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Confinement of Fusion Alphas in ITB Plasmas

T. Kurki-Suonio, V. Tulkki, S. Sipilä, and R. Salomaa

Association Euratom-Tekes

Helsinki University of Technology, P.O. Box 2200, FIN-02015 TKK, Finland

Introduction

The successful operation of a fusion reactor relies on sufficient confinement of the fusion-born alpha particles. If the alphas escape the plasma before they have transferred a significant amount of their energy to the background plasma, fusion conditions can not be maintained in an economical fashion. The fusion alphas, born at the energy of 3.5 MeV, can have very wide orbits, of the order of the minor radius of the fusion device. These orbits become particularly worrisome in the case of so-called internal transport barriers (ITB) [1]. On the other hand, an ITB provides a particularly high performance plasma because it suppresses turbulence fairly deep inside the main plasma. This results in a transport barrier at such a location, allowing very high density and temperature values in the very core of the tokamak, thus facilitating favorable conditions for fusion to occur.

So far, ITBs have only been produced in plasmas with very low or, preferably, reversed magnetic shear. This can only be achieved with very small current in the plasma core, or even a current hole [2]. Unfortunately, the radial widths of the particle orbits are 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 plasma current, the confinement of fusion-born alphas becomes a big concern.

Orbits of 3.5 MeV alphas with normal and reversed q_s-profile

When a particle has a very high energy it can happen under certain conditions that the gradient drift dominates the particle's 'natural' velocity. The gradient drift then pulls the particle across the equatorial midplane before the particle reaches the turning points of its banana orbit. The resulting orbit is called a *potato orbit*, and for ordinary tokamak plasmas with monotonic current density profile such orbits exist only very close to the magnetic axis, occupying a negligible volume, and are thus only of marginal interest.

For fusion alphas the situation is quite different because the magnitude of the gradient drift depends also on the particle energy. Figure 1 shows the potato orbit for a 3.5 MeV alpha launched at r = 0.1 m. The orbit, whose width exceeds 10 cm, was calculated for JET-size, circularly symmetric plasma with I_p = 1 MA, B_T = 2.5 T, and normal q_s-profile shown in Fig. 2(a).

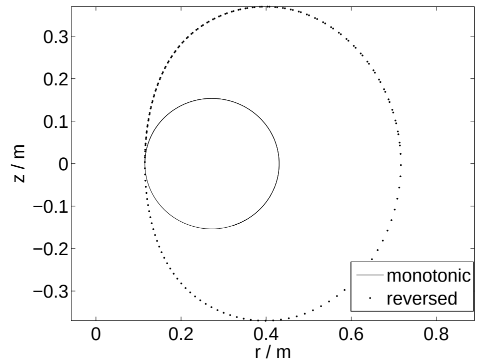

Figure 1: Potato orbits for an 3.5 MeV alpha particle with monotonic (solid line) and reversed (dotted line) q_s-profile. Due to the smaller poloidal magnetic field in the plasma core, in the reversed case the orbit is significantly wider than in the normal, monotonic case.

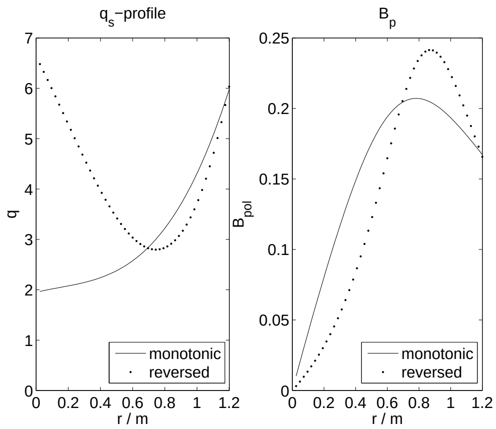

Figure 2: The radial profiles of (a) the safety factor q_s, and (b) the poloidal magnetic field B_p for normal (solid line) and reversed (dotted line) configuration.

Figure 2(a) also shows a reversed q_s-profile corresponding to the same global parameters, typical of a discharge with an ITB. The corresponding profiles of the poloidal field are displayed in Fig. 2(b).

For fusion alphas the potato orbits can thus be very wide, while for thermal ions the width of a potato orbit is usually minuscule. Furthermore, as seen from Fig. 1, the potato orbits are significantly wider with reversed shear than with a normal q_s-profile. This is not, however, the case everywhere in the plasma. Figure 3 shows orbits of 3.5 MeV alphas, launched under the influence of the reversed q_s-profile. The orbits originate at different radii along the equatorial plane and all have the initial pitch of 0.5. It is observed that the orbits curve towards the edge of the plasma instead of the center, which is what one would expect from the direction of their initial parallel velocity $v_{||}$. Figure 3 also displays the orbit of a thermal particle which exhibits this behaviour. An important observation is that the orbit widths shrink strongly when the starting point is moved further out from the plasma centre. As the distance of 0.53 m from the plasma center is reached, the orbits have become nearly nonexistent, with a width of the order of 1 mm.

Orbit domains in an ITB plasma and quenching of alpha losses

The reason behind the orbits' shrinking is the competition between the poloidal component of the particle velocity and the gradient drift.

Figure 4 shows the region in which gradient drift dominates for both (a) normal and (b) reversed q_s-profile of Fig.2(a). The areas of different velocity dominions are shown in the plot.

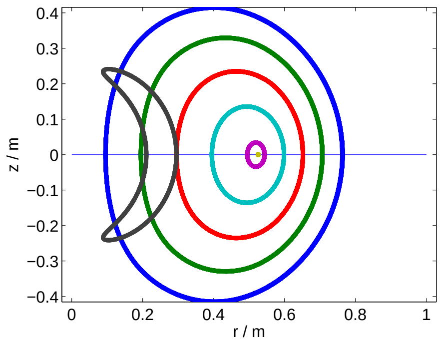

Figure 3: The particle trajectories, calculated by ASCOT [3], for 3.5 MeV alphas with $v_{\parallel}/v = 0.5$ at the equatorial plane. For comparison, the orbit of a thermal alpha, launched at r = 0.3 m, is also displayed. The remarkable observation is the dramatic shrinking of the orbit width as the alpha particle's birth location moves further away from the magnetic axis.

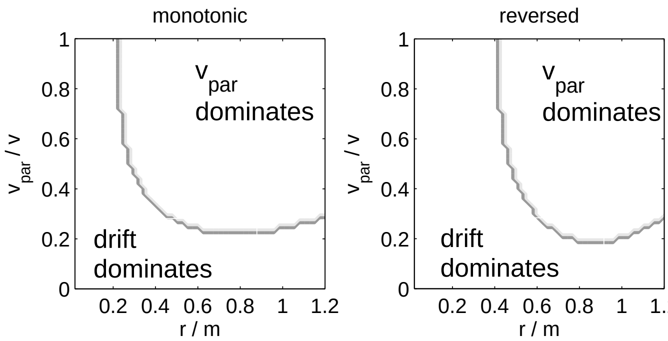

Figure 4: Orbit domains for 3.5 MeV alpha particles with normal (a) and reversed (b) q_s-profile. The region where gradient drift dominates the particle's natural velocity is on the lower left corner of the plots.

Near the axis there exist areas of plasma where the drift dominates at all pitch values. This drift-dominant area is far larger for the reversed q_s-profile than for the normal one. The most interesting region is the area in which the drift and the natural velocity are almost equal in magnitude. This is the border between the different areas. There the velocities cancel out, the particle motion in vertical direction is slowed down considerably, and the orbits become very thin. It is important to notice that the orbit widths become, in fact, smaller than those of thermalized alphas, and thus this 'barrier' is energy selective.

Even for monotonic q_s-profile, regions of dominant drift exist but, as discussed earlier, they occupy a much smaller volume in the plasma center than in the reversed q_s-profile case. As we see from Fig. 3 the orbit width shrinks as the region of equal velocities is approached. This region of small orbit width is far deeper in monotonic q_s-profile plasmas than in the reversed q_s-profile case.

The discussion above concerns alphas that are born with their poloidal velocity component opposing the gradient drift, so that there is a competition. For alphas born with a poloidal velocity component adding to the gradient drift the picture is very simple and unfortunate: these alphas are rapidly lost to the walls. For normal q_s-profile about 70% of these particles were lost to the walls in this JET-size configuration, while the fraction was 90% for reversed q_s-profile.

Conclusions

We found that in ITB plasmas about half of the fusion alphas ought to be unexpectedly well confined as long as their energy remains high. The improved confinement results from the competition between the particle's natural velocity and the gradient drift. For alphas with natural velocity opposite to the gradient drift, even if they are born on very large orbits, diffusion — be it neoclassical or anomalous — brings them ever closer to the region of very low shear where their natural orbit width shrinks and their transport outwards is dramatically reduced. This allows them to deposit most of their energy in a reasonably wide region inside the transport barrier, which is highly desirable because it 1) sustains fusion conditions, 2) increases bootstrap current needed to maintain the ITB, and 3) reduces fast ion damage to the chamber walls.

Acknowledgment

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References

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