Simulation study of the effect of impurities on the ELM dynamics using BOUT++ six-field two-fluid model

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Abstract

- **Impurity seeding** is necessary for achieving **divertor detachment**, and also has essential effects on **ELM control**: possibility of **simultaneous control of the transient and steady-state heat load**.
- To investigate the **mechanism of impurity on ELM behavior**, a systemic simulation study is carried out using **BOUT++ six-field two-fluid module** [1] with **impurity model** [2], based on the **EAST experiment** [3].
- **Linear simulation** indicates impurities introduce **extra vorticity**, enhancing the **stabilizing effect of radial electric field shear** on peeling-ballooning mode, which can be characterized by **impurity mass density ratio**.
- **Nonlinear simulation** shows **a impurity density "threshold"** for ELM suppression and the "**two-stage burst**" feature of ELM evolution:
  - The **first stage** is related to the **P-B stability** (drop with increasing N_{imp})
  - The **second stage** is related to the **magnetic flutter driven by DTM**
  - **ELM size** can be reduced when **the second stage is suppressed**

Impurity effect within the simulation model

- Compared to the original six-field two-fluid model, the dynamic effect of impurities are primarily reflected in the **vorticity expression**:

$$\varpi = \frac{m_i}{B}\left(\nabla_\perp\cdot\left(n_{\mu 0}\nabla_\perp\phi\right)+\frac{1}{Z_i e}\nabla_\perp^2\left(P_i+\frac{A_{\mathrm{imp}}}{A_i}\frac{Z_i}{Z_{\mathrm{imp}}}P_{\mathrm{imp}}\right)\right)$$

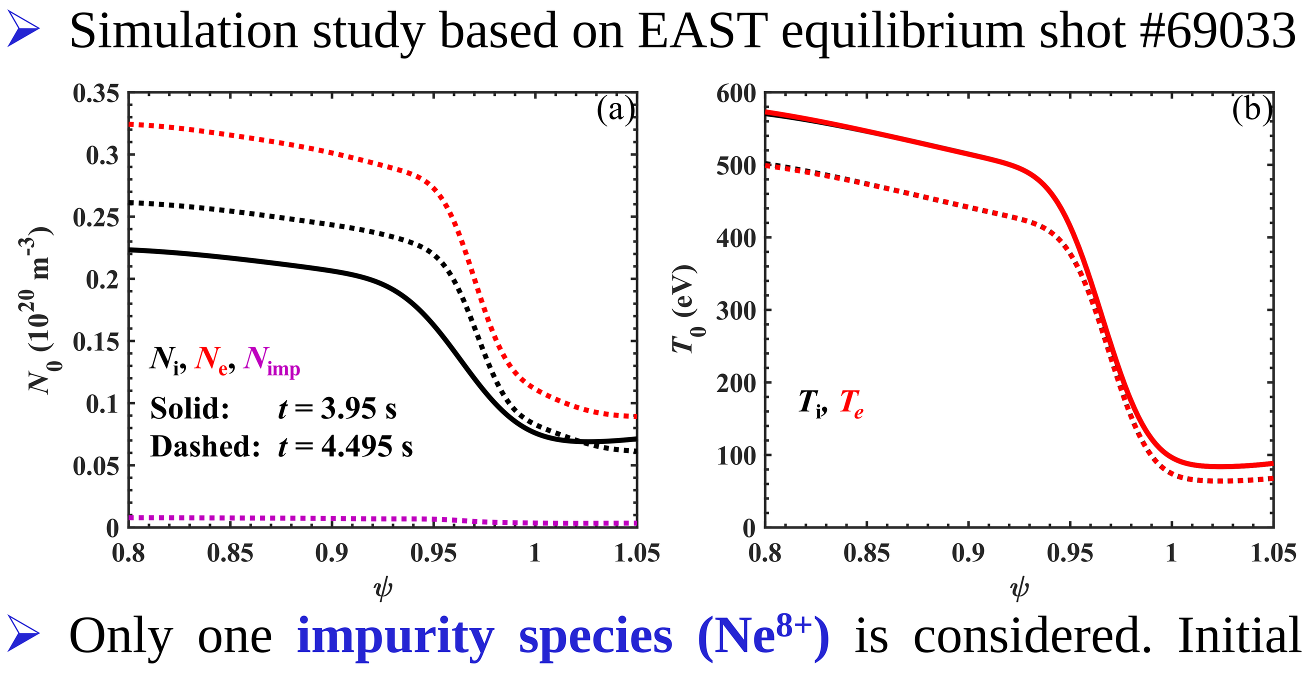
- The effective density increases with impurity seeding (inertia effect)

$$n_i \to n_i + \left(A_{\mathrm{imp}}/A_i\right)n_{\mathrm{imp}}$$

- Net vorticity introduced by impurity (impurity vorticity)

$$E_{r0}\sim\frac{\nabla P_{i0}}{en_{i0}}\to\begin{cases}\varpi_{i0}\sim 0\\ \omega_{\mathrm{imp}0}\sim\frac{m_{\mathrm{imp}}}{B}\left(\nabla_\perp\cdot\left(n_{\mathrm{imp}0}\nabla_\perp\phi_0\right)+\frac{1}{Z_{\mathrm{imp}}e}\nabla_\perp^2 P_{\mathrm{imp}0}\right)\end{cases}$$

- Simulation study based on EAST equilibrium shot #69033



3.95s:
Before seeding
Small ELM

4.495s:
After seeding
Large ELM

- Only one **impurity species (Ne^{8+})** is considered. Initial impurity density is calculated by: $N_{\mathrm{imp0,\,base}}=\left(N_{e0}-N_{i0}\right)/8$
- The strength of radial electric field shear is characterized by:

$$\left|\frac{\partial\langle E\rangle_{k_r}}{\partial r}\right|\sim\left|k_r\langle E\rangle_{k_r}\right|$$

- The contribution of magnetic flutter on the radial electric field shear variation is calculated by:

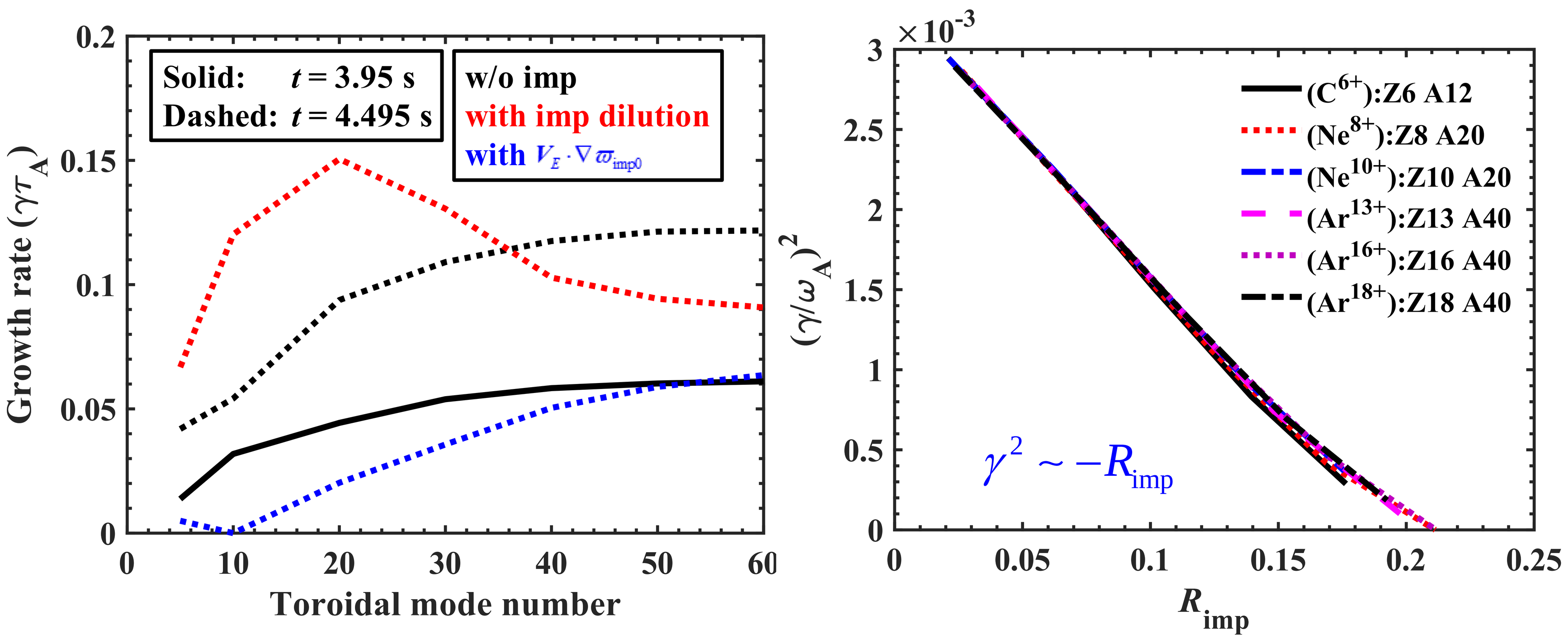
$$T_{\text{magnetic flutter}}\equiv\frac{\partial}{\partial t}\left(\left|\frac{\partial}{\partial r}\langle E_r\rangle_{k_r}\right|^2\right)_{\text{magnetic flutter}}$$
$$\sim-\frac{2n_{\mu 0}B_0}{m_i}\mathrm{Real}\left[\left(B_0^2\nabla_{\|}\frac{j_{\|1}}{B_0}\right)_{k_r}\times\left(\frac{\partial}{\partial r}\langle E_r\rangle_{k_r}\right)^*\right]$$

Reference

[1] T. Y. Xia, et al. Nucl. Fusion 53 (2013) 073009
[2] Z. Li, et al. Nuclear Fusion 62 (2022) 076033
[3] X. Lin, et al. Phys. Lett. A 431 (2022) 127988

Linear simulation: stabilization mechanism

- **Profile change**: growth rate of 4.495s is significantly larger than that of 3.95s.
- **Increase of inertia**: high n stabilized, low n destabilized.
- **Extra vorticity**: significantly stabilized for all n modes.



- According to localized eigenmode analysis, ballooning mode growth :

$$\gamma_b^2\propto\frac{1}{n_i\alpha|1-C|}\left(1-\frac{R_{\mathrm{imp}}}{|1-C|}\right)\sim -R_{\mathrm{imp}}$$

Mechanism: enhancing radial electric field shear stabilization

impurity mass density ratio: $R_{\mathrm{imp}}=A_{\mathrm{imp}}n_{\mathrm{imp}}/\left(A_{\mathrm{imp}}n_{\mathrm{imp}}+A_i n_i\right)=1-n_i/n_\mu$

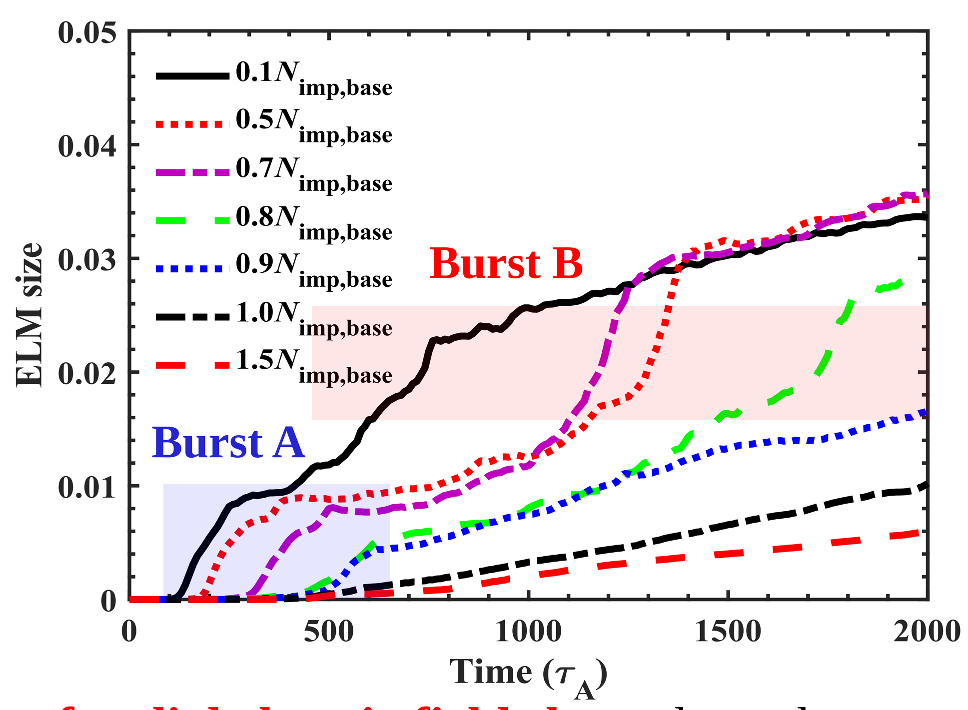
- The square of simulated growth rate of n = 10 mode with different R_{imp} are found in good agreement with theoretical prediction above.

Nonlinear simulation: two-stage burst

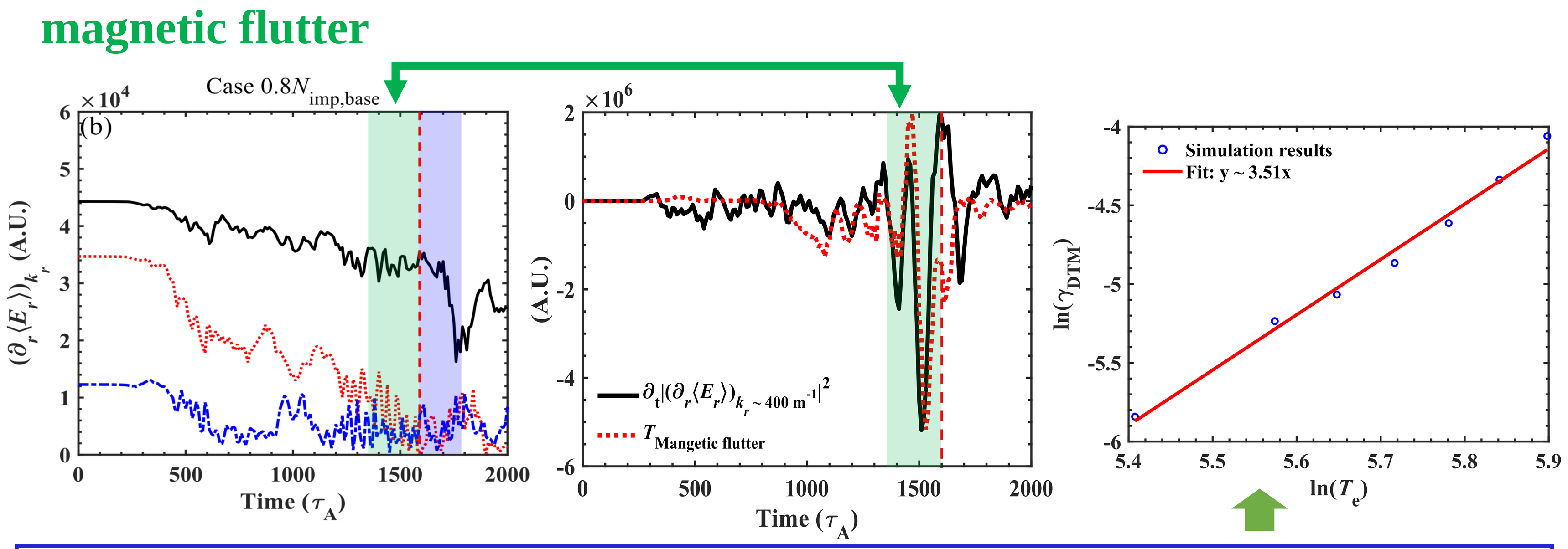
- **Two stage burst**

$0.1\sim0.8N_{\mathrm{imp}}\to$ Burst B unaffected
$>0.9N_{\mathrm{imp}}\to$ Burst B suppressed
ELM suppression

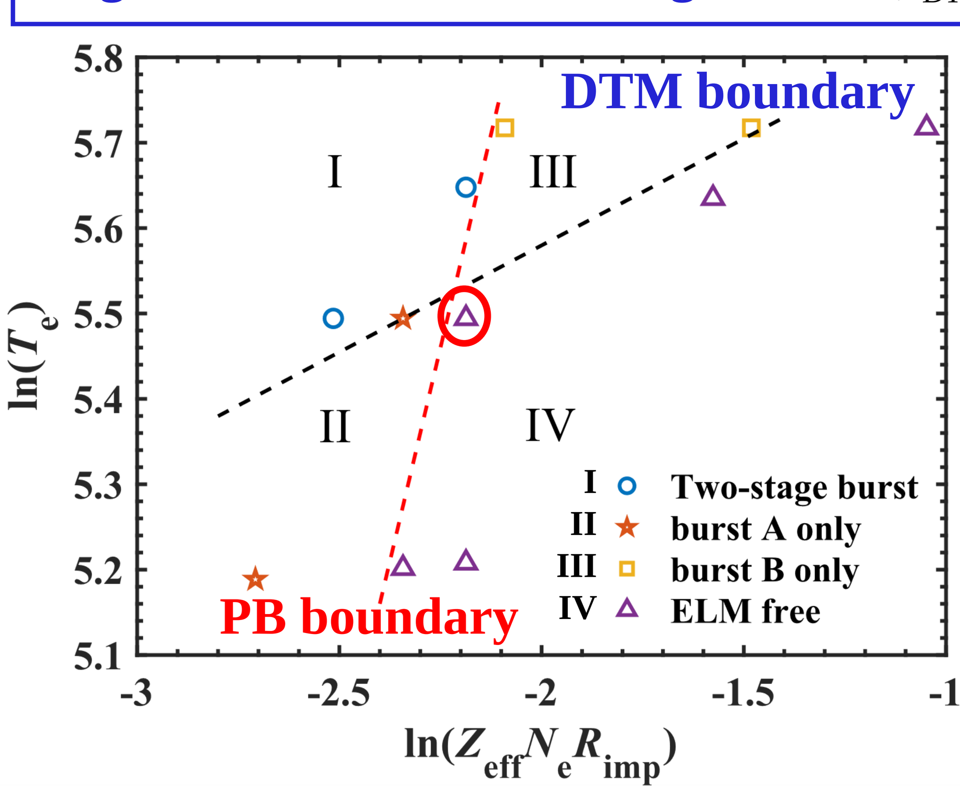
$N_{\mathrm{imp}}\uparrow\ \Rightarrow$ Burst A $\downarrow$



- **Burst B** is triggered by **reduction of radial electric field shear** through **magnetic flutter**



Magnetic flutter: drift tearing mode $\gamma_{DTM}\propto\omega_{*e}^2/\nu_e\sim T_e^{7/2}N_e^{-1}Z_{\mathrm{eff}}^{-1}\left(T_e'/T_e\right)$



Nonlinear response of ELM to the impurity in R_{imp}-T_e space

Effect on ELM size:
- **I→III: No effect**
- **I →II: mitigation**
- **I, II, III →IV: suppression**