Gyro-kinetic analyses of impurity transport within varying triangularity, high-density spherical tokamak plasmas with GENE

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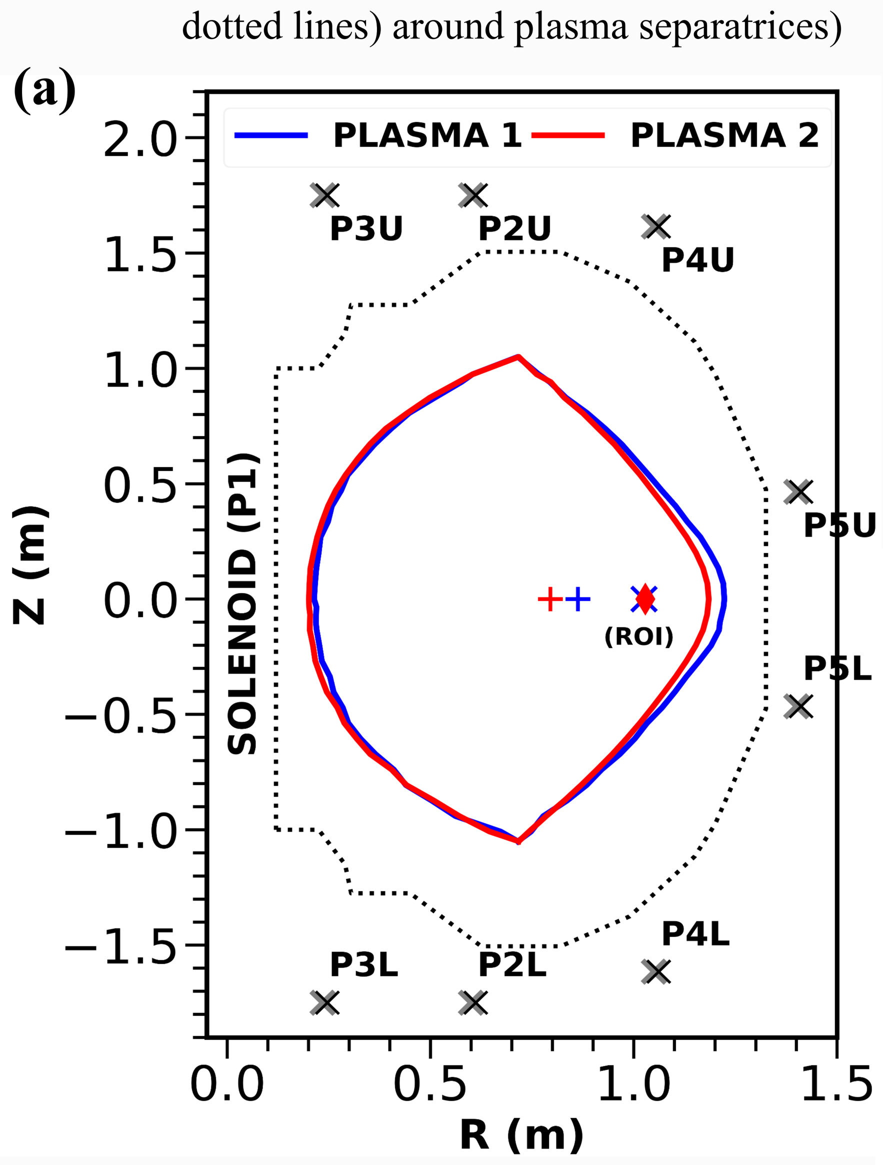
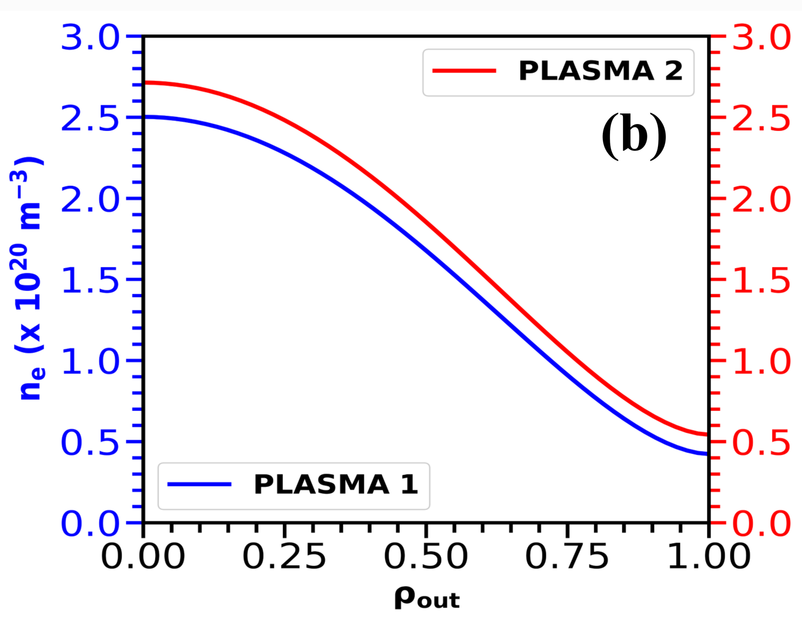
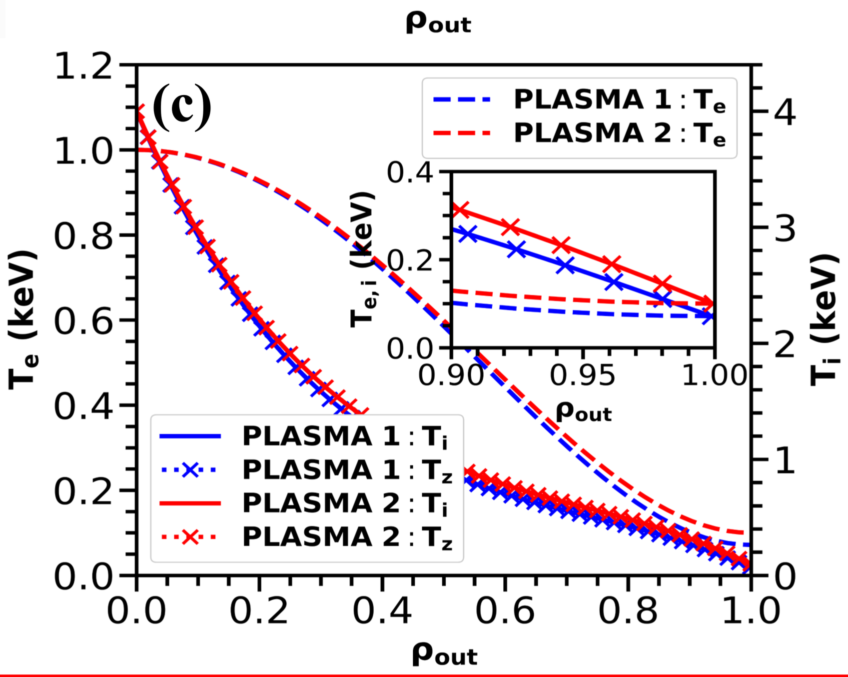
- The present study shows the effects of shape optimization parameters in determining the radial distributions of impurity ions within a plasma. Impurity charge state (Z) distributions collectively contribute to deciding the nature of microinstability at a given region within the plasma.
- Plasma equilibrium conditions are modelled here with a Grad-Shafranov equation solver **FreeGS** [https://freegs.readthedocs.io/en/latest/generated/freegs.html]. Two L-mode plasma equilibria within an arbitrary spherical tokamak (ST) design (fig. a), are modelled with FreeGS and analysed. **Characteristic geometry and plasma parameters are:**

	Major radius (magnetic axis) R_0 (m)	Minor radius a (m)	Central Toroidal magnetic field $B_{t,0}$ (T)	Net plasma current I_p (MA)	Aspect ratio A	Elongation κ, Triangularity δ	Outboard Squareness ζ_{out}	Upper X-point [R, Z] (m)	Lower X-point [R, Z] (m)
PLASMA 1	**0.862**	**0.504**	**1.487**	**1.005**	**1.709**	**2.082, 0.292**	**-0.185**	**[0.715, 1.05]**	**[0.715, −1.05]**
PLASMA 2	**0.795**	**0.492**	**1.487**	**0.627**	**1.616**	**2.136, 0.158**	**-0.224**	**[0.717, 1.05]**	**[0.717, −1.05]**
	Central electron density $n_{e,0}$ (m^{-3})	Edge electron density $n_{e,a}$ (m^{-3})	Central electron temperature $T_{e,0}$ (keV)	Edge electron temperature $T_{e,a}$ (keV)	Central ion temperature $T_{e,0}$ (keV)	Edge ion temperature $T_{e,a}$ (keV)	Central safety factor q_0	Edge safety factor q_a	β_p (no units), β_N (% T-m/MA)
PLASMA 1	**2.502E+20**	**4.234E+19**	**1.000**	**0.0716**	**4.000**	**0.0716**	**0.493**	**3.461**	**0.400, 1.715**
PLASMA 2	**2.713E+19**	**5.427E+18**	**1.000**	**0.1000**	**4.000**	**0.1000**	**1.013**	**5.523**	**0.127, 0.233**

(Pease note: rough design of wall (black dotted lines) around plasma separatrices)





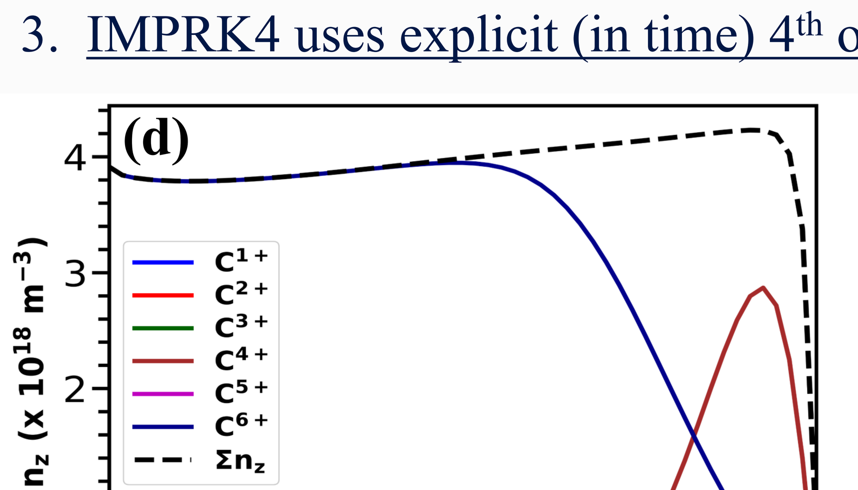


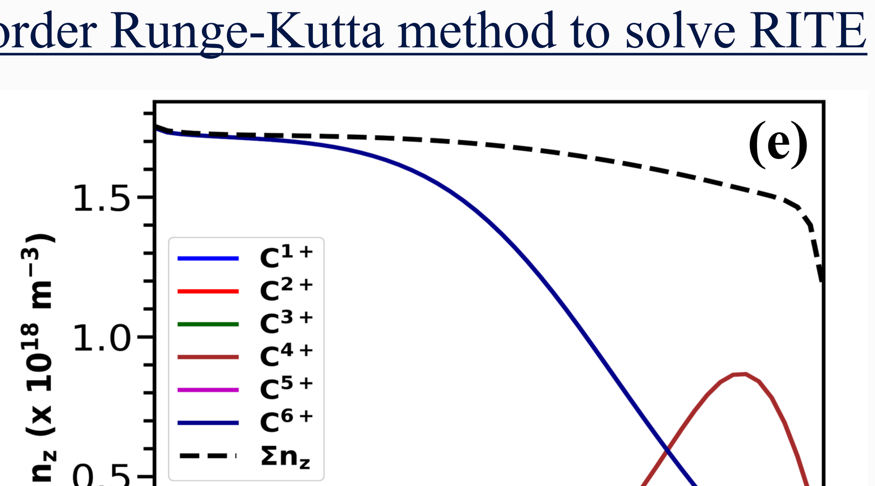
EFFECTS OF SHAPE OPTIMIZATION ON KINETIC PARAMETERS

1. Poloidal beta (β_p), I_p – kinetic constraints set within FreeGS for generating the equilibria; Lower β_p and I_p required for modelling PLASMA 2 with lower δ and higher negative ζ_{out}
2. Kinetic pressure p(ψ) – determined by FreeGS; $T_{e,0}$ and $T_{i,0}$ – provided; $T_{e,a}$ and $T_{i,a}$ – assumed same; with these detail $n_{e,0}$ determined first
3. Edge density ($n_{e,a}$) determined from central and edge pressures ($p_0(\psi)$, $p_a(\psi)$) and $n_{e,0}$ [R. H. Fowler, J. A. Holmes, J. A. Rome, Report – ORNL/TM-6845, July 1979]; $T_{e,a}$ determined next assuming $T_{e,a} \approx T_{i,a}$
4. Lower poloidal beta (β_p) within PLASMA 2 (β_p = 0.127, β_t ~ 0.2%), with same $B_{t,0}$ as PLASMA 1 (β_p = 0.400, β_t ~ 2.3%), lowers p(ψ) within PLASMA 2
5. With same $T_{e,0}$, $T_{i,0}$ for both plasmas – drop in $p_0(\psi)$ within PLASMA 2 implies drop in $n_{e,0}$, drop in $p_a(\psi)$ (with higher $T_{e,a}$, $T_{i,a}$) implies drop in $n_{e,a}$ within PLASMA 2 (over PLASMA 1)
6. n_e and T_e waveforms generated with same peaking factors (1.75 for n_e and 2.05 for T_e) for both plasmas (fig. b, c); T_i obtained from p(ψ), n_e, T_e waveforms
7. Lower density in PLASMA 2 with same $B_{t,0}$, $T_{e,0}$, $T_{i,0}$ as PLASMA 1; Greenwald fraction [J. Wesson, *Tokamaks*, Oxford University Press Inc., NY (2011)] f_G ~ 1.25 for PLASMA 1, ~ 0.21 for PLASMA 2
8. n_e and T_e waveforms determine impurity charge state distributions along radius; Thus, if $n_i \approx n_e >> \Sigma n_z$, then $Z_{eff} \rightarrow 1.0$ changing the impurity effects in deciding the local microinstability
9. Local microinstability (nature) analysed with GENE [F. Jenko et al., *Physics of Plasmas* **7(5)** 1904 – 1910 (2000)]
10. GENE [M. J. Pueschel, F. Jenko, *Physics of Plasmas* **17** 062307 (2010)] EIGEN VALUE (EV) runs conducted with Z_{eff} > 1.0 and Z_{eff} = 1.0 to determine impurity effects during microturbulences

EVALUATION OF Z_{eff} CONSIDERING SINGLE IMPURITY SPECIES

1. Impurity analysed: CARBON [E. A. Belli et al., *Plasma Phys. Control. Fusion* **65** 024001 (2023)]
2. The radial impurity transport equation [A. Bhattacharya et al., *Journal of Fusion Energy* **37(5)** 211 – 237 (2018)] (RITE) solved for obtaining carbon ion distributions (fig. d, e) with a new impurity transport code (IMPRK4)
3. IMPRK4 uses explicit (in time) 4th order Runge-Kutta method to solve RITE

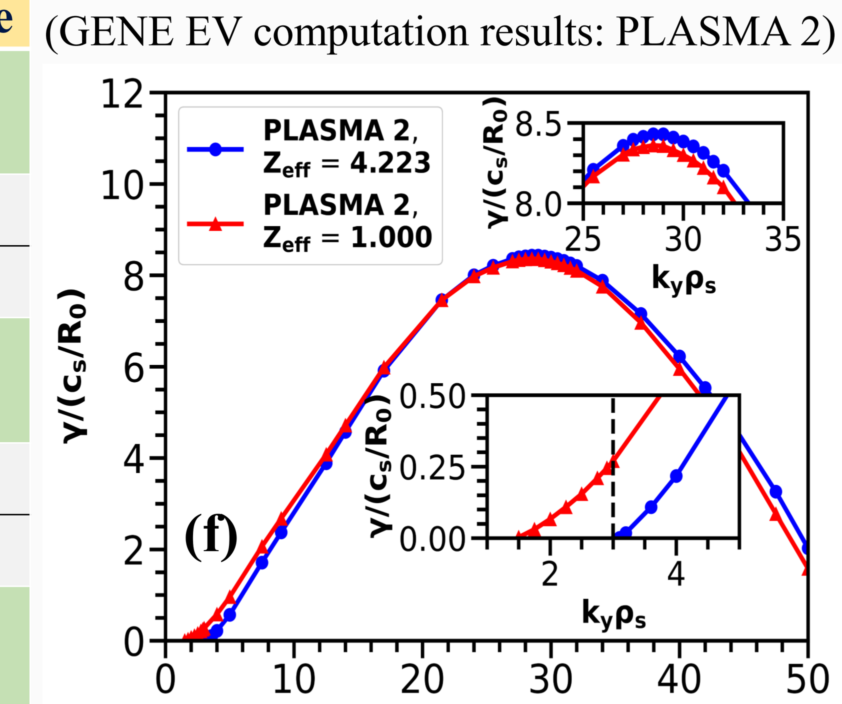


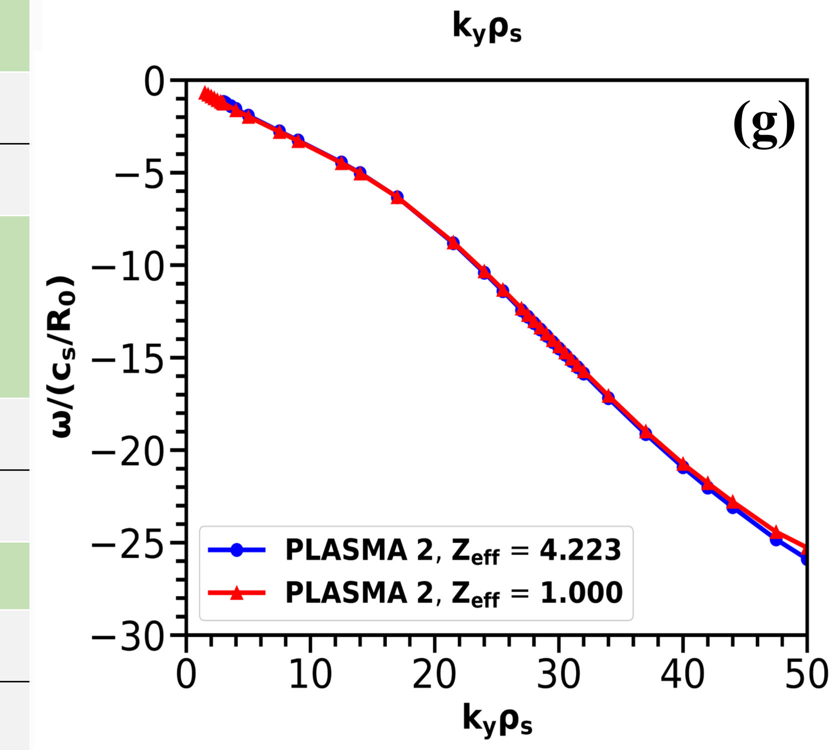


4. Ionization, Recombination, Charge-exchange rate coefficients of impurity charge states (Z = 0 to 6) are from OPEN-ADAS [https://open.adas.ac.uk/] database
5. Near similar (minor edge difference) carbon neutral waveforms ($n_{z,0}$) and same impurity diffusivity (D_z) and velocity (v_z) waveforms are provided to IMPRK4 for both plasmas
6. Effective charge state $Z_{eff} = (n_i + \sum_{Z=1}^{Z=6} Z^2 n_Z)/n_e$ determined from carbon ion distributions; local Z_{eff} set within GENE 'parameters' file to include impurity effects in GENE EV computations

Region Of Interest data provided to GENE 'parameters' file			
	Analysed pt. [R, Z] (m)	Local Shear (S)	Local α
PLASMA 1	**[1.025 , 0.0]**	**0.805**	**0.943**
PLASMA 2	**[1.028 , 0.0]**	**1.053**	**0.435**
	Local Z_{eff}	Geometry, r/R_0	Reference length L_{ref} (m)
PLASMA 1	**1.711**	**Circular, 0.189**	**0.862**
PLASMA 2	**4.223**	**Circular, 0.294**	**0.795**
	Reference mass m_{ref} (amu)	Reference density n_{ref} (m^{-3})	Reference magnetic field B_{ref} (T)
PLASMA 1	**2.014**	**25.021E+19**	**1.487**
PLASMA 2	**2.014**	**2.7135E+19**	**1.487**
	Reference temperature T_{ref}(keV)	L_{ref}/L_n	L_{ref}/L_{Te}, L_{ref}/L_{Ti}
PLASMA 1	**1.000**	**2.656**	**3.578, 6.329**
PLASMA 2	**1.000**	**3.430**	**4.796, 4.502**
	Local n_e/n_{ref}	Local T_e/T_{ref}	Local T_i/T_{ref}
PLASMA 1	**0.793**	**0.735**	**1.221**
PLASMA 2	**0.639**	**0.546**	**0.896**

(GENE EV computation results: PLASMA 2)





INFERENCES

1. **PLASMA 1 with η_i (= L_n/L_{Ti}) > η_e (= L_n/L_{Te}):** GENE EV runs performed for all $k_y\rho_i \leq 1.0$ (searching η_i [S. S. Henderson et al., *Nucl. Fusion* **54** 093013 (2014)] modes); stabilized modes seen (growth rate γ < 0) between $0.91 \leq k_y\rho_i \leq 1.0$ beyond which, no solutions are generated by the EV solver; transport at the ROI within PLASMA 1 (fig. a) possibly neo-classical
2. **PLASMA 2 with η_e > η_i:** GENE EV runs performed for all $k_y\rho_i$ > 1.0; possible destabilized Trapped Electron Modes [A. Skyman, H. Nordman, P. Strand, *Phys. Plasmas* **19** 032313 (2012)] (TEMs) ($1.5 \leq k_y\rho_i \leq 3.0$) (γ > 0) observed with Z_{eff} = 1.0 (pure plasma) for the analysed ROI (fig. f) which would transition to Electron Temperature Gradient (ETG) modes as $k_y\rho_i \gg 3.0$
3. **PLASMA 2:** Only ETG modes ($k_y\rho_i \geq 3.1$) observed when Z_{eff} = 4.223 (fig. f); this is expected as impurity ions collide with trapped electrons turning them into passing particles stabilizing TEMs; Rising negative mode frequency ω (fig. g) from $k_y\rho_i$ > 3.1 onwards indicate low wavelength η_e modes influence dominant electron transport channel