Symmetries of 13C tracer deposition in EAST D and He plasmas investigated on the sub-mm to 100 mm scale by deuteron nuclear reaction analysis

S. Möller[1*], R. Ding[2*], H. Xie[2], B.F. Gao[2,3], B.G. Wang[2,3], J. Peng[1,2], S.C. Liu[2], W. Gao[2], A. Kirschner[1], S. Brezinsek[1]

1 Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung, 52425 Jülich, Germany

2 Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, People's Republic of China

3 University of Science and Technology of China, Hefei 230026, Anhui, China

4 Forschungszentrum Jülich GmbH, Zentralinstitut für Analytik, 52425 Jülich, Germany

*Corresponding author e-mail: s.moeller@fz-juelich.de, rding@ipp.ac.cn

Abstract. In continuation of an earlier study, this work focusses on deposit analysis in the mm region around the tracer injection hole of two $^{13}CD_4$ injection experiments in EAST by using focussed 1.43 MeV deuteron ion beam analysis. This study adds ~1500 data points to the former work on the same samples to assess more details on deposition patterns and symmetry and test the accuracy of former extrapolations.

Mapping of the $^{13}CD_4$ injection-hole vicinity using 0.2 mm lateral resolution yields compatible results as the former 1.8 mm resolution for the local co-deposit thickness. The new data reveal the deposition maximum to be 1±0.2 mm away from the injection hole towards the ExB direction, resembling the triangular shape also seen on the larger scale. The analysis of 3 blocks along the magnetic field vector shows a dominant deposition along the surface area closest to the last closed flux surface. An edge with a factor ~11 drop in deposit thickness within 2 mm spans here along the whole 150 mm tile size along the axis of the magnetic field. The analysis using proton backscattering shows no He retention in the He plasma exposed co-deposits above the 1% limit of detection.

The total deposited ^{13}C amount was underestimated by ~5% in the former study, a value not exceeding the measurement uncertainty. The combination of ~0.2 mm spatial resolution around the injection-hole and at the deposit edge with ~ 2 mm resolution but larger coverage outside these regions is found to provide a reasonable compromise of information quality and analysis effort.

Keywords: Transport studies, tracer, EAST, ion beam analysis, nuclear reaction analysis, ^{13}C

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• Introduction

The analysis of tracer deposition in nuclear fusion experiments represents an important approach for understanding plasma-surface interaction (PSI), namely the deposition, erosion, and re-deposition of plasma species and surface material. The application of tracers enables a separation of processes in nuclear fusion reactors, but the physical understanding of PSI can only be as good as the information provided on the tracer deposition patterns after the experiment. Numerous quantities and physical processes influence PSI inducing equally numerous requirements on accuracy and resolution onto techniques for post-mortem analysis of the resulting deposits. Nuclear reaction analysis (NRA) using deuteron beams was demonstrated to provide a new and powerful method for analysing the deposition of carbon, in particular ^{13}C, and deuterium [1].

Two methane ($^{13}CD_4$) injection experiments were performed in EAST in D and He plasmas. This work extends the previous results [1] on the high throughput approach with new data on spatial distribution and He retention. In the previous work open questions regarding the spatial distribution of the co-deposits and the retention of He after He plasma exposure remained. Effects such as SOL-Flows could induce further inhomogeneities in the deposition patterns [2] which are to be analysed in this work. The localisation of the deposition maximum remained unclear, but it could add additional information on the processing of the injected $^{13}CD_4$. Furthermore, the retention of He in co-deposits is interesting for understanding outgassing and wall fuelling of subsequent plasmas.

- **Experimental setup**

The details of plasma exposure, sample preparation, and sample analysis methodology are described in a previous publication working with the same samples [1]. This work again uses 1430 keV deuteron beams for analysing the central region around the injection hole of the He plasma exposed sample with one order of magnitude increase spatial resolution and 0.1 µC integrated ion dose per point and on two additional outer blocks with reduced lateral resolution but improved detection limits through 1 µC per point. Figure 1 shows the samples and sketches the results obtained in all analysis. For the outer blocks, the analyser rise-time is reduced to 0.6 µs in order to maintain a dead-time <3% for ion beam currents of 20-30 nA. Excessive dead-time would increase the pile-up in the $^{13}C(d, \alpha_0)^{11}B$ peak region. With the given settings, the pile-up contribution is kept <10%. The analysis uses the linear correlations of counts and deposit thickness derived in [1], but scaled linearly to the corresponding ion doses applied here.

Additionally, 2230 MeV protons are applied to determine the He retention on the central block of the He plasma exposed tile in 5 points with 30 µC of protons per point and 1 mm spot size. This energy allows for an optimal ratio of the backscattering signals of carbon (=background) and ^4He close to the surface, therefore providing the best detection limit under the given circumstances. The evaluation applies the elastic backscattering (EBS) cross-sections from [3]. Figure 2 shows a simulation fitted to the experimental data indicating the complicated evaluation of the He retention due to the strong background signal. At 2230 MeV the cross-section of the $^4He(p, p)^4He$ scattering exceeds the Rutherford value by a factor ~200, enabling the detection of He concentrations down to about 1%. Figure 1 shows the analysed areas.

Figure 1: Photos of the two EAST tiles sectioned into 9 blocks each with an overlay of the ^{13}C deposition analysis (varying scales). Left the D and right the He experiment tiles. Red boxes indicate newly analysed regions for ^{13}C and D via D-NRA and white stars indicate the points analysed by proton-EBS for He retention.

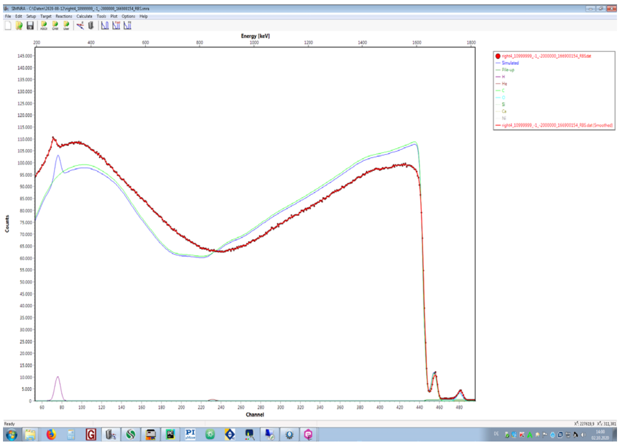

Figure 2: SimNRA simulation of the He EBS signal for a graphite sample with about 80 nm a:^{13}C-D deposition. If He is present in this deposit, the signal adds up to the carbon background at the energy indicated by the black arrow. The small peak on the left side belongs to backscattering on the D in the co-deposit.

- **Ion-beam analysis results**

Figure 3 shows the measured deposit thickness around the injection hole of the He experiment with 0.2 mm lateral resolution. The results show a triangular shape as it was also seen on the larger scale. Besides the ExB asymmetry, the deposition appears symmetric around the injection hole. ^{13}C and D deposition correlate with each other with $D/(D+^{13}C) = 0.6$ to 0.8. The peak value of ^{13}C deposit thickness of $5.5 \pm 0.9 * 10^{23}$ $^{13}C/m^2$ agrees with the value of $5.8 \pm 0.9 * 10^{23}$ $^{13}C/m^2$ found formerly [1]. The evaluation yields a deposition of $1.08 \pm 0.05 * 10^{19}$ ^{13}C in the 5.2 mm x 5.8 mm area scanned around the injection hole. Evaluating the results shown in [1] on the central 16 points corresponding roughly to the area analysed here results in a comparable number of $1.03 \pm 0.1 * 10^{19}$ ^{13}C. This area contains 8.5% of the total ^{13}C deposit on the central block.

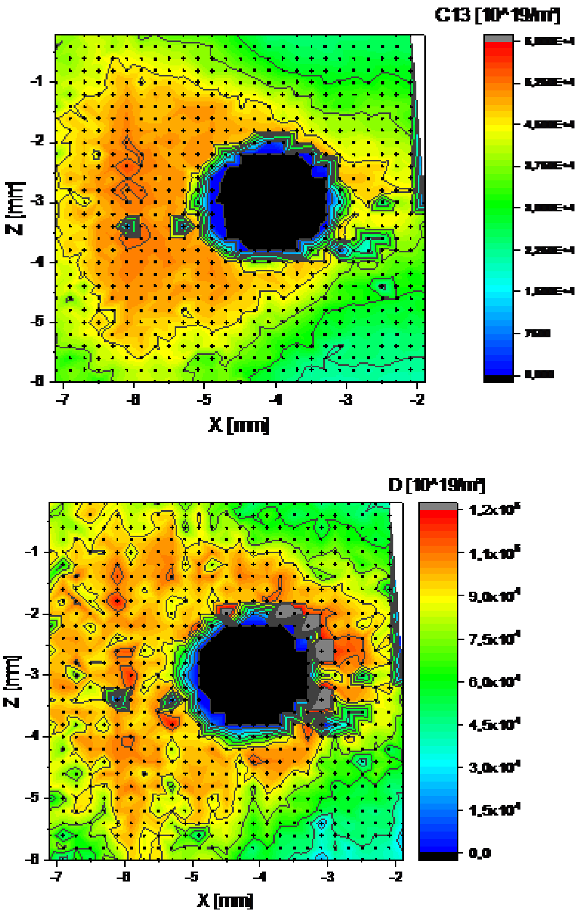

Figure 3: Linear interpolation plots of the D and ^{13}C deposition near the injection hole on the central block of the He experiment. Black dots represent the NRA analysis points. The D and ^{13}C patterns are symmetric about the horizontal axis through the injection hole and the maximum thickness lies 1 mm to the right of the hole. This analysis occurred after SIMS analysis and the craters appear as single point holes around the injection hole.

Figure 4 shows the ^{13}C deposition on the two blocks above and below the central one. Both areas cover 1630 mm², but technical limitations restricted the scanning area, excluding the lower 6 mm of both tiles. Consequently, for the block above the central block the part directly adjacent to the central block is not analysed and we would expect a slightly lower ^{13}C content due to this analysis region offset and the decay of deposit thickness with distance from the injection-hole. The ^{13}C content of the blocks reads $4.65\pm0.6*10^{18}$ (block above the central tile) and ^{13}C $5.5\pm0.6*10^{18}$ ^{13}C (block below the central tile), respectively. These numbers lie significantly above the co-deposition estimated in the former study of $7.4*10^{17}$ ^{13}C per outer block. Consequently, we reconsider the total deposition by summing up the results of the four analysed blocks analysed and assuming the deposition to be identical on the six blocks with screw holes and the Langmuir probe. This yields a number of $14.5\pm1.5*10^{18}$ ^{13}C on the 8 outer blocks plus $178.5\pm18*10^{18}$ ^{13}C on the central block, resulting in $1.93\pm0.2*10^{20}$ ^{13}C on the complete tile compared to $1.84\pm0.2*10^{20}$ ^{13}C extrapolated in [1].

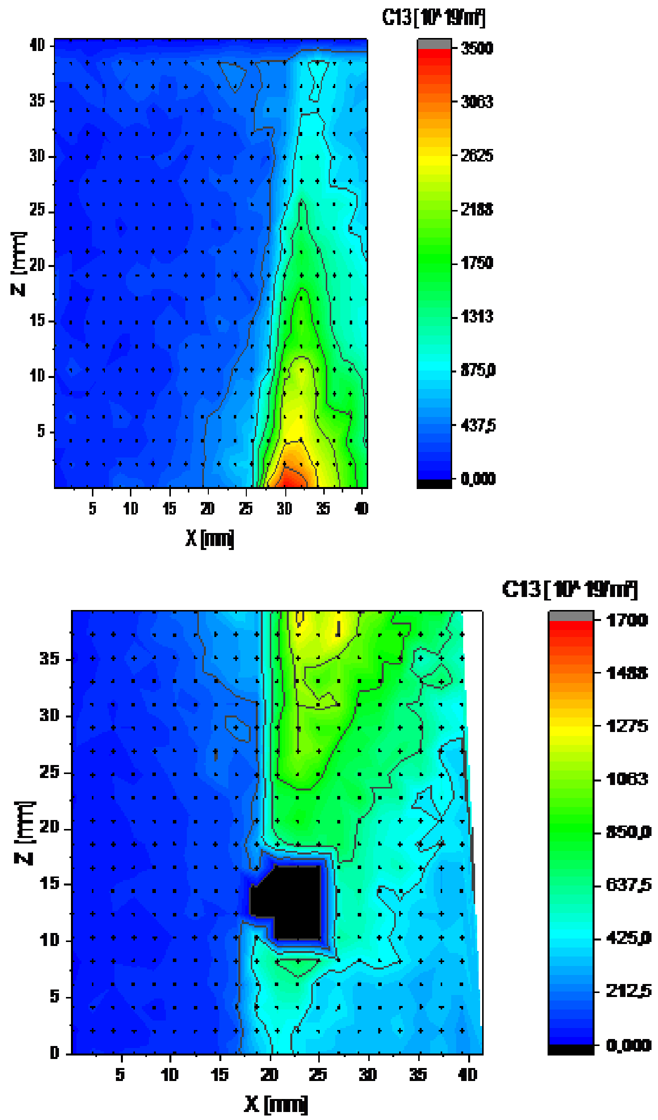

Figure 4: Linear interpolation plots of the ^{13}C deposition on the two tiles above (left) and below (right) the injection-hole tile of the D experiment, see Figure 1. The scan covers only a part of the block surface due to limitations of the sample manipulator travel. Both blocks contain about 3% as much ^{13}C as the central tile. The red arrow indicates ExB drift direction. Black dots represent the individual measurement points. The red circle marks the open hole in the tile.

The Proton EBS measurement revealed small amount of Si, Ni, and Ca in the order of 10^{20} at/m² on the He sample in the two outer locations. A retention of He is not found above the detection limit of 1% in the co-deposits. The sample surface roughness, varying carbon EBS cross-sections, and uncertainties in the detector calibration limit the measurement of He retention in this sample. For example the roughness smears out the low energy part of the ^{12}C signal, exactly where the He EBS signal of the substrate could be expected. The measurement cannot distinguish between these effects and the He signal, worsening the detection limit to 1%. The presence of He shortly after the plasma exposure cannot be excluded.

- **Conclusions**

This works successfully extends the analysis of the EAST exposed samples. We demonstrated increased lateral resolution as well as identical deposit thicknesses in subsequent analysis runs of the same sample region (equal peak values of ^{13}C deposition). The analysis of helium retention in the co-deposits did not show any presence of long-term helium retention above the methods detection limit of 1% concentration.

The deposition found via the highly-resolved analysis of the central region around the injection hole is in line with the former low resolution analysis regarding deposition efficiency. A significant difference between the retention derived from the 16 points with 1.8 mm lateral resolution measurement and the 800 points of the new 0.2 mm resolved measurement is not observed beyond the given uncertainties of a few percent. The 1±0.2 mm distance between deposition maximum and the injection-hole edge in the He experiment supports the assumption of a dominant plasma process of ionisation on the plasma vicinity line with subsequent geometrical deposition of neutrals and ions. A deposition peak around the injection-hole edge where we would expect the highest $^{13}CD_4$ gas density is not found. This somewhat disproves the statement on a radial decay with respect to the injection-hole made in [1], at least in the very vicinity of the injection-hole.

The analysis of three blocks aligned to the magnetic field line potentially reveals the contribution of SOL-flows to the deposition process. SOL-Flows would induce an asymmetry along the B-field (perpendicular to ExB, vertical in Figure 1), but no asymmetry is observed in the ^{13}C deposition here. We can conclude a negligible contribution of SOL-flows on the deposition process and a possible stagnation point (SOL velocity =0) on the mid-plane sample exposure location. The distance to the last closed flux surface, the distance to the injection hole, and the ExB direction appear to be the dominating factors for the deposit thickness. In particular, the two newly analysed outer blocks demonstrate a significant drop in ^{13}C deposition thickness against the ExB direction of a factor ~11 within 2 mm. Processes of re-erosion and deposition (a.k.a. walking) could be responsible for the remaining yet small deposition against ExB besides the direct neutral deposition of energetic neutrals produced in the plasma. The drop of deposition thickness against ExB strongly weakens after this first step, speaking for at most only a short-ranged walking process in addition to another longer ranged process such as neutral deposition. Interestingly, this drop against the ExB direction is significantly stronger in the D plasma exposed tile compared to the He plasma exposed tile, which does not show this consistent sharp vertical edge along the whole tile (compare Figure 1).

Acknowledgments

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