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Generation of energetic electrons by an electron cyclotron wave through stochastic heating in a spherical tokamak

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This study presents novel findings on stochastic electron heating via a random electron cyclotron wave (ECW) in a spherical tokamak. Hard x ray measurements demonstrate the time evolution of hard x ray counts at different energy bands, consistent with predictions from the stochastic heating model. The ECW heating rate shows a positive correlation with applied power, confirming the effectiveness of stochastic heating. Remarkably, the ECW-driven plasma current remains insensitive to ECW incidence angle, consistent with model predictions. The observed stochastic heating of electrons offers potential for exploring innovative non-inductive current drive modes in spherical tokamaks. This research contributes to the understanding of plasma behaviour and motivates the development of new models for non-inductive current drive in fusion devices.

Key words: plasma heating, plasma nonlinear phenomena

1. Introduction

Stochastic acceleration is considered a possible mechanism for the generation of energetic particles in the universe (see Seo & Ptuskin 1994; Ma & Summers 1998; McClements *et al.* 2001; Amano *et al.* 2020), and for the heating of plasma in laboratories through the application of external electromagnetic waves (see Kuckes 1968; Puri 1968; Kawamura *et al.* 1971; Jaeger, Lichtenberg & Lieberman 1972; Ikegami *et al.* 1973; Puri 1974).

An equation of the Fokker–Planck type has been derived by Sturrock (1966) in the weak-field approximation, which can be used to solve the stochastic heating problem for transverse stochastic electric fields with components at electron cyclotron frequencies in a uniform magnetic field. It shows that a relatively weak random electron cyclotron

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wave (ECW) can drive energetic electrons. Smith (see Smith & Kaufman 1975; Smith, Cohen & Mau 1987) proposed a single wave stochastic heating model with strong wave amplitude. When the wave amplitude is greater than a threshold, the electric field of the wave causes the adjacent resonance regions to overlap, and the particle motion becomes random.

The theory of stochastic heating in ECW within mirror (non-uniform magnetic field) plasmas has been developed (see Kuckes 1968; Puri 1968, 1974; Kawamura *et al.* 1971; Jaeger *et al.* 1972; Lieberman & Lichtenberg 1973; Bernhardi & Wiesemann 1982). Puri (1968, 1974) shows that plasma electrons can be stochastically heated by microwave noise in mirror. Kawamura *et al.* (1971) investigated the stochastic heating model for single frequency waves. Unlike the multipass linear absorption model (Ishiguro *et al.* 2012), the phase between the waves and electron gyrations is random at each time that the electron passes through the resonance region due to the effect of background density rise and fall. The random phase leads to stochastic heating, and the maximum particle energy is not limited by the maximum phase velocity of the wave spectrum. Nonetheless, electron loss time remains unaccounted for, and there is an absence of a description regarding the absorption coefficient of ECW.

Ikegami *et al.* (1973) derived the relationship between the hard x ray (HX) energy band and time based on the work of Sturrock by assuming a loss time (τ) of energetic electrons. The relationship is in good agreement with the experimental data. The study shows that the average kinetic energy of the electron is proportional to $\langle \tau \rangle$, and a diffuse k-spectrum (narrow omega spectrum) of the heating field, which is caused by the plasma, is more important than non-adiabatic acceleration in the magnetic mirror. This indicates that stochastic heating can occur in a cavity with plasma and an external magnetic field.

Such a high particle heating rate of random waves, being able to drive energetic electrons and fast ions with low heating power, is very important for future fusion reactors. There is still a significant amount of stochastic heating work, which is not described in detail here except for a few closely related works mentioned below.

Stochastic ion heating by electrostatic waves (Karney & Bers 1977), drift waves (McChesney, Stern & Bellan 1987), lower hybrid waves (Karney 1978) and Alfvén waves (Sun *et al.* 2014) has been widely discussed. Studies of stochastic ion heating have helped us to understand anomalous ion heating and driving of energetic ion tails, especially the latter which has an important role in increasing fusion reaction rates (Citrin *et al.* 2013; Putvinski, Ryutov & Yushmanov 2019; Han *et al.* 2022).

The experiments conducted in QUEST (Q-shu university experiment with steady state spherical tokamak) have shown that the presence of the energetic electrons positively influences the formation of a closed magnetic surface (Ishiguro *et al.* 2012). The experimental work of Wang *et al.* further supports this finding, demonstrating that the current carried by energetic electrons plays a dominant role in shaping the closed magnetic flux surface (Shi *et al.* 2022; Wang *et al.* 2022). Thus, achieving a high energetic electron heating rate is crucial for successful ECW non-inductive current start-up.

In the EXL-50 experiment, a fully non-inductive ECW drive current was observed. This remarkable progress, highlighted by an amps-to-watts ratio of 1 kA kW^{-1} (Shi *et al.* 2022), underscores the importance of energetic electron involvement in driving the plasma current.

This study presents the first experimental evidence of ECW stochastic heating in a spherical tokamak. The temporal evolution of HX counts in different energy bands matches the predictions of the stochastic heating model. Additionally, a positive correlation between the plasma heating rate and the ECW injection power was observed, confirming the effectiveness of stochastic heating. Furthermore, the insensitivity of the ECW-driven plasma current to the incidence angle contradicts the conventional understanding in tokamaks (i.e. one-pass absorption near the electron cyclotron resonance layer) of ECW and indicates the necessity for new models. The findings may motivate further research and model development for non-inductive current drive and energetic electron heating in toroidal fusion devices.

2. Experimental results

2.1. *The EXL-50 spherical tokamak*

The EXL-50 is a medium-sized spherical tokamak without a central solenoid, the major radius of EXL-50 is approximately 0.58 m, the minor radius is approximately 0.41 m, B_T (at $r \sim 0.58$ m) is approximately 0.48 T, and aspect ratio of A >= 1.45. Currently, the highest plasma current recorded in the experiment is 150 kA. The line integral electron density is usually $2 \sim 18 \times 10^{17}\ \mathrm{m}^{-2}$, with an electron cyclotron resonance heating (ECRH) power of approximately 140 kW. The EXL-50 uses two sets of 28 GHz ECW systems (O-mode) to heat the plasma and drive plasma current (Shi *et al.* 2022; Wang *et al.* 2022). System #1 (source power of gyrotron 50 kW) is mainly used to produce the initial plasma and to form a closed flux surface, and system #2 (source power of gyrotron 400 kW) is used to increase the plasma current and sustain the current flattop for several seconds. Referring to the work of (Ikegami *et al.* 1973), EXL-50 uses a smooth metal wall, and observation windows are shielded with 28 GHz shielding materials, and the distribution of the ECWs in the vacuum chamber is approximately stochastic with cold plasma (Ikegami *et al.* 1973). The plasma density is diagnosed using an interferometer (Li *et al.* 2021). Energetic electron energy is diagnosed by the HX bremsstrahlung radiation from the plasma (figure 1*a*). The HX detectors with improved lead shielding are applied. Beside the original shielding (10 mm lead +5 mm steel) (Cheng *et al.* 2021), the CdZnTe detectors have their own independent 50 mm lead shielding. For this improved shielding HX system, there are two detectors with a collimator and one blinded detector without a collimator (figure 1*b*). For the discharges with plasma current less than 100 kA, the HX counts of the blinded detector are much small than the detectors with a collimator. A large number of energetic electron-driven instabilities have be observed in the discharge of EXL-50 (Wang *et al.* 2023*d*,2023*b*,2023*c*).

2.2. *Density fluctuations*

In EXL-50, the bulk electron density and temperature are typically in the range of $4–40 \times 10^{17}\ \mathrm{m}^{-2}$ and 10–200 eV, respectively, while the energetic electron temperature is approximately 100–300 keV (Cheng *et al.* 2021; Ishida, Peng & Liu 2021; Li *et al.* 2021; Guo *et al.* 2022; Li *et al.* 2022; Shi *et al.* 2022; Wang *et al.* 2022, 2023*d*). Figure 2(*a*) illustrates the relationship between single-pass wave power absorption coefficient and electron energy, calculated using GENRAY (Smirnov & Harvey 2001) (with a bulk plasma temperature of 100 eV). The efficiency of single-pass absorption of ECW power by the plasma is notably low. Moreover, as shown in figure 2(*c*), the interferometer often observes significant density fluctuations (Wang *et al.* 2023*a*). When the ECW passes through the plasma, the plasma and its fluctuations can modulate the ECW phase.

Owing to the smooth metal wall and window shielding, the vacuum vessel of the EXL-50 can be approximated as a shielding cavity. Since the single passing absorption efficiency of an electron cyclotron wave is so weak in the present low temperature EXL-50 plasmas, the angle and mode of ECW are randomized during the multiple wall reflections. According to Ikegami *et al.* (1973), the distribution of ECWs in the vacuum vessel is

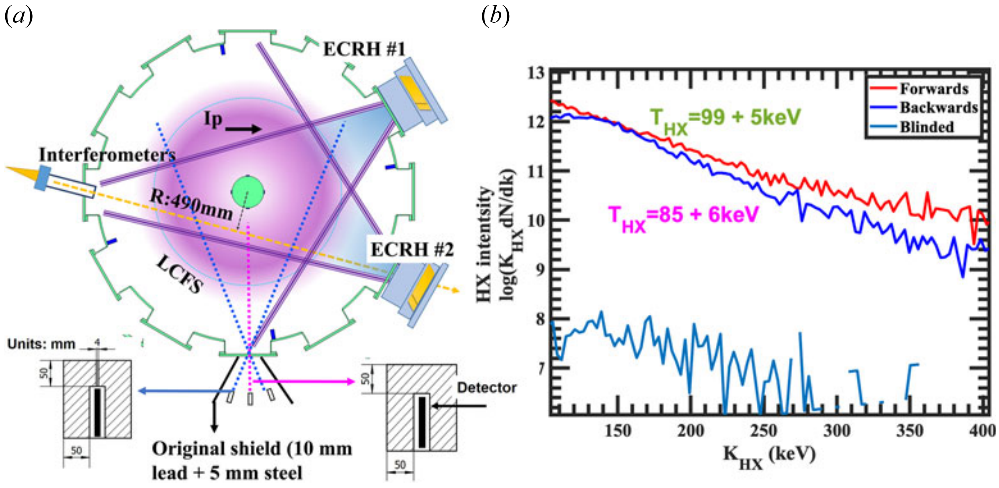

FIGURE 1. (*a*) Top view of the EXL-50. Lines of sight of the interferometer and HX diagnostics are indicated in the figure. The ECW beam is aimed at the centre of the machine when the toroidal injection angles are 0°. (*b*) Typical HX spectra in the forwards, and backwards directions and the blinded during the flat top phase. The boundary marked is the last closed flux surface (LCFS).

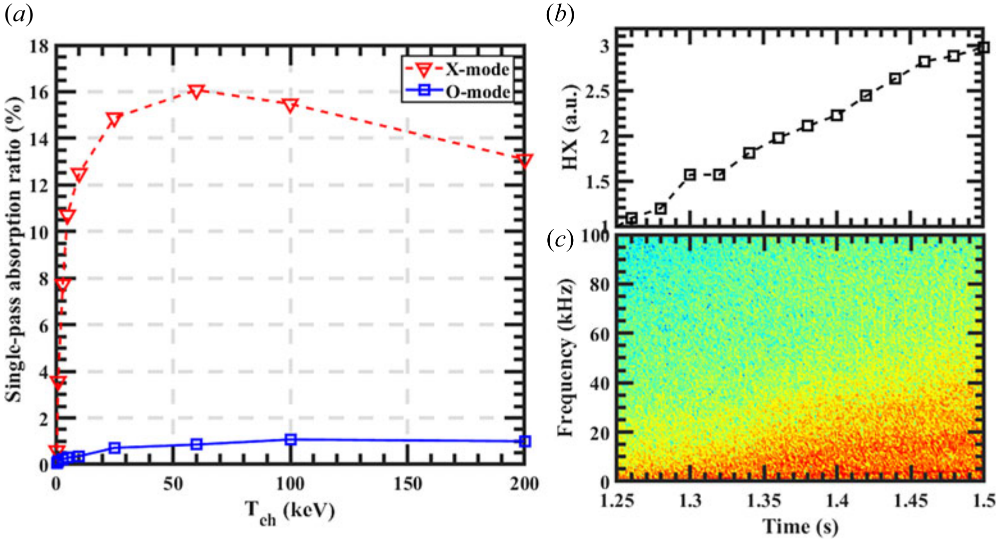

FIGURE 2. (*a*) Relationship between the energy of electrons and wave single passing absorption rate calculated by GENRAY. (*b*) Time evolution of HX intensity and (*c*) density fluctuations.

approximately stochastic. The stochastic electron acceleration model on EXL-50 may hold.

2.3. *Weak ECW stochastic heating of electrons*

When ECW exclusively heat the energy component w perpendicular to the magnetic field direction, the time evolution of the electron distribution function ($f(t, w)$) is described by the Fokker–Planck equation, employing the relationship derived by Sturrock (1966),

$$\frac{\partial f}{\partial t} = R\frac{\partial}{\partial w}\left(w\frac{\partial f}{\partial w}\right) - \frac{f}{\tau} + Q\delta(w), \tag{2.1}$$

where R is the heating rate, which is positively correlated with the strength of the stochastic electromagnetic wave electric field and is assumed to be independent of w (Sturrock 1966). Here Q is the electron source. For the electron energy distribution function obtained from (2.1), the photon number $(\eta(\varepsilon, t))$ of the x ray bremsstrahlung emitted by the statistically accelerated energetic electrons is given by

$$\eta(\varepsilon, t) = \frac{c}{\varepsilon}\int_{\varepsilon}^{\infty}\frac{\mathrm{d}w}{\sqrt{w}}f(t, w)G(w, \varepsilon). \tag{2.2}$$

Here C is a numerical constant, $G(w, \varepsilon)$ is the energy-dependent part of the total cross-section for the bremsstrahlung of photons with energy ε produced by the electrons with energy w. The time development of the x ray bremsstrahlung photon number due to the statistically heated (or accelerated) energetic electrons by the stochastic ECW is as follows (Ikegami *et al.* 1973):

$$\eta(\varepsilon, t) \propto \varepsilon^{-0.5}/R\int_0^{t/\langle\tau\rangle}\mathrm{d}s\, s^{-1}\mathrm{e}^{-s} \times \int_0^{\infty}\mathrm{d}u\ln(u + \sqrt{u^2 - 1})\exp\left(-\frac{\varepsilon}{R\langle\tau\rangle}\frac{u^2}{s}\right), \tag{2.3}$$

where $\langle\tau\rangle$ is the average electron energy decay time. Parameters such as $\langle\tau\rangle$ and R have specific ranges: for 'τ' the reasonable range is several to several hundreds of milliseconds; for 'R' the reasonable range is 0.1 to several tens of megaelectronvolts per second (Ikegami *et al.* 1973).

To validate the generation of energetic electrons through stochastic heating, the time evolution of HX counts at different energy bands was analysed. Figure 3 illustrates the number of x ray bremsstrahlung photons (solid line) and theoretical curves (dotted line) at different energy bands. Numerical calculations (dotted lines) were performed to compare the experimental results with the theoretically derived photon numbers at a specific energy, as described in (2.3). The excellent agreement between the experimental and theoretical curves confirms the presence of stochastic heating and the generation of energetic electrons in the EXL-50 experiment. It is worth mentioning that the EXL-50 optimizes the shielding of the HX system to mitigate the effects of thick target radiation. As a result, the number of photons within the detection system is reduced, leading to a decrease in the system's signal-to-noise ratio. Nevertheless, the basic trend remains reliable and acceptable.

Furthermore, the relationship between ECW input power and heating rate was analysed under the same gas delivery conditions. The heating rate is plotted as a function of the input power in figure 4. The plasma heating rate shows a positive correlation with the applied ECW power, confirming the effectiveness of stochastic heating.

2.4. *The ECW-driven plasma current*

Figure 5 shows time traces of plasma current I_p (figure 5*a*) and line-integral electron density n_{el} (figure 5*b*) under the same heating power (50 kW) and different ECWs incident angles on EXL-50. Although the toroidal and poloidal incidence angles of the ECWs change significantly, the direction and amplitude of the plasma current do not change, meaning that the direction and amplitude of the plasma current are not sensitive to the incidence angle. Meanwhile, the direction of plasma current is dominated by B_V.

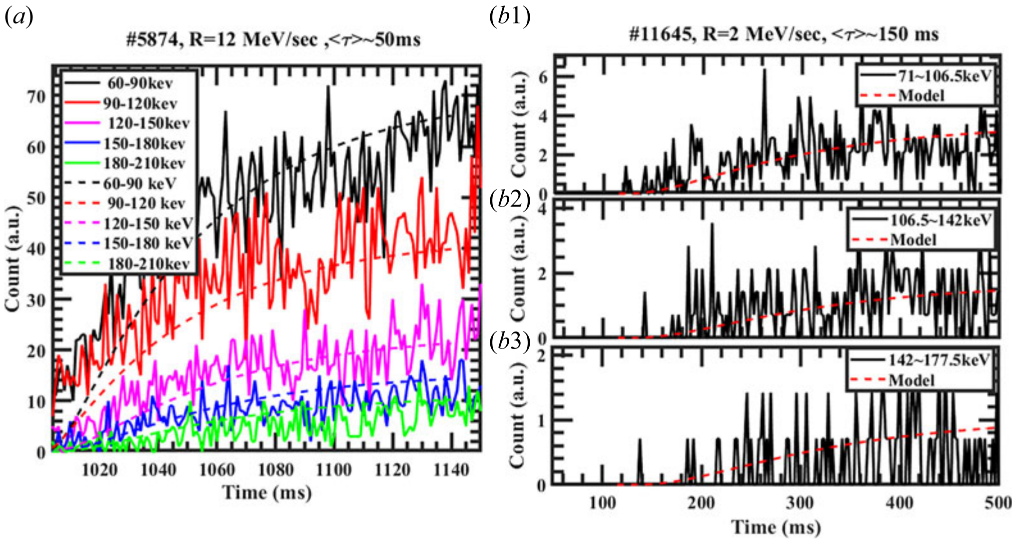

FIGURE 3. Time evolutions of x ray bremsstrahlung photon numbers of specified energy. The ECW injection power is approximately 105 kW (*a*) and 25 kW (*b*). The solid line is the measurement result by HX and the dotted line is the theoretical curves.

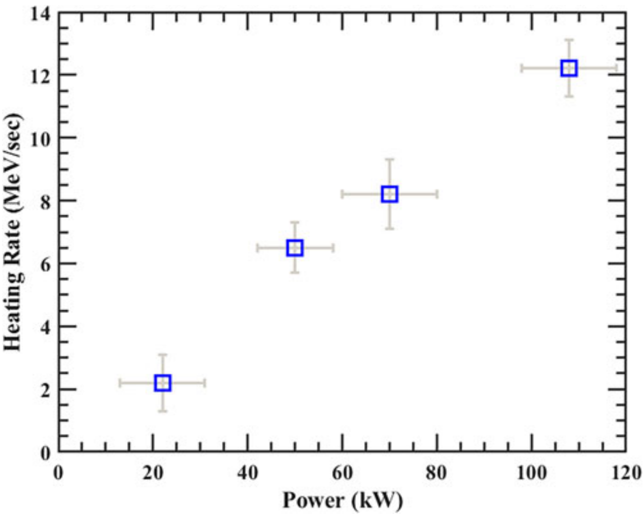

FIGURE 4. Relationship between heating rate and input ECW power; the heating rate is displayed as a function of the input power.

Conventional analyses, such as ray tracing codes, reveal that the direction and amplitude of the plasma current are highly responsive to the angle of the ECW injection, especially when there is efficient absorption of the ECW through signal passage. The insensitivity of the ECW-driven plasma current to the incidence angle is in contrast to the conventional tokamak understanding of the ECW on EXL-50 and implies a requirement for new models.

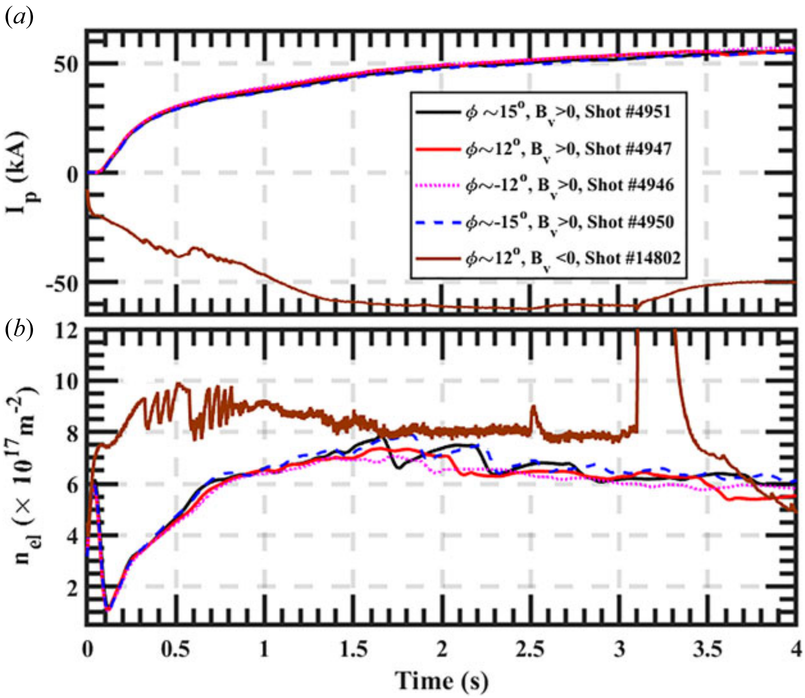

FIGURE 5. Time traces of I_p (*a*) and line-integral electron density (*b*) for different ECW incidence angles (shots #4946, #4947, #4950 and #4951) and for B_V (#14802). The direction and amplitude of plasma current are not sensitive to the incidence angle. Meanwhile, the direction of plasma current is dominated by B_V.

2.5. *Discussion*

From the perspective of conventional ECW current-driving physics, stochastic ECW is not expected to drive the plasma current. However, experimental observations in EXL-50 demonstrate that stochastic ECW can induce remarkably high plasma currents. As the incident power increases, the plasma current also rises, and the average slope exceeds 1 kA kW^{-1} (Shi *et al.* 2022).

Furthermore, a correlation analysis was performed to examine the relationship between the plasma current, T_{HX}, and $N_{eh}T_{HX}$, where T_{HX} represents the temperature of HX emissions within the energy range of (90 ∼ 200 keV) in steady state, and N_{eh} is the HX flux at the same energy range. In this study, $N_{eh}T_{HX}$ was employed to indicate the qualitative trend of energetic electron pressure. Recent work (Maekawa, Peng & Liu 2023) has shown that the energetic electron pressure is related to the energetic electrons current. The results, as depicted in figure 6, demonstrate a positive correlation trend between the plasma current and $N_{eh} * T_{HX}$ during stable plasma current periods.

The observed high heating efficiency of random electromagnetic waves for energetic electrons, coupled with the asymmetric confinement of phase space for energetic electrons by background magnetic fields (Yoshinaga *et al.* 2006; Maekawa *et al.* 2012), provides a plausible explanation for the experimental findings. Firstly, the stochastic heating process generates a large population of energetic electrons. Secondly, considering the collision damping between bulk electrons and energetic electrons and the instability of the energetic electron drive (Wang *et al.* 2023*d*), the parallel temperature of energetic electrons increases

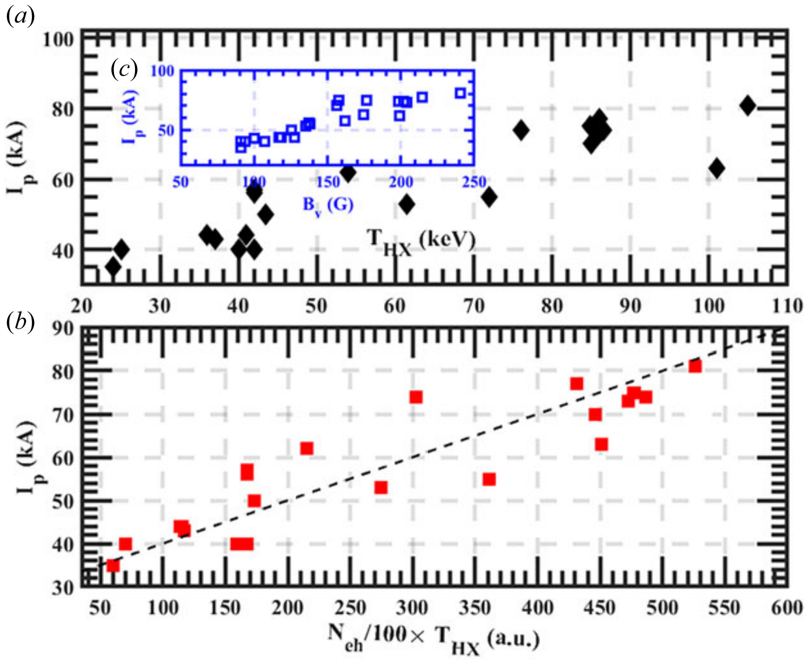

FIGURE 6. Dependence of plasma current on (*a*) $\mathrm{T_{HX}}$, (*b*) $\mathrm{N_{eh}} \times \mathrm{T_{HX}}$ and (*c*) B_V. The plot reveals an approximately positive correlation trend between these parameters and plasma current.

(Gary & Wang 1996; Yoshinaga *et al.* 2006; Lvovskiy *et al.* 2019). Lastly, the asymmetric confinement of phase space for energetic electrons by magnetic fields induces plasma currents (Uchida *et al.* 2010; Maekawa *et al.* 2012; Takase *et al.* 2013; Tanaka *et al.* 2016; Idei *et al.* 2017; Wang *et al.* 2022). These mechanisms collectively contribute to the observed phenomena in the experiment.

3. Summary

In this study, the researchers present the first experimental evidence of stochastic heating of electrons by random ECWs in a spherical tokamak. The time evolution of HX counts at various energy bands aligns with the predictions of the stochastic heating model. Furthermore, the plasma heating rate is shown to be positively correlated with the injected ECW power. Notably, the ECW-driven plasma current is observed to remain independent of the ECW incidence angle.

The findings of this research hold significant implications for broad potential applications in the field of plasma physics and fusion research. Firstly, it introduces a novel model for ECW heating in toroidal devices, providing crucial insights for understanding the EXL-50 ECW non-inductive current drive experiment, as well as potential applications of non-inductive current drive in advanced fusion devices. Secondly, the high efficiency of energetic electron heating and confinement opens up new avenues for investigating wave–particle nonlinear interactions in the laboratory. Lastly, the findings have significant relevance for studying particle acceleration and instability phenomena both in space plasma and laboratory settings.

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Declaration of interests

The authors report no conflict of interest.

Data availability statement

The data that support the findings of this study are available upon reasonable request to the corresponding author.

REFERENCES

AMANO, T., KATOU, T., KITAMURA, N., OKA, M., MATSUMOTO, Y., HOSHINO, M., SAITO, Y., YOKOTA, S., GILES, B.L., PATERSON, W.R., *et al.* 2020 Observational evidence for stochastic shock drift acceleration of electrons at the Earth's bow shock. *Phys. Rev. Lett.* **124** (6), 065101.

BERNHARDI, K. & WIESEMANN, K. 1982 X-ray bremsstrahlung measurements on an ECR-discharge in a magnetic mirror. *Plasma Phys.* **24** (8), 867.

CHENG, S.K., ZHU, Y.B., CHEN, Z.Y., LI, Y.X., BAI, R.H., CHEN, B., HUANG, X.L., DAI, L.L. & LIU, M.S. 2021 Tangential hard x-ray diagnostic array on the EXL-50 spherical tokamak. *Rev. Sci. Instrum.* **92** (4), 043513.

CITRIN, J., JENKO, F., MANTICA, P., TOLD, D., BOURDELLE, C., GARCIA, J., HAVERKORT, J.W., HOGEWEIJ, G.M.D., JOHNSON, T. & PUESCHEL, M.J. 2013 Nonlinear stabilization of tokamak microturbulence by fast ions. *Phys. Rev. Lett.* **111** (15), 155001.

GARY, S.P. & WANG, J. 1996 Whistler instability: electron anisotropy upper bound. *J. Geophys. Res.: Space* **101** (A5), 10749–10754.

GUO, D., SHI, Y., LIU, W., SONG, Y., SUN, T., LIU, B., LI, Y., TIAN, X., ZHANG, G., XIE, H., *et al.* 2022 Experimental study of the characteristics of energetic electrons outside LCFS in EXL-50 spherical torus. *Plasma Phys. Control. Fusion* **64** (5), 055009.

HAN, H., PARK, S.J., SUNG, C., KANG, J., LEE, Y.H., CHUNG, J., HAHM, T.S., KIM, B., PARK, J.-K., BAK, J.G., *et al.* 2022 A sustained high-temperature fusion plasma regime facilitated by fast ions. *Nature* **609** (7926), 269–275.

IDEI, H., KARIYA, T., IMAI, T., MISHRA, K., ONCHI, T., WATANABE, O., ZUSHI, H., HANADA, K., QIAN, J., EJIRI, A., *et al.* 2017 Fully non-inductive second harmonic electron cyclotron plasma ramp-up in the quest spherical tokamak. *Nucl. Fusion* **57** (12), 126045.

IKEGAMI, H., AIHARA, S., HOSOKAWA, M. & AIKAWA, H. 1973 Generation of energetic electrons by electron cyclotron heating in a magnetic mirror field. *Nucl. Fusion* **13** (3), 351.

ISHIDA, A., PENG, Y.-K.M. & LIU, W. 2021 Four-fluid axisymmetric plasma equilibrium model including relativistic electrons and computational method and results. *Phys. Plasmas* **28** (3), 032503.

ISHIGURO, M., HANADA, K., LIU, H., ZUSHI, H., NAKAMURA, K., FUJISAWA, A., IDEI, H., NAGASHIMA, Y., HASEGAWA, M., TASHIMA, S., *et al.* 2012 Non-inductive current start-up assisted by energetic electrons in Q-shu university experiment with steady-state spherical tokamak. *Phys. Plasmas* **19** (6), 062508.

JAEGER, F., LICHTENBERG, A.J. & LIEBERMAN, M.A. 1972 Theory of electron cyclotron resonance heating. I. Short time and adiabatic effects. *Plasma Phys*. **14** (12), 1073.

KARNEY, C.F.F. 1978 Stochastic ion heating by a lower hybrid wave. *Phys. Fluids* **21** (9), 1584–1599.

KARNEY, C.F.F. & BERS, A. 1977 Stochastic ion heating by a perpendicularly propagating electrostatic wave. *Phys. Rev. Lett*. **39** (9), 550.

KAWAMURA, T., MOMOTA, H., NAMBA, C. & TERASHIMA, Y. 1971 Stochastic model of electron-cyclotron heating in a magnetic mirror. *Nucl. Fusion* **11** (4), 339.

KUCKES, A.F. 1968 Limit of the plasma temperature attainable by cyclotron resonance heating in a magnetic mirror. *Phys. Lett.* A **26** (12), 599–600.

LI, H.Y., LI, S.J., XIE, Q.F., LIU, J.H., BAI, R.H., TAO, R.Y., LUN, X.C., LI, N., BO, X.K., LIU, C.Q., *et al.* 2022 Thomson scattering diagnostic system for the XuanLong-50 experiment. *Rev. Sci. Instrum*. **93** (5), 053504.

LI, S.J., BAI, R.H., TAO, R.Y., LI, N., LUN, X.C., LIU, L.C., LIU, Y., LIU, M.S. & DENG, B.H. 2021 A quasi-optical microwave interferometer for the XuanLong-50 experiment. *J. Instrum*. **16** (08), T08011.

LIEBERMAN, M.A. & LICHTENBERG, A.J. 1973 Theory of electron cyclotron resonance heating. II. Long time and stochastic effects. *Plasma Phys*. **15** (2), 125.

LVOVSKIY, A., HEIDBRINK, W.W., PAZ-SOLDAN, C., SPONG, D.A., DAL MOLIN, A., EIDIETIS, N.W., NOCENTE, M., SHIRAKI, D. & THOME, K.E. 2019 Observation of rapid frequency chirping instabilities driven by runaway electrons in a tokamak. *Nucl. Fusion* **59** (12), 124004.

MA, C.-Y. & SUMMERS, D. 1998 Formation of power-law energy spectra in space plasmas by stochastic acceleration due to whistler-mode waves. *Geophys. Res. Lett*. **25** (21), 4099–4102.

MAEKAWA, T., PENG, Y.-K.M. & LIU, W. 2023 Particle orbit description of cyclotron-driven current-carrying energetic electrons in the EXL-50 spherical torus. *Nucl. Fusion* **63** (7), 076014.

MAEKAWA, T., YOSHINAGA, T., UCHIDA, M., WATANABE, F. & TANAKA, H. 2012 Open field equilibrium current and cross-field passing electrons as an initiator of a closed flux surface in EC-heated toroidal plasmas. *Nucl. Fusion* **52** (8), 083008.

MCCHESNEY, J.M., STERN, R.A. & BELLAN, P.M. 1987 Observation of fast stochastic ion heating by drift waves. *Phys. Rev. Lett*. **59** (13), 1436.

MCCLEMENTS, K.G., DIECKMANN, M.E., YNNERMAN, A., CHAPMAN, S.C. & DENDY, R.O. 2001 Surfatron and stochastic acceleration of electrons at supernova remnant shocks. *Phys. Rev. Lett*. **87** (25), 255002.

PURI, S. 1968 Statistical particle acceleration in random fields. *Phys. Fluids* **11** (8), 1745–1753.

PURI, S. 1974 Stochastic heating of plasma electrons using microwave noise. *Plasma Phys*. **16** (6), 517.

PUTVINSKI, S.V., RYUTOV, D.D. & YUSHMANOV, P.N. 2019 Fusion reactivity of the pB11 plasma revisited. *Nucl. Fusion* **59** (7), 076018.

SEO, E.-S. & PTUSKIN, V.S. 1994 Stochastic reacceleration of cosmic rays in the interstellar medium. *Astrophys. J*. **431**, 705–714.

SHI, Y., LIU, B., SONG, S., SONG, Y., SONG, X., TONG, B., CHENG, S., LIU, W., WANG, M., SUN, T., *et al.* 2022 Solenoid-free current drive via ECRH in EXL-50 spherical torus plasmas. *Nucl. Fusion* **62** (8), 086047.

SMIRNOV, A.P. & HARVEY, R.W. 2001 The genray ray tracing code. *CompX Report* CompX-2000-01. Available at: https://www.compxco.com/Genray_manual.pdf.

SMITH, G.R., COHEN, R.H. & MAU, T.K. 1987 Harmonic overlap in electron-cyclotron current drive at high T_e. *Phys. Fluids* **30** (11), 3633–3635.

SMITH, G.R. & KAUFMAN, A.N. 1975 Stochastic acceleration by a single wave in a magnetic field. *Phys. Rev. Lett*. **34** (26), 1613.

STURROCK, P.A. 1966 Stochastic acceleration. *Phys. Rev*. **141** (1), 186.

SUN, J., GAO, X., LU, Q. & WANG, S. 2014 The efficiency of ion stochastic heating by a monochromatic obliquely propagating low-frequency alfven wave. *Plasma Sci. Technol*. **16** (10), 919.

TAKASE, Y., EJIRI, A., KAKUDA, H., OOSAKO, T., SHINYA, T., WAKATSUKI, T., AMBO, T., FURUI, H., HASHIMOTO, T., HIRATSUKA, J., *et al.* 2013 Non-inductive plasma initiation and plasma current ramp-up on the TST-2 spherical tokamak. *Nucl. Fusion* **53** (6), 063006.

TANAKA, H., UCHIDA, M., MAEKAWA, T., BAE, Y.-S., JOUNG, M., JEONG, J.H. & KSTAR TEAM 2016 Non-inductive initiation of closed flux surfaces by ECH/ECCD on KSTAR using an oblique fundamental O-mode injection from the low-field side. *Nucl. Fusion* **56** (4), 046003.

UCHIDA, M., YOSHINAGA, T., TANAKA, H. & MAEKAWA, T. 2010 Rapid current ramp-up by cyclotron-driving electrons beyond runaway velocity. *Phys. Rev. Lett.* **104** (6), 065001.

WANG, M., GUO, D., SHI, Y., CHEN, B., LIU, B., SONG, S., ZHAO, X., SONG, Y., LIU, W., GUAN, Y., *et al.* 2022 Experimental study of non-inductive current start-up using electron cyclotron wave on EXL-50 spherical torus. *Plasma Phys. Control. Fusion* **64** (7), 075006.

WANG, M., LI, J., BAI, Y., DONG, J., SHI, Y., ZOU, X., LIU, A., ZHUANG, G., LI, H., LI, S., *et al.* 2023*a* Particle pump-out induced by trapped electron mode turbulence in electron cyclotron heated plasmas on XuanLong-50 spherical torus. *Nucl. Fusion* **63** (7), 076024.

WANG, M., SHI, Y., DONG, J., GAO, X., LU, Q., WANG, Z., CHEN, W., LIU, A., ZHANG, G., WANG, Y., *et al.* 2023*b* Observation of whistler wave instability driven by temperature anisotropy of energetic electrons on EXL-50 spherical torus. https://doi.org/10.48550/arXiv.2307.06497.

WANG, M., TAN, M., SHI, Y., WANG, Z., DONG, J., LIU, A., ZHUANG, G., LI, S., SONG, S., YUAN, B., *et al.* 2023*c* Experimental investigation of kinetic instabilities driven by runaway electrons in the EXL-50 spherical torus. https://doi.org/10.48550/arXiv.2307.06498.

WANG, M., XIUCHUN, L., XIAOKUN, B., BING, L., ADI, L. & YUEJIANG, S. 2023*d* Radio-frequency measurements of energetic-electron-driven emissions using high-frequency magnetic probe on XuanLong-50 spherical torus. *Plasma Sci. Technol.* **25** (4), 045104.

YOSHINAGA, T., UCHIDA, M., TANAKA, H. & MAEKAWA, T. 2006 Spontaneous formation of closed-field torus equilibrium via current jump observed in an electron-cyclotron-heated plasma. *Phys. Rev. Lett.* **96** (12), 125005.