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

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**1.Introduction.** Sufficiently strong negative triangularity (NT) shaping of tokamak plasma seems to prevent the bifurcation to H-mode while leading to high confinement regimes similar to H-mode plasmas but without Edge Localized Modes (ELMs) [1-6]. It could be a promising regime for fusion reactor. At present there is no complete understanding of the beneficial effect of NT on turbulent transport. In the recent theoretical and numerical studies the conclusions vary depending on the physics included in either local, global, linear or non-linear models, plasma profiles and type of turbulence considered. The most general conclusion is that negative triangularity shaping is mainly stabilizing for the Trapped Electron Modes (TEMs) [1-3,9] and possibly also for Ion Temperature Gradient (ITG) modes [7], which is not general conclusion though [8,9]. In the present paper we aim to make progress on the subject using the gyro-kinetic particle global non-linear code JOREK-GK [9,12].

**2. Model.** The JOREK-GK model describes electrostatic gyro-kinetic ITG/TEM turbulence in realistic X-point tokamak geometry. The kinetic particles are initialized to represent the density and temperature profiles obtained from the fluid MHD version of JOREK code [11] with a Maxwellian distribution. Ions are modelled using the gyro-kinetic formalism. The equation of motion of gyro-centers is solved in a time varying gyro-averaged electric field and time-constant magnetic field. The electrons can be treated in two approaches: adiabatic or kinetic.. With adiabatic electrons the electron density is expressed as a function of the electric potential. In the kinetic approach for electrons we assume that electrons follow the guiding center orbits. In this paper the electron mass was taken to be 100 times smaller than the ion mass for numerical convenience ("heavy electrons"). In this work kinetic electrons approach was used for ITG/TEM turbulence modelling. The electric potential is obtained from the solution of the Poisson equation for quasi-neutrality. In the gyro-kinetic model the Poisson equation includes the long wavelength form of the ion-polarization density. To transform the discrete particle distribution into a continuous representation on the finite element space a projection procedure was implemented using the same basis functions as in finite elements discretization in the fluid MHD version of the code JOREK [11]. The electric potential is discretized with cubic *C1* Bezier finite elements on flux-aligned grid in the poloidal plane and a Fourier series in the toroidal direction. The projection operations include filtering terms to reduce the particle noise. Two types of filters are used, hyper-diffusion in the poloidal plane and a Laplacian in the parallel direction. The time evolution uses an explicit fourth order Runge-Kutta (RK4) scheme with a time-advance of the particles with time steps $dt=2.-5.10^{-8}s$. The linearized electron-ion Lorentz collision operator [13] was used for the modelling of realistic DIII-D pulses described in Sec.4.

**3. Test cases in linear regimes.** Comparison of JORE-GK with other gyro-kinetic codes was done in linear regimes first. The linear growth rates of ITG/TEM in NT/PT triangularity shapes were compared for TCV-like parametrs. In the first test case, the linear growth rates for single modes were compared with ones obtained by flux-tube local gyro-kinetic code GS2 [2]. In this test case the equilibrium without X-point was used for simplicity. The number of particles in JOREK-GK for these cases was $10^9$ (the same for electrons and ions), $N_\psi=110$ in radial and $N_\theta=600$ in poloidal directions. Note that in spite of the large difference in GS2 and JOREK-GK, the mode structures (Fig.1) and linear growth rates (Fig.2) in the TEM dominant regime are similar. In Fig.2, a normalization of the growth rates is similar to [2]. In JOREK-GK we used toroidal harmonics $N_{tor}=10:10:40$. For comparison with [2] we used approximation $k_\theta \sim N_{tor}q_{res}/r_{res}$,, where $q_{res}=2.5$, $r_{res}=0.8*a$, $a=0.25m$ , thermal velocity and ion gyro-radius were estimated for central values $(T_e=2keV, T_i=0.48keV, \rho_i=2.3mm, V_{th}=1.5210^5 m/s)$. Both codes calculated larger linear growth rates for PT case compared to NT. The second test was done for the parameters presented in Fig.3-4 used in the modelling of the plasma layer $\psi_n>0.5$ with the global gyro-kinetic code GENE-X [10], which found similar profiles for NT/PT while the heat flux required to sustain these profiles was more than 30% less in NT. In JOREK-GK code we used full geometry (Fig.5), and hence we set flat profiles towards the centre for $\psi_n<0.5$ for comparison. In Fig. 6 we compare the linear growth rates obtained with local flux-tube code GENE without X-point [14] and JOREK-GK with X-point both run on plasma profiles used by GENE-X code in [10] (Fig.3-4).

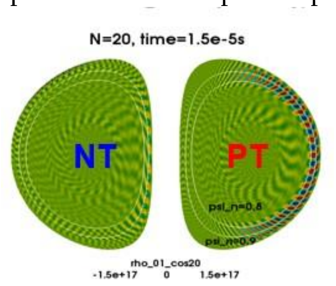


*Fig.1. Single N=20 mode structure in linear phase for NT/PT test cases for comparison with GS2 results [2].*

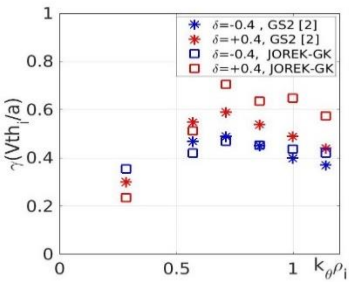


*Fig.2. Linear growth rates for single modes comparison between JOREK-GK and GS2 TCV parameters for PT/NT .*

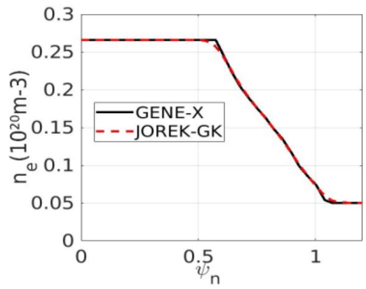


*Fig.3. Density profiles used for test cases in JOREK-GK and GENE [8].*

Note that the linear growth rates are similar (Fig.6) which seems like a generic feature for different gyro-kinetic codes considering the linear phase for single modes. However linear growth rates can give only an initial indication. For the realistic heat and particle transport estimation and comparison with experiment much longer non-linear runs up to the saturated turbulence state are needed.

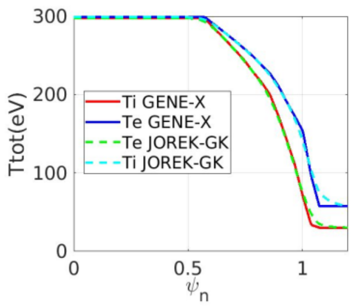


*Fig.4. Temperature profiles used for the second test case in JOREK-GK and GENE codes on profiles used by GENE-X code in [10].*

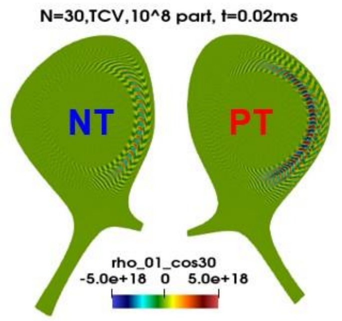


*Fig.5. Single mode N=30 structure in linear phase for NT/PT calculated by JOREK-GK code.*

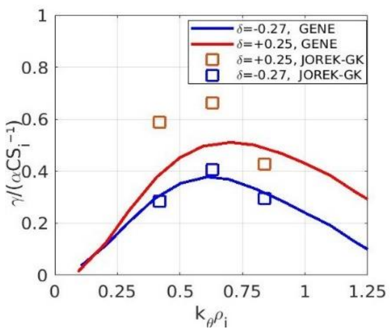


*Fig.6. Linear growth rates for single modes for TCV-like parameters calculated by GENE and JOREK-GK codes.*

**4. Gyro-Bohm ρ*-scaling for negative triangularity DIII-D plasmas.** The previous JOREK-GK modelling results of ITG/TEM turbulence for DIII-D like parameters, equal ion and electron temperatures and PT/NT equilibriums without X-point were presented in [9]. It was demonstrated that heat and particle fluxes are reduced at NT about factor of two compared to PT. The recent 2023 DIII-D dedicated negative triangularity campaign demonstrated spectacular confinement (factors $H_{98y2}>1$) without pedestal and ELMs [5-6] in a wide range of plasma parameters. In DIII-D, positive triangularity L-mode confinement usually is Bohm-like [15-16,17]. The open question is if the confinement in NT configuration is different, better than PT [17] ? The standard procedure to estimate confinement in fusion experiments is dimensionless parameters scaling [16, 17]. Note however that in experiment the perfect match of scaled profiles is rather difficult to obtain [15,17]. In modelling one can scale profiles easily, however because of the stiffness of plasma profiles even small changes in gradients could lead to a significant changes transport coefficients [15]. In this work we modelled two realistic pulses *DIII-D #193778* ($B_T=2T$, $q_{95}=2.7$-*low* $q_{95}$) and *DIII-D #194288* ($B_T=2T$, $q_{95}=4.7$-*high* $q_{95}$). The numerical parameters are: $5\text{x}10^8$ ions and electrons, a grid size of $(N_\psi,N_\theta)=(150,500)$ $=500$ and non-linearly coupled toroidal harmonics in the range $N_{tor}=5:5:40$. The initial density and temperature ($T_e$~$T_i$) profiles are presented in Fig.7-8. The density fluctuations from JOREK-GK modelling for these shots are presented in Fig.9. Using $B_{scale}=0.5$ and $B_{scale}=1.5$ we create scaled equilibria and plasma profiles keeping the $q$-profile exactly the same as at $Bscale=1(B_T=2T)$. Then toroidal magnetic field is scaled as $B_T \to B_{scale}*B_T$; the plasma current $I_p \to B_{scale}*I_p$; density $n_{i,e} \to n_{i,e}*B_{scale}^{(4/3)}$, temperature $T \to T*B_{scale}^{(2/3)}$ (hence the total pressure $P_{tot}$ ~$P_{tot}*B_{scale}^2$). Using definition of ion gyro-radius as $\rho_i = C_s/\omega_i$ where ion sound speed is $C_s = \sqrt{T_e/m_i}$ ; ion gyro-frequency is $\omega_i = 9.5810^7 B_T/A$ , the normalized $\rho^* = \rho_i/a$ will scale as $\rho^* \to \rho^* B_{scale}^{(-2/3)}$. Here we used $A=2$ for deuterium and $a=0.52m$. The $e$-$i$ collisions [13] are taken into account in these cases. Heat conductivity was estimated as time and flux surfaces heat fluxes for electrons and ions divided by corresponding time averaged local pressure gradients. Note that we obtained heat conductivities very close to the experimental values : $\chi_{eff}=(\chi_i + \chi_e)$~$1$-$2m^2/s$ in the center and $4$-$6m^2/s$ at the edge as measured in *DIII-D #193778* (Fig.10). Note also that the ion heat conductivity is about factor of two larger than the electron conductivity in all cases. The higher $q_{95}$ shot *DIII-D #194288* parameters are presented in Fig.7. The effective heat conductivity (Fig.11) is larger compared to the lower *q95* case, suggesting that the plasma current scaling for confinement time remains valid at NT. The normalized to Bohm $\chi_B = 1/16T_{eV}/B_T$ line averaged heat conductivities are shown in Fig.12 as a function of $\rho^*$ taken at $\psi_n=0.5$ for all scaled cases. These JOREK-GK results show that negative triangularity plasmas exhibit a gyro-Bohm scaling in L-mode, which probably explains high confinement factor obtained experimentally.

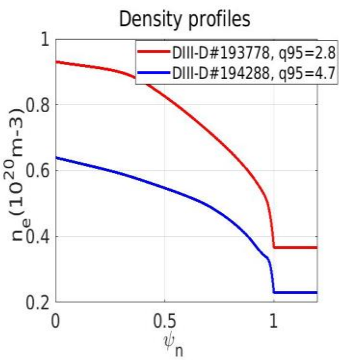


*Fig.7. Density profiles for modelled DIIII-D pulses.*

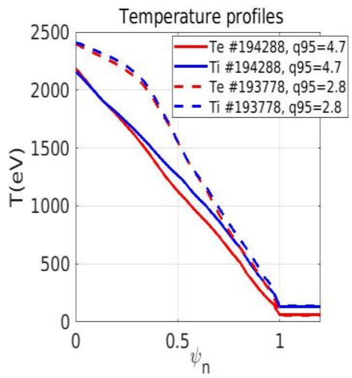


*Fig.8. Temperature profiles for modelled DIII-D pulses.*

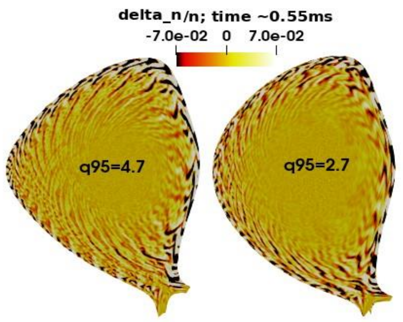


*Fig.9. Density fluctuations at t=0.55ms for modelled DIII-D pulses (#193778 and #194288)*

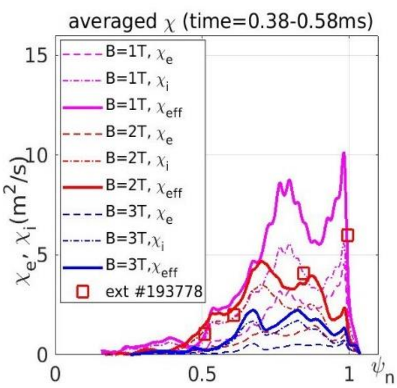


*Fig.10.Thermal conductivity for electrons ($\chi_e$ ), ions($\chi_i$ ), and effective ($\chi_{eff}=\chi_e+\chi_i$) calculated by JOREK-GK for DIII-D# 193778 pulse at $B_T=2T$ and scaled pulses at $B_T=1T$ and $B_T=3T$.*

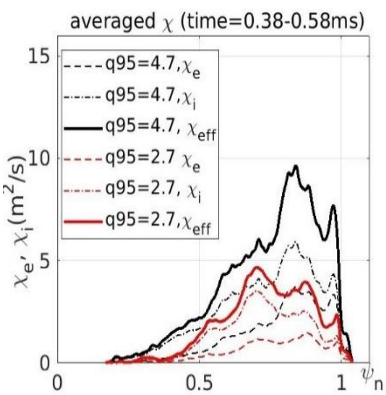


*Fig.11. Comparison of heat conductivities from modelling by JOREK-GK between #193778 (low $q_{95}$) and #194288 (high $q_{95}$).*

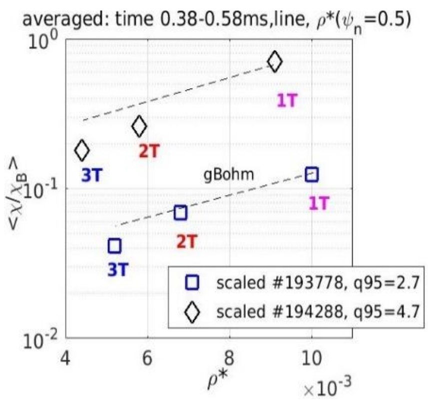


*Fig.12. The effective conductivity ($\chi_{eff}=\chi_e+\chi_i$) normalized to Bohm, calculated from flux surfaces and time (0.38-0.58ms) averaged heat fluxes divided by local pressure gradient and then line averaged in Outer Mid Plane (OMP) as a function of $\rho^*$ at $\psi_n=0.5$. Experimental cases are at 2T.*

**5. Conclusions**. The comparison of the non-linear gyro-kinetic particles code JOREK-GK with gyro-kinetic codes GS2 [2], GENE-X [10] and GENE [14] was done on a few selected NT/PT triangularity TCV–like 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. The global non-linear modelling using JOREK-GK code of the ITG/TEM saturated turbulence for realistic negative triangularity DIII-D pulses suggest gyro-Bohm confinement scaling similar to H-modes. That could probably explain high confinement obtained experimentally for negative triangularity shaped plasmas. A larger parameter range should be explored in the future both experimentally[17] and numerically to confirm or not the gyro-Bohm scaling for NT plasmas. This scaling would be very favorable factor for reactor size machines with high confinement operation without harmful ELMs.

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