Estimations of disruption forces in the COMPASS-U tokamak

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1. Introduction. This paper presents the analysis of disruptions in COMPASS-U tokamak [1], which is a medium-size high-magnetic-field device currently in the conceptual design phase. Due to the high plasma current (up to 2 MA) and the strong magnetic field (up to 5 T), large electromagnetic forces on conducting structures surrounding plasma are expected during disruptions. To address this issue, electromagnetic loads on the vacuum vessel (VV) during disruptions are estimated analytically using a novel approach to the problem [2, 3]. These analytical results will serve as a baseline for more detailed numerical calculations with CarMa0NL [4] considering a volumetric 3D description of conducing structures.

2. Analytical results. To estimate the distribution of the electromagnetic forces during disruptions in the vacuum vessel we use circular tokamak approximation [2] with the following parameters: $b_w / b \approx 2$, $\varepsilon_w \equiv b_w / R \approx 0.5$, $S_w \equiv (2\pi)^2 R b_w \approx 20 m^2$, where b_w and b are the minor radii of the wall and plasma, respectively, and R is the major radius of the plasma, ε_w is the wall inverse aspect ratio and S_w is the full lateral area of the wall.

Results in [2] are valid for the case when the vacuum vessel reacts on perturbations as an ideal conductor. First, we verify this assumption, for $b_w \approx 0.5m$ the characteristic resistive wall time is $\tau_w \equiv \mu_0 b_w d_w / \eta \approx 5ms$, where $\mu_0 = 4\pi \times 10^{-7} H \cdot m^{-1}$ is the vacuum magnetic permeability, $d_w \approx 0.01m$ is the wall thickness and $\eta = 1.26 \mu\Omega \cdot m$ is the electrical resistivity of Inconel 625. According to the scaling laws [5], for the COMPASS-U tokamak one can expect $\tau_{TQ}^* << \tau_w$ and $\tau_{CQ}^* << \tau_w$, where τ_{TQ}^* and τ_{CQ}^* are the times for the fastest thermal quench (TQ) and current quench (CQ), respectively. In these cases, we can treat the wall as ideal and use formula (69) from [2] for the poloidal distribution of the surface density of the magnetic force acting on the wall during disruption,

$$\mathbf{f}_w = \mathbf{n}_w \delta p_m = \mathbf{n}_w (\delta p_{m0} + \delta p_{m1} \cos u), \qquad (1)$$

where $\mathbf{n}_w$ is outwardly directed unit normal to the wall, $\delta p_m = p_m(t) - p_m(t_0)$ is the variation of the magnetic pressure at the inner side of the wall $p_m \equiv \mathbf{B}^2/(2\mu_0)$ before t_0 and after t fast transient event, u is the polar angle linked to geometrical centre of the wall (in the poloidal cross-section), δp_{m0} and δp_{m1} are the variations of amplitudes of $m = 0$ and $m = 1$ poloidal harmonics, respectively:

$$\delta p_{m0} = \frac{\pi}{5}\frac{\delta\beta_J}{S_w \varepsilon_w}\left(\frac{J}{1MA}\right)^2 MN \approx -0.12MPa\,, \tag{2}$$

$$\delta p_{m1} = -\frac{2\pi}{5S_w}\delta\left[\left(\ln\frac{b_w}{b} + \frac{l_i}{2}\right)\left(\frac{J}{1MA}\right)^2\right]MN \approx 0.24MPa\,, \tag{3}$$

where J is the net plasma current, $\beta_J \equiv 2\mu_0 \bar{p}/B_J^2$ is the poloidal beta with p the plasma pressure, $B_J \equiv \mu_0 J/(2\pi b)$ is the averaged poloidal magnetic field at the plasma boundary and $l_i \equiv \overline{B}_p^2/B_J^2$ is the internal inductance per unit length of plasma column with B_p the poloidal magnetic field.

For COMPASS-U scenario with $\beta_J = 0.5$ and $J = 2MA$ from (2) we find $\delta p_{m0} \approx -0.12MPa$, which means that large magnetic pressure on the wall develops already during TQ. For the same parameters and $l_i = 0.6$ from (3) follows that the magnetic pressure on the wall during CQ is twice larger $\delta p_{m1} \approx 0.24MPa$. The total integral radial force is [2]

$$F_r = 0.5S_w(\varepsilon_w \delta p_{m0} - \delta p_{m1}) \approx -3MN\,, \tag{4}$$

where the first term is the radial force due to the TQ $F_r^{TQ} = 0.5S_w\varepsilon_w\delta p_{m0} \approx -0.6MN$ and the second one is due to the CQ $F_r^{CQ} = -0.5S_w\delta p_{m1} \approx -2.4MN$.

3. Preliminary numerical results. The effect of 3D vacuum vessel geometry on the current and force density distribution during disruptions was studied with CarMa0NL code [4]. Time evolution of the plasma configuration during 0.5 ms TQ followed by 1MA/ms CQ is shown in Fig. 1. Strong poloidal and toroidal eddy currents are induced in the vessel. Due to the presence of horizontal ports the currents and the related electromagnetic force are concentrated on their edges, as seen in Figs. 2 and 3. The vector force fields produced by CarMa0NL were exported to ANSYS Mechanical for the following structural analysis.

4. Effect of in-vessel components on current and force distribution. The presence of metal in-vessel components changes vertical stability properties, as well as the current and force

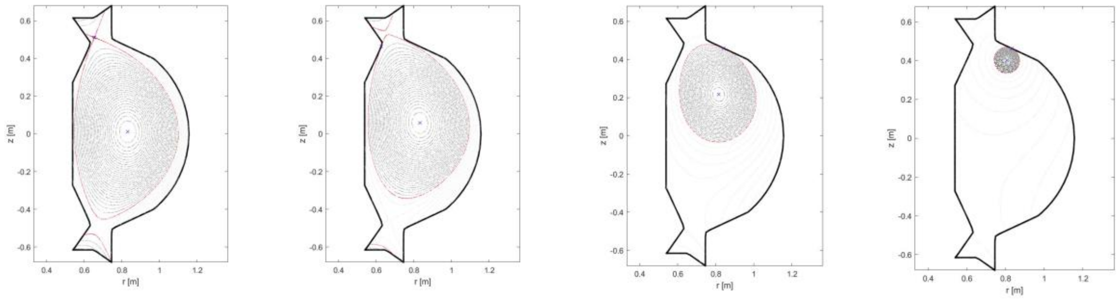

Fig. 1. Plasma configurations during thermal (0 – 0.5 ms) and current (after 0.5 ms) quenches. The four snapshots correspond to 0.25 ms, 0.50 ms, 0.75 ms and 1 ms.

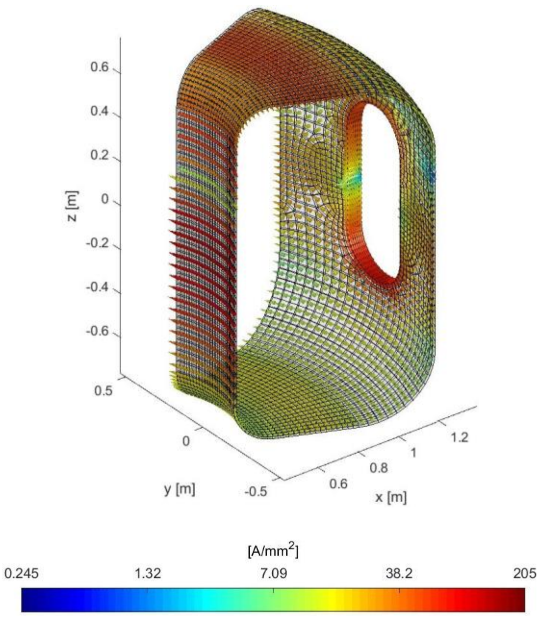

Fig. 2. Current density pattern induced in the 3D vacuum vessel at $t = 1ms$.

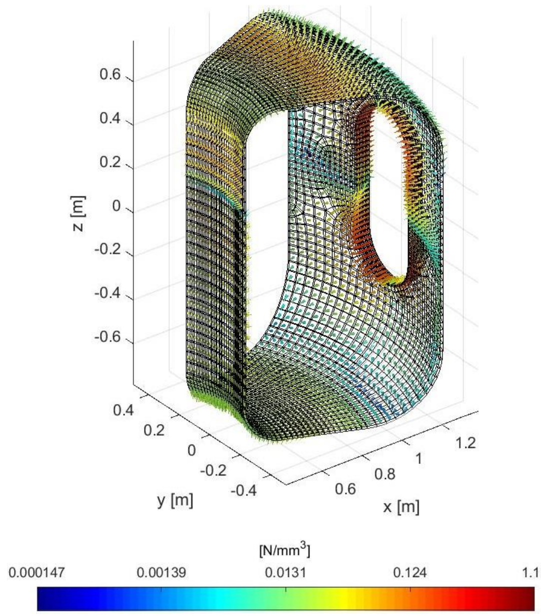

Fig. 3. Electromagnetic force density pattern in the 3D vacuum vessel at $t = 1ms$.

distribution within the VV. This is illustrated in Figs. 4 and 5 for two pairs of copper toroidal stabilizing plates and 8 poloidal coils, which serve as a disruption force damper (DFD) [6].

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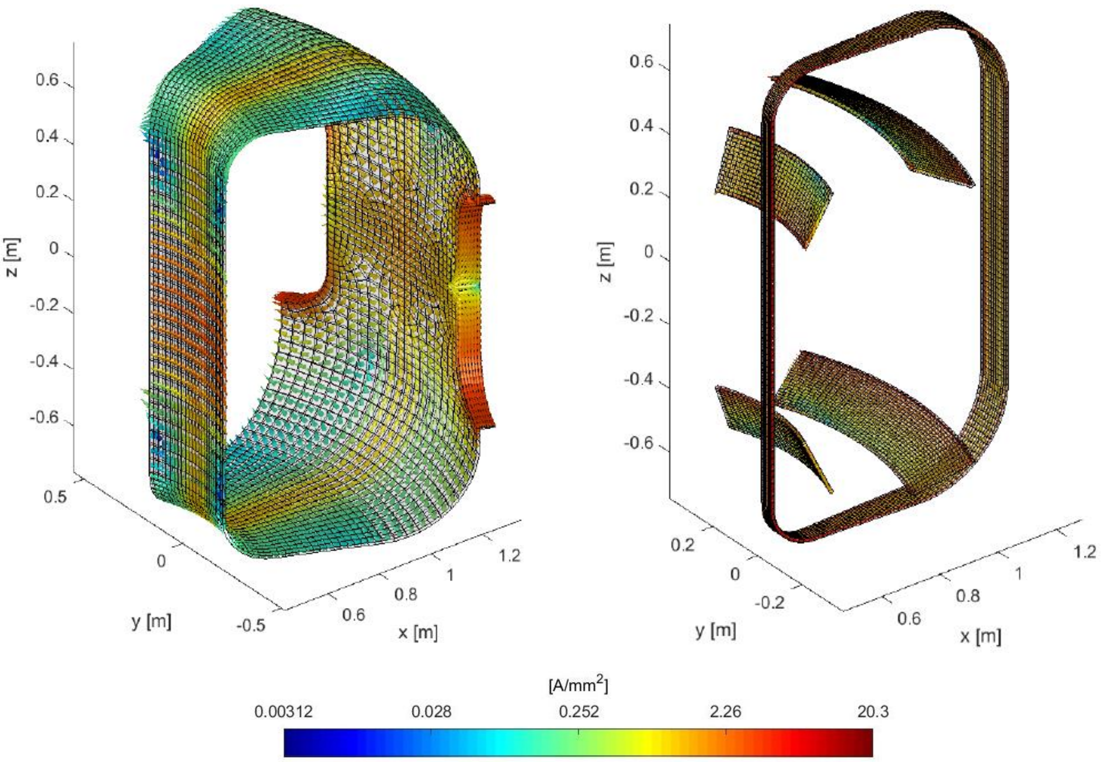

Fig. 4. Current density pattern induced in the Inconel VV (on the left) and in the copper in-vessel components (on the right) during 0.5 ms TQ at $t = 0.25\,ms$.

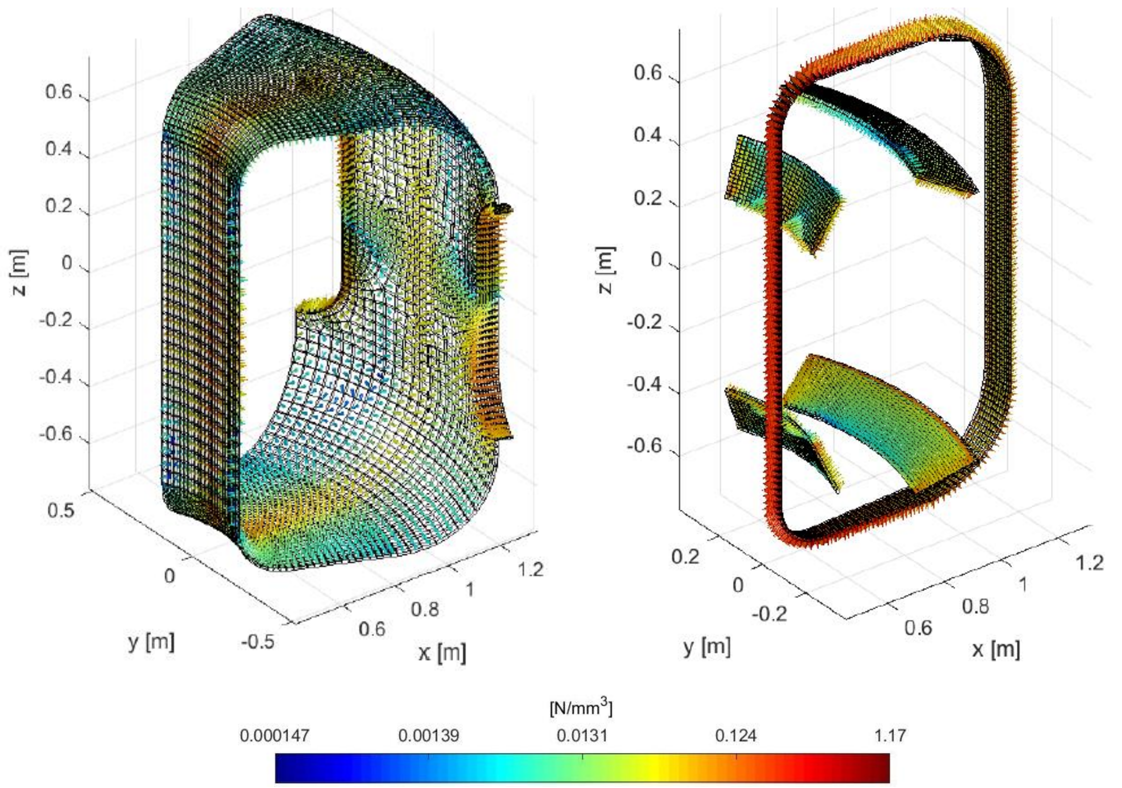

Fig. 5. Electromagnetic force density pattern in the Inconel VV (on the left) and in the copper in-vessel components (on the right) during 0.5 ms TQ at $t = 0.25\,ms$.