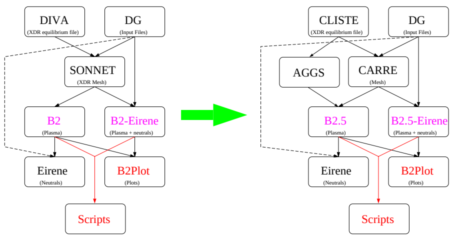
Max-Planck-Institut fur Plasmaphysik, EURATOM Assoziation

Recent developments in tokamak edge physics at Garching

D.P. Coster[a], X. Bonnin[b], K. Borrass[a], H.-S. Bosch[a], B. Braams[c], H. Buerbaumer[d], A. Kallenbach[a], M. Kaufmann[a], J.-W. Kim[a], E. Kovaltsova[e], E. Mazzoli[f], J. Neuhauser[a], D. Reiter[g], V. Rozhansky[e], R. Schneider[b], W. Ullrich[a], S. Voskoboynikov[e], P. Xantopoulos[h], and the ASDEX Upgrade team

[a]Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany
[b]Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-17489 Greifswald, Germany
[c]Courant Institute, NYU, New York, USA
[d]Institut für Allgemeine Physik, TU Wien, Austria, Association EURATOM-OEAW
[e]St. Petersburg State Technical University, St. Petersburg, Russia
[f]Politecnico di Torino, Italy
[g]Düsseldorf University, Düsseldorf, Germany
[h]N.C.S.R. 'Demokritos', GR-15310 A.G. Paraskevi, Greece

The SOLPS Codes



SOLPS 4.0

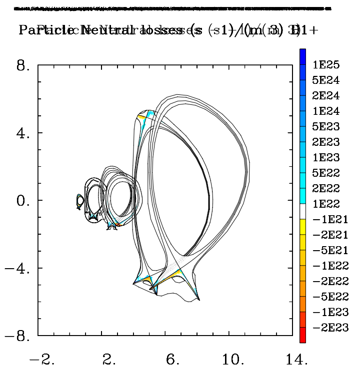
- B2-Eirene
  - B2 solves for
    - ∗ charge state densities
    - ∗ parallel momenta
    - ∗ electron energy
    - ∗ ion energy

SOLPS 5.0

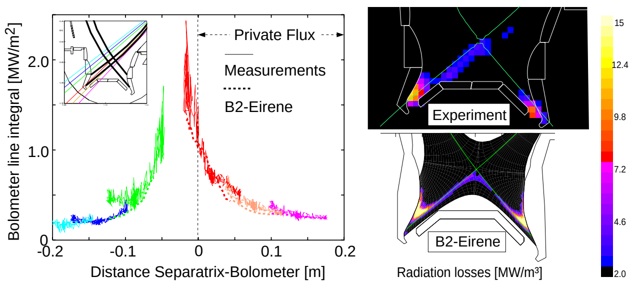
- B2.5-Eirene
  - B2.5 solves for
    - ∗ charge state and neutral densities
    - ∗ parallel momenta
    - ∗ electron energy
    - ∗ ion energy
    - ∗ potential equation
  - includes drifts and currents

SOLPS4.0

- workhorse
- used at large number of sites
  - CMOD
  - AUG
  - JET
  - JT60-U
  - ITER-LAM
  - ITER-FDR
- code development frozen

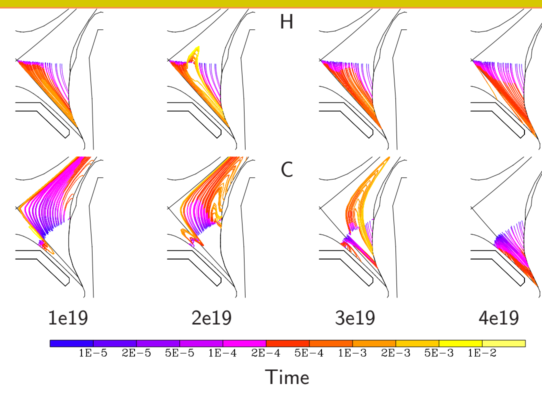


Bolometer comparison for z-shift experiment



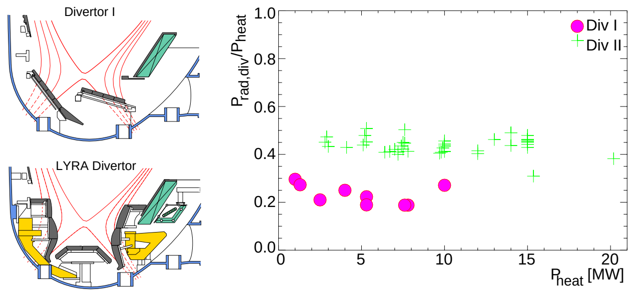
Excellent agreement

C trajectories in divertor show importance of regime



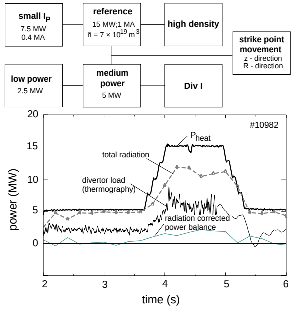
Strong C flow reversal at low divertor densities even in the absence of H flow reversal

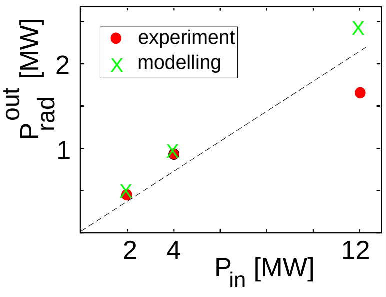
Radiation and Power Loading in the Divertor



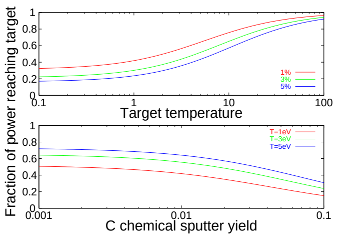
Divertor radiation higher in divertor II (LYRA)

Detailed experimental and modelling campaign



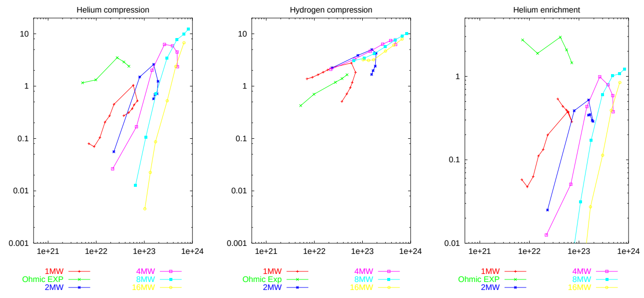


- sputter yield important for determining total radiation
- transport coefficients important for determining peak power fluxes to the target
- use a simplified model to understand results
  - energy flux to target = energy flux into SOL - energy radiated
  - energy radiated assumed to be proportional to the outflux from the target
  - outflux from the target assumed to be proportional to the hydrogen flux to the target



Helium Compression and enrichment

Power and density scan

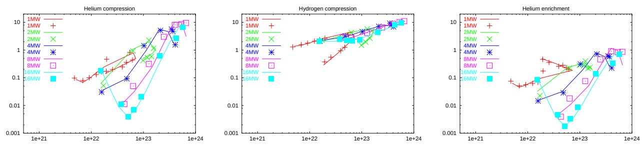


Fit formula

$$F(n_{e,sep}, P_{SOL}, n_{e,break}, \lambda, S) = \exp(-(n_{e,sep}/(n_{e,break} * P_{SOL}^{\lambda}))^{S})$$

$$\begin{aligned} G(P_{SOL}, n_{e,sep}) = {} & F(n_{e,sep}, P_{SOL}, n_{e,sheath}, \lambda_{n_{e,sheath}}, S) * a^2 * P_{SOL}^{b} * n_{e,sep}^{c} \\ & +(1 - F(n_{e,sep}, P_{SOL}, n_{e,sheath}, \lambda_{n_{e,sheath}}, S)) \\ & *(F(n_{e,sep}, P_{SOL}, n_{e,detach}, \lambda_{n_{e,detach}}, S) * d^2 * P_{SOL}^{e} * n_{e,sep}^{f} \\ & +(1 - F(n_{e,sep}, P_{SOL}, n_{e,detach}, \lambda_{n_{e,detach}}, S)) * g^2 * P_{SOL}^{h} * n_{e,sep}^{i}) \end{aligned}$$

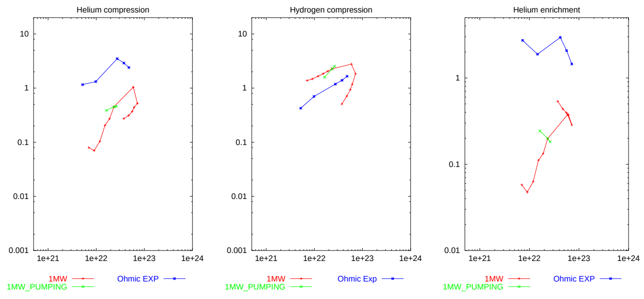
Fit based on input power and separatrix density



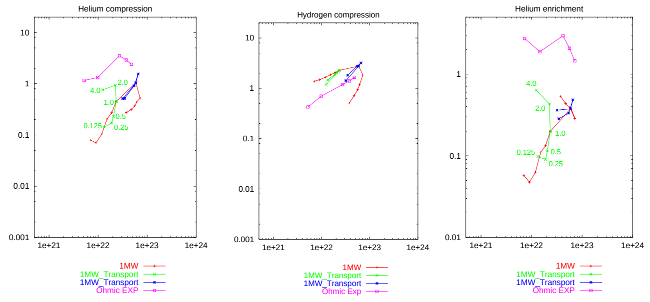
Regime	sheath		high recycling		detached	
Exponent for	P_{SOL}	$n_{e,sep}$	P_{SOL}	$n_{e,sep}$	P_{SOL}	$n_{e,sep}$
Deuterium	-0.129157	0.00	-0.887993	1.0	1.88265	-2.00
Helium	1.36857	-4.00	-4.55607	14.4873	1.46927	-1.0

Coefficients in red imposed

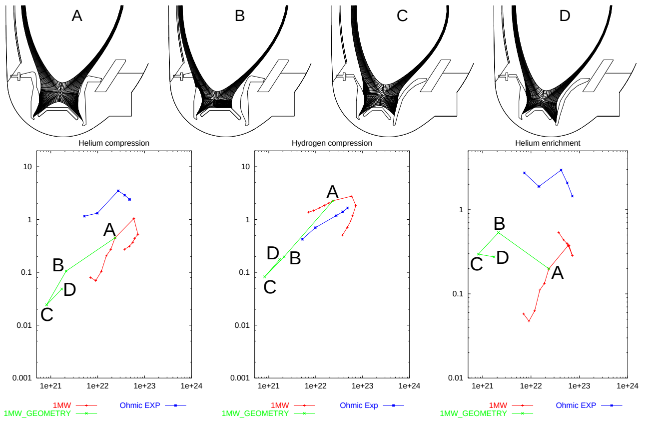
Pumping scan



Transport scan

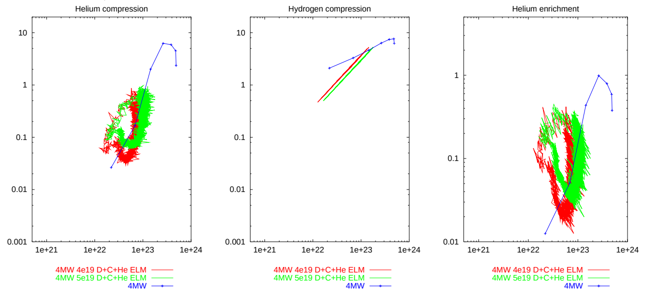


Geometry variation

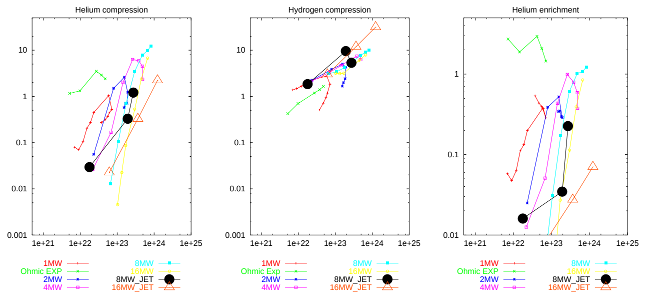


ELMs

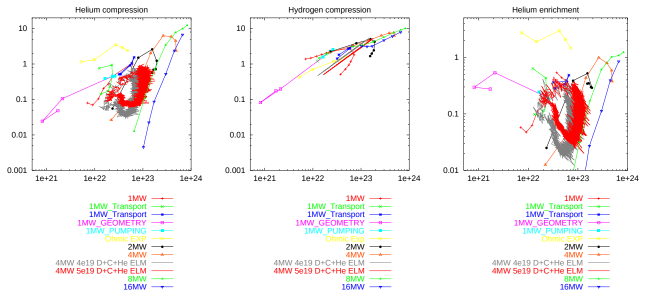
4MW, H+C+He without ELMs versus D+C+He with ELMs



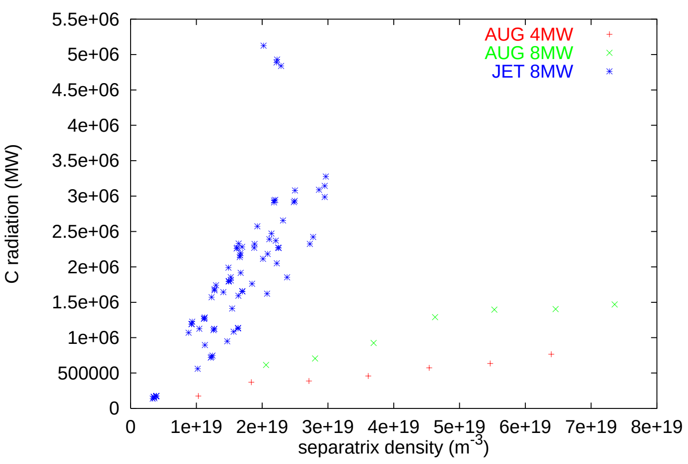
Preliminary results for JET



Combined results



Comparison of C radiation: AUG & JET



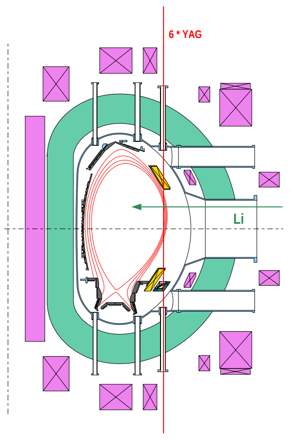
- same assumptions about sputtering yields
  - used a constant 1% chemical sputtering yield (somewhat lower than that which gives the best match for AUG)
- fixed transport coefficients for AUG
- varied JET transport coefficients about the AUG values (mostly decreased them)

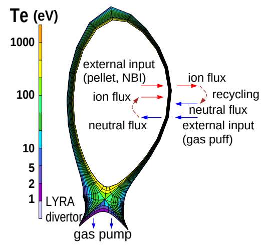
JET almost certainly has a much lower upstream separatrix density than AUG under normal operating conditions

SOLPS5.0

SOLPS5.0 includes the newer version of B2 which incorporates a fluid neutral model as well as equations for the electric current and potential.

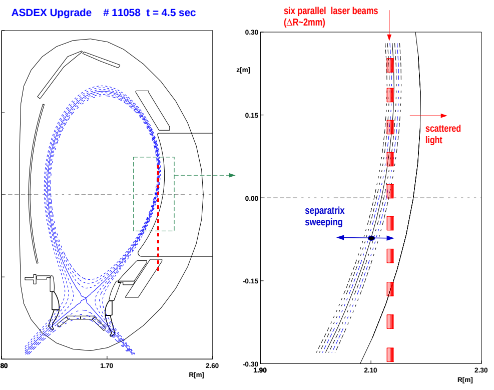
Interpretive fluid code





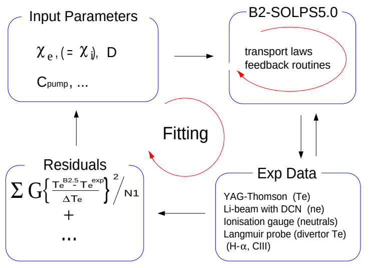
- conservation equations for
  - particles
  - momentum
  - energy
- fluid neutral model
- no drifts

YAG system



Fit Procedure

- Use a NAG routine to vary the **Input Parameters** so as to find the minimum of the **Residuals**
- **Residuals** found by comparing code results with **Exp Data**
- Each function evaluation is a full run of **B2-SOLPS5.0**


Input Parameters

$\chi_e, (=\chi_i)$, D

C_{pump}, ...

B2-SOLPS5.0

transport laws
feedback routines

Fitting

Residuals

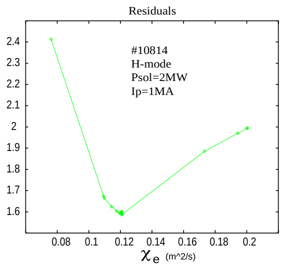
$\Sigma\, G\left\{\frac{T_e^{B2.5} - T_e^{exp}}{\Delta T_e}\right\}^2 / N1$

+

...

Exp Data

YAG-Thomson (Te)
Li-beam with DCN (ne)
Ionisation gauge (neutrals)
Langmuir probe (divertor Te)
(H-α, CIII)



The fitted quantities

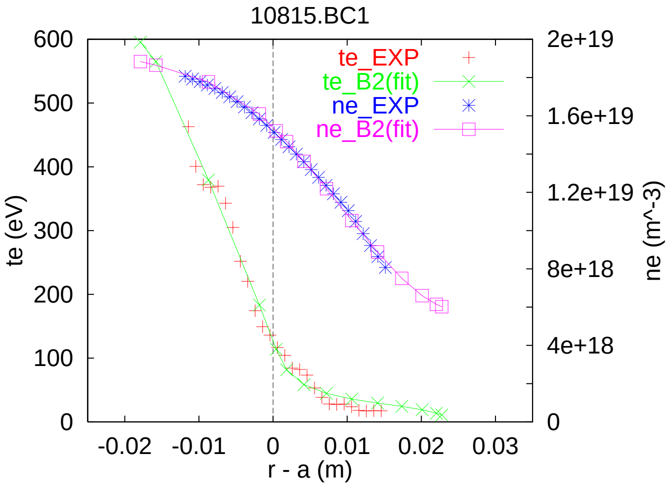
Residual $=$

$$\alpha_1 \frac{1}{M}\sum_M G_{T_e}\left(\frac{T_e^{exp}-T_e^{code}}{\Delta T_e^{exp}}\right)^2 + \alpha_2 \frac{1}{N}\sum_N G_{n_e}\left(\frac{n_e^{exp}-n_e^{code}}{\Delta n_e^{exp}}\right)^2$$

$$+\alpha_3 \frac{1}{N}\sum_N G_{\nabla n_e}\left(\frac{\nabla n_e^{exp}-\nabla n_e^{code}}{\Delta \nabla n_e^{exp}}\right)^2$$

$$+\alpha_4 \left(\frac{\Gamma_{pump}^{exp}-\Gamma_{pump}^{code}}{\Delta\Gamma_{pump}^{exp}}\right)^2 + \alpha_5 \left(\frac{\Gamma_{wall}^{exp}-\Gamma_{wall}^{code}}{\Delta\Gamma_{wall}^{exp}}\right)^2$$

The fitted quantities are D, χ, $n_{e,core}$, c_{pump} and the separatrix position.



Can also fit v_{in}, Γ_{puff} with residuals enhanced by

$$\alpha_6 \left(\frac{T_{e,divin}^{exp}-T_{e,divin}^{code}}{\Delta T_{e,divin}^{exp}}\right)^2 + \alpha_7 \left(\frac{T_{e,divout}^{exp}-T_{e,divout}^{code}}{\Delta T_{e,divout}^{exp}}\right)^2 + \alpha_8 \left(\frac{\Gamma_{core}^{exp}-\Gamma_{core}^{code}}{\Delta\Gamma_{core}^{exp}}\right)^2$$

- experimental profile data is shifted within equilibrium uncertainty to improve fit to code
- use of YAG electron temperature data emphasizes data inboard from the separatrix because of smaller relative errors there (fixed absolute error)
  - could be supplemented by reciprocating Langmuir probe data
- Gaussian weighting functions used to choose position and width of fitted experimental data

- fit to both the density and density gradient
- since no ion temperature measurements, assume $\chi_i = \chi_e$
- main emphasis is on mid-plane measurements
- so far for hydrogen or deuterium only
- instead of D and v_{in} could fit two D's

Data range

D_2, H_2

H-mode (ELM I & III),
L-mode

$0.4MA < I_p < 1.2MA$

$1.7MW < P_{sol} < 11MW$

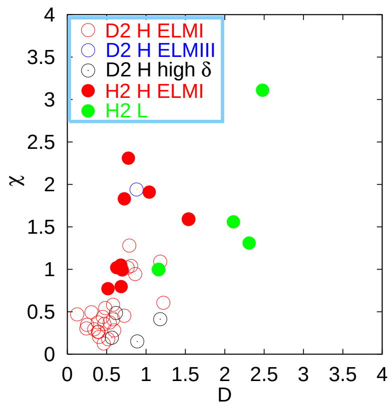
$3.2 < q_{95} < 11$

$1.5T < B_t < 2.6T$

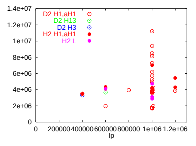
$2.8 \times 10^{19} m^{-3} < \bar{n_e} < 9.8 \times 10^{19} m^{-3}$

$0.34 < \frac{\bar{n_e}}{n_{GW}} < 0.75$

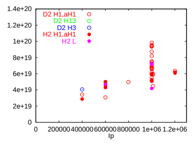
44 points



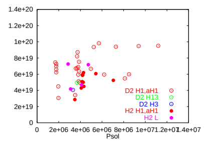
P_{SOL} vs I_p



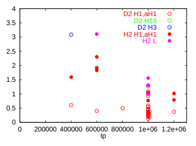
$\bar{n_e}$ vs I_p



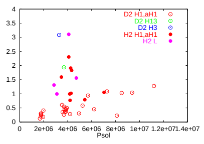
$\bar{n_e}$ vs P_{SOL}



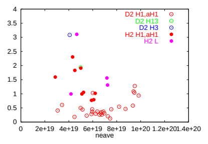
χ vs I_p



χ vs P_{SOL}



χ vs $\bar{n_e}$

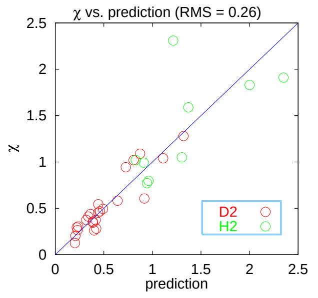


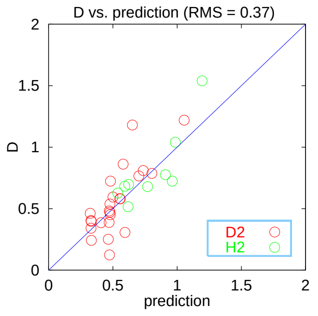
Preliminary Multiple Regression Fit to χ and D

$$\chi \propto I_p^{\,-1.32\pm0.26}\, B_t^{\,-0.60\pm0.39}\, P_{sol}^{\,0.93\pm0.12}\, \bar{n_e}^{\,0.50\pm0.26}\, m_{eff}^{\,-1.57\pm0.27}$$

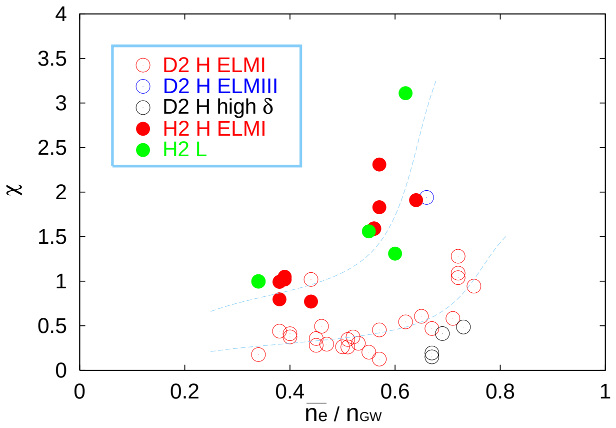
$$D \propto I_p^{\,-0.90\pm0.24}\, P_{sol}^{\,0.48\pm0.14}\, m_{eff}^{\,-0.41\pm0.32}$$

$$m_{eff} \equiv \frac{m_D \bar{n_D} + m_H \bar{n_H}}{m_p(\bar{n_D} + \bar{n_H})}$$



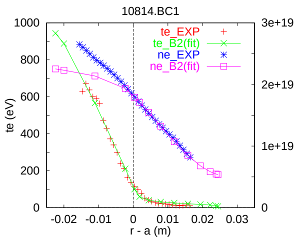


χ increases strongly as the density approaches the Greenwald density

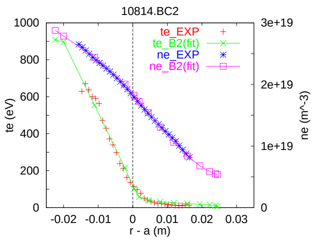


Fitting of an inward pinch velocity

no inward pinch velocity with inward pinch velocity

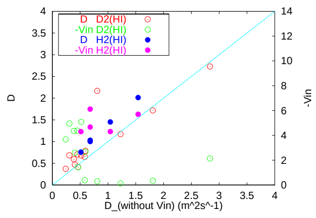


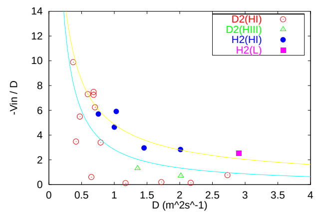
(4 hours CPU time)

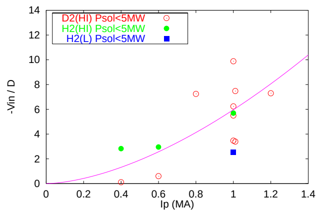


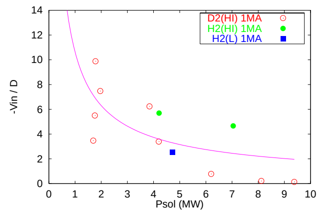
(12 hours CPU time)

Allowing the code to fit an inward pinch velocity can significantly improve the fit to the density profile

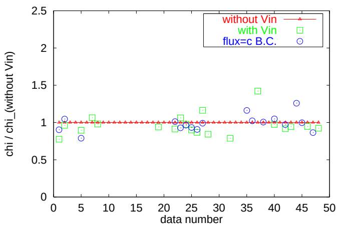


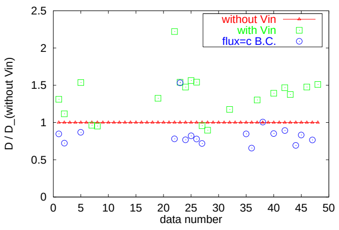






Sensitivity to boundary conditions





χ relatively insensitive to changes of boundary condition

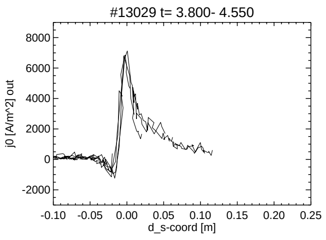
Outlook

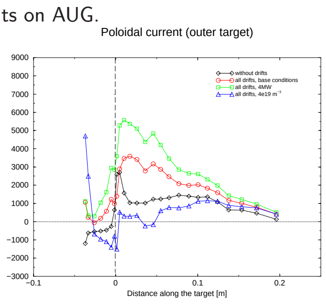
- Code is running successfully
  - but so far only for AUG
- Need to expand the database for AUG
  - and extend the work to other machines
- Possibility of fitting pedestal region as well
- Want to explore different parameterizations of transport
- Fit could be done to more diagnostics
  - at the expense of slowing the code down

Important first step for improving our understanding of edge transport!

Target electric currents

Currents flowing into and out of the target plates have been measured on a number of devices. Early attempts at modelling these results are compared below with Langmuir probe measurements on AUG.

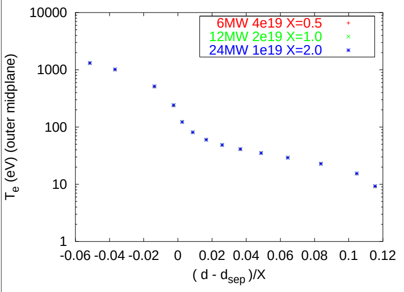


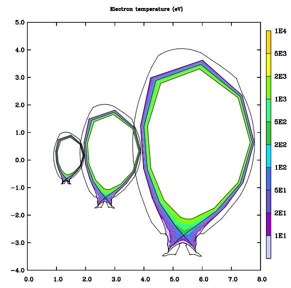


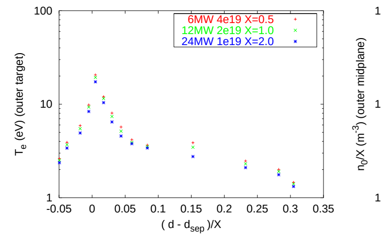
Scaling of B2 code results

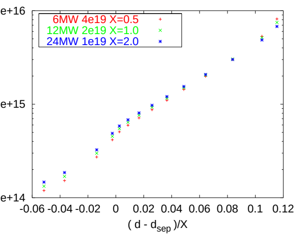
Whatever the scaling of the experiment, the B2-SOLPS5.0 results scale inherently with collisionality and a normalized temperature.

JET was scaled physically by 0.5 and 2.0, and, in keeping with a scaling based on ρ_*, ν_* and T, the density was scaled as R^{-1}, the magnetic field as R^{-1}, the plasma current as R^0 and the heating power as R^1. At the same time the transport coefficients were scaled as $R^{1'}$. The midplane temperature electron profiles then matched, though small deviations remained at the target and in the (normalised) neutral density profiles upstream.









SUMMARY

- development of the SOLPS suite of codes is continuing
- successful comparison with experiment
- better understanding of role of C in the divertor
- better understanding of helium compression and enrichment
- development of an interpretive version for the determination of edge transport
- started modelling current flows in the edge