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A nonlinear simulation study of the effect of toroidal rotation on RMP control of ELMs

by

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Introduction

- Edge Localized Modes (ELMs), a common feature of H-mode tokamak plasmas, can cause severe damage to PFCs
- A resonant magnetic perturbation (RMP) introduced from the edge of the plasma has so far proved the most successful method of controlling ELMs
- The dynamics of ELMs is quite complex. Introduction of an RMP complicates it further. So numerical simulations are a convenient way to study them
- In an actual operational scenario additional physical factors such as plasma rotation can introduce significant modification in the characteristics of ELMs
- Past studies do not yet provide definitive conclusions or a complete understanding of the influence of equilibrium flows on the stability of ELMs.
- So it is important to investigate what happens to the efficacy of RMP to control ELMs in the presence of plasma rotation

Introduction-2

- **Numerical simulation of multiple ELMs cycle with flow -using CUTIE -2-fluid, initial value, nonlinear, global electromagnetic code - periodic cylindrical model with additional curvature terms - mesoscale physics**

- **X-point geometry model: particle and energy sink in the edge SOL region r/a > 0.95 i.e. very low fixed density temperature and current – compensated by particle source in confinement region r/a < 0.95**

- **Profile-turbulence CROSS TALK via equations of motion: profile gradients linearly/nonlinearly drive the turbulence – the latter tends to reduce the driving gradients via enhanced transport with fixed external sources- Such interactions may play a SIGNIFICANT KEY ROLE to modify ELMs dynamics**

- **Reference Case: Earlier Results with static RMP field-No Flow**

(D. Chandra et al, NF 57 (2017) 076001)

- **COMPASS-D Shot 26363:ELMy H :**

RMP Field:

- **R=0.56m, a= 0.17m,**
- **B_T = 2.07 T, I_p =242 kA,**
- **P_{ECH} = 0.5 MW**

$$\psi_{\mathrm{RMP}}(a,\theta,\zeta) = \left(\frac{K a B_{\mathrm{pol}}}{B_0}\right) \sum_{m\neq 0} \left[\frac{1}{m^2+1}\right] \cos(m\theta + 2\zeta)$$

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CUTIE model equations

(A. Thyagaraja, PoP 17 (2010) 042507)

Continuity Eqn: $$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = S_p,$$

Ion Momentum Eqn: $$m_i n \frac{d\mathbf{v}}{dt} = -\nabla p + \frac{\mathbf{j} \times \mathbf{B}}{c} + \mathbf{F}_{\rm eff},$$

Energy Eqns for electrons and ions: $$\frac{3}{2}\frac{dp_{e,i}}{dt} + p_{e,i}\nabla \cdot \mathbf{v}_{e,i} = -\nabla \cdot \mathbf{q}_{e,i} + P_{e,i},$$

Electron momentum Eqn (Ohm's Law): $$\mathbf{E} + \frac{\mathbf{v}_e \times \mathbf{B}}{c} = -\frac{\nabla p_e}{en} + \mathbf{R}_e,$$

Ampere's Law: $$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c}.$$

Poloidal field evolution: $$\frac{\partial \langle B_\theta \rangle}{\partial t} = c\frac{\partial \langle E_\zeta \rangle}{\partial r}$$

Where,

$$\langle E_\zeta \rangle = \eta_{\rm nc}(\langle j_\zeta \rangle - j_{\rm bs} - j_{\rm dyn})$$

$$j_{\rm dyn} = \langle \hat{\mathbf{e}}_\zeta \cdot (\times \ \delta\mathbf{B}) \rangle / c\,\eta_{\rm nc}$$

$$j_\zeta \equiv j_{\rm tor} = (c/4\pi)(1/r)(\partial/\partial r)(rB_\theta)$$

Poloidal flow acceleration due to turbulence:

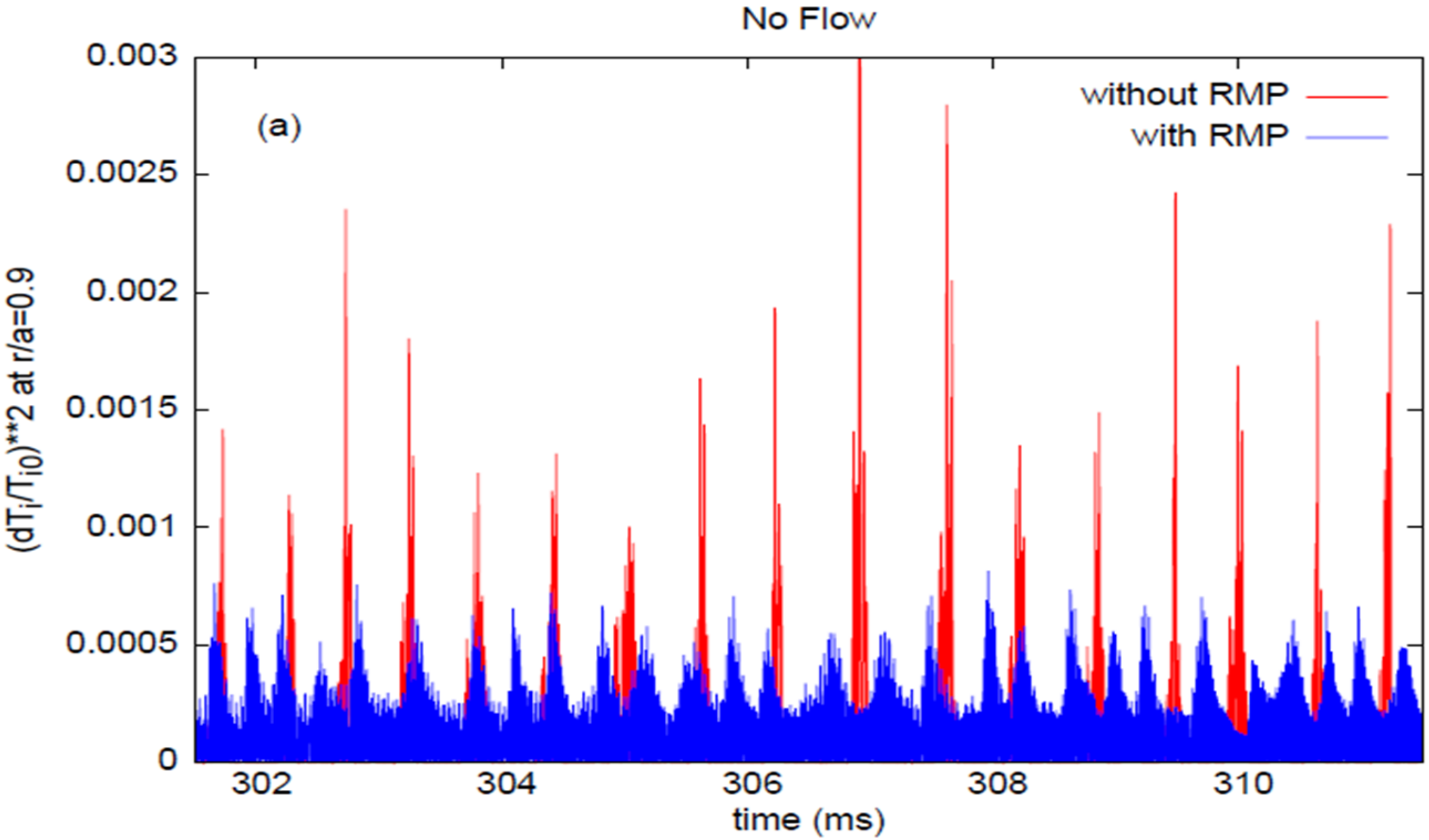
$$\frac{\partial \langle u_\theta \rangle}{\partial t} = -\nu_{\rm nc}[\langle u_\theta \rangle - u_{\rm nc}] + \langle L_\theta \rangle$$

Where,

$$\langle L_\theta \rangle = -\frac{1}{r}\frac{\partial}{\partial r}(r\langle \delta u_\theta \delta u_r \rangle) - \frac{2\langle \delta u_\theta \delta u_r \rangle}{r} + \hat{\mathbf{e}}_\theta \cdot \frac{\langle \delta\mathbf{j} \times \delta\mathbf{B} \rangle}{m_i n}$$

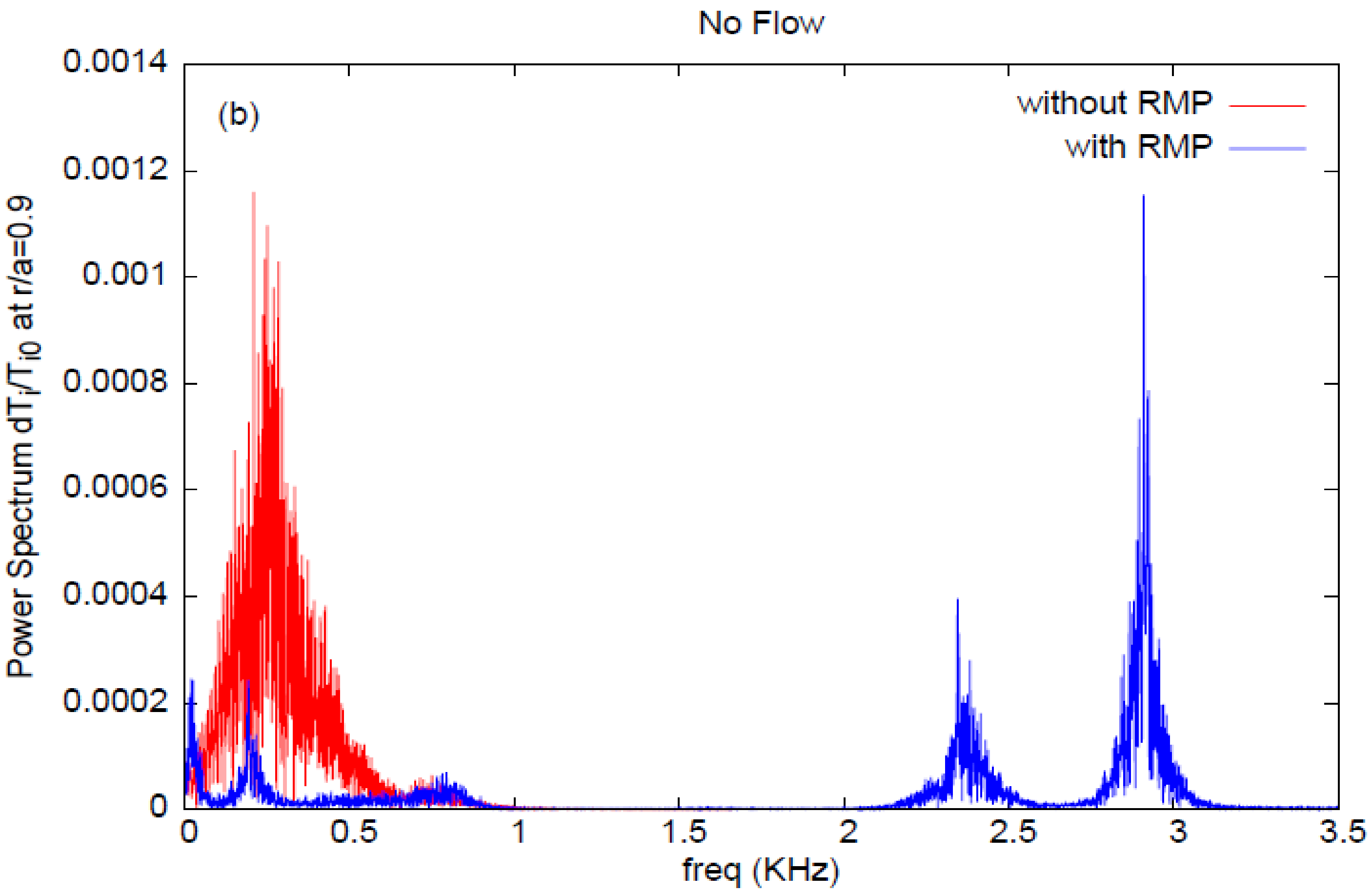
- All fields B,E,v,n,p_i, p_e are sum of flux surface average mean and fluctuation quantities
- Dynamo current is driven by correlation between fluctuations of v, B
- Local variation of turbulent fluctuations cause local evolution of zonal flows and dynamo currents

Control of ELM dynamics with RMP without flow



- Considerable reduction of ELMs amplitude with application of RMP
- As a consequence, Plasma Beta and Energy Confinement of the system improve considerably

Power spectrum of fluctuations with RMP without flow



- Significant change in fluctuation spectra with application of RMP
- Application of RMP causes shift in the spectrum towards higher frequencies

Sheared Toroidal Flows

Evolution of toroidal flow:

$$\frac{\partial v_{0z}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}[rD_{\rm ion}\frac{\partial v_{0z}}{\partial r}] + \Sigma_v$$

Momentum source:

$$\Sigma_v = K_v \exp[-(\lambda(x - x_0)^2)]$$

Where,

$K_v = \frac{\alpha P_0}{m_i n_{e0} V_{\rm th}}$ **, x0=0.7, λ =20**

Self consistent flow profile:

$$M_z(x) = \frac{v_{0z}}{v_A} = M_{0z}\exp[-(20(x - 0.69)^2)]$$

Velocity shear: $dv_{0z}/dx \propto M_{0z}(x - 0.69)$

- **Self consistent flow profile very close to initial momentum source**
- **However the peak of the profile gets shifted slightly inwards**

Influence of off-axis negative (counter current) flows without RMP

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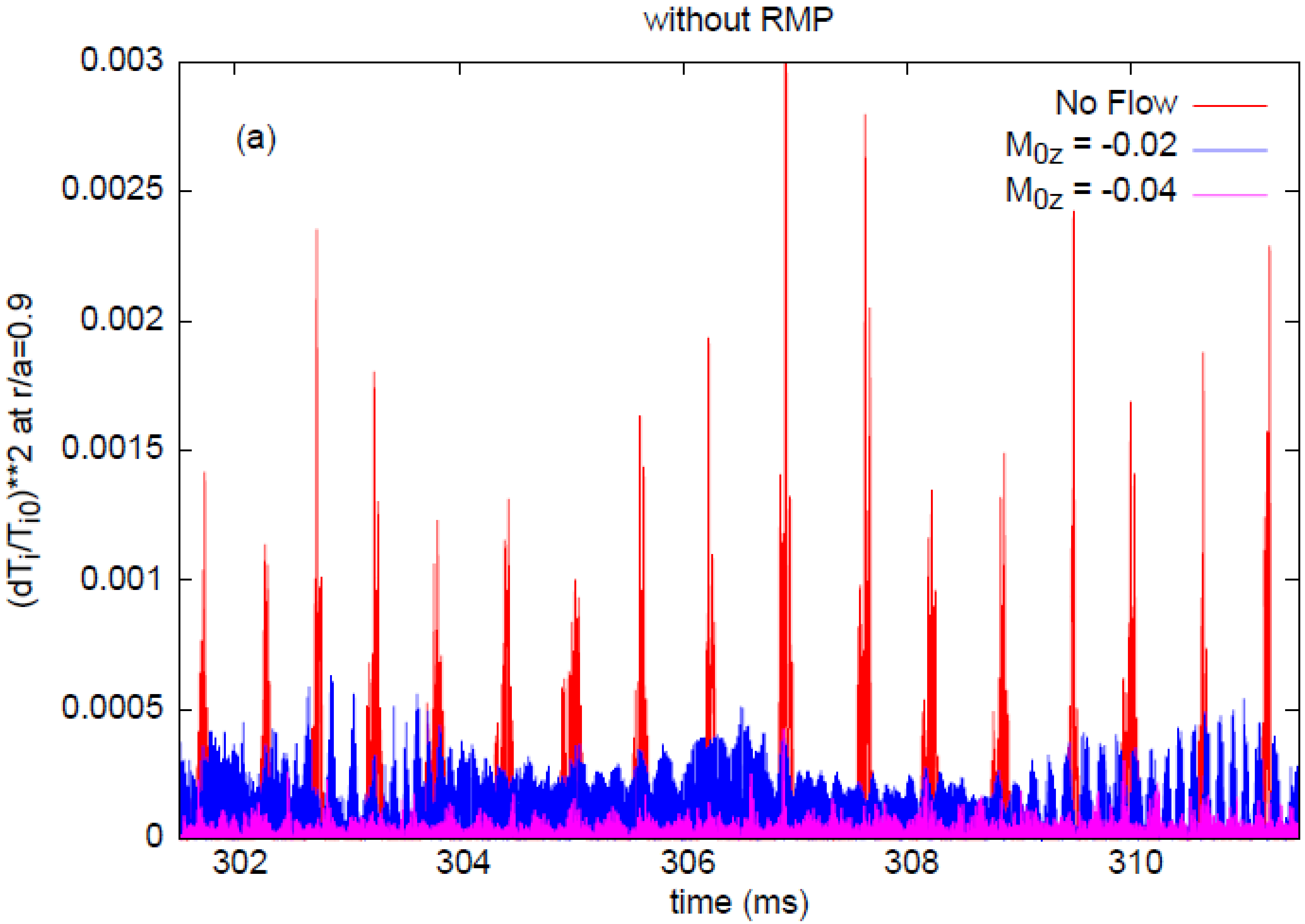
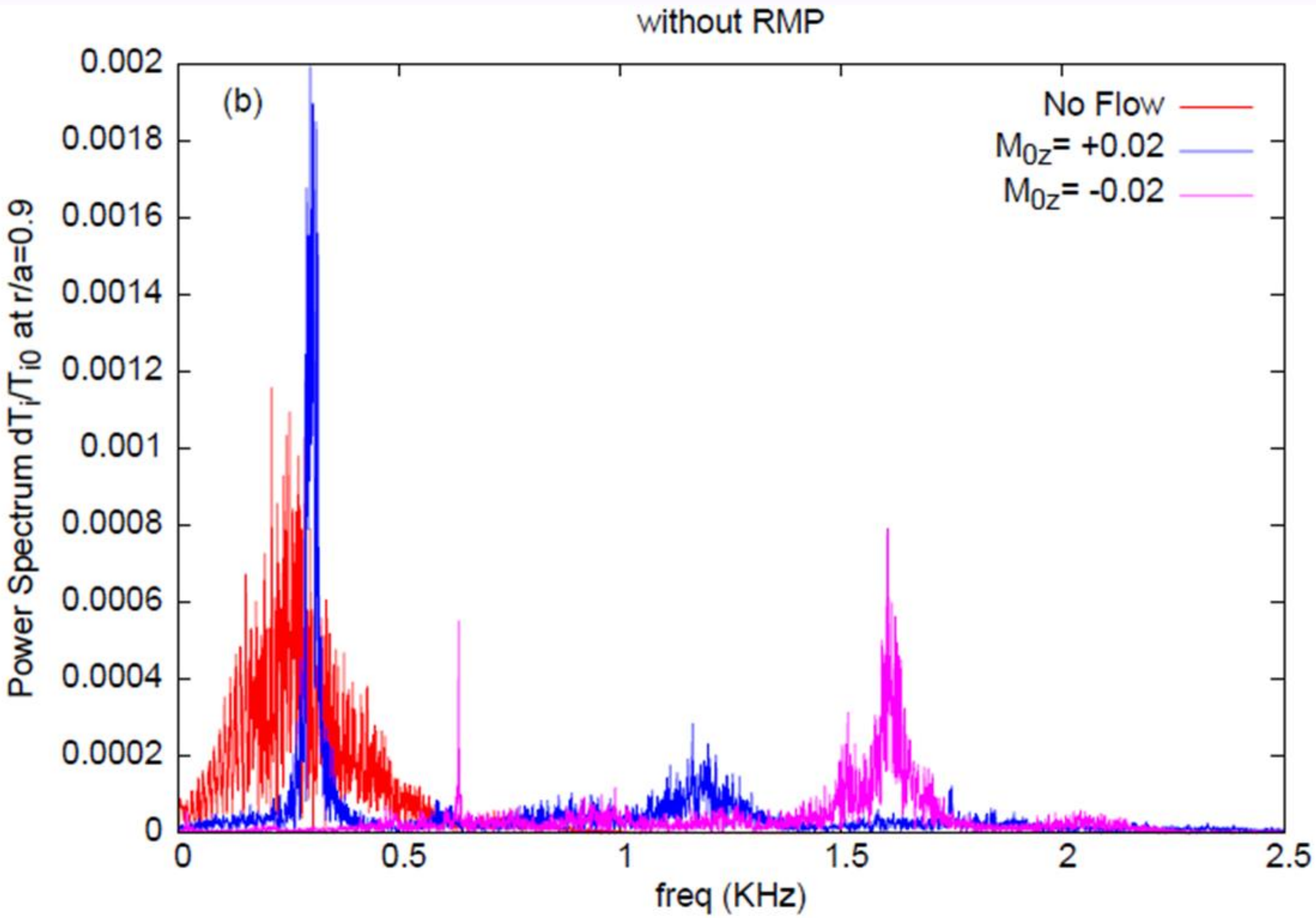


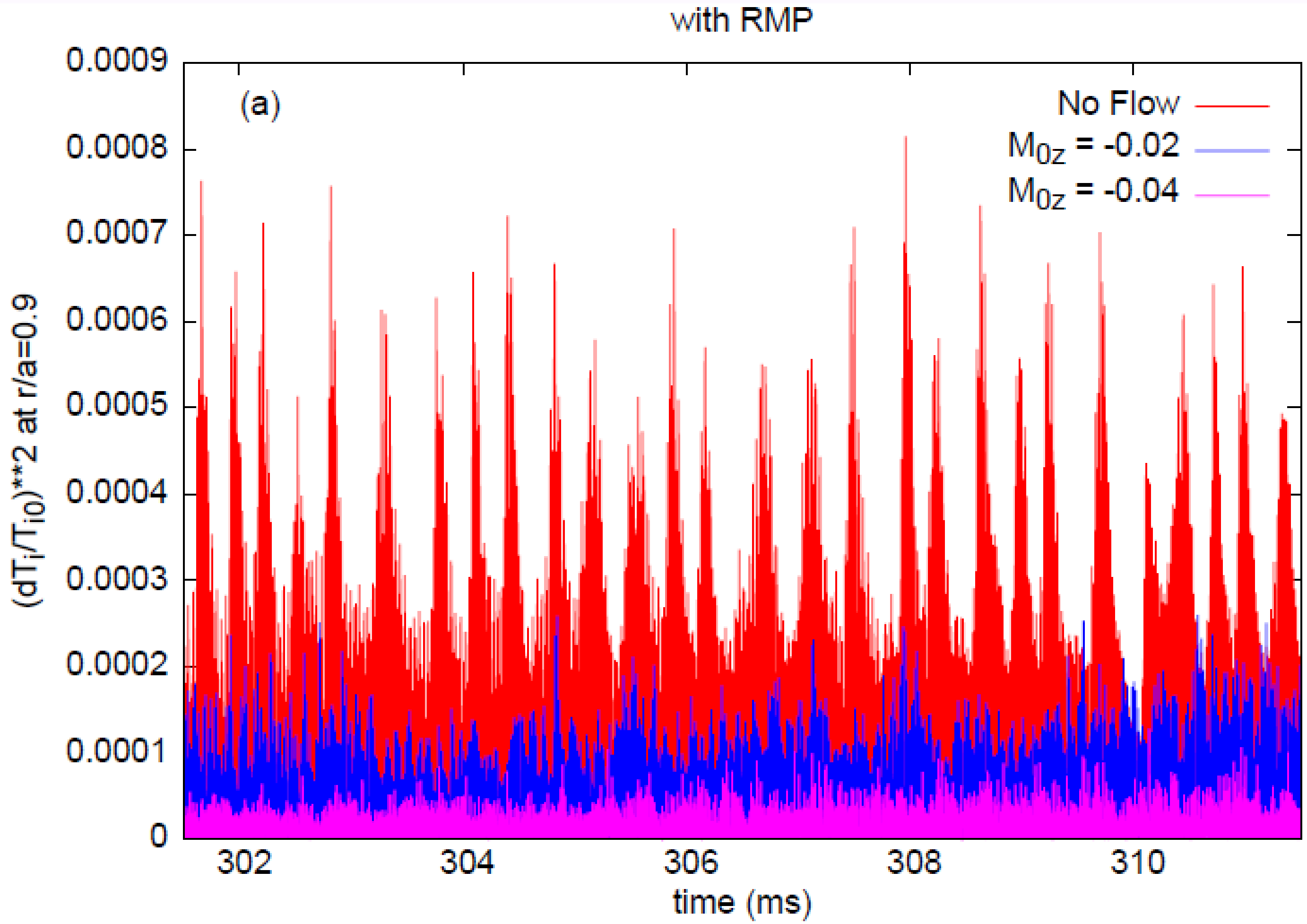
- **The stabilizing effect is seen to be most effective for off-axis negative (counter current) flows**
- **Higher the amount of flow – Smaller the amplitude of ELMs**

Comparison of power spectra pos vs neg flows without RMP



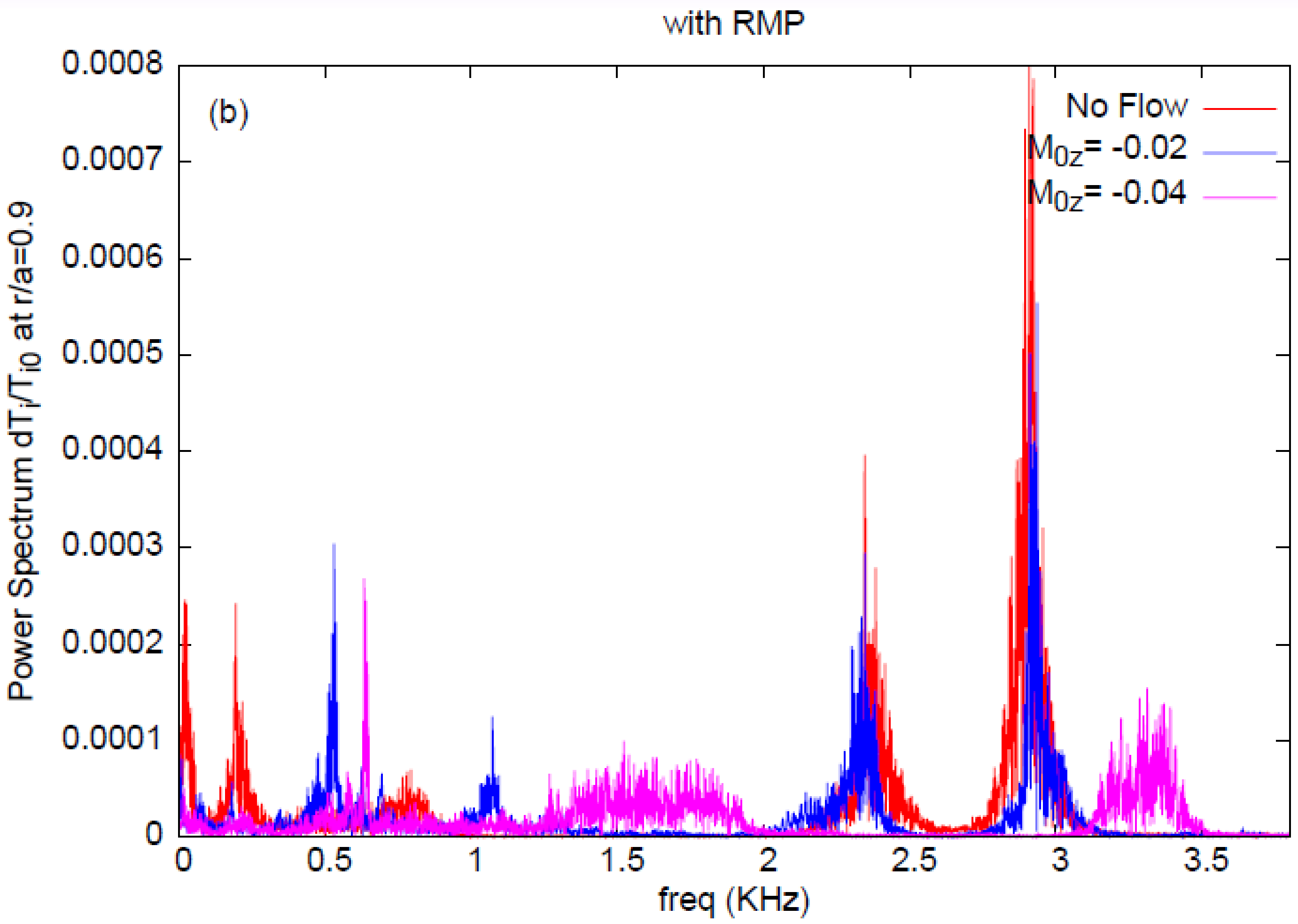
- **The off-axis negative flows spread out the power distribution most and shift the power to more higher frequency**
- **Consequently negative flows have significant influence on ELMs dynamics**

Influence of Off-axis negative flows with RMP



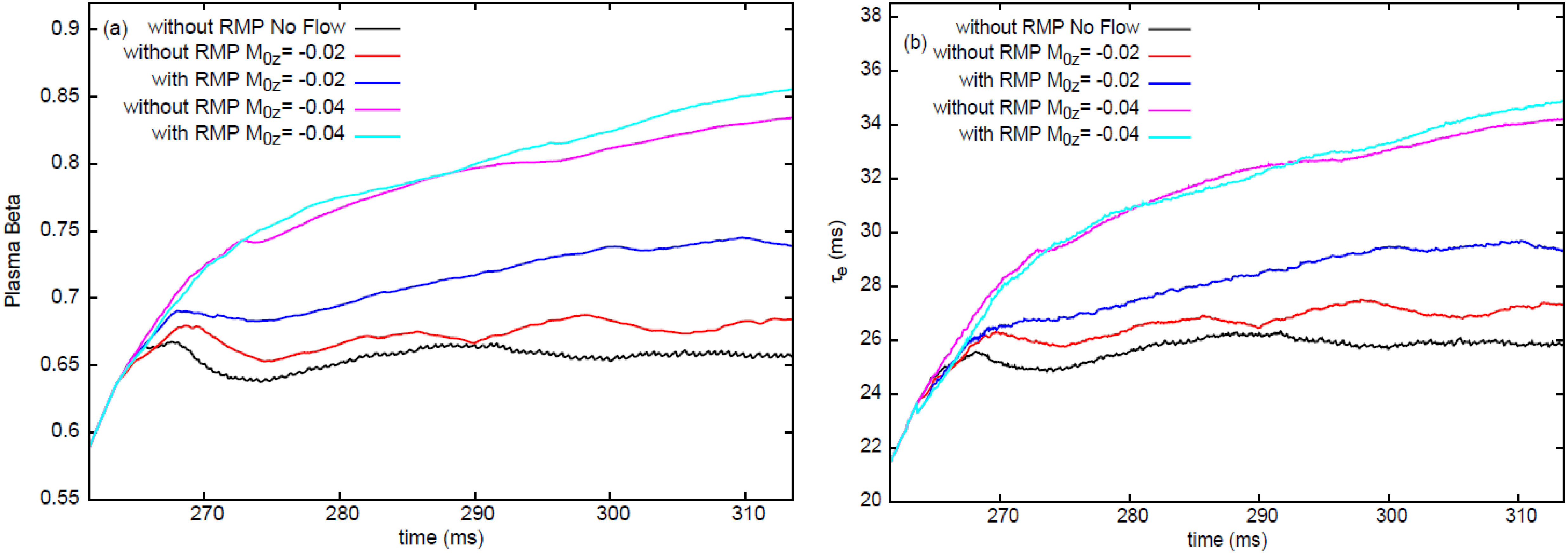
- **The combined presence of RMP and flow further reduce the ELMS amplitude**
- **Higher the amount of flow – Smaller the amplitude of ELMs (for RMP amplitude remaining constant)**

Power spectrum of fluctuations with both RMP and flow



- The combined presence of RMP and flow further spread the power distribution towards higher frequencies
- Consequently further reduction of the amplitude of ELMs

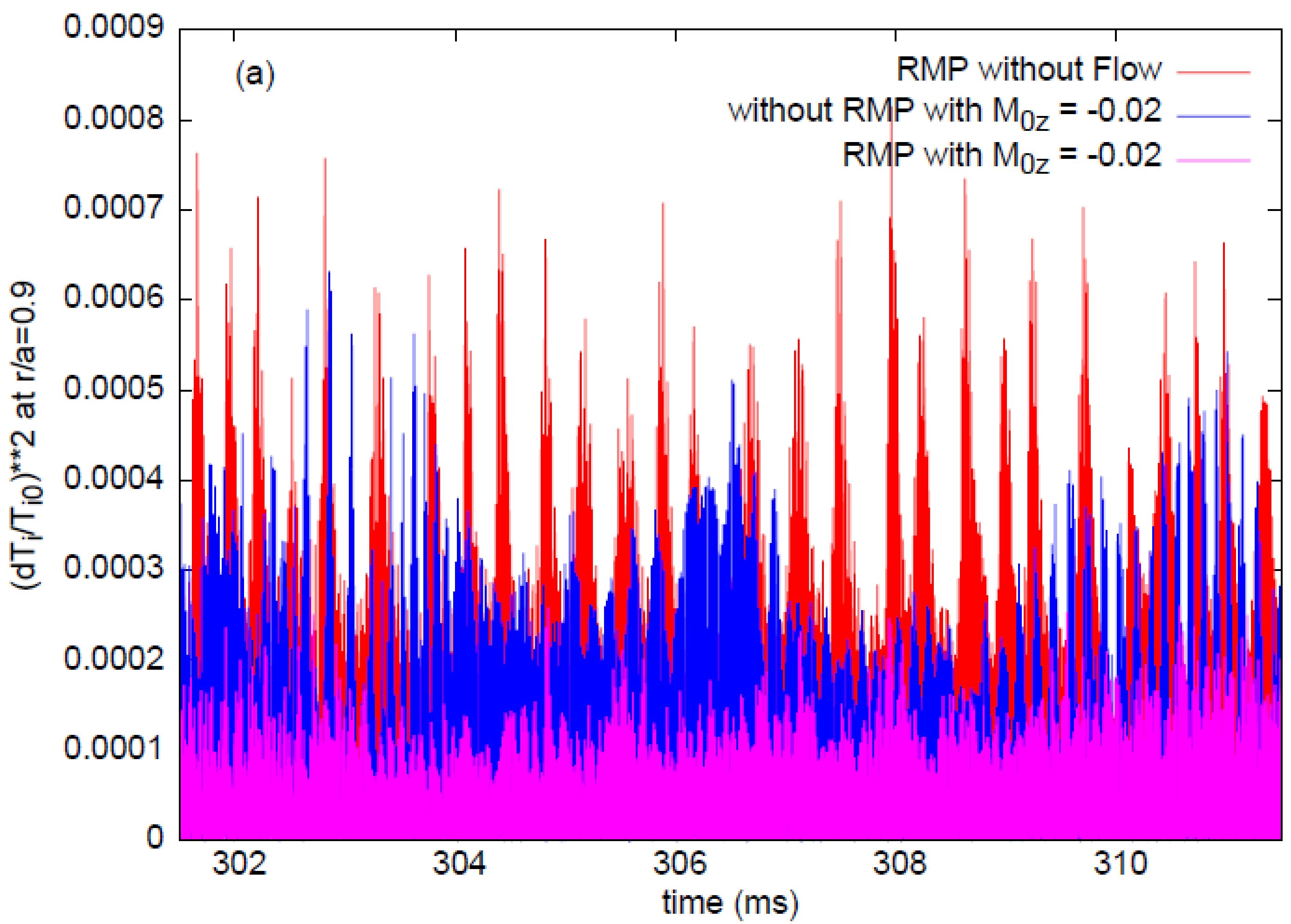
Plasma Beta and Energy Confinement with RMP and flow



- **The relative improvement of plasma beta and energy confinement in presence of RMP and flow**

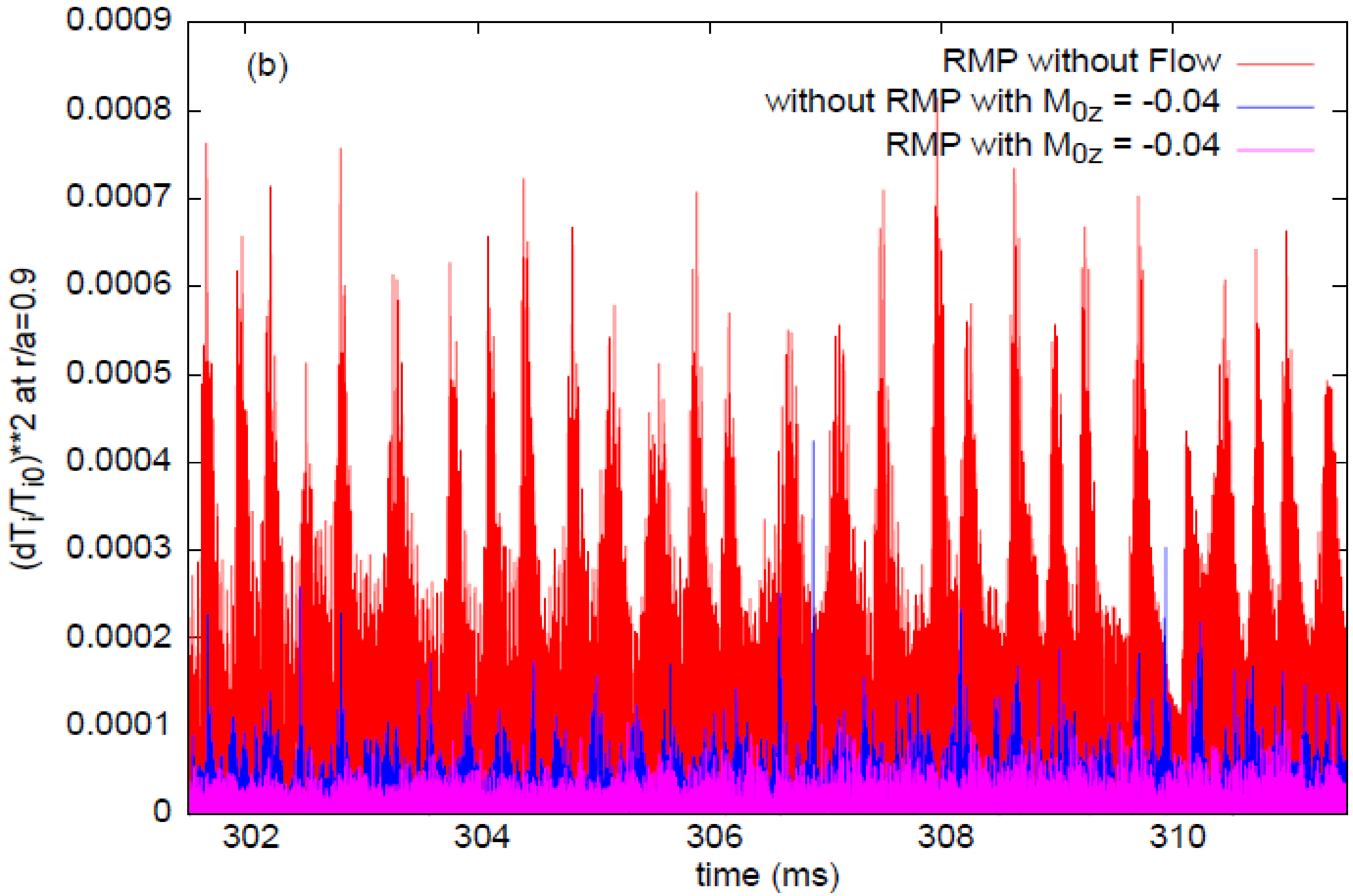
- **However the relative improvement due to synergy of RMP and flows is better for smaller flows**

Synergy of RMP and flow on ELMs



- **The mean level of ELMs fluctuation are minimum in presence of both RMP and flow in comparison to only RMP or only flow cases**
- **So this result along with the relative improvement of confinement suggest clear synergistic influence of RMP and flows on ELMs**

Synergy of RMP and flow on ELMs-2



- **The synergistic effect continues even for higher flows though the relative difference reduces now between RMP and without RMP cases**
- **This can be attributed to the flow screening of RMP**

Summary

- **The ELMs simulations have been carried out using 2-fluid CUTIE code that models ELMs by utilizing particle source in the confinement region and particle sink in the scrape-off layer.**
- **KEY FEATURE: Profile-turbulence cross-talk and self-consistent evolution of plasma gradients**
- **We have studied the multiple ELMs cycle in presence of toroidal rotation**
- **The objective is to understand the combined influence of the sheared equilibrium flows and RMPs on the characteristic of ELMs**
- **We have done comparative studies with different combination of flows for a fixed RMP amplitudes**
- **From all the combinations the relatively weak counter current sheared flows shows the most synergistic impact on the RMP induced ELM mitigation**
- **For strong flows the stabilization mainly due to flows as the RMP effect diminished by flow screening.**

Summary-2

The physical mechanisms underlying ELMs suppression by RMP and flow:

- **The RMP redistributes mode energies and direct cascades the energy to shorter scale lengths through excitation of modulational instabilities**
- **The RMP also influences the nature of ELMs through a modification of the edge profiles by pushing the ELMs regions inwards and steepening the pressure gradient at that location**
- **In a similar fashion the toroidal flow pushes the region of stronger ELMs activity inwards. As both flow and RMP push higher amplitude ELMs inwards away from the boundary so both help to reduce heat loss and improve confinement**
- **The velocity shear can also influence the stability of the peeling-ballooning modes just like MHD modes**
- **Our finding could have interesting experimental consequences for ITER where small flows may aid RMP induced ELMs control in synergistic fashion**

THANK YOU