First quantification of volume recombination in W7-X using EMC3-Eirene

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ABSTRACT

As a potential for the creation of a so-called gaseous divertor [1], molecule-assisted recombination processes (MAR) have attracted considerable attention in both tokamaks and linear devices. In contrast, there has been a paucity of related studies in stellarators, especially in terms of modelling

Recently, a novel 'prediction-correction method' has been developed for EMC3-Eirene to treat MAR [2]. The extended version of the EMC3-Eirene code makes it possible, for the first time, to evaluate the role of volume recombination processes in helical devices.

This paper presents first simulation results of volume recombination in W7-X, including MAR and the electron-ion recombination (EIR) process.

MOLECULE ASSISTED RECOMBINATION (MAR)

MAR processes involve not only electrons and ions, but also molecules.

CX-MAR

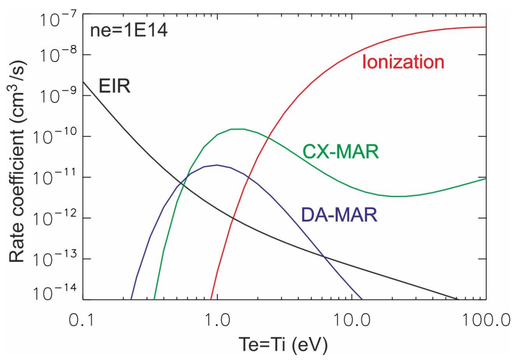
H2 (v) + H⁺→ H2⁺+ H *(charge-exchange)*
H2⁺+ e → H + H
H2⁺+ e → e + H⁺+ H
H2⁺+ e → 2e + 2H⁺

DA-MAR

H2 (v) + e → H + H⁻ *(diss. attach.)*
H⁻ + H⁺→ H + H
H⁻ + H⁺→ H + H⁺+ e
H− + e → H + 2e

Compact form of MAR

H2 (v) + e + H⁺→ 3H



THE EXTENDED EMC3-EIRENE MODEL

$$\nabla\cdot\left(nu_{\parallel}\boldsymbol{b}-D\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla n\right)=S_{\mathrm{ion}}+n^{0}R_{\mathrm{mar}}-n\left(R_{\mathrm{mar}}+R_{\mathrm{eir}}\right)$$

$$\nabla\cdot\left(m_{\mathrm{i}}nu_{\parallel}^{2}\boldsymbol{b}-\eta_{\parallel}\boldsymbol{b}\boldsymbol{b}\cdot\nabla u_{\parallel}-m_{\mathrm{i}}D\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla nu_{\parallel}\right)=-\boldsymbol{b}\cdot\nabla p+S_{m}$$
$$+m_{\mathrm{i}}n^{0}u_{\parallel}^{0}R_{\mathrm{mar}}-m_{\mathrm{i}}nu_{\parallel}\left(R_{\mathrm{mar}}+R_{\mathrm{eir}}\right)$$

$$\nabla\cdot\left(\frac{5}{2}nT_{\mathrm{e}}u_{\parallel}\boldsymbol{b}-\kappa_{\mathrm{e}}\boldsymbol{b}\boldsymbol{b}\cdot\nabla T_{\mathrm{e}}-\frac{5}{2}T_{\mathrm{e}}D\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla n-n\chi_{\mathrm{e}}\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla T_{\mathrm{e}}\right)$$
$$=-\kappa\left(T_{\mathrm{e}}-T_{\mathrm{i}}\right)+S_{\mathrm{ee}}+S_{\mathrm{imp}}+S_{\mathrm{eir}}$$

$$\nabla\cdot\left(\frac{5}{2}nT_{\mathrm{i}}u_{\parallel}\boldsymbol{b}-\kappa_{\mathrm{i}}\boldsymbol{b}\boldsymbol{b}\cdot\nabla T_{\mathrm{i}}-\frac{5}{2}T_{\mathrm{i}}D\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla n-n\chi_{\mathrm{i}}\boldsymbol{b}_{\perp}\boldsymbol{b}_{\perp}\cdot\nabla T_{\mathrm{i}}\right)$$
$$=+\kappa\left(T_{\mathrm{e}}-T_{\mathrm{i}}\right)+S_{\mathrm{ei}}-E_{\mathrm{i}}nR_{\mathrm{eir}}.$$

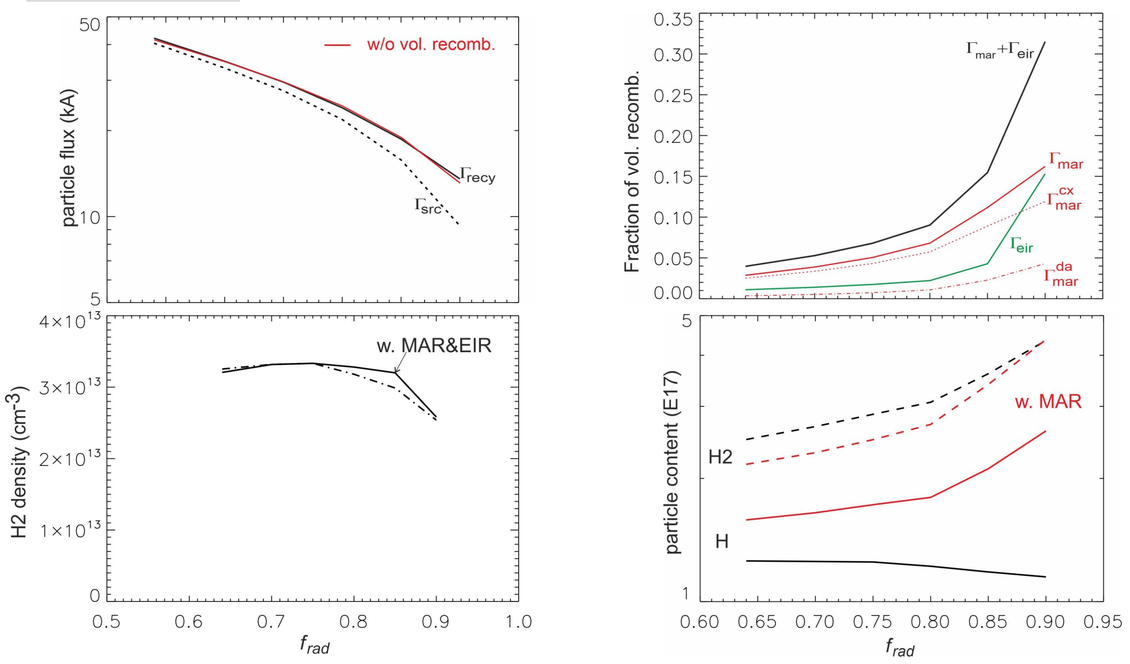
All newly introduced terms appear on the right-hand side of the equations and are indicated by the subscripts 'mar' or 'eir', respectively denoting the MAR and EIR processes.

ROLE OF VOLUME RECOMBINATION IN THE W7-X ISLAND DIVERTOR

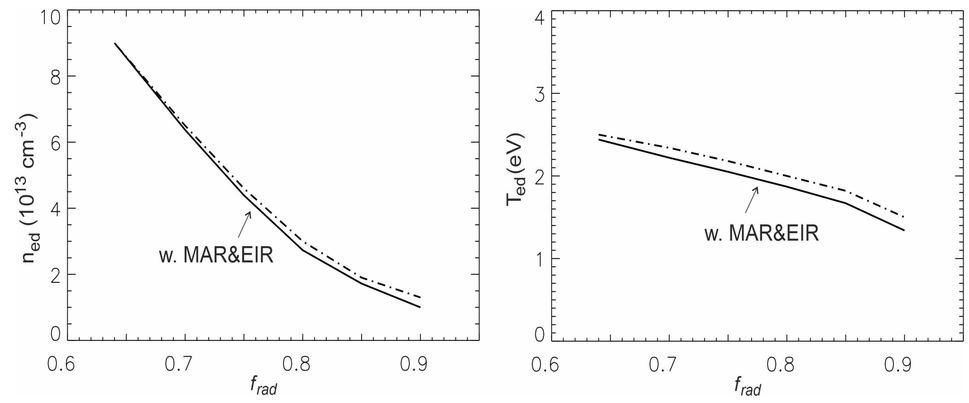
Recycling: $\Gamma_{recy}=\Gamma_{src}+\Gamma_{eir}+\Gamma_{mar}^{cx}+\Gamma_{mar}^{da}$

#20180814.25 P_{ECRH}=5.5 MW
D=0.5m²/s, χ=0.75m²/s

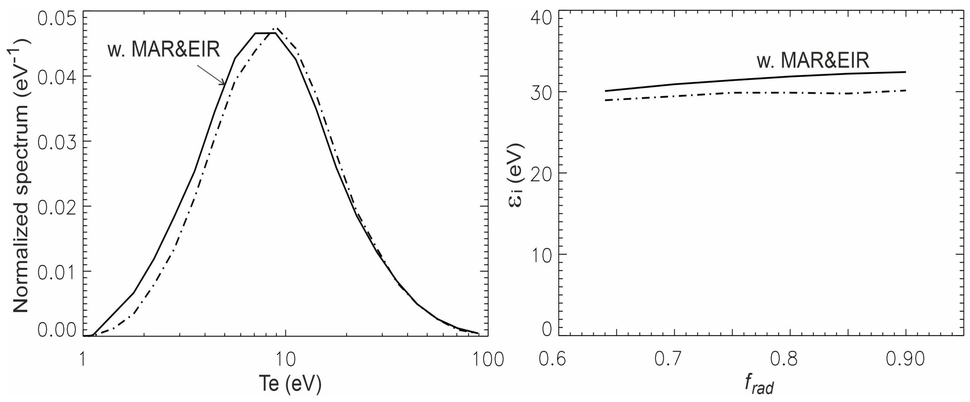
Main results



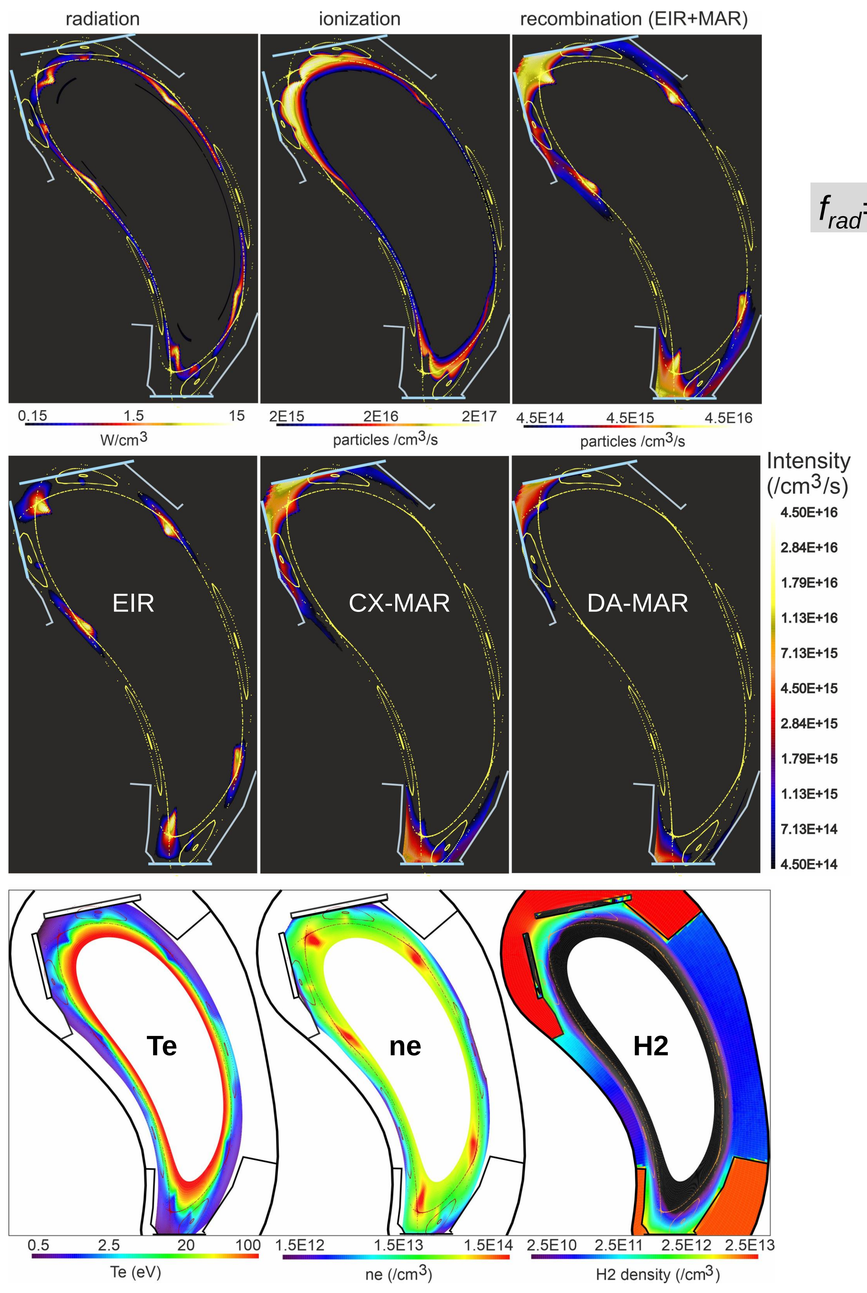
Effect of volume recombination on downstream ne & Te



Shift of ionization to lower Te increases the ionization cost.



Spatial correlation between ionization, radiation, recombination, and plasma parameters



f_{rad}=0.9

CONCLUSION

A new prediction-correction method has been developed to improve the numerical stability of the conventional scheme used in edge plasma transport modeling.

Now, the EMC3-Eirene code is capable of self-consistent treatment of volume recombination, including both MAR and EIR process.

First application results from W7-X show that both EIR and MAR increase with the radiation fraction f_{rad} with the total contribution remaining within approximately 30% of the total recycling neutral source even at f_{rad} = 0.9. There are no noteworthy effects of volume recombination on detachment performance regarding the power load on the target, the neutral pressure in the divertor chamber, or the distribution of impurity radiation. Nevertheless, volume recombination significantly changes the relative population of atoms and molecules in front of the targets, which may be generally important for boundary plasma spectroscopy in fusion devices.

(1) Janev R., et al. 1984 J. Nucl. Mater. 121 10–16
(2) Feng Y. et al. 2025 Nucl. Fusion 65 066008

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