Effects of negative triangularity plasma on boundary plasma physics

Kyungtak Lim and Paolo Ricci

École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Switzerland

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GBS TSVV 2 milestones & deliverables

Within the TSVV 2, we aim to explore:

- Effects of negative triangularity (NT) on boundary plasma turbulence
- Connection with alternative divertor configurations (ADCs), i.e. double-null (DN)
- Other relevant theoretical works, such as density limit, LH transition scaling laws

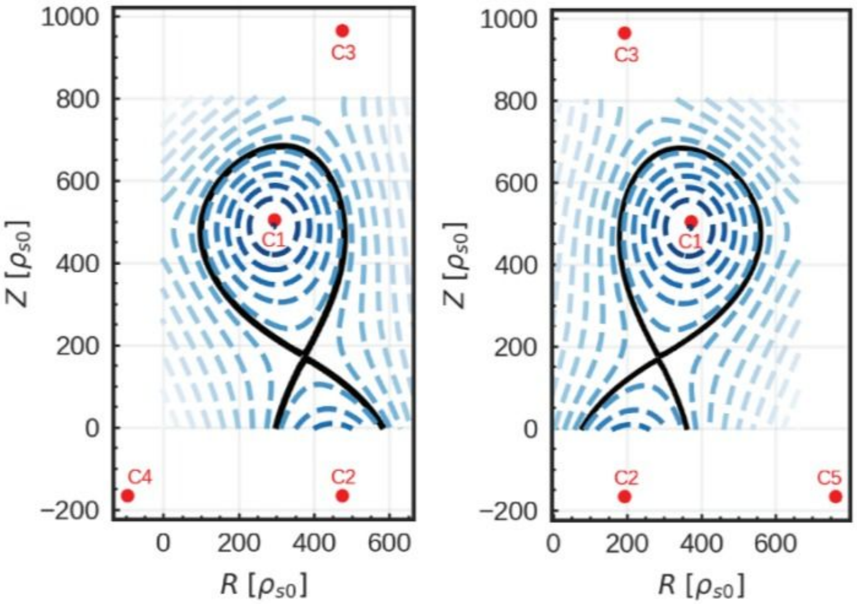
Ongoing projects:

- Effect of triangularity in SOL region and λ_q scaling law in L-mode plasmas **[1]**
- Investigation of physical mechanism and scaling law for heat asymmetry in DN **[2]**
- NT in DN and its impact on power exhaust and edge plasma turbulence **[3]**
- Enhanced L-mode density limit in NT plasmas **[4]**

[1] K Lim *et al* 2023 Plasma Phys. Control. Fusion **65** 085006
[2] In preparation
[3] Master project by Leonard from next week
[4] Planned for the upcoming TCV campaign

- **Effect of triangularity in SOL region and λ_q scaling law in L-mode plasmas**
- Investigation of physical mechanism and scaling law for heat asymmetry in DN
- NT in DN and its impact on power exhaust and edge plasma turbulence
- Enhanced L-mode density limit in NT plasmas

Magnetic equilibria and geometrical operators



$$[\phi, f] = \frac{1}{\mathcal{J}} \epsilon_{ijk} b_i \frac{\partial \phi}{\partial \xi^j} \frac{\partial f}{\partial \xi^k},$$

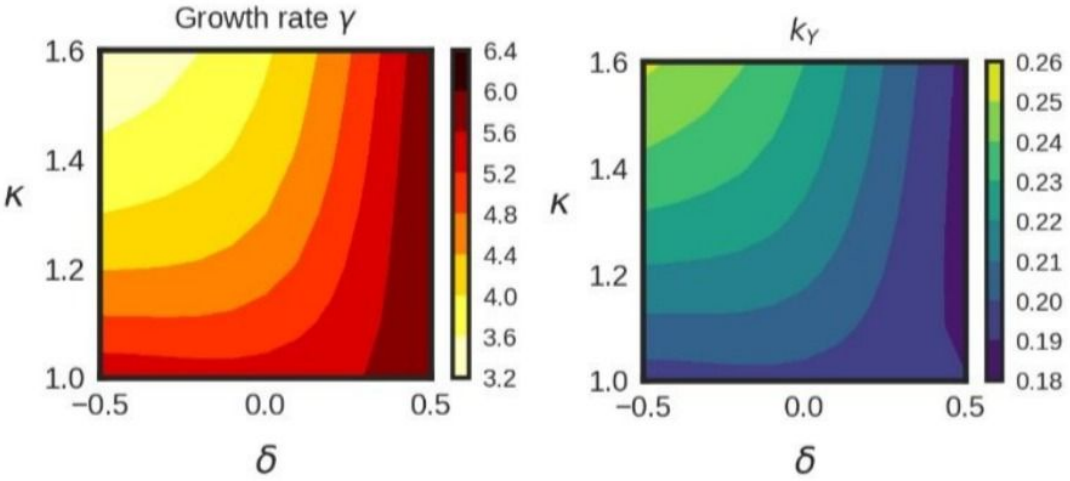
$$\nabla_{\parallel} f = b^j \frac{\partial f}{\partial \xi^j},$$

$$\mathcal{C}(f) = \frac{B}{2\mathcal{J}} \frac{\partial c_m}{\partial \xi^j} \frac{\partial f}{\xi^k} \epsilon_{kjm},$$

$$\nabla_{\perp}^2 f = \frac{1}{\mathcal{J}} \frac{\partial}{\partial \xi^k} \left(\mathcal{J}^{-1} \epsilon_{klm} \epsilon_{i\alpha\beta} g_{mi} b_l b_\alpha \frac{\partial f}{\partial \xi^\beta} \right),$$

- For nonlinear GBS simulations, NT(-0.3)/PT(+0.3) equilibria are analytically generated with constant elongation=1.3
- Effects of plasma shaping are included in the geometrical operators implemented in GBS

Enhanced NT confinement in linear & NL analysis



(Left) the linear growth rate
(Right) the poloidal wave number as a function of δ and κ

- Both linear and nonlinear GBS analyses have identified reduced turbulence levels and enhanced confinement in NT plasmas.
- The main reason for this is the reduction of interchange instabilities in NT plasmas, attributed to the curvature operator.

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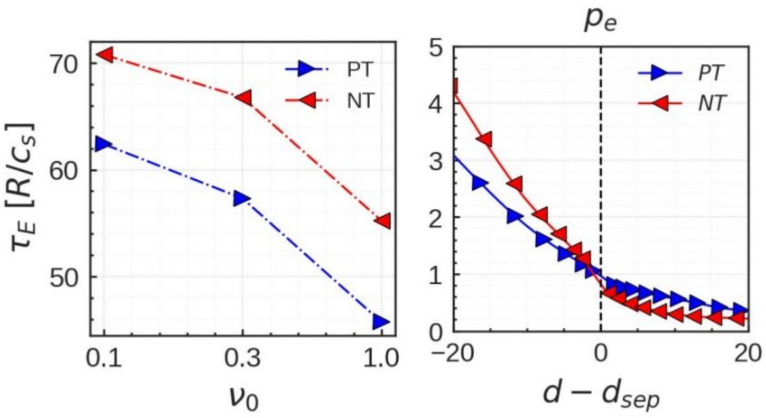
Enhanced NT confinement in linear & NL analysis



With the same input parameters, the only difference is the magnetic equilibrium
(Left) the energy confinement time
(Right) the saturated pressure profile at the outer mid-plane

- Both linear and nonlinear GBS analyses have identified reduced turbulence levels and enhanced confinement in NT plasmas.
- The main reason for this is the reduction of interchange instabilities in NT plasmas, attributed to the curvature operator.

Derivation of the L_p scaling law

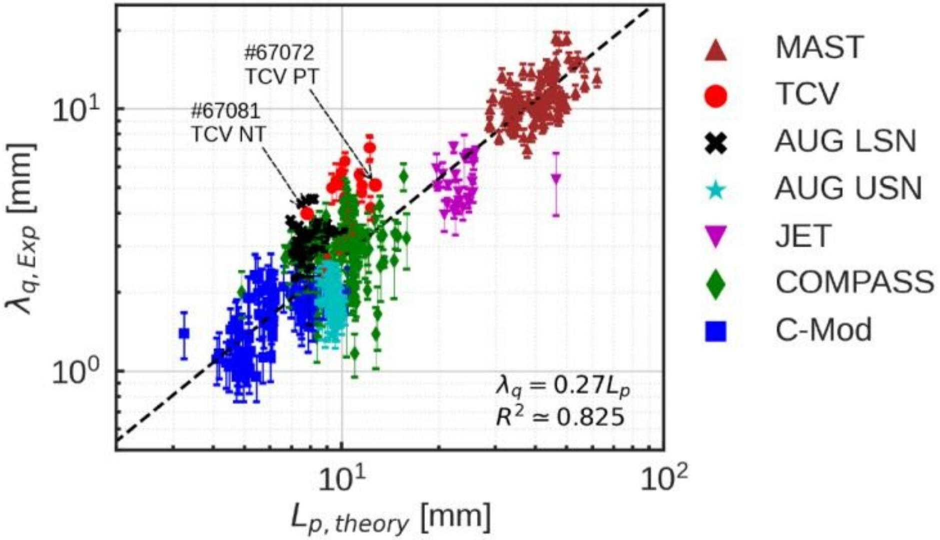
- Based on the idea that ballooning modes (BM) is stabilized in NT plasma, we derived an analytical scaling law for the pressure gradient length L_p
- Main assumptions (i) BM is dominant in L-mode plasmas (ii) injected heating power is balanced heat flux leaving the separatrix

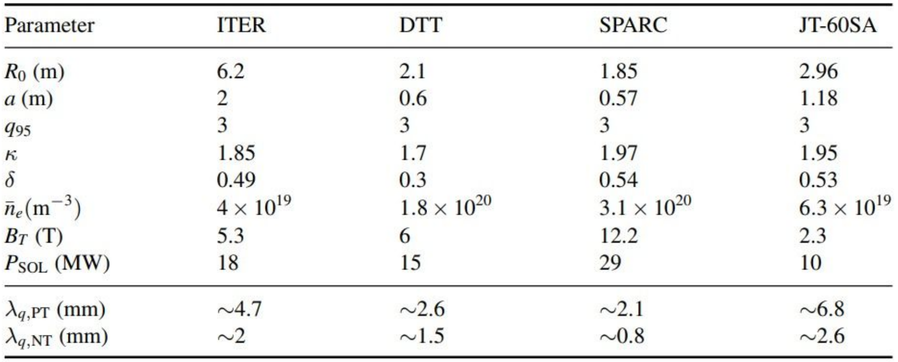
$$L_p \simeq 1.95\,\boxed{C(\kappa,\delta,q)}^{9/17} A^{1/17} q^{12/17} R_0^{7/17} P_{\mathrm{SOL}}^{-4/17} n_e^{10/17} \times B_T^{-12/17} \boxed{L_\chi^{12/17}},$$

with C is the curvature operator related to the growth rate of BM and Lchi is the poloidal length of the separatrix

$$L_\chi \simeq \pi a(0.45+0.55\kappa)+1.33a\delta,$$

Scaling law for λ_q including triangularity





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_{95}	3	3	3	3
κ	1.85	1.7	1.97	1.95
δ	0.49	0.3	0.54	0.53
$\bar{n}_e(\mathrm{m}^{-3})$	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
$\lambda_{q,\mathrm{PT}}$ (mm)	~4.7	~2.6	~2.1	~6.8
$\lambda_{q,\mathrm{NT}}$ (mm)	~2	~1.5	~0.8	~2.6

- The final scaling law captures the trend, reduced power decay length in NT
- The extrapolation to future machines shows almost a factor of 2 between PT/NT
- This indicates the importance of triangularity for the reliable scaling law
- The values of λ_q for **ITER PT H-mode (1mm) < ITER NT L-mode (2mm)**

- Effect of triangularity in SOL region and λ_q scaling law in L-mode plasmas
- **Investigation of physical mechanism and scaling law for heat asymmetry in DN**
- NT in DN and its impact on power exhaust and edge plasma turbulence
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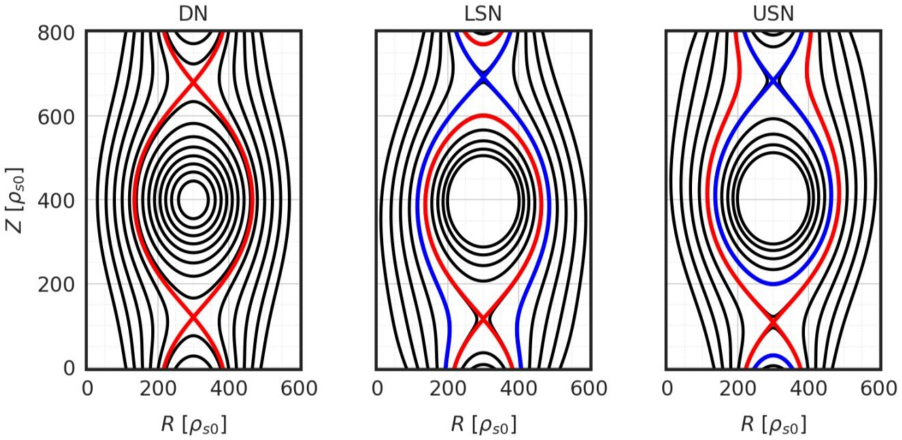
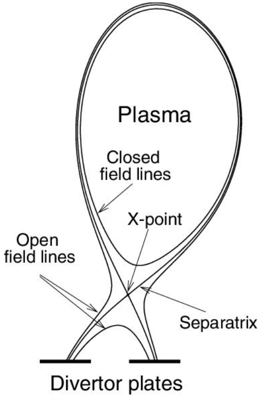
Double-null (DN) : alternative solution to ITER single-null





Single-null (SN)

- DN of particular interest (1) four divertor legs to help handling heat load (2) two X-points for radiative losses.
- Heat asymmetry between different legs depends on magnetic configurations
- We believe that LFS turbulence leads to the upper-lower heat asymmetry

Scaling law for heat asymmetry in DN

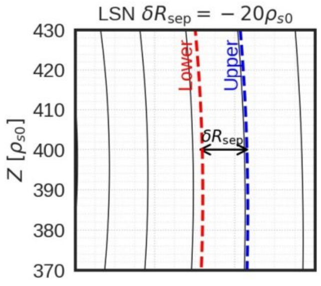
We propose the following scaling law for the heat asymmetry

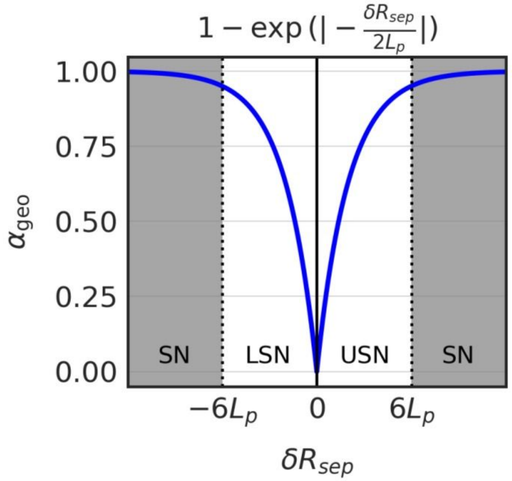
$$|q_{\parallel,\mathrm{LO}} - q_{\parallel,\mathrm{UO}}| = q_{\mathrm{asym}} = q_\psi \left[\alpha_{\mathrm{geo}} + (1-\alpha_{\mathrm{geo}})\alpha_d \alpha_{\mathrm{cst}}\right]$$

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

The main mechanisms:

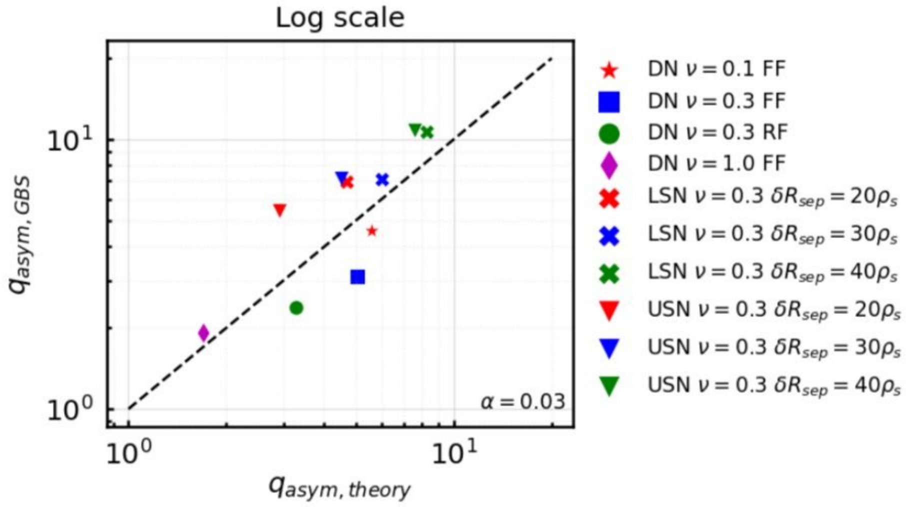
- q_ψ = radial heat flux driven by turbulence
- α_d = vertical diamagnetic effects
- α_{geo} = geometrical effects





The balance between q_ψ vs α_d determines the upper-lower asymmetry

Comparison with nonlinear GBS simulations



- A preliminary comparison with NL simulations shows some coherence between analytical scaling and numerical result.
- What is the optimal DN configuration from a power handling perspective?
- Scaling laws will be used to predict the ideal dRsep values for SPARC, STEP, and DTT

- Effect of triangularity SOL region and λ_q scaling law in L-mode plasmas
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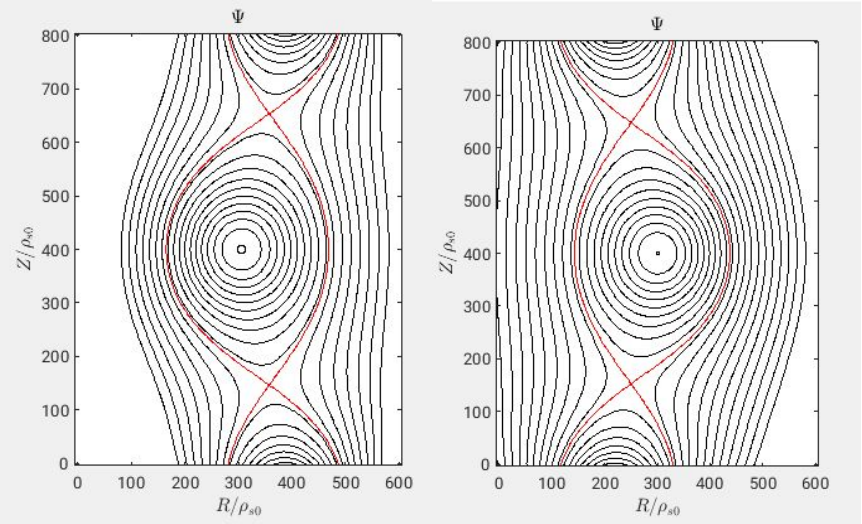
DN configuration + NT = even better option?

- The use of NT plasmas for reduced heat flux
- The use of DN configuration for spreading heat flux

Next step will be the combination of DN and NT with a scan values of delta



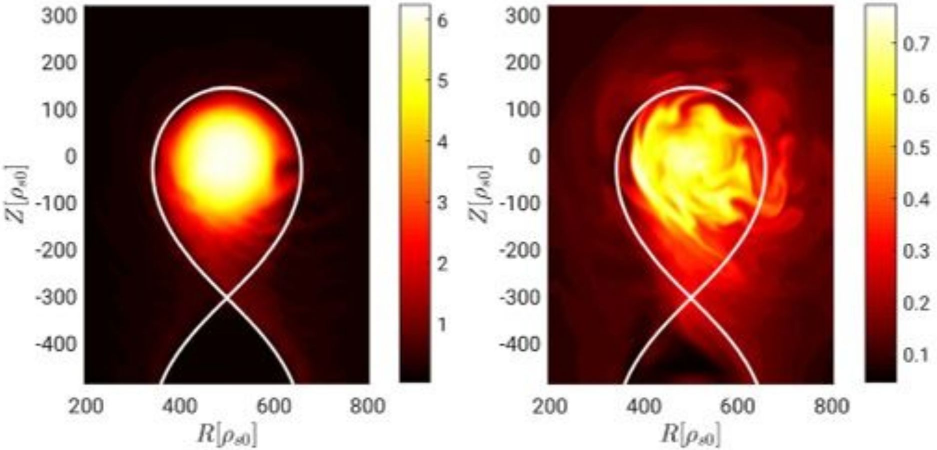
- This will be addressed by Master student, Leonard Lebrun
- Analytical scaling law for the L_p and the effects of NT on blob dynamics?
- Power handling?

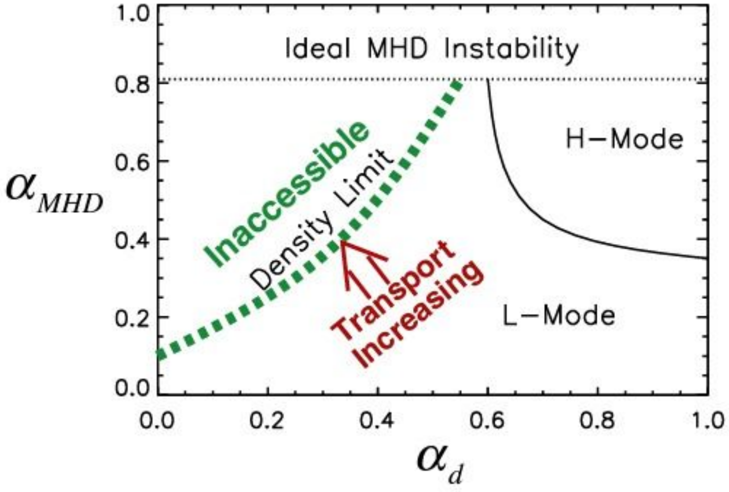
- Effect of triangularity SOL region and λ_q scaling law in L-mode plasmas
- Investigation of physical mechanism and scaling law for heat asymmetry in DN
- NT in DN and its impact on power exhaust and edge plasma turbulence
- **Enhanced L-mode density limit in NT plasmas**

Increased density limit in NT plasmas

- First-principles density limit scaling law derived based on turbulence point of view
- Comparison with different tokamaks was successfully done
- Missing effects of plasma shaping, radiation, shear flow, etc…

BM increasing turb. > L-mode n-limit



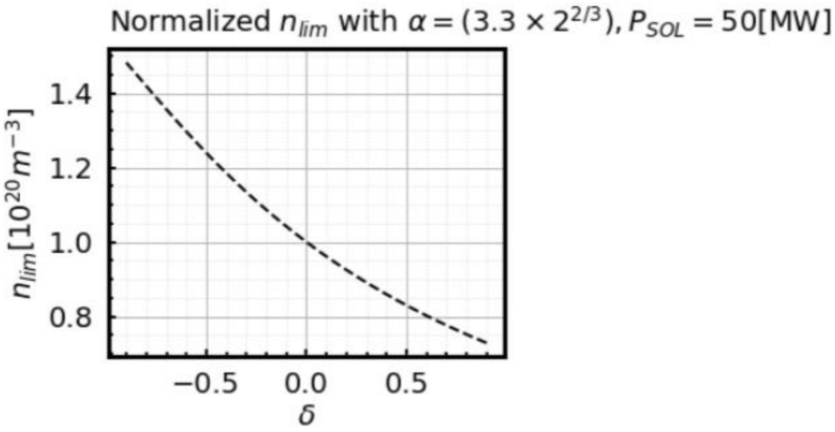


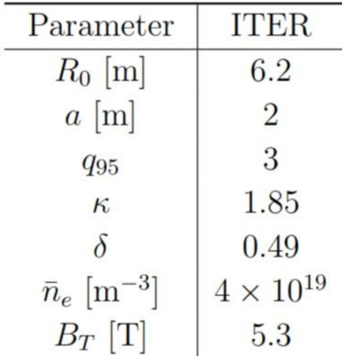
B LaBombard et al 2005 Nucl. Fusion **45** 1658
M Giacomin *et al* 2022 Phys. Rev. Lett. **128**, 185003

Increased density limit in NT plasmas

- Building upon the recent observation $f_{GW} \sim 2$ in DIII-D and reduced turbulence in NT, one can imagine density limit also changes in a strongly shaped plasmas.

$$\boxed{n_{\mathrm{lim}}[10^{20}\mathrm{m}^{-3}] = \alpha \mathcal{C}(\kappa, \delta, q)^{-1/6} A^{1/6} a^{37/42} P_{\mathrm{SOL}}^{10/21} R_0^{-43/42} q^{-22/21} B_T^{2/3} L_\chi^{-2/3}}$$


Normalized n_{lim} with $\alpha = (3.3 \times 2^{2/3}), P_{SOL} = 50[MW]$



Parameter	ITER
R_0 [m]	6.2
a [m]	2
q_{95}	3
κ	1.85
δ	0.49
$\bar{n}_e$ [m^{-3}]	4×10^{19}
B_T [T]	5.3

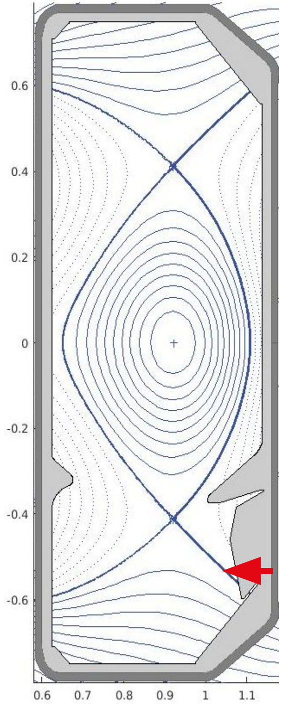
Conclusions

- Various topics are currently being addressed from the GBS simulations and theoretical works.

- NT plasmas seems playing an important role in the boundary region

- For the future works, we want to address
  1. Self-consistent detachment in NT plasmas using neutral injections
  2. Effects of baffled divertor in NT plasmas
  3. TCV size + DN + NT + neutrals + baffled divertor
  4. And a lot of interesting topics….

TCV DN+NT



Neutrals injection

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