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

C.D. Beidler, J. Geiger, H. Maaßberg

N.B. Marushchenko, Yu. Turkin, W7-AS Team

Max-Planck-Institut für Plasmaphysik

IPP–EURATOM Association

Greifswald, GERMANY

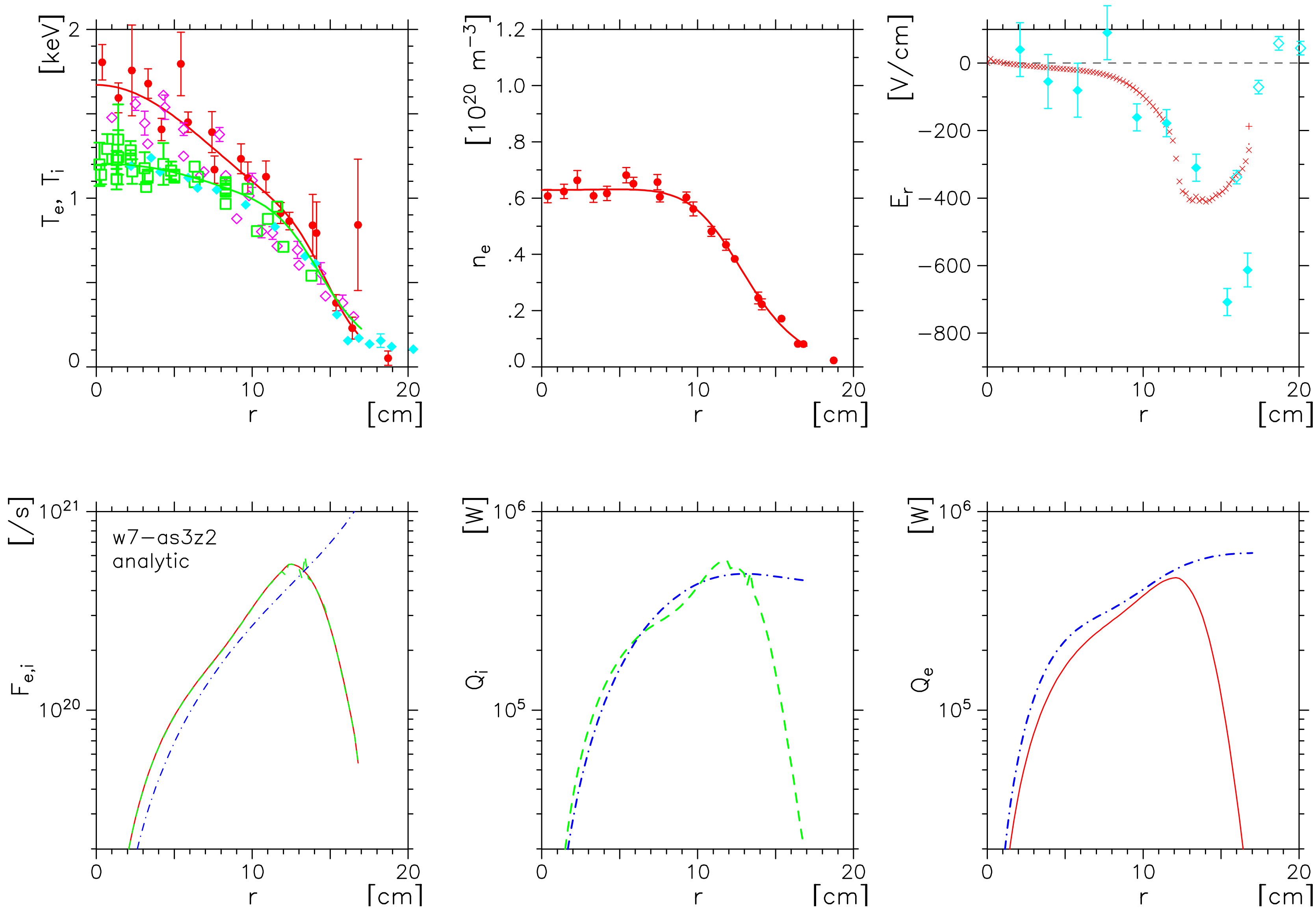
Introduction

- High-performance discharges ($n(0) \geq 5 \times 10^{19}$ m^{-3}, $T \geq 1$ 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

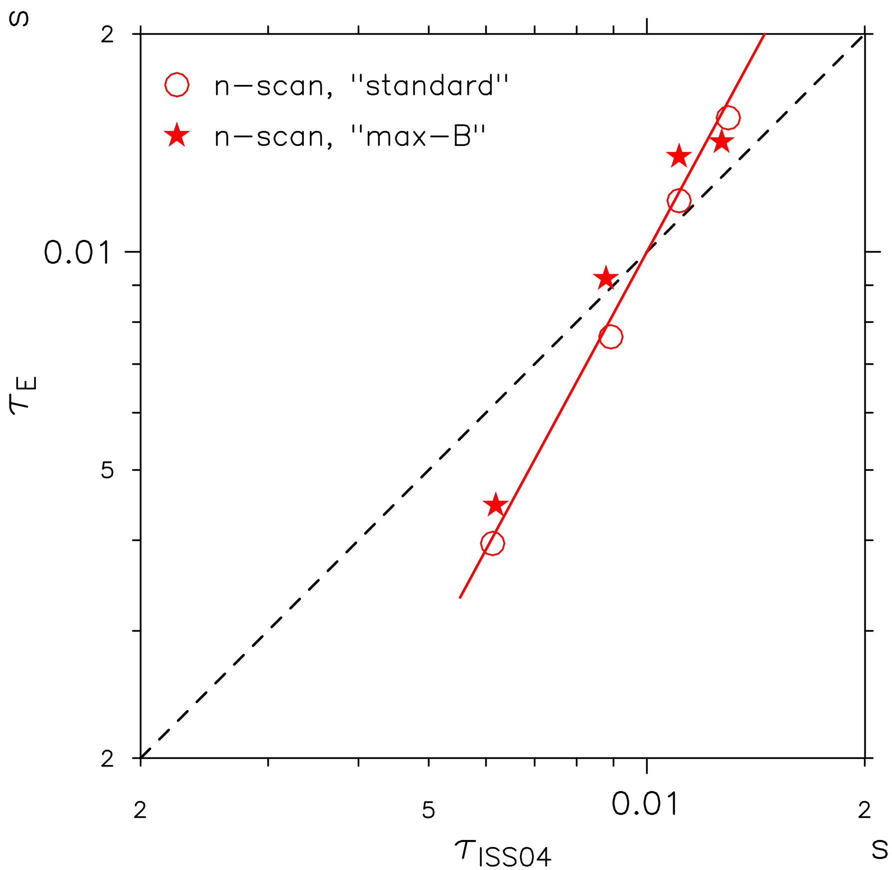
- Brief review of relevant W7-AS results
- Numerical tools employed
- W7-X configurations and their properties
- Scenarios and results of transport modeling
- Summary and outlook

shot 34313: 680 kW NBI, 750 kW ECRH absorbed power



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

W7-AS: τ_E Scaling With n for 1.2 MW ECRH Discharges



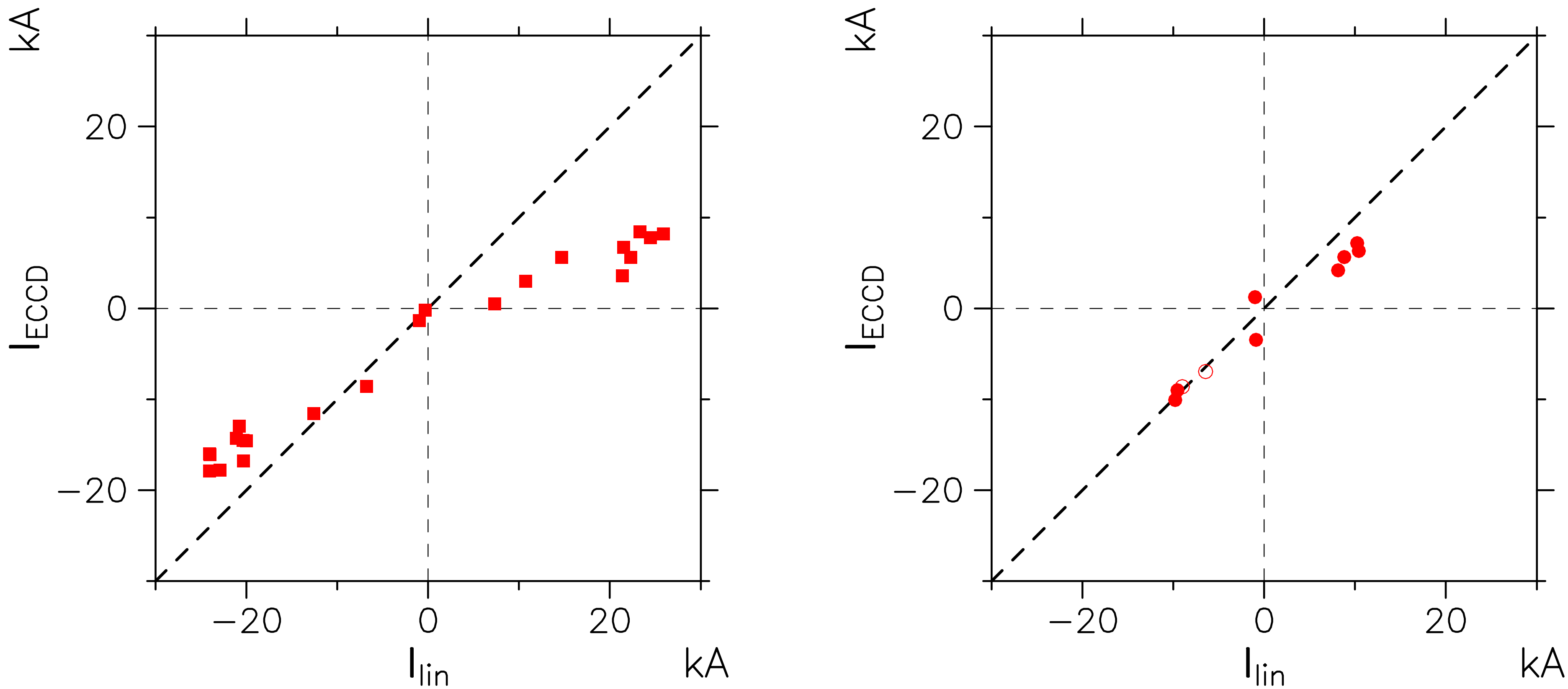
$\chi_{an}^{e} \propto n^{-1}$ in edge region — same dependence as found in the neoclassical $1/\nu$ regime

$$\Rightarrow \tau_E \propto n$$

In contrast, ISS04 scaling has

$$\tau_E^{ISS04} \propto n^{0.54}$$

W7-AS: ECCD Compared to Predictions of Linear Theory



$n^e = 2.5 \times 10^{19}\,\mathrm{m}^{-3}$ $n^e = 6.0 \times 10^{19}\,\mathrm{m}^{-3}$

ECCD launch-angle scans in $\iota = 0.35$ configuration of W7-AS

Predictive Transport Simulations for W7-X

The predictive 1-D transport code used (Yu. Turkin, *et al.*) solves the system of equations

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

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

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

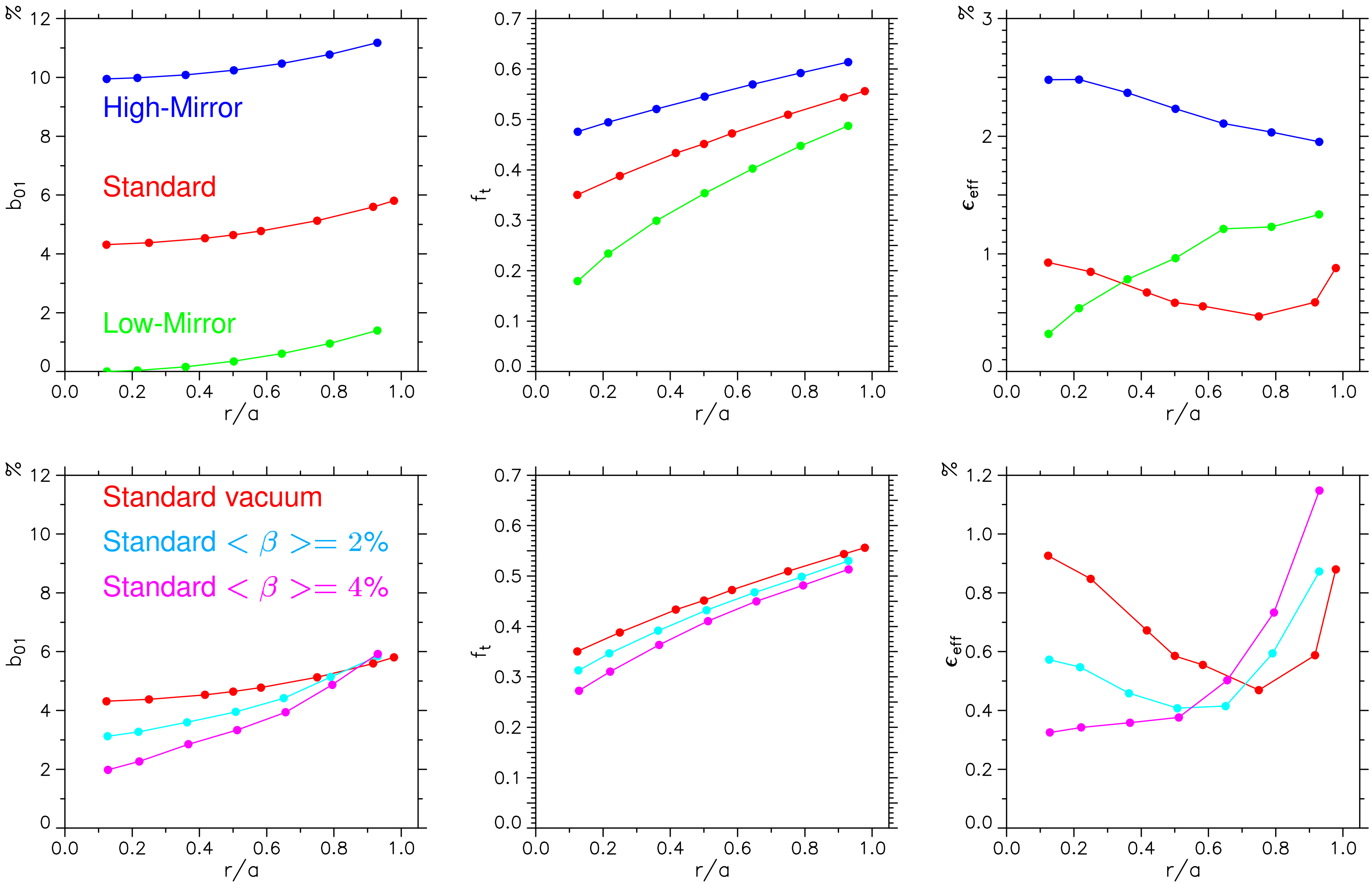
$$\Gamma^\alpha = \Gamma^\alpha_{neo} - \mathbb{D}_{an}\frac{\partial n^\alpha}{\partial r} \qquad Q^\alpha = Q^\alpha_{neo} - \chi^\alpha_{an} n^\alpha \frac{\partial T^\alpha}{\partial r} - \frac{5}{2}\mathbb{D}_{an} T^\alpha \frac{\partial n^\alpha}{\partial r}$$

Ray Tracing With TRAVIS

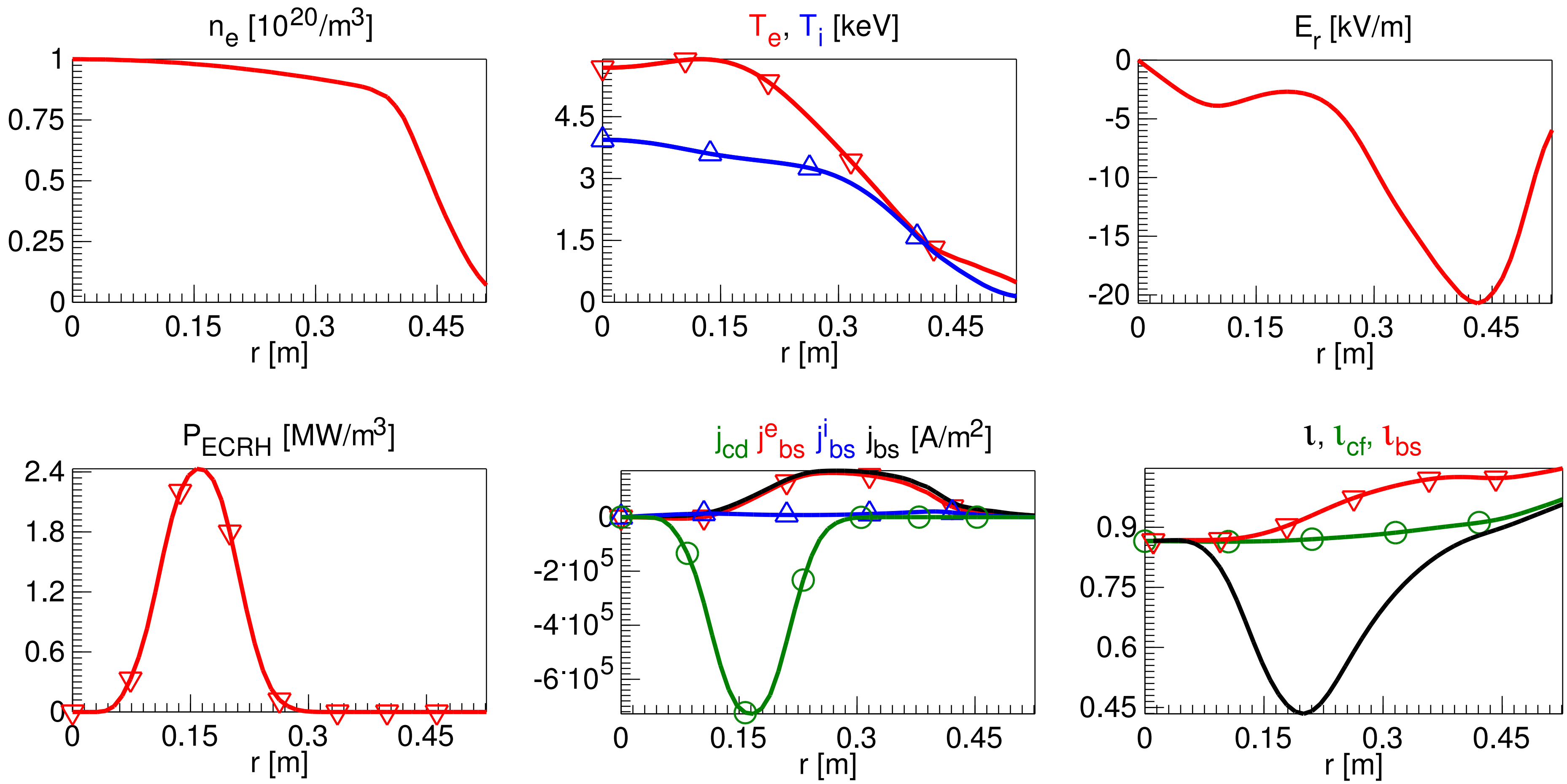
The ray-tracing code TRAVIS (N. B. Marushchenko, *et al.*):

- 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 β



Off-Axis X2 for $<\beta>=2\%$ W7-X Standard Configuration



$I_{bs}=75$ kA

$I_{cd}=-88$ kA

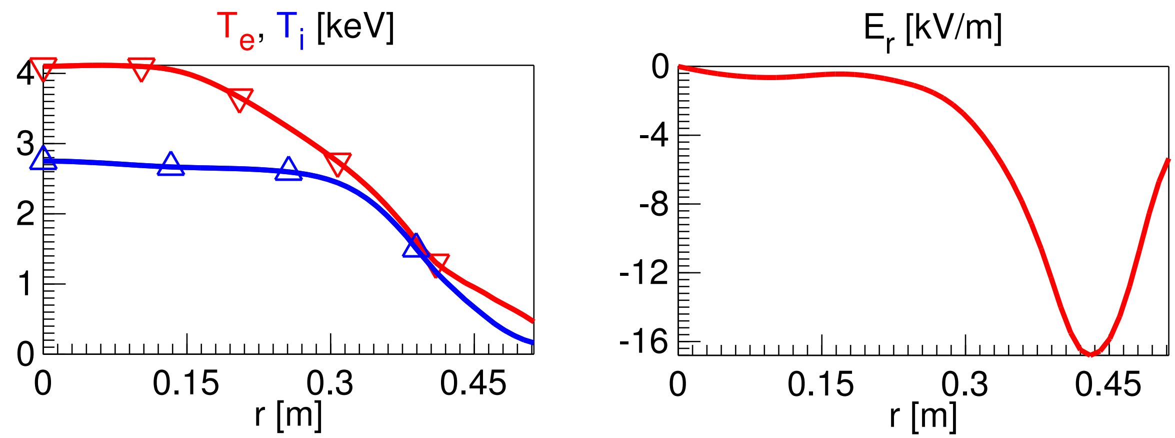
$<\beta>=2.70$ %

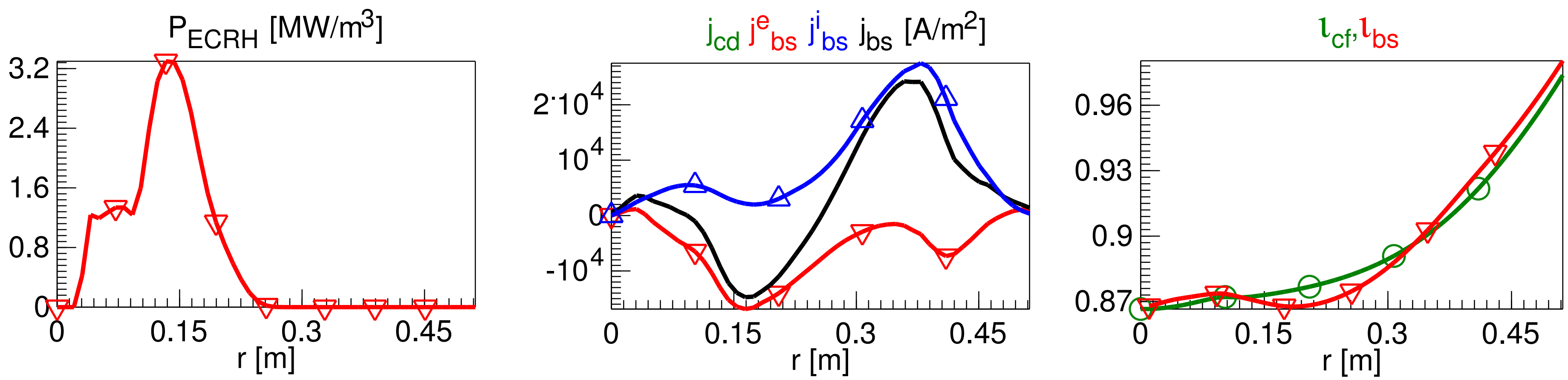
Off-Axis X2 for Vacuum W7-X High-Mirror Configuration

$I_{bs} = 6$ kA

$I_{cd} = -48$ kA

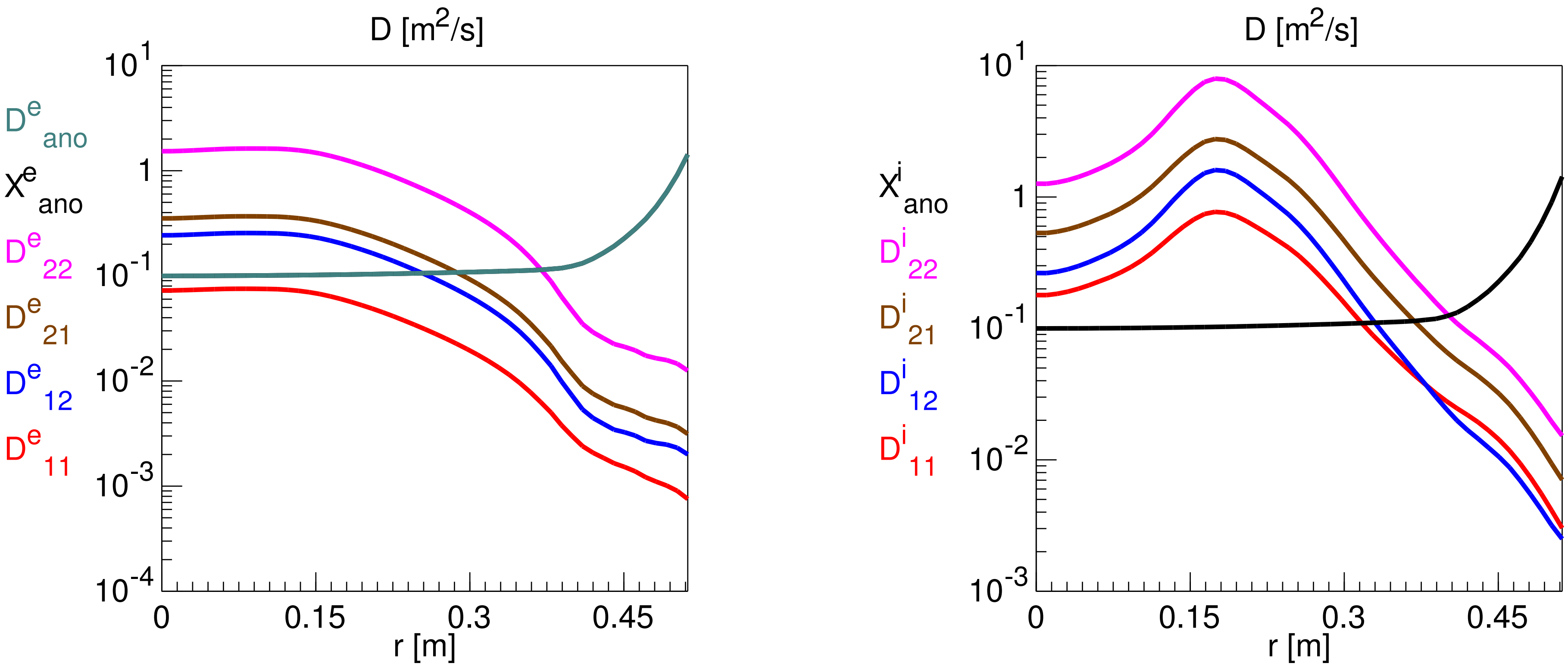
$< \beta > = 2.40$ %



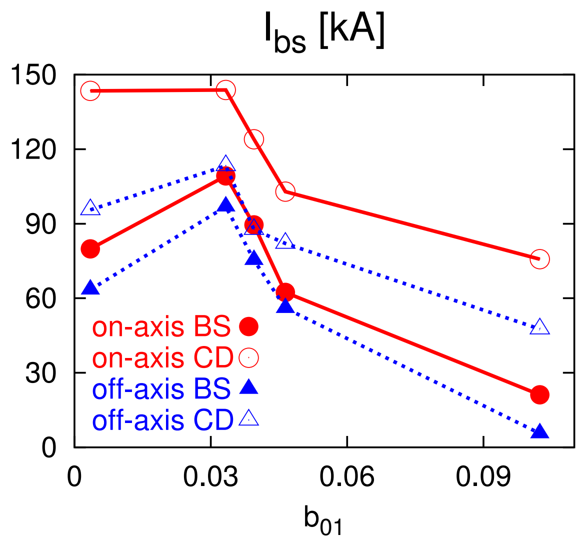


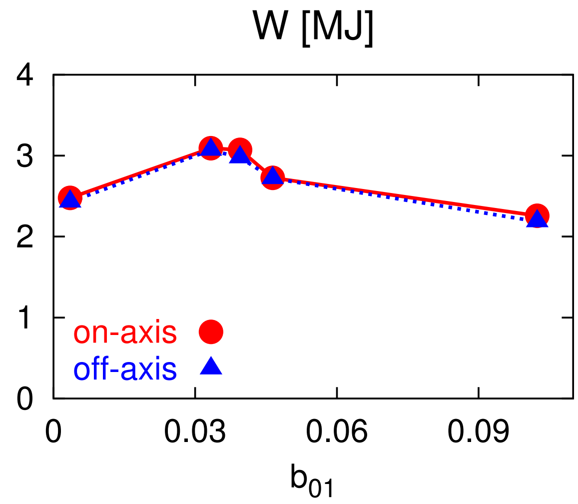
Small ECCD sufficient to balance I_{bs} in High-Mirror Configuration

… and the Underlying Transport Coefficients



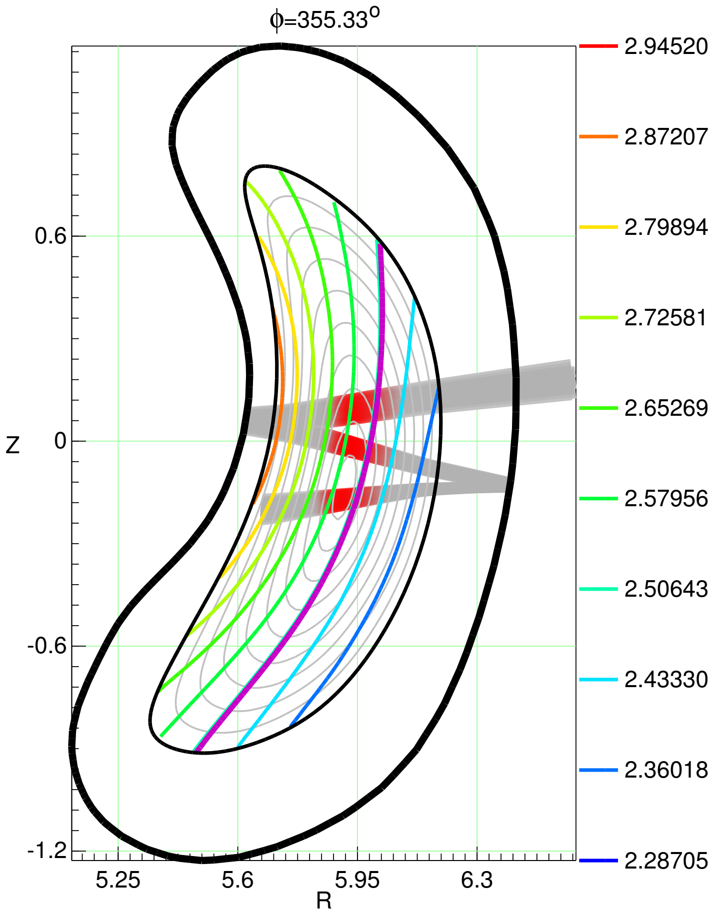
Summary of X2 Results

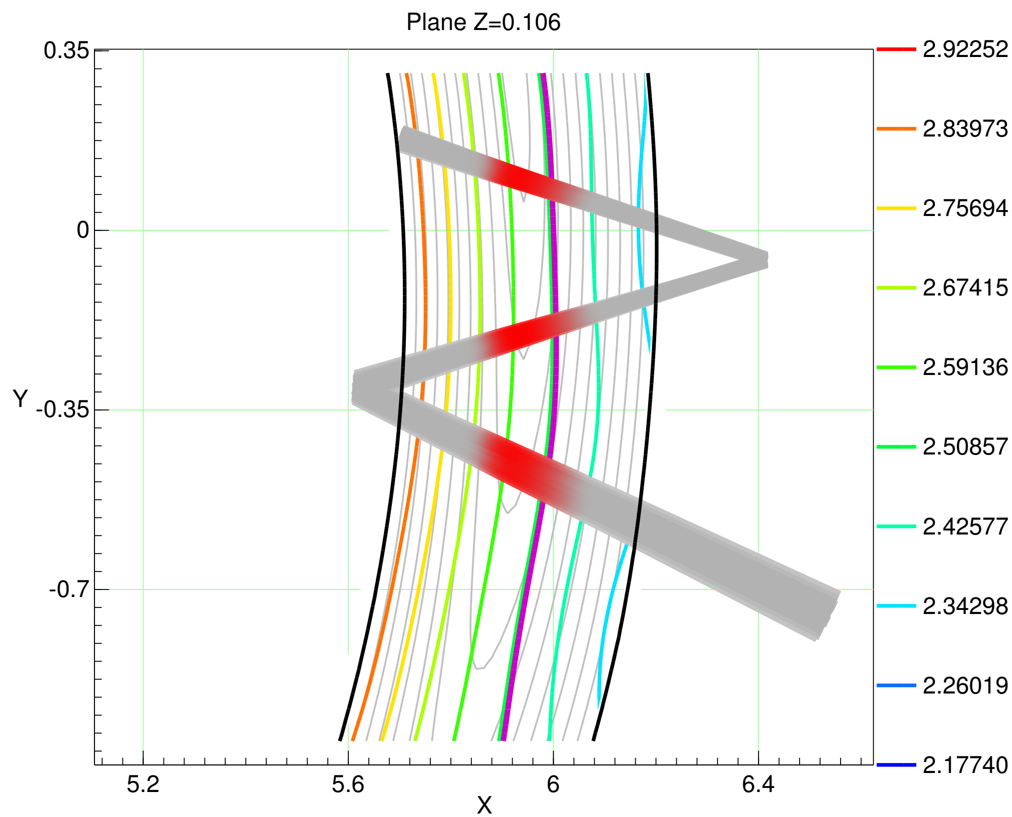




- $I_{bs} + I_{cd} \approx 0$ realistic for all W7-X configurations heated using 10 MW ECRH in X2 mode.
- Off-axis heating preferable $\rightarrow$ avoid $\iota \approx 0$ near plasma center $\rightarrow$ avoid electron root (high-mirror).
- Confinement improves with increasing β (low-mirror?)

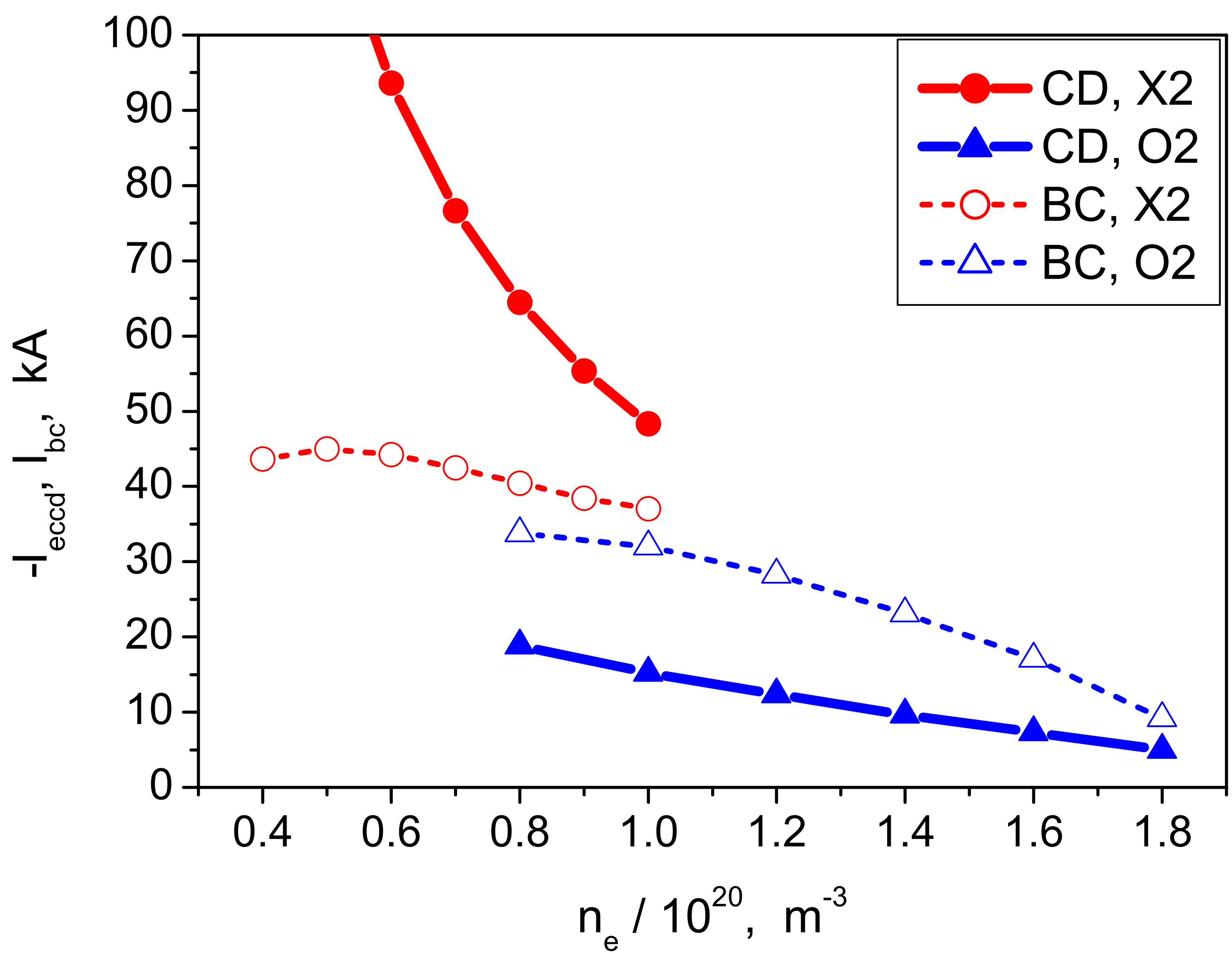
Launch Geometry for the O2 Mode



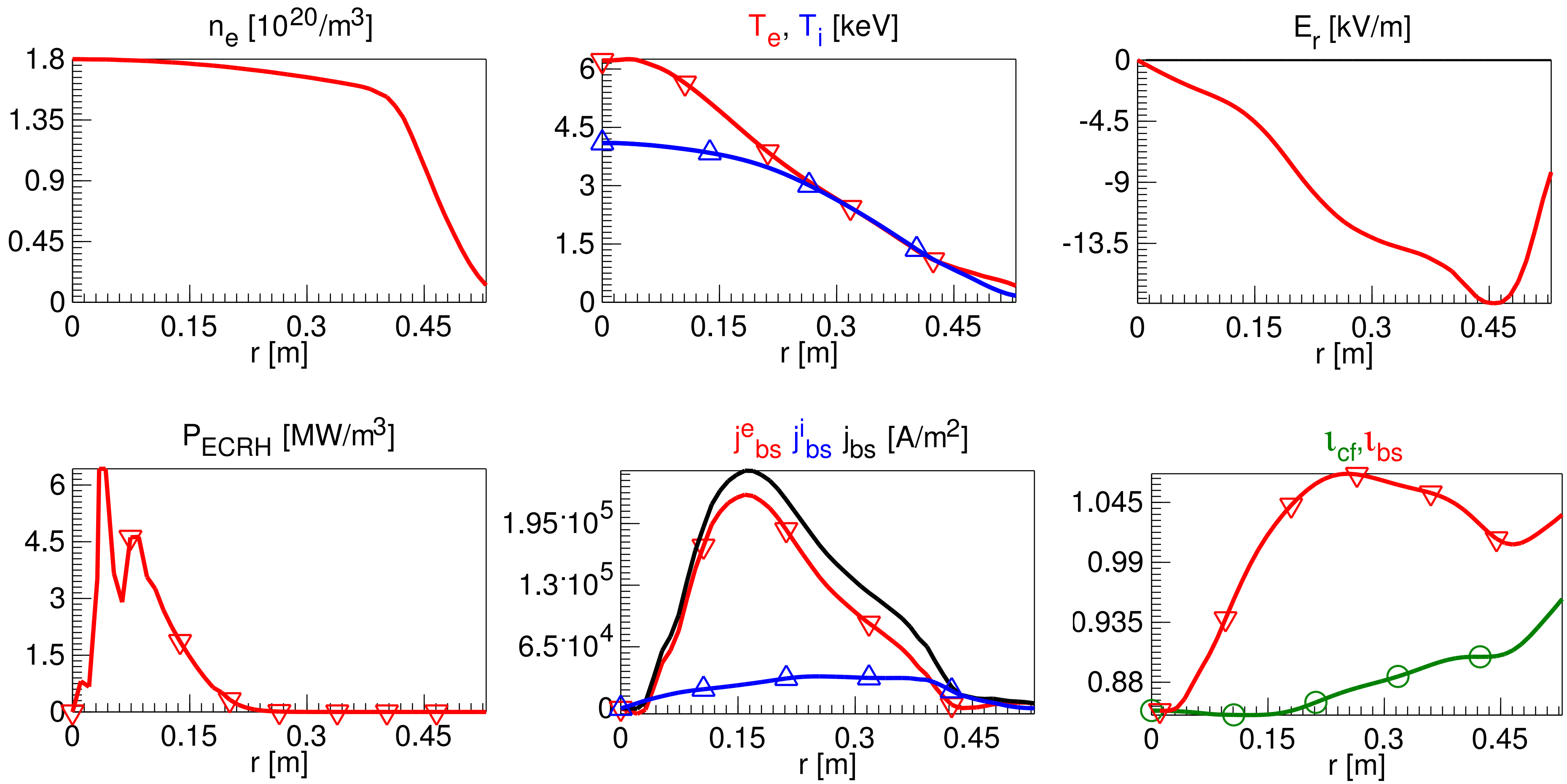


all distances in meters

ECCD and Bootstrap Current for O2 Launch Geometry, 5 MW



On-Axis O2 for $<\beta>= 4\%$ W7-X Standard Configuration



$I_{bs} = 82$ kA $\quad P_{abs} = 9.75$ MW $\quad <\beta>= 4.13$ %

Summary — Outlook

- ECCD compensation of the bootstrap current is possible for all X2 scenarios.
- ECCD becomes marginal for O2 conditions $\rightarrow$ Bootstrap current contribution to ι must be factored into discharge scenario.
- Refinements $\rightarrow$ modeling of $\iota \approx 0$ regions; correction of neoclassical transport coefficients for conservation of momentum.
- Carry out free-boundary VMEC runs including internal current densities determined in simulations $\rightarrow$ 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:

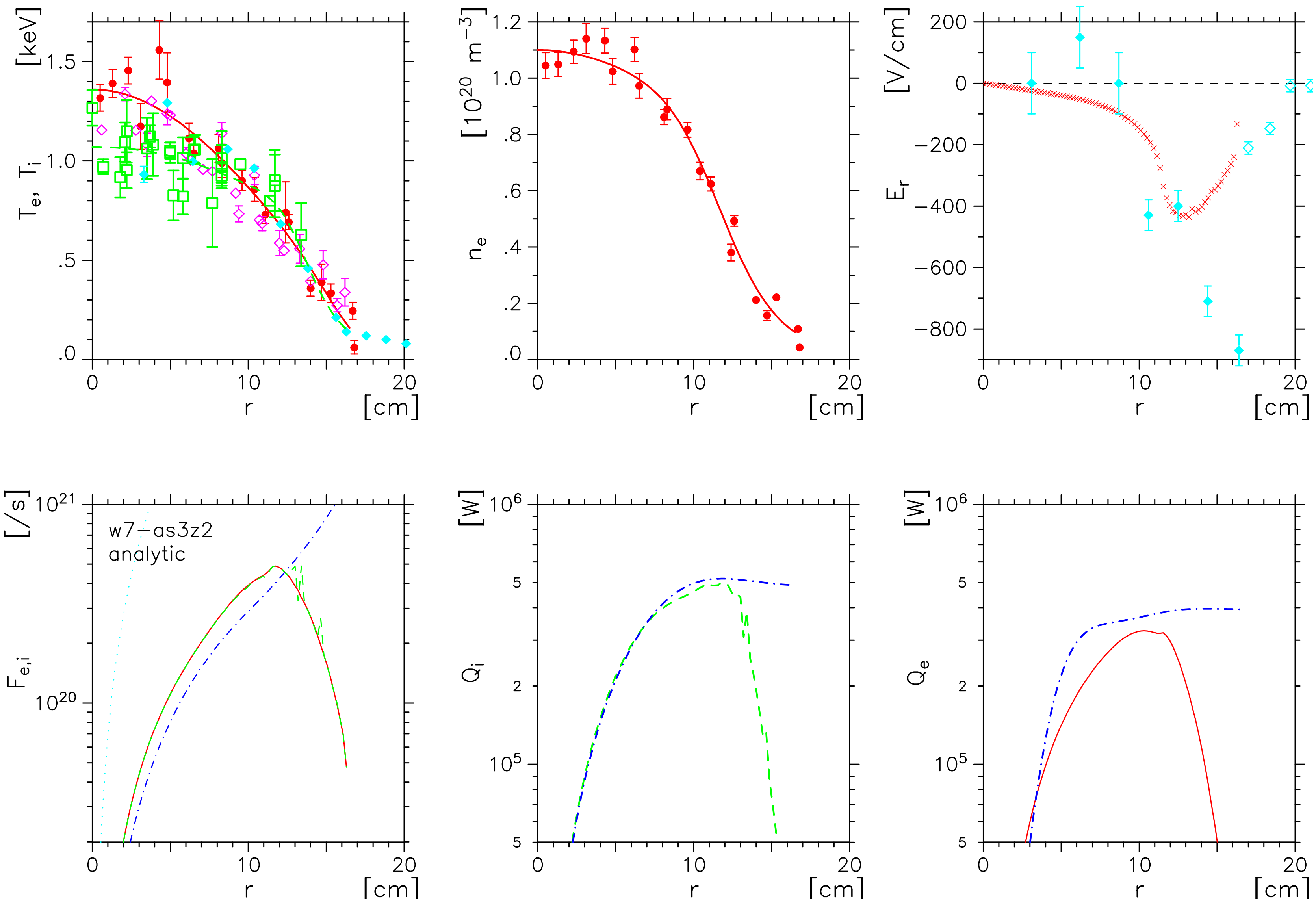
$$D_{1/\nu} \propto \frac{\epsilon_{eff}^{3/2}\, T^{7/2}}{n R_0^2 B_0^2}$$

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

$n\ (10^{20}\ m^{-3})$	W7-AS	W7-X	"classical" W7-X
0.1	0.90 keV	3.50 keV	1.35 keV
0.4	1.25 keV	5.20 keV	2.00 keV
1.0	1.60 keV	6.70 keV	2.50 keV

where possible effects due to E_r have been ignored.

shot 34609: 830 kW NBI, 330 kW ECRH absorbed power



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