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Ray Tracing Study on Top ECCD Launch in KSTAR

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Abstract. The current drive efficiency of electron cyclotron (EC) wave is typically low compared with other RF and neutral beam heating system in tokamak. It is known that EC current drive by outboard launch suffers from low current drive efficiency due to electron trapping. However, the heating and current drive by EC wave is being regarded as a strong candidate for DEMO reactor due to the simplicity of the launcher, none of its interaction with plasma, and no coupling issue at the plasma edge. Also, off-axis heating and current drive by EC wave plays an important role of steady state operation optimization. To enhance the current drive efficiency in DEMO-relevant operation condition having high density and high temperature, the top launch of EC wave is recently proposed in FNSF design [2]. In FNSF, a top launch makes use of a large toroidal component to the launch direction adjusting the vertical launch angle so that the rays propagate nearly parallel to the resonance layer increasing of Doppler shift with higher $n_{||}$. The results shows a high dimensional efficiency for a broad ECCD profile peaked off axis. In KSTAR, the possibility of efficient off-axis ECCD using top launch is investigated using the ray tracing code, GENRAY [3] for the operating EC frequencies (105 GHz or 140 GHz, and 170 GHz). The high current drive efficiency is found by adjusting the toroidal magnetic field and the radial pivot position of the final launcher mirror for fundamental O-mode and second harmonic X-mode. A large Doppler shift is not quite sure in the typical plasma profile in KSTAR, but the simulation results show high current drive efficiency. This paper presents ray tracing results for many cases with the wave trajectories and damping of EC by scanning the launching angle for specific launcher pivot positions and toroidal magnetic field, and two equilibriums of the KSTAR.

1 INTRODUCTION

KSTAR aims to develop DEMO-compatible advanced tokamak operation mode with broad off axis current drive using off-axis NBI and RF heating devices [1]. In the study of FNSF (Fusion Nuclear Science Facility) [2], top launch of electron cyclotron (EC) wave shows improvement in EC current drive (ECCD) efficiency with broad ECCD profile peaked off-axis. It is understood that the top launch of EC wave enables nearly vertical trajectories on the low field side from the cold resonance, so that the resonance approaches slowly with high Doppler shift and waves interact with higher energy electrons, which are less collisional and provide larger ECCD. Eq. (1) is the Doppler-shifted relativistic EC resonance condition at l'th harmonic.

$$\omega = \frac{l\Omega}{\gamma} + k_{||}v_{||} \quad (1)$$

$$\frac{v_\perp^2}{c^2} = \left(1 - \frac{\omega^2}{l^2\Omega^2}\right) + 2n_{||}\frac{\omega^2}{l^2\Omega^2}\frac{v_{||}}{c} - \left(1 + n_{||}^2\frac{\omega^2}{l^2\Omega^2}\right)\frac{v_{||}^2}{c^2} \quad (2)$$

Where, γ is the relativistic factor, ω is EC wave frequency, Ω is the cyclotron resonance frequency, $k_{||}$ ($k_\perp$) is the parallel (perpendicular) component of the wave number of EC wave to the magnetic field, $n = kc/\omega$ is the refractive index, and v is the velocity of electron. Fig. 1 shows ellipses in velocity space using the Doppler-shifted relativistic resonance condition at l'th harmonic. Higher is the parallel component of the refractive index ($n_{||}$), the higher is the maximum energy of the resonant electrons.

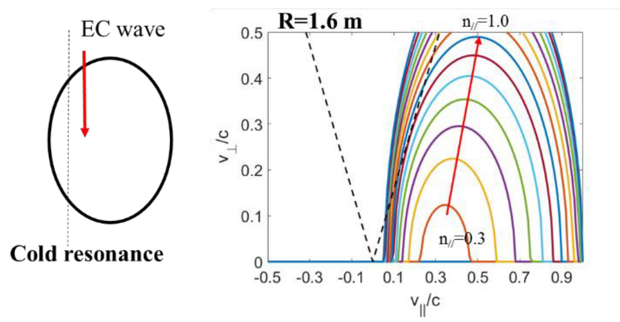

Fig. 1. Doppler-shifted relativistic EC resonance curves using Eq. (2). The dot line is the trapping boundary. The arrow indicates an increase in $n_{||}$ from 0.3 to 1.0.

Upgrade plan of various EC frequencies (105/140/170 GHz) in KSTAR enables both launch from the top and from the outboard and comparison studies. In this paper, the possibility of top launch of EC wave in KSTAR is studied using ray tracing simulations.

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2 Ray Tracing Study

2.1 Simulation code

The EC wave propagation and power absorption is calculated using the ray tracing code, GENRAY and Fokker-Planck code, CQL3D [3]. In some case of the top launch conditions, a computing error in implicit solver in CQL3D code occurred. We found this error is removed using the recent fully-neoclassical finite-orbit-width version of CQL3D [4]. In the ray tracing simulation, the toray module in the genray code is used with the finite beam divergence at the launch position.

2.2 Top launch of 140 GHz EC wave

In this calculation, the plasma density and temperature profile is assumed by the typical H-mode profile with pedestal height and width. The central density is 5 x 10^{19} m^{-3} and the central temperature is 7 keV. Two plasma equilibriums are compared in this calculation. One (equilium I) is basically double null shape with elongation, $\kappa = 2$ with the plasma current $I_p = 1.14$ MA and $B_t = 2.1$ T at the major radius of 1.8 m, in which $q_{95} = 4$. The other one (equilibrium II) is single null shape with lower $\kappa = 1.7$ which is typical shape in recent KSTAR experiments.

Figure 2 shows the ray tracing of 140 GHz X2 EC wave launched from the top position $R_{ant} = 1.62$ m, $Z_{ant} = 1.0$ m with specific injection angles for equilibrium I. The ray tracing shows nearly vertical trajectory parallel to cold resonance layer and broad driven current profile. The cold resonance is located at $R_{X2} = 1.512$ m which corresponds to the toroidal magnetic field 2.1 T at the major radius $R_0 = 1.8$ m.

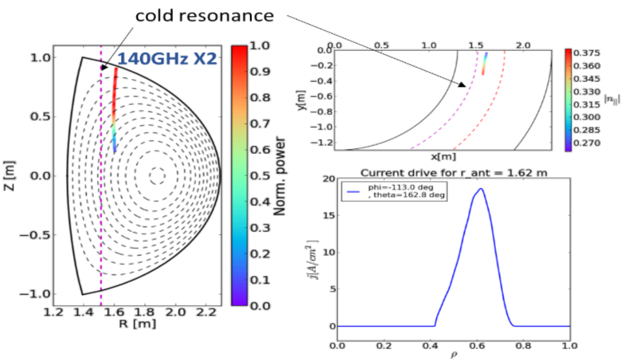

Fig. 2. Top launch of 140 GHz X2 EC wave for ne(0) = 5 x 10^{19} m^{-3} and $T_e(0) = 7$ keV and for equilibrium I.

Figure 3 shows the current drive and peak position of driven current profile for launch angles (ϕ and θ) for equilibrium I. The ϕ is the toroidal angle from the radial direction, and the θ is the poloial angle from the vertical axis. The current drive changes significantly with small change of the launch angles. The highest current drive is about 50 kA/MW for $n_e(0) = 5 \times 10^{19}$ m^{-3} which corresponds to the current drive efficiency, $\eta = I_{CD}R\langle n_e\rangle/P_{abs} = 0.39 \times 10^{19}$ $Am^{-2}W^{-1}$, where, I_{CD} is the total driven current in A, R is major radius in meter, $\langle n_e\rangle$ is the average density in m^{-3}, and P_{abs} is the absorbed power. The current drive profile is ranged with its peak position of $\rho = 0.5 \sim 0.7$. The ρ is the normalized minor radius defined by r/a, where a is the plasma minor radius and 0.5 m in the KSTAR. For equilibrium II, top launch has the similar characteristics on the current drive and peak position as seen fig. 4. It should be noted that the antenna position of $R_{ant} = 1.62$ m for equilibrium I and 1.66 m for equilibrium II are found to be appropriate position to have high current drive with the vertically aligned ray propagation to the cold resonance layer.

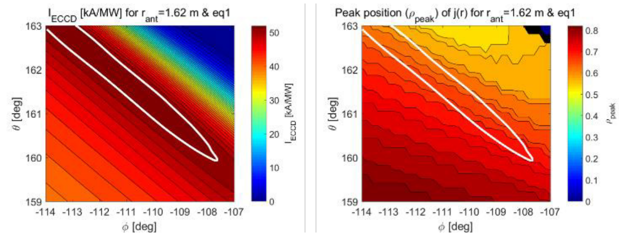

Fig. 3. The current drive and its peak position for various launch angles for equilibrium I. The toroidal angle is clockwise direction for the co-CD. The region enclosed by white line indicates the maximum current drive (left) obtained by ray tracing and the corresponding peak locations (right).

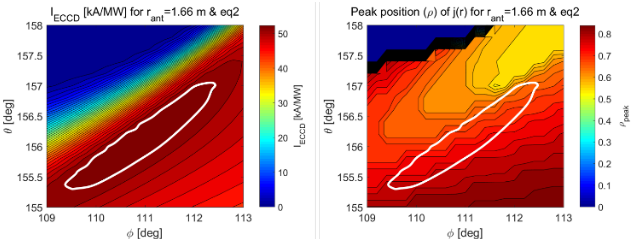

Fig. 4. The current drive and its peak position for various launch angles for equilibrium II. In this case, the toroidal angle is counter-clockwise for co-CD due to the opposite plasma current in equilibrium II. The region enclosed by white line indicates the maximum current drive (left) obtained by ray tracing and the corresponding peak locations (right).

Figure 5 shows the EC wave ray tracing and ECCD profile for launching angles corresponding to current drive comprised between 35 and 52 kA. Depending from the launching angles, the CD peak is located between $\rho = 0.6$ and 0.85.

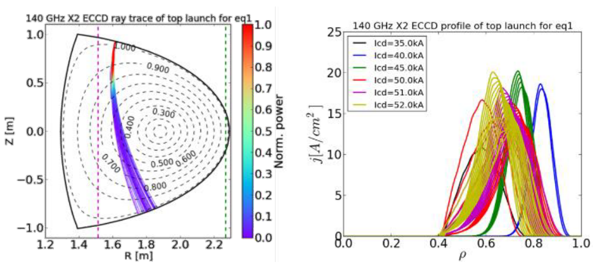

Fig. 5. The ray tracing and ECCD profile by 140 GHz X2 wave top launch for various launch angles.

In this scheme for X2 140 GHz top launch, the outboard launch of 140 GHz EC wave is applicable. But the 3rd

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harmonic parasitic power loss is observed near the plasma edge hence the lower current drive. The downward injection for outboard launch is better to reduce the 3rd harmonic parasitic power loss as seen in Fig. 6.

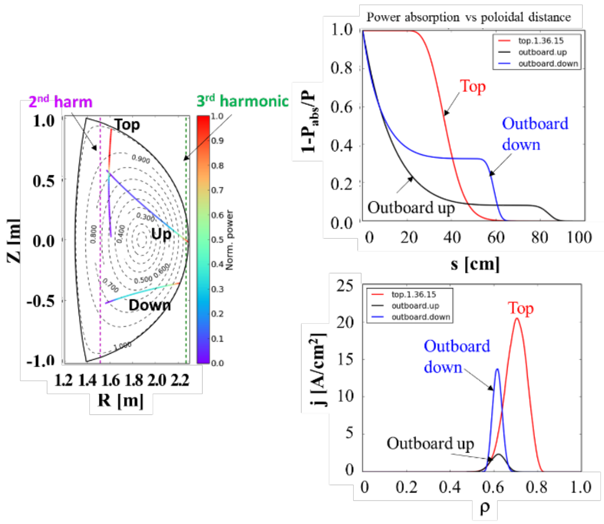

Fig. 6. The comparision between the top launch and two outboard launches of 140 GHz X2 EC wave.

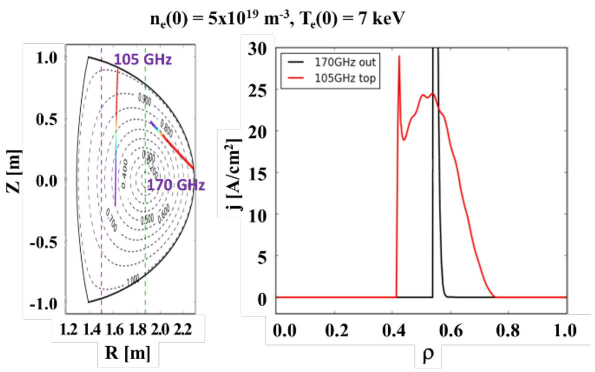

Fig. 7. The ray tracing of top launch of 105 GHz O1 EC wave and the outboard launch of 170 GHz X2 EC wave. Since the peak value of the driven current density is 100 A/cm^2 for the case of outboard launch, the scale is truncated for the comparison between two cases.

2.3 Fundamental Harmonic Top launch of 105 GHz EC wave

In addition to 105 GHz/140 GHz dual frequency gyrotron in KSTAR, the 170 GHz ECH system upgrade is also under consideration. Considering the possibility of higher toroidal magnetic field operation and the use of 170 GHz EC wave, the toroidal magnetic field of 3.125 T at the major radius of 1.8 m is found to provide good current drive scheme for both top launch and outboard midplane launch using 105 GHz O1 mode for top launch and 170 GHz X2 mode for outboard launch. In this case, the cold resonance magnetic field of O1 mode of 105 GHz is 3.75 T located at R_{res} = 1.5 m, and the antenna pivot position is R_{ant} = 1.65 m. For 170 GHz X2 cold resonance is at R_{res} = 1.88 m. Fig. 7 shows two launch cases of top lauch of 105 GHz and outboard launch of 170 GHz. The very broad current density profile is obtained for the 105 GHz O1 top launch, while the peaked current dentisy profile for the 170 GHz outboard launch. The resulting current drive is 83 kA/MW (η = 0.67 x 10^{19} Am^{-1}W^{-1}) for 105 GHz and 34 kA/MW for 170 GHz. For 105 GHz O1 top launch, the current drive efficiency is high even for the high density at $n_e(0)$ = 1 x 10^{20} m^{-3} near the O1-mode cut off density (1.33 x 10^{20} m^{-3} for 105 GHz) with $T_e(0)$ = 7 keV. Fig. 8 shows the ray tracing and current drive profile for both plasma densities of top launch of 105 GHz O1 mode.

2.4 3D Fokker-Planck calculation for 140 GHz ECCD top launch

As described above, the new version of CQL3D with finite orbit with is used for Fokker-Planck calculation. Fig. 9 shows the current drive profiles for different launch angles and ray tracing from GENRAY and Fokker-Planck simulation. In the Fokker-Planck calculation, the power absorption is generally calculated with non-Maxwellian distribution function. As seen in the right figure in fig. 9, the ray propagates further due to the different power absorption, hence the different driven current density profile with the peak position shifted inward. Fig. 10 shows the broad specrum of QL diffusion (DQL) for resonant electrons in velocity space for a specific launch case.

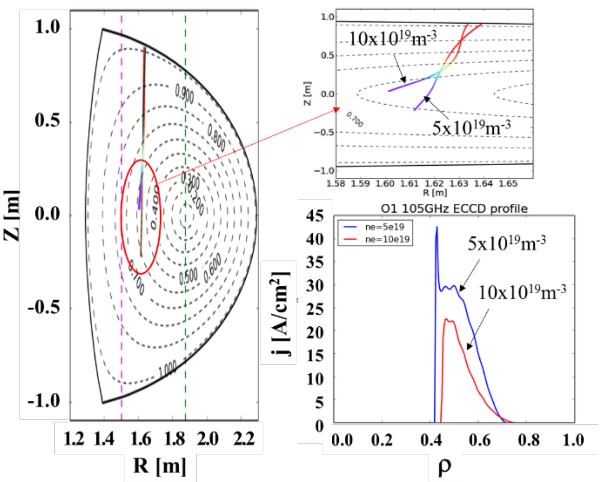

Fig. 8. Ray tracing of top launch of 105 GHz O1 EC wave for two plasma densities, 0.5 x 10^{20} m^{-3} and 1 x 10^{20} m^{-3}.

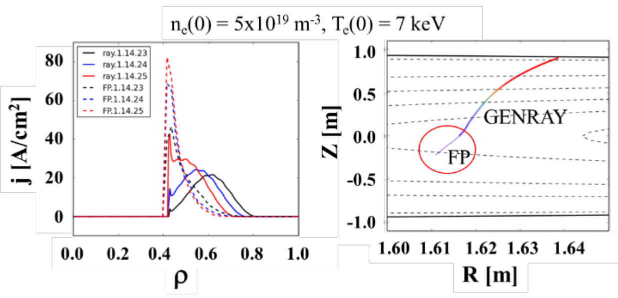

Fig. 9. The Fokker-Planck code CQL3D calculation of top launch of 140 GHz X2 EC wave. The solid line is for the ray tracing and the dash line is for the CQL3D calculation.

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Each current drive profile is obtained for different launch angle.

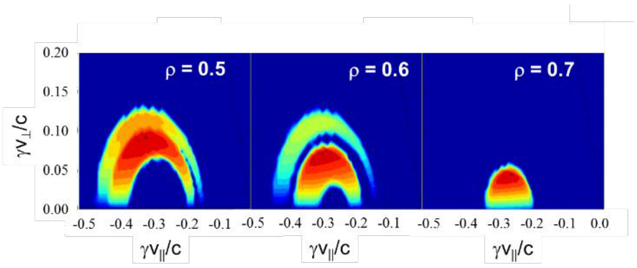

Fig. 10. The quasi-linear diffusion coefficient (DQL) obtained from CQL3D for the top launch of 140 GHz X2 EC wave for a specific case among of Fig. 8.

2.5 Conceptual design of top launcher in KSTAR ECCD

Figure 11 shows a proposed conceptual design for top launcher in KSTAR. It uses basically the vertical port and four mirrors inside vacuum vessel near the upper divertor region. It may requires additional engineering design to accommodate the four mirrors inside vacuum vessel in the aspect of interface issues of mirrors near upper divertor sectors and upper passive plates. Depending on the design of mirrors, the upper divertor may need to be removed allowing only lower single null operation in KSTAR. This is the reason that equilibrium II with single null configuration is included in the ray tracing study of top launch ECCD in KSTAR. From the ray tracing study of ECCD top launch, the best choice of last steerable mirror pivot position would be R_{ant} = 1.62-1.65 m and Z_{ant} = 1.0 m. Considering 170 GHz EC system in the upgrade plan, the fundamental 105 GHz top launch is very attractive to have high current drive at the off-axis with pivot position, R_{ant} = 1.65 m of the last steerable mirror and Bt = 3.125 T.

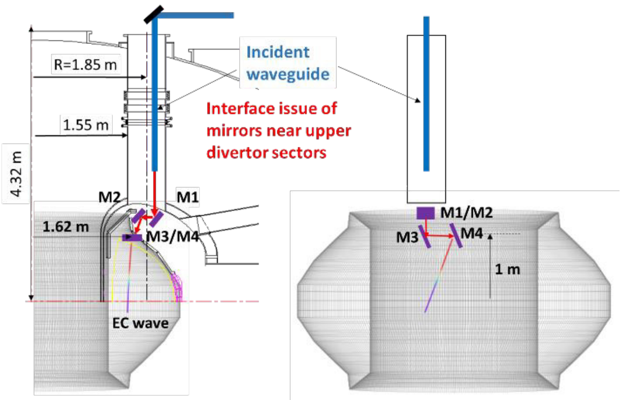

Fig. 11. The conceptual design of top launcher in KSTAR using the vertical port and incident waveguide through the port.

3. Conclusions

The ray tracing simulations for top launch ECCD shows higher current drive efficiency than low field side injection. The 105/140 GHz dual frequency gyrotron and 170 GHz gyrotron will be main power sources in KSTAR ECH system. For the 140 GHz ECCD top launch, the appropriate toroidal magnetic field and antenna pivot position are found for high current drive efficiency considering the operation window of the KSTAR toroidal magnetic field and through scanning of the antenna pivot position for various launching angles. The highest current drive of ~50 kA/MW is obtained for $n_e(0) = 5 \times 10^{19}$ m^{-3} and $T_e(0)$ = 7 keV. It corresponds to the current drive efficiency $\eta = 0.39 \times 10^{19}$ $Am^{-2}W^{-1}$. The fundamental O-mode 105 GHz ECCD top launch is also investigated for the higher toroidal magnetic field operation than 3 T in KSTAR. We obtained very high current drive efficiency (83 kA/MW, $\eta = 0.67 \times 10^{19}$ $Am^{-2}W^{-1}$) for the same density as above. When the density increases to 1×10^{20} m^{-3}, the driven current is similar as that of 140 GHz second harmonic ECCD top launch without the cut-off. The high toroidal magnetic field has an advantage of the current drive at the same flux surface using a second harmonic 170 GHz EC wave from the low field side injection at the same time.

The main task in this paper is to investigate the characteristics and performance of the driven current and the absorbed power for the top launch using single-ray approach. But the Fokker-Planck simulation shows the very different driven current density profile for the specific case of top launch. Therefore, the Fokker-Planck calculation might be needed for more precise top launch study. The driven current density profile also depends on the beam divergence in the single-ray approach. Depending on the launcher mirror design (focused or straight beam), the divergence need to be changed. Note that there is no significant difference in the driven current profile between single-ray tracing and and multi-ray tracing simulation. In conclusion, the top-launch approach of ECCD is very attractive and strongly recommended for the future KSTAR research mainly covering issues relevant for DEMO-compatible advanced tokamak operation scenario with limited available heating power sources.

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