Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence modelling in X-point geometry in negative (NT) and positive (PT) triangularity shapes.

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Outline:

1. **Motivation: high confinement, no ELMs, reactor relevant? Still not clear.**

2. **JOREK-GK code: non-linear particle gyro-kinetic code. Benchmarking with other codes on linear/non-linear cases for TCV parametrs.**

3. **Modelling of realistic DIII-D pulses. Rho* scaling ?**

4. **Comparison of NT (experimental equlibrium) /PT(mirror fliped equilibrium) in non-linear regimes for DIII-D parameters.**

5. **Comparison of correlation of edge density fluctuations at the edge in modelling and experiment: Doppler Backscattering =DBS :**
   - similar to experiment correlation of edge density fluctuations;
   - similar to experiment edge poloidal V_ExB flow;

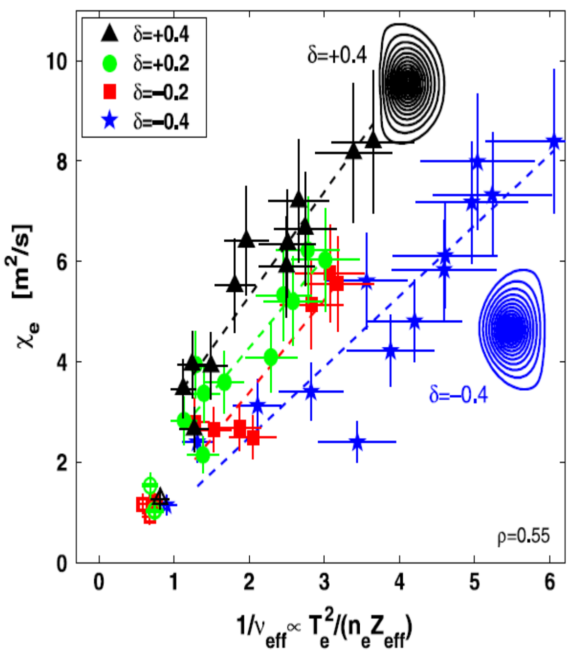
6. **Conclusions.**

Motivation:

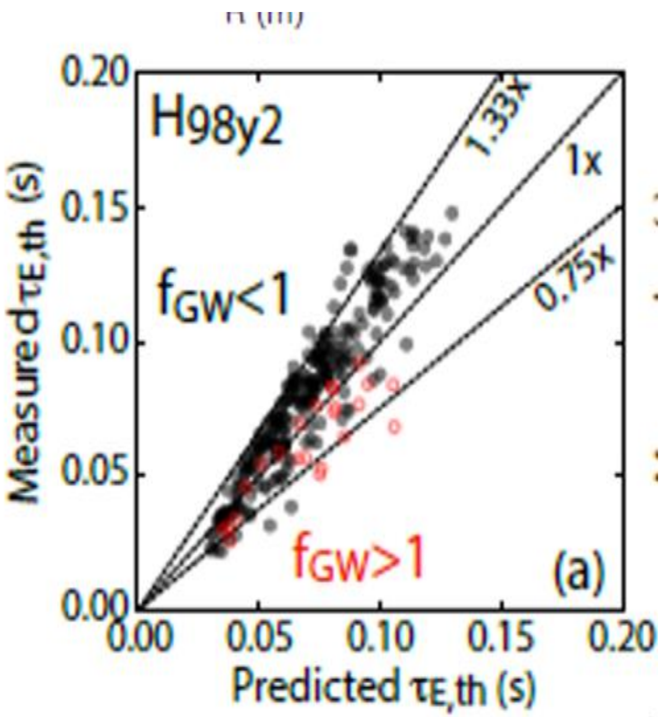
TCV : EC heated L-mode (Te>Ti)=> electron heat transport decreases at sufficiently strong NT (δ~-0.4) and high collisionality. Mainly TEMs are stabilised at NT.

DIII-D: 2023 dedicated NT campaign on diverted plasmas, Te=Ti, low collisionality : high core confinement . No access to 2nd stability limit in strong NT(δ~-0.4)=> no high pressure pedestal, no ELMs. Seems attractive for reactor?

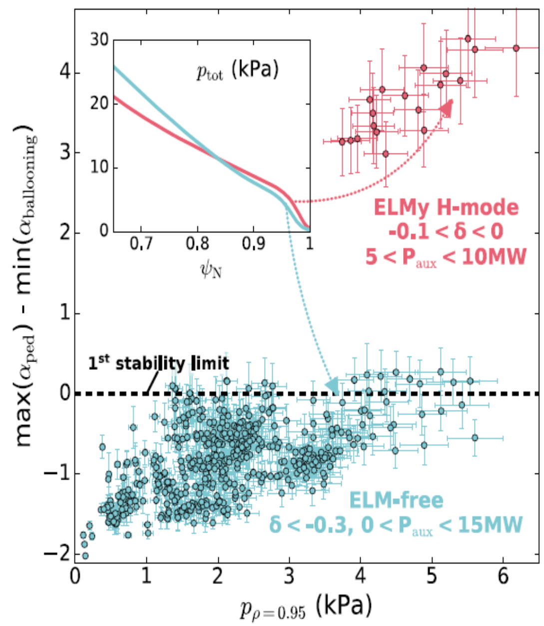
[Y Camenen NF 2007]



[K E Thome PPCF to be pub2024.]



[A Nelson PRL2023]

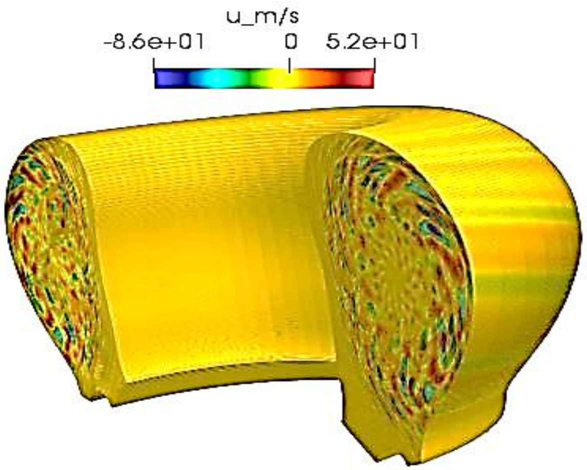


JOREK-GK code.

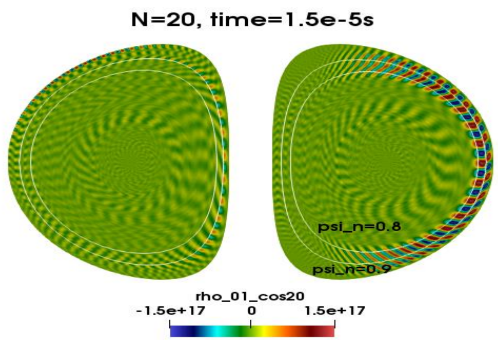
[JOREK as MHD code: G Huysmans, NF 2007, PPCF 2009, M Hoelzl NF2021; JOREK-GK: G Huijsmans EPS 2023, M Becoulet EPS 2023,EPS 2024,IAEA 2023]

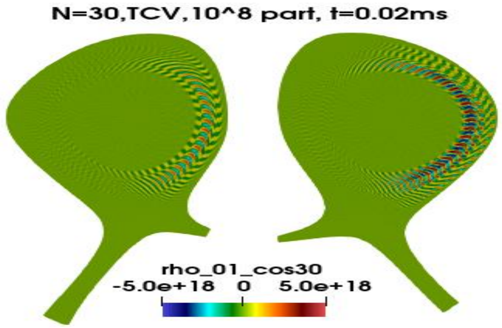
- **Particles are initialized on the equilibrium grid, plasma profiles and magnetic field calculated by JOREK as fluid MHD code => X-point, SOL, divertor, walls, coils geometry can be included.**
- **Non-linear full-f.**
- **Particles are advanced (RK4) in time evolving electric field and static magnetic field –electrostatic turbulence.**
- **Ions: parallel and ExB motion of gyro-centers in gyro-averaged electric field.**
- **Electrons: adiabatic (ITG only) or kinetic electrons (ITG/TEM). Heavy electrons (m_i/m_e=100). Guiding centers.**
- **Projection and solution in weak form using the same basis functions as in fluid MHD. C1 Bezier finite elements on flux-aligned grid in the poloidal plane, toroidal Fourier harmonics. Two types of filters: hyper-diffusion in the poloidal plane and a Laplacian in the parallel direction.**
- **HPC: Typical job (IRENE, France)=> N=5:5:40 toroidal harmonics, 5.10^8 particles, 54 nodes, 48h wall time (~0.5ms to saturation), time step dt~ 5.10^{-8}s. Good (close to ideal) HPC scaling.**
- **Electron-ion collisions model: small angle random scattering [Lana Rekhviashvili , Zhixin Lu et al POP 30 (2023)].**

Example: COMPASS, TEM/ITGs with RMPs

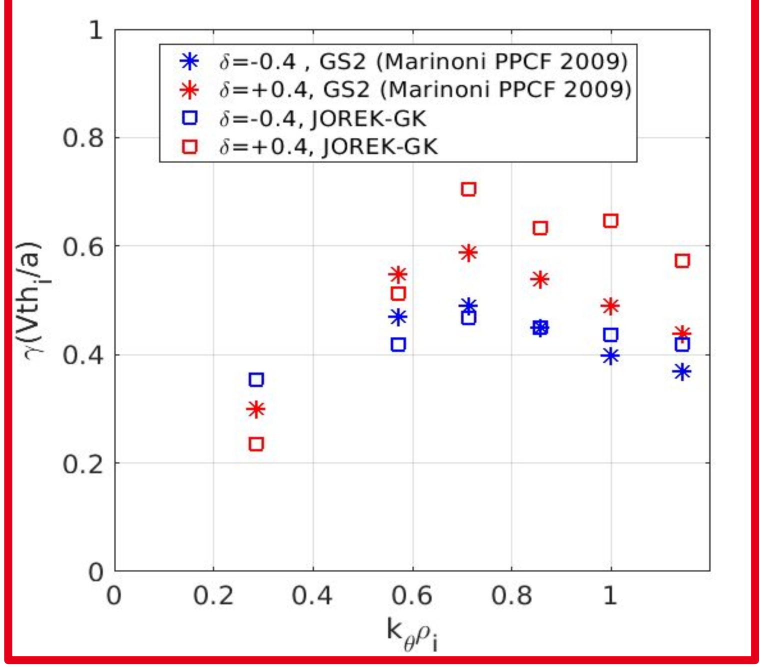


Benchmarking global JOREK-GK with GS2 and GENE (both local flux-tube, w/o X-point) in linear regimes for TCV L- modes in TEM regime ($T_e > T_i$): similar linear growth rates in spite of large difference in the codes , smaller growth rates at NT compared to PT.

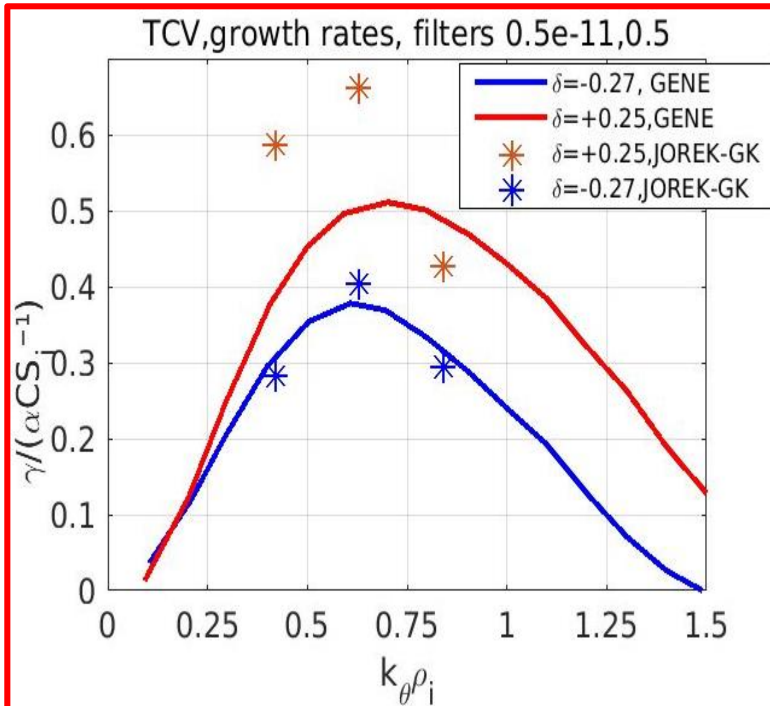




JOREK-GK&GS2



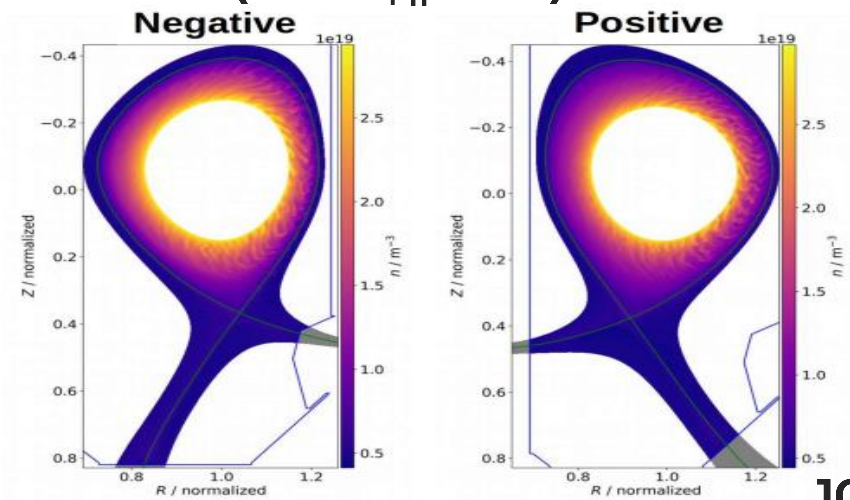
JOREK-GK (with X) with GENE (w/o X)



Comparison of JOREK-GK with GENE-X for TCV parameters: heat fluxes NT<PT, divertor // heat flux is mainly from electrons . Eich's fit (NF 2013): PT λq =4mm; NT λq =3.5mm.

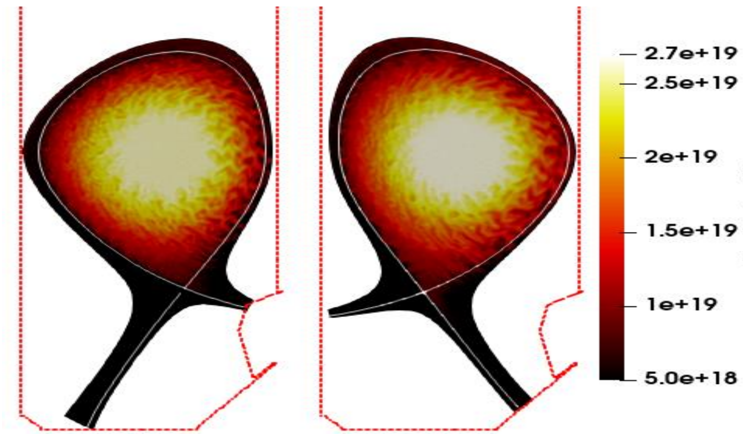
[P Ulbl 29th IAEA 2023]

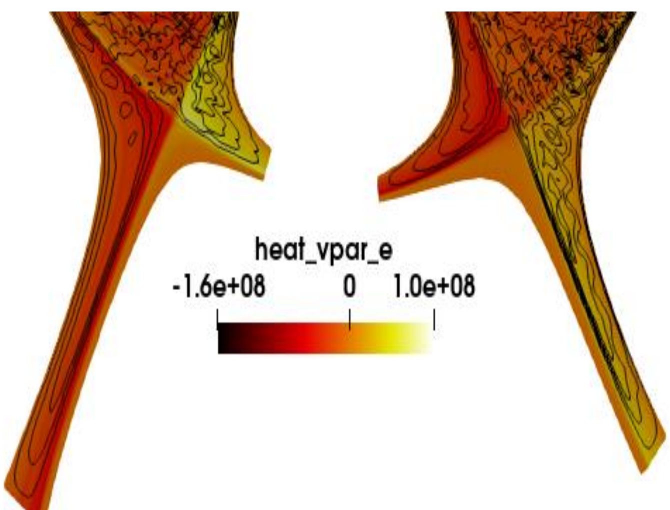
GENE-X (band ψ_n>0.57)



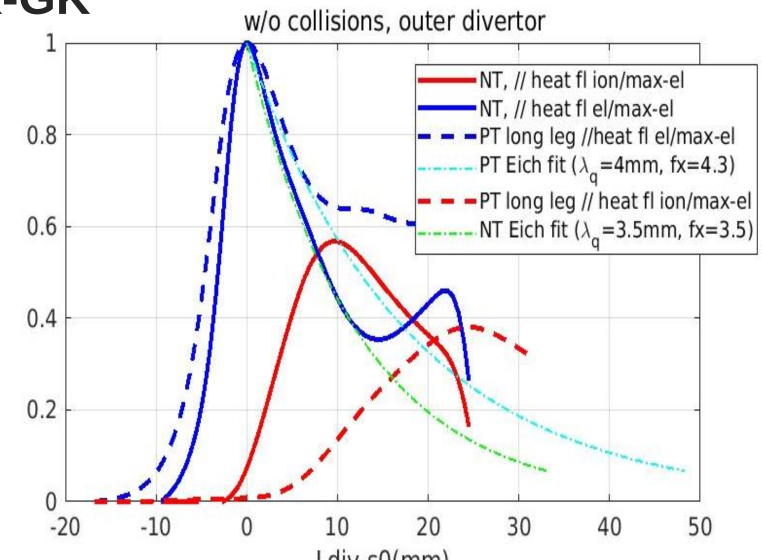
[M Becoulet EPS2024,IAEA 2023]

JOREK-GK (all plasma+SOL, ψ_n>0)



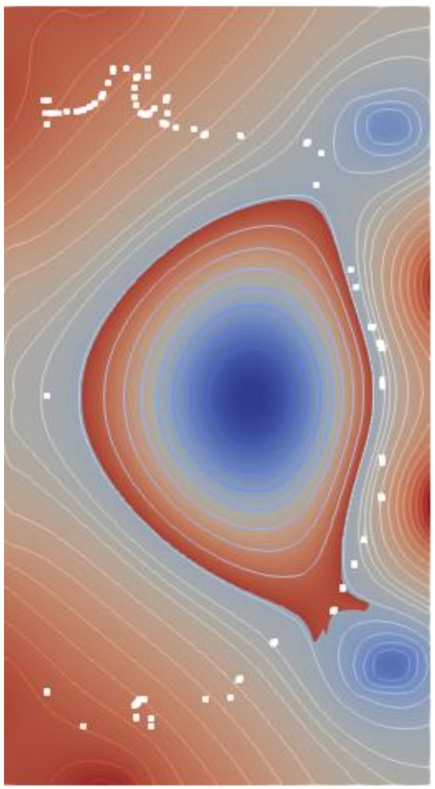


JOREK-GK

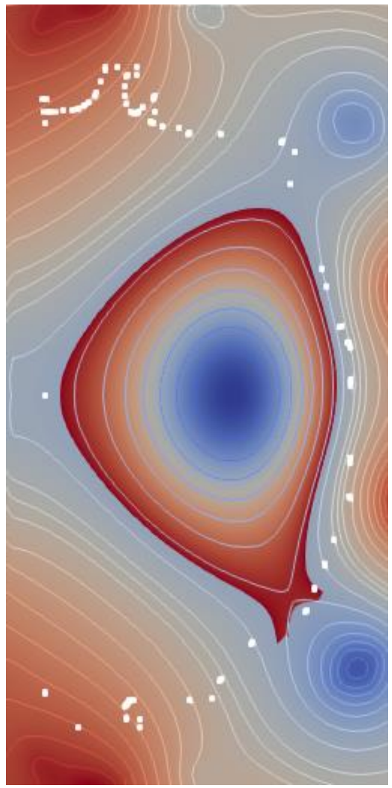


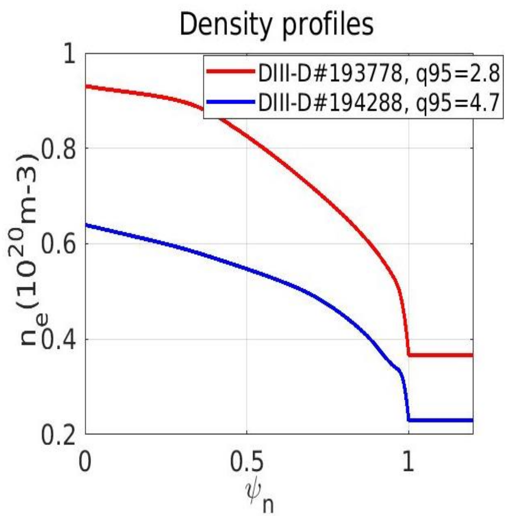
JOREK-GK modelling for DIII-D pulses with X-point from 2023 NT campaign (Te=Ti)

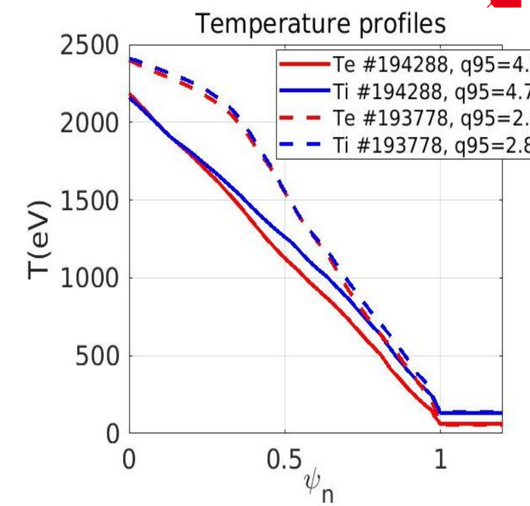
EQDSK 193778, low q95=2.8

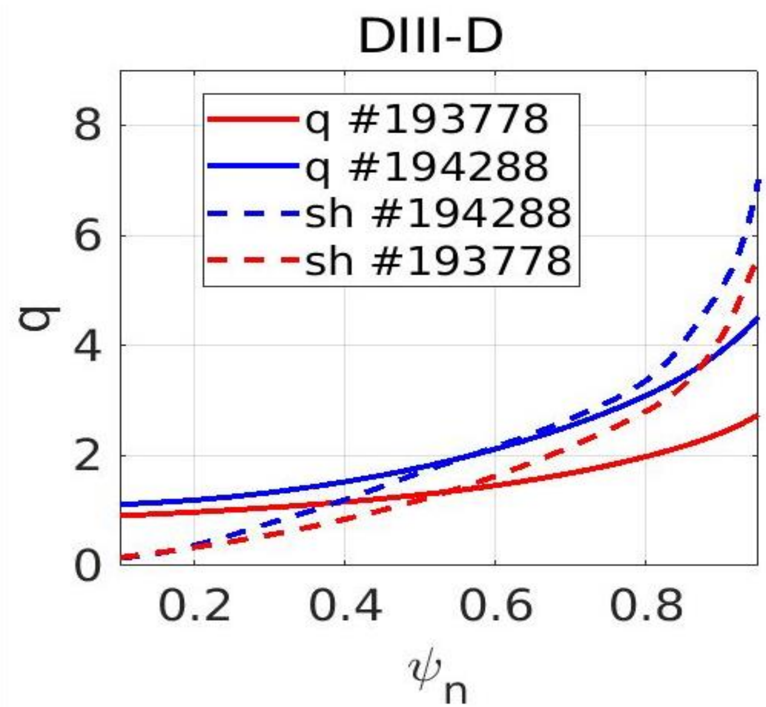


EQDSK 194288, high q95=4.67





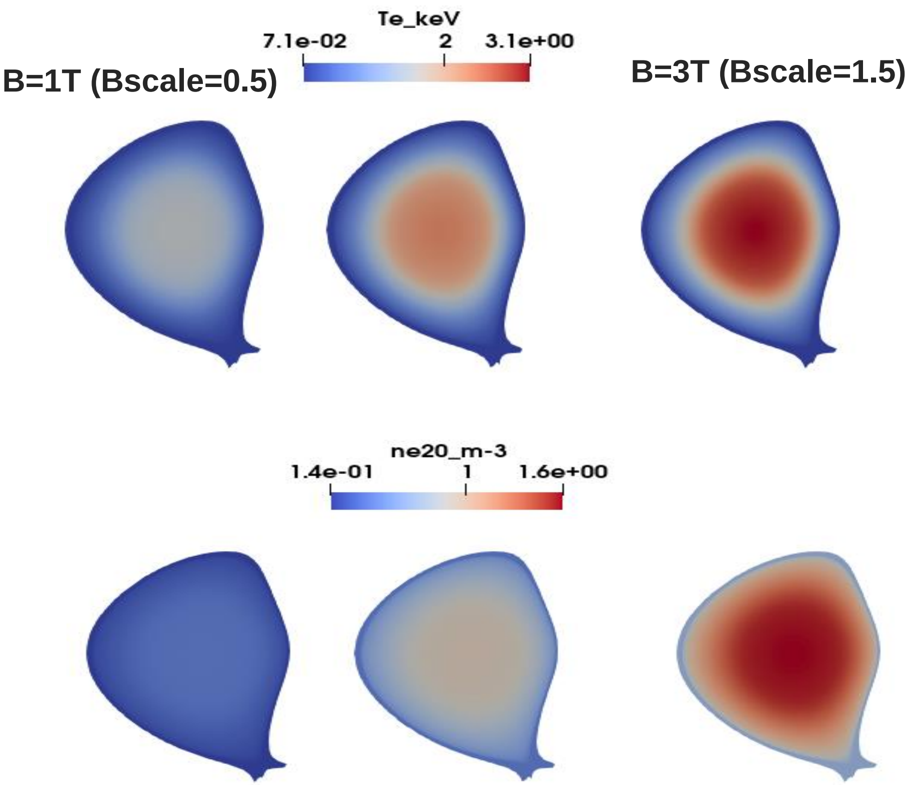




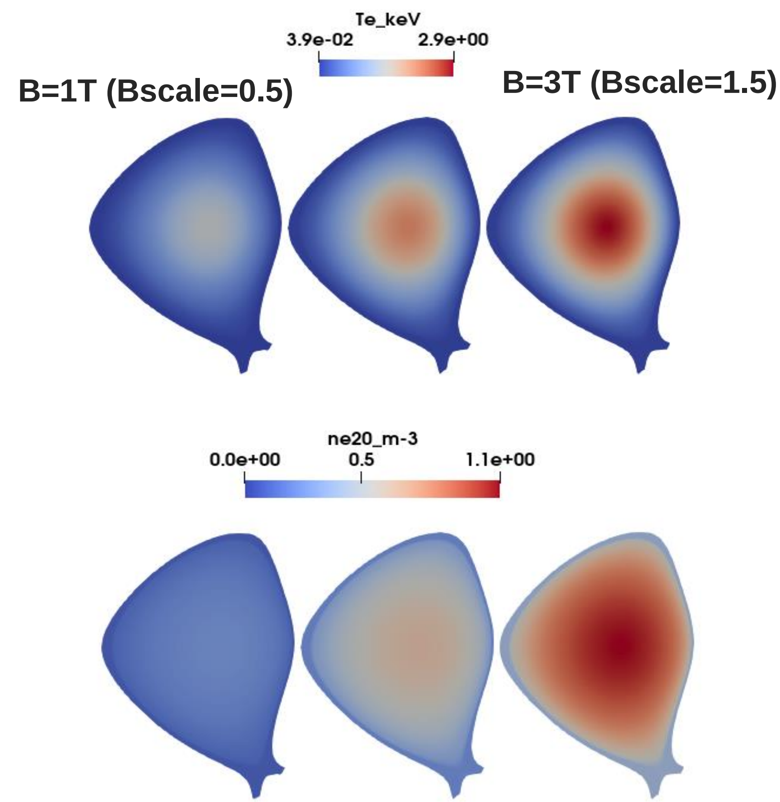
ρ* scaling in NT?

 # 193778 B=2T, low q95=2.7; # 194288 high q95=4.7 = cases Bscale=1. Keeping the same equilibrium and q-profiles constructing new Bt=>Bscale*Bt; Ip=>Bscale*Ip; ne =>ne*Bscale ^(4/3), Ttot=> Ttot*Bscale ^(2/3), Ptot=> Ptot*Bscale^2. As a result ρ*=>ρ*Bscale^(-2/3). Here: Bscale=0.5, Bscale=1, Bscale=1.5. Electron-ion collisions model: small angle random scattering *[Lana Rekhviashvili , Zhixin Lu et al POP 30 (2023)]*

B=2T (Bscale=1 #193778)



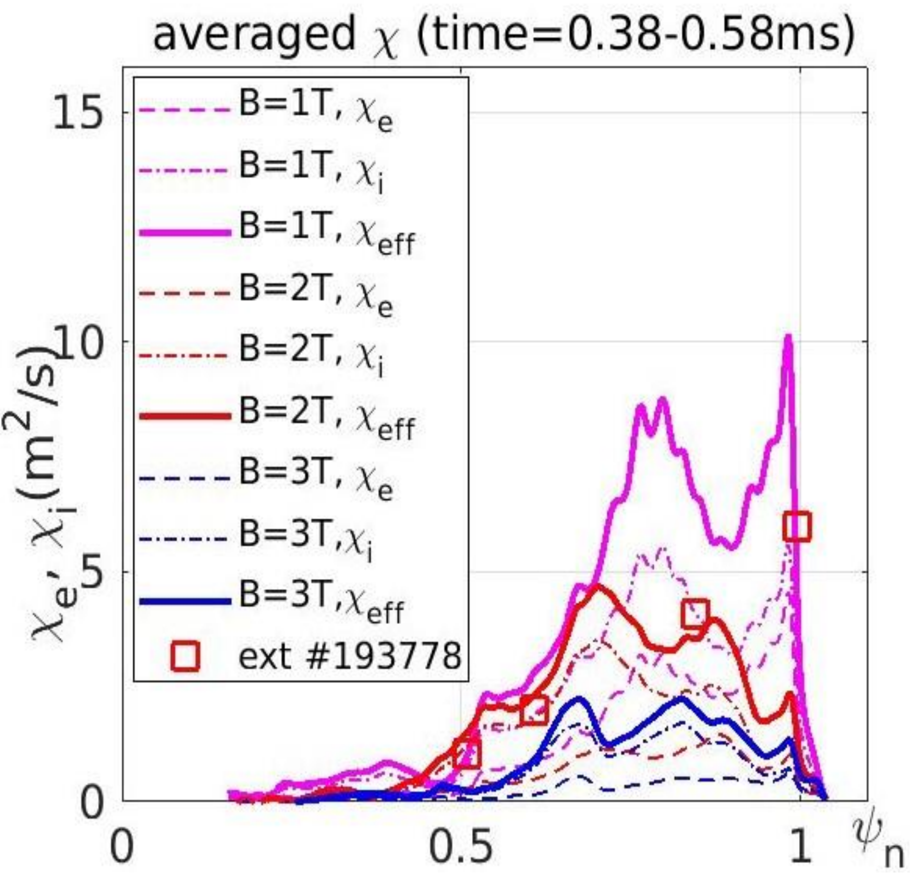
B=2T (Bscale=1 #194288)

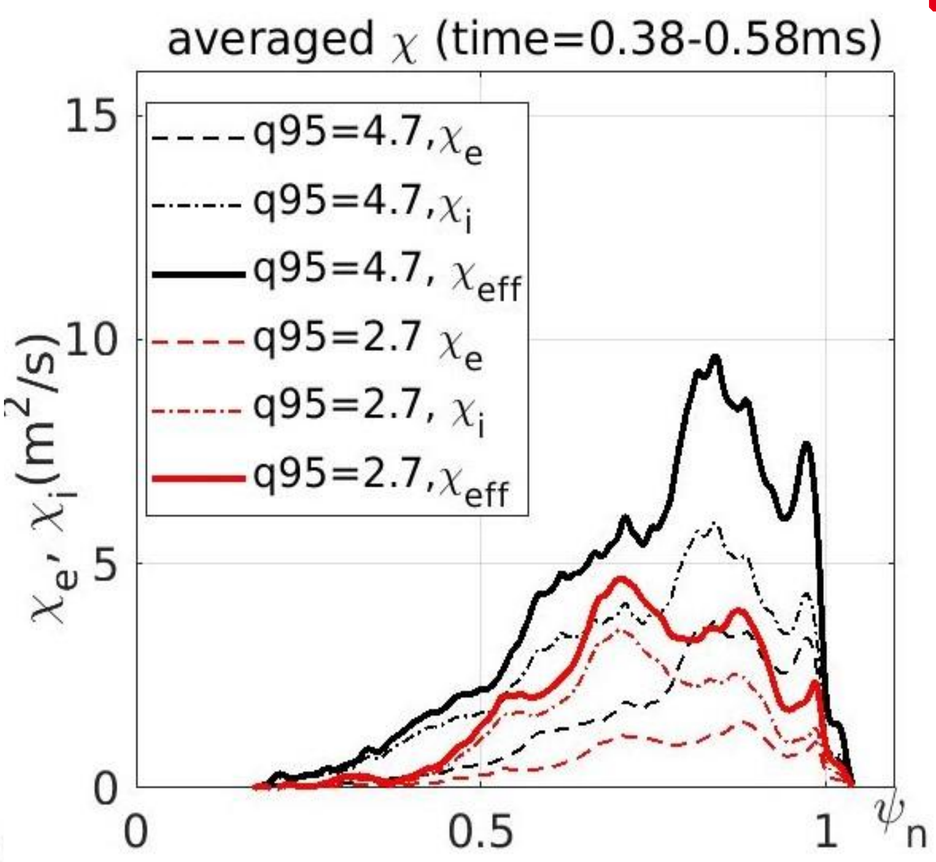


ρ* scaling in NT=>gyro-Bohm in modelling

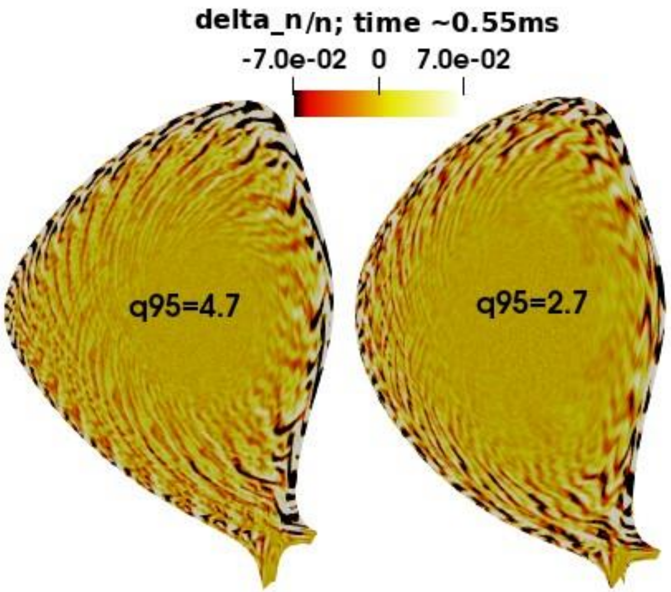
Scaled low q95(#193778) pulse. Time averaged in saturation (0.38-0.58ms) heat conductivity. Confinement improves with decreasing ρ*, gyro-Bohm?

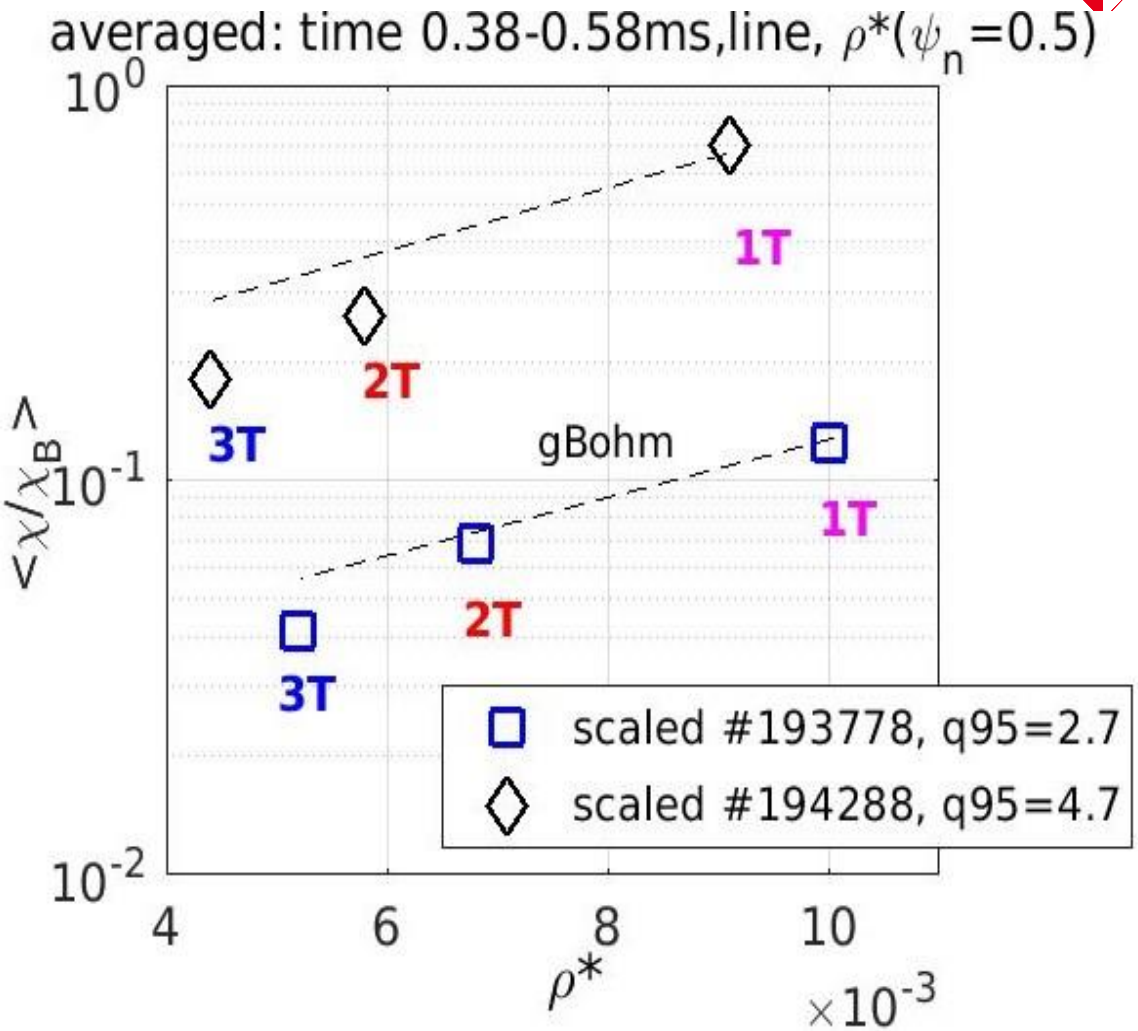
Better confinement at low q95 (#193778) than at high q95 (# 194288) at Bt=2T for both => ~Ip scaling is valid for NT plasmas.



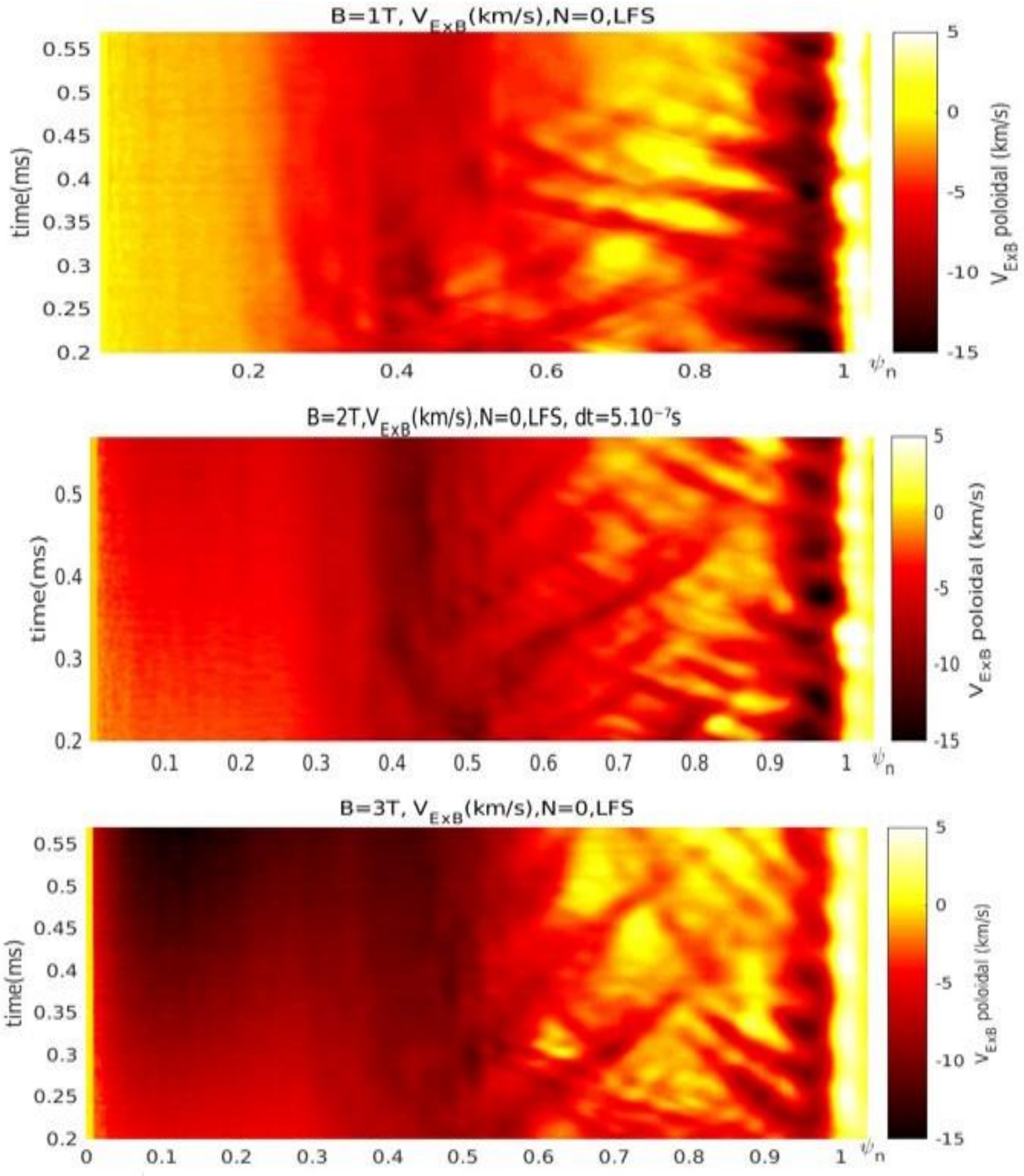


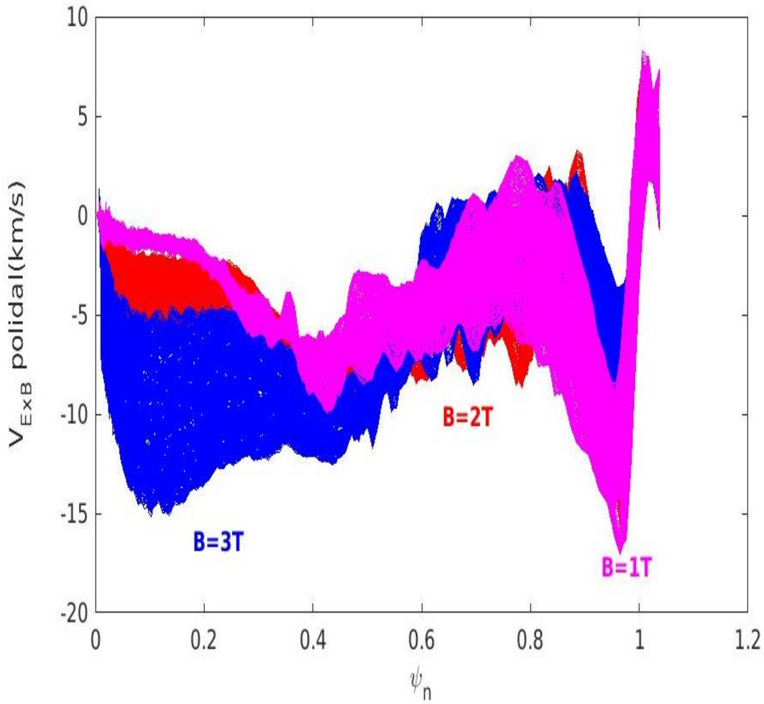
The normalized to Bohm $c_B = 1/16 T_{eV}/B_T$ time and line (OMP) averaged heat conductivities as a function of ρ^* ($\psi_n = 0.5$) for all scaled cases. Gyro-Bohm scaling for NT in modelling





Why confinement increases with decreasing ρ*? Mean poloidal flow V ExB (N=0) increases with Bt for central plasma, ExB 'well' at the edge is larger for B=1T.

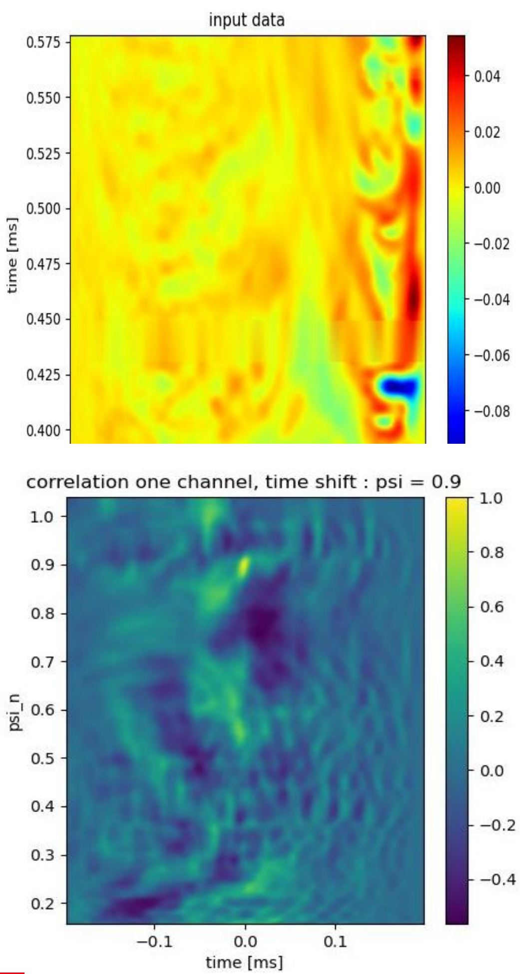




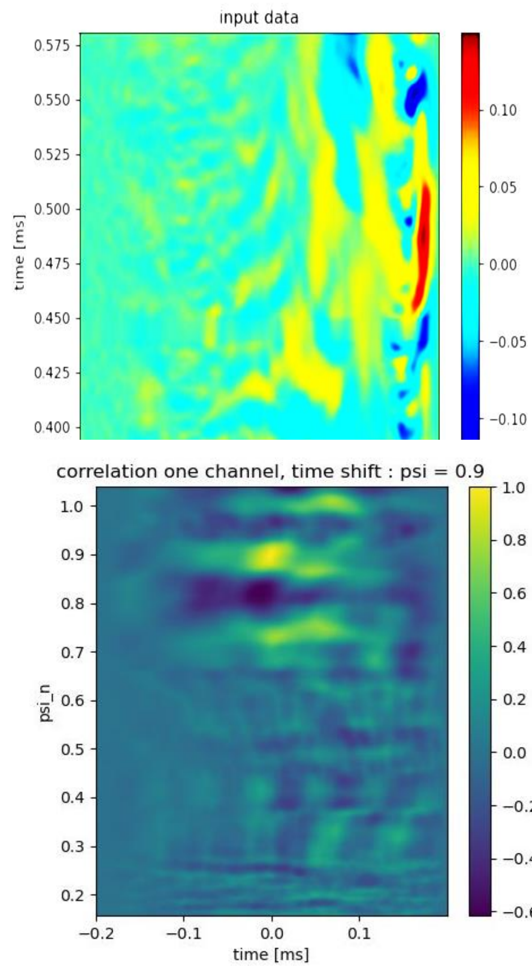
Density fluctuations correlation (ψ_n~<0.7) at outer mid-plane (OMP) decreases with decreasing ρ*.

$$Corr(\boldsymbol{\psi}_1,\boldsymbol{\psi}_2) = \max|_{\delta\tau}[Corr(\boldsymbol{\psi}_1,\boldsymbol{\psi}_2,\boldsymbol{\delta}\tau)];\ Corr(\boldsymbol{\psi}_1,\boldsymbol{\psi}_2,\boldsymbol{\delta}\tau)=\frac{\int_{t1}^{t2}\delta n(\boldsymbol{\psi}_1,t)\ \delta n(\boldsymbol{\psi}_2,t+\boldsymbol{\delta}\tau)dt}{\sqrt{\int_{t1}^{t2}\delta n(\boldsymbol{\psi}_1,t)^2dt}\cdot\sqrt{\int_{t1}^{t2}\delta n(\boldsymbol{\psi}_2,t)^2dt}}$$

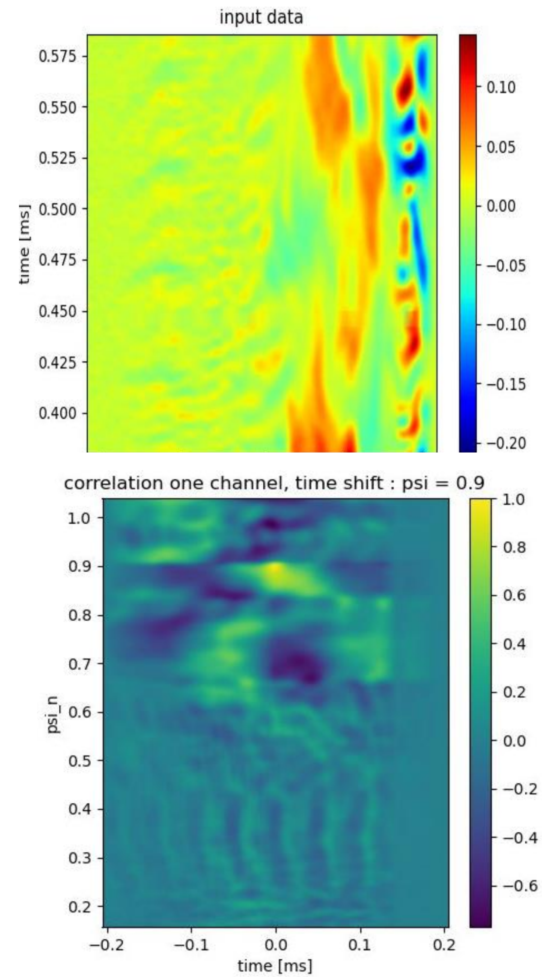
Bscale=0.5(# 193778)



Bscale=1. (# 193778)

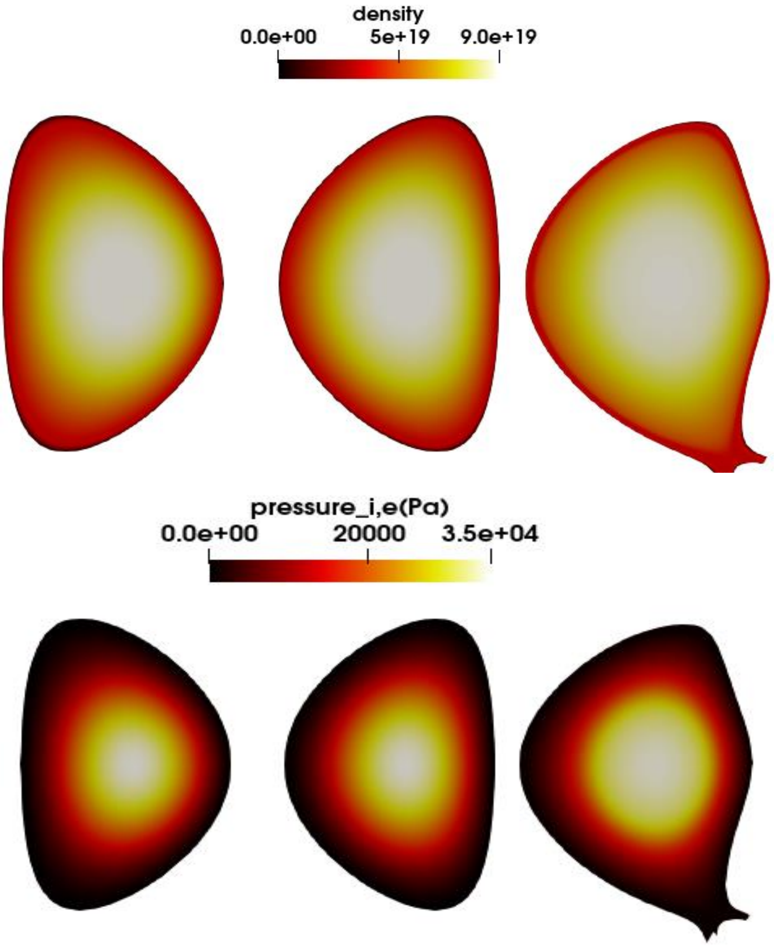


Bscale=1.5 (# 193778)

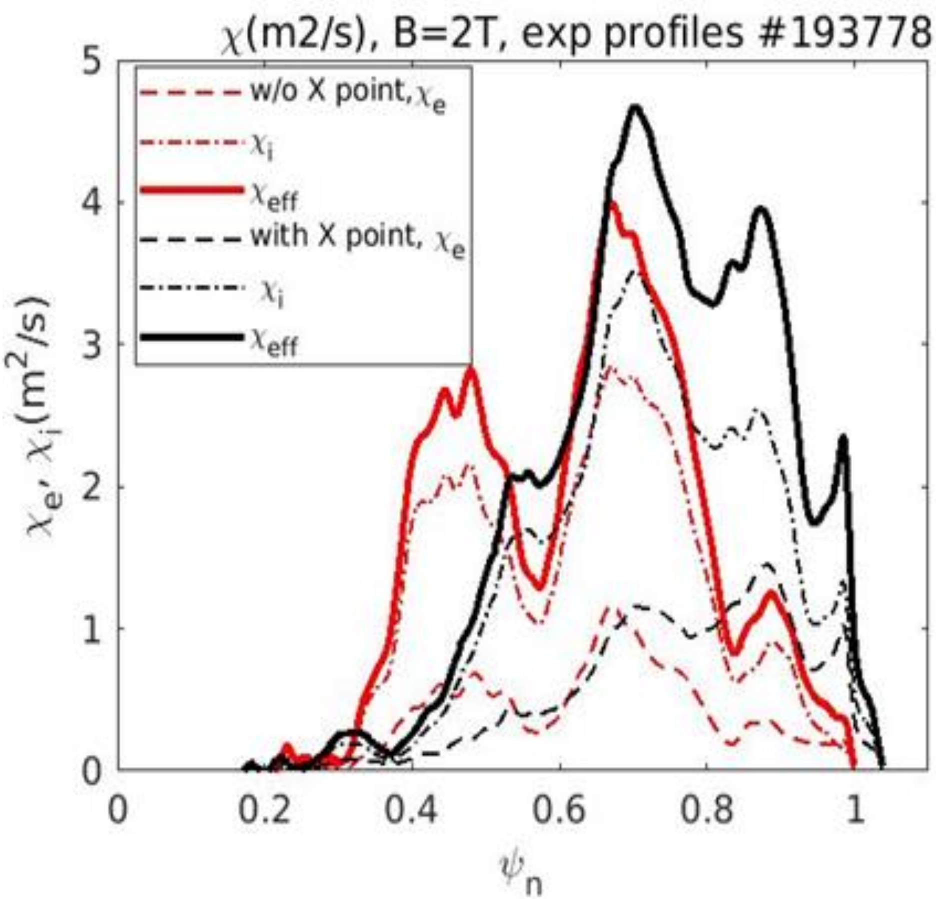


Important comment for modelers: X-point +SOL geometry is important!

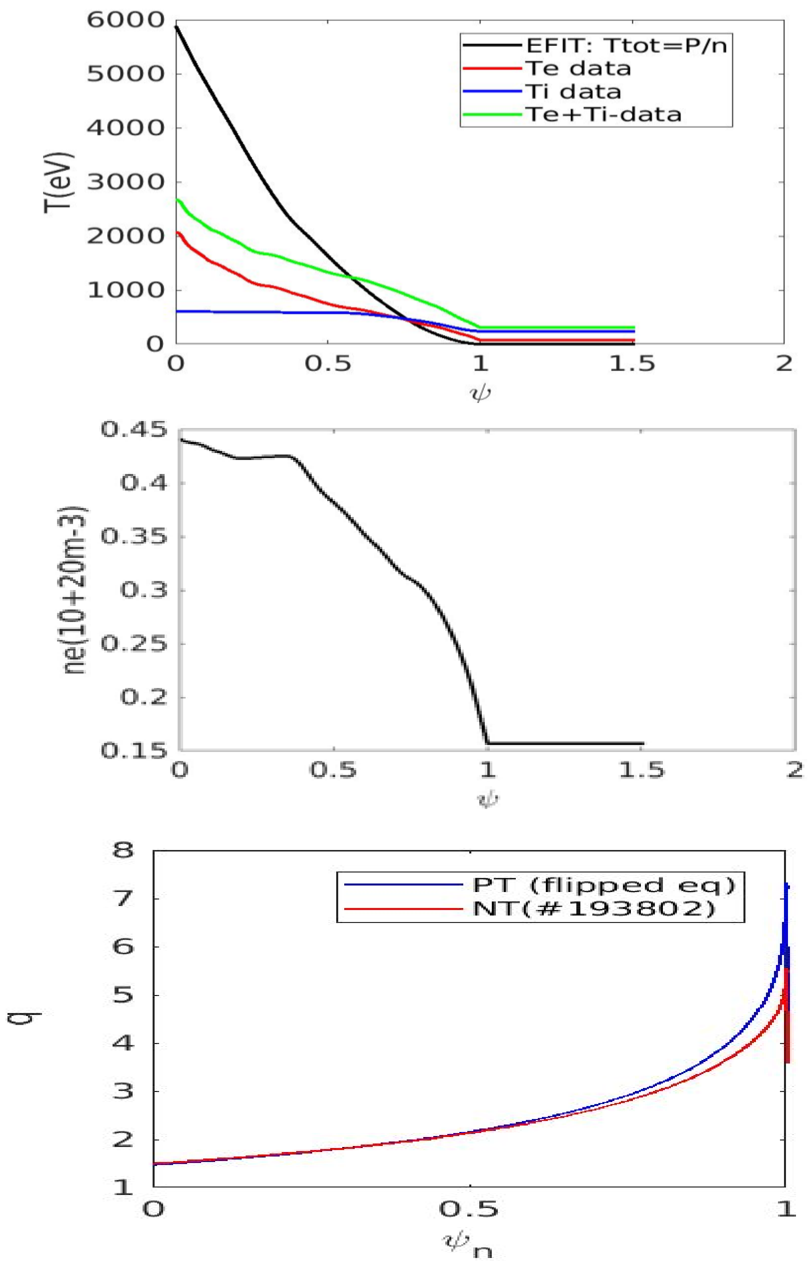
Similar to #193778 plasma size/shape/parametres but w/o X-point in NT. Mirror flipped equilibrium for PT w/o X-point. BUT: because of zero potential perturbation at the boundary w/o X point (boundary conditions) edge turbulence was significantly reduced, no spreading to open field lines as with X-point. BUT : experimentally more turbulence at the edge!

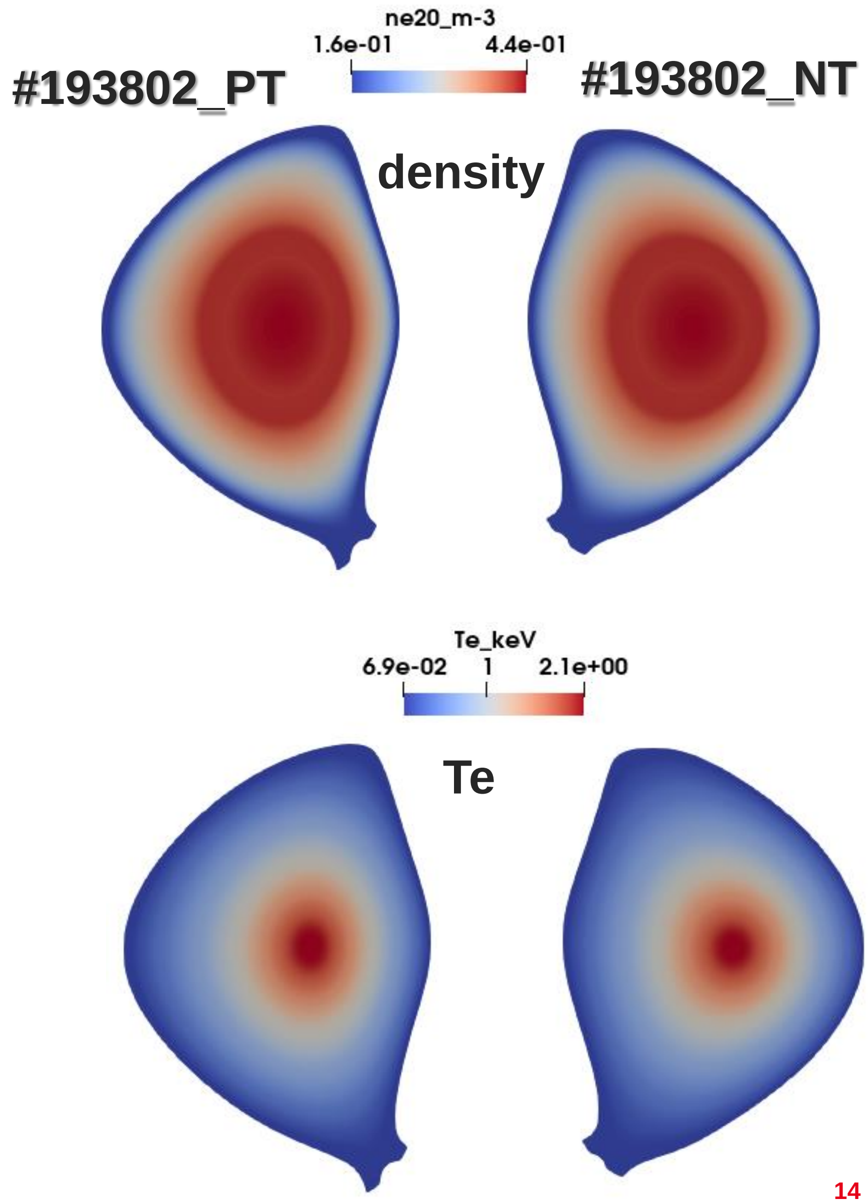


NT

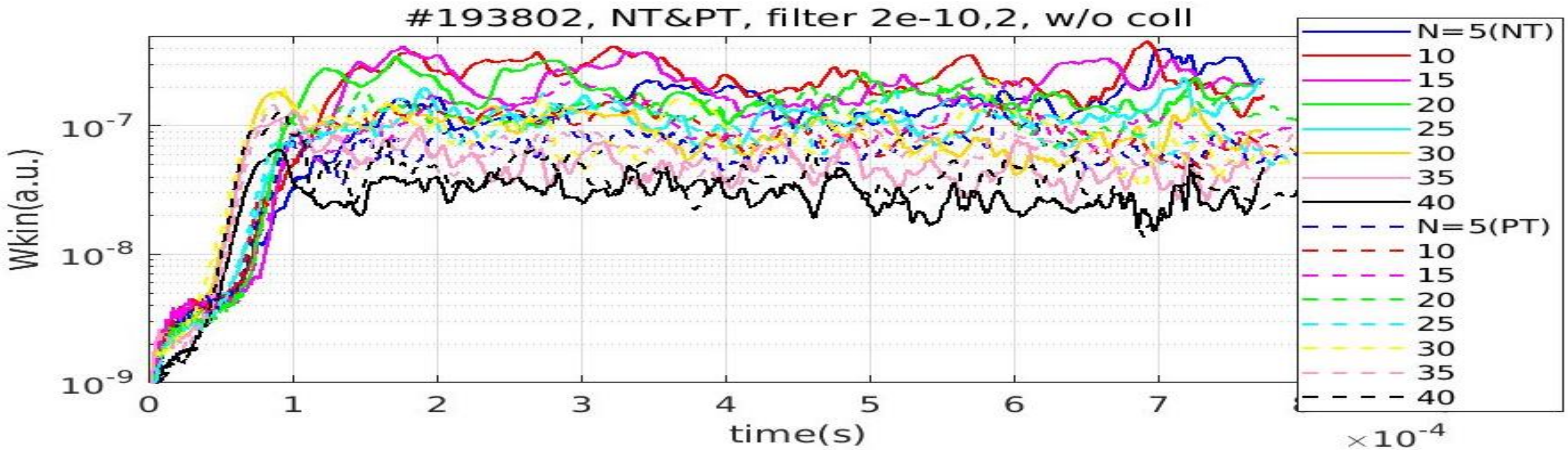


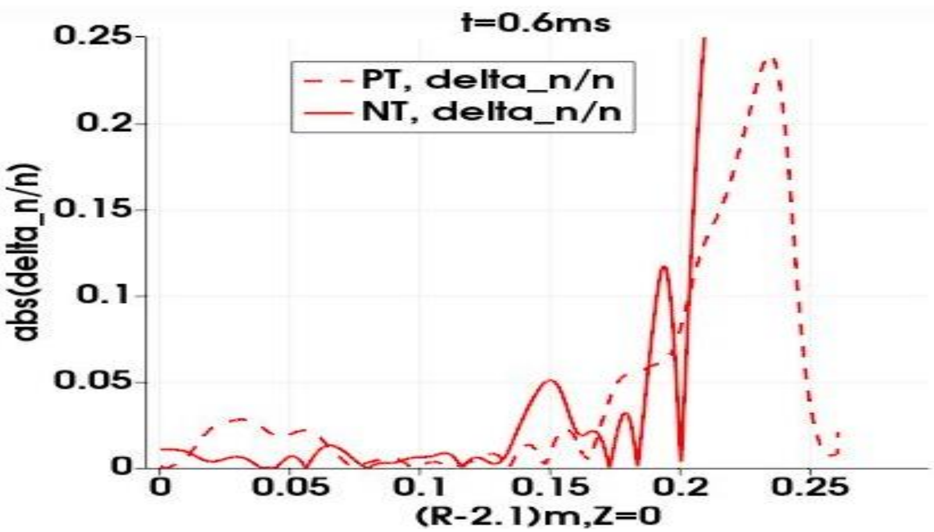
Comparison of NT /PT . NT: DIII-D #193802; PT: "mirror flipped" equilibrium. Te>Ti

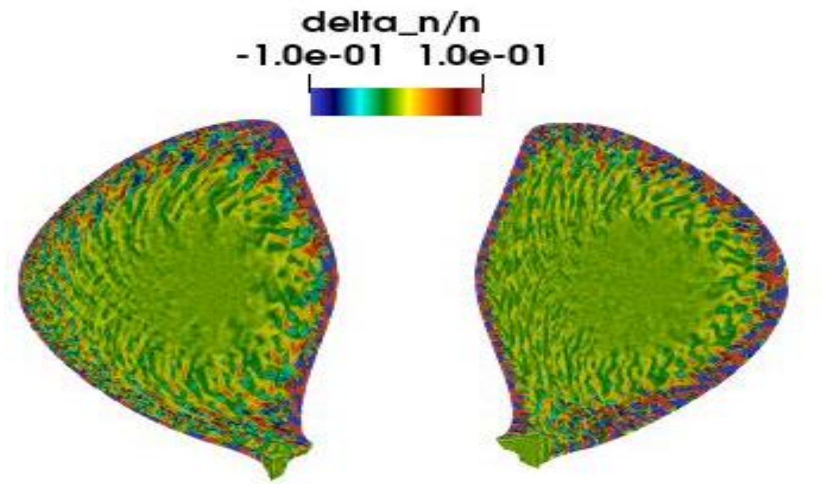




Running NT/PT up to the established saturated quasi-stationary TEM/ITG turbulence (t~0.7ms). Larger edge fluctuations for PT compared to NT.





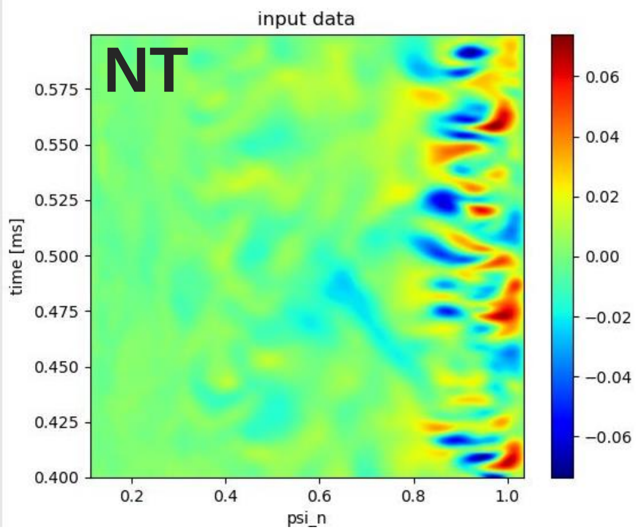


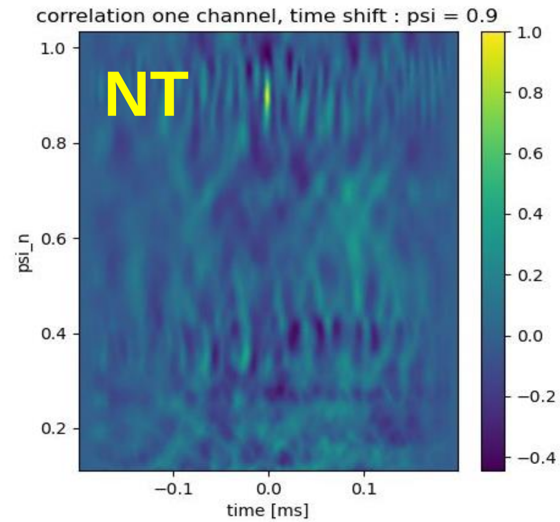
Larger and longer lasting eddies for PT compared to NT. Larger correlation of density fluctuations and heat conductivity in PT.

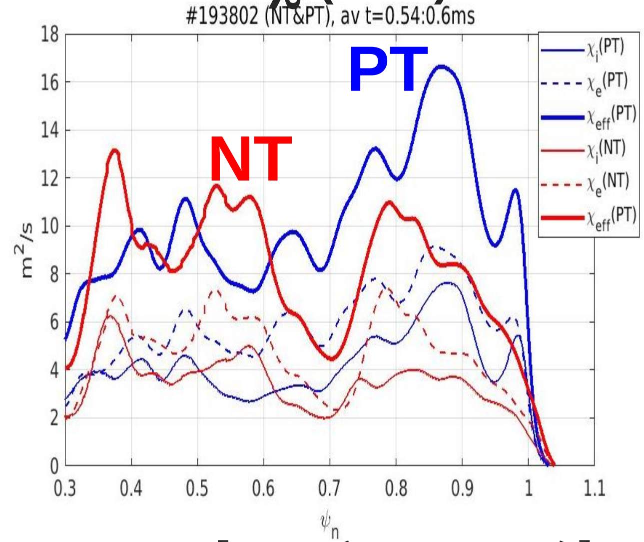
δn -density fluctuations

$Corr(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2 = 0.9, \boldsymbol{\delta}\tau)$

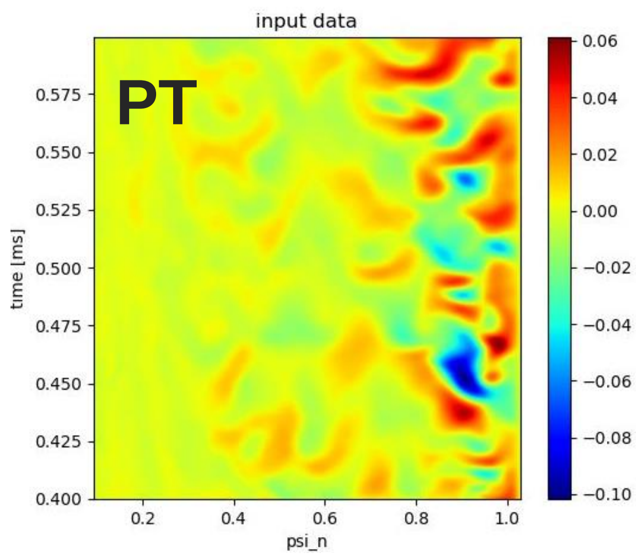
χ (m²/s)

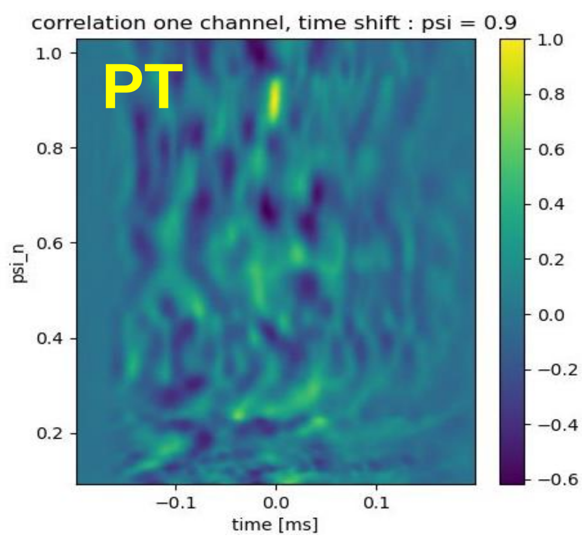


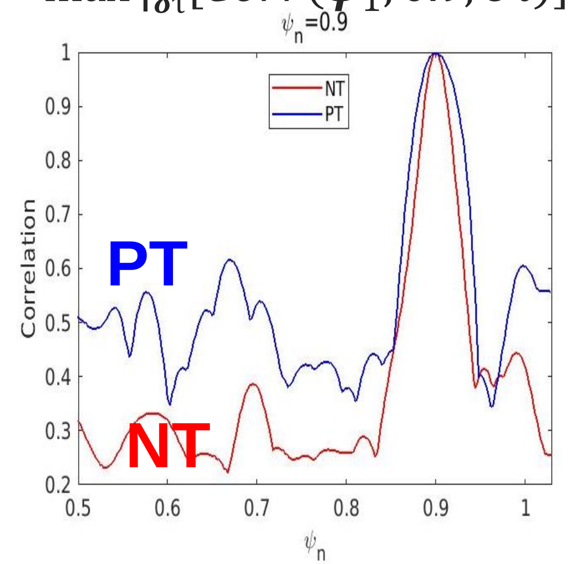




$\max|_{\delta\tau}[Corr(\boldsymbol{\psi}_1, 0.9, \boldsymbol{\delta}\tau)]$

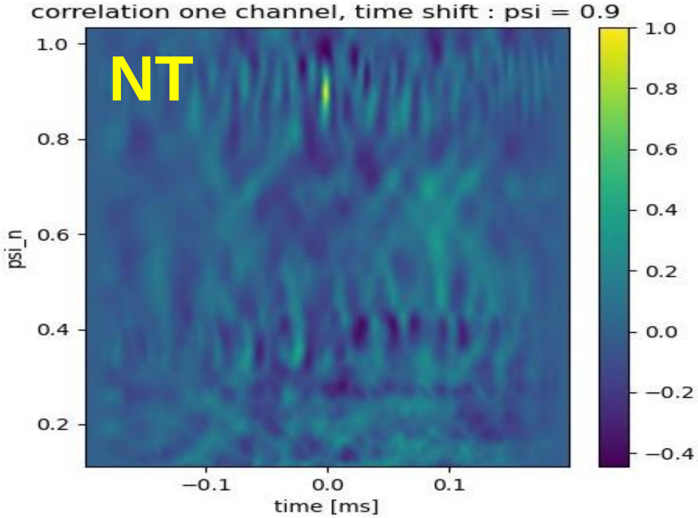


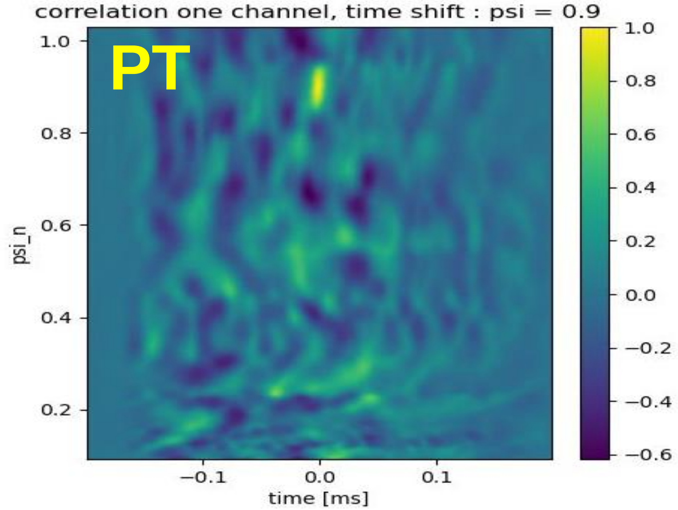




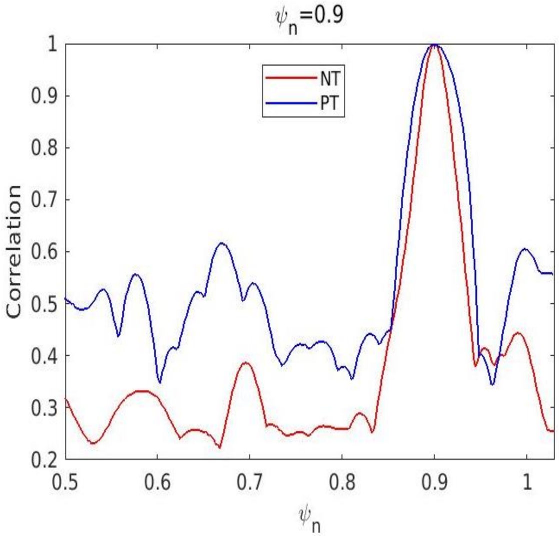
Larger edge (ψ_n>0.8) density fluctuations correlation at PT compared to NT=> larger turbulence, larger heat fluxes

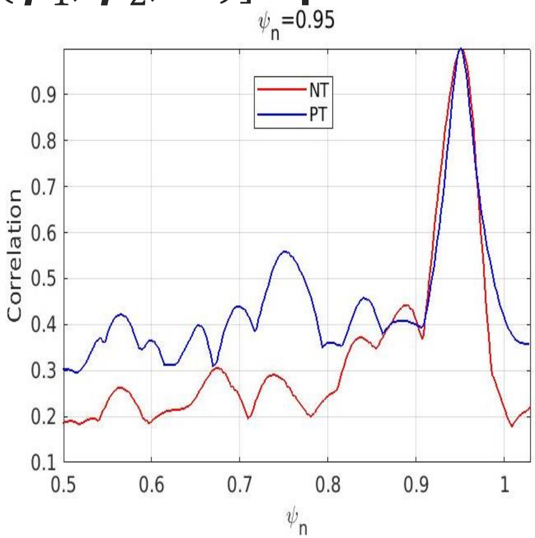
$$Corr(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2 = 0.9, \boldsymbol{\delta}\tau)$$

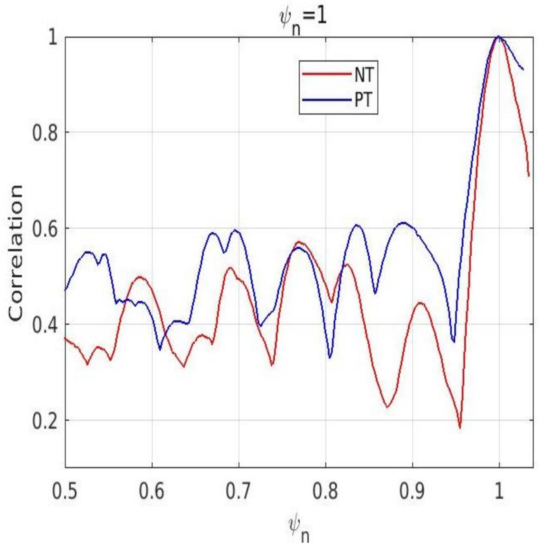




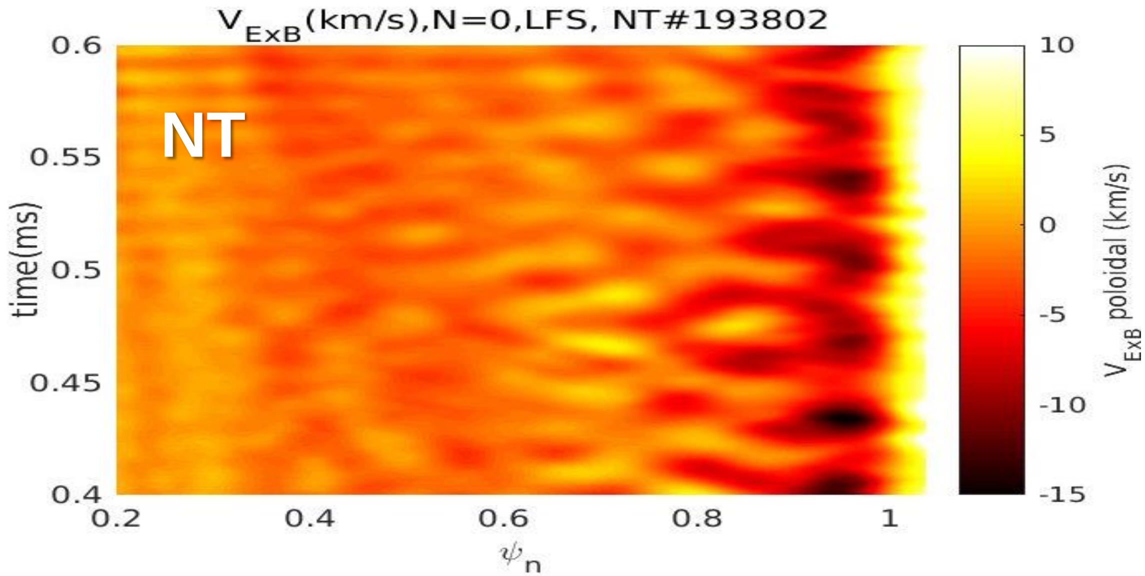
$Corr(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2) = \max|_{\boldsymbol{\delta}\tau}[Corr(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2, \boldsymbol{\delta}\tau)]$ **- plot over line at outer mi-plane (OMP)**

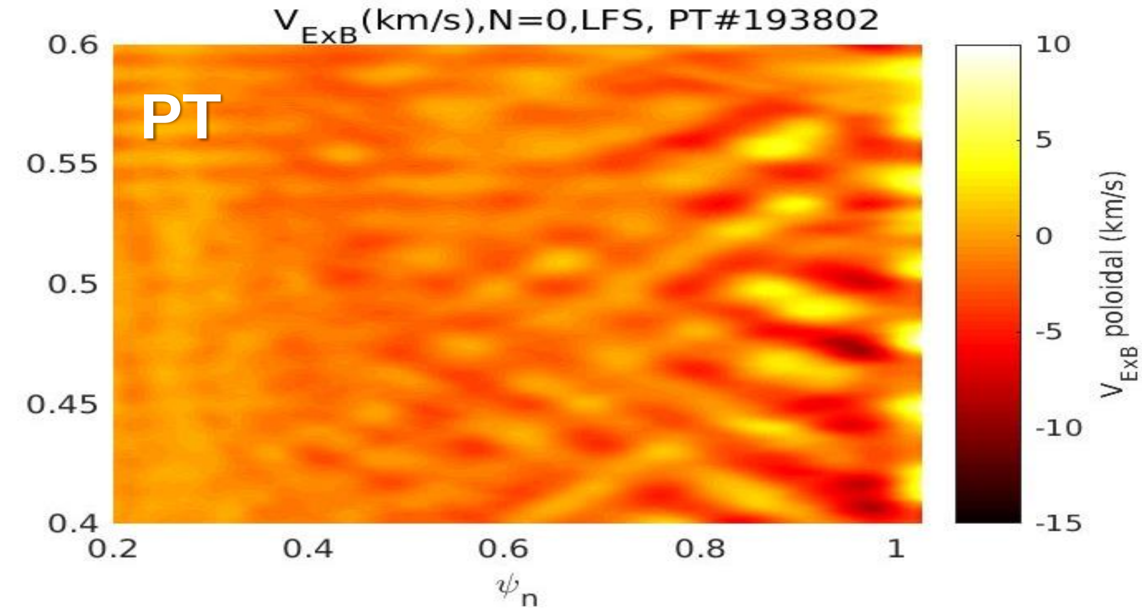


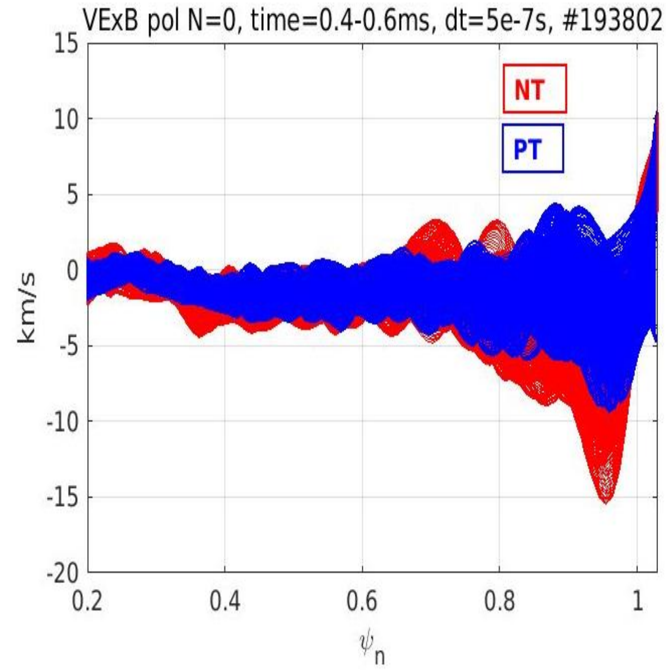




Larger edge V_{ExB} poloidal for NT compared to PT => stabilizing



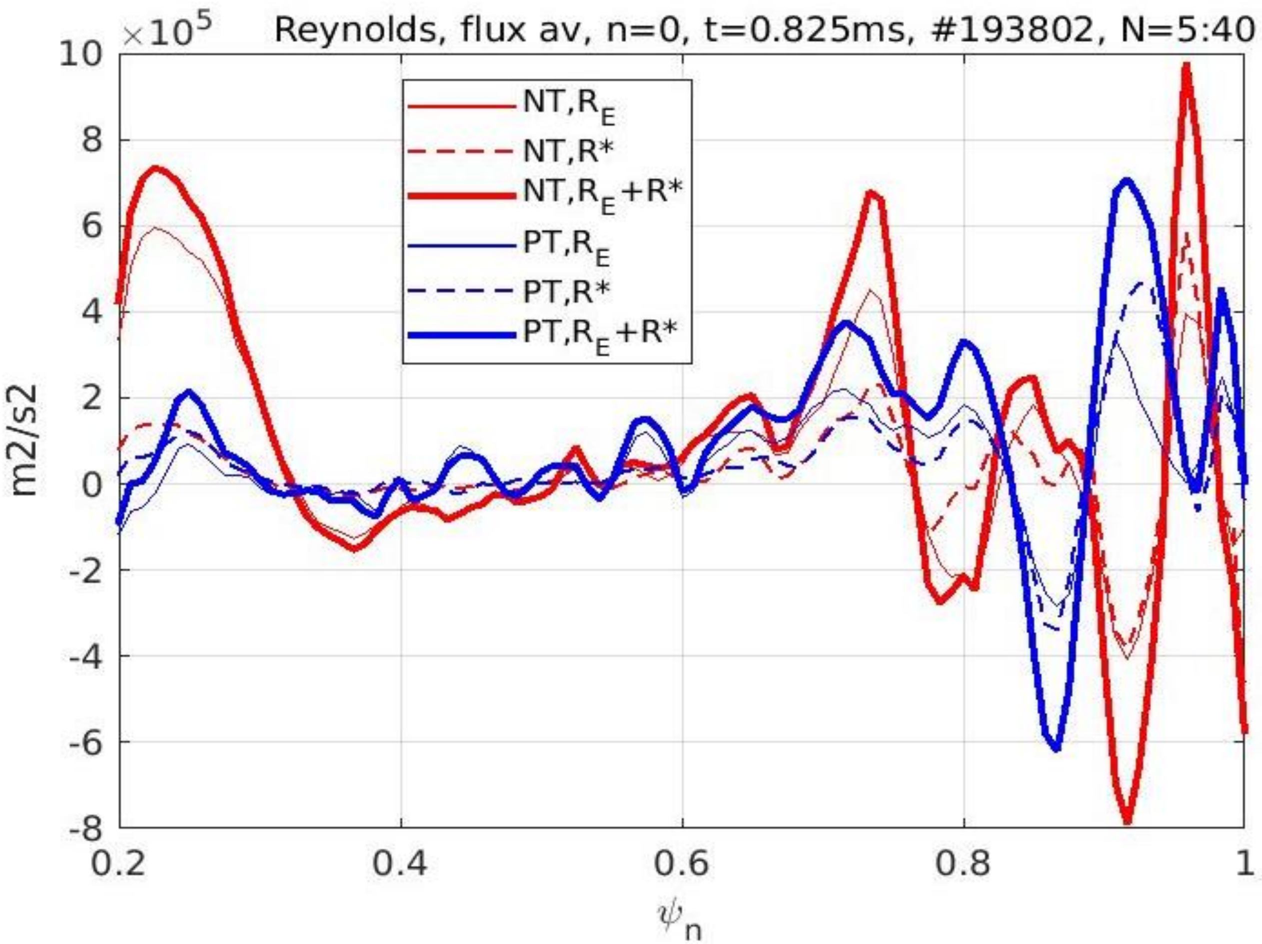




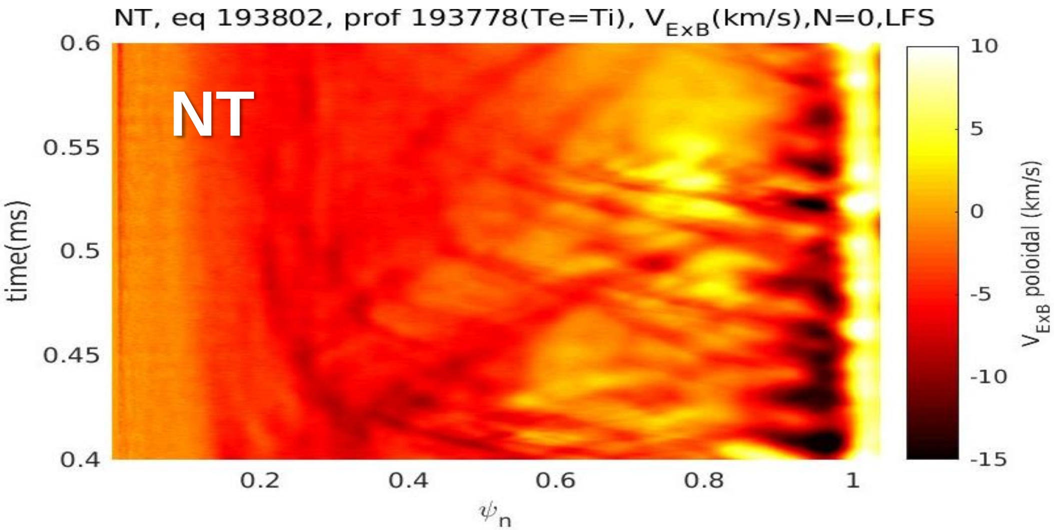
Poloidal zonal flow V ExB is generated by ITG/TEM turbulence via Reynolds tensor: larger and more sheared in NT compared to PT at the edge.

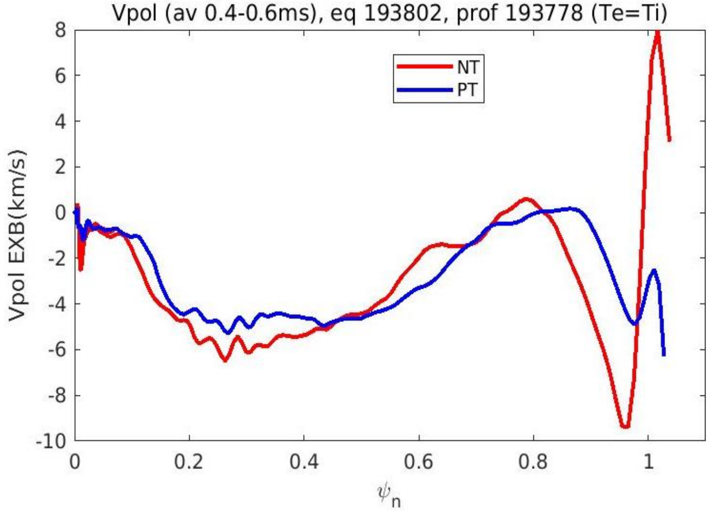
$$\frac{\partial\langle u_{E\theta}\rangle}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2(\pi+\pi^\star)\right]=rhs$$

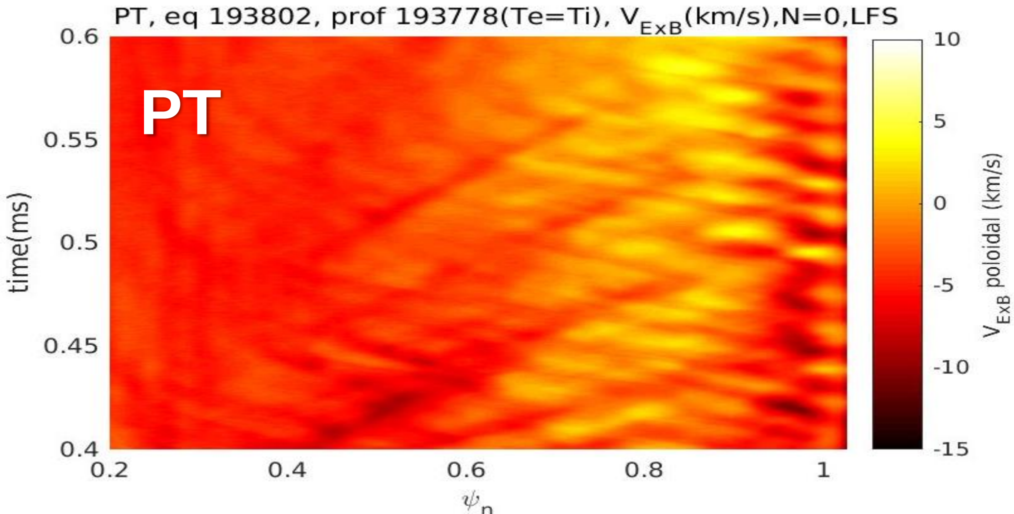
$$\pi = \langle \tilde{u}_{Er}\,\tilde{u}_{E\theta}\rangle$$
$$\pi^\star = \langle \tilde{u}^\star_r\,\tilde{u}_{E\theta}\rangle$$

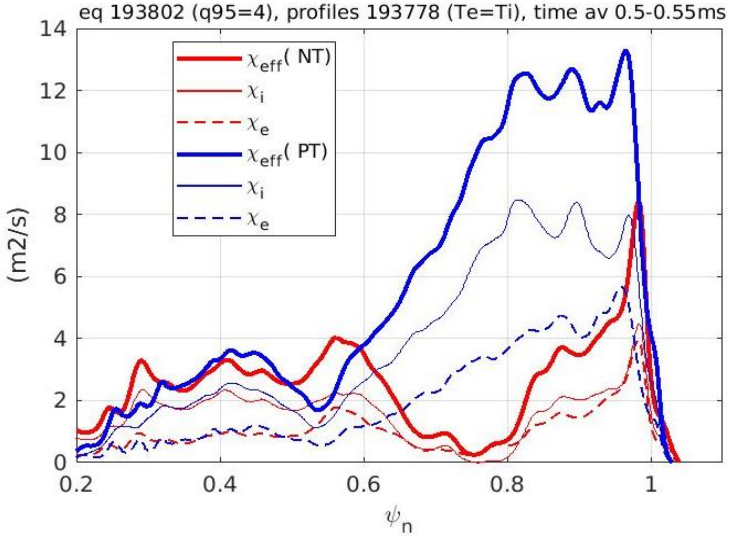


With different profiles #193778 (Ti=Te) the result is similar to #193802(where Te>Ti): larger V ExB flow at the edge at NT => more stabilisation=> smaller edge heat flux and conductivity at NT



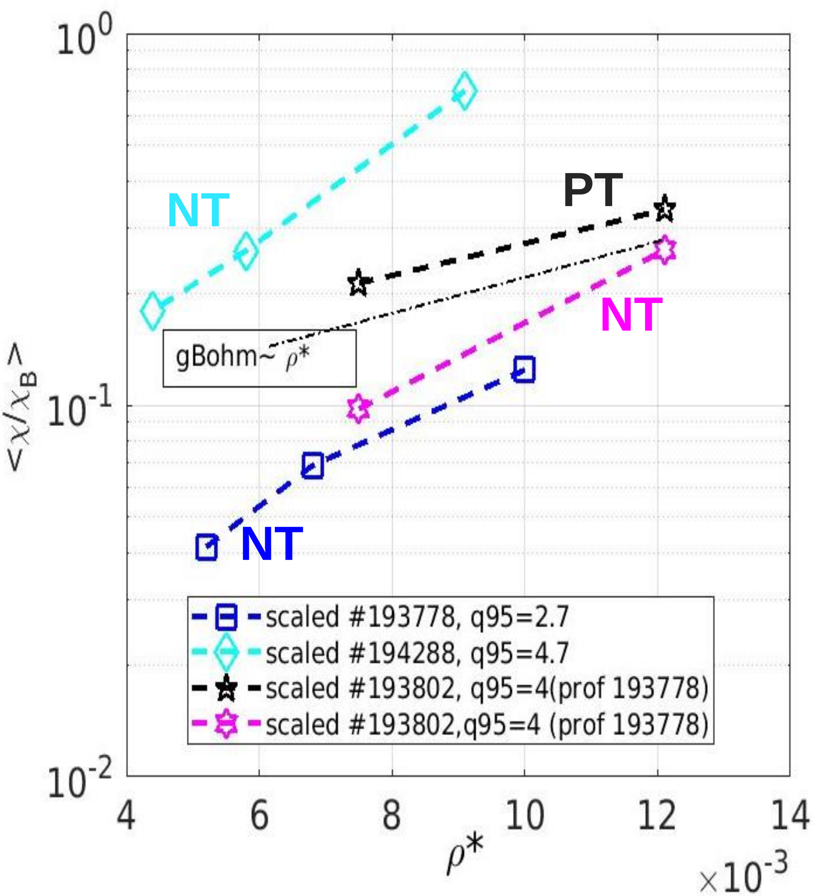




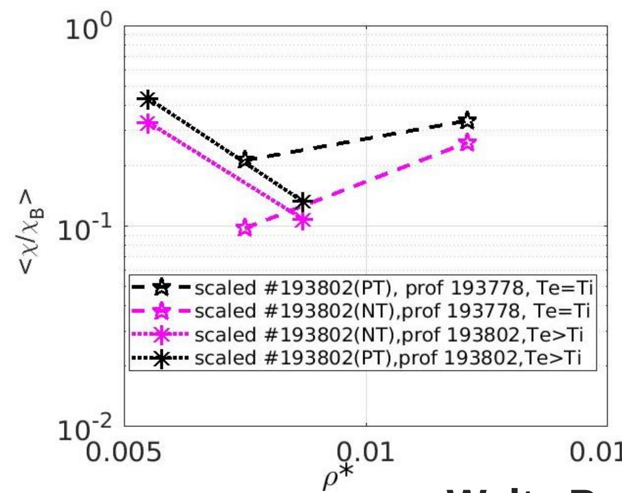


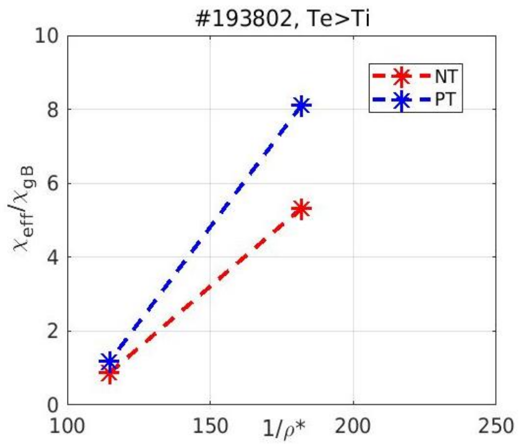
Equilibrium #193802 (q95=4) PT&NT, but with different profiles ρ* scaling is not the same! More work needed, scaling with size?

High dentity, higher temperature gradient, Te=Ti (#193778) => gyro-Bohm in PT (?), slightly better in NT.

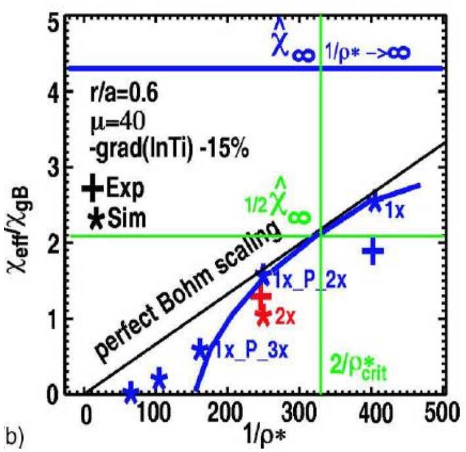


Lower density, lower temperature gradient, Te>Ti (#193802), broken Bohm =stabilisation at higher ρ* if below critical gradient ?



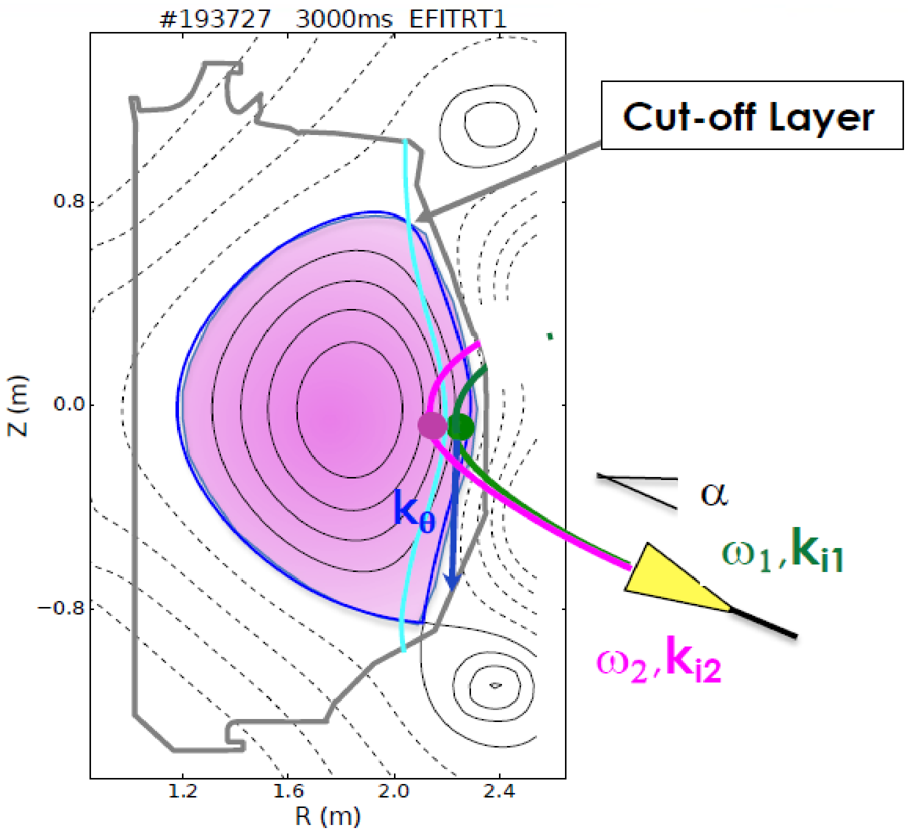


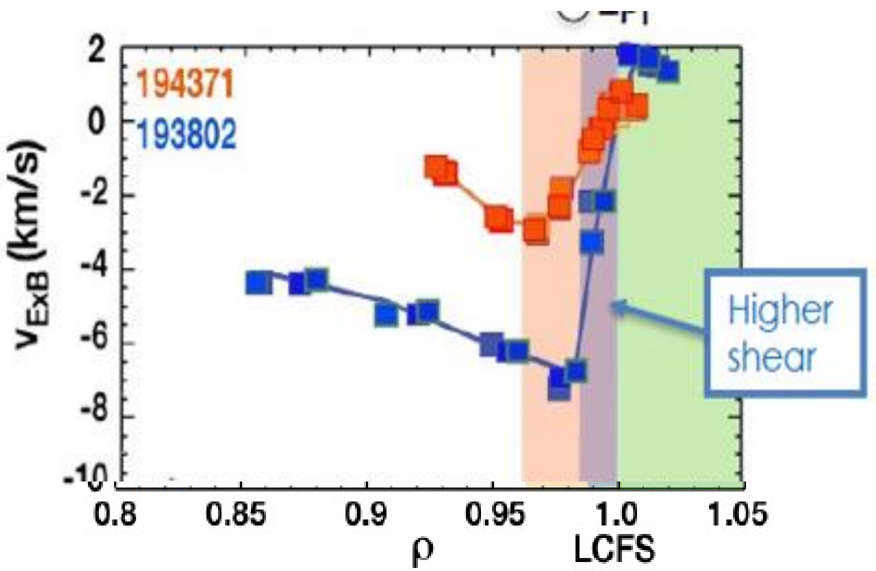
Waltz PoP 2006

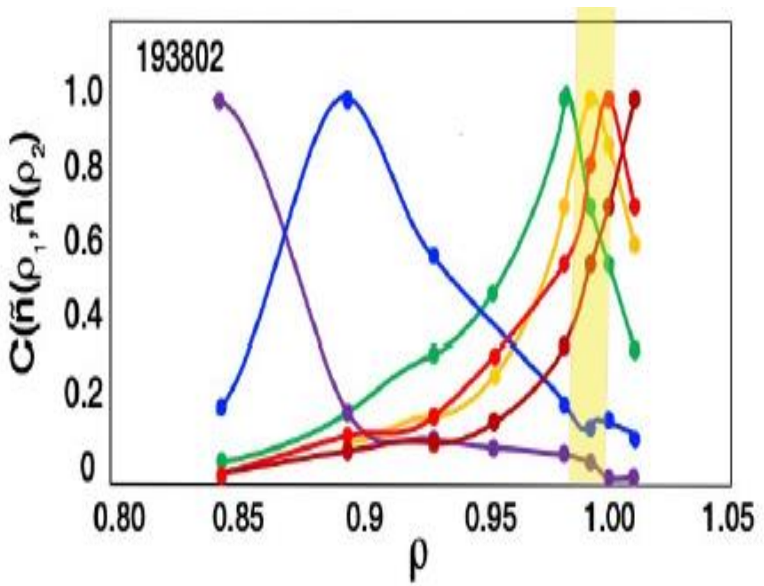


Doppler Backscattering (DBS) measurements in DIII-D: density fluctuations, time-space correlation, V_{EXB} rotation.

L. Schmitz, NT meeting Apr 18 2024.

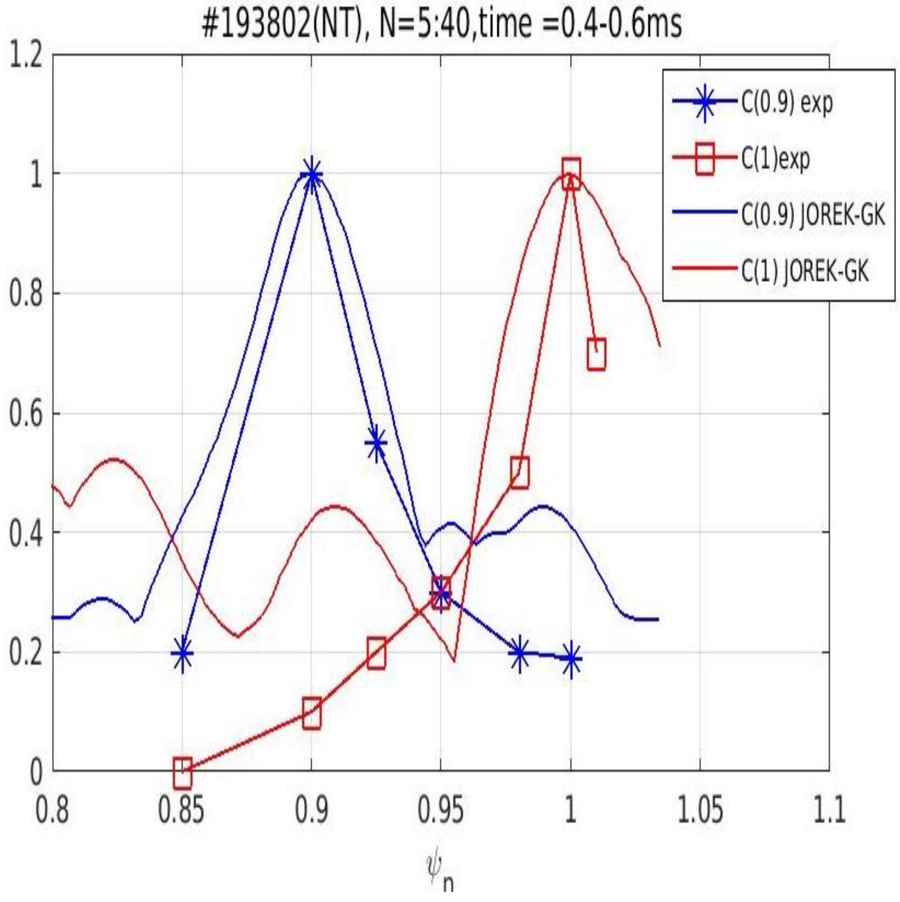




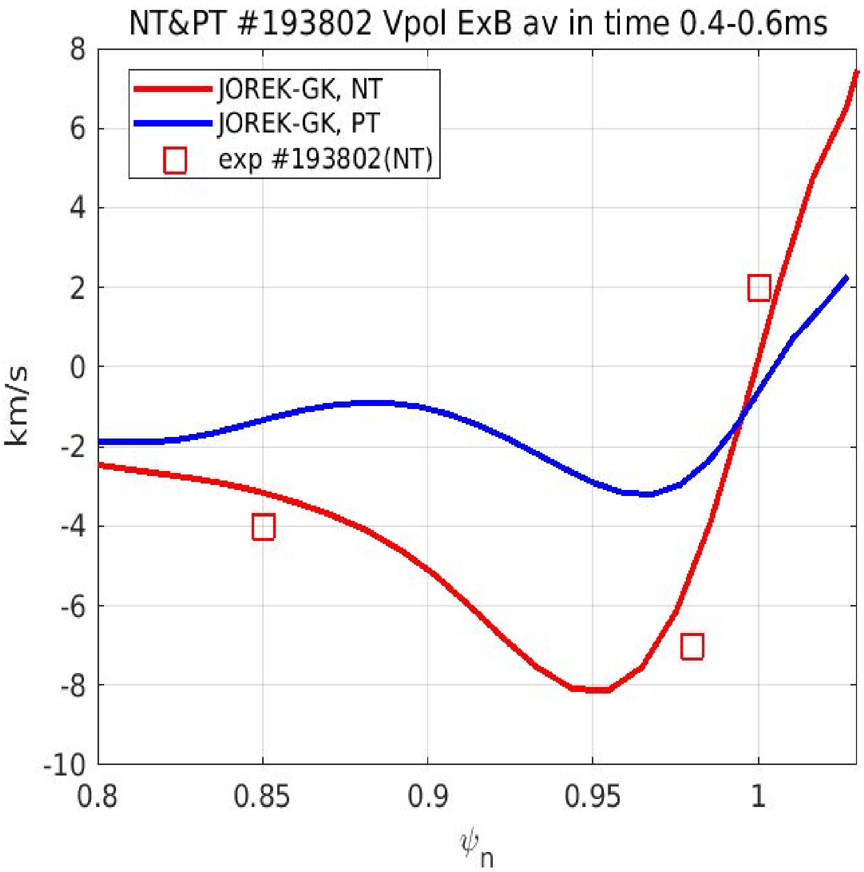


Comparison JOREK-GK with experiment #193802: similar density fluctuations correlation for ψ_n=0.9, but stronger in modelling at ψ_n=1. V $_{ExB}$ close to experimental at NT. Smaller edge rotation V $_{ExB}$ at PT.

$\max|_{\delta\tau}[Corr(\psi_1, \psi_2, \delta\tau)]$- correlation



V $_{ExB}$ -poloidal



Conclusions

1. **Particles in global non-linear JOREK-GK code gyro-kinetic ions+ kinetic electrons in realistic X-point geometry, electrostatic TEM/ITGs turbulence.**

2. **Comparison of JOREK-GK with GENE, GS2 for TCV (Te>Ti) in linear TEM regime for TCV : similar linear growth rates, larger in PT compared to NT.**

3. **Comparison JOREK-GK with GENE-X for TCV parameters (NT&PT). Improved core confinement at NT compared to PT. Divertor heat fluxes: PT λq =4mm; NT: λq =3.5 mm.**

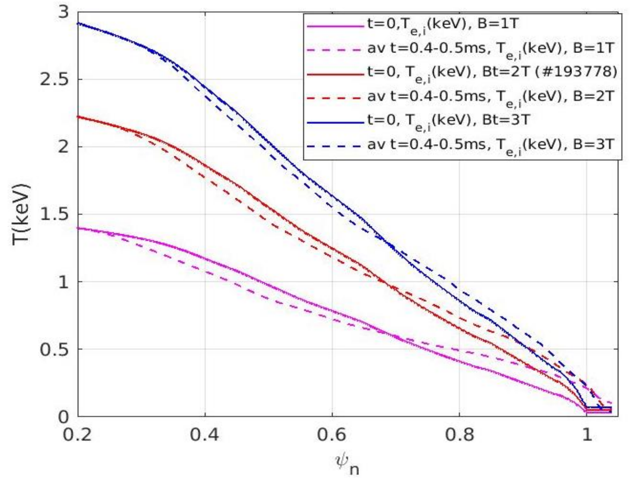
4. **Modelling of realistic DIII-D (low q95,high q95, PT&NT). Gyro-Bohm ρ^* scaling in NT at high density, Te=Ti=> good for reactor? However seems like depends on parameters: at Te>Ti, low density broken Bohm both for NT&PT? More work is needed.**

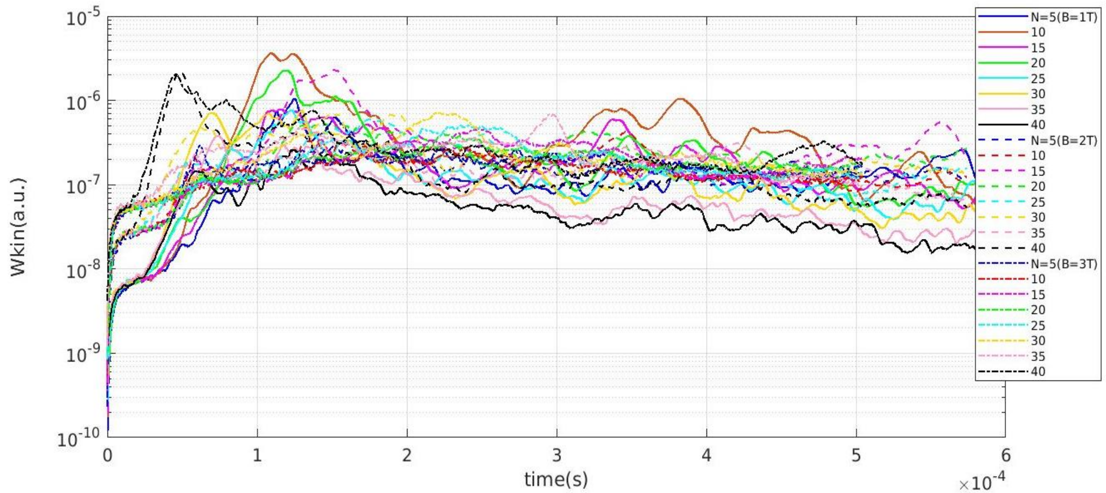
5. **Larger poloidal edge V ExB flow at NT compared to PT=> stabilizing=>smaller correlation of density fluctuations => smaller fluxes=>smaller heat conductivity at NT.**

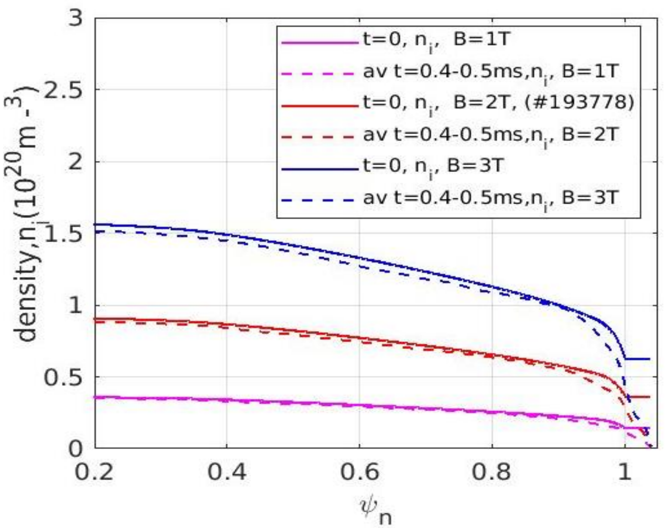
6. **Comparison GOREK-GK modelling results with Doppler Backscattering (DBS) measurements for DIII-D # 193802:**
   - similar to experiment correlation of edge density fluctuations;
   - similar to experiment edge poloidal V ExB flow;

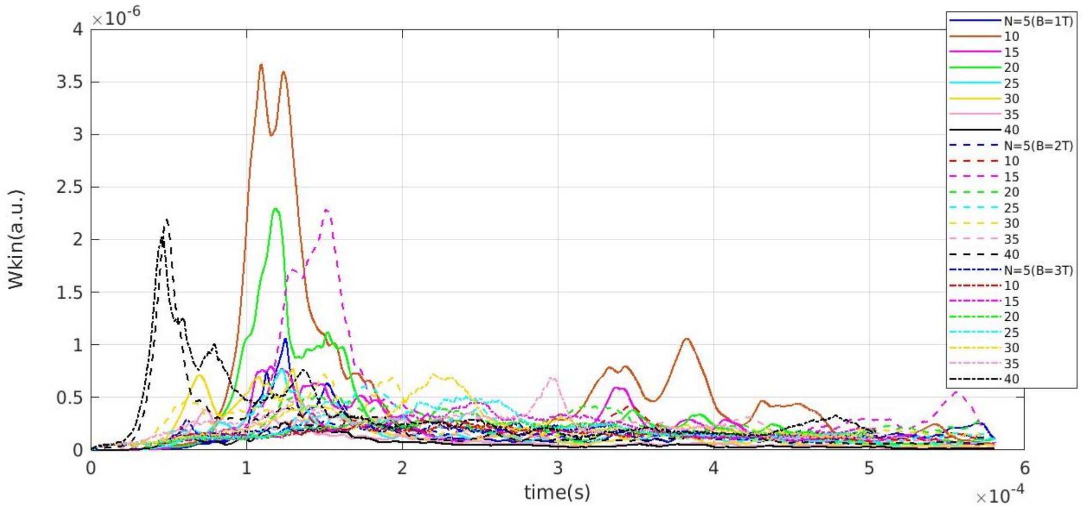
Running JOREK-GK for three cases (B=1T, 2T (exp.# 193778), 3T) up to established saturated quasi-stationary TEM/ITG turbulence.

Filters : perp. 2e-11,// 2, particles 5e8, Npsi=150, Nth=500, mi/me=100, N=5:5:40
Low q95 # 193778 B=2T, q95=2.7

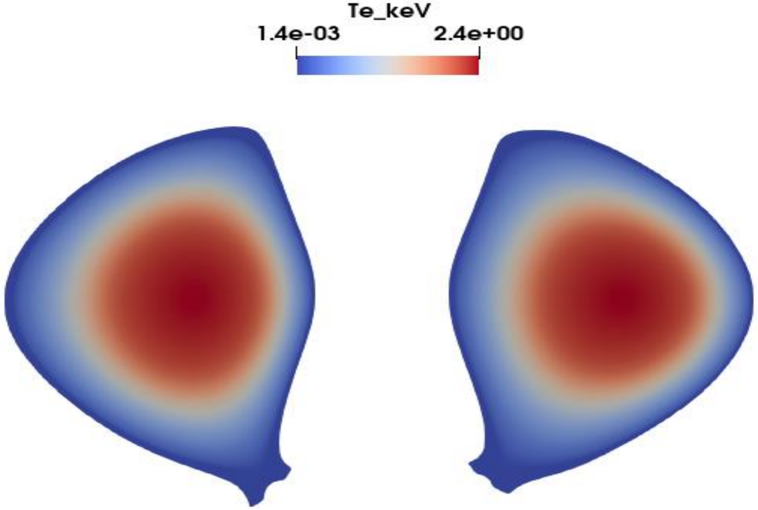


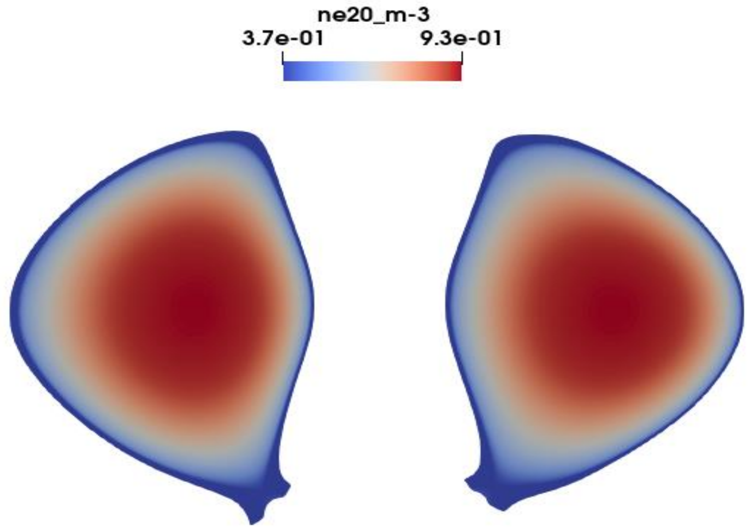


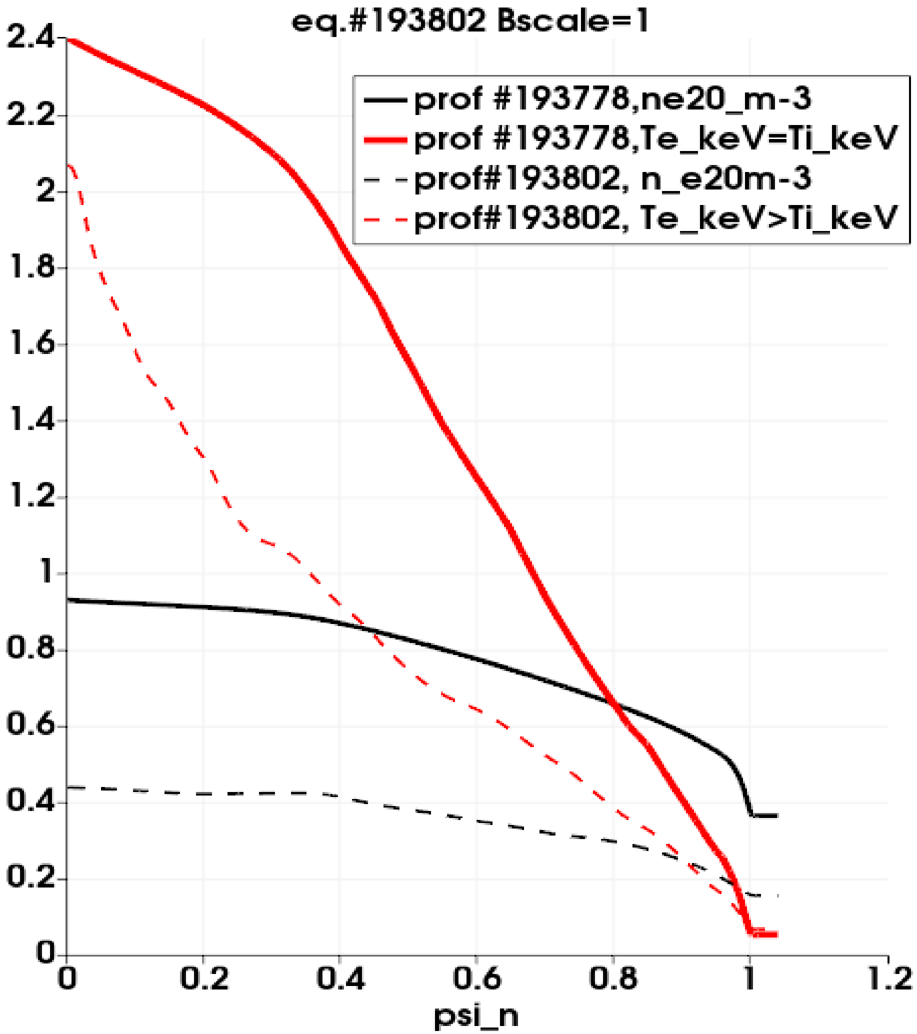




What about different regime? Te=Ti (ITG/TEM). Profiles #193778, equilibrium #193802 (NT) => « mirror » PT.







Here collisions el-ions were used. Results are very similar to #193802 (Te>Ti) w/o collisions: 1) Initial phase gr rates PT>NT, 2) in saturation Wkin total (perp and poloidal integral over volume) NT>PT.