

## Observation of a Rotating Radiation Belt in LHD

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A poloidally rotating radiation belt with helical structure was observed during the high density discharges with detachment by photodiode fan arrays and a fast camera in LHD. The peak of radiation rotates inside the last closed flux surface, and the direction and mode number of the poloidal rotation are electron diamagnetic and one, respectively. During the recombination phase after termination of the plasma heating, the rotation continues, and its rotating radius shrinks with shrinking of the plasma column. The poloidal rotating frequency depends on the heating power, and increases from the orders of several tens of Hz to several hundreds of Hz with shrinking of the rotation radius. The mechanism of the rotation remains uncertain.

### Keywords:

LHD, rotating radiation belt, MARFE, Serpens-mode

In experiments conducted on LHD in 2004, a poloidally rotating radiation belt was observed during the high density discharges with detachment by absolute extreme ultraviolet photodiode (AXUVD) fan arrays [1] and a fast camera (20,000 frames/s). The belt appeared similar to MARFE in tokamaks [2] and ARC (asymmetric radiative collapse) in LHD [3] with respect to the localized radiation volume, but there was a crucial difference in terms of whether or not the position of the radiation volume moved continuously.

Figure 1 shows the time evolutions of plasma parameters during a discharge with the magnetic axis radius of 3.65 m in which the rotating radiation belt was observed. With gas puffing and injection of two hydrogen ice pellets, the line averaged density,  $n_{\text{ebar}}$ , reaches about  $1.6 \times 10^{20} \text{ m}^{-3}$ , and is kept only by recycling after the pellet injection. It should be noted that pellet injection is not essential in this paper. The total radiation,  $P_{\text{rad}}$ , measured by a resistive bolometer with a wide-angle view of the plasma [1] is about 40% of the input power during the high density phase. Usually in LHD, 30–40% of  $P_{\text{rad}}$  – input power ratio is transiently observed just before the radiative collapse, that is, ARC. At that stage, the plasma column shrinks, and plasma is detached from the divertor. During the discharge in Fig. 1, shrunk column is stably maintained after the termination of gas puffing, and this state is called Serpens-mode [4]. The ion saturation current measured by the Langmuir probe arrays on the divertor plates,  $I_{\text{sat}}$ , decreases, and intermittent spikes appear during Serpens-mode. Figure 2(b) shows the time evolution of the sight volume integrated radiation power,  $\langle P_{\text{rad}} \rangle$ , profile during Serpens-mode, measured by an AXUVD fan array in a nearly horizontally elongated

poloidal cross-section [1] (see Fig. 2(a)). This figure shows that the poloidal mode number of the rotation is one, and the rotating frequency is several tens of Hz, varying with input power. The turn-rounds of the  $\langle P_{\text{rad}} \rangle$  peak are channel numbers 4 and 17 (see Fig. 2(a)). This indicates that the peak location of the rotating radiation volume is inside the LCFS. Figure 2(c) shows that the rotation continues in the recombination phase after the NBI termination ( $t = 3.3$  s). The rotation radius and the frequency become smaller and about 10 times higher than during Serpens-mode, respectively. The shrinking of the rotation radius is considered to correlate with the shrinking of the  $T_e$  profile during the recombination phase, and this suggests that the rotating location is not tied to a rational surface, unlike in the Snake-mode [5]. The rotating radiation volume is also observed in other toroidal sections. The fast camera ( $108^\circ$  away toroidally from the above-mentioned AXUVD fan array, AXUVD#1) viewing the torus inboard and the lower helical coil can from an outboard port in a horizontally elongated cross-section revealed that the poloidal direction of the rotation is electron-diamagnetic. The time evolutions of the  $\langle P_{\text{rad}} \rangle$  profile similar to those in Figs. 2(b) and (c) were observed by another AXUVD fan array (about  $144^\circ$  toroidally away from AXUVD#1) viewing the torus inboard side from the outboard port in the adjacent toroidal section obliquely [1]. From this observation, it is reasonable to suppose that the rotating radiation volume forms a helical radiation belt. Density condensation is considered to cause localized radiation belts such as that observed in MARFE, though the main radiator of the radiation belt, mechanism and onset condition of the rotation have not been revealed. It should be noted that the

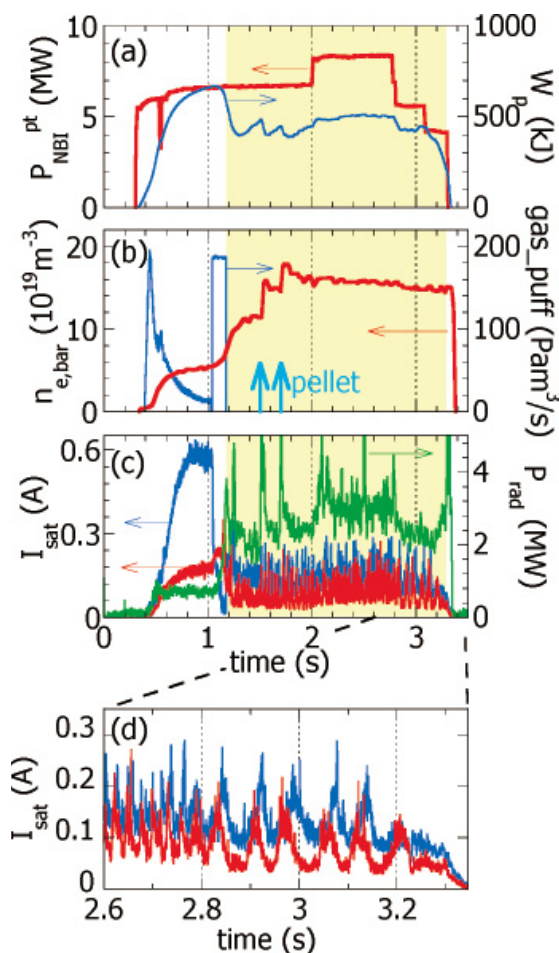


Fig. 1 Time evolutions of plasma parameters in the self-sustained detached discharge. The hatched area indicates Serpens-mode. Two pellets were injected at  $t = 1.5$  and  $1.7$  s.  $I_{\text{sat}}$  is measured by top (red) and inboard (blue) divertor probe array, respectively. The former is about  $162^\circ$  toroidally away from the latter. Shot#53630.

frequency of the intermittent spikes in the  $I_{\text{sat}}$  signals is close to the rotation frequency of the radiation belt (see Fig. 1(d) and Fig. 2(b)). The phases of the  $I_{\text{sat}}$  spikes differ according to the positions of the divertor plates as shown in Fig. 1(d). In the LHD helical divertor, the poloidal magnetic component is larger than the toroidal component, and the field line length between the residual X-points and divertor plate is typically a few m [6]. Thus, the phase difference of the spikes indicates that the origin of the particle flux also rotates, and that means that the rotating radiation belt is closely related to particle transport in the edge plasma during Serpens-mode. The rotating radiation belt has been named *Serpent*.

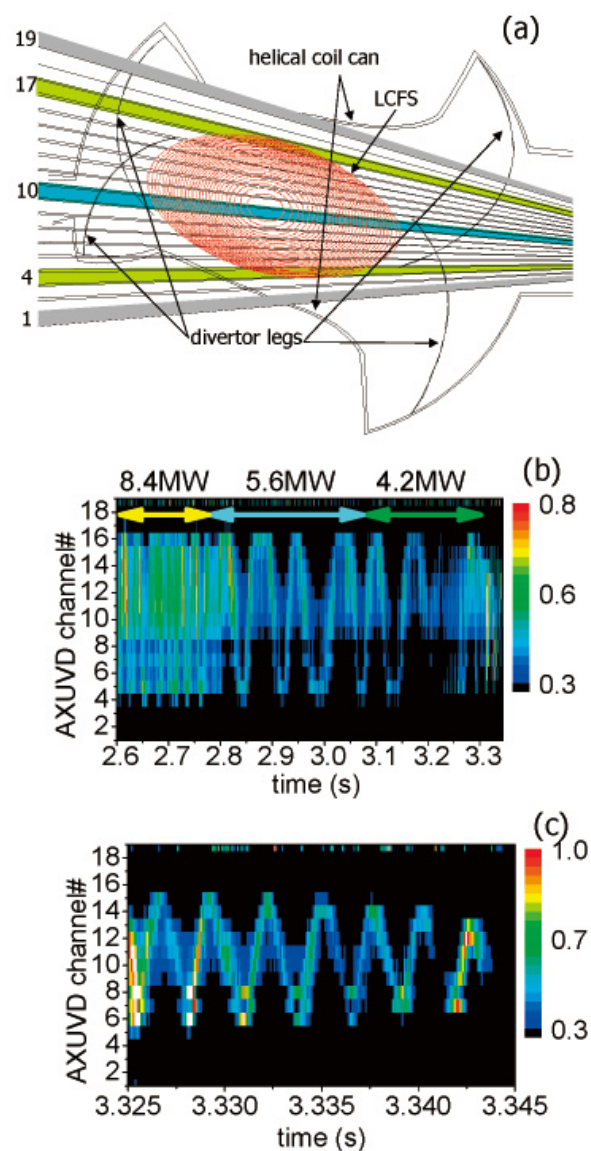


Fig. 2 AXUVD sight areas (a). Time evolutions of the  $\langle P_{\text{rad}} \rangle$  profile at (b)  $t = 2.6$ – $3.345$  s (NBI power is shown) and (c) after termination of NBI, at  $t = 3.325$ – $3.345$  s in Shot#53630. The unit of  $\langle P_{\text{rad}} \rangle$  is arbitrary.

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