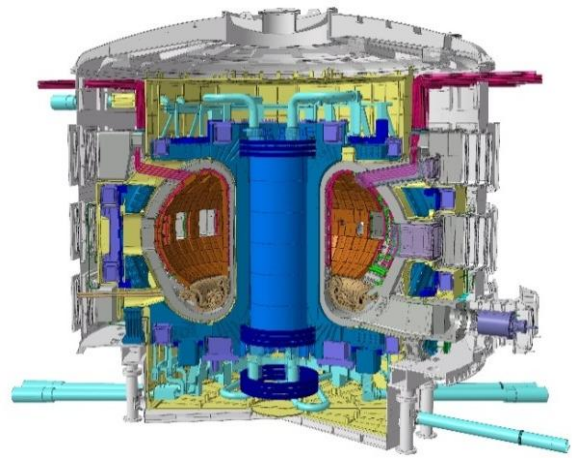


Density Limit Disruption Induced by Core-localized Alfvénic Ion Temperature Gradient Instabilities in HL-2A NBI Plasmas

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European Physical Society Plasma Physics Conference 2026, 29 June - 3 July, Edinburgh

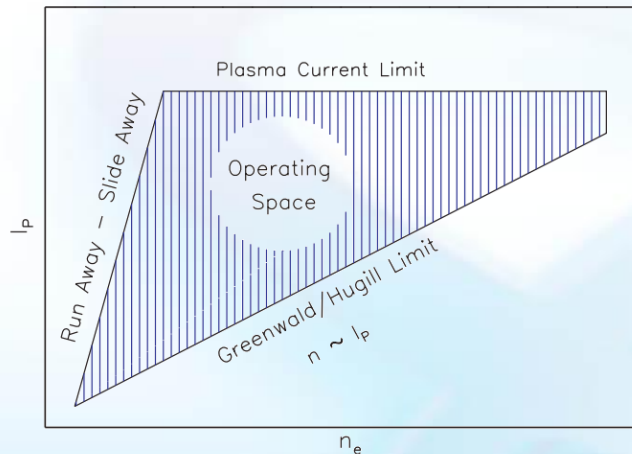


Brief Introduction of Density Limit

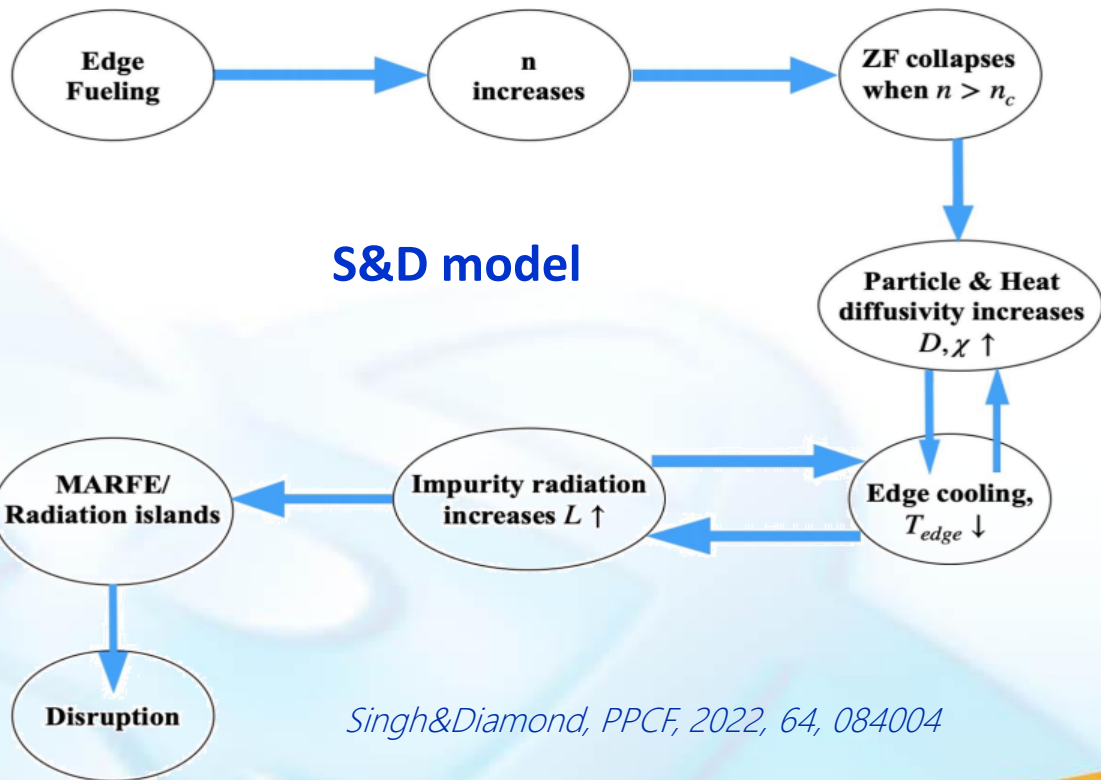
Greenwald density: $n_{GW} = I_p / (\pi a^2)$

ITER Baseline: $n_e/n_{GW} \sim 0.8 \sim 1.2$

Density limit: **mysterious barrier, unresolved**

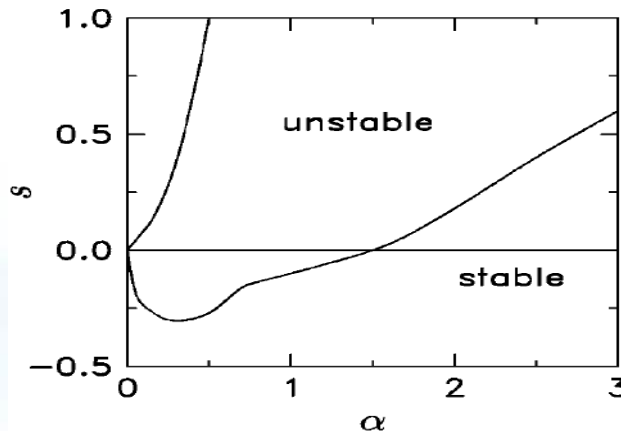
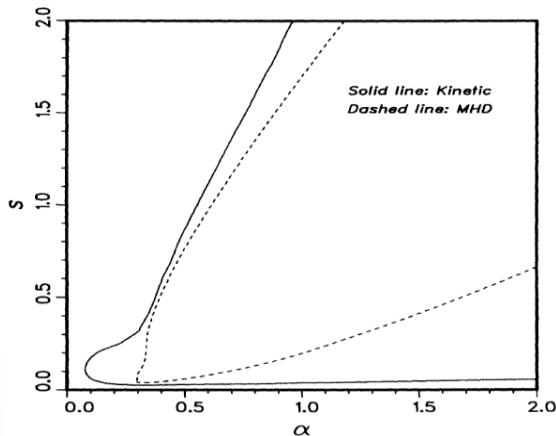


M. Greenwald, PPCF, 2002, 44, R27



Singh&Diamond, PPCF, 2022, 64, 084004





■ Magnetic shear:

$$s = \frac{rdq}{qdr}$$

■ Pressure gradient parameter:

$$\alpha = q^2 \beta_i [(1 + \eta_i) + \tau(1 + \eta_e)] R_0 / L_n$$

- AITG/KBMs are instabilities driven by the magnetic field curvature and plasma pressure gradient considering the various kinetics effects, such as FLR, etc.
- At weak positive/negative shear $s \sim 0$, the first threshold of alpha becomes very small or vanishes and the AITG/KBM is unstable in the region $0 < \alpha < 1.0$.
- For equilibriums with reverse shear where q_{\min} is off axis and α_{\max} near q_{\min} , the existence of an unstable low- n global branch of AITG and trapped electron dynamics can further destabilize it.
- The growth rate of AITGs depends on the magnetic shear and is strongly affected by Shafranov shifts.

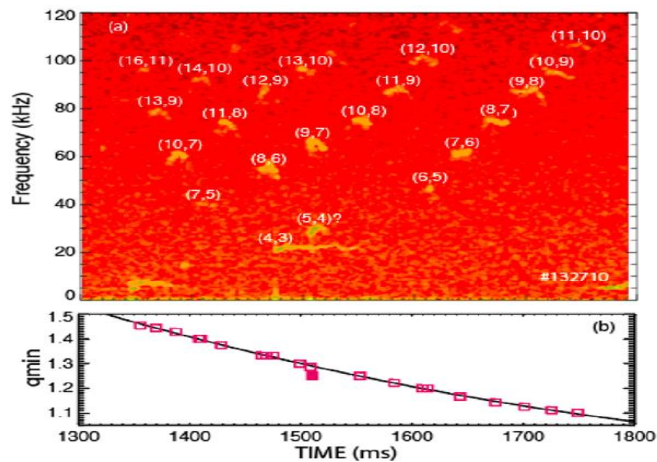
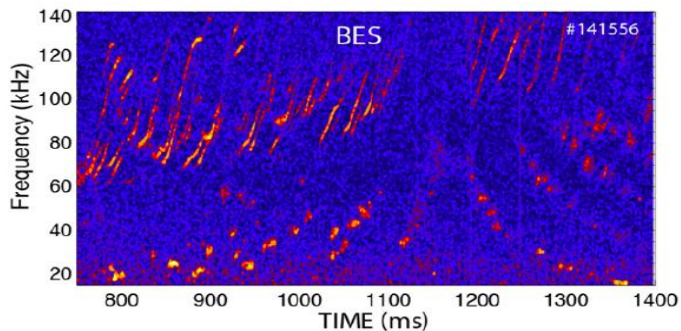
A. Hirose, PRL94&96&PoP03.

Ganesh&Vaclavik, PRL05.

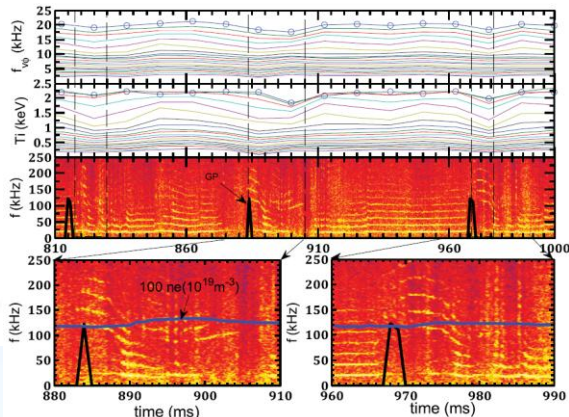
Dong, PoP04; Ganesh, PoP04.



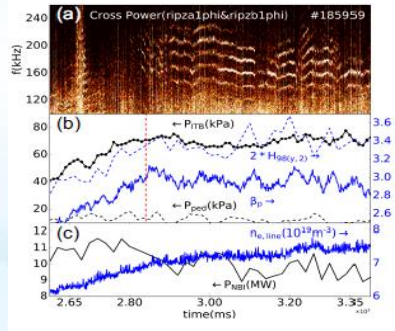
AITG/KBM in Auxiliary Heating Plasmas



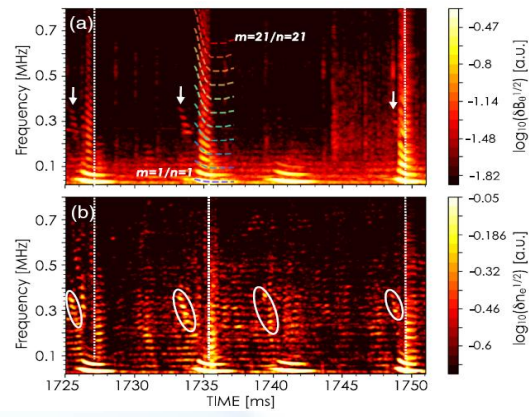
W. Heidbrink, et al, NF2021



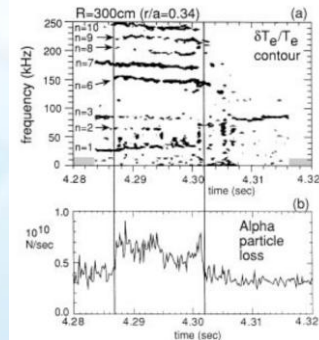
W. Chen, et al, NF2018



X. Jian, et al, PRL2023



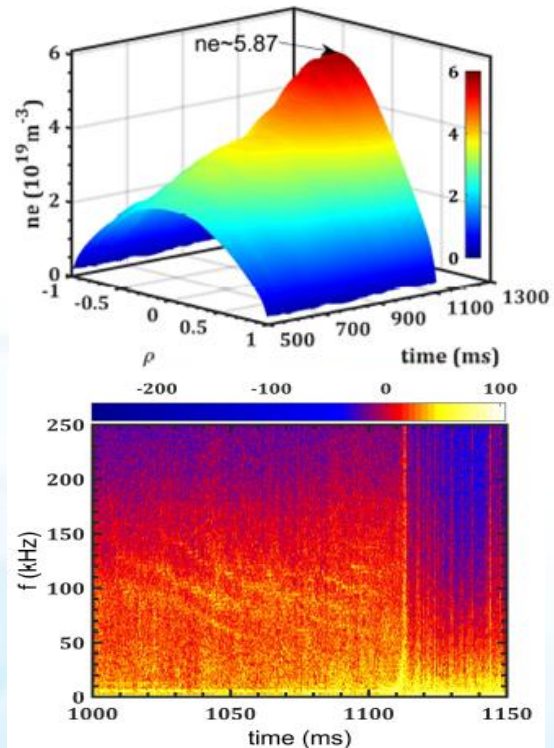
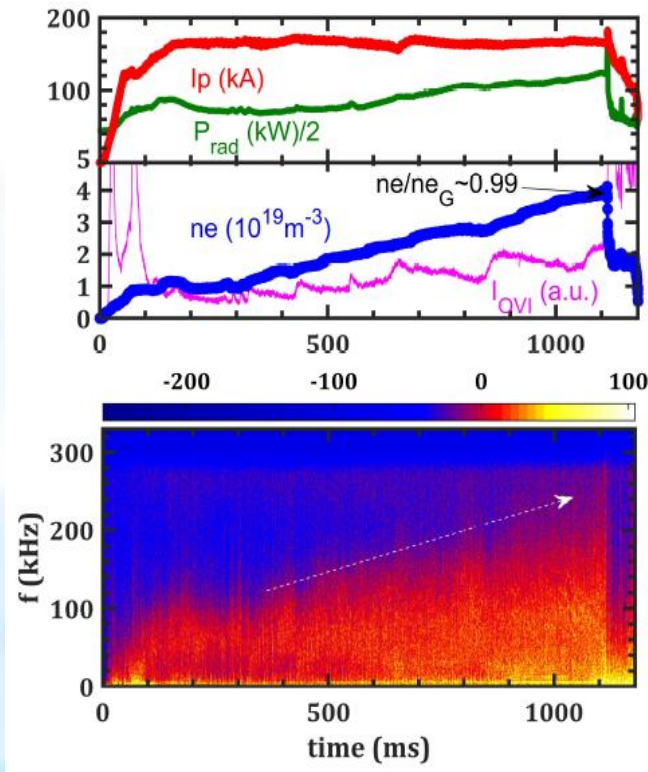
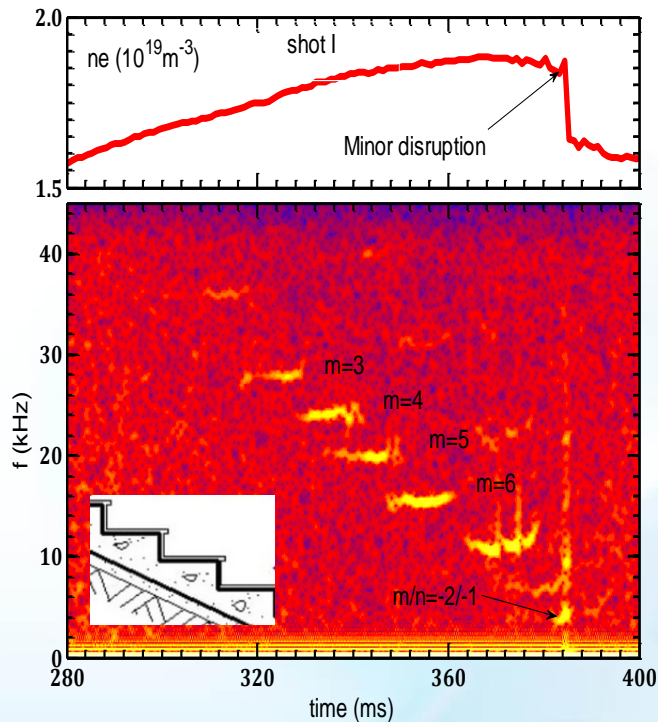
X. Du, et al, PRL2021



Chang, et al, PRL96

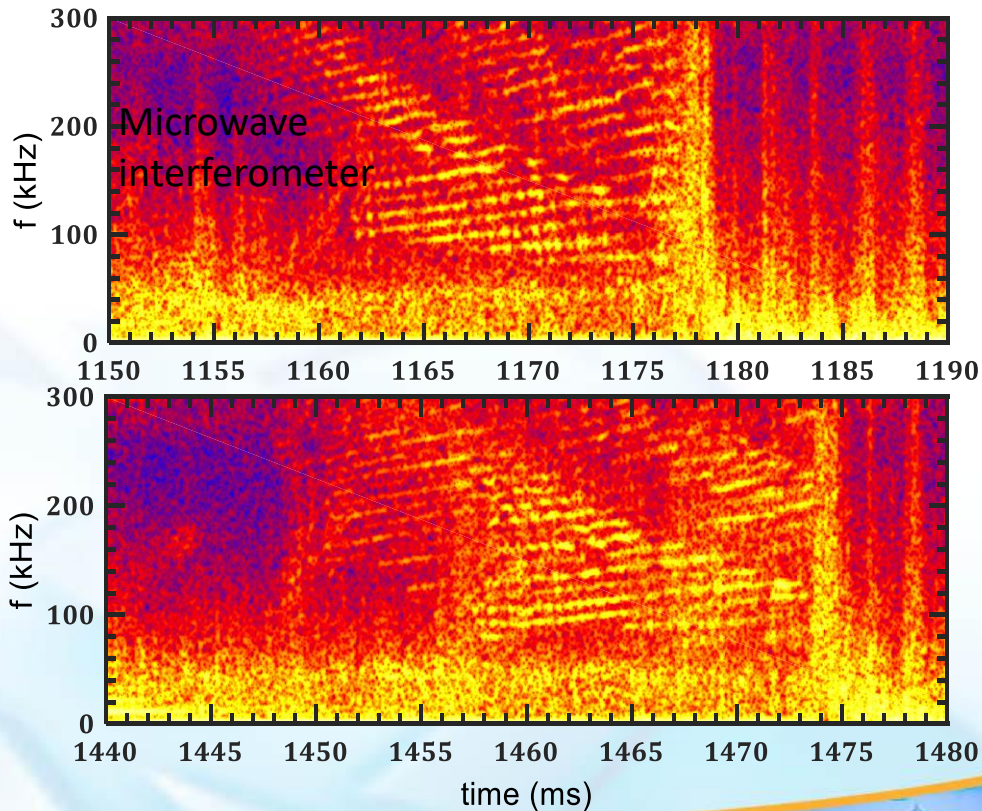
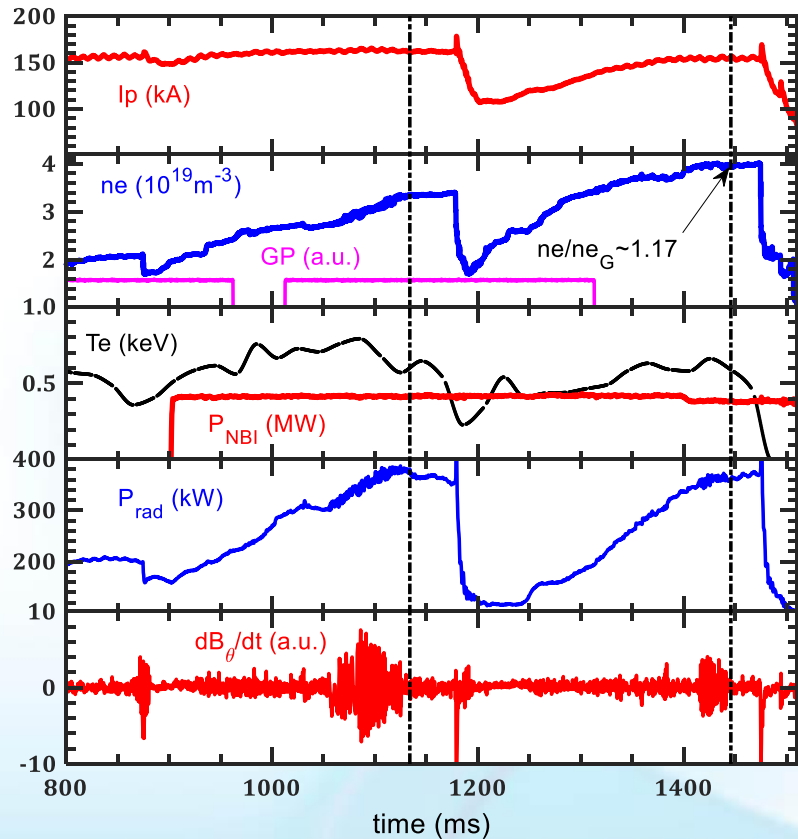


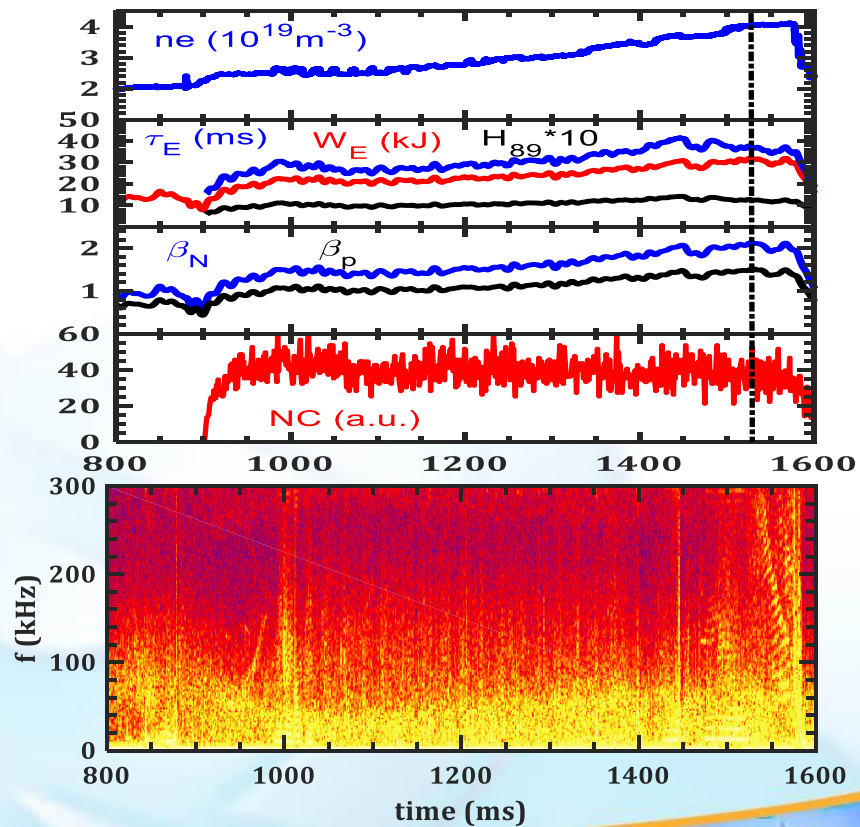
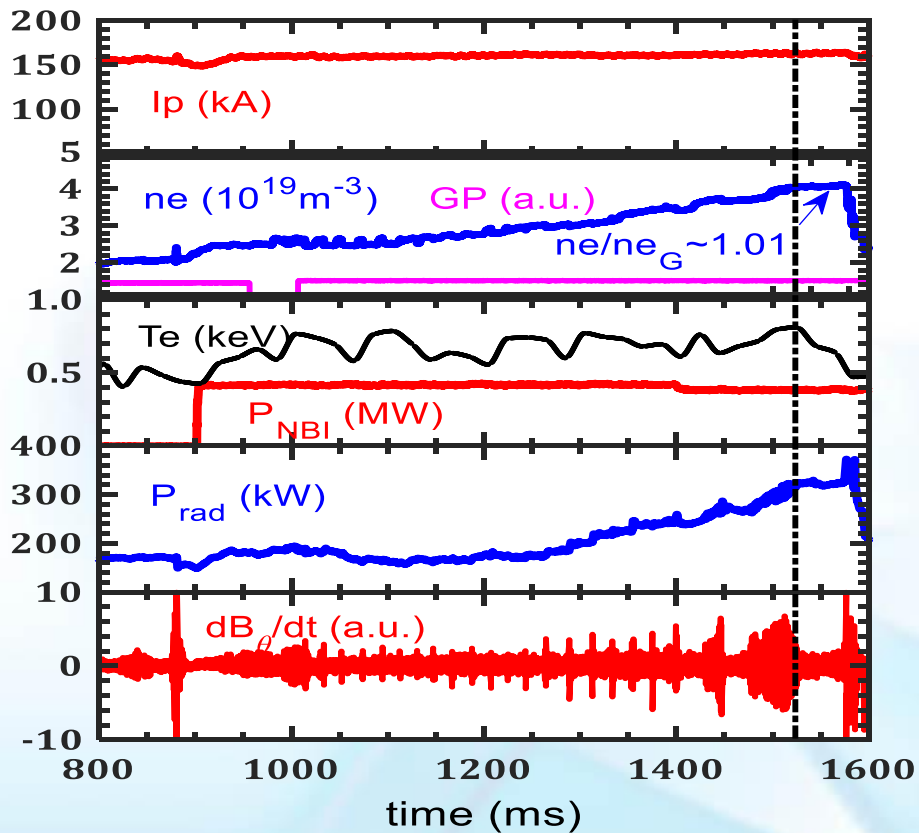
AITG/KBM before disruptions in Ohmic Plasmas

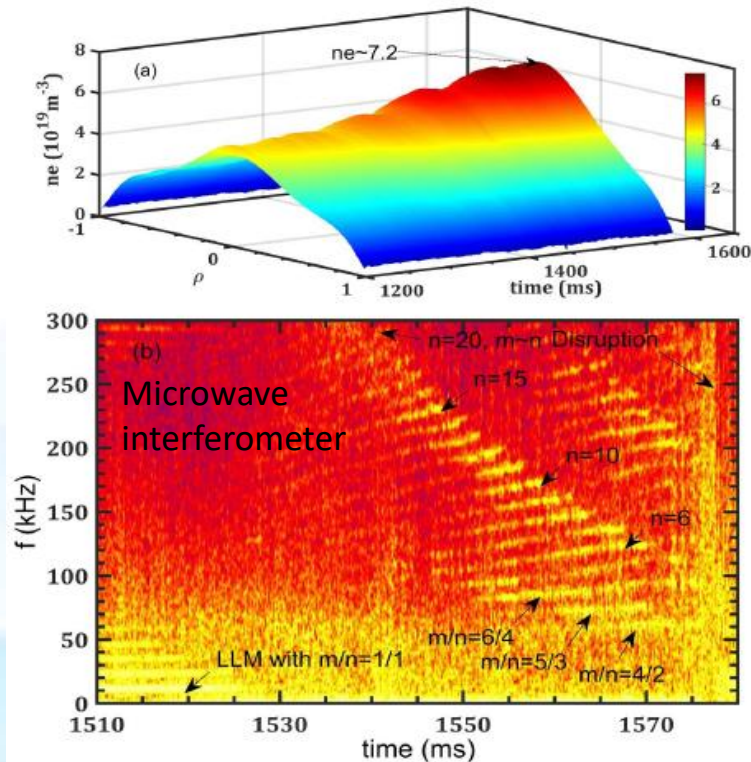
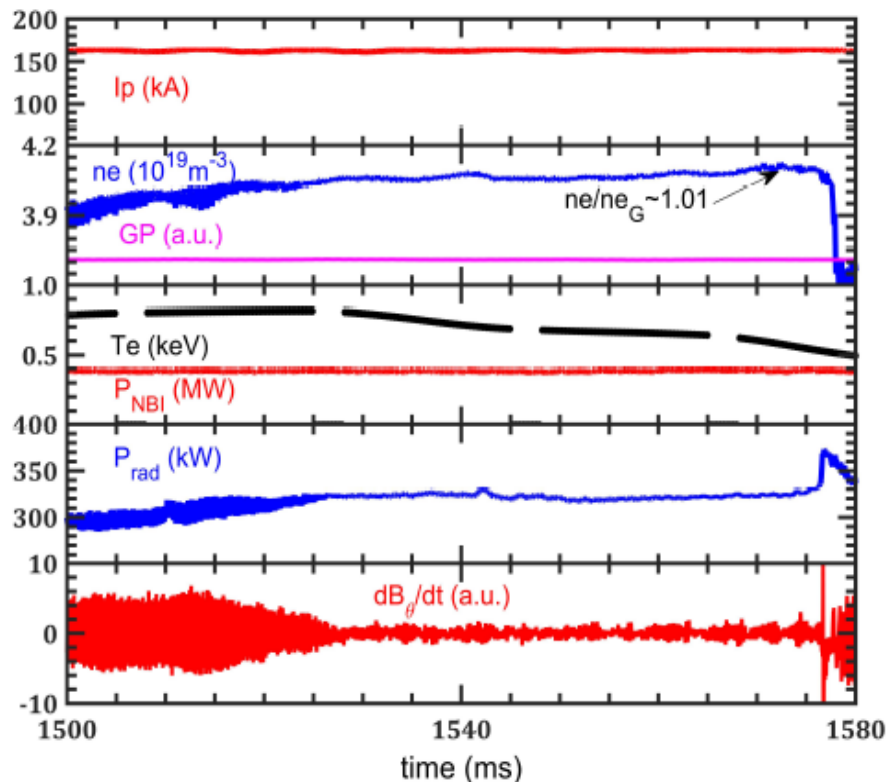


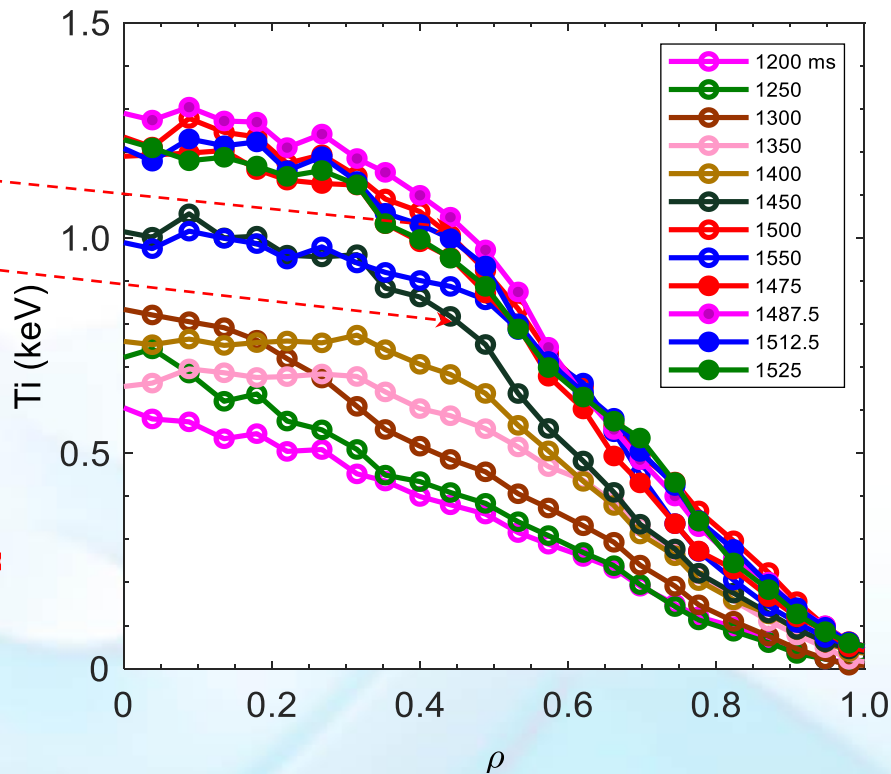
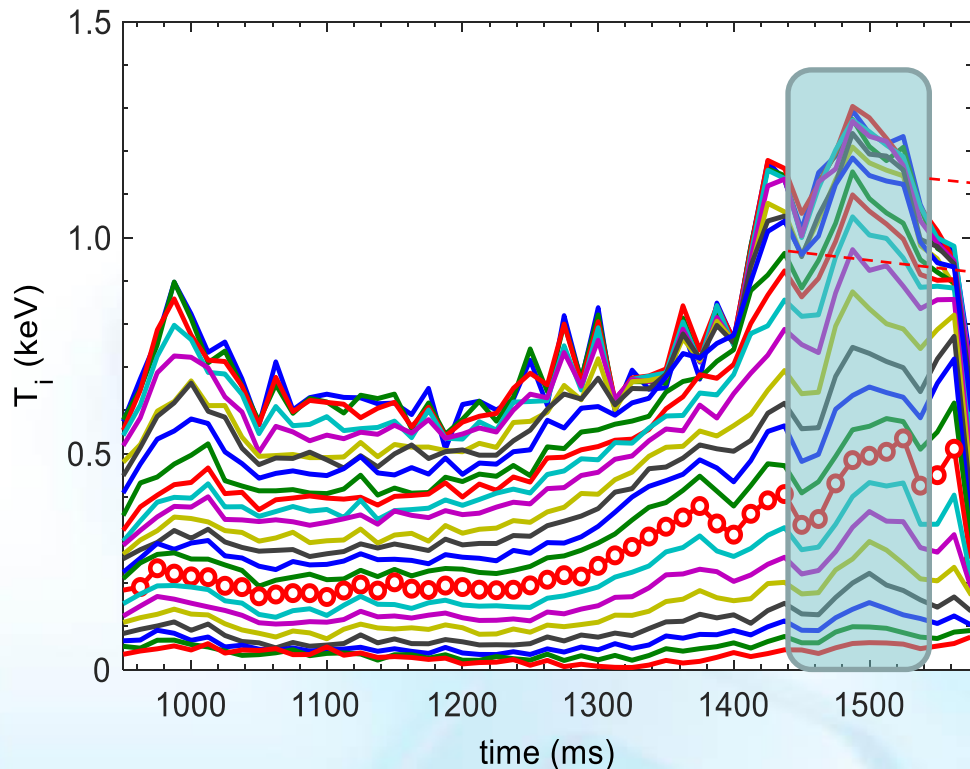
W. Chen et al 2016 EPL 116 45003





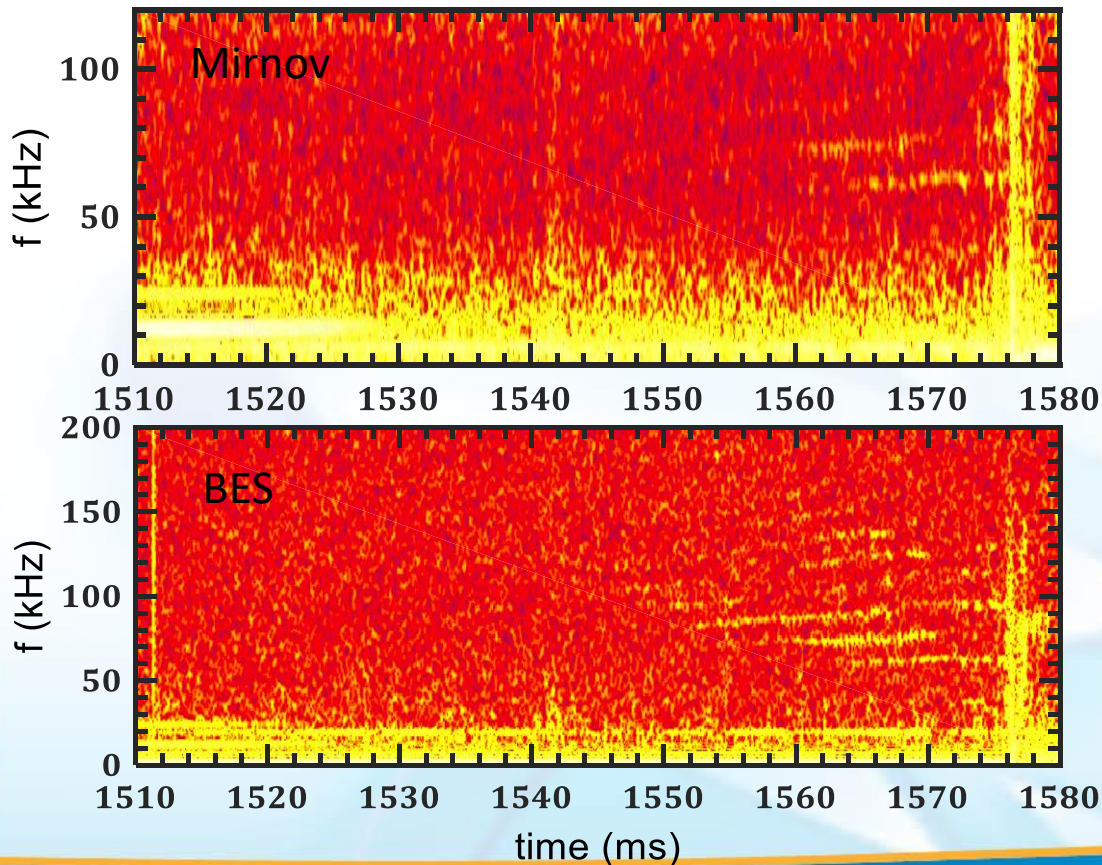






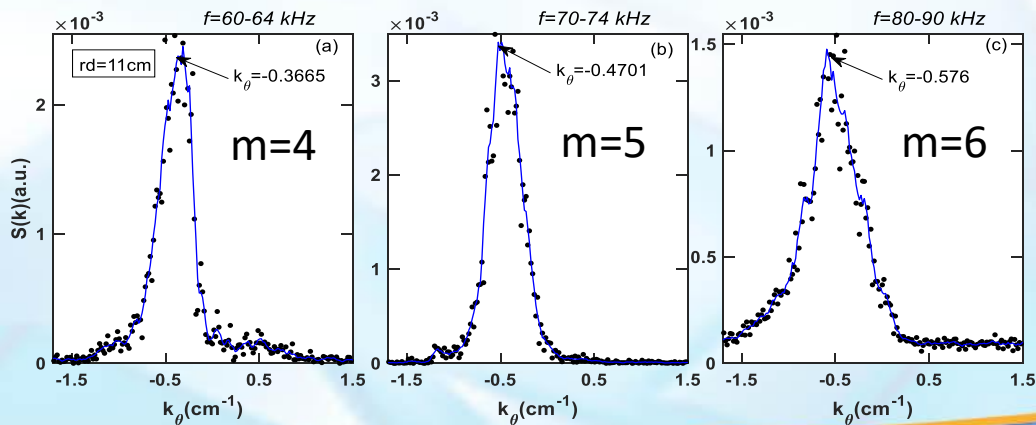
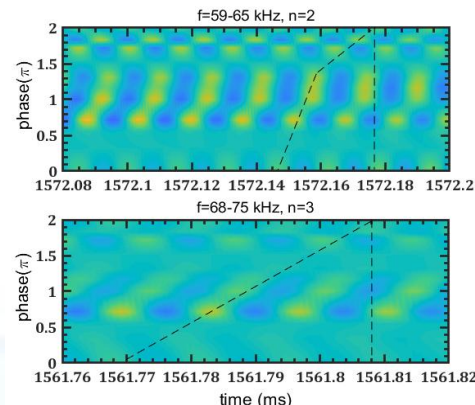
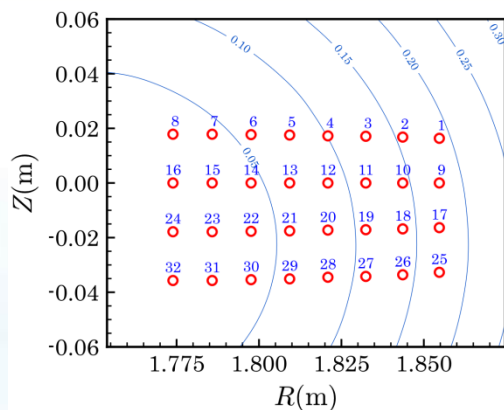
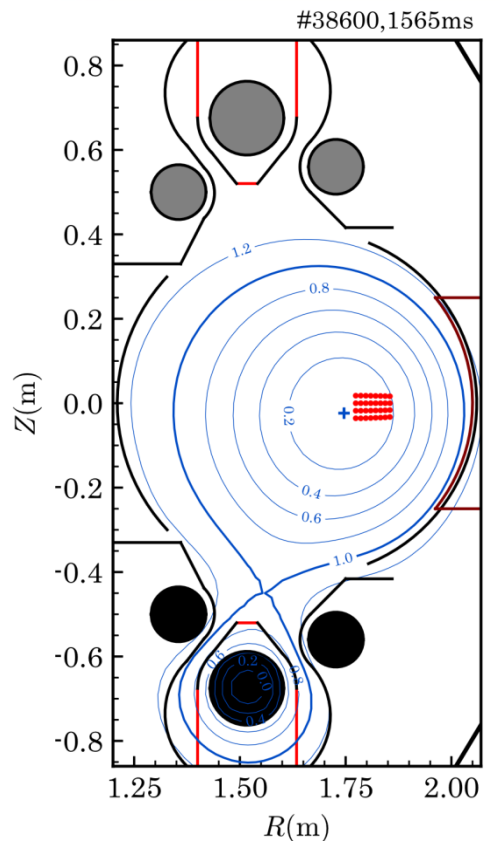
■ Core Ti decrease and Ti-profile broaden after kinetic MHD Instabilities are driven unstable





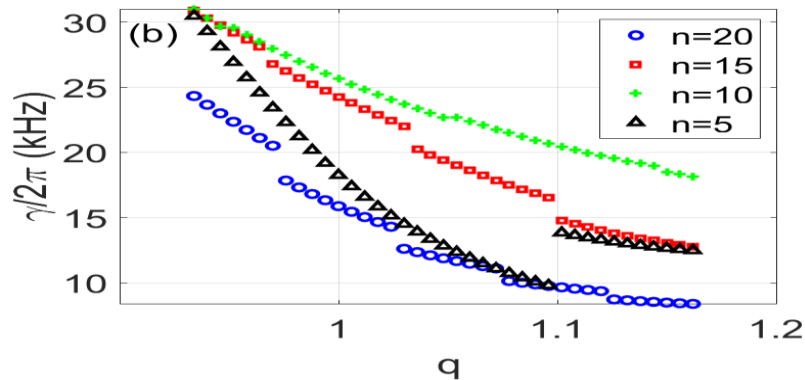
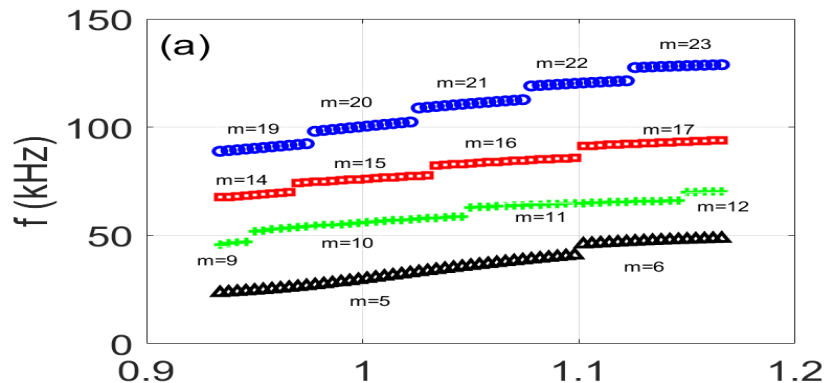
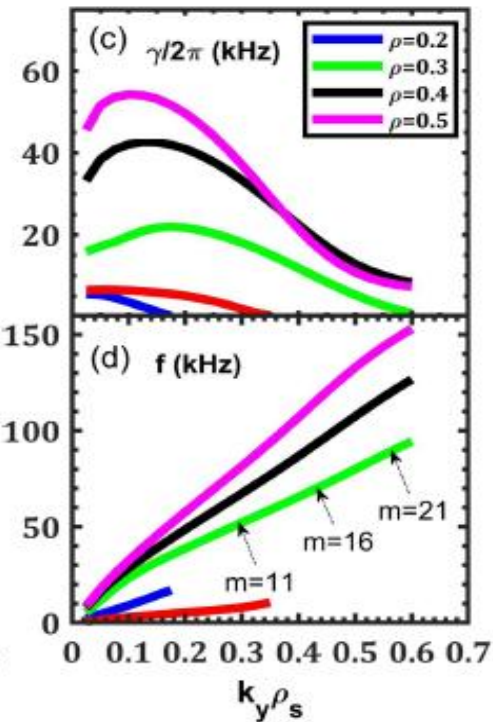
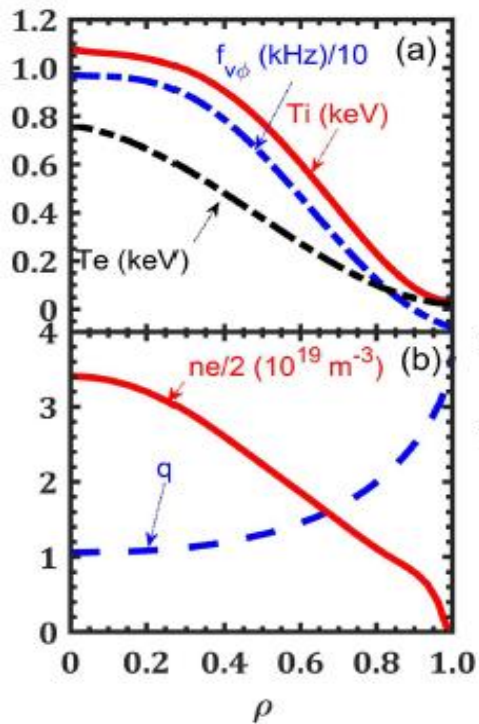
- By magnetic pick-up probes
 - Only measured LF modes with $n=2-4$
 - Determination of toroidal mode-numbers
- By beam emission spectroscopy (BES)
 - Only measured LF modes with $m=4-10$
 - Determination of poloidal mode-numbers
- By microwave interferometer
 - Optimal response for $f=0-500\text{kHz}$





$$m = r_d * k_{\theta}$$

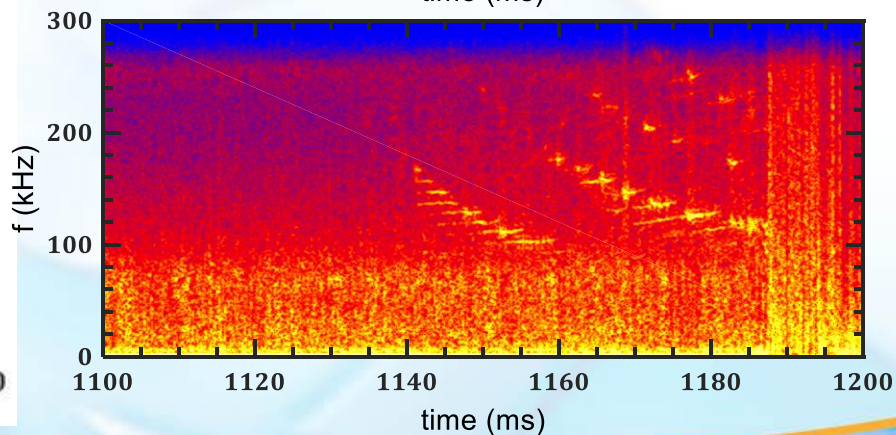
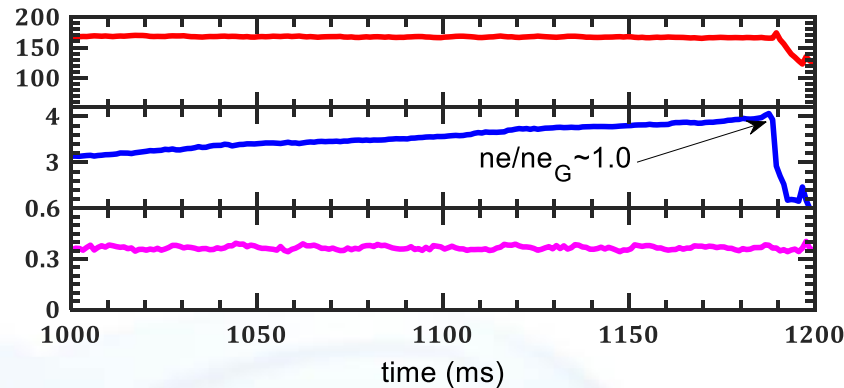
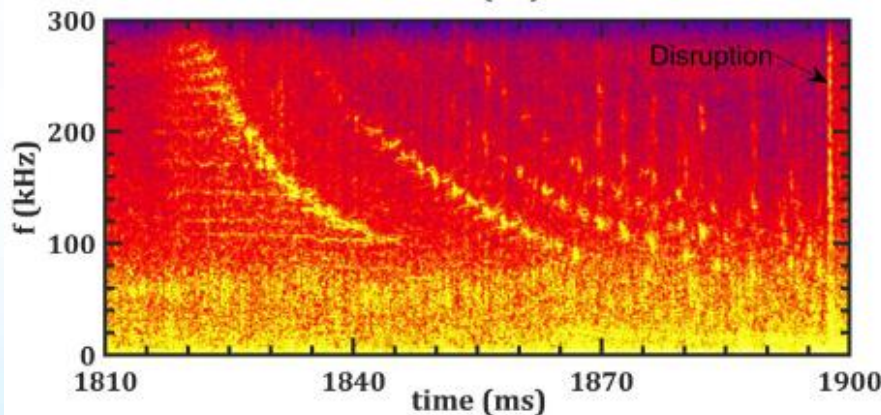
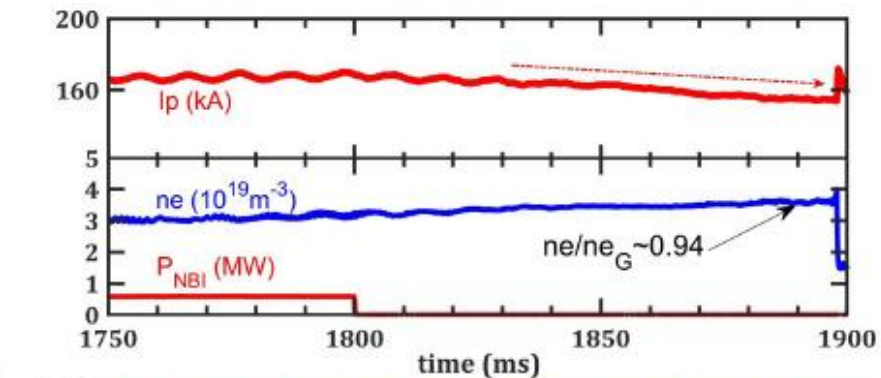




$$f_{lab} = f + n * f_d$$

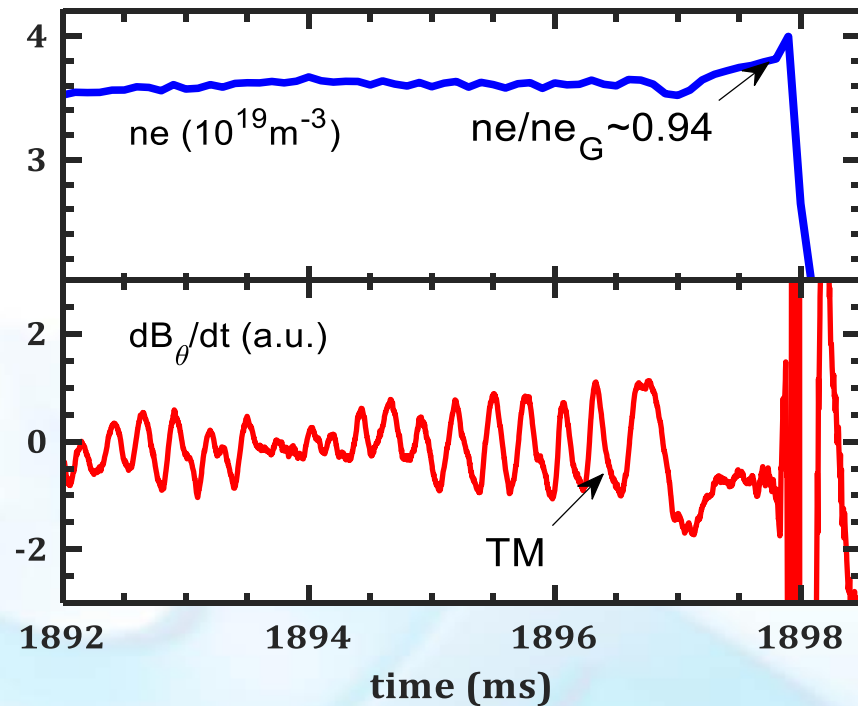
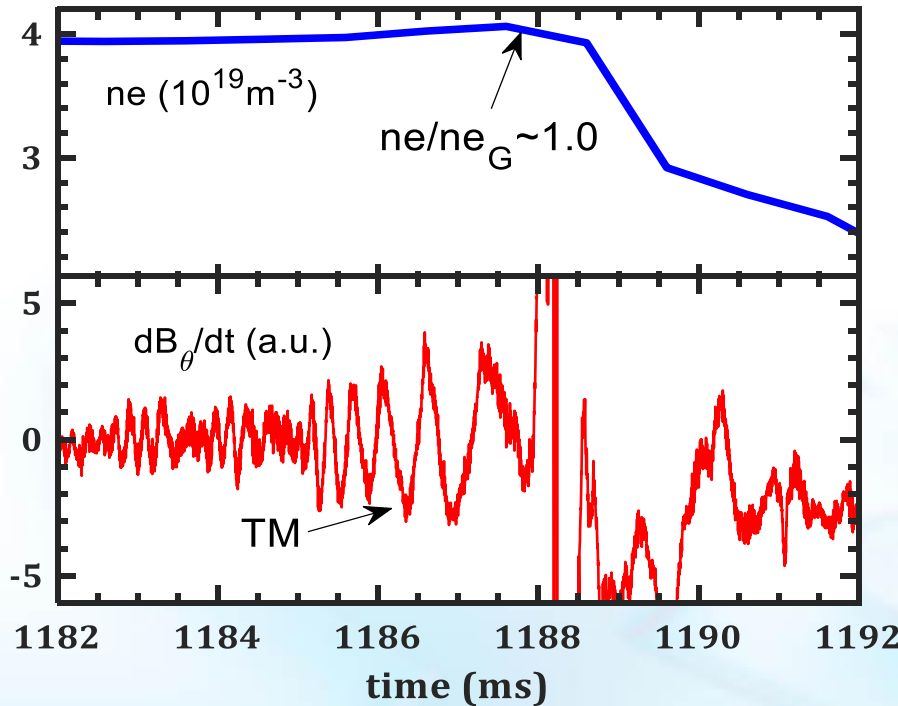


Different Patterns of AITG/KBM Frequencies



■ Coexistence, Frequency jump, Stair, Christmas lights, Mountain peaks

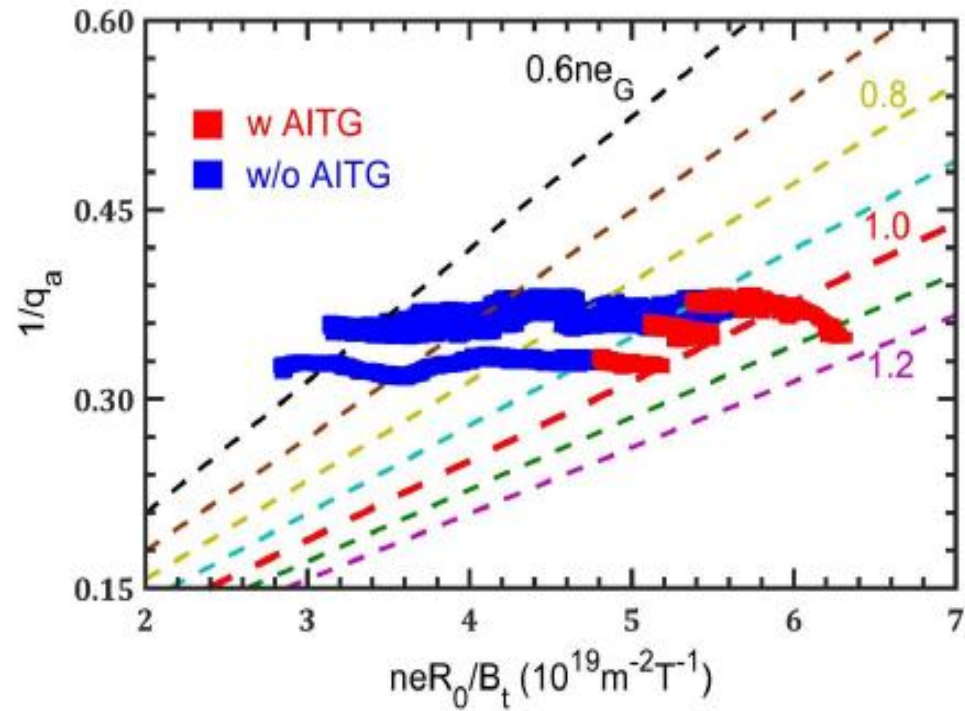




- These AITG/KBM instabilities are prior to the 2/1 TM growth ($t < 4$ ms), and then the disruption appears.

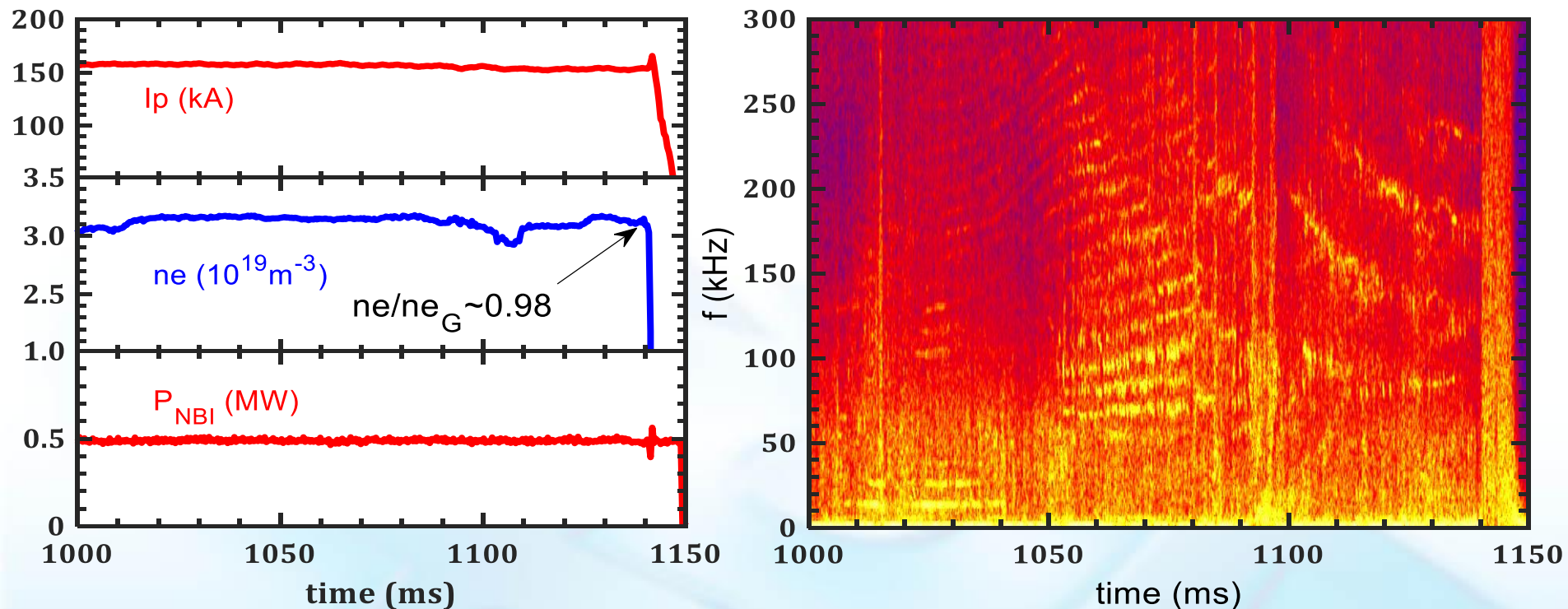


Hugill diagram



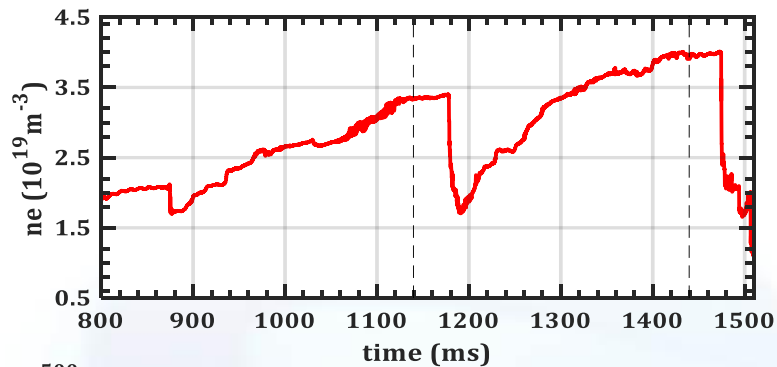
- Generally, these AITG instabilities become unstable while $f_{GW} > 0.85$.
- Experimental results indicate the q , s and L_n have important effects for the mode stability.
- Challenging all theory models of the density limit disruption
 - Global, core->edge
 - Electromagnetic



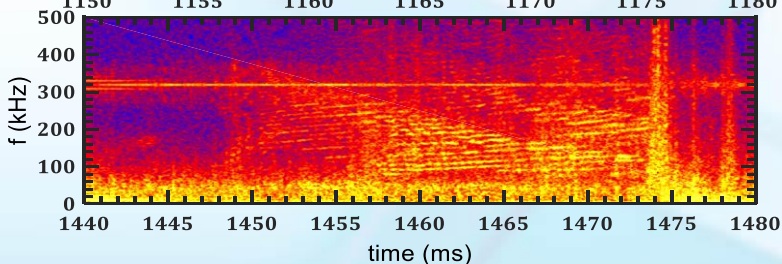
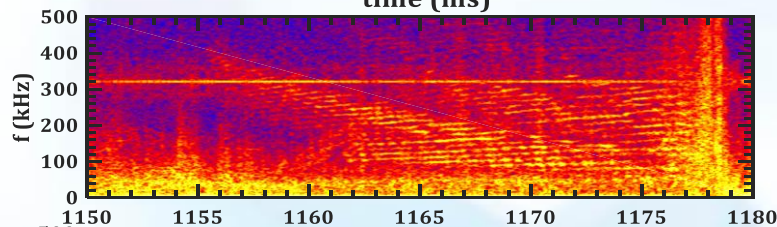


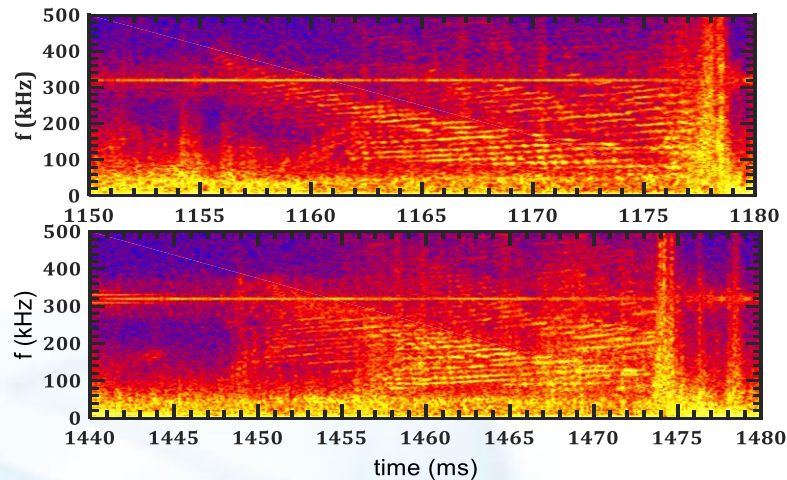
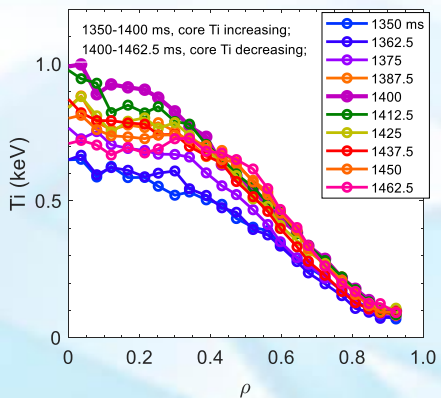
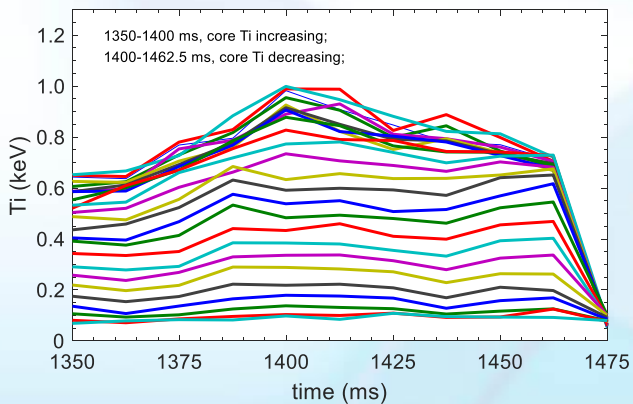
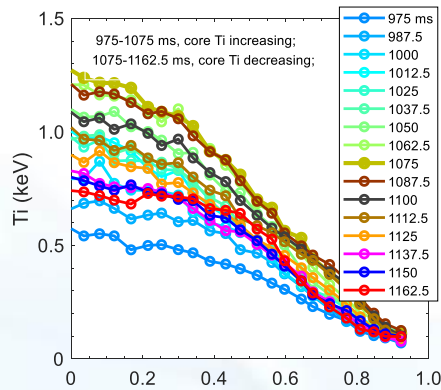
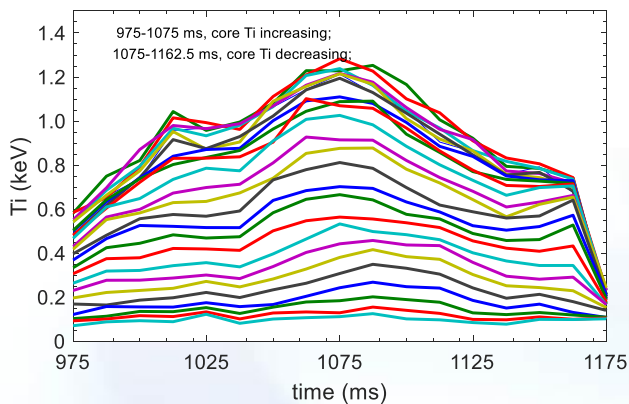
- Mode frequency appears nonlinear chirping in higher NBI heating power, namely, existence of wave-particle resonance. KBM+EP- \rightarrow EPM, *Tsai&Chen, Phys. Fluids B, 3284 (1993)*.





- $dn_e/dt > 0 \rightarrow dn_e/dt \sim 0$ at $t \sim 1140 \text{ ms}$ and at $t \sim 1440 \text{ ms}$, it indicates that AITG/KBM instabilities induce particle transport outward in radial direction.
- Accompanied by the evolution of these instabilities, disruptions appear.





- With core Ti&ne increasing, AITG/KBM instabilities are excited, therewith the core Ti drops and Ti-profiles collapse, and large-radius ITBs form in this process.
- It indicates that these instabilities induce strong ion heat transport.



*The AITG is appearing due to ion compression effects on SAWs while $\Omega_{*pi} \sim \sqrt{7/4 + \tau q}$. It can be understood as a branch connecting KBM (diamagnetic effects be dominant, $\Omega_{*pi} > \sqrt{7/4 + \tau q}$) and BAE (ion compression effects be dominant, $\Omega_{*pi} < \sqrt{7/4 + \tau q}$).*

Zonca&Chen, PPCF96;PoP14

While the ITG modes is completely stabilized via its coupling to SAWs, AITG becomes more unstable with increasing beta values. The electromagnetic AITG turbulence could be a paradigm which can bridge electron and ion transport channels via finite-beta effects.

Dong, PoP04; Ganesh, PoP04.

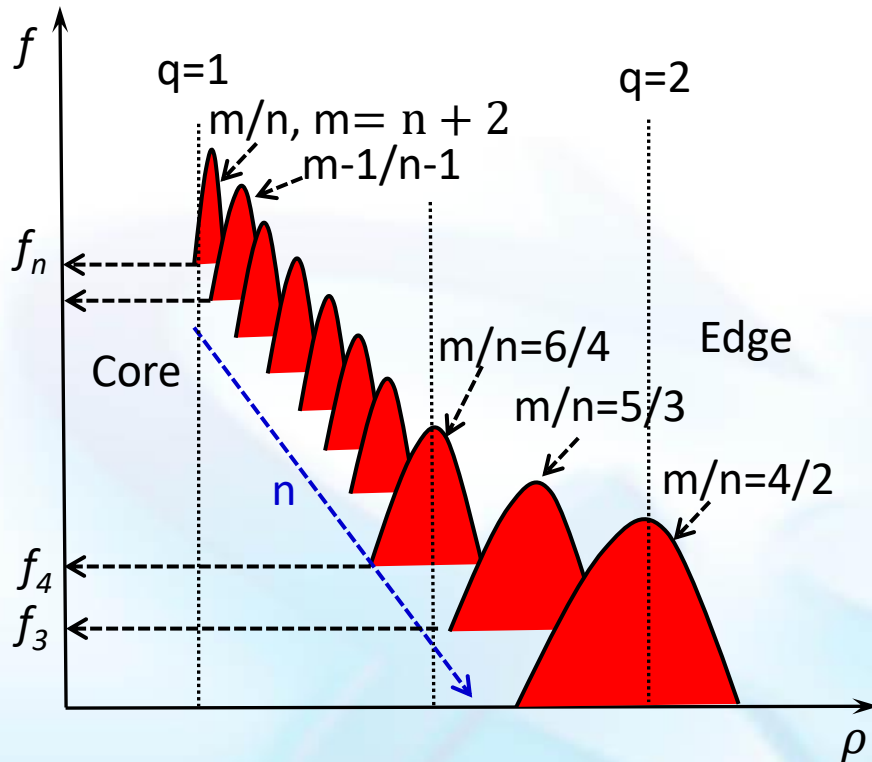
For the AITG, it may become unstable for η_i larger than a critical value η_{ic} give by

$$\eta_{ic} = \frac{2}{\sqrt{7 + 4\tau q}} \frac{\omega_{ii}}{\omega_{*ni}}$$

Zonca&Chen, PPCF96

With the density peaking and ion temperature decreasing, η_{ic} drops, therefore the MHD instabilities become unstable easily.



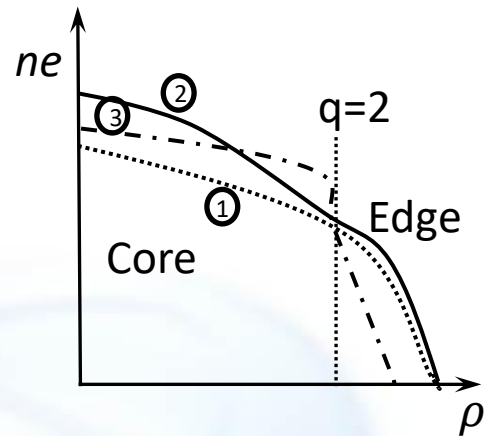
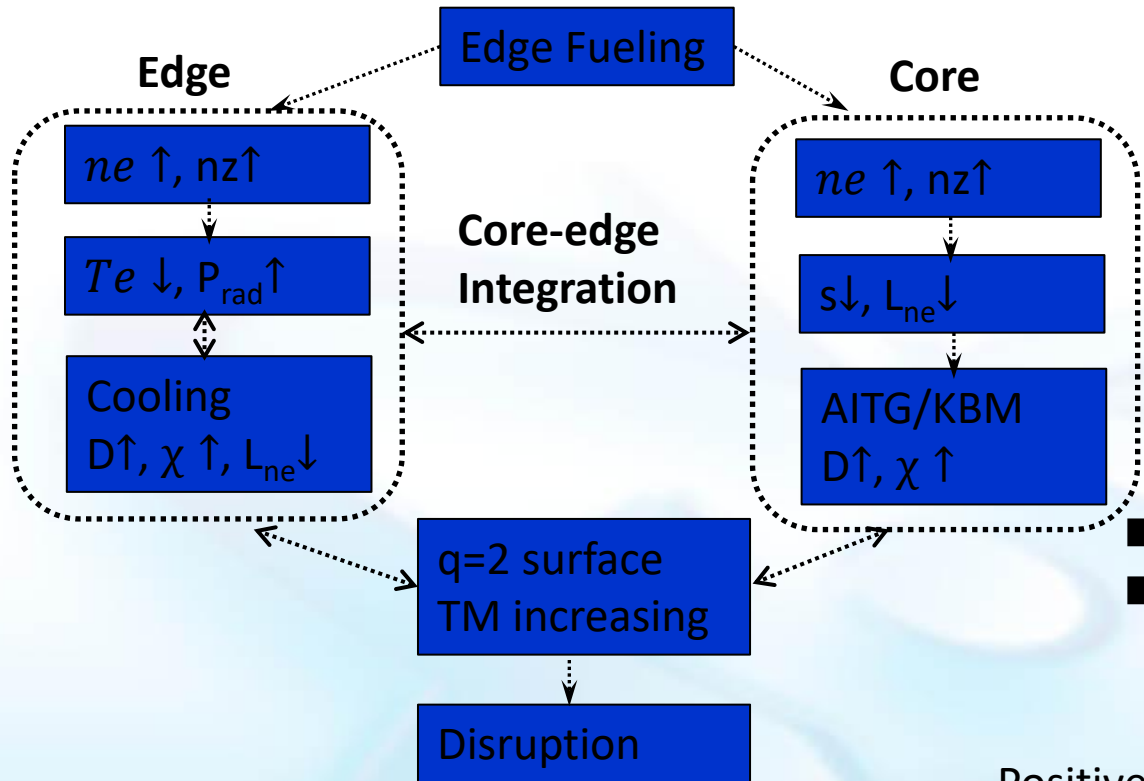


These AITG/KBM instabilities:

- Driven in sequence or simultaneously
- From high- n to low- n
- From $q=1$ to $q=2$ surface localization
- From small- (high- n) to large-scale (low- n) (Inverse cascading?)
- Induce global ballistic transport outward, Domino&avalanche in radial direction
- Result in $m/n=2/1$ TM growth and trigger disruption



New Physics Picture of Density Limit Disruption



- 1→2, Fueling & ne peaking
- 2→3, edge cooling, core AITG/KBMs unstable, ne flattening, TM growth, disruption

Positive feedback system: Unstable



We present the recent experimental results of the density limit disruption and core-localized kinetic MHD instabilities in HL-2A NBI plasmas.

- Firstly, the high density discharges with $n_e/n_{eG} \sim 1$ has been achieved by the GF fuelling method.
- Secondly, it is found for the first time that there are multiple branch MHD instabilities in the core plasmas while $n_e/n_{eG} \sim 1$.
- The analysis suggests that the core localized (from $\rho_{q=1}$ to $\rho_{q=2}$) MHD activities belong to AITG/KBM modes, and firstly it is found on experiment that they trigger the disruption of bulk plasmas while the density is peaked.
- These instabilities can be used as disruption predictors, and tens of milliseconds ahead.
- These new findings are of great importance to figure out and understand the origin of the density limit.



Thank you for your listening.

谢谢垂听！

敬请批评指正！

