# Overview — Impact of 3D fields (RMP) on edge turbulence and turbulent transport

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*Thanks to: all contributors and the TEXTOR team !*

# Outline

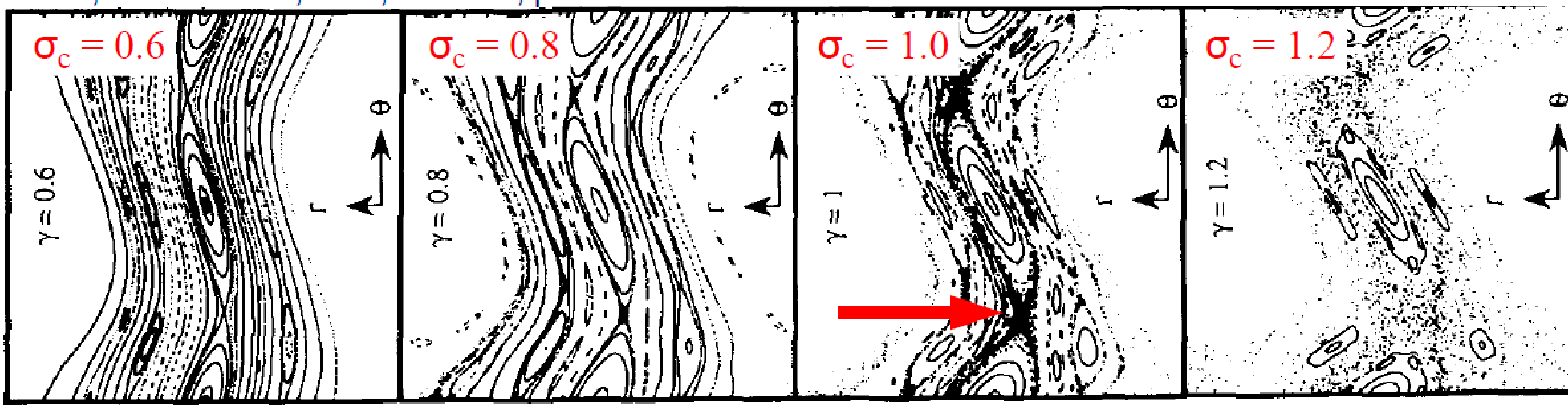
- **Introduction** (how/why RMP affects edge turbulence?)
- **Experimental setup**
- **Experimental results** (TEXTOR + other machines)
  - **Impact of RMP on edge equilibrium profiles ($T_e$, $n_e$, $\phi$, $E_r$)**
  - **Impact of RMP on edge fluctuation amplitude and transport**
  - **Impact of RMP on edge turbulence spectrum** [S(f), S(k)]
  - **Impact of RMP on blob transport in the SOL**
  - **Impact of RMP on GAM zonal flows**
- **Summary**

# Introduction

- How/Why does the RMP affect edge turbulence ?

RMP coils $\Rightarrow$ Magnetic perturbation of $B_r$ ($\delta B_r/B \sim 10^{-3}$)
$\Rightarrow$ island (chains) at resonant surfaces $\Rightarrow$ overlap (stochastic)

TEXT, A.J. Wootton, JNM, **176-177**, p.77




— $\delta B_r$ induces radial electron current $\Rightarrow$ new charge balance of $j_r$

— $\delta B_r$ induces radial field-line diffusion/transport by $D_M=(\delta B_r/B)^2 L_c$ ($D_\perp \propto D_M C_s$)

— $\delta B_r$ modifies the $k_{//}$ dynamics, $\nabla_{//}=(\mathbf{b}_0+\delta \mathbf{b}_r)\bullet\nabla$ $\Rightarrow$ affect turbulence eddies

— $\delta B_r$ opens field lines at plasma boundary $\Rightarrow$ increase sheath dissipation

— ……

# Distinction of ergodic zone (EZ) and laminar zone (LZ)

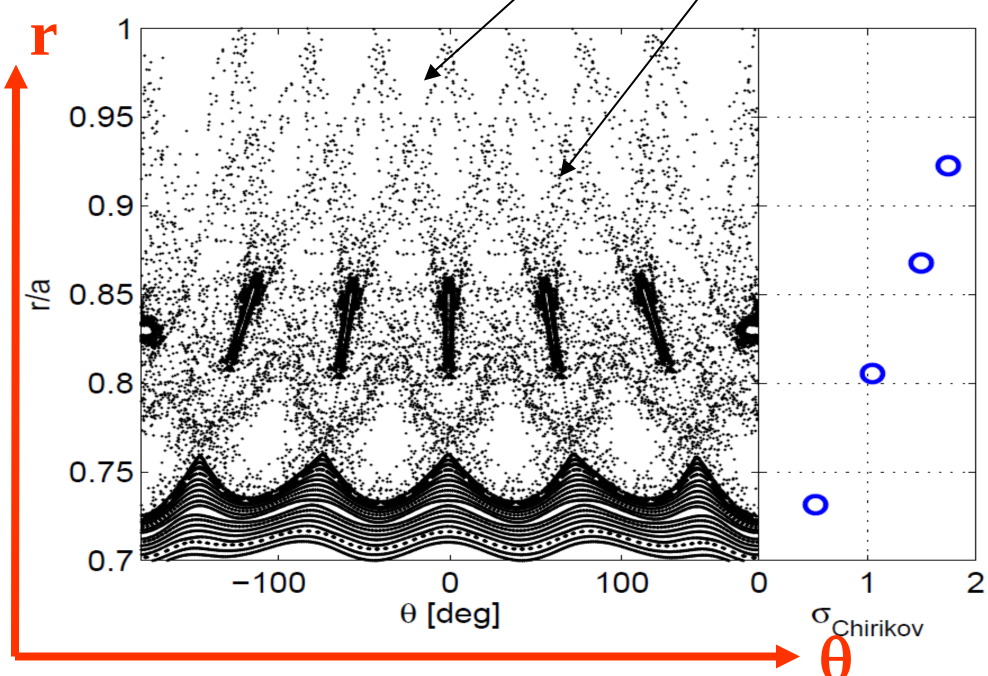
**EZ:** (i) $L_c > L_k$ (e-folding length of adjacent field lines); (ii) $\sigma_c > 1$

**LZ:** $L_c < L_k$, stochasticity has no meaning / parallel transport dominates

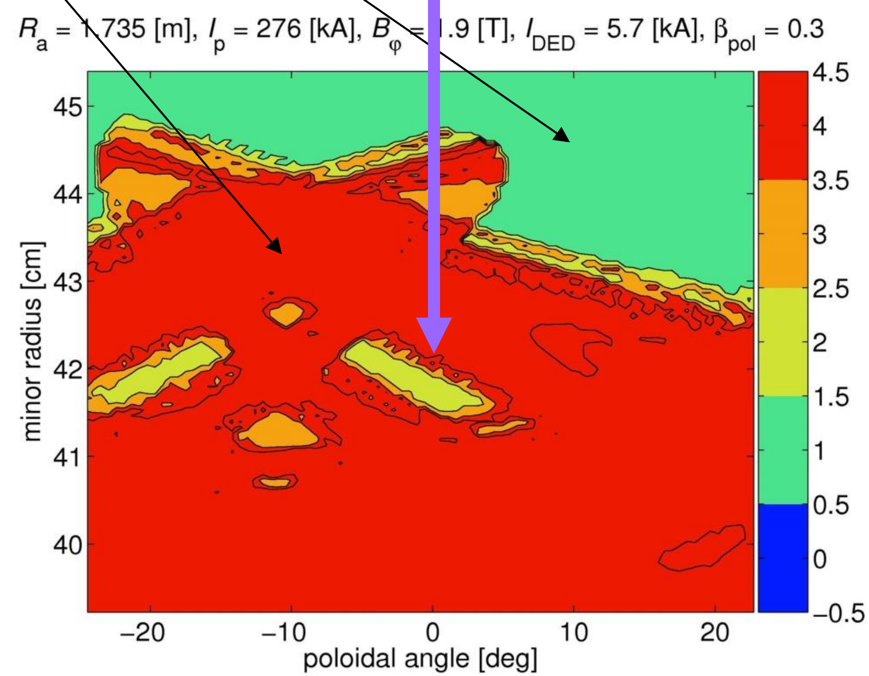
*Laminar zone*

*Ergodic zone*

**fast probe**




**Poincaré plot**

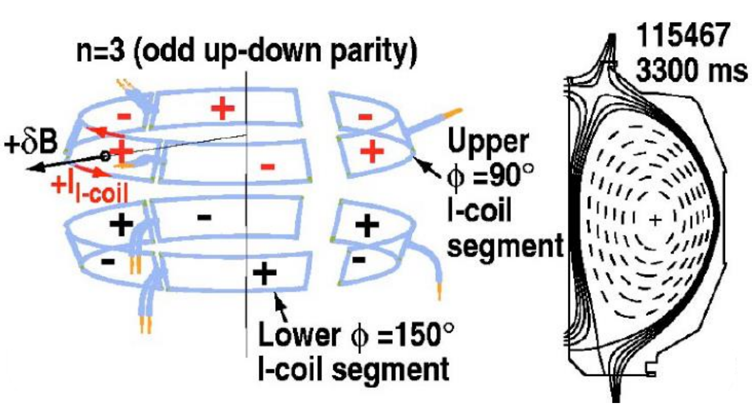



**Laminar plot**

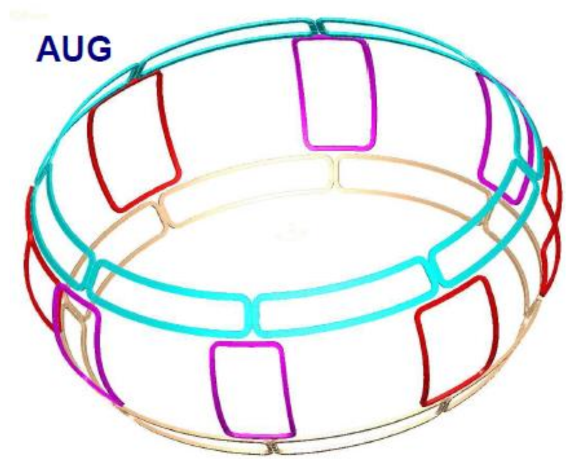
[different colors – number of poloidal turns]

**provided by M. W. Jakubowski**

# Experimental setup (RMP)

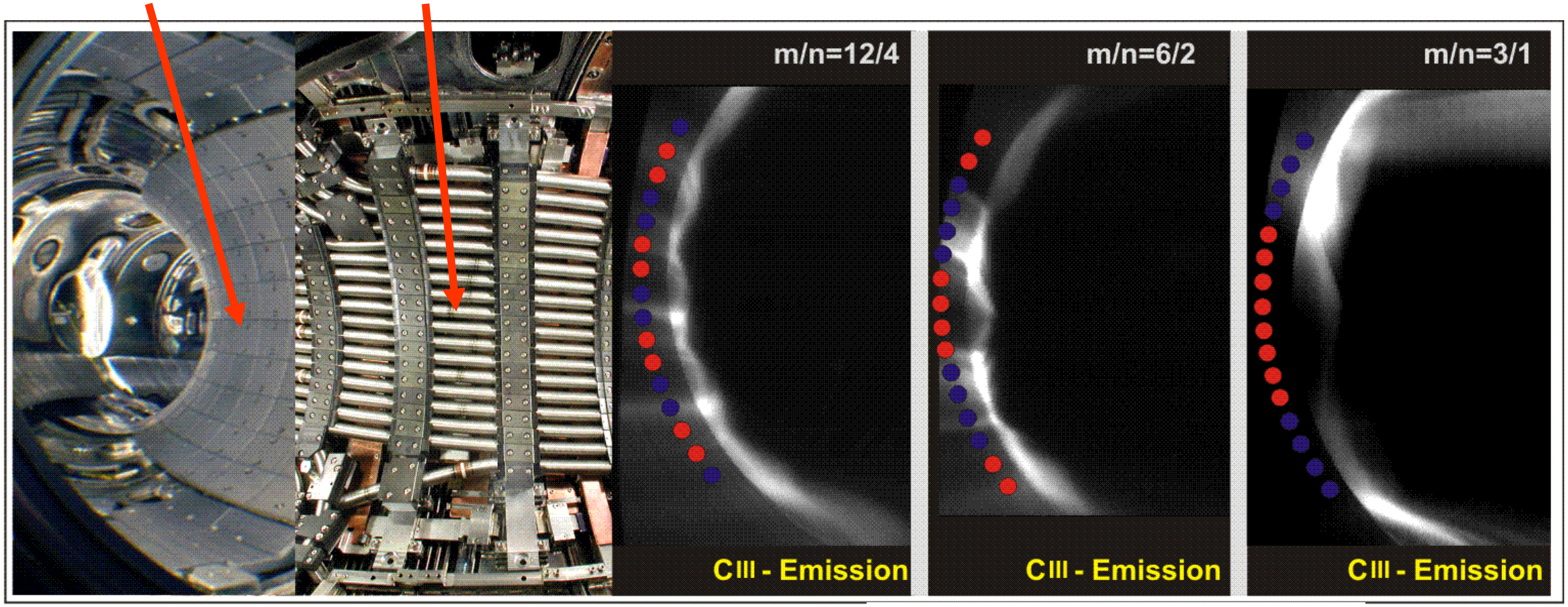



**DIII-D** (R. Moyer, PoP12, 056119)




| | |
|---|---|
| **TEXT** | 7/2, 7/3 |
| **Tore Supra** | 18/6 |
| **DIII-D** | 8-15/3 |
| **JET** | 2-3/1-2 |
| **MAST** | 20/3+5/3 |
| **AUG** | m/1-4 |
| **TEXTOR** | 3/1,6/2, 12/4 |

Carbon tile DED coil (@ HFS)

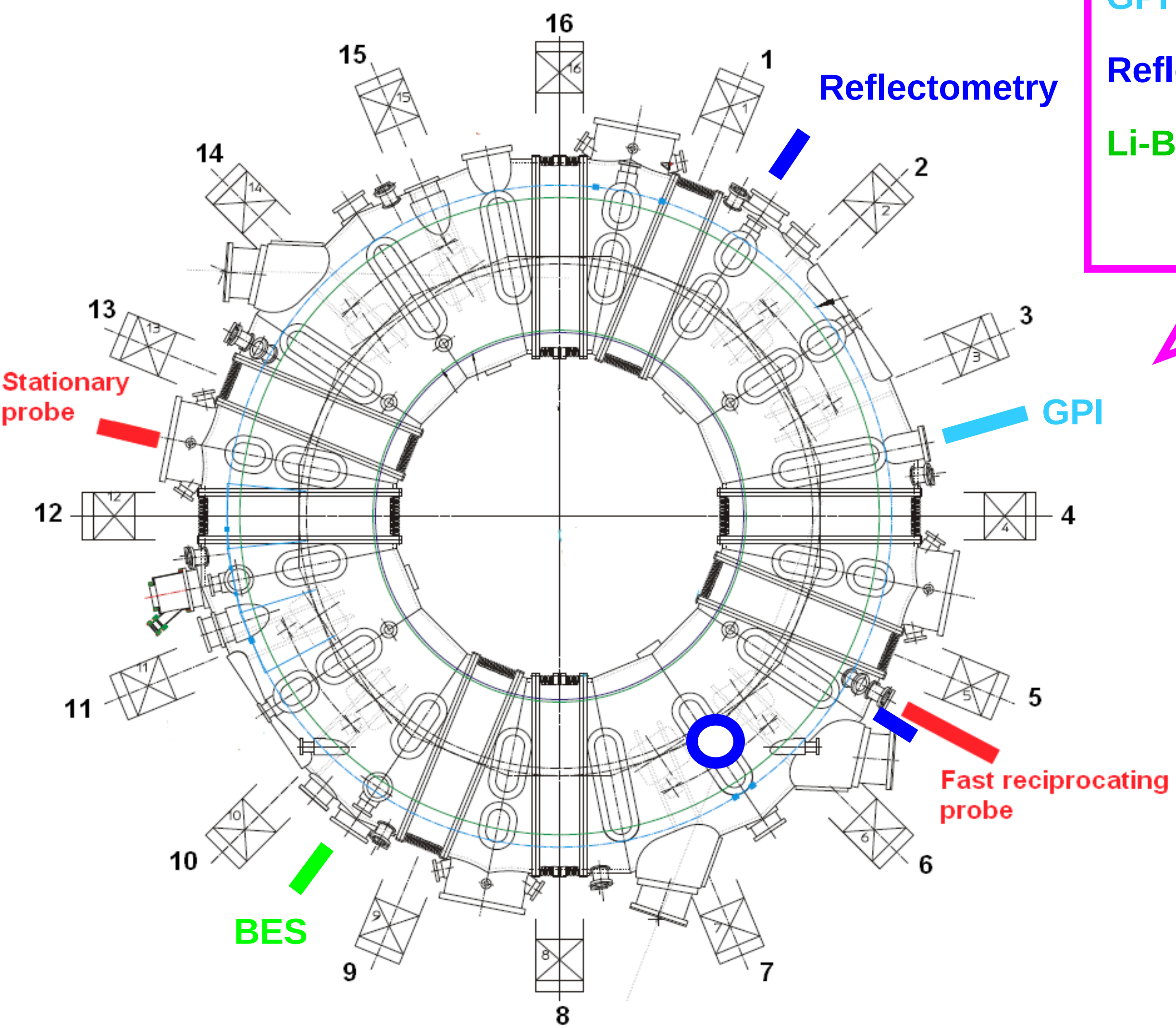



**TEXTOR-DED** (O. Schmitz, NF48, 024009 )

Resonant surface at *q* ~3

# Diagnostics for edge turbulence study at TEXTOR

## Top-View of TEXTOR



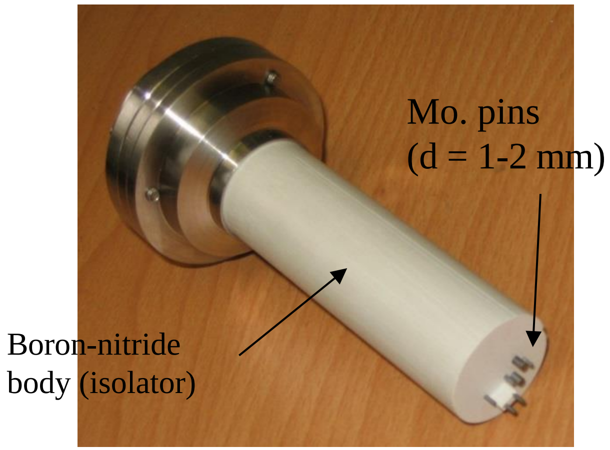

**Langmuir probes** — ERM, Belgium

**GPI (gas puff imaging)** — ERM, Belgium

**Reflectometry** — FZJ, Germany

**Li-BES (Beam emission spectroscopy)** — KFKI, Hungary

### Probe head



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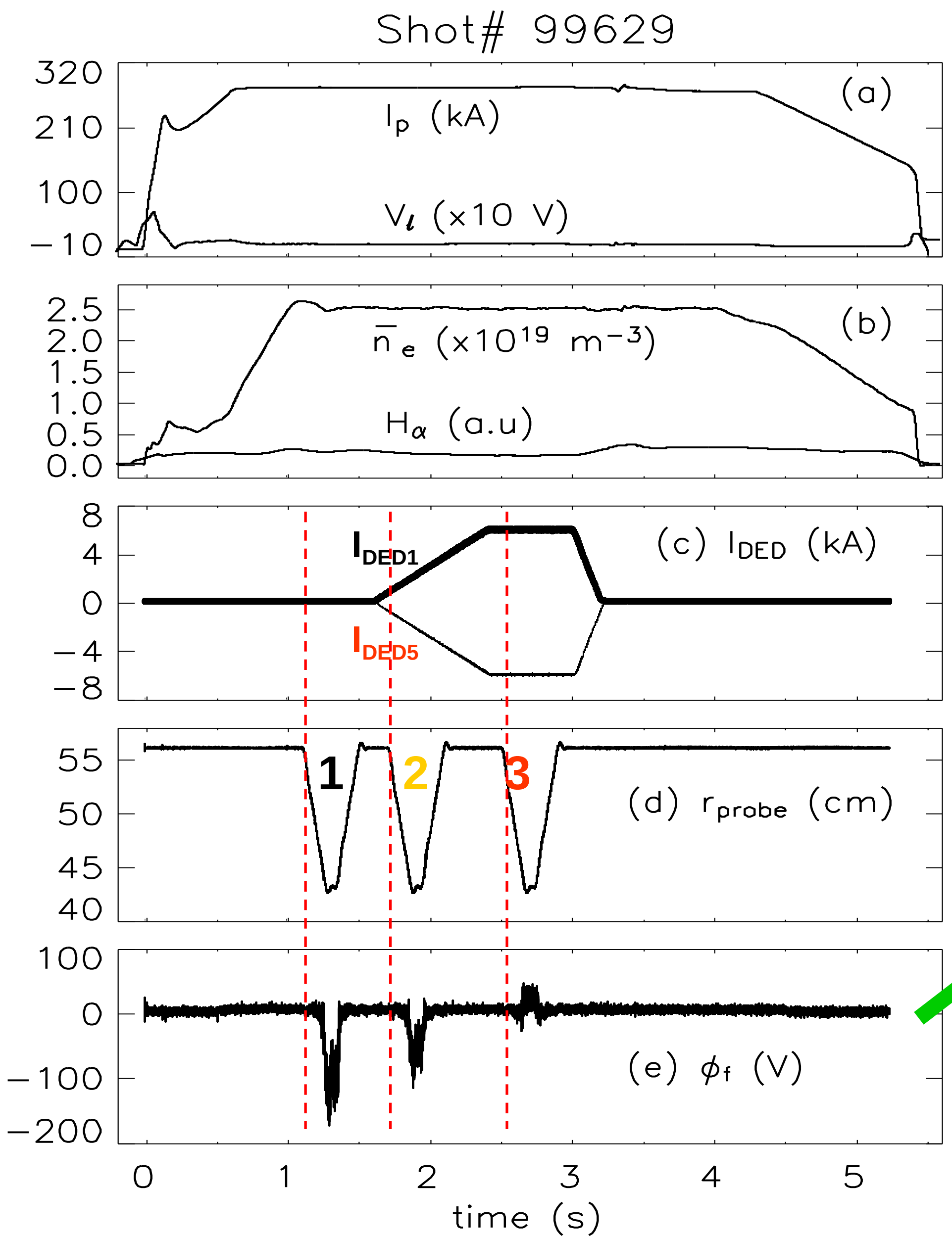
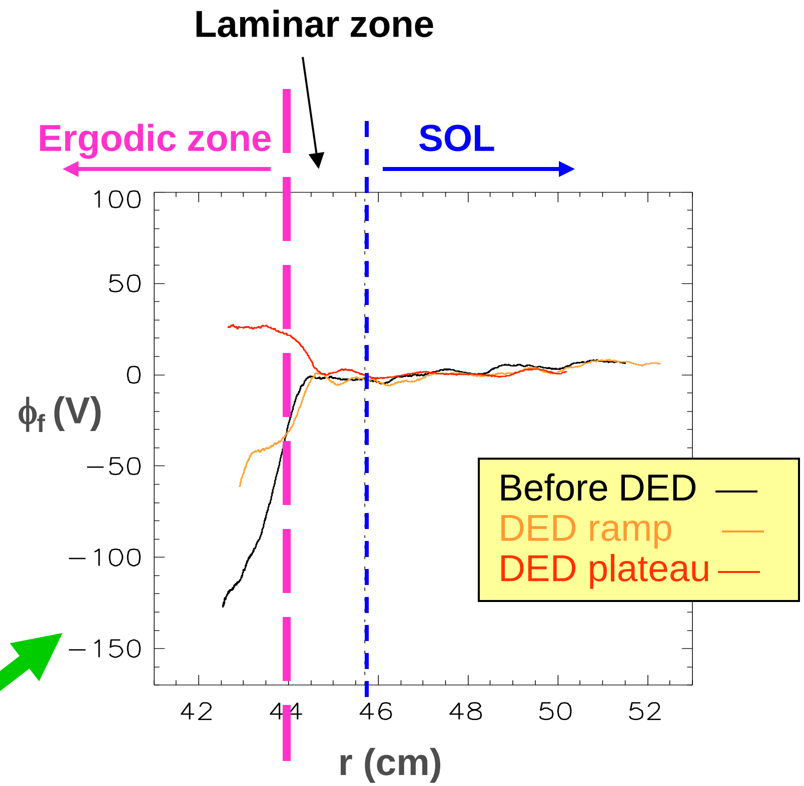
# Impact of RMP on edge equilibrium profiles (I)




Typical RMP discharge waveform at TEXTOR (6/2 DED)

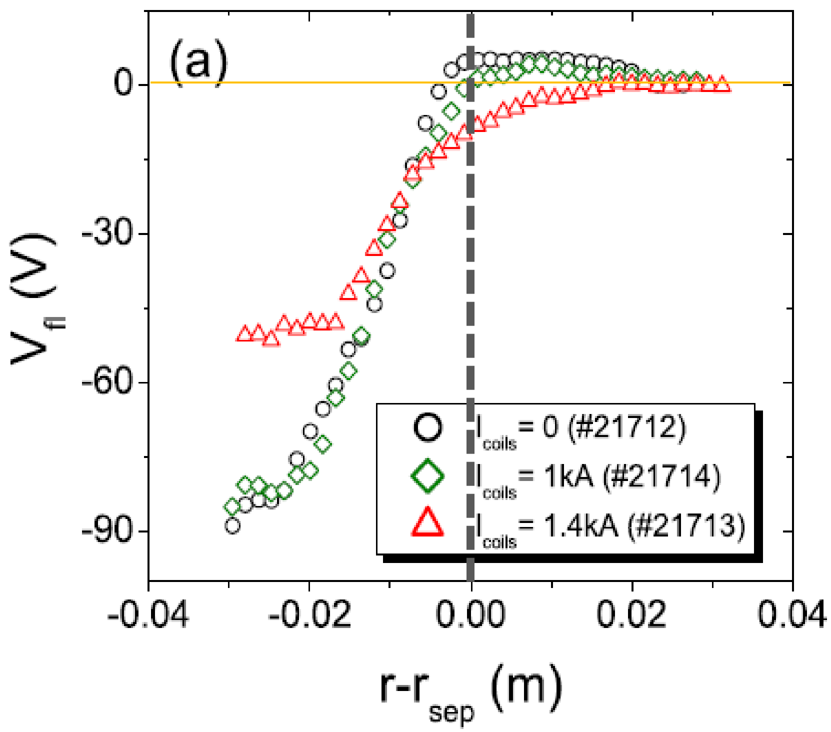



Radial dependence of floating potential

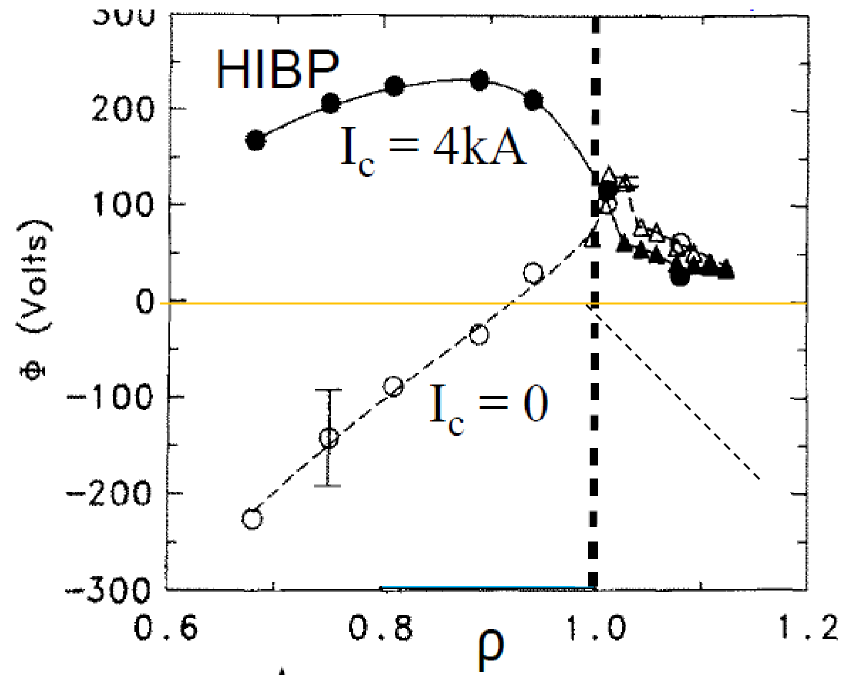
Y. Xu, EPS(2008), O4-6

# Similar impact of RMP on $V_f$ profile in other machines

MAST




TEXT




**$V_f$ profile affected by RMP in MAST**

(SOL / X-point)

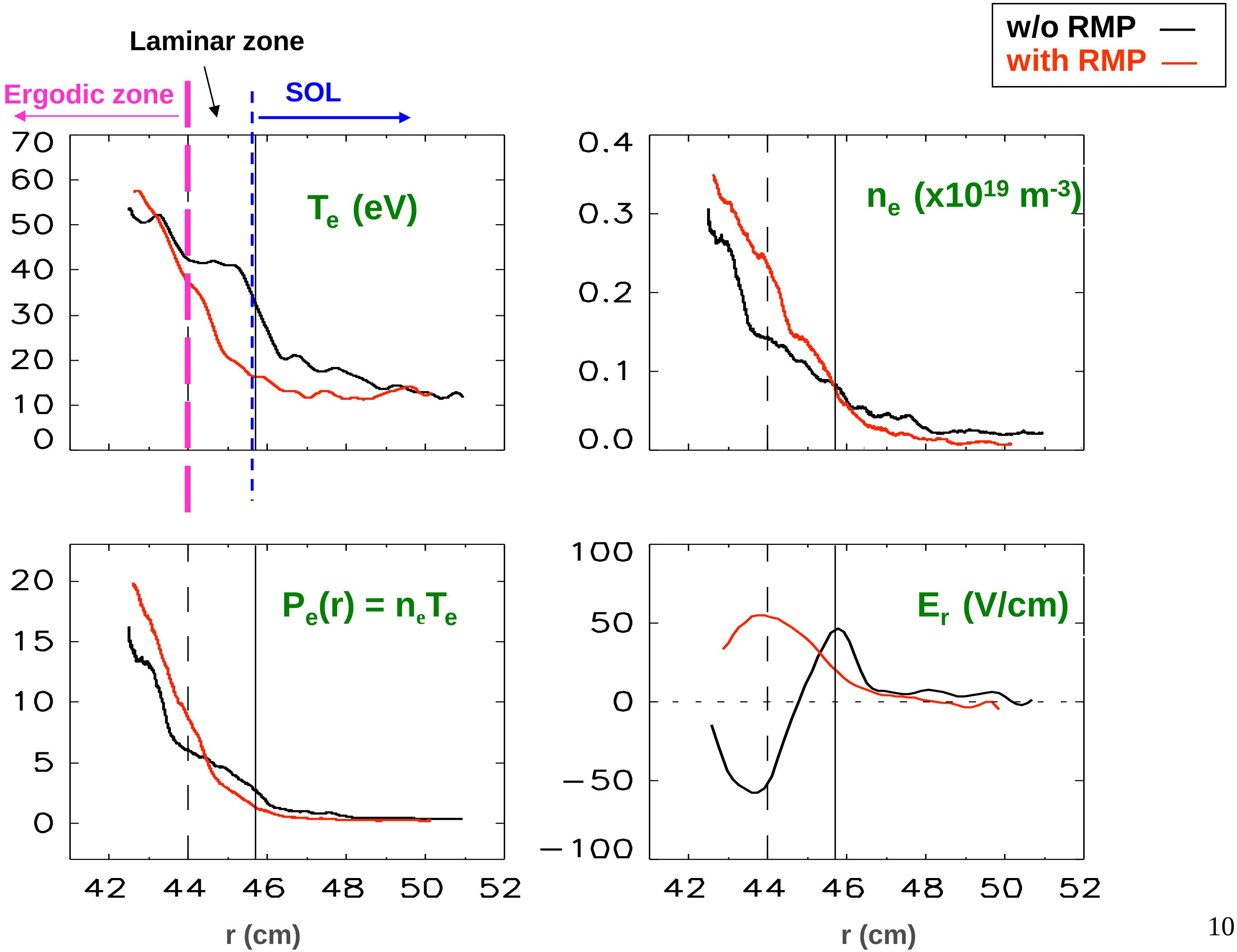
**$V_f$ profile affected by RMP in TEXT**

(Limiter)

P. Tamain, PPCF **52**, (2010)

A. Wootton, JNM **176-177** (1987)

# Impact of RMP on edge equilibrium profiles (II)



# Understanding the change of $E_r$ by RMP

What is neoclassical $E_r$ ?

$$\begin{cases} \dfrac{\partial (mn\vec{V})}{\partial t} + \vec{\nabla}\cdot(mn\vec{V}\vec{V}) + m\vec{\nabla}\cdot(n\vec{\vec{RS}}) = -\vec{\nabla}p - \vec{\nabla}\cdot\vec{\vec{\Pi}} + \vec{J}\times\vec{B} - \nu\vec{V}, \\ \dfrac{\partial n}{\partial t} + \vec{\nabla}\cdot(n\vec{V}) = 0, \end{cases}$$

$$\Rightarrow \begin{cases} \left\langle B\cdot\dfrac{\partial (mnV_{||})}{\partial t}\right\rangle = -\langle\vec{B}\cdot\vec{\nabla}\cdot\vec{\vec{\Pi}}\rangle - \langle\nu B V_{||}\rangle - m\langle\vec{B}\cdot\vec{\nabla}\cdot(n\vec{\vec{RS}})\rangle, \\ \left\langle\dfrac{1}{B_\theta}\dfrac{\partial (mnV_\phi)}{\partial t}\right\rangle = -\left\langle\dfrac{1}{B_\theta}(\vec{\nabla}\cdot\vec{\vec{\Pi}})_\phi\right\rangle + \langle J_r^i\rangle - \left\langle\dfrac{1}{B_\theta}\nu V_\phi\right\rangle - m\left\langle\dfrac{1}{B_\theta}(\vec{\nabla}\cdot(n\vec{\vec{RS}}))_\phi\right\rangle. \end{cases}$$

$$V_{||} = \frac{1}{\sin\alpha}\cdot\left[\frac{1}{\xi}\cdot\frac{F(r)}{R_0} - \xi\cos^2\alpha\frac{V(r)}{B_0}\right] = 0, \qquad \frac{F(r)}{R_0} = \langle V_\theta\rangle$$

$$V_\phi = \frac{1}{\Theta}\cdot\left[\frac{1}{\xi}\cdot\frac{F(r)}{R_0} - \xi\frac{V(r)}{B_0}\right] = 0, \qquad \frac{V(r)}{B_0} \sim \langle V_\perp\rangle$$

$$\Rightarrow \boxed{J_r = J_r^{\mathrm{i}} = J_r^{\mathrm{neo}} = \sigma^{\mathrm{neo}}(E_r - E_{r,\mathrm{amb}}^{\mathrm{neo}})}$$

$$\sigma^{\mathrm{neo}} = \frac{mn\nu^*}{\Theta^2 B_0}\cdot\frac{C^*/\nu^* + \Theta^2(1+2q^2)}{C^*/\nu^* + (1+\Theta^2)} \qquad \cong \mathbf{10^{-3}}\ /\Omega\mathrm{m}$$

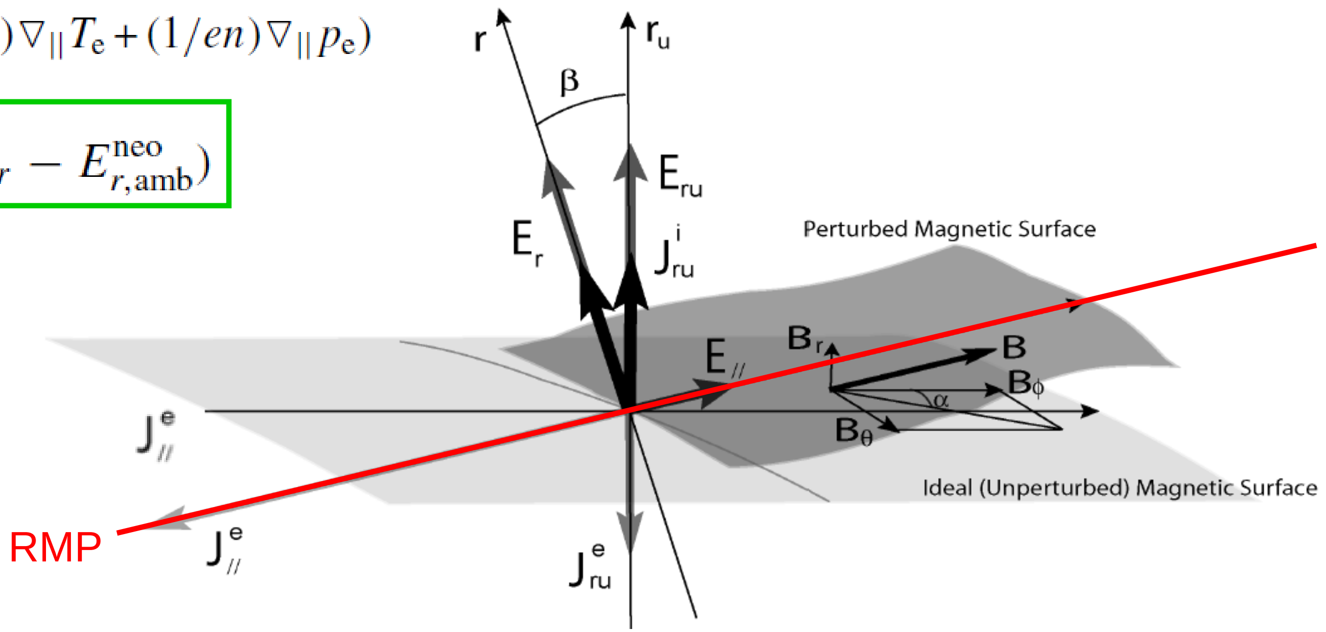
$$E_{r,\mathrm{amb}}^{\mathrm{neo}} = \frac{1}{en}\frac{\partial p_{\mathrm{i}}}{\partial r} - \frac{1}{\sigma^{\mathrm{neo}}}\left(\frac{CV^{\mathrm{neo}}}{\Theta B_0^2}\cdot\frac{1}{C^*/\nu^* + (1+\Theta^2)} + \frac{m}{B_0}\frac{1}{r^2}\frac{\partial}{\partial r}(r^2(n\vec{\vec{RS}})_{r,\theta})\right)$$

# Understanding the change of $E_r$ by RMP

**no RMP, $J_{//}^{e}$ doesn't across magnetic surface**

$$J_{//}^{e} = \sigma_{||}\widehat{E_{||}} = \sigma_{||}(E_{||} + 0.71(1/e)\nabla_{||}T_e + (1/en)\nabla_{||}p_e)$$

$$\boxed{J_r = J_r^{i} = J_r^{\rm neo} = \sigma^{\rm neo}(E_r - E_{r,\rm amb}^{\rm neo})}$$




With RMP $J_r^{e} \approx J_{ru}^{e} = J_{||}(B_r/B) = \sigma_{||}\widehat{E_{||}}(B_r/B) = \sigma_{||}\widehat{E_r}(B_r/B)^2 = \sigma^{\rm ST}(E_r - E_{r,\rm amb}^{\rm ST})$

$$\boxed{J_r = J_r^{\rm neo} + J_r^{e} = \sigma^{\rm TOT}(E_r - E_{r,\rm amb}^{\rm TOT})}$$

$$\sigma^{\rm TOT} = \sigma^{\rm neo} + \sigma^{\rm ST}$$

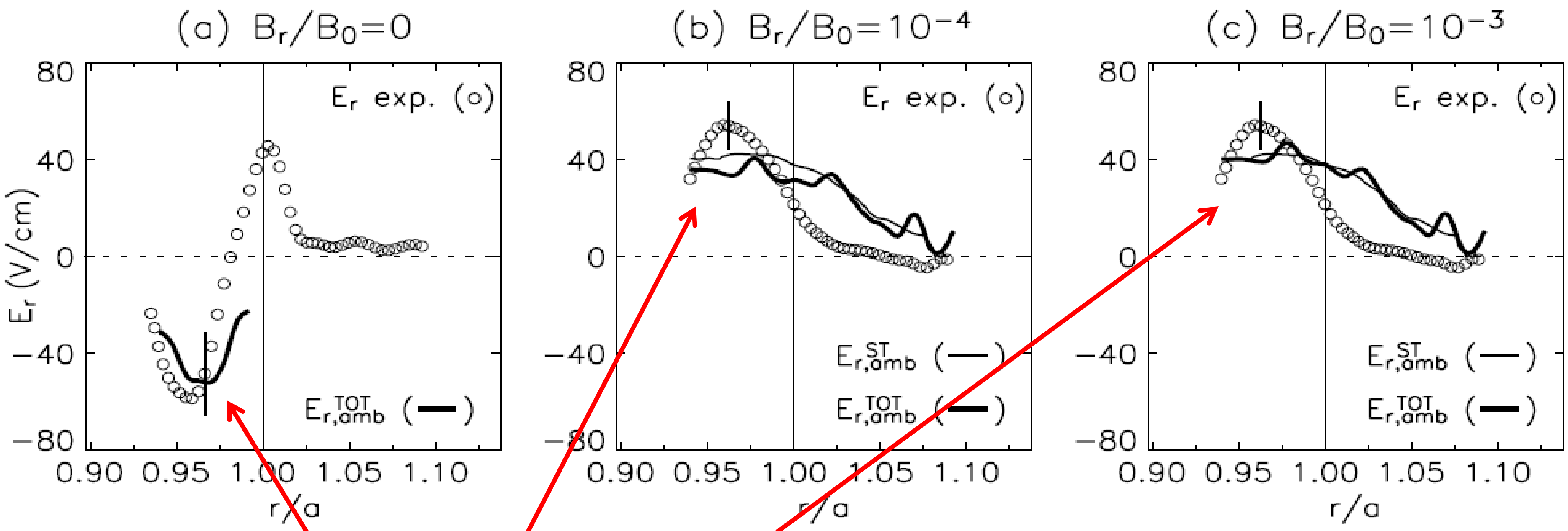
$$E_{r,\rm amb}^{\rm TOT} = \frac{\sigma^{\rm neo}E_{r,\rm amb}^{\rm neo} + \sigma^{\rm ST}E_{r,\rm amb}^{\rm ST}}{\sigma^{\rm neo} + \sigma^{\rm ST}} \approx E_{r,\rm amb}^{\rm ST}$$

$\boldsymbol{\sigma^{neo} \approx 10^{-3}}$ /Ωm

$\boldsymbol{\sigma^{ST} = \sigma_{||}(B_r/B)^2 \approx 10^{-2}}$ /Ωm

Y. Xu, M. Schoor, et al.,
NF **47**, 1696 (2007)

# Comparison with theoretical modelling on $E_r$ profiles




Y. Xu, M. Schoor, et al., NF **47**, 1696 (2007)

Inside the plasma edge, theoretical modelling of $E_r$ agrees well with experimental results both w/o RMP.

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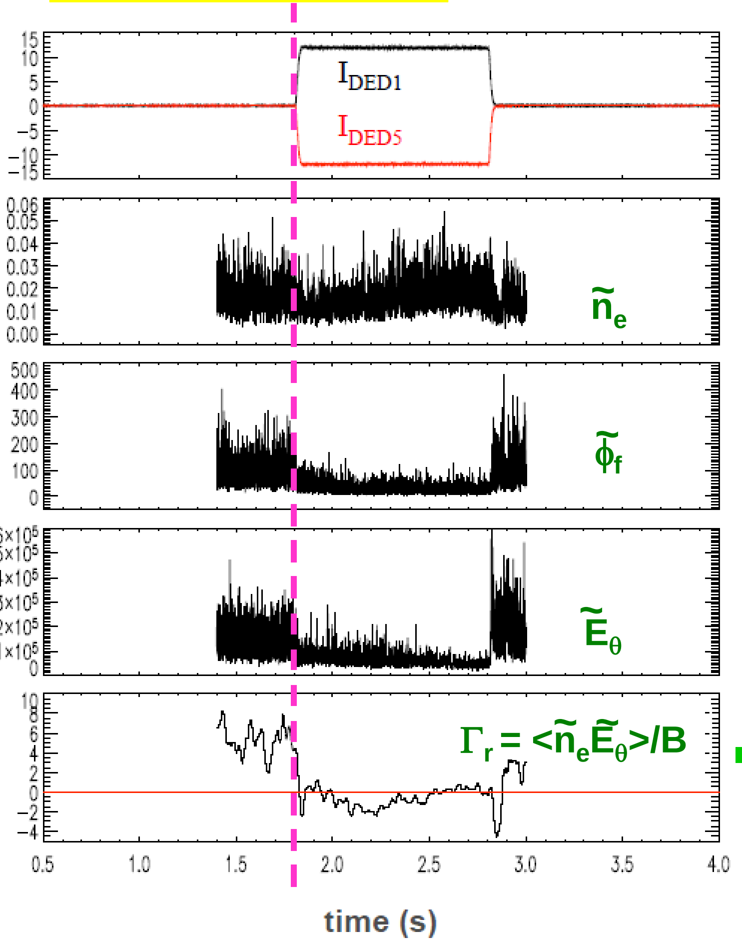
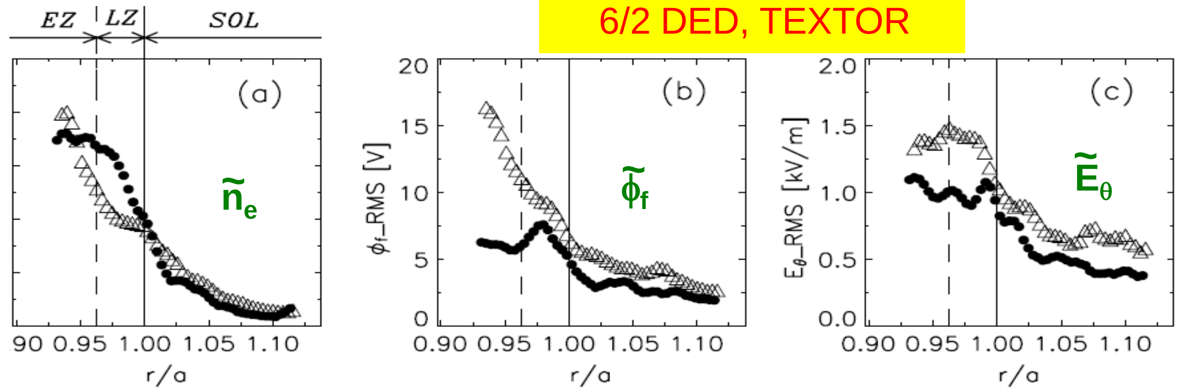
# Impact of RMP on edge fluctuation amplitude and transport

12/4 DED, TEXTOR



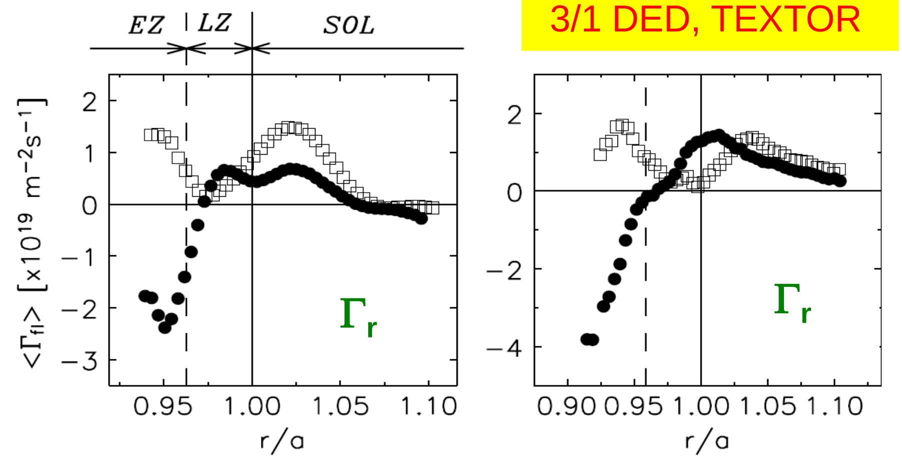

12/4 DED, stationary probe in Ergodic Zone

6/2 DED, TEXTOR




6/2 DED, TEXTOR

3/1 DED, TEXTOR

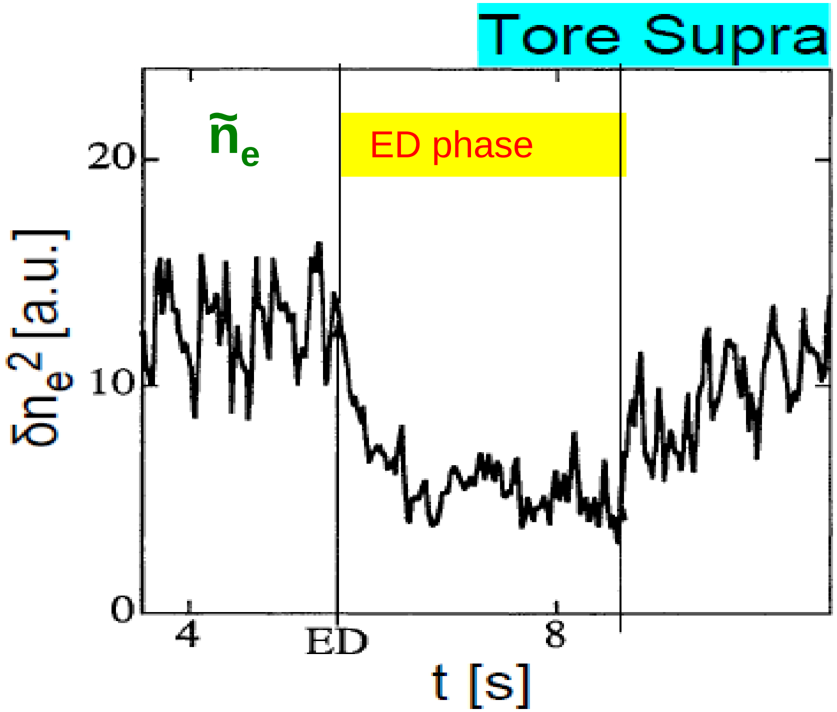



Radial profiles of fluctuations without (open points) and with (solid points) RMP.

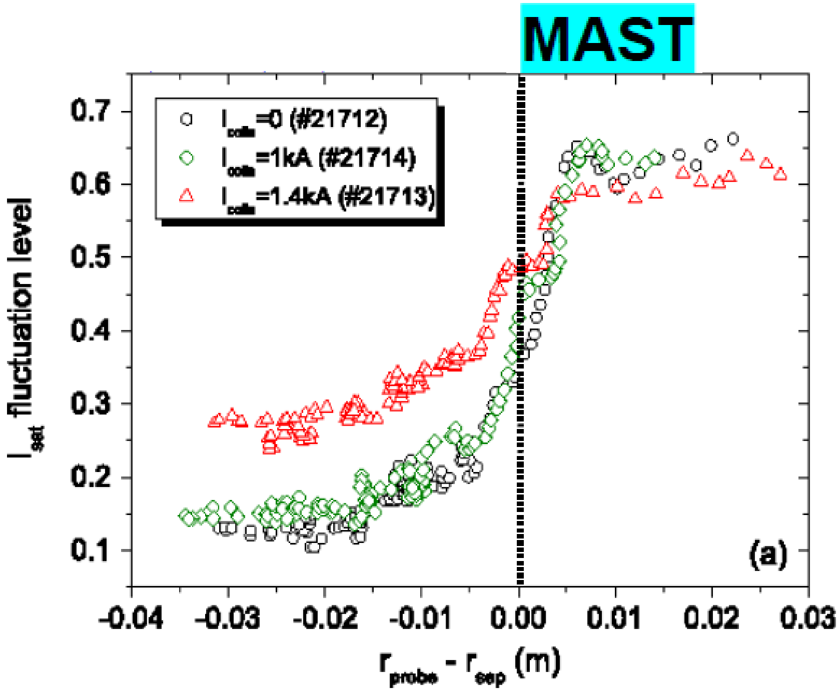
Y. Xu et al., NF **47**, 1696 (2007)

Y. Xu et al., PRL **97**, 165003 (2006)

# Impact of RMP on edge fluctuation amplitude and transport




J. Payan, NF **35**, 1357 (1995)




P. Tamain, PPCF **52**, 075017(2010)

Very similar to TEXTOR results !

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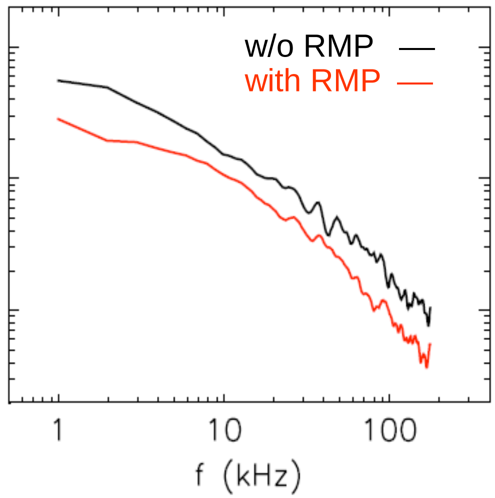
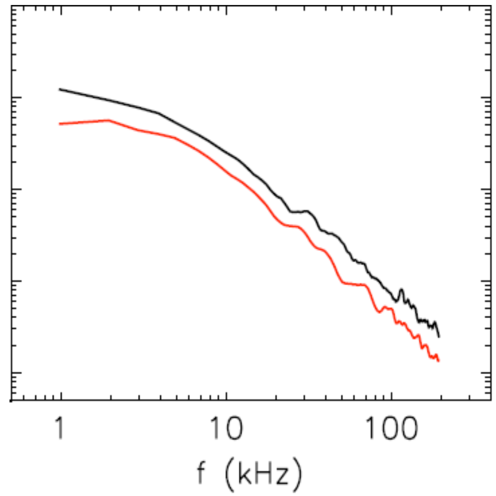
# Impact of RMP on edge turbulence spectrum [S(f)]

SOL

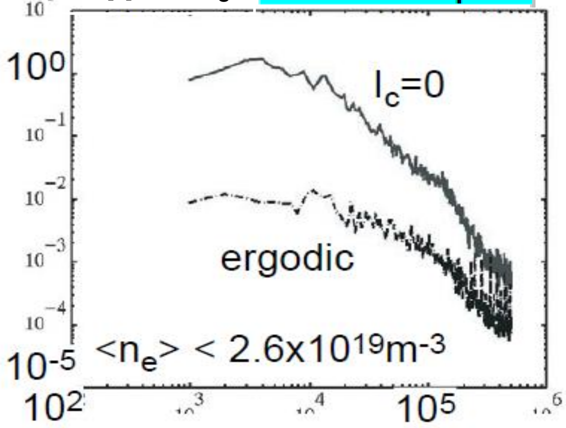
S(f) of $\tilde{\phi}_f$ (3/1 DED TEXTOR)




S(f) of $\tilde{n}_e$ (6/2 DED TEXTOR)



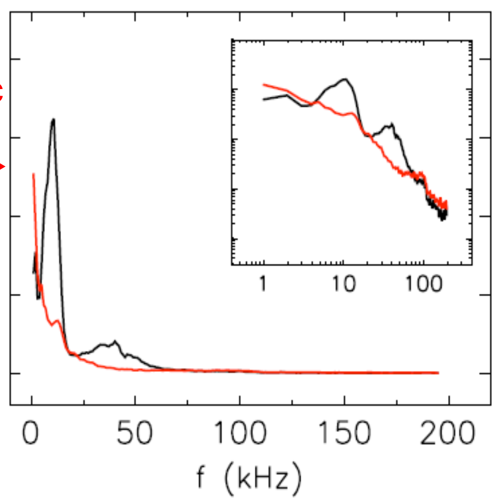

S(f) of $\tilde{n}_e$ Tore Supra



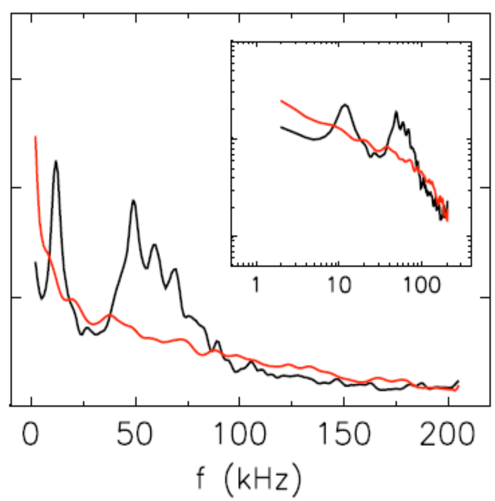

P. Devynck, NF **42**, 697 (2002)

Ergodic Zone

S(f) of $\tilde{\phi}_f$ (12/4 DED TEXTOR)

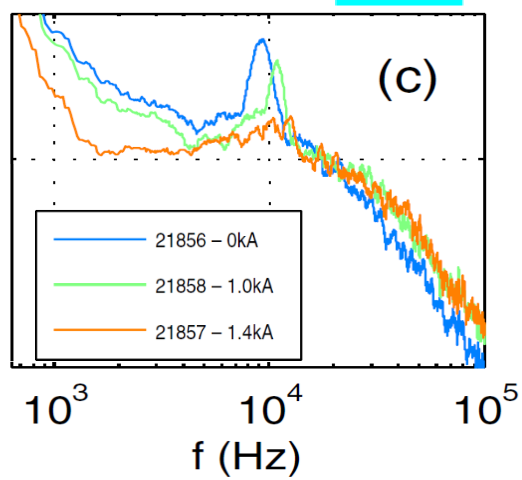



S(f) of $\tilde{n}_e$ (6/2 DED TEXTOR)



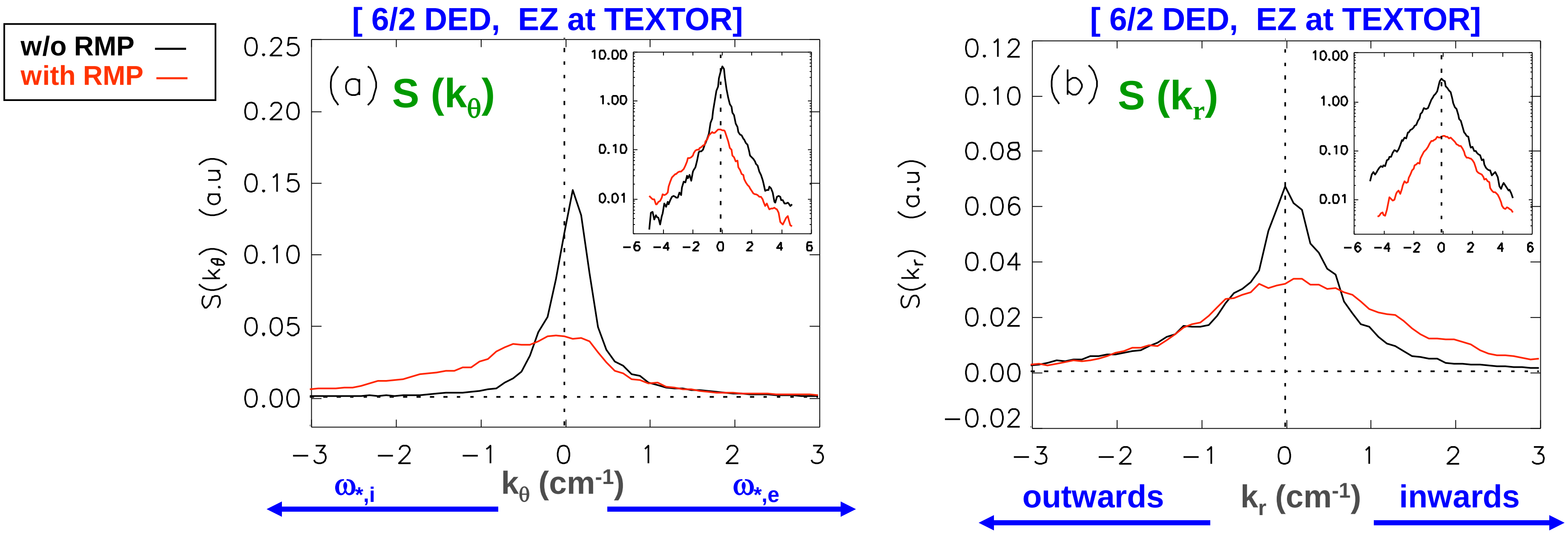

Y. Xu et al., NF**47** (2007), PRL**97**,(2006)

S(f) of $\tilde{\phi}_f$ MAST



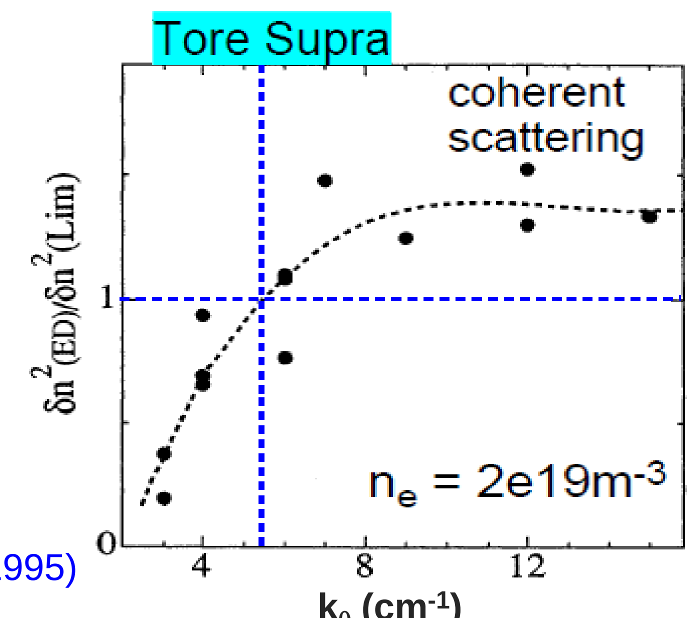

J. Robinson, PPCF54, 105007 (2012)

# Impact of RMP on edge turbulence spectrum [S(k)]



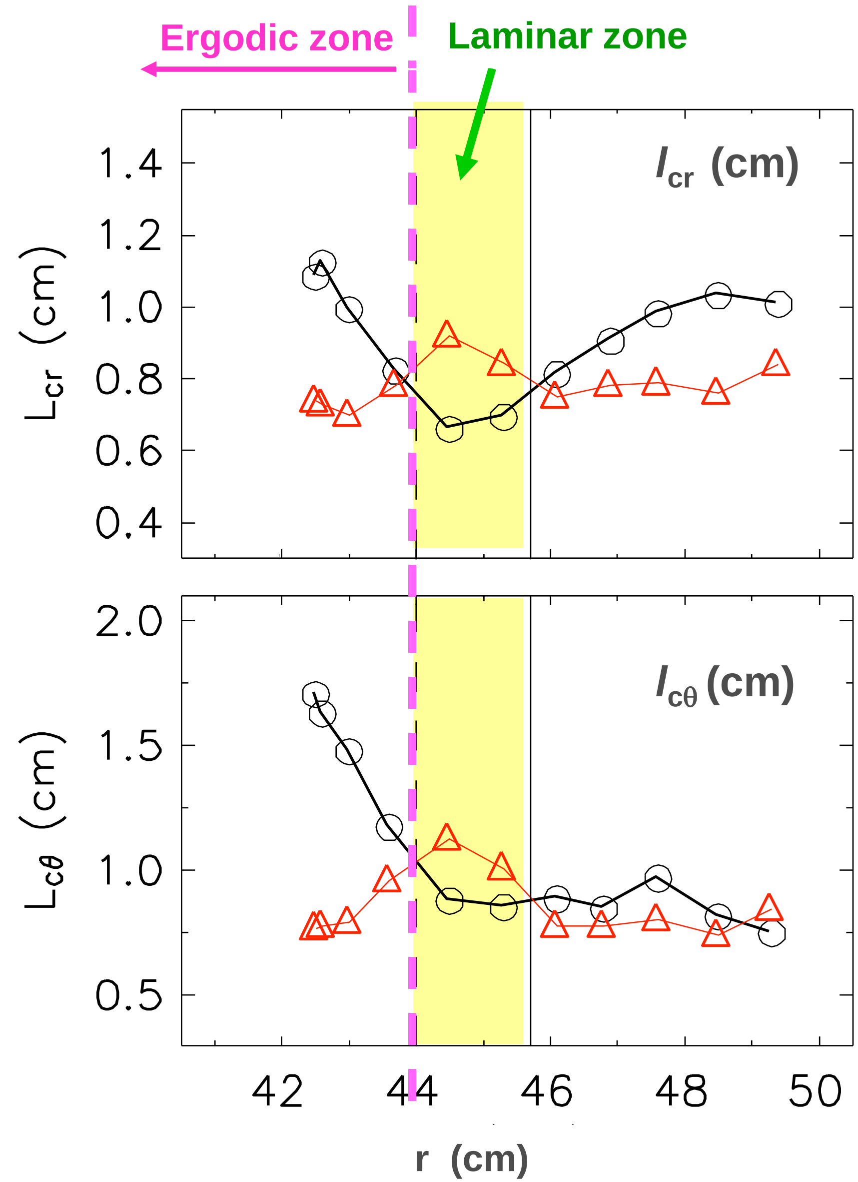

Y. Xu et al., NF **47**, 1696 (2007)

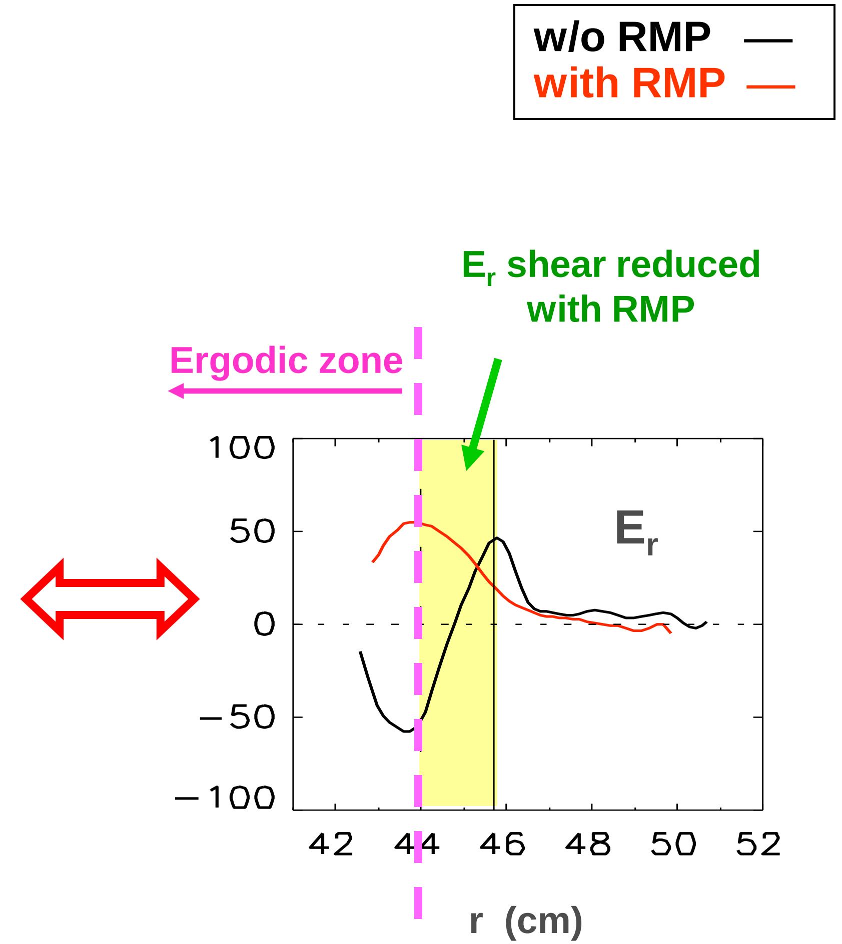
- Suppression of large-structure turbulence (*small $k_\theta$ and $k_r$*)
- Reduction of correlation length (*broadening of k spectra*)




J. Payan, NF **35**, 1357 (1995)

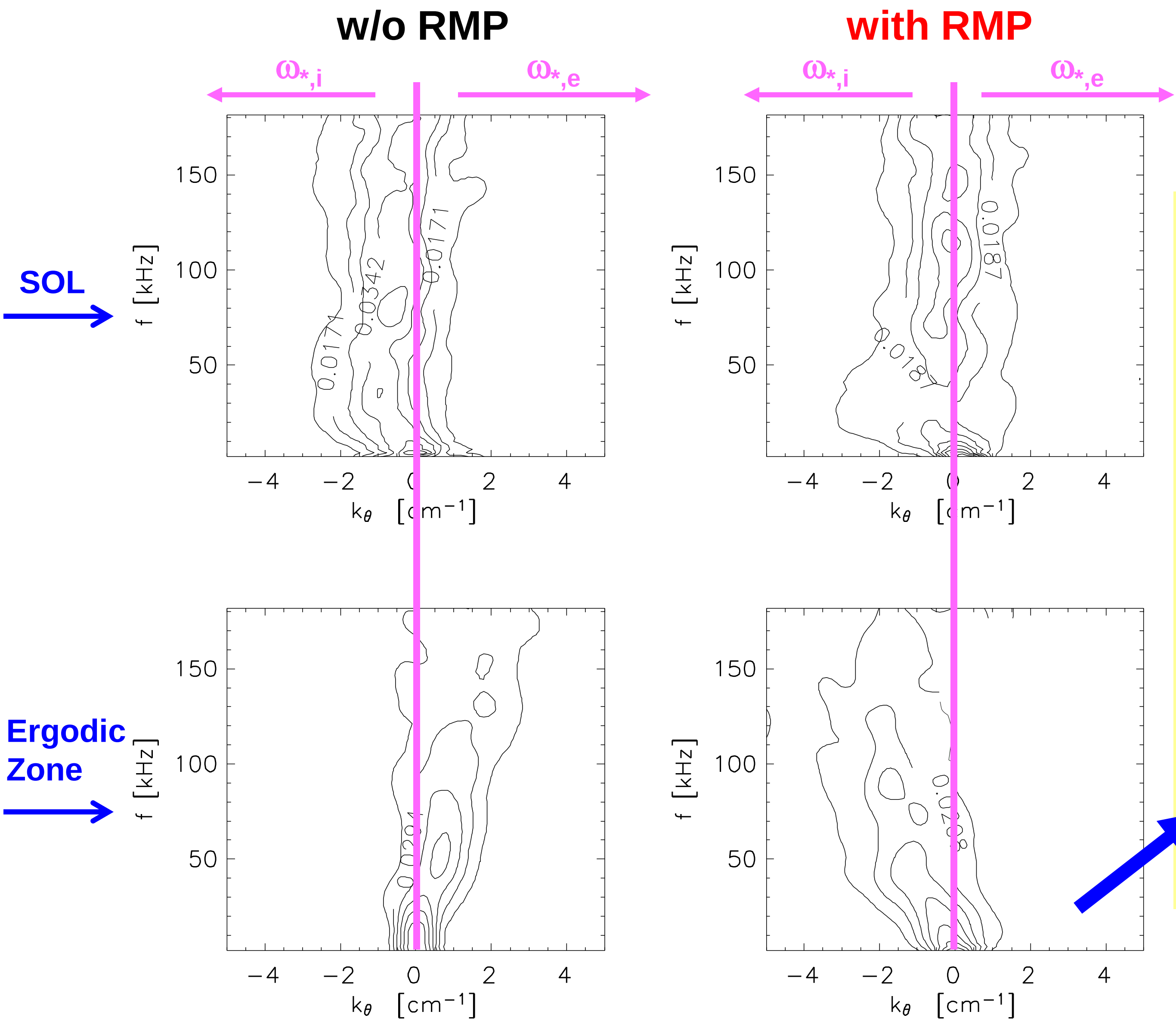
# RMP effects on "correlation length"




- **LZ and EZ show distinctive features !**

# RMP effects on turbulence propagation

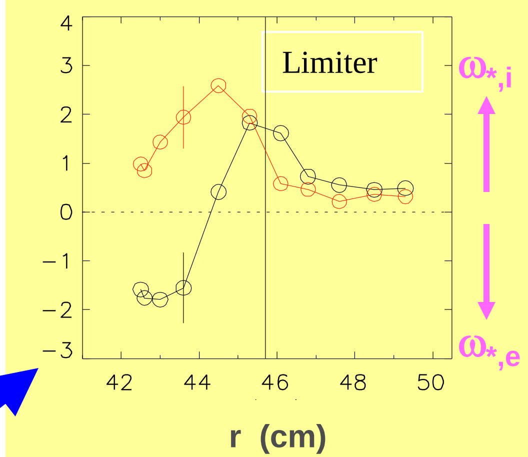



Contour plots of $S(k_{\theta}, f)$

w/o RMP —
with RMP —

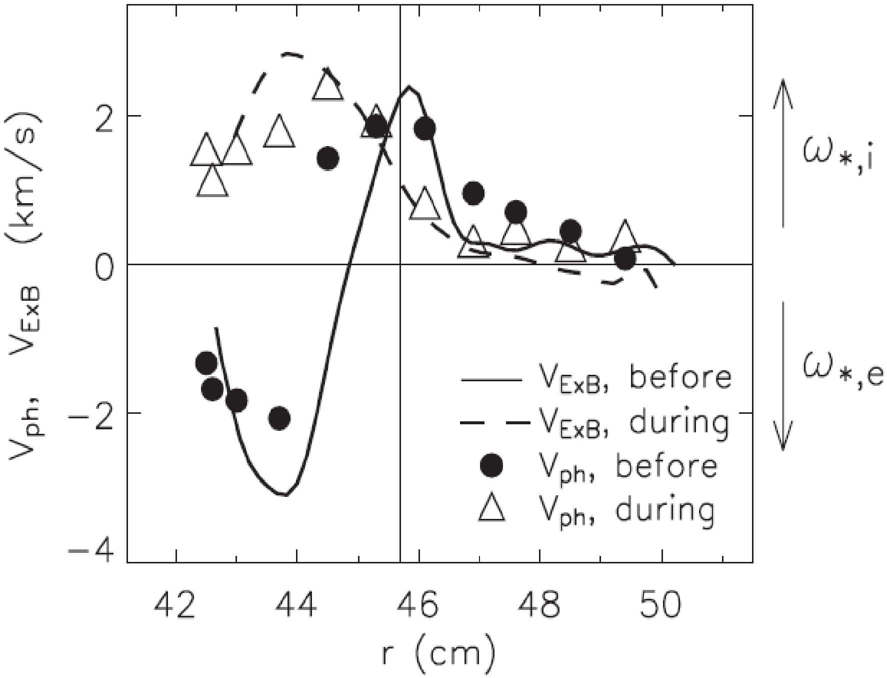
$$V_{ph} = \frac{\sum_{k_\theta, f} \frac{2\pi f}{k_\theta} \cdot S(k_\theta, f)}{\sum_{k_\theta, f} S(k_\theta, f)}$$

**Profile of poloidal $V_{ph}$** (km/s)



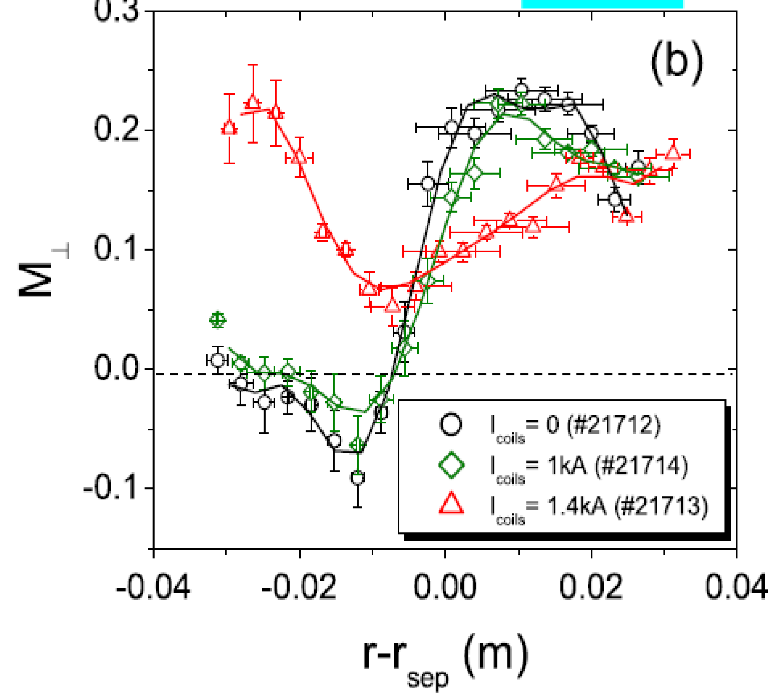
# RMP effects on turbulence propagation

TEXTOR




Y. Xu et al., PRL **97**, 165003 (2006)

MAST




P. Tamain, PPCF **52**, 075017(2010)

— **At TEXTOR, influence of RMP on the poloidal rotation is consistent with $E_r$xB drift.**

— **In MAST tokamak, a similar reversal of poloidal rotation is observed.**

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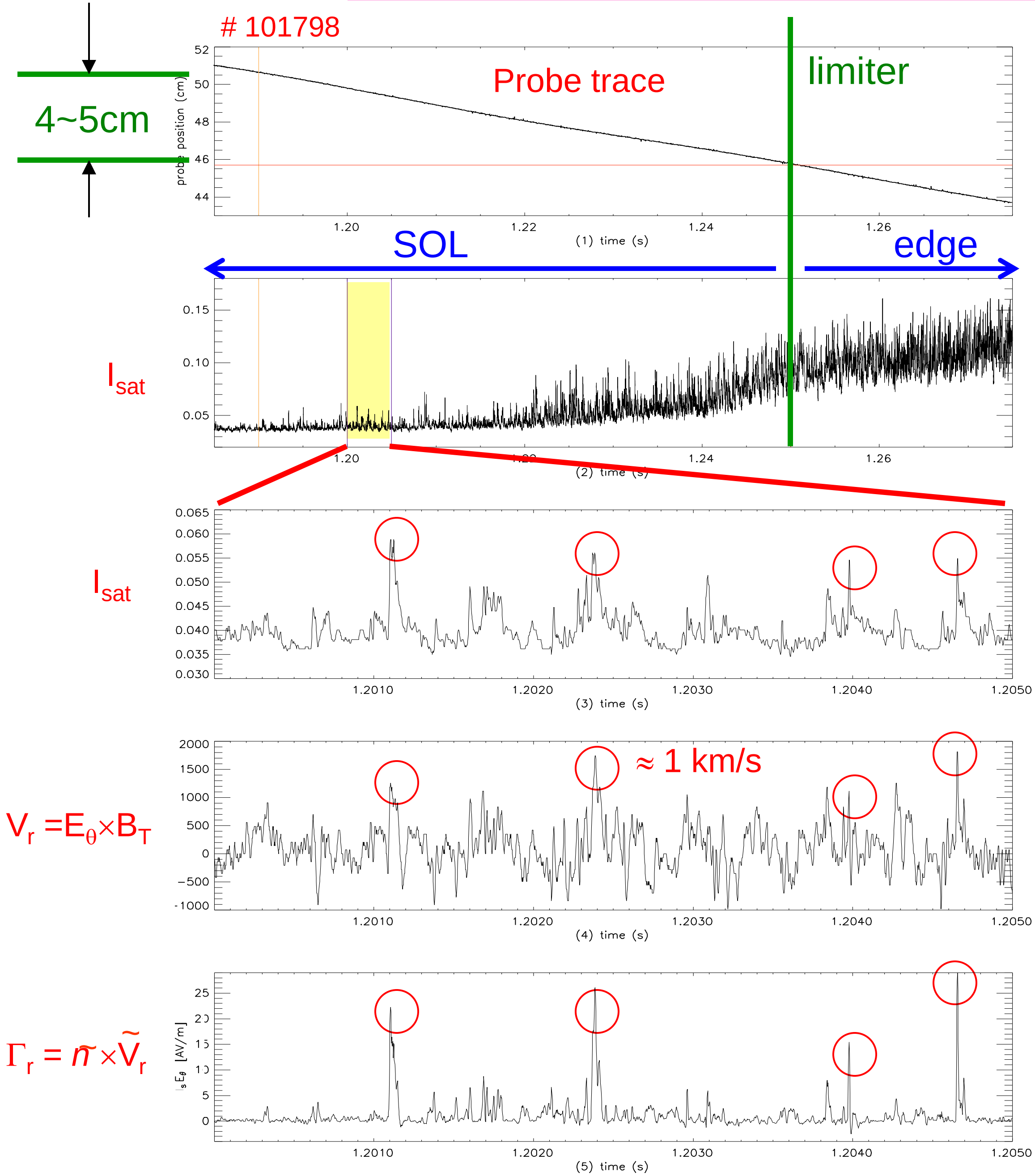
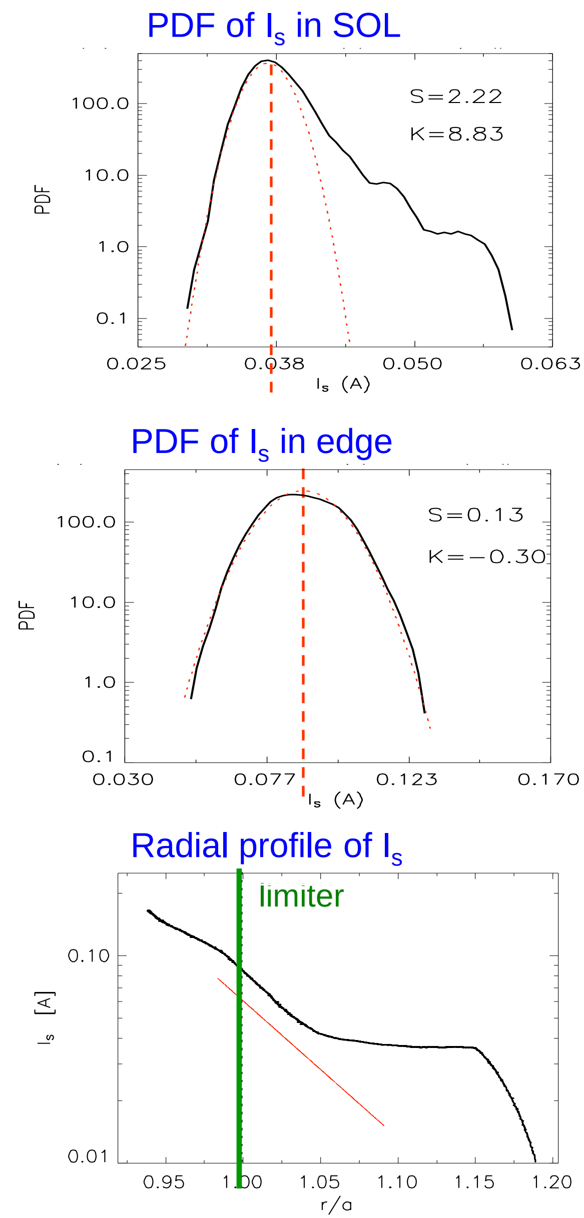
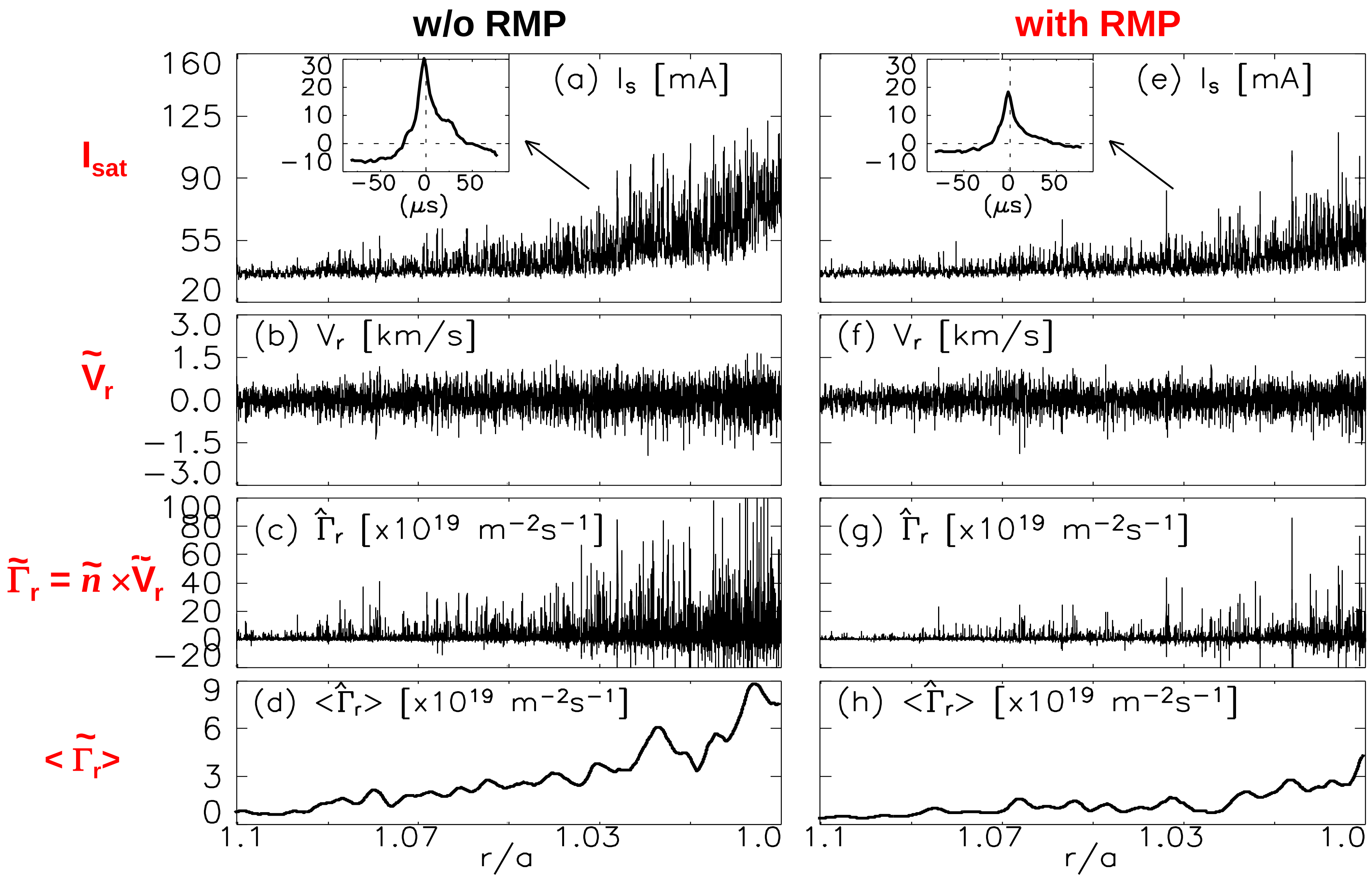
# Intermittent blob transport in the SOL




Y. Xu et al., PPCF(2005), NF(2009)

# Impact of RMP on blob transport in the SOL




*** Independent of edge profile / RMP-phase variations ➡ global effects**

Y. Xu et al., NF49, 035005 (2009), consistent with modelling D. Reiser PoP 14, (2007)

# Impact of RMP on blob transport in the SOL

## Interpretation:

**Blob dynamics:**

$$\begin{cases} \dfrac{M_i n_0}{B^2}\dfrac{\partial}{\partial t}\nabla_\perp^2\tilde{\phi} = \nabla_{//}\tilde{J}_{//} - \kappa(\tilde{p}) \\ \dfrac{\partial\tilde{n}}{\partial t} = -\tilde{V}_{E,r}\nabla n + \nabla_{//}\tilde{J}_{//}/e - \nabla_{//}(n_0\tilde{V}_{//,i}) + n_0\kappa(\tilde{\phi}) - \dfrac{T_e}{e}\kappa(\tilde{n}) \end{cases}$$

— generation $\kappa \times \nabla n$

— dissipation $\nabla_{//}J_{//} \propto neC_s / L_c$ O. Garcia, PoP (2006)

(i) Nonzero $k_{//}$ damp turbulence eddy development
=> suppress large eddy (blob) structures.

(ii) Shorter $L_c$ with RMP enhances the sheath dissipation
=> radial velocity decreases.

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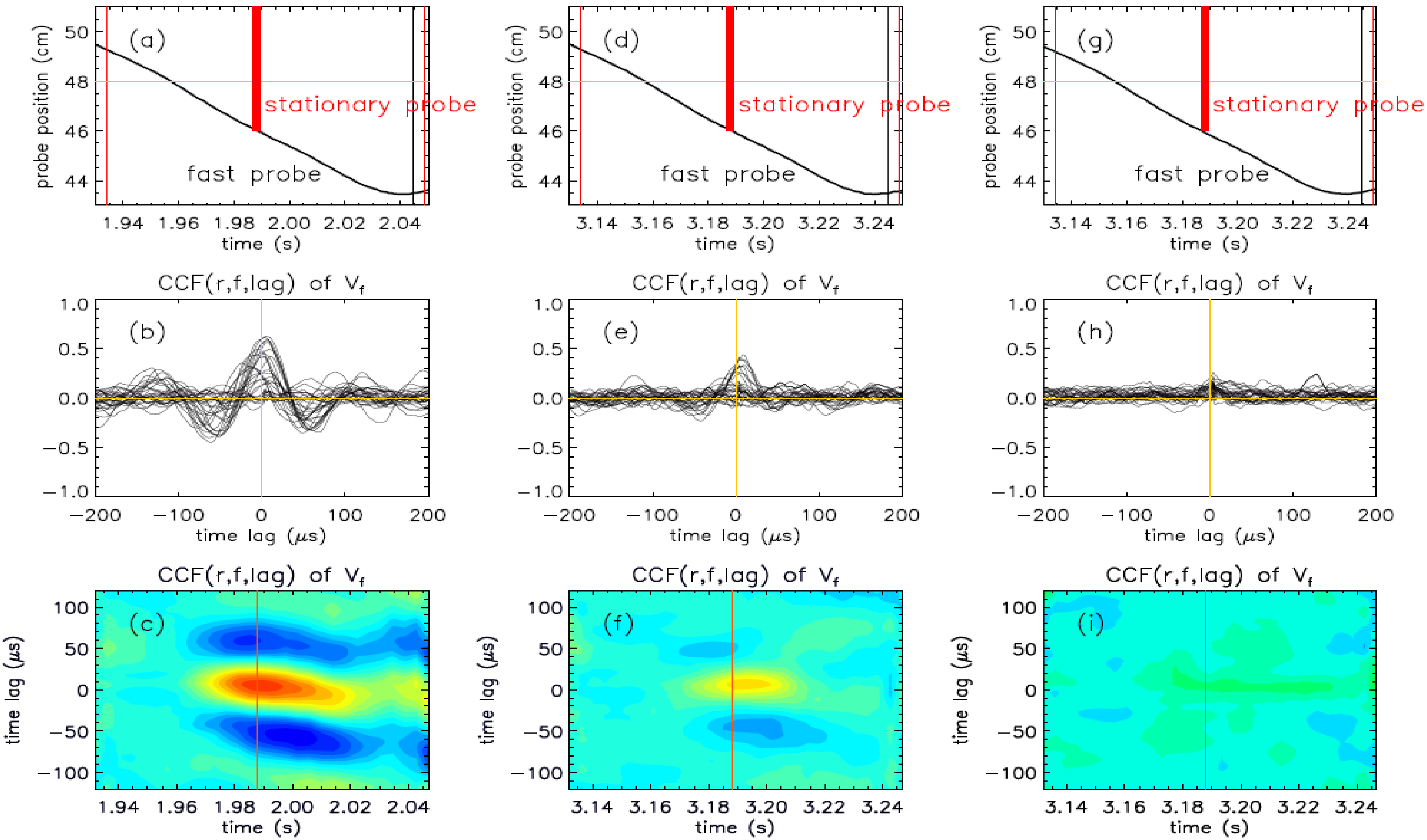
  - — **Impact of RMP on blob transport in the SOL**
  - — **Impact of RMP on GAM zonal flows**
- **Summary**

# Impact of RMP on GAM zonal flows

6/2 DED

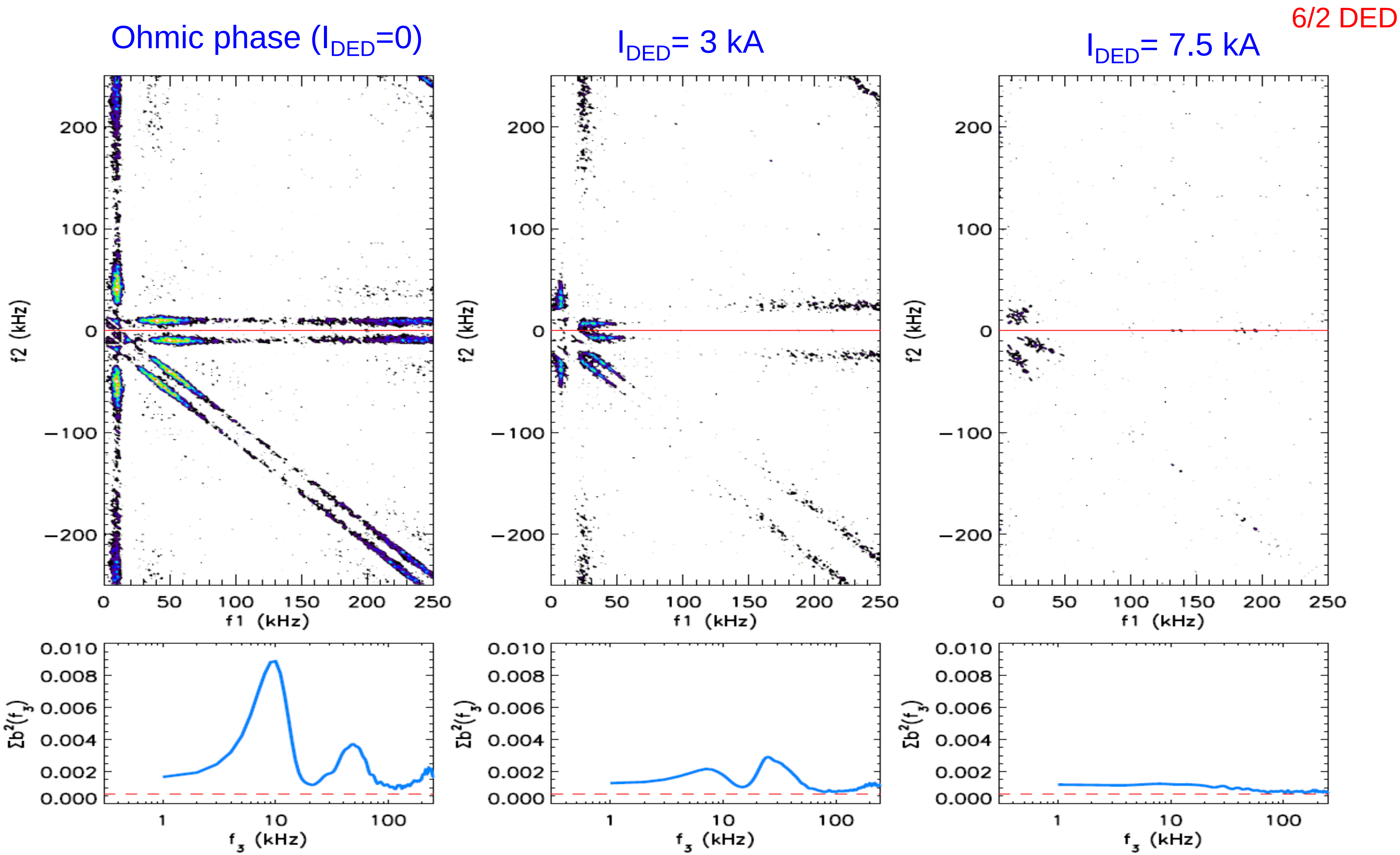
Ohmic phase ($I_{DED}$=0) | $I_{DED}$= 3 kA | $I_{DED}$= 7.5 kA




RMP reduces the LRC ($V_f$), which is dominated by GAM oscillations.

Y. Xu et al., IAEA (2010), EXC/9-3

# Impact of RMP on GAM zonal flows

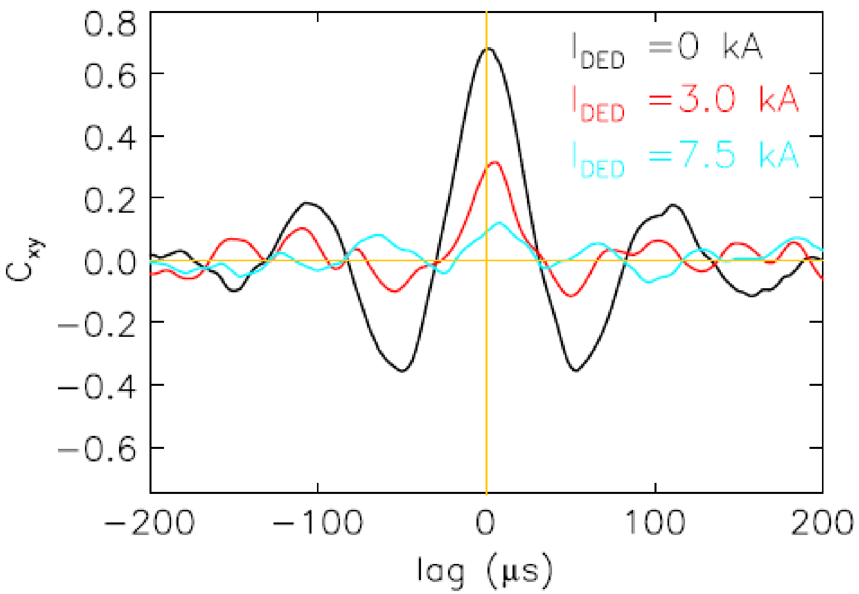



Y. Xu et al., PPCF**53**, 095015 (2011)

# Impact of RMP on GAM zonal flows

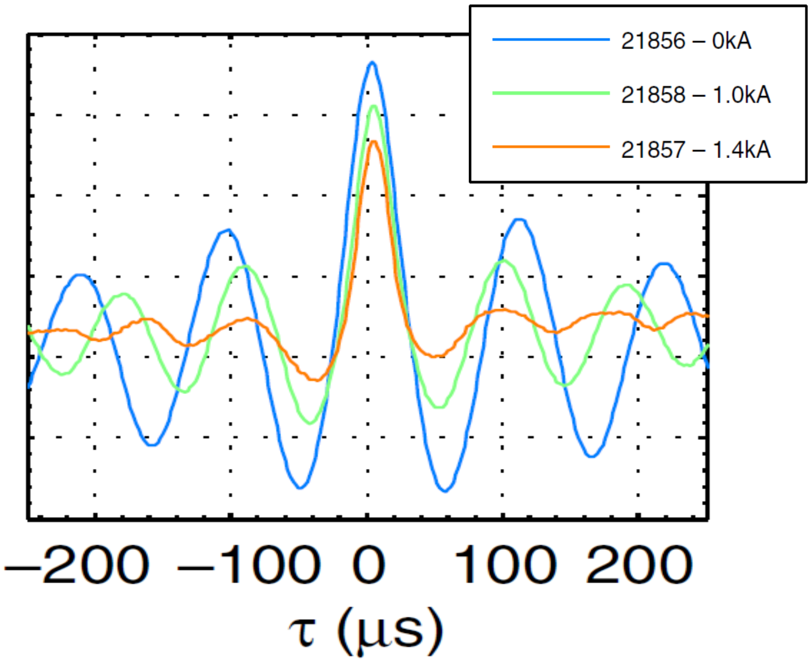
GAM frequency ≈ 10 kHz

**TEXTOR**



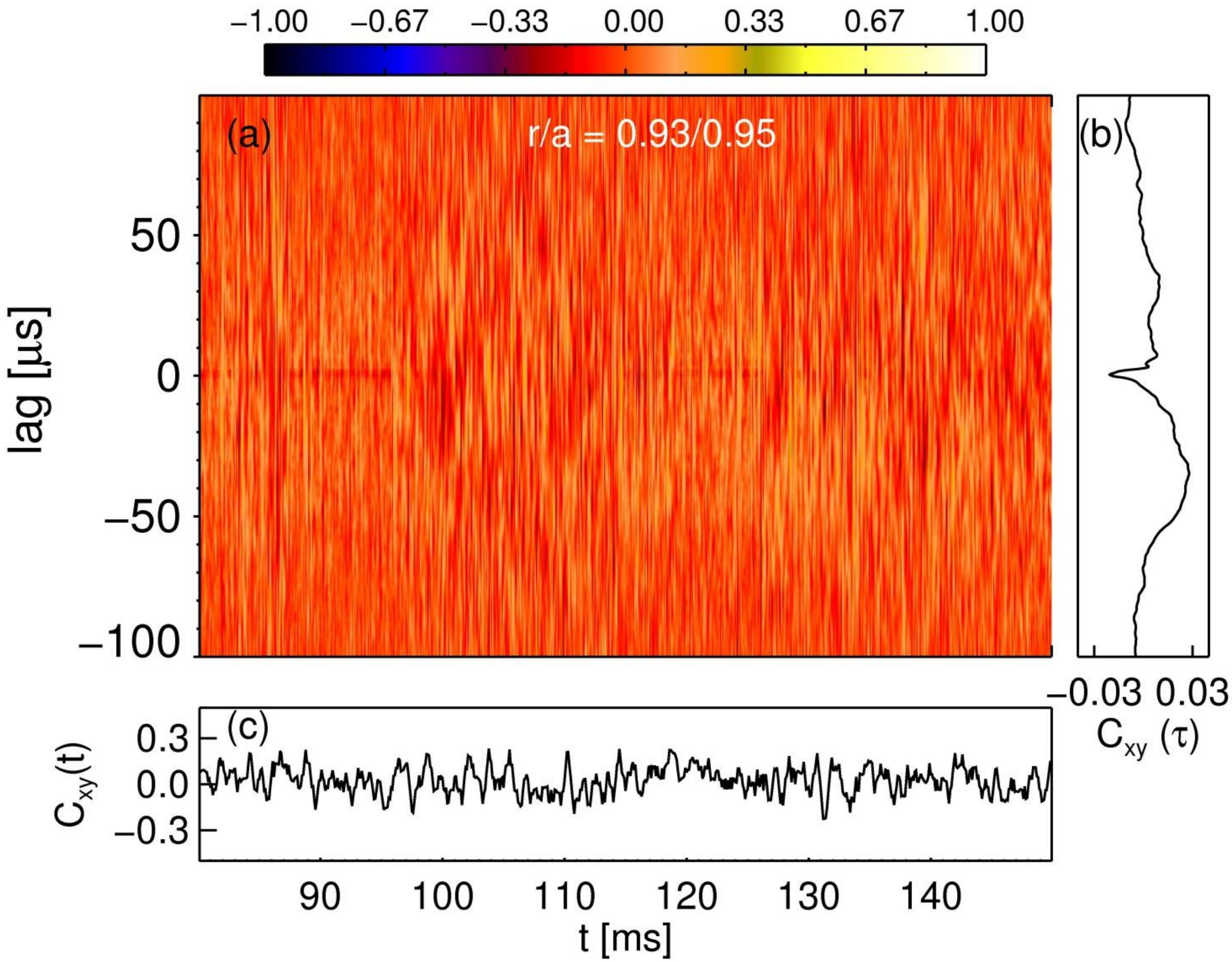

Y. Xu et al., NF**51**, 063020 (2011)

**MAST**




J. Robinson, PPCF**54**, 105007 (2012)

# Impact of RMPon LRC and zonal flows (RFX-mod)




- Whereas LRCs are observed in tokamaks & stellarators, no clear signature of the LRC was seen hitherto in the edge of RFX-mod.
- The absence of LRC (ZF) in the RFP may due to magnetic stochasticity of island chains.

P. Scarin et al., IAEA (2010), Daejeon

# Possible mechanism – parallel dynamics (D. Reiser, et al.,)

$$\frac{M_i n_0}{B^2}\frac{\partial}{\partial t}\nabla_\perp^2\tilde{\phi} = \nabla_{//}\tilde{J}_{//} - \kappa(\tilde{p}) \qquad (1)$$

$$M_i n_0 \frac{\partial \tilde{V}_{//,i}}{\partial t} = -\nabla_{//}(\tilde{p}) \qquad (2)$$

$$\frac{\partial \tilde{n}}{\partial t} = \frac{1}{e}\nabla_{//}\tilde{J}_{//} - \nabla_{//}(n_0\tilde{V}_{//,i}) + n_0\kappa(\tilde{\phi}) - \frac{1}{e}\kappa(\tilde{p}) \qquad (3)$$

$$\nabla_{//}\tilde{p}_e - n_0 e\eta_{//}\tilde{J} - n_0 e\nabla_{//}\tilde{\phi} = 0 \qquad (4)$$

$$\kappa = \frac{2}{B_0 R_0}\left(\sin\theta\frac{\partial}{\partial r} + \cos\theta\frac{\partial}{r_0\partial\theta}\right)$$

$$\nabla_\perp^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r_0^2}\frac{\partial^2}{\partial\theta^2}$$

$$\nabla_{//} = \boxed{\frac{1}{qR_0}\frac{\partial}{\partial\theta} + \cancelto{0}{\frac{1}{R_0}\frac{\partial}{\partial\varphi}}} \boxed{+\frac{1}{r_0 B_0}\left(\frac{\partial A^*}{\partial\theta}\frac{\partial}{\partial r} - \frac{\partial A^*}{\partial r}\frac{\partial}{\partial\theta}\right)}$$

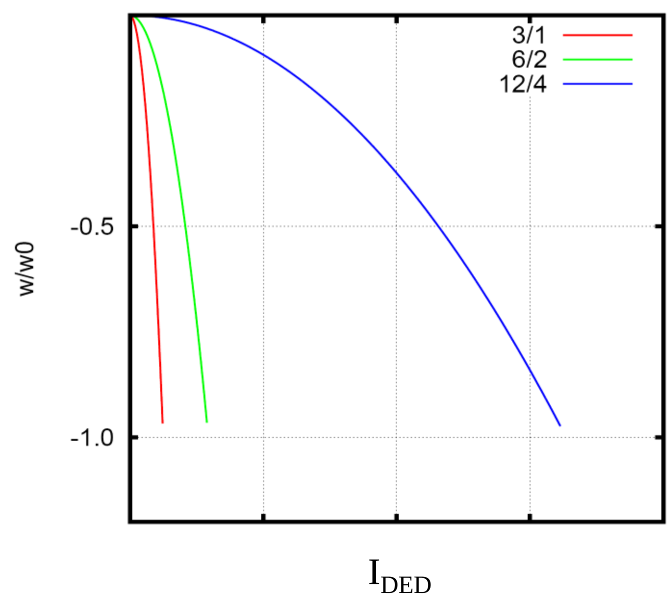
$$A^* = A_0(r)\cos(m_*\theta - n_*\varphi), \qquad B_r = m_* A_0 / r_0$$

$$\frac{\partial\tilde{V}}{\partial t} = -\frac{C_s^2}{R_0 n_0}\tilde{n} - \gamma_{RMP}\tilde{V}, \qquad \gamma_{RMP} = \frac{m_*^2 A_0^2}{2r_0^2 m_i n_0 \eta_{//}}$$

$$\omega^3 + i\gamma_{RMP}\omega^2 - \frac{2C_s^2}{R_0^2}\left(1+\frac{1}{2q^2}\right)\omega - i\frac{\gamma_{RMP}C_s^2}{q^2R_0^2} = 0$$

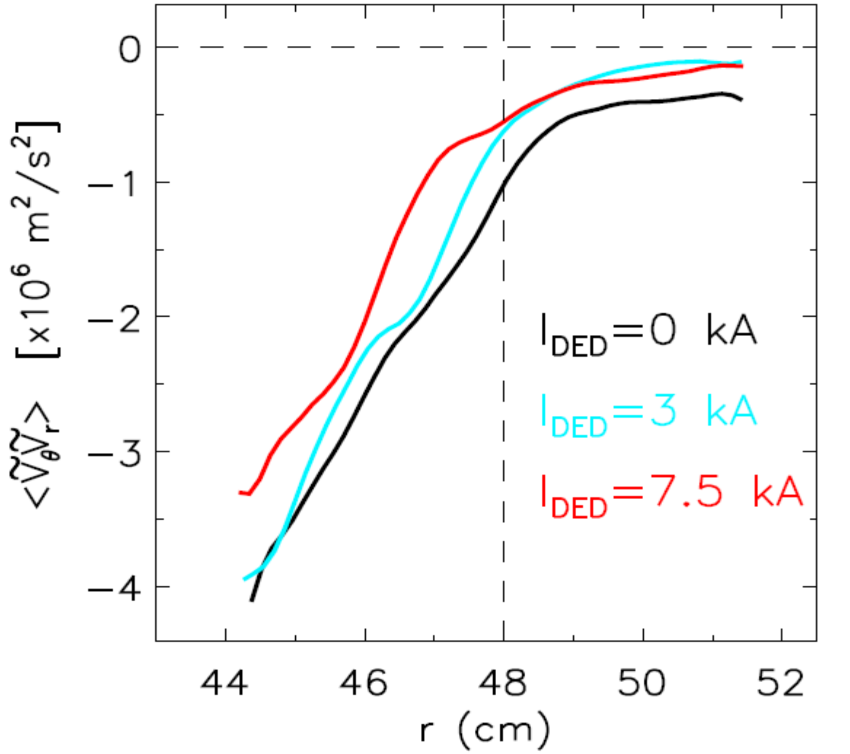
w/o RMP, $\gamma_{RMP}=0$ $\Rightarrow$ $$\omega^2 = \frac{2C_s^2}{R_0^2}\left(1+\frac{1}{2q^2}\right)$$

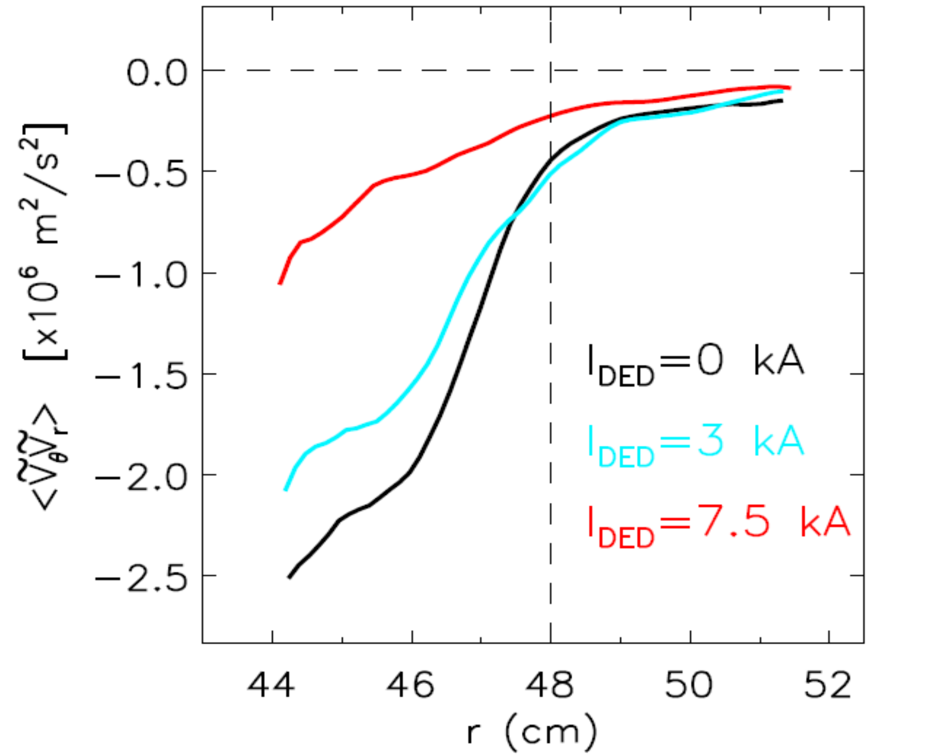
With RMP, $\gamma_{RMP} \neq 0$ $\Rightarrow$ damping effects on GAM !




**However, the complete effects by RMP on turbulence coupling are much more complex !**

# Impact of RMP on the radial profile of Renolds stress




$I_p$=200kA, q(a)=6.3, $\langle n_{e0} \rangle$=1.0x10$^{19}$ cm$^{-3}$

$I_p$=250kA, q(a)=5.9, $\langle n_{e0} \rangle$=1.5x10$^{19}$ cm$^{-3}$

# More sophisticated model

$$\frac{M_i n_0}{B^2}\frac{\partial}{\partial t}\nabla_\perp^2\tilde{\phi} = \nabla_{//}\tilde{J}_{//} - \kappa(\tilde{p}) \quad + \langle \tilde{V}_r \widetilde{V_\theta} \rangle$$

by **M. Leconte and P. Diamond**

Phys. Plasmas **18**, 082309 (2011)

Phys. Plasmas **19**, 055903 (2012)

$$M_i n_0 \frac{\partial \tilde{V}_{//,i}}{\partial t} = -\nabla_{//}(\tilde{p})$$

$$\frac{\partial \tilde{n}}{\partial t} = \frac{1}{e}\nabla_{//}\tilde{J}_{//} - \nabla_{//}(n_0 \tilde{V}_{//,i}) + n_0\kappa(\tilde{\phi}) - \frac{1}{e}\kappa(\tilde{p}) \quad - \widetilde{V_E}\cdot\nabla n$$

$$\nabla_{//}\tilde{p}_e - n_0 e \eta_{//}\tilde{J} - n_0 e \nabla_{//}\tilde{\phi} = 0$$

RMP induce a linear coupling of zonal potential and zonal density

➡ reduction of zonal flow energy by a *predator-prey* process.

➡ Increase of L-H transition power threshold

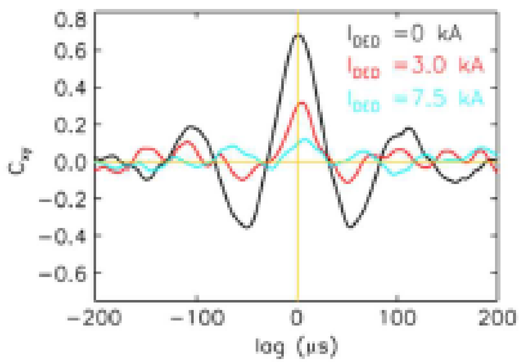
# What is the "cost-benefit ratio" of RMP ?

(P. Diamond, Alfven Lecture 2011, Strasbourg)

## Progress I: ZF's with RMP (with M. Leconte)

- ITER 'crisis du jour': ELM Mitigation and Control
- Popular approach: RMP
- ? Impact on Confinement?

Y. Xu '11




⇒ RMP causes drop in fluctuation LRC, suggesting reduced Z.F. shearing

⇒ What is "cost-benefit ratio" of RMP?

- Physics:
  - in simple H-W model, polarization charge in zonal annulus evolves according:

$$\frac{dQ}{dt} = -\int dA \left[ \langle \tilde{v}_x \tilde{\rho}_{pol} \rangle + \left( \frac{\delta B_r}{B_0} \right)^2 D_\parallel \frac{\partial}{\partial x} (\langle \phi \rangle - \langle n \rangle) \right]_{r_1}^{r_2}$$

  - Key point: $\delta B_r$ of RMP induces radial electron current → enters charge balance

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# Summary

- With RMP, edge equilibrium profiles ($n_e$,$T_e$, $V_f$, $E_r$) are modified.
- With RMP, edge fluctuation amplitudes and transport are affected.
- With RMP, both S(f) and S(k) are modified.
- With RMP, turbulence correlation lengths are changed.
- With RMP, turbulence poloidal propagation changes sign, consistent with $E_r$XB flow change.
- With RMP, blob transport is reduced in the SOL.
- With RMP, GAM zonal flows are suppressed.

All above results suggest that a stochastic magnetic boundary by RMP may have profound influence on edge turbulence and turbulent transport, and hence, for plasma-wall interaction / plasma confinement.