Fundamental aspects of edge physics – a brief overview of our ER achievements
Disentangling fundamental edge phenomena

- TURBULENT RADIAL TRANSPORT
- NEUTRAL ATOMS, ATOMIC PHYSICS
- IMPURITIES
- PARALLEL TRANSPORT
- SHEATH PHYSICS
In simple configurations, we can simulate this complexity using first-principles codes.

... and disentangle it, e.g.

\[
L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_{\phi}^{-4/7} T_{e,LCFS}^{-2/7} n_{e,LCFS}^{2/7} \left(1 + \frac{T_{i,LCFS}}{T_{e,LCFS}}\right)^{1/7}
\]

in good agreement with experimental results.
A collective theoretical effort...

BOUT++

HESEL

TOKAM3X

GBS
A collective theoretical effort...

BOUT++

- Different assets:
  - BOUT++ (flexibility, …)
  - HESEL (manageability, …)
  - GBS (accurate model, …)
  - TOKAM3X (advanced geometry, …)

- Ideal for validation exercises, by implementing different models

HESEL

TOKAM3X

GBS
...together with a collective experimental effort
Summarizing our activities...

- Our simulation approach
- Verification and Validation
- Our main achievements
- What’s next?
Our plasma models to evolve edge turbulence

Fluid model

Collisional Plasma

Drift-reduced fluid model

\[ \rho_i \ll L, \ \omega \ll \Omega_{ci} \]

\( T_e, T_i, \Omega \) (vorticity) → similar equations

\( V_{||e}, V_{||i} \) → parallel momentum balance

\[ \nabla^2 \phi = \Omega \]

We implemented energy conserving collisions, finite \( T_i \) and advanced boundary conditions [Madsen, PoP 2016; Olsen, PPCF 2016; Dudson, PPCF submitted]
Our models to evolve neutrals self-consistently

+ kinetic neutrals

\[
\frac{\partial f_n}{\partial t} + \mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}} = -\nu_{\text{ion}} f_n - \nu_{\text{CX}} (f_n - n_n f_i / n_i) + \nu_{\text{rec}} f_i
\]

STREAMING
IONIZATION \( \nu_{\text{ion}} = n \langle v_e \sigma_{\text{ion}} \rangle \)

CHARGE EXCHANGE \( \nu_{\text{CX}} = n \langle v_{\text{rel}} \sigma_{\text{CX}}(v_{\text{rel}}) \rangle \)

RECOMBINATION \( \nu_{\text{rec}} = n \langle v_e \sigma_{\text{rec}} \rangle \)

Wersal & Ricci, NF 2015

or fluid, or diffusive neutral, or coupling with EIRENE

Thrysøe, PPCF 2016; J. Leddy, JNM (in press)

Solved in 2D or 3D geometry, taking into account plasma outflow from the core, turbulent transport, ionization and charge exchange processes, and losses at the vessel
Code verification, the techniques

1) Simple tests
2) Code-to-code comparisons (benchmarking)
3) Convergence tests
4) Order-of-accuracy tests

Only verification ensuring convergence and correct numerical implementation

Riva et al., PoP 2014; Ricci et al., PoP 2015
Order-of-accuracy tests

Our model: $A(f) = 0$, $f$ unknown

We solve $A_n(f_n) = 0$, but $\epsilon_n = f_n - f = ?$

Method of manufactured solution:

1) we choose $g$, then $S = A(g)$

2) we solve: $A_n(g_n) - S = 0$

For GBS:

For $GBS$: $\epsilon \sim h^2$
Order-of-accuracy tests, MMS

Our model: \( A(f) = 0, \ f \) unknown

We solve \( A_n(f_n) = 0, \) but \( \epsilon_n = f_n. \)

Method of manufactured solution:

1) we choose \( g \) then
2) we solve:

For GBS:

\[ n T v \parallel i, v \parallel e, \omega, \Phi \]

All our codes verified with MMS

[Riva, PoP 2014; Dudson, PoP 2016; Tamain, JCP 2016]

\[ \epsilon_n = g_n - g \]
Order-of-accuracy tests, MMS

Our model: \( A(f) = 0, \ f \) unknown

We solve \( \epsilon_n = f_n \), but

\[
A(n(f_n)) = 0, \quad \epsilon_n = f_n
\]

We also developed new verification techniques

Method of manufactured solutions with MMS

1) we choose \( \epsilon \sim h^2 \)

2) we solve

For GBS:

\[
g \Rightarrow h^2 = \frac{\Delta x}{\Delta x_0} = \frac{\Delta y}{\Delta y_0} = \left(\frac{\Delta t}{\Delta t_0}\right)^2
\]

All our considerations are based on:

[Cartier-Michaud, PoP 2016; F. Riva, PoP (in press)]

[Riva, PoP 2014; D. Doan, PoP (in press) – 2016]
A stepladder approach

Motivation

The plasawall transition

GBS turbulence simulations

Sheath e

ects on turbulence

Conclusions

The GBS code

Developed by steps of increasing complexity

Drift-reduced Braginskii equations

Global, 3D, Flux-driven, Full-

[Ricci et al PPCF 2012]

Jx Loizu et al

13 z 24 The role of the sheath in magnetized plasma fluid turbulence

TORPEX, SPC

TCV, SPC

TORE-SUPRA, CEA

ISTTOK, IST

MAST, CCFE

RFX, Padua

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A stepladder approach

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The GBS code

Examples of 3D simulations

The GBS code, a tool to simulate open field line turbulence

Developed by steps of increasing complexity

Drift-reduced Braginskii equations

Global, 3D, Flux-driven, Full-

[Ricci et al PPCF 2012]

Jx Loizu et al 2013

The role of the sheath in magnetized plasma fluid turbulence

TORPEX, SPC

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RFX, Padua
The Simple Magnetized Plasma (SMT) TORPEX
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TORPEX key elements

Source (EC and UH resonances)
Plasma gradients
Parallel dynamics and losses
Magnetic curvature

Unique diagnostic capabilities
Blob dynamics in TORPEX

Used 5 models to simulate TORPEX blobs

Showed importance of sheath currents and equilibrium flows

[Riva et al., PPCF (2016)]
A stepladder approach

Understanding of
- Turbulence driving mechanisms
- Blob properties
- Turbulent regimes

Exp/sim discrepancy
- Fluctuation amplitude

The GBS code, a tool to simulate open field line turbulence

Developed by steps of increasing complexity
- Drift-reduced Braginskii equations
- Global, 3D, Flux-driven, Full-
  \[ \text{Ricci et al PPCF 2012} \]

Examples of 3D simulations

TORPEX, SPC

MAST, CCFE

ISTTOK, IST

TORE-SUPRA, CEA

TCV, SPC

RFX, Padua
**A stepladder approach**

- **Motivation**
- The plasmawall transition
- GBS turbulence simulations
- Sheath effects on turbulence

**Conclusions**

The GBS code, a tool to simulate open field line turbulence developed by steps of increasing complexity:

- Drift-reduced Braginskii equations
- Global, 3D, Flux-driven, Full

Ricci et al PPCF 2012

Jx Loizu et al 13 z 24 The role of the sheath in magnetized plasma fluid turbulence

TORPEX, SPC

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TORE-SUPRA, CEA

Limited SOL

RFX, Padua

MAST, CCFE
Full-turbulence simulation, a large validation effort

Simulations carried out with 4 codes
[Jorge, PoP 2016]

What is the heat flux to the wall? i.e., the SOL width and temperature drop?
Recent measurements: 2 scale lengths

Infrared Measurement in TCV and COMPASS

[Nespoli et al., JNM 2015
Nespoli et al., NME (in press)]

ITER inner wall was redesigned
The role for the shear flow was also pointed out for the formation of an H-mode like transport barrier [Madsen PPCF 2015; Nielsen PLA 2015; Rasmussen PPCF 2016]
Far SOL transport dominated by blobs

A shoulder forms with increasing collisionality and connection length [Nielsen PPCF 2017]
Scaling for the SOL width

\[ L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_{\phi}^{-4/7} T_{e,\text{LCFS}}^{-2/7} n_{e,\text{LCFS}}^{2/7} \left( 1 + \frac{T_{i,\text{LCFS}}}{T_{e,\text{LCFS}}} \right)^{1/7} \]
Upstream/limiter temperature drop

\[ T_e \]

Time Average

\[ \langle T_e \rangle \]

\begin{align*}
 n_0 &= 5 \cdot 10^{12} \text{cm}^{-3} \\
 n_0 &= 5 \cdot 10^{13} \text{cm}^{-3}
\end{align*}

Christoph Wersal - EPFL, SPC

Neutrals in the turbulent tokamak edge 22 / 43

Introduction
Model
GBS
Insights
Conclusions

Simulations with different densities

\begin{align*}
 n_0 &= 5 \cdot 10^{12} \text{cm}^{-3} \\
 n_0 &= 5 \cdot 10^{13} \text{cm}^{-3}
\end{align*}

Time
Average

\begin{align*}
 T_e &
\end{align*}

\begin{align*}
 T_{e,u} &
\end{align*}

\begin{align*}
 T_{e,t} &
\end{align*}

- L
S
L

\begin{align*}
 n_0 = 5 \cdot 10^{12} \text{cm}^{-3} \\
 n_0 = 5 \cdot 10^{13} \text{cm}^{-3}
\end{align*}

Wersal, PPCF 2017
Upstream/limiter temperature drop

Simple two-point model

Refined two-point model

$T_{e,u}/T_{e,t}$ (Two point model)

$T_{e,u}/T_{e,t}$ (Simulation)

$T_{e,u}/T_{e,t}$ (Simulation)

Wersal, PPCF 2017
A stepladder approach

Understanding of
- Basic mechanisms at play
- Fluctuation properties
- SOL width
- Plasma rotation and potential

Exp/sim discrepancy
- Narrow feature strength
A stepladder approach

Diverted SOL

GBS turbulence simulations

GBS code

Examples of 3D simulations

Developed by steps of increasing complexity

Drift-reduced Braginskii equations

Global, 3D, Flux-driven, Full-

[\text{Ricci et al PPCF 2012}]

Jx Loizu et al

The role of the sheath in magnetized plasma fluid turbulence

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ISTTOK, IST
Large development of numerical algorithms

Non-orthogonal field aligned coordinate system to match arbitrary geometry [Leddy, CPC 2016]

Development of a non-field aligned coordinate system [Hill, CPC (in press)]

Extension to 3-D geometry [Shanahan, JP-CS 2016]
Study of blob dynamics in X point configuration

Blob in X point TORPEX configuration

[Avino, PRL 2016]

Simulations allowed understanding mechanisms determining blob velocity

[Shanahan, PPCF 2016]
Blobs in MAST double-null configuration

Visible light emission

Single blob identification

Initial conditions for simulations

Walkden, NME (submitted)
Blobs in MAST double-null configuration

Simulations carried out with 4 codes

BOUT++

GBS

TOKAM3X

HESEL
Blobs in MAST double-null configuration

Simulations carried out with 4 codes

- Perpendicular dissipation for stability
- Ion temperature for radial velocity
- Electron temperature for vertical velocity
- 3D effects for toroidal rotation

[ Militello, PPCF 2016 ]
Turbulence similar to limited case, except at X point; good agreement for parallel velocity

[D. Galassi, NF (in press)]
What’s next?

- Detailed analysis of **diverted** and **advanced exhaust** configurations

- Approach **H-mode** scenarios
  
  • Going beyond the **drift approximation**, using high order methods on unstructured meshes
    
    [Minjaud, JCP 2016]

  • Going beyond the Braginskii model, including **kinetic effects**
Concluding remarks

• By using first-principles approach, we can now disentangle the complex dynamics at the tokamak edge

• Significant advances in physics models and simulation capabilities, rigorously verified

• By using a stepladder approach, progress in physics understanding, starting from relatively simple configurations

• Leveraging this expertise, we are increasing the complexity of simulations, continually approaching target reactor conditions