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Predictive transport modeling for the W7-X

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INTRODUCTION: One of the optimization criteria for the stellarator W7-X is the minimization of the bootstrap current [1], which is not needed for producing the magnetic field in W7-X and must be compensated. The plasma current alters the rotational transform and affects the magnetic configuration, especially near the edge area of plasma. Due to plasma current the last closed magnetic surface (LCMS), X-points, and islands change their spatial position. A simple estimation gives the following value of maximum displacement: dZ[cm] ~ $0.42 I_P$[kA]. This represents a potential danger for the island divertor [2] used in W7-X, because the typical distance of target plates from LCMS is about 10cm. Preliminary calculations have shown that a tolerable value of current is about 10kA, while the maximum value of the bootstrap current for the expected plasma parameters of W7-X varies from 10kA to 40kA, depending on the magnetic configuration used. W7-X is not equipped with an Ohmic transformer, so the only means for compensating this current is electron cyclotron current drive (ECCD) and/or neutral beam current drive (NBCD). In this report we study the compensation of residual bootstrap current by using ECCD.

METHOD: To model the control of the toroidal current we use a predictive 1D transport code, which is under development. The transport code is based on a system of equations, which consists of particle and power balance equations augmented by diffusion equations for the radial electric field and the toroidal current density:

$$\begin{aligned}
&\frac{\partial n_e}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho} V'\Gamma_e = S_P, \\
&\frac{3}{2}\frac{\partial n_e T_e}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho} V'Q_e = P_e - \Gamma_e E_r, \quad \frac{3}{2}\frac{\partial n_i T_i}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho} V'Q_i = P_i + z_i \Gamma_i E_r, \\
&\varepsilon_0 \frac{c^2}{V_a^2}\left(1 + \frac{2}{\iota^2}\right)\frac{\partial E_r}{\partial t} - \frac{1}{V'}\frac{\partial}{\partial \rho} V' D_E\left(E_r' - \frac{E_r}{\rho}\right) = |e|\left(\Gamma_e - z_i \Gamma_i\right), \\
&\frac{\sigma}{2\pi R_0}\frac{\partial}{\partial t}\psi_p - \frac{1}{2\pi R_0 \mu_0}\frac{1}{V'}\frac{\partial}{\partial \rho} V' \frac{\partial}{\partial \rho}\psi_p = j_{bs} + j_{cd},
\end{aligned} \tag{1}$$

The neoclassical fluxes Γ_a and bootstrap current j_{bs} in Eq. (1), are given by

$$\Gamma_\alpha = -n_\alpha\left[D_{11}^\alpha\left(n_\alpha'/n_\alpha - z_\alpha E_r/T_\alpha\right) + D_{12}^\alpha T_\alpha'/T_\alpha\right],$$

$$j_{bs}^\alpha = -|e z_\alpha|\, n_\alpha\left[D_{31}^\alpha\left(n_\alpha'/n_\alpha - z_\alpha E_r/T_\alpha\right) + D_{32}^\alpha T_\alpha'/T_\alpha\right], \; j_{bs} = \sum_\alpha j_{bs}^\alpha, \quad \alpha = e,i$$

where n_α, T_α and Z_α are the density, temperature and charge number of electrons or ions, the prime denotes the partial derivative with respect to the effective radius ρ. For evaluation of the transport coefficients D^α_{jk} and the parallel conductivity σ we use a data-base precomputed by applying the DKES-code [3] and results from an international collaboration on neoclassical transport in stellarators [4]. Boundary conditions for the poloidal flux (the last equation of (l)) are the following:

$$\text{Center)}\ \ I(\rho=0,t)=0\ \Rightarrow\ \left.\frac{\partial\psi}{\partial\rho}\right|_{\rho=0}=0;\quad \text{Edge)}\ \ \psi(a,t)=L\ I(a,t)\ \Rightarrow\ \left.\frac{a}{\psi}\frac{\partial\psi}{\partial\rho}\right|_{\rho=a}=-\frac{R_0\mu_0}{L},$$

where $L=R_0\mu_0\left(\ln\left(8R_0/a\right)-2+0.25\mu\right)\approx 19\mu H$ is the plasma inductance.

RESULTS: In our simulation we determine the radial electric field, neoclassical fluxes, bootstrap currents, and parallel conductivity self–consistently, while the density and temperatures are kept fixed. Before studying of the plasma response to ECCD we equilibrate system (1) to steady state without applying ECCD. Then we ‘turn on’ the counter-ECCD with total value of 15kA. The prescribed current distribution $j_{eccd}\propto\exp\left(-(\rho-\rho_c)^2/w^2\right)$ is used for modeling of ECCD. In Figure 1 the expected density and temperatures for the electron cyclotron resonance heating (ECRH) scenario along with the calculated radial electric field are shown. The electric field has a positive solution (electron root) in the central part. This behavior of the electric field is typical for such temperature profiles.

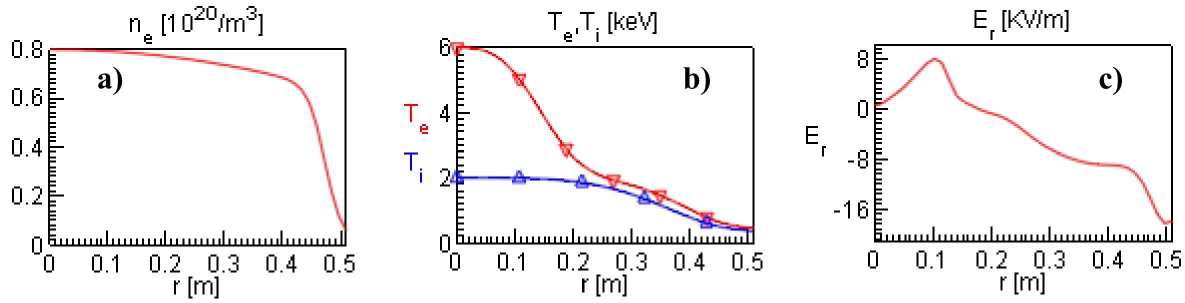

Figure 1: Plasma profiles: a) the electron density; b) the electron (∇) and ion (Δ) temperatures; c) the radial electric field.

The parallel conductivity, bootstrap current distributions and counter-ECCD used are shown on Figure 2. After switching on of ECCD the loop voltage arises. The radial dependencies of the loop voltage are shown on Figure 2c for several times: in 0.2sec, in 2sec, and in 25sec after applying ECCD. The diffusion time of the loop voltage (‘skin time’ – time needed for the loop voltage to reach the plasma edge) is about 2sec, $a^2\sigma\mu_0$ is a rough estimation of this time. The relaxation time of the toroidal current is longer than the ‘skin time’. The total toroidal current reaches steady state after 100 seconds with the decay time $L/R\approx 19\,\mathrm{sec}$, see

Figure 3a. Initial and final current distributions and associated rotational transforms are shown on Figure 3b and 3c. For calculating the rotational transform we use the formulas [5]:

$$\iota = \frac{\mu_0 I_{tor}}{S_{11}\Phi'} - \frac{S_{12}}{S_{11}}, \quad S_{jk} = \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}\frac{g_{jk}}{g}\sqrt{g}\, d\theta\, d\varphi$$, where g_{jk} is the metric tensor elements.

This approach allows us to describe the current free part $\iota_{CF} = -S_{12}/S_{11}$ of the rotational transform in a transparent way [5]. We also use the fact that the susceptance matrix S and current-free contribution to the rotational transform have a weak dependence on current [5].

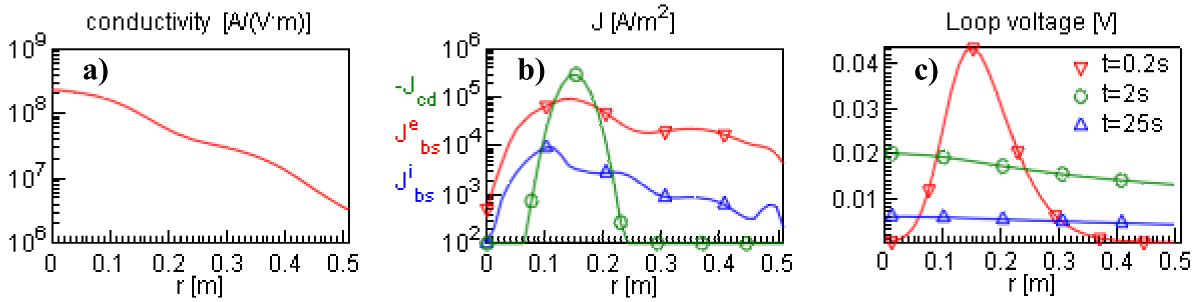

Figure 2: a) plasma conductivity; b) the electron (∇) and ion (Δ) bootstrap current densities, ECCD (O) density; c) time evolution of the loop voltage.

The bootstrap current (curve marked by ∇ on Figure3b) increases the edge value of the rotational transform; rotational transform going to 1 at the edge area (∇-curve on Figure3c) means that the X-point and islands move inward. This represents a potential danger for the proper functioning of the island divertor used in W7-X. Counter-ECCD compensates the bootstrap current and decreases the edge value of the rotational transform, while in the bulk plasma the shear of the rotational transform changes sign due to highly localized ECCD (Δ-curve on Figure3c).

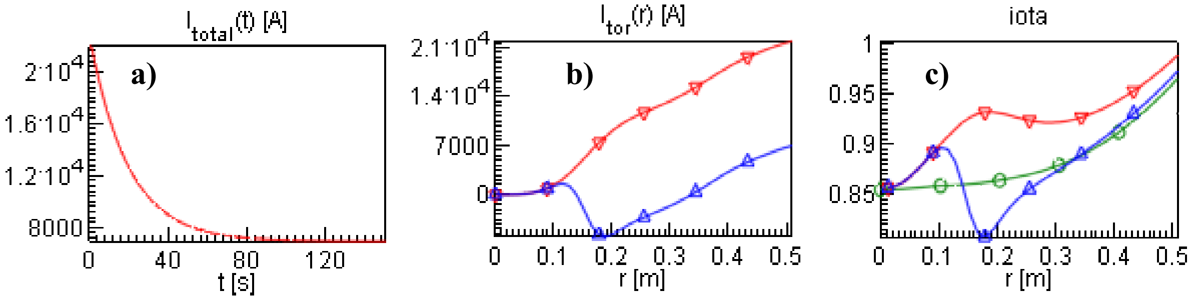

Figure 3: a) time evolution of total current; b) the initial (∇) and final (Δ) toroidal current distributions; c) the initial (∇), final (Δ), and current free (O) rotational transform.

Let us consider the case of the on-axis current drive. We use the same plasma profiles and total value of ECCD as in previous case. Results of the simulation are shown on Figure 4. On-axis localization of ECCD leads to a strong decrease of the rotational transform in the central region of plasma, whereas the edge ι-value is the same as in the case of off-axis

ECCD, see Δ-marked curve on Figure 4c. The central part of plasma can be treated as a region with the strong mixing due to the large deviation of particle orbits from the flux surfaces [6]. More comprehensive analysis is needed to study this problem including MHD equilibrium calculation.

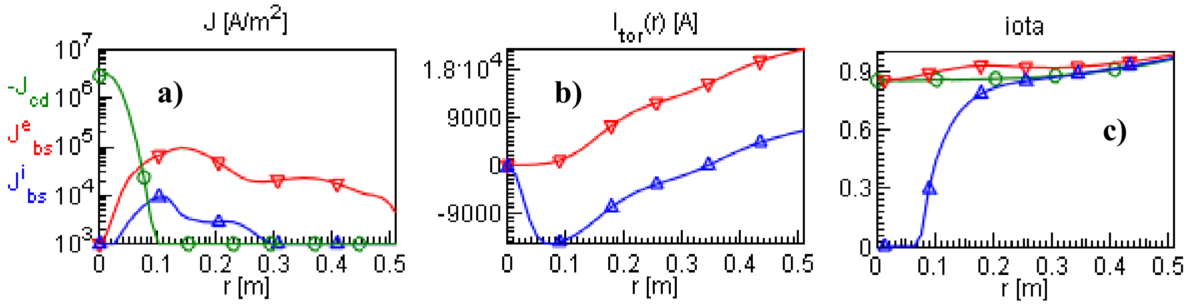

Figure 4: a) the electron (∇) and ion (Δ) bootstrap current densities, ECCD (O) density; b) the initial (∇) and final (Δ) toroidal current distributions; c) the initial (∇), final (Δ), and current free (O) rotational transform.

SUMMARY: In the present work we have performed computer simulations of the compensation of the bootstrap current by means of ECCD. The usage of ECCD and/or NBCD [7] provides a flexible manner to control the current profile and to compensate the residual bootstrap current. It is worth noting that NBCD will only be available during 10sec at an early stage of W7-X operation, a period much shorter than the relaxation time of the current. Thus, the only means to control the bootstrap current at the initial stage of the experimental campaign will be the usage of ECCD. Here we have studied the current evolution in W7-X using modeling with densities and temperatures fixed. Our near-future plan is to include in the transport simulation a beam-tracing code and to study the electron cyclotron resonance heating and current evolution self-consistently with power balance equations enabled.

REFERENCES

[1] C.D Beidler et al. *Fusion Technology* **17,** 148(1990).

[2] R. König et al. *Plasma Phys. Control. Fusion* **44,** 2365(2002).

[3] W.I. van Rij and S.P. Hirshman, *Phys. Fluids* B 1 563(1989).

[4] C.D. Beidler et al. *30th EPS Conference on Plasma Phys*., ECA Vol. **27A**, P-3.2(2003)

[5] P.I. Strand and W.A. Houlberg.. *Physics of Plasmas*. **8,** 2782(2001).

[6] J. Geiger, H. Maassberg, N.B.Marushchenko, M.Rome, *this conference,* P1-207.

[7] M. Schmidt and A. Werner. *this conference*, P1-200.