Theoretical approach to the maximum vertical force on ITER vacuum vessel

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Abstract

Vertical displacement events (VDEs) and subsequent plasma disruptions induce severe electromagnetic force on the vacuum vessel (VV) of the ITER machine. Recently, a useful model is presented for calculating the force without using knowledge of eddy and halo currents [S. Miyamoto, Plasma Phys. Control. Fusion **53** (2011) 082001]. According to the model, two factors dominate the force on VV; the force between plasma and PF coil and the current quench time. The former is easily evaluated from current of the plasma that deviates from equilibrium position. On the other hand, a large uncertainty remains in the latter. In this paper, we present a possible constraint on the current quench time and discuss the upper limit of the vertical force.

1. Theoretical model of vertical force

The conventional approach to calculating the vertical force involves first estimating the eddy and halo currents in the vessel, usually with the help of computer simulation. Recently a model of the vertical force is presented [1] in the style of linear response formalism,

$$F_{\mathrm{v}}(t) = \frac{1}{\tau_{\mathrm{L/R}}}\int_{-\infty}^{t} F_{p,c}(t')\exp\left(-\frac{t-t'}{\tau_{\mathrm{L/R}}}\right)\mathrm{d}t'. \tag{1}$$

Here F_{v} is the force on the vessel, $F_{\mathrm{p,c}}$ the force between plasma and PF coils. The exponential term represents the electromagnetic shielding of the vessel with a time constant $\tau_{\mathrm{L/R}}$. This formula does not require information on eddy and halo currents; nevertheless the formula well accounts the DINA result of vertical force on ITER VV during VDE. VDE and current quench produce a pulse of the force $F_{\mathrm{p,c}}$. To roughly estimate maximum of F_{v}, only the height and width of the pulse are required. The former is estimated from the current of the plasma that deviates from the equilibrium position and is about 150 MN for ITER [2]. In this paper, the width of the pulse, in particular, a possible constraint on the duration of current quench will be discussed.

2. Attainable T_e in halo region during current quench

Thermal quench (TQ) of disruption expels almost all of plasma thermal energy. After TQ, magnetic energy of the plasma current is consumed to sustain electron temperature T_e through joule heating. Therefore, the rate of magnetic energy consumption or current quench (CQ) time τ_{cq} largely depends on plasma resistance or T_e during current quench. Usually, it is assumed the joule input power dissipates to the wall as impurity radiation. However, as impurity level is reduced or plasma temperature increases, another loss channel, i.e., heat conduction through a sheath at the plasma-wall interface becomes important. Figure 1 shows DINA simulation of joule energy loss E_{joule} and sheath transmission energy E_{sheath} for ITER VDE. In this simulation, DINA solves ohm's law to give correct values for E_{joule} but T_e is specified arbitrarily and not determined consistently to the energy balance. As the result, E_{sheath} increases in proportion to T_e^3 ($E_{sheath} \propto \tau_{cq}\gamma k T_e \Gamma_{se}^{\ i} \propto \eta^{-1} k T_e c_{se} \propto T_e^3$, where γ is the sheath transmission factor, $\Gamma_{se}^{\ i}$ ion flux at sheath entrance, η plasma resistivity and c_{se} sound speed at sheath entrance respectively) and largely exceeds E_{joule} with increasing the specified T_e at last. From the plot, T_e = 35 eV can be considered a maximum temperature in the halo region attainable during CQ.

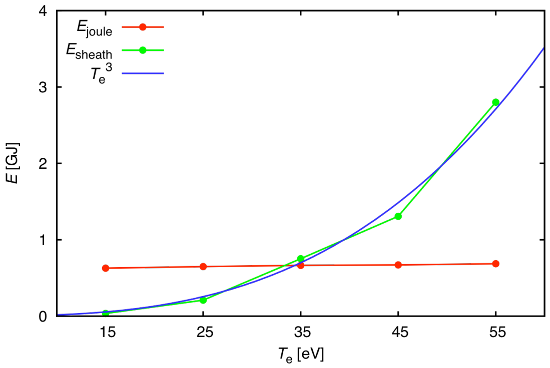

Fig. 1 T_e dependence of joule energy loss E_{joule} and sheath transmission energy E_{sheath} during ITER VDE, calculated by the DINA code.

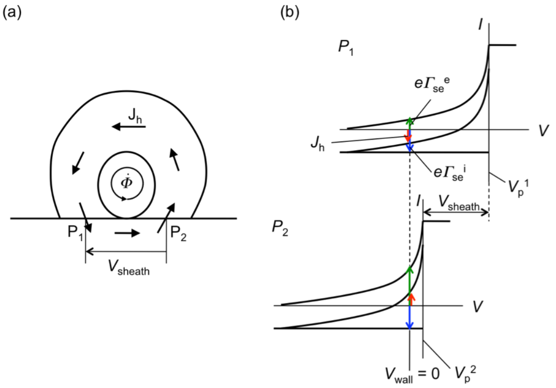

Fig. 2 (a) Magnetic induction $\dot{\Phi}$ and halo current J_h. (b) Relation between particle fluxes and sheath current. A sheath potential V_{sheath} is formed by J_h.

Another important factor is the sheath potential at the plasma-wall interface. In figure 2, halo current generation due to a magnetic induction $\dot{\Phi}$ is schematically drawn. A halo current density J_h flows in the wall at P_1 and flows out at P_2 producing sheath potential difference V_{sheath}. If J_h is small and V_{sheath} can be neglected, power balance eq. is written as,

$$\frac{1}{\eta l}\dot{\Phi}^2 = 2\gamma k T_e \Gamma_{se}^{\mathrm{i}}, \tag{2}$$

where l is the length of field line in the flux tube being considered. Perpendicular heat transport and radiation are ignored. Because the both sides of eq. have the same dependency on T_e ($T_e^{3/2}$), only a specific value of $\dot{\Phi}$ suffices (2).

$$\dot{\Phi}_c = \left(\frac{11.8\gamma\cdot n_{\mathrm{o}}[10^{20}\mathrm{m}^{-3}]\cdot l[\mathrm{m}]\cdot Z_{\mathrm{eff}}\cdot \log\Lambda}{A^{1/2}}\right)^{1/2}, \tag{3}$$

where Z_{eff} is an effective charge, $\log\Lambda$ the coulomb legalism and A the mass number of the ion. An induction lower than (3) cannot support the plasma since joule input is less than the sheath transmission for any T_e. If induction exceeds the critical value (3), T_e will rise until radiation balances the joule heat.

When J_h approaches the ion saturation current $J_{\mathrm{sat}}^{+} = e\Gamma_{\mathrm{se}}^{\mathrm{i}}$, joule input power is bounded by J_{sat}^{+}. Thus T_e is determined by

$$(\dot{\Phi} - V_{\mathrm{sheath}})J_{\mathrm{sat}}^{+} = \eta l (J_{\mathrm{sat}}^{+})^2 = 2\gamma k T_e \Gamma_{\mathrm{se}}^{\mathrm{i}} \quad \text{or}$$

$$T_e[\mathrm{eV}] = \left(\frac{3.0 n_{\mathrm{o}}[10^{20}\mathrm{m}^{-3}]\cdot l[\mathrm{m}]\cdot Z_{\mathrm{eff}}\cdot \log\Lambda}{\gamma A^{1/2}}\right)^{1/2}. \tag{4}$$

In a halo plasma limited by walls, eq. (4) gives an apparent upper limit of T_e. The magnetic induction that satisfies the power balance can be strictly determined as a function of T_e using the sheath equations. The result is shown in figure 3. If uncertainty of parameters is considered, the upper limit of T_e is about 30 eV. Note that $\dot{\Phi}$ is roughly proportional to $1/\tau_{\mathrm{cq}}$. The intersection point with this curve determines the halo temperature. If halo temperature T_e is arbitrarily specified higher than these limiting values in the VDE simulations, the global energy balance would be violated and/or halo current density would exceed the ion saturation current.

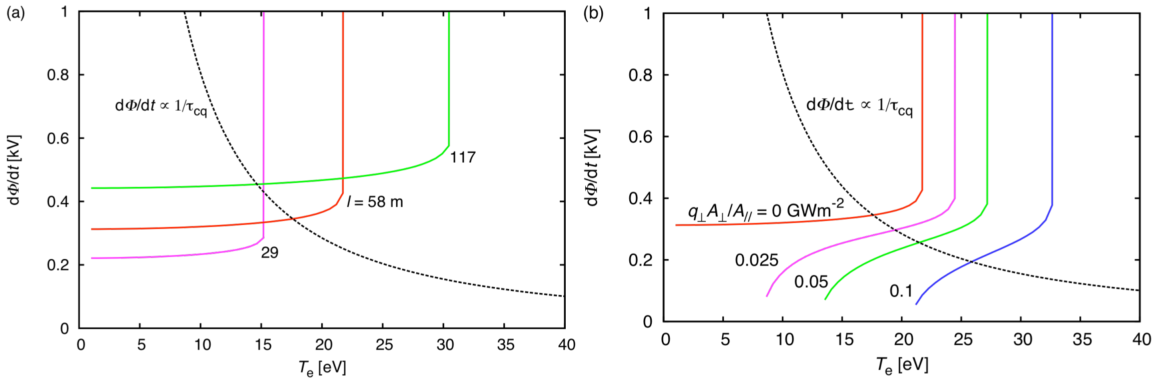

Fig. 3 Magnetic induction that satisfies the power balance as a function of T_e. (a) Dependence on l. In ITER case, $l = 2\pi R q_e$ ($q_e = 1.5$: edge safety factor) = 58 m. (b) Dependence on perpendicular heat flux.

3. Implication of halo modelling and upper limit of vertical force

The current specification of maximum vertical force on ITER VV was derived from a DINA simulation for a downward VDE with slow current quench (T_e = 55 eV). If the above constraint on T_e (below 30 eV) is simply applied to these simulations, τ_{cq} becomes short and halo current becomes small. As the result, the evaluated maximum vertical force is reduced significantly as shown in figure 4. However, the present disruption/VDE simulations by 2D code, DINA or TSC, have been performed based on rather simplified modelling and assumptions, e.g., halo and core temperature being same and constant spatially and temporally, simple halo width model preserving constant average current density and so on. Therefore, it is of primary importance to develop a comprehensive halo current model including the above constraints to fully understand the effect of temperature upper limit. It is very likely that the time duration of VDE event would be significantly shorter, though maximum halo current in the vessel would not be so modified.

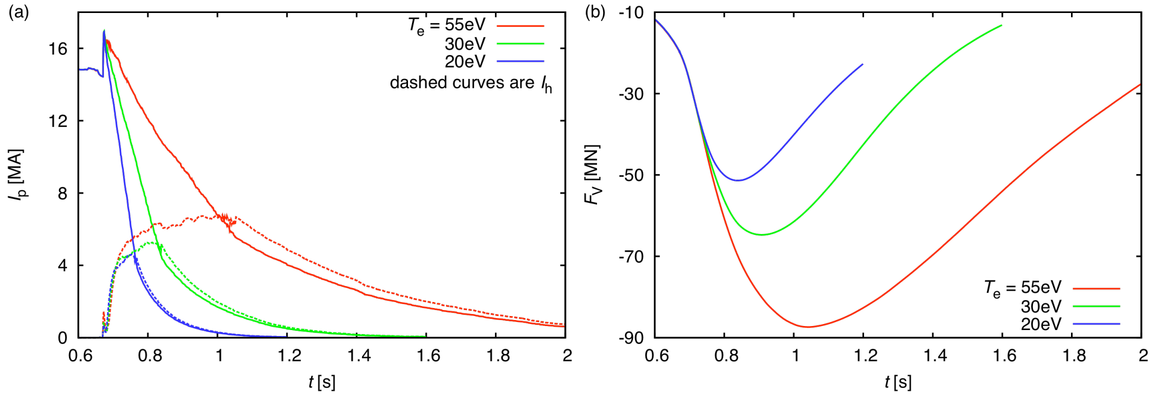

Fig. 4 Reference scenario of ITER VDE (red curves). If T_e is constrained below 30 eV, (a) τ_{cq} becomes short and halo current becomes small. (b) As the result, maximum vertical force mitigated significantly.

4. Conclusion

Analysis on the possible maximum of T_e was performed based on the power balance in the halo plasma. It was shown that thermal energy transferred through a sheath exceeds joule input energy for Te > 35 eV in DINA simulation and these high temperatures would not be attained during current quench. Another upper limit is set to T_e when effect of sheath potential is taken into account. For high $T_e > 30$ eV, joule input never exceeds the sheath transmission energy because the sheath current is strongly limited by ion saturation current. In conclusion, boundary conditions as well as energy balance are very important constraints to correctly evaluate the maximum amplitude of halo current and event time duration, which are essential for ITER design. Work still progresses, especially on the following point: At a temperature range $T_e < 30$ eV, only a 30% of halo current fraction is observed in DINA simulations. How can the large halo current fraction observed in experiments (~ 40-50%) be explained?

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER organization.

References

[1] S. Miyamoto "A linear response model of the vertical force on a vessel applicable to ITER and future tokamaks" Plasma Phys. Control. Fusion 53 (2011) 082001

[2] S.V. Putvinski "Maximum vertical force on ITER vacuum vessel" ITER_D_2MBAPU (2009)