Simulation of kinetic Peeling-Ballooning mode with bootstrap current under the BOUT++ gyro Landau Fluid code

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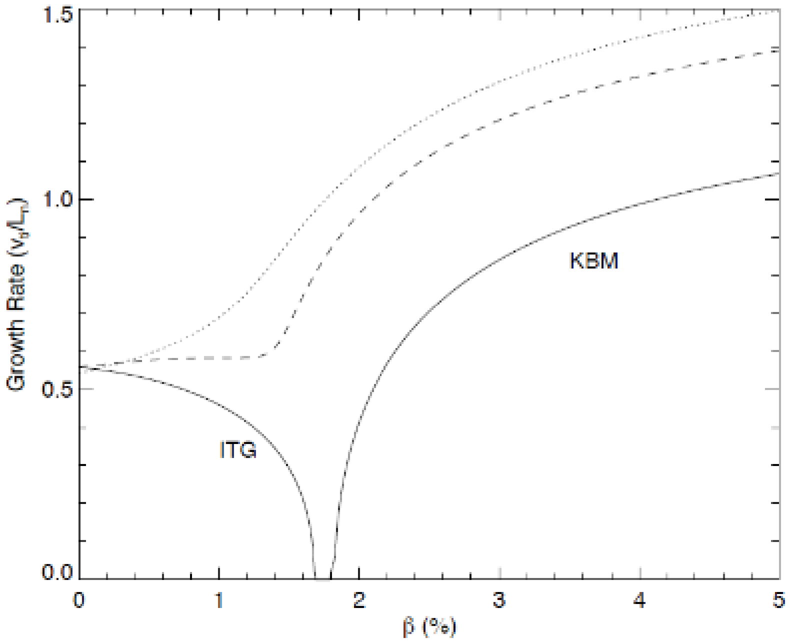
Outline

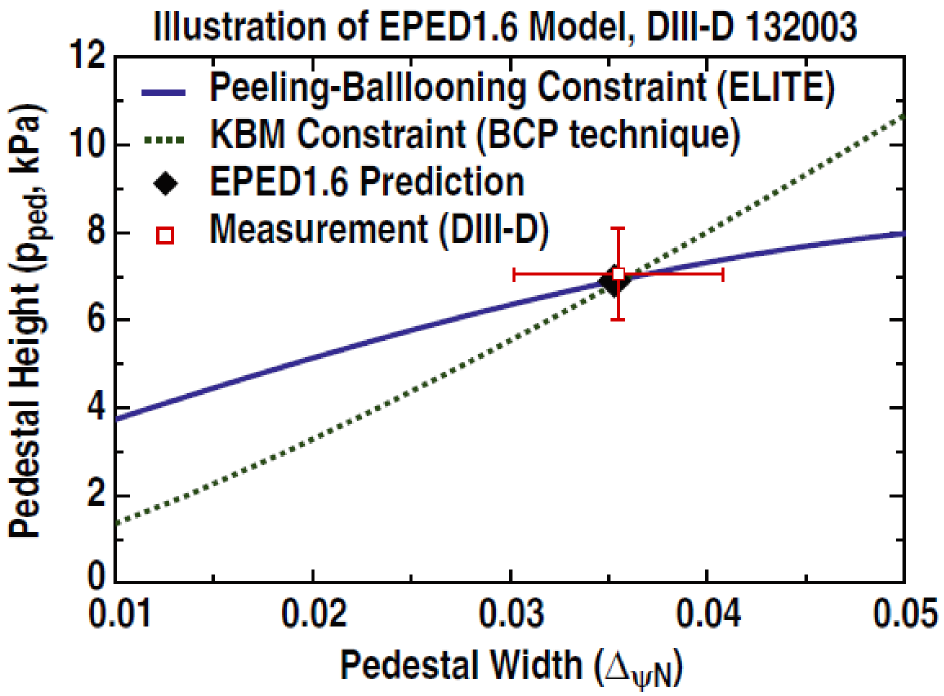
- **Background**
- **Equilibrium and GLF 3+1 model**
- **Linear analysis of KPBM**
- **Nonlinear analysis of KPBM and verification of EPED model**
- **Summary**

Outline

- **Background**

Kinetic Peeling-Ballooning mode (KPBM) is important to transport





[1]P. B. Snyder 1999 Doctoral thesis

[2]2P. B. Snyder 2009 POP

- **As the plasma beta increases, the Ion temperature gradient mode (ITG) will be stabilized, but the kinetic ballooning (KBM) mode be destabilized.**
- **The KBM turbulence transport is important to the fusion confinement, especially in transport barriers.**
  - **The linear KBM physics in EPED model successfully predicts the pedestal height and width in H mode**
- **The global simulations of KBM with bootstrap current are needed.**

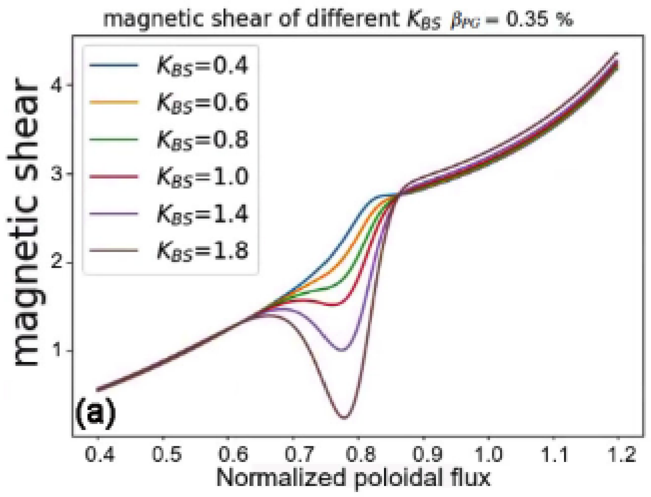
Outline

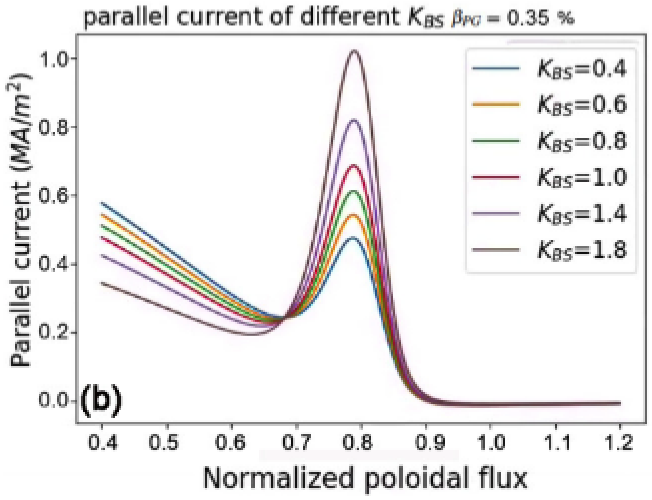
- **Background**
- **Equilibrium and GLF 3+1 model**

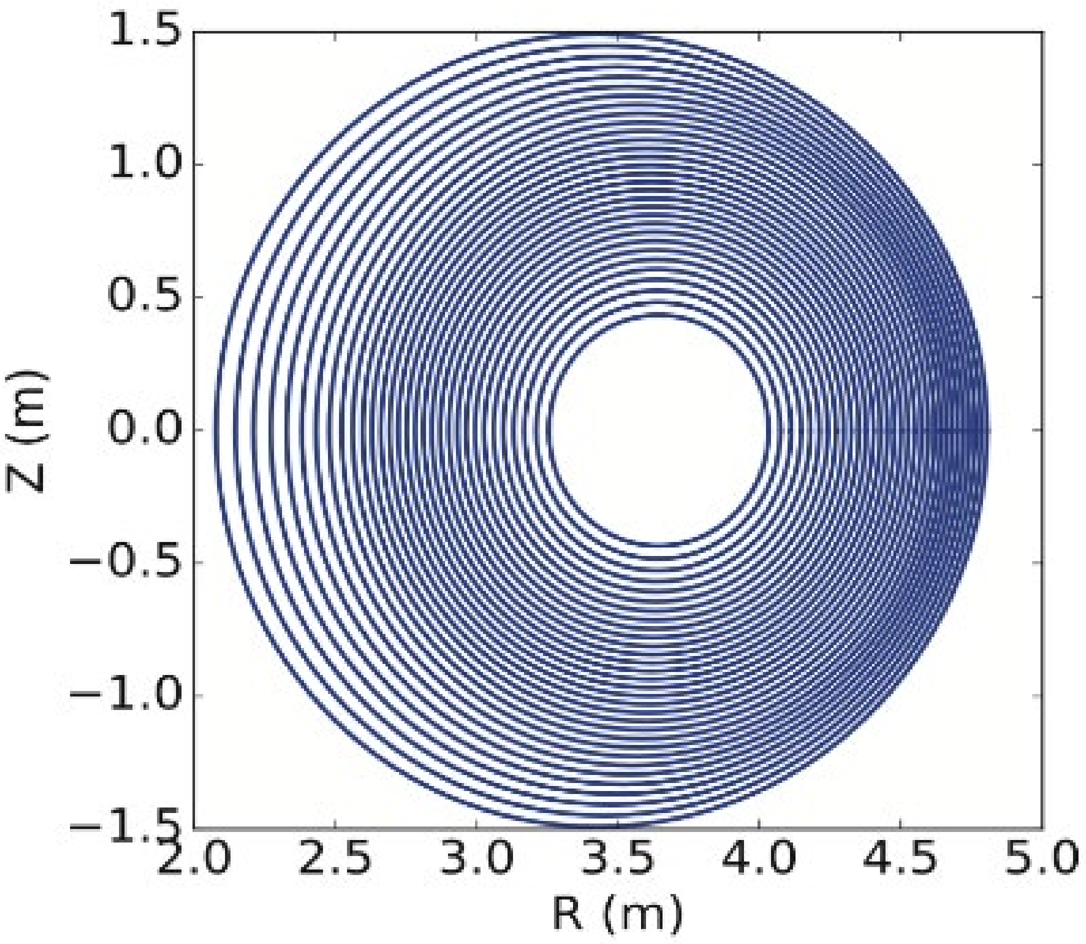
Gyro-Landau-Fluid (GLF) 3+1 model

- **BOUT++ 3D GLF 3+1 electromagnetic model evolves**
  - ✓ **density n_i**
  - ✓ **parallel ion pressure $p_\parallel$**
  - ✓ **perpendicular ion pressure $p_\perp$**
  - ✓ **parallel velocity $v_\parallel$**
  - ✓ **electron temperature T_e**
  - ✓ **vorticity ϖ**
  - ✓ **perturbed magnetic vector potential $A_\parallel$**
- **Closures are carefully chosen to match kinetic effects**
  - ✓ **Gyro-averaged and Padé approximations**
  - ✓ **Landau damping**
  - ✓ **Ion toroidal drift resonance**

For J_{BS} scan, Pressure is fixed







(1) Shifted circular geometry

(2) Keeping total current I_{total} fixed, and the shape of J_0 and J_{BS} fixed

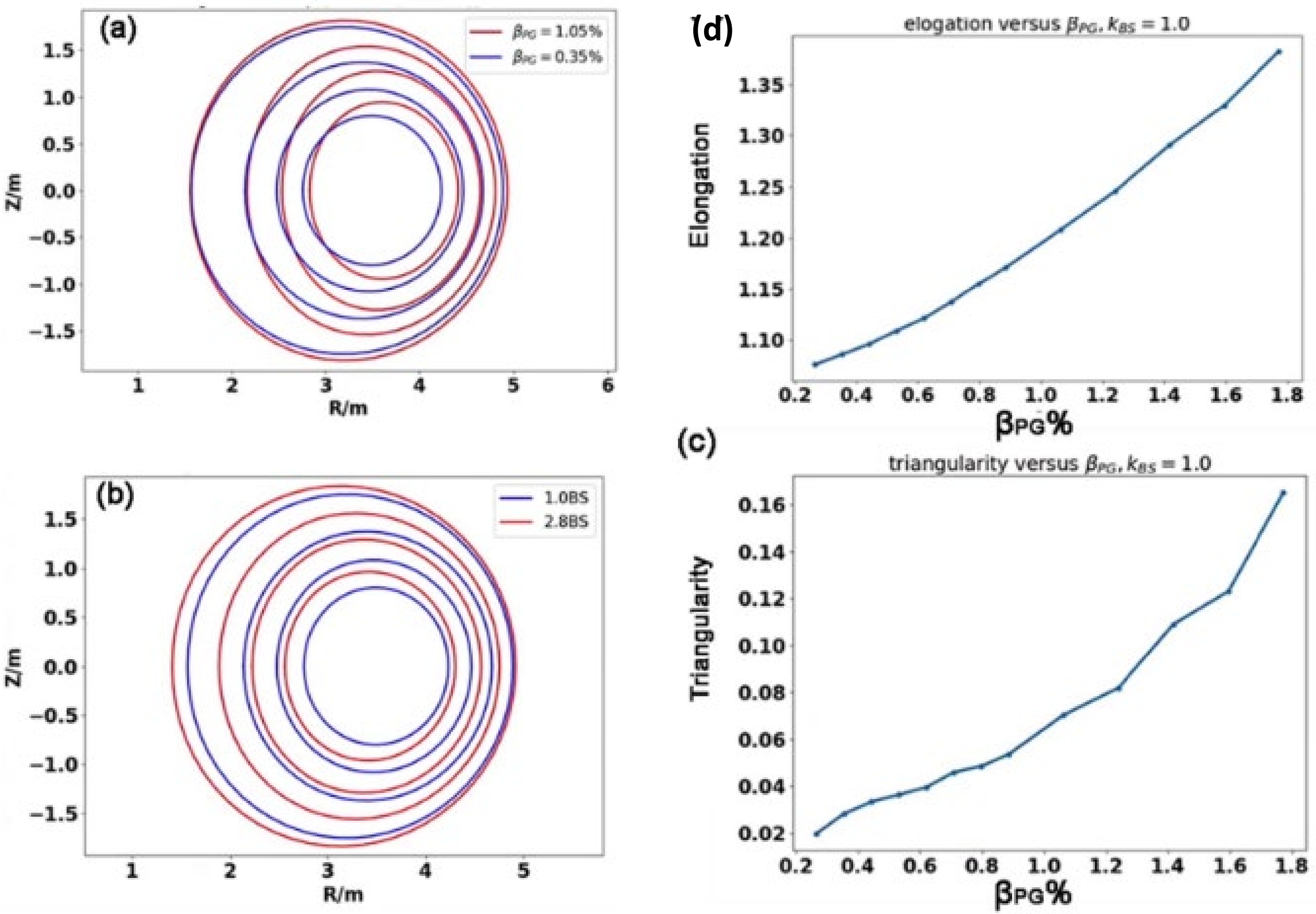
$$J_{total} = k_0 J_0 + k_{BS} J_{BS}$$

For a given k_0, k_{BS} can be changed correspondingly

J_{BS} is calculated from Sauter bootstrap current model.

O. Sauter 1999 Phys. Plasmas

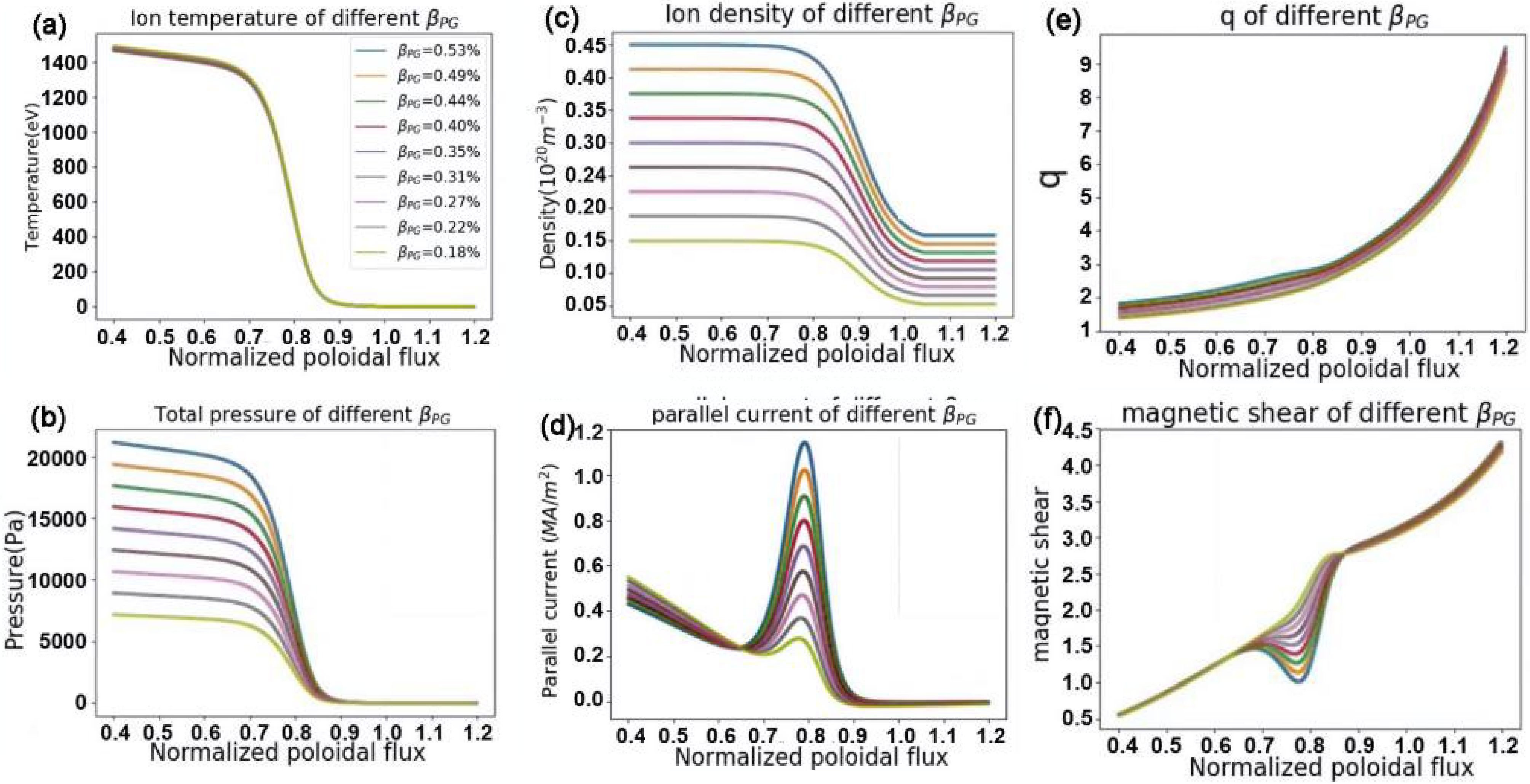
Shift circular geometry with self consistent shape effect



The magnetic surface at the poloidal cross section, (a) for different $\boldsymbol{\beta_{PG}}$ ($\boldsymbol{\beta_{PG} = \frac{P_{0,PG}}{B_0^2/2\mu_0}}$) = 0.35% and 1.05% when $\boldsymbol{k_{BS}}$ = 1.0; (b) for different $\boldsymbol{k_{BS}}$ = 1.0 and 2.8 when $\boldsymbol{\beta_{PG}}$ = 0.35 %

The elongation parameter κ versus normalized poloidal flux with $\boldsymbol{\beta_{PG}}$ = 1.06%, (b) the κ versus $\boldsymbol{\beta_{PG}}$, (c) the triangularity parameter δ versus $\boldsymbol{\beta_{PG}}$, all the $\boldsymbol{k_{BS}}$ = 1.0. The κ and δ are chosen at the pedestal top.

For β scan, T_e and T_i and k_{BS} are fixed and density varied



Outline

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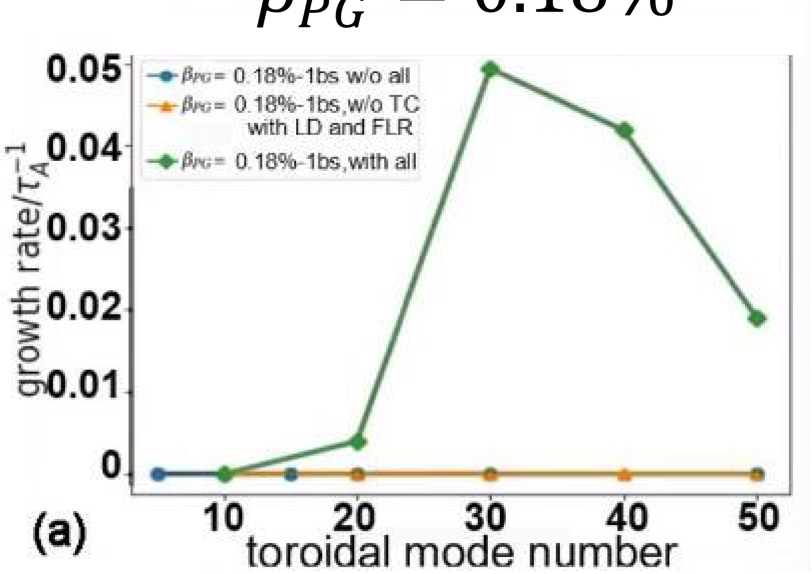
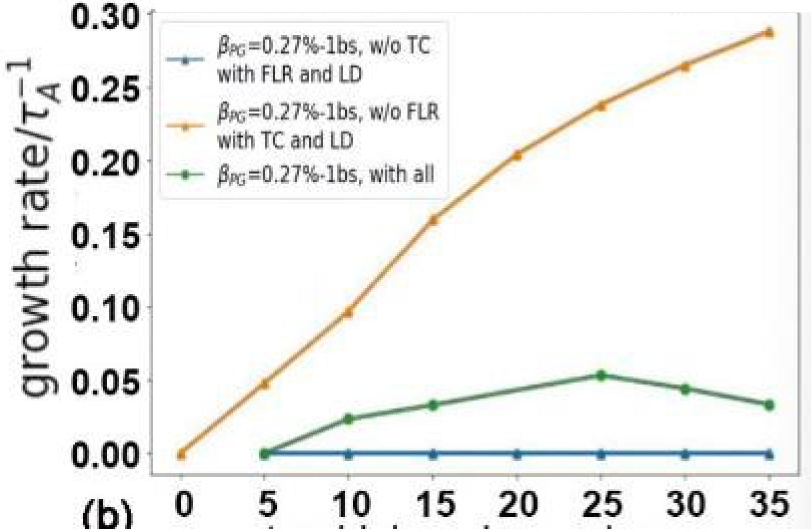
- **Linear analysis of KPBM**

Linear results of pressure scanning. Ion toroidal drift resonance drives the KPBM.

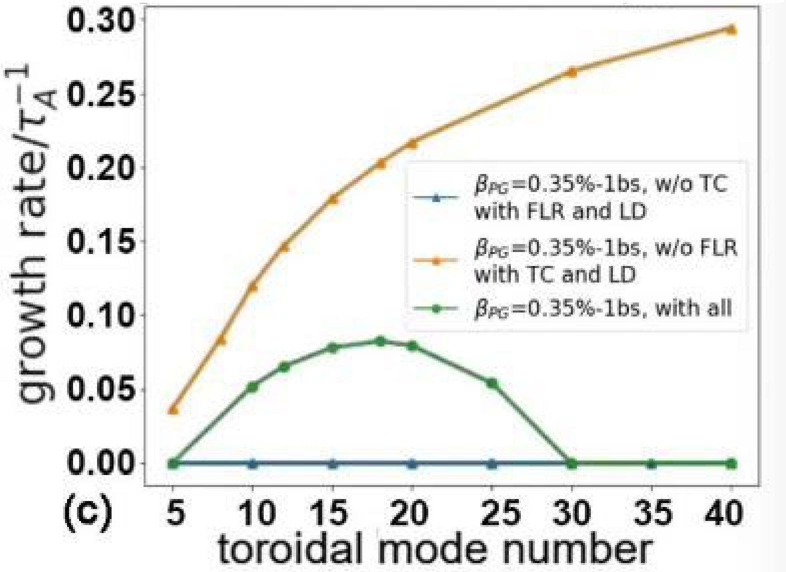
$\beta_{PG} = 0.18\%$



$\beta_{PG} = 0.27\%$

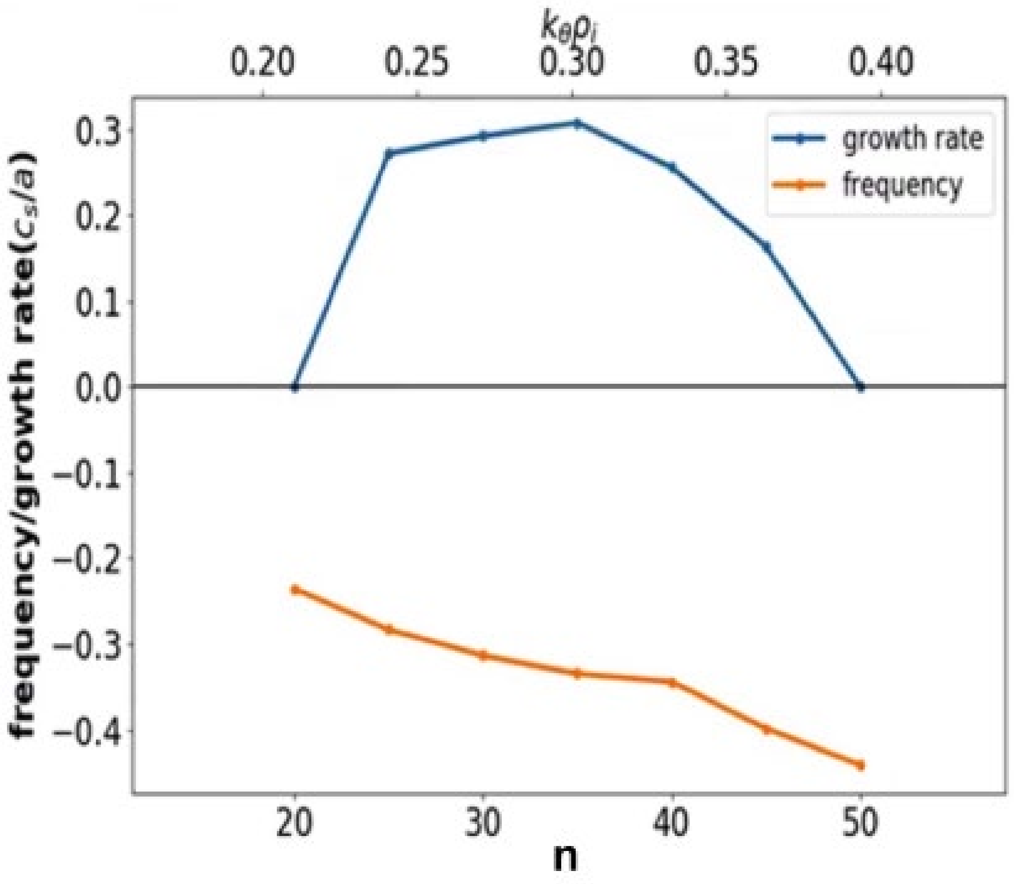


$\beta_{PG} = 0.35\%$



- **The ion toroidal drift resonance drives the KPBM under the ideal peeling-ballooning threshold.**
- **Linear growth rate increases with β_{PG} .**
- **The shift of the mode spectrum to small N (toroidal mode number) can be observed because the bootstrap current increases with pressure gradient.**

KPBM frequency and The poloidal-averaged ion drift frequency

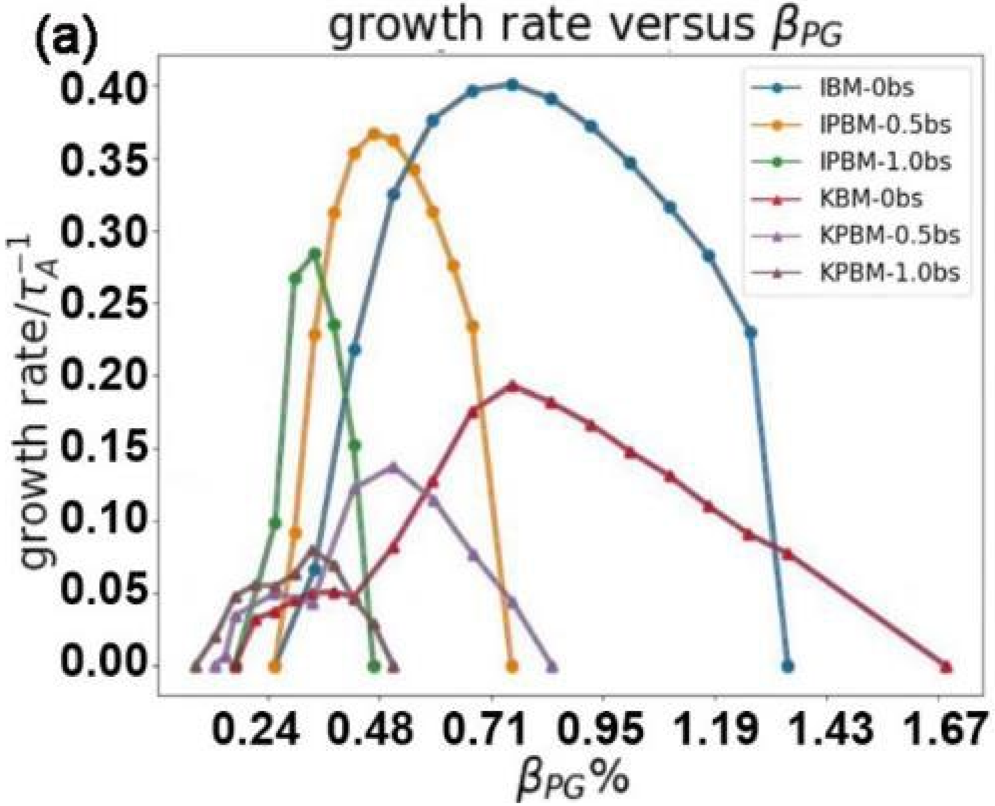


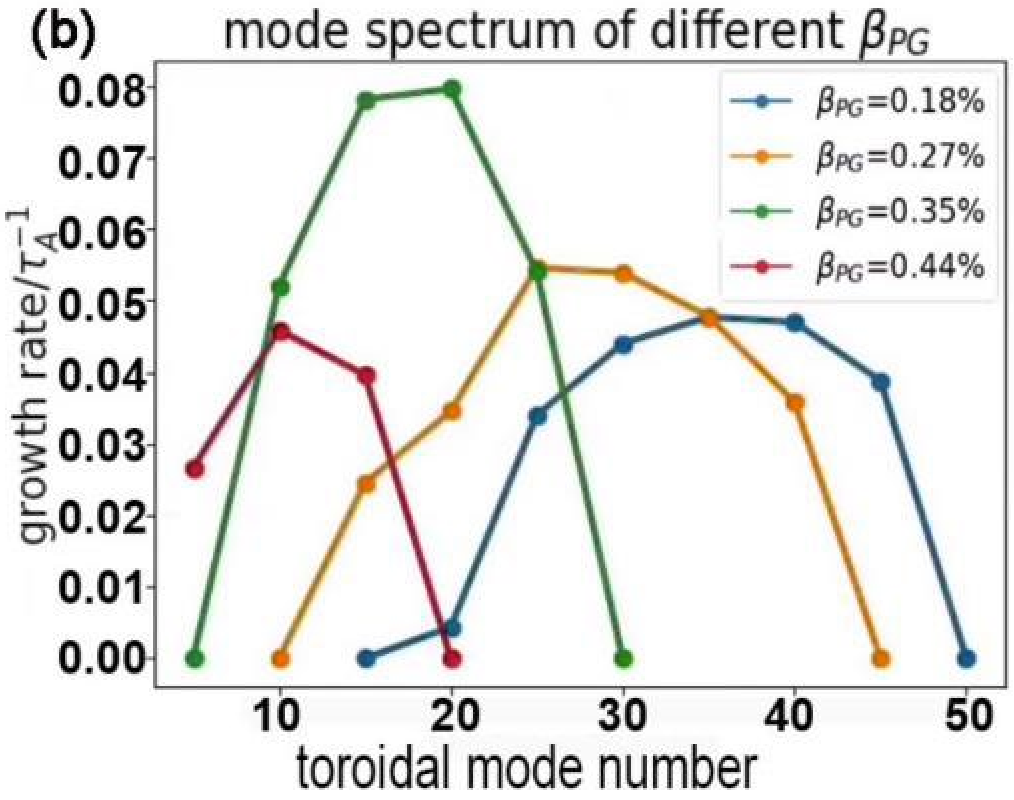
Growth rate and frequency normalized in c_s /*a* for β_{PG} = 0.22%. $c_s = \sqrt{T_i/m_i}$is the ion sound speed.

The mode frequencies (yellow curve) decrease with mode number and are negative which means the modes are on the ion diamagnetic direction.

The poloidal-averaged ion drift frequency *< ω_d >=0.15* c_s */a* , $\omega_{\mathrm{KPBM}} \sim$ 0.2 - 0.4 c_s */a* , It indicates that the poloidal averaged ion toroidal drift resonance is a drive of KPBM.

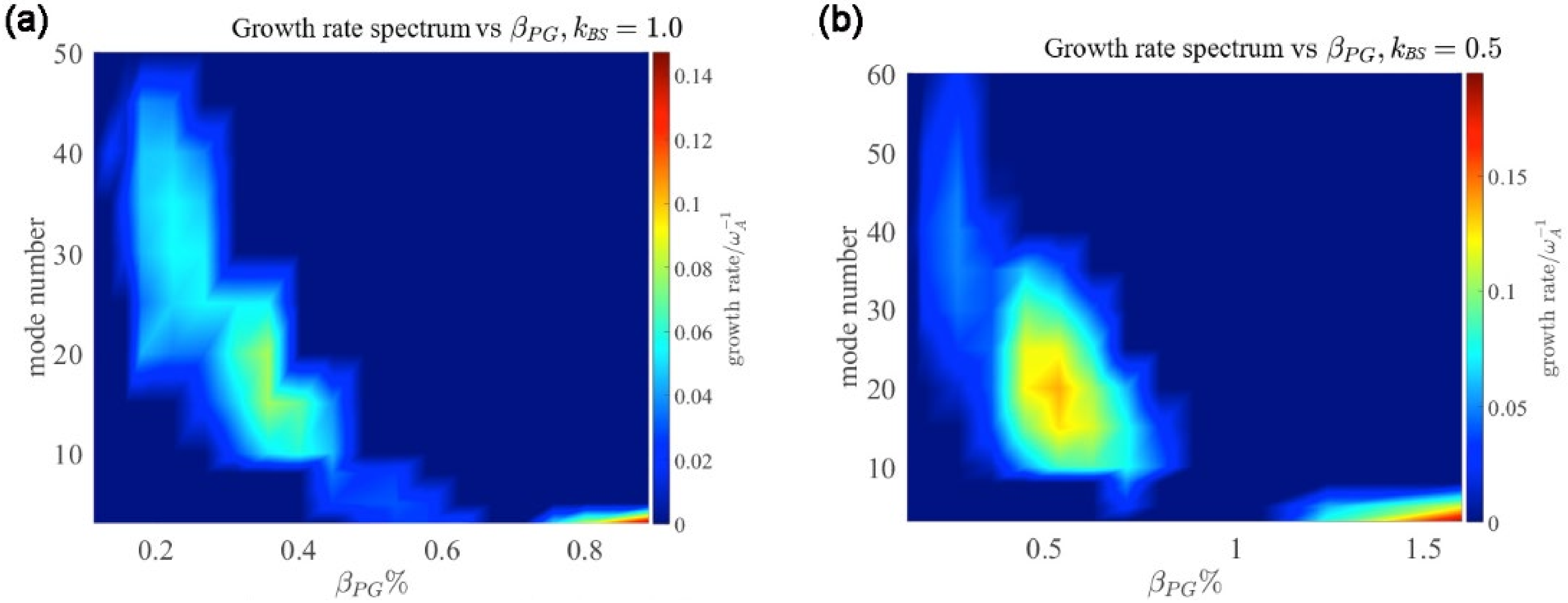
Bootstrap current has stabilizing effect on KPBM
The 2nd stable region is observed





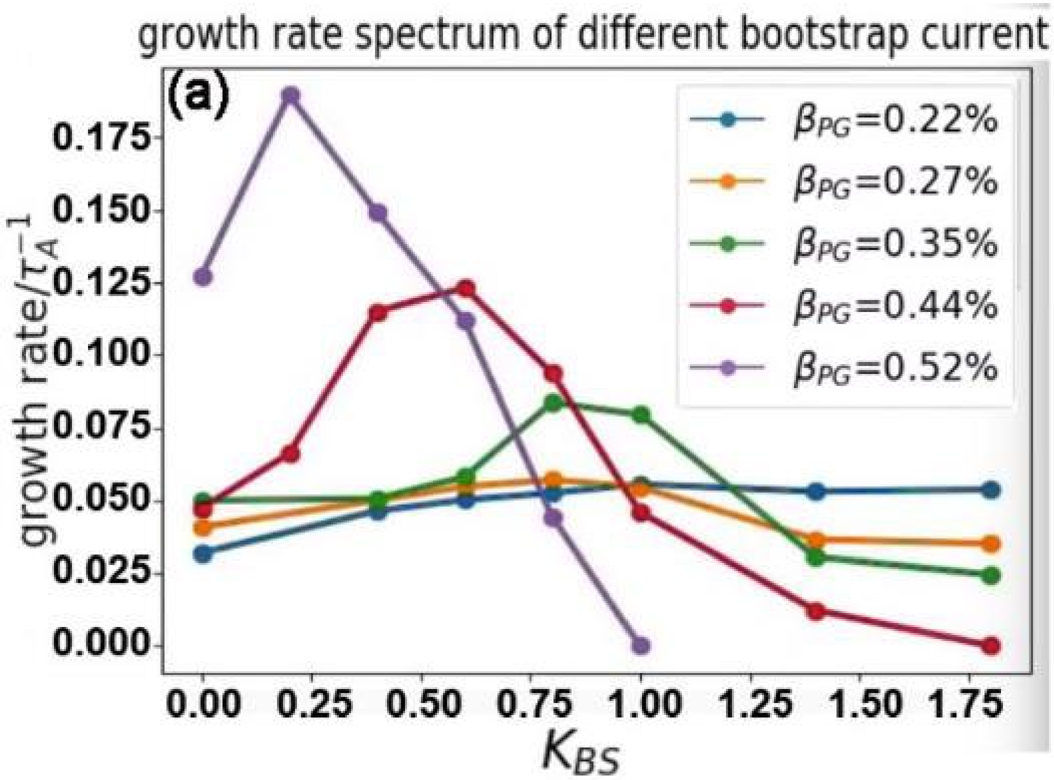
- **The bootstrap current has stabilizing effect on KPBM.**
    - **The unstable region and the maximum growth rate of KPBM decreases when the bootstrap current increases.**
- **The 2nd stable region of KPBM is observed.**
    - **The kinetic effects drives the KPBM unstable beyond the 1st and 2nd threshold of ideal ballooning mode (IPBM).**
- **The major mode number decrease because the bootstrap current increases with pressure gradient.**

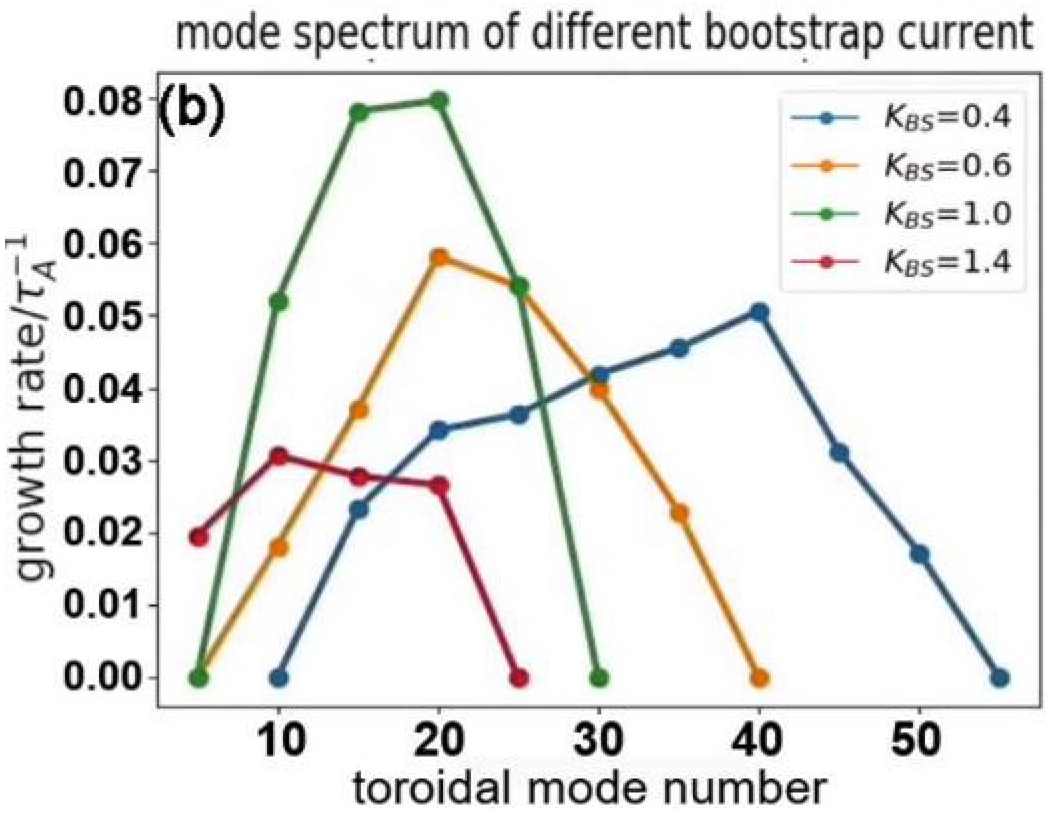
High bootstrap current drives the low-n kink modes only in relative high β_{PG}, eliminating the 2nd stable region



- The large bootstrap current drives the kink mode which prevents the 2nd stable region extending to the large beta direction.
- When the fraction of bootstrap current k_{BS} is large enough the 2nd stable region may disappear.

The major mode number of KPBM decreases when the Bootstrap current increases


growth rate spectrum of different bootstrap current


mode spectrum of different bootstrap current

- **Large bootstrap current has stabilizing effect on KPBM.**
- **The range of unstable toroidal mode number of KPBM decreases when the bootstrap current increases.**

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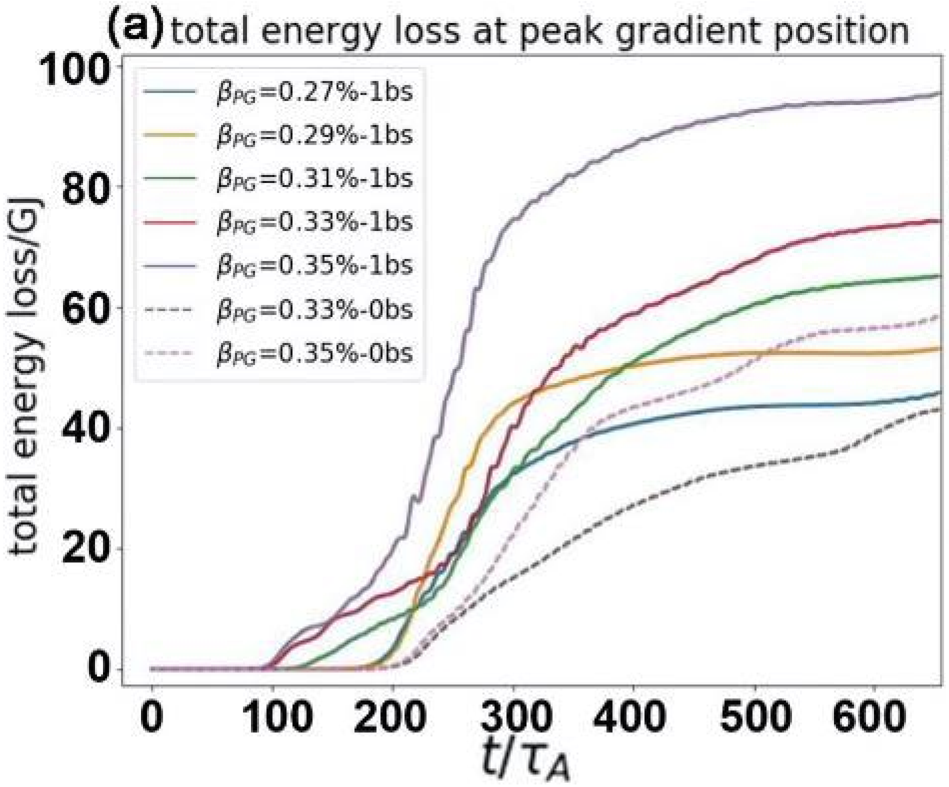
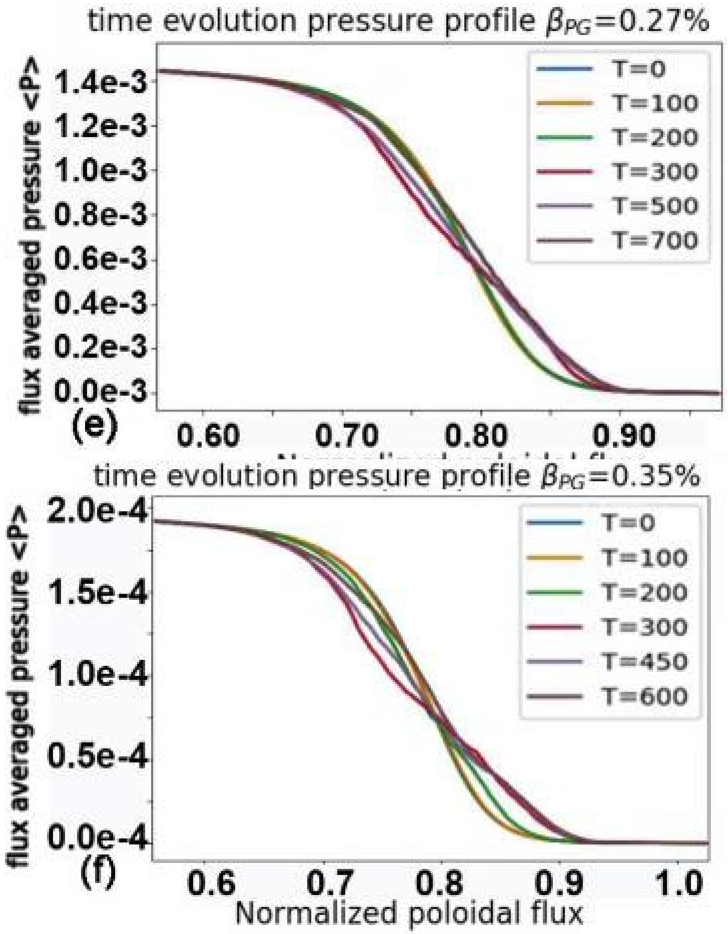
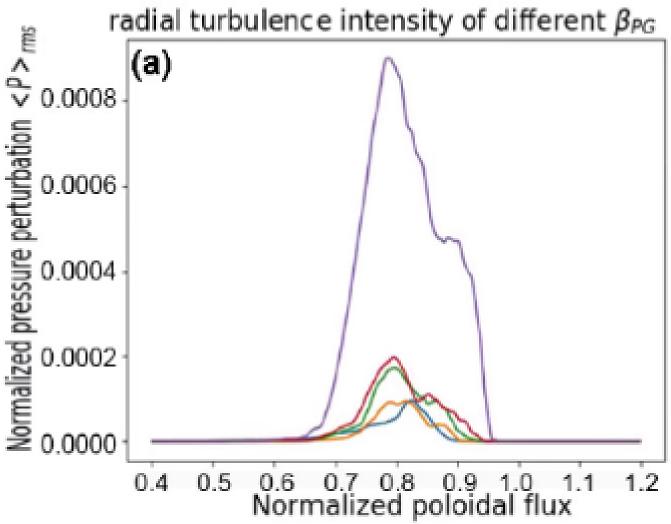
Energy loss increases with the bootstrap current and pressure gradient

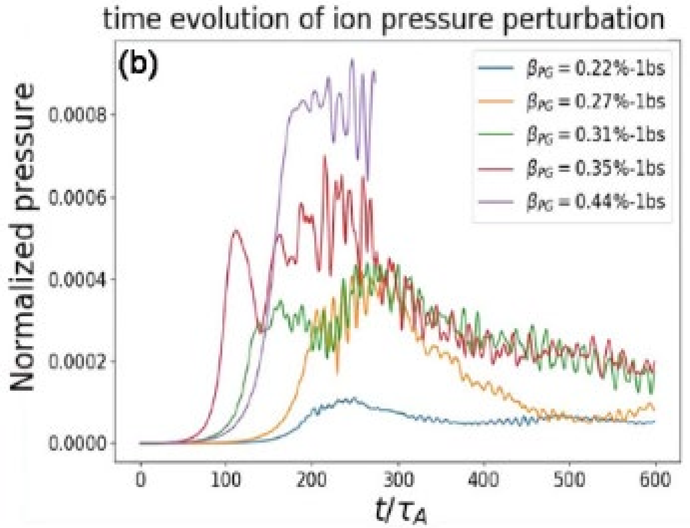


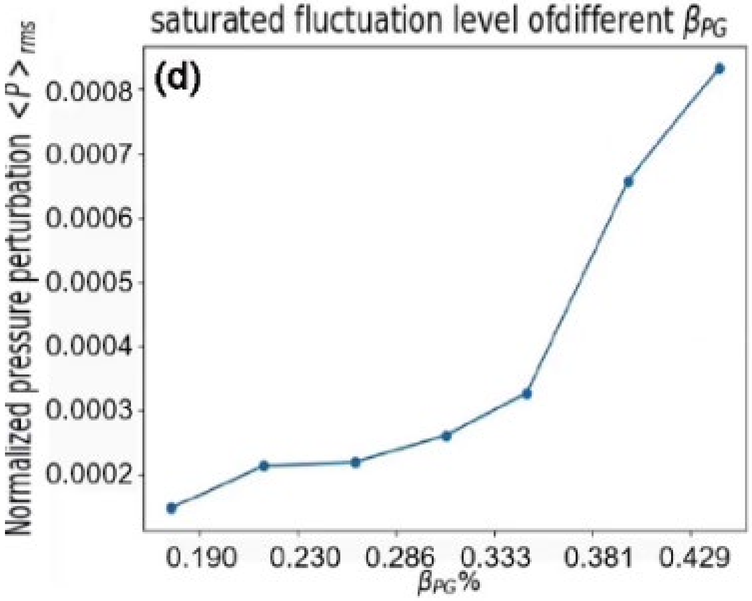


- **Energy loss increases with the pressure gradient and bootstrap current.**
- **When plasma beta is close to the 2nd stable region, the collapse of the pedestal makes the plasma into a more unstable state & more energy loss as plasma beta decreases.**

The fluctuation level and the propagate speed increase with the pressure



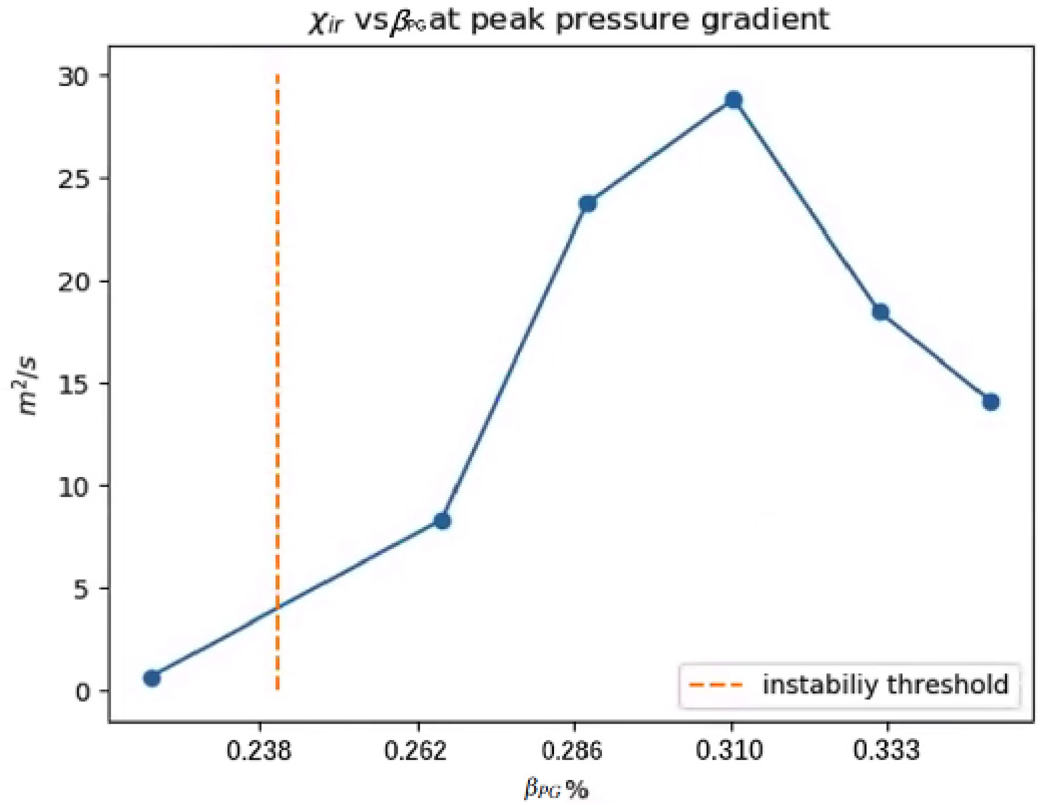




The fluctuation level in the qusi-steady state after the initial crash phase increases with pressure.

The turbulence intensity and propagate speed increases with the pressure increasing.

The ion heat transport coefficient first increases and then decreases with β_{PG}

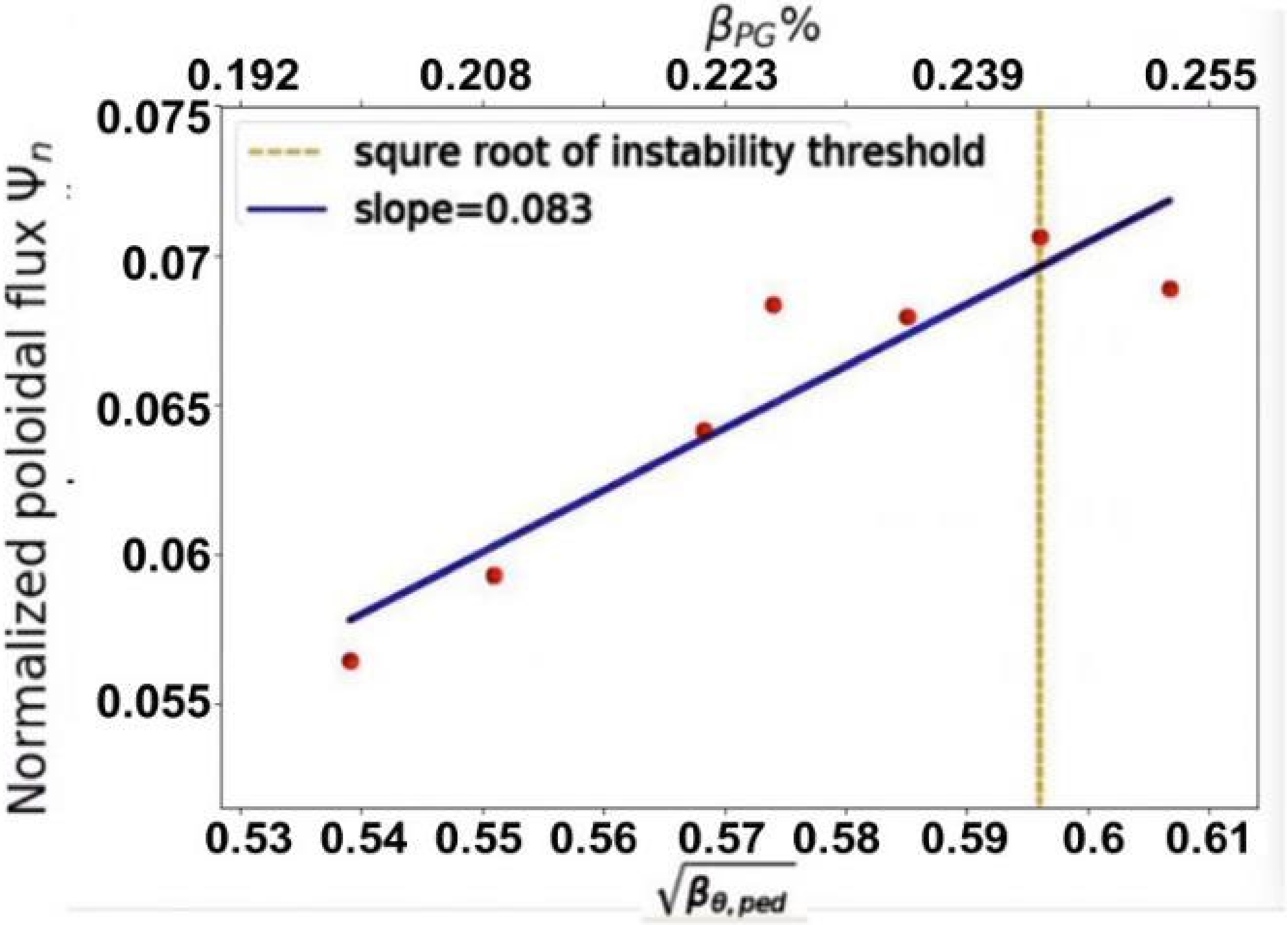


The radial ion heat transport coefficient first increases and then decreases with pressure. And the β_{PG} of the peak linear growth rate is different from the β_{PG} of the peak ion heat transport coefficient.

$$Q_{ir} = < n_i T_i V_{ir} > = < n_i T_i \frac{(b_0 \times \nabla\phi)_r}{B_0} > + < n_i T_i V_{\parallel i} b_{1r} >$$

$$\chi_{ir} = \frac{Q_{ir}}{<\frac{\partial}{\partial r}(n_i T_i)>}$$

The pedestal width scaling of EPED 1.6 model is reproduced in the nonlinear KPBM simulation



- **The pedestal width scaling with pedestal height from EPED model is reproduced $\Delta_{ped} = c\beta_{\theta,ped}^{1/2}$.**
- **The coefficient c is 0.083 which is inside the interval of typical tokamak [0.07,0.1].**
- **The pedestal profiles are averaged from 400-500 τ_A, then fitted by modified hyperbolic tangent to get the width.**

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Summary

(1)The bootstrap current has stabilizing effect on the KPBM.

(2)The 2nd stable region of KPBM is observed. But the current drive kink mode prevents the 2nd stable region extends to large beta direction and may even disappear when bootstrap current is large enough.

(3)Ion toroidal drift resonance drives the KPBM beyond the 1st and 2nd threshold.

(4)The turbulent intensity and energy loss increase with β_{PG}. And a large k_{BS} also leads to a large energy loss, which has a different trend with the linear growth rate with different bootstrap current.

(5)The ion heat transport coefficient first increases and then decreases with β_{PG}. And the β_{PG} of the peak linear growth rate is different from the β_{PG} of the peak ion heat transport coefficient.

(6)The scaling law of the pedestal width and height in the global GLF3-1 nonlinear simulation fits well with the EPED model.