Experimental study of pedestal turbulence on EAST tokamak

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on behalf of EAST team

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EAST experimental setup

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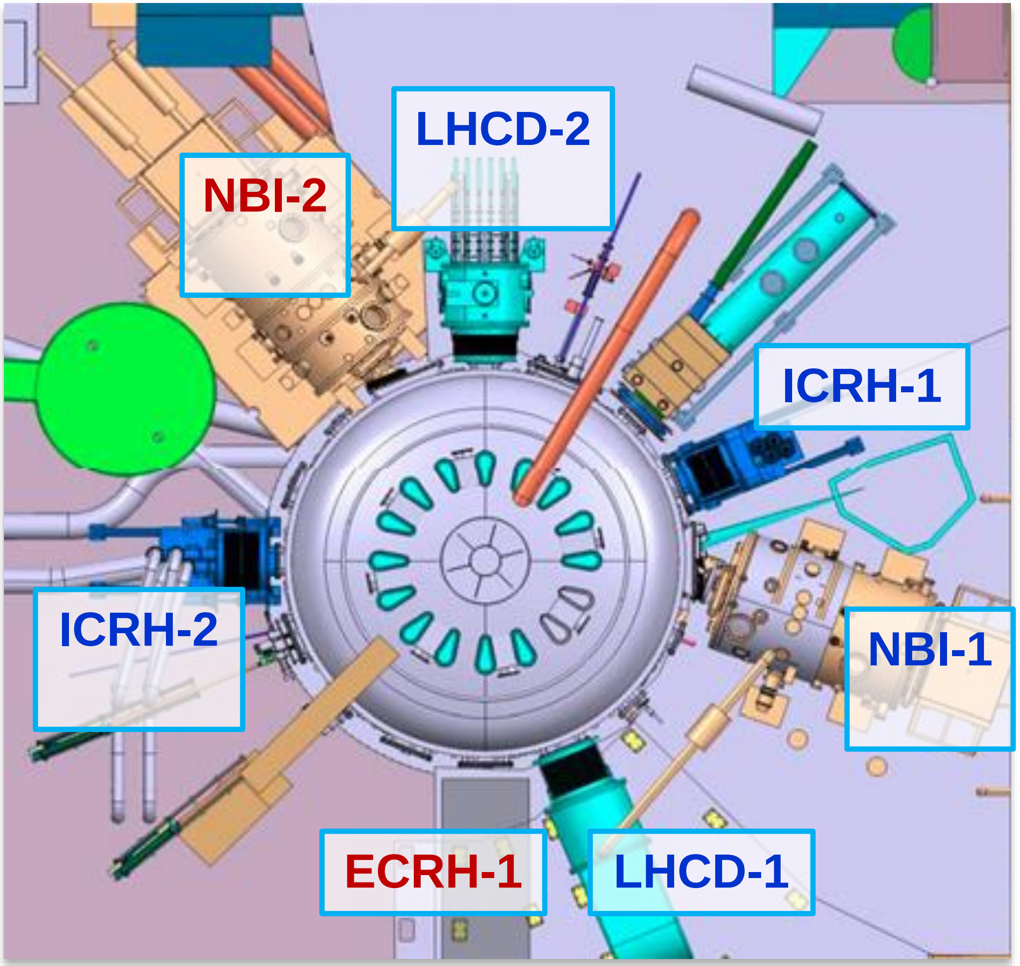

EAST	Parameters
R_0	1.9 m
a	0.45 m
B_t	1.6-2.8 T
I_p	0.3-0.6 MA
κ	1.5-2

Available in 2015 (MW)	Injection power	Source power
LHCD @ 4.6G	3	6
LHCD @ 2.45G	1.5	4
NBI	4	8
ICRF	3	12
ECRH	0.5	1
Total power	12	31

First wall

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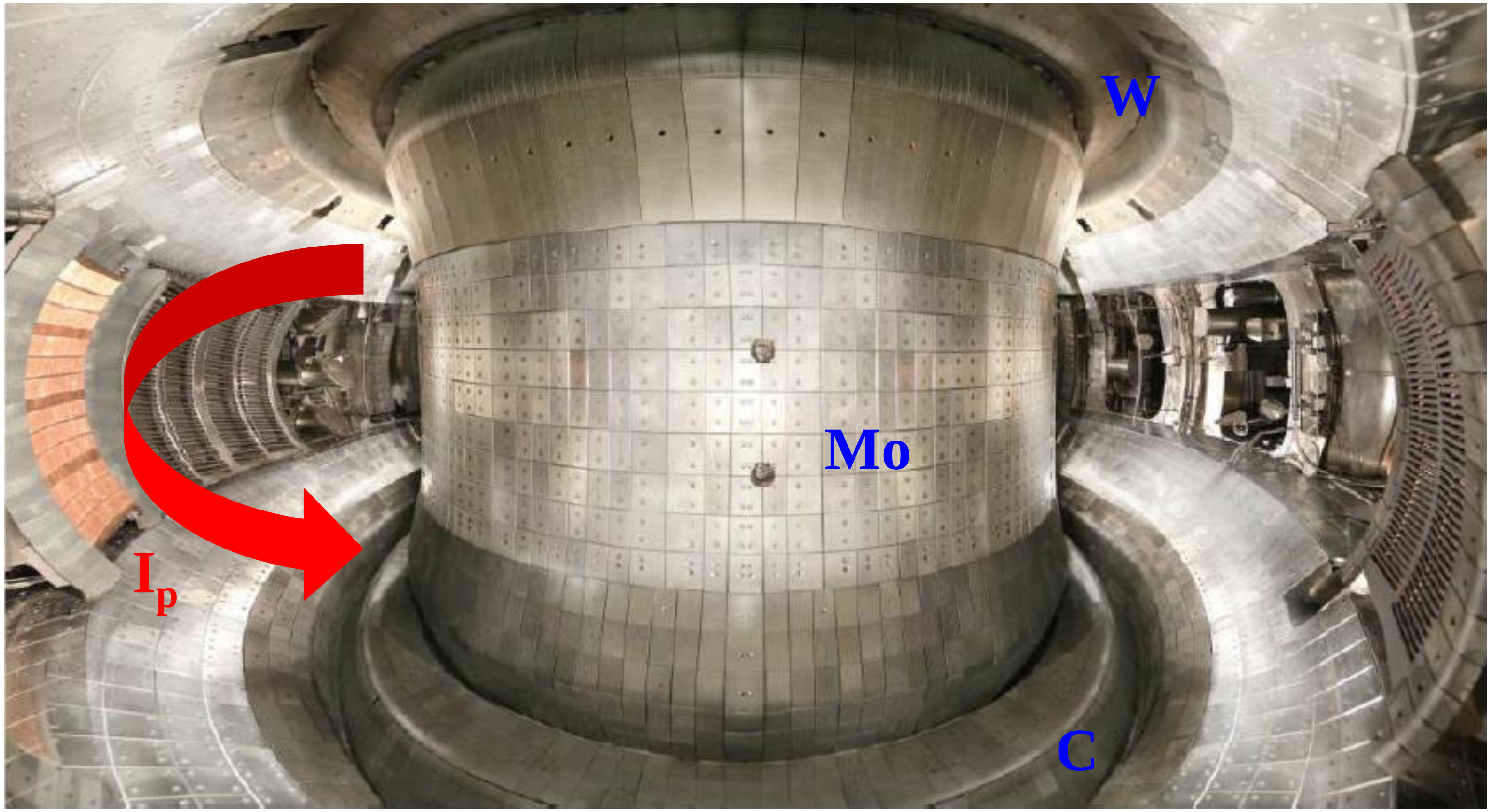
EAST first wall



Outline

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- H-mode plasma on EAST 2015
  - (1) L-H transition threshold power
  - (2) High beta-N discharges
- Pedestal turbulence study on EAST
- Relevant results on BOUT++
- Summary

L-H transition threshold in lower hybrid wave heated plasma

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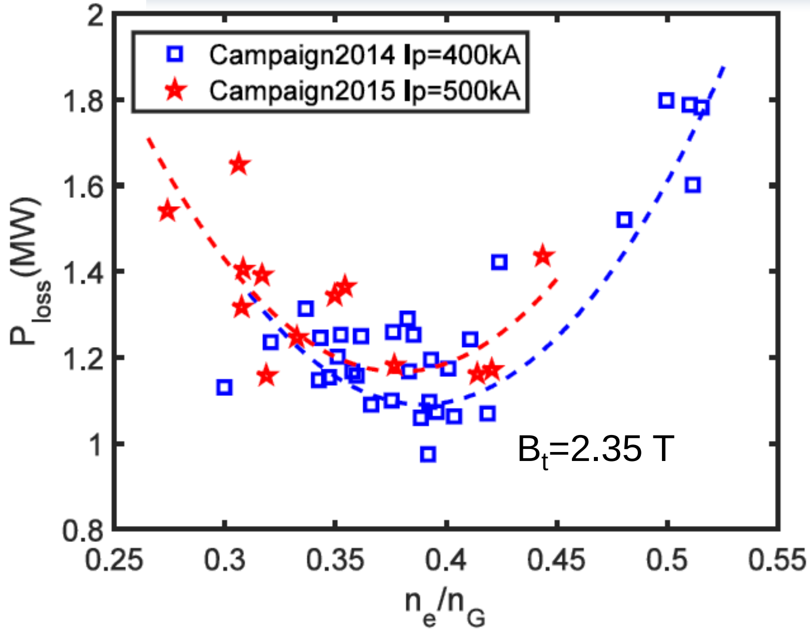
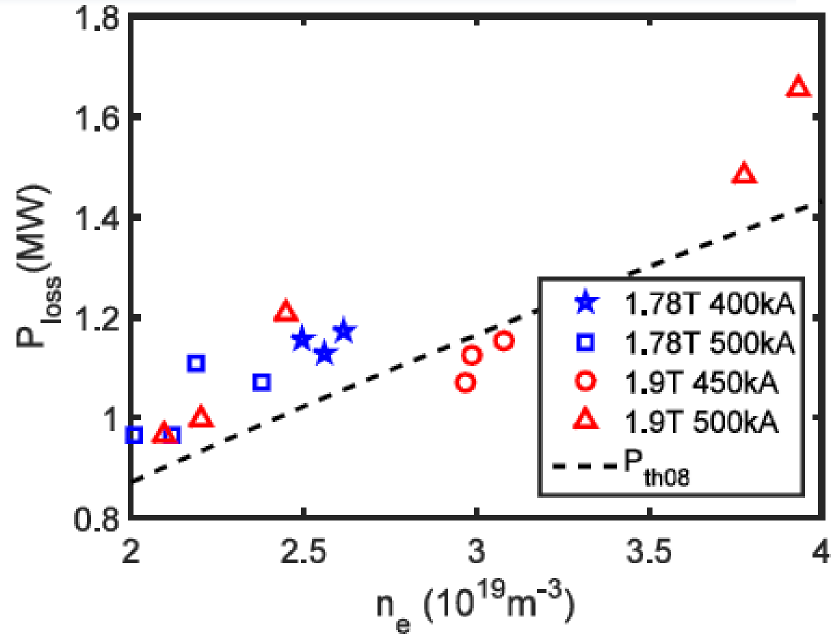


C.B.Huang, 2015 submitted to PPCF



Z.X.Liu, 2012 PPCF

- For plasma with B_t=2.35 T, a ‘U’ shape density dependence of P_{LH} was observed and the $n_{e,min}/n_G$~0.38 for plasma current of 400 and 500 kA (where $n_{e,min}$=2.4~2.8×10^{19} m^{-3}).
- For plasma with B_t=1.7-1.9 T, P_{LH} increased with the density. If $n_{e,min} \propto B_t^{0.8}$ (JET scaling), the $n_{e,min}$<2×10^{19} m^{-3} which is beyond the density range in experiment. This could explain why no ‘U’ shape dependence is observed in the low B_t plasma.

β_N>1.5 plasmas on EAST

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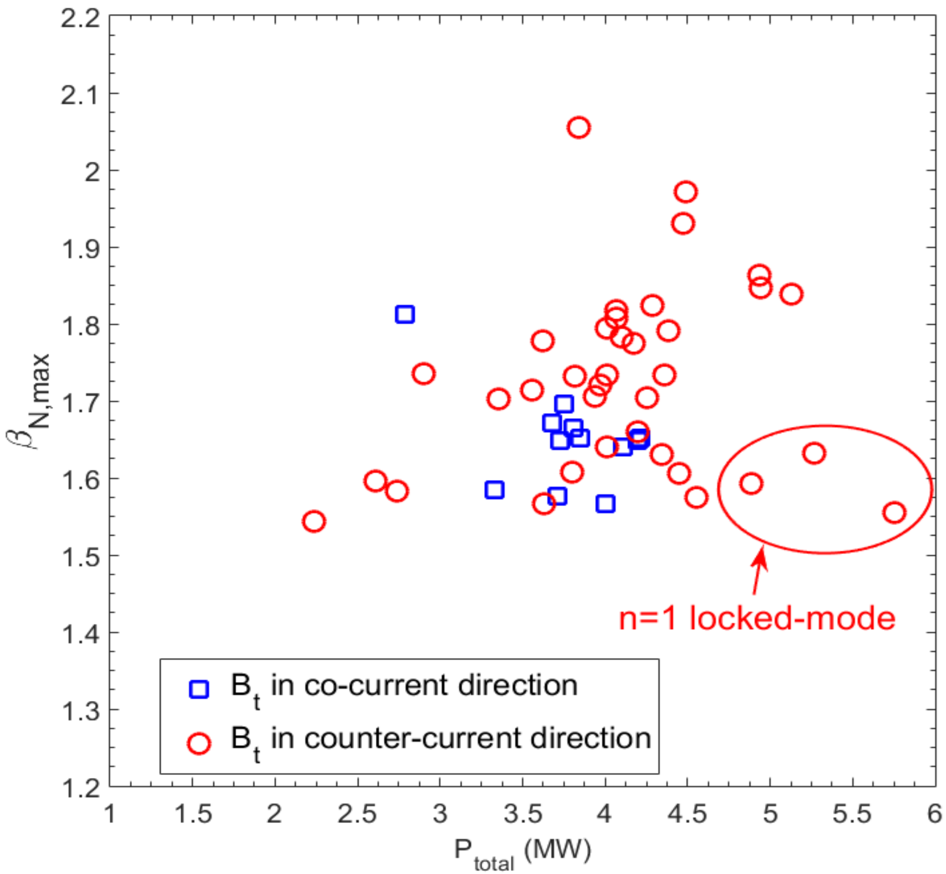

- β_N generally increases with heating power. The effective heating power is smaller than 6 MW in EAST 2015.

High β_N plasma discharges

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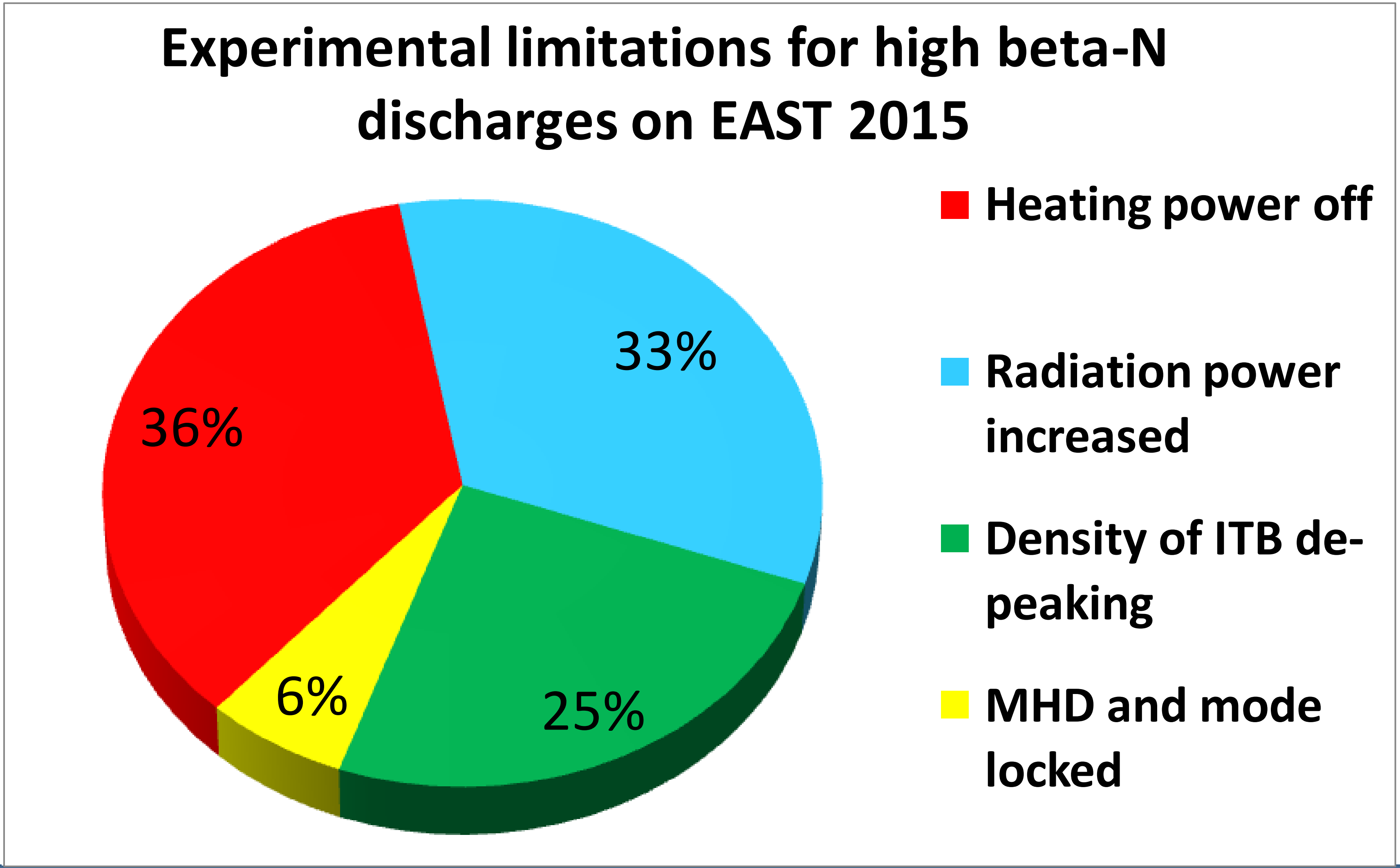

Heating power switched off

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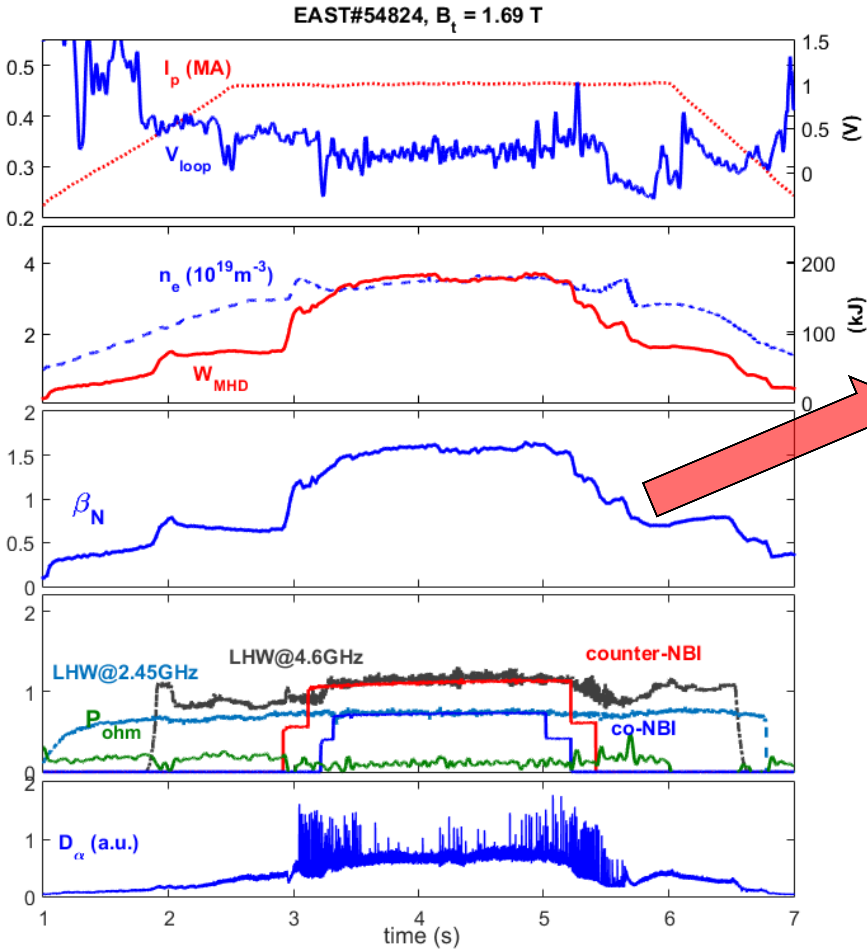
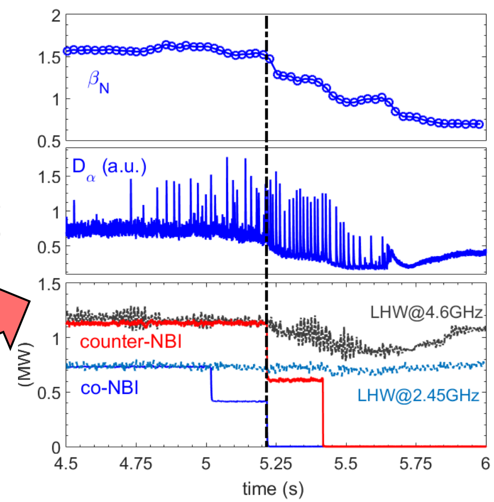
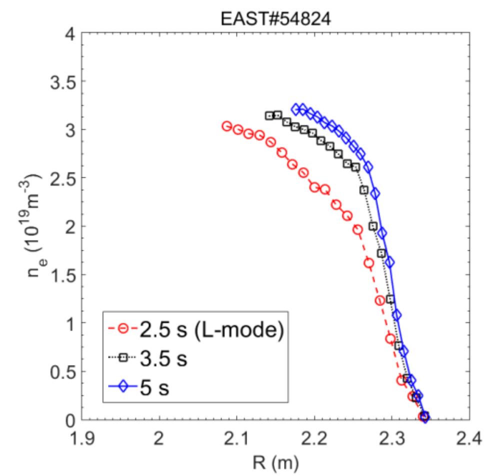
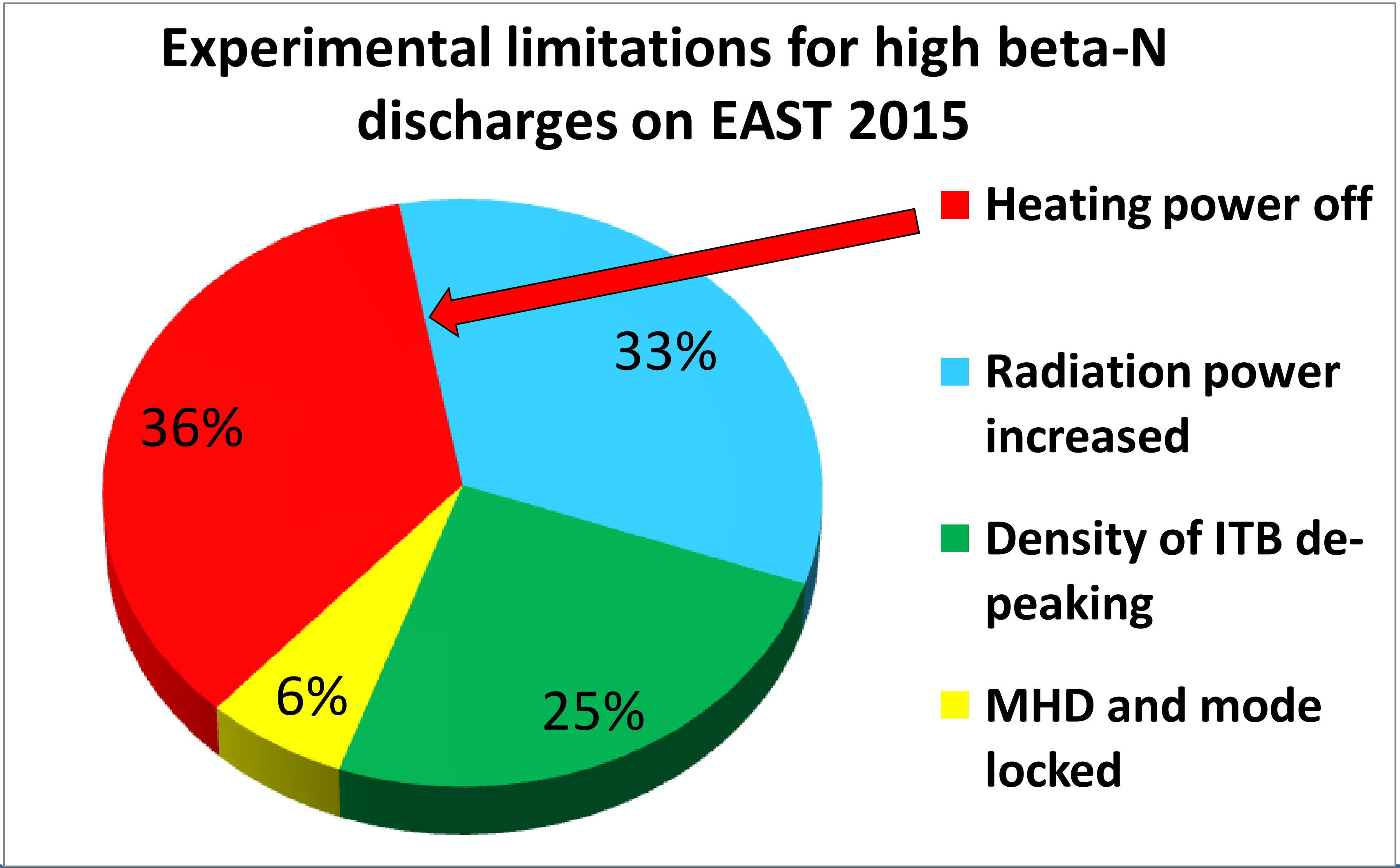




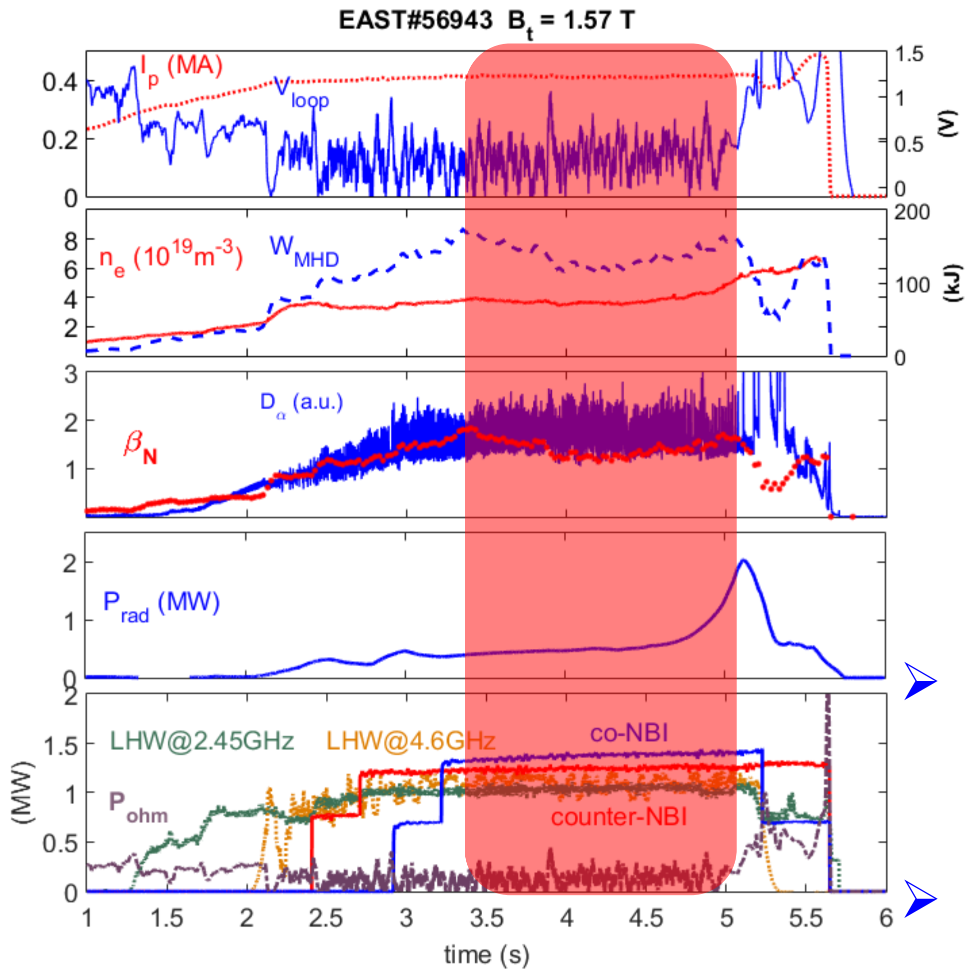


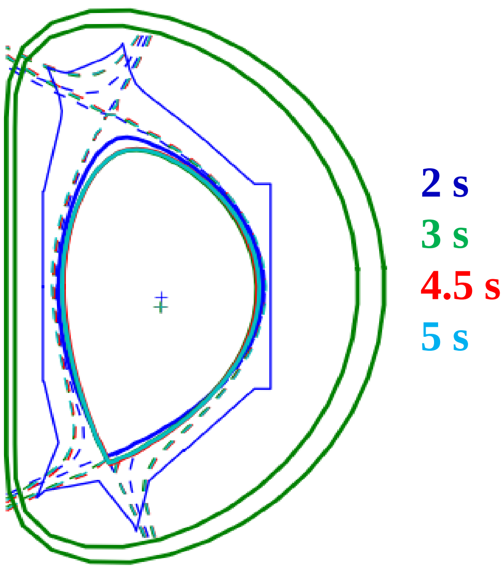
- Plasma with $\beta_N > 1.5$ sustained till t = 5.25 s, where the half of NBI heating power is switched off so that the total heating power and β_N decreased.

36% shots due to heating power off



Radiation increase leading β_N decrease





- With strongly NBI heating, plasma of $\beta_N > 1.5$ is observed at t = 3.4 s, but the impurity radiation power is increased gradually.
- Finally, β_N crash is observed at t = 5.1 s.

Radiation increase leading β_N decrease

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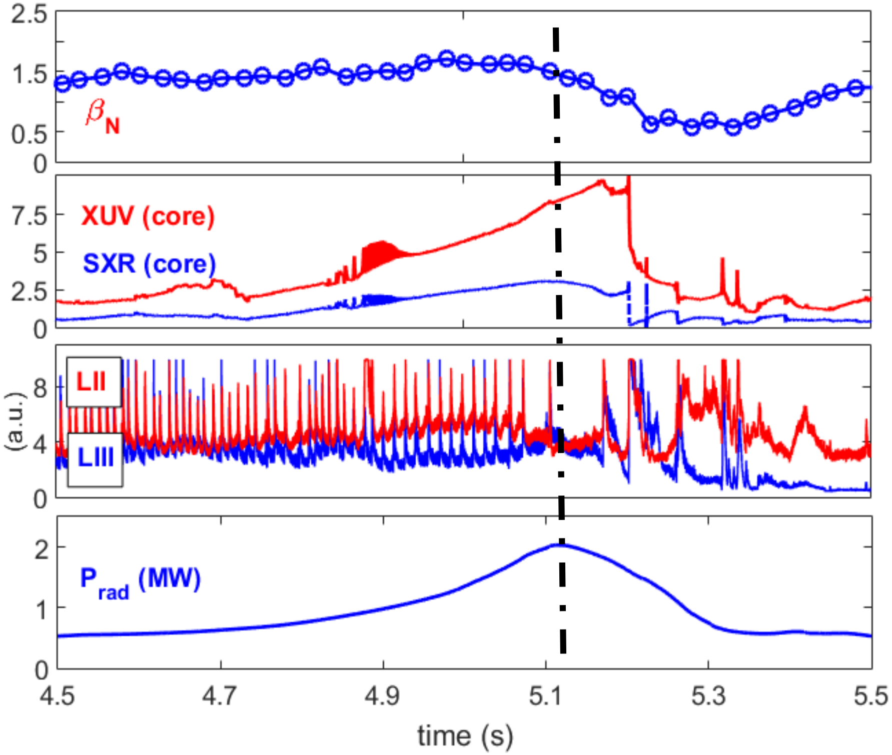

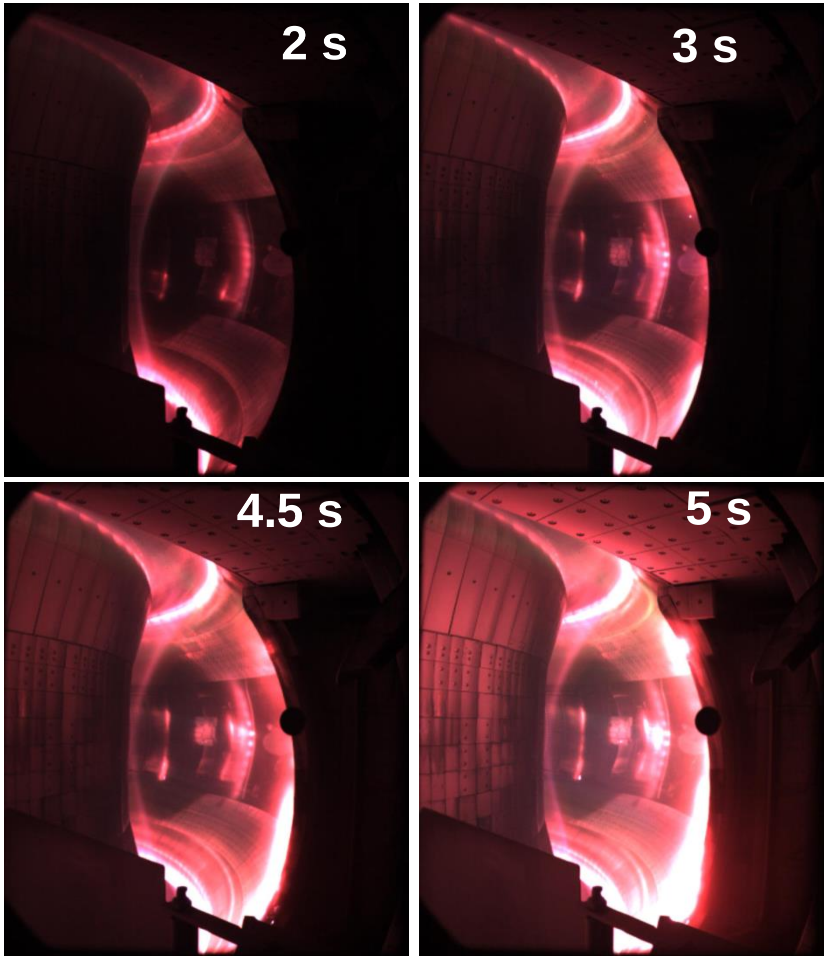

33% shots due to impurity radiation increased

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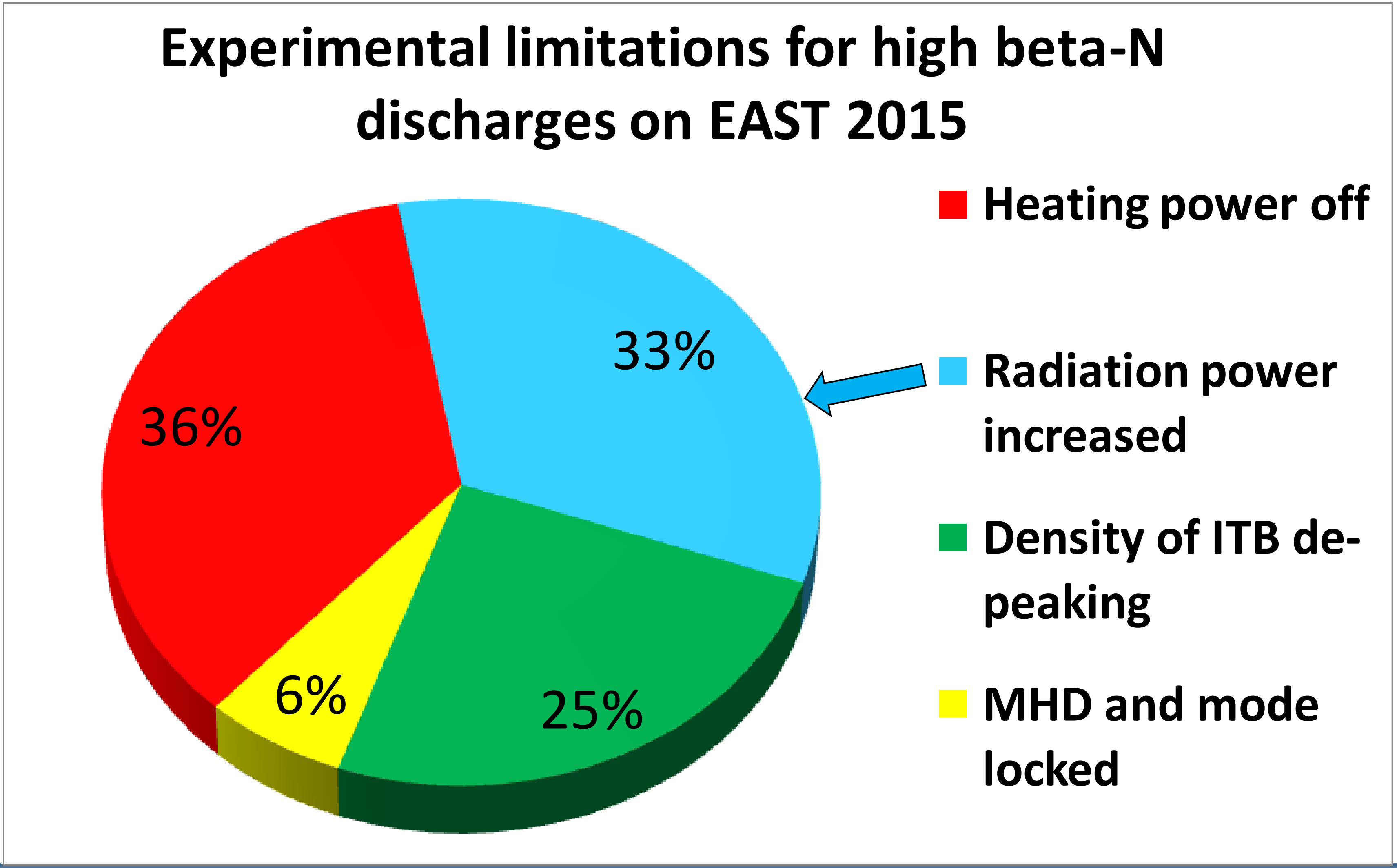

ITB density de-peaking leading to β_N decrease

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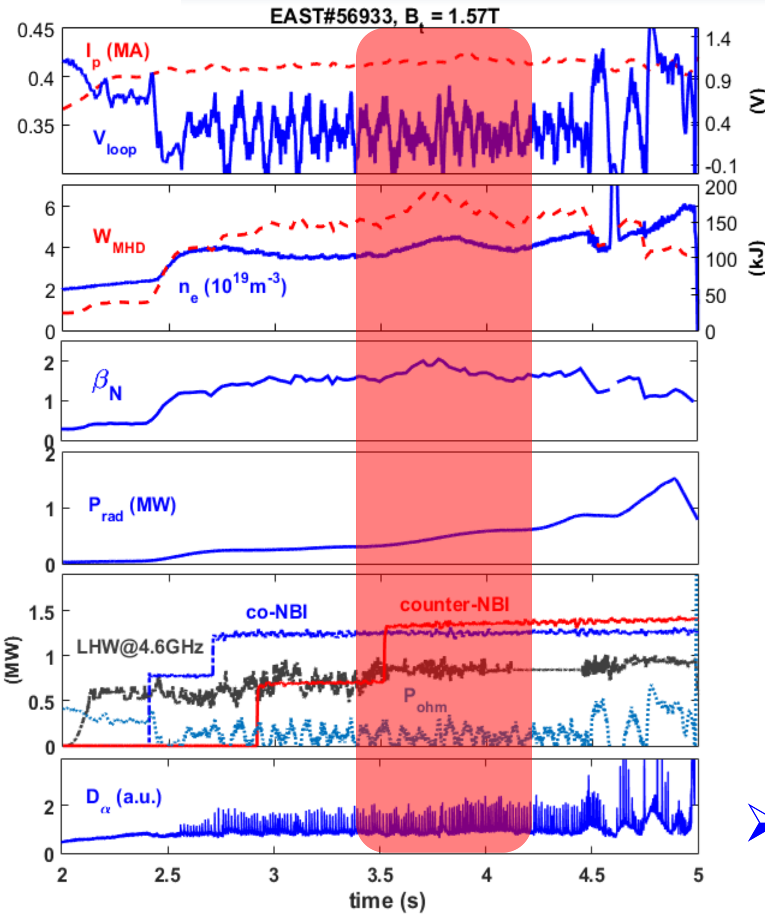

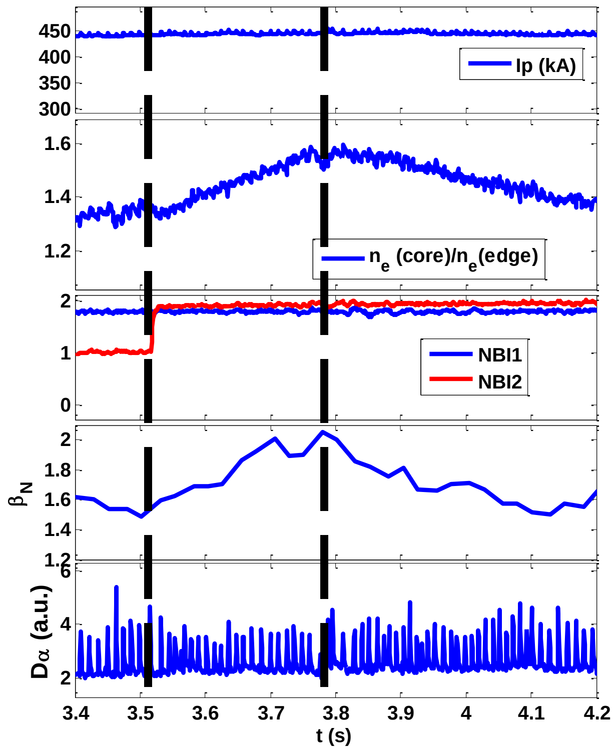

- Application of 2nd counter-NBI leads to ITB formation and density peaking started at 3.5 s, and β_N increased till 3.8 s.
- But this high β_N can not sustain due to density peaking effect disappeared.

ITB formation at 3.5 s

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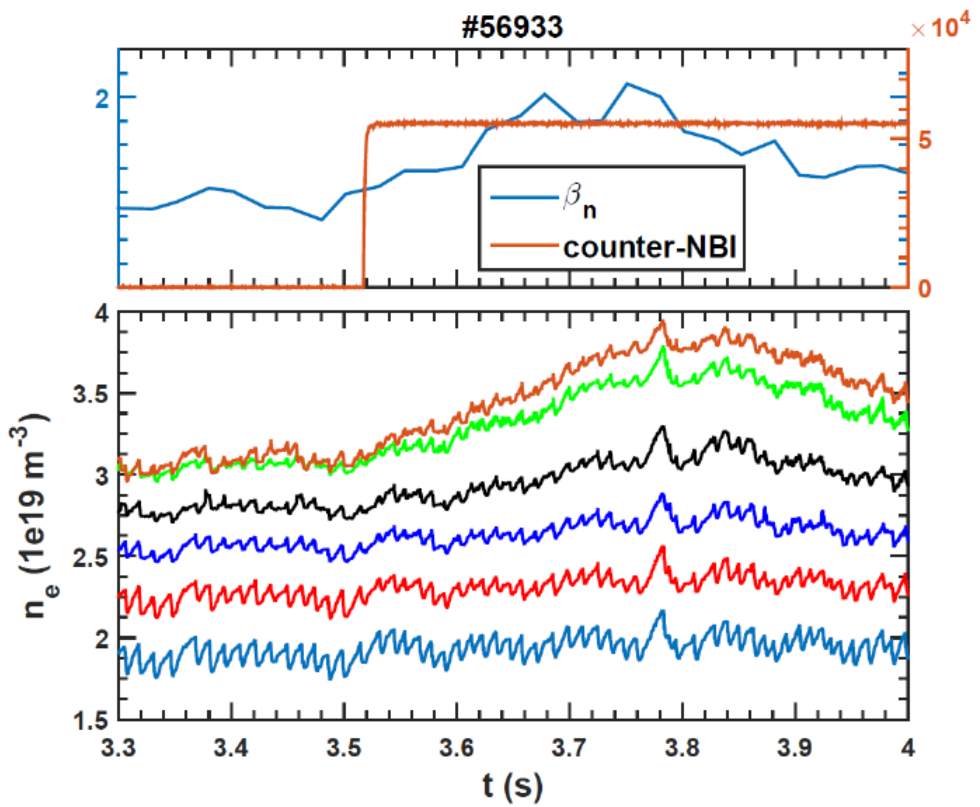
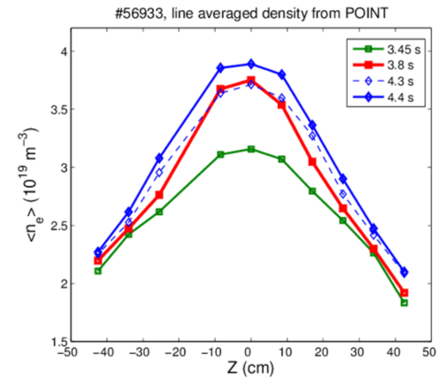
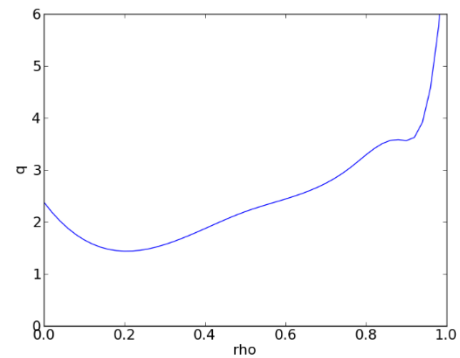
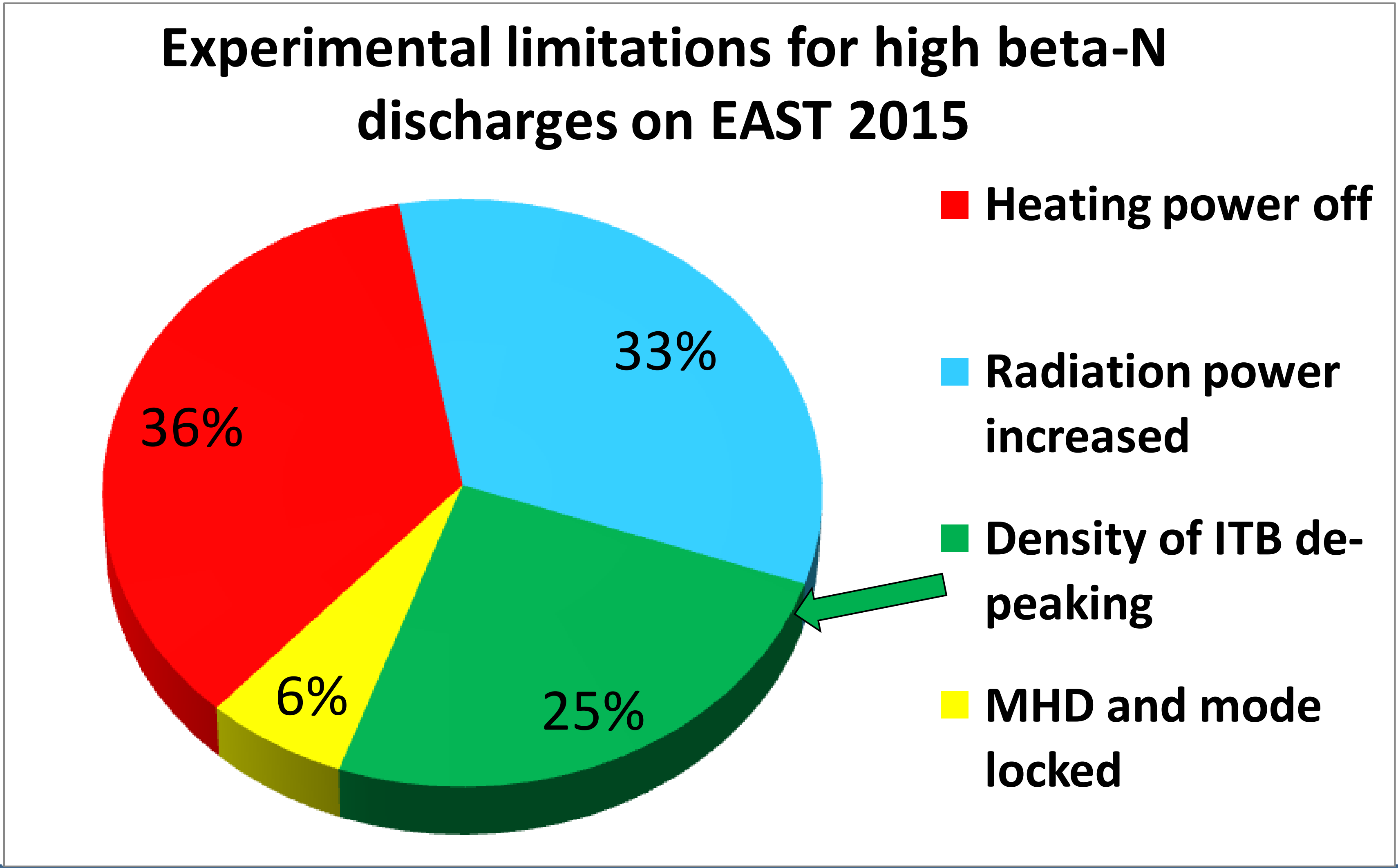






- ITB observed from density profiles by FIR laser diagnostics started at 3.5s.
- Density peaking effect disappeared since 3.8 s.
- Reversed shear is confirmed by the simulation.

25% shots due to ITB density de-peaking



Locked mode induce β_N collapse

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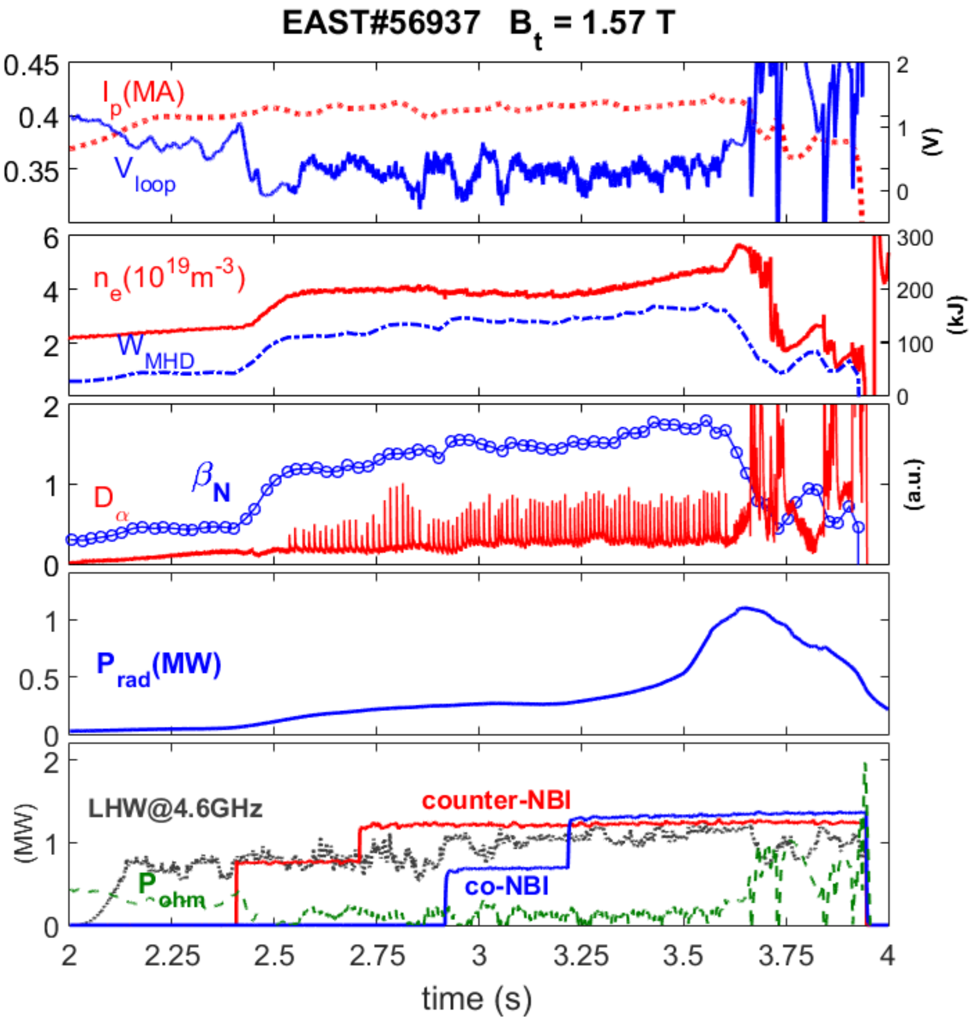

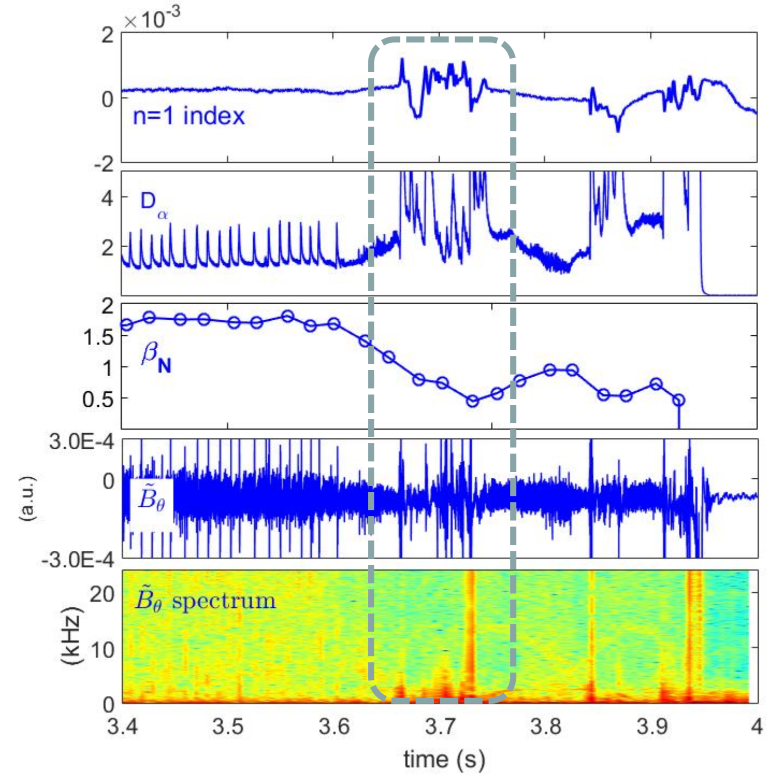

- Recycling and density increased, and beta-N decreased at 3.6 s.
- The mode locked at 3.65 s.

6% shots due to MHD and mode locked

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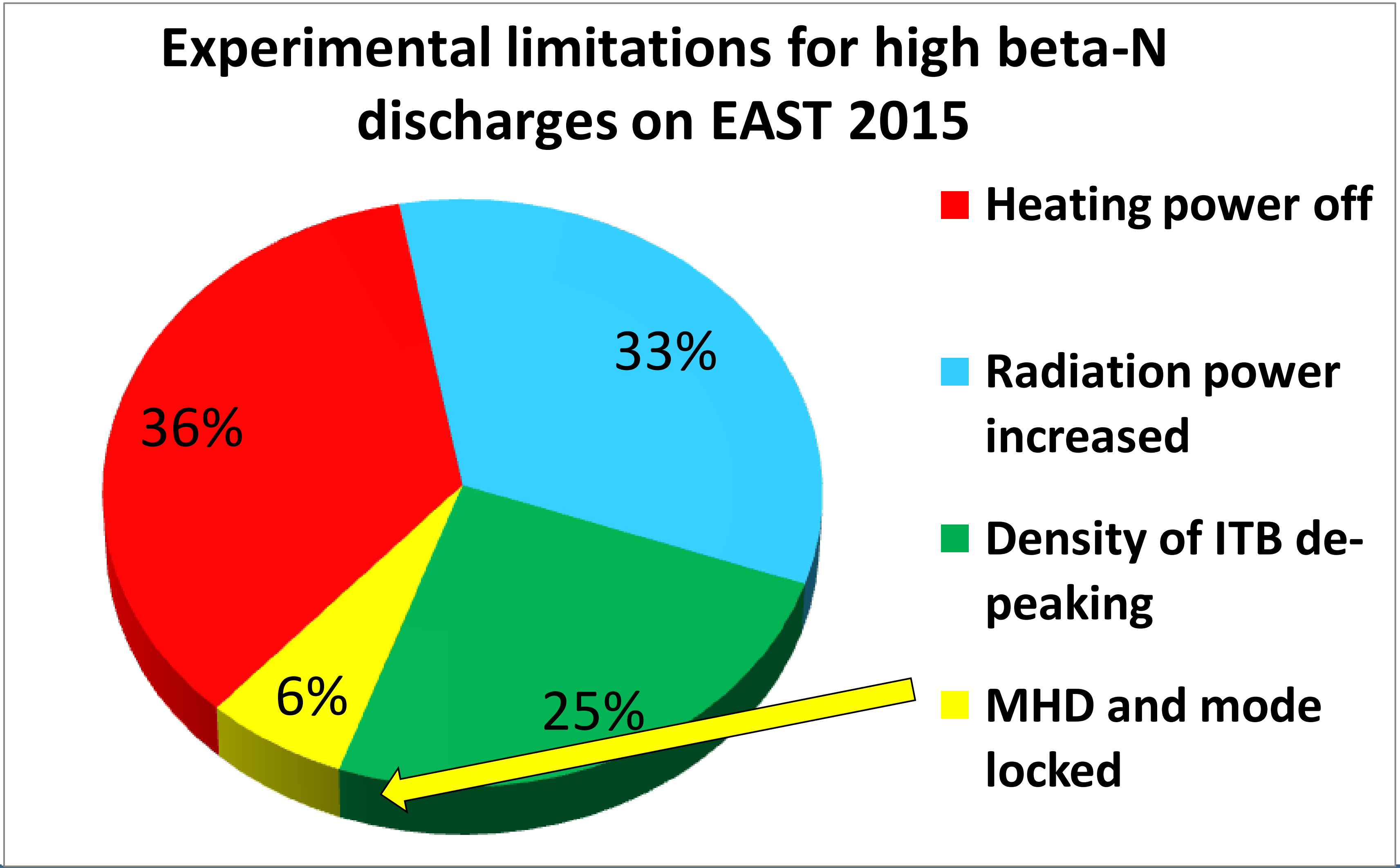

Parameter space is limited

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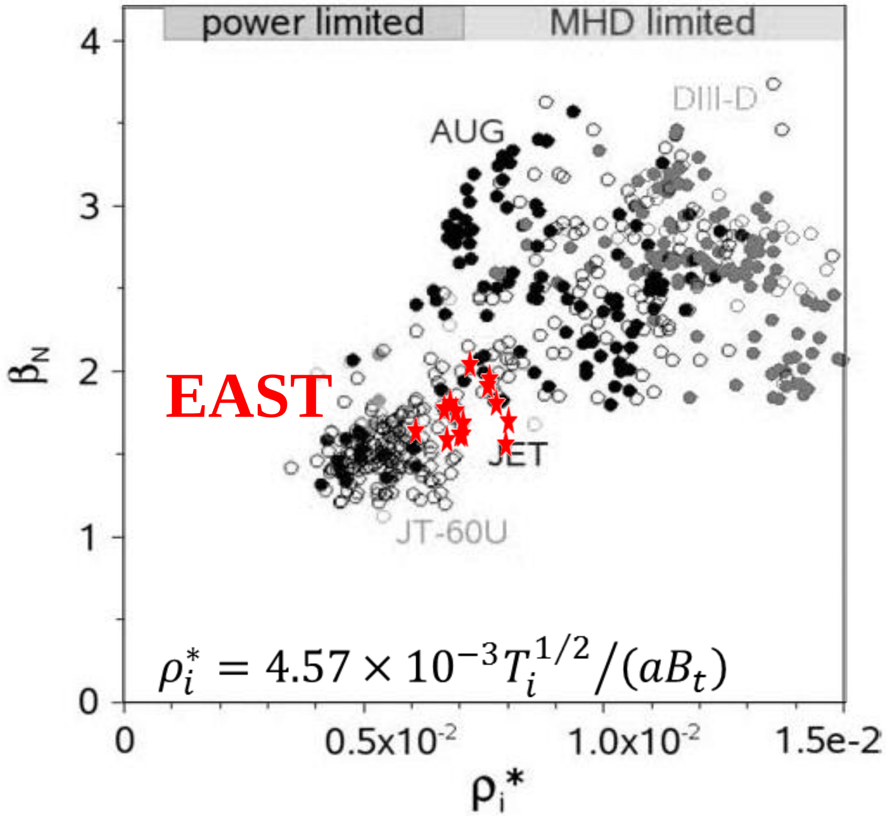
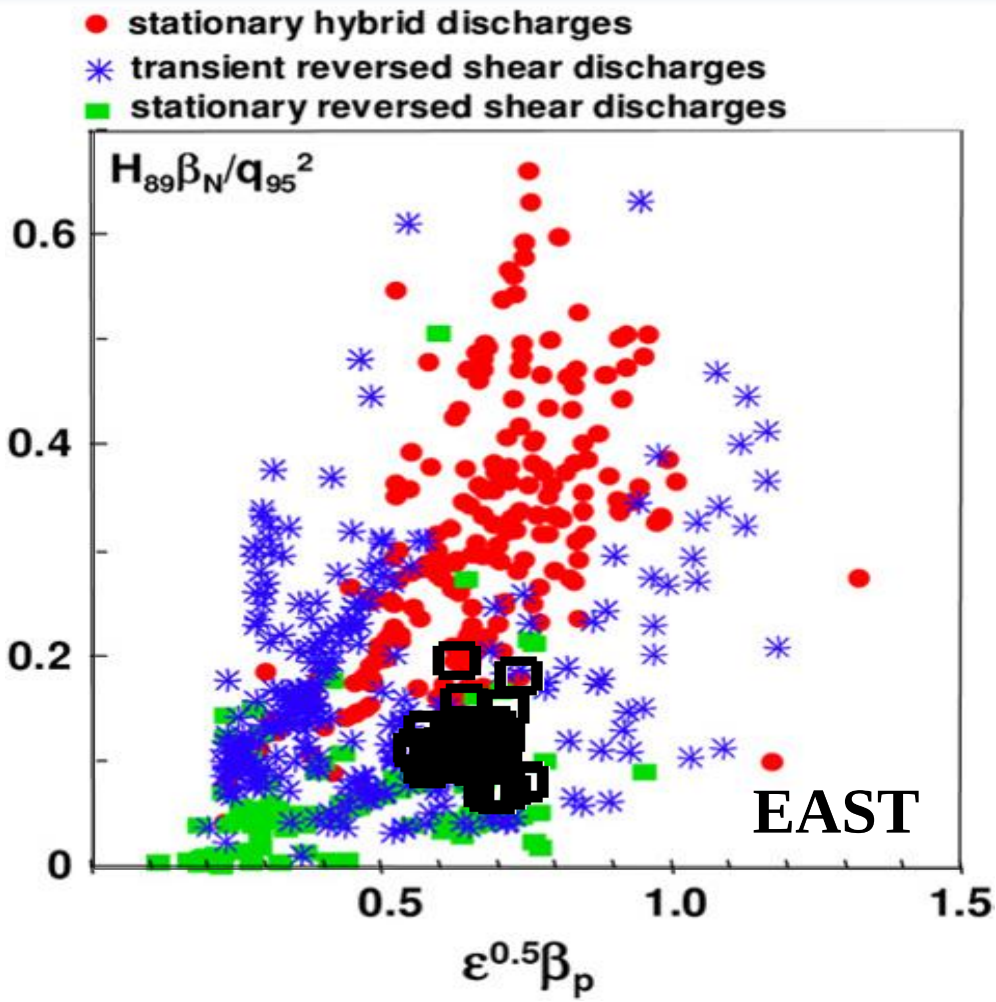
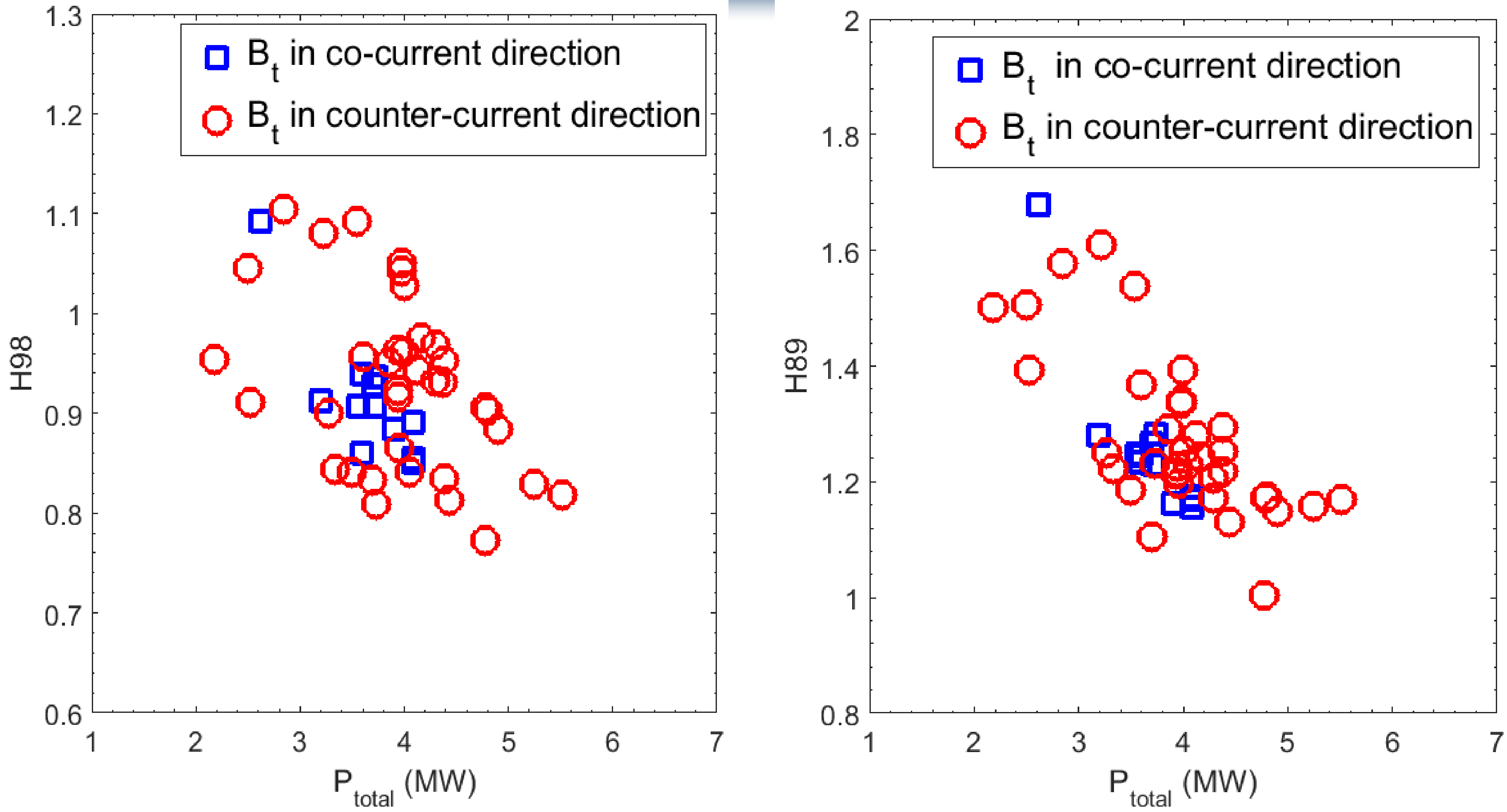


Gormezano C. *et al* 2007 *Nucl. Fusion* 47 S285



- **Reversed shear discharges are produced by NBI+LHCD on EAST**

Gormezano C. *et al* 2007 *Nucl. Fusion* **47** S285



- H factor on EAST is mostly lower than on ITER baseline and hybrid discharges.

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Coherent structures in ELM-free phase

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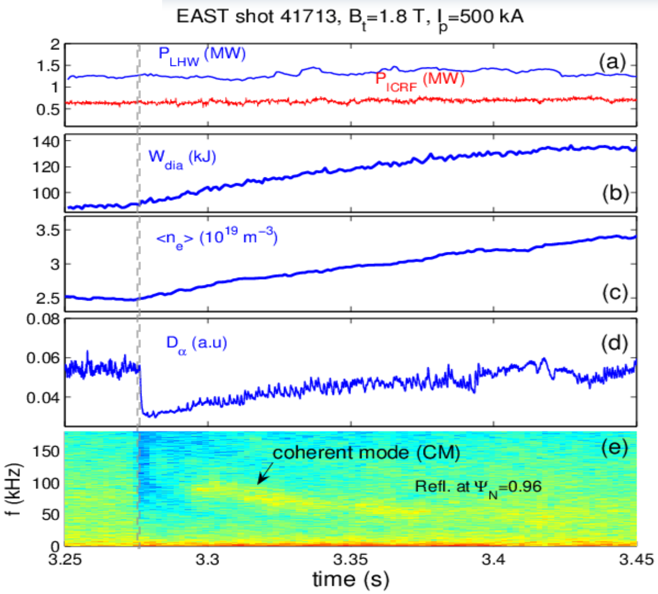

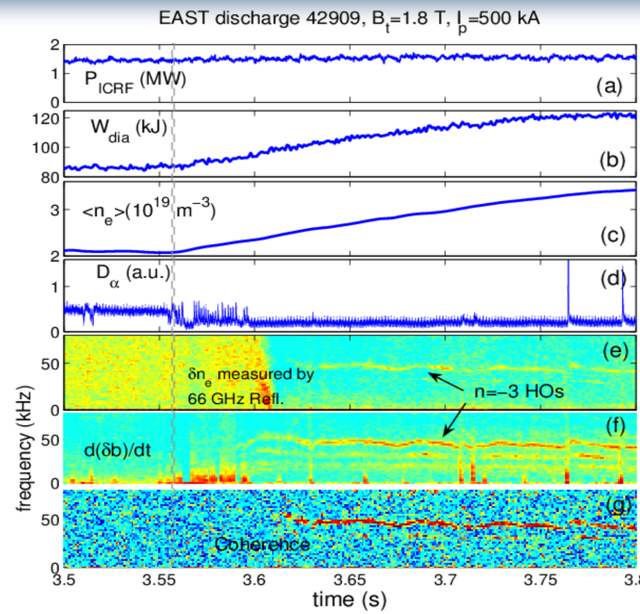

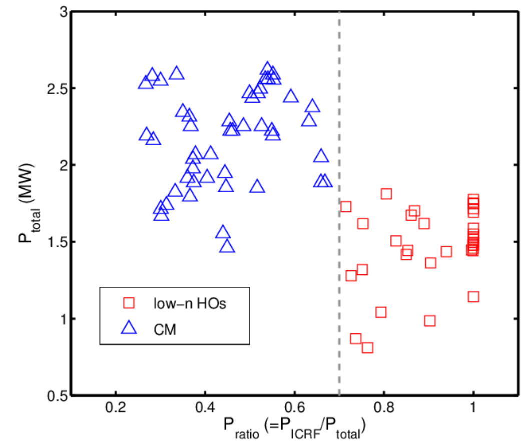

X.Han, et al, PoP (2014) 21,102504

- In 2012 campaign, the H-mode was realized using LHW or ICRF. Two different structures were observed in pedestal region in the ELM-free phase:

  1. low-n harmonic oscillations (HOs): both density and magnetic fluctuation are observed.

  2. Coherent mode (CM): only density fluctuation is observed.

- It was found that the low-n HOs were mainly observed in ICRF dominated plasma while CM was mainly observed in LHW dominated plasma. Next we will show more analysis on CM.

Coherent mode (CM) in pedestal region

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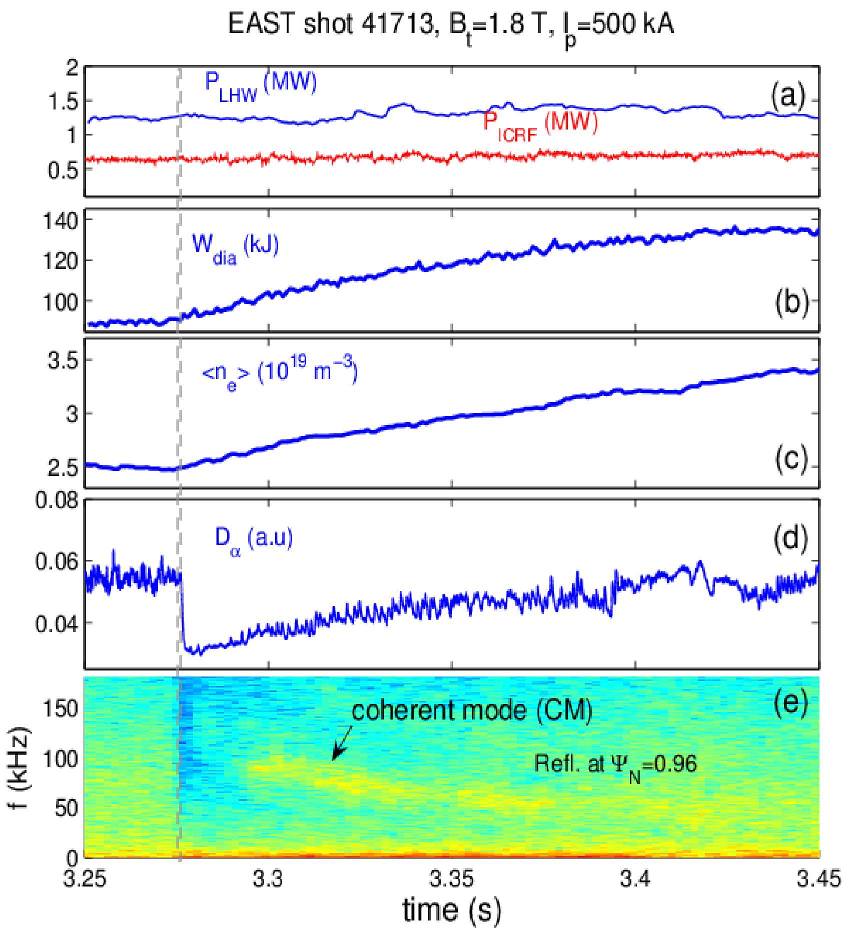

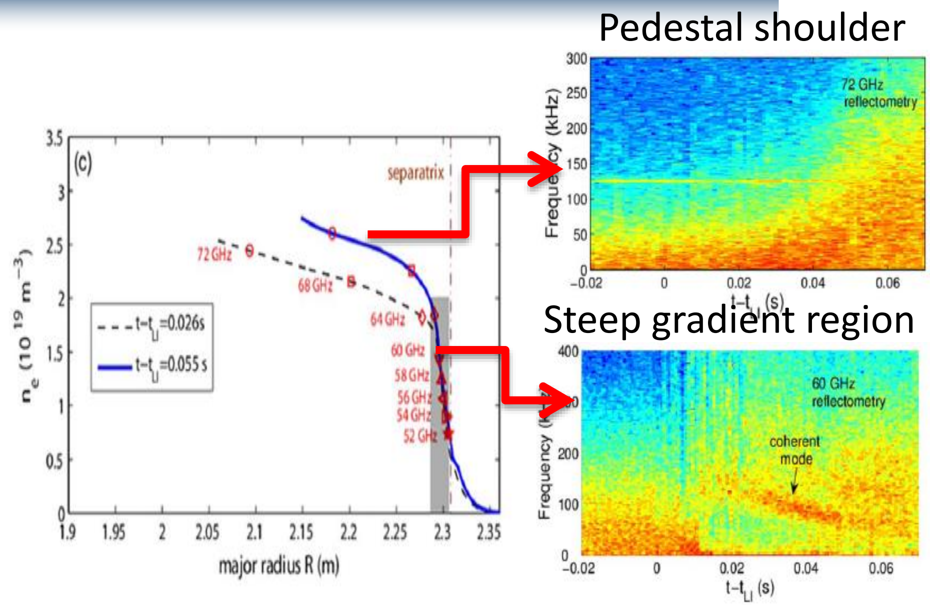

X. Gao, et al., PST, 2013
T. Zhang, 4th APTWG, 2014

- Coherent mode (CM) with frequency sweeping down is most usually observed in ELM-free phase after L-H transition.
- The coherent mode is observed in steep pedestal region by reflectometry.

CM is also observed in NBI heated plasma

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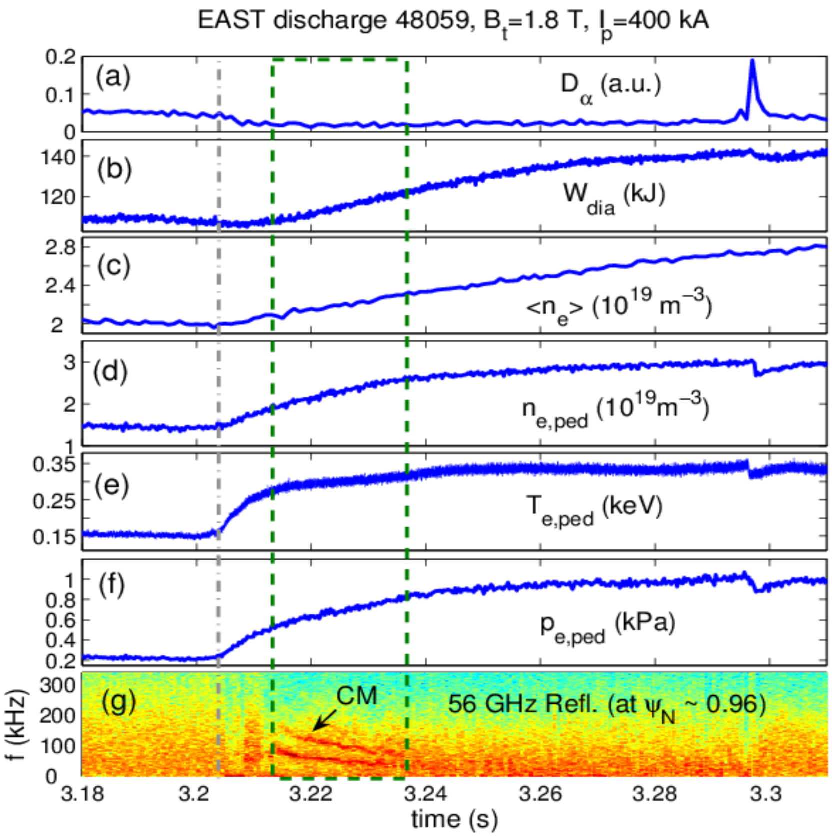
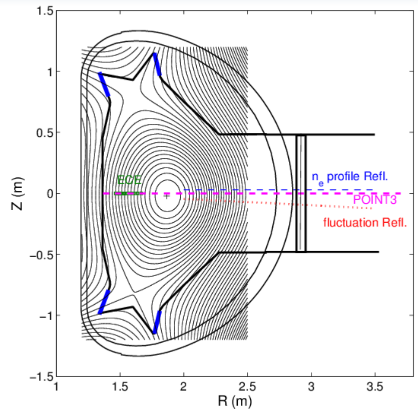
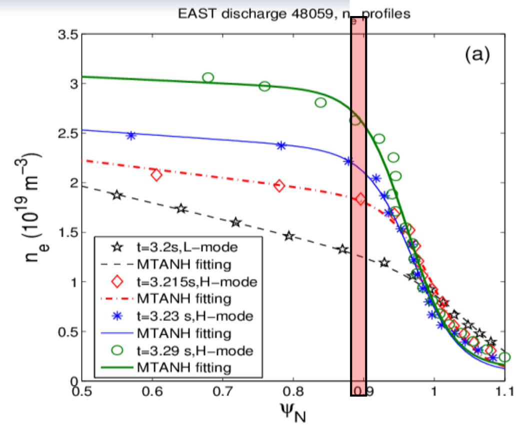
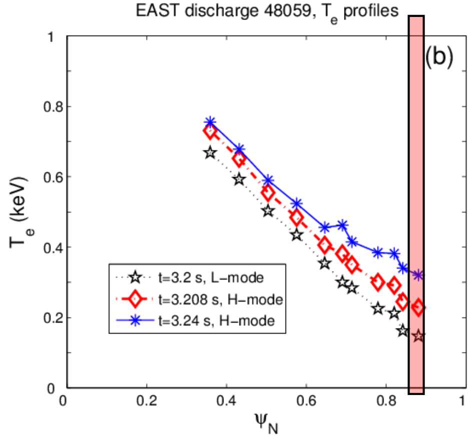








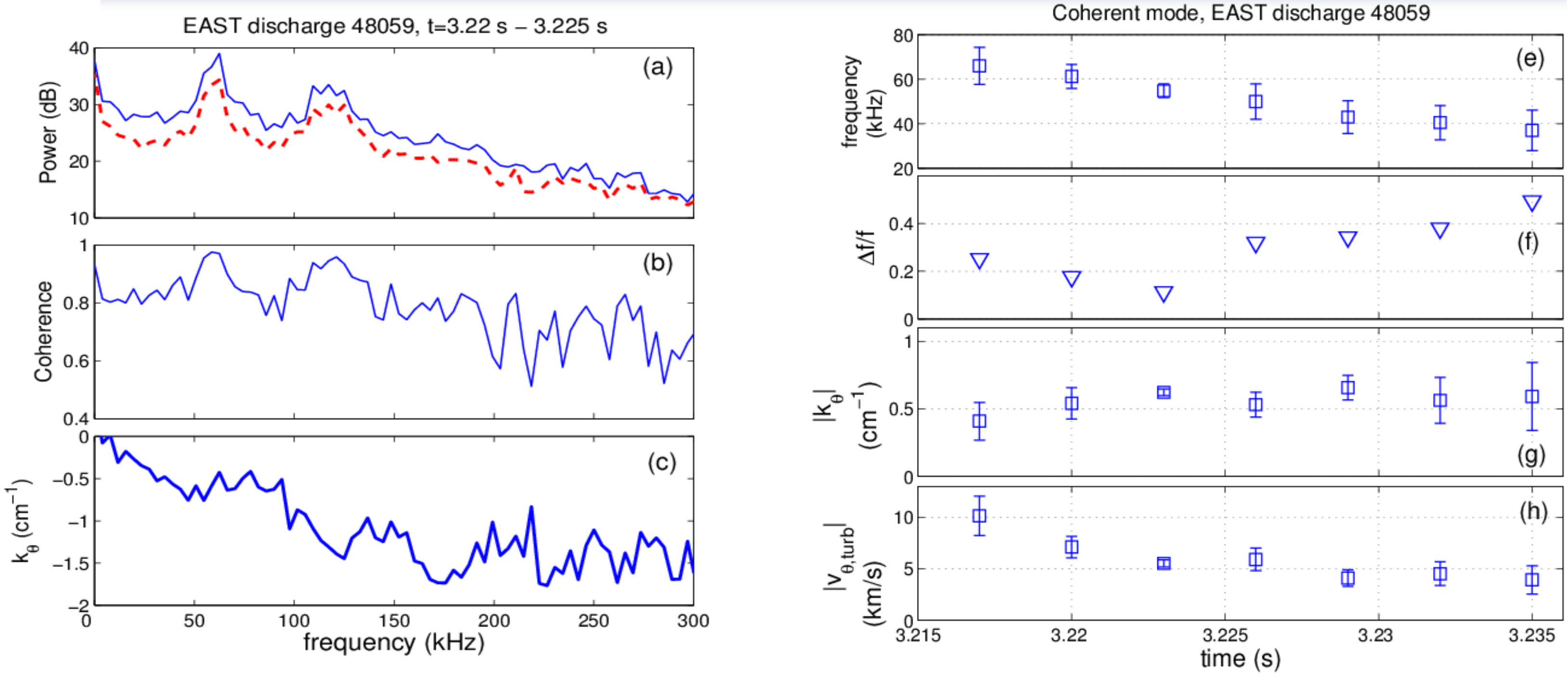
Due to limitation of Te measurement in pedestal:

$n_{e,\psi=0.88} \rightarrow n_{e,ped}$

$T_{e,\psi=0.88} \rightarrow T_{e,ped}$

- In 2014 campaign, co-NBI was installed and has been used to produce H-mode.
- The CM is also observed in the ELM-free phase in NBI heated H-mode plasma and we have density (Refl.) and electron temperature measurement (ECE) close to pedestal.

Characteristics of CM by poloidal correlation analysis



- Poloidal correlation analysis on reflectometry signals give an estimation of k_θ of CM base mode about 0.5 cm^{-1} to 0.7 cm^{-1}($k_\theta \rho_s$=0.12-0.16), rotating in electron diamagnetic drift direction in lab frame.
- The CM frequency sweeping down is mainly due to the turbulence velocity decrease.

Appearance and disappearance of CM related to electron pressure

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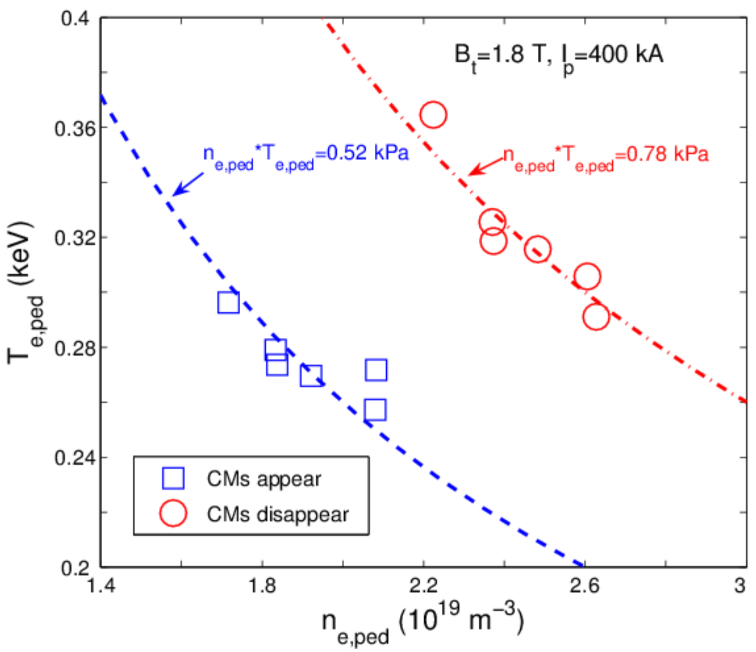

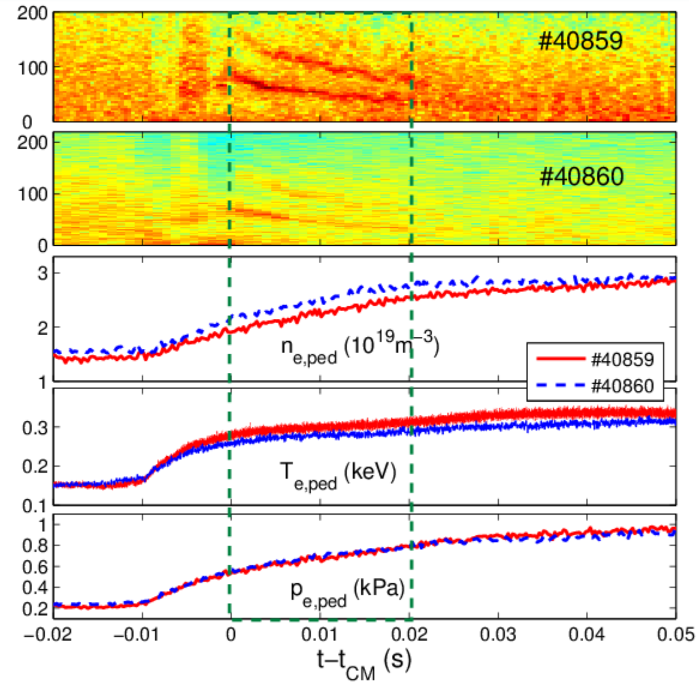

- Analysis on a series of companion discharges show that the appearance of CM is correlated to the electron pedestal pressure, implying CM is a pressure driven instability. It is also found the disappearance of CM is correlated to pressure.

CM on pedestal evolution

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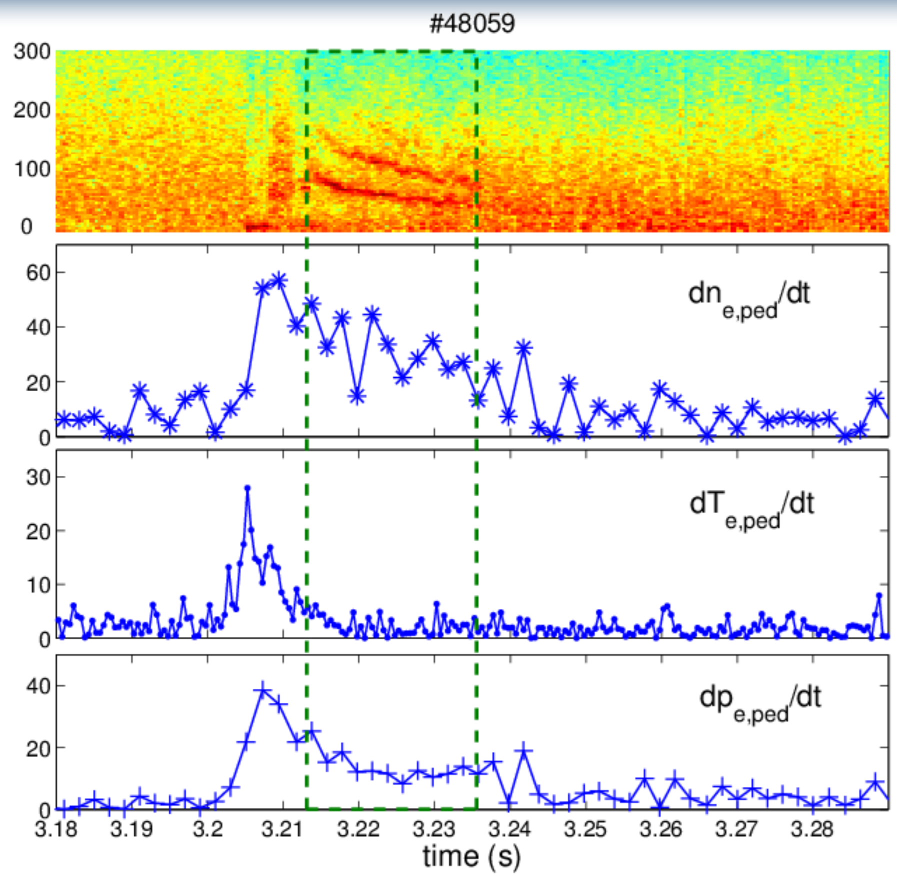

- During CM phase, the increasing rates of $n_{e,ped}$, $T_{e,ped}$ and $p_{e,ped}$ are reduced, implying an effect of CM on outward pedestal transport.

Broadband fluctuation in between ELMs

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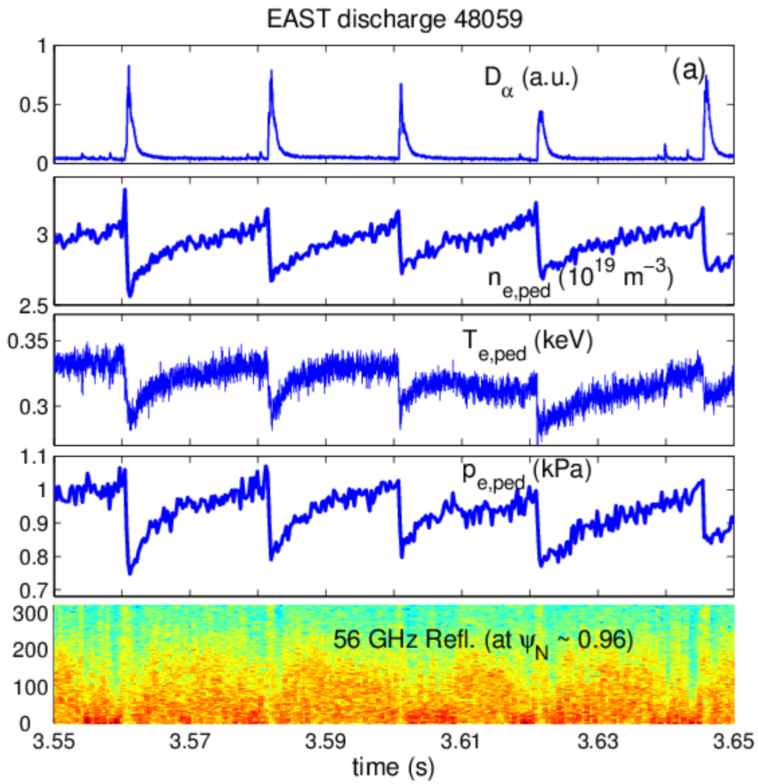

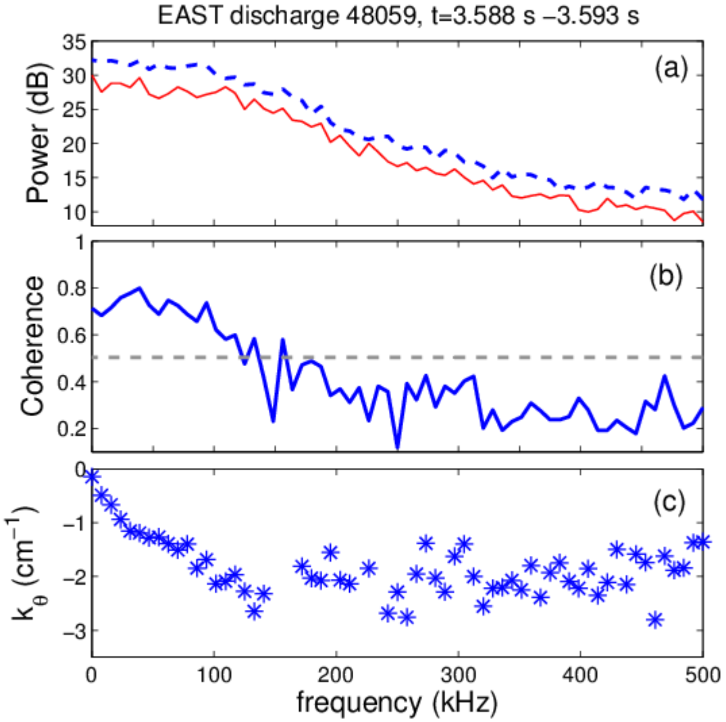

- In between ELMs, pedestal turbulence is usually dominated by broadband (BB) fluctuation.
- k_θ is from 0 to ~ -3 cm^{-1}, in electron diamagnetic drift direction in lab frame.

Relation between BB fluctuation and pressure increasing rate

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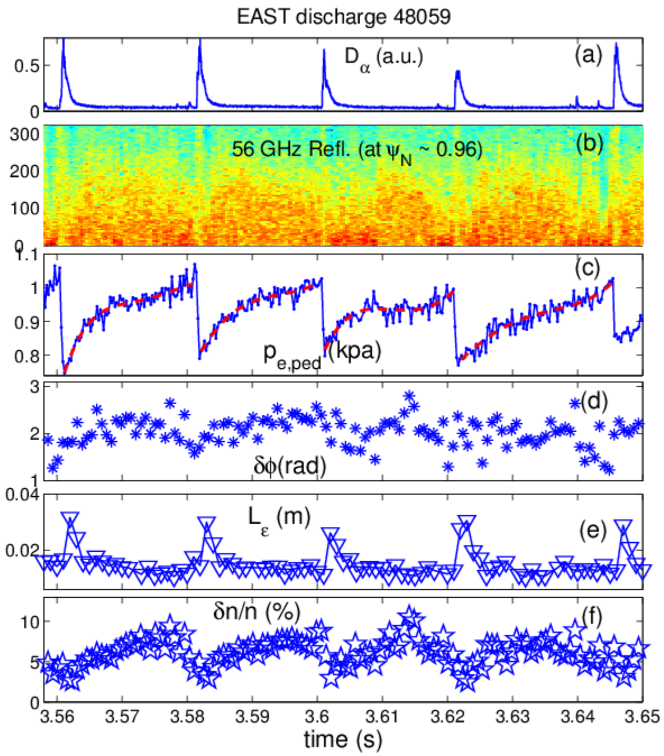

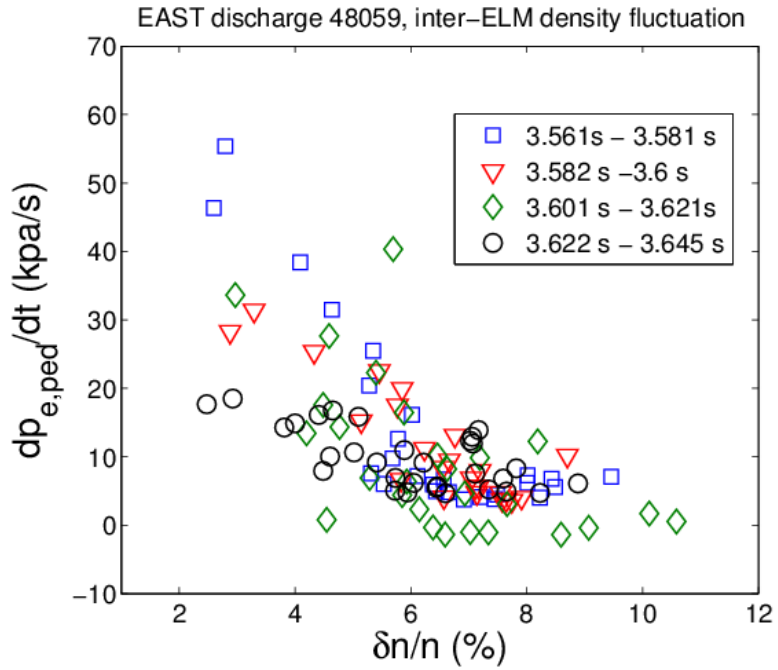

1D estimation of δn/n:

$$\frac{\delta n}{n} = \frac{\delta \phi}{2k_0 L_\varepsilon}$$

$$L_\varepsilon = \frac{1}{1/L_n + (\omega_{ce}\omega_0/\omega_{pe}^2)/L_B}$$

- Broadband fluctuation has an effect to reduce the increasing rate of pedestal pressure.

Turbulence in and inside pedestal

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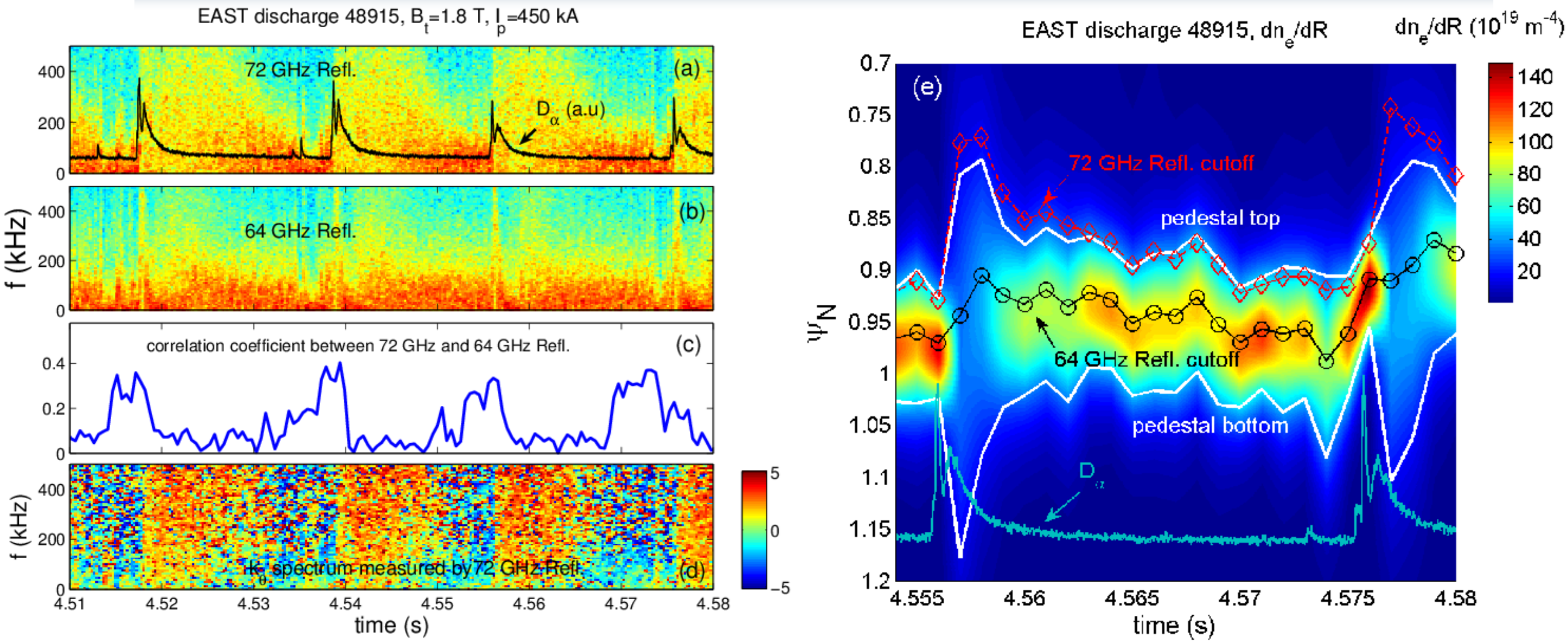
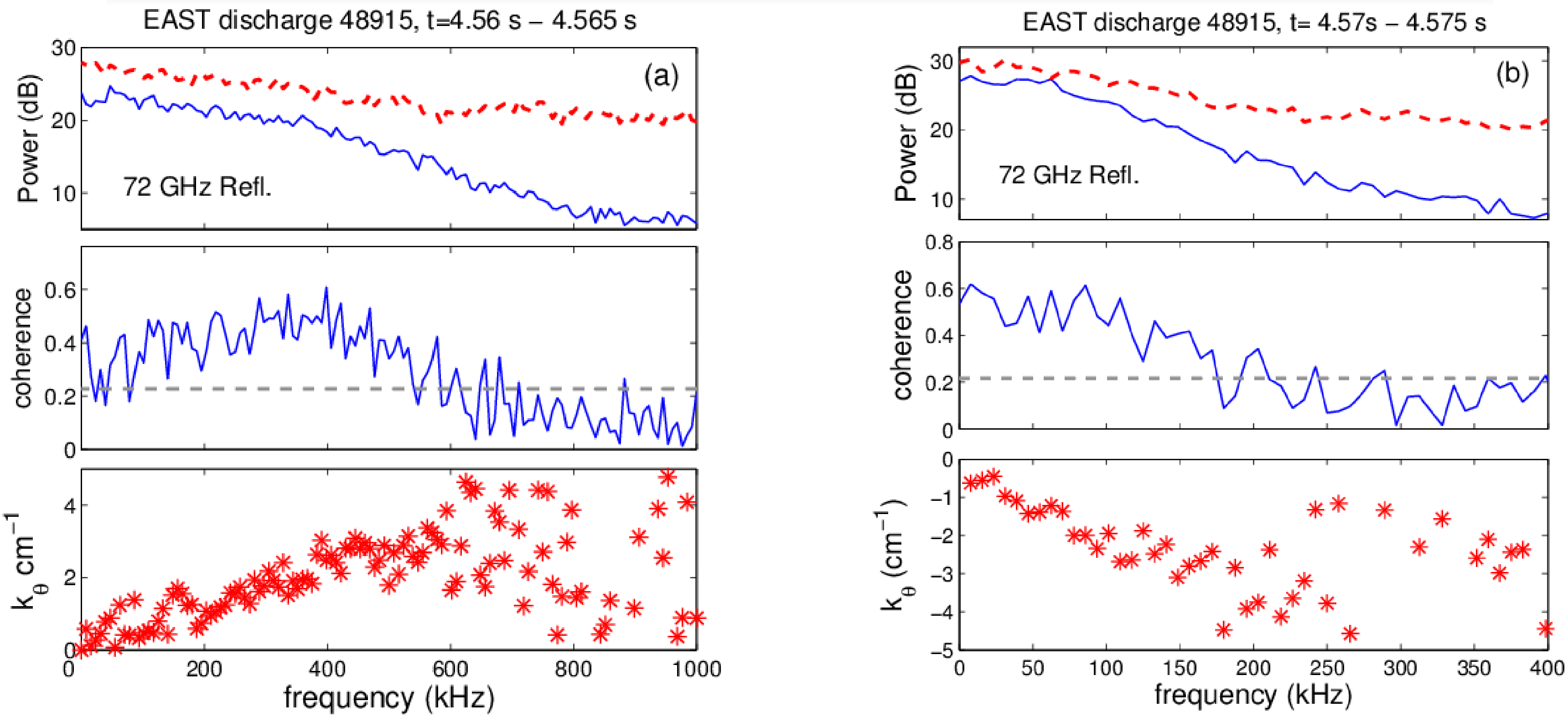


➢ For #48915, the 72 GHz refl. cutoff is just inside pedestal at the first half of inter-ELM phase but moves into pedestal later as pedestal evolves. The fluctuation rotating direction in lab frame changes from ion to electron direction.

X. Gao, et al., NF, 2015

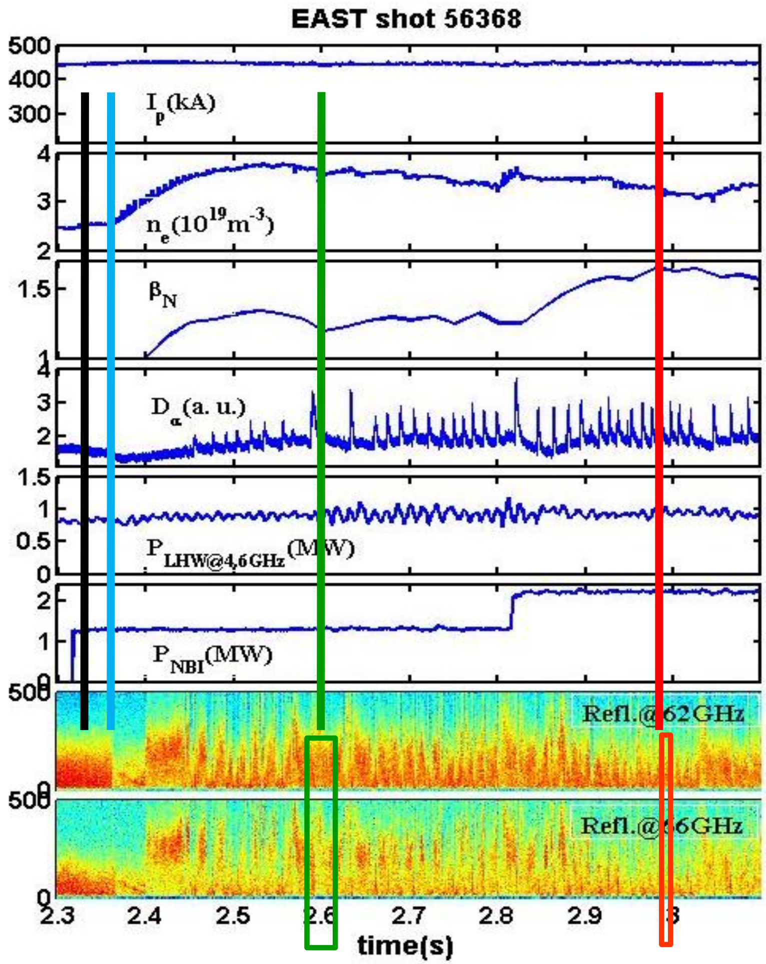
Turbulence in and inside pedestal (cont.)

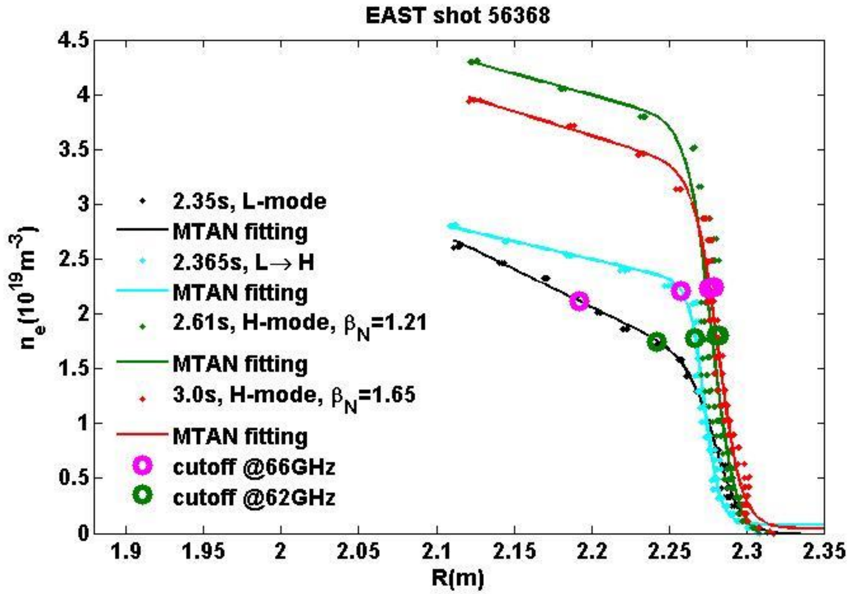
ASIPP

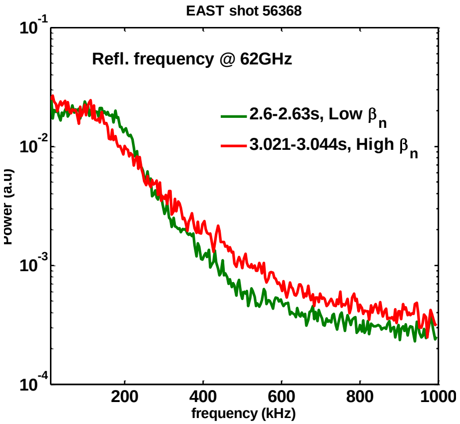


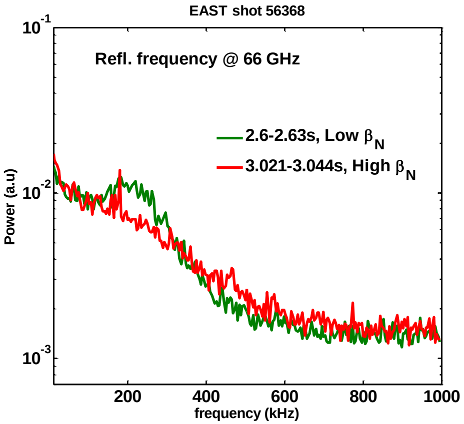
- For fluctuation just inside pedestal the frequency component with significant coherence can be up to 600 kHz, corr. $k_\theta=0 - 3\ cm^{-1}$ in ion diamagnetic drift direction.
- For fluctuation in pedestal, the frequency spectrum is narrower, up to ~200 kHz, corr. $k_\theta=0 - -3\ cm^{-1}$ in electron diamagnetic drift direction.

Pedestal turbulence for high β_N plasmas is studying









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Application of BOUT++

ASIPP

- Three dimensional nonlinear simulations of ELMs on EAST using BOUT++ code (Zixi Liu)
- I-mode pedestal stability analysis (Zixi Liu)
- Impact of pedestal density and Er on P-B stability (Defeng Kong)
- Impact of edge current profiles on P-B stability (Guoqiang Li)

Three dimensional nonlinear simulations of ELMs on EAST using BOUT++ code

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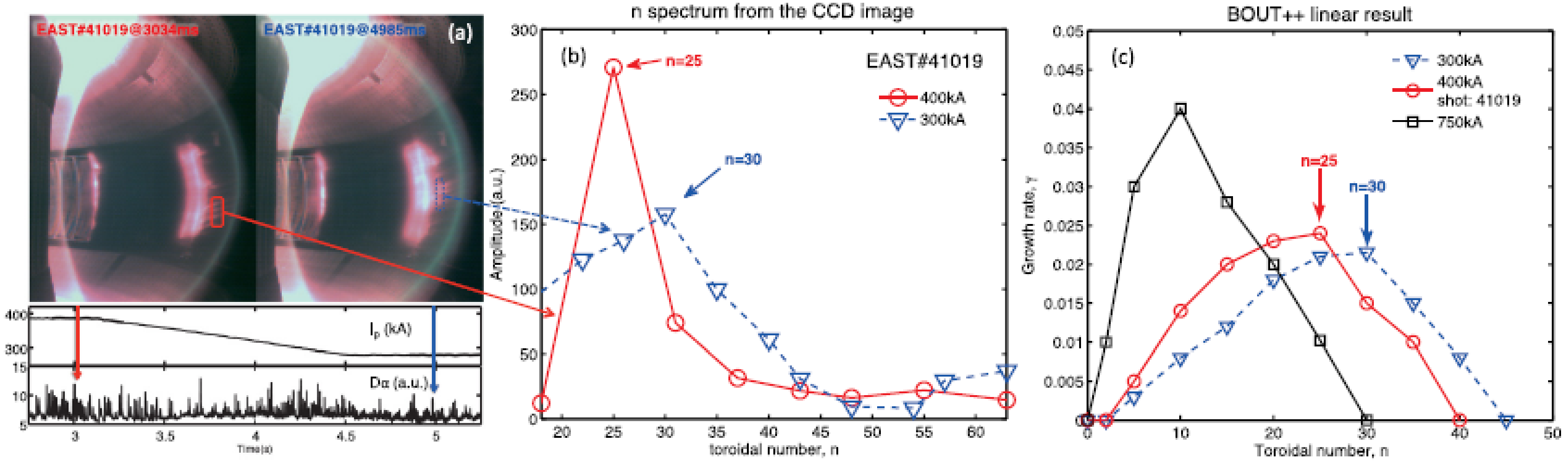

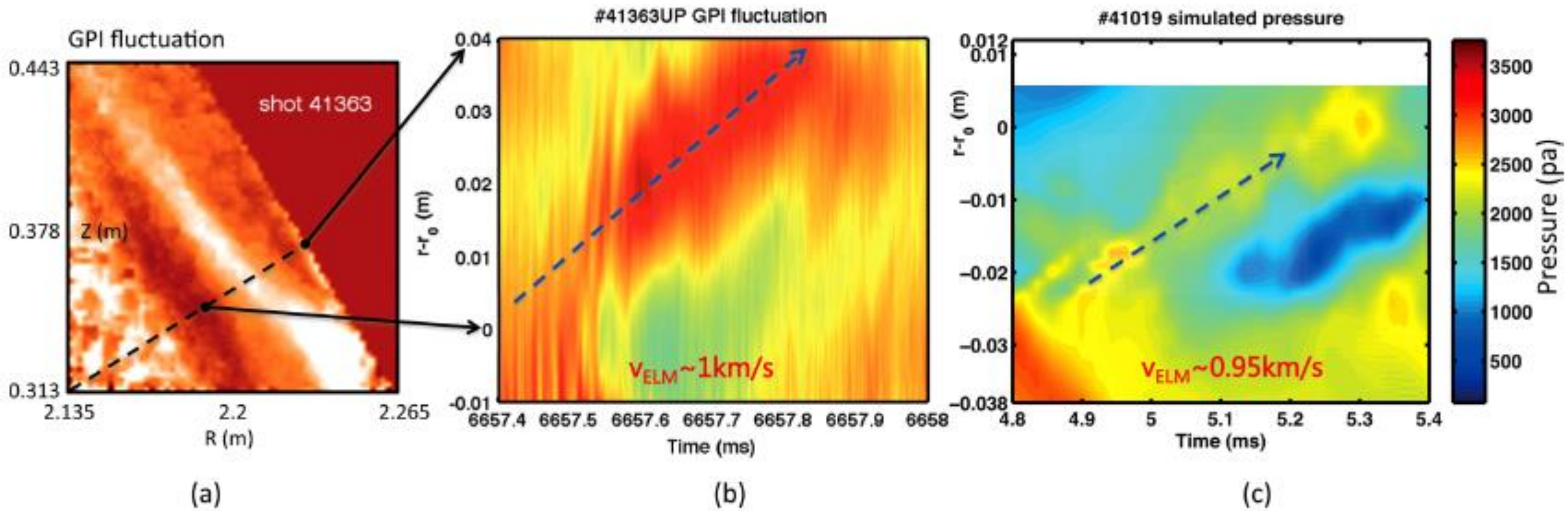

Z.X.Liu, 2014 PoP

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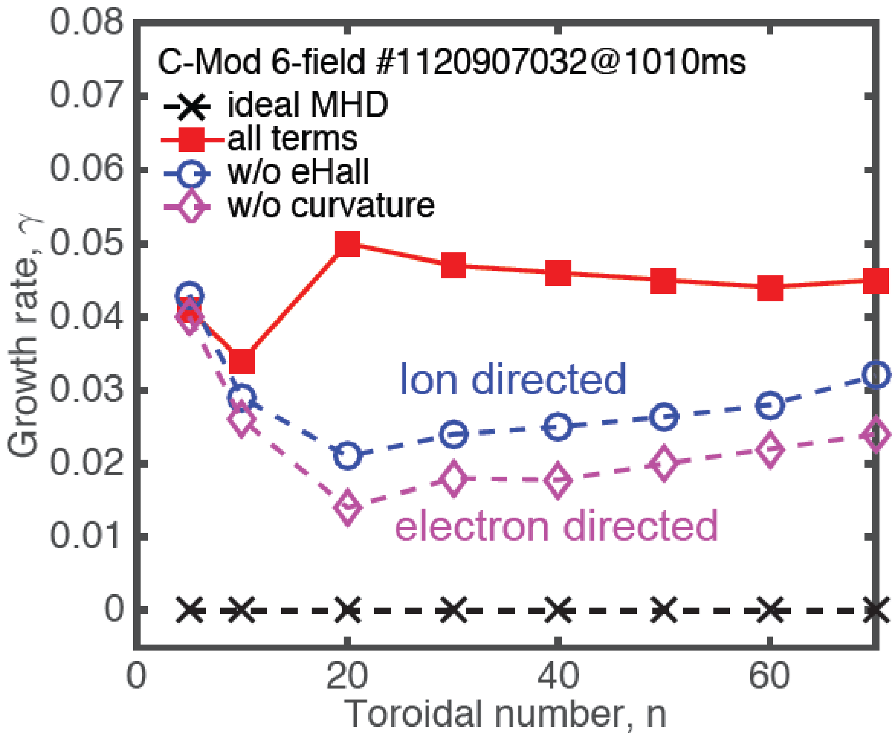
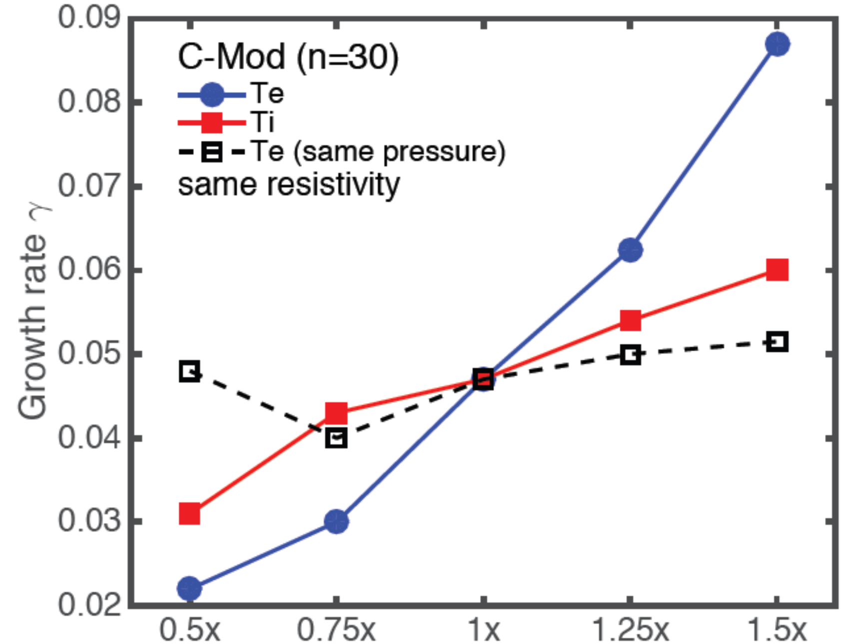
Stability analysis of I-mode pedestal using 6-field BOUT++





Zixi Liu, 2015 APS

- I-mode pedestal is stable to ideal MHD but unstable to drift Alfven wave mode and resistive ballooning mode.
- Free energy of the unstable modes is mainly from electron pressure gradient.

Two coherent modes in nonlinear phase

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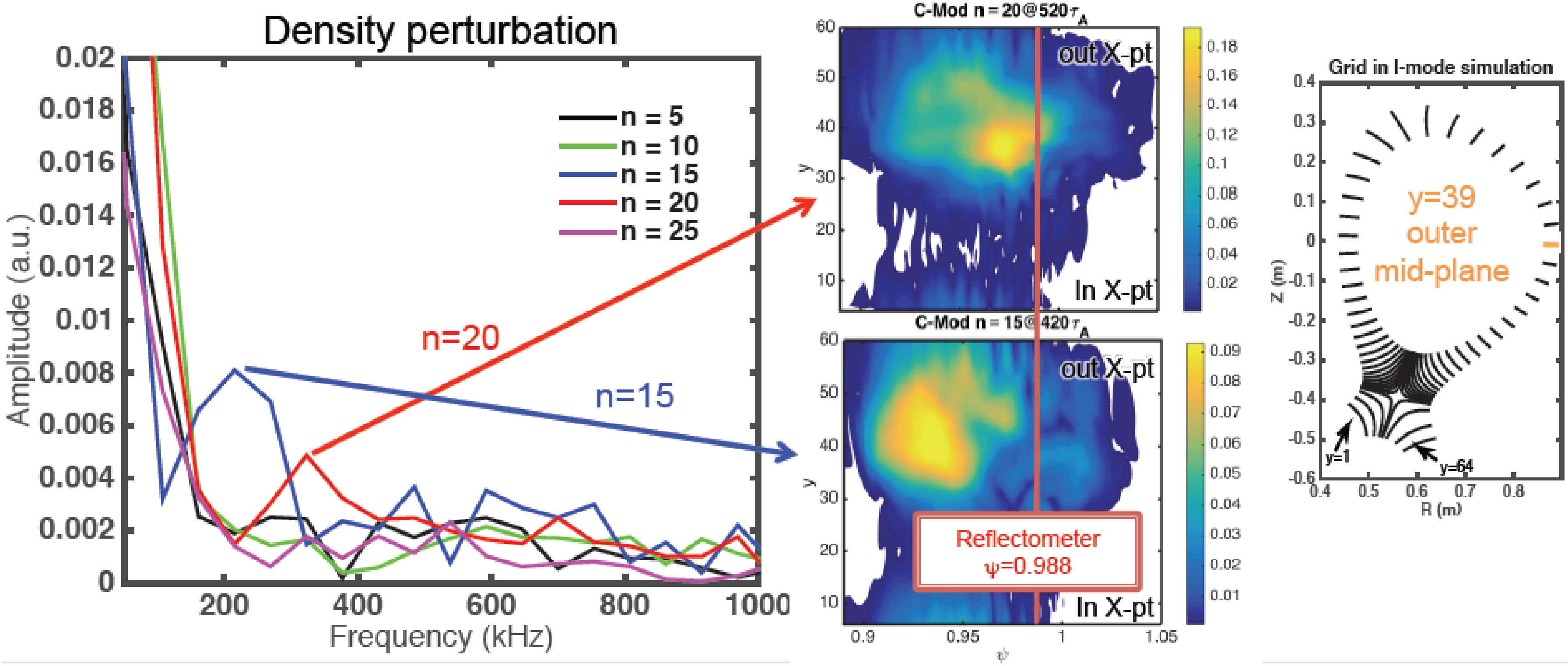
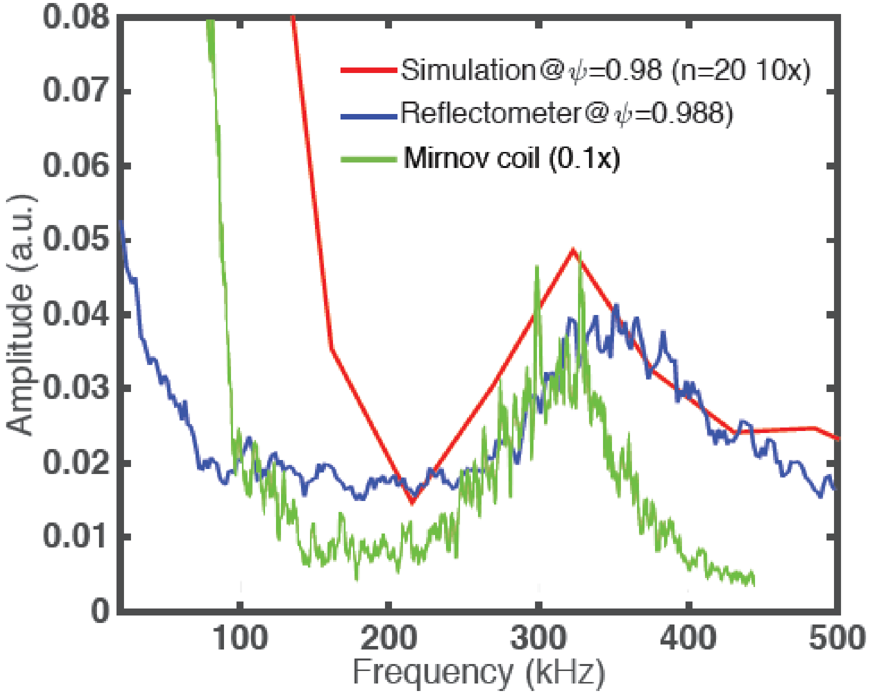
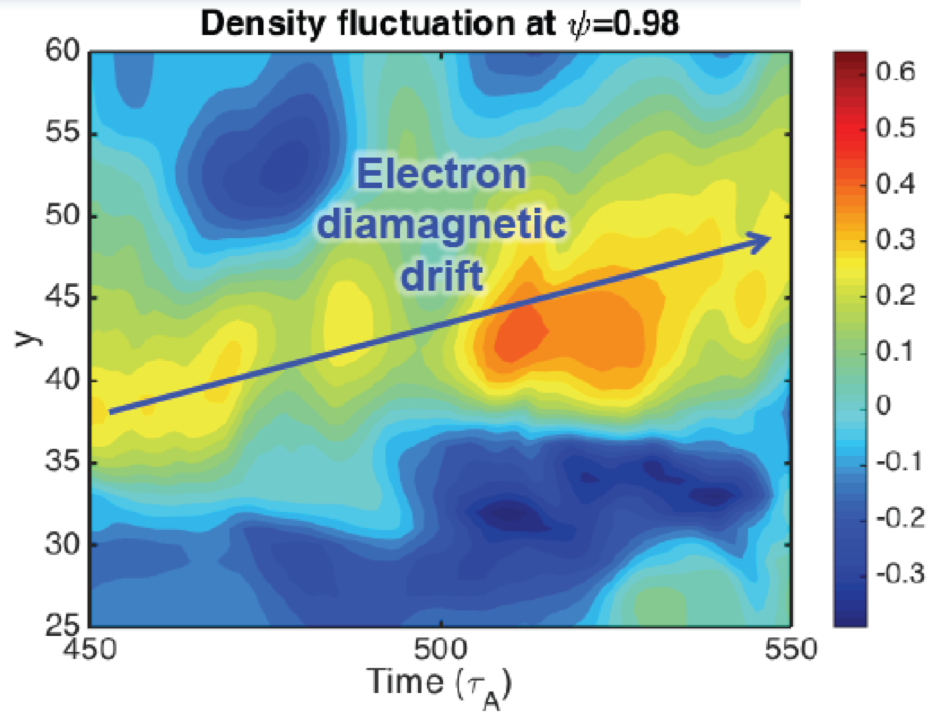


- Two coherent modes were observed in the nonlinear phase:
  - n=15, f~200 kHz, close to pedestal top
  - n=20, f~300 kHz, close to separatrix and reflectometer cutoff position.

Simulation Vs Experiment

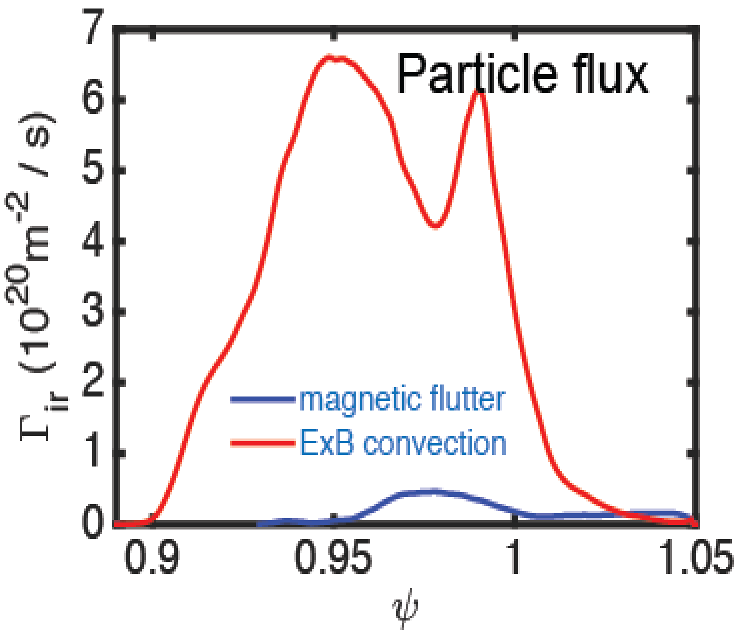
ASIPP

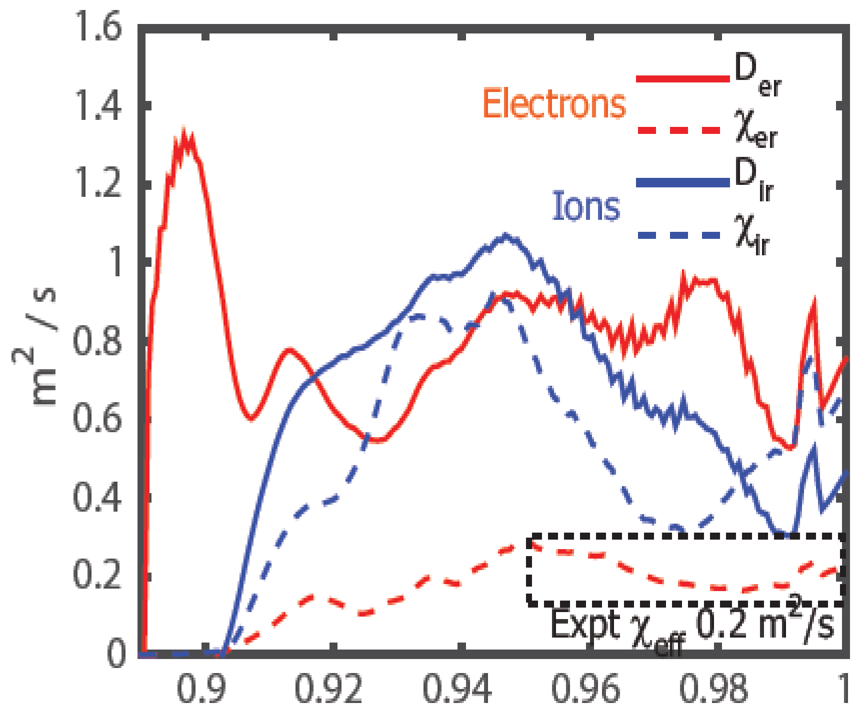




- n=20 mode is similar to the experimental results from the reflectometer and Mirnov coil, including mode spectrum and rotation direction.
- n=15 mode is not observed in experiment.

Particle diffusivity is larger than thermal; Both values are roughly consistent with C-Mod expt





- **Larger particle diffusivity is consistent with the key feature of I-mode;**
- Predicted χ_e and χ_i (dashed lines) are close to experimental χ_{eff} (from power balance over $0.95 < \psi < 1$);
- Particle flux Γ is ~4x larger than determined in Dominguez, PhD Thesis, MIT (2012) (in a lower ne I-mode, so value is reasonable).

Zixi Liu, 2015 APS

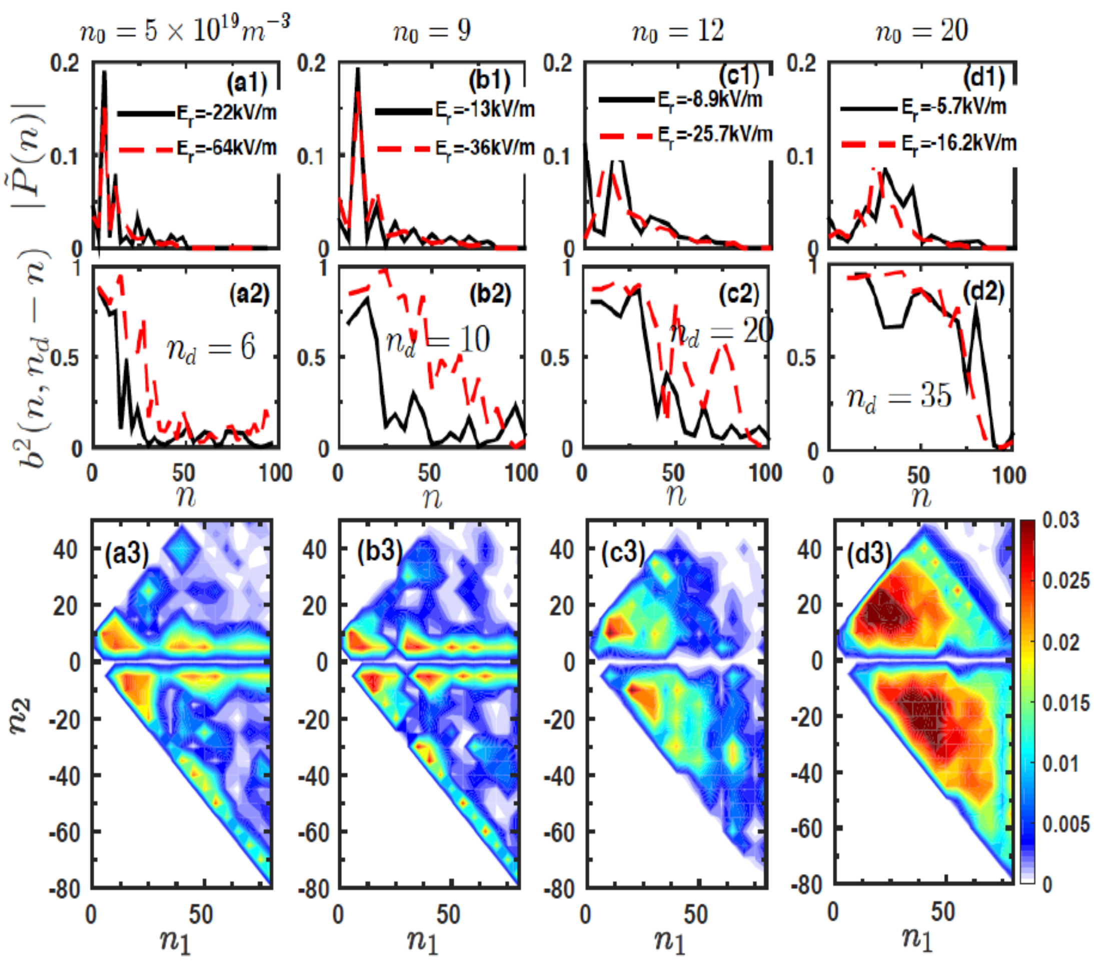
Application of BOUT++

ASIPP

- I-mode pedestal stability analysis (Zixi Liu)
- Impact of pedestal density and Er on P-B stability (Defeng Kong)
- Impact of edge current profiles on P-B stability (Guoqiang Li)

Impact of collisionality and E_r on amplitude spectrum and bispectrum of peeling and ballooning mode

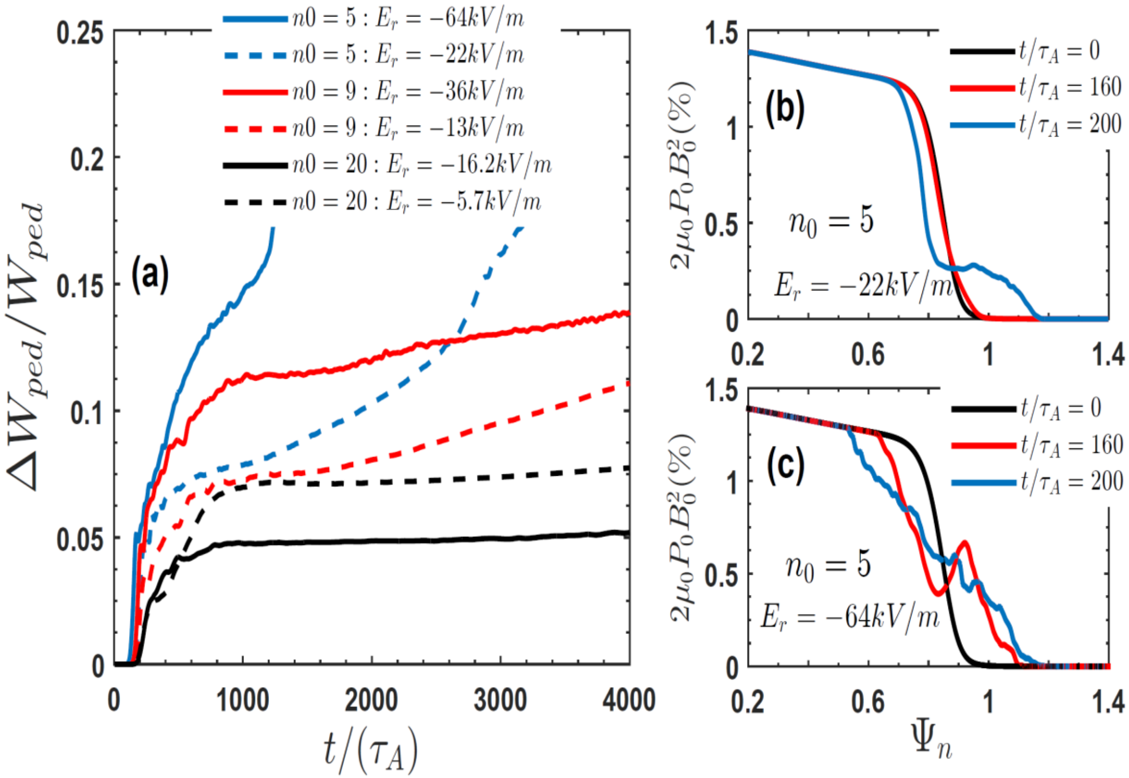
ASIPP



D.F.Kong, 2015 APS

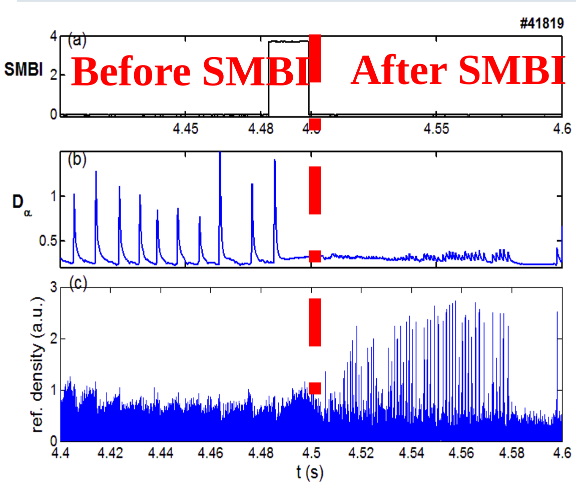
- By increasing collisionality, nonlinear simulations show that:
  - (a) amplitude spectrum becomes broad;
  - (b) the dominant mode changes from n=10 to n=35;
  - (c) nonlinear interactions are strongly enhanced.
- The increase Er can also enhance the nonlinear coupling between modes.

Impact of E_r on ELM size



- For low collisionality (n0=5 and n0=9), the increase Er can enhance the ELM size;
- For high collisionality (n0=20), the increase Er would suppress the ELM size and delay the crash of pedestal.

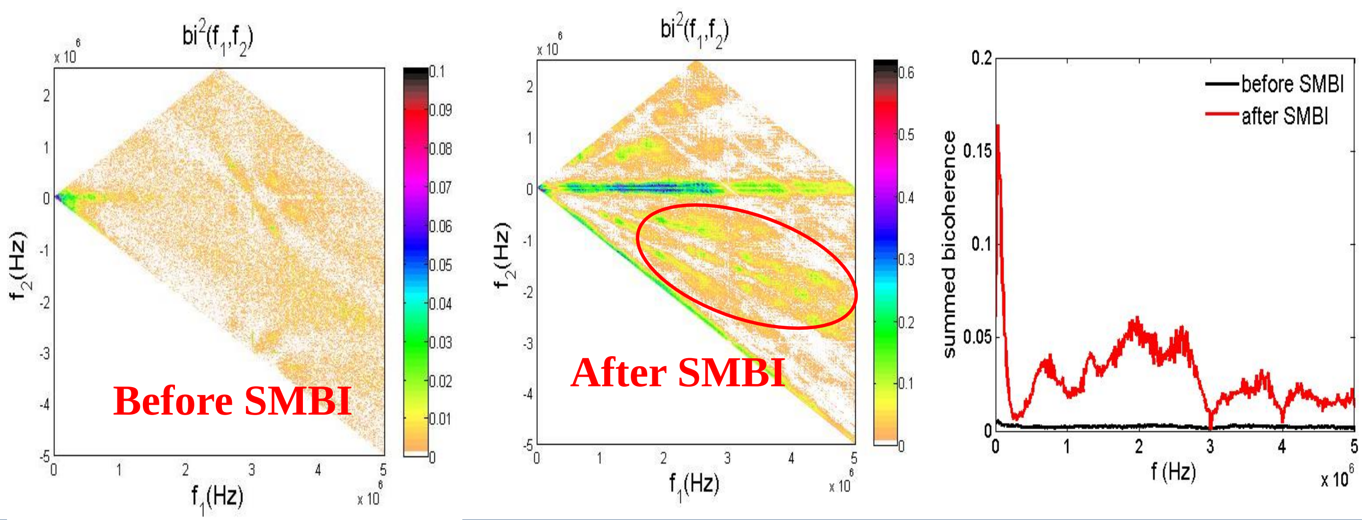
Experimental results on EAST: Impact of collisionality (with SMBI) on ELM size



After SMBI (collisionality increased):

1.ELM size is mitigated and particle transport is mainly contributed by high frequency turbulence;
2.Bispectrum analysis indicate that the nonlinear interactions are greatly enhanced at high collisionality.

1. X. L. Zou. 24th IAEA FEC, San Diego, US, (PD/P8-08), 2012.
2. Bispectrum analysis results are provided by Adi Liu (USTC)



Application of BOUT++

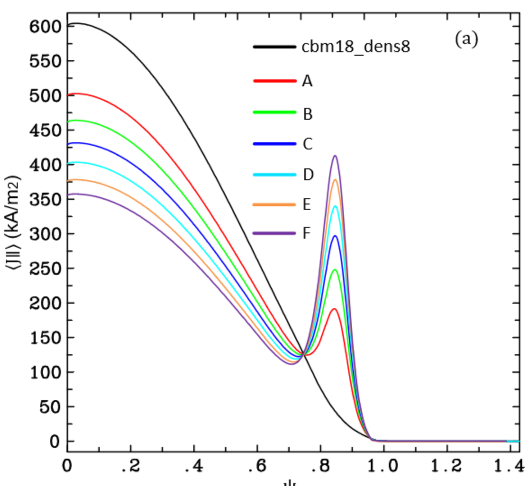
ASIPP

- I-mode pedestal stability analysis (Zixi Liu)
- Impact of pedestal density and Er on P-B stability (Defeng Kong)
- Impact of edge current profiles on P-B stability (Guoqiang Li)

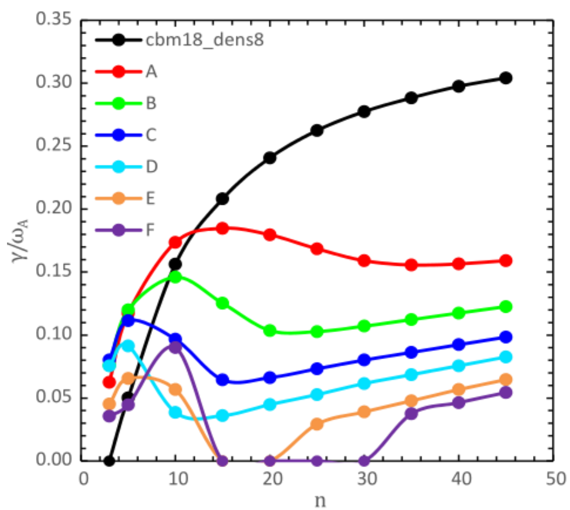
Edge current can stabilize the ballooning modes

ASIPP

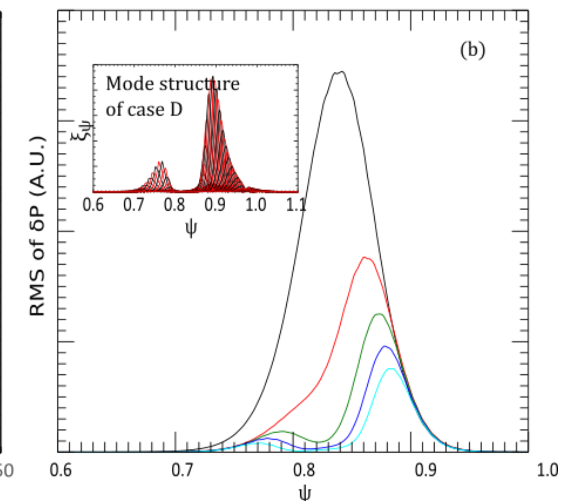
- using the CORSICA code, a sequence of equilibria with different edge current are created
- As the edge current increases, the medium n ballooning modes are stabilized, the dominant mode is changed from ballooning modes to low-n kink modes
- The ballooning stabilization effect is due to the increase of local shear at the outer mid-plane



Current profiles of sequence of equilibria



Linear growth rate v.s. toroidal mode number



RMS of perturbed pressure, the height is normalized with linear growth rate

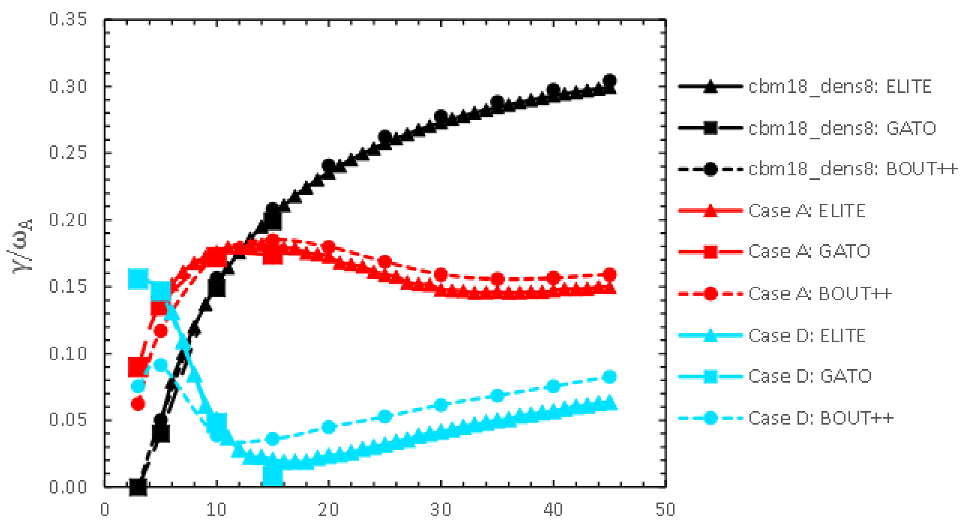
BOUT++ and GATO/ELITE benchmark

ASIPP

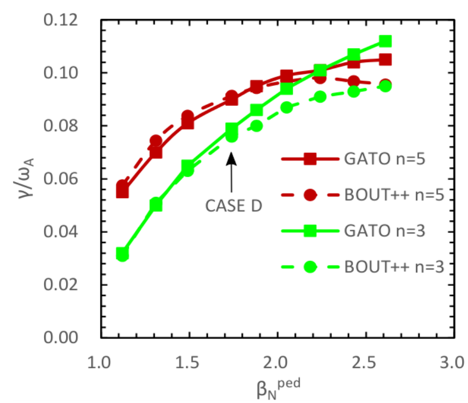
- As edge current increases, the difference between BOUT++ and GATO/ELITE results becomes large
- This difference is due to the vacuum treatment

G.Q.Li, 2014 PoP

- Reduced MHD model neglects compressional Alfven waves with $\delta B_{||}$~0, which may become important in high beta plasmas
- Our calculations shows that reduced MHD model is still valid for $\beta_N^{ped} = 1.8$, which is higher than maximum β_N^{ped} in real experiments (~1.4)



Linear growth rate from BOUT++, ELITE and GATO



Outline

ASIPP

- H-mode plasma on EAST 2015
- Pedestal turbulence study on EAST
- Relevant results on BOUT++
- Summary

Summary

ASIPP

- The plasma β_N has arrived at 2.0 due to recent upgrade of plasma heating system on EAST. But high β_N phase can not be sustained due to plasma radiation, locked mode or density de-peaking. Further optimization of plasma performance is needed.
- Pedestal turbulence and its role in pedestal evolution has been studied. CM is usually observed in ELM-free phase while broadband fluctuation dominated the inter-ELM phase. Analysis show that both turbulence mode may play important role in pedestal evolution.
- We have a good collaboration in the application on BOUT++ and abundant outputs have been achieved. More collaborations are expected.

ASIPP

Thanks for your attention!

56932@3740的1D分析

- 使用ONETWO+NUBEAM+GENRAY开展模拟分析
- Ip=409 kA, I_{LHCD}=51 kA, I_{NBI}=37 kA, I_{BS}=123 kA, I_{ohm}=198 kA
- Fast ion contributed stored energy: 35 KJ
- 低杂波沉积在rho=0.2附近
- 形成反剪切q剖面，这可能是形成ITB的原因