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Observation of neutron emission anisotropy by neutron activation measurement in beam-injected LHD deuterium plasmas

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Information of confined energetic ions can be obtained by the neutron measurement because neutrons are mainly emitted from the reactions between energetic and thermal ions in current deuterium plasmas.
The large helical device (LHD) has several neutron measurement systems, and energetic-particle physics studies have been performed based on the neutron measurement.
When the deuteron velocity distribution functions are anisotropic, the neutron emission spectrum also has an anisotropic angular distribution because the $\mathrm{D(d,n)^3He}$ reaction has a large anisotropy against the deuteron incident direction.
The neutron emission anisotropy may provide further understanding of energetic-particle physics in helical/stellarator devices; for instance, interaction between energetic ions and instabilities could be discussed from the point of view of the anisotropy of the energetic-ion velocity distribution function.
Energetic deuterons generated by neutral beam (NB) injection form the anisotropic slowing-down distribution function because NB is injected in a particular direction.
The LHD has three tangential and two perpendicular NB injectors.
We can produce some different anisotropic neutron emission spectra by changing combination of the NB injectors.

The shot-integrated neutron yield is measured with the neutron activation system (NAS) in LHD deuterium plasmas by exposing the activation foils and counting gamma-rays emitted from the irradiated foils.
The activation foils are sent by the pneumatic transfer system to two irradiation ends located at horizontal and lower ports.
The indium foil is employed for measurement of fast neutrons emitted by the $\mathrm{D(d,n)^3He}$ reaction by using the $\mathrm{^{115}In(n,n')^{115m}In}$ reaction which has a threshold energy of 336 keV.
Thermal neutrons can simultaneously be measured by using the $\mathrm{^{115}In(n,\gamma)^{116m}In}$ reaction.
When neutrons are anisotropically emitted, the ratio of the neutron flux at the horizontal port to that at the lower ports should be different from the case when neutrons are isotropically emitted.

In this study, we have observed the neutron emission anisotropy by the NAS in NB-injected LHD deuterium plasmas and performed numerical analyses.
We have conducted experiments to investigate the dependence of the neutron emission anisotropy on the NB-injection direction by comparing three injection patterns: use of only three tangential, only two perpendicular, and all NBs.
The clear difference of the ratio of the fast neutron flux [the reaction rate of $\mathrm{^{115}In(n,n')^{115m}In}$] at the horizontal to that at the lower ports between the cases of tangential and perpendicular injections was observed, whereas no difference of the ratio of the thermal neutron fluxes [the reaction rate of $\mathrm{^{115}In(n,\gamma)^{116m}In}$] was not seen.
We have calculated the reaction rates of $\mathrm{^{115}In(n,n')^{115m}In}$ and $\mathrm{^{115}In(n,\gamma)^{116m}In}$ by the MCNP-6 code.
The double-differential neutron emission spectra as the source spectra for the neutron transport analysis were calculated from the deuteron velocity distribution function and the differential cross-section of the $\mathrm{D(d,n)^3He}$ reaction.
The distribution function of energetic deuterons generated by NB injection was evaluated by following the guiding-center orbits of test particles.
The obtained numerical results is consistent in the dependence of the neutron anisotropy on the NB-injection direction with the observed experimental data.

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