

ESTELL, a quasiaxisymmetric stellarator

The Evolutive Stellarator of Lorraine (ESTELL), shown in Fig. 1, is a project proposed by the University of Lorraine (Nancy, France) in the framework of the “Investissement d’Avenir” program of the French Research Ministry. The main goal of ESTELL is to provide the first experimental demonstration of quasiaxisymmetry (QA) as a valuable concept for efficiently confining magnetized plasmas. The aim is to investigate the frontier between the tokamak and stellarator concepts through dedicated experiments in QA geometry. As is well known to the stellarator community, such a configuration could offer solutions to some of the problems of tokamaks (e.g., ITER): inherent steady state; absence of disruptions; reduced requirements for plasma control systems; no current drive system required, resulting in low recirculating power; and the potential for high-density operation.

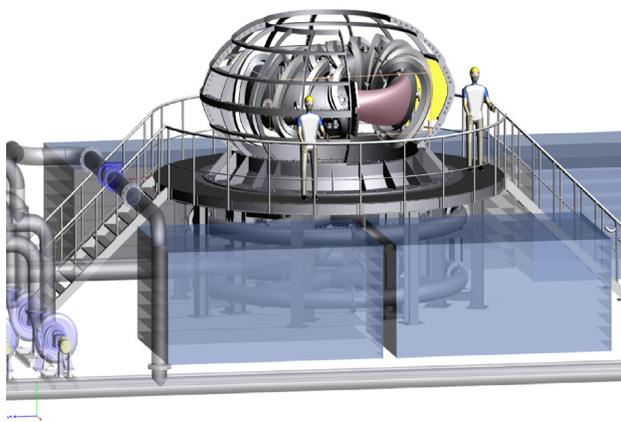


Fig. 1. Cutaway view of ESTELL.

ESTELL aims at becoming a worldwide open facility with high flexibility and accessibility, intermediate in size between small laboratory devices and large international facilities. It will require approximately 13 M€ for con-

struction. In addition to plasma confinement studies, the device will be useful for strengthening the bridge between academic research and fusion studies in several critical areas: plasma turbulence, heating, plasma-surface interactions, and diagnostics. ESTELL will be suited to test innovative concepts at lower risk and cost than on larger facilities. It also aims at addressing other fundamental issues, notably in astrophysics, through the investigation of three-dimensional (3D) magnetic reconnection.

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ESTELL, a quasiaxisymmetric stellarator

The University of Lorraine is proposing to build a medium-size, modular, quasiaxisymmetric stellarator to test new concepts, perform supportive research for larger devices, and train new scientists and engineers. The coil configuration was designed by IPP Greifswald..... 1

Observation of intrinsic toroidal rotation in Large Helical Device

A spontaneous rotation in the co-direction is observed in plasmas with an ion internal transport barrier (ITB), where the ion temperature gradient is relatively large ($dT_i/dr \sim 5$ keV/m and $R/L_{T_i} \sim 10$) in the Large Helical Device (LHD). In these conditions, the magnitude of the spontaneous toroidal flow, V_ϕ^{spon} , becomes large enough to cancel the toroidal flows driven by tangential injected neutral beams (NBs) and the net toroidal rotation velocity is almost zero at the outer half of the plasma minor radius, even in plasmas with counter-dominant NB injection. The effect of velocity pinch is excluded even if it exists because of the zero rotation velocity. The spontaneous toroidal flow appears in the direction of co-rotation after the formation of the ITB, not during or before the ITB formation. The relationship between the change in V_ϕ^{spon} and dT_i/dr clearly shows that the spontaneous rotation is driven by the ion temperature gradient as the off-diagonal terms of momentum and heat transport. 4

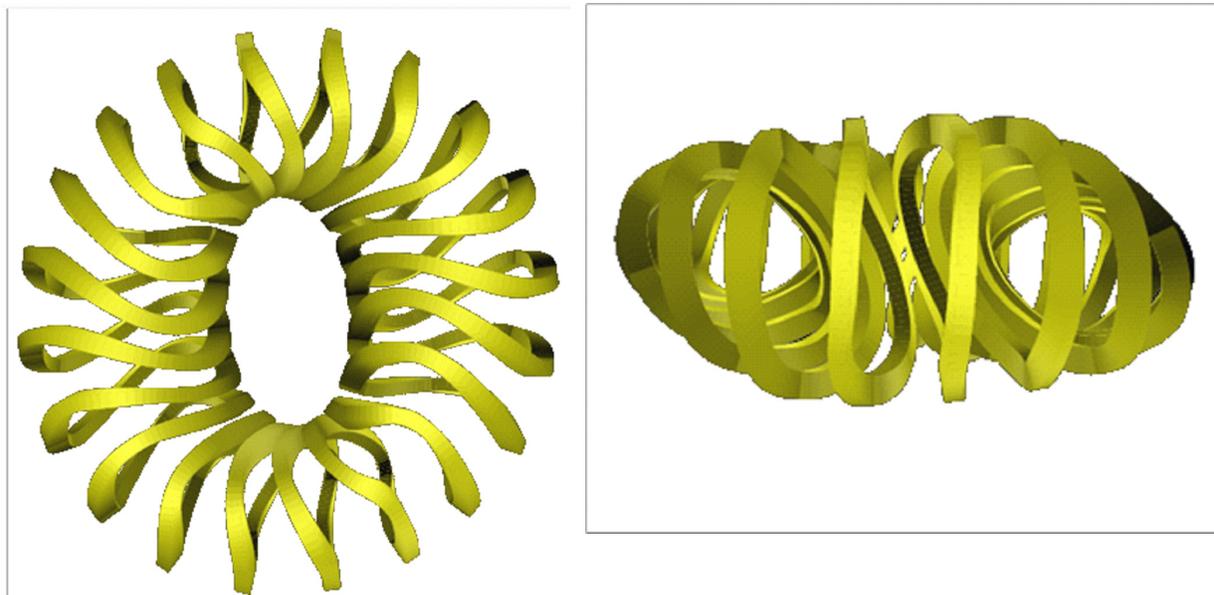


Fig. 2. Top view and side view of ESTELL 20 modular coils as designed by IPP Greifswald.

Summary of main features and parameters

ESTELL is a two-field period modular stellarator with an aspect ratio ~ 5 , formed by 20 optimized modular copper coils of 5 different types (Fig. 2). The magnetic configuration and the coil design come from the Stellarator Theory Division at Max Planck Institute for Plasma Physics, Greifswald. Aiming for operating at a plasma β value of 0.5%, a low rotational transform of $\iota \sim 0.2$ was chosen, making it possible to achieve quasisymmetry to a high degree of accuracy with relatively simple coils. As a result of the large spacing between coils (up to 80 cm, never less than 14 cm, but keeping reasonable magnetic ripple $\sim 1\%$), it will be possible to install up to 100 ports of vari-

ous sizes, whereas about only 20 will be needed for basic operation of the device. Consequently, many ports will be available for installing additional diagnostics or auxiliary systems (e.g. additional heating systems). 3D magnetic flexibility and plasma shaping will be achieved by using 5 separate power supplies, one for each type of modular coil. The main parameters of ESTELL in its starting configuration are given in Table 1.

Such a flexible, worldwide open, medium-size facility would be a suitable locale to perform fundamental investigations needed to support the research programs at larger facilities such as Wendelstein 7-X (W7-X). The experimental and theoretical programs will also closely follow

Configuration	Quasisymmetric
Number of field periods	2
Number of coils	20 of 5 different kinds
Major radius $\langle R \rangle$	1.4 m
Minor radius $\langle a \rangle$	0.28 m
Vacuum chamber volume	3 m ³
Magnetic field strength	≤ 0.5 T (continuous)
Heating Power	400 kW ECH (20 s pulse)
Plasma β	0.5%, or up to 1% given enough heating power
Rotational transform	0.23 ($\beta = 0$) 0.35 ($\beta = 0.37\%$)
Plasma density n_e	$5 \times 10^{18} \text{ m}^{-3}$
Peak electron temperature	1 keV
Ion temperature	100 eV

Table 1. main parameters of ESTELL.

the HSX device program, in order to compare specific properties of quasihelical and quasiaxisymmetric geometries.

Connection to training and education programmes

Nancy University is known to be a special node in the French plasma science community and also in the European fusion education networks through its participation in initiatives to organize master, doctoral, and post-doctoral levels in plasma science (<http://www.em-master-fusion.org>, www.em-fusion-dc.org). ESTELL will substantially help to improve the university's education for both plasma physicists and engineers. As a flexible facility designed for experiments and demonstrations, ESTELL will be the focus of dedicated training courses for experienced machine operators, experienced engineers, and fusion scientists who will potentially operate future facilities such as W7-X, ITER, and DEMO.

Status of the project

Most of the ESTELL equipment requires customized design. In order to overcome specific technical issues and to reduce the costs, conservative and successful technologies have been chosen for most critical components (e.g., water-cooled copper coils). This makes it possible to focus on innovative relevant components, couplings, and designs. Feasibility studies have been carried out in 2011 with the participation of the ALORIS private engineering group and a consortium of several industrial partners, most already involved in the Fusion Program. These studies have concluded that all the essential elements, without any exception, can be manufactured and delivered by industrial partners at very low risks, by using conservative technological options already successfully tested elsewhere. The complete proposal was submitted to the French Research Ministry in September 2011, and the final decision will be known in early 2012. The Nancy urban agglomeration and Lorraine regional council have already decided to underwrite the construction of the building that will host ESTELL in Nancy. If ESTELL is approved, its construction is scheduled to be completed in mid 2016, and first plasmas are expected in the second half of 2016.

ESTELL has been designed in order to permit future upgrades, which could be undertaken given adequate financial resources. In particular, the vacuum vessel will be large enough (the distance between the wall and last closed flux surface will be about 10 cm) to evolve from a limiter configuration to a more promising divertor configuration. Given ESTELL's flexibility, a relatively inexpensive divertor limited to some specific value of ι is possible. The numerous ports which will be available, some of them very large, will make it possible to install a large set of diagnostics for measurements ranging from

turbulence and transport characterization to fundamental investigations of plasma-wall interactions. They will also make it possible to extend heating capabilities, thus further extending the range of plasma parameters, by including lower hybrid and RF systems.

Acknowledgments

The ESTELL project has already benefited from the help of many people throughout the world, who have participated in its design or by providing strong support letters. We thank all of them warmly.

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Observation of intrinsic toroidal rotation in Large Helical Device

1. Background

Spontaneous rotation has been observed in many tokamaks. It has been observed in ohmic discharges in PLT [1], PDX [2], and Alcator C-mod [3], where there is no external momentum input. Spontaneous rotation becomes more significant in plasmas with additional heating with no momentum input, such as ICRF heating in JIPP-TIHU [4], JET [5], and Alcator C-mod [6] and ECH in CHS [7] and D-IIID [8]. The rotation can be in either the same (co) or opposite (counter) direction as the plasma current; it is usually co in H-mode and counter in the internal transport barrier (ITB) mode and can be either co or counter in L-mode, depending on the plasma conditions. The momentum transport analysis to investigate the mechanism of spontaneous rotation has been done, and a non-diffusive term of the momentum transport was found in JT-60U [9] and JFT-2M [10,11]. Therefore it is important to investigate intrinsic rotation in a plasma with an ITB, and an ion

temperature gradient large enough to drive intrinsic toroidal rotation in the Large Helical Device (LHD).

2. Effects of NBN injection on toroidal rotation

Since spontaneous rotation driven by the temperature gradient may be in either the co- or the counter-direction to the plasma current (equivalent toroidal current in helical plasmas), this spontaneous rotation appears as the disparity of co- and counter-driven toroidal rotation profiles in discharges with neutral beam (NB) injection in the co and counter direction with similar injection power [12]. This disparity is mainly due to spontaneous rotation in the co-direction (parallel to the equivalent plasma current). Because of the existence of spontaneous rotation, a large toroidal rotation velocity peaked at the plasma center in the co-direction is observed as indicated by the blue arrows in Fig. 1, when the NB is injected in the co-direction (parallel to the spontaneous rotation). In contrast, the toroidal rotation is almost zero (a slight counter rotation at the center as indicated by the red arrows in Fig. 1, when the NB is injected in the counter-direction (anti-parallel to the spontaneous rotation).

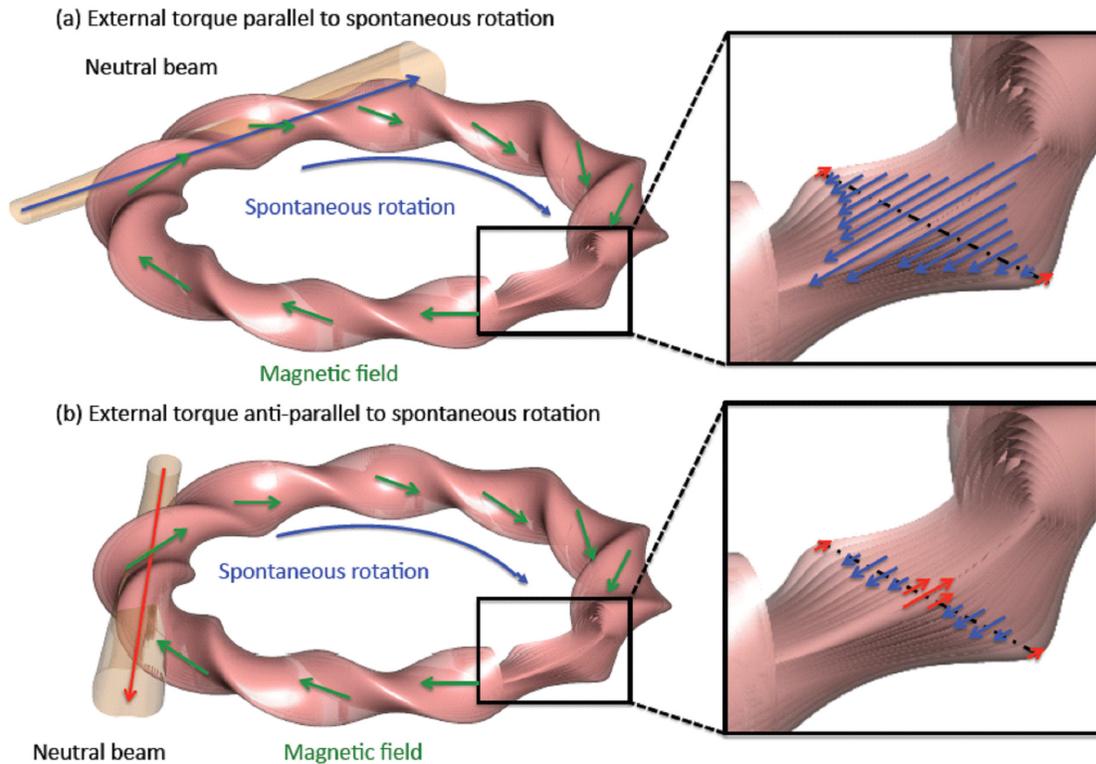


Fig.1. Toroidal rotation velocity i when external torque is (a) parallel and (b) anti-parallel to the direction of spontaneous rotation. The lengths of arrows are proportional to the rotation velocity. Red arrows indicate rotation in the counter-direction (anti-parallel to equivalent plasma current), and blue arrows indicate rotation in the co-direction (parallel to equivalent plasma current).

Figure 2 shows the radial profiles of toroidal rotation velocity, ion temperature, and torque deposition in plasmas with one NB injector (NBI) (co- or counter-injection) and with three NBIs (2 co-, 1 counter-injection and 1 co-, 2 counter-injection) discharges in LHD. The sign of the toroidal rotation velocity is positive for co-rotation and negative for counter-rotation. In plasmas with one NBI, the toroidal rotation profile in the plasmas with co-injection is similar to that in plasmas with counter-injection except for the sign differences. Toroidal rotation velocity is measured from the Doppler shift of fully ionized carbon impurities using charge-exchange spectroscopy viewing the plasma tangentially.

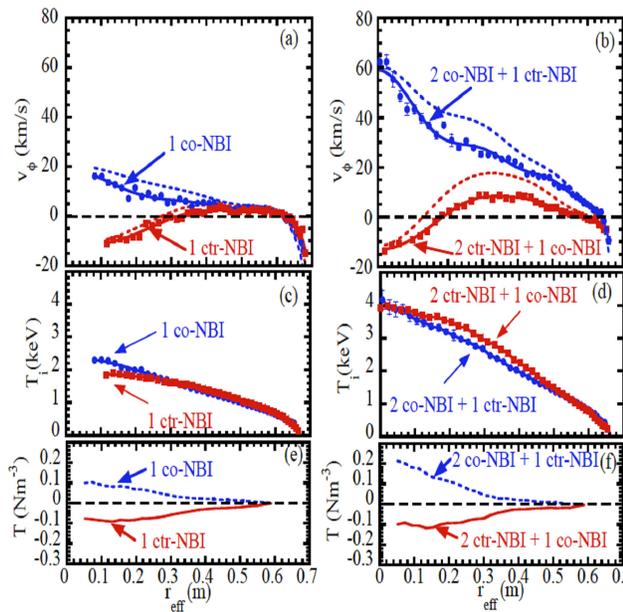


Fig. 2. Radial profile of (top) toroidal rotation velocity, v_ϕ measured from carbon impurity, (middle) ion temperature, T_i , and (bottom) torque deposition, T for the plasmas with either co-injecting (blue) or counter-injecting (red), and (right) three NBIs, either two co-injecting and one counter-injecting (blue) or one co-injecting and two counter-injecting (red).

The main ion in this experiment is hydrogen. Since the toroidal rotation is measured using carbon impurities, the velocity difference between the main ion and the impurity is evaluated with a neoclassical formula in the heliotron configuration. The main ion rotates more in the co-direction than do the carbon impurities, as shown by the dashed lines in Fig. 2. Therefore the spontaneous rotation observed in the carbon impurity cannot be explained by the neoclassical effect. The spontaneous rotation evaluated for the main ions should be even larger than that evaluated using carbon impurities, because the spontaneous rotation observed in LHD is in the co-direction.

In this plasma, the radial profiles of toroidal rotation velocity are mainly determined by the external torque resulting from NB injection, and by radial diffusion of toroidal momentum and parallel viscosity, which increase sharply towards the plasma edge, similar to the toroidal rotation profiles reported in CHS. In heliotron plasmas no momentum pinch has been observed. As seen in Fig. 2(e)(f), the net toroidal torques are somewhat similar (especially for 1 counter-NBI and 2 counter- plus 1 co-NBIs) in discharges with one counter-NBI and with three counter-dominant NBIs.

Here the deposited torque profiles are calculated using the FIT code based on a database calculated using a three-dimensional Monte Carlo simulation code including orbit loss and charge-exchange loss of fast ions. In plasmas with three NBIs, however, the radial profile of the toroidal rotation velocity in plasmas with a counter-NBI dominant discharge is quite different from that in plasmas with a co-NBI dominant discharge. The plasma rotates in the co-direction in the outer part of the plasma minor radius when counter-NB injection is dominant. The disparity of co- and counter-driven toroidal rotation profiles is significant in plasmas with three NBIs and a large ion temperature gradient because of the formation of the ITB. Three NBIs are required to achieve ITB plasmas in LHD. The sharp increase of toroidal rotation in the counter-direction near the plasma periphery is due to spontaneous rotation driven by the positive radial electric field, which is strongly localized near the plasma edge in this discharge. The direction of the spontaneous rotation due to the radial electric field is opposite to that observed in tokamak plasmas, where spontaneous rotation in the co- (counter-) direction is observed in the region with positive (negative) electric fields.

3. Relation between ion temperature gradient and intrinsic rotation

Figure 3 shows contour plots of ion temperature gradients and toroidal rotation velocity gradients in plasmas with counter-NBI dominant and co-NBI dominant discharges. As seen in Fig. 3(a), the ITB region appears at $r_{\text{eff}}/a_{99} = 0.7$ and $t = 2.15$ s, as indicated by an abrupt increase of the ion temperature gradient. After the formation of the ITB, the ion temperature gradient exceeds 5 keV/m and the ITB region, where the ion temperature gradient is large, expands toward the plasma center. A positive velocity gradient ($-dV/dr < 0$) appears near the plasma center in the plasmas with a counter-NBI dominant discharge, while a negative velocity gradient ($-dV/dr > 0$) is observed near the plasma center. These gradients are due to the external NBI torque. The negative gradients observed at $r_{\text{eff}}/a_{99} = 0.7$ in both the co- and counter-NBI discharges are due to the non-diffusive term of momentum flux as seen in Fig. 3(b) and (c).

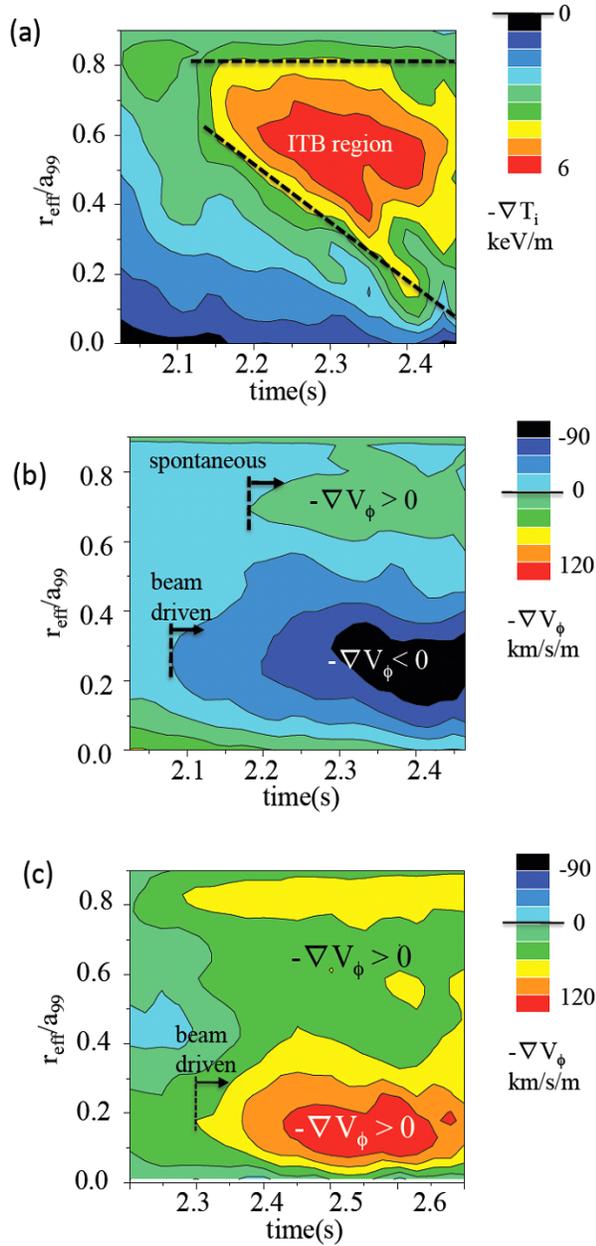


Fig. 3. Contour plot of (a) ion temperature gradient and (b) and (c) toroidal rotation velocity gradient in plasmas with (b) dominant counter-NB injection and (c) dominant co-NB injection [12].

A clear hysteresis is observed for the stronger ITB, where the ion temperature gradient reaches 9 keV/m as seen in Fig. 4. Note that this is a discharge with the co-NBI dominant and that the velocity shear near the plasma center increases in the direction of co-NBI. Although the ion temperature gradient starts to decrease in the later phase of the ITB period, the velocity gradient maintains a large value at $r_{\text{eff}}/a_{99} = 0.35, 0.85$. This observation indicates that the spontaneous rotation is a transition phenomena

and there are two modes in the spontaneous rotation, one small, and the other large. The control parameter for this transition seems to be a temperature gradient. It is interesting that the non-diffusive term as well as the diffusive term of the momentum transport (μ_1^N and μ_2^N as well as μ^D) can bifurcate, while only the diffusive term χ_i can be bifurcated in the heat transport.

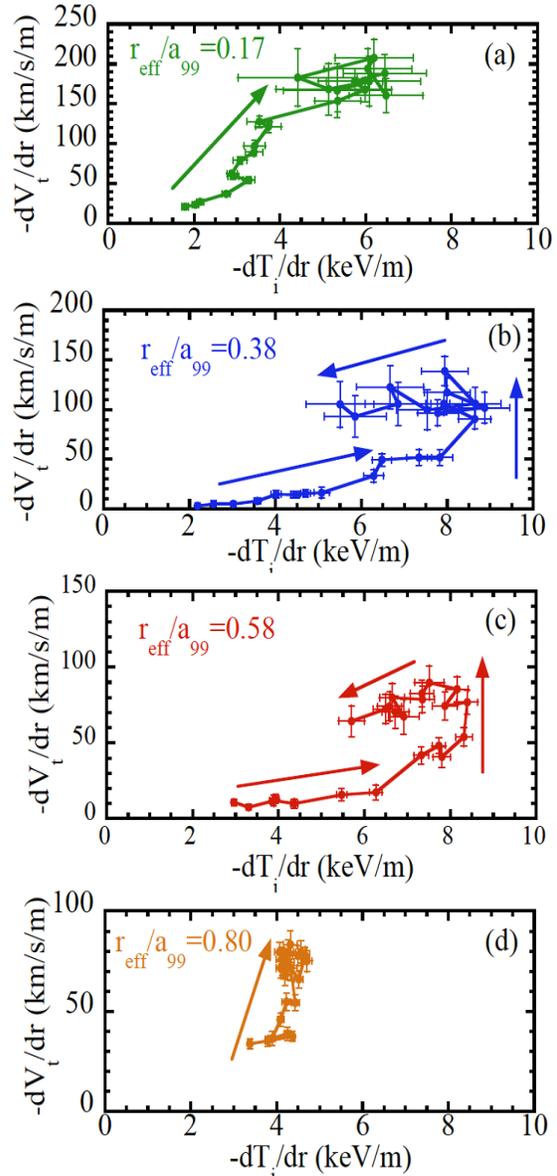


Fig. 4. The hysteresis curve in the relation between the ion temperature gradient and toroidal rotation velocity gradient in plasmas dominated by co-injected NBs [12].

4. Mechanism

The mechanism of spontaneous rotation has been investigated theoretically. The symmetry breaking of turbulence with the existence of radial electric field shear can produce an internal toroidal torque and results in a spontaneous velocity gradient [13]. Plasma turbulence is driven by the temperature gradient, and the radial electric field shear should be related to the curvature of the ion temperature profiles because $E_r \propto \partial T_i / \partial r$ when the pressure term is dominant in the radial force balance equation of bulk ions. Figure 5 shows a conceptual image of the symmetry breaking of turbulence. When the tilting direction of the vortex of turbulence is random, turbulence plays a role as a viscosity that causes momentum transfer in the direction of reducing the velocity gradient. However, when the tilting direction of the vortex of turbulence is aligned, it can cause the momentum transfer to increase the velocity gradient. This is a possible mechanism to cause momentum transfer against the velocity gradient, which results in intrinsic toroidal rotation in the plasma.

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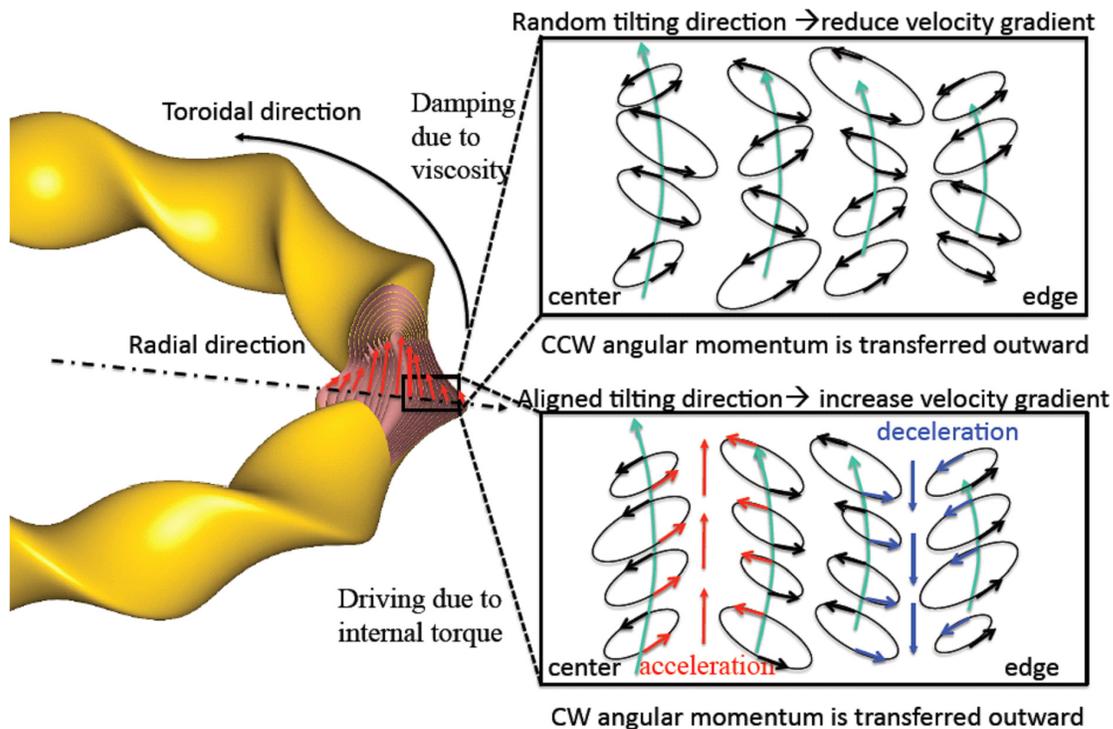


Fig. 5. Mechanism of intrinsic rotation and angular momentum transfer when the tilting direction of the vortex is random or aligned.