac{I_0^{a,b}}{A_{\text{eff}}} \exp\left(-\frac{(U_G - U_0)}{ZT_i^{a,b}}\right) + j_{\text{offset}}$$

The electron density n_e can be calculated using the saturation current density in the I-U-characteristics of the sweeping biased Langmuir probe pin [4]:

$$n_e = \frac{j_{\text{sat}}}{0.49 c_s}$$

Where 0.49 is the sheath expansion coefficient [5] of the Langmuir probe pins and $c_s = \sqrt{(T_i + ZT_e)/m_i}$ the ion sound speed.

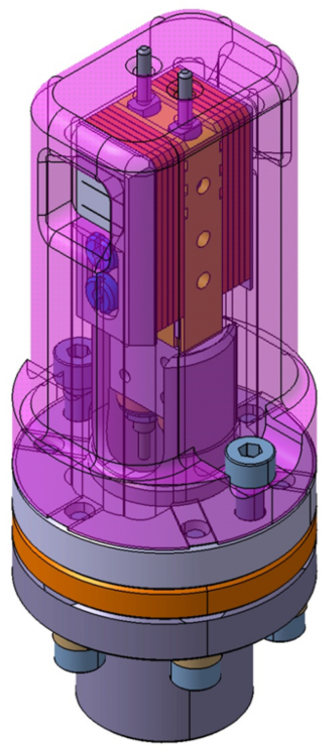

Figure 1: Design of the multi-channel retarding field analyzer including 2 RFA modules, each with 3 channels, Langmuir probe pin and floating pin.

The manipulator is able to plunge up to 50 cm [6] and with a maximum velocity of 2 m/s [6]. The ion temperature profiles measurements reached a spatial resolution of less than 0.2 mm. During commisioning, the MC-RFA probe was able to measure up to the last closed flux surface (LCFS), so it is possible to measure the whole radial profile in the SOL.

Figure 2 shows two radial ion temperature profiles from the ion flow side of the MC-RFA.

During the EAST campaign ion temperature decay lengths between 3.6 mm and 6.7 mm and ion temperatures up to 30 eV were measured.

As shown in figure 3, the ion saturation current profiles, measured by different channels with a distance of 4 mm, fit, so that the probe is capable of multi-channel measuring. Therefore the MC-RFA probe can be used to measure simultaneously at different fixed radial positions or to measure several profiles e.g. to investigate radial particle and heat transport.

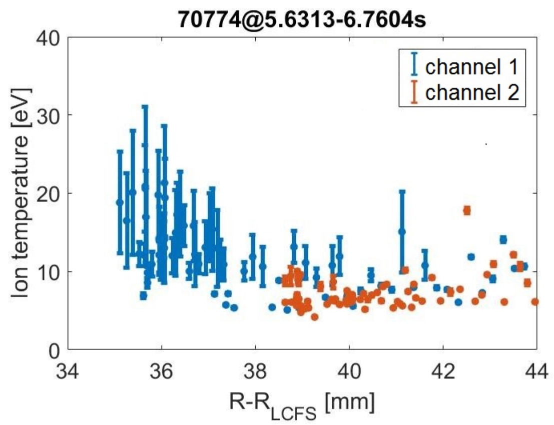

Figure 2: Radial ion temperature profiles in the SOL from ion flow side, measured with a distance of 4 mm.

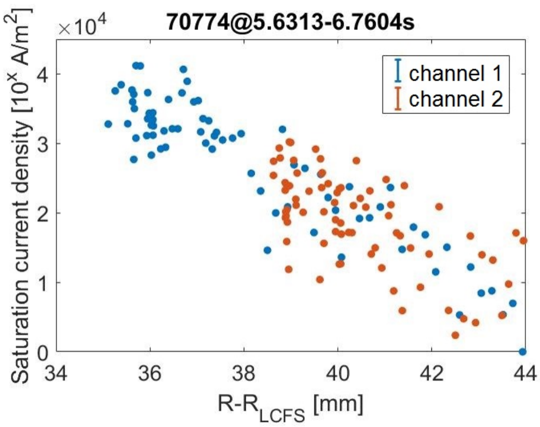

Figure 3: Radial ion saturation current profiles in the SOL from ion flow side, measured with a distance of 4 mm.

The MC-RFA can also be used for fast particle measurements, e.g. induced from ELM burst, as shown in figure 4. In this case the sweeping voltage U_G is set at a fixed potential and the probe head stays at a fixed parking position for time tracing.

For such fast particle measurements (e.g. during ELM burst) the radial propagation can also be investigated. As shown in figure 5, the time trace of fast particle losses can be measured at fixed position. In combination with other diagnostics, e.g. Langmuir probes, the radial propagation as well as the radial profile of fast particles can be investigated. On EAST measurements in upper single-null configuration on EAST were done and in H mode plasma 3 phases could be observed. In the pre-ELM phase, fast ions dominate initially, followed by fast electrons dominating. During ELM crush the thermal ions dominate, and in the post-ELM phase fast ions again dominate. This observation demonstrated that the radial transport dynamic of fast particles differs from those of the thermal particles and has to be investigated further.

In conclusion, an MC-RFA was developed for measurements on the EAST tokamak and the W7-X stellarator. It was commissioned on EAST and it could be shown that multi-channel measurements work and ion temperature profiles and fast particles can be measured. Therefore the MC-RFA probe will be used for experiments in the upcoming campaign of W7-X.

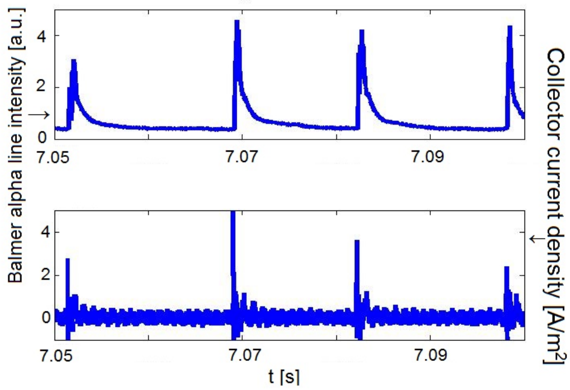

Figure 4: Signal from MC-RFA collector (ions and fast electrons) and Balmer alpha lines from divertor filter scope during ELM events.

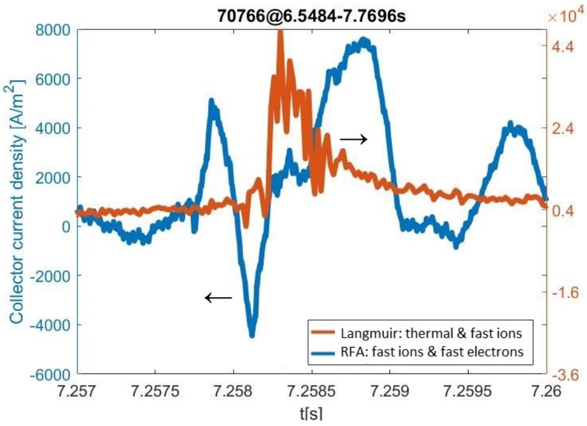

Figure 5: Signal from MC-RFA collector (ions and fast electrons) and divertor Langmuir pin (electrons and fast ions) of fast particles during an ELM burst, measured at fixed position.

References

[1] R. Wolf et al.: *Wendelstein 7-X Program - Demonstration of a Stellarator Option for Fusion Energy*, IEEE transactions on plasma science 54 (2016)

[2] B. Wan et al.: *Advances in H-mode physics for long-pulse operation on EAST*, Nuclear Fusion 55 (2015)

[3] S. Elmore et al.: *Upstream and divertor ion temperature measurements on MAST by retarding field energy analyser*, Plasma Physics And Controlled Fusion 54 (2012)

[4] S. Shen and T. Sekiguchi: *Instantaneous Direct-Display System of Plasma Parameters by Means of Triple Probe*, Journal of applied physics 36 (1965)

[5] E. R. Harrison and W. B. Thompson: *The Low Pressure Plane Symmetric Discharge*, Proceedings of the Physical Society 74 (1959)

[6] W. Zhang et al.: *Fast reciprocating probe system on the EAST superconducting tokamak*, Review of scientific instruments 81 (2010)

Acknowledgements

The author would like to thank Z. Huaxiang, H. Zhang and N. Yan of the Institute of Plasma Physics, Chinese Academy of Sciences, handling the midplane manipulator during EAST experiments and G. Xu to be host of this expriments.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.