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Discovery of Electric Pulsation in a Toroidal Helical Plasma

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Abstract

A self-organized pulsation in electrostatic potential has been discovered in a low density plasma of CHS heliotron/torsatron with combined ECH+NBI heating. The potential profiles repeat transition between two distinctive states ($\Delta\phi(0) \sim 0.5T_e \sim 0.6$kV) in a constant external magnetic field when there is a continuous supply of particles and energy. Each transition, which occurs on microseconds time scale that is much faster than the diffusive one of milliseconds, is accompanied with drastic changes in density and temperature profiles. This discovery clearly demonstrates that spontaneously generated 'electric' field can affect transports and other properties of 'magnetically' confined plasmas.

keywords; self-organized pulsation, potential, electric field, bifurcation, transition, toroidal helical plasmas, nonlinearity, multiple steady states

Various phenomena associated with nonlinearity has been observed in magnetically confined toroidal plasmas. The L-to H-mode transition in the ASDEX tokamak [1] is one of the most important discoveries for plasma physics and fusion oriented research since the transition shows structural reformation which is accompanied with a drastic change in transport properties. Bifurcation of radial electric field has been discussed as a predominant working hypothesis to understand the H-mode transition [2–4]. The nonlinear property to cause the bifurcation also realizes a dynamic steady state, that is known as the edge localized mode (ELM) [5]. The phenomenon can be regarded as repetitive transitions or a limit cycle between L-and H-modes [6]. Sawtooth oscillations, which was found for the first time in the ST tokamak [7] and commonly observed in various toroidal plasmas, are another example of a self-organized nonlinear process reforming the magnetic field structure.

Amongst fusion oriented devices, toroidal helical devices (e.g., stellarator, torsatron, heliotron) are supposed to realize a 'plasma with static state'. This is because static external coils alone can produce the necessary magnetic field for confinement, without internal plasma current sometimes leading to violent instabilities such as disruptions [8]. Nonlinear nature of radial electric field, however, allows existence of multiple equilibrium states in toroidal helical plasmas [9,10], and can induce dynamic behavior in the plasma [11]. In fact, we have discovered a 'dynamic steady state' in a toroidal helical plasma, where the plasma exhibits a self-organized oscillation in its electrostatic potential profile. This phenomenon, denoted as 'electric pulsation', indicates the toroidal helical plasma can self-organize dynamic steady states under a constant and static external condition. The phenomenon shows that 'electric field' can give an essential impact on properties of 'magnetically confined plasmas', and provides a formation of plasma structure associated with dynamics of electric field.

The Compact Helical System (CHS) is a heliotron/torsatron device whose major and averaged minor radii are 1.0m and 0.2m, respectively [12]. The periodicity of magnetic field is toroidally 8 and poloidally 2. The electrostatic potential of the plasma interior has been directly measured with a heavy ion beam probe(HIBP) [13]. In our HIBP measurements, Cs^+ beam is injected into the plasma, then Cs^{2+} beam, which is produced at a point of the plasma through an ionization process, is detected with an energy analyzer. The energy difference between injected and detected beams corresponds to the potential energy at the ionization point. Simultaneously, the detected beam intensity gives some information about density profiles $n_e(r)$. This is because the detected beam intensity I_D is expressed as $I_D(r) \propto Q_{12}(r)A(r)\Delta v$, where $Q_{12}(r)$ and $A(r)$ represent local ionization rate from singly charged state to doubly one and the beam attenuation along the beam orbit, respectively, and Δv is the sample volume. If the electron temperature is sufficiently high, the ionization rate is proportional to electron density (e.g., $Q_{12}(r) \propto n_e(r)$). The attenuation term is explicitly written as $A(r) \equiv \exp[-\int_r Q\mathrm{d}l]$, with Q being the total ionization cross section from singly (or doubly) to the other higher charged states.

The electric pulsation was found in hydrogen plasmas with rather low density($n_e = 3 \sim 7 \times 10^{12}\mathrm{cm}^{-3}$) and high electron temperature($\sim$ 1 keV) when the magnetic field strength was 0.88T on the axis. The plasmas in this regime are produced by using the second harmonic resonance of electron cyclotron heating (ECH, 53.2GHz, ~300kW) on target plasmas sustained by neutral beam injection (NBI, the port-through power ~ 700kW). The internal plasma energy measured by a diamagnetic loop is about 400J and the average β is about 0.2%. Figure 1 shows the electric pulsation observed in the potential at the plasma center, together with time evolution of the line-averaged electron density. The combined ECH+NBI heating continues from t=44ms to t=96ms in this case. After the ECH is on, the electron density decreases and relaxes to a steady state of $n_e \simeq 4 \times 10^{12}\mathrm{cm}^{-3}$ approximately in 5ms. In the steady state($55 < t < 95$ms), negative bursts of potential by -0.6kV occur quasi-periodically in every 2ms. The pulsations appear to repeat swinging between two states of higher and lower potential of $\phi(0) = 0.8$kV and 0.2kV. The plasma stays longer in the higher potential state. The potential collapses and recovers in typical timescales of 30μs and 140μs, respectively. These timescales (~ a few dozen microseconds) are much faster than the diffusive one (~ a few milliseconds). This fast timescale manifests the transitory nature of the phenomenon

Potentials at other locations also exhibit quasi-periodic bursts with similar interval but different amplitude and polarity. In contrast to the bursts near the plasma center, positive bursts are observed in outer plasma radius. The pivot point at which the burst changes its polarity is located around the normalized plasma radius $\rho = 0.53$, as is shown in Fig. 2a to 2c. In Fig. 2d, the averages of local maximums and minimums in the periods including a burst are plotted as a function of normalized radius. Hence, the fitting curves represent two states before and after the crashes. The plotted data was sequentially taken shot by shot with an identical operational condition. Around the center, the derivative of potential (the electric field) does not change so much before and after the crashes. A large change of the electric field, as a result, occurs around the pivot during a crash.

Other plasma parameters are also pulsating with the potential(Fig. 3a); soft X-ray emission, electron cyclotron emission(ECE)(Fig. 3b), internal energy change estimated from Mirnov coils (Fig. 3c), line-averaged electron density measured with an HCN interferometer, H_α-emission (Fig.3d), and detected beam intensity of HIBP(Fig. 3e). The soft X-ray emission along the central line of sight ($\rho^* = 0$) decreases with the potential crashes, while the soft X-ray emission on an outer line of sight ($\rho^* = 0.4$) increases. Here, ρ^* indicates the normalized radial distance of a chord from the plasma center. This is interpreted as that heat flux may propagate from the inner to the outer region. An increment of the ECE (93.5GHz) signal from an outer region of plasma ($\rho > 0.5$) supports the interpretation, although the plasma in such a low density is not optically thick to be regarded as a black body for the ECE to reflect the electron temperature. It is not sufficient to deduce the detailed change in electron temperature profiles after and before crashes. Mirnov coils at the inner and outer points of the equatorial plane indicate that the plasma starts moving inward, when the potential reaches its minimum during a pulse. The inward shift implies that the plasma loses its internal energy about 20J (approximately $\Delta\beta \simeq 0.01\%$) with a potential burst. The good correlation of H_α emission with the potential bursts also shows that the electric pulsation should affect the plasma periphery.

The line-averaged density signals on chords of $\rho^* < 0.4$ show an increase synchronized with a potential crash, while the other ones on outer chords show no clear correlation.

The detected beam intensity also exhibits a good correlation with the potential signal; the intensity increases (or decreases) when the potential drops (or rises) at observation points of $\rho < 0.7$. The similar timescale of this change to the potential suggests that the particle transport is closely related to the electric field (e.g., $I_{\mathrm{D}} \propto n_e$). Figure 3f demonstrates the change in the detected beam intensity signals before and after crashes; the plotted points represent the detected beam intensity when the potentials take a local maximum or minimum during a burst.

In this low density plasma, the beam attenuation term $A(r)(= \exp[-\int Q \mathrm{d}l])$ is supposed to be sufficiently small. Using Lotz's empirical formula, the attenuation terms around the core are approximately 0.45 for both assumptions of a completely flat density profile and a parabolic one. Around the edge the electron temperature change during crash should be taken into account in estimation of the attenuation term, since the cross-section Q is strongly dependent on the electron temperature when it is below a few hundred eV. If the electron temperature change is neglected, the attenuation term around the edge $A(r \simeq a)$ is about 0.5 and 0.6 for the flat and parabolic density profiles, respectively. Thus, the change of the detected beam intensity $\delta I_{\mathrm{b}}(r)$ reflects mainly local density change, except the periphery of the plasma. A rough Able-inversion of the interferometer signals suggests that higher potential state has a flatter or slightly hollow profile. By combining these information, it is inferred that a slightly hollow profile becomes a peaked one after crash, with a change of central density from $n_e \simeq 4$ to $6 \times 10^{12}\mathrm{cm}^{-3}$. The detail will be discussed in another article.

The electric pulsation should be indicative of a bifurcation of the radial electric field. The nonlinear relationship between radial electric field and current to cause such bifurcation has been experimentally confirmed in the CHS device [11]. There should exist a parameter to control this self-organized oscillation. The close link between potential and density profiles suggests that density or its gradient may be the parameter amongst other candidates, such as temperature and its gradient. The soft X-ray emission on the outside chord has a delay of 200μs to that at the central chord (see Fig. 3b). The time at the soft X-ray peak on the outside chord coincides with that at a potential signal on the outside of the pivot. Thus, the structural change propagates outward in the radial direction. The structural reformation contains richer process than a simple process of swinging between two clearly defined states in Fig. 2d. The plasma structure should be dynamically evolving in a more complicated way in time and space.

The presented example of the electric pulsation was obtained in plasmas with the line-averaged density of $\sim 4 \times 10^{12}\mathrm{cm}^{-3}$. As the density increases for a fixed heating power, the electric pulsation is limited to a narrower region around the center; simultaneously the oscillation period becomes shorter and its amplitude becomes smaller. Finally, the pulsation disappears above a certain critical density. The threshold power to induce the electric pulsation appears to become higher as the density increases. The effect of this 'localized' electric pulsation to plasma periphery is small, judging from the fact that the correlated signal of H_α becomes ambiguous. In a future laboratory plasma relevant to a fusion reactor, fusion producing power can be a source of energy to cause the 'global' electric pulsation, and its effect to walls, diverters and so on, could be so severe to be anticipated. Further investigation is needed to clarify dependence of oscillation characteristics on plasma parameters.

In conclusion, our discovery of the electric pulsation demonstrates that toroidal helical plasmas are not static but can be dynamic, even in a low β regime owing to nonlinearity inherent with radial electric field. The electric pulsation, - a global and sudden structural change of the plasma, is of significant importance for understanding structural formation of a toroidal plasma as a non-equilibrium and nonlinear system, as well as fusion application.

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REFERENCES

[1] F. Wagner et al., Phys. Rev. Lett. **49** 1408(1982).

[2] S.-I. Itoh, K. Itoh , et al., Phys. Rev. Lett. **67** 2485(1991).

[3] K. C. Shaing, E. Crume, Jr., Phys. Rev. Lett., **63** 2369(1989).

[4] For review, K. Itoh, S.-I. Itoh, Phys. Contr. Fusion **38**, 1(1996).

[5] H. Zohm, F. Wagner et al., Nucl. Fusion **32** 489(1992).

[6] S.-I. Itoh, K. Itoh, Phys. Rev. Lett., **60** 2276(1988).

[7] Von Goeler, S. W. Stodiek, and N. Sautoff, Phys. Rev. Lett., **33**, 1201(1974).

[8] L.A. Artsimovich, Nucl. Fusion **12** 215(1972).

[9] D. E. Hastings, W. A. Houlberg, K. C. Shaing. Nucl. Fusion **25** 445(1985).

[10] L. M. Kovrizhnykh, Nucl. Fusion **24**,435(1984).

[11] A. Fujisawa, H. Iguchi, et al., Phys. Rev. Lett **79** 1054(1997).

[12] K. Matsuoka, S. Kubo, M. Hosokawa, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1988 (Proc. 12th Int. Conf. Nice, 1988), International Atomic Energy Agency,Vienna,1989, Vol. 2, 411.

[13] A. Fujisawa, H. Iguchi, et al., Phys. of Plasmas **4** 1357(1997).

FIGURES

FIG. 1. Self-organized oscillation is observed in electrostatic potential profile of a CHS plasma in a combined ECH+NBI heating phase; the phenomenon is referred to as 'electric pulsation'. The central potential (solid line) measured with a heavy ion beam probe repeatedly swings between two states of higher and lower potential. The dashed line represents the line averaged electron density measured with an HCN interferometer.

FIG. 2. Spatial structure of a global electric pulsation. (a) Time evolution of potential at $\rho = 0.43$ (b) that at $\rho = 0.53$ (c) that at $\rho = 0.63$, and (d) spatial structural change of potential before and after crashes. Here ρ is the normalized minor radius.

FIG. 3. Correlation of potential structural change with other plasma parameters. (a) Potential signal at $\rho = 0.1$. (b) Chord integrated soft X-ray emissions of two lines of sight whose distances from the plasma center are $\rho^* = 0.4$, $\rho^* = 0.0$, together with electron cyclotron emission from the plasma edge region ($\rho > 0.5$). Here ρ^* indicates the normalized distance of a chord from the plasma center. (c) Change of plasma internal energy normalized by magnetic pressure $\Delta\beta$, which is estimated from plasma shift. The plasma shift is measured by Mirnov coils located at the inner and outer points on the equatorial plane; the plasma shift is proportional to the change of the plasma pressure. (d) Line-averaged electron density with $\rho^* = 0.4$, and H_α emission from the plasma edge. (e) Detected beam intensity of heavy ion beam probe. (f) Profiles of detected beam intensity after and before crashes. This suggests the density profile after a crash becomes centrally -peaked one.

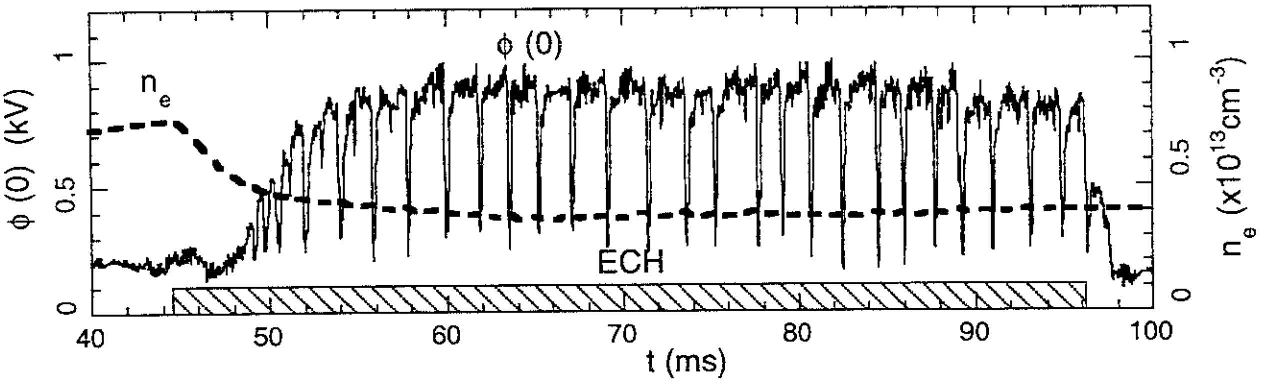

Figure 1

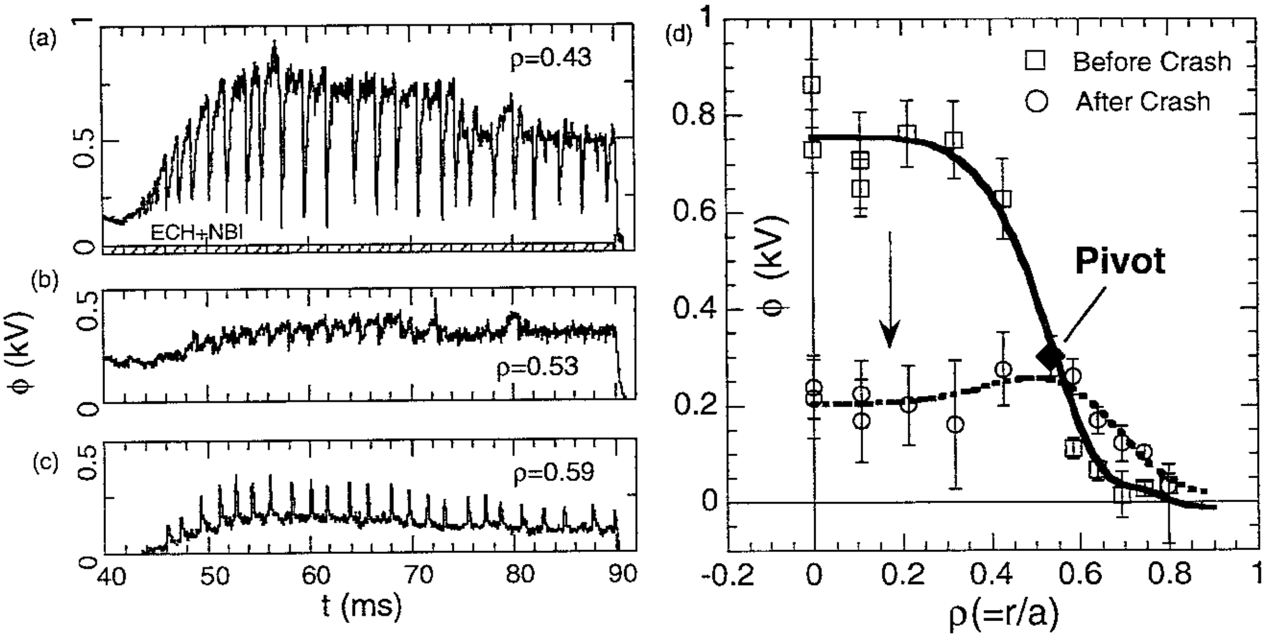

Figure 2

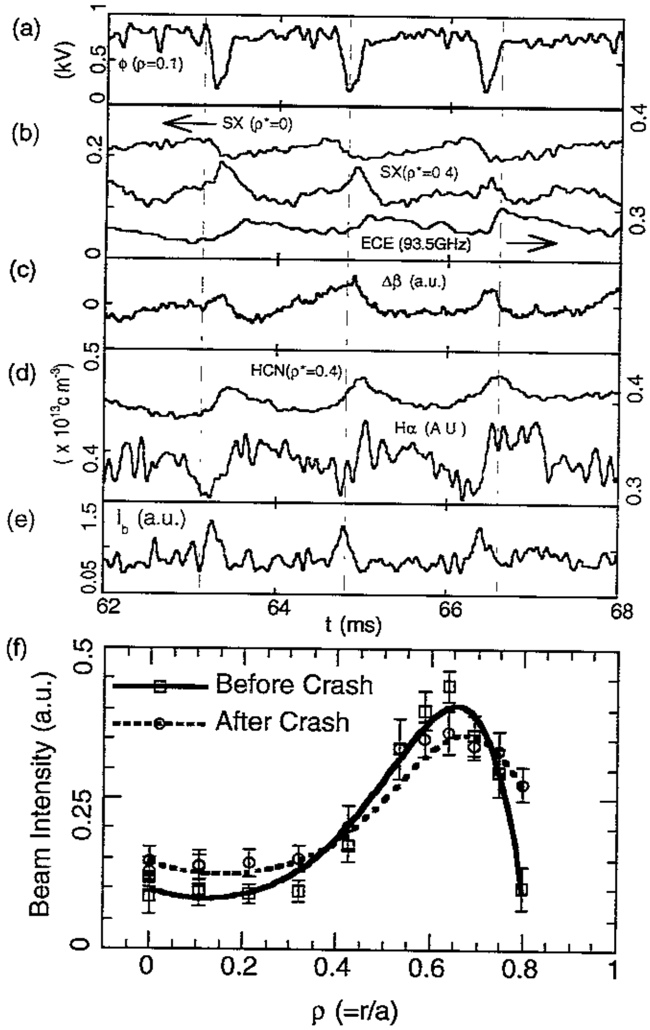
(a)
(kV)
1
0.5
0
φ (ρ=0.1)
(b)
SX (ρ*=0)
0.2
0
SX(ρ*=0.4)
ECE (93.5GHz)
0.4
0.3
(c)
Δβ (a.u.)
0
(d)
(x 10^13 cm^-3)
0.5
0.4
HCN(ρ*=0.4)
Hα (A U)
0.4
0.3
(e)
i_b (a.u.)
1.5
0.05
62
64
66
68
t (ms)
(f)
Beam Intensity (a.u.)
0.5
0.25
0
Before Crash
After Crash
0
0.2
0.4
0.6
0.8
1
ρ (=r/a)

Figure 3

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