# §17. Upgrade of ECH System and Improvement of Plasma Parameter by Applying High-frequency Gyrotrons in LHD

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NIFS collaboration research program with University of Tsukuba has been conducted for the sake of development of high power, long pulse, high frequency gyrotrons and improvement of plasma parameter in LHD by use of the gyrotrons. Following to the successfully accomplished former program which resulted in three 77 GHz and two 154 GHz gyrotrons actively working for LHD experiment, a plan of manufacturing next sixth high power gyrotron is ongoing.

In 2015, design of new antenna system for the next gyrotron was performed. According to the success of EC-wave beam injections from 2-O port, the power injection port for the next gyrotron was decided to be O port. Considering the existing routes of EC-wave transmission lines and the conditions of several O ports, 9-O port was selected. The antenna system was designed to consist of three mirrors: slightly convex mirror M3, focusing mirror M2, and plane 2-D steerable mirror M1, as one of the 2-O antenna systems 2-OUR.

Investigation on the design of the next gyrotron was also performed. A gyrotron with the ability of dual-frequency oscillation is an attractive candidate. A dual- or multi-frequency gyrotron is applicable for a wide range of magnetic field setting, and having various options of operating frequency extends heating scenarios, such as simultaneous second and third harmonic heatings. In LHD, not only the conventional fundamental ordinary mode (O1) and the second harmonic extraordinary mode (X2) heatings but also third harmonic extraordinary mode (X3) heating have been investigated to extend the plasma parameter region to higher $\beta$ and higher density.[1] Using 77 GHz EC-waves, the X2 heating is realized with the magnetic field $B$ = 1.375 T and the cut-off density is $3.7\times10^{19}$ m$^{-3}$, while the X3 heating is realized by lowering $B$ to 0.917 T but the cut-off density becomes higher to $4.9\times10^{19}$ m$^{-3}$. Meanwhile, if keeping $B$ at 1.375 T and applying higher frequency of 115.5 GHz for X3 heating, the cut-off density can be much extended to $11.02\times10^{19}$ m$^{-3}$. An improvement in the heating efficiency of the X3 heating is expected by the simultaneous X3 by 115.5 GHz with X2 by 77 GHz.

As a dual-frequency gyrotron for LHD, one frequency is supposed to be 154 GHz so that it can be used with existing 154 and 77 GHz single-frequency gyrotrons for high power heating experiments at $B$ = 2.75 T. Another frequency $f$ should satisfy the no-reflection condition at the gyrotron output window, $f = (m/n)\times154$ GHz with $n$ and $m$ integer numbers. The frequency 115.5 GHz for the X3 heating at $B$ = 1.375 T satisfy the relation with $n$ = 4 and $m$ = 3. As a practical criterion, the frequency difference $\Delta f = f_{\rm res}$ - 115.5 GHz should be minimized, $f_{\rm res}$ being realized oscillation frequency.

Also, the EC-waves at both frequencies should propagate the same path from the cavity to the output window for the compatibility of a mode convertor and mirrors inside the gyrotron, and the power transmission line. To find a combination of oscillation modes in the cavity, as the main mode oscillating at 154 GHz, $TE_{28,8}$, $TE_{28,9}$, and $TE_{28,10}$ were considered. Here, for example, $TE_{28,8}$ denotes a transverse electric mode with the azimuthal mode number of 28 and the radial mode number of 8. The oscillation mode of the existing 154 GHz single-frequency gyrotrons is $TE_{28,8}$. The difference in the radiation angles between the EC-waves with the frequencies of 154 GHz and $f_{\rm res}$ released from the mode convertor, $\Delta\theta_{\rm rad}$, can be calculated, and $\Delta\theta_{\rm res}$ should also be minimized.

For each of the three 154 GHz main modes, various sub modes oscillating with the frequency near 115.5 GHz were investigated by calculating $f_{\rm res}$ and $\Delta\theta_{\rm rad}$. Figure 1 shows $\Delta\theta_{\rm rad}$ as functions of $k$ number, where $k$ is the radial mode number of the sub mode such as $TE_{j,k}$. From the investigation, a combination of a main 154 GHz mode $TE_{28,9}$ and a sub mode $TE_{21,7}$ seems suitable. Figure 1 shows that $\Delta\theta_{\rm rad}$ between the $TE_{28,9}$ and $TE_{21,7}$ mode waves is very small, only 0.52 deg. The oscillation frequency of the $TE_{21,7}$ mode is 116.02 GHz, and $\Delta f$ of 0.5 GHz causes a reflection at the output window of sufficiently low level, 0.2%.

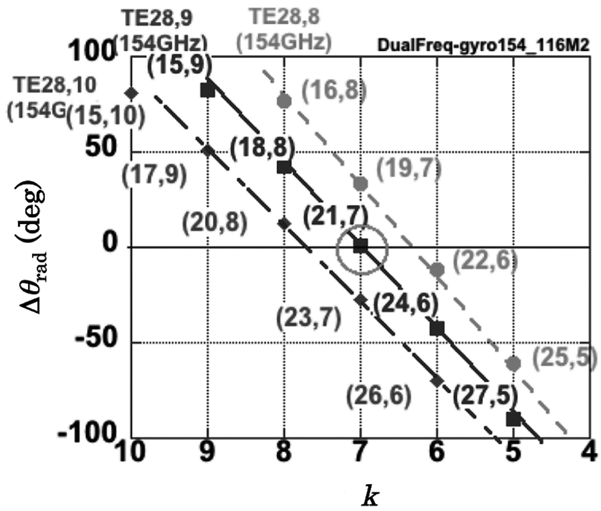


Fig. 1. The differences in the radiation angles between the EC-waves of the main 154 GHz modes and the sub $TE_{j,k}$ modes released from the mode convertor, $\Delta\theta_{\rm rad}$, are plotted against $k$ number of the sub modes. The mode numbers of the sub modes ($j$, $k$) are noted by the plot points.

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1) Shimozuma, T.: Nucl. Fusion **55** (2015) 063035.