Experimental profiles of Helicon wave power in the core of DIII-D plasmas

S. Chowdhury[1], N.A. Crocker[1], W.A. Peebles[1], Q. Pratt[2], L. Zeng[1], T. L. Rhodes[1], B. Van Compernolle[3], J.B. Lestz[3], R. I. Pinsker[3], S. X. Tang[3]
[1]*University of California, Los Angeles, California 90095, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451, USA*
[3]*General Atomics, San Diego, California 92186-5608, USA*

Email : schowdhury@physics.ucla.edu

The DIII-D tokamak continues advancing steady-state operation with innovative diagnostic and heating techniques, including the development of helicon-based RF heating and current drive. For the first time, the helicon wave power distribution has been measured locally in the plasma core (Fig. 1) as demonstrated by recent experiments using a newly developed millimeter-wave Doppler Backscattering (DBS) system [1, 2]. These new profile measurements of helicon wave power are consistent with initial 3D ray tracing calculations of helicon wave propagation and will allow more detailed code validation that will improve understanding for application to future burning plasma devices [3-5].

The DBS system uses dynamic frequency sweeping (60-90 GHz) during a single discharge to scan from the plasma edge to the core during high-power helicon injection. Density fluctuations are measured across a broad frequency range: 0–10 MHz for turbulence and 450–500 MHz for high-frequency density fluctuations associated with the launched helicon wave. Observations in an H-mode discharge (#201171) reveal a broadband feature (Δf~2 MHz) close to the frequency of the injected helicon wave (f ~ 476 MHz). This high-frequency broadband feature shows a small frequency shift away from the helicon frequency (476 MHz) that tracks the changing Doppler shift of simultaneously measured turbulence. This strongly indicates that the broadband response is produced by helicon wave modulation of the

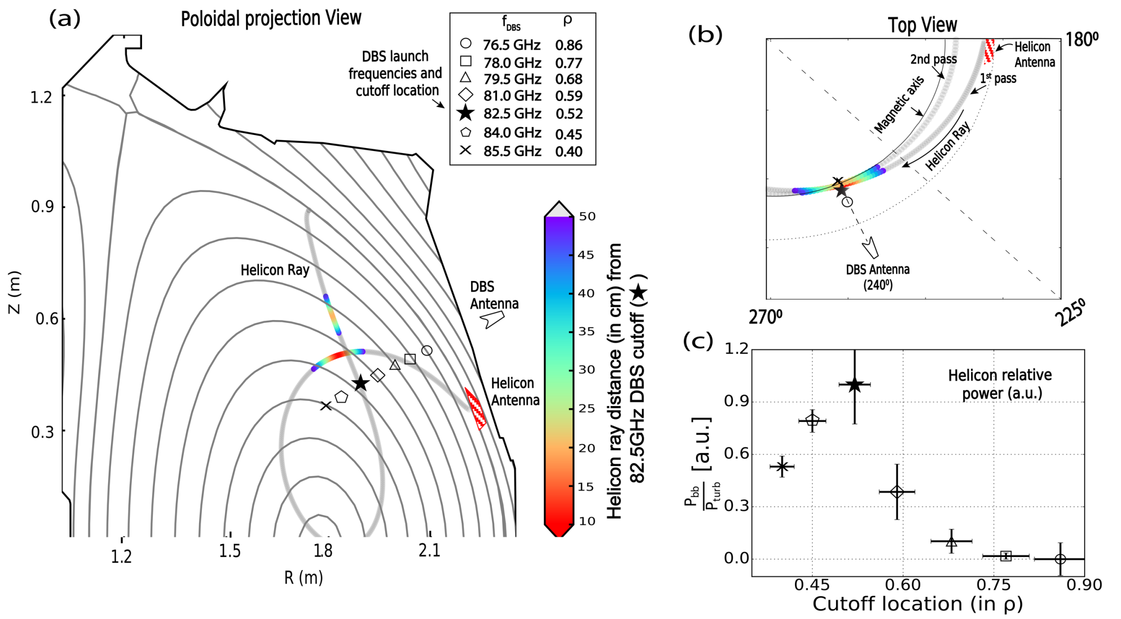

FIG. 1. (a) GENRAY raytracing for Helicon ray and DBS cutoff locations (for different frequencies launch during frequency sweeping) for an H-mode plasma (Shot#201171). The color contour on the helicon ray shows the ray distance from the 82.5 GHz DBS cutoff location (★). Helicon ray color is shown only for the nearest proximity (within 0 - 50 cm) to DBS, and distance > 50 cm is marked by the shaded gray color. The symbols show the DBS measurement locations during the frequency sweep. (b) Top view of the tokamak 1-quadrant with helicon ray (both 1st and 2nd pass) and DBS measurement locations. (c) Relative spectral power of helicon broadband fluctuation compared to local turbulence vs ρ at DBS cutoff locations. Relative helicon power peaked at ρ ~ 0.52 (when probed with 82.5 GHz DBS ray).

measured turbulence. In particular, the helicon wave electric field $\tilde{E}_{hel}$ generates an oscillating $E \times B$ velocity that modulates the Doppler shift of the measured turbulence at the helicon frequency (476 MHz), thereby producing the broadband feature. Figure 1c shows the ratio P_{bb}/P_{turb} vs. ρ at the measurement location for each probe frequency, where P_{bb} is the integrated spectral power of the high-frequency broadband signal and P_{turb} from the low-frequency turbulence signal. The value of this normalized ratio determines the strength of the Doppler shift modulation, and thus the relative helicon wave power at the measurement location. As can be seen, the relative helicon power initially is very low towards the edge plasma but then increases significantly as the measurement location moves towards the core plasma followed by a gradual reduction deeper in the core.

The observed spatial dependence is consistent with the 3D modeling of the helicon wave and the DBS measurement locations via GENRAY ray tracing. Figures 1a & b show GENRAY predictions of a launched helicon ray together with the DBS probe locations for the same H-mode plasma (#201171). Figure 1a shows a *poloidal projection* of the helicon ray trajectory, which propagates both poloidally and toroidally away from the launch antenna. DBS cutoff locations (marked by symbols) for the various launch frequencies (76.5–85.5 GHz, X-mode) are found to probe radial locations from the edge ($\rho\sim0.86$) to the core ($\rho\sim0.4$). Figure 1b shows a top view of the tokamak 1st quadrant illustrating both the first and second pass of the helicon ray near the 240° DBS location (note that the second pass predicted power is ~40% of the first pass). A midplane projection of these cutoff locations is also shown as shaded symbols in Fig. 1b. The Helicon ray paths are color-mapped by their proximity to the 82.5 GHz DBS cutoff location at mid-radius (ρ ~0.52). Red shows the closest proximity (~10cm) of the helicon ray to the 82.5 GHz DBS cutoff in both Figs. 1a and 1b. This visualization highlights the spatial overlap between the helicon wave propagation and the localized region of maximum signal intensity probed by DBS (see Fig 1c). As can be seen, as the measured relative helicon power decreases in the deep core (ρ < 0.5), the separation between the measurement location and the predicted helicon path increases.

These findings provide critical insights and confirmation of helicon wave propagation and the interaction with the background turbulence. The GENRAY code prediction of the 3D helicon wave propagation is consistent with the DBS measurements. The measured peak DBS signal lies in the core plasma region where the helicon wave is also in close proximity. In contrast, the DBS measurements in the edge plasma (where signals are very small) are far away from the predicted helicon wave propagation. Further work will allow more detailed validation of code predictions. This work also enhances understanding of RF-wave/turbulence interactions via the observed E×B modulation of the background turbulence. Finally, it should be noted that it directly addresses an identified fusion knowledge gap as identified in the 2007 US FESAC report 'Priorities, Gaps, and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy"- "4.b.6.b: *To localize RF current drive there is a need to improve the understanding of RF wave coupling to plasma".*"

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-SC0020649, and DE-SC0020337.

Reference:

1. Chowdhury et al., Rev. Sci. Instrum. 94, 073504 (2023); https://doi.org/10.1063/5.0149654
2. Chowdhury et al., Rev. Sci. Instrum. 96, 033505 (2025). https://doi.org/10.1063/5.0233601
3. Pinsker et al., Nucl. Fusion 64 126058 (2024). https://doi.org/10.1088/1741-4326/ad78e8
4. Pinsker et al., EPJ Web Conf. (2019). https://doi.org/10.1051/epjconf/201920302008
5. Pinsker et al., Nucl. fusion (2018). https://doi.org/ 10.1088/1741-4326/aad1f8