Contribution ID: **897** Type: **Regular Poster**

PROGRESS IN UNDERSTANDING ALPHA CHANNELLING

Tuesday, May 11, 2021 12:10 PM (20 minutes)

Background. Alpha channelling [1] is a mechanism to deposit the energy of the fusion-generated alpha particles directly into the bulk ion population through wave-particle interaction. The alpha-channelling mechanism relies on the interaction between the fusion alphas and a high-frequency wave (typically an ion Bernstein wave (IBW) obtained via mode conversion of a Fast Wave injected by an external antenna) that extracts the kinetic energy associated with perpendicular motion through a resonant interaction that breaks the magnetic moment. The crucial point is that diffusion in velocity and diffusion in space are tied together. Thus, the extraction of alpha particle energy by the IBW is associated with a radial displacement of the alpha particle towards the plasma edge but this requires unrealistically high toroidal mode numbers. In Ref.[1] it was proposed to overcome this limitation by using an additional low-frequency wave (e.g. a mode belonging to the shear Alfvén branch) to facilitate the transport of the alphas across the minor radius and possibly allow the extraction of the kinetic energy associated with the alpha particle parallel motion.
Methodology. An analysis has been performed to understand the details of the mechanism and provide a solid foundation to a possible experimental demonstration. The alpha channelling dynamics has been separately described in two domains in phase space[2,3]: a domain in which the IBW quasi-linear diffusion dominates and the effect of the Alfvén wave can be neglected and the complement to such a domain in which the Alfvén wave dominates. The explicit form of the alpha particle distribution function has been obtained in the IBW dominated region. This region corresponds to a vertical strip in the (R, Z) plane, located between the IBW mode conversion radius R=RMC and the absorption radius R=Rabs. The plasma edge behaves as an absorbing boundary for particles with E, μ and Pφ values such that they intersect the surface ψ=ψwall, with ψ the poloidal flux. The solution has been obtained via a multiple time scale analysis. The effect of the low frequency wave is described through an imposed outward radial flux Q at the boundary in velocity space μ=μmin with wave-particle interaction occurring for μ≥μmin.
Results. It has been shown that the outward flux is the most effective control parameter of alpha channelling [2]. By varying Q between zero and the maximum flux associated with the alpha particle production, it is possible to obtain an amount of alpha channelling between 20% and the theoretical maximum of 66%. More important, the maximum alpha channelling is obtained at values of the IBW toroidal mode number that are consistent with what is achievable in experiments (nφ≤30). The problem of "hard landing" (alpha particle ejection at the plasma boundary before all the energy is released) has been also considered showing that the direct losses (i.e. those due to IBW-induced diffusion from the centre to the plasma boundary) can be reduced to arbitrarily small values by lowering the toroidal wave number.
The theoretical results have been benchmarked with the Monte Carlo simulation using the ORBIT code [4]. The simulation has been carried out so far without the effect of Alfvénic instabilities and shows a cooling of the alpha particle population and negligible fast particle losses (although at energies higher than the birth energy), in line with the theoretical results. However, the cooled down distribution tends to accumulate in the plasma core and so far an Alfvén mode spectrum capable of extracting the alpha particles has not been found.
The theoretical distribution function has been used as input both to the XHMGC and HYMAGYC codes [5] to determine self-consistently the amount of radial flux due to the Alfvénic instabilities generated by the alpha particle distribution function (as modified by the IBW). It has been found that this distribution function is unstable with respect to Alfvén, much more than the unperturbed slowing down distribution. Fluxes have been computed after Alfvén mode saturation. Three different quantities are relevant for the model: the flux at the μ=μmin surface, the flux at the mode conversion surface, ψ=ψmc , and the flux at ψ=ψwall. The latter quantity comes out to be almost negligible in all the simulations performed. The other two quantities, whose difference should be compared with the expected value of Q, are of the same order of magnitude and, separately, much larger than that value. Moreover, the results strongly depend on the toroidal and poloidal numbers retained, for the Alfvénic modes, in the simulations, as well as on the equilibrium parameters. These preliminary findings may suggest that the effect of the Alfvénic modes may lead to a bursting behaviour rather than to a steady state flux. An estimate of the linear growth rate of the Alfvénic modes with the modified alpha particle distribution function has been made using perturbation theory. There are two competing effects. On one hand the alpha particles are flushed out by the IBW induced diffusion and this reduces their driving effect.

On the other hand a gradient in the alpha particle density is formed at the inner side of the IBW dominated region that tends to drive the mode strongly unstable.

The conditions that the mode converted IBW has to satisfy in order to avoid electron Landau damping and be absorbed by the thermal ions have been determined by solving the IBW ray equations up to the cyclotron resonance. The analytic results (benchmarked with the numerical solution of the ray trajectories) can be expressed in the form of a criterion that involves a quadratic combination of the ray poloidal angle and of the ray parallel wave number at the mode conversion layer. In order to have negligible absorption, both these quantities must be sufficiently small. This means that the poloidal extension of the fast wave antenna must be limited (corresponding to an extension of ˜1m for ITER parameters) and that a spectrum with a mθ ˜q nφ must be produced.

Possible scenarios for burning plasma conditions have been investigated [3]. In this case the injected fast wave has a frequency slightly below the deuterium ion cyclotron frequency at the plasma edge, it is mode converted to an IBW near the deuterium-tritium hybrid resonance and it is absorbed at the tritium cyclotron resonance. A parameter scan in the position of the mode conversion layer has been performed using ITER parameters to determine the set of parameters that maximize the alpha channelling effect.

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Session Classification: P1 Posters 1

Track Classification: Magnetic Fusion Theory and Modelling