Anomalous fast ion redistribution in burning plasma experiments

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Abstract. The numerical simulations of the neutral beam ion turbulent transport in three tokamak experiments are presented. The analysis is carried out with an updated version of the VENUS code which now includes a microturbulent transport term estimated with the GENE code. It is shown that a small beam ion redistribution characterizes ITER. On the other hand, moderate to large fast ion transport is present in DEMO and TCV. Two quantities regulate the importance of small scale turbulence over the fast ion motion. Smaller transport is expected for large of E_{nbi}/T_e. Larger redistribution is expected for small collisionality which results in longer beam slowing down times.

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1. Introduction

Microturbulent fields in tokamaks can significantly transport fast ions in tokamaks, thus degrading the beneficial heating provided by these particles. Several theoretical investigations [1, 2] and experimental analyses [3, 4, 5, 6] were recently carried out on this topic. It is generally observed that fast ions in tokamaks are more strongly transported if their energy E_{fast} and the background temperature T_e are comparable, i.e. $E_{\mathrm{fast}}/T_e < 10$. The reason for such observations is the presence of resonances at lower energies [7] and decreasing gyroaveraging effects [2]. Furthermore, we demonstrate in this work that increasing plasma temperature also lowers plasma collisionality and results in longer slowing down times τ_{sd}. As fast ions take longer to thermalize, they interact with turbulence on longer time scales and their anomalous diffusion increases.

2. Predicting the fast ion transport from gyrokinetic simulations

To estimate the fast ion transport we perform simulations with the local version of the gyrokinetic code GENE [8, 9]. The analytical formalism in [10] is then employed to extract the fast ion diffusivity as a function of the particle energy and pitch

$$D_v\left(\mathbf{v}\right) = -\frac{\delta f\left(\mathbf{v}\right)\delta u\left(\mathbf{v}\right)}{\nabla_r f_0\left(\mathbf{v}\right)}. \qquad (1)$$

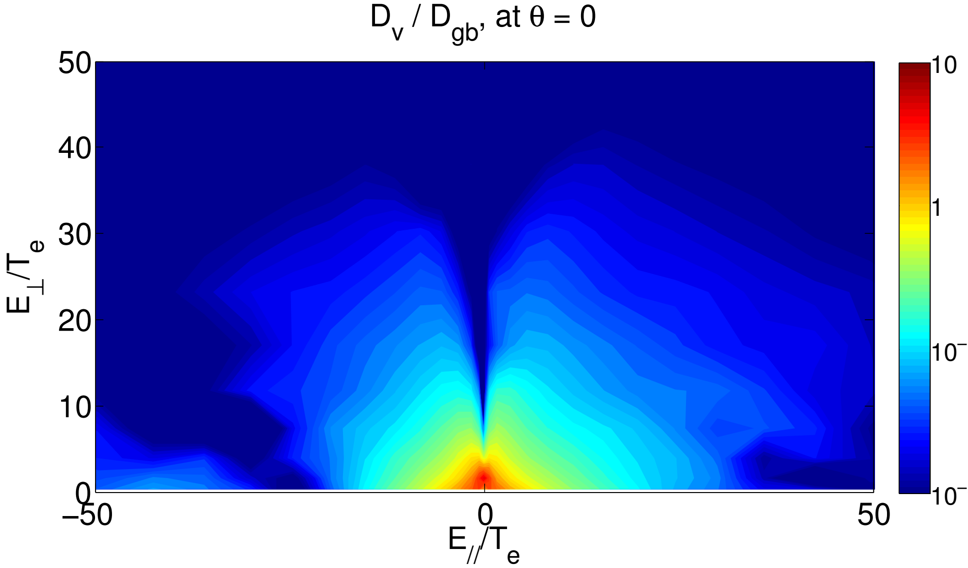

Figure 1: Electrostatic diffusivity as calculated by the GENE code for a deuterium population in the ITER steady state scenario. Negative values of the parallel energy correspond to counter-passing particles.

Here, δf represents perturbations in the equilibrium distribution function f_0. The perturbed drift δu is defined as

$$\delta u = -\left(\frac{\boldsymbol{\nabla}\delta\bar{\Phi}\times\mathbf{B}}{B^2} + v_{\parallel}\frac{\boldsymbol{\nabla}\delta\bar{A}_{\parallel}\times\mathbf{B}}{B^2}\right)\cdot\hat{\mathbf{e}}_r \tag{2}$$

Magnetic perturbations [2] are retained in this work, although they are negligible for the cases studied here. The subscript "r" in (1) indicates a radial projection.

We first study the ITER steady state scenario and we perform nonlinear simulations with the parameters of [11]. The chosen grid size is $(n_x, n_y, n_z) = (192, 64, 48)$ and $(n_{v_\parallel}, n_\mu) = (64, 32)$. In the GENE code x is the radial variable, while z and y are the field-aligned and the binormal coordinate, respectively). The box size in real space is $(L_x, L_y) = (125, 80)\rho_s$, and one poloidal turn in z. The extent of the velocity space domain is $(L_{v_\parallel}, L_\mu) = (3v_{th_j}, 9\,T_j)$ for the j-th species. The background species are characterized by similar temperatures ($T_i = 0.8\,T_e$), flat density profiles and $\Omega_T = 3.5$. We use the nominal value of $\beta_e = 1.5\%$. The background turbulence is generated by a mixture of ITG and TEM modes. Results of figure 1 demonstrate that the particle diffusivity strongly decreases with energy. Alpha particles are characterized by $E_{\mathrm{fast}}/T_e > 200$ and their anomalous diffusivity is therefore negligible, as already observed in a recent work [12]. For neutral beam ions some effects might be present as $E_{\mathrm{nbi}}/T_e \simeq 35$. To assess potential redistribution of the neutral beam injection in ITER the single particle slowing down must be considered together with anomalous transport. An updated version of the VENUS code is employed for this purpose.

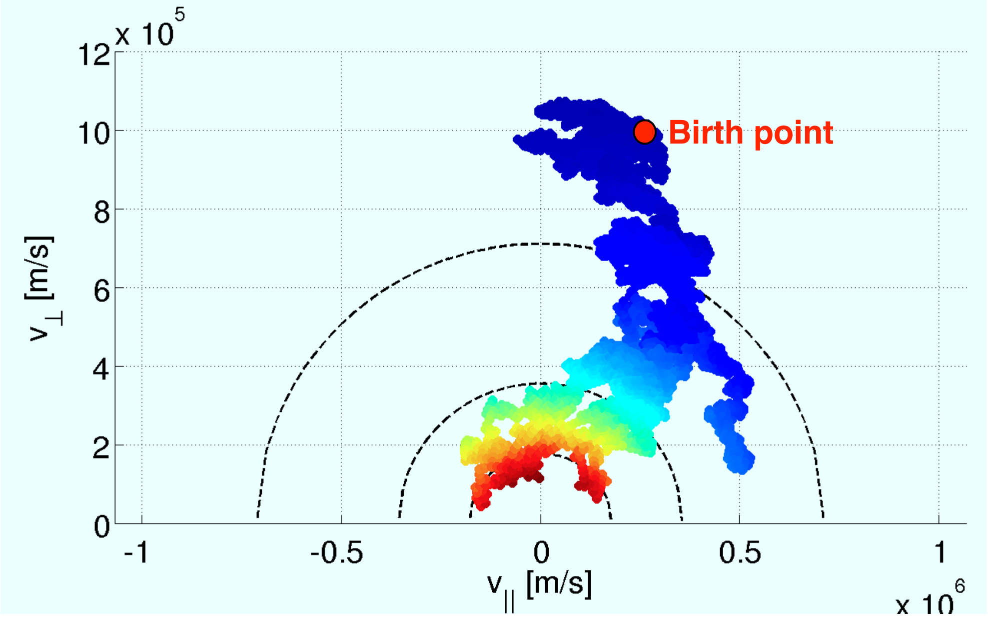

Figure 2: Slowing down under the influence of Coulomb collisions in a tokamak plasma. The particle birth energy is represented by a red circle. The color code is proportional to the anomalous particle diffusivity calculated by the GENE code.

3. The VENUS code

VENUS [13] is a guiding center drift code originally developed for the study of the fast ion motion in tokamaks. The set of equations regulating the guiding-center motion have recently been updated [14]. The code works with magnetic equilibrium quantities reconstructed with the VMEC code [15] and a 4th order Runge-Kutta scheme. Updates were recently introduced [11] to study the fast ion motion under the influence of collisions and anomalous transport. The latter is evaluated from the GENE code and a stochastic radial diffusion term is introduced to simulate the influence of microturbulence. A beam deposition module was also developed [11]. To clarify the importance of both collisions *and* turbulence, the slowing down of a fast ion in velocity space is illustrated in fig 2. The color code is proportional to the radial diffusivity D_r obtained with the GENE code and defined in (1). As the particle loses energy, the E_{fast}/T_e ratio diminishes and stronger radial diffusivities D_r are experienced. If the particle collisionality is small, the particle experiences turbulent fields for long time scales and radial diffusion is enhanced. One could therefore predict the influence of anomalous transport by evaluating the turbulent fast ion spread with respect to the machine size [16]

$$\Delta = \text{beam spread/minor radius} \simeq \sqrt{\langle D\rangle\, \tau_{\mathrm{sd}}}/a. \tag{3}$$

Here, $\langle D\rangle$ represents the fast ion diffusivity averaged over an appropriate distribution function (i.e. a slowing down function [17]). The particle slowing down τ_{sd} can be simply evaluated with numerical calculations or with analytical estimates, such as those found in [18]. Estimating the energy diffusivity $D(E)$ to insert in the average

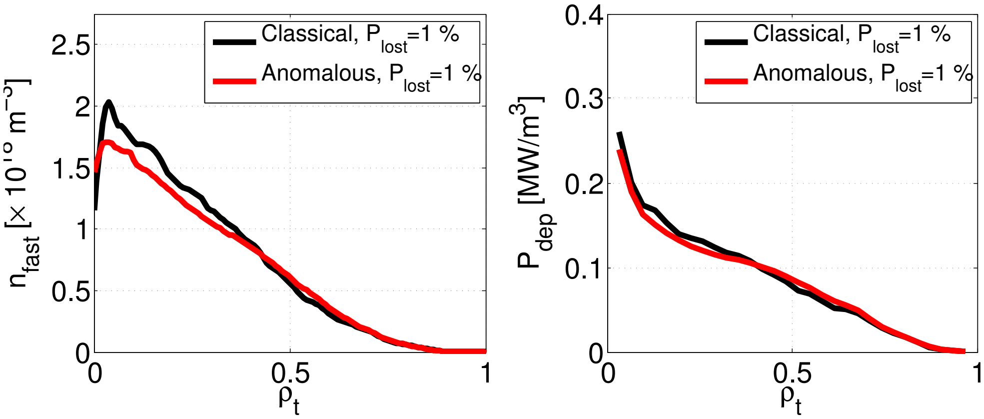

Figure 3: (Left panel) Neutral beam density profile under the influence of collisions (black) and with the addition of turbulent transport. (Right panel) Power deposition profile from the neutral beam system with and without the influence of small scale fields (same color code as the left panel).

of (3) is a non-trivial task given that the shape of D changes with the phase velocity of the underlying turbulence. Before performing GENE simulations, we can estimate this parameter with the analytical form proposed in [7]. First, we assume the diffusivity to be constant up to 5 T_e. Then, the fast ion diffusion coefficient scales as $D(E) \simeq E^{-1.5}$, a value consistent with the findings of a recent work [1]. Using this simple approach we can predict small redistribution for ITER ($\Delta = 0.1$) and moderate redistribution for DEMO ($\Delta = 0.6 - 0.8$). For TCV, the wide range of temperatures and densities achievable with the machine makes it possible to obtain small to large redistribution ($0.1 < \Delta < 0.7$). We can now use the numerical VENUS-GENE interface to assess the goodness of this parameter.

4. Results

4.1. ITER

In ITER, the large beam injection energy guarantees a sufficiently small particle diffusivity and a very small redistribution of the beam ion density profile is observed (figure 3). Furthermore, the power loss does not increase as turbulent fields are included in the simulation. While minor modifications to the n_{nbi} profile are observed, the beam power deposition is unchanged when anomalous transport is taken into account. This indicates that redistribution affects lower energy particles rather than very energetic ions, i.e. the energy source to the background plasma. Results therefore confirm the predictions of the simple model in (3).

4.2. DEMO

We employ the same fast ion diffusivity obtained for ITER to estimate the beam ion redistribution in DEMO [19]. We work on a scenario with the same background density as in ITER [19]. A peak electron temperature of 50 keV (i.e. almost 50% larger than

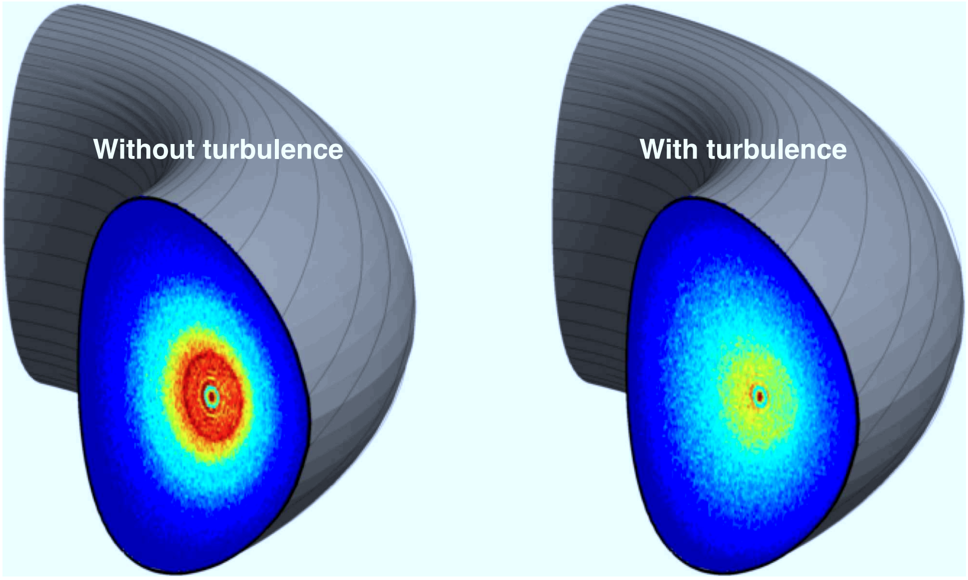

Figure 4: Beam ion density in DEMO. The left panel describes the results obtained with only the inclusion of collisional transport. The results in the right panel are obtained by also including turbulent transport.

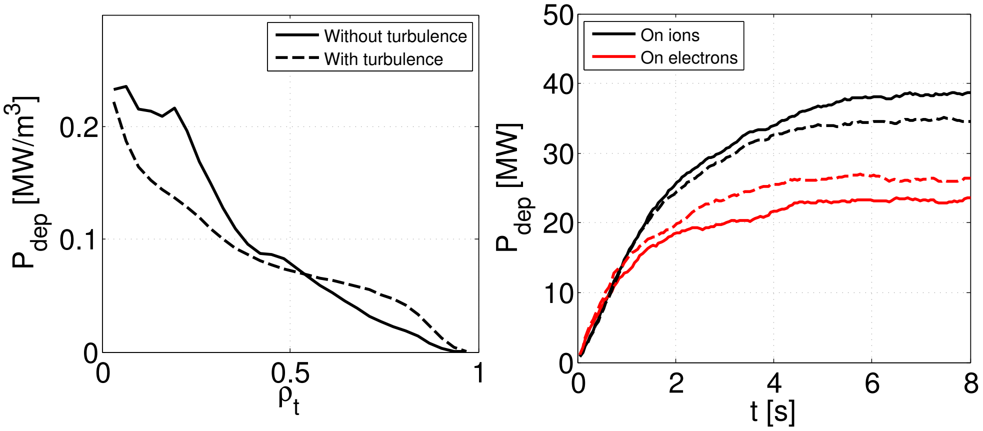

Figure 5: Heat deposition from the neutral beam system in DEMO. In the left panel the deposition profile with and without anomalous transport (dashed and solid lines, respectively) is illustrated. The power given to ions (black) and electrons (red) is also illustrated in the right panel.

in ITER) is chosen. The redistribution of the beam ion population can be observed in figure 4. Such a strong displacement of particles from the core to the edge of the plasma modifies the heat deposition. From figure 5 we observe a redistribution of the beam power from the core to mid-radius. Particles therefore slow down in regions

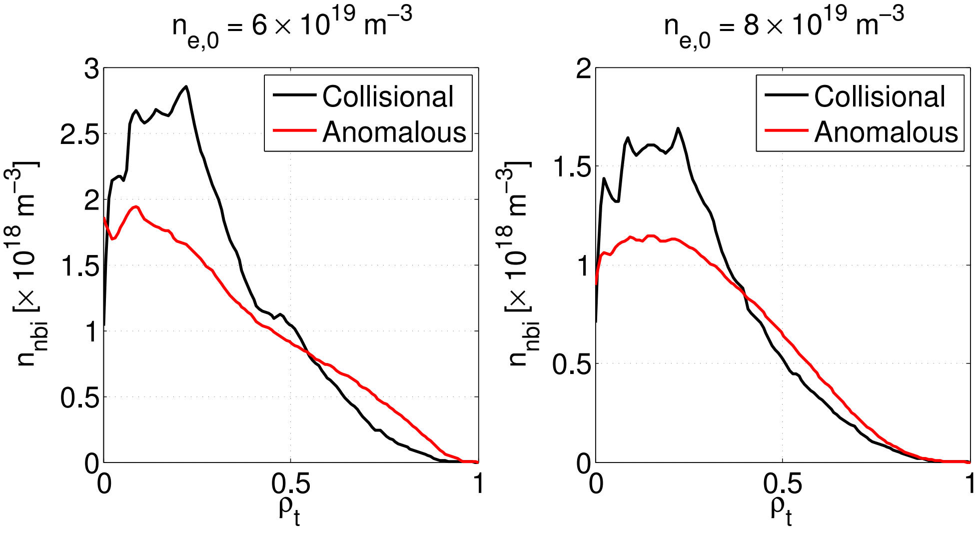

Figure 6: Beam ion density profile for the DEMO scenario presented in figure 4 (left) and in a higher density case (right). Black curves represent results obtained with only the inclusion of Coulomb collisions, while red lines characterize simulations with also the inclusion of GENE diffusivities.

far from the core where the temperature and the critical energy E_c are lower. As a consequence, more energy then expected is given to electrons while ions are heated less efficiently. Therefore, the redistribution of the heat deposition profile predicted by the large theoretical value of $\Delta = 0.8$ is particularly detrimental.

Some improvement in particle confinement can be obtained by increasing the background density by 33% (figure 6). In such a configuration, the particle slowing down time decreases and the beam spread lowers. Consequently, less redistribution is observed for the higher density scenario which is characterized by a lower $\Delta = 0.6$.

4.3. TCV

The planned neutral beam upgrade in TCV envisages the injection of 15 to 35 keV of deuterium beams. With a powerful ECE system, TCV can achieve temperatures in excess of 10 keV. Redistribution can therefore play a role as Δ can vary between 0.1 and 0.7 for a 25 keV NBI system. To verify this conjecture, we simulate TCV turbulence employing the parameters of a previous work [20]. The background turbulence in this scenario is generated by a mixture of ITG and TEM microinstabilities, a typical situation for TCV. We present the results for two plasma discharges with different densities and temperatures. The first is plasma discharge #25013, whose large temperature ($T_e = 10$ keV) and intermediate density ($n_{e,0} \simeq 2 \times 10^{19}$ m^{-3}) result in a large value of $\Delta = 0.1$. The beam ion redistribution in the plasma discharge #25013 is therefore rather large, as confirmed by simulations with the VENUS code (figure 7). The combination of the long slowing down time (0.1 seconds) and the large anomalous diffusivity (E/T_e is only 2 for this plasma temperatures) is therefore the cause for such observations.

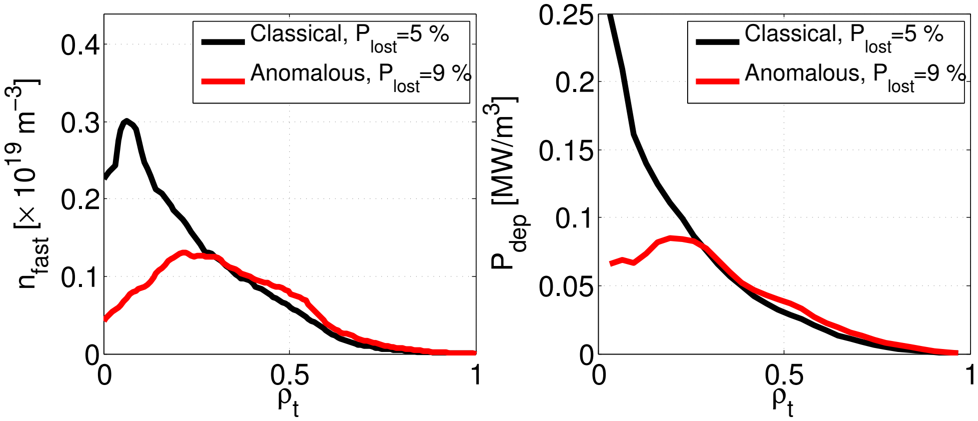

Figure 7: Beam ion density (left panel) and heat deposition (right panel) for the NBI-heated plasma discharge #25013. Results obtained with the inclusion of turbulent transport are represented in red. Profiles resulting from purely collisional simulations are characterized by black lines.

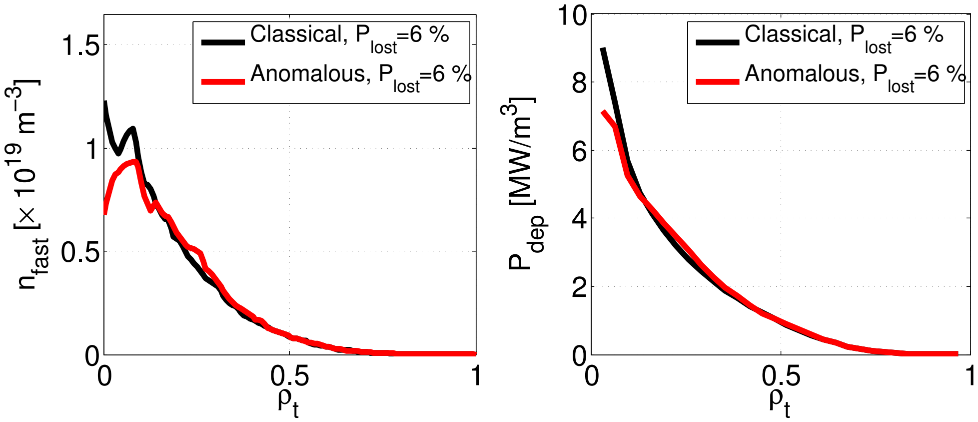

Figure 8: Neutral beam density (left panel) and heat deposition (right panel) for TCV plasma discharge #24789 with the inclusion of a neutral beam source. Results are shown both for a collisional (black) and anomalous (red) simulations.

The second plasma discharge (#27489) studied in this work is characterized by a high density, low temperature plasma ($n_{e,0} = 4.5 \times 10^{19}$ m^{-3}, $T_{e,0} < 1$ keV). The fast ion slowing down time decreases to 10^{-2} seconds, the E/T_e ratio increases accordingly and a small value of $\Delta = 0.1$ is obtained from our simple model. Beam ion redistribution is therefore not expected in this scenario and VENUS simulations confirm this prediction (figure 8). The powerful ECE system in TCV could therefore be employed to regulate the beam ion transport once the planned NBH-upgrade will be successfully installed.

5. Conclusion

The numerical platform recently developed to study the interaction between energetic ions and turbulence was presented in this work. The microturbulent fields were generated with the gyrokinetic code GENE. The fast ion diffusivity was then obtained from the numerical simulations with a set of quantities developed for this analysis. The VENUS code was then used to simulate the interplay between guiding center drift motion, collisions and stochastic anomalous diffusion in three different tokamaks. It was demonstrated that beam ions are well confined in ITER as turbulence plays only a minor role. This is a result of the large E_{nbi}/T_e ratio and of the relatively small slowing down time. On the other hand, turbulent beam ion redistribution was observed for DEMO plasmas, where the large temperatures reduce E_{nbi}/T_e and extends the fast ion slowing down time. Heat deposition is redistributed, although larger density plasmas can facilitate the fast ion thermalization and reduce the anomalous fast ion spread. It was finally demonstrated that beam ion redistribution can be either strong or negligible in TCV, depending on the plasma temperature achieved with the powerful ECE system. Therefore, the fast ion transport phenomenon could easily be investigated in the planned NBH-upgrade of this flexible machine.

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