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Implementation and Application of EMC3-EIRENE at ASDEX Upgrade

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Introduction

Due to the toroidal symmetry tokamak plasmas are usually simulated by 2D models. However, as soon as local limiters are introduced in the plasma edge, the problem becomes intrinsically 3D. In existing divertor tokamaks like ASDEX Upgrade (AUG) as well as in ITER discrete limiters are applied to protect wall elements and diagnostics. They can receive a significant amount of the total heating power, in particular during the start-up phase before the separatrix formation. Recently, the Edge Monte Carlo 3D - Eirene (EMC3-Eirene) code was used to model the edge plasma transport and the limiter power load in ITER [1]. So far, however, comparative studies validating the numerical results by experimental data from existing tokamaks are very rare. For this reason, the EMC3-EIRENE code is currently being implemented at ASDEX Upgrade. Here we will report on the code implementation at AUG together with several previous benchmarks and on the first results of its application for startup configurations bounded by several discrete limiters in ASDEX Upgrade.

1D Benchmarking

The Edge Monte Carlo 3D (EMC3) code solves the Braginskii equations on a three dimensional grid. A detailed description of the code can be found in [2]. In a first step the energy equation was solved in a geometry without vacuum vessel or limiters. The vertices of the grid are labeled by three indices, j, k and l. Grid points with the same j lie on the same magnetic surface, whereas grid points with the same l are situated on the same magnetic field line. We assume the density to be constant on a magnetic surface and linearly decaying in radial direction $n_{j,k,l} = n_j = n_0 - \alpha \cdot j$. As expected the 3D temperature field computed by EMC3 is then also constant on magnetic surfaces $T_{j,k,l} = T_j$ and so the problem is actually 1D. Since no heat sources or sinks are assumed the total heat flux passing through a magnetic surface

$$Q_j = \sum_{j,k} q_{\perp,j,k,l} \Delta A_{j,k,l} = -n_j \chi_\perp \left(T_{j+1} - T_j\right) g_j - \frac{5}{2} T_j D_\perp \left(n_{j+1} - n_j\right) g_j \qquad (1)$$

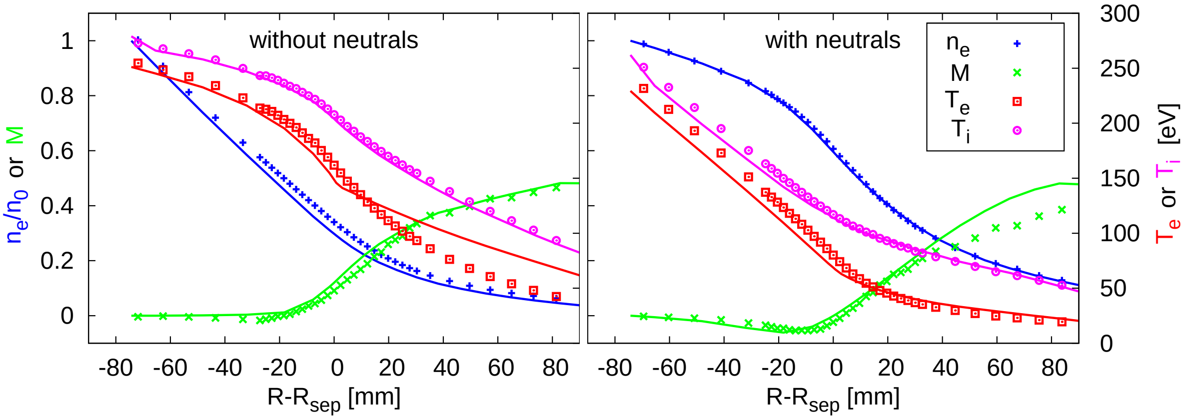

Figure 1: Toroidally symmetric limiter configuration simulated by EMC3-Eirene (data points) and by SOLPS 5.0 (solid lines) without (left) and with (right) neutrals. The n_e profiles are normalized to $n_0 = 2.0 \times 10^{19}$ m^{-3} assumed by both codes at the innermost flux surface ($\rho = 0.95$).

is a constant equal to the power flux Q_{core} through the innermost surface. The factors $g_j = \sum_{k,l} \Delta A_{j,k,l}/\Delta r_{j,k,l}$, where $\Delta r_{j,k,l}$ is the radial extension of a grid cell and $\Delta A_{j,k,l}$ its boundary surface pointing radially outward, depend only on the geometry of the magnetic surfaces. By resolving Eq. 1 with respect to T_{j+1} and assuming a given temperature T_0 at the innermost grid shell, the temperature profile can be reconstructed iteratively. The results obtained with EMC3-Eirene could be reproduced very well by this 1D calculation.

2D Benchmarking with SOLPS

In a second step the AUG plasma pulse 14918 at 7.1 s, where the plasma is limited by the toroidally symmetric inner heat shield is simulated. This 2D situation was already modeled by the SOLPS 5.0 code package by Geier et al. [4]. SOLPS is based on a more comprehensive physics model and includes - in contrast to EMC3-Eirene - flux limiters [3]. Rather than performing a numerical benchmarking of the codes, here we are interested in profiles of the plasma parameters running the two codes as they are. Fig. 2 shows the grids used by SOLPS (blue) and by EMC3-Eirene (red). Along the thick lines in the lower part of the grid n_e, T_e, T_i and M (Mach number) are compared. These profiles are shown in Fig. 1. The left plot shows runs without neutrals, while in the right figure neutral particles were simulated by Eirene. Both codes assume particle and heat diffusion coefficients $D_\perp = 1$ m^2/s and $\chi_\perp = 3$ m^2/s, a core heating power of 3 MW and $n_0 = 2 \times 10^{19}$ m^{-3}. In general a good agreement

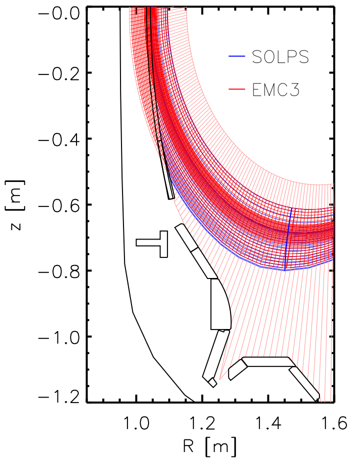

Figure 2: AUG vacuum vessel (black), SOLPS grid (blue) and EMC3 grid (red)

between the profiles far from the limiter is found, which shows that the two codes - based on completely different numerical methods - find very similar solutions for the particle, momentum and energy transport in the bulk plasma. However, in the immediate vicinity of the limiter surface SOLPS predicts supersonic streaming velocities, while EMC3 forces M=1 as a boundary condition. Since a transition to supersonic streaming velocities has the same effect as a target plate located further upstream, the EMC3 profiles are shifted by about 5 mm radially outward. In order to remove the same amount of heat at the limiter surface the sheath heat transmission factors had to be increased artificially by a factor of about 1.5. A more refined physical benchmarking eliminating this problem is planed as one of the next steps.

3D Simulation of the AUG startup phase

Finally the fully three dimensional situation was addressed by simulating the startup phase of AUG plasma pulse 23367 (at 0.4 s) with EMC3-Eirene. Fig. 3 shows a poloidal projection of the grid, the vessel structures and the limiters. While the grid for the neutral particles (Eirene) covers the region from $\rho = 0.9$ up to the wall (light red), the plasma is simulated only in the region from $\rho = 0.95 \ldots 1.04$ (dark red). As before the diffusion coefficients were $D_\perp = 1/3\chi_\perp = 1\ \mathrm{m}^2/\mathrm{s}$. At $t = 0.4$ s the core was heated by 600 kW ECRH and by 1.1 MW ohmic power. 1.1 MW of this power is lost again by radiation and about 100 kW are absorbed by the core increasing its stored energy, and so we assume a power flux into the computational domain of 500 kW. n_0 was set to $9.6 \times 10^{18}\ \mathrm{m}^{-3}$ at the innermost surface to match the measured value. Fig. 4 shows simulated profiles for n_e and T_e compared to the ones measured by the Li-beam [5] and the ECE [6] diagnostics. The solid curves represent n_e and T_e along the line where the diagnostics actually measure in 3D space. In the case of n_e the simulated flux surface averaged profile is also indicated by the dashed curve. It is clearly seen that this curve matches the measured profile far worse, which shows that a 3D simulation is actually required for such a

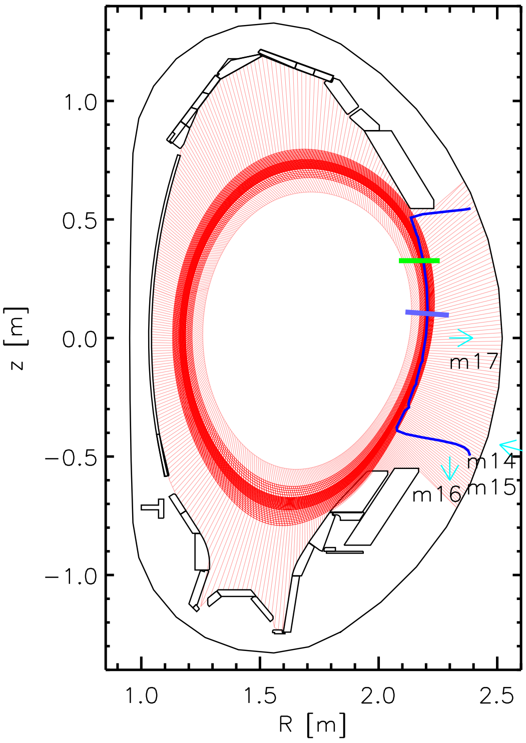

Figure 3: AUG vacuum vessel (black), poloidal limiter (blue), computational grid for neutrals (light red) and for plasma (dark red), manometers (cyan), Li-beam (green) and ECE (light blue) diagnostics.

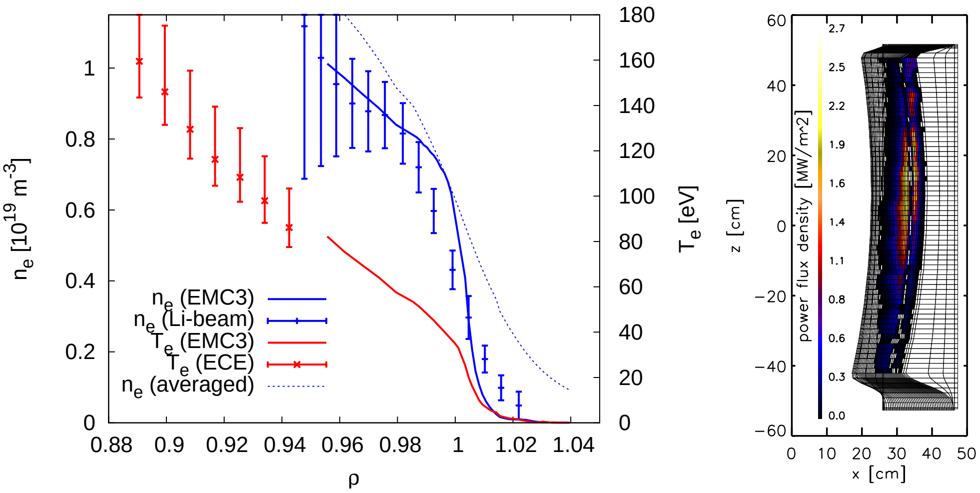

Figure 4: Left: profiles simulated by EMC3-Eirene (solid lines) compared to the Li-beam and the electron cyclotron emission (ECE) diagnostics. Right: computed power deposition pattern.

code-experiment comparison. Although no values for T_e were available for positions $\rho > 0.94$ the temperature profile also seems to be consistent with the ECE diagnostics assuming that the T_e profile can be extrapolated linearly. The right part of the figure shows an energy deposition pattern computed by EMC3-Eirene. Similar pattern have been observed by infrared cameras.

Finally the the simulated neutral particle densities were compared to those measured by several ionizing manometers (m 1…m 17) installed in AUG [7]. The measured values are of the right order of magnitude but differ by factors up to more than 5. In view of the fact that the manometers are close to the detection limit and that we assumed a highly simplified geometry of the remotely located wall structures we cannot expect a better agreement so far. A more refined analysis with a more realistic geometry and a finer grid for the neutrals is planned for the near future.

In summary we can say that EMC3 was implemented at AUG and benchmarked with respect to SOLPS calculations. A limiter configuration was simulated successfully under realistic physical assumptions. The simulated density and temperature profiles agreed well with the measured ones by the Li-beam and ECE diagnostics.

The next important step will be to model a divertor configuration.

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