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IMPURITY RADIATION SEEDING OF NEOCLASSICAL TEARING MODE GROWTH

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ABSTRACT

- NIMROD simulations show that local impurity radiation cooling can drive resistive tearing mode and provide the seed island for the subsequent neoclassical tearing mode (NTM) instability.
- The seed island is further driven by the perturbed bootstrap current arising from the neoclassical electron viscous stress within the extended Ohm's law.
- The detrimental effects arising from the persistent NTM growth in the burning plasma regime are evaluated.

BACKGROUND

- NTM is well known to be detrimental to fusion plasmas, limiting the achievable plasma beta, degrading confinement, and potentially triggering disruptions.
- The critical question of the seed island required for nonlinear NTM growth remains insufficiently understood and demands further study.
- Impurity radiation plays a crucial role in steady-state tokamak operation and the impurity radiation-induced resistive tearing mode could be a potential seed mechanism for NTM.

IMPURITY RADIATION INDUCED SEED ISLAND

SIMULATION MODEL

Our simulations are based on the single-fluid resistive MHD model implemented in the NIMROD code, which incorporates KPRAD:

$$\rho\frac{d\vec{V}}{dt} = -\nabla p + \vec{J}\times\vec{B} + \nabla\cdot(\rho\nu\nabla\vec{V}) - \nabla\cdot\vec{\Pi}_i, (1)$$

$$\frac{dn_{i,z}}{dt} + n_{i,z}\nabla\cdot\vec{V} = \nabla\cdot(D\nabla n_{i,z}) + S_{ion/rec}, (2)$$

$$n_e\frac{dT_e}{dt} = (\gamma-1)[n_eT_e\nabla\cdot\vec{V} + \nabla\cdot\vec{q}_e - Q], (3)$$

$$\vec{q}_e = -n_e[\kappa_\parallel\vec{b}\vec{b} + \kappa_\perp(\mathcal{I} - \vec{b}\vec{b})]\cdot\nabla T_e, (4)$$

$$\vec{E} = -\vec{V}\times\vec{B} + \eta\vec{J} - \frac{1}{en_e}\nabla\cdot\vec{\Pi}_e. (5)$$

SEED ISLAND GROWTH

The nonlinear growth of the seed island is consistent with the Rutherford model $\tau_R dw/dt \simeq \Delta' - \Delta'_c$ (except during the peaking phase, where stabilizing curvature effect is enhanced), with the tearing stability parameter Δ' emerging as the primary driver (Fig. 1a).

LINEAR Δ′

The linear Δ' represents a simplification of Ampère's law: $\Delta'\psi \simeq \int\nabla^2\psi dr \simeq \int\delta J dr$, which includes perturbed local pressure induced current perturbations by local impurity radiation cooling around r_s (Fig. 1b).

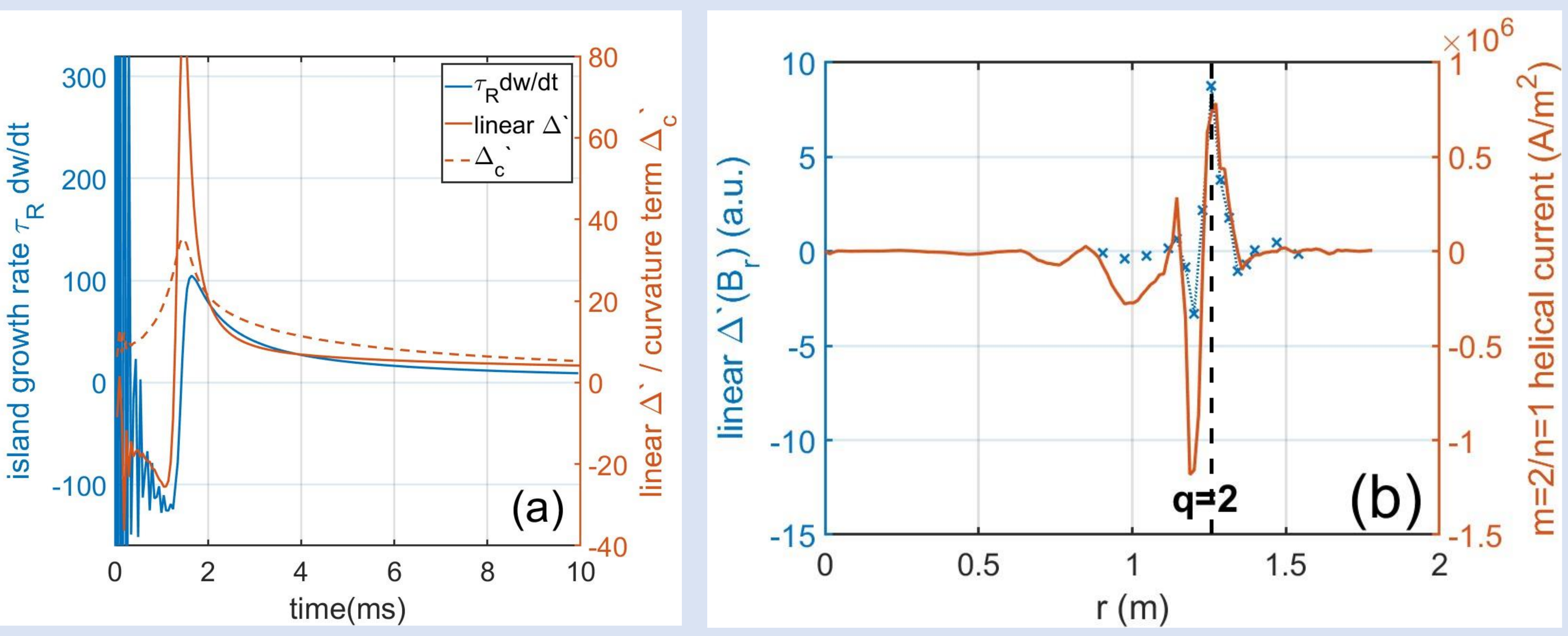


Fig. 1 (a) The island growth rate dw/dt, linear Δ', and the curvature term Δ'_c as functions of time. (b) the 2/1 helical current and discrete values of Δ' at t=2.5ms.

IMPURITY RADIATION SEEDED NTM GROWTH

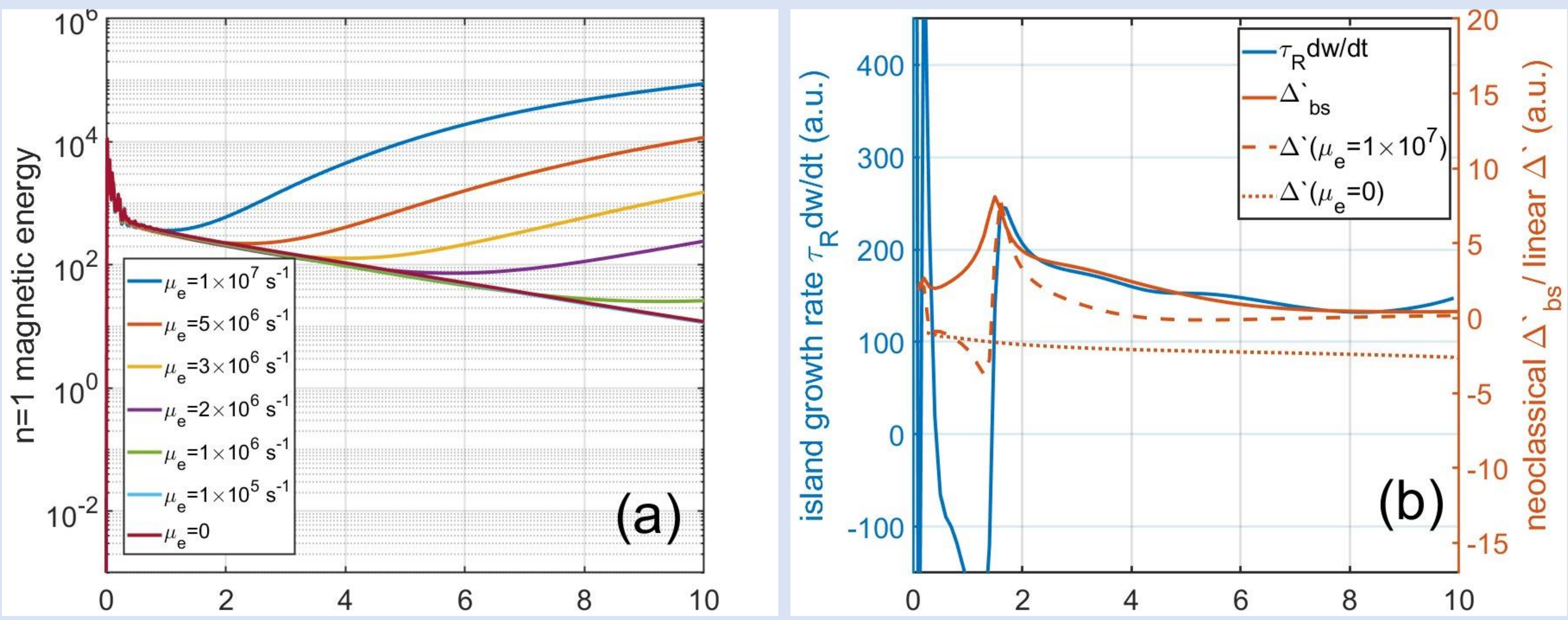
NEOCLASSICAL ELECTRON VISCOSITY

When the neoclassical electron viscosity is included in the extended Ohm's law. A threshold is identified in the coefficient μ_e ($\mu_e = 1\times10^6 s^{-1}$), above which the seed island begins to grow rather than continue to decay (Fig. 2a).

NEOCLASSICAL DRIVING

- The heuristic electron force $\nabla\cdot\vec{\Pi}_e/(en_e)$ drives the bootstrap current perturbation in the extended Ohm's law, which agree well with a simplified theoretical model for the perturbed bootstrap current, $\delta J_{bs} = \epsilon^{1/2}/B_\theta(d\delta p/dr)$.
- The neoclassical driving term $\Delta'_{bs} = (\sqrt{\epsilon}/w)\beta_p L_q/L_p$ measured from simulation results agrees well with nonlinear island growth in the same simulation (Fig. 2b).

Fig. 2 (a) the magnetic energy of n=1 with various coefficient μ_e. (b) The island growth rate dw/dt, neoclassical driving Δ'_{bs}, linear Δ' in the NTM case ($\mu_e \neq 0$) and resistive tearing case ($\mu_e = 0$) as functions of time.



BURNING PLASMA REGIME

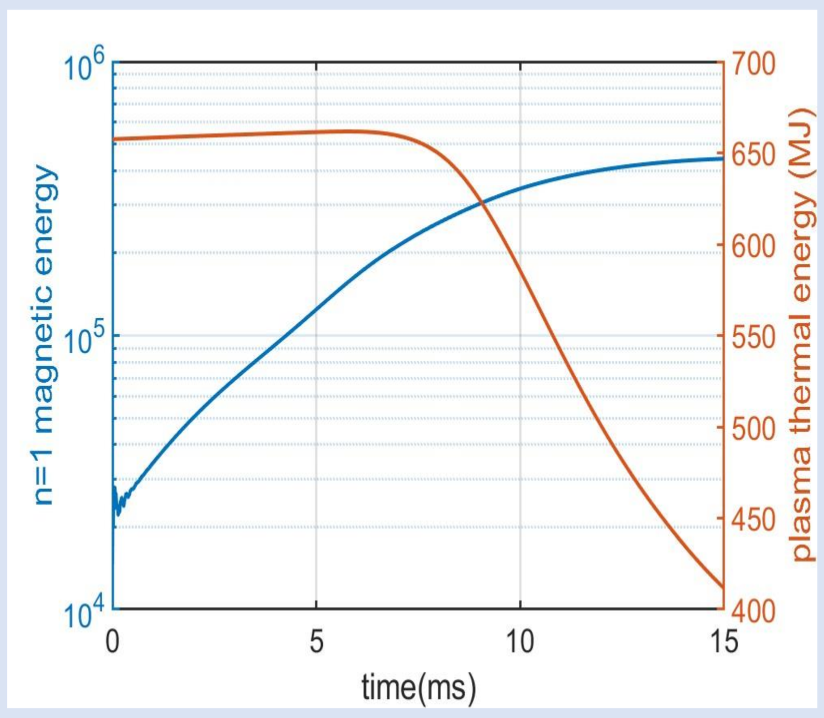
SIMULATION SETUP

Taking the α particle heating power $P_\alpha = 1/4n_i^2\langle\sigma v\rangle_{DT}E_\alpha$ and the corresponding helium ash radiation cooling into the source term Q of the energy Eq. (3).

RESULTS

The magnetic island grows toward saturation and the thermal energy drops rapidly once the island width exceeds a certain threshold (Fig. 3).

Fig. 3 The magnetic energy of n=1 mode and the thermal energy as functions of time.



CONCLUSION

NIMROD simulations show that local impurity radiation cooling can seed NTM. The physics of this seeding process and the subsequent neoclassical island growth have been demonstrated.

ACKNOWLEDGEMENTS

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