Formation of a non-monotonic energy distribution of energetic ions in NSTX

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Introduction. The energy distribution of fast ions, $F_b(E)$, is normally monotonically decreasing because of Coulomb collisions. However, experiments on the NSTX spherical torus have shown that a big bump on $F_b(E)$ – so-called "high-energy feature" (HEF) – can arise at the maximum energy of injected ions (E_b) and pitch angles $\chi \equiv V_{\parallel}/V \sim 0.7-0.9$ (V is the particle velocity) in discharges with NBI power $P_{inj} \geq 4$ MW during high frequency Alfvén instabilities [1]. This work is aimed at elucidation of physics of the HEF.

Mechanisms of HEF formation. The energy E_b in NSTX well exceeds $(M_i/M_e)^{1/3}T_e$, where T_e is the electron temperature, $M_{i/e}$ is the ion/electron mass. In this case, the main effect of the Coulomb collisions on the beam ions is the drag produced by the electrons, whereas effects of the ion drag and the pitch-angle scattering are small. Neglecting the scattering leads to $F_b(E) \propto E^{-3/2}$. However, strictly speaking, this neglect is justified only when the energetic-ion source is isotropic in velocity space. Otherwise, Coulomb scattering leads to a depleted particle population at the pitch angles of injection (χ_{inj}), thus decreasing the slope of $F_b(E)$ at $\chi = \chi_{inj}$. If the scattering were sufficiently strong, a HEF could arise. Specific calculation is required to clarify the role of the pitch-angle scattering in the NSTX experiments. For this purpose we use the following equation [2]:

$$\frac{\partial F_b}{\partial t} = \frac{1}{\tau_s^e V^2}\frac{\partial}{\partial V}\left[\left(V^3+V_c^3\right)F_b\right] + \frac{\alpha}{\tau_s^e}\frac{V_c^3}{V^3}\frac{\partial}{\partial \chi}\left(1-\chi^2\right)\frac{\partial F_b}{\partial \chi} + S(r,V,\chi) + \frac{1}{r}\frac{\partial}{\partial r} r D_r \frac{\partial F_b}{\partial r}, \qquad (1)$$

where τ_s^e is the fast ion slowing down time caused by electrons, $S(r,V,\chi)$ is the source term describing the injection, r is the radial coordinate, the last term describes the radial diffusion with the diffusion coefficient D_r, $V_c \propto \left(M_e/M_i\right)^{1/3} V_{Te}$, $\alpha \sim 1$. Solving Eq. (1) with $D_r = 0$, we find that the energy dependence of the injected ion distribution at $\chi = \chi_\mathrm{inj}$ is considerably weaker than $E^{-3/2}$. Numerical modeling with the TRANSP code, which includes the classical diffusion, confirms this, giving even a weaker dependence of F_b on E, but still $\partial F_b / \partial E < 0$. Thus, Coulomb pitch-angle scattering in the NSTX experiments was not sufficient to produce the HEF.

Alfvén instabilities in the discharges where HEFs were observed can be divided into three groups: (i) low frequency (LF) instabilities with the frequencies in the range of f ~ 20–100 kHz; (ii) high frequency (HF) instabilities with $f \sim 500-1000$ kHz; (iii) very high frequency (VHF) instabilities, 1–2 MHz. Maxima of the perturbed magnetic field (δB) at the plasma edge during HF-instabilities correlate with the HEF formation and correspond to minima of δB associated with LF-instabilities. This indicates that HF-instabilities are responsible for the HEF. Because the signals of HF instabilities on Mirnov coils were rather weak, it is likely that HF instabilities were core localized. Global Alfvén Eigenmodes (GAE) rather than Compressional Alfvén Eigemodes (CAE) because CAEs are normally located at the plasma periphery.

We investigate the influence of HF instabilities on $F_b = F_b(E, \mu, r, t)$ (μ is the particle magnetic moment) by means of a bounce-averaged equation of quasilinear (QL) theory given in Ref. [3].

The waves affect the circulating particles through the resonance $\omega = \left(1 + s\lambda^{-1}\right)k_{\|}V_{\|} + l\omega_B$, where s and l are integers, $\lambda = k_{\|}qR_0$, q is the safety factor, R_0 is the major radius of the torus, $k_{\|}$ is the longitudinal wave number, ω_B, is the gyrofrequency.

Let us first consider effects of the $l = 0$ resonance. Analysis shows that the HF instabilities can affect $F_b(V)$ at $V \sim V_b$ due to the $s > 1$ resonances. For instance, for $s = 2$ and $V_{\|}/V_A = 2$ we obtain $\lambda = 4$ from the resonance condition, which corresponds to $f = 640/q$ kHz in the case of $\omega = k_{\|}V_A$, with V_A the Alfvén velocity. This is within the frequency range of the HF instabilities. On the other hand, the QL-diffusion with $l = 0$ conserves μ. Therefore, like Coulomb pitch-angle scattering, it competes with the collisional drag, for which $\chi \approx \text{const}$. This means that the QL-diffusion in the velocity space tends to produce the HEF provided that there are resonances for $V \sim V_b$. Moreover, as seen from Fig. 1, it may lead to two kinds of HEF. One of them, HEF-1, is characterized by a depleted velocity region with $V < V_b$ at $\chi \cong \chi_{\text{inj}}$. HEF-2 arises at $\chi > \chi_{\text{inj}}$. This means that $F_b(V \approx V_b)$ exceeds that in the absence of the waves in the case of HEF-2.

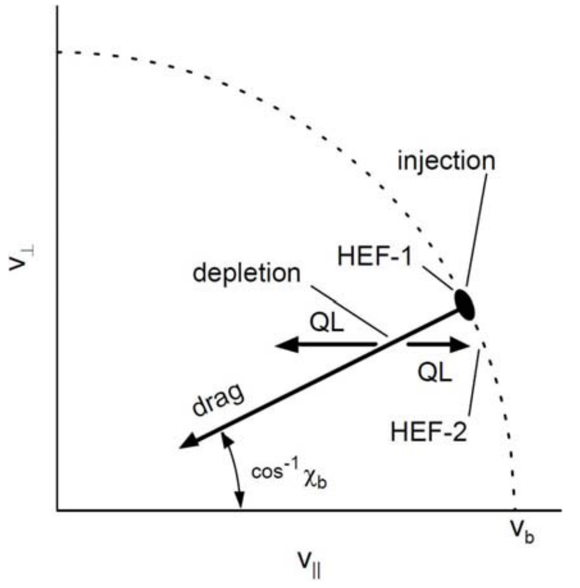

Fig. 1. Sketch explaining the formation of the HEF-1 and HEF-2 due to QL-diffusion in the velocity space when $\mu = const$.

We found numerically, that the considered mechanism cannot explain the formation of HEFs with large height, $H \equiv F_{b,\max} / F_{b,\min} \sim 10$, which were observed in many NSTX discharges. Taking into account the $l = 1$ resonance does not change this conclusion.

It is known a strongly non-monotonic $F_b(E)$ arises when the confinement time of the fast ions (τ_n) is very small, $\tau_n << \tau_s$ [4]. However, when $\tau_n << \tau_s$, almost all the injected energy is lost to the wall. Clearly, this was not the case in the NSTX experiments. On the other hand, as follows from the QL-equation, the radial diffusion is accompanied by the velocity diffusion, so that

$$\frac{\Delta r}{\rho} = k_g \rho \frac{\omega_B}{2\omega} \frac{\Delta E}{E}, \qquad E = E_b \exp\left[-\frac{\omega}{l\omega_B} \left(\chi^2 - \chi_b^2 \right) \right], \tag{2}$$

where $l \neq 0$, $\rho = V / \omega_B$, $\Delta E = E_b - E$. For instance, when $\Delta E / E \sim 0.1$, $l = 1$, and a particle is displaced by $\Delta r \sim 10$ cm, the particle pitch angle changes by $\Delta\chi \sim 0.2$ provided that $f \sim 700 - 1000$ kHz and $k_g \rho = 3 - 4$. This estimate and calculation by the code ORBIT show that particles observed by NPA (the distance from the major axis of the torus is $R = 78$ cm and $\chi \sim 0.7$) can reach the limiter and be lost. The wave amplitudes should be sufficiently large to provide the inequality $\tilde{D}_\chi \equiv D_\chi \tau_s^e > 1$ where D_χ is the pitch-angle diffusion coefficient. Let us see whether it can be satisfied. Using an explicit form of D_χ given in Ref. [58] and taking $l = 1$, we obtain:

$$\tilde{D}_\chi = \pi \omega \tau_s^e \left(\chi^{-2} - 1 \right) \left(\frac{L_n}{2\rho} \frac{\omega_B}{\omega} \frac{\delta n_e}{n_e} \right)^2 \tag{3}$$

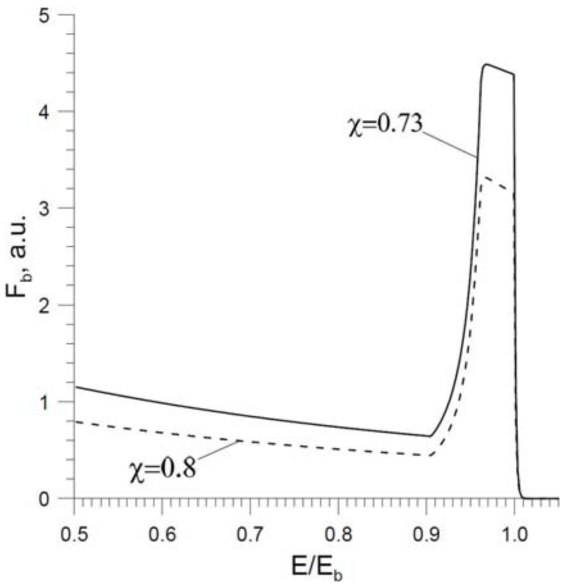

Fig. 2. Modelling of quasilinear $F_b(E)$-distortion accompanied by the loss of some particles in NSTX.

where δn_e is the perturbed electron density, $L_n = |d \ln n_e / dr|^{-1}$. We find that the $\tilde{D}_\chi \sim 5$ when $\delta n_e / n_e \sim 2\times 10^{-4}$ in the instability region.

Due to the fact that the QL-characteristics at $l = 1$, $\omega_B / \omega >> 1$ are close to $V = \text{const}$, we can model this mechanism by Eq. (1) with artificially large pitch-angle scattering parameter α in the assumption that $D_r = 0$ and that particles are lost at a certain pitch angle due to pitch-angle diffusion. The result of the calculation is shown in Fig. 2. We observe that a HEF with $H \approx 7$ is formed, that corresponds to, e.g., the HEF in the NSTX discharge SN132800. Note that because the particles move along the characteristics determined by Eq. (2), even a very large radial diffusion coefficient does not lead to the escape of particles from the core region to the wall.

Summary. Coulomb pitch-angle scattering makes the dependence of F_b on E at $\chi \sim \chi_{inj}$ much weaker than $E^{-3/2}$. The instabilities affect $F_b(E)$ in various ways. Most of mechanisms lead to small bumps, with $H = F_{\max} / F_{\min} \sim 1$. The only found mechanism leading to large H in NSTX is the quasilinear evolution of $F_b(E, \chi, r)$ in the phase space and the concomitant loss of some particles, which occurs due to the cyclotron interaction of the particles with destabilized modes having sufficiently high frequencies, $f \sim 700 - 1000$ kHz. The calculated wave amplitudes required are quite reasonable.

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