§12. Study on Energy Spectra of NB-injected Fast Ion in LHD Plasmas by Means of Natural Diamond Detectors

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Energetic ion behavior is one of major concerns in heliotron and/or stellarator experiments because of the symmetry breaking of the system. We have so far measured energy spectra of NB-injected fast ion by use of charge exchange (CX) neutral particle analyzers based on the natural diamond in various magnetic configurations of LHD. In order to check whether fast ion behavior in LHD is consistent with that from the neoclassical prediction, we analyze perpendicular energy spectra of tangentially injected NB ions by the theoretical approach. In this work, in addition to the Coulomb collision term, the source term originated from NBI, CX loss and orbit loss terms are introduced into the kinetic equation which describes an evolution of distribution function f. Adiabatic invariants J used here are given by $J = J_0 + \delta J_1$ with

$$J_0 = \int \frac{\partial L}{\partial(\partial\phi/\partial t)} d\phi$$

where L is the Lagrangian which describes the free motion of the charged particle and the interaction between the charged particle and magnetic field in the guiding center approximation ;

$$L = \pm mu \frac{B_\psi}{B}\frac{d\psi}{d\phi} + \left(\pm mu \frac{B_\theta}{B} + \frac{e}{\delta}\psi\right)\frac{d\theta}{d\phi} + \left(\pm mu \frac{B_\phi}{B} + eA_\phi\right) - E\frac{dt}{d\phi}$$

Expanding the distribution function into the Legendre polynomial P_l, the solution of kinetic equation is derived analytically as

$$f(v,\xi) = \sum_{l=0}^{\infty}\left(l+\frac{1}{2}\right)\frac{\tau_s}{v^3+v_c^3}\exp\left(-\tau_s\int_v \frac{\alpha(v')}{v'\tau_{CX}}dv'\right) \times \sum_{n=1}^{4} S_n\sigma_l(v,\xi;v_n,\xi_n)P_l(\xi)$$

By comparing the energy spectra of fast ions calculated by this distribution function with those experimentally measured by a natural diamond detector (NDD) installed at a vertical diagnostics port, the validity of this solution is checked. We have computed the energy spectra for three different configurations (R_{ax}=3.53 m, 3.6 m and 3.75 m) and two models of magnetic field were adopted for each configuration. One (field model 1) is

$$B(\psi,\theta,\phi) = \overline{B}_0\left[\varepsilon_0(\psi,\theta) - \varepsilon_1(\psi,\theta)\cos(l\theta - m\phi)\right]$$

with

$$\varepsilon_0(\psi,\theta) = 1 + \varepsilon_a\rho\cos\theta$$

$$\varepsilon_1(\psi,\theta) = \sqrt{\left[\varepsilon_h + \left(\varepsilon_h^{-1} + \varepsilon_h^{+1}\right)\cos\theta\right]^2 + \left[\left(\varepsilon_h^{-1} - \varepsilon_h^{+1}\right)\sin\theta\right]^2}$$

The other (field model 2) is

$$B(\psi,\theta,\phi) = B_0\sum_{l,m}\varepsilon_{l,m}(\psi)\cos(l\theta - mN\phi)$$

An example of calculation for the cases of R_{ax}=3.75 m is shown in Fig. 1.

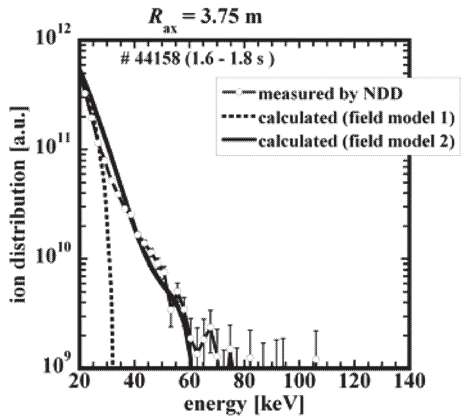

Fig.1 Comparison of the energy spectrum of fast ion computed by analytical solution with those measured experimentally by NDD installed at a perpendicular port for the cases of R_{ax}=3.75 m.

As can be seen, the calculation with the magnetic field model 2 reproduces experimental energy spectrum of fast ions, suggesting that fast ions behaves neoclassically in the LHD plasma. Detailed results were available in Ref. 1.

Energetic ion transport induced by kinetically driven MHD instabilities such as EPM and/or TAE[2,3] is also of our interests. Currently, we use a conventional circuit system consisting of a charge-sensitive preamplifier (CANBERRA-2001A) and a spectroscopy amplifier (CANBERRA-2024) for NDD. This combination is suitable for measurement of energy spectra of fast ions in quiescent steady state plasmas. However, in the viewpoint of counting rate capability, the present system is not suitable for TAE/EPM physics because the conventional circuit can not follow the rapid event induced by TAM/EPM instabilities due to the low counting rate capability (~2x10^5 cps). In order to overcome this situation, we have tested a new circuit, i.e. digital-signal-processor (DSP) in actual experiments of FY2006 instead of a spectroscopy amplifier. DPS can potentially increase the maximum counting capability over 1x10^6 cps. In the DPS system, all output pulses from the preamplifier are digitized in the sampling frequency of 100 MHz and are stored on a personal computer. Recorded pulses are subsequently analyzed to know pulse height for each pulse by use of software program and energy spectrum of fast neutrals are finally obtained. DSP showed energy spectrum of fast particles similar to that obtained from the conventional electronics. In FY2007, DSP will be applied to the TAE experiment to study fast ion transport induced by instabilities.

References

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