Modelling of local ^{13}C tracer injection via MPM in Wendelstein 7-X

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Erosion, migration and deposition of wall materials in fusion devices are crucial processes as they determine the lifetime of wall components, long-term tritium retention via co-deposition and impurity concentration in the core plasma. Tracer experiments are vital methods for detailed studies of the involved processes and rarely used in stellarators like Wendelstein 7-X (W7-X).

Experiment

During two hydrogen discharges in standard magnetic configuration with a total duration of ~12s ^{13}C-marked methane CH_4 was injected for ~10s with a rate of ~1E20/s through the multi-purpose manipulator (MPM) [1] at the outboard midplane. The top surface of the probe head in this experiment was located at a major radius R = 6.11 m in the far scrape-off layer of W7-X. Post-mortem analysis of the graphite probe head applying colorimetry, NRA (Nuclear Reaction Analysis) and RBS (Rutherford Backscattering Spectrometry) revealed a ^{13}C deposition efficiency on the probe head of ~2% and thus ~98% of the injected ^{13}C atoms is not locally deposited, but somewhere else within W7-X or pumped out as volatile hydrocarbon. Figure 1 shows a photograph of the probe head after exposure, a horizontal and vertical profile of the NRA measurements and the simulation volume used for ERO.

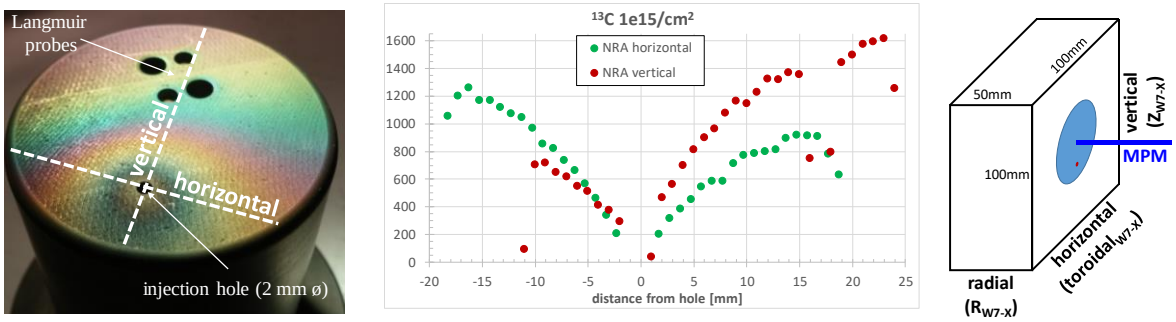

Figure 1 *MPM probe head after exposure, NRA profiles and ERO simulation volume.*

Modelling

The 3D erosion and migration code ERO [2] has been applied to model the local transport and resulting ^{13}C deposition of the injected $^{13}CH_4$ considering its full dissociation chain. Langmuir probe measurements with the MPM cannot be done during the $^{13}CH_4$ injection, but are available for reference standard plasmas without gas injection. The according radial profiles of the electron temperature and density are fitted exponentially and used as input for ERO, see figure 2. The ion temperature is assumed to be equal to the electron temperature.

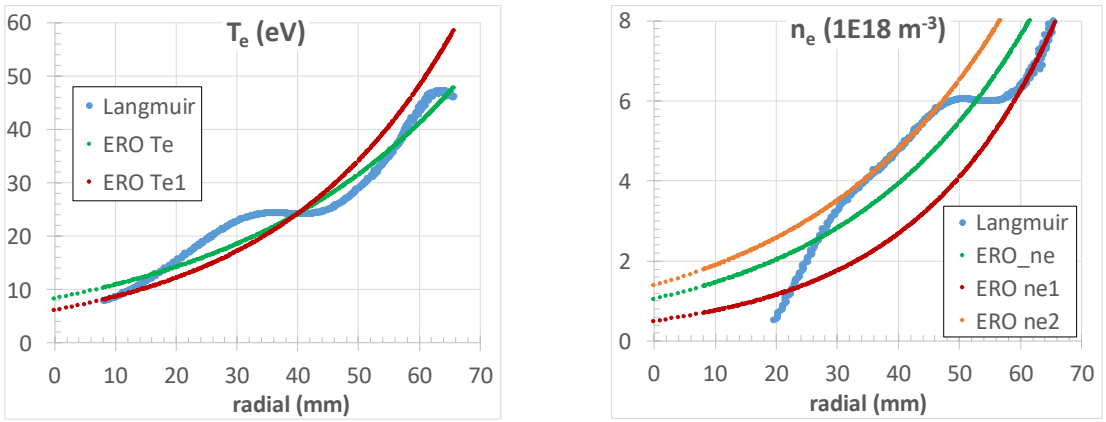

Figure 2 *Radial profiles of electron temperature and density. Blue: Langmuir probe data. Green: Exponential fit used in ERO. Red and orange: Profiles for parameter studies in ERO. The radial position of 0 mm corresponds to the MPM head surface.*

Due to deviations between the measurements and fitted values, sensitivity studies for the plasma parameters are performed in the modelling. In the background plasma a ^{12}C carbon impurity of 2% is assumed. Anomalous cross field diffusion is set to 0.2 m^2/s.

The ERO simulations show that ~32% of the injected ^{13}C atoms return to the MPM head surface, 9% as atoms and 91% as $^{13}CH_x$. Also ~30% of the injected H returns to the MPM head surface, 32% as H and H_2 and the remaining 68% within the returning $^{13}CH_x$. Assuming standard yields for physical sputtering based on SDTrimSP [3], a chemical erosion yield of 0.5%, TRIM-based reflection coefficients for carbon atoms and ions and "standard assumptions" for reflection coefficients of $R_{neutral}$=0.9 for neutral CH_x and R_{ion}=0.5 for ionised CH_x^+ leads to a ^{13}C deposition efficiency of ~14%, thus much larger than measured. Also the modelled deposition pattern is much more localised with a maximum around the injection hole, which is in contradiction to the experimental pattern, see figures 3a and 1. The simulations reveal that ^{13}C erosion is dominated by chemical erosion due to low energy H returning from the injection. Physical sputtering by returning ^{13}C is comparably small and also chemical and physical erosion by the background plasma is negligible due to small background plasma flux and low plasma temperature (less than 10 eV at the MPM head surface).

The "standard assumptions" for hydrocarbon reflection are geared to earlier modelling of ^{13}C tracer experiments at TEXTOR, see e.g. [4]. Due to smaller electron temperature in the W7-X experiment, the returning hydrocarbons have smaller impact energies (less than 20 eV), which typically leads to larger reflection as can be seen from Molecular Dynamics (MD) simulations [5]. As extreme case, full reflection for all hydrocarbon species has been assumed to study the influence on the resulting ^{13}C deposition. Moreover, instead of TRIM-based reflection for returning carbon atoms and ions (which typically is zero for the small impact energies but not very realistic due to the limits of the binary collision approximation applied in TRIM), a value of R=0.4 is assumed, again suggested by MD simulations. The resulting 2D distribution of deposited ^{13}C is shown in figure 3b together with the horizontal and vertical profiles.

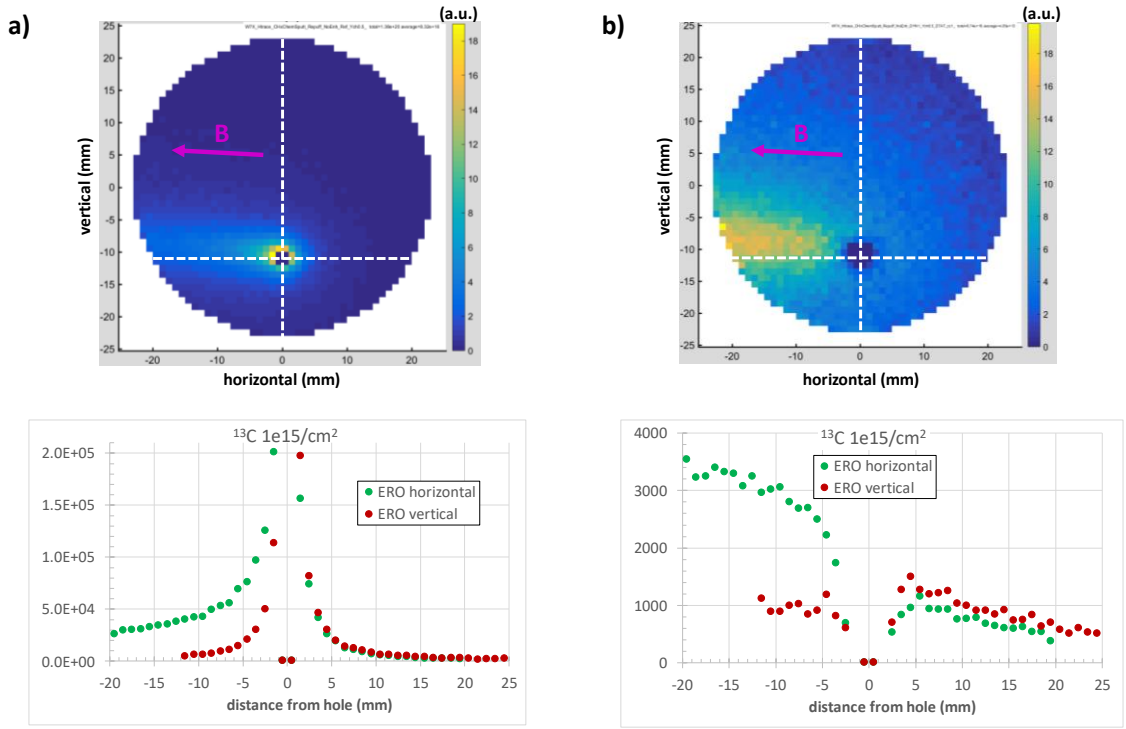

Figure 3 *2D pattern and profiles of the modelled ^{13}C deposition along the horizontal and vertical dashed lines indicated in the 2D figures:* ***a)*** *"Standard assumptions" for the reflection of hydrocarbons.* ***b)*** *Full reflection for all hydrocarbons.*

The deposition pattern is now much less localised and thus more similar to the experimental one. Also, the modelled ^{13}C deposition of ~1.4% is now comparable to the measured value. However, in contrast to the experiment the modelled pattern has a preferential deposition area (with deposition larger than measured) along the magnetic field line towards the negative horizontal direction as the deposition is dominated by carbon ions moving along the magnetic field line. Figure 4 shows the distribution of $^{13}CH_4$ and $^{13}C^+$ above the MPM head surface (integrated along the W7-X z-coordinate, which is the vertical axis of the ERO simulation volume shown in figure 1) illustrating the movement of $^{13}C^+$ ions along the magnetic field. As consequence of that movement, the deposition modelled in particular at areas towards the positive vertical and horizontal directions is smaller than measured.

The effect of the $E_{rad}\times B$ drift, which is directed towards the positive vertical direction, has been studied. The radial electric field E_{rad} is proportional to dT_e/dr, for details see e.g. [2] and references therein. It is seen that even a ten times increased radial electric field does not significantly change the overall deposition pattern. Also the influence of the electric field within the sheath on the deposition pattern is negligible due to the small thickness of the sheath.

Parameter studies of the electron temperature and density have been done (see profiles in figure 2) revealing, as expected, an increased (decreased) overall deposition if temperature and/or density are increased (decreased). However, the general pattern of the modelled ^{13}C deposition does not change significantly and in particular no improved agreement with the observed pattern can be achieved.

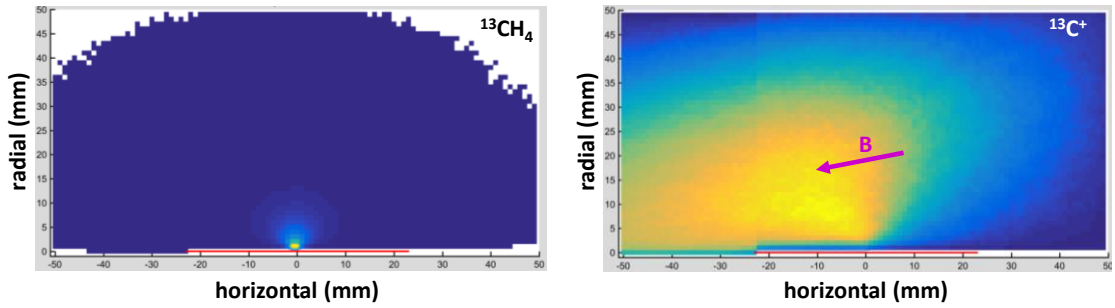

Figure 4 *Modelled particle distribution of $^{13}CH_4$ and $^{13}C^+$ above the MPM head surface (indicated in red) for the case of full reflection of hydrocarbons.*

Also, possible local cooling of the plasma due to the strong injection source has been studied in a simplified way. Within the whole simulation volume the electron temperature has been divided by a certain factor f_cool and the density multiplied by the same factor thus keeping the pressure unchanged. Studies with f_cool up to 10 show no strong change of the ^{13}C deposition pattern and also the deposition efficiency is almost unchanged.

Conclusions

Only with high reflection near to one for all hydrocarbons the modelled ^{13}C deposition efficiency is similar to the experimental value. However, the ^{13}C deposition pattern still deviates from the measured one. One possible explanation could be an enhanced re-erosion of deposited ^{13}C in particular at locations with large depositing flux, which already has been discussed earlier, see e.g. [4]. This would decrease the modelled deposition at areas of large deposition and finally lead to an overall deposition pattern as observed. In addition, in the simulations a constant chemical erosion yield of 0.5% has been assumed. According to [6], in particular near to the injection hole a smaller yield of 0.1% or less is more realistic due to the large H flux from the injection at that location. Thus, again an enhanced erosion caused by the large depositing ^{13}C flux would be a possible explanation for the larger erosion yield near to the hole.

References

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