Carl Sovinec Panel (A) on Disruptions, Oral talk requested.

Thin wall model for disruption simulations in the presence of sinks/sources currents

Leonid E. Zakharov (PPPL, `zakharov@pppl.gov`*), Calin V. Atanasiu (NILPRP, Bucharest)*

1 Introduction. Applicability of the thin wall model

In tokamak disruptions, the plasma is in strong interaction with the wall surface. One of the physics effects is the excitation of electric currents in the conducting in-vessel structures. The present theory of disruptions distinguishes 3 types of currents in the wall: (a) the eddy currents due to magnetic perturbations at the wall, (b) Hiro currents specifically excited by the plasma flow to the wall, and (c) the halo, or Evans, currents from the open field lines to the surface of plasma facing tiles or the wall.

In electromagnetic simulations, all these currents can be subdivided into two categories: (a) divergence free currents, and (b) sink/source currents due to galvanic contact of the plasma with the conducting surfaces of the wall or limiters. The eddy currents are in the first category, while the Evans currents are in the second. The Hiro currents for the pure $n = 0$ vertical disruptions (as in the EAST device) are in the first category. In the presence of the kink modes they are shared with the free plasma surface through a disruption specific Scrape Off Layer and, accordingly, are in the second category.

The thin wall model considers these currents as localized in the plasma facing surface layer as surface δ-functional currents. For stainless vacuum vessel walls the current penetration time is $\simeq 0.5 \cdot 10^{-4} h_{cm}^2 < 1$ ms (h_{cm} is the thickness of the wall), and the thin wall approximation is valid with high accuracy. This approximation is also reasonable in the presence of 2 cm thick copper stabilizers (NSTX-U, EAST) with the skin layer depth $d_{cm} \simeq 0.7\sqrt{\Delta t_{ms}^{disr}}$ (Δt_{ms}^{disr} the disruption time in ms) smaller or comparable to the copper thickness.

The presence of poloidal limiters, as in the JET tokamak, does require the modification of the thin wall model.

After JET large disruptions in 1996 and my theory of Wall Touching Kink Modes it becomes evident that disruption simulations require the implementation of a realistic model of the 3-D wall and plasma facing surfaces in tokamaks. The thin wall model is an important practical step in this direction.

2 Two types of surface currents in the wall

The surface current density $h\mathbf{j}$ in a thin wall can be represented in terms of a stream function I and a sink/source electric potential ϕ^{SS}

$$h\mathbf{j} = \mathbf{i} - \bar{\sigma}\nabla\phi^{SS}, \quad \mathbf{i} \equiv \nabla I \times \mathbf{n}, \quad (\nabla \cdot \mathbf{i}) = 0, \quad \bar{\sigma} \equiv h\sigma_E^{wall}, \tag{2.1}$$

where $\mathbf{n}$ is the unit normal vector to the wall surface.

The sink/source current is determined by the following equation

$$(\nabla \cdot (h\mathbf{j})) = -(\nabla \cdot (\bar{\sigma}\nabla\phi^S)) = -j_\perp, \tag{2.2}$$

where $j_\perp$ is the density of the current coming from/to the plasma and determined self-consistently with the plasma and plasma-wall interaction model.

Faraday's law for the stream function I has the form

$$\frac{(\nabla I \times \mathbf{n})}{\bar{\sigma}} = -\frac{\partial \mathbf{A}^I}{\partial t} - \frac{\partial \mathbf{A}^{SS}}{\partial t} - \frac{\partial \mathbf{A}^{pl+PFC}}{\partial t} + \nabla(\phi^{SS} - \phi^E) \tag{2.3}$$

where $\mathbf{A}, \phi^E$ are the vector and scalar potentials and the superscripts $I, S, pl + PFC$ specify contribution from $\mathbf{i}, -\bar{\sigma}\nabla\phi^S$ currents, from the plasma and the external PFCoils. It is remarkable that Eq. (2.3) is coupled with (2.2) by the right hand side terms. At the edges of separate wall elements and of the holes I =const.

Both equations can be obtained by minimization of the following energy principles

$$\begin{aligned} W^{SS} &= \int \left\{ \frac{\bar{\sigma}(\nabla\phi^S)^2}{2} + j_\perp \phi^S \right\} dS_{wall}, \\ W^I &\equiv \frac{1}{2} \int \left\{ \frac{\partial(\mathbf{i}\cdot\mathbf{A}^I)}{\partial t} + \bar{\eta}|\nabla I|^2 + 2\left(\mathbf{i}\cdot\frac{\partial\mathbf{A}^S}{\partial t}\right) + 2\left(\mathbf{i}\cdot\frac{\partial\mathbf{A}^{pl+PFC}}{\partial t}\right) \right\} dS_{wall+plasma} \end{aligned} \tag{2.4}$$

with positively defined integrands. The free plasma surface is included in integration for calculation of the vacuum magnetic fields. It is assumed that there are no currents crossing the edges.

These two energy principles give the finite element algorithms for generating stable numerical schemes reduced to solving linear equations with positively defined symmetric matrices.

3 Triangle model of the thin wall

The triangle representation of the thin wall gives a practical approach for the electromagnetic model representation of the thin wall and plasma surface. It is based on the following expressions for the vector potential $\mathbf{A}$ and magnetic field $\mathbf{B}$ of the uniform surface current $\mathbf{i}$=const inside the triangle

$$\begin{aligned} \mathbf{A}(\mathbf{r}) &= h\mathbf{j}\phi(\mathbf{r}) = [(\nabla I \times \mathbf{n}) - \bar{\sigma}\nabla\phi^{SS}]\phi(\mathbf{r}), \quad \phi(\mathbf{r}) \equiv \int \frac{dS'}{|\mathbf{r}-\mathbf{r}'|}, \\ \mathbf{B}(\mathbf{r}) &= (h\mathbf{j}\times\mathbf{e}) = \left\{[(\nabla I \times \mathbf{n}) - \bar{\sigma}\nabla\phi^{S}]\times\mathbf{e}\right\}, \quad \mathbf{e}(\mathbf{r}) \equiv \int \frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|^3} dS', \end{aligned} \tag{3.1}$$

where ϕ is the electric potential of a triangle with a uniform unit charge, $\mathbf{e}$ is its electric field, $\mathbf{r}, \mathbf{r}'$ are the coordinates of the observation and the source points, and the integrals are taken over the surface of the triangle. Both ϕ and $\mathbf{e}$ have analytical expressions in terms of elementary functions.

The triangle model of the thin wall gives a non-singular (unlike the WALLEN code wire grid model) representation of the vector potential and magnetic fields of wall currents, suitable for simulation the Wall Touching Kink Modes in tokamak disruptions.

4 The shell simulation code SHL (PPPL)

The triangular model for calculation of the stream function I on both plasma surface and thin wall was implemented in the shell simulation code SHL in 2008 and tested against the calibration shots for the LTX tokamak (PPPL) copper shell. The code utilizes the symmetry of the segmented wall structure, typical in real machines (16 sectors in EAST, 8 in JET, 12 in NSTX-U, and approximately 9 in ITER).

At the moment, the code SHL code is linked to the 2-D version of the Vertical Disruption Code (VDE), developed in 2014 in PPPL, and will be tested and calibrated against EAST experimental data.

The calibration and testing of SHL code is a part of my proposal on a new DoE project on 2- and 3-D theory/code developments, utilizing the recently formulated Tokamak MHD model, for VDE simulation on JET and ITER.