Coupled nonlinear MHD-particle simulations for ITER with the JOREK+particle-tracking code

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Abstract

The JOREK [1] MHD code is coupled to a newly developed particle tracer to simulate heavy impurity radiation and other effects. Particle-fluid sputtering, needed as boundary condition, as well as neoclassical transport is implemented and verified. We show that W sputtering, transport and radiation need to be coupled with MHD for accurate simulation.

Introduction

For stable tokamak operation the accumulation of heavy impurities in the plasma core must be prevented. Disruptions and radiative collapse could be triggered when the fraction of tungsten (W) in the core plasma reaches 10^{-4}. The core W density depends on production at the divertor, transport into the core plasma and flushing by ELMs. The production of W has a large contribution [2] during ELMs due to the enhanced heat and particle flux. When the W density is too large the influence on the background (MHD) fluid is non-negligible. Predicting the interplay of these effects calls for a simulation capability which couples the particle modelling for heavy impurities (and other appropriate particles like neutrals or fast ions), with MHD.

We therefore present a two-way coupling between the MHD code JOREK [1] and its kinetic particle extension. It combines a state-of-the-art MHD solver with a kinetic particle-in-cell model based on the Boris pusher [3, 4]. A model for ionization, recombination and radiation is implemented, based on OPEN-ADAS data. Collisional transport is implemented with the Binary Collision Model [5, 6]. Sputtering yields are calculated from the Eckstein formulas [7, 8]. A projection operator is described to convert the particle distribution into continuous fields suitable for a coupling to the MHD equations. This model is

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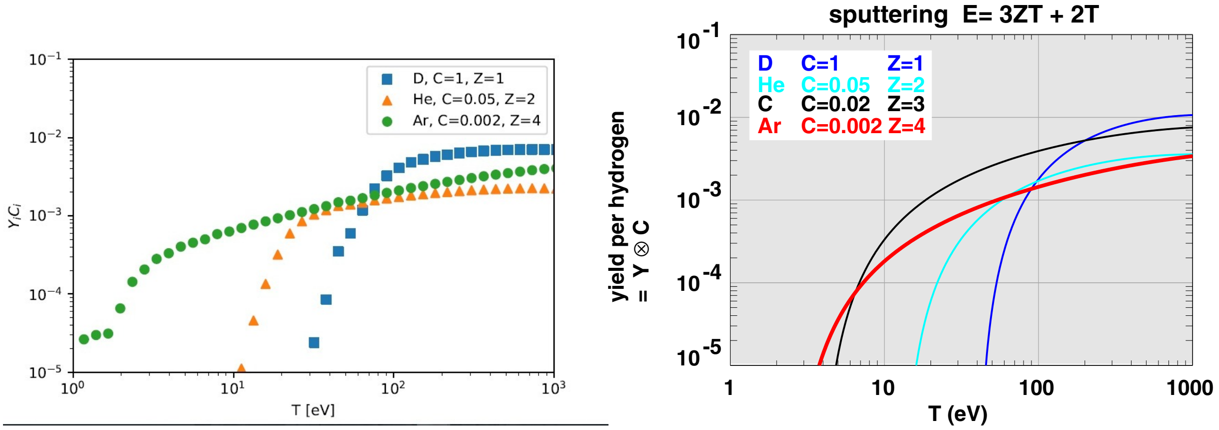


Figure 1: Comparison of the sputtering yields versus temperature for this implementation (left) and the yield at single energy of Kallenbach (adapted from [9].)

applied to an ASDEX Upgrade-like Inter-ELM period to evaluate the sputtering yields, W production and transport.

Physical sputtering sources

The main source for W impurities in most machines is (self-)sputtering at the divertor. We distinguish between sputtering from incoming fluid (from JOREK) and incoming impurity particles. The impurity particles sputter directly according to the Eckstein formulas [8]. For the sputtering from the incoming fluid a set of 2D linear edge elements is constructed around the JOREK domain. On these elements the sputtering yield, as calculated from the integral over the local incoming energy distribution function (IEDF) is projected. This yield is normalized to produce a probability density function (PDF). A set of new simulation particles is sampled from the PDF. We calculate the energy of the sputtered particle from the IEDF and the local sputter yields. A comparison of the sputter yields calculated with our method and Kallenbach [9] is shown in figure 1. This model has been applied to a JET-like ELM with results shown in figure 2.

Neoclassical transport with the Binary Collision Model (BCM)

To calculate the transport of W in the SOL correctly, neoclassical transport must be taken into account. To do that we parametrize a shifted distorted Maxwellian velocity distribution with the MHD variables T and n_i (and gradients, plus $v_{\|}$). From this distribution ions are sampled for the tracer particles to collide with. This reproduces neoclassical transport for heavy ions [5, 6].

Projecting particle moments for feedback to MHD

Once the particle trajectories can be calculated we need to have a way to incorporate feedback from the particles into the MHD equations. This is done with a projection op-

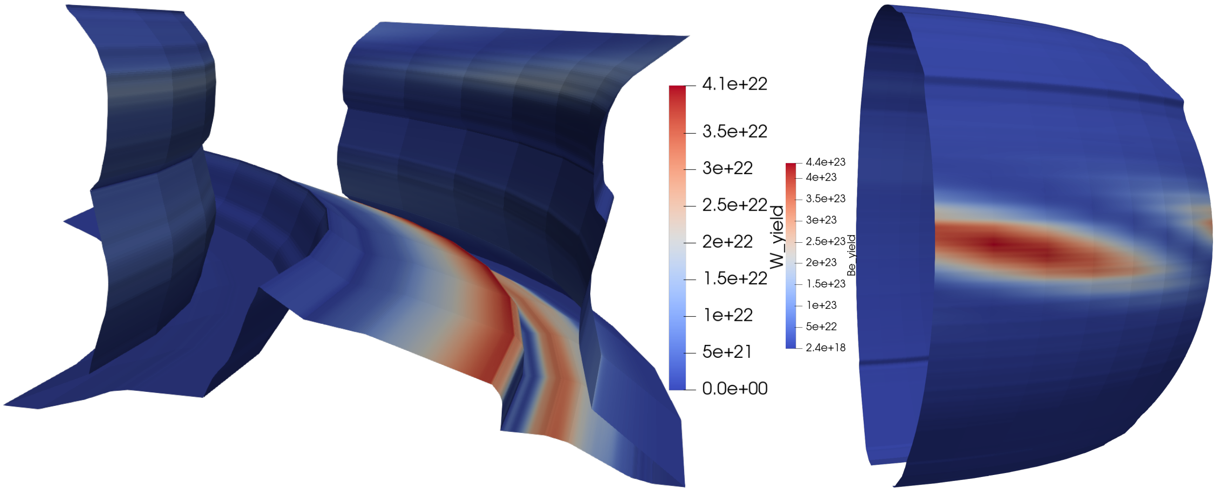


Figure 2: Sputtering in the divertor region and on the wall from an artificially boosted ELM filament in JET (S. Pamela) with high resistivity.

eration onto the JOREK finite elements. We try to find the closest approximation p to a moment X_i of set of particles with weights w_i.

$$\int_V p(s,t,\phi)v_m + \lambda v_m \nabla^2 p(s,t,\phi)dV = \int_V \sum_i S(\mathbf{x}-\mathbf{x}_i)X_i w_i v_m dV,$$

where v_m is a test function (chosen from basis of p), and p is described in the JOREK elements as

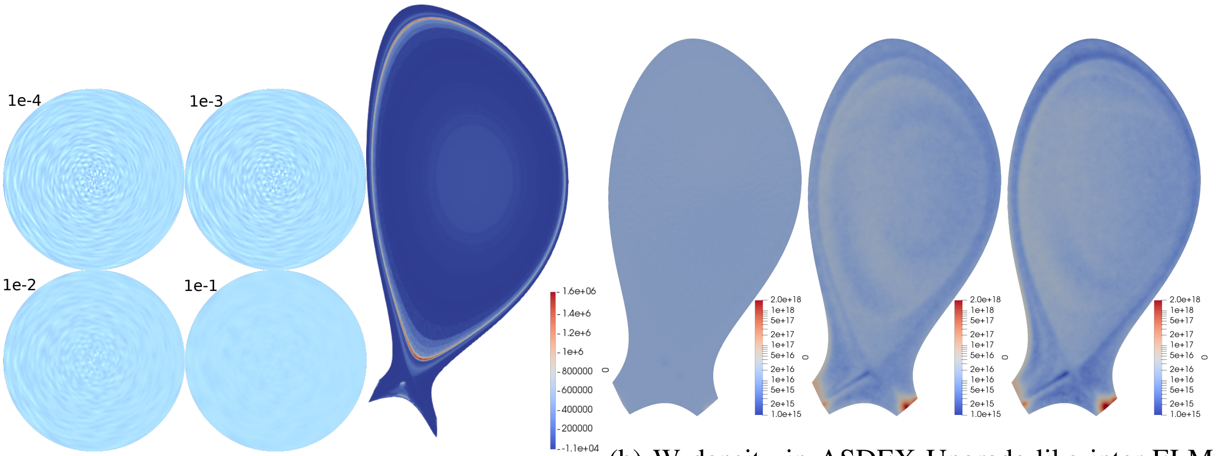
$$p(s,t,\phi) = \sum_{k=1}^{N_{vert}} \sum_{j=1}^{N_{ord}} \sum_{l=1}^{N_{tor}} \texttt{nodes(i)\%values(l,j,}\nu\texttt{)} \cdot \texttt{H(k,j;s,t)}$$

$$\cdot\, \texttt{element\%size(k,j)} \cdot \texttt{Z}_{\texttt{l}}(\phi),$$

Useful quantities X to project are the number density, the radiated power per atom L_z, the ionisation source, the recombination source, the energy sources and sinks related to ionisation, recombination and charge exchange and the parallel momentum. Figure 3a shows the effect of the smoothing factor λ, the projection of number density with a sputtering source and the projection of power radiated by a uniform distribution of W in the ITER 15MA H-mode reference equilibrium [10].

Application to ASDEX Upgrade-like H-mode equilibrium

We apply this model to the inter-ELM phase of discharge #33616 [11]. Here we follow $4 \cdot 10^6$ simulation particles, with an initial density of $3 \cdot 10^{15}$ m^{-3}. Sputtering at the divertor and neoclassical transport up the SOL is included. The initialisation with a local Maxwellian is not a steady-state solution for the W density including $E \times B$-drifts. This equilibriates in milliseconds. In the same time a high divertor W density can be seen in figure 3b, indicating the need for coupling local plasma parameters with W radiation and ionization to set up an equilibrium including sputtering yield and incoming heat fluxes.



(a) Effect of smoothing on projection (left) and W radiated power density in W/m^3 (right) in ITER.

(b) W density in ASDEX Upgrade-like inter-ELM phase at 0, 1 and 2 ms after start of simulation.

Figure 3: Projection smoothing and examples (a) and projection of W density in ASDEX Upgrade (b).

Current and future applications of the model

Currently we are applying this model to W impurity transport in steady state and during ELMs in ASDEX Upgrade and ITER reference scenarios. It is planned to investigate also transport in QH-mode and RMP equilibria. We will investigate the impact W radiation has on MHD to look at radiative collapse of plasmas. Tracing NBI ions during an ELM and comparing the results with FILD measurements is an ongoing investigation. Additionally it is planned to investigate the impact of fast ions on MHD through a pressure coupling scheme. A project is underway to improve the edge modelling in JOREK by adding kinetic neutrals as particles.

References

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