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ABSTRACT.
In a fusion reactor the sufficient confinement of and heating by fusion-born alphas is of great importance. Their wide orbits become particularly worrying in the presence of a reversed qprofile, typical for plasmas with an Internal Transport Barrier (ITB). Thus, it is important to find out whether the benefits of improved thermal particle confinement by ITB are offset by reduced heating efficiency by fusion alphas.

In this work, heating by energetic alpha particles is studied using the 5D Monte Carlo guidingcenter code ASCOT. Results obtained with an analytical magnetic background and a circularly symmetric geometry indicate that the overall alpha performance is better for an ITB plasma than for a standard H-mode one. Due to the stagnation orbits, the alpha particles do not escape the core as quickly as was feared which, combined with the typical ITB plasma profiles, seems to lead to more effective use of the fusion fuel. The results obtained with an analytical magnetic background are refined with an authentic JET magnetic geometry.

The results are qualitatively similar to those obtained by Constant-of-Motion (COM) 3D Fokker-Planck calculations [1]. However, in the COM approach it is not inherently guaranteed that all orbit topologies, and especially the boundaries between them, are accurately modeled. The strength of guiding-center orbit following approach is in its natural ability to take into account all the possible orbit topologies in phase space. Indeed, ASCOT simulations have been able to resolve e.g. the effect of stagnation orbits on alpha heating, seen in tritium injection experiments [2]. Because alpha heating is localized at the stagnation points, their location can be important, for instance, for the stability of an ITB.

1. INTRODUCTION.

The successful operation of a fusion reactor relies on sufficient confinement of the fusion-born alpha particles. The 3.5MeV fusion alphas can have orbit widths of the order of the size of the plasma column, and their confinement generally requires a very large plasma current. Therefore the alpha particle confinement becomes particularly worrisome for plasmas with a so-called Internal Transport Barrier (ITB) [1], which is facilitated by very low or, preferably, reversed central magnetic shear [2]. For brevity we shall refer to such a profile simply as reversed, and it implies very low plasma current over a significant part of the plasma. The orbit widths are generally inversely proportional to the poloidal magnetic field, the strength of which scales with the plasma current. Therefore, in the presence of a current hole or very low central plasma current, the confinement of fusion-born alphas becomes a major concern. We study the confinement and heating profile of fusion alphas both in a normal JET H-mode plasma (Pulse No: 52009) with a monotonic q-profile and in an ITB plasma (Pulse No: 51976) with a reversed q-profile and a Current Hole (CH), see Fig. 1(a). The work is carried out using the Monte Carlo -based guiding-center-following code ASCOT [3] which naturally and accurately resolves all possible orbit topologies as well as the transitions between them [4]. This work complements the recent Fokker-Planck analysis [5] not only by using a completely different method but also by allowing the experimental flux surface structure shown in

Fig. 1(b) which, in the center of an ITB plasma, does not easily render itself to simple parametrization.

2. ORBITS OF 3.5 MEV ALPHAS WITH NORMAL AND REVERSED Q-PROFILE.

Figure 2 shows drift orbits for a 3.5MeV alpha launched at various locations along the midplane for Pulse No's: 51976 and 52009. The orbit topologies are dominated by potatoes and passing orbits, with bananas existing only in a very limited region. The orbit width reaches a local minimum when the starting point is moved outwards from the plasma center and the poloidal field reaches a critical value at which the particle's own poloidal velocity at the midplane is cancelled by the gradient drift. For fusion alphas in JET geometry this field is given by [6] $B_p = mv{=}R_0 e \approx 90$ mT. As such a location is reached, the spatial extent of the particles' orbits in the poloidal plane is reduced to that of their gyromotion, not resolved by the present technique. These orbits are called stagnation orbits [7]. The trace tritium experiments [8] on JET indeed report a concentration of fast ions at the stagnation distance from the magnetic axis on the outboard midplane.

Stagnation orbits only take place when the poloidal component of the parallel velocity opposes the gradient drift, so that there is a competition. Alphas born with a poloidal velocity in the direction of the gradient drift have very wide orbits and can even suffer a prompt loss to the walls. For Pulse No: 51976, about 24% of the orbits starting from the High Field Side (HFS) intersect the wall, as do about 35% from the Low Field Side (LFS). The same numbers for Pulse No: 52009 are 18% and 8%, respectively.

3. ALPHA HEATING WITH NORMAL AND REVERSED Q-PROFILE.

The vital aspect of the slowing down of the alpha particle is how it heats its surroundings. All energy lost by a fast particle via collisions is deposited in the surrounding plasma, affecting the plasma profiles. When the alpha particle heating is assumed to take place classically, via slowing down [9], it can be studied by ensemble simulations using ASCOT, which accurately accounts for all neoclassical physics.

When ASCOT initializes particles, it divides the tokamak into slots uniform in the poloidal angle and rpol-coordinate. An ensemble of test particles, with isotropic velocity distribution, is initialized in each slot. These test particles represent the fusion alphas born within the slot, and they are given weight factors according to the local fusion reactivity [10]. The background plasma is assumed stationary and to represent a situation where the amount of alpha-heating is consistent with the background temperature profile. The background plasma profiles for Pulse No's: 51976 and 52009 are shown in Fig.3 together with the corresponding alpha production rate. A population of 3.5MeV fusion alpha particles was simulated using an ensemble of 105 000 test alphas. During the simulation, the change in particle energy is recorded, along with its location in the poloidal cross-section, yielding the power deposition profile. The radial profile of the alpha heating power, in watts, is illustrated in Fig.4. To facilitate the comparison, the profiles are normalized to their maximum value. As function of ρ the H-mode shot yields more distributed heating, mostly due to the radically different plasma profiles. This was verified by repeating the H-mode simulation using the plasma profiles of the ITB shot. Also, the physical volume corresponding to r is quite different in these two shots.

The power density profile in the poloidal cross-section is displayed in Fig. 5, again normalized to its maximum value. Any poloidal differences have to be attributed to the magnetic structures because plasma profiles are flux functions. In the H-mode, Pulse No:52009, the heating strongly peaks in the center, favoring only slightly the LFS due to the trapped orbits. For the Pulse No: 51976 with an ITB, the heating shows structure around the two competing magnetic axes inside the current hole. The differences in the LFS/HFS asymmetry between the two shots reflect the orbit topologies: H-mode favors the LFS due to the trapped orbits that exist only there, while with a CH the presence of potato orbits even on the HFS keeps the heating power more uniform. Neither H-mode nor ITB shot exhibits any poloidally localized heating maximum due to stagnation orbits, as was observed in an earlier study [6]. Also, from this figure it is clear that the physical area over which the alphas deposit energy is larger for the ITB shot.

CONCLUSIONS.

In agreement with a recent study [11], advanced scenarios based on current hole were found to provide a broad, uniform alpha heating profile. This allowed the same total heating with 20% smaller plasma current. Next the simulations will be refined with a particle loading better adapted for current holes.

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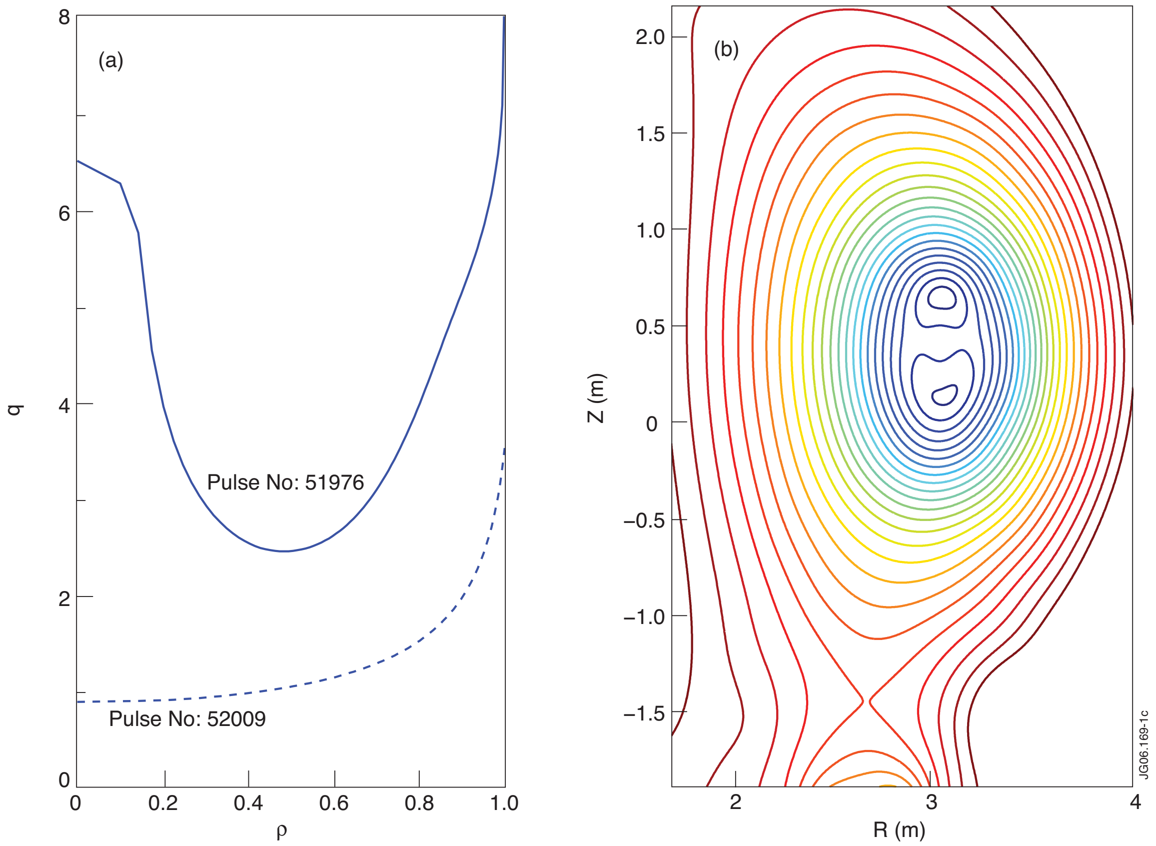

Figure 1: The q-profiles of the simulated shots (a) and the flux surface structure of the ITB plasma with a current hole (b).

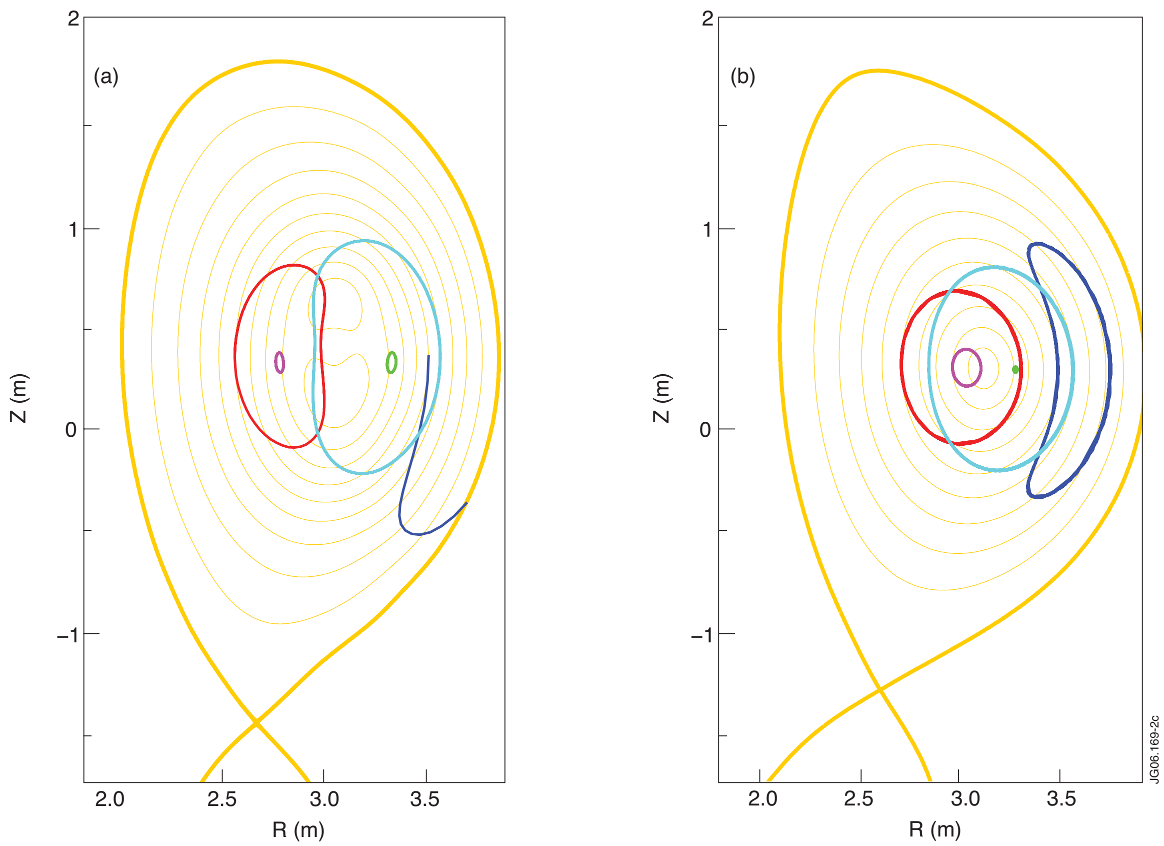

Figure 2: Sample orbits for (a) an ITB discharge (I_p = 1.9MA), and (b) an H-mode discharge (I_p = 2.5MA).

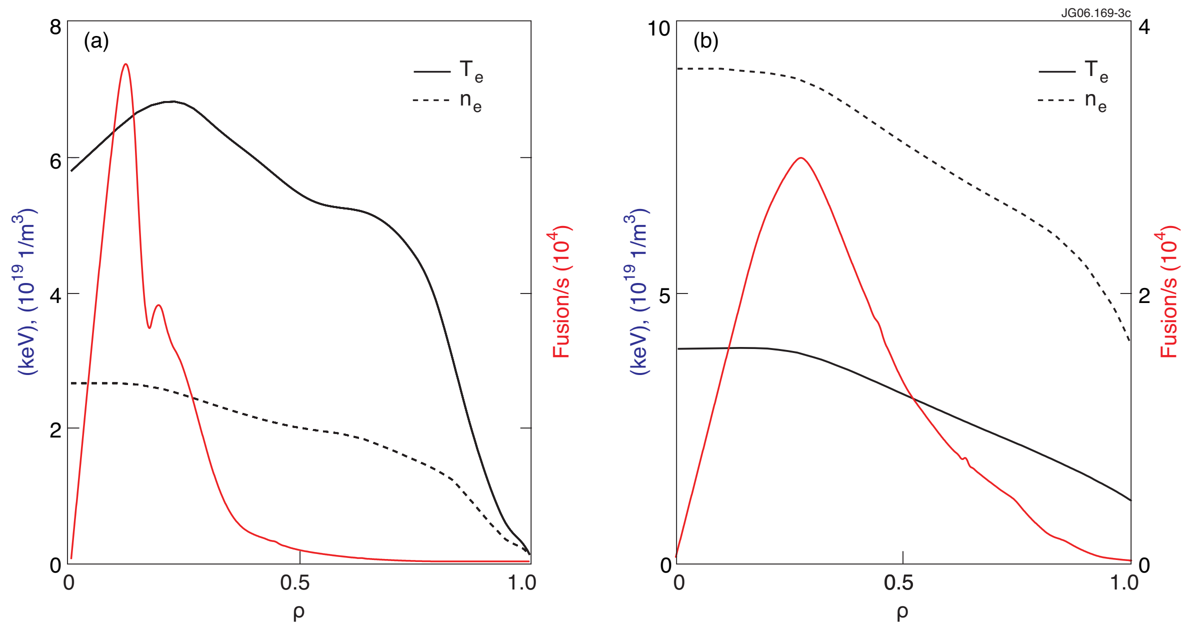

Figure 3: The plasma profiles for an ITB (a) and Hmode (b) discharges. Also shown is the local fusion alpha production rate, particles per second.

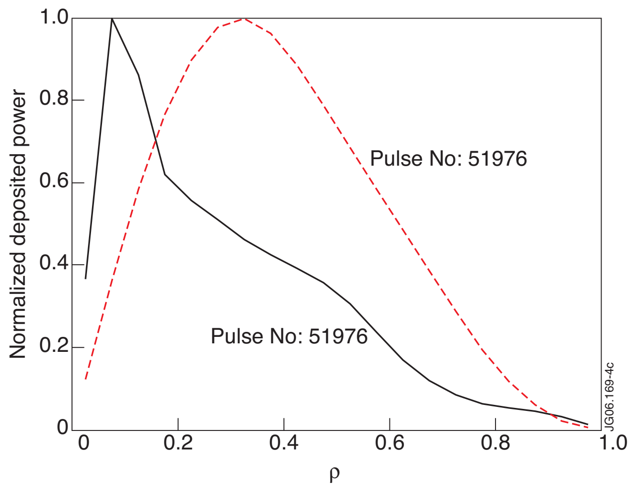

Figure 4: The power (W) deposited to plasma by fusion alphas. The values are normalized to maximum value.

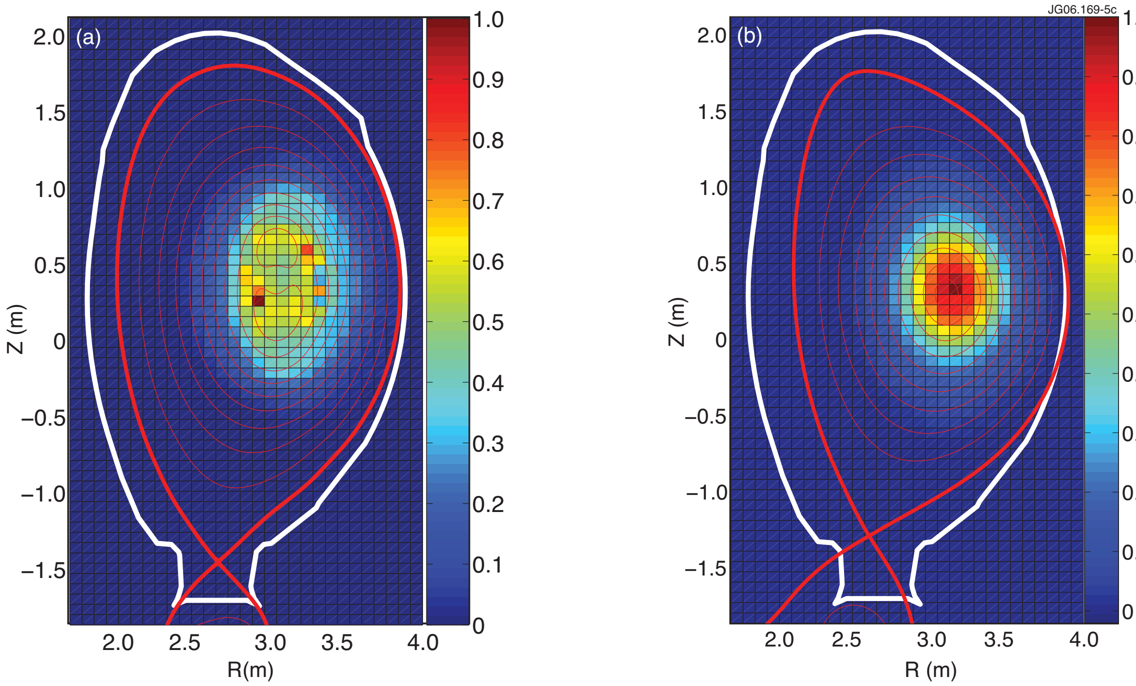

Figure 5: Poloidal distribution of the alpha heating power density (W/ m^3) for a) an ITB discharge, and b) an H-mode discharge. The power is normalized to its maximum value.