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Validation of halo current model with DINA code against JT-60U disruption shots

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Introduction. During a major disruption or a vertical displacement event (VDE) in a tokamak plasma, both the plasma current and cross-section plasma area decay to zero. Both decays generate an electric field that drives around the core plasma a current flow along the helical field lines in the peripheral region, which is so-called "halo" current. The poloidal component of halo current flowing in the wall, when crossed with the toroidal magnetic field, gives the big additional mechanical forces in the structure around the plasma. Such forces have to be predicted and taken into account in the physics basis of high-current tokamak as ITER.

To predict a behavior of halo current during disruption a model for the width of the halo region was included in DINA code [1], which is being used for disruption modeling in ITER plasma [2]. That model is based on conservation of toroidal magnetic flux within the plasma cross-section and which is taken to include the halo region once a vertical instability develops.

This paper presents the physical model of halo area expansion in DINA code and the results of halo current behavior analysis in the JT-60U shots 31949 and 36655 [3, 4] during the plasma disruption coming out from VDE process. These results include the comparison between the modeled poloidal component of halo current evolution and the experimental data measured by means of Rogowski's coils.

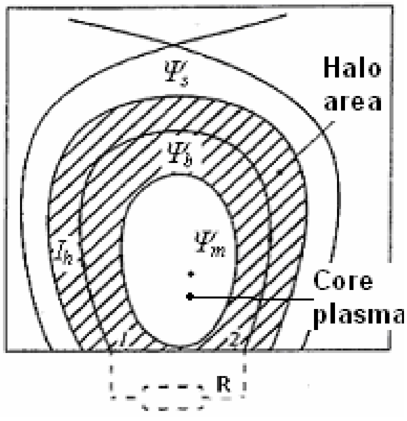

Fig. 1 Limited core plasma together with halo area

Physical model of halo area expansion. Due to electron temperature drop after thermal quench the plasma current is decreasing during disruption and electric field in toroidal direction E_φ is showing up. That field is a reason of the toroidal component of halo current. Poloidal halo current component I_h is determined by the toroidal magnetic flux changing inside of the last closed magnetic plasma surface. Such changing is becoming particularly significant if the plasma is in the limiter state during VDE and a part of toroidal flux is shrinking by limiter together with plasma as shown in Fig. 1. Here inside of core plasma the poloidal flux Ψ is changing within poloidal flux in plasma axis Ψ_m and plasma boundary Ψ_b. Inside of halo area the value of Ψ is decreasing from Ψ_b up to Ψ_s. We define the halo area width w as $w = \frac{\Psi_b - \Psi_s}{\Psi_m - \Psi_b}$ [5]. The value of R is a resistance of surrounding conducted structure between the points 1 and 2. Accepted in DINA code physical model of the halo area expansion during the plasma disruption is based on the assumption of the approximate conservation of the toroidal magnetic flux inside the poloidal surface S combining the core plasma and the halo region. Because the toroidal magnetic flux is proportional to S the scaling for the halo width in DINA code looks like the implicit expression with regard to the $w(t)$ value

$$\frac{S_0}{S(t,w)}\left(C + \frac{I_p(t,w)}{I_{p0}}\right)\frac{1}{C+1} = 1, \tag{1}$$

which has to be valid at each time moment t during the plasma disruption event. Here S_0 and I_{p0} are correspondingly the poloidal surface and the plasma current values before the thermal quench beginning, $S(t,w)$ and $I_p(t,w)$ are the mentioned parameters at the current time moment t after thermal quench. The S value is the total core plasma and halo area surface. That is before the halo current generation the value of w is supposed to be equal 0. The term $\left(C + \frac{I_p(t,w)}{I_{p0}}\right)\frac{1}{C+1}$ in expression (1) is taking into account the possible decrease of toroidal flux, which is assumed to be proportional to I_p. Here C is a fitting coefficient, which can be different for various tokamaks. In present paper the scaling (1) is being validated against the JT-60U disruption data with use of evolution fitting mode of DINA code.

Fitting mode in DINA code. In fitting mode the values of PF coils and total plasma currents, magnetic flux loops and probes signals are taken from the experiments in each time step. In DINA fitting mode the plasma magnetic configuration (Ψ_m, Ψ_b), halo area location (Ψ_s), plasma current density including halo region and the vessel current distribution are obtained as a results of "fitting" of calculated poloidal flux values in flux loops and poloidal magnetic field values in magnetic probes S_h^{calc} to the experimentally measured quantities $S_h^{\exp}$ as described in [6]. The "fitted" plasma parameters provides the

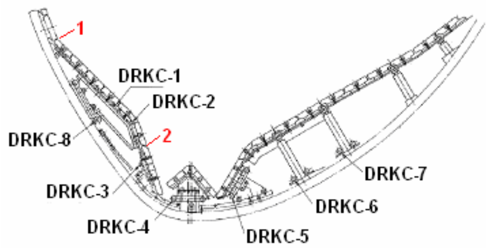

Fig. 2 Rogowski's coils in JT-60U for halo current measurements

minimum of the $\chi^2 = \sum_h \chi_h^2 = \chi^2_{loops} + \chi^2_{probes} + \chi^2_{PF}$ value, where χ_h^2 is determined as $\chi_h^2 = \sum_l \{(S_h^{calc} - S_h^{\exp})^2 / \sigma_h^2$. Here σ_h is the relative error between measurement and simulation, index l denotes the number of sensor. In result of fitting simulations the both poloidal $I_{h\,pol}$ and toroidal $I_{h\,tor}$ components of halo current can be obtained [5] correspondingly as $I_{h\,pol} = \int_{\Psi_s}^{\Psi_b} \frac{dF}{d\rho}\frac{d\rho}{d\Psi} d\Psi$ and $I_{h\,tor} = \frac{\mu_0}{4\pi}\iint_{\text{Halo}} \frac{\left(F^2\right)'}{R}\frac{d\rho}{d\Psi} dS$.

Poloidal component of halo current is being compared with those measured in JT-60U by the Rogowski coils presented in Fig. 2.

Halo current validation results. Present results concern the halo currents study during VDE in the 31949 and 36655 JT-60U shots. In these experiments, downward (toward the X-point) VDE have been created by the intentional small kick with switching off the vertical control system afterward. Study is being carried out with use of expression (1) by means of DINA fitting mode. Analysis includes the sensitivity study of discrepancy between the experiment data and modelled poloidal halo current component ones as function of coefficient C in (1). The modeling time moment of halo initiation was chosen to be consistent with the halo current starting time in the experiment. Experimental halo current data in 31949 shot include the $I_{h\,pol}$ measurements flowing only through DRKC-8 Rogowski coil between the 1 and 2 points shown in Fig. 2. Reconstructed plasma equilibriums during 31949 shot at 13.043 s and 13.045 s time moments with DINA code is presented in Fig. 3. Here magenta colour covers the magnetic surfaces inside the halo area, which is restricted by the green line. Evolution of the both DINA poloidal halo current component and experimental one through the DRKC8 Rogowski coil during the 31949 shot for the different values of C coefficient are presented in Fig. 4. One can see that the DINA results for C>0.5 give the acceptable coincidence with the experimental data and the peak value is reproduced with discrepancy 5%.

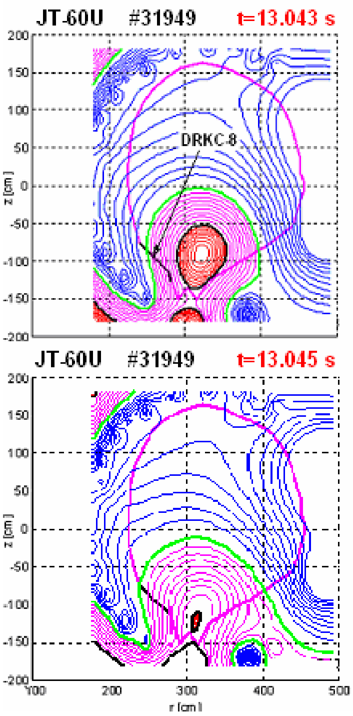

Fig. 3 DINA reconstructed plasmas during 31949 shot at 13.043 s and 13.045 s time moments

The 36655 shot in JT-60U belongs to the discharges with major disruption and runaway electrons generation, which are terminating when the plasma boundary safety factor q_b is going down to 2.5 during VDE [3]. Then the generation of halo currents is showing up. In the early paper [3] the first comparisons between the experimental halo current behaviour in 36655 JT-60U shot and the DINA modelling results have been obtained. An accuracy of such comparison has been around 20%.

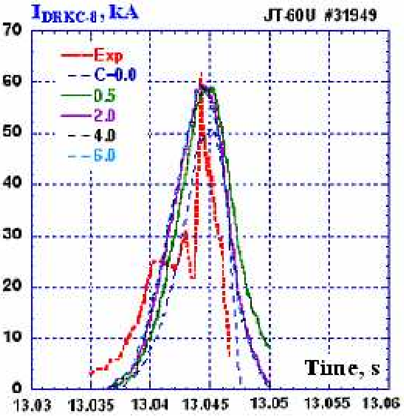

Fig. 4 Evolution of measured poloidal component of halo current in 31949 JT-60U shot and DINA fitting modeling results

In present paper the DINA fitting modeling of the halo current evolution in 36655 shot is carried out with use of updated relation (1). The both experimental and DINA poloidal halo current data in that shot are presented in Fig. 5. One can see that for $C > 2$ the DINA results give the acceptable coincidence of maximum halo current value with the experimental data. The peak value is reproduced with discrepancy ~10 % if $C \geq 0.5$.

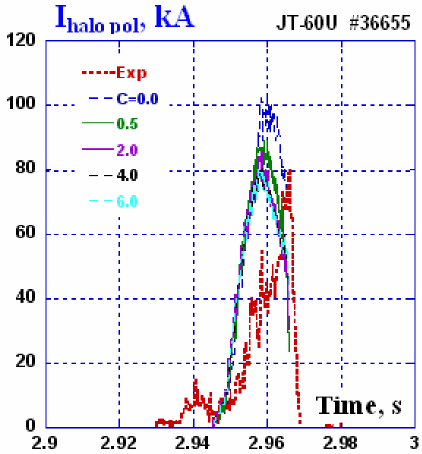

Fig. 5 Evolution of measured poloidal component of halo current in 36655 JT-60U shot and DINA fitting modeling data with different *C*

Conclusion. The resulting agreement between the experimental and modeled halo current behaviour in JT-60U disruptive plasma, performed with the fitting mode of DINA code and proposed empirical relation for the halo region width is quite encouraging. The peak value of halo current is reproducing within accuracy 5-10%.

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