EPFL

Validation of the theoretical scaling law for the H-mode density limit

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TSVV1 Progress Workshop, June 27-29, 2023

GBS Deliverables 2021-2023

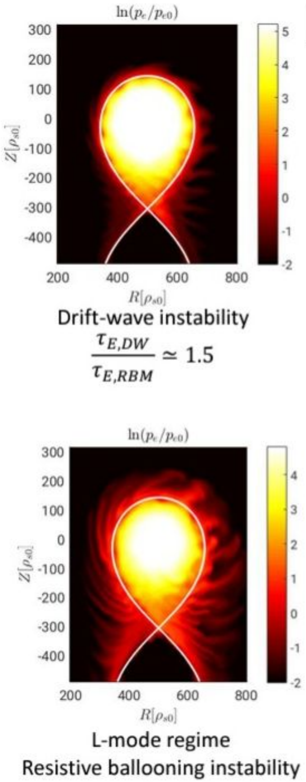
Within the topic of TSVV1 regarding **the physics of the LH transition,**

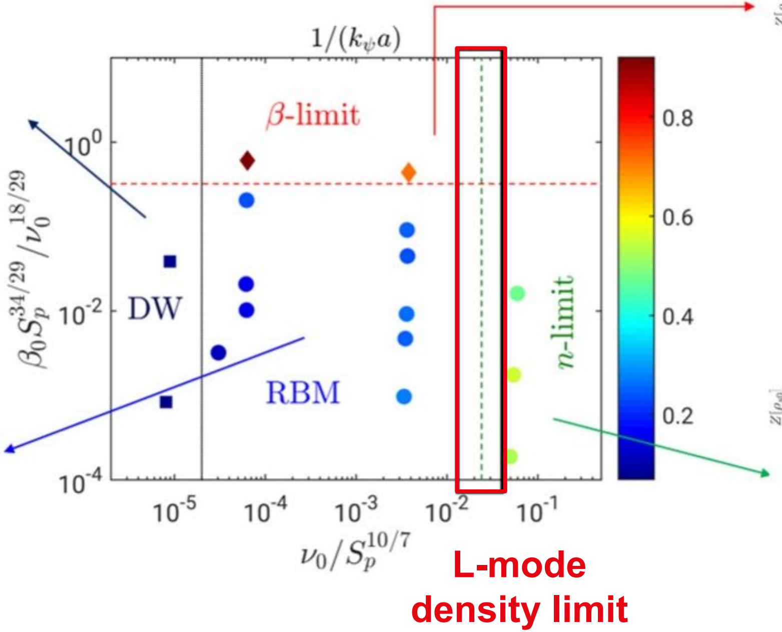
1. Predictive capabilities of the edge turbulence regime transitions based on a large scan of GBS simulations Its validation with experimental results

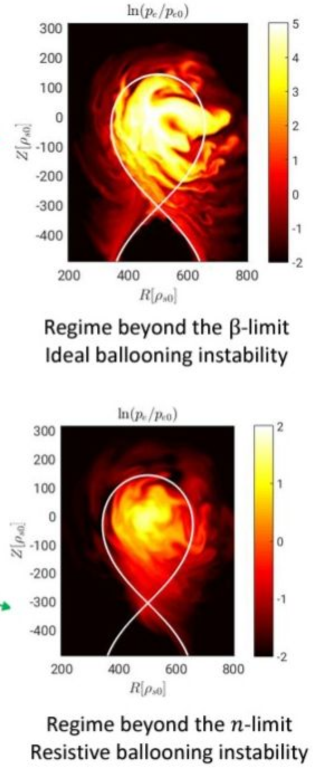
TSVV1 - GBS Milestones & deliverables:

a) Theory based scaling law for λ_q in L-mode plasma **[M. Giacomin, NF (2021)]**
b) L-mode density limit scaling law and its validation **[M. Giacomin, PRL (2022)]**
c) Identification of four turbulence regimes **[M. Giacomin, PoP (2022)]**
d) Extended scaling law in (a) including triangularity **[K. Lim, PPCF (2023)]**
e) Validation of the HL back transition scaling law derived in (c) **[In progress]**
f) Heat asymmetry scaling law in double-null (DN) configuration **[In preparation]**
g) Effect of negative triangularity on the L-mode density limit **[In 2024]**

Phase space of edge turbulence







In Ref. Giacomin and Ricci, PoP 22', an electromagnetic phase space of edge turbulence where four turbulent transport regimes are identified.

Different models for the density limit

Disruptions due to the density limit (DL) are typically described by the Greenwald scaling

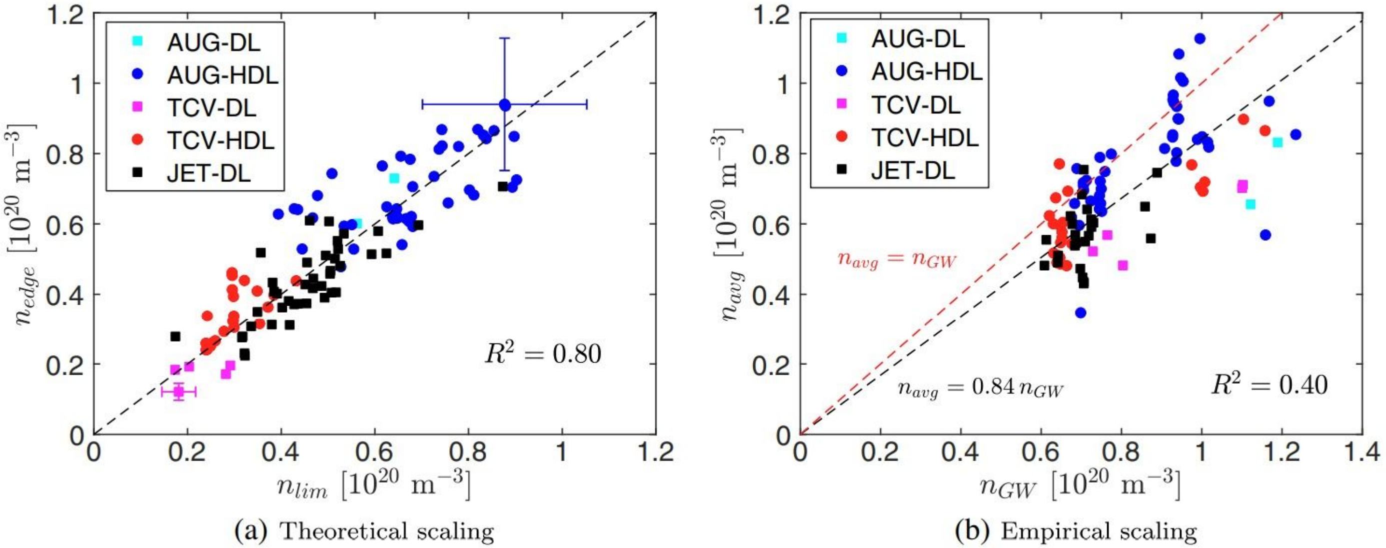
$$\bar{n}_{\mathrm{GW}} = \frac{I_{\mathrm{p}}}{\pi a^2}$$

The recently proposed models use different physical mechanisms:

(1) Radiation collapse **[Zanca 19' Storth 22']**
(2) Collapse of the outer shear layer **[Singh 22']**
(3) Enhancement of turbulence **[Rogers 98' LaBombard 07' Giacomin 22']**

Based on the idea (3), the L-mode density limit can be related to the transition of different turbulent regimes.

Validation of the first-principles density scaling law

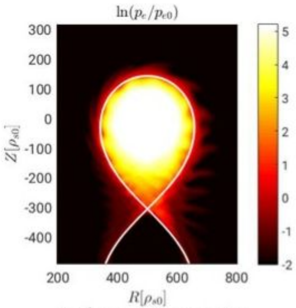


First-principles L-mode density limit scaling law in [Giacomin et al, RPL 22'] shows a good agreement with experimental data.

This indicates that the L-mode density limit is related to enhancement of RBM.

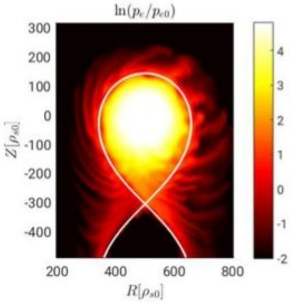
New scaling law revises the Greenwald scaling law, predicting a higher density limit in ITER.

Phase space of edge turbulence

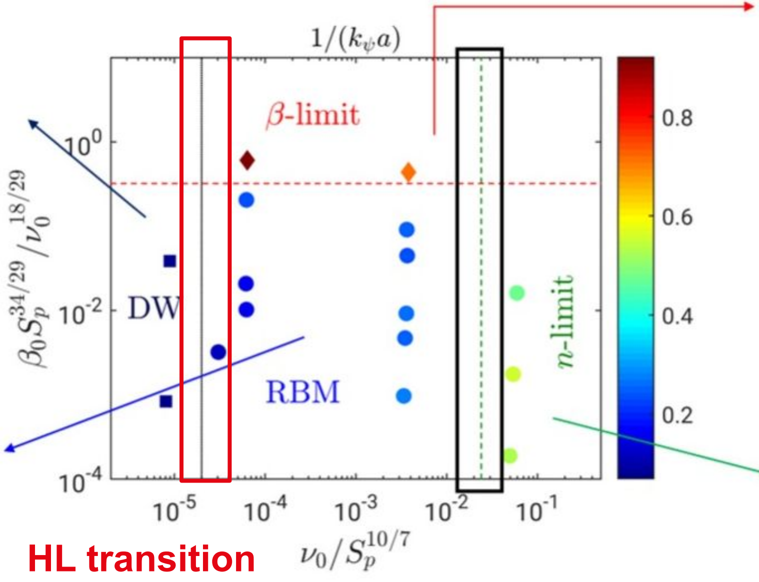


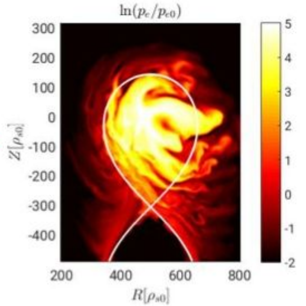
Drift-wave instability

$\frac{\tau_{E,DW}}{\tau_{E,RBM}} \simeq 1.5$

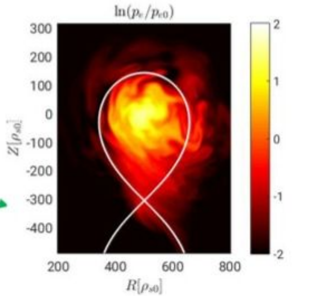


L-mode regime
Resistive ballooning instability





Regime beyond the β-limit
Ideal ballooning instability



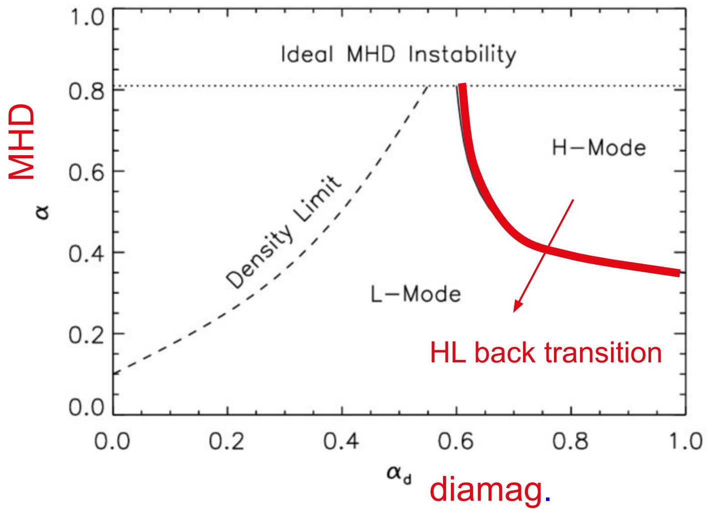
Regime beyond the n-limit
Resistive ballooning instability

In Ref. Giacomin and Ricci, PoP 22', an electromagnetic phase space of edge turbulence where four turbulent transport regimes are identified.

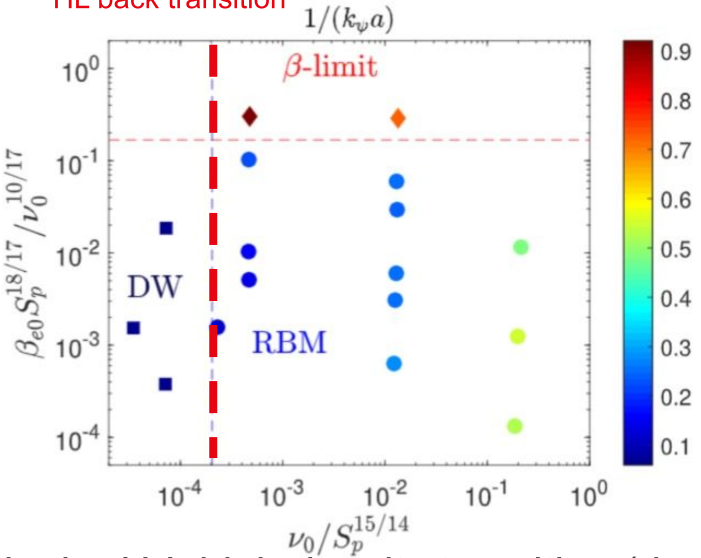
The transition from DW to RBM is associated with the H-mode density limit.

The goal of the work

Edge plasma phase space [Rogers 98']



Transition =
HL back transition



The validity of the fluid model is more justified in the H-L high density transition (due to high collisionality), compared to L-H transition.

Validation with experimental measurements: **TCV, AUG** and **JET**.

Derivation of the scaling law for HL transition

Based on the **gradient removal mechanism (1)** turbulence drive outward fluxes, **(2)** outward fluxes flatten gradients and **(3)** saturation, we consider turbulence is saturated when the radial gradient of the background plasma pressure is of the same order of the radial gradient of the pressure fluctuations. $\partial_r \bar{p}_e \sim \partial_r \tilde{p}_e$

The analytical estimate of the pressure gradient length L_p can be derived for both DW and BM regimes, based on the gradient removal mechanism.

$$L'_{p,\mathrm{RB}} \sim \left[\rho_*^{-1/29} L_\chi^{28/29} a^{-8/29} \nu_0^{14/29} q^{36/29} \bar{n}^{42/29} \chi_{\parallel e0}^{-8/29} L_\parallel^{8/29} S_p^{-20/29}\right]$$

$$L'_{p,\mathrm{DW}} \sim L_\chi^{7/11} \rho_*^{-4/11} a^{-4/11} q^{4/11} L_\parallel^{4/11} S_p^{-3/11} \chi_{\parallel e0}^{-4/11} \bar{n}^{7/11}$$

The transition occurs when $L_{p,RB} \sim L_{p,DW}$

Derivation of the scaling law for HL transition

By arranging the previous relation ($L_{p,RB} \sim L_{p,DW}$) for the estimate of the HL transition density, one obtains:

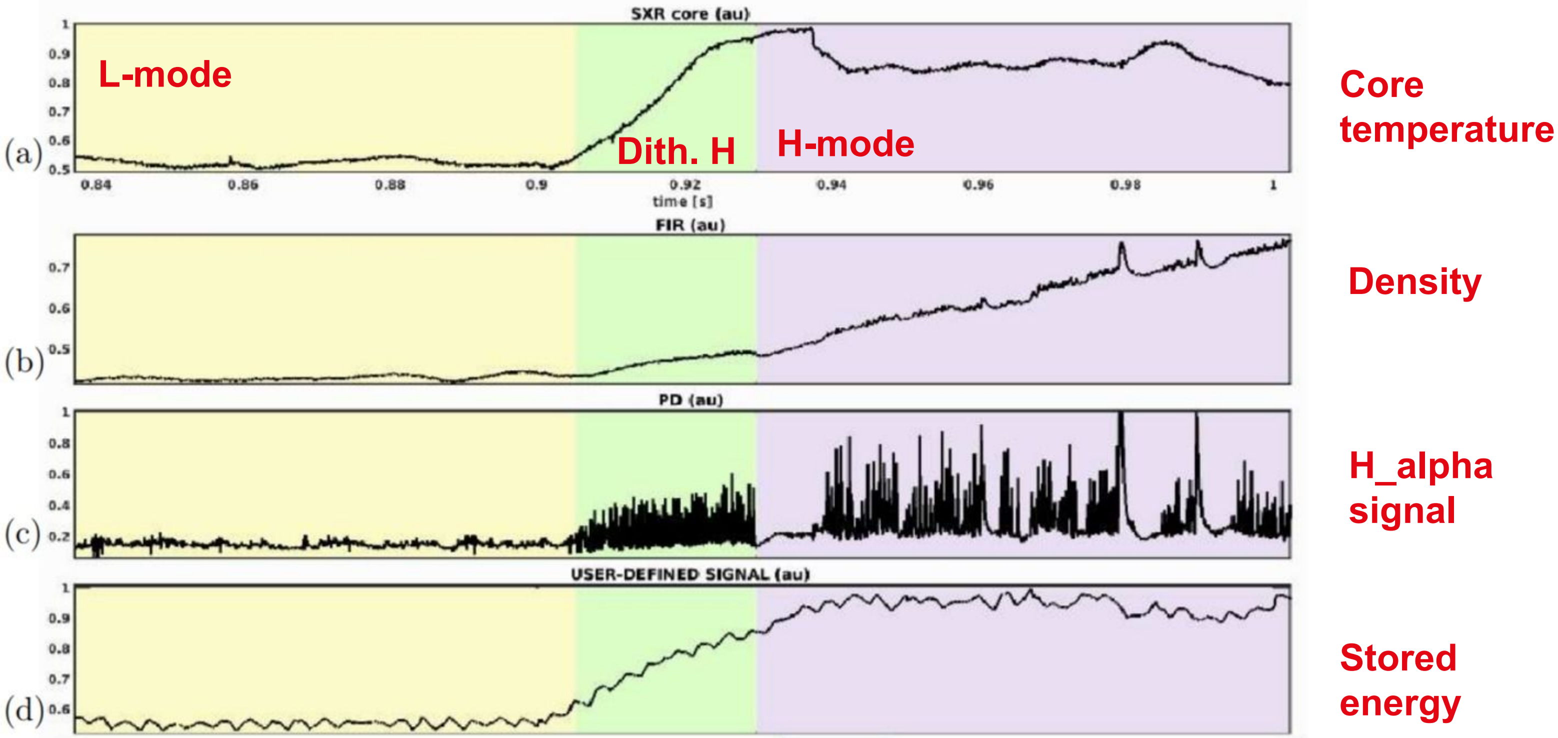
$$n'_{\rm HDL} \sim C_{\rm geo}^{-15/37} A^{8/37} P_{\rm SOL}^{19/37} a^{-19/37} q^{-36/37} R_0^{-22/37} B_T^{15/37}$$
$$\sim C_{\rm geo}^{-15/37} A^{8/37} P_{\rm SOL}^{19/37} R_0^{14/37} B_T^{-21/37} \frac{I_p^{36/37}}{a^{91/37}}$$

where $C_{\rm geo} \equiv 0.45\pi + 0.55\pi\kappa + 1.33\delta.$

The analytical scaling law is derived in both sheath- and conduction-limited regimes. However, in high-density scenario, the conduction-limited regime is more appropriate.

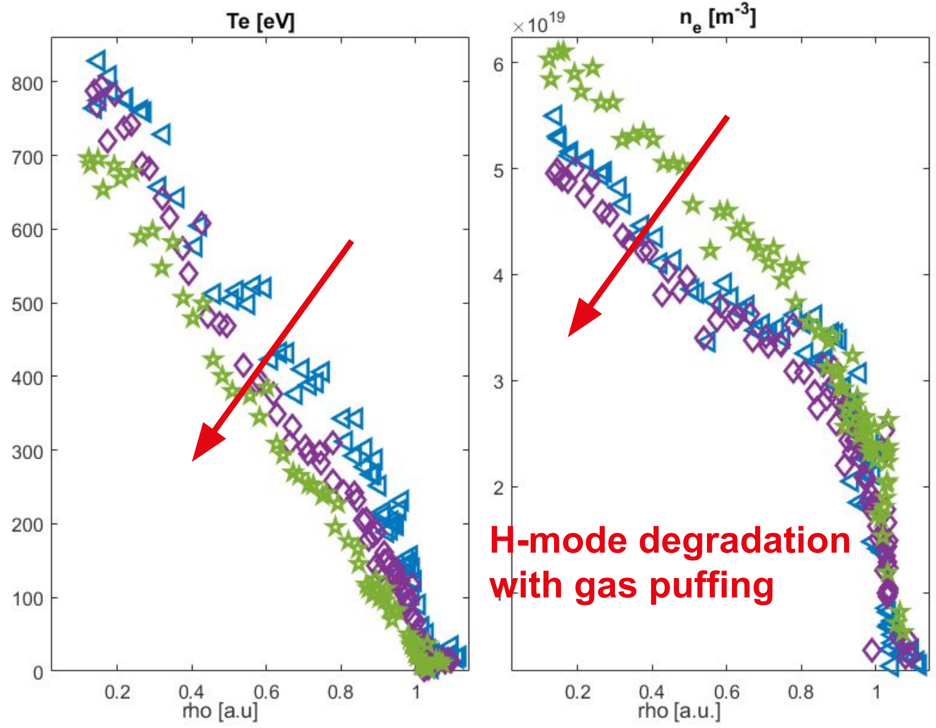
Label the HL back transition

TCV #65318 discharge

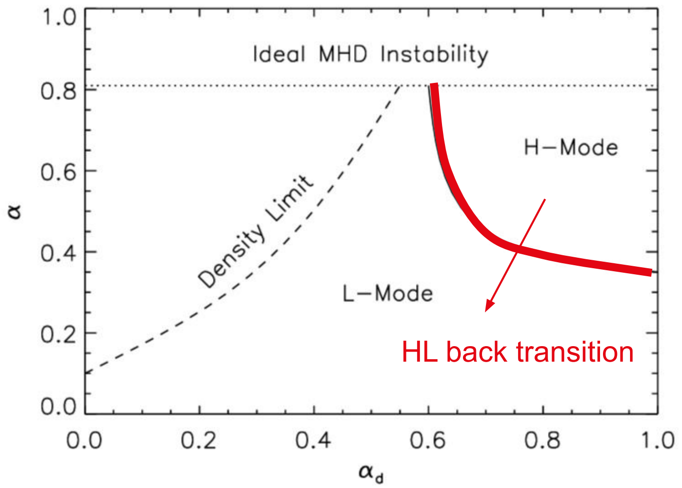


First of all, we label the time when the HL back transition occurs for each discharge.

Label the HL back transition



Edge plasma phase space [Rogers 98']



The prediction of the density when HL back transition occurs.

Different modes labelling in time

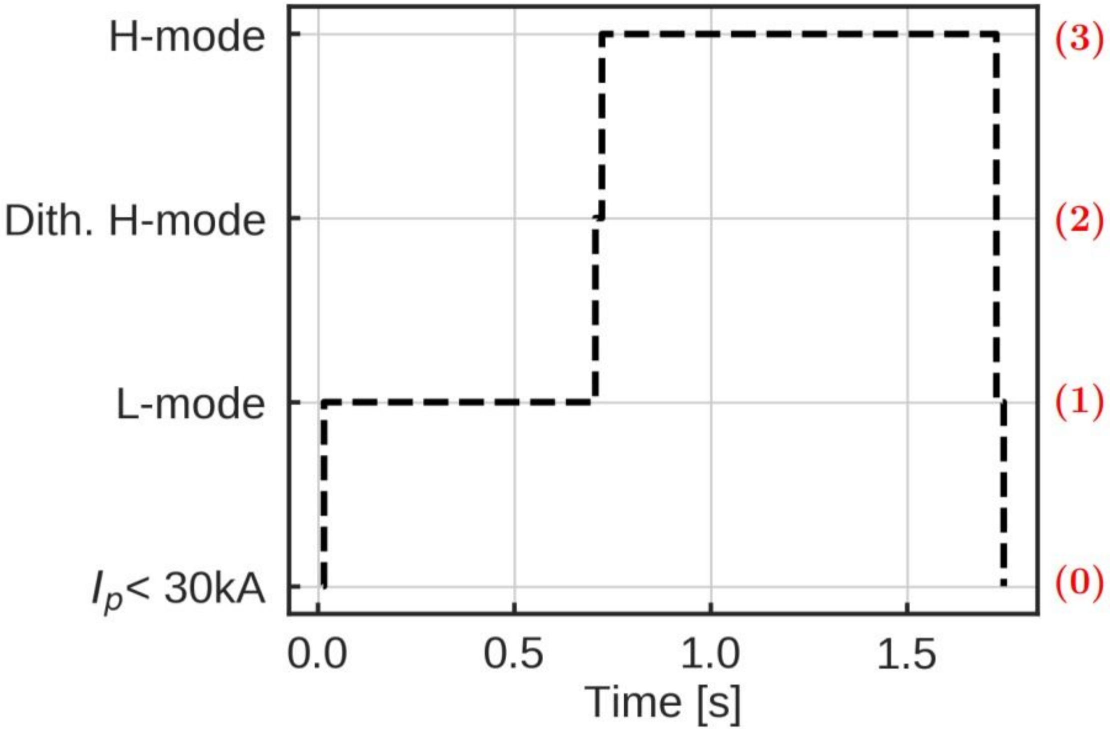
Different back transitions:

(3) to (2) : Dithering cycle

(3) to (1) : HL back transition

(3) to (0) : Disruption

We consider all of thems.



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Preliminary result of the scaling law

Two things should be noted that:

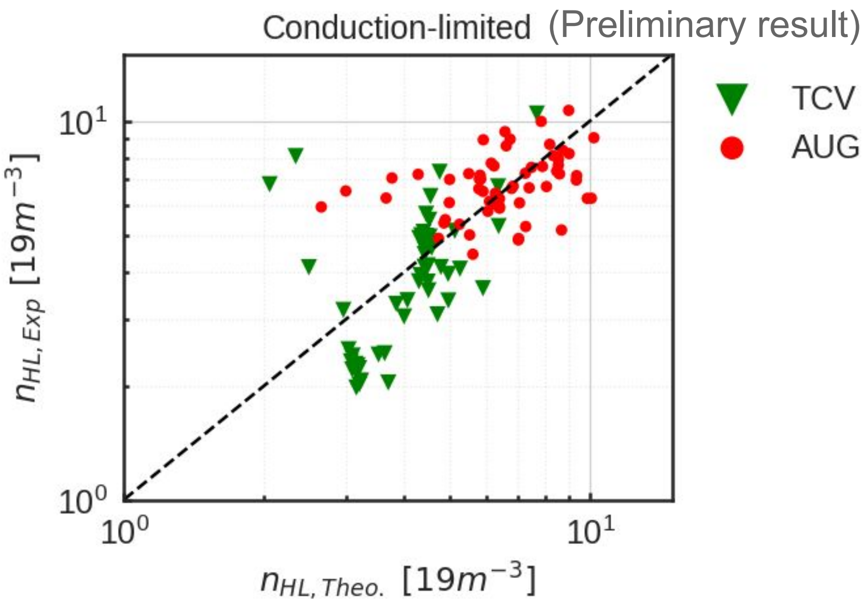
(1) The measurement of P_{SOL} leads to the biggest error (up to 40%)

(2) The signal is often polluted when the transition occurs. This requires to use a proper time window (a few ms before) to choose values of experimental dataset

H-dithering and disruption show some scattered points in the validation result.

JET data will be added as well and more accurate P_{SOL} and time window estimates carried out.

$$n'_{\mathrm{HDL}} \sim C_{\mathrm{geo}}^{-15/37} A^{8/37} P_{\mathrm{SOL}}^{19/37} a^{-19/37} q^{-36/37} R_0^{-22/37} B_T^{15/37}$$



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Conclusion & future works

The theoretical scaling law for the HL back transition, derived in Giacomin's paper, is validated against TCV and JET discharges.

Different transitions, i.e. Dithering cycle, HL transition and HL disruption, are considered.

The preliminary result with TCV and AUG discharges shows that some points are quite off, especially from H-mode to H-dithering.

Considering the uncertainty in P_{SOL} and the use of a proper time window are essential.

The additional JET data will clarify the validity of the scaling law.

Double-null (DN)

Double-null (DN) : alternative solution to ITER single-null

DN of particular interest:

- Four strike points to help handling heat load
- Two X-points for radiative losses
- Quiescent high-field side for safe antenna installation

DN is considered in present and future tokamaks

- TCV, MAST-U, AUG, WEST, DIII-D, EAST, KSTAR, SPARC, DTT

Alternative exhaust solution to ITER single-null

First GBS-DN simulations carried out in [Beadle JPP 21'], as well as the derivation of the density length L_n and its comparison.

Magnetic equilibrium generated with current carrying coils

Gaussian current carrying coils:

1 magnetic axis + 7 external

By adjusting amplitude of each coil, one can generated balanced/unbalanced DN config.

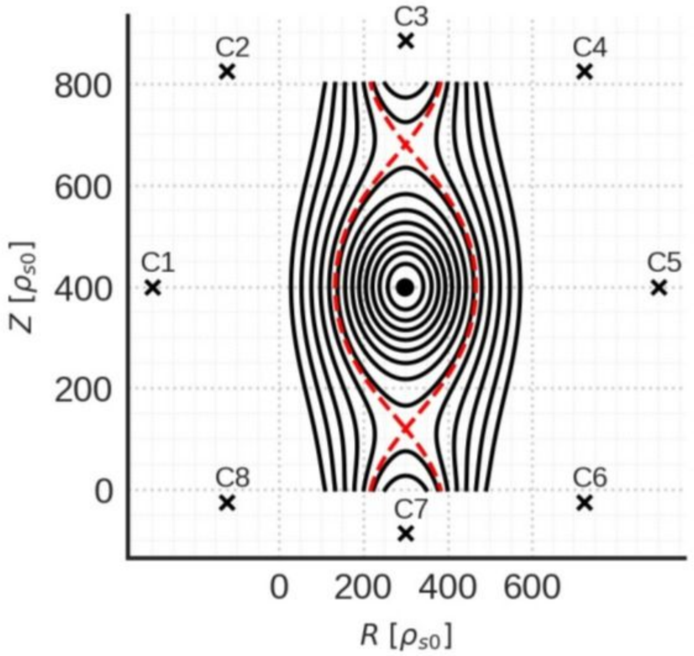

FIG. 1: Magnetic equilibrium profile used for the nonlinear GBS double-null simulations. The black cross represent the position of the coils carrying current that generated the magnetic field. The red dashed line is the separatrix.

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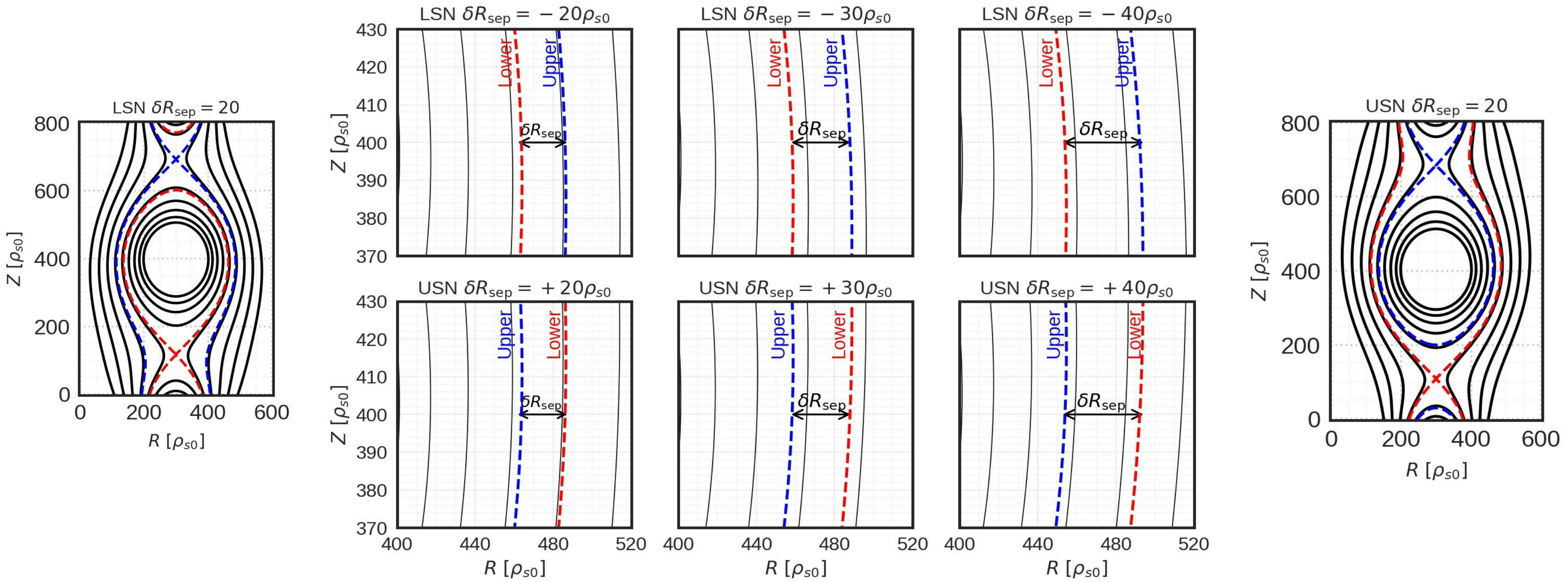
Scan of the values of dR_{sep} in unbalanced DN



1. **The inter-separatrix distance dR_{sep}** is an important parameter determining power sharing between upper and lower targets.

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The derivation of the characteristic pressure length L_p

The pressure gradient length L_p in DN is identical to the SN cases.

$$L_p \sim \mathcal{C}(\kappa, \delta, q)\left[\rho_*(\nu_0 \bar{n} q^2)^2 \left(\frac{L_\chi \bar{p}_e}{S_p}\right)^4\right]^{1/3}$$

with C = geometrical factors

The values of dR_{sep} have no impact on the turbulence -> same Lp

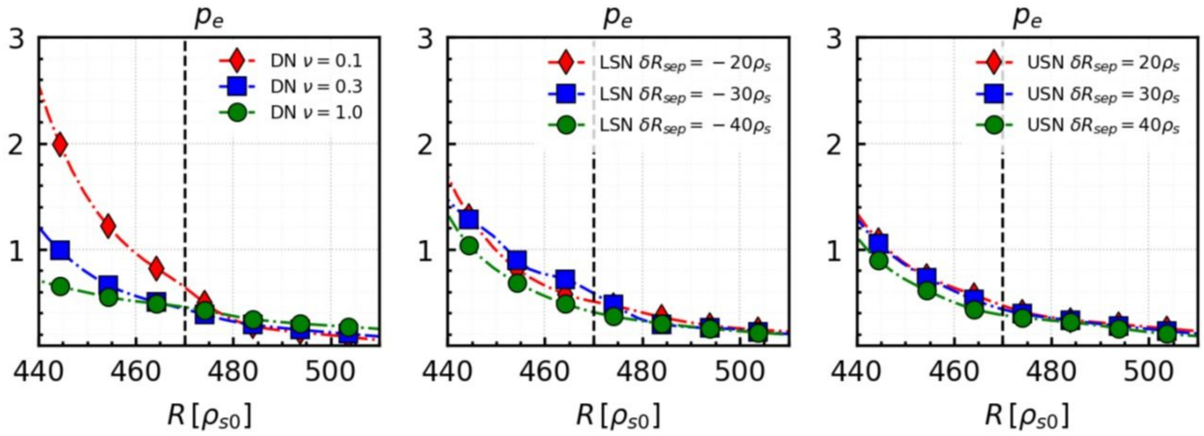
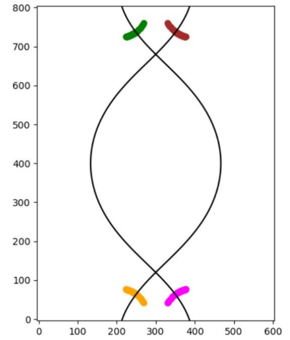


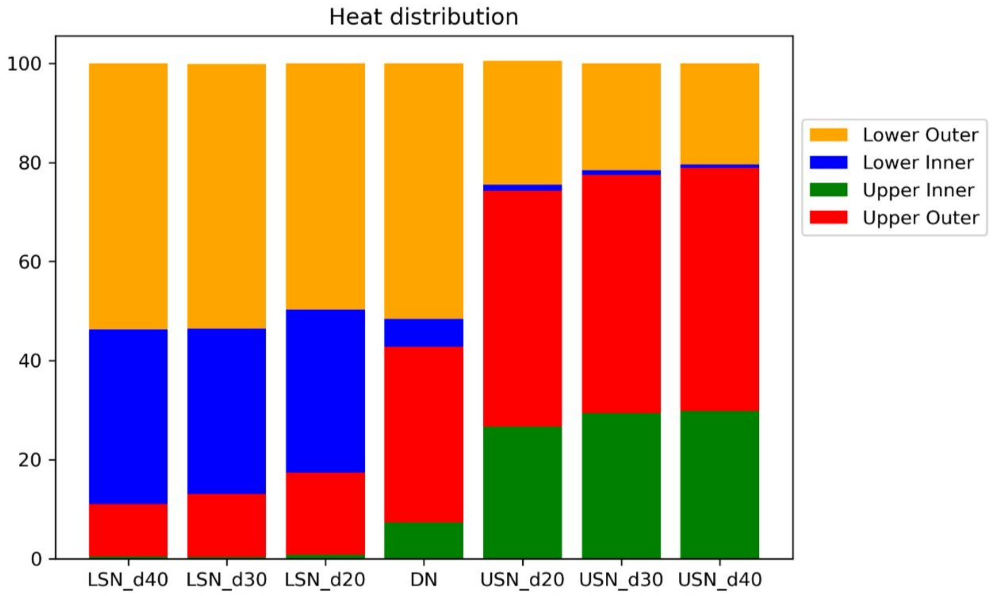
FIG. 4: Radial profiles of electron pressure.

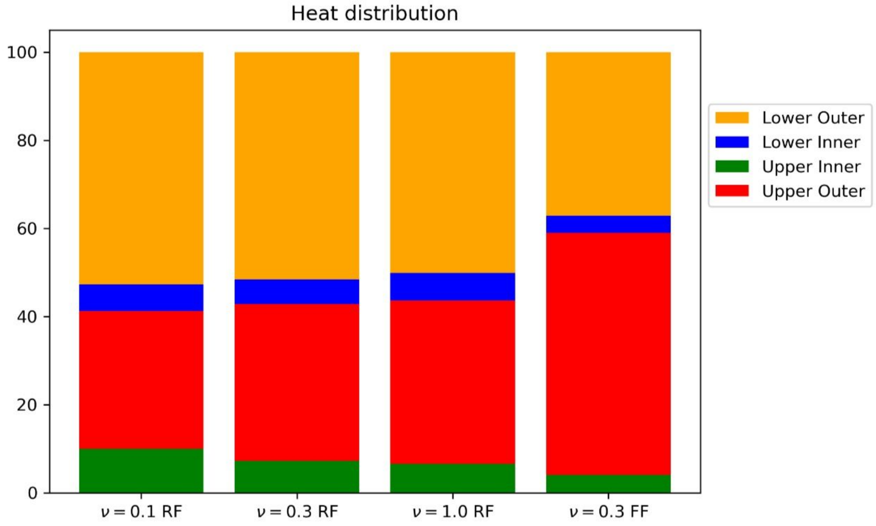
Heat asymmetry in DN

The heat asymmetry is observed repeatedly in DN configuration, even in the balanced DN configuration.

1. Most of the heat flux flow into the outer target
2. Increasing turbulence level reduces the degree of heat asymmetry





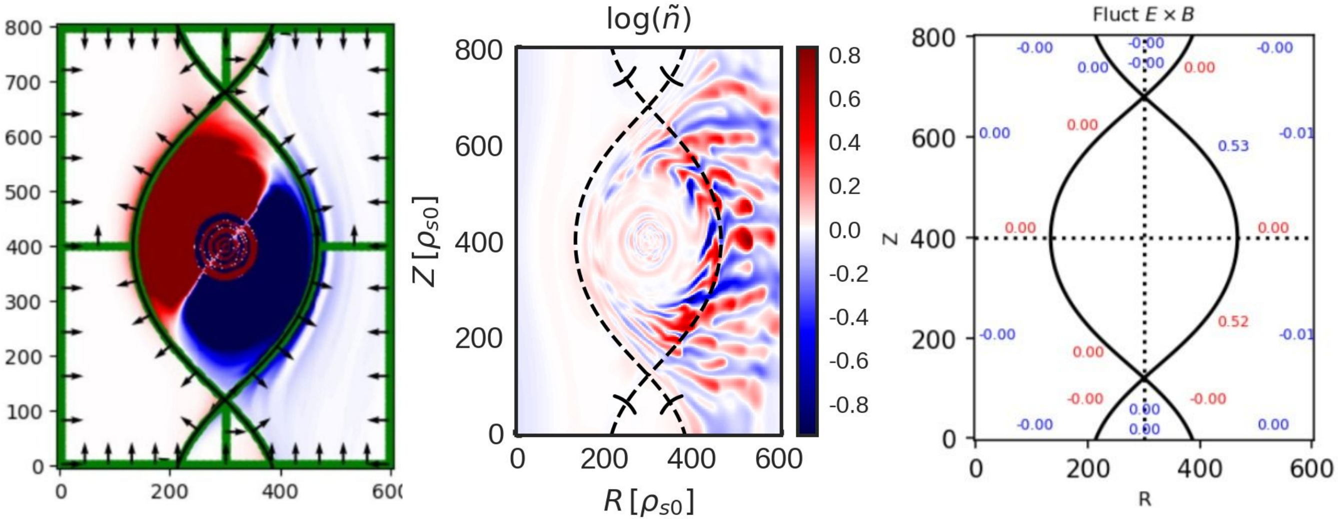


What is the mechanism driving for the asymmetry?

Different mechanisms have been proposed, such as:

ExB and diamag. drifts, **ballooning modes**, Pfirsch-Schluter (PS) flows, different recycling rates on targets, biased electric potential, etc.

In GBS-DN simulations with L-mode plasma, we observe **the fluctuating ExB term mainly drives particle & heat fluxes.**



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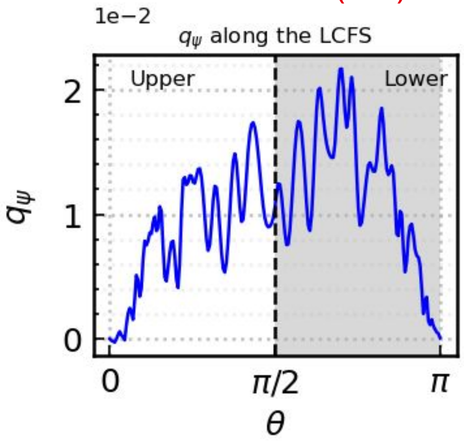
What is the mechanism driving for the asymmetry?

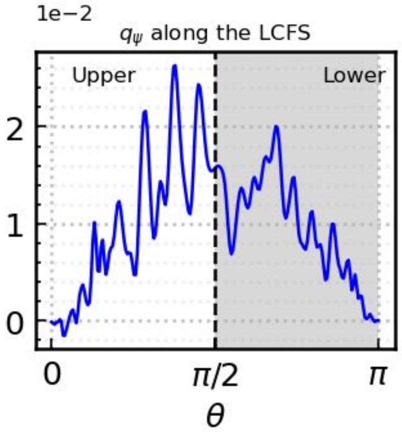
BM is found to be a main factor that determines heat asymmetry.

Also, the sign of B_T affects the degree of heat asymmetry.

Reverse Field (RF)



Forward Field (FF)



$$[\phi, f] = \boldsymbol{b} \cdot (\nabla\phi \times \nabla f)$$

$$\mathcal{C}(f) = \frac{B}{2}\left(\nabla \times \frac{\boldsymbol{b}}{B}\right) \cdot \nabla f$$

$$\nabla_{\parallel} f = \boldsymbol{b} \, \nabla f + \frac{1}{B}[\psi, f]$$

$$\nabla_{\perp}^{2} f = \nabla \cdot \left[(\boldsymbol{b} \times \nabla f) \times \boldsymbol{b}\right]$$

Heat asymmetry scaling law

Based on the driving mechanism as BM, one can drive scaling law for heat asymmetry.

We introduce a diamagnetic parameter α_D to capture its dependence on B_T

Thus, we propose the following scaling law:

$$\boxed{|q_{\mathrm{LO}} - q_{\mathrm{UO}}| = q_{\mathrm{asym}} = q_{\psi}\left[\alpha_{\mathrm{geo}} + (1 - \alpha_{\mathrm{geo}})\alpha_d \alpha\right]}$$

- When $\delta R_{\mathrm{sep}} = 0$, $\alpha_{\mathrm{geo}} \to 0$, this leads to $q_{\mathrm{asym}} = q_{\psi}\alpha_d\alpha$
- When $\delta R_{\mathrm{sep}} = \infty$, $\alpha_{\mathrm{geo}} \to 1$, this leads to $q_{\mathrm{asym}} = q_{\psi}$

The above trend is consistent from what we expected.

with

$$\alpha_{\mathrm{geo}} = \frac{1}{L_p}\int_0^{\delta R_{\mathrm{sep}}} \exp\left\{-\frac{x}{2L_p}\right\} dx = 1 - \exp\left\{-\frac{\delta R_{\mathrm{sep}}}{2L_p}\right\}$$

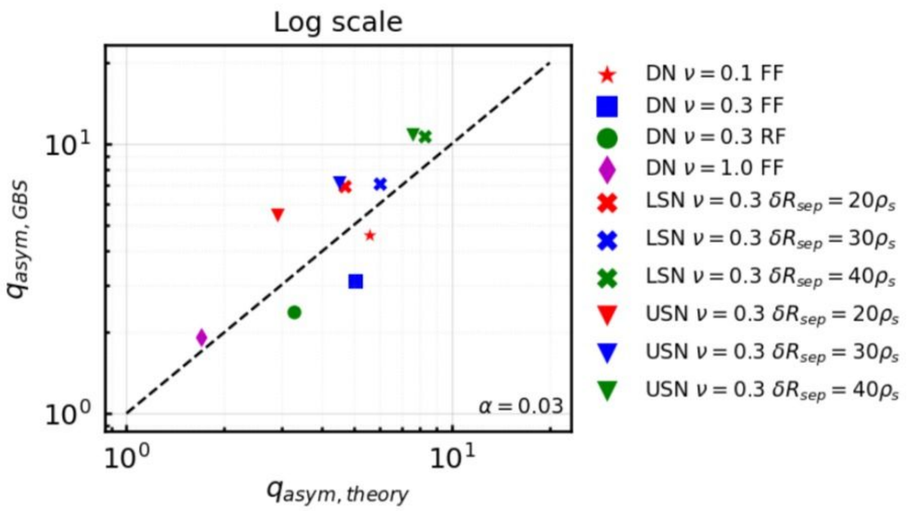
Comparison with nonlinear GBS simulations

A preliminary comparison with NL simulations shows some coherence between analytical scaling and numerical result.

A few discharges are reserved to check the validity of the scaling law.

Prediction of power sharing for present and future machines,

i.e. DTT, SPARC, MAST-U, DIII-D etc



Conclusion & future works

GBS simulations with balanced/unbalanced DN configurations are carried out.

Effects of dR_{sep} in power sharing are observed and BM is believed to the main factor driving the asymmetry.

Indeed, the fluctuating ExB term is found to be dominant term, and based this observation, it is possible to derive analytical scaling law for the observed heat asymmetry.

Comparison between NL simulations and analytical scaling law shows some consistent results.

A few TCV-DN discharges will be compared and the power sharing prediction for other machines will be interesting aspect.