Relevant processes for hydrocarbon transport, break-up, and light emission in an ITER divertor-relevant plasma

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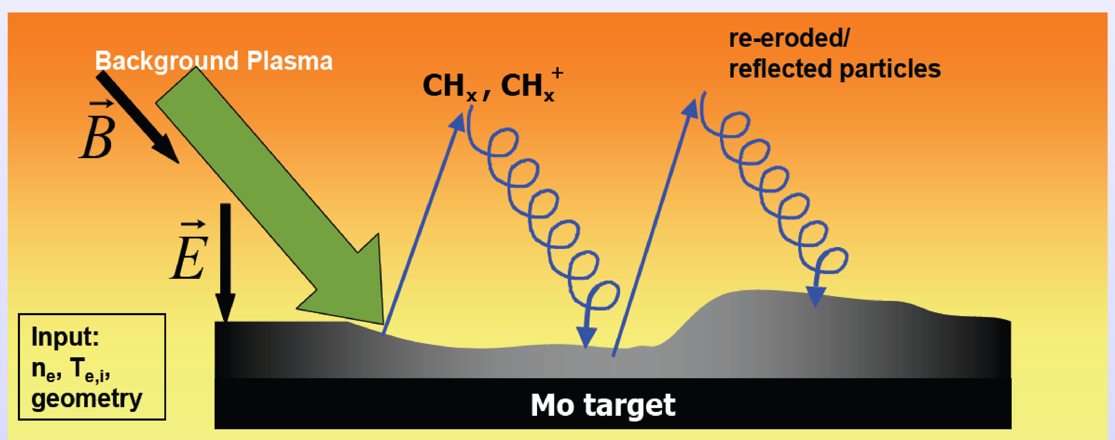
Background

Spectroscopy of the CH A-X Gerö band is a commonly used diagnostic in PWI research. But which processes excite this CH band under ITER divertor conditions? And can we validate reaction rates used for ITER hydrocarbon transport modeling?

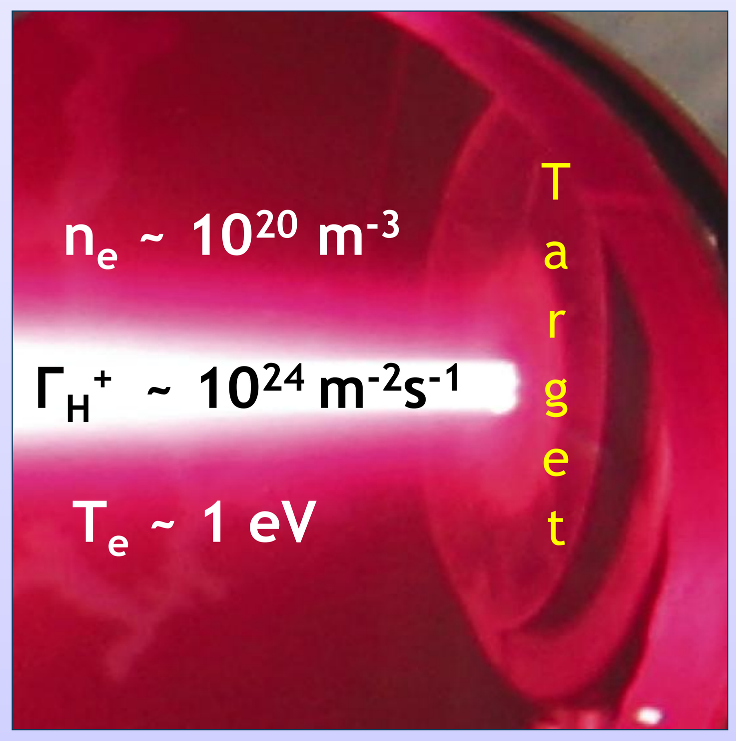
Modelling: ERO



ERO [1]: 3-D Monte Carlo impurity tracing code; impurity-impurity collisions are neglected. Dissociation of hydrocarbons in the plasma follows reaction rates from Janev and Reiter [2]

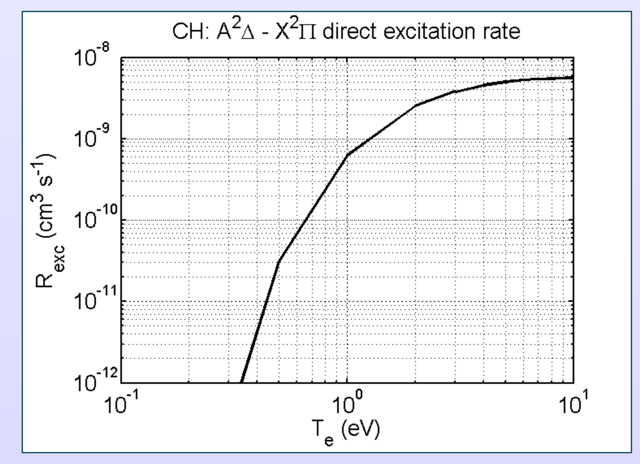
The experiment: Pilot-PSI

Linear plasma generator capable of generating high density, low temperature plasma for PWI research. Diagnostics include Thomson scattering for measuring T_e and n_e, and CH spectroscopy.



Edge plasma hydrocarbon chemistry

Below T_e = 2 eV, methane break-up is dominated by charge exchange (CX) and dissociative recombination (DR) [2]. Below 1 eV, electron impact excitation of the CH A level rapidly drops to zero... But the DR process has enough exothermicity to excite this level!



CH electron excitation rate [3]

Origin of Species: CH

Dissociative recombination (**DR**)

- $e + CH_4^+ \rightarrow CH$ (*) $+ H_2 + H$
- $e + CH_3^+ \rightarrow CH$ (*) $+ H_2$
- $e + CH_2^+ \rightarrow CH$ (*) $+ H$

Excess energy of each is enough to excite CH A-X band (2.88 eV)!

The main questions:

- Do all DR channels produce photons?
- Which fraction of each DR channel produces photons?
- Can we verify the reaction rates by Janev and Reiter [2]?

Methane puffing experiments

Methane was injected in the plasma through a 0.6 mm hole, at a rate of 3 sccm. CH emission around 430 nm was measured with an absolutely calibrated CCD camera and compared to simulation. Total emission is quantified by $\Pi_{phot} = \frac{\text{photons}}{CH_4 \text{ molecule}}$

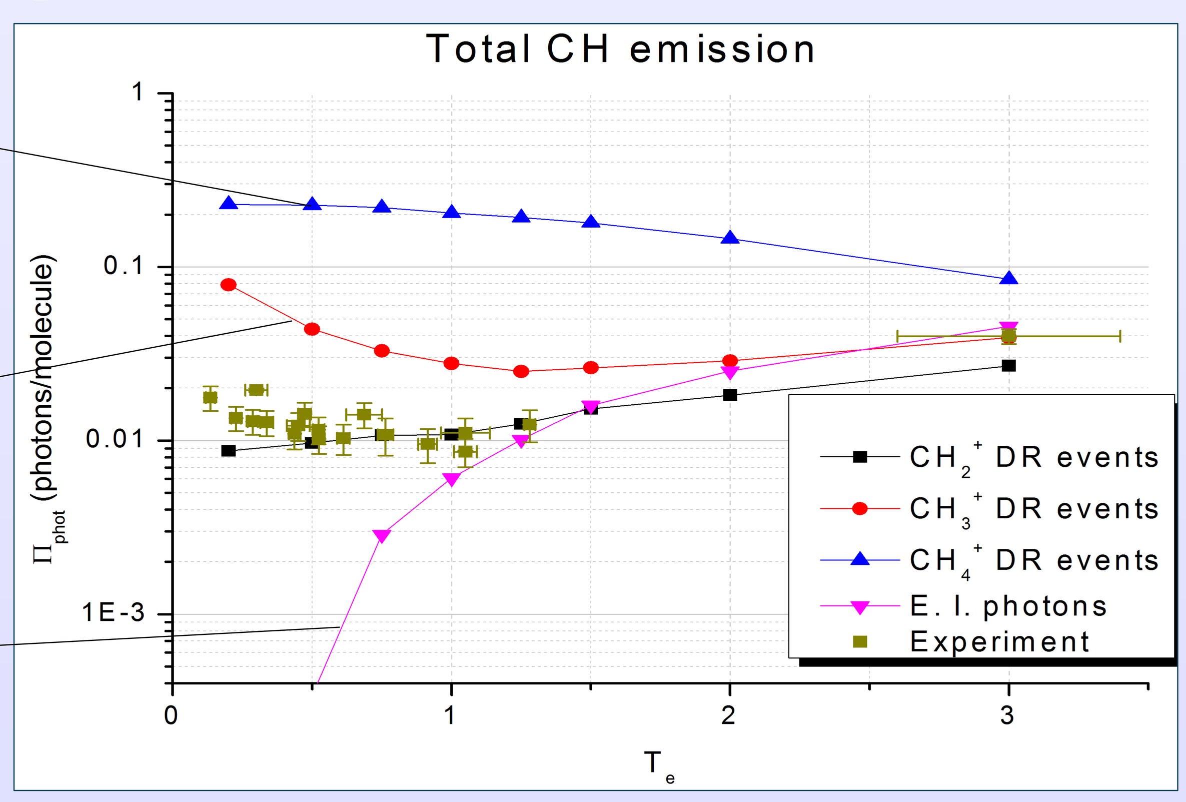
Puffing into the center of the beam

Methane puffing through a hole in a metallic target was performed in [4]. At the nozzle, plasma parameters were: T_e=1.28 eV, n_e=1.02*10^{20} m^{-3}. In the modeling, the number of occurences of each DR channel was registered. Energetically, dissociative recombination of CH_2^+ and CH_3^+ to CH are expected to be most favorable for excitation as the resulting H atom or H_2 molecule cannot easily absorb the excess energy.

Excessively many CH_4^+ DR events are registered

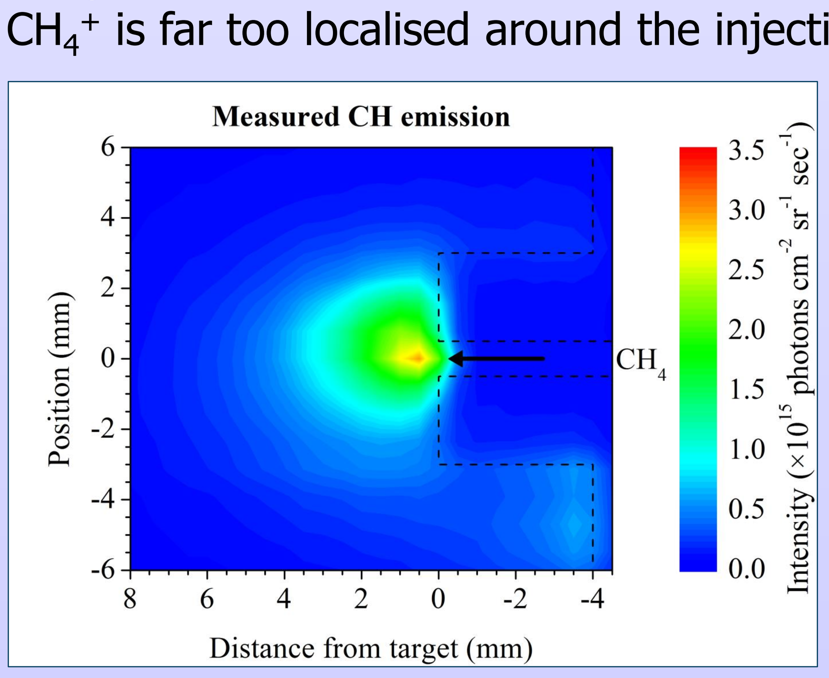
DR of CH_2^+ and CH_3^+ occurs enough to explain light at low T_e

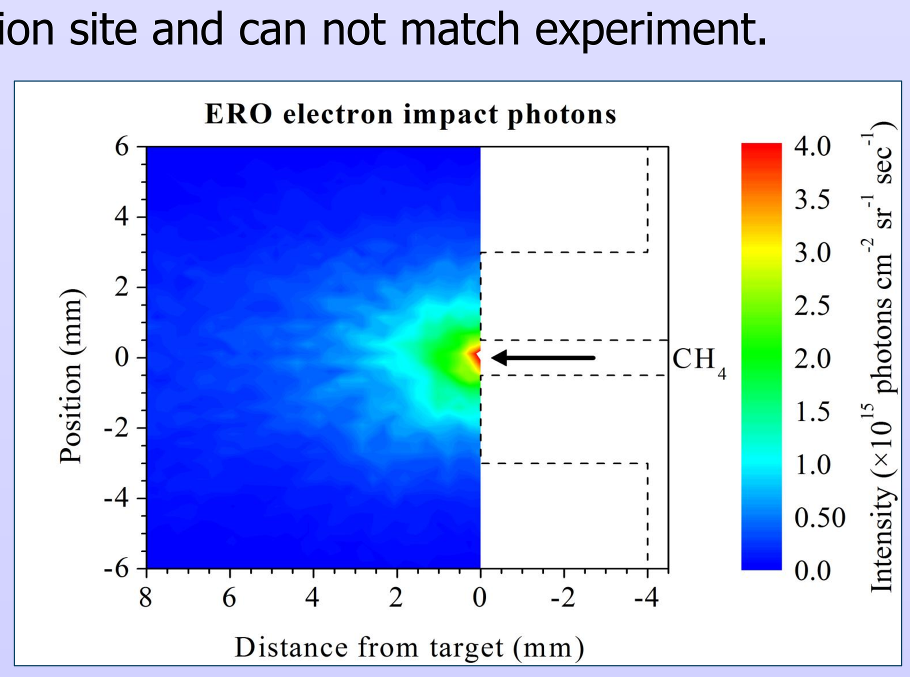
Light from electron excitation goes to zero at low T_e



Plume shapes

At T_e=1.25 eV, electron excitation produces plumes that match experiment well. DR of CH_4^+ is far too localised around the injection site and can not match experiment.





Revision of some reaction rates is recommended:

CH_4^+ dissociative recombination:

$e^- + CH_4^+ \rightarrow$ products (including CH?)

Currently, the given branching ratio is extrapolated from CH_3^+ and CH_5^+ measurements but not directly measured.

CH_x charge and particle exchange

$p^+ + CH_x \rightarrow CH_{(x-y)}^+ + H_{(y+1)}$

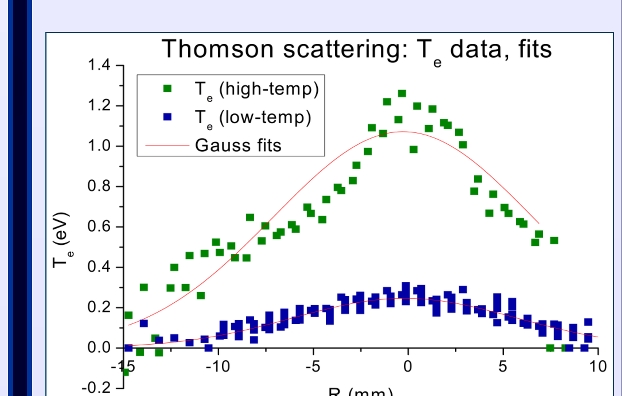
These cause destruction of CH, but are not directly measured at low impact energies [2].

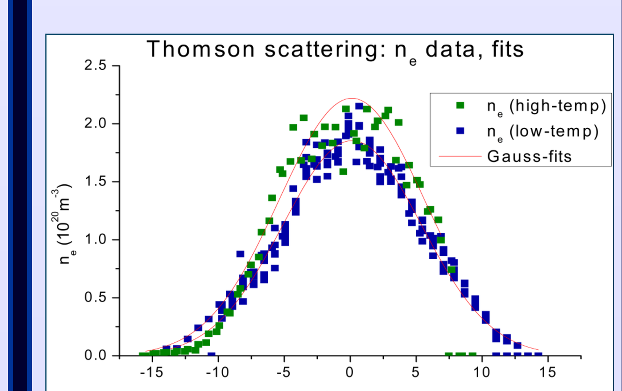
Puffing into the side of the beam

To separate methane dissociation and recycling at the target, methane was injected through a nozzle 17 mm outside the plasma center, 25 mm away from the target. The plasma flow velocity at the nozzle was taken from experiments under comparable conditions as 30% of the sound speed. Possible rotation of the plasma has been neglected.

Plasma conditions

measured by Thomson scattering at the nozzle location



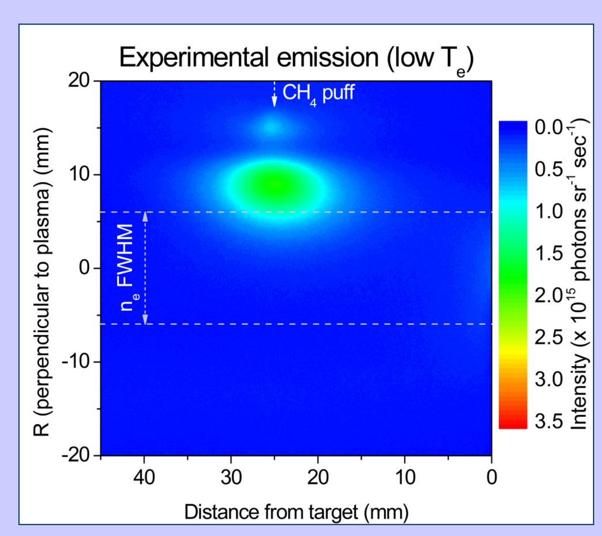


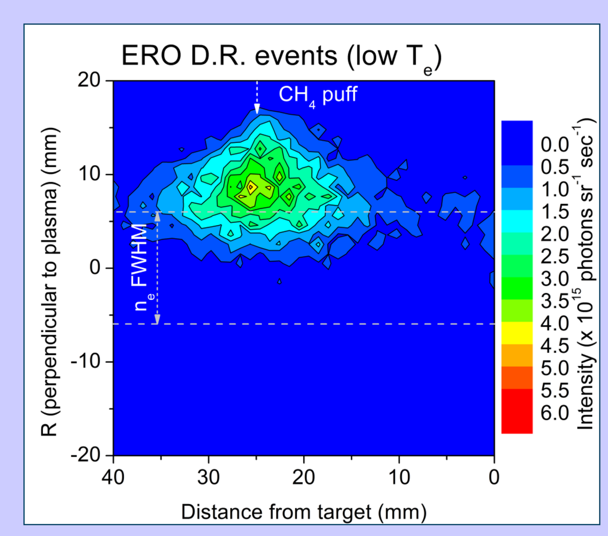
Low T_e case (~0.2 eV)

At these conditions, electron-impact excitation is negligible, so all CH band excitation must come from dissociative recombination.

Π_{phot}:
- DR of CH_4^+: 0.096
- DR of CH_3^+: 0.054
- DR of CH_2^+: 0.016
- **Experiment: 0.039**

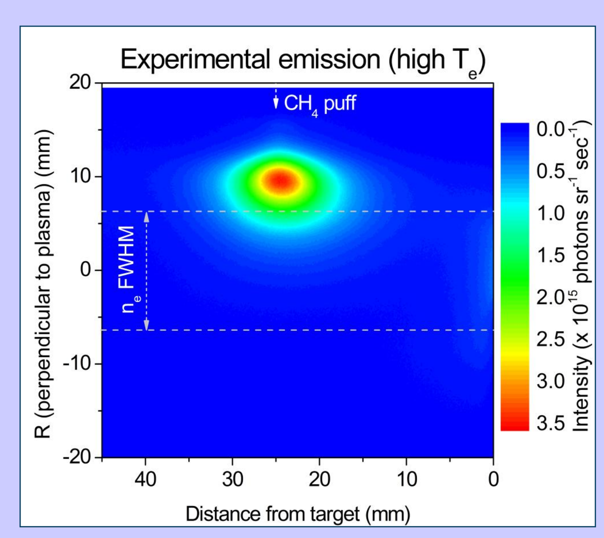
Plume characteristics are qualitatively reproduced by DR events; the energetically unfavourable CH_4^+ channel is NOT needed to account for all the observed photons.

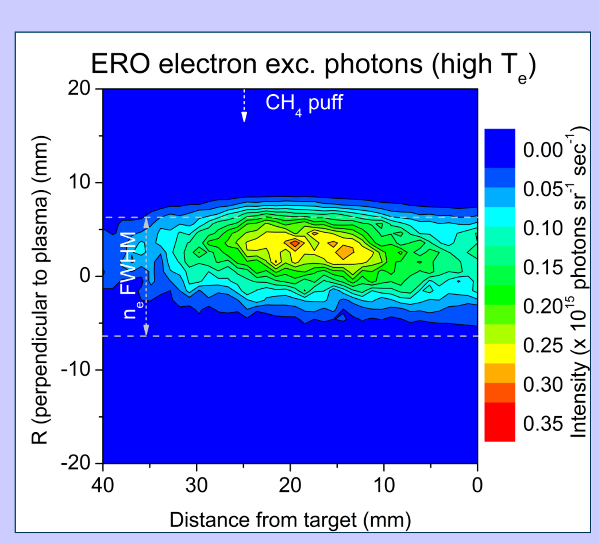


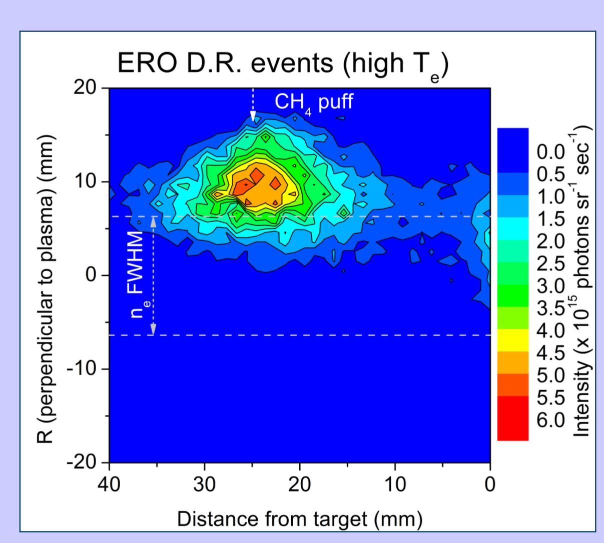


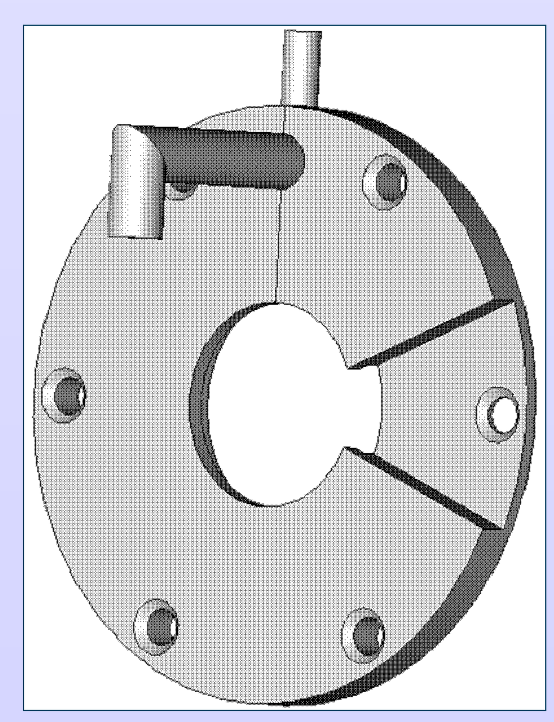
High T_e (~ 1.2 eV)

Π_{phot}:
- E.I excitation: 0.015
- DR of CH_4^+: 0.144
- DR of CH_3^+: 0.044
- DR of CH_2^+: 0.030
- **Experiment: 0.033**









Nozzle design

In both geometries, at high and low T_e, assuming CH excitation probabilities of 0 for DR of CH_4^+ and approximately 0.2 – 0.6 for DR of CH_2^+ and CH_3^+ fits experiments reasonably well.

Conclusions

- Experimental and modeled CH emission were compared in two conditions
- Energetically unfavourable CH_4^+ DR not needed to account for all photons
- Several reaction rates are recommended for revision

Outlook

- E-field and plasma flow from B2.5
- Inclusion of plasma rotation
- Further modeling: deposition/re-erosion

References

[1] A. Kirschner et al., Nuclear Fusion **40**, 5 (2000) 989-1001
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[3] R. Celiberto et al., PPCF **51** (2009) 085012
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