Application of modified ASTRA-SPIDER code to simulation of free boundary equilibrium evolution

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In our studies a coupling of the equilibrium solver with a transport code is considered. In such 1.5D codes the evolution of poloidal magnetic flux, density and temperatures of plasma species are simulated in 1D approximation on the flux grid and with metric coefficients calculated consistently by 2D equilibrium solver. Our simulations are based on the Automated System for Transport Analysis (ASTRA) [1] and equilibrium solver SPIDER [2]. In the original coupling of the SPIDER to ASTRA7.0 [3] the evolution of the poloidal magnetic flux is computed outside the equilibrium solver. We modified the iteration loop to include the poloidal flux evolution into the internal iteration loop of the equilibrium solver and circuit equations using the grid adapted to magnetic fluxes. So the 2D Grad-Shafranov (GSE) equation in a fixed or free boundary configuration is solved by iterations together with the set of two one-dimensional equations relative to poloidal Ψ and toroidal Φ fluxes on the common grid inside the fixed plasma boundary by means of the SPIDER code [4]:

$$\begin{cases} \mu_0 \cdot \left(\dot{\Psi}\Phi' - \dot{\Phi}\Psi'\right) = \dfrac{1}{\sigma_{\parallel}}[\alpha_{33}\Phi' \cdot (\alpha_{22}\Psi')' - \alpha_{22}\Psi' \cdot (\alpha_{33}\Phi')'] + \dfrac{1}{\sigma_{\parallel}}\left\langle \vec{j}_B, \vec{B} \right\rangle_V \\ \Psi' \cdot (\alpha_{22}\Psi')' = (\alpha_{33}\Phi')'\Phi' + \mu_0 \cdot P' \cdot V' \end{cases}, \qquad (1)$$

where the first equation of (1) is the poloidal magnetic field diffusion equation derived from the Ohm's law $\sigma_{\parallel}(\vec{E},\vec{B}) = (\vec{j},\vec{B}) - \left(\vec{j}_B,\vec{B}\right)$, and the second equation is the flux averaged Grad-Shafranov Equation (GSE). Here metric coefficients α_{22}, α_{33} and the plasma boundary are taken from the solution of 2D GSE, plasma conductivity, $\sigma_{\parallel}$, plasma pressure, P, and external current, j_B, are taken from the transport block, $\left\langle \vec{j}_B, \vec{B} \right\rangle_V = \dfrac{d}{dV}\int_V \left(\vec{j}_B, \vec{B}\right) dV$ - volume averaging between two magnetic surfaces, V - volume inside the magnetic surface, $f' = \dfrac{\partial f(a,t)}{\partial a}$, $\dot{f} = \dfrac{\partial f(a,t)}{\partial t}$ - designations of derivatives by the flux variable *a(R,Z)* and by time. Additionally the iteration loop includes the circuit equations for each current filament in control and passive coils, which determine the control coil voltages and passive coil currents.

Such a modification of the code is shown to improve noticeably the convergence reducing the number of iterations in the equilibrium solver with evolving shape and profiles. It also reduces the total computational time of 1.5D transport evolution, where 2D equilibrium is the most time-consuming part. These effects are manifested especially for the cases with strong pressure and current density gradients near the edge for the H-mode operation in tokamak plasmas thus proving to be the most efficient approach to free boundary simulations with 1.5D transport codes. The efficiency of the proposed scheme further increases for highly shaped plasmas and fast evolution of plasma parameters.

The plasma shape and the plasma current evolution during the discharge strongly depend on the plasma heat and particle transport. The ASTRA-SPIDER code allows to develop a scenario of control coil currents self consistently with the plasma transport. The inverse problem of the control coil currents determination is solved by means of the SPIDER code [4] and the following algorithm on the development of the plasma evolution scenario is implemented: (1) setting the evolution of the plasma boundary; (2) simulation of the transport problem in the fixed boundary mode; (3) solution of the inverse problem of determining the currents in the control coils for chosen time slices; (4) the calculation of the direct problem with a free boundary equilibrium with a given evolution of currents in the control coils. Currents in the passive structures and in the chamber are calculated. The artificial controller for vertical plasma stabilization in a free boundary case is implemented to fix the plasma in a vertical position.

As an application of the modified 1.5D solver we demonstrate free boundary simulations of plasma evolution with increasing elongation in the tokamak ST40 [5]. Plasma density, temperature and current density evolution is simulated with the coupled transport and equilibrium code consistently with the free boundary plasma shape change. The development of the plasma evolution scenario according to the proposed algorithm was provided in the following way. The initial stage of this scenario was taken to correspond to the condition reached in experiment after the merging compression start scenario [5] with B_0=0.7T, $\langle n_e \rangle = 10^{20}\mathrm{m}^{-3}$, $T_e(0)$=200eV, k=1.1, a=13cm, R_0=31cm. For this geometry we set I_{pl}=100kA that is little less than one was reached in the experiment in order to provide q-value at the edge around 3. The time evolution of the geometry parameters was prescribed (step (1)), the fixed boundary evolution scenario was calculated consistently with the heat transport and OH heating with prescribed electron density and plasma current (step (2)) and the inverse problem of coil current determination was solved at time moments 10ms and 50ms (step (3)). The plasma

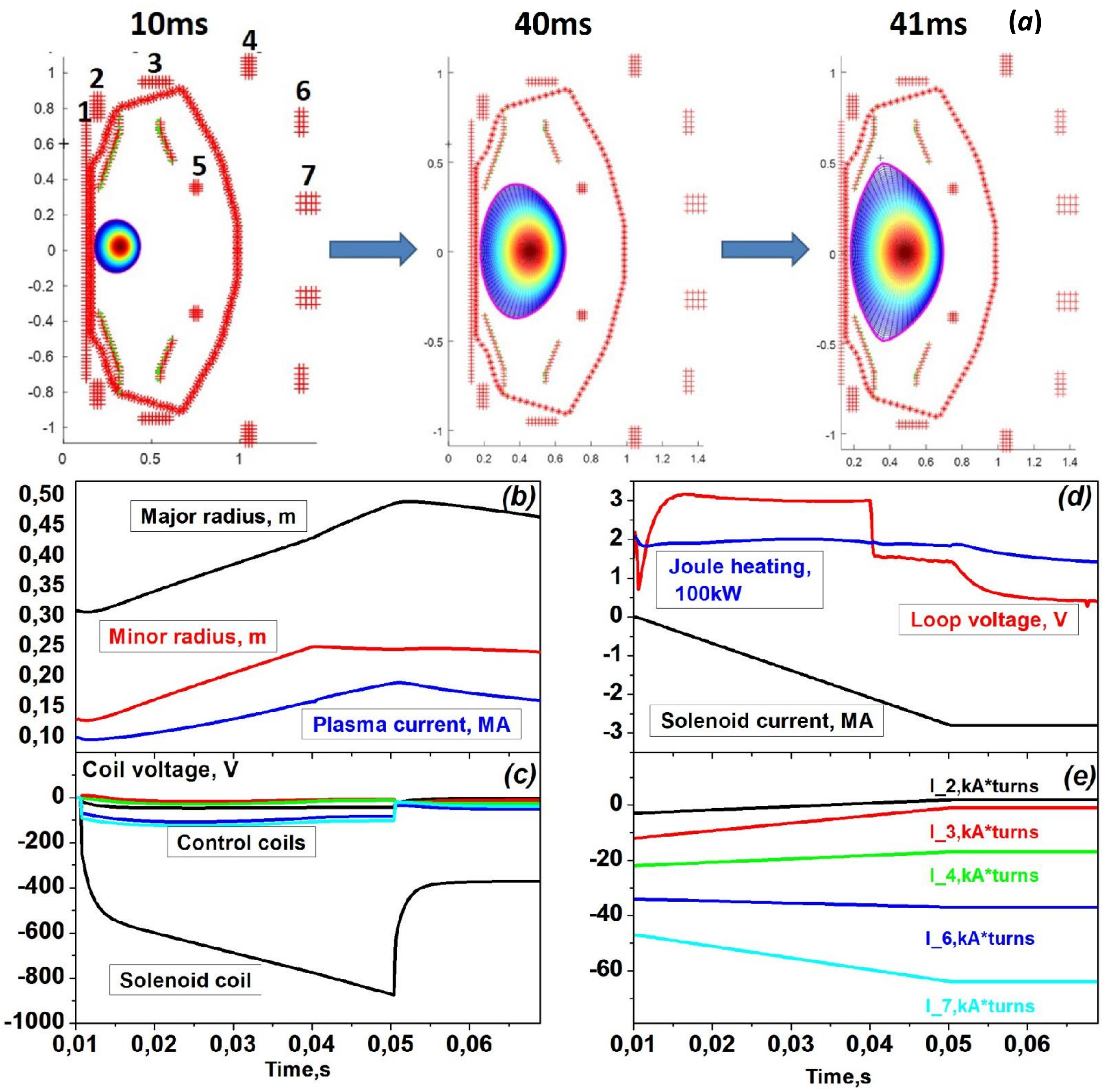

Fig.1 Plasma shape evolution and transition from the limiter to the separatrix configuration (*a*), the temporal evolution of plasma parameters *(b),(d)*, control coil and solenoid voltages (*c*) and control coil currents (*e*) in calculations with $\tau_E = \tau_E^{neo\text{-}Alcator}$. Solenoid current (*d*) and control coil currents I_2 – I_7 (e) correspond to numbers of coils in (*a*) 10ms, I_5=0 (not shown).

parameters evolution for ST40 device calculated with the energy confinement time prescribed by the neo-Alcator scaling law [6] for OH plasma is shown in figure 1. It is obtained that the plasma current and volume rise is impossible without the poloidal flux source from the solenoid coil 1. The control coils 2-7 determine mainly the plasma position and the size except the merging compression coil 5 which is switched off in this scenario. The control coil voltages are in the reasonable ranges. The separatrix configuration is formed at the time 40ms causing the loop voltage drop. However the plasma current and electron temperature continue to rise after the transition to the separatrix configuration and the plasma current reaches 200kA at the end of the solenoid stage.

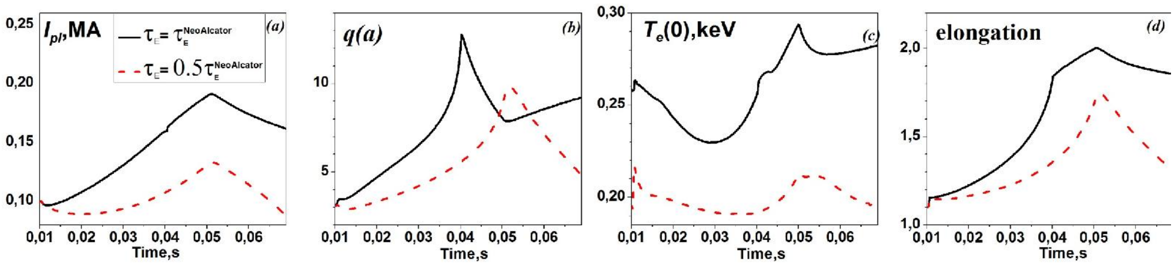

Fig.2 The evolution of plasma current (a), the safety factor at the flux surface with Ψ_{95}=0.95 Ψ_{sep} (b) the electron temperature on the axis (c) and the plasma elongation (d) in calculations with the same coil currents evolution but different energy confinement time τ_E : $\tau_E = \tau_E^{neo\text{-}Alcator}$ (solid) and $\tau_E = 0.5\tau_E^{neo\text{-}Alcator}$ (dash).

The plasma current and the elongation evolution depends strongly on the electron temperature as it is shown in figure 2. The temperature decrease up to 20% results in the decrease of these parameters and can cause an unstable plasma configuration q_a<3 at the beginning of the solenoid stage.

Summary.

The paper presents the modification of the code ASTRA+SPIDER: the use of algorithm of calculation of diffusion of the magnetic field, implemented in the SPIDER code, to calculate scenarios of the evolution of the plasma in the code ASTRA; the implementation of the inverse problem the determination of currents in the control coils. The SPIDER code algorithm is used to develop a current scenario in the control coils for a given or calculated evolution of plasma parameters, including the shape of the plasma column. The plasma shape evolution scenario with the rise of plasma elongation is developed for ST40 tokamak using modified ASTRA-SPIDER code.

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