Vorticity equation in full-F electromagnetic gyrofluid model and currents' role in $\boldsymbol{E} \times \boldsymbol{B}$ and diamagnetic momentum

R. Gerrú[1], M. Wiesenberger[1], A. H. Nielsen[1], V. Naulin[1], J. Juul Rasmussen[1] and EUROfusion MST1 Team*

[1]Department of Physics, Technical University of Denmark, Fysikvej, DK-2800 Kgs.-Lyngby, Denmark

*See author list of B.Labit et al. 2019 Nucl. Fusion **59** 086020

E-mail: `rgemi@dtu.dk`

1. Introduction

Recent studies in ASDEX-Upgrade (AUG) have pointed to the maximum value of the $\boldsymbol{E} \times \boldsymbol{B}$ plasma velocity of the transport barrier as the key parameter for the transition from Low to High confinement (L-H transition)[1]. However, experiments in EAST have pointed to the shear of the perpendicular flows (strongly coupled with $\boldsymbol{E} \times \boldsymbol{B}$ flows) as the key parameter [2]. These investigations show the crucial role that the radial electric field driven flows play in the transition, and the necessity of understanding in depth its dynamical behaviour.

In general, when the radial electric field related with this transport barrier is studied, it is obtained using the radial force balance [3, 4]:

$$E_r = \frac{1}{n_i Z_i e}\frac{\partial P_i}{\partial r} - (\boldsymbol{v}_\perp \times \boldsymbol{B}) \cdot \hat{\boldsymbol{e}}_{\boldsymbol{r}} = \frac{1}{n_i Z_i e}\frac{\partial P_i}{\partial r} - v_\theta B_\phi + v_\phi B_\theta \tag{1}$$

Unfortunately, this expression is derived from a steady state plasma, so it is not the optimal way of looking at the electric field when it changes between two different states. At the same time, this expression does not include how other plasma parameters affect the radial electric field like different magnetic field configurations [5] or magnetic field perturbations [6], in addition to more magnetic field parameters that affect the power threshold that are not involved in this description (∇B drift direction, the X-point height or the triangularity [7, 8, 9]).

All of these experimental observations point to the necessity of describing the electric field in the edge of the plasma in a dynamical way and keeping the ingredients that can address the effects mentioned above. In fluid type models this is usually achieved by deriving the vorticity equation following the conservation of currents $\boldsymbol{\nabla} \cdot \boldsymbol{J} = 0$. In these models, this equation describes both small scale eddies usually related to turbulence as well as large scale dynamics such as transport barriers.

In this contribution, we present the vorticity equation in a full-F electromagnetic gyro-kinetic model applying drift-ordering, which will allow us to analyze different scales in future simulations, and the currents that appear in the equation and that can address the experimental observations mentioned in the introduction.

Vorticity equation in full-F electromagnetic gyrofluid model and currents' role in $\boldsymbol{E}\times\boldsymbol{B}$ *and diamagnetic m*

2. Vorticity Equation in gyro-fluid form

The derivation of this equation is based in the full-F, electromagnetic gyro-kinetic model on the long wavelength limit without any assumption on the distribution function, as presented in [10].

Our vorticity equation is described as follows:

$$\frac{\partial \Omega}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{\nabla}\cdot(\boldsymbol{\omega u_E})) = \boldsymbol{\nabla}\cdot(J_{\|}\hat{\boldsymbol{b}} + \boldsymbol{J_{b_\perp}} + \boldsymbol{J_{curv}}) + \Omega_S \tag{2}$$

With the following definitions:

$$\Omega = \boldsymbol{\nabla}\cdot\omega = \sum_{\text{s}} \boldsymbol{\nabla}\cdot\left[\boldsymbol{\nabla}_\perp\left(\frac{mP_\perp}{qB^2}\right) + \frac{mN\boldsymbol{\nabla}_\perp\phi}{B^2}\right] \tag{3}$$

$$\Omega_S = \boldsymbol{\nabla}\cdot\omega_S = \sum_{\text{s}} \boldsymbol{\nabla}\cdot\left[\boldsymbol{\nabla}_\perp\left(\frac{mS_{P_\perp}}{qB^2}\right) + \frac{mS_N\boldsymbol{\nabla}_\perp\phi}{B^2}\right] \tag{4}$$

$$\boldsymbol{b}_\perp = \frac{\hat{\boldsymbol{b}}\times\nabla A_{1,\|}}{B} \qquad \boldsymbol{u_E} = \frac{\hat{\boldsymbol{b}}\times\nabla\phi}{B} \quad J_{\|} = \sum_{\text{s}} qNU_{\|} \tag{5}$$

$$\boldsymbol{J_{curv}} = \left[\sum_{\text{s}}(P_{\|} + mNU_{\|}^2) + J_{\|}A_{1,\|}\right]\frac{\nabla\times\hat{\boldsymbol{b}}}{B} + \sum_{\text{s}} P_\perp \frac{\hat{\boldsymbol{b}}\times\nabla\ln B}{B} \tag{6}$$

$$\boldsymbol{J_{b_\perp}} = (J_{\|} + j_{mag})\boldsymbol{b}_\perp - \boldsymbol{\nabla}\cdot(\boldsymbol{M^{em}}\boldsymbol{b}_\perp) \tag{7}$$

$$\boldsymbol{M^{em}} = \sum_{\text{s}} \boldsymbol{\nabla}_\perp\left(\frac{m\|\mu B v_{\|}\|}{qB}\right) = \sum_{\text{s}} \boldsymbol{\nabla}_\perp\left(\frac{m(Q_{\|} + P_\perp U_{\|})}{qB}\right) \tag{8}$$

$$\sum_{\text{s}} qNU_{\|} - \boldsymbol{\nabla}\cdot(\boldsymbol{M}^{\text{gy}}\times\hat{\boldsymbol{b}}) = -\frac{1}{\mu_0}\Delta_\perp A_{1,\|} = J_{\|} + j_{mag}, \tag{9}$$

All these definitions contain the following: $\sum_{\text{s}}$ is the addition over the species (electrons and all ion species), m and q the mass and charge of the species, $B\hat{\boldsymbol{b}}$ the magnetic field, the gyro-fluid moments for each specie(N the gyro-center density, $U_{\|}$ the parallel velocity, $P_\perp$ and $P_{\|}$ the perpendicular and parallel pressures and $Q_{\|}$ the parallel heat flux), ϕ and $A_{1,\|}$ the electric and magnetic potential perturbation and S_N and $S_{P_\perp}$ the gyro-center density and pressure sources.

In the definitions we have: the vorticity and the vorticity sources in equations (3) and (4), the perturbed magnetic field $\boldsymbol{b}_\perp$, the $\boldsymbol{E}\times\boldsymbol{B}$ drift and the parallel current in equation (5), the curvature current in (6), the perturbed magnetic field current in equation (7), the definition of the electromagnetic magnetization density in equation (8) and the Ampere's law in equation (9) with the relation between the Maxwell stress $\Delta_\perp A_{1,\|}$ and the currents.

In the vorticity equation (2) we have that the change in the vorticity is being produced by the $\boldsymbol{E}\times\boldsymbol{B}$ advection, the external sources of vorticity (related with the sources of density and pressure) and the divergence of the currents. The vorticity is strictly related to the $\boldsymbol{E}\times\boldsymbol{B}$ and diamagnetic flows as we are working in a full-F model and do not separate small-scale fluctuations (although the ordering implies subsonic $\boldsymbol{E}\times\boldsymbol{B}$ flows).

Vorticity equation in full-F electromagnetic gyrofluid model and currents' role in $\boldsymbol{E}\times\boldsymbol{B}$ and diamagnetic m

3. Discussion

The equation contains ingredients that have been experimentally observed to be relevant in the dynamics of the edge and the L-H transition: in ELM dynamics, it has been observed a large current density on the edge, due mostly to the bootstrap current produced by the large density gradients, that would be included in our parallel current ($J_{\|}\hat{\boldsymbol{b}}$), and strong changes in it when close to the ejection of plasma [11], at the same time that the radial electric field is also strongly influenced [3] by the ejection. Also, resonant magnetic perturbations (RMP) like the ones applied in [12, 13, 14, 15] are usually used in ELM suppression and seem to affect strongly the structure of the radial electric field in the edge [6], which could be analyzed in our model by the fluctuation current ($\boldsymbol{J_{b_\perp}}$). At the same time, the effects that the ∇B drift has on the L-H transition threshold and in the dynamics of the radial electric field [5] could be accounted due to the curvature current ($\boldsymbol{J_{curv}}$), as well as the other magnetic effects mentioned in the introduction. The ion orbit losses, related to the ∇B drift, are included in the curvature current, as no distribution function is assumed in our model. These losses with the ones that would happen on the opposite side of a tokamak to the electrons, would be connected on the edge region by the parallel dynamics, that would be present by the parallel current term ($J_{\|}\hat{\boldsymbol{b}}$).

This new equation allows us to do a detailed analysis of an equilibrium like it is done in [16, 17] using FELTOR gyrofluid code [18]. In this equilibrium, we will be able to look at the currents that play a fundamental role on the creation of momentum on the edge, to split effects between fluctuations and main parallel current, at the same time that we do it in a more realistic magnetic field configuration with an X-point and even with different magnetic field configurations like Upper Single Null or Double Null, and to look at the poloidal dependence of the currents and the creation of momentum.

Experimentally, the effect of the currents on the radial electric field could be approached in two ways: looking at the radial electric field structure or poloidal flows in the edge in different poloidal positions like in [19], as effects of Pfirsch-Schlüter or curvature currents are strongly poloidally dependent and most measurement are only done in the Outer Mid-Plane, or inducing some parallel currents on the edge via off-axis ECCD [20, 21, 22], and seeing how this might affect the radial electric field, being even possible to do it close to the L-H transition.

It will be also interesting to see how the radial electric field structure is affected by the change of magnetic field configuration like in [5] in other machines, as it is proposed under MST1-01-P18 "Radial electric field in 'favorable' versus 'unfavorable' configuration", that might take place in the next experimental campaign at WEST.

Acknowledments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Cavedon M, Birkenmeier G, Pütterich T, Ryter F, Viezzer E, Wolfrum E, Dux R, Happel T, Hennequin P, Plank U *et al.* 2020 *Nuclear Fusion* **60** 066026

[2] Liang A, Zou X, Zhong W, Ekedahl A, Duan X, Shi Z, Yu D, Yang Z, Wen J, Xiao G *et al.* 2020 *Nuclear Fusion* **60** 092002

[3] Viezzer E, Pütterich T, Angioni C, Bergmann A, Dux R, Fable E, McDermott R, Stroth U, Wolfrum E *et al.* 2013 *Nuclear Fusion* **54** 012003

[4] McDermott R, Lipschultz B, Hughes J, Catto P, Hubbard A, Hutchinson I, Granetz R, Greenwald M, LaBombard B, Marr K *et al.* 2009 *Physics of Plasmas* **16** 056103

[5] Meyer H, Carolan P, Conway G, Cunningham G, Horton L, Kirk A, Maingi R, Ryter F, Saarelma S, Schirmer J *et al.* 2005 *Nuclear fusion* **46** 64

[6] Schmitz L, Kriete D, Wilcox R, Rhodes T, Zeng L, Yan Z, McKee G, Evans T, Paz-Soldan C, Gohil P *et al.* 2019 *Nuclear Fusion* **59** 126010

[7] Chen L, Xu G, Yan N, Nielsen A, Liu J, Gao W, Chen R, Qu H, Ding F, Mao H *et al.* 2018 *Physics of Plasmas* **25** 072504

[8] Gohil P, Evans T, Fenstermacher M, Ferron J, Osborne T, Park J, Schmitz O, Scoville J and Unterberg E 2011 *Nuclear Fusion* **51** 103020

[9] Carlstrom T 2005 *Fusion science and technology* **48** 997–1010

[10] Wiesenberger M and Held M 2020 *Nuclear Fusion* **60** 096018

[11] Dunne M, McCarthy P, Wolfrum E, Fischer R, Giannone L, Burckhart A *et al.* 2012 *Nuclear Fusion* **52** 123014

[12] Petrie T, Evans T, Brooks N, Fenstermacher M, Ferron J, Holcomb C, Hudson B, Hyatt A, Luce T, Lasnier C *et al.* 2011 *Nuclear Fusion* **51** 073003

[13] Sun Y, Jia M, Zang Q, Wang L, Liang Y, Liu Y, Yang X, Guo W, Gu S, Li Y *et al.* 2016 *Nuclear Fusion* **57** 036007

[14] In Y, Jeon Y, Park J K, Loarte A, Ahn J W, Lee J, Lee H, Park G, Kim K, Kim H *et al.* 2019 *Nuclear Fusion* **59** 056009

[15] Kirk A, Suttrop W, Chapman I, Liu Y, Scannell R, Thornton A, Orte L B, Cahyna P, Eich T, Fischer R *et al.* 2015 *Nuclear Fusion* **55** 043011

[16] Bufferand H, Baudoin C, Bucalossi J, Ciraolo G, Denis J, Fedorczak N, Galassi D, Ghendrih P, Leybros R, Marandet Y *et al.* 2017 *Nuclear Materials and Energy* **12** 852–857

[17] Held M, Wiesenberger M and Kendl A 2019 *Nuclear Fusion* **59** 026015

[18] Wiesenberger M, Einkemmer L, Held M, Gutierrez-Milla A, Saez X and Iakymchuk R 2019 *Computer Physics Communications* **238** 145–156

[19] Vermare L, Hennequin P, Gürcan Ö D, Garbet X, Honoré C, Clairet F, Giacalone J, Morel P, Storelli A and Team T S 2018 *Physics of Plasmas* **25** 020704

[20] Murakami M, Wade M, Greenfield C, Luce T, Makowski M, Petty C, DeBoo J, Ferron J, Jayakumar R, Lao L *et al.* 2003 *Physical review letters* **90** 255001

[21] Wong K, Chu M S, Luce T, Petty C, Politzer P, Prater R, Chen L, Harvey R, Austin M, Johnson L *et al.* 2000 *Physical review letters* **85** 996

[22] Maraschek M, Gantenbein G, Goodman T, Günter S, Howell D, Leuterer F, Mück A, Sauter O, Zohm H *et al.* 2005 *Nuclear fusion* **45** 1369