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DIFFUSIVE MODELLING OF ENHANCED BEAM ION TRANSPORT IN TFTR PLASMAS HEATED WITH DEUTERIUM AND TRITIUM BEAMS

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ABSTRACT. A search is made for signs of enhanced beam ion transport in a set of TFTR plasmas heated with various numbers of tritium and deuterium beams. Our investigation is based on the time dependent, $1\frac{1}{2}$-D simulation code TRANSP, and an ad hoc diffusion model of enhanced fast ion transport. Spatially constant and spatially variable diffusion models are used (the code was upgraded to allow for $D_f(r)$ modelling). Simulations with spatially constant diffusion coefficients resulted in an upper bound of $D_f \leq 0.2$ m^2/s for a set of high power DT supershots. One discharge is analysed in particular detail, in terms of both various diffusion models and the effects of systematic errors. Best agreement between the measured neutron flux in this discharge and the corresponding TRANSP predictions is obtained by assuming that D_f has low values in the inner half of the plasma column ($D_f \leq 0.1$ m^2/s) and then rises rapidly in the outer half, suggesting that stochastic ripple diffusion is the likely mechanism for the enhanced beam ion transport. This hypothesis is supported by the modelling results from two other plasmas with large major radii.

1. INTRODUCTION

Beam injected ions, ion cyclotron range of frequencies (ICRF) heated minority ions and fusion products are known under the common name of fast ions. They have an important role in the physics of tokamak fusion reactors. The $d(t,n)^4He$ reactions are self-sustaining only if the alpha particles do not escape before they transfer most of their 3.5 MeV energy to the thermal background plasma. Bringing the plasma to this regime requires an auxiliary source of energy, and heating in the ICRF is the most likely choice. ICRF and neutral beam injection are considered as a means of maintaining the toroidal current, which is essential for plasma confinement.

Fast ion transport in excess of the neoclassical values is usually quantified with a zero dimensional fast ion diffusion coefficient D_f . This parameter describes the quality of the fast ion confinement and is used in reactor design. For example, confinement times ≥ 1 s are required for alpha particles in ITER, which sets the limit $D_f < 0.5$ m^2/s [1].

The first reported value of a fast ion diffusion coefficient ($D_f < 0.5$ m^2/s) was obtained from the absolute magnitude of the 2.5 MeV neutron emission in a PLT plasma heated with ~ 45 keV deuterium beams [2].

The flux of 100 keV protons from a hydrogen minority ICRF heated TFTR plasma was observed with a vertically viewing charge exchange analyser [3]. The radial dependence of the signal implied $D_f < 0.05$ m^2/s for these trapped ions. The good agreement between the measured stored energy of tail ions produced by hydrogen minority ICRF heating at JET, and the prediction from the Stix model, set a limit of $D_f < 0.2$ m^2/s [4]. Analysis of burnup measurements in supershots at TFTR [5] and JET [6] plasmas with $\tau_{se} \geq 2$ s resulted in $D_f \leq 0.1$ m^2/s and $D_f = 0.1$–0.3 m^2/s, respectively. Simulations of the partial DT experiments at JET [7] showed that no enhanced fast ion transport is required to explain the time evolution and absolute magnitude of the measured 2.5 and 14 MeV neutron signals. Analysis of the 14 MeV neutron emission from a 50 ms DT beam pulse ($P_{NBI} = 23.5$ MW) at TFTR set a low upper limit of $D_f < 0.05$ m^2/s on the tritium beam ion transport [8].

Substantial fast ion loss is associated with strong MHD activity or deviations in the toroidal magnetic field symmetry. Such losses were observed in DIII-D plasmas with strong TAE [9] and BAE [10] activity. The effect of the enhanced toroidal field ripple was studied at JET by turning off every other of the 32
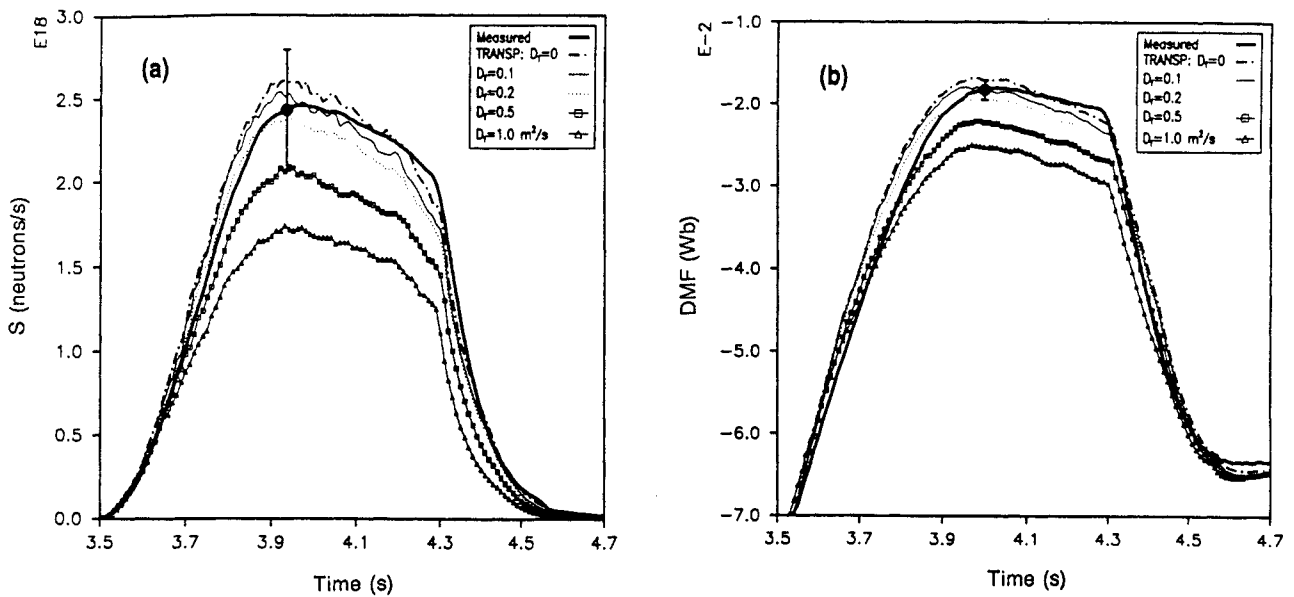
FIG. 1. Measured and TRANSP predicted total neutrons (a) and diamagnetic flux (b) from a high power DT shot (No. 76 748, 7 MW peak fusion power). The error bars are 15% (one sigma) for the neutron emission and 1.2 mWb (absolute uncertainty) for the diamagnetic flux.

toroidal field coils, which increased the field ripple from 1 to 12.5% [11]. As a result, the stored energy in L mode plasmas decreased by 30%, a 3.5 fold reduction of fast protons and deuterons was seen in ICRH heated plasmas, and the triton burnup decreased by 40%.

In this paper we focus on high power, reactor relevant DT plasmas. We use the $1\frac{1}{2}$-D time dependent transport code TRANSP [12, 13] to predict the total neutron emission, the neutron fluxes along ten chordal positions and the diamagnetic flux (DMF). The goal is to establish an upper limit on D_f in plasmas without fast ion driven instabilities and to check if spatially variable fast ion diffusion coefficients can reproduce the measurements better (we modified TRANSP to allow $D_f(r)$ modelling). The comparison between simulation and experiment is based on 15% (one sigma) uncertainty for the neutron measurements [14] and 1.2 mWb absolute uncertainty for the DMF measurement [15].

Section 2.1 summarizes the results [8] from transport models with spatially constant fast ion diffusion coefficients; the new material is for the two plasmas with large major and minor radii (Section 2.2). In Section 3 the results from models with spatially variable fast ion diffusion coefficients are outlined (they will be published in more detail elsewhere).

2. MODELLING FAST ION TRANSPORT WITH SPATIALLY CONSTANT DIFFUSION COEFFICIENTS

2.1. Plasmas with small beam ion transport

Before January 1995, TRANSP was able to model enhanced fast ion transport either with diffusion coefficients D_f that are spatially constant or that are proportional to the electron particle diffusivity D_e. We choose to use the spatially constant D_f modelling because it provides easier comparison of the fast ion behaviour among various discharges. Models with $D_f = 0.1, 0.2, 0.5$ and 1.0 m^2/s are routinely explored.

The measured and TRANSP predicted neutron emission and diamagnetic flux for one high power DT shot are shown on Fig. 1. While the neutron emission shows little sensitivity[1] to fast ion diffusion modelling (all models with D_f up to 0.5 m^2/s are within the error bar), the diamagnetic flux, fortunately, is sensitive, thus excluding models with $D_f > 0.2$ m^2/s.

The observations such as those from Fig. 1 motivated a more systematic study of DT plasmas. Eight plasmas heated with beams in the 12 to 30 MW range,

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[1]The insensitivity of the neutron emission can be traced to the large number of thermonuclear neutrons in the high power DT plasmas [8].

TABLE I. ANALYSED DT PLASMAS

| Shot number	I_p (MA)	R (m)	a (m)	P_{NBI} (MW)	$S_{M,max}$ (10^{16})	T/D beams	U_{max} (MJ)	Comments
72 613	1.5	2.52	0.87	14	1.98	Trace T	2.16	2% T in 1 beam
73 234	2.0	2.52	0.87	28	72.6	1/10	4.14	DT
73 235	2.0	2.52	0.87	24.5	150	4/5	3.98	DT
73 255	2.0	2.52	0.87	29	210	5/6	4.95	DT
73 268	2.0	2.52	0.87	30	227	7/4	5.13	DT
73 306	1.8	2.52	0.87	12.6	32.9	1/4	1.98	DT
73 446	1.8	2.52	0.87	22	139	5/3	3.81	DT
73 452	1.8	2.52	0.87	20	123	5/3	3.49	DT
73 457	1.8	2.52	0.87	21	90	2/6	3.24	DT
74 652	1.8	2.61	0.96	23.5	114	5/4	3.71	DT (ripple loss)
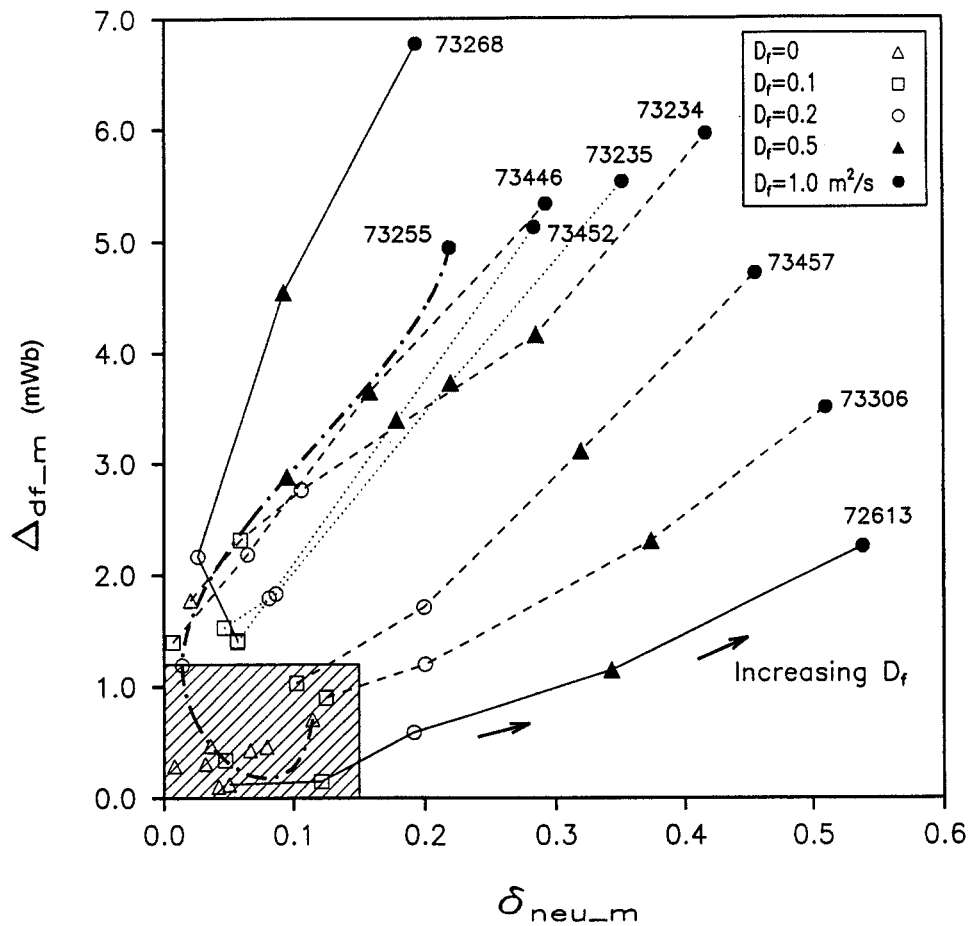
FIG. 2. Map showing the discrepancy between simulation and measurement, for the diamagnetic flux (y axis) and the total neutron emission (x axis), for a set of nine DT discharges. The line segments connect various D_f simulations of the same shot. The number at the end of a segment identifies the shot. The shaded box defines boundaries of simulations within the accepted error bars.
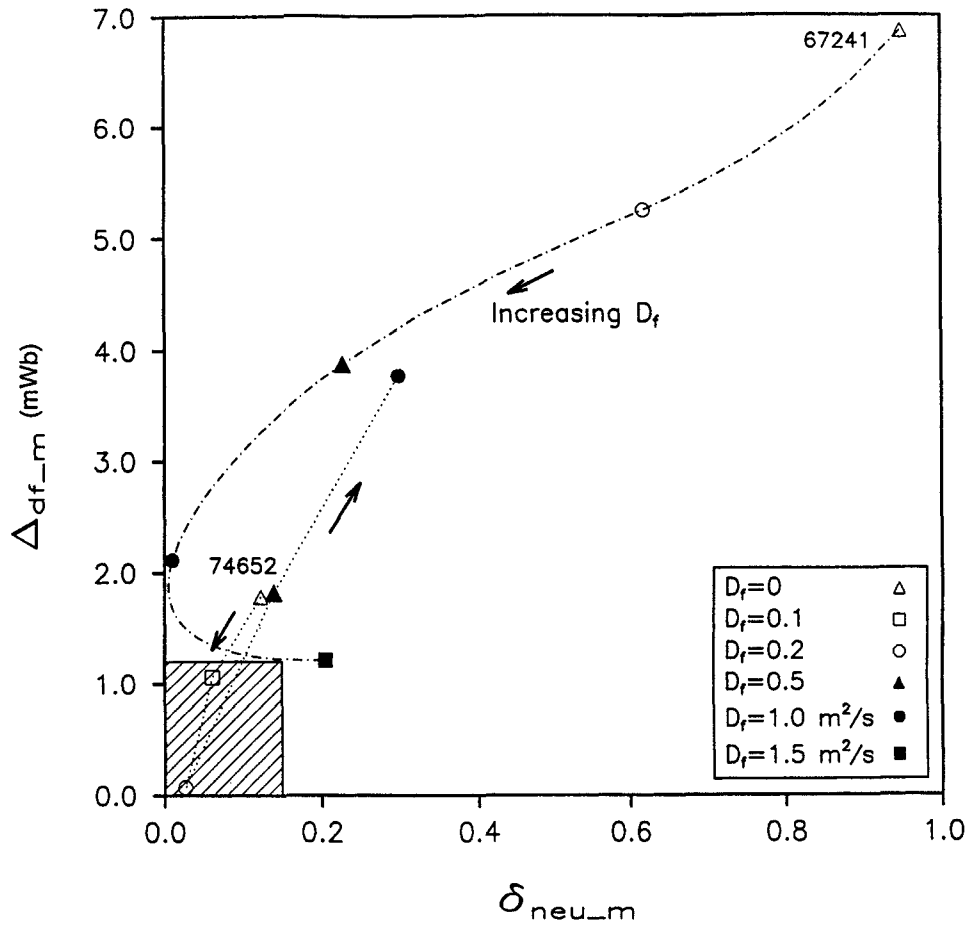
FIG. 3. Map showing the huge discrepancy between baseline ($D_f = 0$) simulation and measurement for the DD shot 67241 and the substantial discrepancy for the DT shot 74652. Both discharges have R = 2.61 m and a = 0.96 m, thus being susceptible to stochastic ripple loss of beam ions.

and tritium beam fractions in the 0.10 to 0.64 range are selected (Table I). The first trace tritium shot (No. 72613) is included in the set of the eight DT shots because its neutron emission is not affected by tritium wall recycling, thus making it a member of a group of discharges with neutron emission relatively independent of this process.

To quantify the agreement between measurement and simulations, we define

$$\Delta_{df\_m} = |DMF_{tr} - DMF_m| \qquad (1)$$

$$\delta_{neu\_m} = \frac{|S_{tr} - S_m|}{S_m} \qquad (2)$$

where DMF_m/DMF_{tr} is the measured/predicted diamagnetic flux averaged over 200 to 400 ms (depending on the plasma discharge) around the time of peak stored energy and S_m/S_{tr} is the peak measured/predicted neutron emission.

The quality of agreement between simulation and measurement cannot be judged on the basis of these two numbers only; the temporal evolution has to be taken into account as well. Since we choose baseline simulations that are in good agreement with the measured neutrons and diamagnetic flux (both in peak value and shape), and the fast ion diffusion modelling monotonically decreases the baseline values, the (δ_{neu_m}, Δ_{df_m}) pairs represent the departure from measurement well.

A (δ_{neu_m}, Δ_{df_m}) measurement comparison map (Fig. 2) summarizes our findings about plasmas heated with deuterium and tritium beams. Points that lie within the shaded box in Fig. 2 are consistent with neutron and DMF measurements (within experimental errors). The obvious feature of the map is that increasing D_f causes the (δ_{neu_m}, Δ_{df_m}) points to 'run away' from the box defining the boundaries of acceptable simulations. In other words, as D_f increases there is a

simultaneous increase in the discrepancy between the measured neutron and DMF values and the TRANSP simulations. This confirms the fact that high values of D_f are incompatible with the measurements. While some of the simulations with $D_f = 0.1$ m^2/s remain within the shaded box, for $D_f \geq 0.2$ m^2/s all escape. Therefore, an upper limit on the fast ion diffusion coefficient can be set for these DT plasmas: $D_f \leq 0.2$ m^2/s.

A detailed systematic error analysis for one DT shot (No. 73 457) was undertaken in order to check how the choice of physics models and the errors in the input data affect the established upper bound on D_f [8]. For example, the electron temperature and density were varied within the measurement uncertainties, and different models for thermal hydrogenic ion transport were used. The results from this analysis confirmed that $D_f \leq 0.2$ m^2/s.

2.2. Plasmas with enhanced beam ion transport

Discharges with enhanced beam ion transport have quite different trajectories on the measurement comparison map ($\delta_{neu\_m}, \Delta_{df\_m}$). Two such discharges are shown in Fig. 3. The first one is a large ($R = 2.61$ m, $a = 0.96$ m), low current (0.9 MA) DD plasma heated with 13.5 MW of deuterium beams (No. 67 241). Its stored energy is 40% less then the baseline TRANSP predicted value. The measured neutron emission is one half of what the simulation predicts. With fast ion diffusion modelling the simulated curves approach the measured values as D_f increases. A large diffusion coefficient $D_f \cong 1.5$ m^2/s seems appropriate for this plasma.

The second discharge is again a large plasma ($R = 2.61$ m, $a = 0.96$ m), but with 1.8 MA current and heated by four deuterium and five tritium beams ($P_{NBI} = 23$ MW, discharge 74 652). The insensitivity of the simulated neutrons to diffusion is due to the large concentration of tritium beam ions [8]. Initially, the simulated neutrons and DMF are above the measured values. As D_f increases they approach the measurements (for $D_f = 0.2$ m^2/s) and then start departing along their low end. This feature is manifested in the 'U turn' of the trajectory on the measurement comparison map. An appropriate upper limit on D_f for this plasma is 0.3 to 0.4 m^2/s.

Stochastic ripple diffusion is the process that is probably responsible for the enhanced beam ion transport in these two discharges. Several arguments support this claim. First, a survey [16] of possible diffu-

sive fast ion loss mechanisms concluded that, owing to the orbit averaging effect, most of them are negligible. The only serious candidate left was the stochastic ripple transport. This mechanism operates in the regions of substantial errors of the toroidal magnetic field, near the outer edge of plasmas with large major radii (stochastic ripple loss domain) and has a dangerous feature of concentrating the fast ion loss just below the outer midplane.

Experiments employing the detector shadowing technique have been used to estimate the diffusion rate of 1 MeV tritons and 3 MeV protons near the outer midplane in TFTR DD plasmas [17, 18]. Their analysis showed that the trapped fraction of these charged fusion products was subjected to large diffusion ($D_f > 1.0$ m^2/s) and that the numerically inferred amplitude of the diffusion step size agreed well with the theoretical calculations based on the stochastic ripple diffusion model. Recently, by using a guiding centre code, it has been found that collisions have a synergistic effect on ripple losses [19] and that the plasma energy missing from a low current TFTR experiment, with $R = 2.6$ m, can be attributed to collisional stochastic ripple diffusion of beam ions. Additional fast ion diffusion processes were not required to explain the observations. The results from the next section also point to the stochastic ripple losses as the mechanism that is probably responsible for enhanced beam ion transport.

3. MODELLING FAST ION TRANSPORT WITH SPATIALLY VARIABLE DIFFUSION COEFFICIENTS

Transport coefficients such as the particle and heat diffusivities depend on the local plasma parameters and usually increase towards the plasma periphery. The physics operating behind the enhanced fast ion transport is different from that of the thermal plasma transport, but nevertheless, it is reasonable to expect similar spatial behaviour. Indeed, analysis of the neutron flux and charge exchange signals from a deuterium beam pulse into on ohmic plasma [20], as well as the neutron flux from one DT plasma [21], found that the data were consistent with low values of D_f at the plasma centre, but higher values away from the centre.

In order to check this hypothesis, we modified the TRANSP code to accept any user supplied fast ion diffusion profile. Since the neutron sensitivity to fast ion diffusion modelling critically depends on the fraction

of beam–beam neutrons [8], a discharge from Table I with the greatest beam–beam neutron content is chosen (~40%, No. 73 457) for modelling with various $D_f(r)$ profiles. The goal is to match the temporal evolution of the measured neutron fluxes along the ten radial chords of the TFTR neutron collimator [22]. Fast ion diffusion redistributes beam ions from the plasma centre to the outer regions, resulting in lower neutron fluxes at the core, and higher neutron fluxes outside, thus providing a 'knob' for adjusting the simulated neutron emissivity. The study with spatially constant D_f models showed that only neutron fluxes at 222.6, 247.2, 268.5 and 299.5 cm are sensitive enough to discriminate measurements against various models. These four channels are used in the subsequent comparison with the spatially variable fast ion diffusion models.

The first, and obvious, choice to investigate is the linear $D_f(r)$ profiles. We have set $D_f(0) = 0$ and $D_f(a) = 0.1\%$, 0.5 and 1.0 m^2/s, and found that the predicted total neutron emission and the DMF flux are similar to those from the constant D_f models, with $D_f \cong D_f(a/2)$. It became apparent that stronger shaping of the profiles is necessary to improve the agreement between the neutron flux predictions and the measurements. We tried profiles that vary as ξ^n, with $n = 2, 3, 4, 5$ and 6 (ξ is the normalized radial co-ordinate), and have common values $D_f(0) = 0$ and $D_f(a) = 1.0$ m^2/s. While the parabolic profile removes too many fast ions from the plasma interior, and reduces the total neutron emission and DMF below the measurement, the fast ion diffusion defined with the profiles $n = 5, 6$ is too weak (for $n = 5$, $D_f(\xi \leq 0.6) < 0.1$ m^2/s) and predicts neutron fluxes similar to that of the zero diffusion model. The best fit to the total neutron emission, neutron flux and DMF measurements is achieved with the quartic profile ($n = 4$).

4. SUMMARY

Analysis of nine high power DT supershots shows that the deuterium and tritium beam ions are well confined. An upper limit for the fast ion diffusion coefficient, for this set, is estimated at $D_f \leq 0.2$ m^2/s. Poorer beam ion confinement is found in plasmas with large major radius, possibly owing to stochastic ripple diffusion. Better fits to the measured neutron flux are obtained by assuming that D_f has low values in the inner half of the plasma column ($D_f \leq 0.1$ m^2/s), and then rises rapidly in the outer half. Details of the modelling with the spatially variable $D_f(r)$ profiles will be reported elsewhere. We plan to model plasmas with theoretically calculated $D_f(r)$ profiles and to extend the study to other discharges sensitive to fast ion diffusion modelling.

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