Gyrokinetic turbulence simulations of the pedestal region at various lithium doses in NSTX

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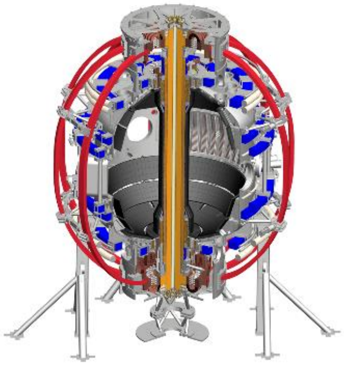


ABSTRACT

It is shown that lithium-coated walls alter the pedestal structure by, for instance, improving the energy confinement and reducing recycling. Recent work shows improved discharge characteristics with increasing lithium doses in highly shaped discharges. Edge-localized modes triggered by large edge pressure and current gradients are altered, even suppressed with increasing lithium doses.

In this work, the plasma edge characteristics under increasing lithium doses are investigated with GS2 gyrokinetic code. Using experimental discharges as input parameters, microinstabilities are investigated in the pedestal region and the effect of increasing lithium doses on these microinstabilities is discussed.

Outline

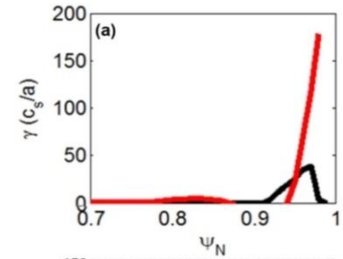
- Background
  - Linear analysis of modes in low δ confinement regime with – without Li
- Motivation: H-mode regime
  - Comparison of discharge profiles with – without Li in H-mode regime
- Linear analysis of modes : overview
- Wavenumber scans: W – W/O Li
  - Low $k_\theta \rho$-TEM/KBM/MTM/ITG
  - High $k_\theta \rho$ – TEM/ETG
- Summary

Background: low δ confinement regime

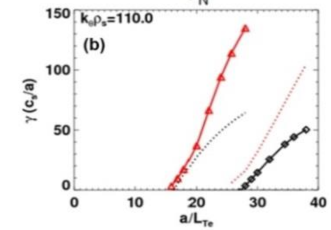
J. Canik, NF, **53** (2013): Analysis of edge plasma in NSTX w-w/o Li coatings

Figures after J. Canik
γ growth rate
ω real frequency

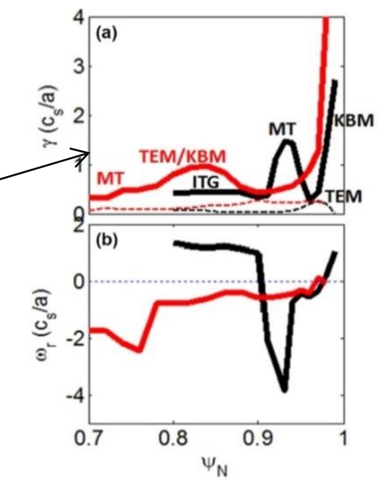
- ✓ ETG more unstable with Li



- ✓ Stabilization of MT modes due to the flattening of ∇ne with Li
  - ✓ Reduction of the energy transport at the top of the pedestal region



- ✓ ELMs stabilization and confinement improvement with Li due to the flattening of ∇ne
  - ✓ ∇p and thus $j_b \propto \nabla p$ are reduced → stabilization of peeling-ballooning modes responsible for type-I ELMs

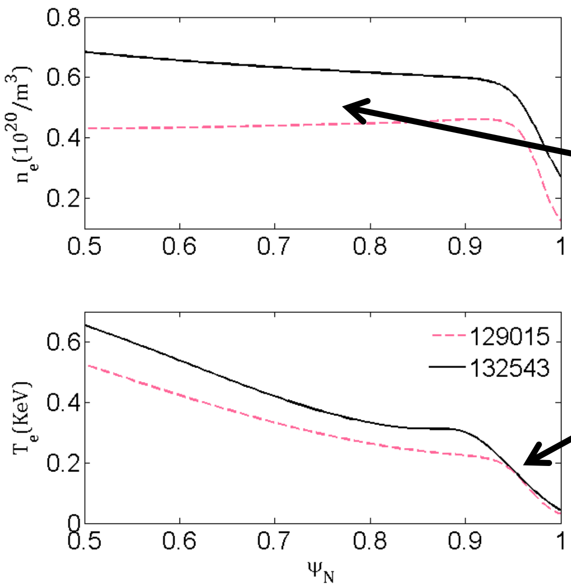


- ✓ Hybrid TEM/KBM observed at steep ∇n, ∇T w-w/I Li

In all the figures: without (black) and with (red) lithium

Influence of the plasma shaping on the confinement geometry

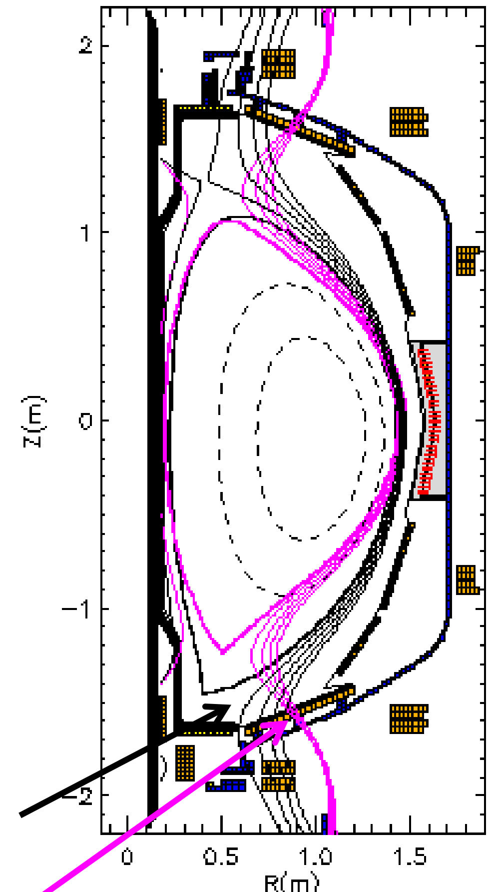
R. Maingi, JNM, **463** (2015): Dependence of recycling and edge profiles on lithium evaporation



Increase in n_e in high δ discharges mainly towards the core

No clear change in T_e within the pedestal

Edge profiles of the reference shots in low and high δ confinement discharges



Clear geometry change between low and high δ confinement regimes (increase in the confinement volume in high δ)

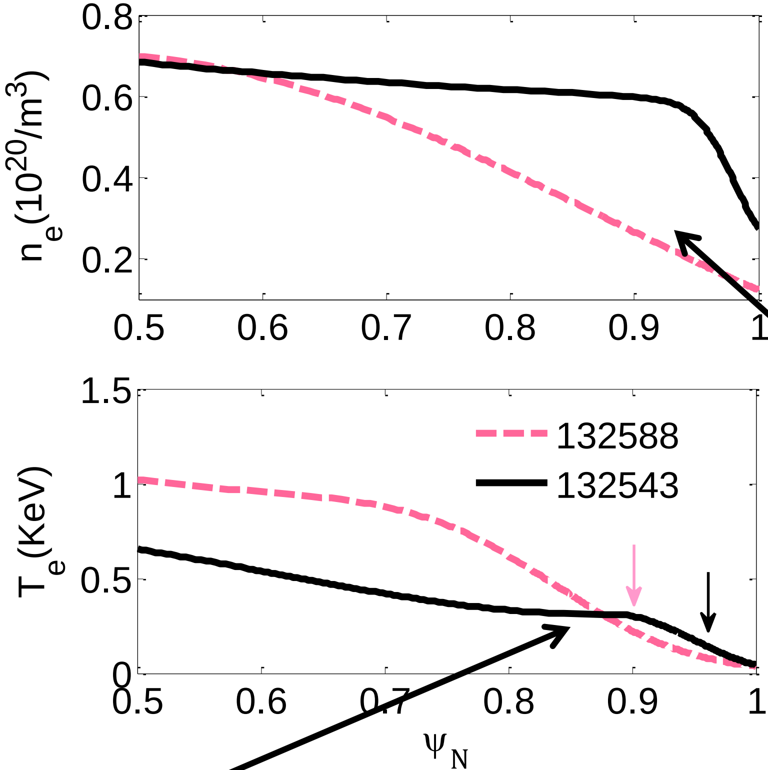
Shot #132543 (H)

Shot #129015 (low δ)

Li coating widens the edge pedestal in H-mode discharges

R. Maingi, JNM, **463** (2015): Dependence of recycling and edge profiles on lithium evaporation

Profiles of the reference and 550mg Li shots

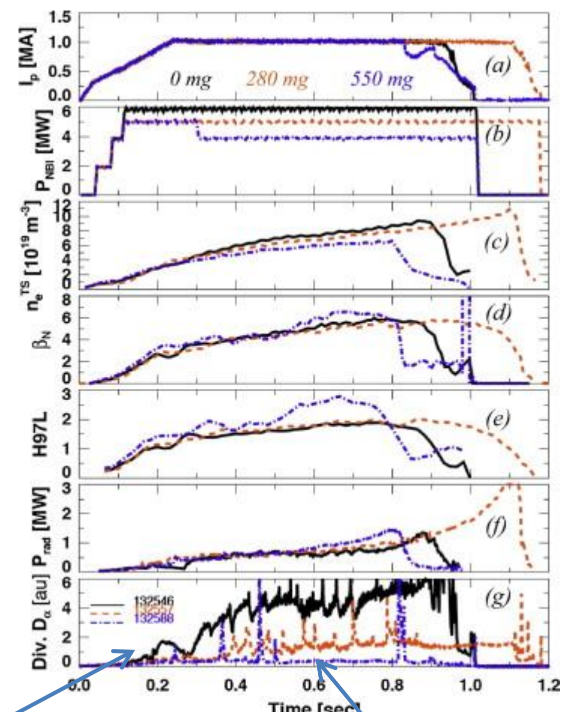


→Discharge performance improved with increased Li doses due to reduced recycling

→ Elimination of ELMs with 550mg Li

Flattening of the edge profiles with Li
→ suppression of ELMs

Figure 2 after R. Maingi:
Comparison of discharges at
280 mg #132557
550 mg Li doses #**132588**
Reference non-Li #**132543**



Increase of T_e with Li at $\psi_N < 0.9$

$\downarrow D_\alpha$ signal with ↑ Li doses (reduced recycling)

Suppression of ELMs with ↑ **Li doses**

Linear analysis of modes for the reference and high Li dose study cases: overview

GS2 (*) continuum local (flux tube) code solving gyro averaged (5D) Boltzmann equation coupled with Maxwell's equations →Simulation of turbulence (δf) and fluxes in linear approximation or non linear generalization

- Linear analysis of modes using the local gyrokinetic code GS2 :
  - 3 species: e^-,D,C; electromagnetic; fixed geometry;
  - Eingenfunctions parity;
  - Sign of real frequency:+ (-) ω ion (electron) diamagnetic direction;
  - Convergence tests and linear scans over $\beta, \nabla n, \nabla T_e, \nu_e, \nabla T_i$….

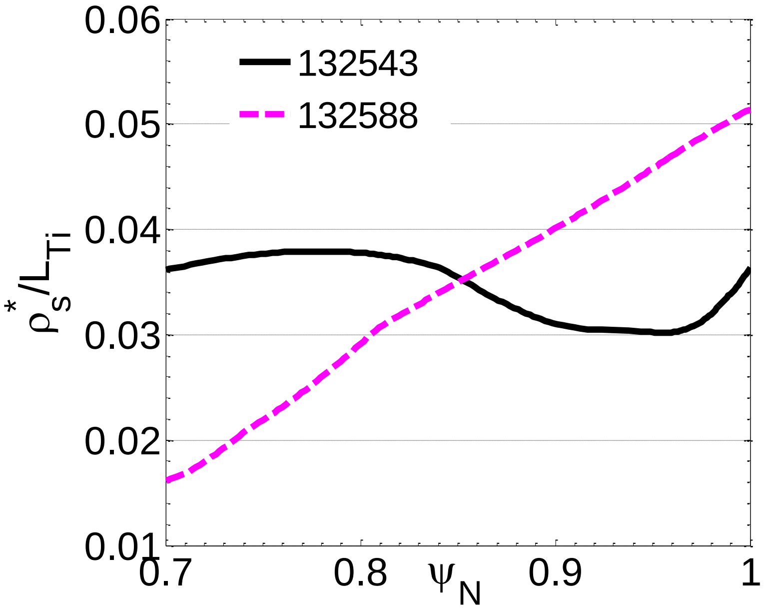
Goals:

- ➢Investigation of the onset of KBM
- ➢Investigation of ETG limiting ∇Te at plasma edge
- ➢Investigation of the flattening of profiles with Li → Elimination of ELMS?…..

(*) M. Kotschenreuther, CPC, 88 (1995)

Validation of the gyrokinetic assumption

Gyrokinectic ordering Rutherford and Frieman 68:
$\frac{\rho}{L} \ll 1$, with ρ the gyroraduis and L the gradient length



Ratio of the ion gyroradius ρ^* over the smallest gradient length L for the reference and 550 mg Li shots

→For local scale length close to the ion gyroradius→ reaching the limit of the gyrokinectic ordering ?
Shot # 132543 at $\psi_N = 0.95 \ - \frac{\rho}{L} \sim 0.03$
Shot # 132588 at $\psi_N = 0.90 \ - \frac{\rho}{L} \sim 0.04$

→Local and global analyses converge for $1/\rho^* > 300$[(*)] → Global (and non-linear) calculations needed to study transport properties

[(*)]B. F. McMillan, PRL 105, 155001 (2010)

Approach used for modes identification

Identification of modes:

- From the spectrum and at a given ψ_N , select wavenumbers from 'branches' in the spectrum
- At a given ψ_N and wavenumber:
  - Check the parity of the eigenfunctions and the sign of the frequencies
  - Perform parameter scans around the experimental values (keeping fixed GS2 geometry parameters calculated from numerical equilibria based on experiments) to identify thresholds

For instance:

ETG → driven by critical ∇Te : -ω , 'high' $k_\theta \rho$, 'high' γ , electrostatic nature, ….scan around $\nabla Te, exp$

KBM →unstable at 'high' β, driven by steep ∇p : +ω , 'low' $k_\theta \rho$, twisted $A_{//}$, electromagnetic nature,….scan around $\nabla T/n,$ exp; $\beta_{e,exp}$

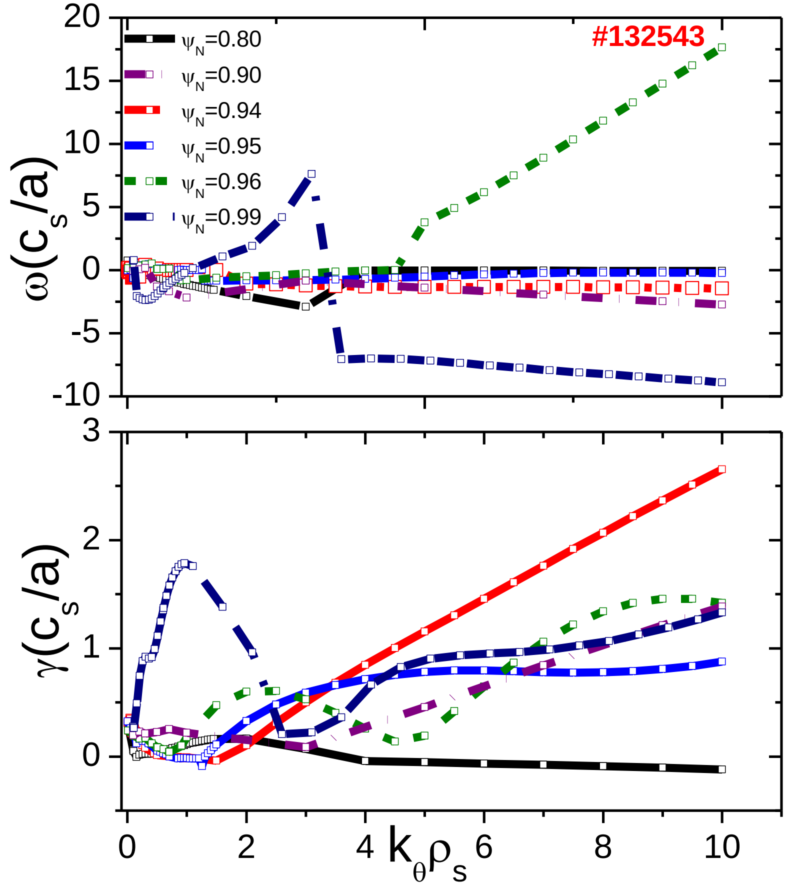
W. Guttenfelder Plasma Conference 2011 - NSTX turbulence and transport
W. Guttenfelder N.F. **53** 093022 (2013)

Modes survey at various ψ_N: at 'low' $\boldsymbol{k_\theta}\rho$

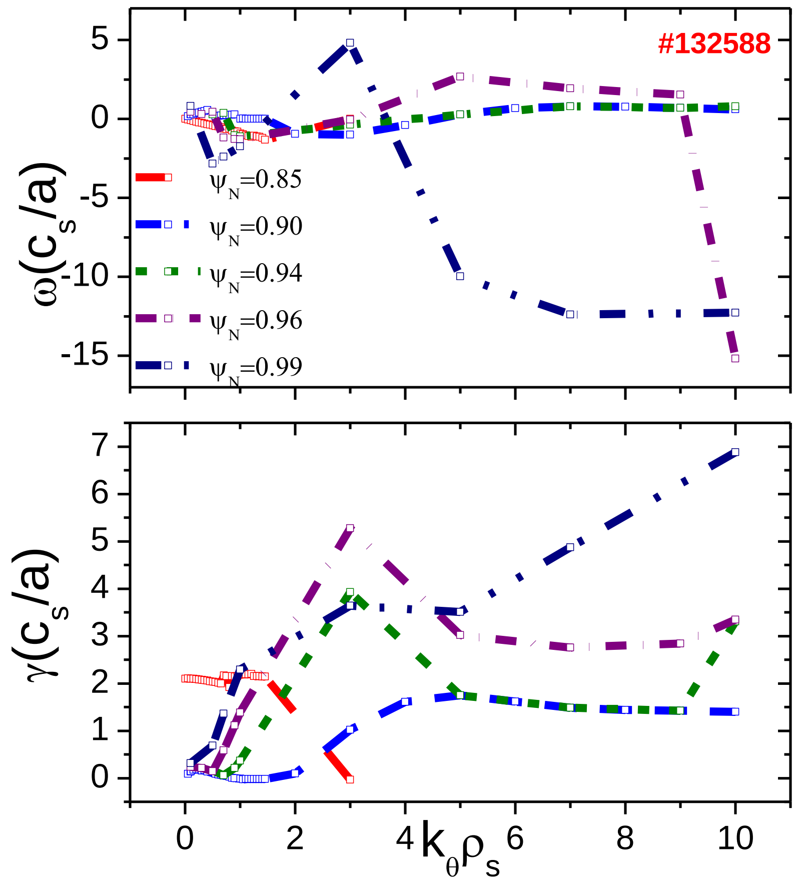
At a sameΨ_N:
- series of $\boldsymbol{k_\theta}\rho$ 'ranges' with (−) and (+) ω

→ Competing modes:
ITG/KBM/MTM/TEM?

No Li



550mg Li

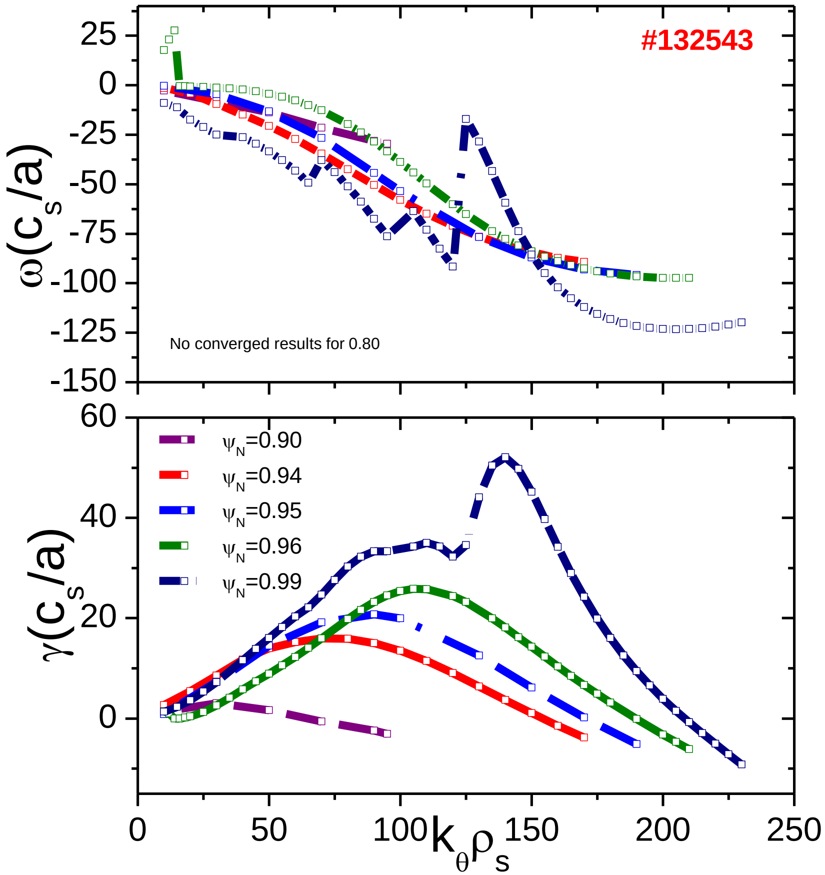


Modes survey at various ψ_N : at 'high' $k_\theta \rho$

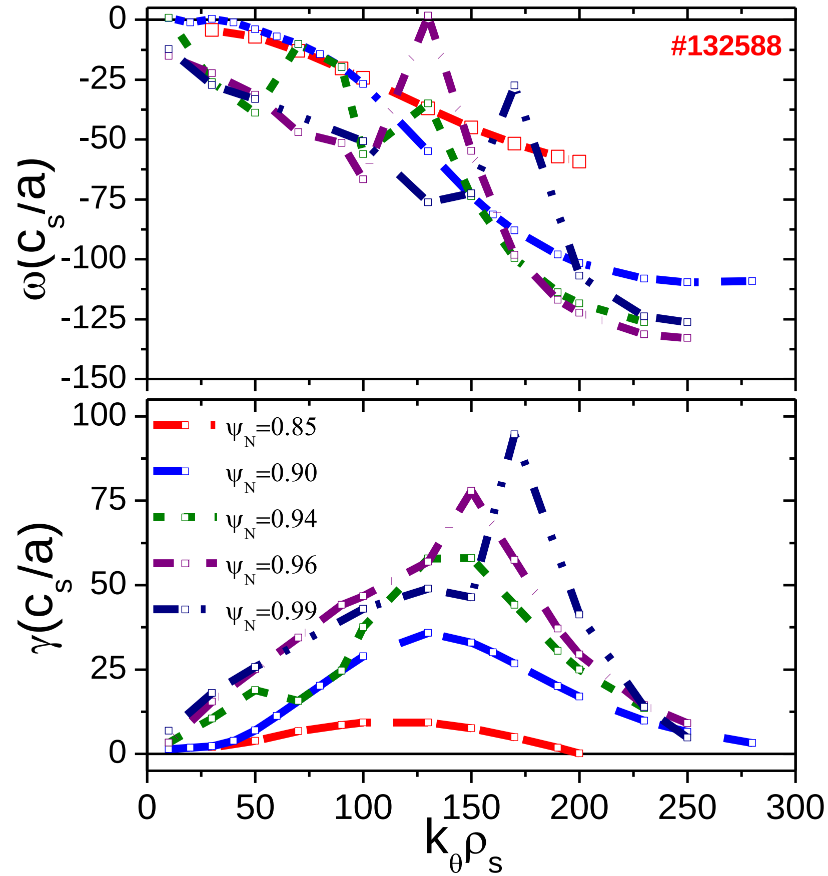
- $-\omega$: e- direction
- 'high' γ
- *'continuous'* $k_\theta \rho$ *range*

→TEM/ETG signature?

No Li



550mg Li



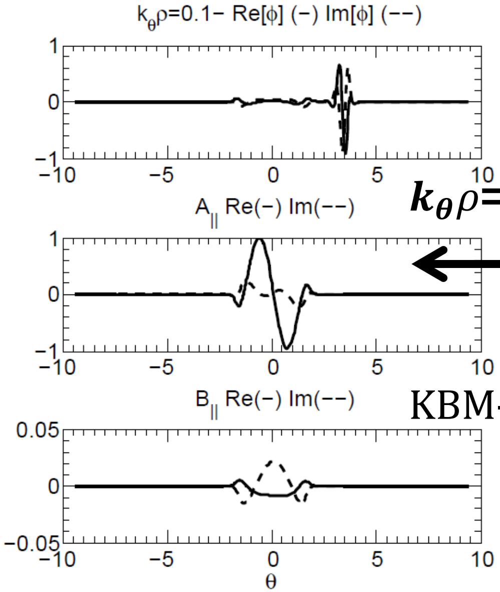
No Li– at $\psi_N = 0.96$; $k_\theta\rho$~0.10-0.2: different eigenfunction structures are observed

Example case study: #132543

$\phi/A_{//}$~0.7 magnetic/electrostatic nature?

twisted $A_{//}$, ϕ?, + ω~0.4,γ~0.18

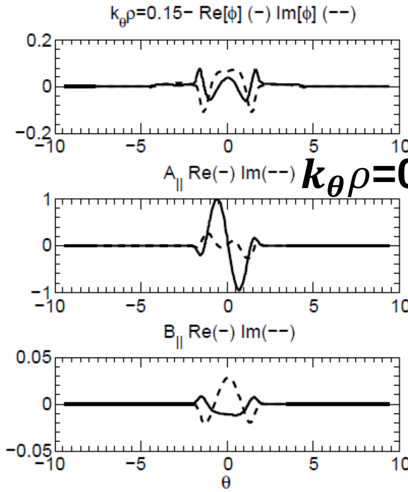
magnetic nature



$k_\theta\rho$=0.1

KBM-like

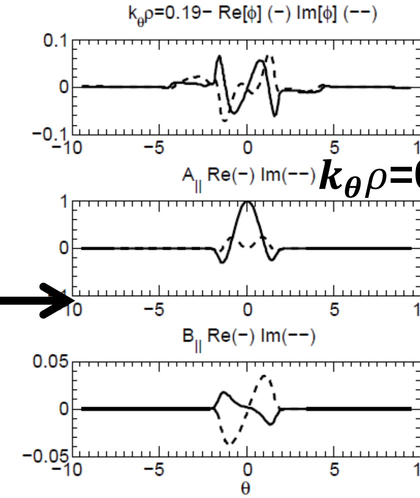
ballooning structure



$k_\theta\rho$=0.15

KBM-like

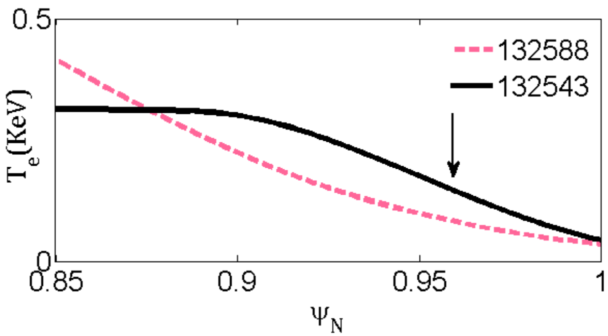
tearing parity



$k_\theta\rho$=0.19

MTM-like

Normalized eigenfunctions of the modes at $k_\theta\rho$=0.1,0.15,0.19 ; θ normalized poloidal angle;



a different eigenfunction structure is found for each wavenumber

→ hybrid/competing modes?

→ $k_\theta\rho$=0.1: check results of the parameter scans $\nabla T/n, exp$, $\beta_{e,exp}$

No Li−at $\psi_N = 0.96; k_\theta\rho$~0.1: the parameters scan suggests that the mode is sensitive to ∇n around β_{exp}

Example case study: #132543

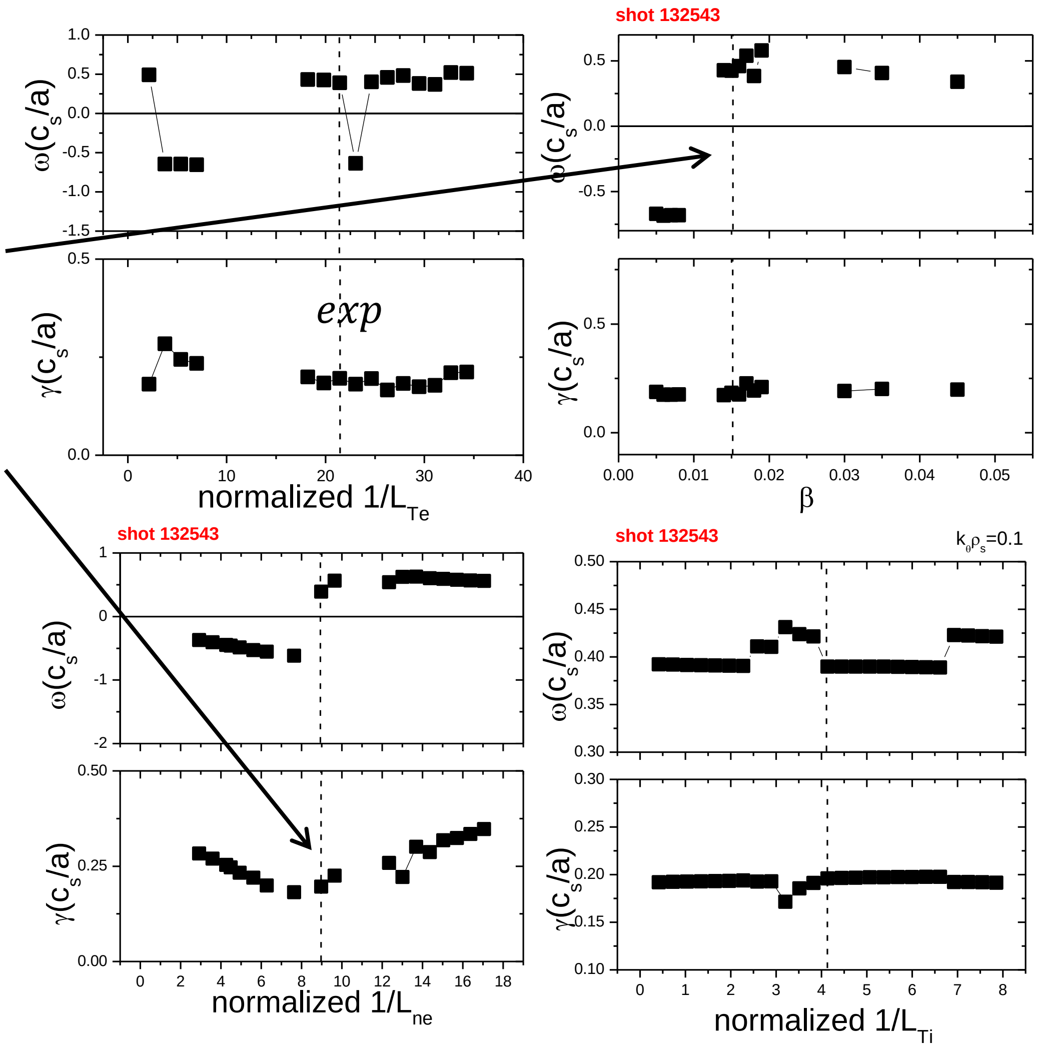
Parameter scans

→ change from $-\omega$ to $+\omega$ around $\nabla nexp$, β_{exp}

→ Sensitivity to ∇n:
increase in γ with increasing $\nabla nexp$

no clear sign of KBM
→(no sensitivity to β)

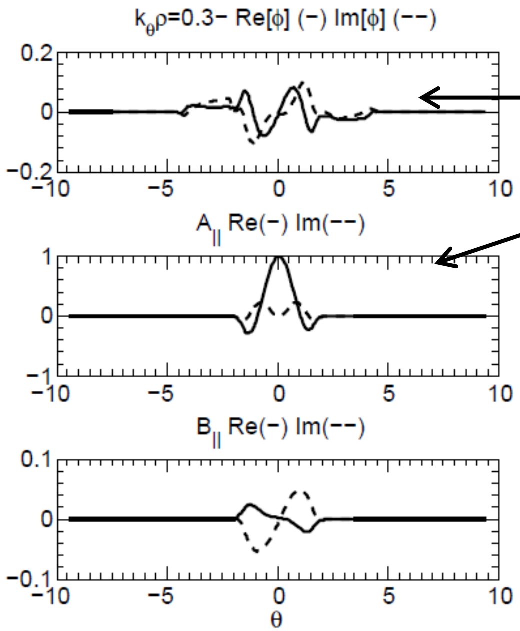
hybrid mode…?



No Li– $at\ \psi_N = 0.96; k_\theta \rho \sim 0.3$: the eigenfunctions present a tearing parity

Example case study: #132543

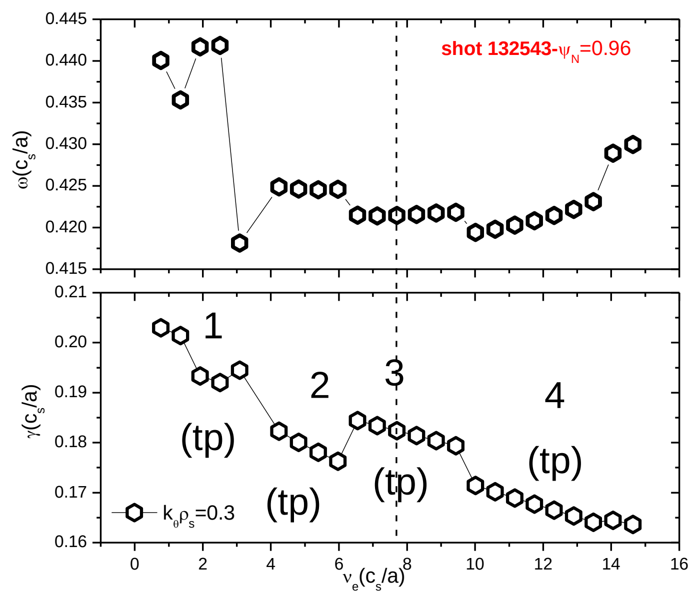
Ø/$A_{//}$<1 magnetic nature



tearing parity (tp) → MTM

however: + ω → KBM

exp ratio $\frac{\nu e}{\omega} \sim 18 > 1$ → KBM



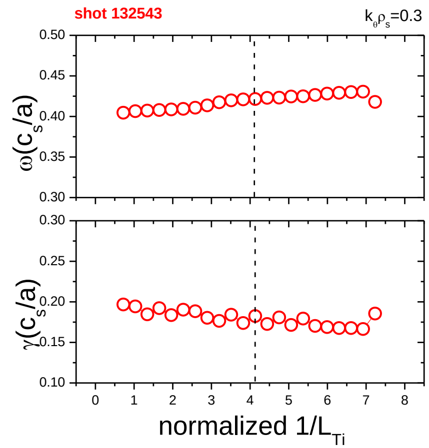
Normalized eigenfunctions of the mode at $k_\theta \rho$=**0.3**;

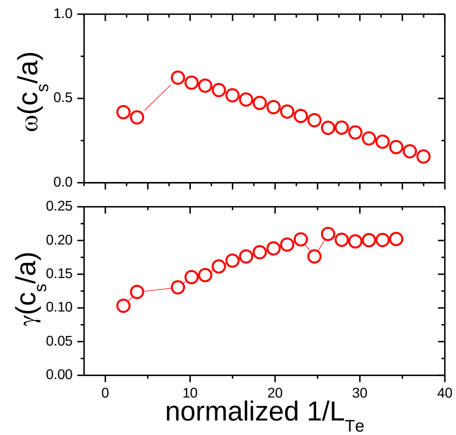
example scan around the experimental νe
→weak dependency on νe
→observation of 'branches' 1,2,3 ,4…→need to check the eigenfunction parity for each branch (tp for all branches)

No Li−at $\psi_N = 0.96; k_\theta \rho \sim 0.3$: the mode is found to be driven by $\nabla T, n$ above $\beta crit$

Example case study: #132543

Parameter scans





→sensitivity to β with an increase in γ with increasing β above β_{crit}

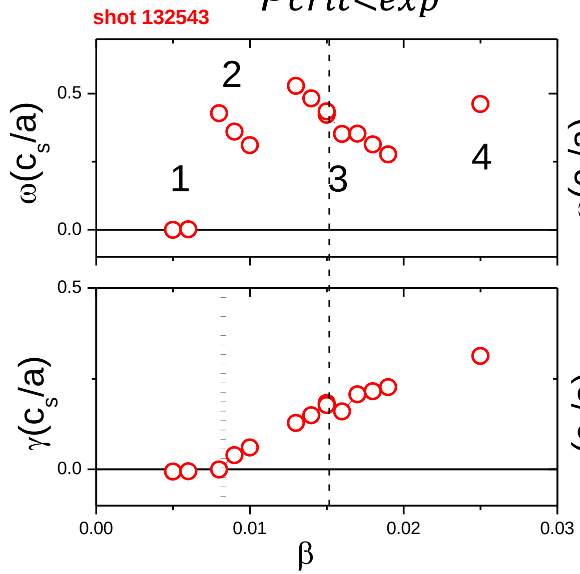
→ sensitivity to ∇n with an increase in γ with increasing ∇n and a shift from − to +ω at ∇n_{crit}

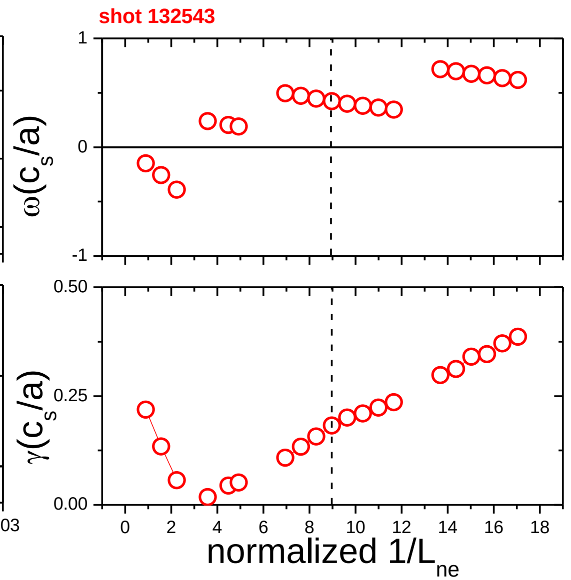
→'small' sensitivity to ∇Te (no clear ∇Te_{crit} from this first scan)

→ $\beta_{crit<exp}$

→observation of 'branches' with eigenfunctions having different parity:

1→(β =0.006) ballooning-like structure
2→(β =0.009) ballooning-like structure
3→(β =0.015) tearing parity
4→(β =0.025) ballooning-like structure



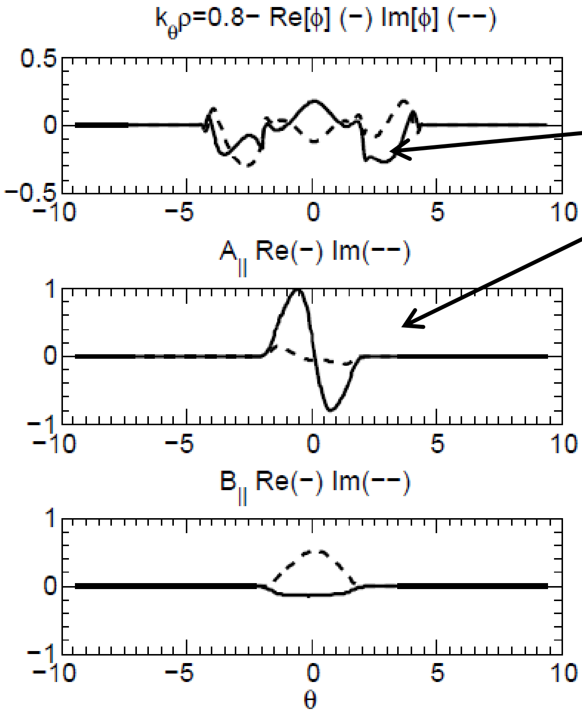


MTM, KBM, hybrid mode…

No Li–at $\psi_N = 0.96$; $k_\theta\rho \sim 0.8$: the eigenfunctions present ballooning-like structures of KBM

Example case study: #132543

Ø/$A_{//}$<1 magnetic nature

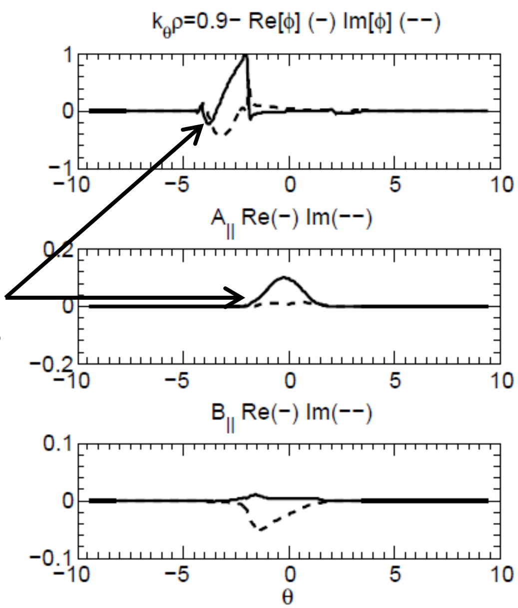


ballooning structure- KBM

odd $A_{//}$, + ω → KBM

exp ratio $\frac{\upsilon e}{\omega} \sim 73 > 1$ KBM

$k_\theta\rho$=0.9



(−)ω , tearing parity-MTM?
→electrostatic nature-TEM?

Normalized eigenfunctions of the mode at ***$k_\theta\rho$*=0.8**;

KBM is usually predicted at $k_\theta\rho$<0.2

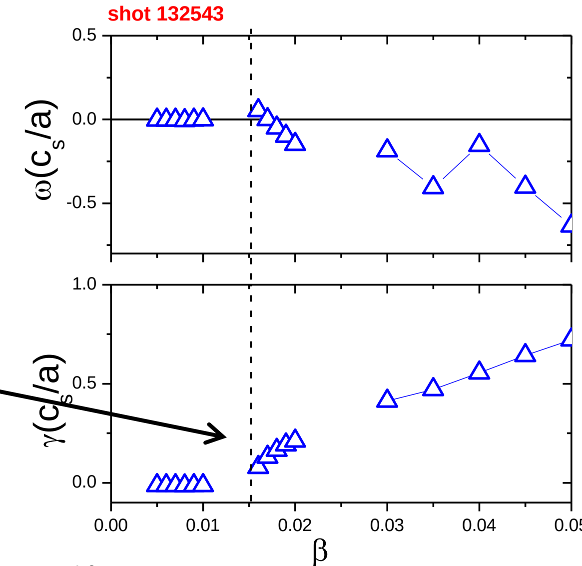
No Li–at $\psi_N = 0.96; k_\theta\rho$~0.8: KBM found to be driven by $\nabla T, n$ above $\beta crit$ around experiments

Example case study: #132543

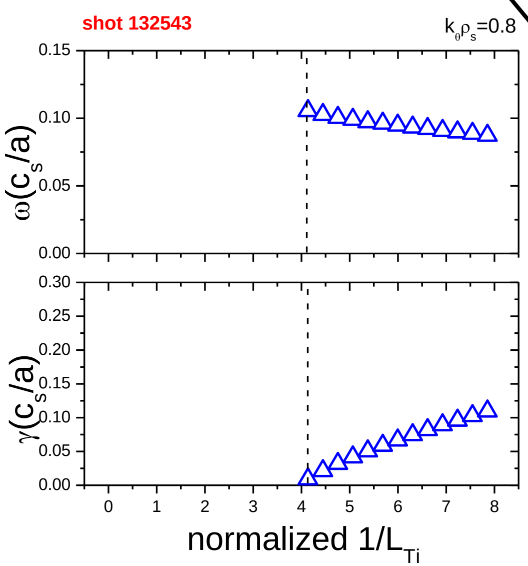
Parameter scans

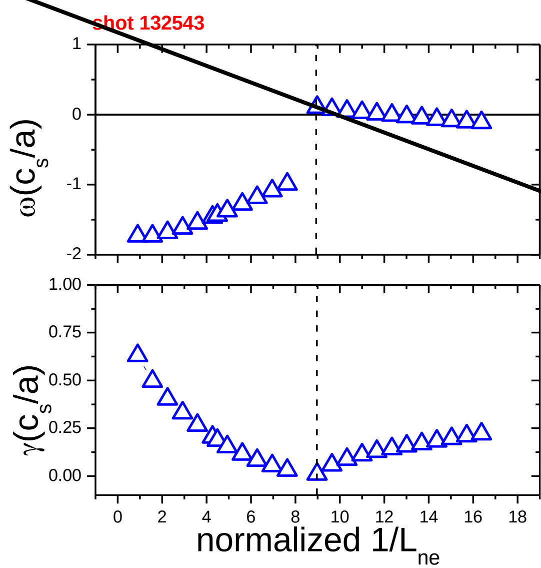
→sensitivity to β with an increase in γ with increasing β above β_{crit} found around experiments

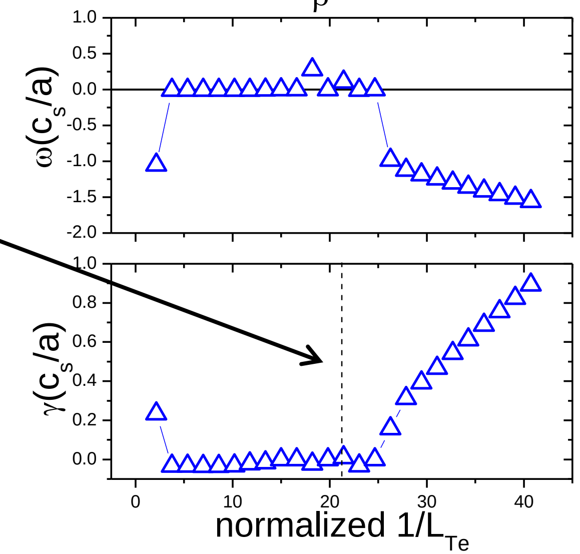
→ sensitivity to $\nabla T, n$ with an increase in γ with increasing gradients above critical gradients at around experiments



KBM



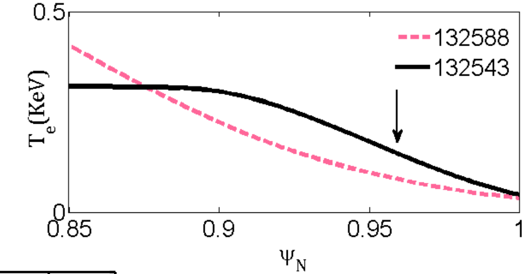




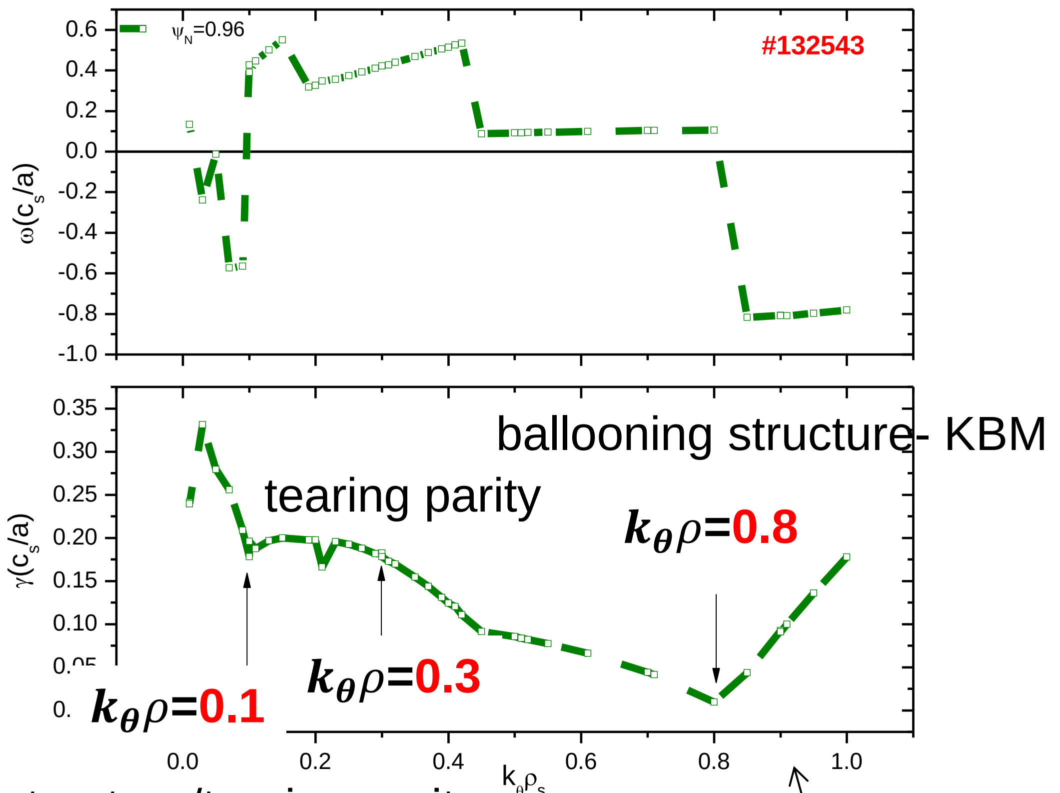
No Li−Low $k_\theta \rho$-summary mode survey at at $\psi_N = 0.96$

Example case study: $\#132543, \psi_N = 0.96$

→summary of first observations



wavenumber scan
$\#132543, \psi_N = 0.96$



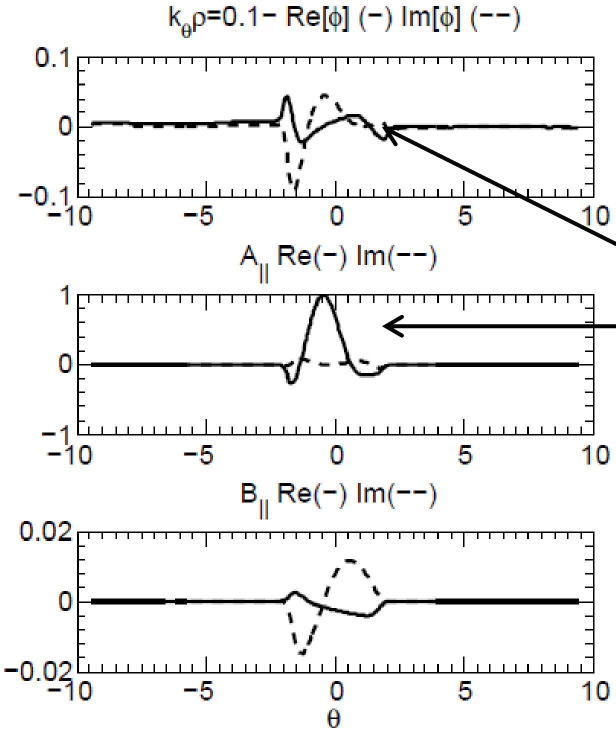
ballooning structure/tearing parity

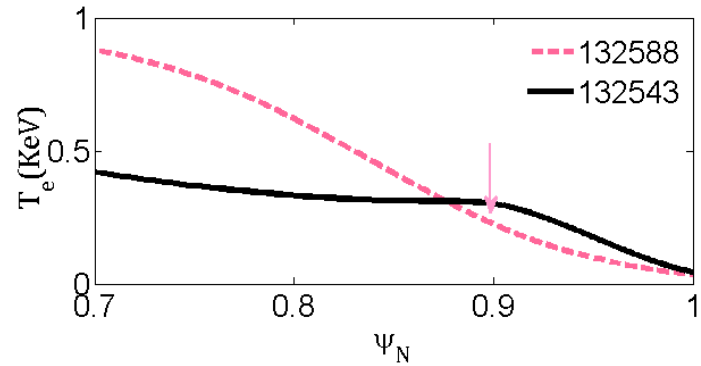
tearing parity

Li−at $\psi_N = 0.90$; $k_\theta \rho$=0.1-0.3: eigenfunctions with tearing-like parities and (+)ω suggest competing modes

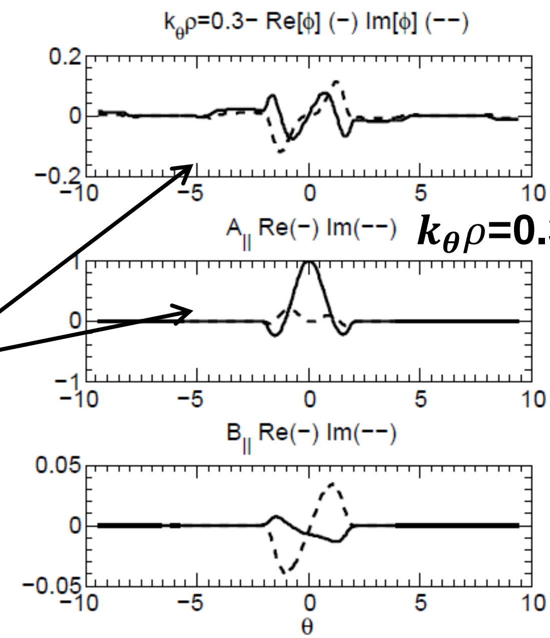
Example case study: #132588

$\emptyset/A_{//}$<1 magnetic nature





tearing parity- MTM
(+) ω → KBM



$k_\theta \rho$=0.3

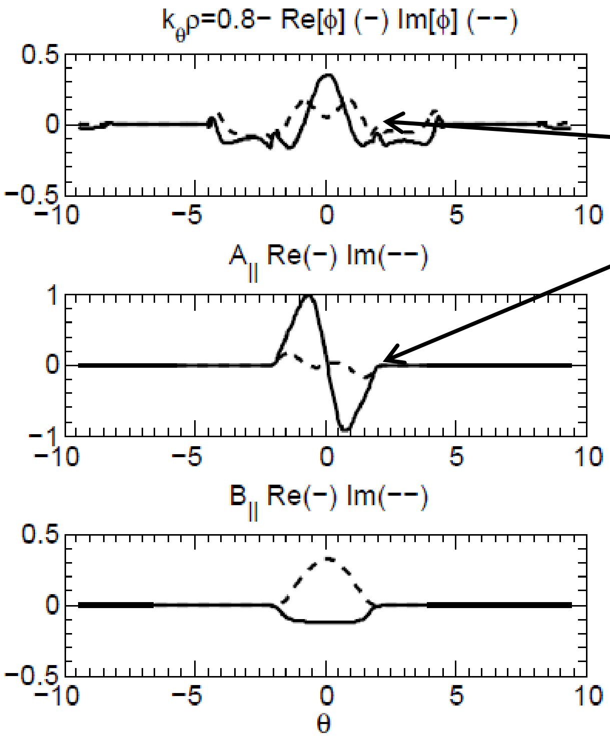
(+)ω - tearing parity
KBM - MTM

Normalized eigenfunctions of the mode at $k_\theta \rho$=0.1;

Li−at $\psi_N = 0.90$; $k_\theta\rho$=0.8: eigenfunctions with ballooning-like structures and (+)ω suggest KBM

Example case study: #132588

Ø/$A_{//}$<1 magnetic nature



Normalized eigenfunctions of the mode at $k_\theta\rho$**=0.8**;

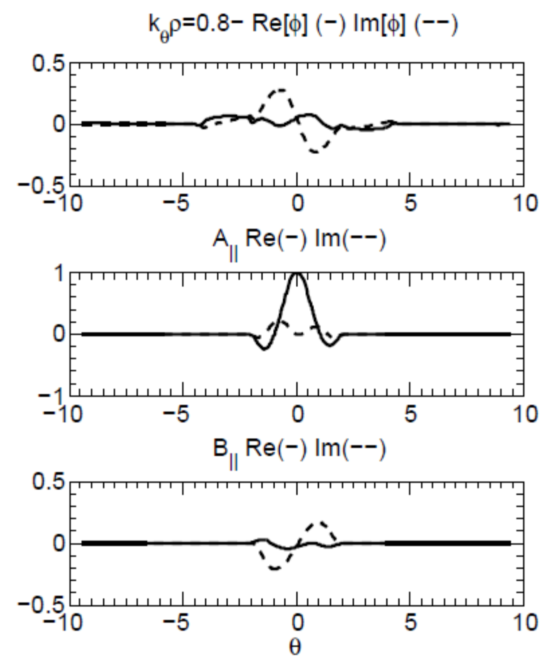
ballooning structure
(+) ω → KBM

β increased

tearing parity

MTM-like structure

$k_\theta\rho$**=0.8** β=0.03



Li–at $\psi_N = 0.90; k_\theta\rho$~0.1-0.8: KBM found to be driven by $\nabla T, n$ above $\beta crit$ around experiments

Example case study: #132588

Parameter scans

$k_\theta\rho$**=0.1-**tearing parity

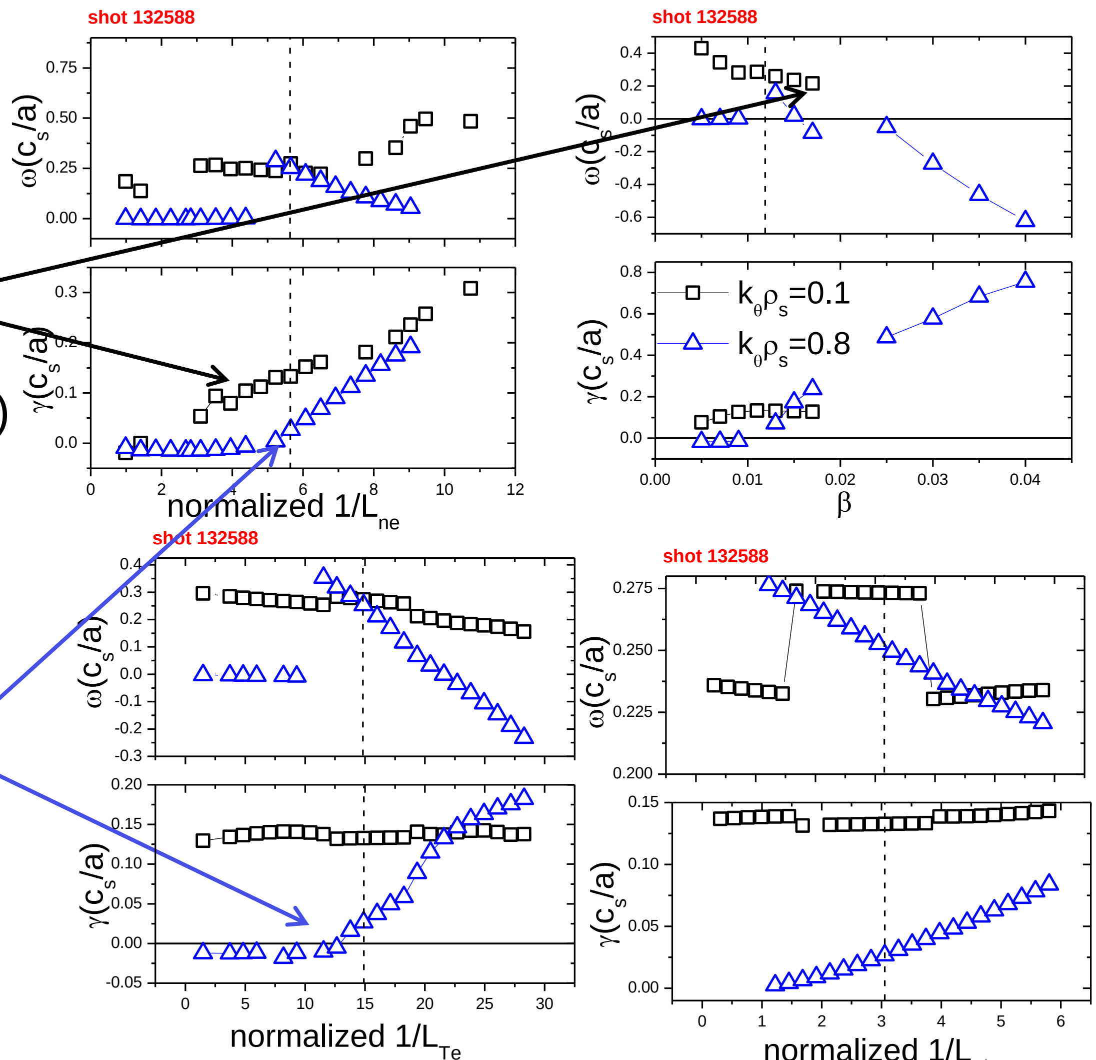
→sensitivity to β : mode suppressed with increasing β

ITG? (no clear sensitivity to ∇Ti)

→ sensitivity to ∇n mainly

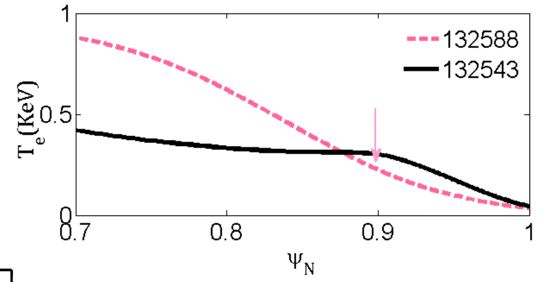
$k_\theta\rho$**=0.8-** KBM

→sensitivity to $\beta, \nabla T, n$: increase in γ with increasing $\beta, \nabla T, n$ above β_{crit} found around experiments



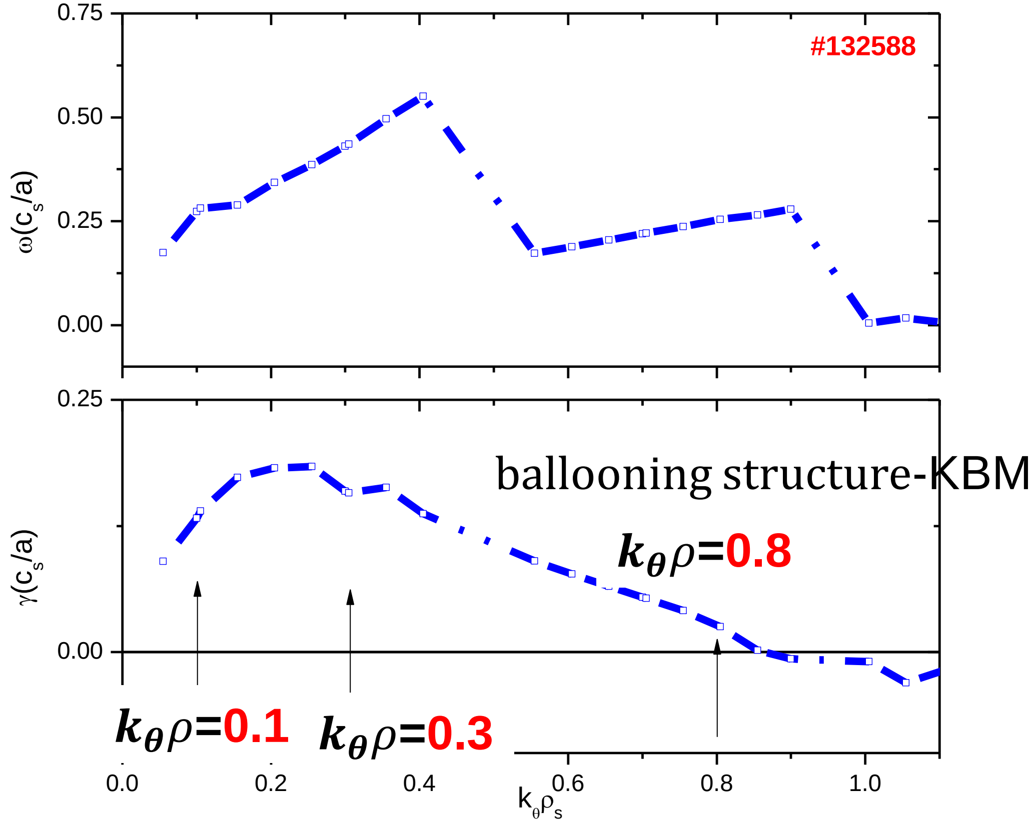
Li–Low $k_\theta \rho$-summary mode survey at $\psi_N = 0.90$

Example case study: $\#132588, \psi_N = 0.90$



→summary of first observations

wavenumber scan
$\#132588, \psi_N = 0.90$

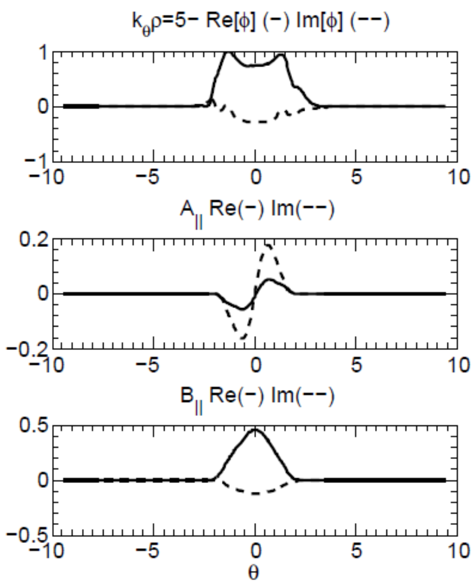


tearing parity

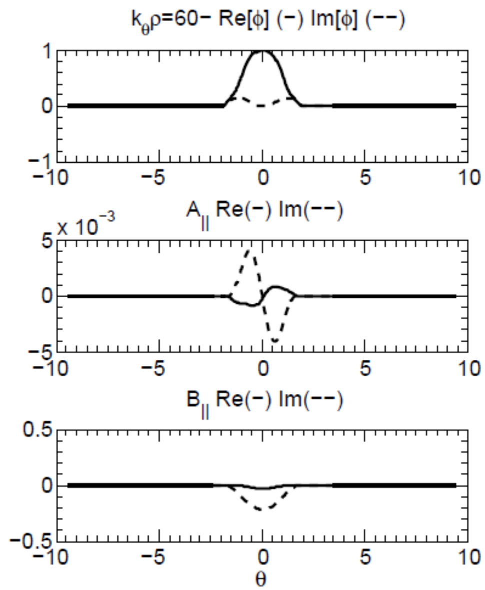
No Li–at $\psi_N = 0.96; k_\theta \rho = 5.0 - 150.0$: Signature of TEM/ETG with -ω and ballooning-like eigenfunctions

Example case study: #132543

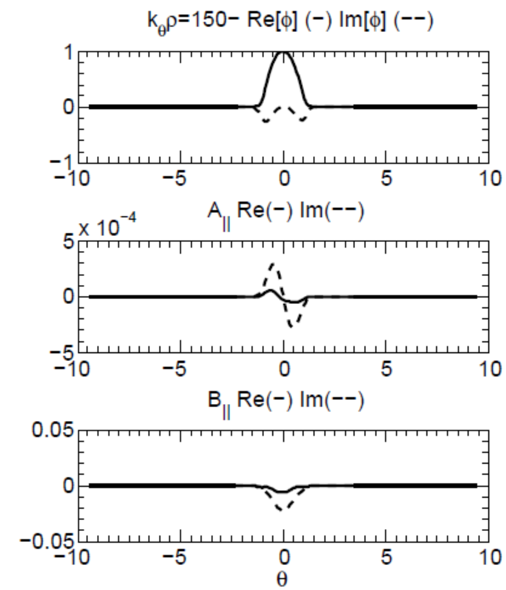
Ø/$A_{//}$>1 electrostatic nature



Normalized eigenfunctions of the mode at $k_\theta \rho$=5.0;



Normalized eigenfunctions of the mode at $k_\theta \rho$=60.0;



Normalized eigenfunctions of the mode at $k_\theta \rho$=150.0;

even ϕ, electrostatic nature:
→TEM? however Re($A_{//}$) and Im($A_{//}$) are in phase are in phase and +ω

even ϕ, - ω → TEM/ETG

No Li–at $\psi_N = 0.96; k_\theta\rho = 5.0 - 150.0$: the modes are found to be driven by $\beta, \nabla T, n$

Example case study: #132543

Parameter scans

$k_\theta\rho$**=5.0:**twisted $A_{//}$, electrostatic nature

→ small ↑ in γ with ↑ β

→ little dependency on $\nabla n, Te$

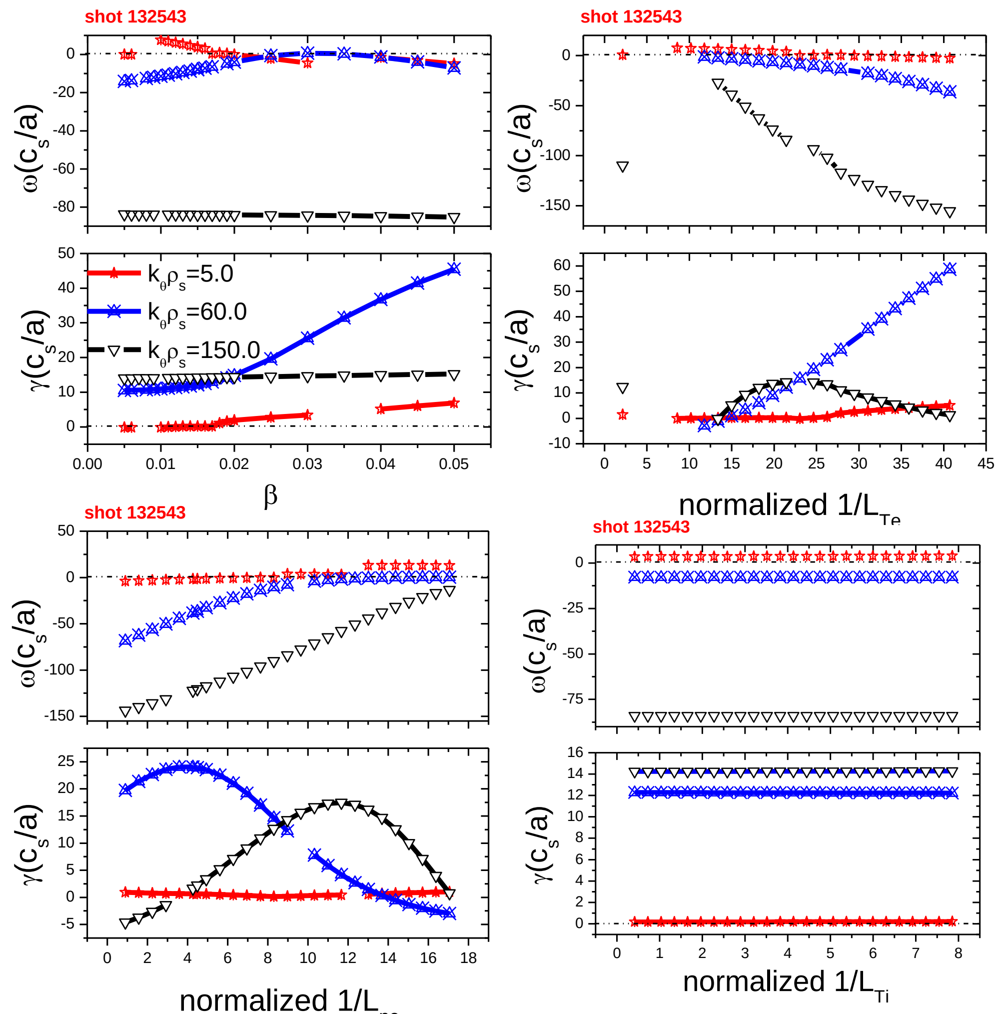
$k_\theta\rho$**=60.0:TEM/ETG**

→ clear dependency on $\nabla Te, n, \beta$

→ ↑ γ *with* ↑ β and ∇Te

$k_\theta\rho$**=150.0:ETG**

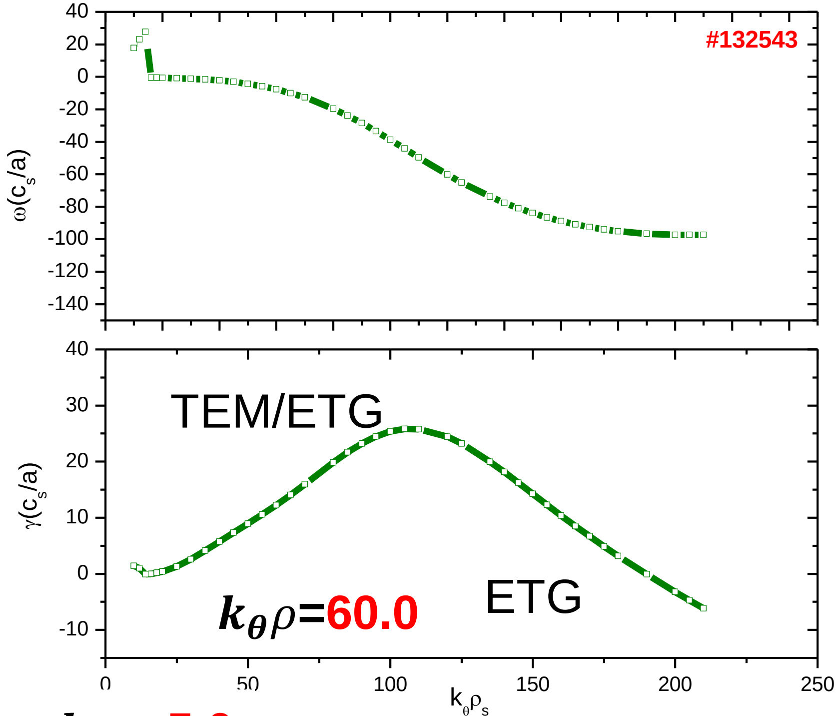
→ Dependency on $\nabla Te, n$



No Li–high $k_\theta \rho$-summary mode survey at $\psi_N = 0.96$

Example case study: $\#132543, \psi_N = 0.96$

→summary of first observations



wavenumber scan
$\#132543, \psi_N = 0.96$

$k_\theta \rho$=5.0

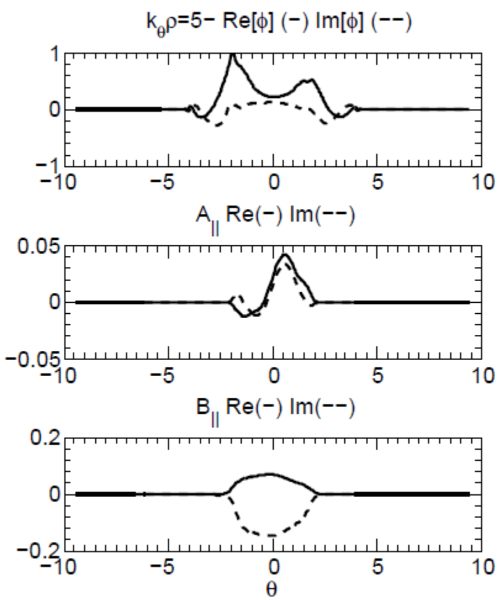
$k_\theta \rho$=150

twisted $A_{//}$, electrostatic nature

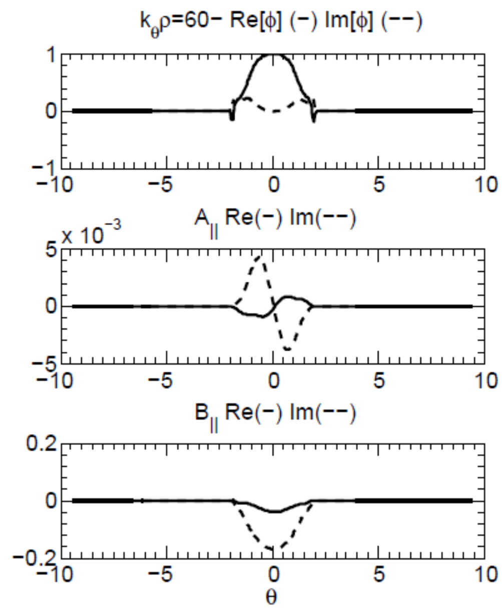
Li−at $\psi_N = 0.90; k_\theta\rho = 5.0 - 150.0$: Signature of TEM/ETG with -ω and ballooning-like eigenfunctions

Example case study: #132588

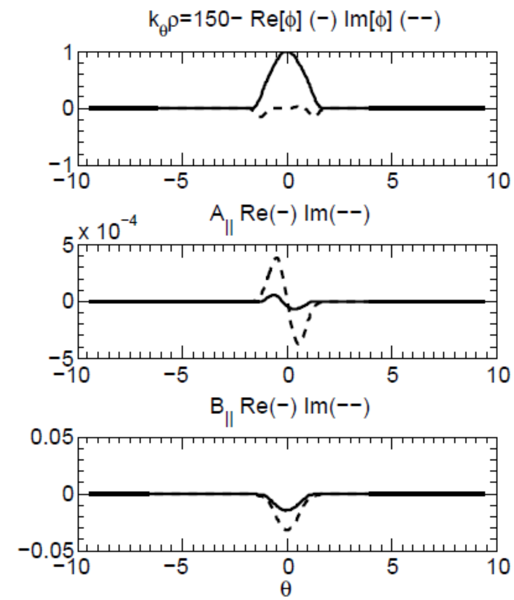
Ø/$A_{//}$>1 electrostatic nature



Normalized eigenfunctions of the mode at $k_\theta\rho$=**5.0**;



Normalized eigenfunctions of the mode at $k_\theta\rho$=**60.0**;



Normalized eigenfunctions of the mode at $k_\theta\rho$=**150.0**;

even ϕ, electrostatic nature TEM? however Re($A_{//}$) and Im($A_{//}$) are in phase and +ω

even ϕ, - ω → TEM/ETG

Li–at $\psi_N = 0.90; k_\theta\rho = 5.0 - 150.0$: the modes are found to be driven by $\beta, \nabla T, n$

Example case study: #132588
Parameter scans

$k_\theta\rho$**=5.0:** twisted $A_{//}$, electrostatic nature

→ small ↑ in γ with ↑ β and ∇Te

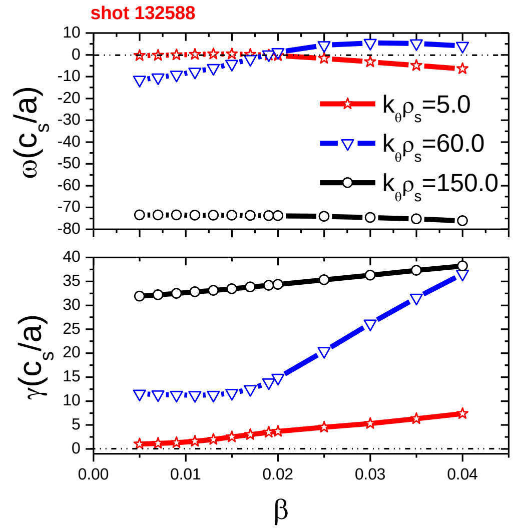
$k_\theta\rho$**=60.0:TEM/ETG?**

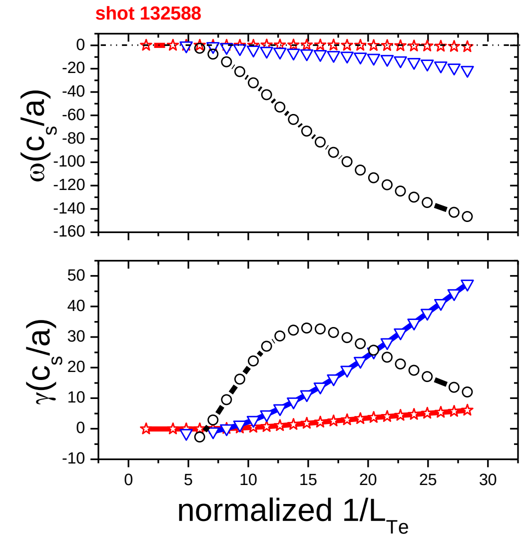
→ clear dependency on $\nabla Te, n, \beta$

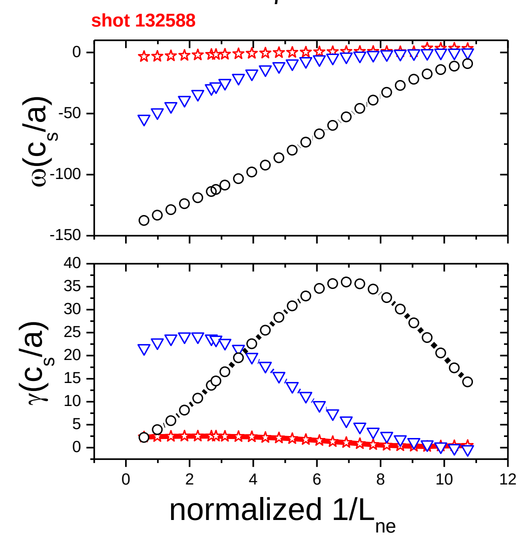
→ ↑ γ *with* ↑ β and ∇Te

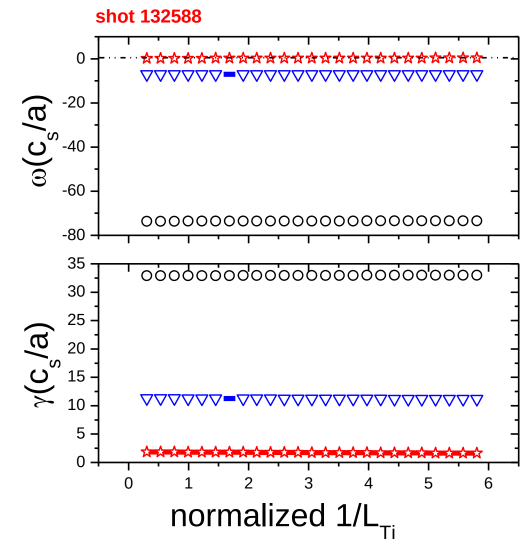
$k_\theta\rho$**=150.0: ETG?**

→ Dependency mainly on $\nabla Te, n$





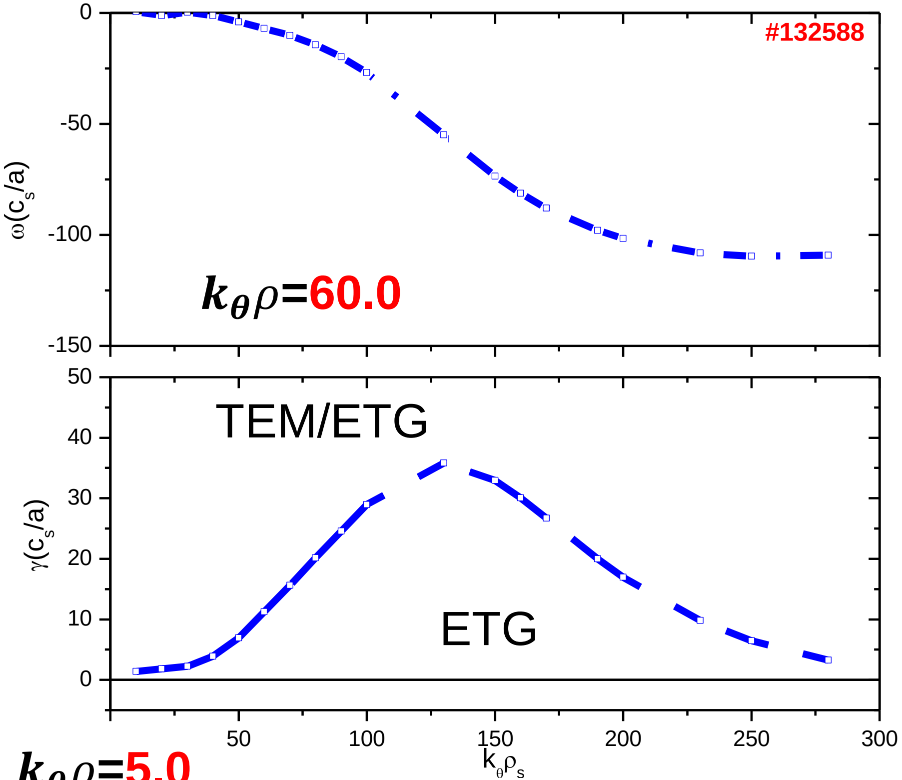




Li–high $k_\theta \rho$-summary mode survey at $\psi_N = 0.90$

Example case study: #132588

→summary of first observations



$k_\theta\rho$=5.0

twisted $A_{//}$, electrostatic nature

$k_\theta\rho$=150

wavenumber scan
#132588, $\psi_N = 0.90$

Summary

- Survey of modes for the reference and 550 mg Li shots:
  - Complexes eigenfunction structures are found for both study cases at low wavenumbers
    - The parameter scans suggest the presence of competing modes such as MTM/KBM
  - Signature of TEM/ETG modes at higher wavenumbers for both study cases

- Work in progress:
  - Extend the parameter scans to other ψ_N with-w/o Li
  - Refine parameter scans (e.g. geometry reconstruction) to identify competing modes
  - Identify most unstable modes for each ψ_N with-w/o Li
  - Non linear runs: infer heat / particle fluxes with-w/o Li
    - Investigation of the onset of KBM
    - Investigation of ETG limiting ∇Te at plasma edge
    - Investigation of the widening of the pedestal region with Li → Elimination of ELMS?…..

GS2 convergence tests

Example case study: $\#132543, \psi_N$ 0.96,$k_\theta\rho$=0.3

nperiod=2,big=1

ntheta	$k_\theta\rho$	ω	γ
192	0.3	0.41967	0.18349
144	0.3	0.42144	0.18239
72	0.3	0.41016	0.1648