Progress in ASTRA-B2SOLPS coupling for integrated tokamak modeling

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Analysis of existing tokamak experiments and designing of new devices requires integrated modeling of all relevant phenomena in the core and the edge plasmas simultaneously. The important part of such a modeling is the coupling of core and edge transport codes, since processes in the tokamak edge define 'boundary conditions' for core plasma, and therefore may affect core profiles and tokamak regimes.

Recently a possibility of core (ASTRA [1]) and edge (B2SOLPS 5.2 [2]) codes coupling was reported in [3]. The distinguishing feature of this coupling scheme is a presence of an overlap region of the core and the edge computational domains (Fig. 1). The outer boundary of 1D core domain is choosen to be situated at the position of pedestal, the inner boundary of 2D edge domain is 3-5 cm deeper, so the most of wall neutrals ionize before reaching this boundary.

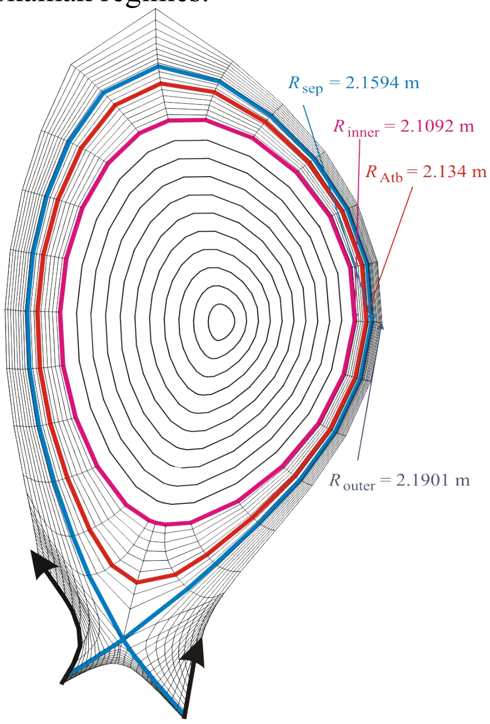

Figure 1. Computational domains for ASTRA and B2SOLPS codes. Blue line represent a separatrix, red one – outer boundary of ASTRA domain, magenta one – inner boundary of B2SOLPS domain.

To make the transport equations in two codes exactly the same (in spite of the flux surfaces shapes may be different) they were expressed through the same independent variable R_{out} - the major radius at equatorial midplane at low field side – and then the correction to metric coefficients caused by different flux surface shapes were introduced into ASTRA equations. For example, the stationary particle balance equation of B2 code reads

$$\frac{\partial \Gamma_{eB}^{tot}}{\partial R_{out}} = \frac{\partial V_B}{\partial R_{out}} \langle S_B \rangle ,$$

where Γ_{eB}^{tot} is a total electron flux through the flux surface, V_B is a volume inside this surface, $\langle S_B \rangle$ is the flux surface averaged electron source (per unit volume). The subscript index *B* means that this equation is from B2 code. Similar equation

$$\frac{\partial \Gamma_{eA}^{tot}}{\partial R_{out}} = \frac{\partial V_A}{\partial R_{out}} S_A ,$$

is solved in ASTRA code. The notations have same meaning, but the subscript index *A* denotes that this equation is from ASTRA code. Evidently, total fluxes would coincide (being considered as functions of R_{out}) if the electron source in the ASTRA code is related to one from B2 code according to

$$S_A = \left(\langle S_B \rangle \frac{\partial V_B}{\partial R_{out}} \right) / \left(\frac{\partial V_A}{\partial R_{out}} \right) = \left(\int \sqrt{g}\, S_B \, dx\, dz \cdot \frac{\partial y}{\partial R_{out}} \right) / \left(\frac{\partial V_A}{\partial R_{out}} \right) .$$

Total fluxes are defined in following way:

$$\Gamma_{eA}^{tot}=\frac{\partial V_A}{\partial \rho}\langle(\nabla\rho)^2\rangle\left(-D_A\frac{\partial n_e}{\partial \rho}+u_A n_e\right); \qquad \Gamma_{eB}^{tot}=\int\frac{\sqrt{g}}{h_y}\left(-D_B\frac{\partial n_e}{h_y\partial y}+u_B n_e\right)dxdz\ ,$$

where ρ is an effective minor radius (proportional to square root of toroidal flux), which is used in ASTRA as radial coordinate. These fluxes are the same $\Gamma_{eA}^{tot}(R_{out})=\Gamma_{eB}^{tot}(R_{out})$, if

$$D_A=\frac{\int\frac{\sqrt{g}D_B}{h_y^2}dxdz\cdot\frac{\partial R_{out}}{\partial y}}{\frac{\partial R_{out}}{\partial \rho}\frac{\partial V_A}{\partial \rho}\langle(\nabla\rho)^2\rangle}; \qquad u_A=\frac{\int\frac{\sqrt{g}u_B}{h_y}dxdz}{\frac{\partial V_A}{\partial \rho}\langle(\nabla\rho)^2\rangle};$$

These relation are written as correction to transport coefficients only because it is a convenient way to introduce the metric corrections into the ASTRA equations.

Similar correction should be done for coefficients standing by electrons and ions heat diffusivities in ASTRA heat balance equations:

$$\chi_{eA}=\frac{\int\frac{\sqrt{g}\chi_{eB}}{h_y^2}dxdz\cdot\frac{\partial R_{out}}{\partial y}}{\frac{\partial R_{out}}{\partial \rho}\frac{\partial V_A}{\partial \rho}\langle(\nabla\rho)^2\rangle}; \qquad \chi_{iA}=\frac{\int\frac{\sqrt{g}\chi_{iB}}{h_y^2}dxdz\cdot\frac{\partial R_{out}}{\partial y}}{\frac{\partial R_{out}}{\partial \rho}\frac{\partial V_A}{\partial \rho}\langle(\nabla\rho)^2\rangle};$$

No correction to metric coefficients standing by convective heat fluxes is necessary. The correction is done for all flux surfaces from magnetic axis up to the separatrix.

Consequently, the core and the edge density and temperature profiles, heat and particle fluxes calculated with each of the codes should coincide in the overlap region. This is achieved by running two codes one after another in an iterative manner, while output profiles of one code are used to set boundary conditions for the other one.

In the B2SOLPS 5.2 code the full model of drifts and currents is used, which allows to calculate radial electric field. For modeling of the neutrals the Monte-Carlo EIRENE [4] code runs as a subroutine called from B2SOLPS5.2. Thus the neutrals distribution is calculated in 2D code, while ASTRA accepts electron source in the overlap region. Deeper in the core the electron source is extrapolated exponentially keepeing the particle balance.

In a similar way the codes NCLASS [5] and NUBEAM [6] are coupled to ASTRA in order to calculate neoclassical transport coefficients and heating power due to NBI respectively, thus providing a correct distribution of the power between electron and ion channels. The neoclassical ion heat conductivity calculated by NCLASS is then used in the B2SOLPS transport equations to rescale Luciani flux limiting.

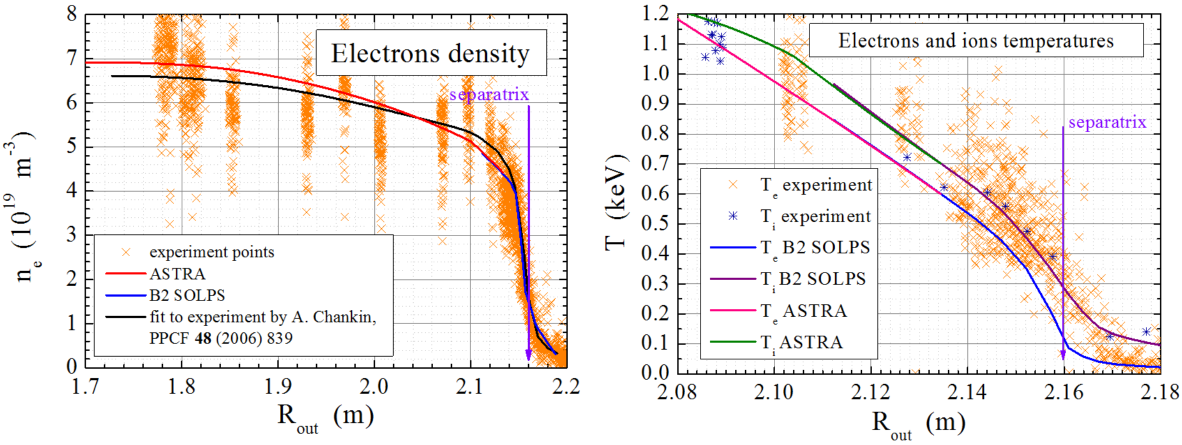

Figure 2. Calculated density and temperature profiles at equatorial midplane in AUG.

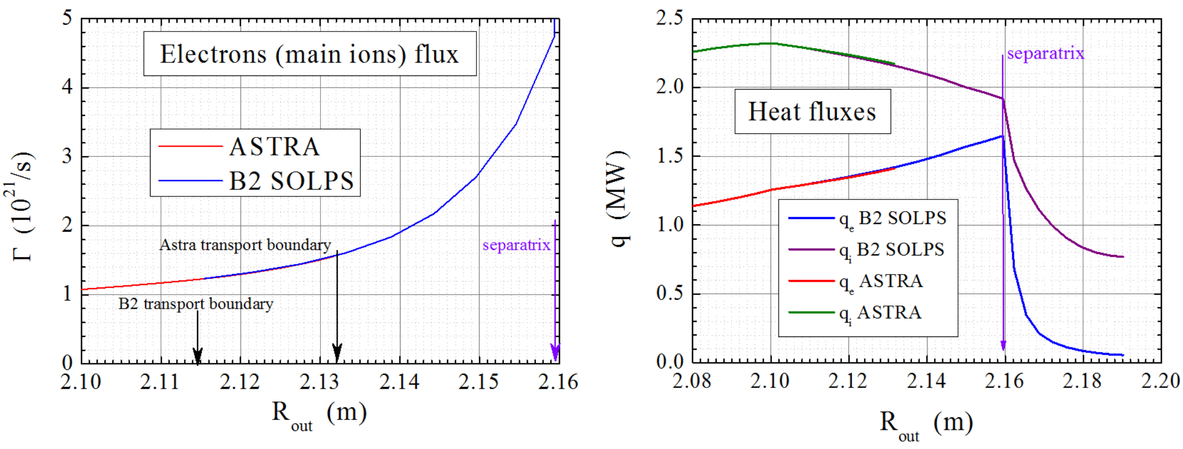

Figure 3. Calculated total particle and energy fluxes through flux surface in AUG.

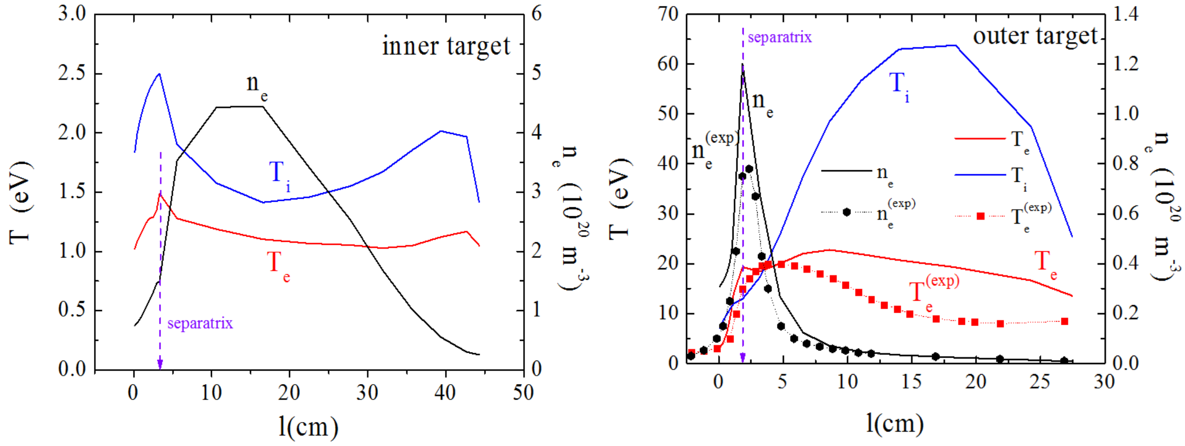

Figure 4. Temperature and density profiles at targets calculated for ASDEX-Upgrade. Distance is measured along plates in poloidal direction as shown by black arrows in Fig. 1.

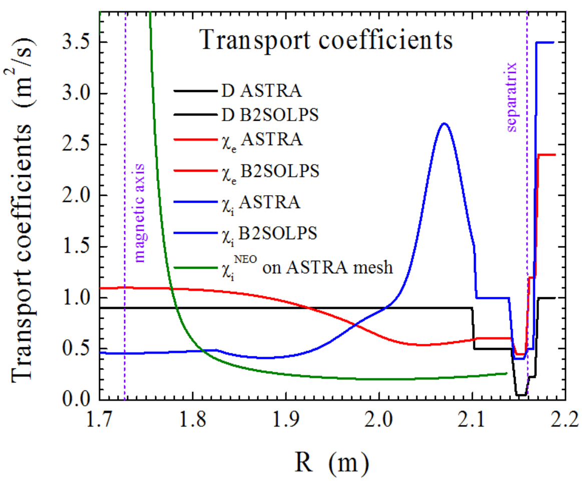

Figure 5. Transport coefficients used in calculations for ASDEX Upgrade.

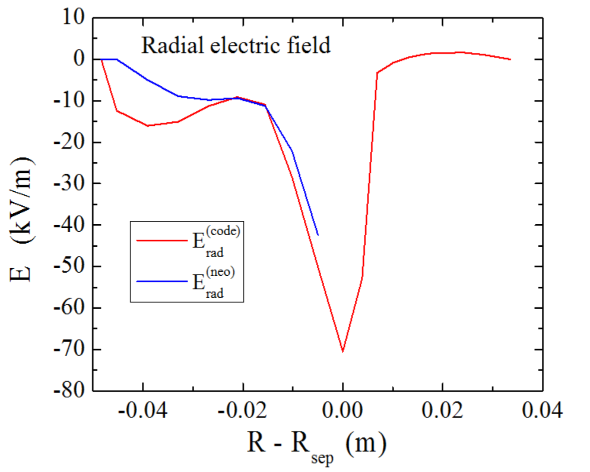

Figure 6. Radial electric field at equatorial midplane and neoclassical formula for AUG.

The boundary condition for B2SOLPS is that total flux of electrons and neutrals at inner boundary is equal to net NBI electrons source in the core $\Gamma_{eB}^{tot} + \Gamma_{NB}^{tot} = \int S_{eA}^{(NBI)} dV$

Transport coefficients are fitted to obtain the best fit to experimental density and temperature profiles – no self-consitent subroutine to calculate them is used at present.

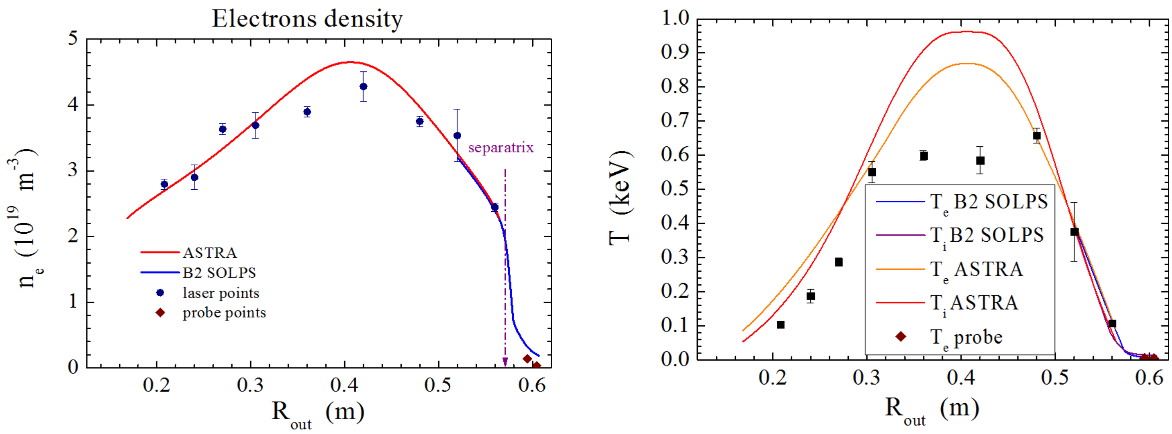

Figure 7. Resulting density and temperature profiles for Globus-M shot #29076.

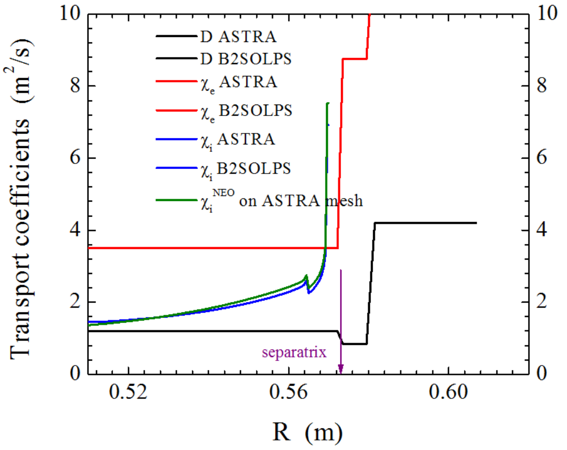

Figure 8. Transport coefficients used in calculations for Globus-M shot #29076.

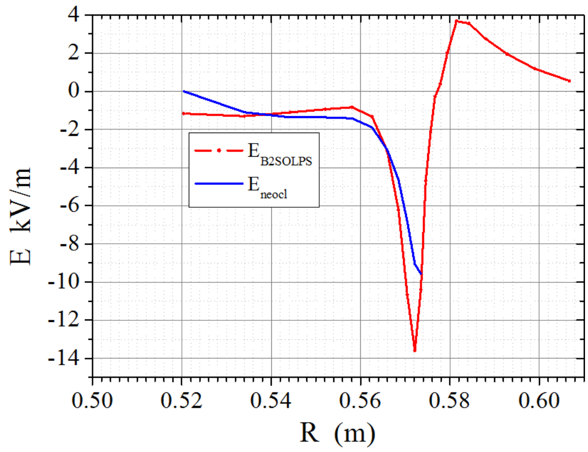

Figure 9. Radial electric field at equatorial midplane and result of neoclassical formula for Globus-M shot #29076.

Modeling was performed for H-mode NBI-heated shots of ASDEX Upgrade (shot #17151) and spherical tokamak Globus-M (shot #29076). The results for ASDEX Upgrade are shown in Figs 2-6, and for Globus-M – in Figs 7-9. One can see that indeed density and temperature profiles together with particle and heat fluxes profiles are continuous from the magnetic axis to the wide SOL.

Thus created is a tool for integrated tokamak modeling, which is based on core and edge transport codes coupling and which alows to calculate all the profiles for given transport coefficients.

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