1 MeV Triton Orbit Analysis in EAST Plasmas*)

Kunihiro OGAWA[1,2], Guoqiang ZHONG[3], Ruijie ZHOU[3], Kai LI[3], Mitsutaka ISOBE[1,2] and Liqun HU[3]

[1]*National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan*
[2]*The Graduate University for Advanced Studies, SOKENDAI, Toki 509-5292, Japan*
[3]*Institute of Plasma Physics Chinese Academy of Sciences, Hefei, China*

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A fusion burning plasma is sustained by deuterium-tritium (DT)-born energetic alpha particles. Therefore, energetic alpha particles must be well confined. In a deuterium experiment, 1 MeV tritons are created by D(d,p)T reactions. 1 MeV triton is regarded as simulated DT-born alpha particles because their kinetic parameters are almost same. A study of 1 MeV triton confinement has been widely and intensively performed in fusion devices in order to understand alpha particle confinement. To understand 1 MeV triton confinement/loss in EAST plasmas, 1 MeV triton orbit analysis is performed in various plasma current (I_p) cases using LORBIT codes. It is shown that the number of lost tritons decreases with an increase in I_p. The number of lost tritons rapidly increases at 10^{-6} s; then, it is almost saturated at 10^{-5} s regardless of I_p. The pitch angle distribution of confined 1 MeV triton shows that tritons that exist in a wider pitch angle range can be confined in the higher I_p case compared with the lower I_p case.

Keywords: EAST, Triton burnup, energetic particle confinement, Lorentz orbit analysis

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1. Introduction

The confinement of energetic particles has been intensively studied in magnetic confinement fusion machines because fusion burning plasma is sustained by deuterium (D)-tritium (T)-born alpha particles. Therefore, energetic alpha particles must be confined well in order to realize a fusion reactor [1]. In a deuterium plasma experiment, the following two reactions mainly occur: D(d,n)^{3}He and D(d,p)T. By the former reaction, 2.45 MeV neutrons are created, whereas 1 MeV tritons are created by the latter reaction. It is worth noting that the number of two reactions is almost the same. DD-created 1 MeV triton can undergo a secondary reaction with bulk deuteron if the triton slows down in the plasma to approximately 100 keV where the DT cross section has a peak. The confinement property of 1 MeV tritons is intensively studied as DT-born alpha particles because their kinetic parameters (e.g., Larmor radius and precession the frequency of the tritons) are almost the same as those of alpha particles. In addition, 1 MeV tritons have the isotropic birth profile as alpha particles. In the abovementioned studies, the triton burnup ratio, which is the DT neutron yield divided by the DD neutron yield, is one of the common indices in 1 MeV triton confinement [2–11].

In EAST, integrated neutron diagnostics (e.g., neutron flux monitor, radial neutron camera, and neutron spectrometers) are installed and successfully work [12]. From the 2018 experimental campaign, the neutron activation system (NAS) was newly installed in order to evaluate the shot-integrated neutron yield [13]. Triton burnup measurement was initiated with NAS. Secondary DT neutron was measured using 10 g silicon foil. Initial measurements showed that the DT neutron yield was approximately 10^{11} n/shot. The measurement continued in order to obtain neutron yield for various configurations. In this paper, a 1 MeV triton orbit analysis is reported in order to understand 1 MeV triton confinement in EAST.

2. Setup for the Triton Orbit Calculation

We surveyed 1 MeV triton confinement in various plasma current (I_p) conditions in EAST plasmas. Figure 1 shows the flowchart of this analysis. The equilibrium is given by EFIT results, which are reconstructed on the basis of the experimental results (shot numbers of #78401, #78343, #75266, #79866, and #34128 for I_p of 300 kA, 450 kA, 600 kA, 800 kA, and 1 MA, respectively). Electron temperature and electron density in the plasma center are 6.0 keV and 3.2×10^{19} m^{-3}, respectively. The radial profiles of electron temperature and electron density are assumed to have a parabolic profile. The triton emissivity profile is calculated by the NUBEAM code, where we assumed that the co-injected neutral beam injector (NBI) is used with the same injection power (4 MW) and acceleration voltage (80 keV). Here, the calculation time is set

author's e-mail: kogawa@nifs.ac.jp
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to be one second with one millisecond time bin [14]. Figure 2 (a) shows the radial profile of triton emissivity calculated by the NUBEAM code in I_p of 450 kA. Triton emissivity has a peaked profile. Most tritons are created in the $r/a < 0.5$ region. The collisionless Lorentz orbit of 1 MeV tritons is followed by the LORBIT code [15]. The orbit following time is set to one millisecond, which is much shorter than the Spitzer slowing down time (typically more than 100 ms). Toroidal field ripple is not considered in this calculation. The velocity of triton is randomly distributed using random numbers. We randomly launched 10^6 1 MeV tritons using a random number according to the 1 MeV triton emissivity calculated using the NUBEAM code as shown in Fig. 2 (b). When the triton reached the vacuum vessel of EAST shown with blue lines in Fig. 2 (b), we determined that the triton was lost.

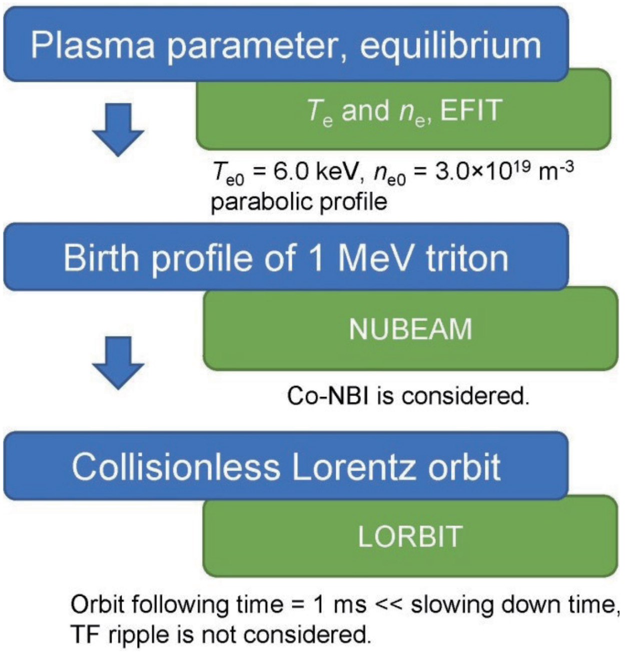

Fig. 1 Flowchart of the 1 MeV triton orbit analysis. Collisionless Lorentz orbit are followed using the LORBIT code according to the birth profile of 1 MeV triton calculated by the NUBEAM code.

3. Result of the Calculation

Figure 3 shows the typical 1 MeV triton orbit in I_p of 300 kA, 450 kA, and 1 MA cases. Here, the toroidal magnetic field strength is approximately 2.3 T, and the ion grad-B drift is directed upward. Co-going transit 1 MeV triton with the pitch angle of 175 degrees is launched at (R, Z) of (2.25 m, 0.0 m). Counter-going transit 1 MeV triton with the pitch angle of 5 degrees is launched at (R, Z) of (2.05 m, 0.0 m). Banana 1 MeV triton with the pitch angle of 80 degrees is launched at (R, Z) of (2.15 m, 0.0 m). In I_p of the 300 kA case shown in Fig. 3 (a), none of 1 MeV tritons have a confined orbit. All tritons directly go to the vessel. Not only co-going transit triton but also counter-going transit triton are confined in I_p of the 450 kA case, as shown in Fig. 3 (b). However, banana triton has lost orbit. In I_p of 1 MA case shown in Fig. 3 (c), all 1 MeV tritons are confined. The behavior of orbit is consistent with that ex-

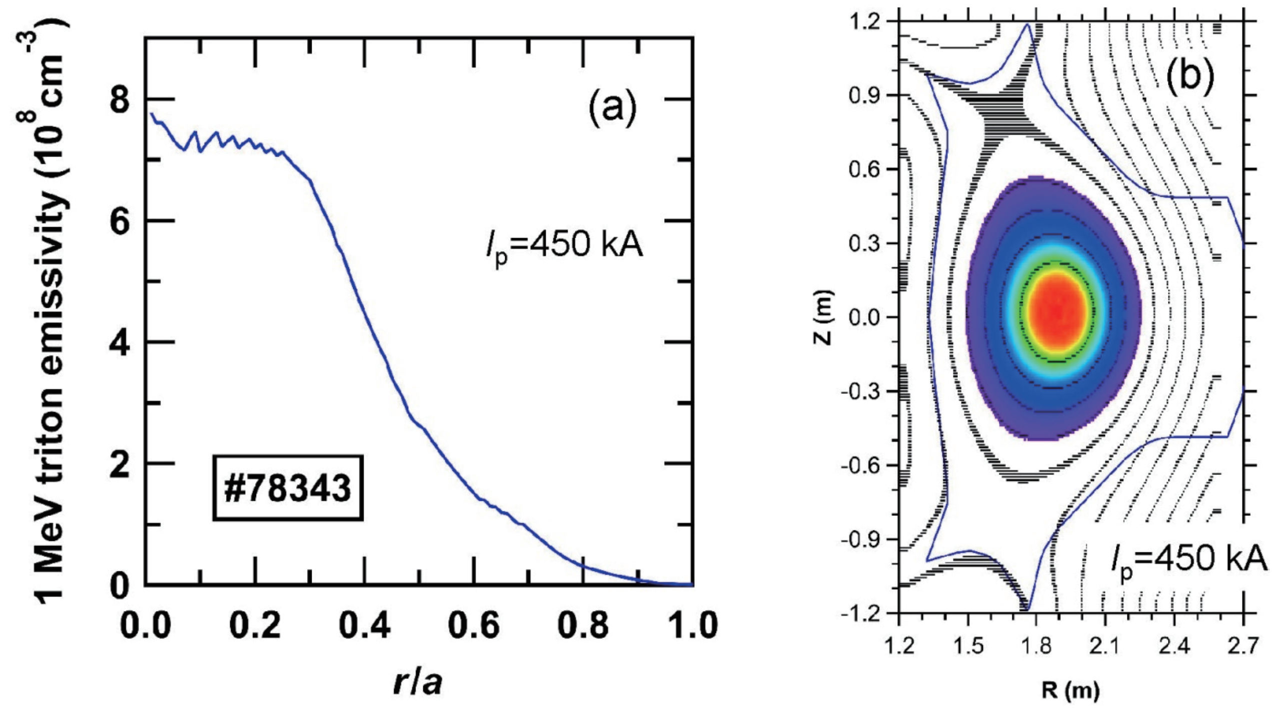

Fig. 2 (a) Radial profile of 1 MeV triton emissivity calculated by the NUBEAM code. (b) Two-dimensional triton birth profile used in the LORBIT calculation. Blue line shows the vacuum vessel of EAST.

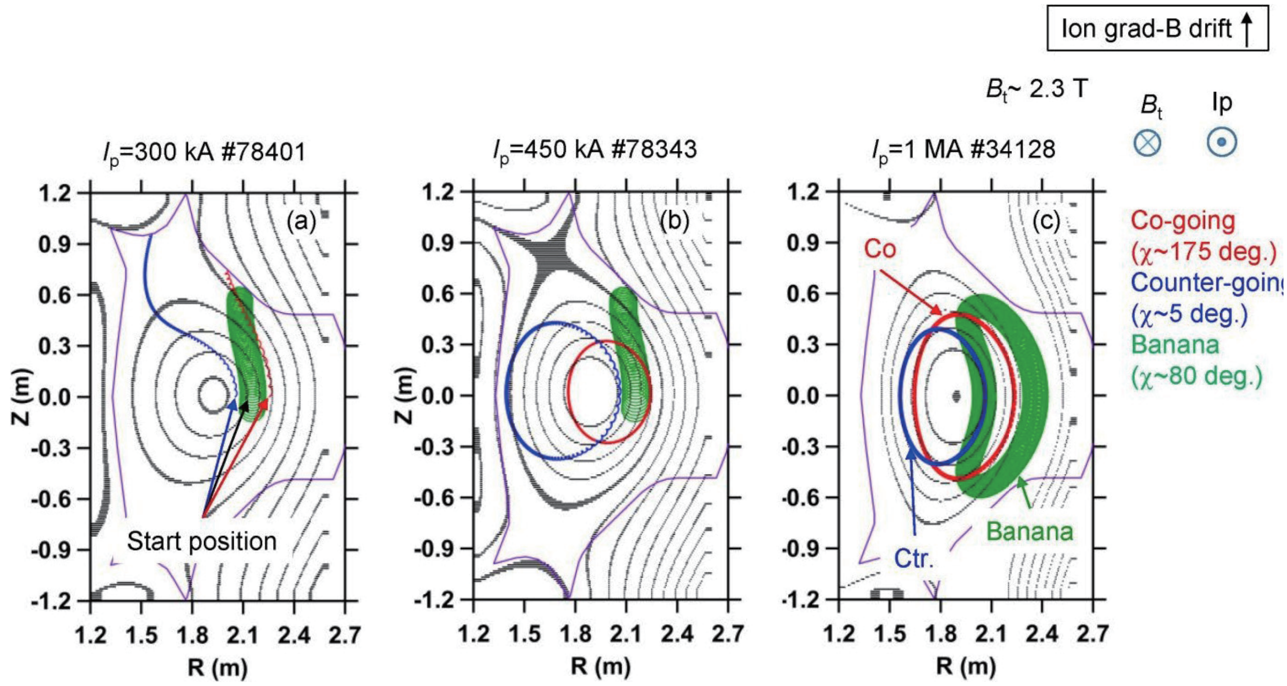

Fig. 3 Typical 1 MeV triton orbit calculated by the LORBIT code. The deviation of orbit from the flux surface decrease with an increase in Ip. Purple line shows the vacuum vessel of EAST.

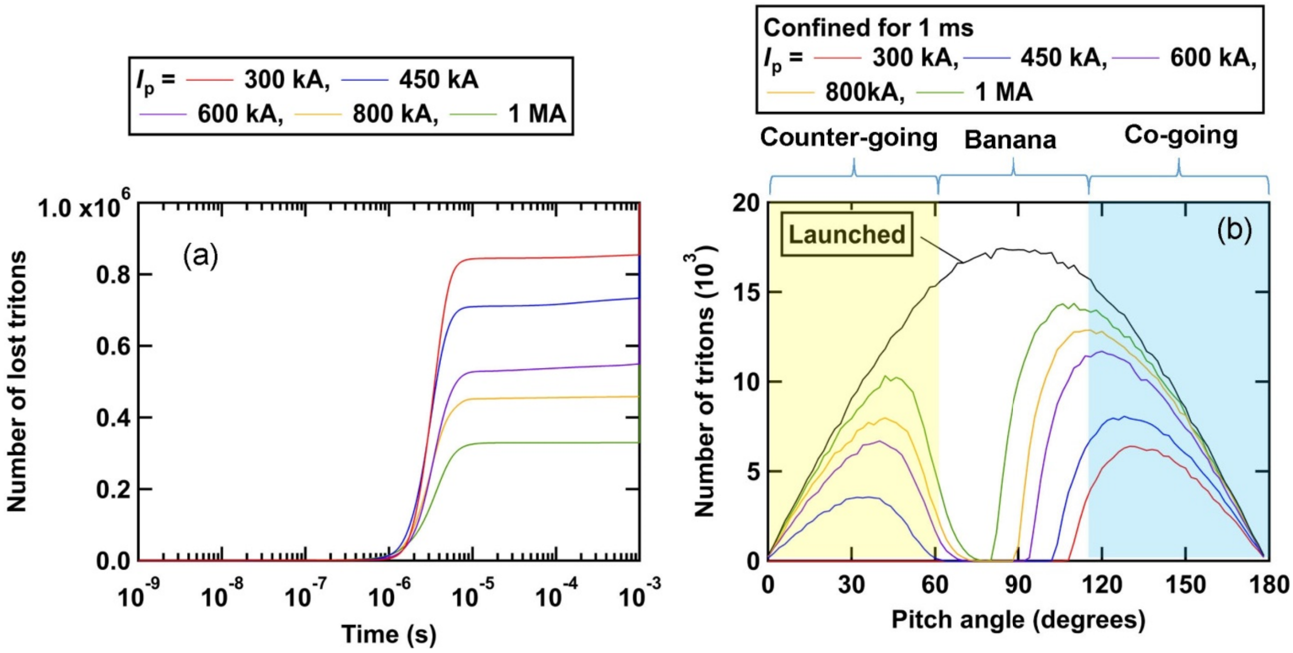

Fig. 4 (a) Time evolution of number of lost 1 MeV tritons. Number of lost ions is almost saturated at t of 10^{-5} s. (b) Pitch angle distribution of confined 1 MeV tritons.

pected by classical theory [16]. An increase in I_p induces the reduction of orbit deviation from the flux surface owing to an increase in the poloidal magnetic field. The confinement of 1 MeV triton becomes better with an increase in I_p. Although the deviation of orbit from the magnetic flux surface becomes smaller with an increase in I_p, the deviation is relatively large even in the 1 MA case owing to the high energy. The Larmor radius of banana orbit is more than 10% of the plasma minor radius.

The confinement of 1 MeV triton is surveyed at I_p of 300 kA, 450 kA, 600 kA, 800 kA, and 1 MA cases. Figure 4 (a) shows the time evolution of the 1 MeV triton loss. The number of lost 1 MeV tritons rapidly increases from 10^{-6} s and then almost saturates at 10^{-5} s in all the cases.

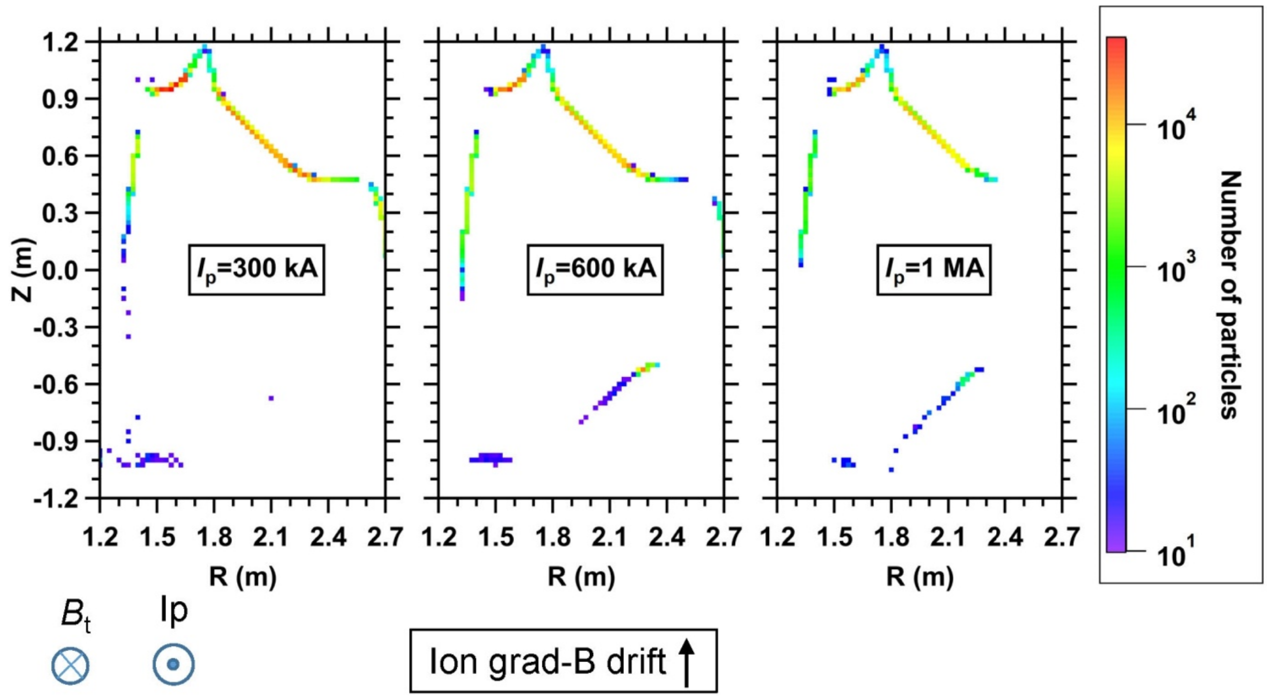

Fig. 5 Distribution of the strike point of 1-MeV tritons. Because the ion grad-B drift is directed upward, strike points are mainly located on the upper panel of the vacuum vessel. Strike points are almost unchanged regardless of I_p.

The loss that occurred at t of less than 10^{-5} s is classified as a prompt loss. This time evolution shows that prompt loss is dominant up to 10^{-3} s. The prompt loss ratio at I_p of 300 kA, 450 kA, 600 kA, 800 kA, and 1 MA reached 85%, 73%, 55%, 46%, and 33%, respectively. The prompt loss ratio decreased with an increase of I_p, as expected. The pitch angle distribution of confined 1 MeV tritons are plotted in Fig. 4 (b). Here, the bin size of pitch angle is set to be 2 degrees. The black line shows the pitch angle distribution of launched particles. The confinement of co-going transit particles is better than that of counter-going transit and banana particles. 1 MeV tritons existing in a wider pitch angle range can be confined in higher I_p cases. Some of the co-going transit particles are confined even if I_p of 300 kA, whereas none of counter-going transit and banana particles are confined in I_p of the 300 kA case. Most banana particles are lost even in I_p of the 1 MA case because the banana width is comparable with that of a minor radius of the plasma.

The strike points of 1 MeV tritons in I_p of 300 kA, 600 kA, and 1 MA cases are plotted in Fig. 5. The strike points of 1 MeV tritons are mainly located at the upper panel of vacuum vessel because the ion grad-B drift is directed upward. Although the number of particles decreases with an increase in I_p, the major strike points of 1 MeV tritons are almost unchanged. The strike points of the 1 MeV triton are located at the lower panel if we changed the direction of toroidal magnetic field. As expected, the locations of strike point are consistent with the direction of the ion grad-B drift.

4. Summary

A study of 1 MeV triton confinement is performed using the Lorentz orbit code LORBIT in order to understand 1 MeV triton confinement characteristics in EAST plasmas. Typical 1 MeV triton orbit shows that the deviation of orbit from the flux surface decreases with an increase in I_p, as expected. The Larmor radius of banana particle is comparable with that of the minor radius of plasma owing to the high-energy of tritons. The time evolution of the 1 MeV triton loss shows that the prompt loss of the triton occurs at $t < 10^{-5}$ s in all I_p cases. 1 MeV tritons, which exist in the wider pitch angle region, are confined in higher I_p cases compared with lower I_p cases. The strike points of the 1 MeV triton show that most particles are lost on the upper panel of the vacuum vessel, which is consistent with the direction of the ion grad-B drift.

Acknowledgments

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[1] A. Fasoli *et al.*, Nucl. Fusion **47**, S264 (2007).
[2] C.W. Barnes *et al.*, Nucl. Fusion **38**, 597 (1998).
[3] J. Källne *et al.*, Nucl. Fusion **28**, 1291 (1988).
[4] M. Hoek *et al.*, Nucl. Instrum. Methods Phys. Res. A **368**, 804 (1996).
[5] W.W. Heidbrink, R.E. Chrien and J.D. Strachan, Nucl. Fusion **23**, 917 (1983).

[6] H. Duong and W.W. Heidbrink, Nucl. Fusion **33**, 211 (1993).
[7] P. Batistoni *et al.*, Nucl. Fusion **27**, 1040 (1987).
[8] M. Hoek, H.S. Bosch and W. Ullrich, "Triton burnup measurement at ASDEX Upgrade by neutron foil activation" (1999) IPP-Report IPP-1/320.
[9] J. Jo *et al.*, Rev. Sci. Instrum. **87**, 11D828 (2016).
[10] M. Isobe *et al.*, Nucl. Fusion **58**, 082004 (2018).
[11] K. Ogawa *et al.*, Nucl. Fusion **59**, 076017 (2019).
[12] G.Q. Zhong *et al.*, Plasma Phys. Control. Fusion **58**, 75013 (2016).
[13] K. Li *et al.*, Fusion Eng. Des. **148**, 111278 (2019).
[14] A. Pankin *et al.*, Comput. Phys. Commun. **159**, 157 (2004).
[15] M. Isobe *et al.*, J. Plasma Fusion Res. SERIES **8**, 330 (2009).
[16] R.B. White, *The Theory of Toroidally Confined Plasmas: Third Edition* (Imperial College Press, 2014) Section 3.3.