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"Velocity Boundary Conditions at a Tokamak Resistive Wall"

[Phys. Plasmas **21**, 032506 (2014)]

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Comment on "Velocity boundary conditions at a tokamak resistive wall" [Phys. Plasmas 21, 032506 (2014)]

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The paper gives the derivation of the MHD boundary condition for the plasma flow to the wall during disruptions. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4894533]

In December 2007, when the theory of Wall Touching Kink Mode just emerged,[1] one of us (LZ) revealed the importance of the plasma physical contact with the wall and the necessity of including the plasma flow to vessel surface into simulations of disruptions. This also revealed a significant flaw in all existing 3-dimensional magneto-hydrodynamic codes in using an improper boundary condition $V_{normal} = 0$ at the wall.

Initially, the correction seemed to be easy to make. In the magneto-hydrodynamic (MHD) model, an absorption boundary condition would be consistent with the basic physics of plasma interaction with the wall. Indeed, the plasma ion, moving with an ionized plasma toward the wall in accordance with MHD equations, picks up an electron from the wall with a high probability and becomes a neutral atom, not participating anymore in plasma dynamics. In fact, due to the ion gyro-rotation in a magnetic field this probability is essentially 1. It is clear that $V_{normal} = 0$ is in sharp contradiction with the plasma physics, which strips the ability of numerical codes to simulate disruptions processes, where the interaction of the plasma with the wall starts from the beginning of a disruption.

After 6.5 years, the wrong boundary condition, $V_{normal} = 0$, taken from the hydro-dynamics of conventional fluids remains uncorrected. The recent publication by Strauss[2] is another attempt to justify this condition in M3D code.

In this paper,[2] the author claims that "There are at least four possible boundary conditions that may be applied to the normal velocity at a plasma-wall boundary." The first three of them, listed as Eqs. (1)–(3) in Ref. 2, are not applicable to the plasma at all, while the forth one in Eq. (4), although reasonable, is only approximate.

There is no mystery in deriving a boundary condition for the plasma velocity. Thus, in the moving plasma, Faraday (or Ohm's) law in MHD approximation has the well known form

$$-\frac{\partial \mathbf{A}}{\partial t} - \nabla \phi_E^{pl} + (\mathbf{V} \times \mathbf{B}) = \eta_{pl} \mathbf{j}_{pl}. \tag{1}$$

Here, $\mathbf{A}$ is a vector potential of a magnetic field $\mathbf{B}$, $\nabla \phi_E$ is a scalar potential of an electric field, $\mathbf{V}$ is the plasma velocity, $\mathbf{j}$ is the current density, and η is the local resistivity. The subscript "*pl*" refers to the plasma.

In a conducting wall, the same equation is simply

$$-\frac{\partial \mathbf{A}}{\partial t} - \nabla \phi_E^{wall} = \eta_{wall} \mathbf{j}_{wall}. \tag{2}$$

Regarding the component of the current densities perpendicular to the wall surface, the matching condition is

$$\mathbf{j}_{wall,\perp} = \mathbf{j}_{pl,\perp}. \tag{3}$$

Another matching condition is the continuity of the surface electric field $\mathbf{E}_{\parallel}$ parallel to the wall surface

$$\mathbf{E}_{\parallel} \equiv -\frac{\partial \mathbf{A}_{\parallel}}{\partial t} - \nabla_{\parallel} \phi_E^{wall} = -\frac{\partial \mathbf{A}_{\parallel}}{\partial t} - \nabla_{\parallel} \phi_E^{pl}, \tag{4}$$

thus, giving the boundary condition for the plasma velocity

$$(\mathbf{V} \times \mathbf{B})_{\parallel} = \eta_{pl} \mathbf{j}_{pl,\parallel} - \eta_{wall} \mathbf{j}_{wall,\parallel}. \tag{5}$$

If the plasma current contribution is neglected, Eq. (5) gives the approximate condition, listed by Strauss as Eq. (4).

In contrast to this transparent physics, Strauss claims that $V_{normal} = 0$ is a good approximation for disruption dynamics. This, might be true for the M3D code, which is a hydro-dynamic code modified by an additional $\mathbf{j} \times \mathbf{B}$ force, where the numerical scheme is driven by plasma inertia and when any process, slower than the Alfven transit time, looks slow and negligible.

This is not the case for the plasma dynamics in disruptions, which are much slower than the Alfven transit times. In disruptions, the balance of MHD forces, which are much bigger than the inertia, is the dominant effect. Accordingly, in Eq. (3), the current density in the wall is determined by the force balance, while the plasma velocity is determined by this equation as the secondary variable. This physics makes disruption forces determined by the plasma deformation, rather than by resistivity of the wall as in Ref. 2.

Being irrelevant to disruption modeling in many aspects, including the inability to implement Eq. (5) as the most visible one of them, the M3D needs manipulations and tricks in order to make its results looking as reasonable. Thus, Ref. 3, which pretends to simulate forces in ITER, in fact, is hiding deeply in the text such a "minor" detail as "the current enhancement factor" of 1.6.

Introduced by the authors in order to present a benign internal $m/n = 1/1$ mode in tokamaks as a driver of disruptions, this hidden factor elevates the plasma current in M3D simulations to the level of 24 MA, not made clear to the community and to the ITER project, where the planed value is $I_{pl} = 15$ MA. Without this 1.6 times amplification, hidden from the reader in Ref. 3 in the middle of a large paragraph, the internal kink mode would not produce appreciable forces. In Ref. 2 on boundary conditions, Strauss relies on the same disruption simulations with the same hidden scaling factor, which makes M3D simulations irrelevant to ITER and to other tokamaks.

Another claimed "result" of M3D is a recent "discovery" that the sideways forces are produced by the $m/n = 2/1$ kink mode.[4] The reality is that a comprehensive disruption data base of JET tokamak,[5] containing thousands of cases, clearly indicates that the sideway forces are result of a $m/n = 1/1$ mode, well distinguished from the $m/n = 2/1$ mode, which is invisible in measurements.

Returning to the boundary conditions on plasma velocity to the wall, in fact, the MHD physics does not require any. The Faraday law (1) in the plasma and the Ohm's law (2) in the wall are the part of the MHD model. Accordingly, the *electromagnetic* boundary condition on continuity of $\mathbf{E}_{\|}$, which is claimed to be implemented in 3-D numerical codes, automatically determines the plasma velocity to the wall. The necessity of a special boundary condition is only a reflection of the fact of internal inconsistency of numerical schemes of these codes.

It is not possible to correct the M3D code simply by implementation of boundary condition Eq. (5), which is valid for all MHD regimes, including irrelevant to tokamak disruptions fast instabilities, which M3D code, driven by plasma inertia, simulates, and for the plasma dynamics on intermediate Alfven-resistive time scales as in experiments. In tokamak MHD, the meaning of this condition is reversed with respect to an electro-dynamic interpretation: the current in the wall is determined by the force balance in the plasma, while the plasma flow velocity to the wall is a derived variable. This meaning is inconsistent with the hydro-dynamic nature of numerical schemes in 3-D codes and requires special implementation. As an example, this was done in the simulations of the $m/n = 1/1$ disruption mode in Ref. 6.

Another important property of Eq. (5) is that it reverses the direction of velocity in the areas of the wall, where the current density has the same direction as the plasma current. It shows the basic inconsistency of substitution of the vacuum region by a fluid in all MHD codes with plasma physics. In the plasma MHD, a "vacuum" bubble would be created, but for the present hydro-dynamic numerical schemes, these areas should "supply" plasma from the wall surface, which is not physical. As a practical manner, the problem could be mitigated in the hydro-dynamics schemes only with a special care and understanding of this inconsistency with the plasma physics. E.g., for these areas, a artificial supply of a low density plasma in accordance with Eq. (5) can be arranged in the codes with a care about force balance in the plasma core.

The issue of sideways forces, which the M3D code for 6.5 years pretends to address, was, in fact, resolved for ITER 7 years ago. Discovered in 1995 and explained in 1996 by JET engineers, the sideways forces in JET cases of disruptions were scaled for the ITER project in 2007 and then used as a guidance for its vessel design. The LZ theory of Wall Touching Kink Mode (WTKM) in 2007–2009 confirmed the engineering scaling and gave the understanding of details. The broader physics of disruptions requires the development of numerical codes using field aligned adaptive grids,[7] capable of providing the physics scale separation for highly anisotropic tokamak plasmas, of reproducing the surface and Hiro currents during disruptions and of providing the basis for implementation of realistic plasma-wall interactions.

Note some other issues with the Strauss paper. The formulas (15, 16) in Ref. 2 are not applicable for disruptions conditions, where high voltage is generated along field lines. For the same reason, it is incorrect to make assessment of the sheath potential based on the plasma temperature.

[1] L. E. Zakharov, "The theory of the kink mode during the vertical plasma disruption events in tokamaks," Phys. Plasmas **15**, 062507 (2008).
[2] H. R. Strauss, "Velocity boundary conditions at a tokamak resistive wall," Phys. Plasmas **21**, 032506 (2014).
[3] H. R. Strauss, R. Paccagnella, and J. Breslau, "Wall forces produced during ITER disruptions," Phys. Plasmas **17**, 082505 (2010).
[4] H. Strauss, R. Paccagnella, J. Breslau, L. Sugiyama, and S. Jardin, "Sideways wall force produced during tokamak disruptions," Nucl. Fusion **53**, 073018 (2013).
[5] S. N. Gerasimov, T. C. Hender, J. Morris, V. Riccardo, L. E. Zakharov, and JET EFDA Contributors, "Plasma current asymmetries during disruptions in JET," Nucl. Fusion **54**, 073009 (2014).
[6] L. E. Zakharov, S. A. Galkin, S. N. Gerasimov, and JET-EFDA Contributors, "Understanding disruptions in tokamaks," Phys. Plasmas **19**, 055703 (2012).
[7] X. Li and L. E. Zakharov, "Adaptive grids in simulations of toroidal plasma starting from MHD equilibrium," Plasma Sci. Technol. (to be published in Vol. 16, No. 11 (2014)).

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