ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

CRPP

The validation project on the TORPEX basic plasma physics experiment

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on behalf of the TORPEX team:

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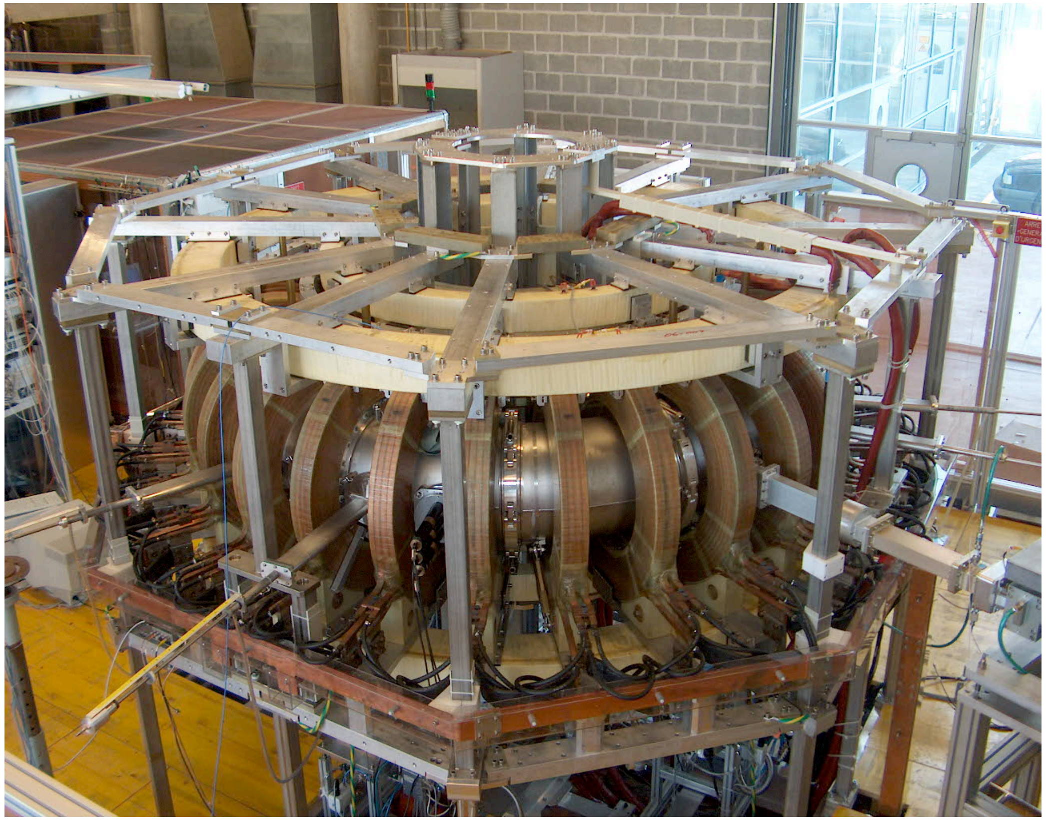
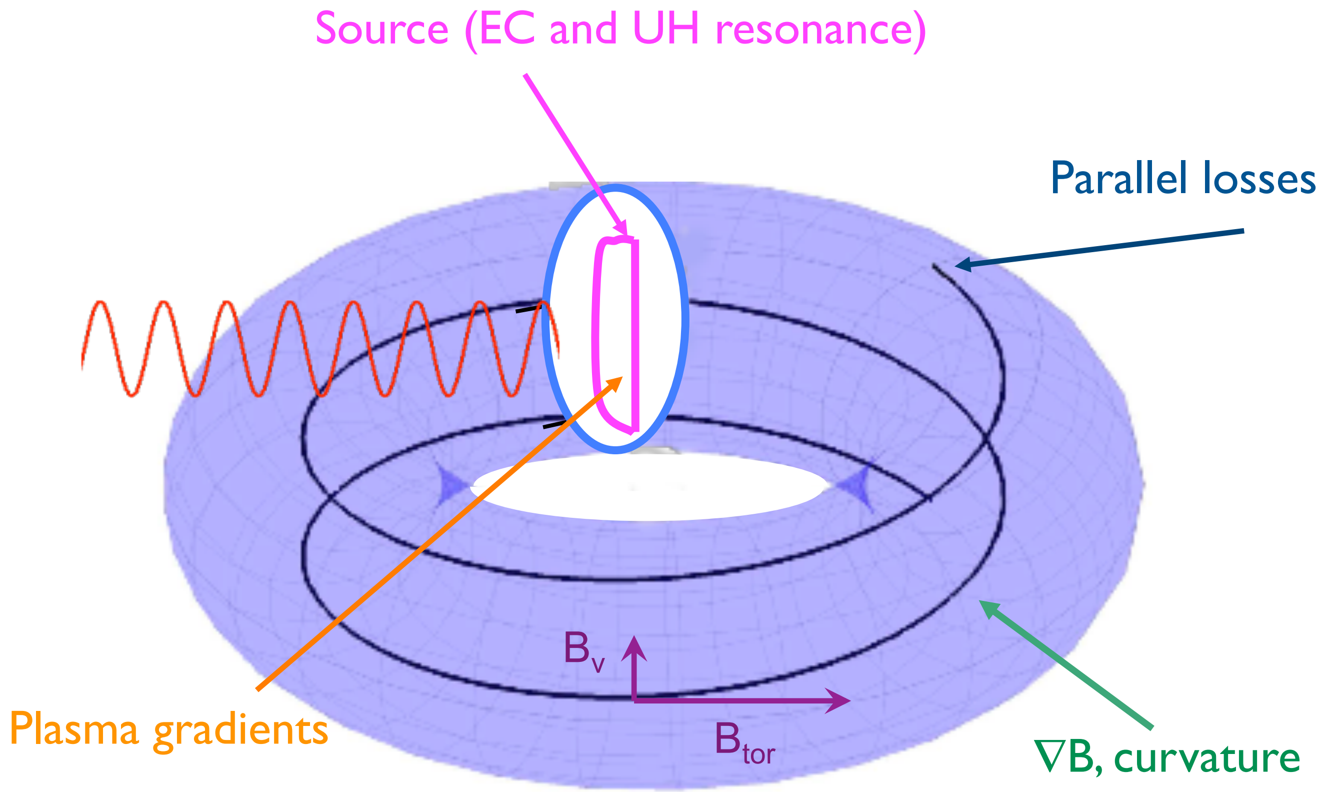
Joint EU-US Transport Task Force Workshop San Diego, California – April 6-9

The TORPEX device



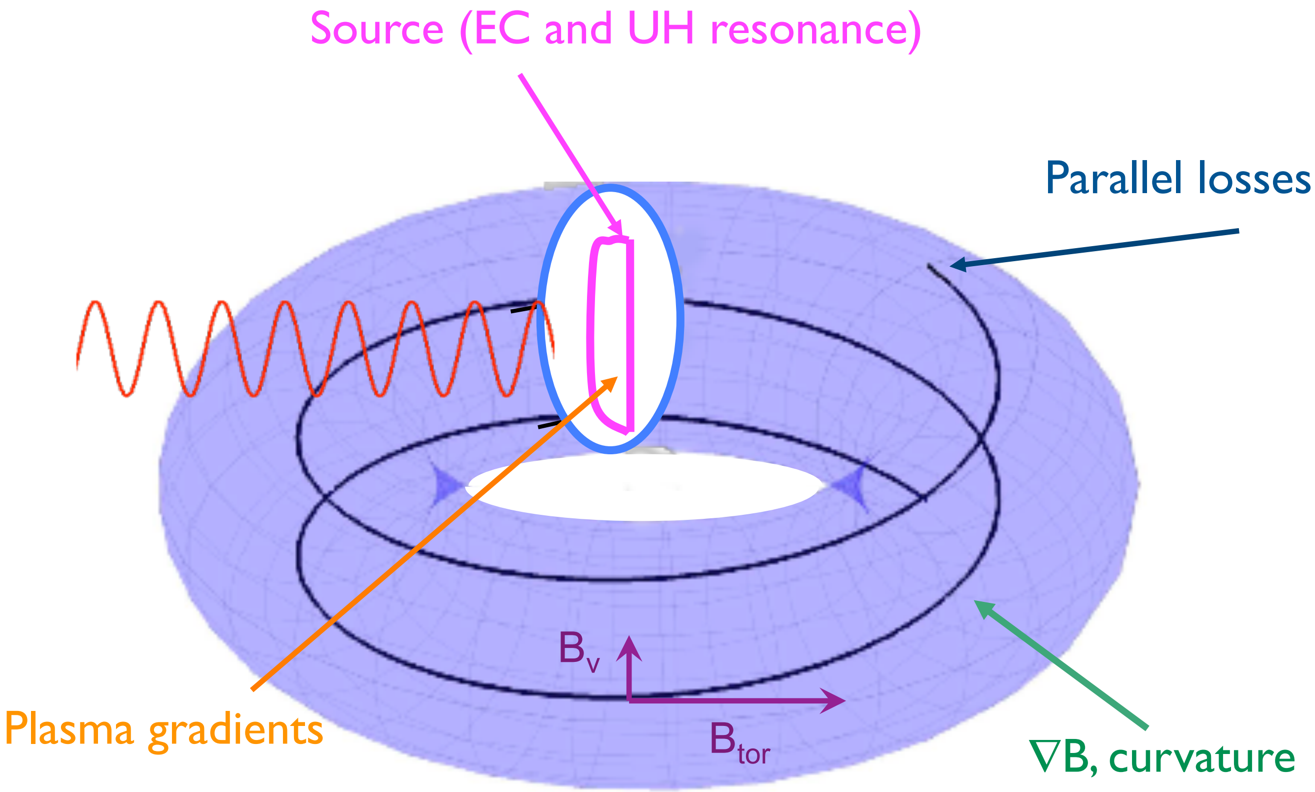
A paradigm for edge turbulence

The TORPEX device



Fundamentals of SOL turbulence

The TORPEX device

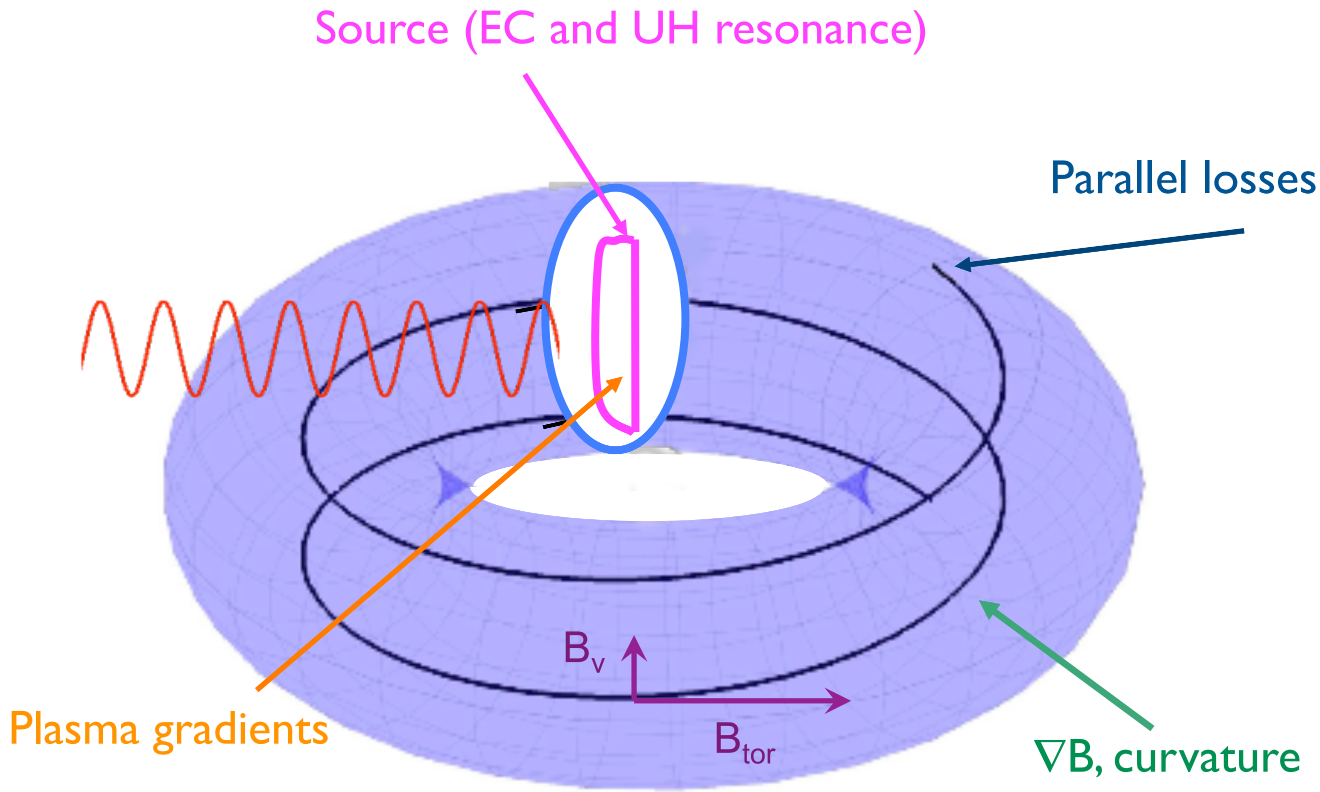


$$|B_T| \approx 76mT \qquad n_e \le 10^{17} m^{-3}$$

$$|B_z / B_T| \le 5\% \qquad T_e \le 15eV$$

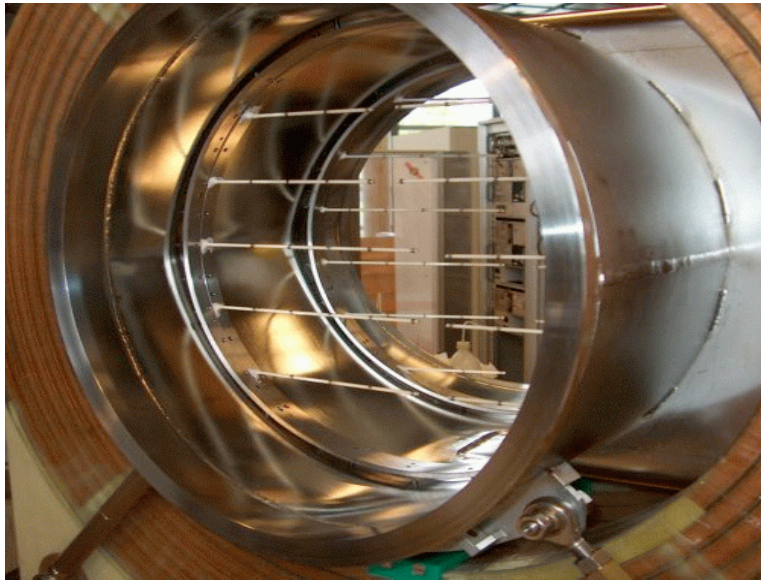
$$T_i << T_e$$

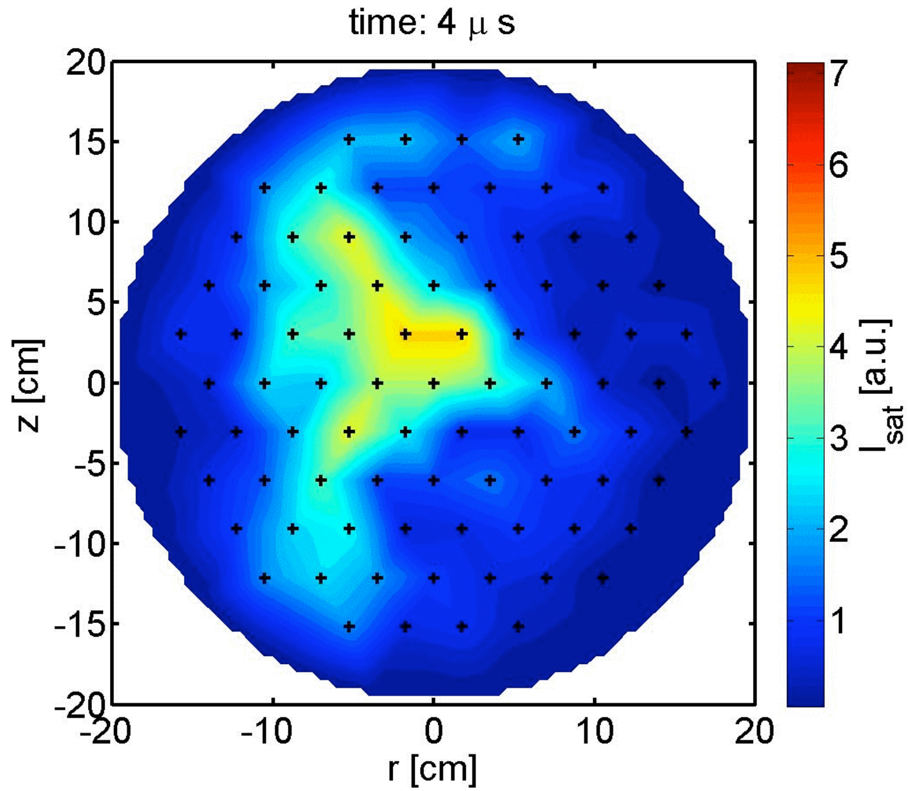
The TORPEX device



N : number of field line turns

The TORPEX device





High resolution diagnostics with full coverage

The GBS simulations

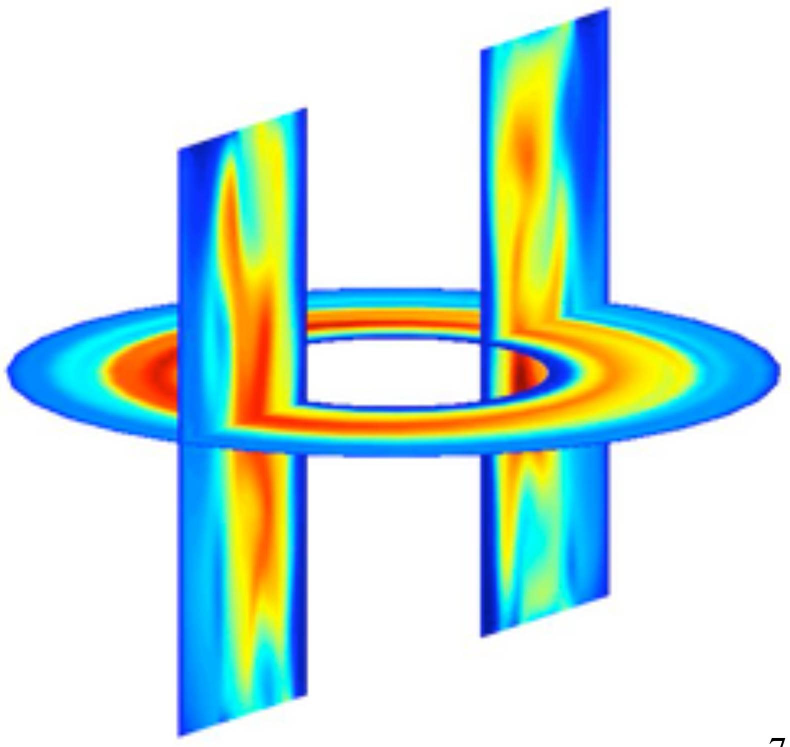
Collisional plasma → **Braginskii model** → ($\rho_i \ll L$, $\beta \ll 1$; $\omega \ll \Omega_{ci}$, $n_e \approx n_i$) → **Electrostatic drift-reduced Braginskii equations** → ($T_i \ll T_e$) → **GBS model**

Evolves full n, T_e, Φ, $V_{||i}$, $V_{||e}$.

Quasi-steady-state

=

Balance between parallel losses, perpendicular transport and sources.



The validation project

[Based on the ideas of P. W. Terry *et al.*, PoP 2008]

Defining the observables

what can we measure/compute ?

Classifying the observables

how directly can we get an observable from exp/sim data ?

Uncertainty analysis

what is the uncertainty of measurements/simulations data ?

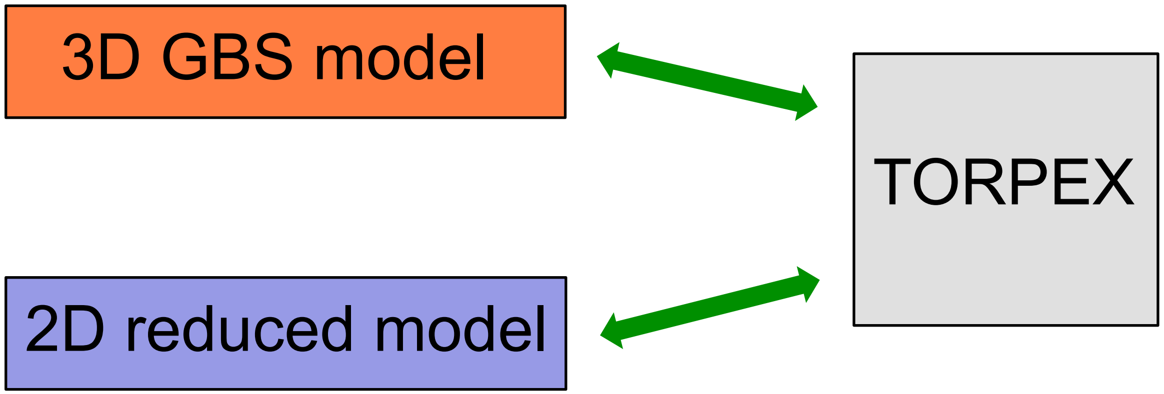
Distance and level of agreement

how to define the level of agreement between exp/sim for one observable ?

Composite metric

how to evaluate the global agreement and how to interpret it ?

The validation project



11 observables, with radial profiles, and for different values of N

What are the observables?

Direct from the simulation: n, T_e, Φ, $V_{||i}$, $V_{||e}$

$$I(\phi_b) = \frac{1}{2} e n c_s A \left[1 - \exp\left(\Lambda + e \frac{\phi_b - \phi}{T_e} \right) \right]$$

Direct from the experiment: I_{sat}, V_{float}, I-V

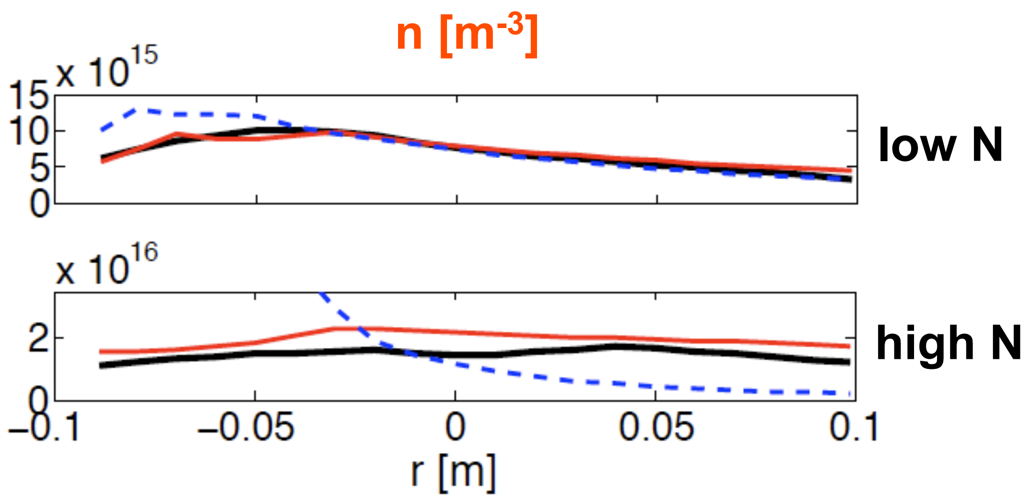
Validation observables:

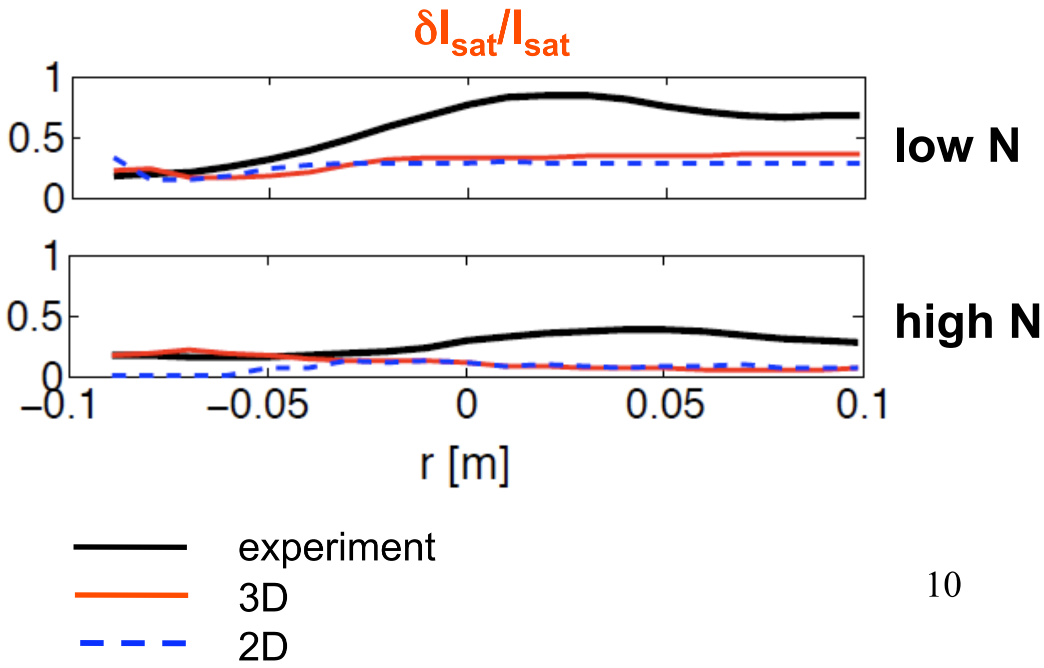
$\langle n \rangle$, $\langle T_e \rangle$, $\langle \Phi \rangle$

I_{sat}, δI_{sat}

k_z, k_φ

δT_e, Γ





Classifying the observables

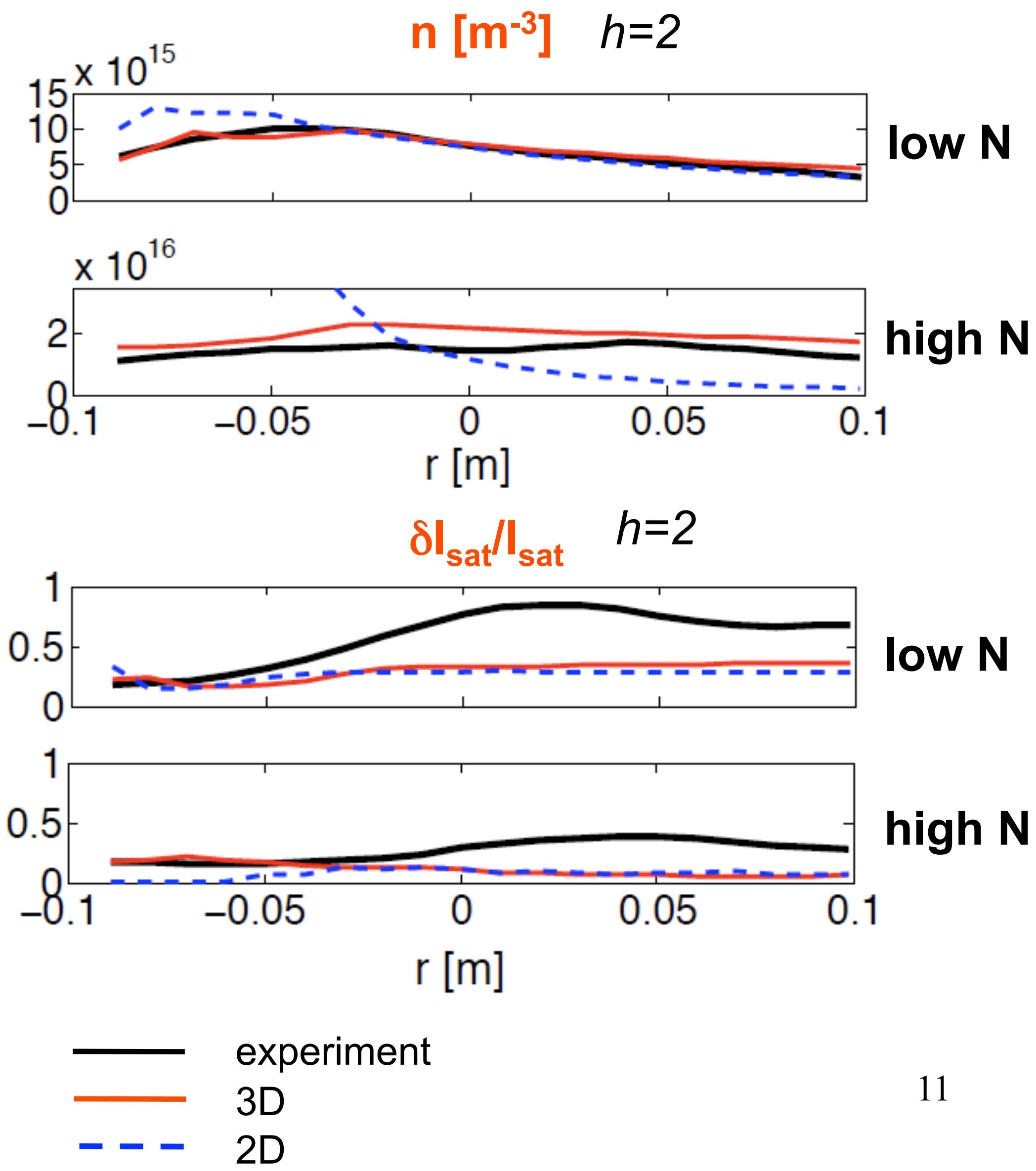
1st level: $\langle n\rangle^{sim}$, $\langle T_e\rangle^{sim}$, $\langle \Phi\rangle^{sim}$, I_{sat}^{exp}, δI_{sat}^{exp}

2nd level: $\langle n\rangle^{exp}$, $\langle T_e\rangle^{exp}$, $\langle \Phi\rangle^{exp}$, I_{sat}^{sim}, δI_{sat}^{sim}

3rd level: δT_e^{exp}, Γ^{exp}

$$h_j = h_j^{\exp} + h_j^{sim} - 1$$

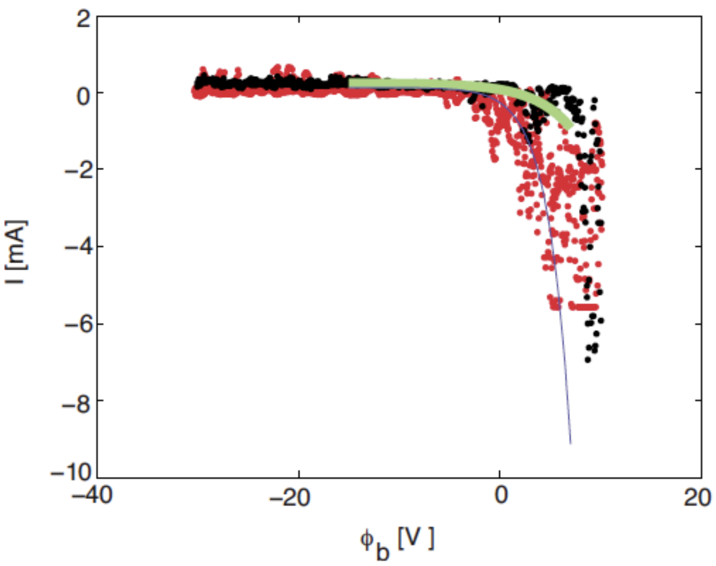
	Experimental hierarchy h^{exp}	Simulation hierarchy h^{sim}	Comparison hierarchy h
I_{sat}, I_{sat} statistics	1	2	2
$\overline{T}_e$, $\overline{n}$, $\overline{\phi}$	2	1	2
k_z, k_φ	2	1	2
T_e, δT_e	3	1	3
Γ	3	2	4
Γ_{struc}	3	4	6

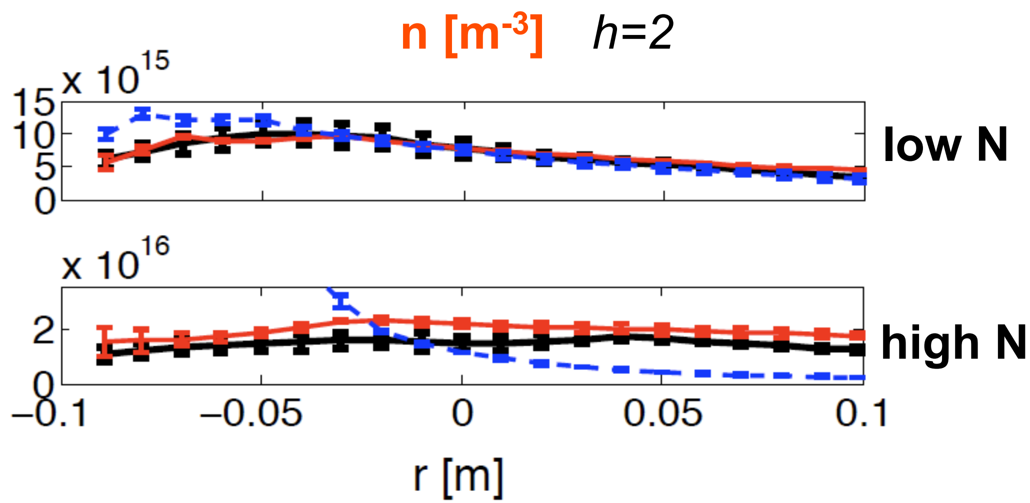


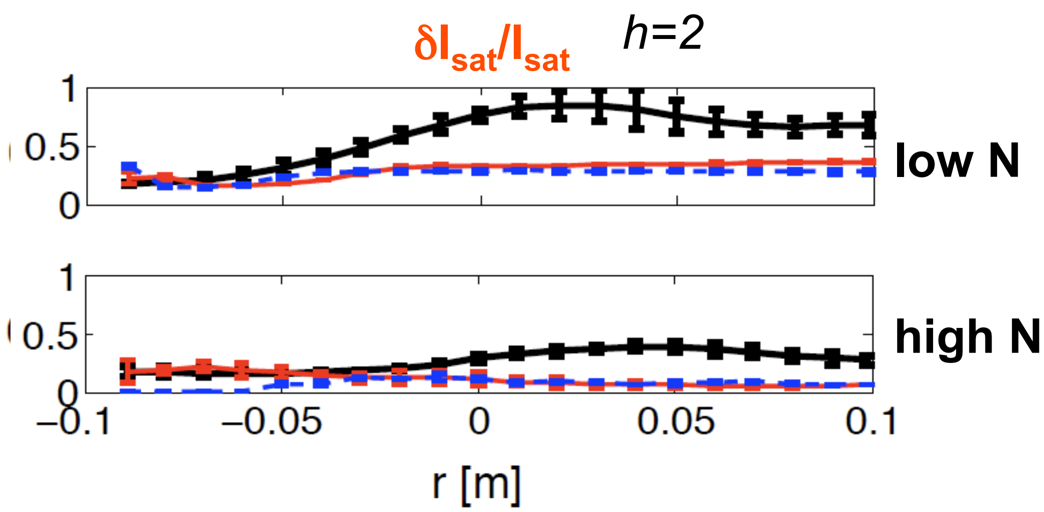
Uncertainty analysis

$$\Delta x_{j,i}^2 = (\Delta x_{j,i}^{\mathrm{fit}})^2 + (\Delta x_{j,i}^{\mathrm{prb}})^2 + (\Delta x_{j,i}^{\mathrm{rep}})^2 + (\Delta x_{j,i}^{\mathrm{fin}})^2$$

$$\Delta y_{j,i}^2 = (\Delta y_{j,i}^{\mathrm{num}})^2 + (\Delta y_{j,i}^{\mathrm{inp}})^2 + (\Delta y_{j,i}^{\mathrm{fin}})^2$$







Comparison of individual observables

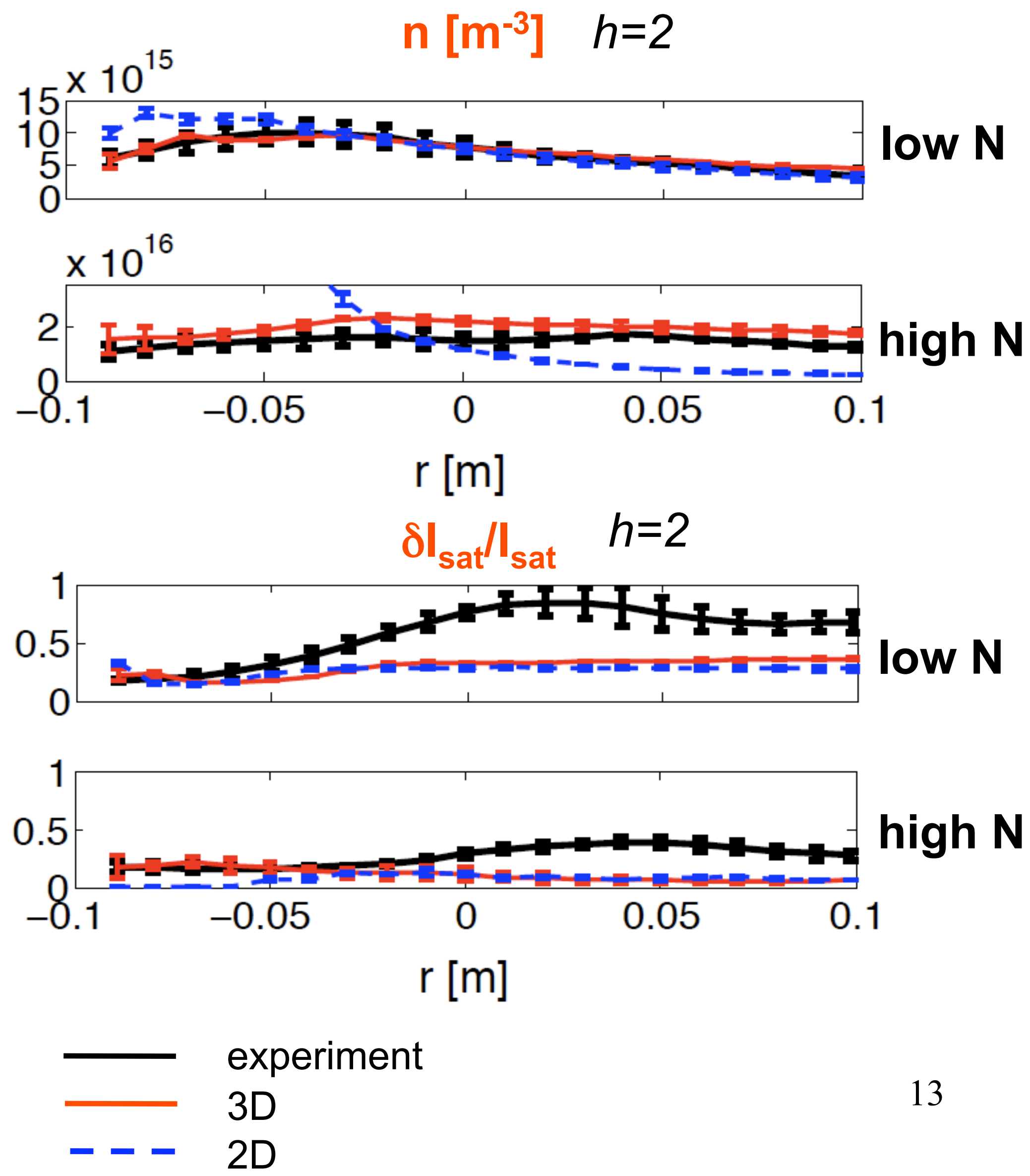
$$d_j = \sqrt{\frac{1}{N_j}\sum_{i=1}^{N_j}\frac{(x_{j,i}-y_{j,i})^2}{\Delta x_{j,i}^2+\Delta y_{j,i}^2}}$$

d_{2D}=1.3
d_{3D}=0.8

d_{2D}=7.8
d_{3D}=2.0

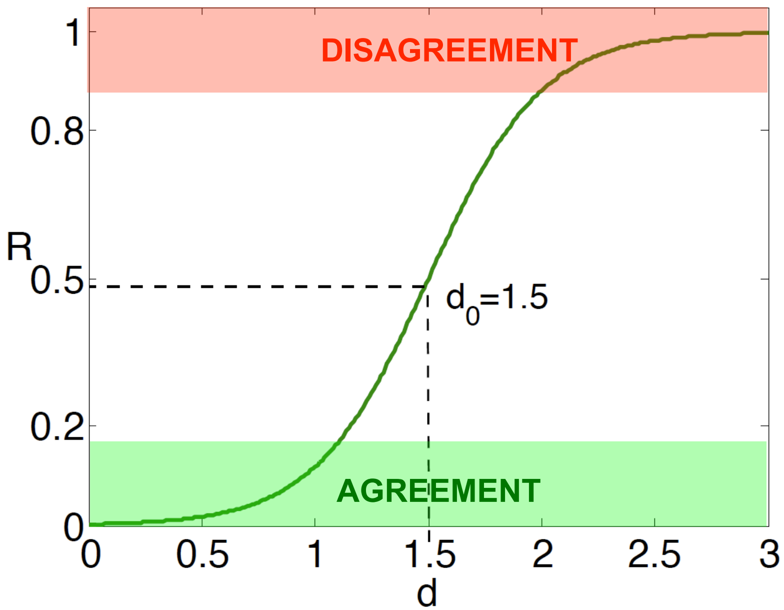
d_{2D}=4.5
d_{3D}=3.9

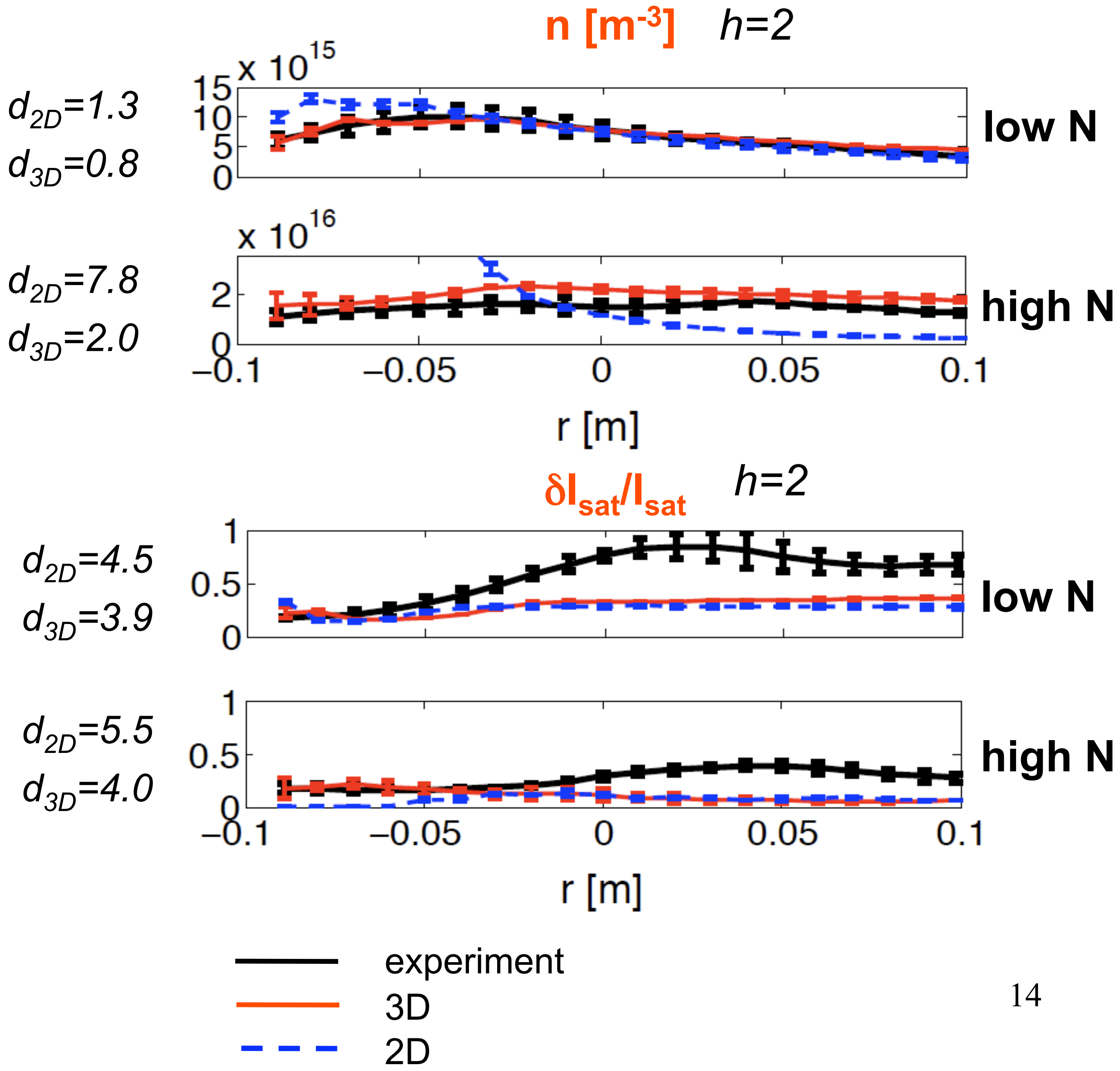
d_{2D}=5.5
d_{3D}=4.0



Comparison of individual observables

$$R_j = \frac{\tanh[(d_j - d_0)/\lambda] + 1}{2}$$





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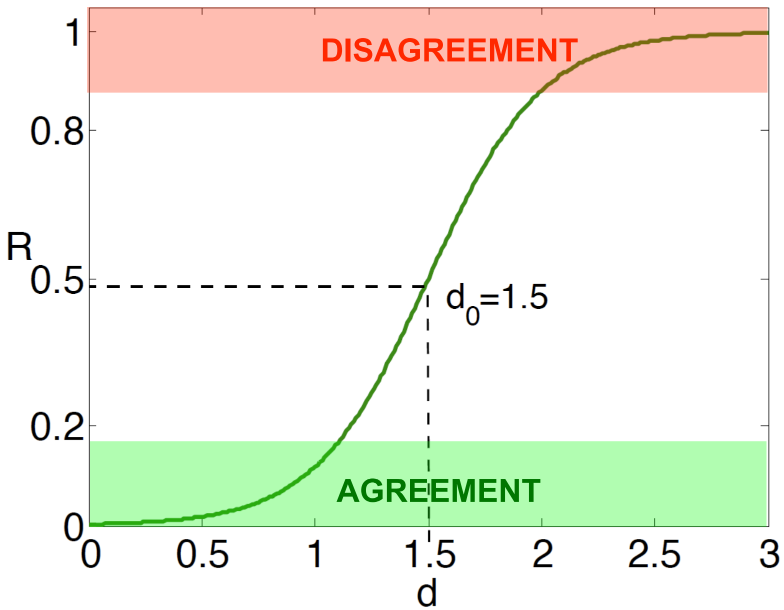
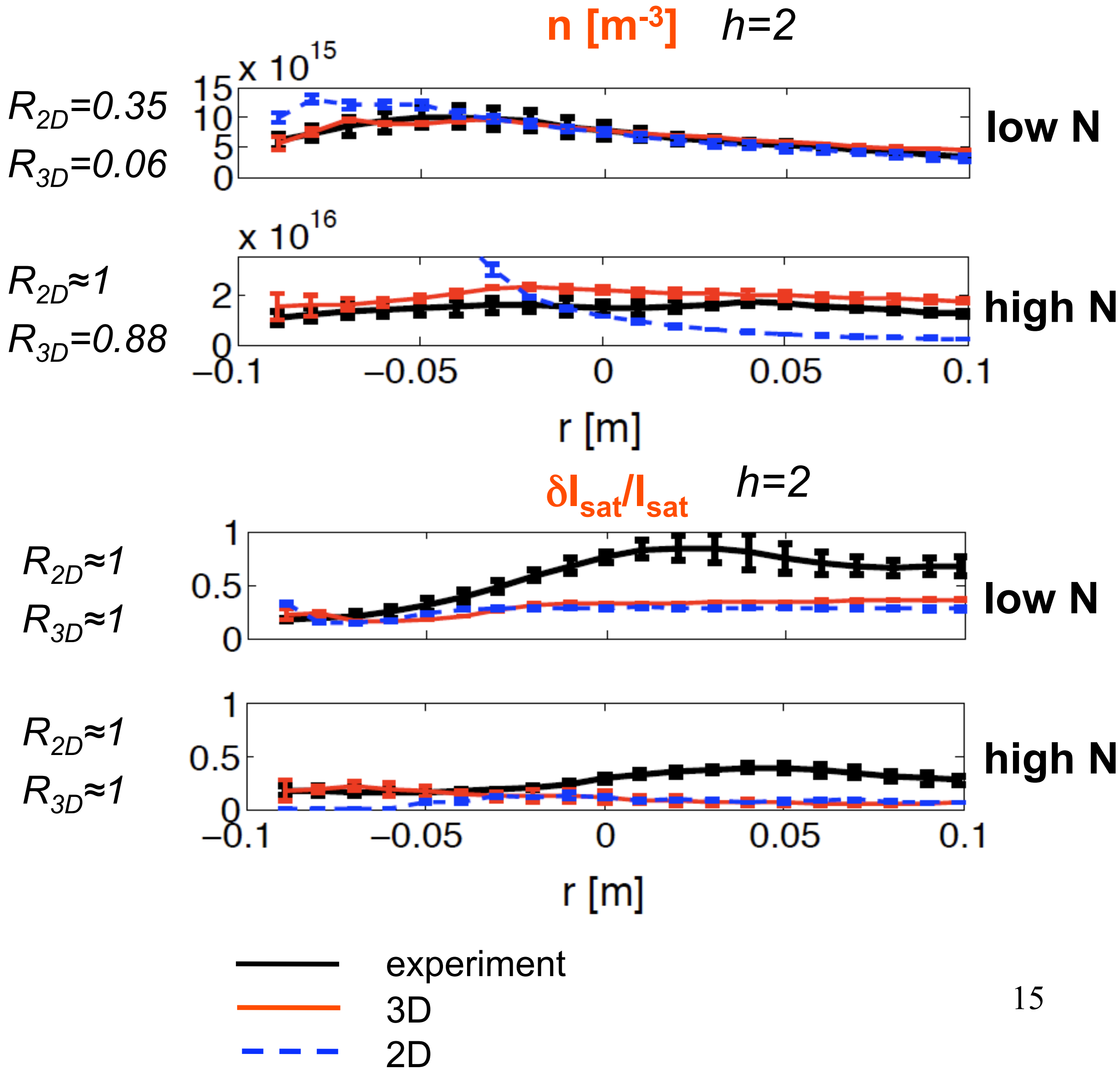
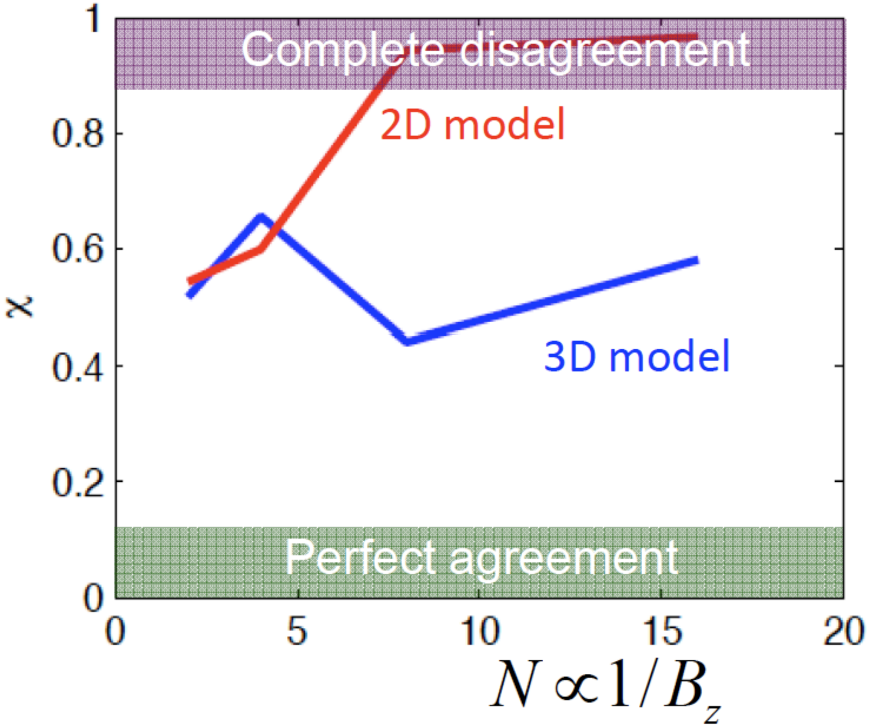




Global agreement

$$\chi = \frac{\Sigma_j R_j H_j S_j}{\Sigma_j H_j S_j}$$

$$Q = \sum_j H_j S_j$$



$$R_j = \frac{\tanh[(d_j - d_0)/\lambda] + 1}{2}$$

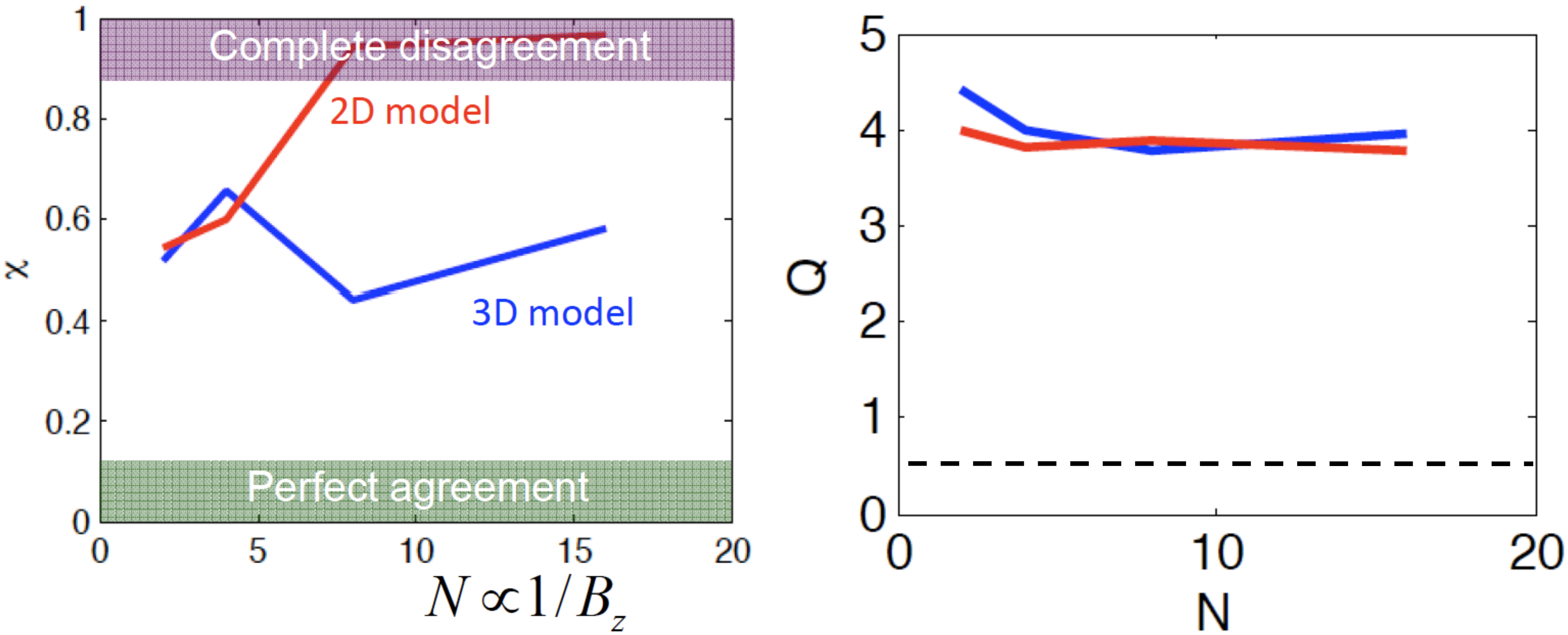
$$H_j = 1/h_j$$

$$S_j = \exp\left(-\frac{\Sigma_i \Delta x_{j,i} + \Sigma_i \Delta y_{j,i}}{\Sigma_i |x_{j,i}| + \Sigma_i |y_{j,i}|}\right)$$

Global agreement

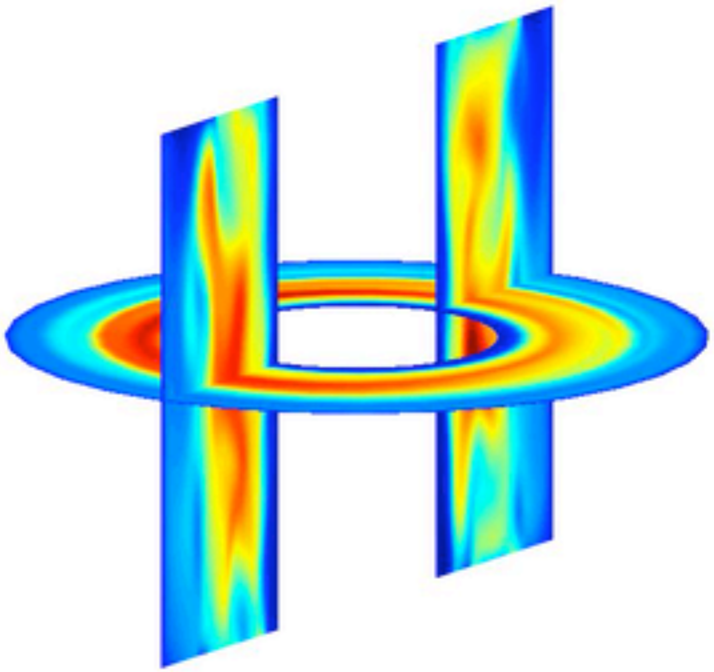
$$\chi = \frac{\Sigma_j R_j H_j S_j}{\Sigma_j H_j S_j}$$

$$Q = \sum_j H_j S_j$$



Interpretation

low N

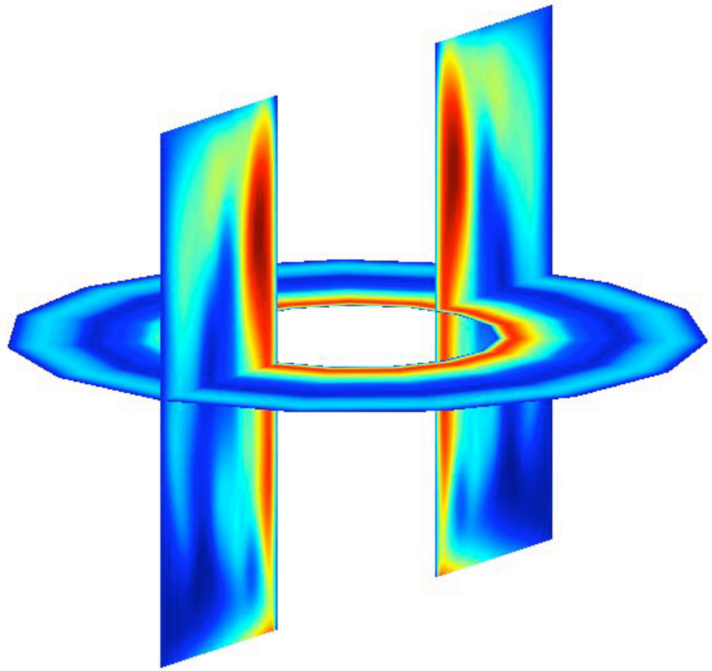


$k_{||} = 0$

$k_{tor} \neq 0$

$k_{ver}\ \alpha\ N$

high N



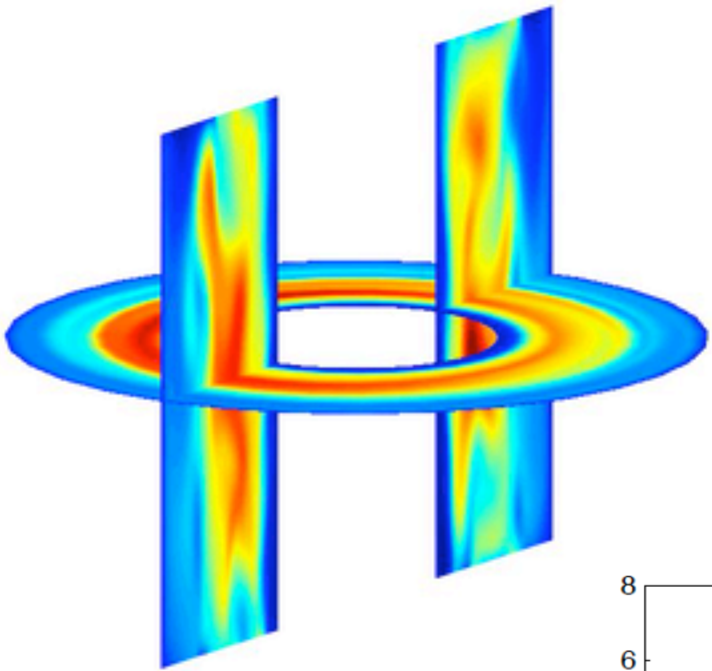
$k_{||} \neq 0$

$k_{tor} = 0$

$k_{ver} \approx 0$

Interpretation

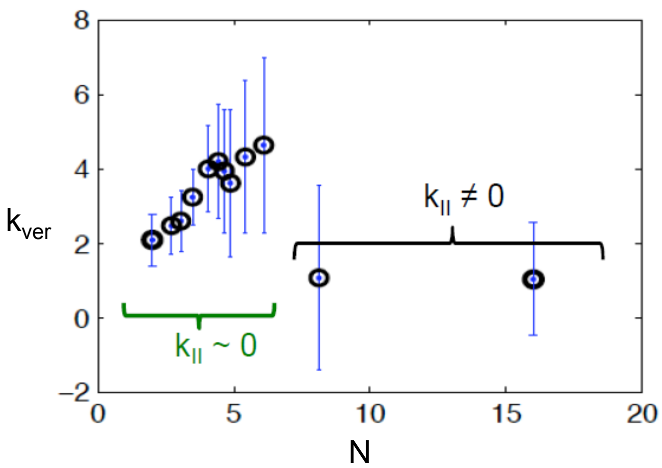
low N



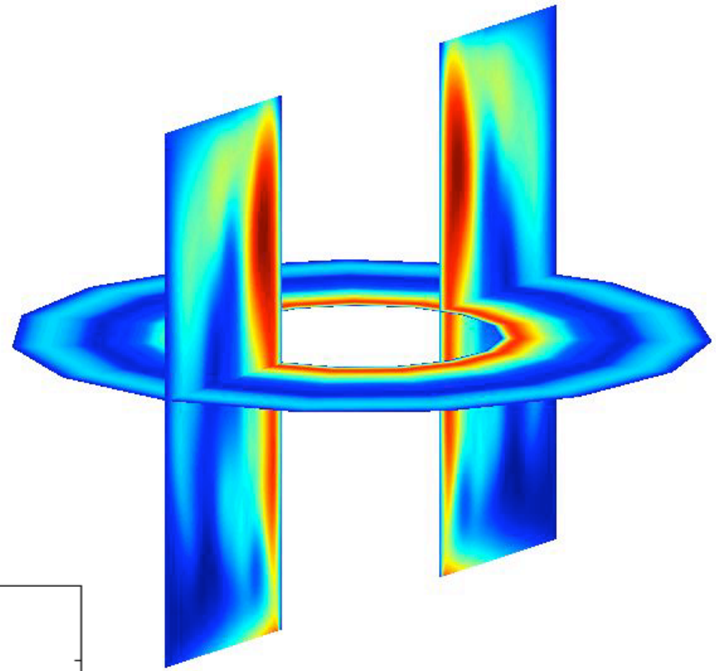
$k_{||} = 0$

$k_{tor} \neq 0$

k_{ver} α N



high N



$k_{||} \neq 0$

$k_{tor} = 0$

$k_{ver} \approx 0$

Conclusions

Achievements of the validation project [1],[2] :

1. Assess the predictive capabilities of a code

3D simulations predict (within error bars) profiles of n, Φ, I_{sat}, and k_v, k_{tor}, but fail at predicting profiles of T_e and fluctuation levels.

2D simulations agree similarly to 3D only for low N.

2. Compare codes

Global 3D simulations are needed to describe the plasma dynamics **at high N**.

3. Assess the relative importance of missing physics

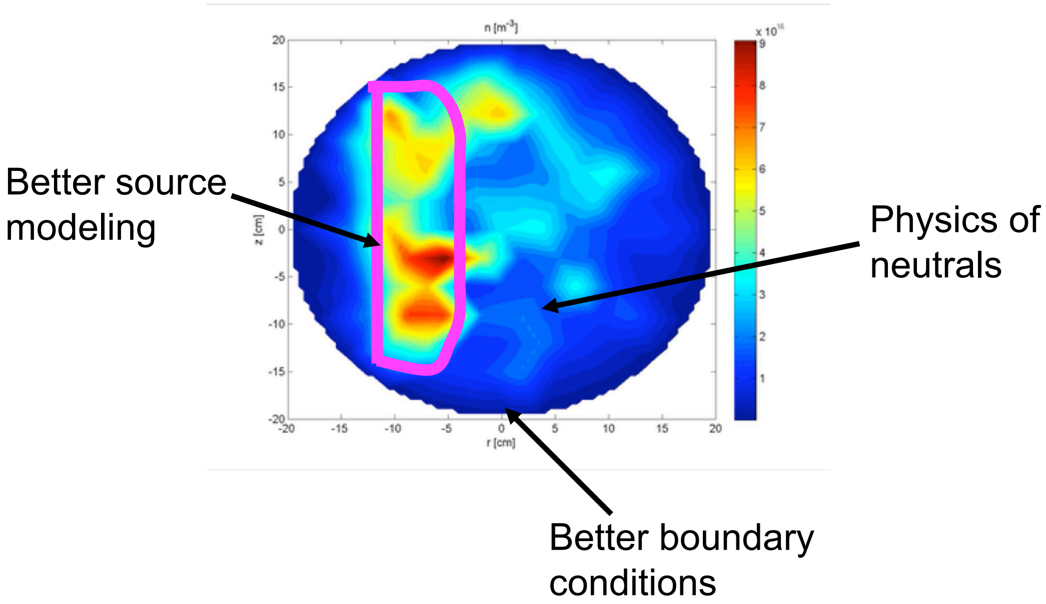
More accurate boundary conditions and source modeling, implementation of plasma-neutral collisions, etc.

[1] P. Ricci *et al.*, Langmuir probe-based observables for plasma-turbulence code validation and application to the TORPEX basic plasma physics experiment, PoP 2009.

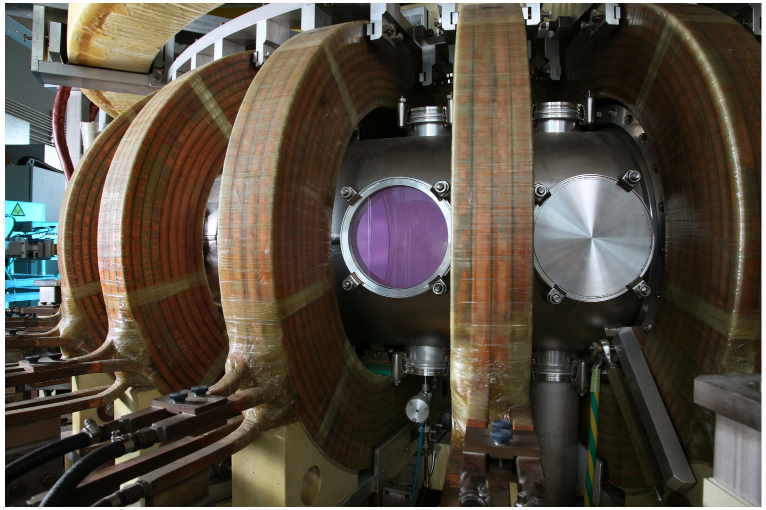
[2] P. Ricci *et al.*, Methodology for turbulence code validation: quantification of simulation-experiment agreement and application to the TORPEX experiment, PoP 2011.

Future work

Missing ingredients for a complete description of plasma dynamics in TORPEX:



Use of other diagnostics as Mach probes, Triple probes or Bdot probes to compare other interesting observables.



V&V

A validation project requires a four step procedure:

(i) Model qualification

(ii) Code verification

(iii) Definition and classification of observables

(iv) Quantification of agreement

$$\frac{\partial n}{\partial t} = R[\phi, n] + 2\left(n\frac{\partial T_e}{\partial y} + T_e\frac{\partial n}{\partial y} - n\frac{\partial \phi}{\partial y}\right) + D_n \nabla_\perp^2 n - n\frac{\partial V_{\|e}}{\partial z} - V_{\|e}\frac{\partial n}{\partial z} + S_n, \tag{1}$$

$$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = R[\phi, \nabla_\perp^2 \phi] - V_{\|i}\frac{\partial \nabla_\perp^2 \phi}{\partial z} + 2\left(\frac{T_e}{n}\frac{\partial n}{\partial y} + \frac{\partial T_e}{\partial y}\right) + \frac{1}{n}\frac{\partial j_\|}{\partial z} - \frac{\eta_{0i}}{n}\left(2\frac{\partial^2 V_{\|i}}{\partial y\, \partial z} + \frac{\partial^2 \phi}{\partial y^2}\right) + D_\phi \nabla_\perp^4 \phi, \tag{2}$$

$$\frac{\partial T_e}{\partial t} = R[\phi, T_e] - V_{\|e}\frac{\partial T_e}{\partial z} + \frac{4}{3}\left(\frac{7}{2}T_e\frac{\partial T_e}{\partial y} + \frac{T_e^2}{n}\frac{\partial n}{\partial y} - T_e\frac{\partial \phi}{\partial y}\right) + D_T \nabla_\perp^2 T_e + \frac{2}{3}\frac{T_e}{n}0.71\frac{\partial j_\|}{\partial z} - \frac{2}{3}T_e\frac{\partial V_{\|e}}{\partial z} + S_T, \tag{3}$$

$$\frac{m_e}{m_i}n\frac{\partial V_{\|e}}{\partial t} = \frac{m_e}{m_i}nR[\phi, V_{\|e}] - \frac{m_e}{m_i}nV_{\|e}\frac{\partial V_{\|e}}{\partial z} - T_e\frac{\partial n}{\partial z} + n\frac{\partial \phi}{\partial z} - 1.71n\frac{\partial T_e}{\partial z} + n\nu j_\| + \frac{4}{3}\eta_{0e}\frac{\partial^2 V_{\|e}}{\partial z^2} + \frac{2}{3}\eta_{0e}\frac{\partial^2 \phi}{\partial y\, \partial z} - \frac{2}{3}\frac{\eta_{0e}}{n}\frac{\partial^2 p_e}{\partial z\, \partial y} + D_{V_e}\nabla_\perp^2 V_{\|e}, \tag{4}$$

$$n\frac{\partial V_{\|i}}{\partial t} = nR[\phi, V_{\|i}] - nV_{\|i}\frac{\partial V_{\|i}}{\partial z} - T_e\frac{\partial n}{\partial z} - n\frac{\partial T_e}{\partial z} + \frac{4}{3}\eta_{0,i}\frac{\partial^2 V_{\|i}}{\partial z^2} + \frac{2}{3}\eta_{0,i}\frac{\partial^2 \phi}{\partial y\, \partial z} + D_{V_i}\nabla_\perp^2 V_{\|i}, \tag{5}$$