

STABLE OPERATING REGIMES IN NET WITH RESPECT TO ALFVEN WAVE
INSTABILITIES DURING NEUTRAL BEAM CURRENT DRIVE

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Supra-thermal ions can contribute to the steady-state current in future large tokamak machines like NET or ITER. The fast-ion population is generated by collisional slowing-down of high-energy ions which were injected as neutral atoms in quasi-tangential direction and ionized by plasma interactions. Depending on the initial beam shape these fast ions can excite microinstabilities of the Alfvén-wave type which are driven by the gradients in velocity-space. The ensuing plasma turbulence is expected to slow down the fast ions very quickly. This effect reduces the current drive efficiency which otherwise is comparable to that of other current drive schemes like lower hybrid waves where the toroidal current is carried by high-energy resonant electrons.

According to linear theory one type of this class of instabilities is excited when the following two criteria are violated at the same time: (1) the fast ion velocity component parallel to the magnetic confining field is lower than the local Alfvén-speed v_A :

$$v_{b\parallel} < v_A = \sqrt{B^2/\rho \cdot \mu} \quad (1)$$

where ρ is the mass density of the plasma $\int n_i m_i$. (2) The energy density stored in the fast ion population, normalized to the energy density of the thermal plasma, remains below a certain threshold:

$$\frac{n_b \cdot E_b}{3/2 \cdot (n_e T_e + n_i T_i)} < C \cdot v_b/v_e \quad (2)$$

where v_b and v_e are the velocities of the beam ions and thermal electrons, resp., and C is a number which depends on details of the shape of the injected beam, and is likely to exceed 4 [1]. The energy density in the fast ions grows linearly with the power $P_b = (E_b \cdot I_b)$ of the injected neutral beam. The two stability conditions can be re-formulated when referring to typical plasma scenarios which are anticipated for neutral beam current drive in NET and for which the deposition of neutral beam power and particles was calculated numerically [2]. In particular, for the injection of a beam of neutral deuterium atoms of energy E_b in a DT-plasma with $Z_{\text{eff}} = 2$ (fully ionized carbon) one has for the condition of eq. (1):

$$E_b < 207,3 B^2/n_i, \quad (3)$$

where E_b is in keV, B in Tesla, n_{10} in units of 10^{19} m^{-3} . The second condition eq. (2) can be expressed by using a relation from [3] for the average energy density of the fast ions (assuming $n_{eT} = n_i T_i$):

$$\frac{P_b}{e \cdot V_p} \cdot H(n_e, E_b) \frac{\tau_{se}(T_e, n_e)}{6 \cdot n_e \cdot T_e} \cdot G_e(E_b/T_e, \tau_{se}/\tau_{cx}) < 4 \cdot \frac{v_b}{v_e} \quad (4)$$

Here V_p is the plasma volume, H is the radial deposition profile, or "shape-factor" of Ref. [2], describing the local production rate of fast ions in this particular plasma-beam configuration, τ_s is the Spitzer ion-electron momentum exchange time, G_e is the electron energy-transfer factor, it is a function of E_b/T_e and τ_{se}/τ_{cx} , where τ_{cx} is the lifetime of a fast ion before it leaves the fast-ion population via a charge exchange collision with either a neutral fuel atom or a partially ionized impurity ion, or via radiative recombination with a plasma electron. If we assume these processes to be sufficiently frequent, G_e varies rather slowly with (E_b/T_e) in the parameter range of our interest [3], hence we can set it constant: $G_e = 0.15$. We now re-write eq. (4) to show the dependences on the main beam and plasma parameters:

$$\frac{P_b \cdot T_e}{E_b^{1/2}} \cdot H(E_b/n_e) < C^* \cdot n_e^2 \quad (5)$$

where C^* is another numerical constant. When comparing the two stability criteria, eqs. (3) and (5), with respect to their explicit density dependences, two opposite trends become apparent: eq. (3) favours low-density operation by allowing to raise the beam energy prop. n_e^{-1} , eq. (5) favours high-density scenarios since the right-hand side grows as n_e^2 . Hence, by combining the two criteria into one we might expect to find a region in parameter space where the risk of exciting Alfvén-wave instabilities becomes independent of plasma density.

Using the NET model plasma of Ref. [2] and the deposition calculations based thereupon for quasi-tangential injection (40° with respect to the major radius direction), we have evaluated the two local criteria point by point along the minor radius for a number of scenarios. It turned out that the ratio of energy densities (cf. eq. (4)) decreases monotonically outwards from the plasma centre owing to the fact that the deposition profiles peak on axis (except for very high plasma densities and very low beam energies). This implies that the condition on energy densities is fulfilled everywhere in the plasma when it is satisfied at its centre. In addition, the data of Ref. [2] show that the central deposition rates $H(0)$ have a smooth dependence on the ratio (E_b/n_{e0}) tending towards saturation (or even descent) beyond the maximum value considered in [2], namely $E_{b,0}/n_{e,0} = 10/7,5$, where the deuteron beam energy is in units of 0,1 MeV, and the electron density in 10^{19} m^{-3} . In the following calculations we assume a constant value of $H(0)$ for higher (E_b/n_e) -values (which is an even more pessimistic approach). The above relation between H and E_b/n_e is now used to establish the stability criterion eq. (4) in the (E_b, n_e) -plane, see Fig. 1. Here we show, as an example, the curves labelled

(1) and (2) for two different values of the product ($P_b \cdot T_e$): stability is ensured on the right-hand, high-density side of either curve. Another border-line between areas of stability and instability in the (E_b, n_e)-plane is defined by the condition that the particle velocity is smaller than the Alfvén-velocity, cf. eq. (3). It is plotted in Fig. 1 as the curve $E_b(v_A)$ for $B = 5$ Tesla: the parameters for stable operation are in the hatched part below the curve. By combining both sets of curves we find a "stability-diagram" of the beam-plasma configuration in NET, for which the deposition calculations of Ref. [2] were made. It can be interpreted as follows: both conditions, eqs. (3) and (5), must be violated at the same

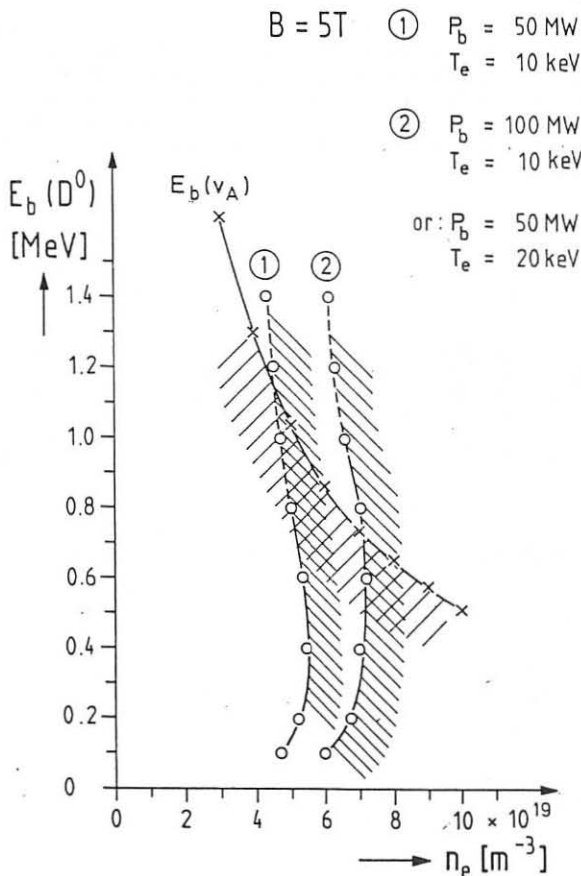


Fig. 1

time for an unstable situation to arise. Hence, in the low-temperature case there is stability at all densities for deuteron beam energies below 1,13 MeV, or for all beam energies as soon as the density is higher than $5,5 \cdot 10^{19} \text{ m}^{-3}$. In the high-temperature case we find stability at all densities if the beam energy is below 0,75 MeV, or alternatively, with all beam energies for densities higher than $7,2 \cdot 10^{19} \text{ m}^{-3}$. If one wanted to work with a higher deuteron energy in the high-temperature case, say 1 MeV, one has to accept the risk of instabilities in the density range between $5,2 \dots 6,6 \cdot 10^{19} \text{ m}^{-3}$. If theory would predict a lower number for the numerical constant C in eq. (2), higher plasma densities are needed for stability, hence the two curves (1) and (2) in Fig. 1 are shifted to the right.

In summary: for a given beam plasma configuration with fixed values of the magnetic confining field B and of the product $(P_b \cdot T_e)$, we can identify numbers of the beam energy E_b and of the plasma density n_e , for which no Alfvén-wave instability occurs. The exact location in parameter space of these stable operating regimes depends on the number value of the constant C in eq. (2) and, to a lesser extent, on the lifetime τ_{CX} of the fast ion during slowing down.

REFERENCES:

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