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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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Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

This work was carried out using the HPCs: CEA TGCC IRENE (France) and CINECA MARCONI (Italy)

Abstract.

The comparison of the non-linear gyro-kinetic particles code **JOREK-GK** with gyro-kinetic codes **GS2** [*A Marinoni et al Plasma Phys Control Fus 51(2009) 055016*], **GENE-X** [*P Ulbl et al 29th IAEA FEC 2023, London, UK*] and **GENE** [*F. Jenko, W. Dorlan et al Phys of Plasmas 7, 1904 (2000)*] was done on a few selected negative/positive (NT/PT) triangularity TCV plasma parameters. It showed rather good agreement between codes in linear growth rates of ITG/TEM single modes in linear phase and clear beneficial effect of negative triangularity on core confinement compared to positive triangularity shape.

The global non-linear gyro-kinetic modelling using JOREK-GK code of the ITG/TEM saturated turbulence for realistic negative triangularity DIII-D pulses suggest gyro-Bohm ρ^* confinement scaling similar to H-modes. That could probably explain high confinement obtained experimentally for negative triangularity shaped plasmas. This scaling would be very favorable factor for reactor size machines with high confinement operation without harmful ELMs.

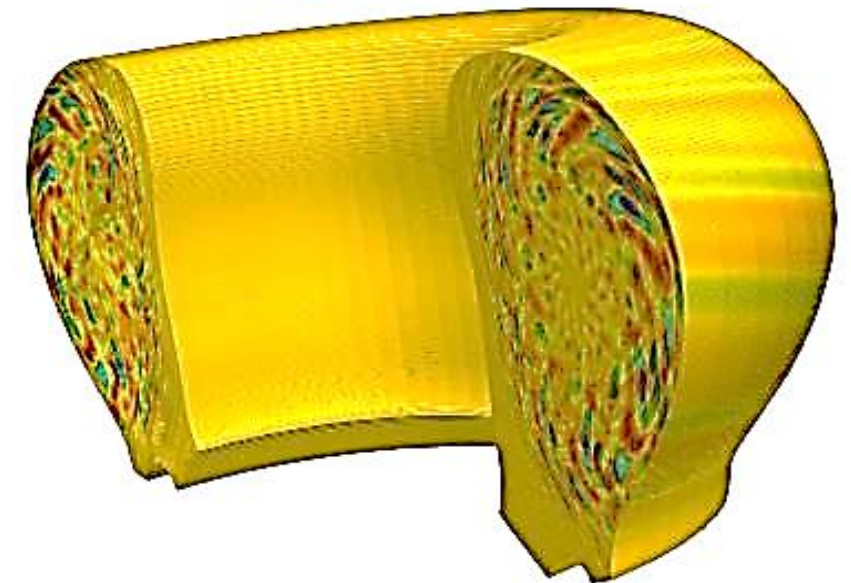
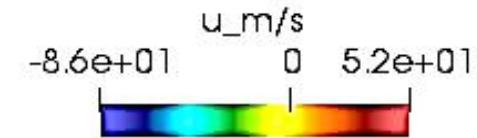
A larger parameter range should be explored in the future both experimentally and numerically to confirm the gyro-Bohm scaling for NT plasmas.

Kinetic particles in JOREK-GK code. Non-linear gyro-kinetic modelling of electrostatic turbulence ITG/TEMs in realistic tokamak X-point geometry.

[JOREK as MHD code: G Huysmans, NF 2007, PPCF 2009, M Hoelzl NF2021; JOREK-GK: G Huijsmans EPS 2023, M Becoulet EPS 2023, 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 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. Two types of filters are used, hyper-diffusion in the poloidal plane and a Laplacian in the parallel direction.
- HPC: MARCONI(Italy), JFRS-1(Japan), IRENE-ROME (France): typical job N=5:5:40 toroidal harmonics, $5 \cdot 10^8$ particles (depending on the tokamak size) on 54 nodes, 48h wall time (~ 0.5 ms to saturation), time step $dt \sim 5 \cdot 10^{-8}$ s. Good (close to ideal) scaling for particles on HPC compared to fluid non-linear MHD.

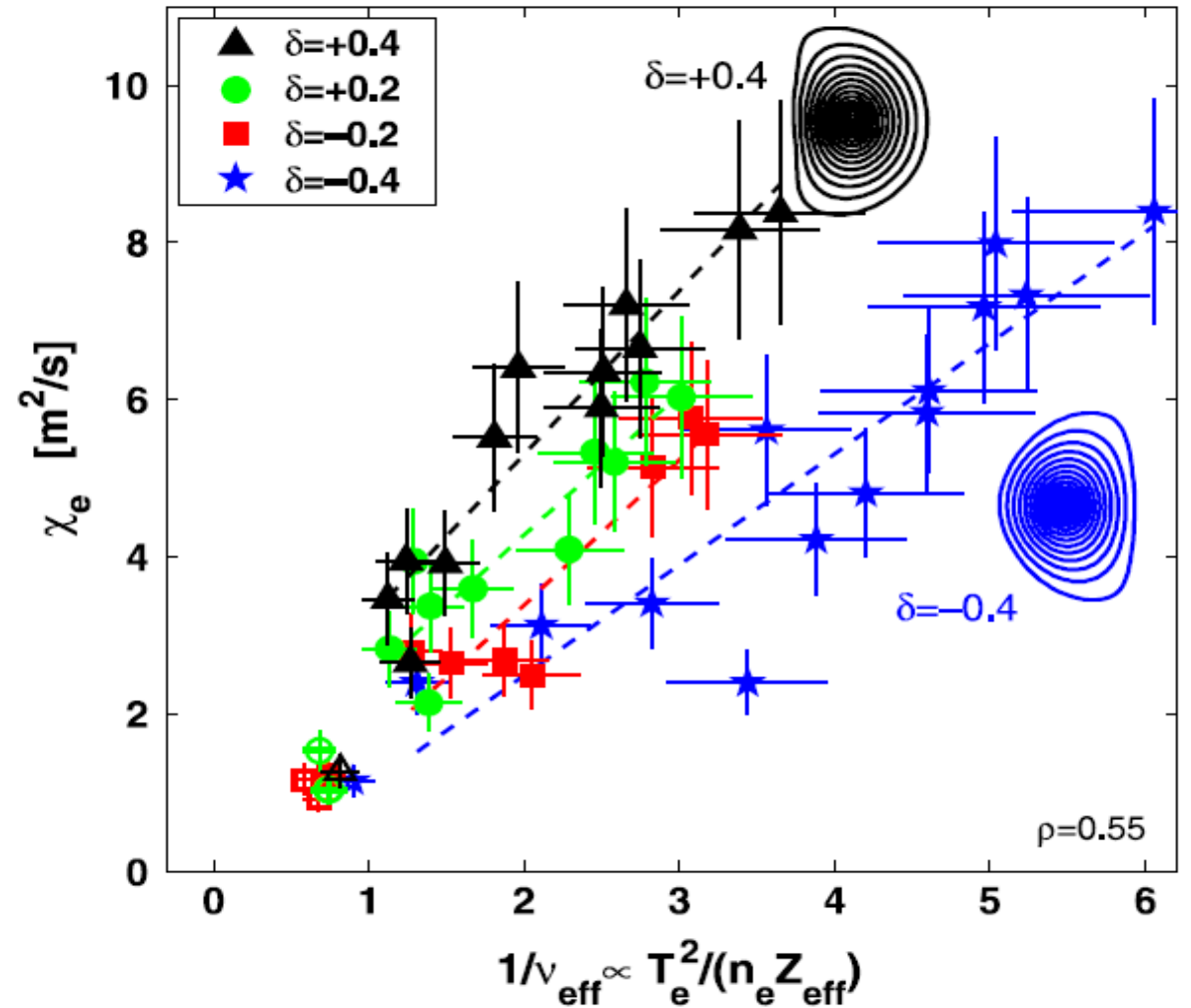
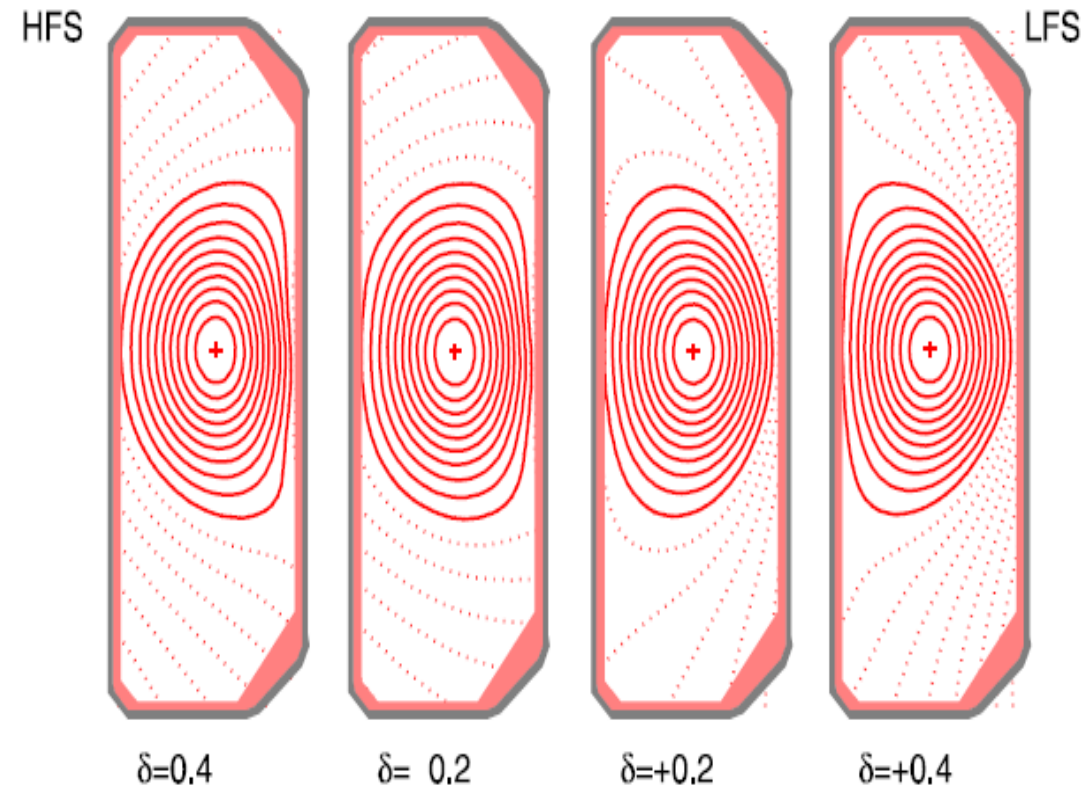
Example:
COMPASS, TEM/ITGs with RMPs



Motivation (I):

Initial studies on TCV : EC heated L-mode ($T_e > T_i$) => electron heat transport decreases at sufficiently strong negative triangularity (NT). TEMs are stabilised at NT.

[Y Camenen NF 2007]

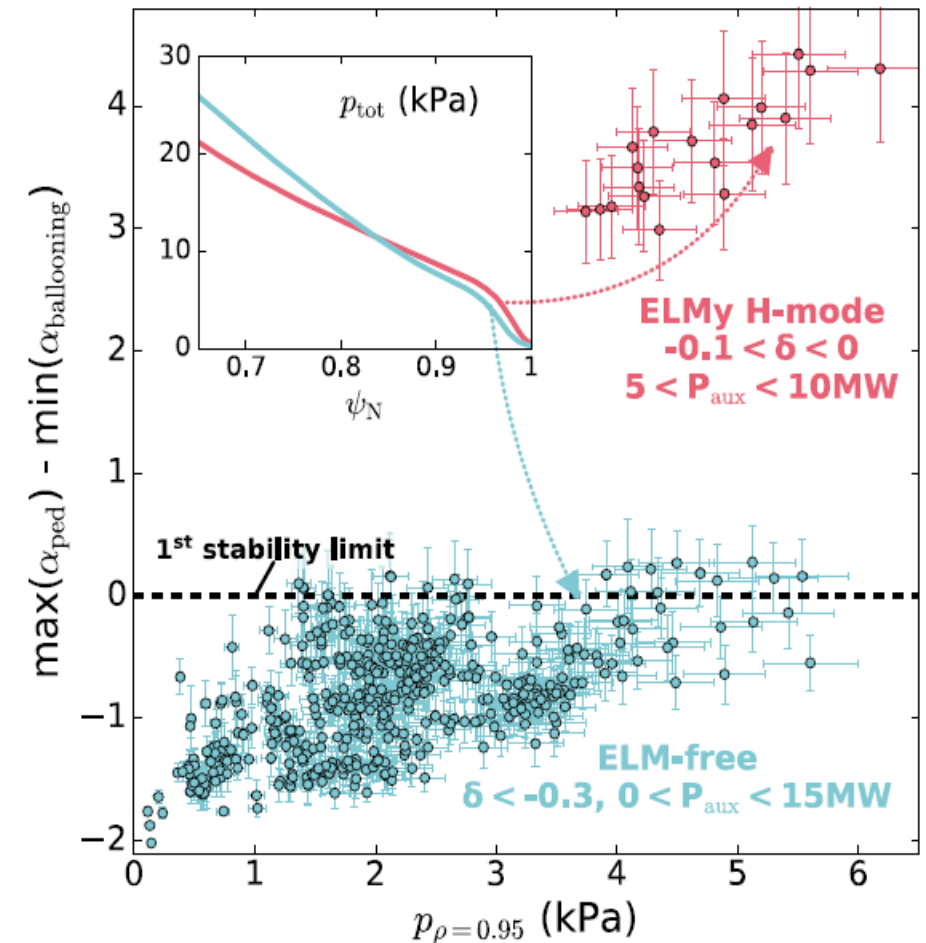
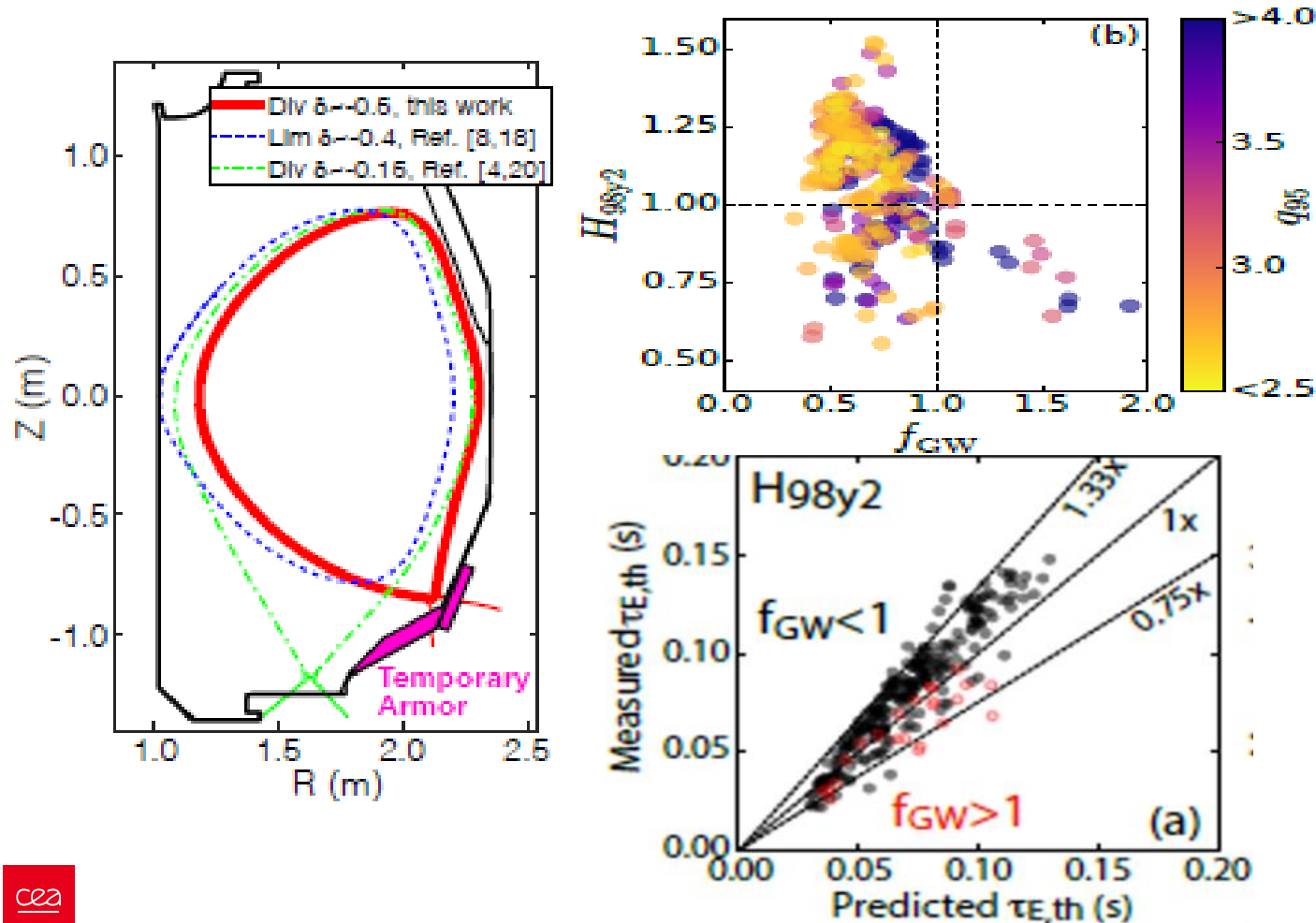


Motivation (II): Seems attractive for reactor!

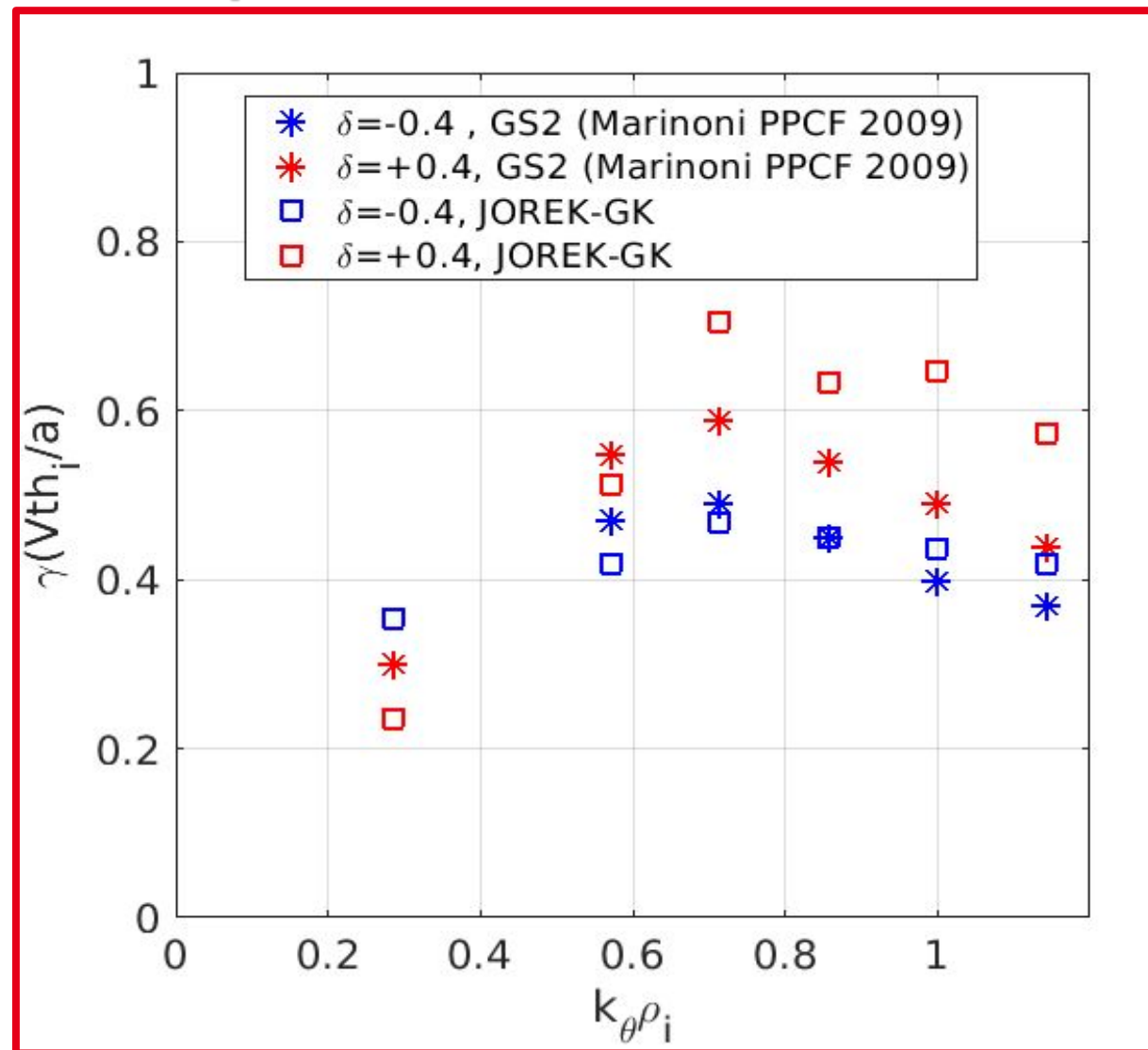
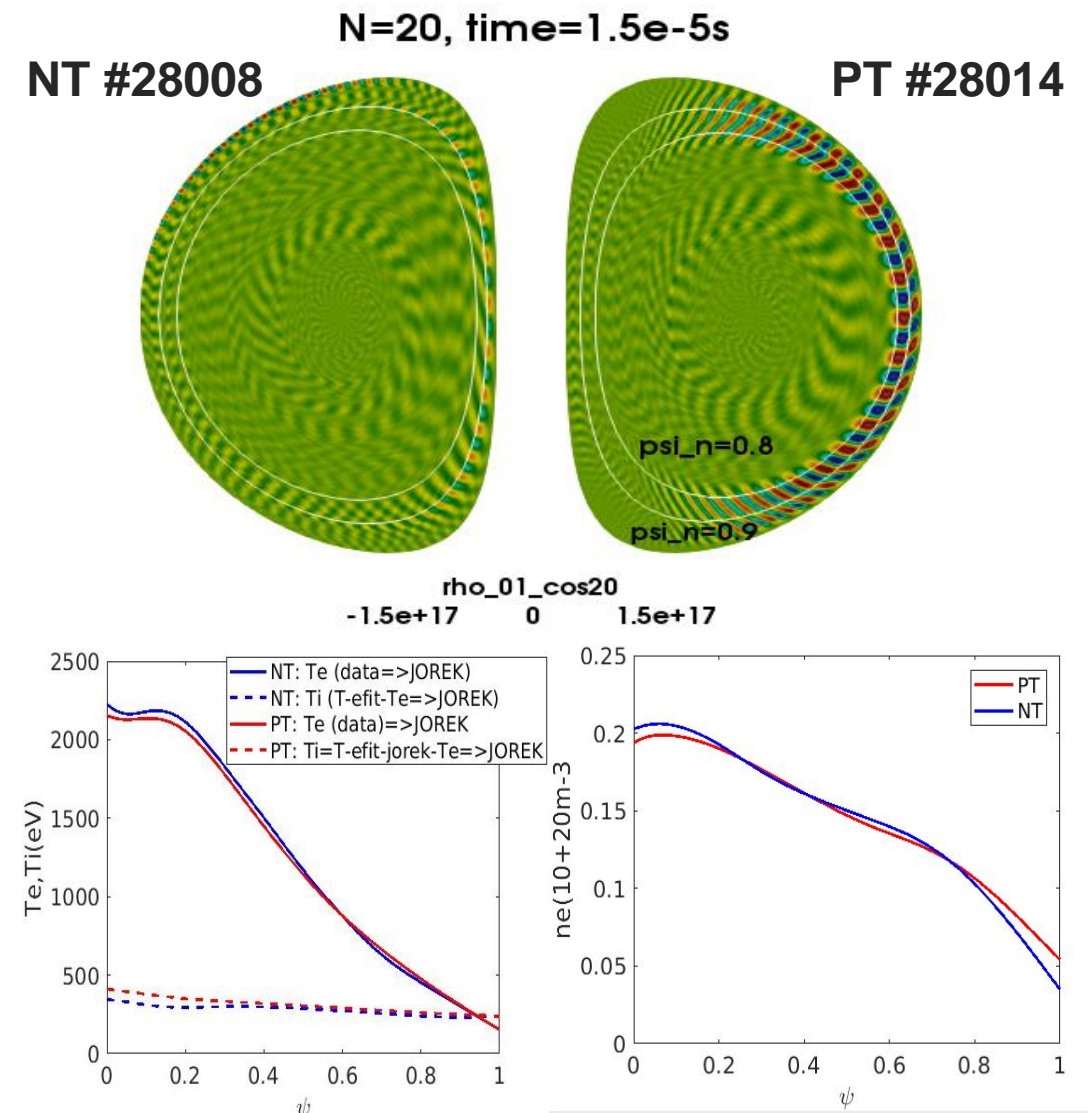
- 1) DIII-D initial NT/PT experiments. $T_e=T_i$ [M Austin PRL2019, A Marinoni NF2021]: no pedestal, no ELMs, high core confinement ~as in H-mode, but without ELMs.
- 2) 2023 dedicated NT campaign on DIII-D diverted plasmas, $T_e=T_i$, low collisionality : high core confinement . No access to 2nd stability limit in NT=> no high pressure pedestal, ELMs.

[K E Thome et al PPCF to be published 2024.]

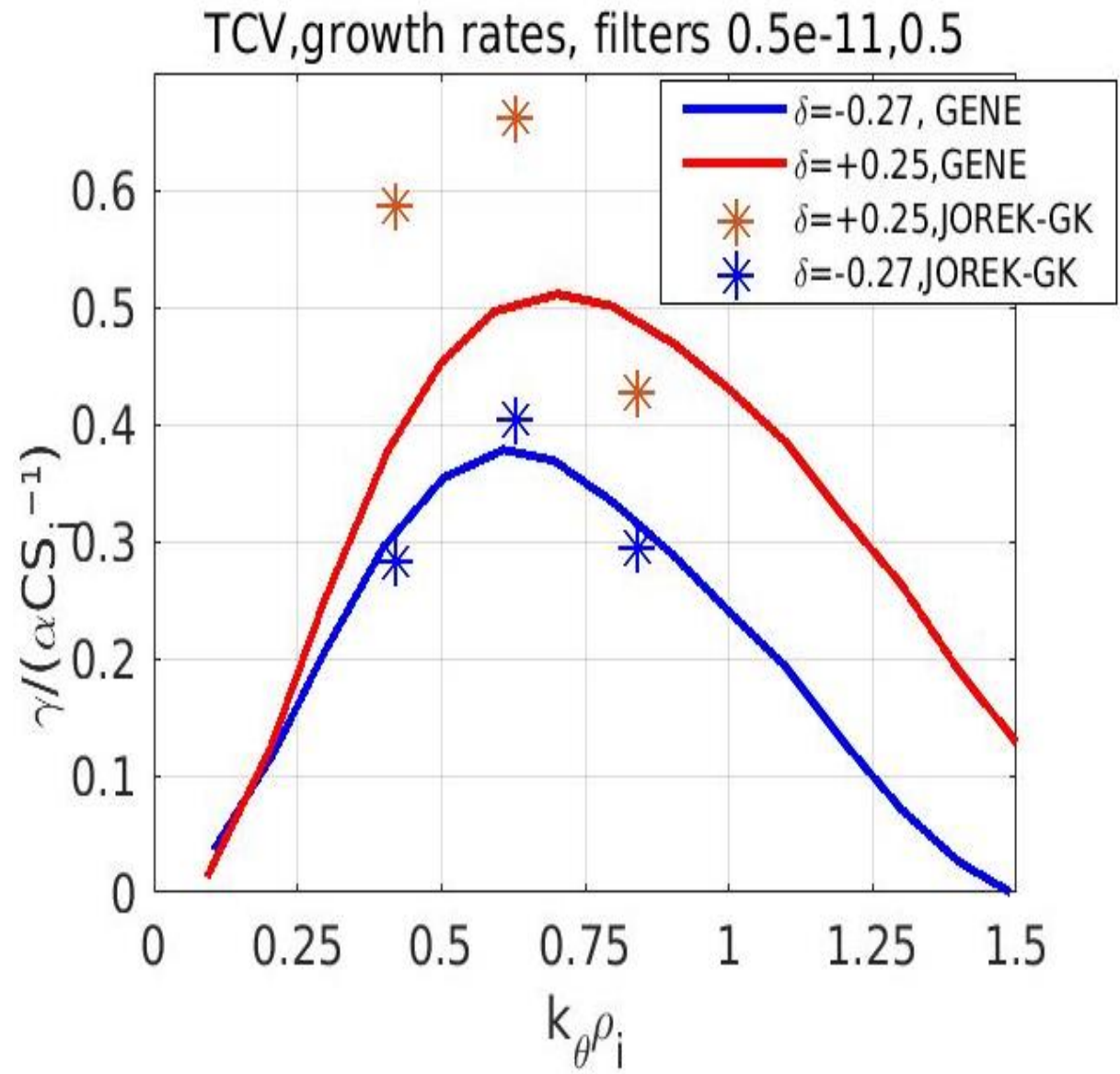
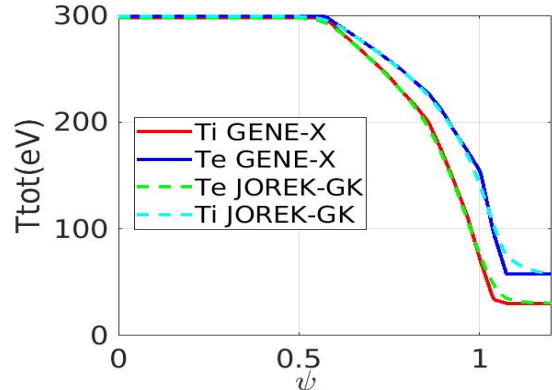
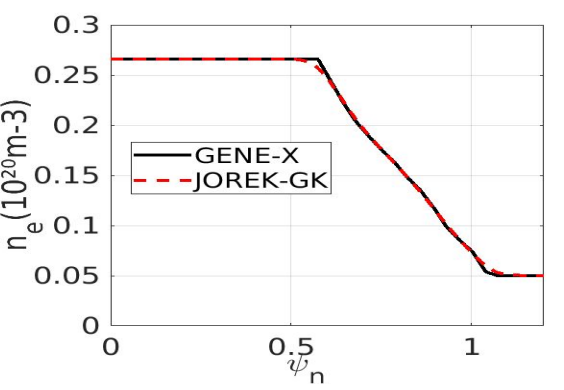
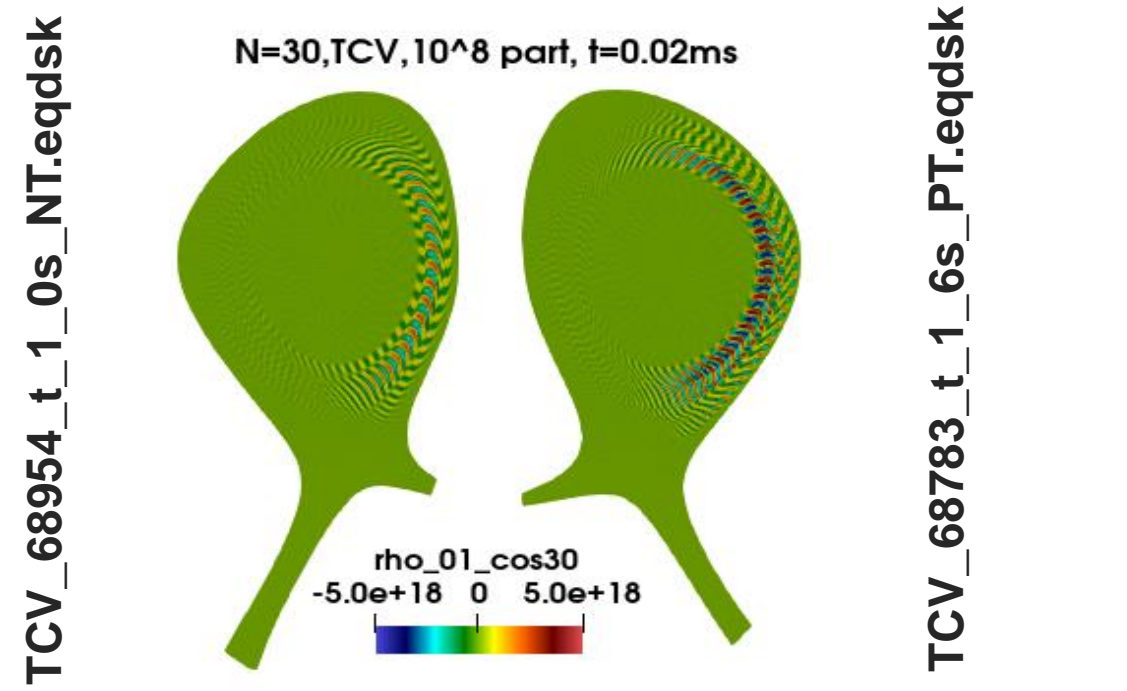
[A Nelson PRL2023]



Comparison global JOREK-GK with local flux tube GS2 code [A Marinoni et al PPCF 2009] for TCV L- modes in TEM regime ($T_e > T_i$), similar linear growth rates, smaller at NT compared to PT.



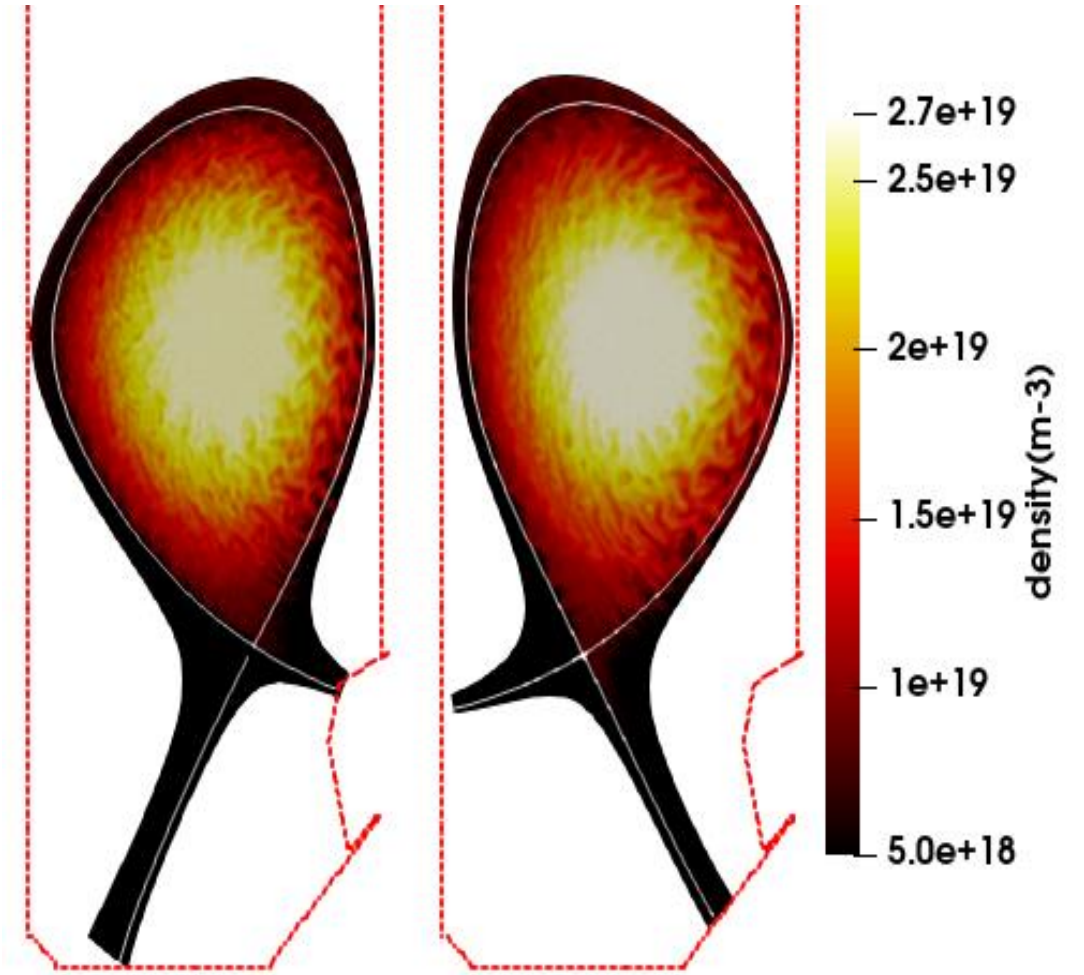
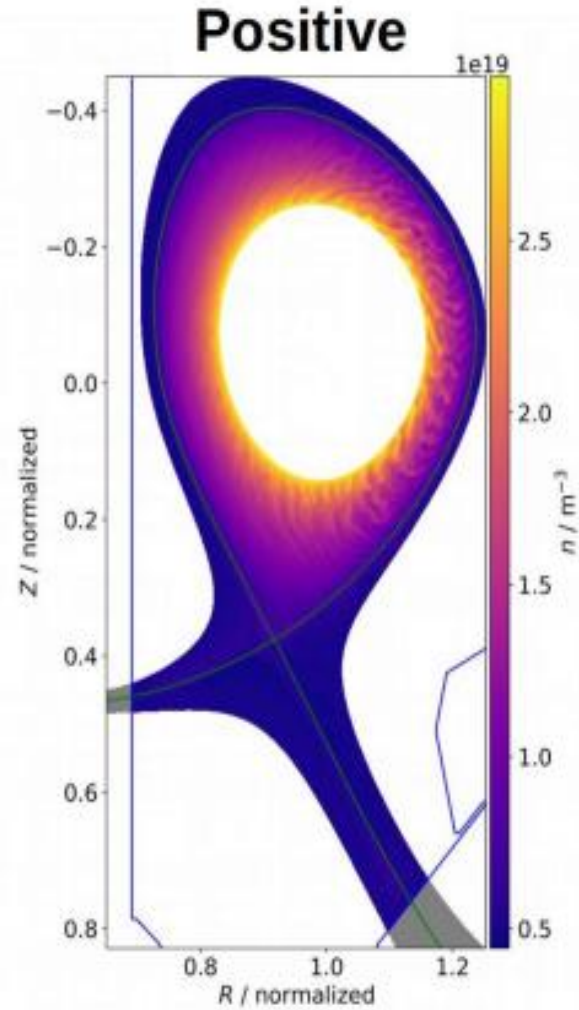
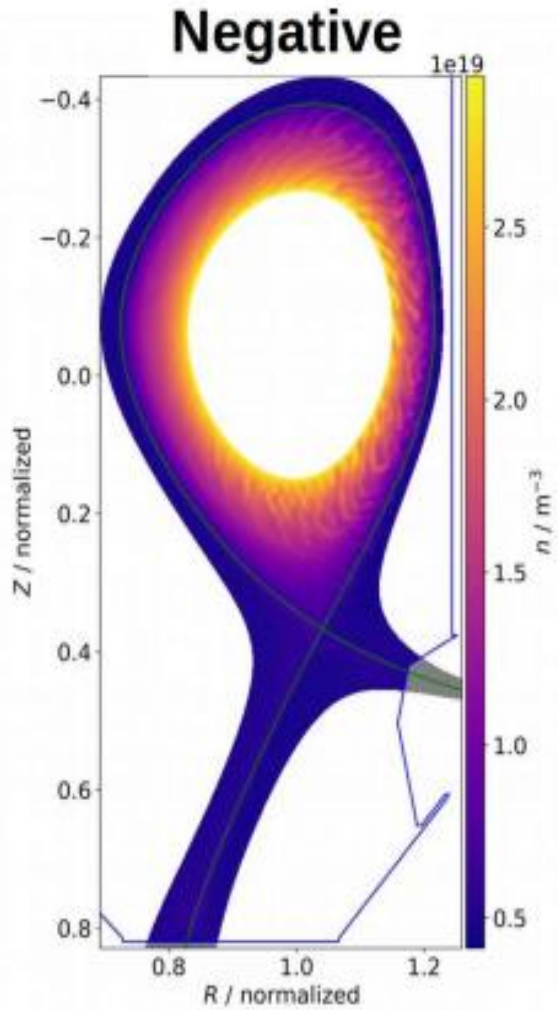
Comparison of global JOREK-GK with GENE (w/o X-point) [F. Jenko et al PPCF 7, 1904 (2000)] in linear TEM dominant regime ($T_e > T_i$) for TCV parameters: similar linear growth rates, smaller at NT compared to PT.



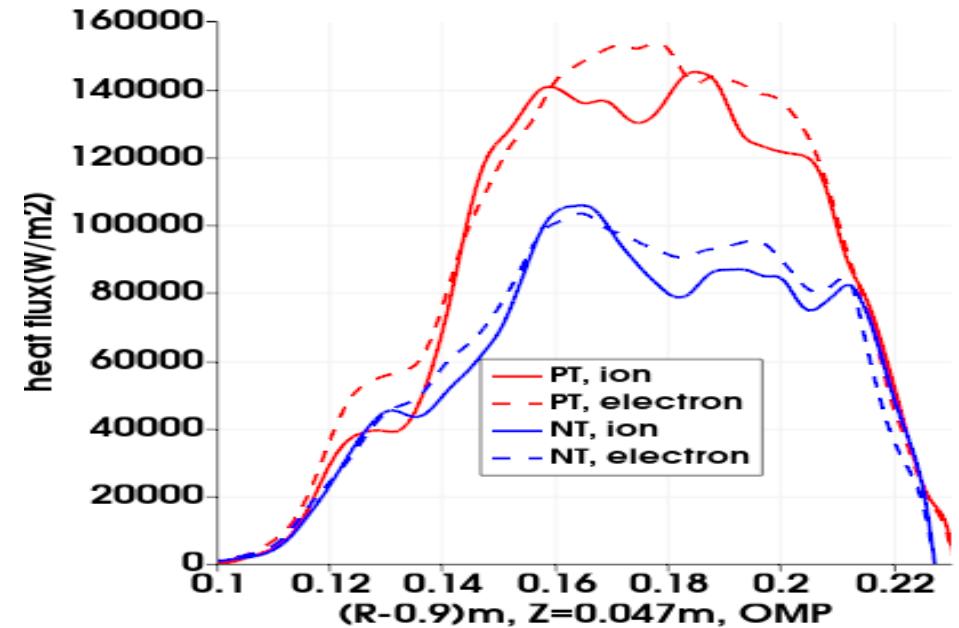
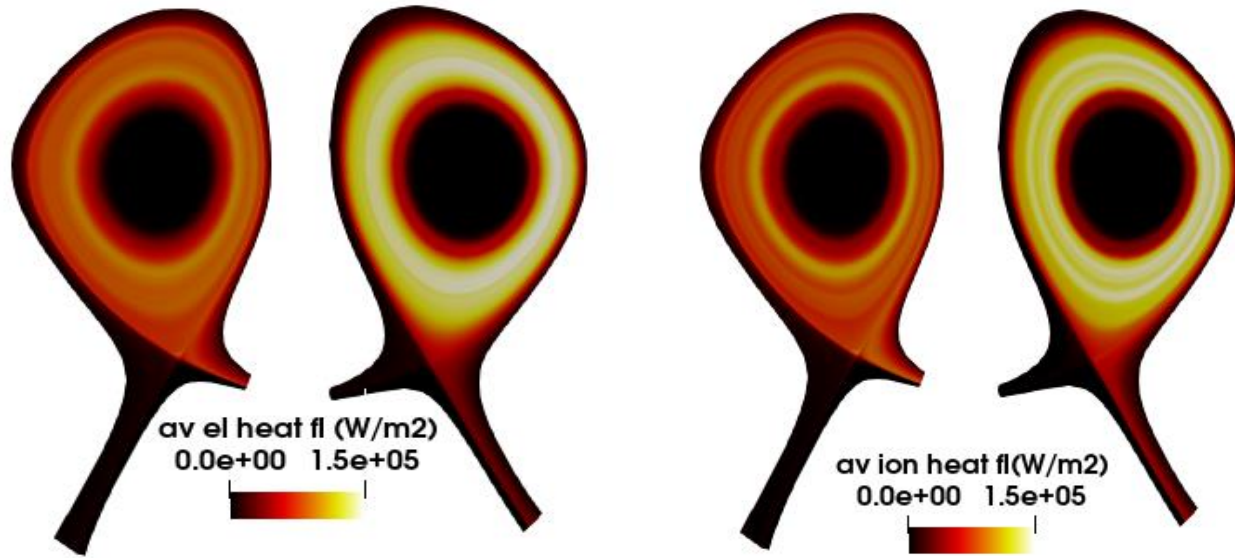
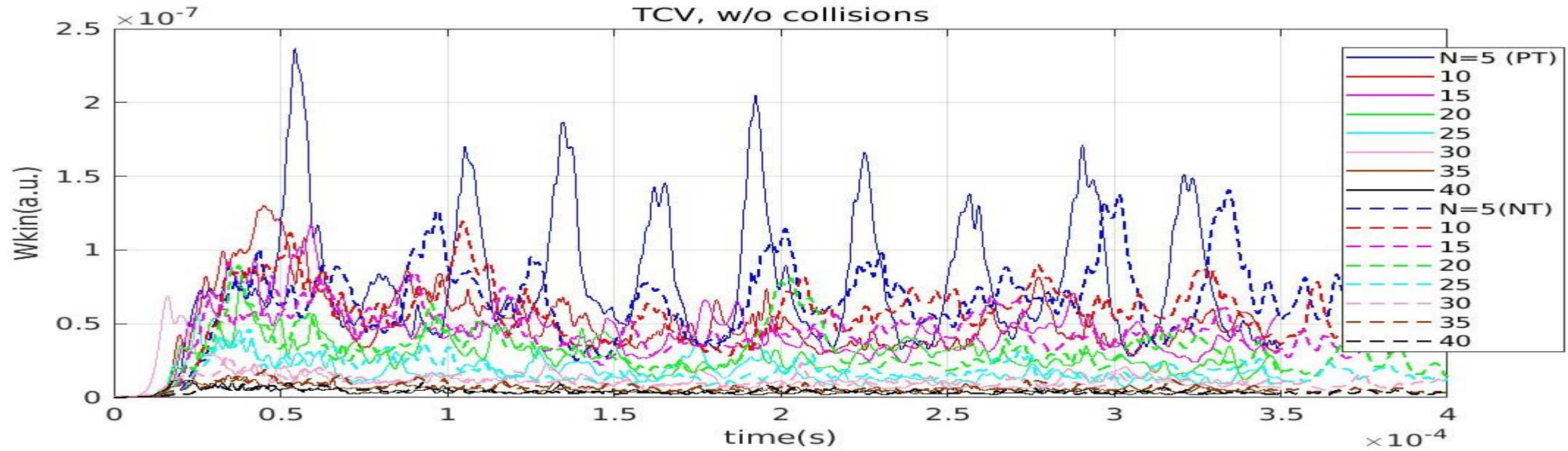
Comparison of JOREK-GK with GENE-X with the same profiles and equilibrium

GENE-X (band $\psi_n > 0.57$)

JOREK-GK (all plasma+SOL $\psi_n > 0$)



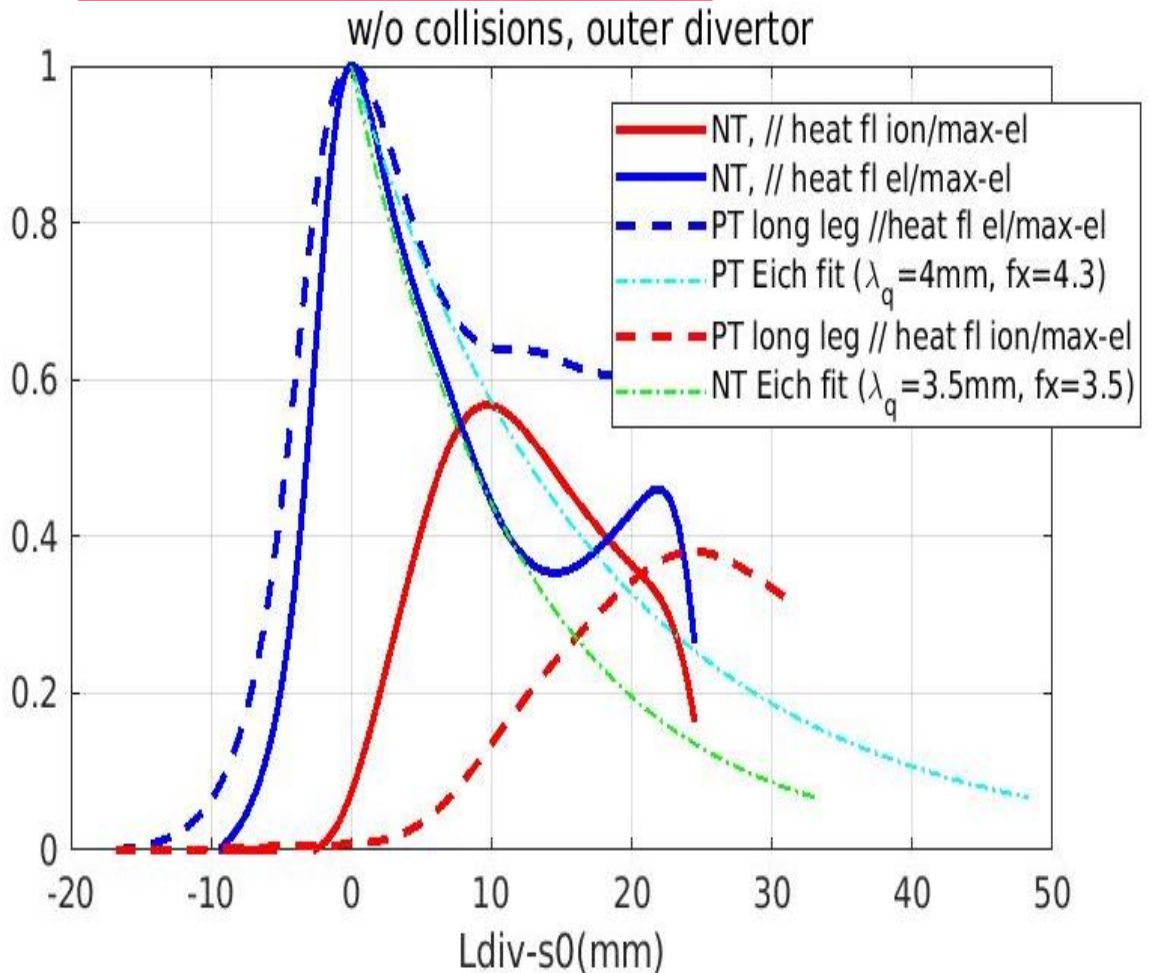
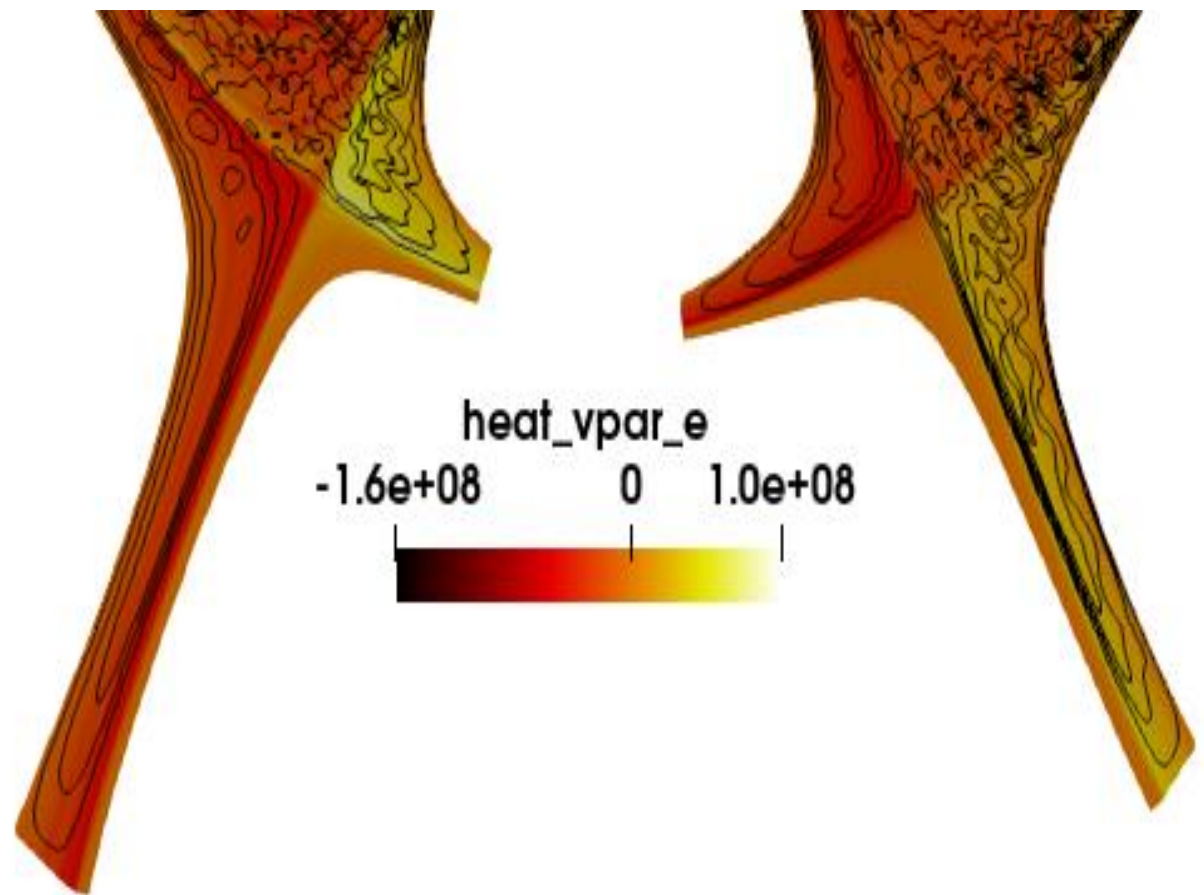
Larger avalanches at PT triangularity => Larger perpendicular heat fluxes



Flux expansion NT (short leg) $f_x=3.5$, PT (long leg) $f_x=4.3$. Divertor // heat fluxes are mainly from electrons. From Eich's fit (NF 2013) for // electron heat flux: PT $\lambda_q = 4\text{mm}$; NT $\lambda_q = 3.5\text{mm}$.

$$\lambda_q \text{ (mm)} = (0.7 \pm 0.2) \cdot B_{tor}^{-0.8 \pm 0.1} \cdot q_{95}^{1.05 \pm 0.2} \cdot P_{SOL}^{0.1 \pm 0.1} \cdot R_{geo}^{0 \pm 0.1}$$

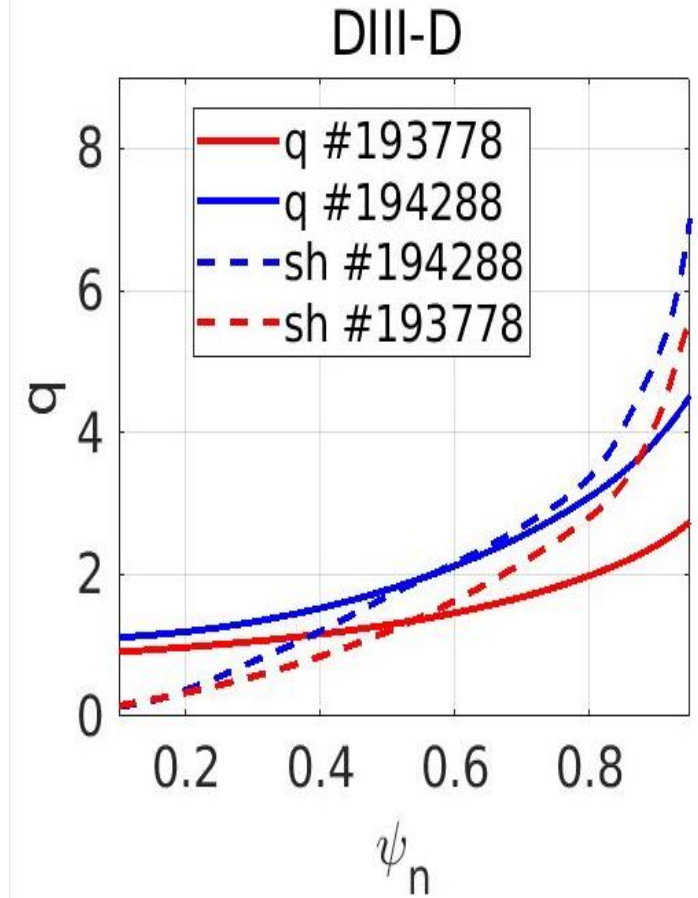
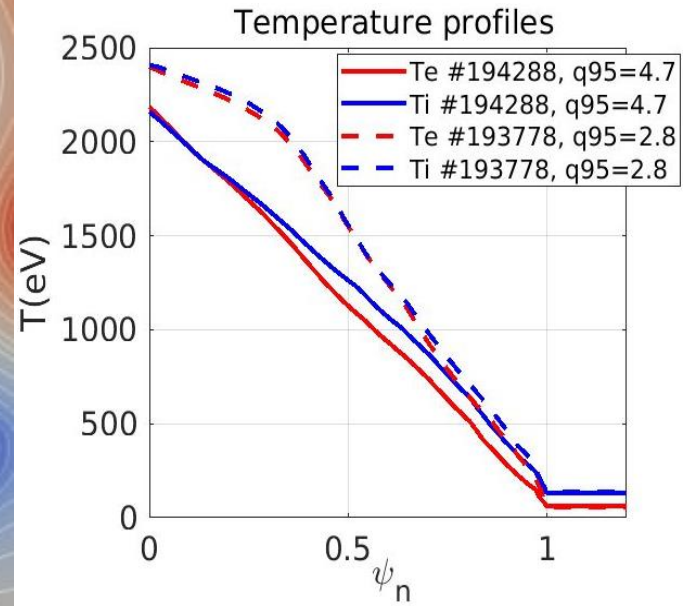
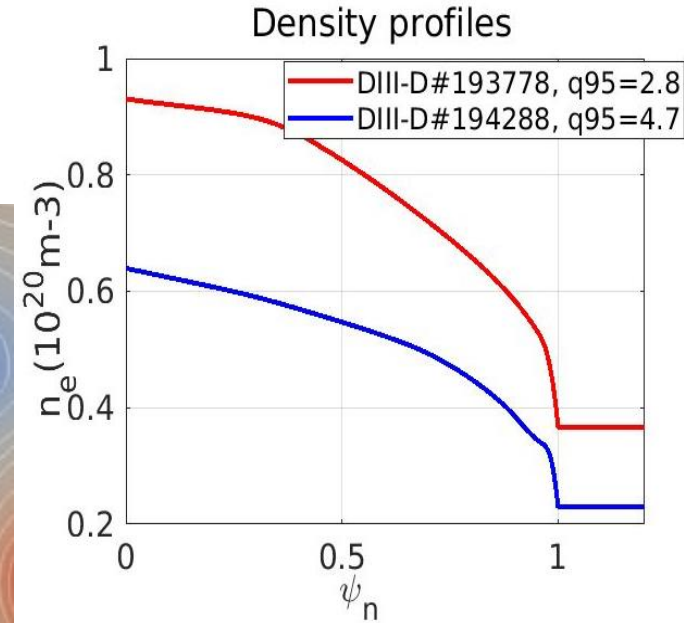
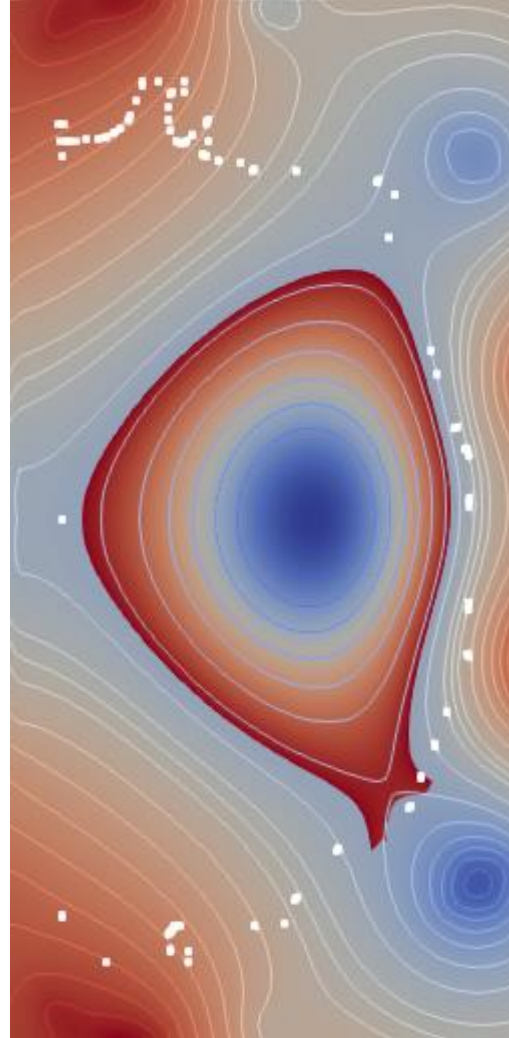
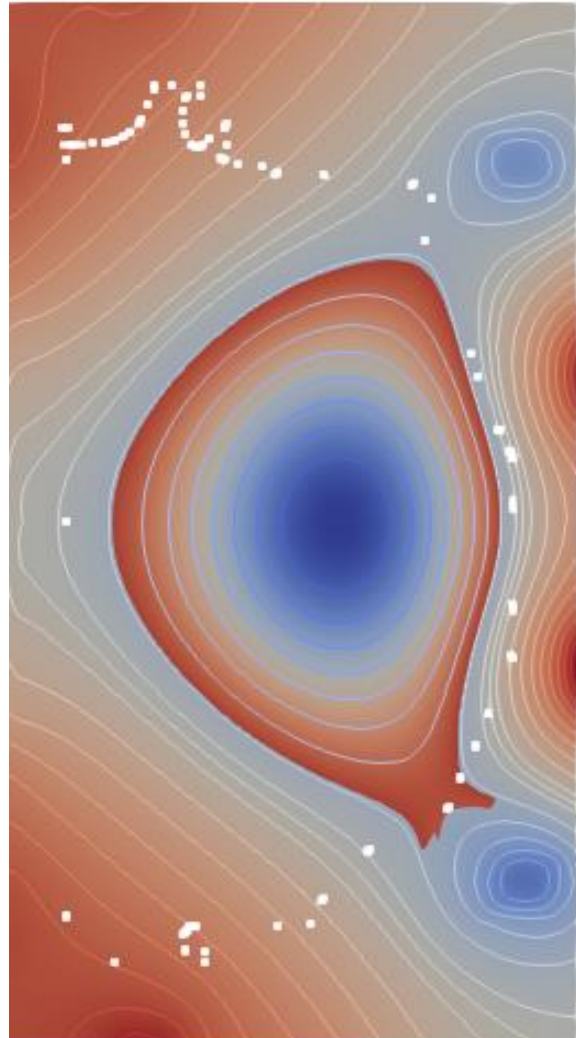
$$q(s) = q_0 \cdot \exp\left(-\frac{s-s_0}{\lambda_q f_x}\right) \quad \text{Eich's fit (NF2013)}$$



JOEK-GK modelling for DIII-D pulses with X-point from 2023 NT campaign

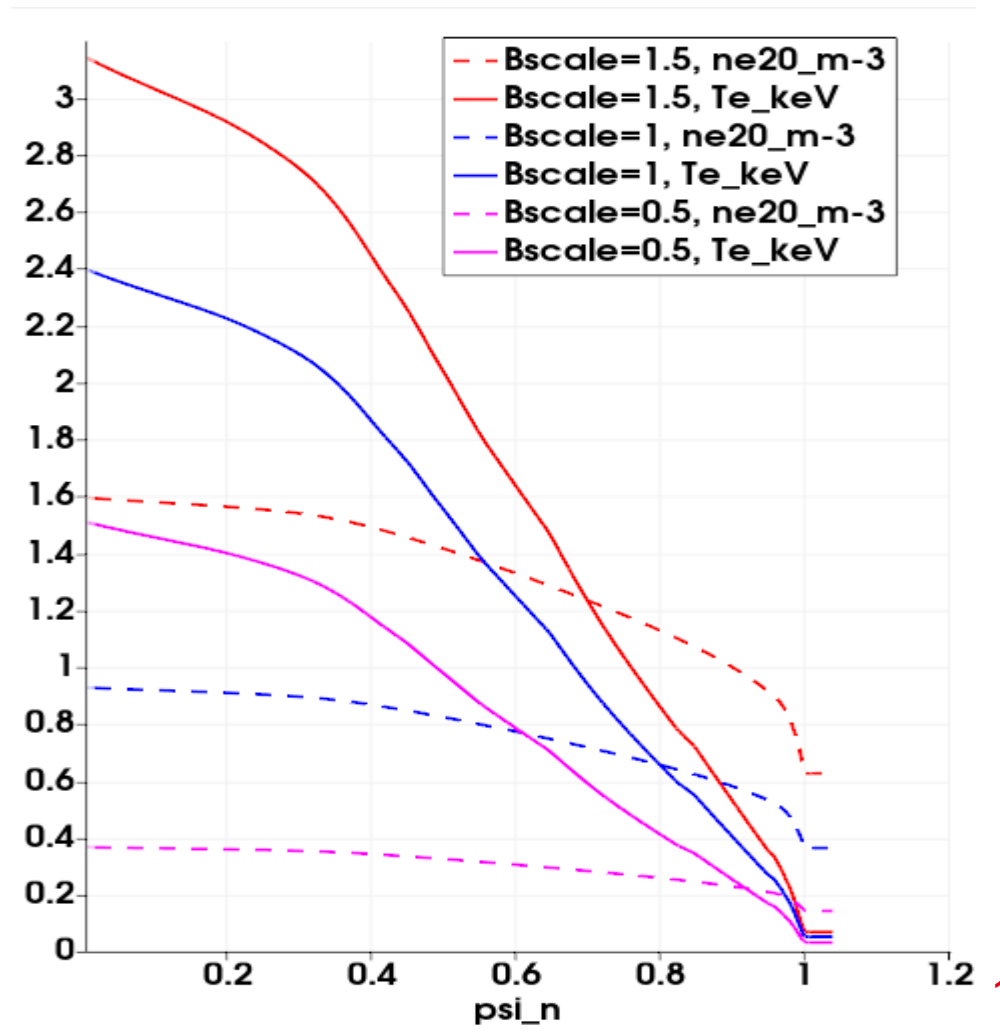
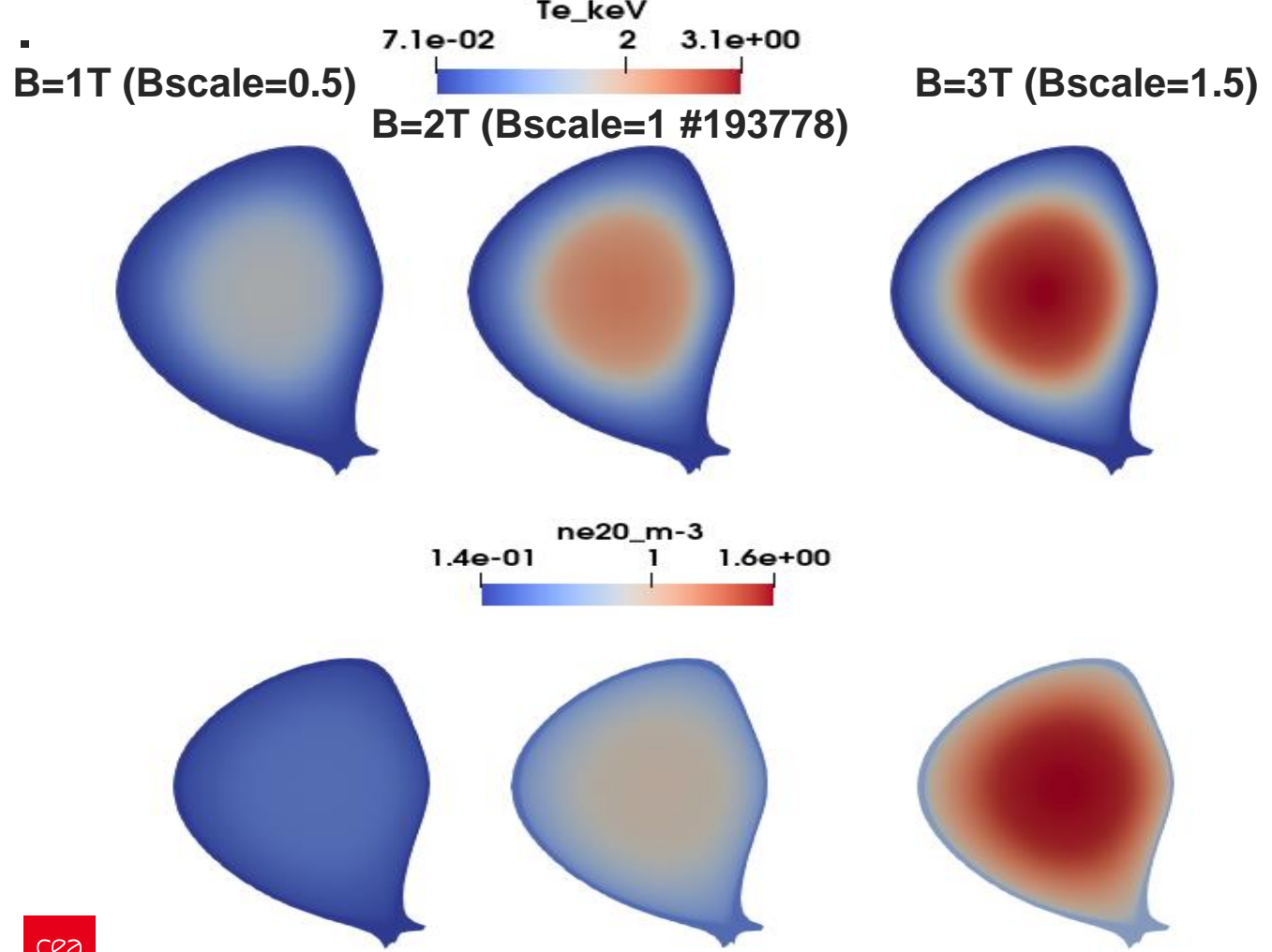
EQDSK 193778,
low $q_{95}=2.8$

EQDSK 194288,
high $q_{95}=4.67$



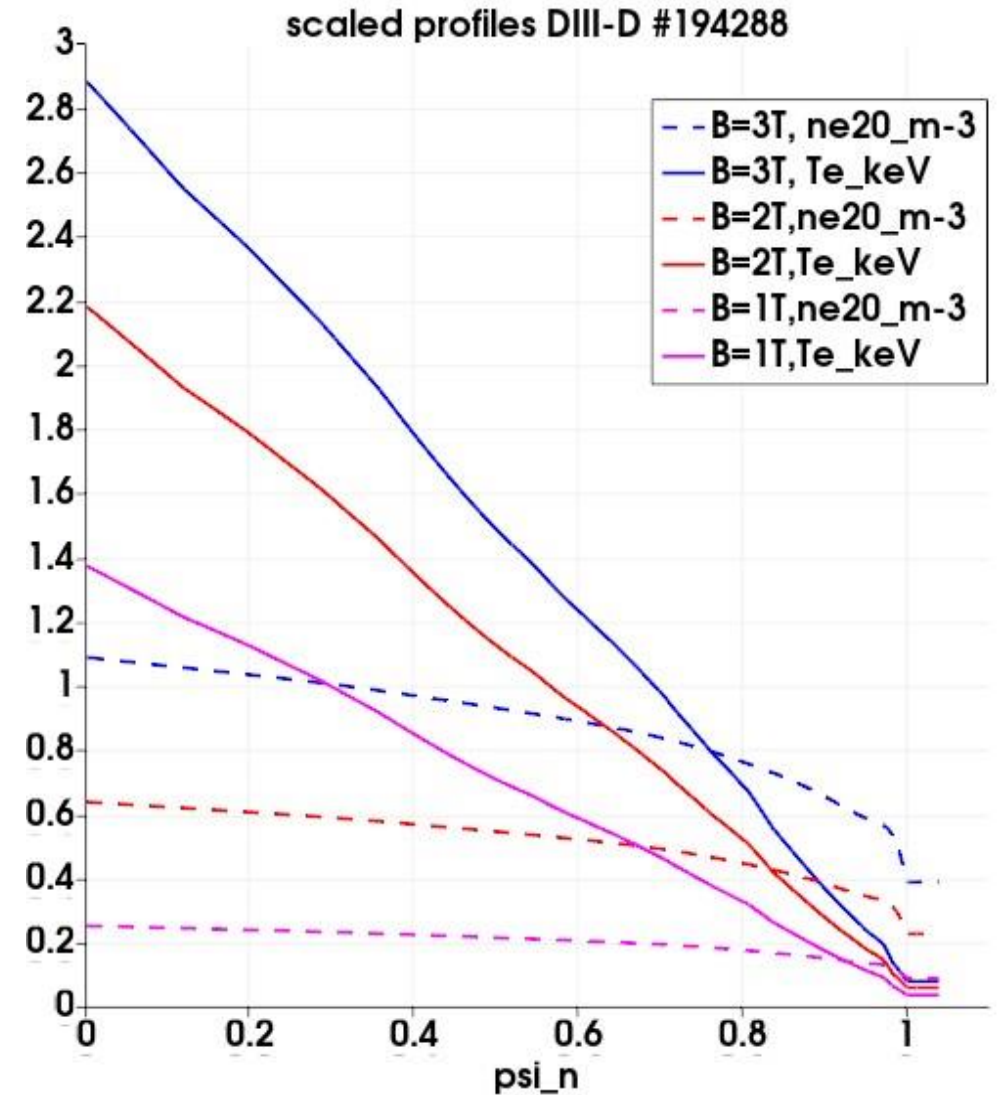
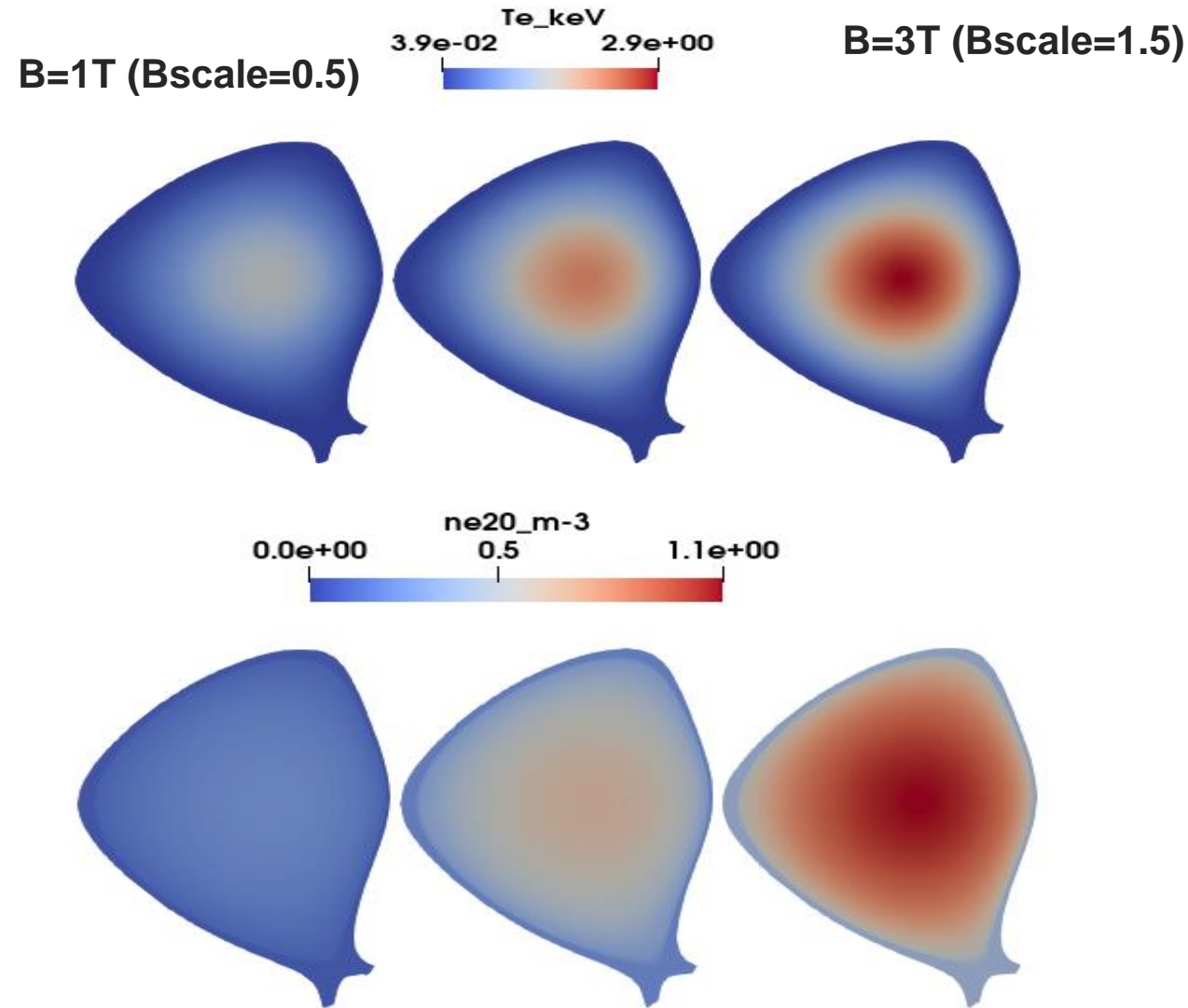
ρ^* scaling in NT?

Low q95 # 193778 B=2T, q95=2.7 - this is a case Bscale=1. Keeping the same equilibrium and q-profile 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 $\rho^* \Rightarrow \rho^* \text{Bscale}^{-2/3}$. 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)]



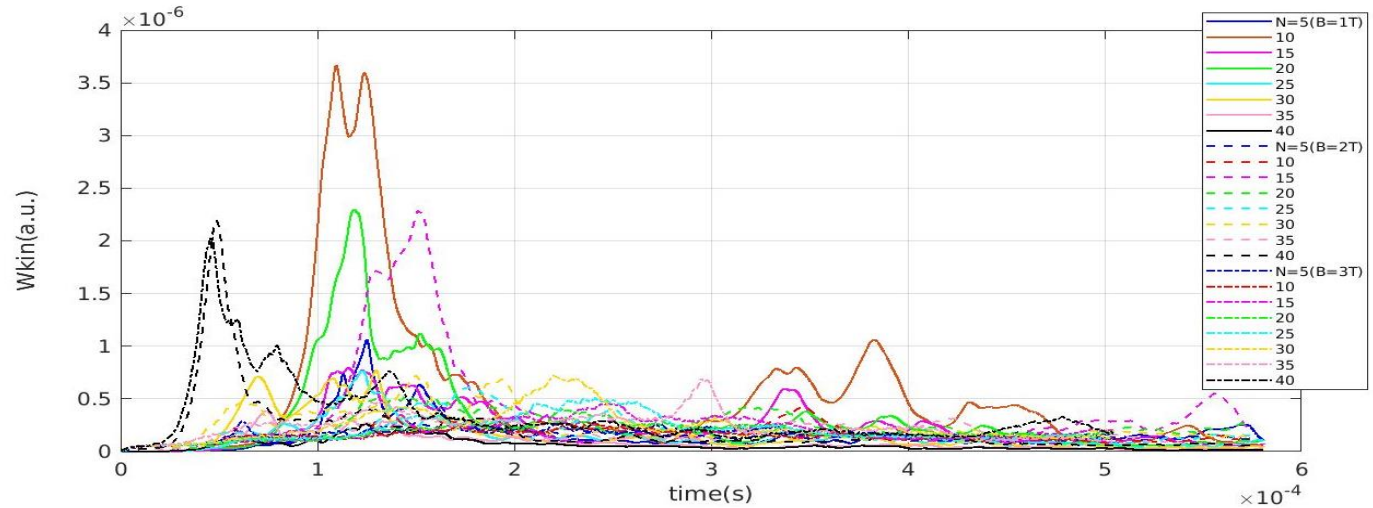
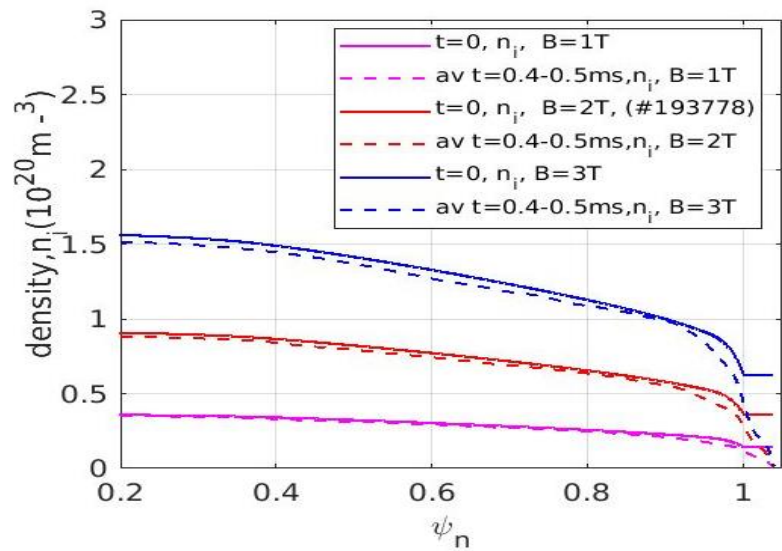
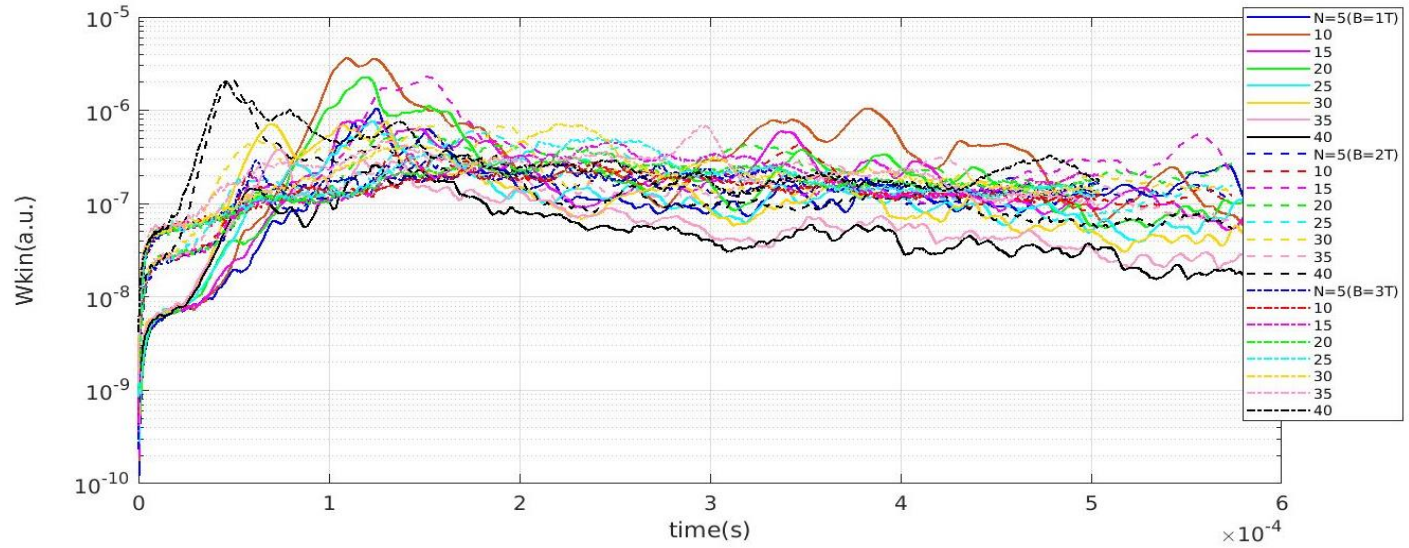
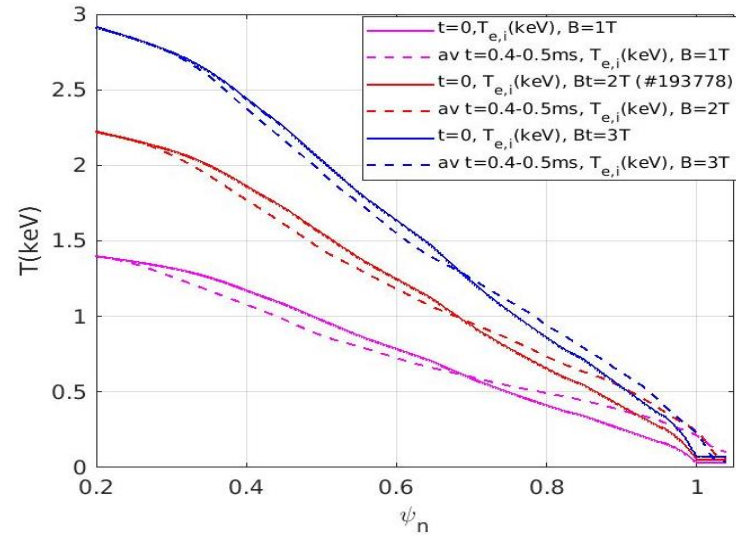
High $q_{95}=4.7$ (# 194288), $B=2T \Rightarrow$ initial case $Bscale=1$.

$B=2T$ ($Bscale=1$ #194288)

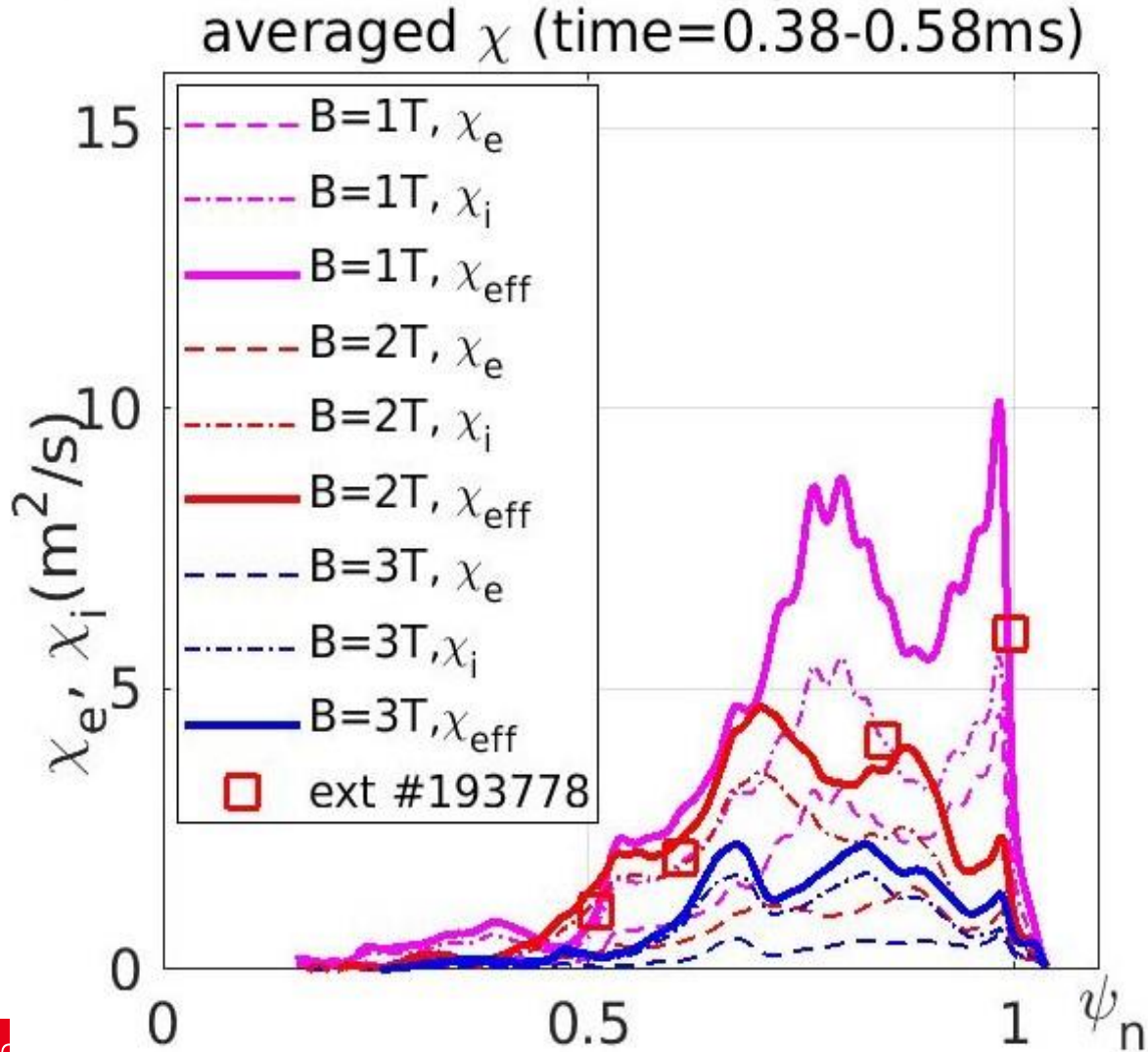


Running JOEK-GK for three cases (B=1T, 2T, 3T) up to established saturated quasi-stationary TEM/ITG turbulence.

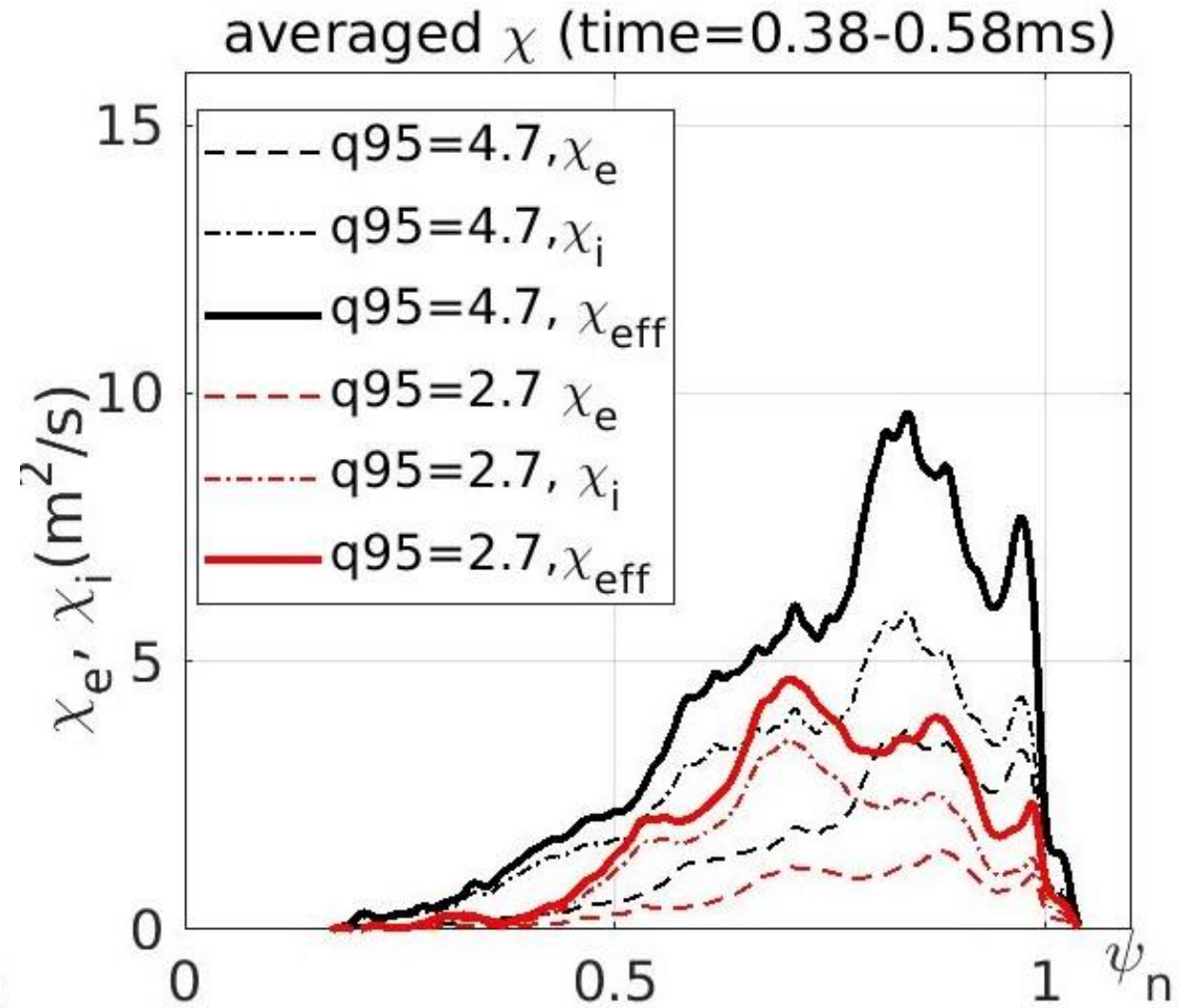
Filters : perp 2e-11, parallel 2, particles 5e8, Npsi=150, Nth=500, mi/me=100, harmonics N=5:5:40



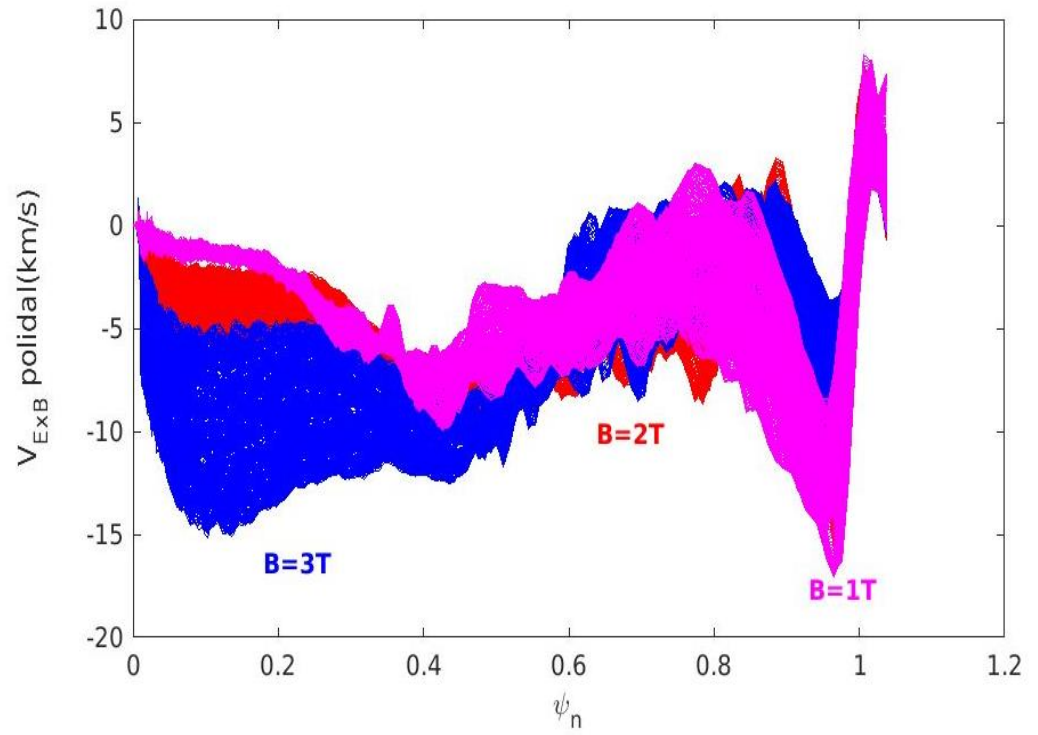
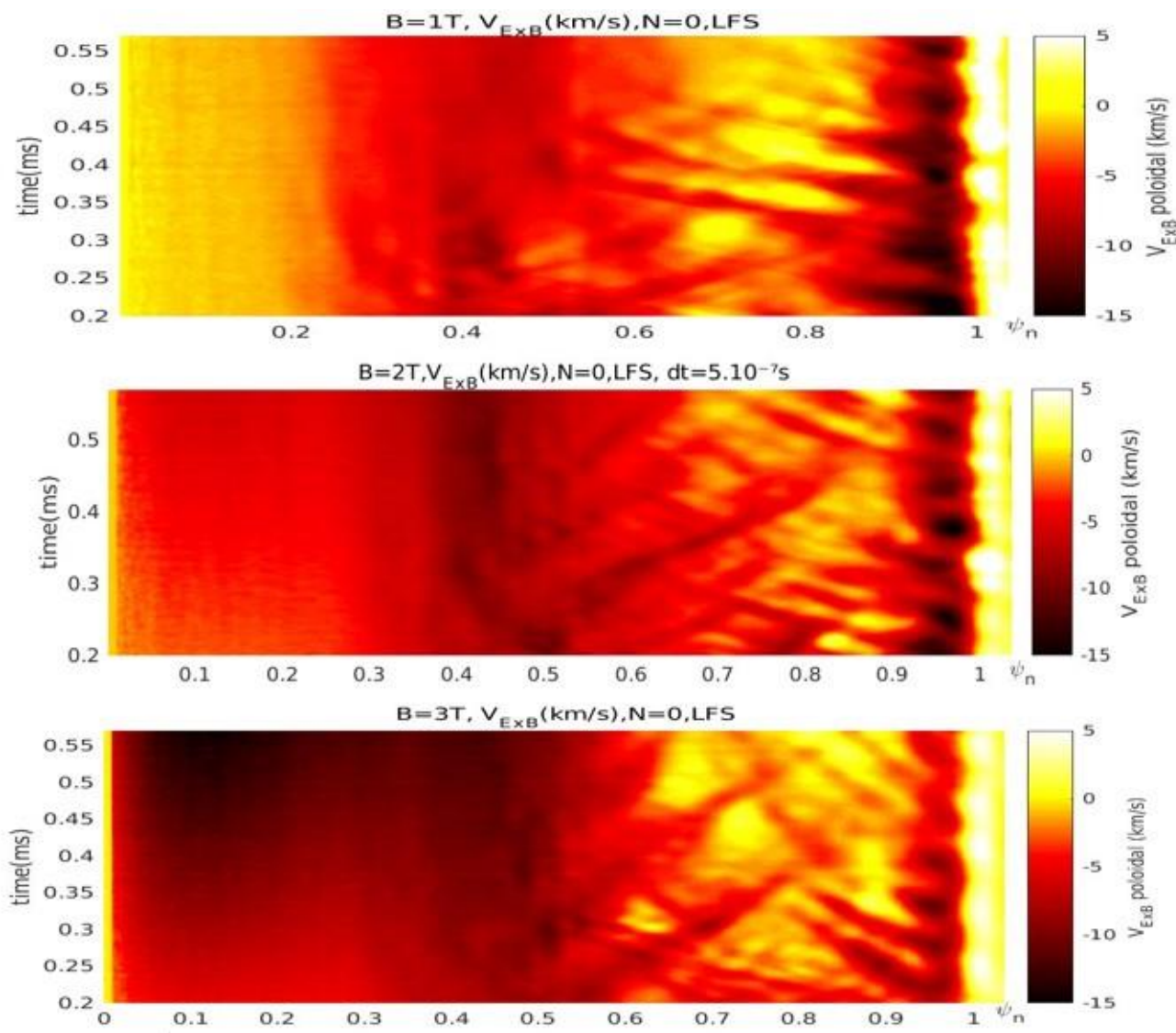
Scaled low q95(#193778) pulse. Time averaged in saturation (0.38-0.58ms) heat conductivity. Confinement improves with decreasing ρ^* .



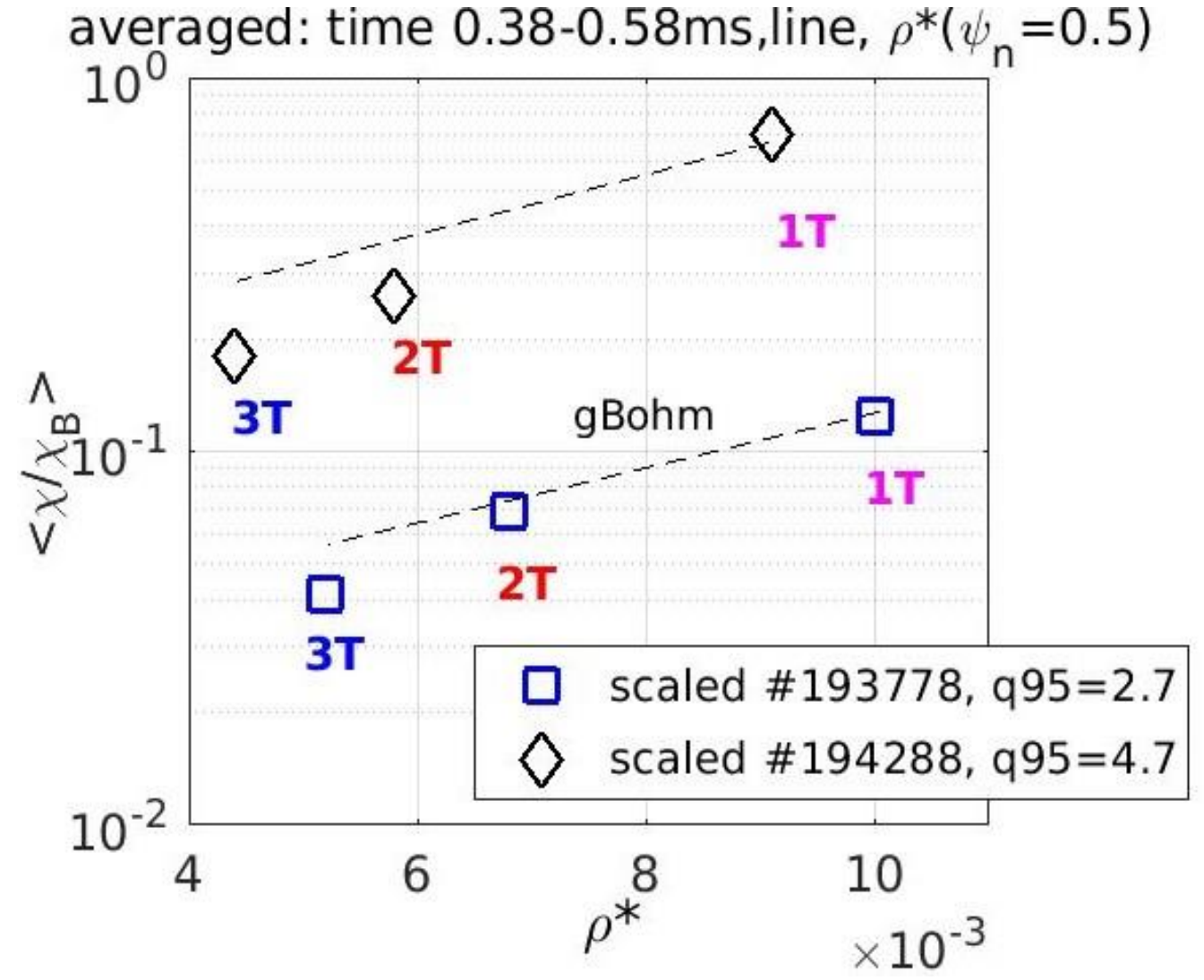
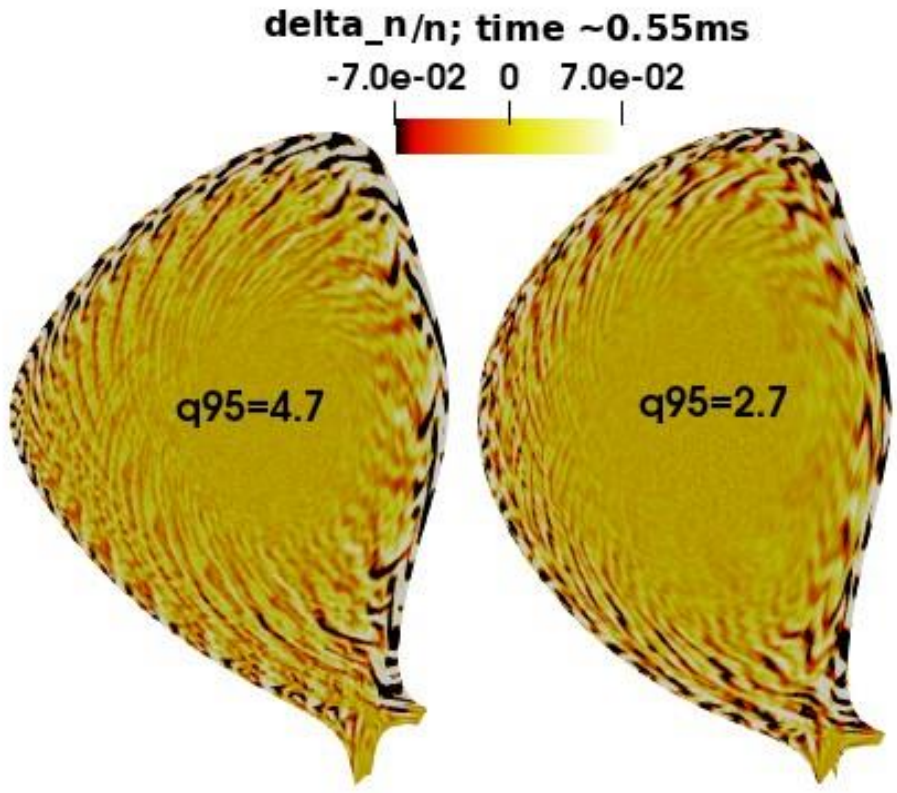
Better confinement at low q95 (#193778) than at high q95 (#194288) at $B_t=2\text{T}$ for both \Rightarrow $\sim I_p$ scaling is valid for NT plasmas.



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 $B=1T$.



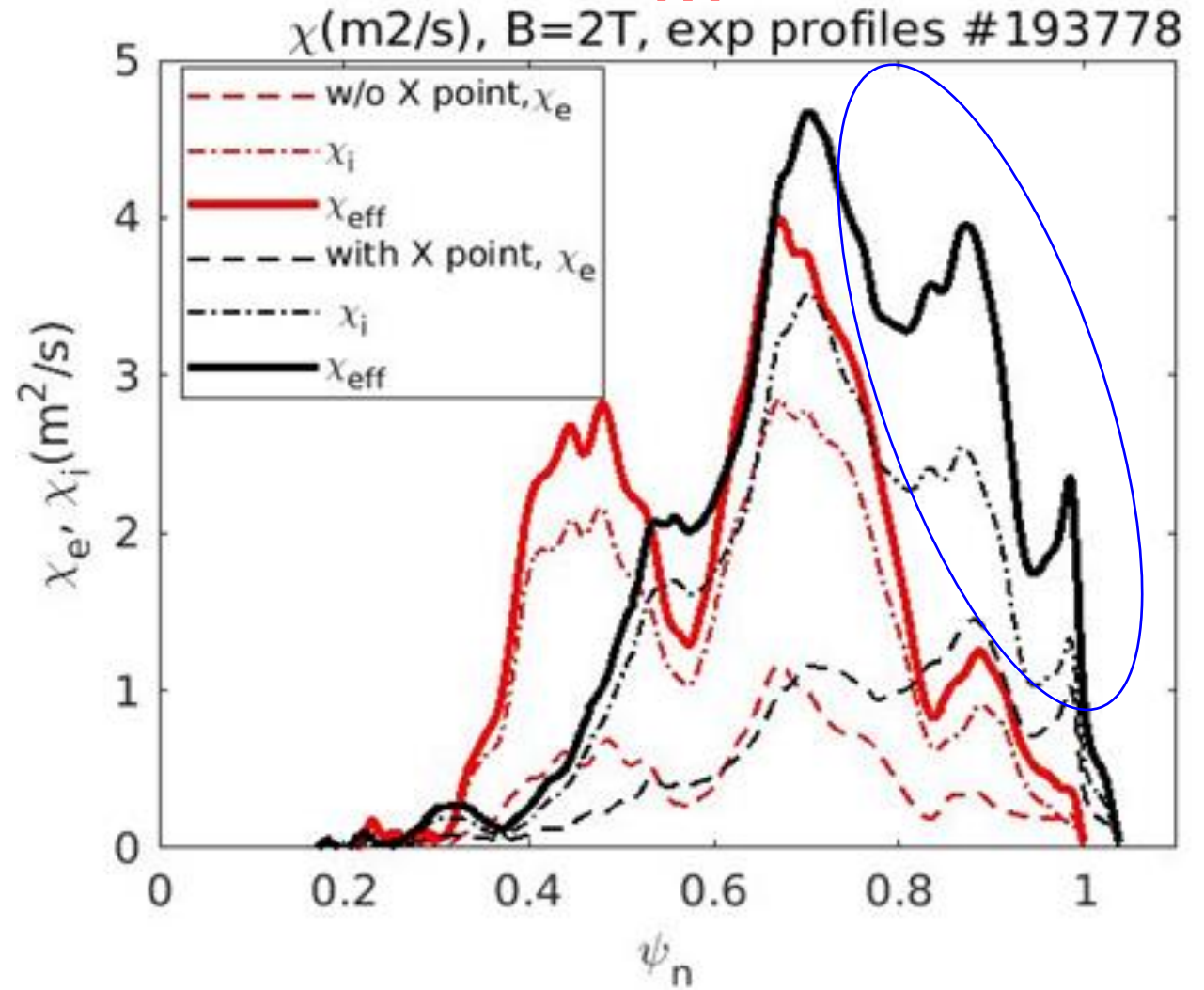
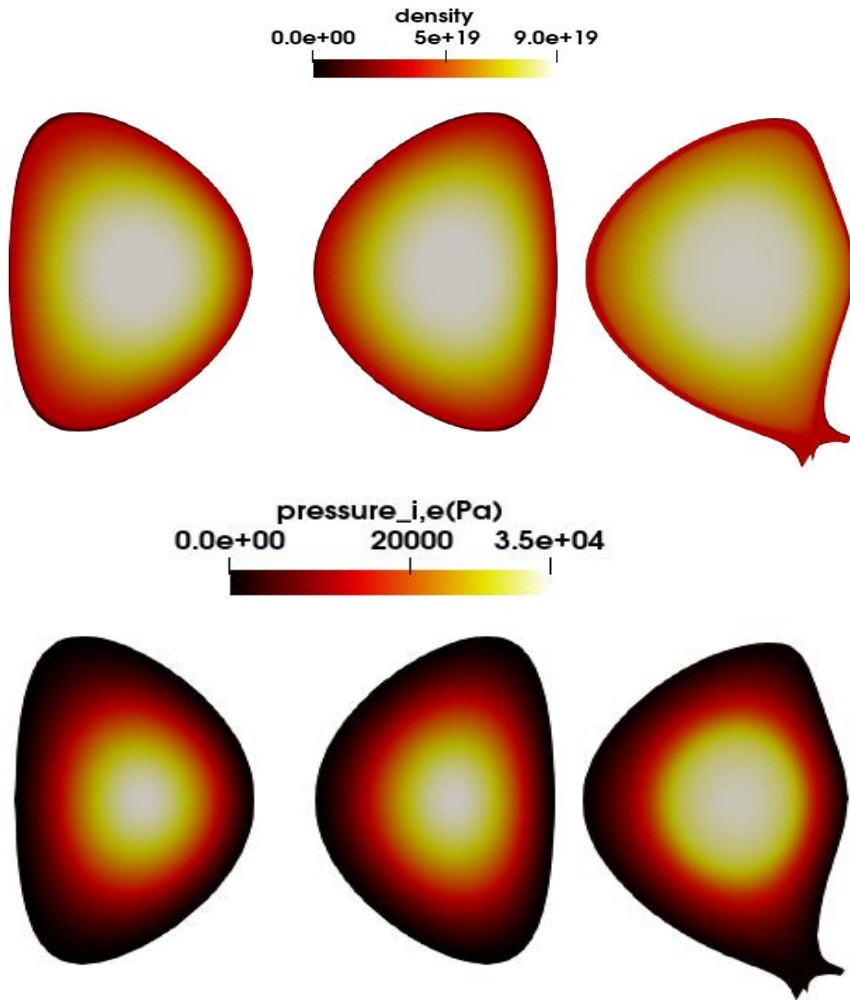
The normalized to Bohm $\chi_B = 1/16T_e v/B_T$ time and line (OMP) averaged heat conductivities as a function of ρ^* ($\psi_n=0.5$) for all scaled cases.
Gyro-Bohm scaling for NT.



X-point +SOL geometry is important!

Similar to #193778 plasma size/shape/parameters 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 toward the edge,

NT

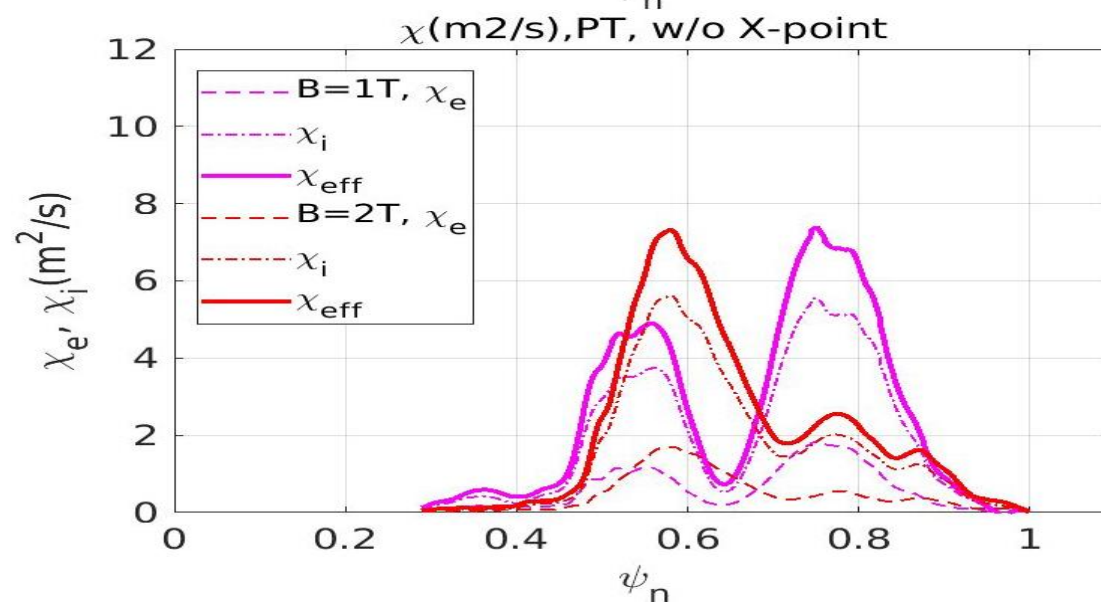
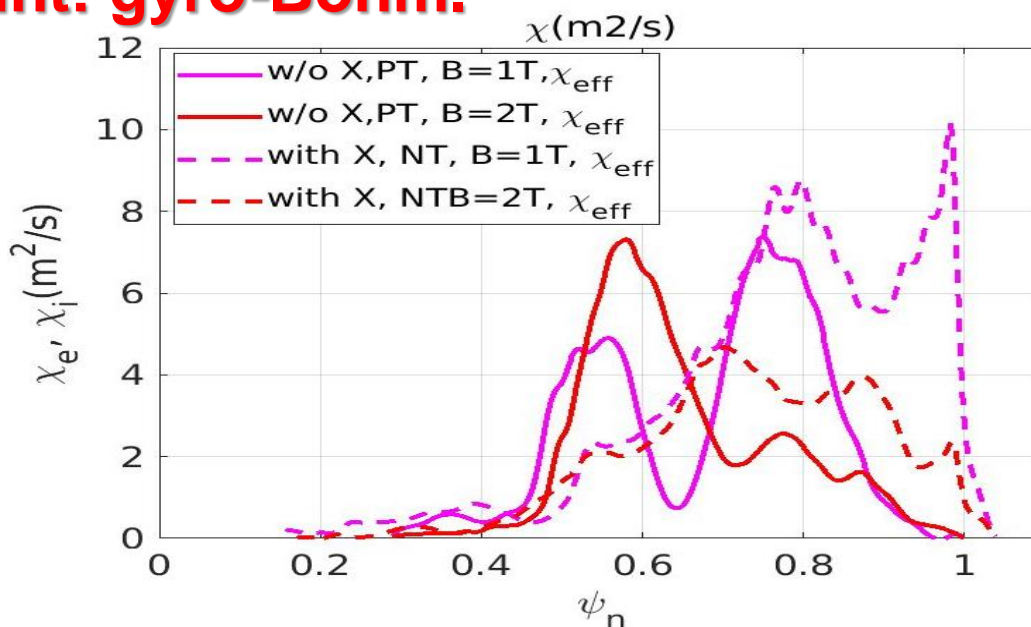
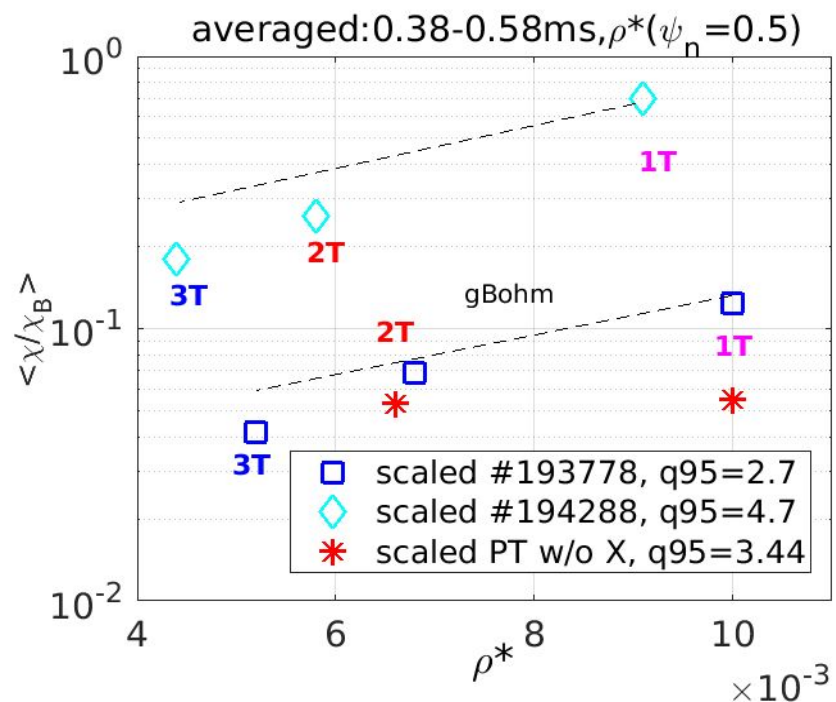
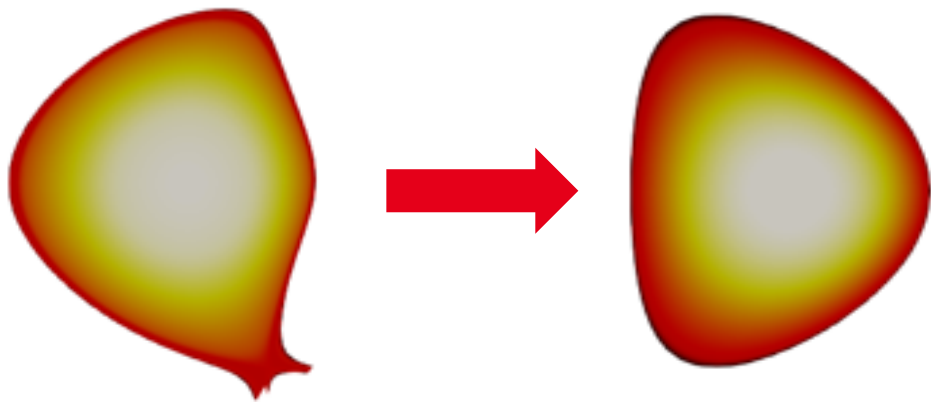


Preliminary: Bohm-like ρ^* scaling for PT, but w/o X-point here (similar heat conductivity for Bt=1T and Bt=2T). Should be done with X-point (future work).

For NT with X-point: gyro-Bohm.

NT #193778 with X

PT w/o X



Conclusions

1. **Particles(gyro-kinetic ions, guiding center electrons) in global non-linear JOREK-GK code in realistic X-point geometry. Modelling of electrostatic turbulence : gyro-kinetic ions+ adiabatic (ITGs only) or kinetic electrons (TEM/ITGs) can be modelled.**
2. **Comparison of JOREK-GK with GENE, GS2 for TCV ($T_e > T_i$) in linear TEM regime : similar linear growth rates for single modes, which are usually larger in PT compared to NT.**
3. **Divertor heat fluxes in divertor for TCV cases: PT $\lambda_q = 4\text{mm}$; NT: $\lambda_q = 3.5\text{ mm}$.**
4. **Modelling of realistic DIII-D pulses at low q_{95} , high q_{95} . Gyro-Bohm ρ^* confinement scaling in NT. Bohm ρ^* scaling in PT (preliminary, since done w/o X-point).**
5. **Future: A larger parameter range should be explored both experimentally and numerically to confirm the gyro-Bohm scaling for NT plasmas. Collisions model to improve (now only electron-ion). Decrease electron mass (now heavy electrons $m_i/m_e = 100$)**