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Extended possibility of an active control of co-axially nested shear plasma formation due to electron cyclotron heatings

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Coaxially nested intense $E \times B$ sheared flow realized an upgraded stable mirror plasma regime. After such an external control of high vorticity formation due to electron cyclotron heating, significantly unstable plasmas appeared. Thereby, the associated cross-field transport caused a crash of plasmas. Its generalized physics and interpretation could prepare or extend to another possibility of stability in a field-reversed configuration (FRC), for instance. Such underlying physics bases of vorticity formation were essentially or partially performed in tokamaks and stellarators (solved problems). Nevertheless, it remains to be seen whether this mirror-based experimental evidence is applicable or not to open ended FRC devices. This open issue may give a solution of one of unsolved important problems, and possibly provide more generalized and externally controllable opportunities for not only FRC but wider plasma confinement improvements.

Key words: magnetized plasmas, plasma confinement, plasma instabilities

1. Introduction

Anomalous cross-field transport is one of the most important and long-term investigative issues in fusion-oriented magnetic plasma confinement as well as in the physical understanding of universal confinement in magnetized plasmas. Previously, some phenomena with reduced anomalous transverse transport have been observed in tokamaks (Fujita *et al.* 1997; Connor & Wilson 2000; Kishimoto *et al.* 2000; Diamond *et al.* 2005; and references therein) and stellarators (Takeiri *et al.* 2007; and references therein).

Transition with improved plasma confinement regimes (H-mode) or the formation of internal transport barriers (ITB) in toroidal systems was associated with an increase in non-uniform radial electric fields E_r and an enhancement of sheared plasma rotation. In particular, the low-frequency (LF) turbulence and the associated anomalous transport in such various devices showed rather common features.

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In addition to toroidal devices, intermittent LF turbulent vortex structures and physics effects of their suppression due to strongly sheared plasma rotation were clearly observed in a mirror device (Cho *et al.* 2005*a*; Cho, Hirata & Pastukhov 2006; Cho *et al.* 2008). The suppression of turbulence and the associated significant reduction due to cross-field transport of the mirror showed behaviour that was similar to those seen for Low-to-High (L-H) mode transitions in tokamaks. Mirror devices (Budker, Mirnov & Ryutov 1971; Pastukhov 1974; Fowler & Logan 1977; Post 1987; Cho *et al.* 2001; Pastukhov & Chudin 2011) having open ended regions, provided intrinsic advantages in terms of easy control of radial potential or sheared $\boldsymbol{E} \times \boldsymbol{B}$ rotation profiles on the basis of axial particle loss control (Pastukhov 1974; Cho *et al.* 2005*a*, 2006, 2008; Pastukhov & Chudin 2011).

Therefore, these three types of devices essentially showed improvement from the viewpoint of sheared plasma confinement. Each of them, however, had the intrinsic characteristic property of electron or ion confinement (Fujita *et al.* 1997; Kishimoto *et al.* 2000; Diamond *et al.* 2005; Cho *et al.* 2005*a*, 2006; Takeiri *et al.* 2007; Cho *et al.* 2008; Pastukhov & Chudin 2011).

In this context, these three types of plasma devices were categorized as a part of solved problems with common physical fundamentals despite different topologies.

Recently, in a magnetic field-reversed configuration (FRC) at Tri Alpha Energy, a confinement improvement due to E_r shear formation has been reported (Guo *et al.* 2015; Smirnov 2016). The detailed physical interpretation of the encouraging FRC experiments may still have partially opened issues to be discussed from experimental viewpoints with further additional stability methods for plasma confinement.

A longer plasma duration due to further stable plasma operation is proposed from the viewpoint of essentially similar physics in relation to a mirror device, as described above. This may provide a further possibility of a solved problem (i.e. integrated or combined physics background for FRC and mirror devices, if experiments were to be performed). This is one reason that we show the previous unpublished data as well as further considerations in this article after the mirror presentation at the American Physical Society (APS) (Cho 2007), since recent stimulated presentation from Tri Alpha Energy was shown (Smirnov 2016).

In fact, one such experimental method was reported at a previous APS meeting in a mirror device (Cho 2007). However, after the meeting, such confinement experiments with a mirror were suddenly shut down. Therefore, no reports regarding this theme have been made. However, it would be of use on the basis of the APS presentation, as well as further continuous analyses up to this time, including the associate considerations. If such data and experimental method would be useful for the plasma community, for application to the above-described unsolved problem for instance, we would have an opportunity to provide a useful experimental method as well as to undertake stimulated physics solutions.

In this report, we present results obtained by means of an active control and plasma sustainment of radial potential or radial vorticity (or E_r shear) profiles in a mirror (Cho *et al.* 2005*a*, 2006; Cho 2007).

2. Experiments and theoretical background

As a theoretical basis in the manuscript, a value of W is defined as a key parameter and a measure of velocity shear in rotating plasmas with radially non-uniform plasma density (for more detail, see figure 1). The axial (z) component of normalized dynamic vorticity $W = [\nabla \times (n\boldsymbol{V}_E)]_z/n_0 = d/dr_c[nr_c^2\Omega]/(n_0r_c)$ (where n_0 is the on-axis density)

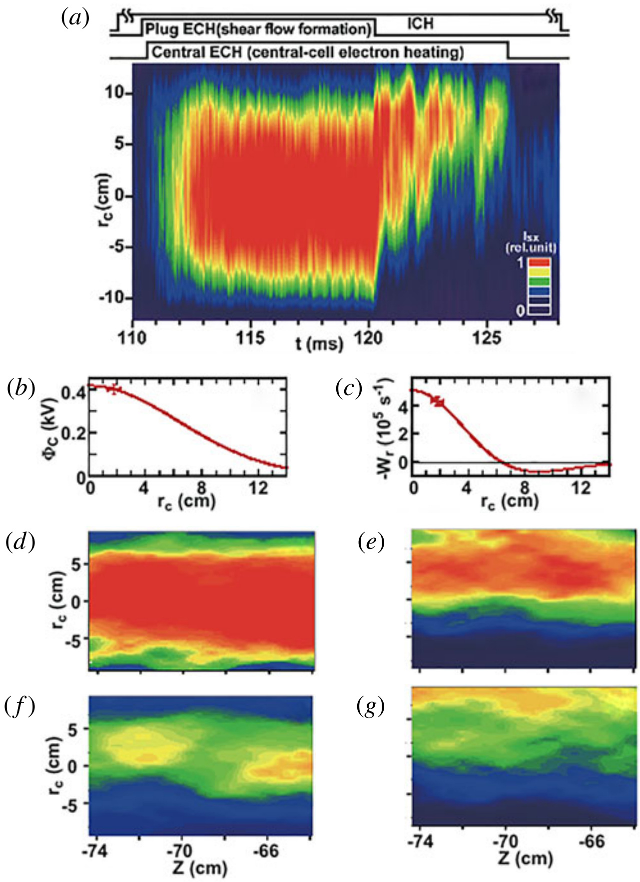

FIGURE 1. (*a*) Time evolution of central X-ray radial intensities at the shot number of 200 400. Heating timings are also plotted in (*a*). Plug electron cyclotron heating (ECH) for radial shear formation was applied during 110.6–120.4 ms. (*b*) Central potential Φ_C and (*c*) vorticity profiles $-W_r$ were plotted at 118.5 ms. Axially placed multichannel (two-dimensional) soft X-ray measurements are shown (*d*) during and (*e*)–(*g*) after the turn-off time of plug ECH ((*d*) 119.00 ms as well as (*e*) 122.50, (*f*) 124.61 and (*g*) 125.33 ms). The other main parameters were obtained as follows: the central line density $nl_c = 3.6 \times 10^{13}$ cm^{-2}, $T_{i0} \sim 5$ keV and $T_{e0} = 0.5$ keV with central (180 kW) and plug (360 kW) ECHs.

is chosen to characterize $\boldsymbol{E} \times \boldsymbol{B}$ velocity ($\boldsymbol{V}_E$) shear). (Pastukhov 2005; Cho *et al.* 2005*a*, 2006). The rotational frequency $\Omega(r_c)$ characterizes the azimuthal plasma drift flow. A radial density profile of n is described as a function of central radii r_c.

Experiments were carried out in a large mirror device of GAMMA 10. The detailed machine parameters in the employed standard operation were easily found in various references (Cho *et al.* 2001, 2005*a*,*b*).

The presented paper by Smirnov (2016) was also characterized by E_r shear effects of FRC plasmas on confinement improvement. Also, after the improvement, it was shown that plasma was drifting towards the wall without a rotation axis. These properties seemed to have similar essentials to those in figure 1(*e*–*g*) of mirror plasmas during loss of the shears (see below).

3. Experimental data and discussion

The presentation of a mirror at the APS in Orlando (Cho 2007) was highlighted by the following characteristic properties: plasmas were basically produced and heated in ion temperatures of ∼5 keV by ion-cyclotron heatings (ICH), initiated by magneto plasma dynamic guns. Externally controllable plasmas were formed by central electron cyclotron heating (central ECH) (figure 1) together with the other ECHs for shear flow formation (plug ECHs) (for more details, see Cho *et al.* 2005*a*,*b*). It was, nevertheless, noted that preceding plug ECH was needed for stability for an electron temperature (T_e) rise due to central ECH. Further, central ECH effects of the T_e rise to 500 eV from an ultra-low-energy observable X-ray pulse height analyser (Kohagura *et al.* 1995) and microchannel plate X-ray tomography detectors (Hirata *et al.* 1992) were observed during the plug ECH injection.

In fact, when we injected the central ECH alone, plasmas strongly migrated and drifted towards a wall, and then crashed. An earlier time injection of the plug ECH (figure 1*a*) has successfully formed high electron and ion temperature plasmas. In this article, analyses of the data for possibly wider uses of the common physics background were carried out.

In figure 1(*a*), the above-described sequence was performed. Central potential Φ_C in figure 1(*b*) was measured with a radially scannable heavy-ion (Au^0) beam probe (HIBP) (Ishii *et al.* 1989). Gaussian shapes of central density and central potential profiles were again employed, as reported by previous various articles. When we utilized these values for the calculation of vorticity (see § 2), the curve of figure 1(*c*) was obtained. These profiles were nearly the same as those reported in previous articles (Cho *et al.* 2005*a*,*b*).

The data in figure 1(*a*) and (*c*) showed the formation of a higher shear regime (core plasmas with $-W_r > 1 \times 10^5\ \text{s}^{-1}$ in this experimental region) within $r_c < 5$ cm. On the contrary, the outer region of $r_c > 5$ cm was characterized as a lower vorticity one ($-W_r < 1 \times 10^5\ \text{s}^{-1}$). Here, the suffix r denotes radially varied values of W.

As we expected from figure 2 of our previous report (Cho *et al.* 2005*a*) (that is, turbulent core plasmas with smaller vorticity ($-W_r < 1 \times 10^5\ \text{s}^{-1}$) were stabilized by higher vorticity formation ($-W_r > 1 \times 10^5\ \text{s}^{-1}$) due to plug ECH), turbulent plasmas again clearly disappeared within $r_c \sim 5$ cm having an appreciable amount of vorticity ($-W_r > 1 \times 10^5\ \text{s}^{-1}$) as shown in figure 1(*a*) and (*c*).

After the turn-off time of shear flow formation (plug ECH), a striking characteristic property was highlighted. Lower shear plasmas again appeared with no 'substantial plasma axis' at $r_c = 0$, and no stable plasma conditions without a rotational axis were followed just after the turn-off time of $t = 120.4$ ms.

In fact, figure 1(*e*–*g*) clearly demonstrated the detailed structure of the unstable plasmas; that is, our developed multichannel X-ray detector placed axially ($/\!/ \boldsymbol{B}_0$) using a combination of micro-channel plates (Hirata *et al.* 1992) and charge coupled devices in the central cell also demonstrated the complicated unstable plasma structures without a substantially symmetric axis. During the period with both ECHs, the axial structure of the soft X-ray detector signals was uniform in the core plasma regime with high vorticity (see figure 1*a*–*d*)]. On the other hand, a strongly unstable plasma structure appeared together with a strong radial transport, despite the original magnetic lines of force existed (figure 1*e*–*g*). This showed that unstable plasmas triggered a quick cross-field transport towards the plasma wall without a steady rotation axis.

From a more generalized physics viewpoint, these data and our previous reports (Cho *et al.* 2005*a*, 2006) totally and consistently indicated that an externally stable plasma control required a strong vorticity region together with a steady and substantial circulation axis.

In other words, core plasmas were guarded and maintained in terms of co-axially nested shear plasma formation using a slight loss of heated electrons into both end regions through loss cones for the radially sheared potential formation due to controlled ECH (Cho *et al.* 2005*a*; Cho 2007).

From this experimental evidence, FRC plasmas, for instance, also would have a possibility of a longer lifetime due to an externally controllable strong ECH; namely, co-axially nested shear plasma formation with a steady circulation axis. In addition, it would be of use in particular for high beta plasmas to employ off-axis ring-shaped flow plasmas due to ECH (Cho *et al.* 2006, 2008). Such off-axis flow should be located between a separatrix surface and main FRC plasma for power saving and cost minimum vorticity stabilization.

For the experiments, it is noted from our experimental experiences that wall conditions with minimized recycling rate (i.e. clean walls) or only a little remaining gas near the wall were of importance for suppressing an additional uncontrollable plasma production. This contributed to produce a steady circulation axis axisymmetrically. A larger wall diameter or a higher pumping speed in the peripheral region (i.e. a large vacuum conductivity) should contribute much to the formation of (i) co-axially nested shear plasmas with the same individual rotational velocity as a function of r_c around a substantial rotation axis or (ii) internal transport barrier formation (Cho *et al.* 2006, 2008). Also, ECH fortunately minimized gas inlet as compared to neutral beam injections. Even if FRC plasmas had a rather short lifetime as compared to tokamaks, high quality stabilized plasmas would be of great use. Successive 'pulsed' formation of short but stable high quality and high beta plasmas, for example, might be of significant use similar to high quality laser plasmas. As a final note, a better performance of plug ECH was anticipated as compared to end plate biasing. Re-ionizing clouds of recombined ambient gas resulting from plasma outer flows into the end plate region would give possibilities of uncontrollable phenomena with high bias voltages. In relation to this, it is noteworthy that radial electric fields without end plates in rotating plasmas were in fact proposed for alpha channelling (Fetterman & Fisch 2008, 2010).

This predicted extension of mirror data to FRC experiments is, at this time, a candidate for possible improvements for plasma upgrades. However, an opportunity for such extension on the basis of plasma physics fundamentals would be important and essential. In other words, a similar external plasma control method having wider and common physics bases might contribute to various plasma devices more generally.

4. Summary

Co-axially nested shear plasma formation with a substantial and steady rotation axis has been demonstrated (figure 1) for the first time by the use of both plug and central ECHs. Each nested multi-shell-like structure had a good axisymmetry with the same individual rotational velocity circularly as a function of r_c; in other words, this showed that difference of the circular velocity (angular momentum) in each nested 'ring-shaped shell' guarded and co-axially wrapped up the core plasmas ($r_c < 5$ cm) by themselves.

It was noteworthy that the highly improved central plasma heating due to central ECH with ICH could only be carried out in association with plug ECHs. This was interpreted in terms of high vorticity shear formation.

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Its wider application or extension, for instance to FRC plasmas, would possibility help to solve one of presently unsolved problems through a similar essential physics viewpoint. At that time, either nested shear plasma formation or transport barrier formation in rather peripheral plasmas (Cho *et al.* 2006, 2008) within the separatrix of FRC (Smirnov 2016) would be a useful candidate for making stabilized upgrades of FRC or more generalized plasmas.

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