Transport Modeling for W7-X
on the Basis of W7-AS Experimental Results

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Introduction

- High-performance discharges \( n(0) \geq 5 \times 10^{19} \text{ m}^{-3}, \ T \geq 1 \text{ keV} \) in W7-AS were well described by neoclassical theory.
- Although \( B \) chosen to reduce neoclassical losses in W7-X, their strong temperature dependence remains unchanged.
- ECRH power deposition and current drive (ECCD) in W7-AS discharges conformed to theoretical predictions.
- High-temperature discharges in W7-X should allow O2 heating (relevant for high-density operation).
Outline

- Brief review of relevant W7-AS results
- Numerical tools employed
- W7-X configurations and their properties
- Scenarios and results of transport modeling
- Summary and outlook
shot 34313: 680 kW NBI, 750 kW ECRH absorbed power

neoclassical ion and electron fluxes compared to fluxes from particle and energy balance
\( \chi_{an}^e \propto n^{-1} \) in edge region —
same dependence as found in
the neoclassical \( 1/\nu \) regime

\[ \Rightarrow \tau_E \propto n \]

In contrast, ISS04 scaling has

\[ \tau_{\text{ISS04}} \propto n^{0.54} \]
W7-AS: ECCD Compared to Predictions of Linear Theory

\[ n^e = 2.5 \times 10^{19} \text{ m}^{-3} \]

ECCD launch-angle scans in \( \epsilon = 0.35 \) configuration of W7-AS
The predictive 1-D transport code used (Yu. Turkin, et al.) solves the system of equations

\[ \frac{3}{2} \frac{\partial}{\partial t} (n^\alpha T^\alpha) + \frac{1}{V'} \frac{\partial}{\partial r} (V'Q^\alpha) = P^\alpha + q^\alpha \Gamma^\alpha E_r \]  \[ \alpha = e, i \]

\[ \frac{1}{V'} \frac{\partial}{\partial r} \left( V' r D_E \frac{\partial}{\partial r} \left( \frac{E_r}{r} \right) \right) - \epsilon_0 \left( \frac{c}{v_a} \right)^2 \left( 1 + \frac{b_{1,0}^2}{\epsilon_i^2} \right) \frac{\partial E_r}{\partial t} = \sum_{\alpha} q^\alpha \Gamma^\alpha \]

\[ \sigma \frac{\partial \psi_p}{\partial t} - \frac{1}{\mu_0} \frac{1}{V'} \frac{\partial}{\partial r} \left( V' \frac{\partial \psi_p}{\partial r} \right) = 2\pi R_0 \left( J_{bs} + J_{cd} + J_{ohm} \right) \]

\[ \Gamma^\alpha = \Gamma_{neo}^\alpha - D_{an} \frac{\partial n^\alpha}{\partial r} \]

\[ Q^\alpha = Q_{neo}^\alpha - \chi_{an} n^\alpha \frac{\partial T^\alpha}{\partial r} - \frac{5}{2} D_{an} T^\alpha \frac{\partial n^\alpha}{\partial r} \]
Ray Tracing With TRAVIS

The ray-tracing code TRAVIS (N. B. Marushchenko, et al.):

- calculates ray trajectory accounting for anomalous dispersion,
- calculates absorption in the fully relativistic approach,
- accounts for parallel electron momentum conservation (ECCD),
- can separate the trapped- and passing-electron contributions to macroscopic quantities it determines,
- allows for multiple-ray and multiple-pass scenarios,
- is user-friendly with extensive graphical interface,
- loads $B$ from “magnetic configuration” library,
- operates stand-alone or coupled to the transport code.
Relevant W7-X Characteristics – Dependence on $b_{01}$ and $\beta$
Off-Axis X2 for $\langle \beta \rangle = 2\%$ W7-X Standard Configuration

\[ I_{bs} = 75 \text{ kA} \quad I_{cd} = -88 \text{ kA} \quad \langle \beta \rangle = 2.70\% \]
$I_{bs} = 6 \text{ kA}$

$I_{cd} = -48 \text{ kA}$

$< \beta >= 2.40 \%$

Small ECCD sufficient to balance $I_{bs}$ in High-Mirror Configuration
... and the Underlying Transport Coefficients

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Transport coefficients for W7-X.}
\end{figure}
$I_{bs} + I_{cd} \approx 0$ realistic for all W7-X configurations heated using 10 MW ECRH in X2 mode.

- Off-axis heating preferable $\rightarrow$ avoid $t \approx 0$ near plasma center $\rightarrow$ avoid electron root (high-mirror).

- Confinement improves with increasing $\beta$ (low-mirror?)
Launch Geometry for the O2 Mode

all distances in meters
ECCD and Bootstrap Current for O2 Launch Geometry, 5 MW

\[ \mathbf{l}_{\text{eccd}}, \mathbf{l}_{\text{bc}}, \text{ kA} \]

\[ n_e / 10^{20}, \text{ m}^{-3} \]
On-Axis O2 for $<\beta> = 4\%$ W7-X Standard Configuration

- $I_{bs} = 82$ kA
- $P_{abs} = 9.75$ MW
- $<\beta> = 4.13\%$
Summary — Outlook

- ECCD compensation of the bootstrap current is possible for all X2 scenarios.
- ECCD becomes marginal for O2 conditions → Bootstrap current contribution to $t$ must be factored into discharge scenario.
- Refinements → modeling of $t \approx 0$ regions; correction of neo-classical transport coefficients for conservation of momentum.
- Carry out free-boundary VMEC runs including internal current densities determined in simulations → extend field to vacuum region to model effects on divertor strike points.
- Develop plausible discharge scenarios.
**Scalings of \(1/\nu\) Transport with Dimensional Examples**

\(1/\nu\) transport scales as:

\[
D_{1/\nu} \propto \frac{\epsilon_{\text{eff}}^{3/2} T^{7/2}}{n R_0^2 B_0^2}
\]

Parameters for which \(\chi_{\text{neo}}^e > 1 \text{ m}^2/\text{s} \) at \(r/a = 0.5\)

<table>
<thead>
<tr>
<th>(n \times 10^{20} \text{ m}^{-3})</th>
<th>W7-AS</th>
<th>W7-X</th>
<th>“classical” W7-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.90 keV</td>
<td>3.50 keV</td>
<td>1.35 keV</td>
</tr>
<tr>
<td>0.4</td>
<td>1.25 keV</td>
<td>5.20 keV</td>
<td>2.00 keV</td>
</tr>
<tr>
<td>1.0</td>
<td>1.60 keV</td>
<td>6.70 keV</td>
<td>2.50 keV</td>
</tr>
</tbody>
</table>

where possible effects due to \(E_r\) have been ignored.
shot 34609: 830 kW NBI, 330 kW ECRH absorbed power

neoclassical ion and electron fluxes compared to fluxes from particle and energy balance