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Effect of the Radial Electric Field on the Confinement of NBI Ions in Wendelstein 7-X

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Introduction. The purposes of this work are (i) to study the confinement of the energetic ions in the presence of the radial electric field in W7-X, (ii) to develop a numerical code describing the orbits in stellarators, (iii) to visualize numerically calculated orbits for subsequent implementation of the developed tool to "a virtual stellarator" [1]. This research is motivated as follows.

There will be several sources of the energetic ions in W7-X. They are the Neutral Beam Injection (NBI), Ion Cyclotron Resonance Heating (ICRH), and Negative-ion-based Neutral Beam Injection (NNBI) on the later stage of operation, which will provide the plasma heating [2]. In addition, it is planned to install an NBI injector for the diagnostics [3]. Thus, energetic ions with various energies and pitch-angles will be produced in W7-X plasmas. It is known that the basic idea to provide a good confinement of the energetic ions in Wendelstein-line stellarators is to achieve a reactor relevant β (the ratio of the average plasma pressure to the magnetic field pressure), $\beta \sim 5\%$ [4]. On the other hand, a similar influence on the energetic ions may produce the radial electric field (E_r) provided that it is sufficiently strong. A simple estimate based on the assumption that $e|\Phi| = T = 2 - 3$keV (Φ is the scalar potential of the electric field, T is the plasma temperature) leads to $E_r \sim 5$ kV/m in the whole plasma volume in W7-X. In reality, the electric field can be much stronger, especially, the local electric field in the region of the transport barriers. For instance, $|E_r| = 20$ kV/m was generated during perpendicular NBI in W7-AS [5]. One can expect that such electric fields will affect the confinement of the energetic ions in W7-X, especially, the particles with small pitch angles.

Basic equations and the code ORBIS. We are interested in the particle motion in a stellarator magnetic field, $\mathbf{B}(\mathbf{r})$, and a radial electric field. We choose the flux coordinates r, ϑ, φ, where r is defined by $\psi = B_0 r^2/2$, with ψ the toroidal magnetic flux and B_0 the average magnetic field at the magnetic axis; ψ, ϑ and φ being the Boozer coordinates. For this case, we obtained the following guiding center equations:

$$\dot{x} = -v_d \frac{R_0}{a^2 x B} \frac{\partial B}{\partial \vartheta}, \quad \dot{\vartheta} = \iota\, \omega_{B0} \frac{\rho_\parallel}{R_0} \left(\frac{B}{B_0}\right)^2 + \frac{v_d R_0}{a^2 x B} \frac{\partial B}{\partial x} + \Omega_E,$$

$$\dot{\varphi} = \omega_{B0} \frac{\rho_\parallel}{R_0} \left(\frac{B}{B_0}\right)^2, \quad \dot{\rho}_\parallel = -\frac{v_d}{B} \left(\frac{\partial B}{\partial \varphi} + \iota \frac{\partial B}{\partial \vartheta}\right), \tag{1}$$

where $x = r/a$, a is the average plasma radius, $\Omega_E = -cE_1/(B_0 r)$ is the frequency of the electric-field-induced motion in the poloidal direction, $\iota = B^2/B^3$ is the rotational transform, the superscripts and subscripts denote the contra-variant and co-variant vector components, respectively, R_0 is the large radius of the torus, v_d is the "tokamak" drift velocity given by $v_d = \left[\rho_\parallel^2 + \lambda \mathcal{E}_0 B_0/(M\omega_{B0}^2 B)\right] (B/B_0)^2 \omega_{B0}/R_0$, $\lambda = \mu_p B_0/\mathcal{E}_0$, $\mathcal{E}_0 \equiv \mathcal{E}(t=0)$, $\mathcal{E} = Mv^2/2$, $\omega_{B0} = eB_0/(Mc)$; $\rho_\parallel$ at the initial moment is $\rho_\parallel(t=0) = \sigma \omega_{B0}^{-1} B_0/B \sqrt{2\mathcal{E}_0/M} \sqrt{1 - \lambda B/B_0}$, σ is the sign of the particle velocity along the magnetic field. Note that Eqs. (1) neglect the influence of the small components of the magnetic field, B_1 and B_2, on the particle drift motion.

In order to solve Eqs. (1) a code ORBIS (Orbits in Stellarators) was developed. The code solves the initial value problem. It uses the equilibrium data as input. The outputs are the graphical representation of the particle motion in the poloidal and toroidal cross-sections in Boozer coordinates, the orbits in real coordinates, the magnetic field along the particle orbits.

Qualitative analysis. Because the number of the field periods, N, well exceeds unity, the particle motion can be presented as a superposition of the "fast" motion and "slow" motion. Due to this, Eqs. (1) can be averaged over the fast motion, which leads to the following equations (we restrict ourselves to the consideration of the well trapped particles):

$$\dot{r} = u \sin\vartheta, \quad r\dot{\vartheta} = u \cos\vartheta + v_d R_0 \left(\epsilon_0' - \epsilon_h \epsilon_h'/\epsilon_H\right) + v_E, \tag{2}$$

where "prime" means the radial derivative, $v_E = r\Omega_E$, $u = (v_d R_0/r)\left[\epsilon_m \epsilon_h/\epsilon_H - \epsilon_t\right]$; ϵ_m, ϵ_h, ϵ_t, and ϵ_0 are main Fourier harmonics of the magnetic field (the mirror harmonic, helical harmonic, toroidal harmonic, and diamagnetic harmonic), $\epsilon_H = \epsilon_H[\epsilon_h, \epsilon_m]$ [6].

Let us assume that $E(r) = const$ and ϵ_m is a dominant harmonic. Then taking $\epsilon_0'(r) \approx const$ (which is justified in the region far from the magnetic axis) we obtain the following solution of Eqs. (2):

$$\frac{r}{r_0} \approx \frac{\delta + \cos\vartheta_0}{\delta + \cos\vartheta}, \tag{3}$$

where $\delta = (r\epsilon_0'/\epsilon_h)(\epsilon_H/\epsilon_m) + (v_E/u)$. It follows from Eq. (3) that when $|\delta| \gg 1$, a particle moves approximately along a flux surface. In contrast to this, a particle is quickly lost when $|\delta| \ll 1$: then $r\cos\vartheta \approx const$. This simple analysis demonstrates that the particles are well confined in the Helias configurations provided that ϵ_0' and/or v_E are large enough. In addition, it shows that when $E_r > 0$, the term associated with the electric field competes with the term proportional to the ϵ_0, which implies that the electric field may deteriorate the particle confinement.

Orbits of the beam ions in W7-X. Although NBI produces well-circulating ions (with the energy $\mathcal{E} \lesssim 60$ keV), a considerable amount of the trapped energetic ions ($\mathcal{E} \lesssim 30$ keV) will be present in W-7X, at least, in high-temperature regimes ($T \gtrsim 2$ keV) with $z_{eff} > 1$ (z_{eff} is the effective charge number). This conclusion is confirmed by our numerical calculations (we solved a kinetic equation for the distribution function of the beam ions neglecting the spatial diffusion), see Fig. 1. In addition, trapped particles will be directly produced by the diagnostic NBI.

Taking this into account, we calculated the orbits of the particles with both the injection energy and lower energy by the code ORBIS. We took the electric field term in Eq. (1) in the form: $\Omega_E = -\alpha v_{Ti}^2 f_E(x)/[2a^2\omega_B x]$, where $\alpha = const$, $\alpha > 0$ corresponding to $E_r > 0$, $v_{Ti} = \sqrt{2T_i/M}$; in particular, $\alpha = 1$ and $f_E(x) = 1$ correspond to a homogeneous electric field with $e|\Phi| \sim T_i$. It was found that even a weak negative electric field localized in the periphery region provides the confinement of those partly slowed down particles ($\mathcal{E} \sim 20$ keV), which quickly (for the time $\Delta t \ll \tau_s$, with τ_s the slowing down time) escape from the finite-β plasma of the "standard" W7-X shot with $E_r = 0$ (Fig. 2). On the other hand, we observed 54-keV protons that are confined in the absence of the electric field but escape from the plasma in the presence of a moderate positive electric field, in accordance with our qualitative analysis above. In addition, we observed that transitioning particles can either escape from the plasma for $\Delta t \lesssim \tau_s$ or only be radially displaced depending on the magnitude and the profile of $E_r(r)$. This implies that the stochastic diffusion responsible for the transport of these particles is considerably affected by the E_r-field.

Summary and conclusions. The code ORBIS (Orbits In Stellarators) for the investigation of the particle orbits in stellarators is developed. To show the orbits of the confined particles and lost particles clearly, their motion since the birth moment is visualized.

The effect of the radial electric field on the confinement of the NBI produced ions in W7-X is studied. The carried out analysis of the orbits of the energetic ions in the W7-X standard configuration has shown that the negative electric field always improves the confinement, whereas a positive electric field may lead to a quick loss of well-trapped particles from the plasma. A conclusion is drawn that the electric field affects also the transitioning particles. Because of this, a theory of stochastic diffusion [6] (the diffusion that is mainly responsible for the classical transport and concomitant loss of the energetic ions in optimized stellarators of the Wendelstein line) should be generalized to include effects of the electric field.

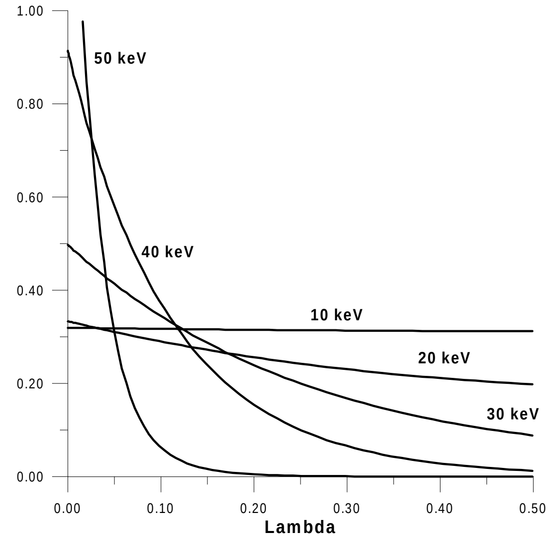

FIG. 1. *The λ-distribution of the protons with the initial energy $\mathcal{E}_0 = 55\ keV$ injected along the magnetic field ($\lambda = 0$) into a deuterium plasma with $T = 2\ keV$, $z_{eff} = 3$, and the oxygen impurity.*

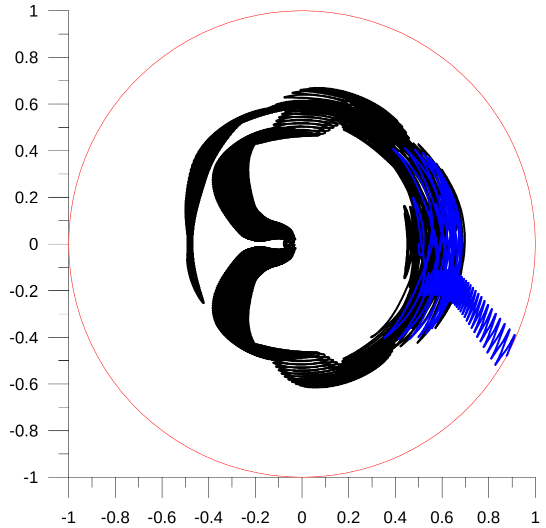

FIG. 2. *Motion of a 20-keV proton in the poloidal cross section of the standard W7-X configuration for $E_r = 0$ (in blue) for $\Delta t = 1.3ms$ and $E_r < 0$ (in black) for $\Delta t = 13ms$. We used $E(x) = -\widehat{E}e^{-(x-x_0)^2/\gamma^2}$, $\widehat{E} = 7\ kV/m$, $x_0 = 0.9$, $\gamma = 0.2$.*

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