Monte Carlo ion cyclotron heating and fast ion loss detector simulations in ASDEX Upgrade

S. Sipilä[1], J. Varje[1], T. Johnson[2], T. Kurki-Suonio[1], J. Galdón Quiroga[3], J. González Martín[4], the ASDEX Upgrade Team[5] and the EUROfusion MST1 Team[6]

[1] *Department of Applied Physics, Aalto University, FI-00076 AALTO, Finland*
[2] *Fusion Plasma Physics, EES, KTH, Stockholm, Sweden*
[3] *Dept. of Atomic, Molecular and Nuclear Physics, University of Seville, 41012 Seville, Spain*
[4] *Dept. of Mechanical Engineering and Manufacturing, Univ. of Seville, 41012 Seville, Spain*
[5] *Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, 85748 Garching, Germany*
[6] *See the author list of H. Meyer et al., Nuclear Fusion 57 (2017) 102014*

Introduction. Proposed radiofrequency (RF) heating and current drive schemes with tens of megawatts of absorbed power are a potential source of high local wall loads in large-scale fusion devices due to escaping RF-heated ions. The ASCOT-RFOF code, consisting of the orbit-following Monte Carlo code ASCOT [1] interfaced with the radiofrequency heating Monte Carlo code library RFOF [2], makes it possible to study RF-heated ion populations taking into account the machine-specific 3D magnetic background and wall configuration. ASCOT-RFOF's ability to simulate the fast ion loss detector (FILD) signal makes it a useful tool for, e.g., optimizing the position of the detectors or understanding the transport processes involved in measured FILD signals. In the present work, ASCOT-RFOF based on ASCOT's current production version 4 is applied to fundamental mode ion cyclotron heating of hydrogen in the well-diagnosed ASDEX Upgrade discharge #33147 at time $t \approx 1$s to validate the model. In the interval $t \approx 1$s…1.1s, the actual FILD signal was observed to split into two distinct gyroradius ranges, posing an interesting challenge for future simulations.

Ion cyclotron heating simulation. First, a hot hydrogen tail distribution corresponding to the IC resonance location and absorbed power in AUG discharge #33147 at $t \approx 1.0$s was established using ASCOT-RFOF. An ensemble of 500.000 bulk hydrogen markers was created at local Maxwellian energies, random pitch $\xi = v_{||}/v$ and random (R, ϕ, z) location. The initial hydrogen density and temperature in the IC heating simulation were assumed to represent an isotropic Maxwellian hydrogen population at deuterium temperature and 3% of total ion density, maintaining quasineutrality by reducing the deuterium main species density accordingly. Coulomb collisions with the Maxwellian background plasma were modelled. The density and temperature profiles of the plasma, exported from AUG database, are shown in Figure 1. The RFOF input parameters were selected to model just one antenna with frequency $f = 36.5$MHz and two toroidal modes ($n_\phi = -13$ and $+13$, with $k_\perp = 40$) to reduce the CPU load of calculating the wave field and energy transfer at resonance. The selected frequency matched that used in discharge #33147, placing the resonance layer for fundamental mode IC heating of hydrogen at $R \cong 1.75$m. The power absorbed by the hydrogen population was assumed to be 3.2MW (90% of the total IC power used at $t \approx 1.0$s).

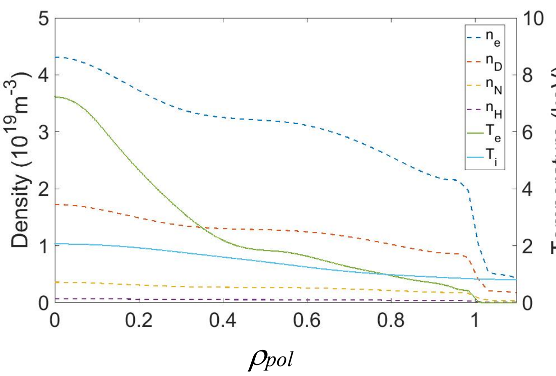

Figure 1. The background plasma density and temperature profiles used in the IC heating simulation vs. ρ_{pol}.

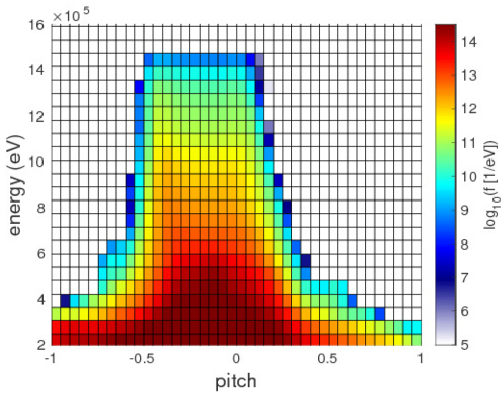

Figure 2. IC-heated hot hydrogen tail in (ξ,E) space, integrated over volume and divided by ξ and E slot size.

The resulting hot hydrogen tail distribution (at $E > 200$keV) arising from a 100ms heating simulation, collected in 4D space (R,z,ξ,E), is shown in Figure 2 in pitch and energy space (ξ,E). To avoid a thinning number of markers absorbing more and more of the given IC power, lost markers were replaced by new ones to keep the population constant during the simulation. The simulation took about 20 hours on EUROfusion Marconi with 2208 cores.

FILD signal simulation. The heating simulation, starting from a Maxwellian hydrogen population, models the whole hydrogen distribution from bulk energies to the MeV range. The Larmor radii measured by FILD1 in ASDEX Upgrade discharge #33147 at $t \approx 1.0$s, however, indicate ion energies in excess of 150keV. In that energy range, the statistics of the simulated FILD signal from the heating simulation will be poor in relation to the required CPU time, as the great majority of markers will spend most of their time well below the energy range that is of interest.

In order to improve the statistics and save CPU time, ASCOT-RFOF was fitted with a distribution-sampling marker source module that samples a given 4D (R,z,ξ,E) distribution. The distribution created in the IC heating simulation was used as input, and the sampling was limited to energies above 200keV. 500.000 hot ion markers were followed until they either hit the wall or slowed down below 100keV by Coulomb collisions with the background plasma species. As the time scale of the hot ion losses can be assumed to be short compared to that of significant IC heating, the IC interaction was not present in the FILD signal simulation. The simulation took about 1.5 hours on EUROfusion Marconi with 2208 cores.

The FILD present in ASDEX Upgrade discharge #33147, as seen by ASCOT, is shown in Figure 3 along with the wall load distribution recorded in the FILD signal simulation. The aperture of the detector was not modelled, as an excessive amount of computation time would then be required for satisfactory signal statistics. Instead, the signal was recorded in the same manner as the rest of the wall load, recording marker hits with their weight factor, energy and time t for each individual triangular element of the wall and FILD. The triangles of the FILD were postprocessed separately to yield an unrefined signal which was then further postprocessed by FILDSIM to take into account the instrument response of the detector. For a realistic wall load distribution, ASCOT switched from guiding center formalism to following full gyro orbits when markers came within one gyroradius of the wall.

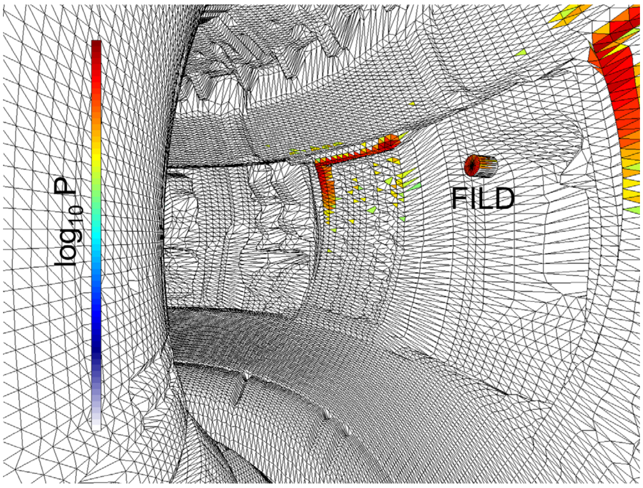

Figure 3. The simulated FILD as a part of the 3D AUG wall structure and the qualitative wall load distribution from the escaping hot hydrogen ions.

The simulated FILD1 signal from the hot hydrogen tail is shown in Figure 4 with a comparison to the measured signal from FILD1 of ASDEX Upgrade discharge #33147 at t = 1.031s and 1.082s. The signals include the effect of the instrument response. The measured signal at t = 1.031s and the simulated signal are in reasonable qualitative agreement.

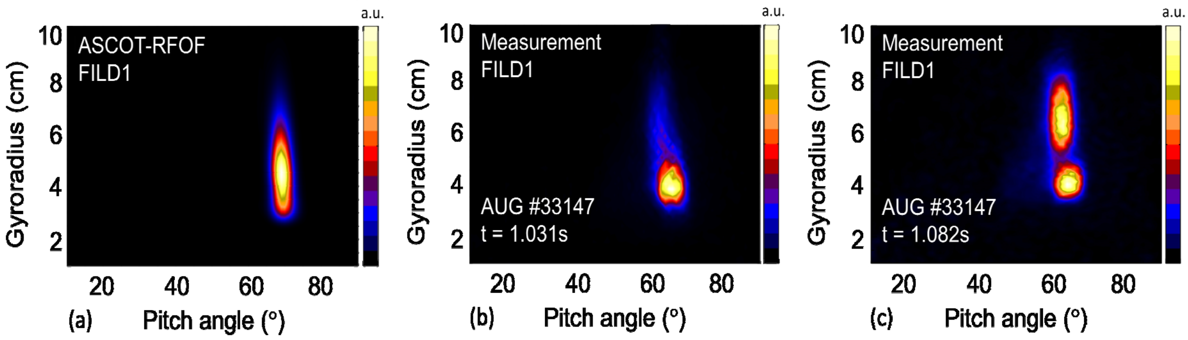

Figure 4. (a): FILD1 signal simulated by ASCOT-RFOF, postprocessed with FILDSIM to include the instrument response. (b) and (c): measured FILD1 signal in ASDEX Upgrade discharge #33147 at t = 1.031s and 1.082s, respectively. The pitch angle is 180°–acos($v_{||}/v$).

Summary and future work. ASCOT-RFOF has been demonstrated to simulate the IC-heated hot tail distribution in the realistic, machine-specific geometry of ASDEX Upgrade. The resulting 4D hot tail distribution has been used as a hot ion marker source for a simulation of the FILD signal in the well-diagnosed ASDEX Upgrade discharge #33147 at $t \approx$ 1.0s, yielding a reasonable qualitative agreement with the measured FILD signal.

Future work involves making use of ASCOT's capability to model the effects of several MHD modes simultaneously. The FILD signal simulations will be extended to include the effects of TAE and NTM modes to study the proposed beat effect mechanism behind the observed splitting of the FILD signal (see Fig. 4c) in ASDEX Upgrade discharge #33147 [3]. As ITER will have a total of 20MW of ion cyclotron heating power, one of ASCOT-RFOF's key applications in the future will be modelling the wall loads arising from IC-heated ions.

Acknowledgments. The simulations were carried out using the Marconi-Fusion supercomputer at CINECA, Bologna, Italy. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] E. Hirvijoki et al., Computer Physics Communications 185 (2014) 1310.
[2] T. Johnson et al., AIP Conference Proceedings 1406 (2011) 373.
[3] M. García-Muñoz and S. Sharapov, MST1 AUG 1.7-2 Meeting, Seville, Spain, 28 July 2016.