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Study of plasma Initiation in ITER with use of 2D breakdown Model

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Currently in most cases the plasma column formation and current ramp-up at this stage is analyzed within the homogeneous (0D) model when the transverse column dimension *a*, as well as the plasma major radius *R* are derived from the avalanche breakdown condition and considered constant throughout the entire stage [1-3]. Plasma is considered as a single filament and the force balance equations are solved only for one point corresponding to the plasma center. Such description is not accurate and especially is not acceptable as initial conditions for ramp-up scenario simulations by use of evolution codes. To improve an accuracy of simulations and make more self-consistent discharge simulations at tokamaks, a new plasma initiation description (full 2D model) has been developed recently [4]. In this model a force free plasma equilibrium in external poloidal magnetic fields is calculated by use of Grad-Shafranov equation. The plasma conductivity is determined from 0D-model. Plasma current distribution is determined from the solution of poloidal field diffusion equation self- consistently with magnetic surfaces evolution. Plasma allows to flow along the opened magnetic field lines. This situation is similar to the picture of Halo-currents formation during disruption [5].

In present work we are considering the ITER plasma formation and current ramp-up after breakdown with use of 2D model and waveforms of PF coil currents, Z_{eff} and plasma temperatures from 0D modelling results [3]. Comparison between the full model results and 0D ones are performed.

0D modelling results

In this work we apply the approach following [2,3] for ITER plasma. The energy balance equations for electrons and ions in 0D approximation are written in the form

$$\frac{3}{2}\frac{d}{dt}(n_e T_e)\cdot 0.016 = P_{OH} - P_{\Delta} - P_{ion} - \frac{3}{2}\frac{n_e T_e}{\tau_E} \qquad (1)$$

$$\frac{3}{2}\frac{d}{dt}(n_e T_i)\cdot 0.016 = P_{\Delta} - P_{cx} - \frac{3}{2}\frac{n_e T_i}{\tau_E} \qquad (2)$$

Particle balance: ions n_e (10^{19} m^{-3}) and neutrals n_0 (10^{19} m^{-3}) respectively:

$$\frac{dn_e}{dt} = 10^{19} n_0 n_e S_i - \frac{n_e}{\tau_p} \qquad (3) \qquad\qquad V_V \frac{dn_0}{dt} = \frac{n_0 V_p}{\tau_p} - 10^{19} n_0 n_e S_i V_p \qquad (4)$$

Circuit equation for plasma current I_p (MA): $L_p \frac{dI_p}{dt} + R_p I_p = -\sum_i M_{pi} \frac{dI_i}{dt} - \sum_j M_{pj} \frac{dI_j}{dt}$, (5)

where M_{pi} is the mutual inductance between the plasma and PF coil currents I_i, M_{pj} is the mutual inductance between the plasma and the current of the conducting structure I_j, L_p and R_p are the plasma inductance and resistance. The plasma displacements in R and Z directions are estimated from the following system of equations:

$$\langle B_r^{ext}(R,Z)\rangle = 0, \quad \langle B_z^{ext}(R,Z)\rangle = -\frac{\mu_0 I_p}{4\pi R}\left[\ln\left(\frac{8R}{a}\right) + \beta_p + \frac{l_i}{2} - \frac{3}{2}\right] \tag{6}$$

In (1-4) the following notations are applied: V_p is the volume of plasma region, V_v represents the vacuum chamber volume, T_e и T_i are the electrons and ions temperatures respectively [keV], P_{OH} describes Ohmic heating specific power [MW/m^3], P_Δ is equilibration specific power between electrons and ions in plasma [MW/m^3], P_{ion} is neutral gas ionization specific losses [MW/m^3], P_{cx} describes charge exchange specific losses [MW/m^3], τ_E and τ_P are the energy and particles confinement times.

Waveforms of PF coil currents are adjusted in 0D model to provide (within the limits on the magnetic fields and power):

- the breakdown with the toroidal electric field 0.3V/m and the stray magnetic field lower than 1 mT
- after breakdown a stable plasma equilibrium in R = 7.48 m and Z= 0.62 m with a = 0.8 m, l_i = 0.85 and β_p = 0.

The results of 0D analysis concerning I_p, T_e and $n_e(10^{19}\text{m}^{-3})$ during ITER plasma initiation are presented in Fig.1 where 850ms is the breakdown time moment. One can see that after breakdown following the 0D the plasma current ramp up has a rate ~530 kA/s.

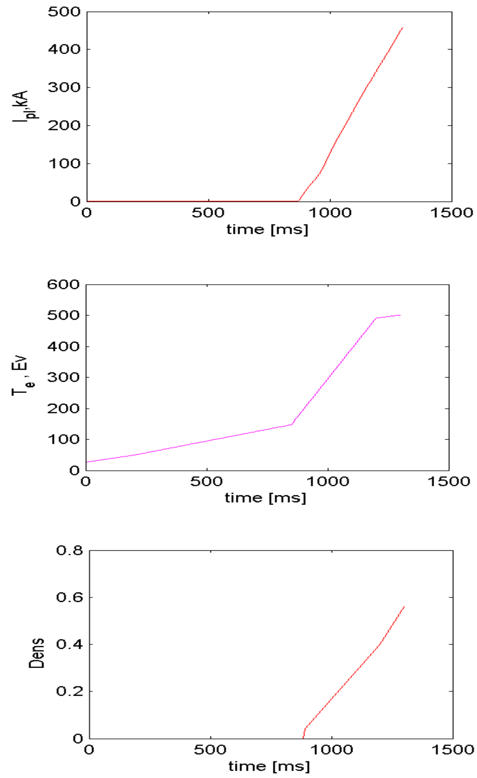

Fig.1 Time evolution of plasma current, electron temperature and plasma density during ITER plasma initiation

2D modeling results

To check the quality of plasma equilibrium in the obtained with 0D modeling plasma initiation scenario we are using now the 2D model with prescribed PF coil current waveforms obtained by means of 0D modeling. Plasma equilibrium in tokamaks is described by Grad-Shafranov equation when a condition that plasma pressure is constant along magnetic surfaces is used. In our case plasma pressure is small, so this requirement is not important. Electric field was calculated from solution of 1D diffusion of magnetic field equation self-consistently with shape of magnetic surfaces. Poloidal current function F is calculated using averaged Grad-Shafranov equation and it is used further as part of toroidal current density to solve 2D equilibrium and to find structure of magnetic surfaces. Energy transport equations were not solved. Instead, a plasma temperature and Z_{eff} waveforms were taken so that the plasma current increase rate was near to 0D modeling waveform: 530 kA/s. Plasma current was calculated using magnetic field diffusion equation. In Fig. 2 the external magnetic field structure with use of I_{PF} waveforms from 0D modeling results in breakdown time moment is presented. To correct a 5 Gs of the vertical magnetic field the two additional pairs of model PF coils (PF_z and PF_r) were introduced. The two variants of ITER breakdown simulations have been carried out. In Variant 1 the currents in PF_z and PF_r coils are supposed to be constant in time. In Variant 2 the currents in PF_r coil is specified in time to prevent a plasma movement in radial direction during ramp up after breakdown

The plasma current value to obtain a first plasma equilibrium is chosen to be 17 kA at the time moment of 890 ms. Transition from 0 to 17 kA is assumed to be linear in time during time period of 40 ms. In case of Variant 1 it was found out that the plasma is non-stable in radial direction and is moving outwards (see Fig.3 and

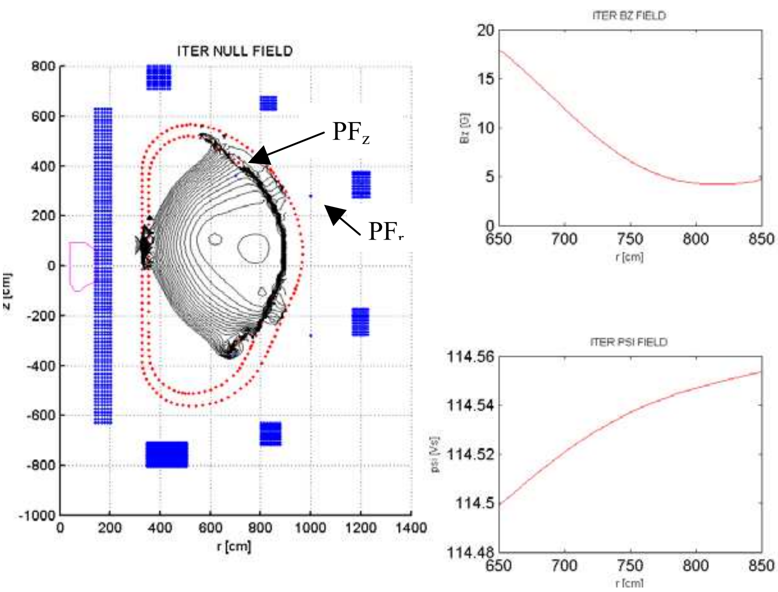

Fig.2 External magnetic field structure, radial dependence of B_z and ψ at time moment of plasma current formation (t = 850 ms) without plasma with use of I_{PF} waveforms from 0D modeling.

Fig.4). In case of Variant 2 when a correction of poloidal field configuration is carried out to prevent a plasma movement in radial direction one can obtain the plasma current ramp up after breakdown (see Fig.5). One can conclude that the 0D analysis data for plasma breakdown process has to be verified with 2D time evolution plasma equilibrium code.

t = 890 ms
I_p = 17 kA

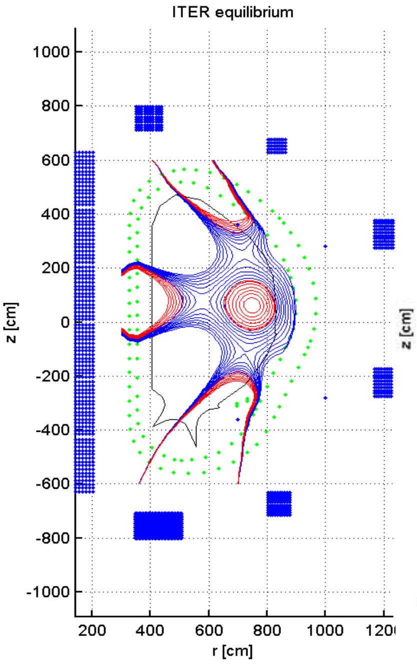

Fig.3 Plasma equilibrium in 890 ms time moment with prescribed PF coil currents from 0D modeling results (additional PF coil currents are not changed in time)

t = 950 ms
I_p = 44 kA

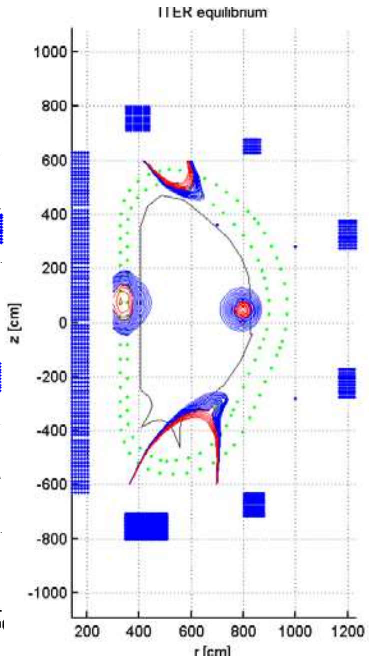

Fig.4 Plasma equilibrium in 950 ms time moment obtained in result of 2D time evolution modeling with prescribed 0D modeling PF coil current waveforms (additional PF coil currents are not changed in time)

t = 1115 ms
I_p = 260 kA

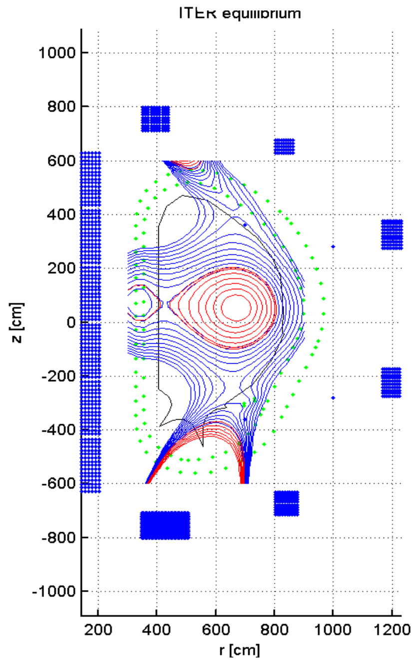

Fig.5 Plasma equilibrium in 1115 ms time moment obtained in result of radial stable plasma time evolution 2D modeling (**additional PF coil currents are specified to obtain radial stable plasma**)

Conclusion

It is shown that the 0D PF coil current scenario can lead to ITER plasma configurations with no plasma equilibrium and plasma position stability. Modeling of plasma current breakdown stage should be carried out with use of 2D equilibrium solver self-consistently with magnetic field diffusion equation decision.

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