Investigation of the plasma dynamics in double-null configurations

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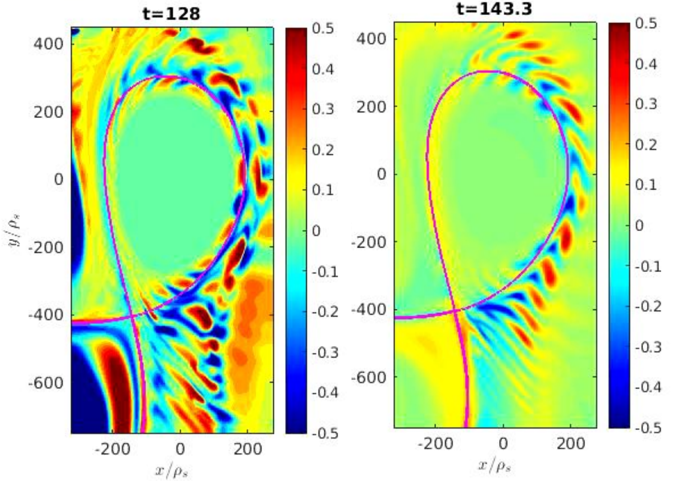
GBS Deliverables 2021-2022

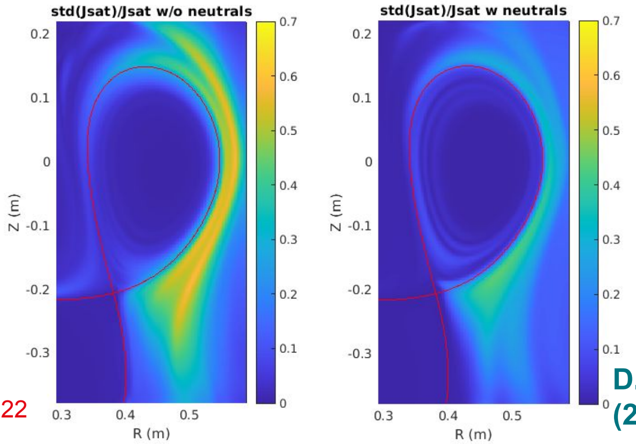
1. Develop the GBS code
   a. to avoid the Boussinesq approximation
   b. to include electromagnetic effects
   c. to implement neutral coupling

2. Explore theoretical aspects
   a. Different turbulent regimes
   b. First-principle theory based scaling law
   c. Density limit
   d. Neutral dynamics -> density shoulder
   e. etc…

w Boussinesq w/o Boussinesq



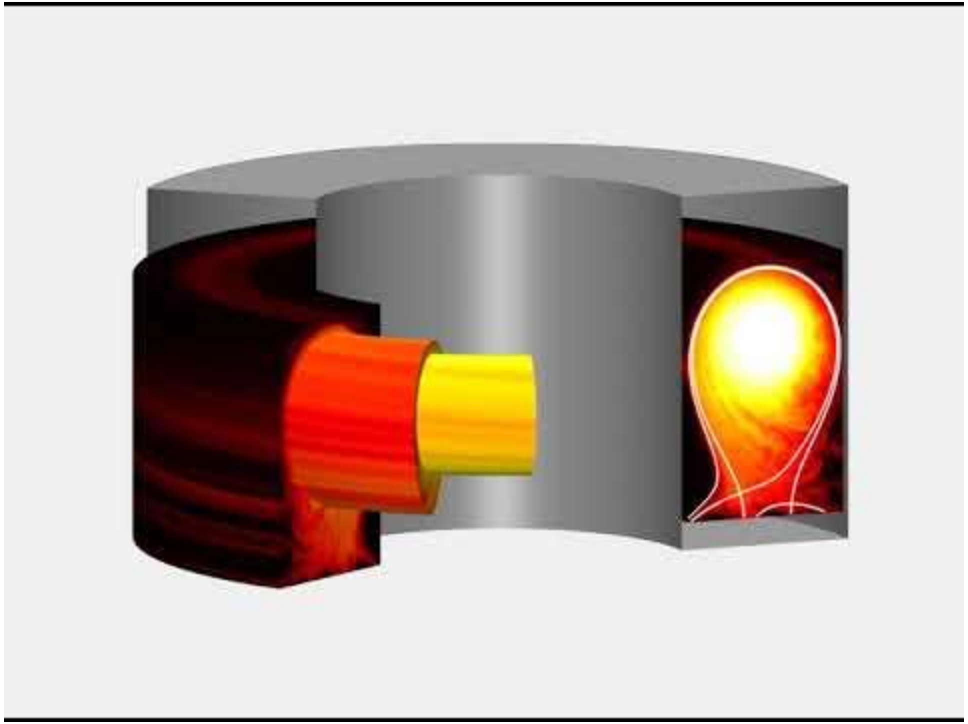
w/o Neutrals w Neutrals



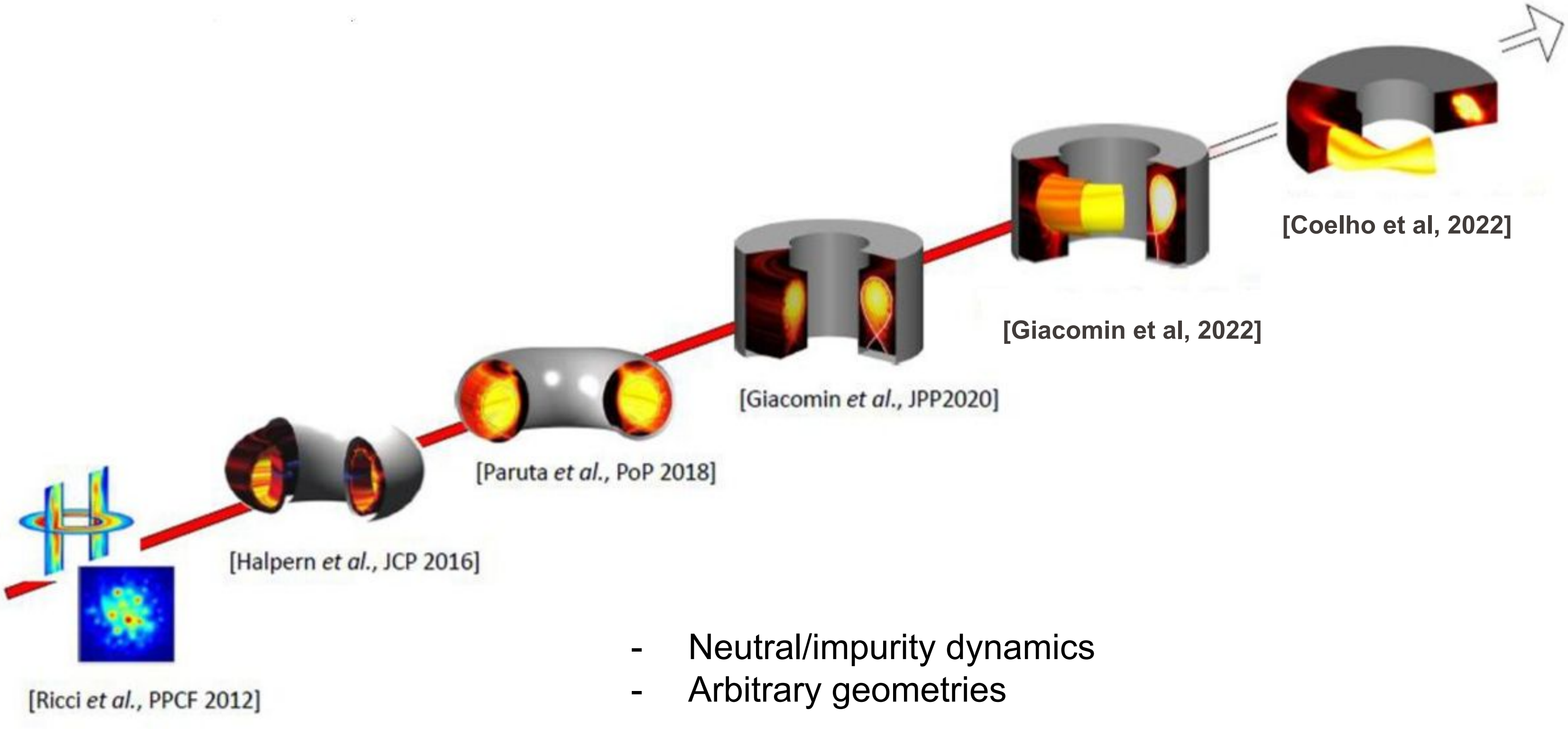
D. Galassi (22)

GBS : a 3D fluid code for edge plasma turbulence

1. Two-fluid, self-consistent, global, flux-driven turbulence code

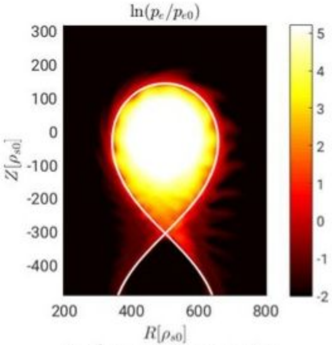


GBS model



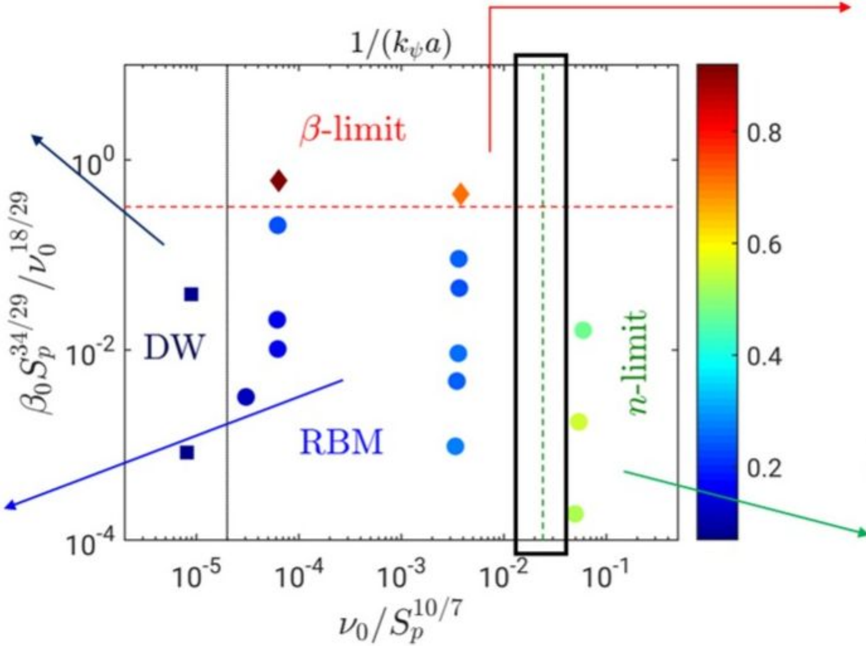
- Neutral/impurity dynamics
- Arbitrary geometries

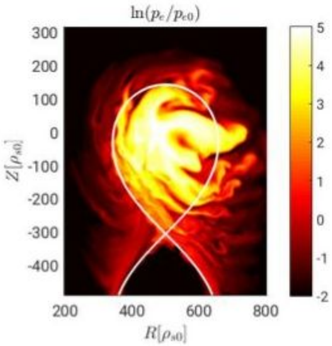
Phase space of edge turbulence



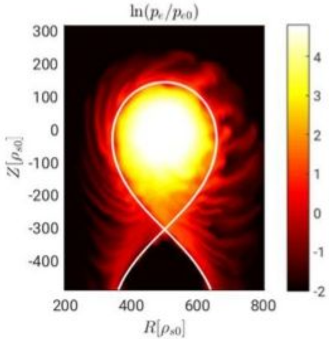
Drift-wave instability

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

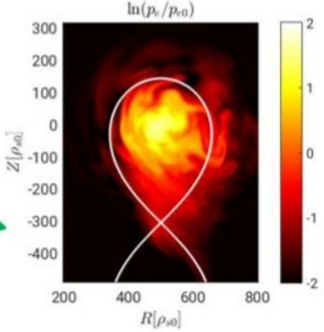




Regime beyond the β-limit
Ideal ballooning instability



L-mode regime
Resistive ballooning instability

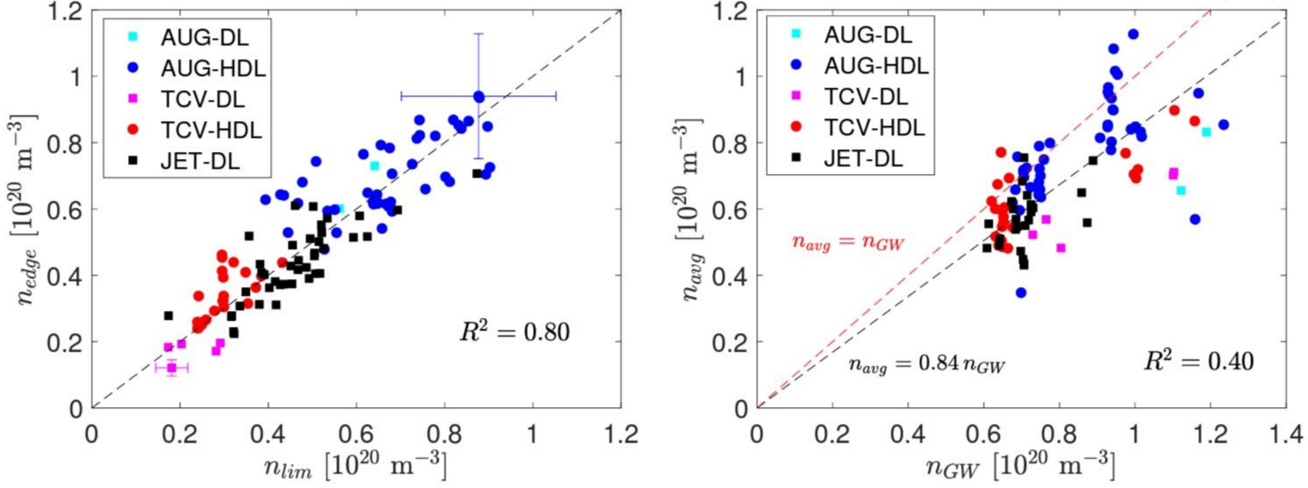


Regime beyond the n-limit
Resistive ballooning instability

M. Giacomin (22)

Comparison of the density limit with experiments

M. Giacomin, PRL (22)



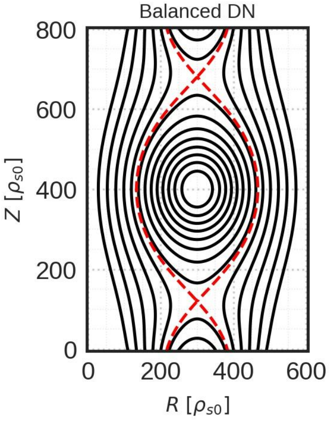
(a) Theoretical scaling

(b) Empirical scaling

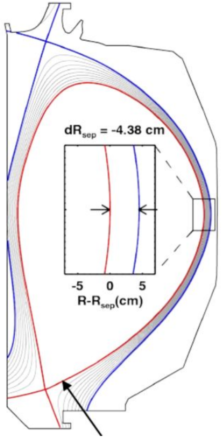
A first-principles scaling law, in agreement with experimental results, shows that the increase of boundary turb. transport with plasma collisionality sets the maximum density achievable in tokamaks.

What is next?

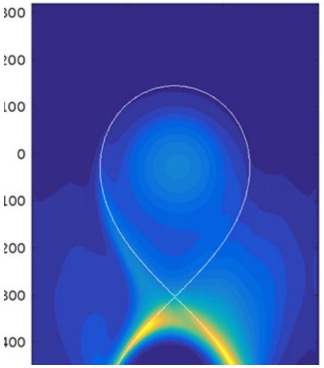
1. SN simulations with positive/negative triangularity (to be submitted)
2. DN simulations with different magnetic balance (ongoing)
3. DN simulations + triangularity + neutrals + realistic wall geometry



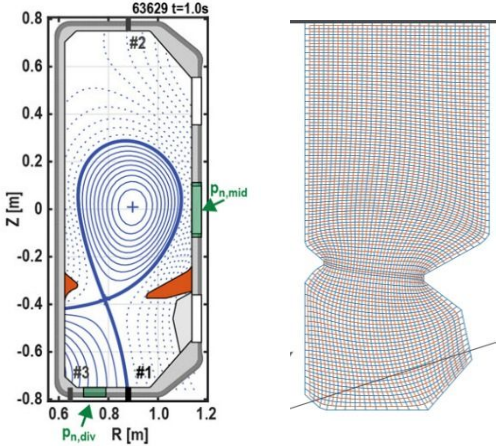
DN config.



Triangularity



Neutrals



Realistic wall Geometry

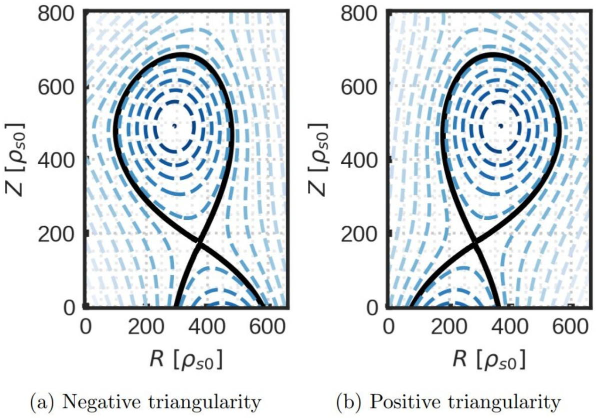
Reduced boundary plasma turbulence in negative triangularity

1. **Conventional D-shaped H-mode** plasma for ITER
    a. H-mode with ELMs

2. Power handling first?
    a. **Negative triangularity (NT) in L-mode plasma**
    b. No ELMs, reduced core/boundary plasma turbulence, mitigated heat flux, but narrow SOL width (with respect to L-mode PT)

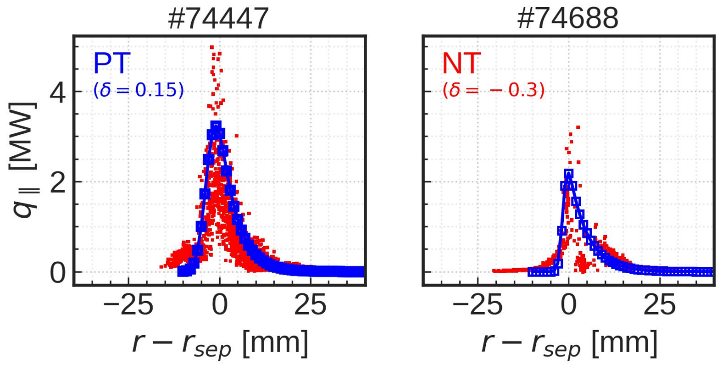
3. Recent work with GBS negative/positive triangularity simulations showed
    a. Reduced edge plasma turbulence in NT plasma
    b. Smaller power decay length

GBS NT/PT plasma

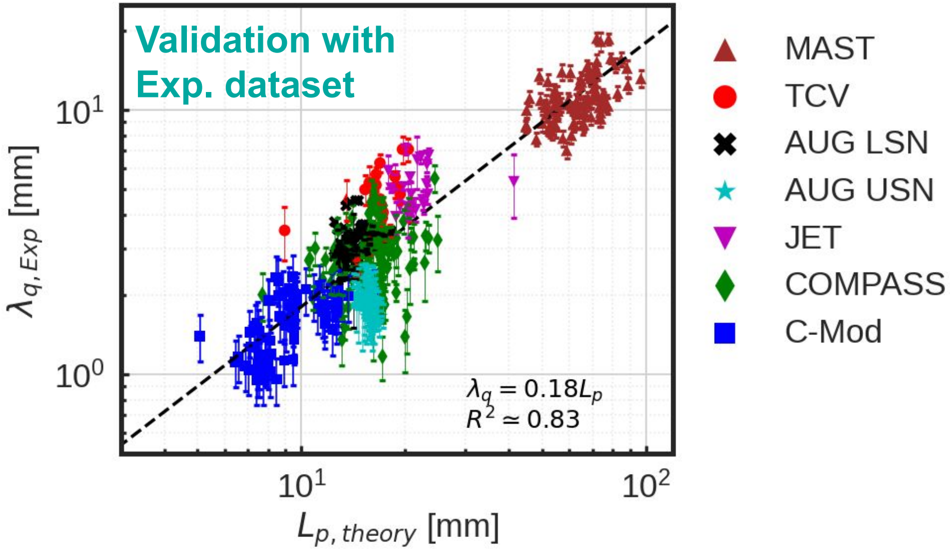


(a) Negative triangularity (b) Positive triangularity

Heat flux loaded on TCV outer target



Validation of theory-based scaling law for SOL-width



AUG data by D. Silvagni

Extrapolation to larger machines

Parameter	ITER	DTT	SPARC	JT-60SA
R_0 [m]	6.2	2.1	1.85	2.96
a [m]	2	0.6	0.57	1.18
q	2	3	3	3
κ	1.85	1.7	1.97	1.95
δ	0.49	0.3	0.54	0.53
$\bar{n}_e$ [m^{-3}]	4×10^{19}	1.8×10^{20}	3.1×10^{20}	6.3×10^{19}
B_T [T]	5.3	6	12.2	2.3
P_{SOL} [MW]	18	15	29	10
$\lambda_{q,PT}$ [mm]	~3.7	~2.7	~2.3	~ 7.1
$\lambda_{q,NT}$ [mm]	~2.2	~1.8	~1	~ 3.3

Power fall-off length extrapolation of future tokamaks for NT/PT L-mode
The values of $\lambda_{q,\mathrm{NT}}$ are computed using $-\delta$ in the scaling law.

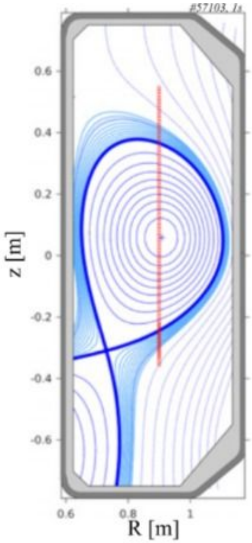
- → Successful comparison with different tokamaks for L-mode plasma
- → In L-mode, pressure gradient length Lp in the SOL is the same as in the edge -> important for the L-H transition

Double-Null (DN) configuration, an alternative to Single-Null (SN)

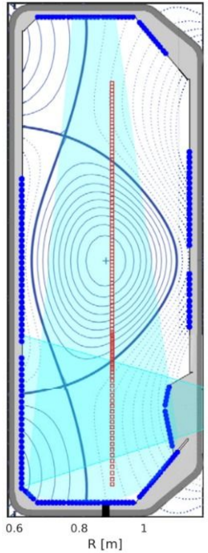
1. The DN configuration is of particular interest
    a. Four strike points to spread the heat load
    b. Two X-points for large radiative losses
    c. Quiescent high-field side to place antennas
    d. Alternative to the detached SN H-mode for ITER
    e. Implemented in DIII-D, TCV, MAST-U tokamaks

2. Investigation of the plasma dynamics in the boundary of DN tokamak configurations using GBS

TCV SN

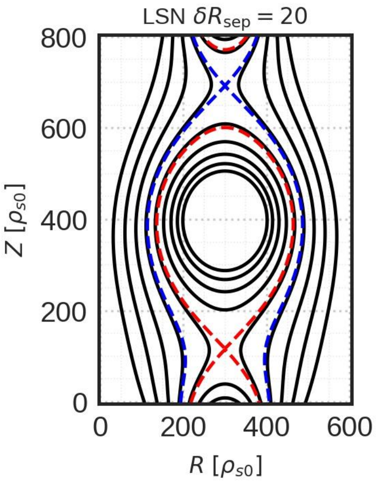


TCV DN

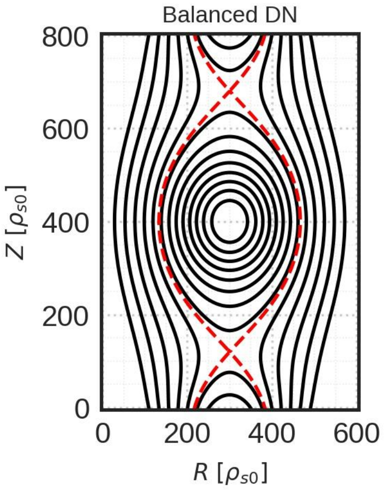


Balanced / unbalanced DN configurations, effect of magnetic balance

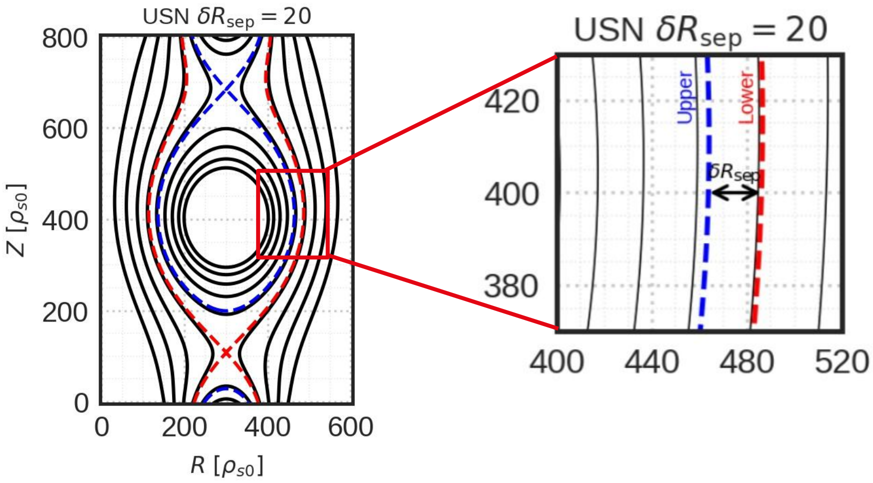
The up/down asymmetry controls heat exhaust



Lower Single Null (LSN)



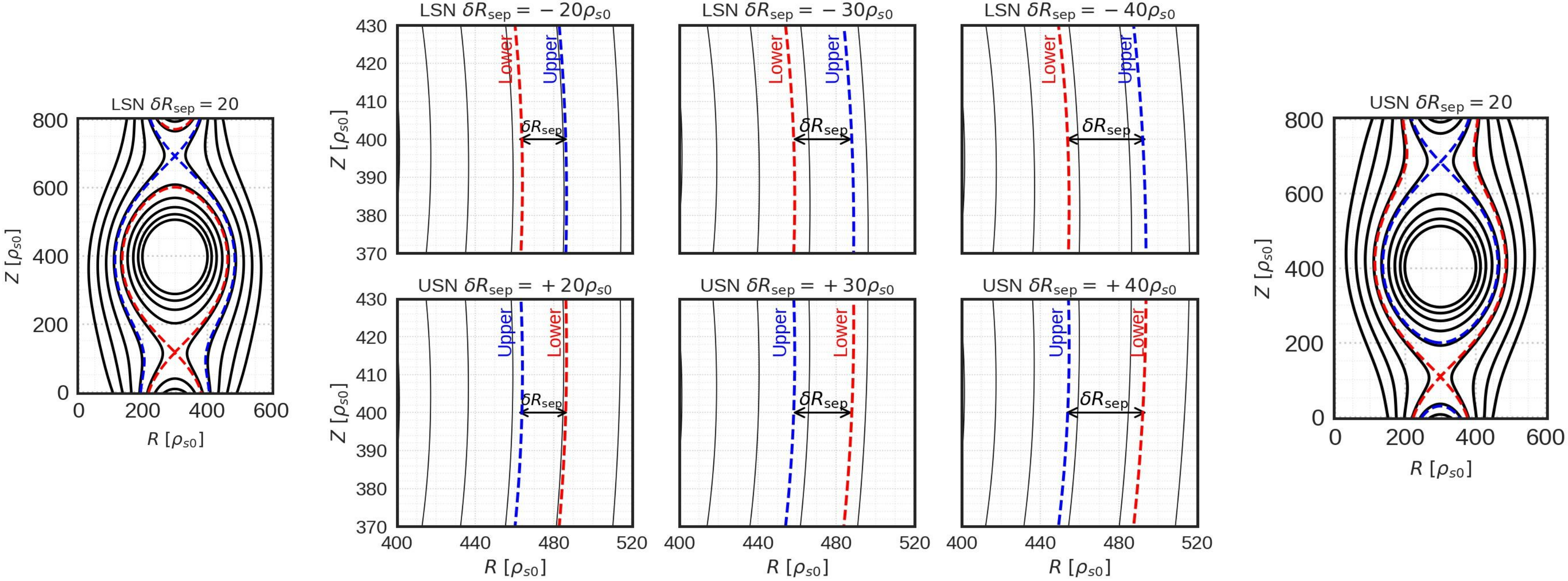
Balanced Double Null (DN)



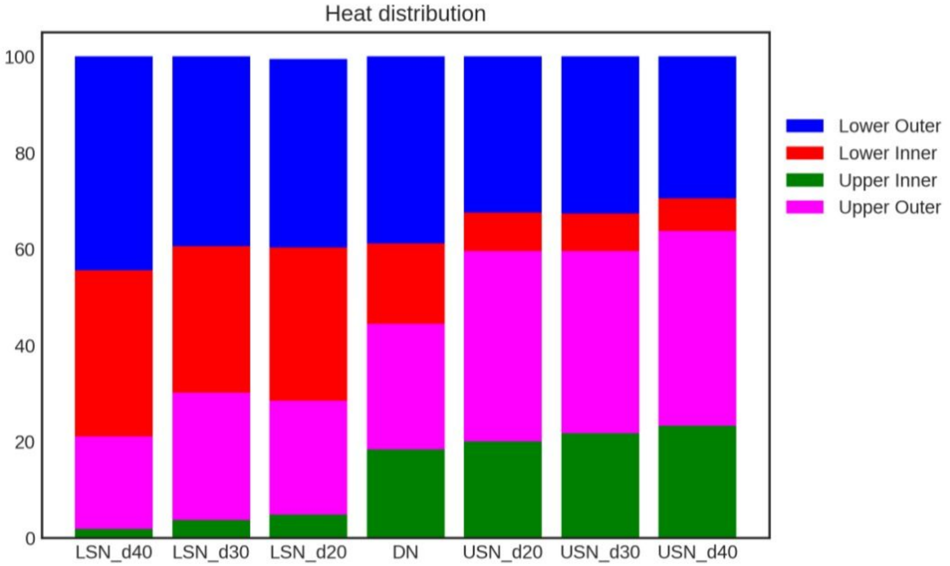
Upper Single Null (USN)

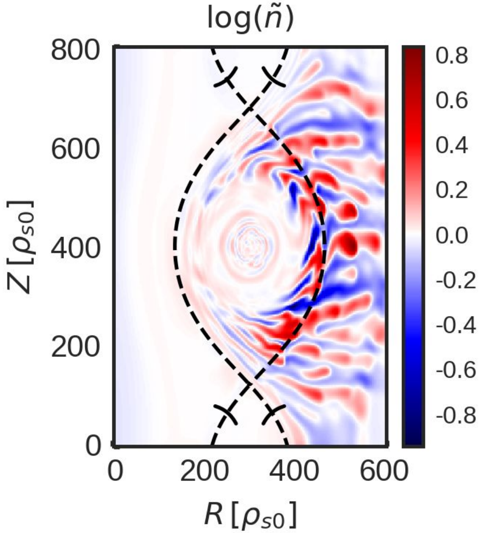
Balanced / unbalanced DN configurations, effect of magnetic balance

The up/down asymmetry controls heat exhaust



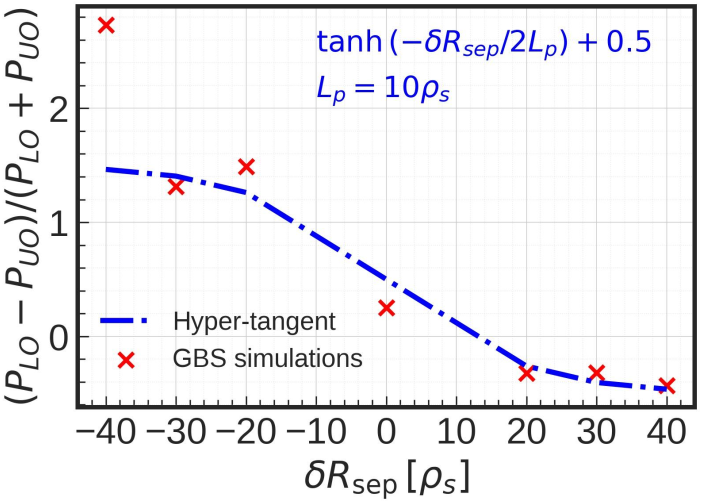
Heat asymmetry over four divertor legs





- → Heat asymmetry due to magnetic geometries
- → More than 60-70% heat on outer targets
- → **LSN_d40 -> 80%** lower region / **USN_d40 -> 60%** upper region
- → **Favourable** magnetic field -> **∇B-drift downwards**

Heat asymmetry over four divertor legs



$$\frac{P_{\mathrm{LFS,l}} - P_{\mathrm{LFS,u}}}{P_{\mathrm{LFS,l}} + P_{\mathrm{LFS,u}}} = \tanh\left(-\frac{\delta R_{sep}}{2L_{pe}}\right)$$

1. Heat asymmetry as a function of ‘dRsep’
2. Empirical scaling law gives the logistic function (hyper tangent)
3. Analytical scaling law? mechanisms? (on-going)

Back-up Slides

GBS model

1. Collisional plasma in edge => Drift-reduced Braginskii equations M. Giacomin (2022)

$$\frac{\partial n}{\partial t} = \underbrace{-\frac{R_0}{B}[\phi, n]}_{E \times B\ \text{CONV.}} + \underbrace{\frac{2}{B}\Big[C(p_e) - nC(\phi)\Big]}_{\text{CURVATURE}} - \underbrace{\nabla_{\parallel}(n v_{\parallel e})}_{\text{PARALLEL FLOW}} + \underbrace{S_n}_{\text{SOURCE}}$$

$T_e, \ T_i$ ➡ similar equations

$v_{\parallel e}, \ v_{\parallel i}$ ➡ Parallel momentum balance

$\phi, \ \psi$ ➡ Poisson and Ampère equations

+ Kinetic neutral model (not used here)

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