I-7

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Observation of Non-Collisional Bulk Ion Heating by Energetic Ion Driven Geodesic Acoustic Modes in LHD

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Outline

1. Introduction and Motivation
2. RSAE and EGAM in Reversed Magnetic Shear (RS-) Plasmas of LHD
3. Correlation of T_{io}-rise with Micro-Turbulence & EGAM Activities
4. Sudden Termination of T_{io}-Rise
5. Additional Power Input to Bulk Ions during T_{io}-Rise
6. Summary and Future Prospect

Introduction

Effects of energetic ion driven instabilities (Alfven eigenmodes, EGAM, EPMs) are intensively studied in tokamak and stellarator/helical plasmas.

◆**Hazardous effects: Redistribution and/or losses of EPs and damages of PFCs**

Suppression of these modes are actively investigated by ECCD/ECH, RMP etc.

◆**#1 Favorable effect => non-ambipolar EP transport by the bursts**

=> strong E_r shear generation

=> improvement of bulk confinement

A clear example in an LHD is EIC

(resistive interchange mode driven

by helically trapped EPs) bursts.

Strong E_r and shearing rate by EIC bursts:

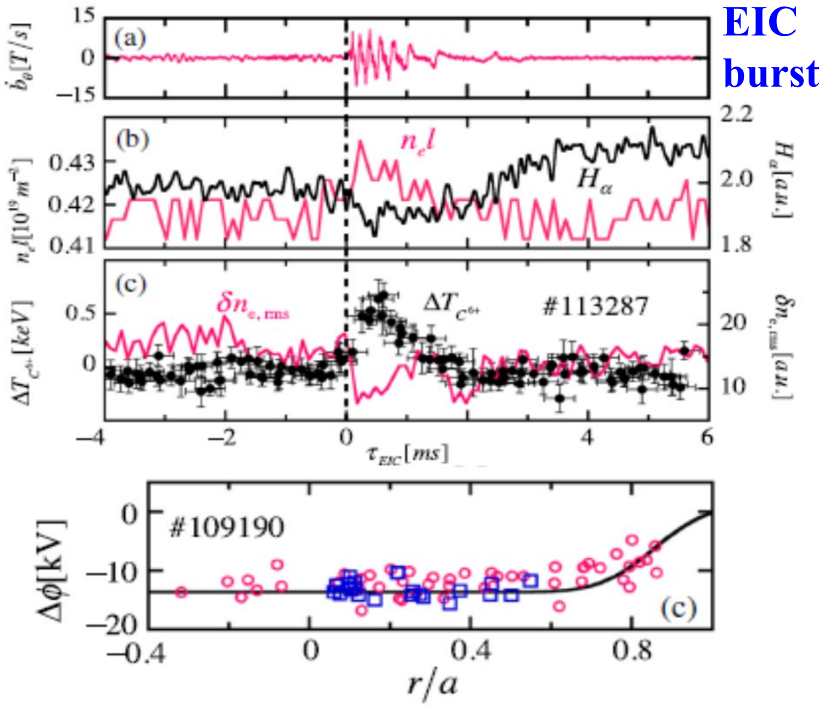
$E_r \sim 85$ kV/m and

$\upsilon'_{EXB} \sim 2.5 \times 10^5\ \mathrm{s}^{-1}$ at $\rho \sim 0.85$ ($\iota = 1$)

=> transient improvement

(X.D. Du et al., PRL 2015)

also by TAE bursts (K. Toi et al., PPCF 2012)



Introduction and Motivation

◆**#2 Favorable effect** => **Energy channeling from EPs to bulk ions and saturation of EP-driven modes**

Theoretical ideas of *alpha channeling* and the alternatives:

N. J. Fisch e al. PRL 1992 , M. Sasaki et al., PPCF 2011, A. Bierwage et al., PRL 2015

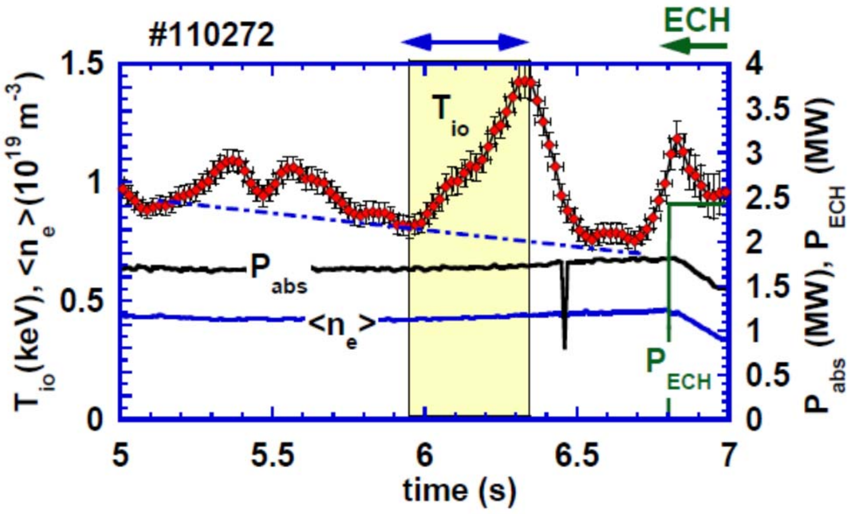
=> "hot ion" improved confinement mode & EP-driven mode saturation

So far, no experimental observation !

In LHD, spontaneous increase in bulk ion temperature T_{io} is often observed in reversed shear (RS-) plasmas, on strong electron heating condition: $E_b/T_e \sim 100 - 200$.

◆ **Possible mechanisms of the phenomenon**

1. **Confinement improvement by suppression of microturbulence (ITG, TEM, …)**
2. **Bulk ion heating by bulk ion Landau damping of EP driven geodesic acoustic mode (EGAM)**

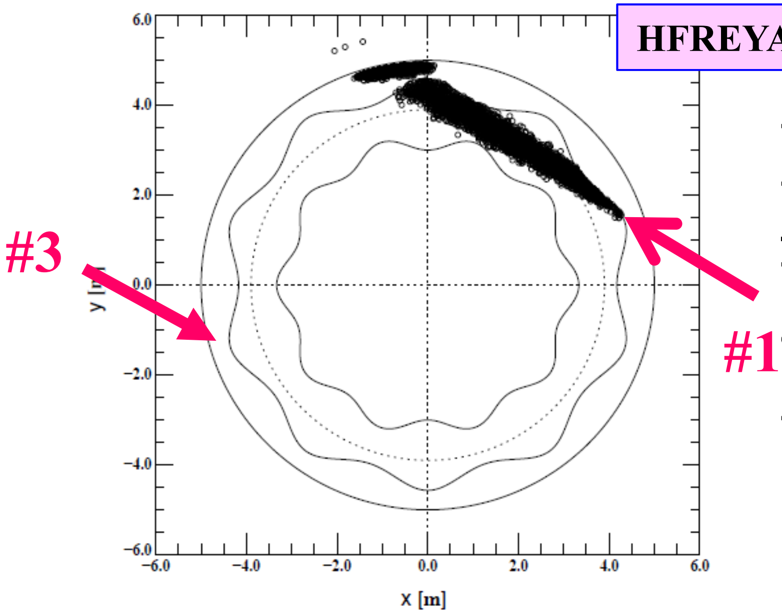


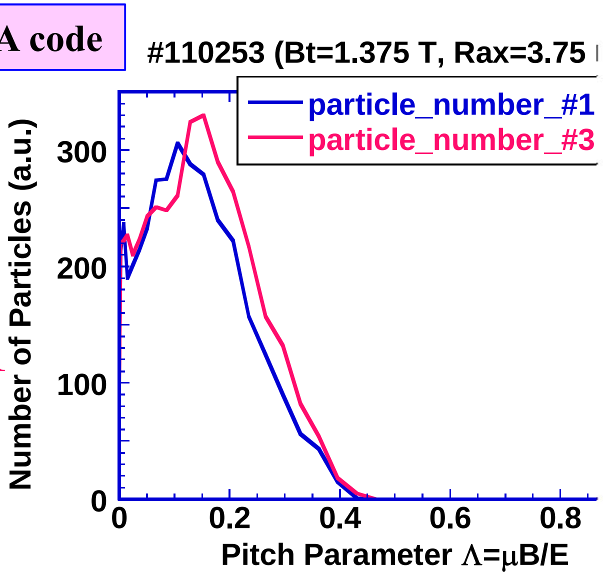
Spontaneous T_{io}-rise during constant $<n_e>$ and P_{abs} in an RS-plasma of LHD. At the end of T_{io}-rise phase, $T_{io} \sim T_{eo}$.

NBI Heating scenario of This Campaign

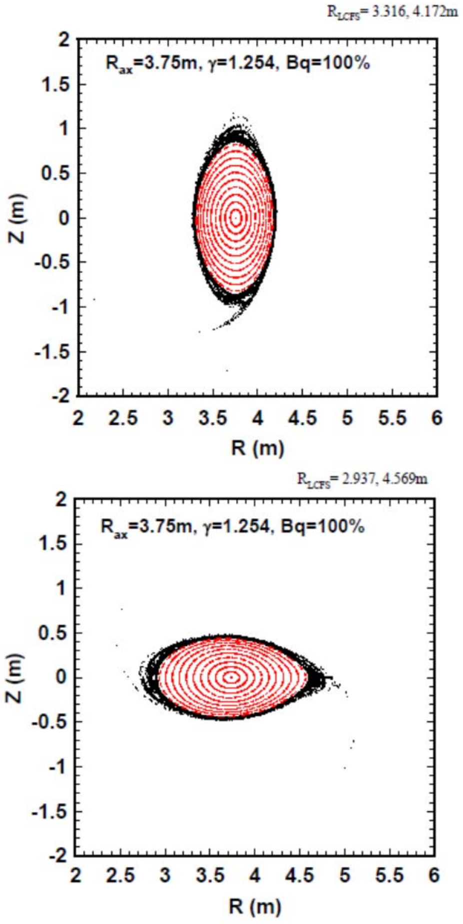
R_{ax}=3.75 m,
<a>=0.62 m
ℓ = 2, N=10

HFREYA code





Vacuum magnetic surfaces of Rax=3.75 m configuration



- B_t=1.375 T, R_{ax}=3.75 m, $\langle n_e \rangle \sim$ 0.4-0.6 x 10^{19} m^{-3}, $T_{eo} \sim$ 1.3 – 1.4 keV
  Two tangential NBIs : counter dir. (to reduce the external rotational tra
  #1 NBI (H-beam, E=170 keV), #3 NBI (H-beam, E=145 keV)
- Initial pitch parameter Λ=μB/E:
  $g_{EP}(\Lambda)=\exp[-(\Lambda-\Lambda_o)/\Delta\Lambda)2]$ where Λ_o=0.125 and $\Delta\Lambda$=0.175

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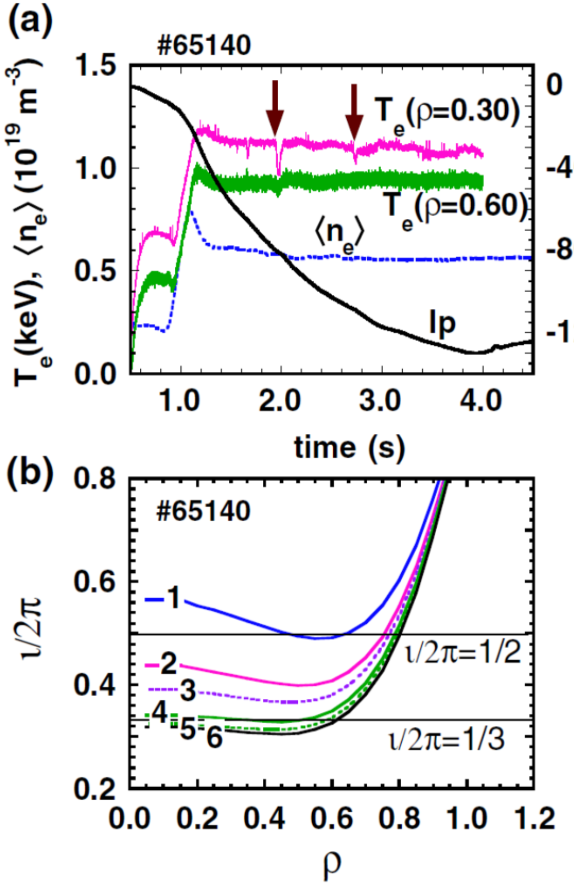
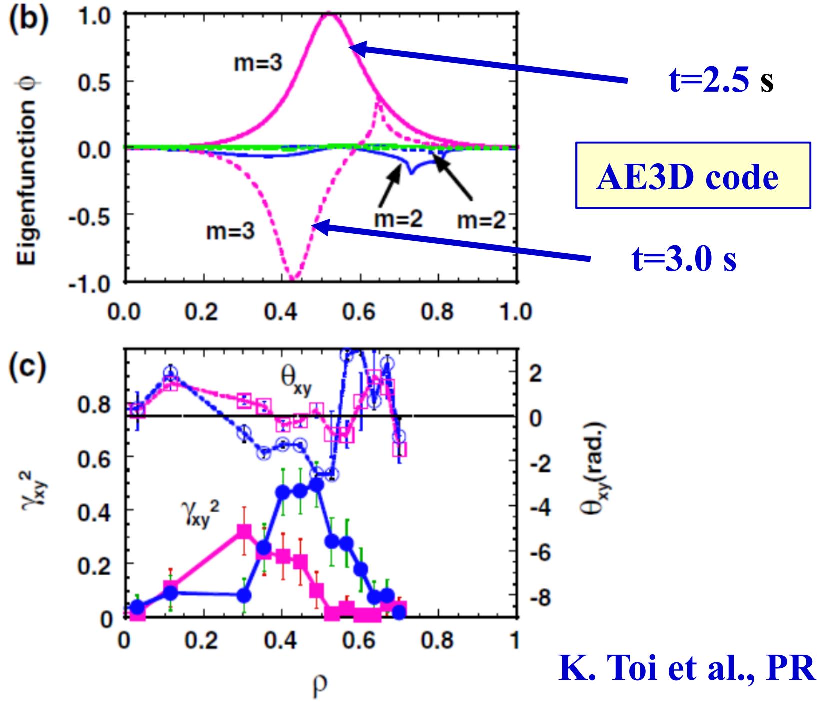
Formation of Reversed Magnetic Shear Plasma having Off-axis Minimum of the Rotational Transform by Counter NBCD





t=2.5 s

AE3D code

t=3.0 s

K. Toi et al., PRL 2010

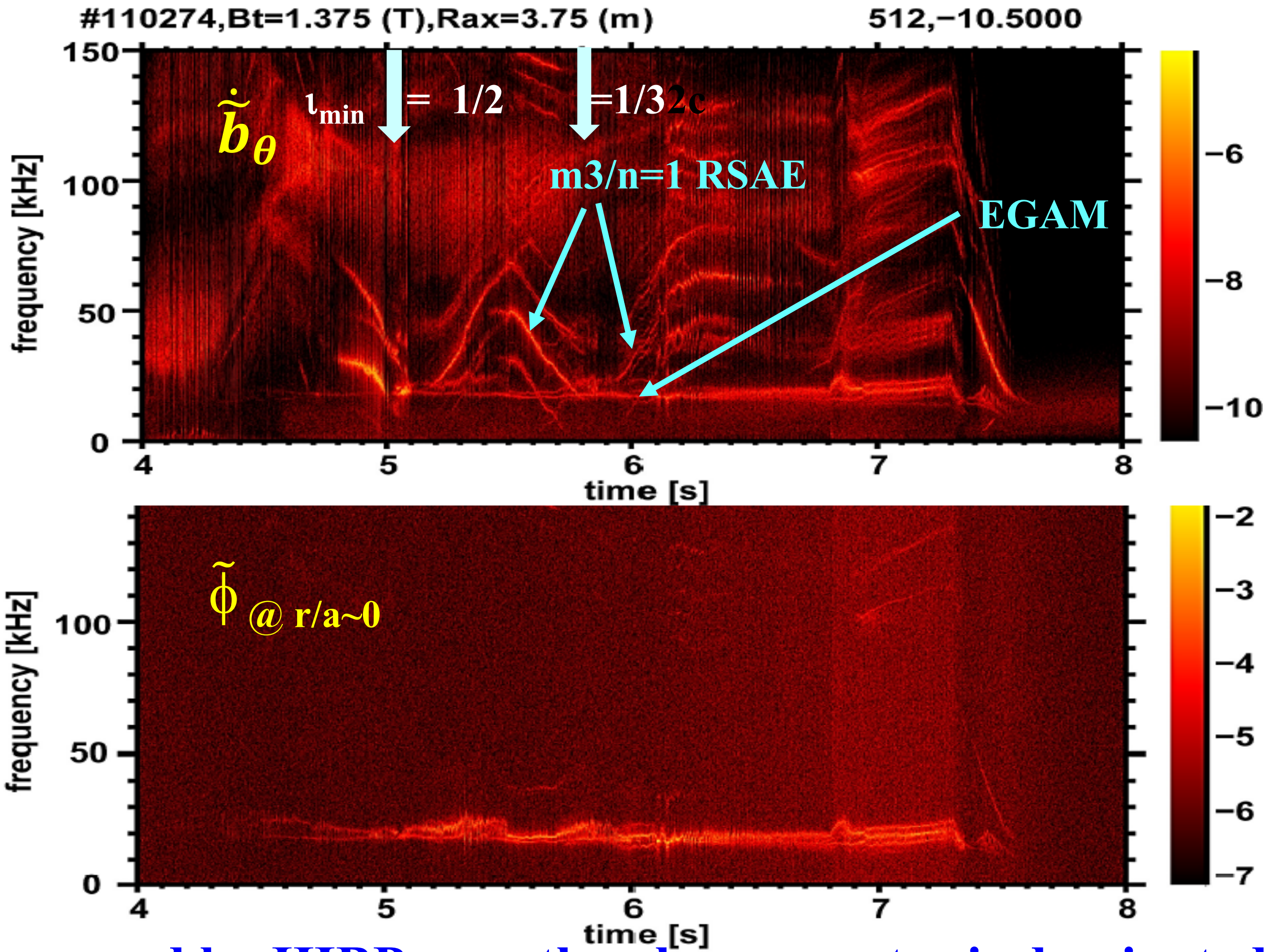
Correlation analyses between ECE And MP signals.

MSE data show the RS configuration, but the central value is less accurate.

RSAEs are excited, having characteristic frequency sweeping.

Note: Neon puff is applied to maximize NB driven current.

Magnetic and Potential Fluctuations of EGAM



f_{htr}/f_{EGAM} ~ 3-5

f_{htr}: EP transit frequency

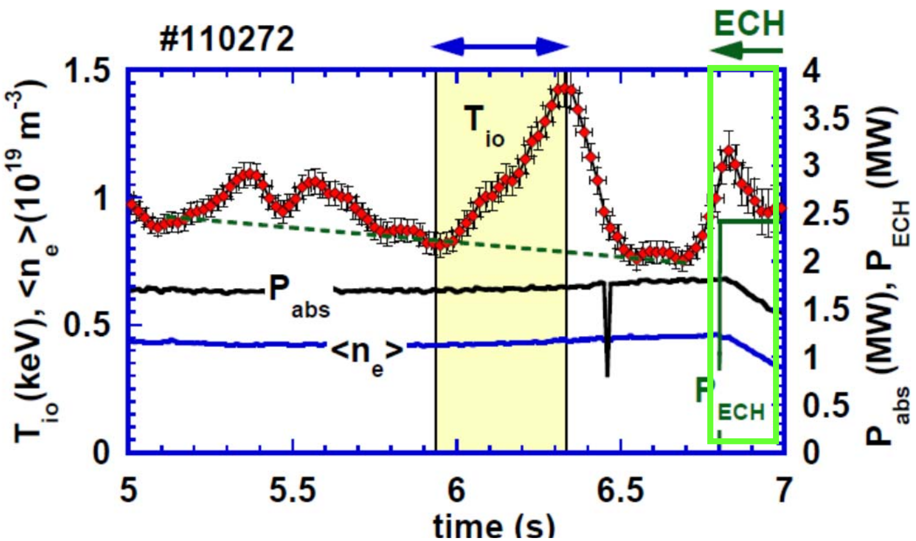
=> EGAM can be destabilized.

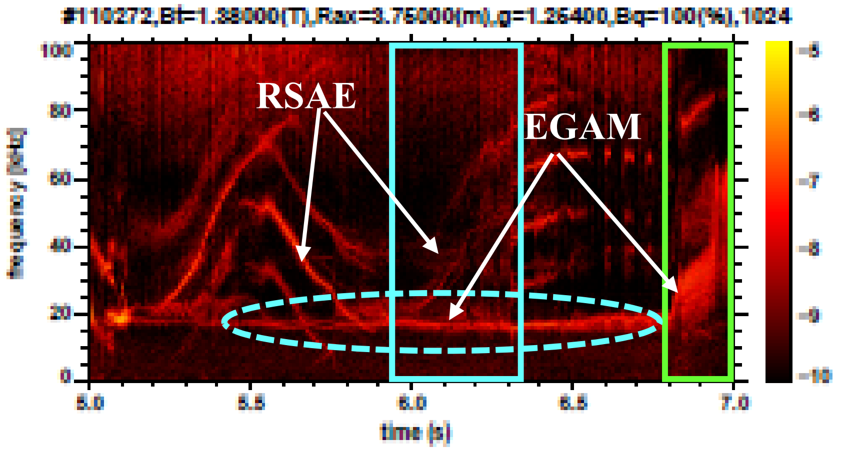
$\tilde{\phi}$ measured by HIBP near the plasma center is dominated by EGAM.

EGAMs having nearly constant frequency (f ~18 kHz) are excited .

m=3/n=1 RSAE frequency is swept down and swept up via the minimum during constant $\langle n_e \rangle$ -phase

Dependence of EGAM frequency on T_i and T_e in LHD RS plasmas





- ➢ EGAM frequency f_{EGAM} is nearly constant in the T_{io}-rise phase.
- ➢ EGAM frequency f_{EGAM} increases, responding to T_e-rise by ECH.
- ➢ GAM frequency from GK-theory :

$$f_{GAM-GK} = \frac{1}{2\pi R}\sqrt{\frac{2T_e}{C_z m_i}}\sqrt{1+\frac{1}{2q^2}}\sqrt{1+\frac{7}{4}\frac{T_i}{T_e}}$$

= 24.1=>29.0 kHz (Too high during T_{io}-rise)

EGAM frequency observed in LHD:

$$f_{EGAM-LHD} = \frac{1}{2\pi R}\sqrt{\frac{2T_e}{C_z m_i}}\sqrt{1+\frac{1}{2q^2}}$$

= 17.1 kHz

(good agreement with observed frequency)

⇒ Very weak T_i-dependence in f_{EGAM} and

The value $f_{EGAM-LHD} \simeq$ (0.6-0.7) $f_{GAM-GK}(0)$

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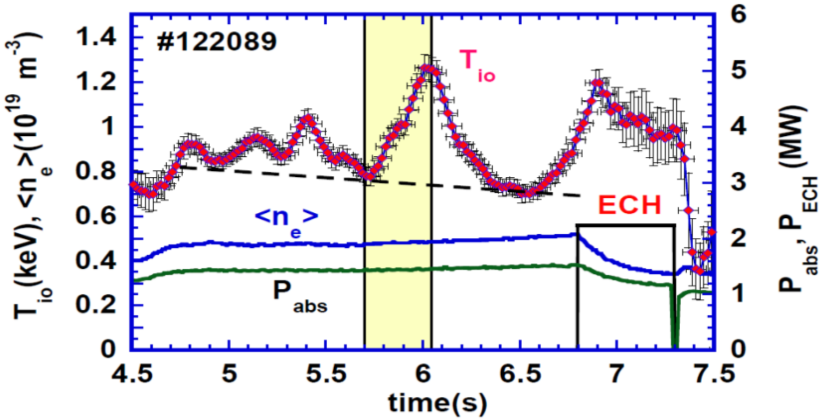
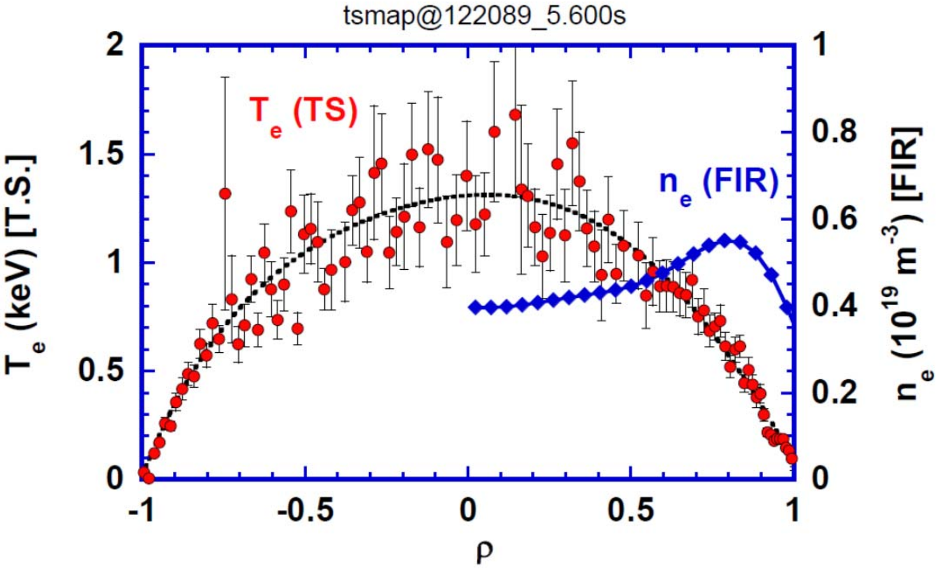
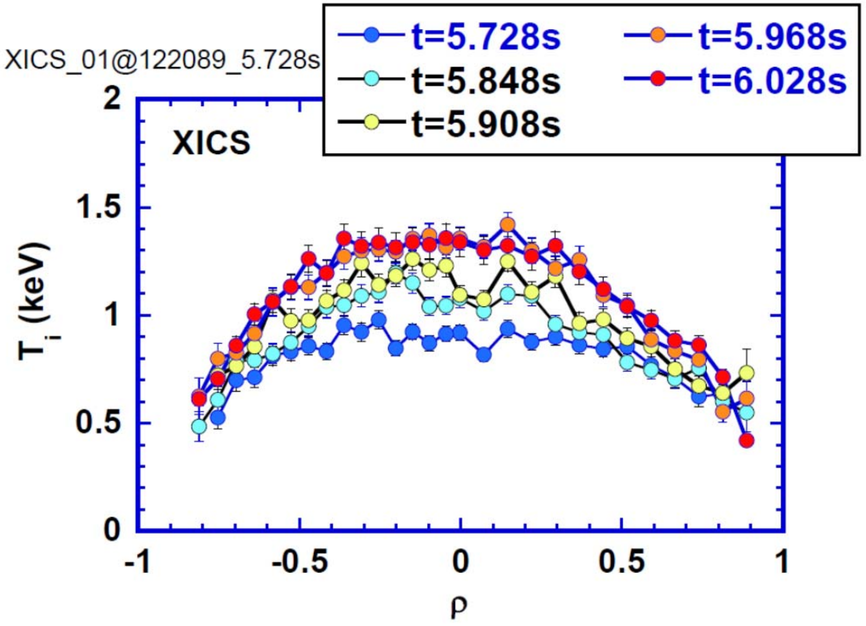
Time Evolution of T_i- & T_e-profiles measured by CS, XICS & TS



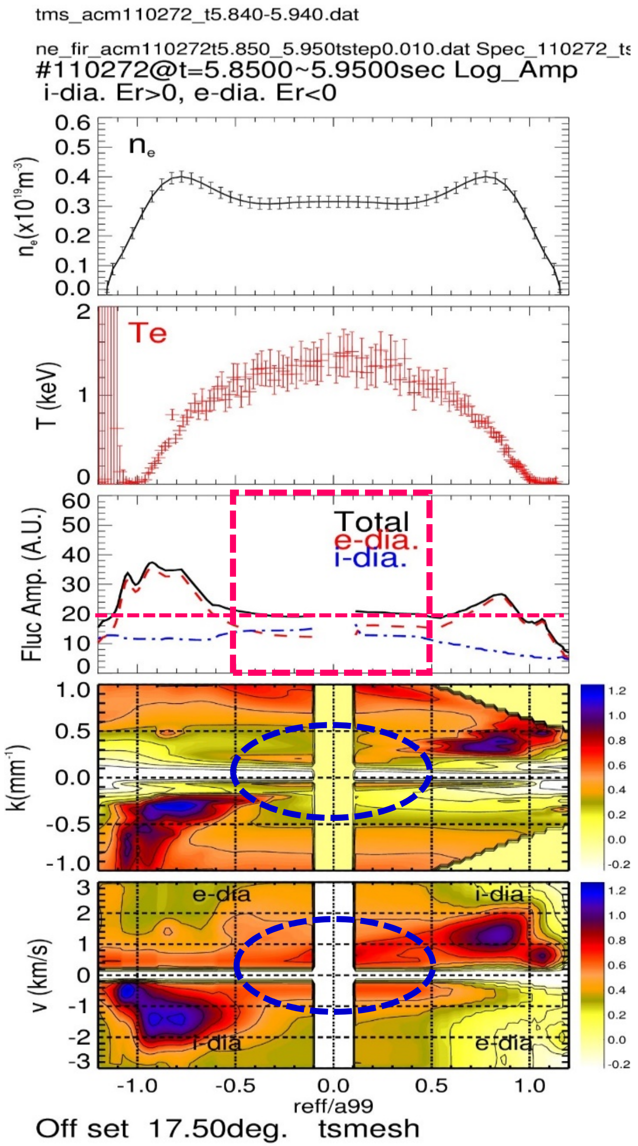
Nearly same parabolic T_e-profile is maintained during T_{io}-rise phase.
A hollow n_e-profile is also maintained.

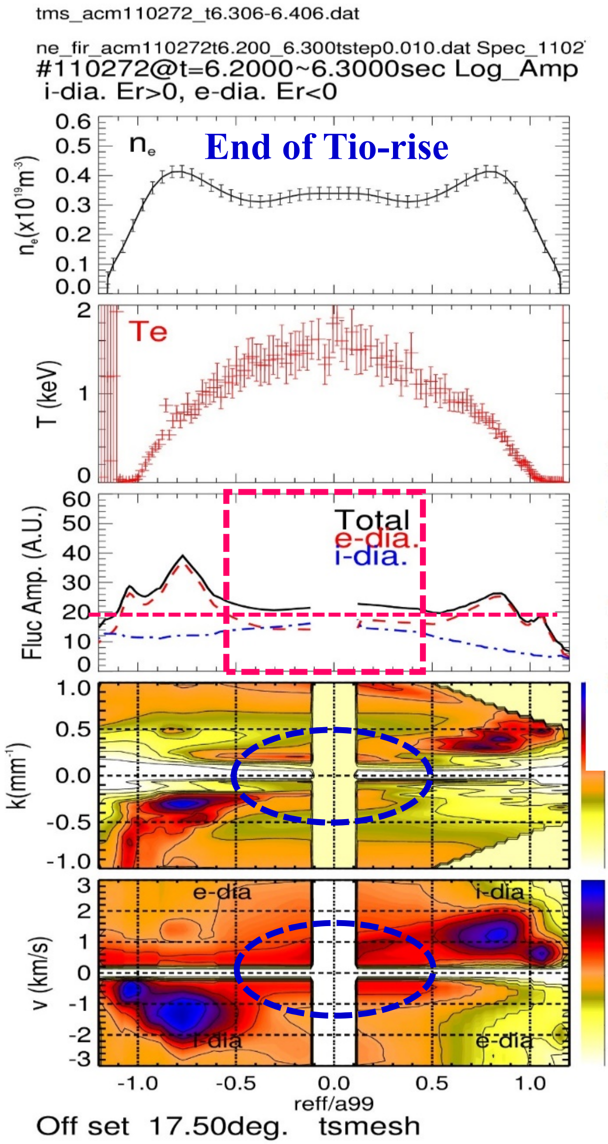


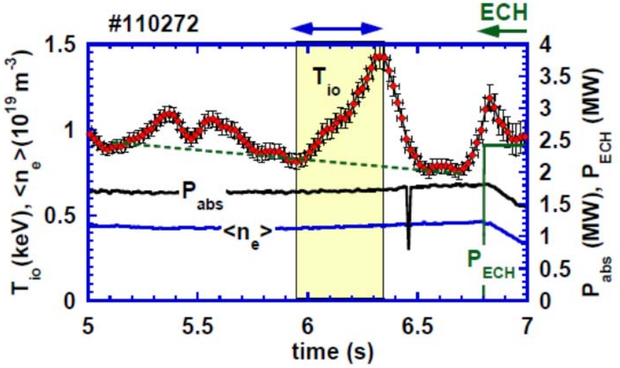


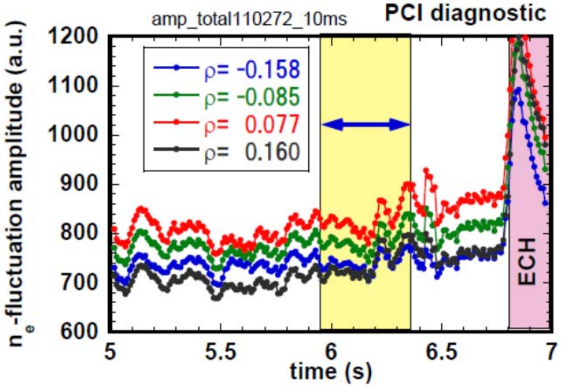
- ➢ **T_i measured by XICS increases in the core region.**
- ➢ **At the beginning of T_{io}-rise phase: $T_i < T_e$ in the plasm core region**
  at the end of T_{io}-rise phase: $T_i \sim T_e$ in the plasma core region

Correlation between Turbulent Density Fluctuations and T_{io}-rise




End of Tio-rise

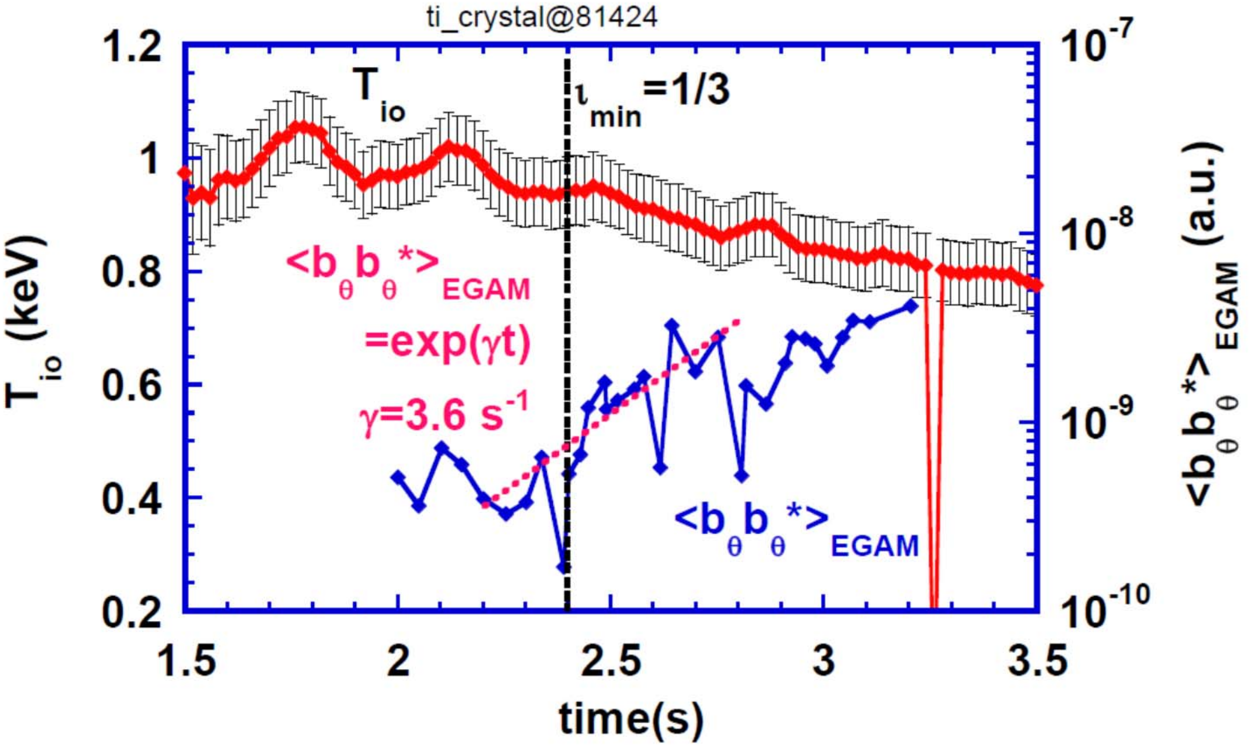




Density fluctuation amplitude in the range of $k_\perp \sim 0.3$ mm^{-1} ($k_\perp \rho_i \sim 0.7$) during the T_{io}-rise phase increases by about 10%.

Phase contrast imaging diagnostic using CO_2 laser

Behaviors of EGAM magnetic fluctuation power and T_{io} in a slightly high $<n_e>$ shot without T_{io}-rise



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$<n_e>\sim0.85\times10^{19}$ m^{-3}

I_{pmax}=137 kA

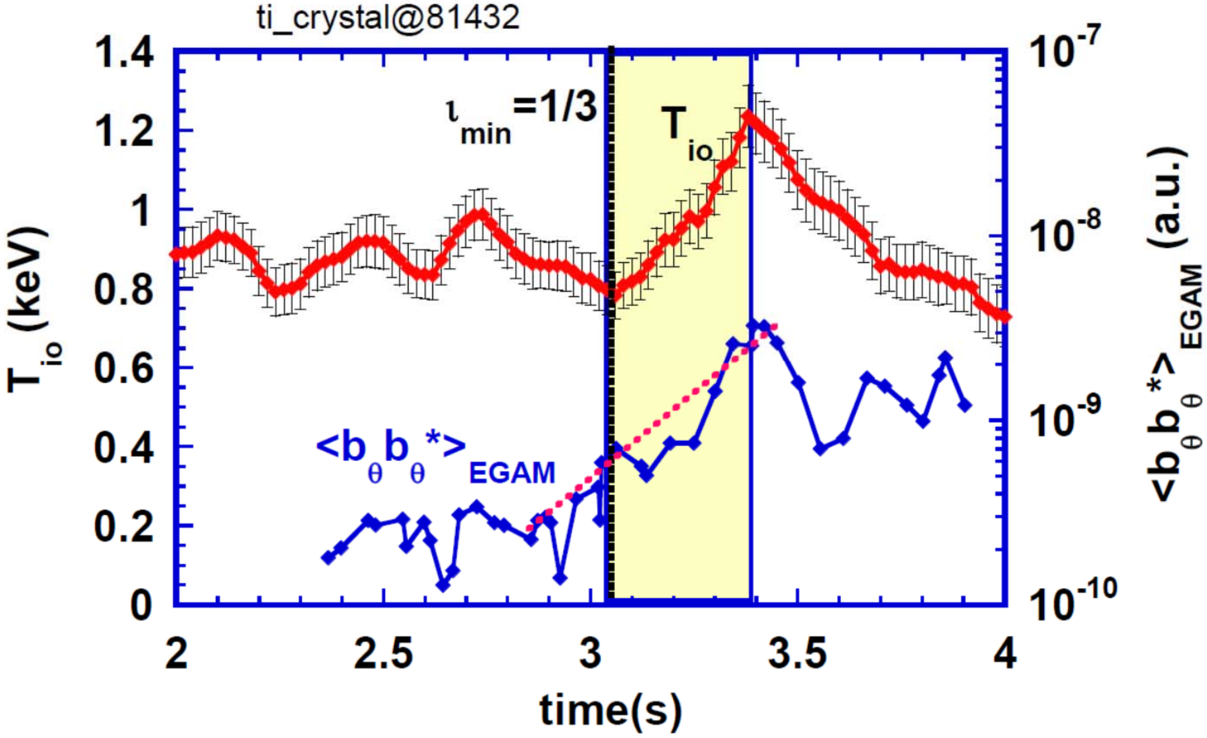
$t(\iota_{min}=1/3)$=2.39 s

- ➢ Monotonic decrease in T_{io}
- ➢ EGAM fluctuation power increases gradually.

$$\gamma_{hEG} - \gamma_{dEG} = 3.6 > 0, \qquad |\gamma_{hEG} - \gamma_{dEG}| / \gamma_{dEG} << 1$$

γ_{hEG} is very close but slightly higher than γ_{dEG} in this shot.

Behaviors of EGAM magnetic fluctuation power and T_{io} in a relatively low $<n_e>$ shot with T_{io}-rise



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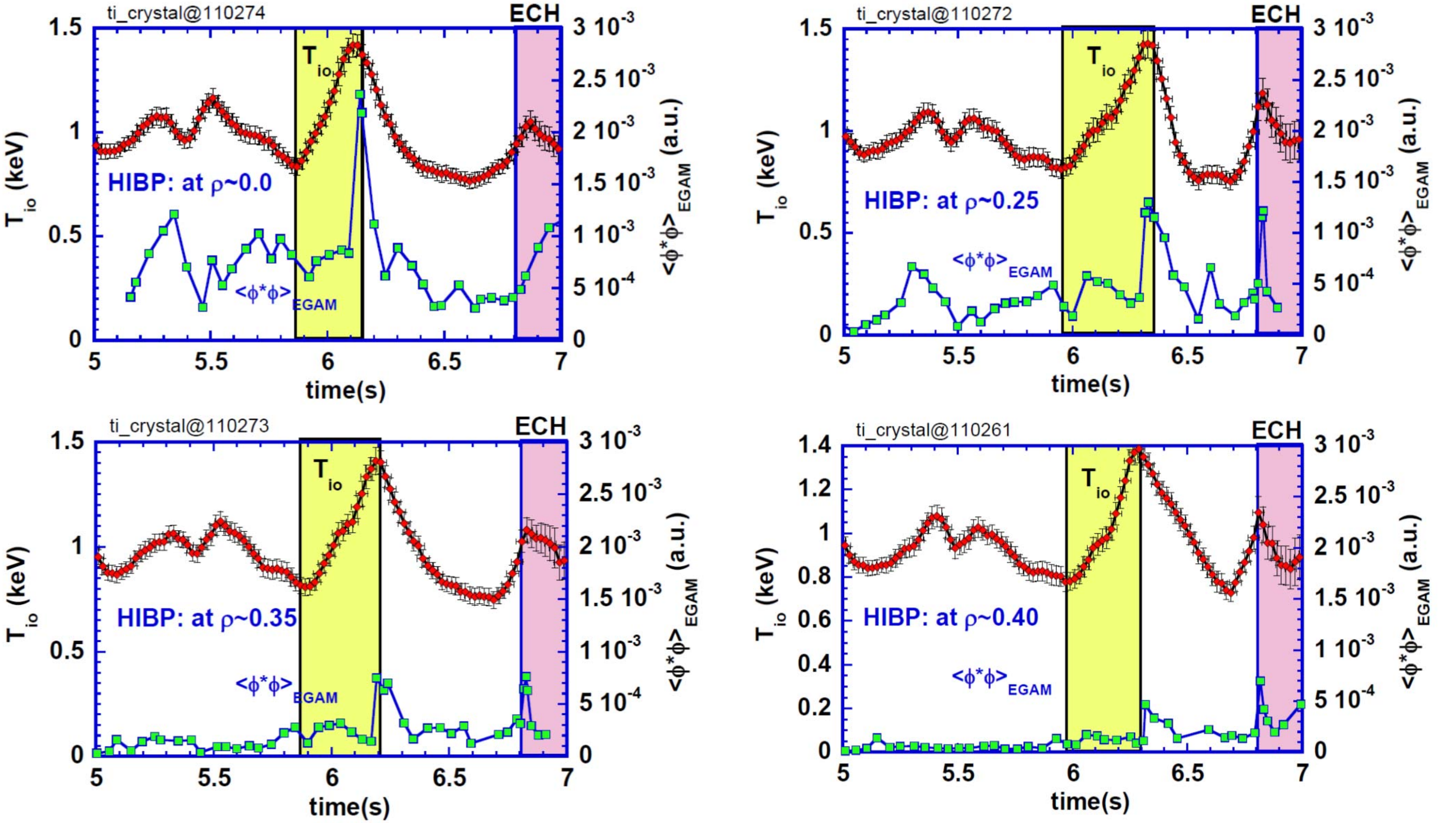
$<n_e>$~0.51x10^{19} m^{-3}

I_{pmax}=109 kA

$t(\iota_{min}=1/3)$=3.03 s

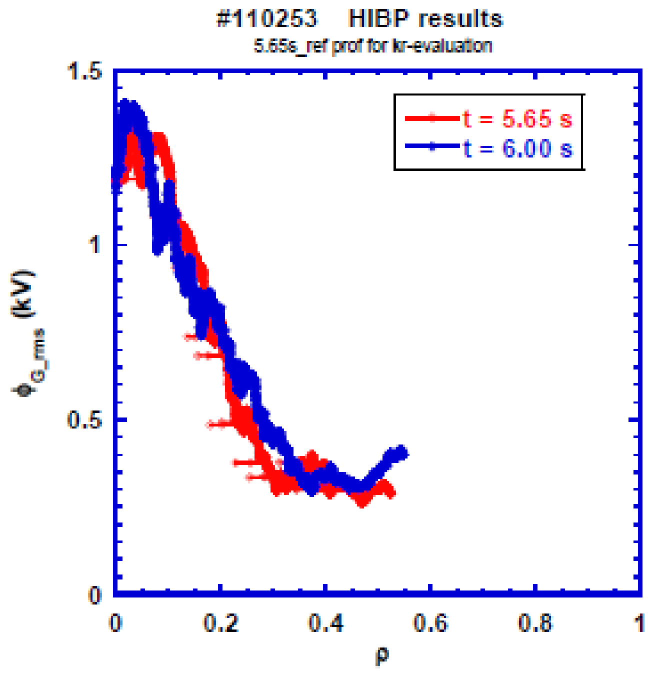
- **Spontaneous increase in T_{io} just after ι_{min} passes 1/3 at the off-axis minimum of the ι-profile ($\rho=\rho_o$)**
- **Noticeable decrease in EGAM fluctuation power during the T_{io}-rise phase, compared with the shot without T_{io}-rise.**

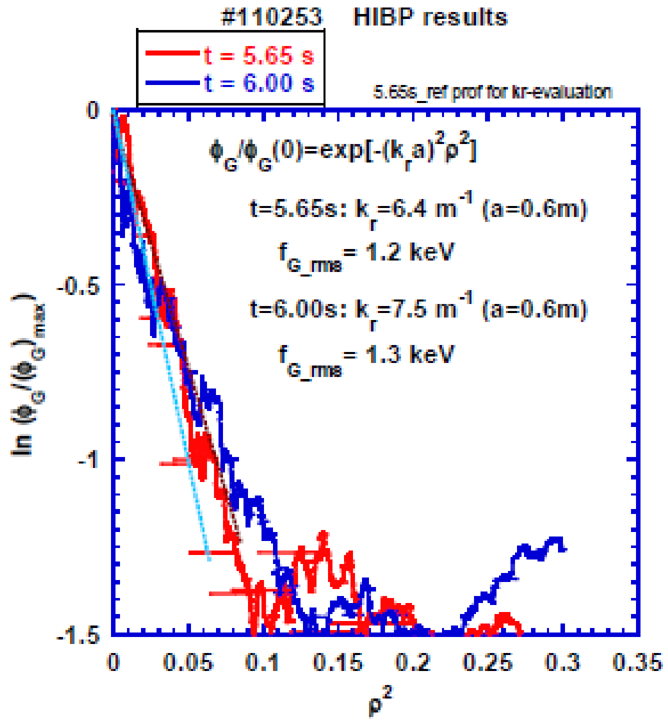
EGAM Potential fluctuations at different radial locations



EGAM potential fluctuations measured by HIBP keep nearly constant value during T_{io}-rise, and suddenly jump up. This jump terminates the T_{io}-rise.

Radial Profiles of EGAM Measured by HIBP





- **Potential fluctuations measured by HIBP localize near the plasma center.**

  $\phi_G(\rho)=\phi_G(0)exp[-(k_r a)^2\rho^2]$, **where**

  Radial wave number: $k_r \sim 7.0\ \mathrm{m}^{-1}$,

  Root-mean square amplitude: $\phi_{G\text{-}rms}=\phi_G(0) = 1.2 \sim 1.4$ kV

- **EGAM frequency will be determined by plasma parameters near the center.**

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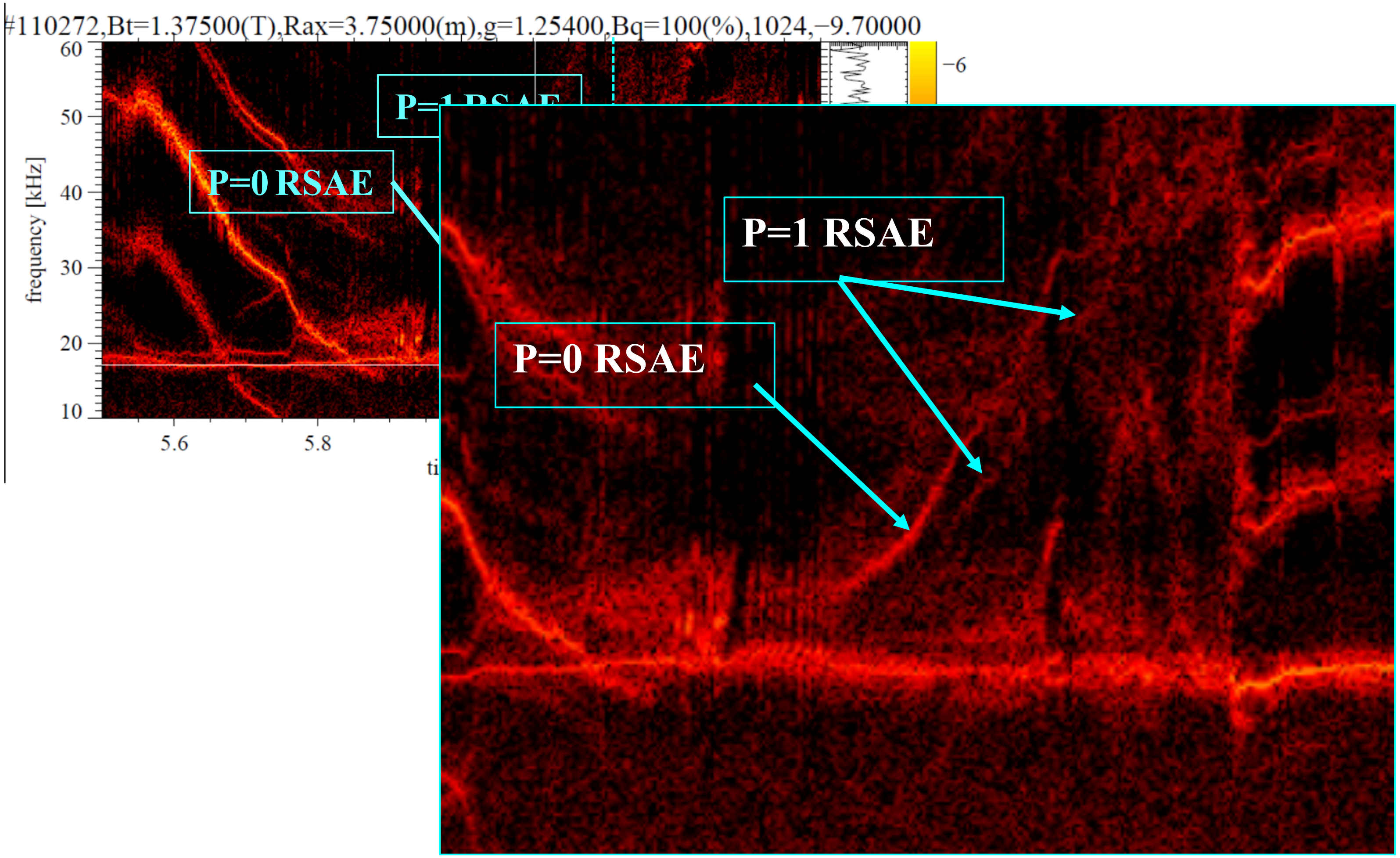
Prediction of ι(0) from observed RSAE frequencies



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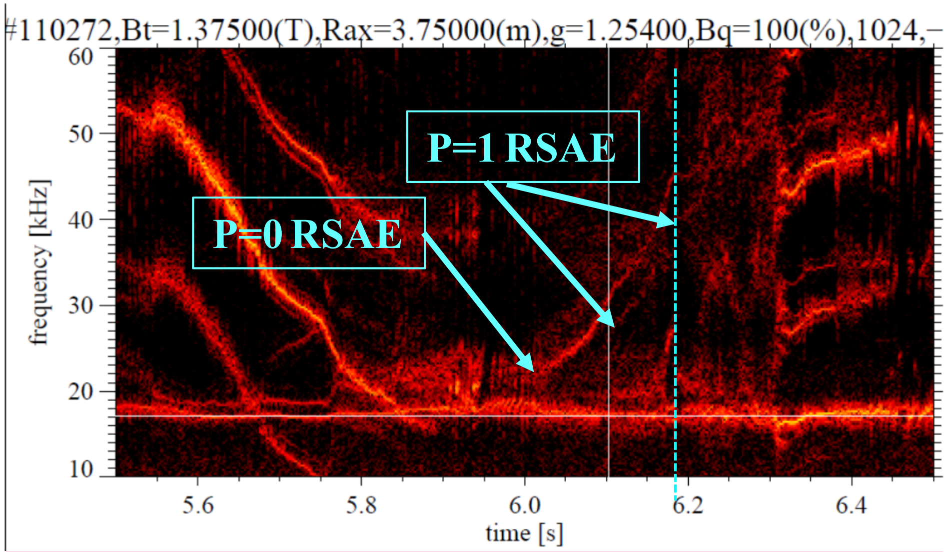
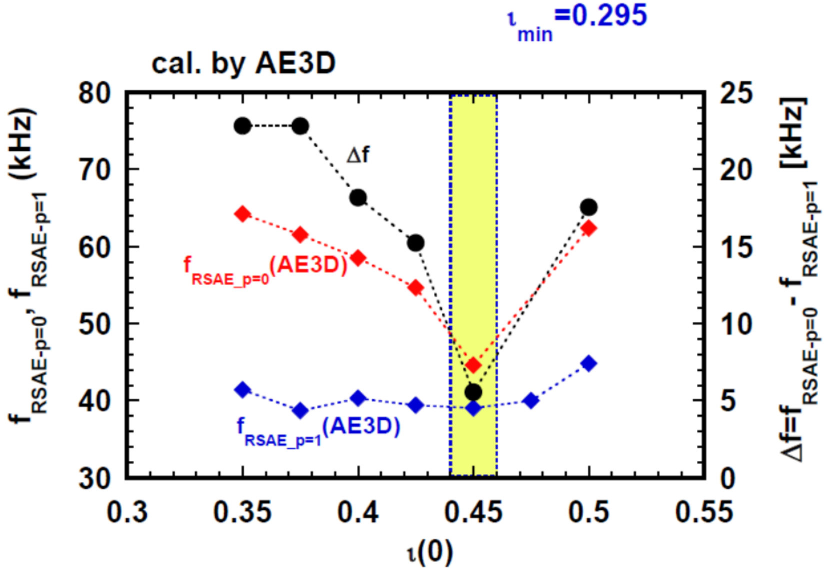




RSAE frequency: $f_{RSAE}(\mathrm{t})=\frac{v_A}{2\pi R}\left[m\iota_{min}(\mathrm{t})-n\right]$

$\left(=\frac{v_A}{2\pi R}[\mathrm{m}\iota_{min}(\mathrm{t})-\mathrm{n}]+f_{min}\right.$ near $\iota_{min}=\mathrm{n/m}$)

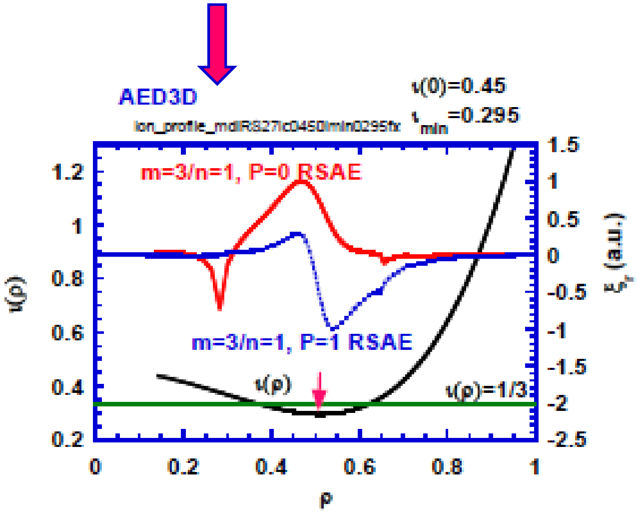
=> Aculate prediction of ι_{min}

Frequency difference between 2nd RSAE with p=1 (radial mode number) and 1st RSAE with p=0

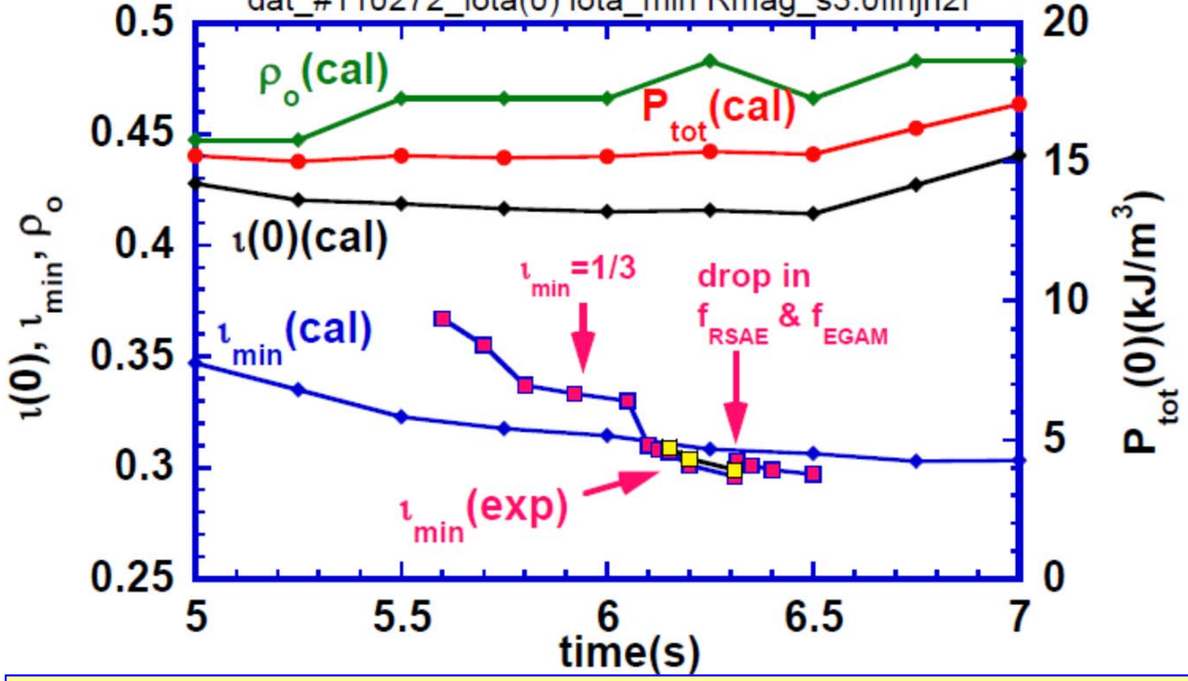
=> information of ι”(ρ=ρ_o) => ι(0)

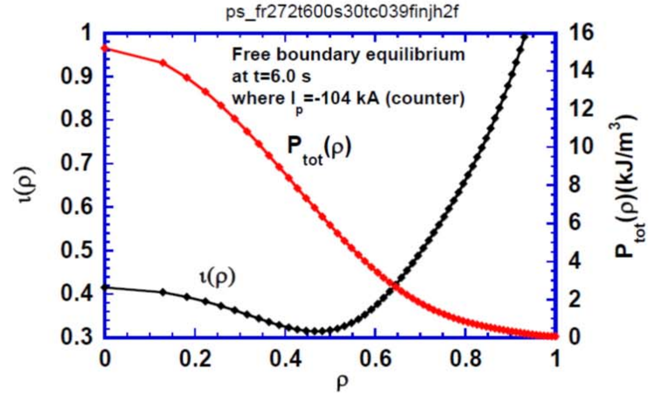
Calculations by AE3D code for various *RS* profiles

⇒ ι(0) = 0.45 is fit for the exp. data for the case of ι_{min}=0.295.



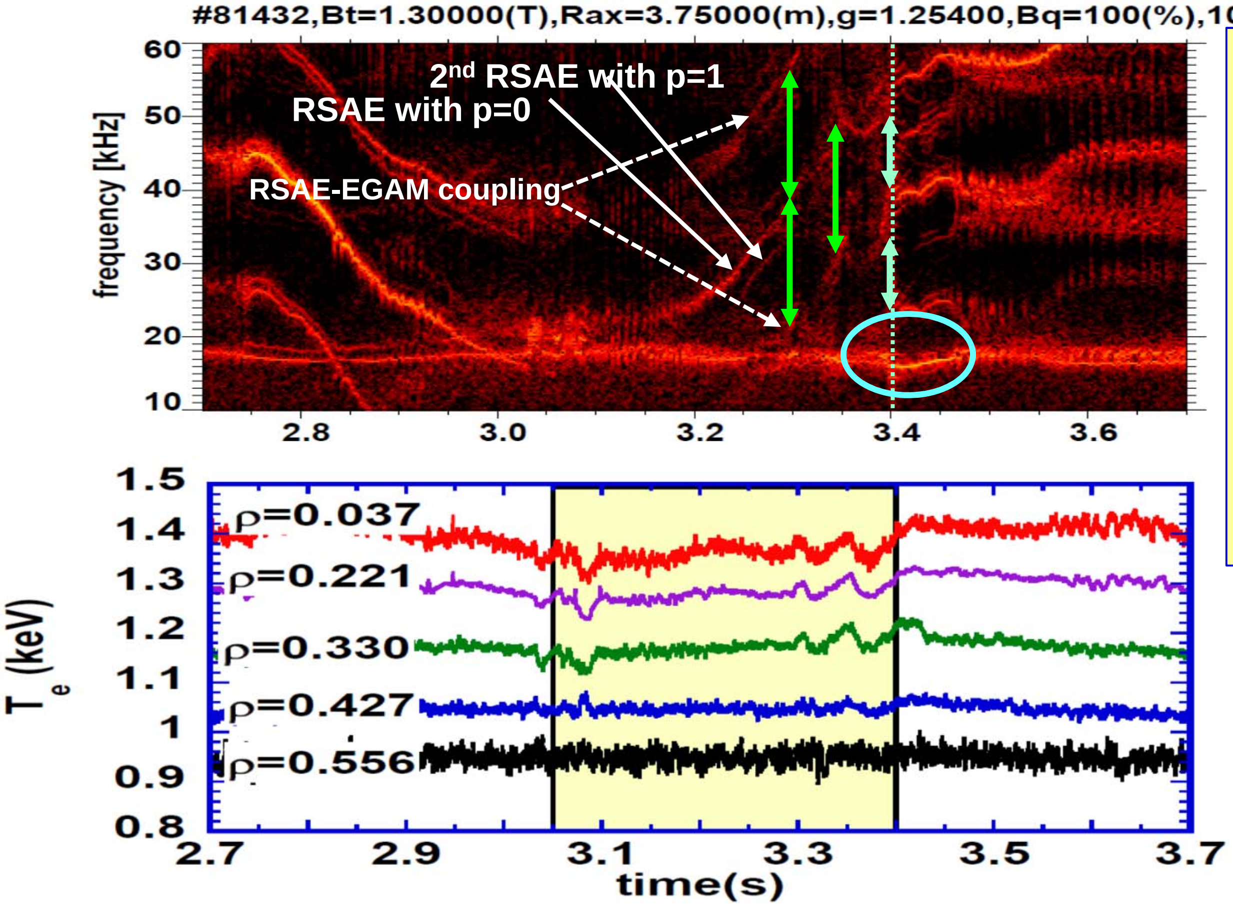
Prediction of ι(0) from VMEC Equilibria





- **Total plasma pressure profile: by TS, CS, XICS & FIR data with effective EP lifetime : $\tau_{eff}=(1/\tau_{sE} + 1/\tau_c)^{-1}$, τ_{sE} including N_e^{+10}, $\tau_c \sim 1/(\nu_{hb}\rho_h^2)$ using D-beam blip exp. data (this conf. H. Nuga, P2-26)**
- **j_{tor}-profile is fixed to a hollow shape: $j_{tor}=j_o(1+\rho^2)$ (Peaked j_{tor} gives too low ι_{min}!)**
- **ι(0) is mainly determined by $P_{tot}(0)$. ι_{min} is dependent on counter plasma current. Calculated ι_{min} is close to the observed values after ι_{min} decreases below 1/3. => ι(0)=0.42**

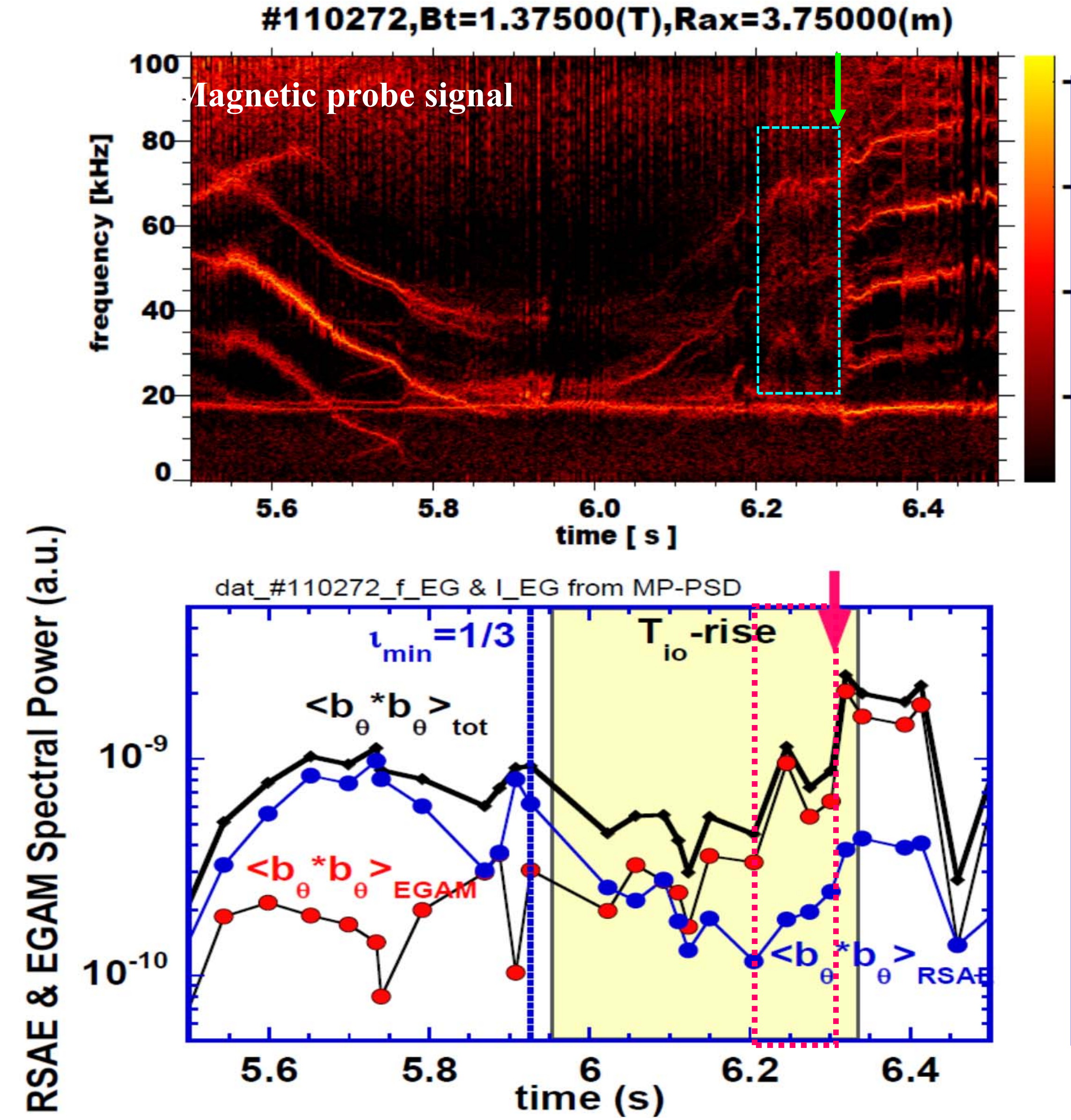
Sudden Drop in RSAE & EGAM Frequencies at the end of T_{io}-rise phase



Just before the sudden drop in EGAM and RSAE frequencies at the end of spontaneous T_{io}-rise phase, T_e near the center shows small relaxation oscillations. Then T_{io}-rise ceases and decays to the initial value of T_{io}-rise.

- **Sudden drop in f_{RSAE}: Sudden increase of ι_{min}**
- **Tiny drop in f_{EGAM} : Sudden drop of $\iota(0)$ [No drop in T_e ,no change in <R>]**

Behaviors of RSAEs & RSAE-EGAM coupled modes just before Frequency drop phenomena



Just before frequency drop (indicated by arrows) spectra of RSAE and RSAE-EGAM coupled modes become broad and chaotic (see inside a blue frame).

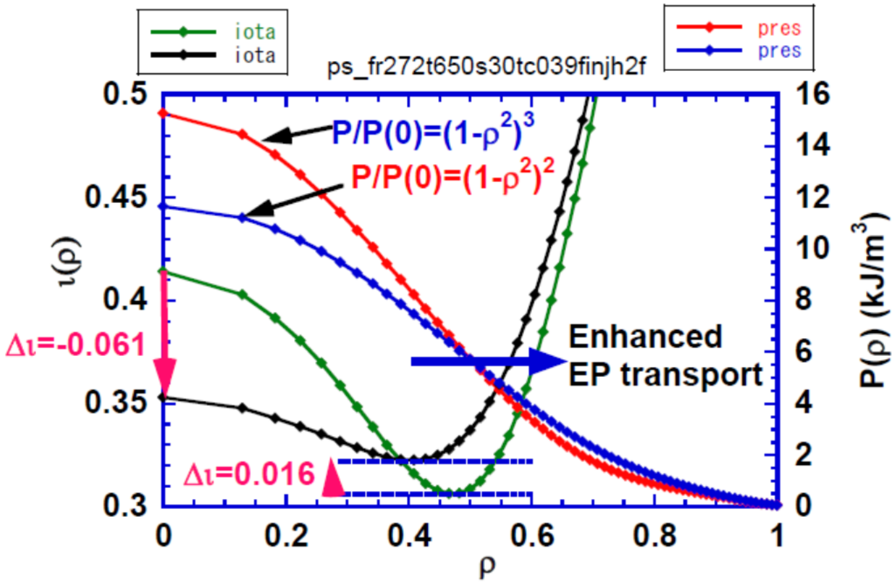
RSAE magnetic spectral power also increases by a factor of 3.

⇒ Enhanced radial transport by RSAEs & coupled modes at ρ~0.4-0.5

⇒ EP-pressure profile broadening

⇒ MHD equilibrium may change?

Possible Scenario of Termination of T_{io}-Rise



◆ **[Possible scenario 1]**

MHD instabilities related to double rational surfaces of $\iota=1/3$ in an RS plasma

Tearing and/or resistive interchange modes (K. Ichiguchi, PFR 2001)

=> No clear change in T_e at the frequency drop is observed.

These MHD instabilities are unlikely.

◆ **[Possible scenario 2] MHD equilibrium bifurcation**

Enhanced radial transport of EPs when RSAEs becomes more active just before the frequency drop (as shown in the previous slide) => Broadening of P_h

VMEC calculations suggest MHD equilibrium change may occur,

increasing ι_{min} from 0.306 to 0.322 and decreasing $\iota(0)$ from 0.414 to 0.353.

The $\iota(0)$ decrease => ~50% reduction of EGAM damping rate

The condition $\gamma_{hEG} \approx \gamma_{dEG}$ (*constant amplitude*) during T_{io}-rise phase

=> condition of $\gamma_{hEG} > \gamma_{dEG}$ (*growing amplitude*).

=> Large growth of EGAM & Sudden drop of bulk ion heating

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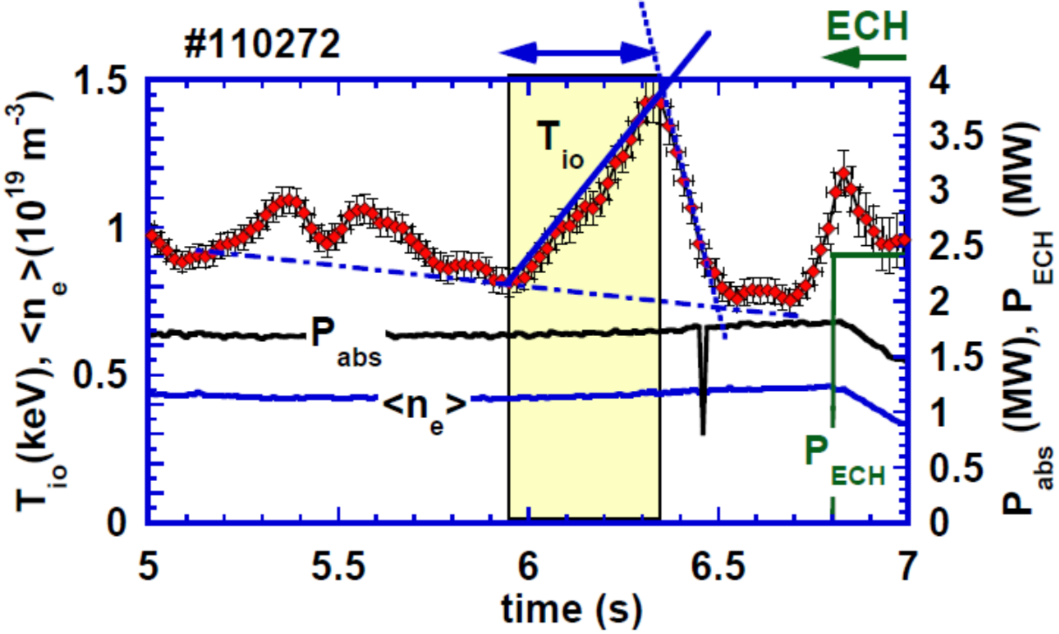
Power balance of bulk ions in the T_{io}-rise phase



- ➢ **Constant NBI coll. heating power density:**

  to bulk ions: $<P_{NBi}>$~2- 3 kW/m^3

  to electrons: $<P_{NBe}>$ ~60kW/m^3

  where E_b/T_e~100-250

- ➢ **Dominant electron heating by NBIs with high beam energy**

Estimation of additional bulk ion heating power at the end of T_{io}-rise phase:

$\Delta(dw_i(0)/dt)_{off} \sim -3\ kW/m^3$; $[w_i(0)/\Delta(1/\tau_{Ei})]_{off} \sim -7\ kW/m^3$

$-\{\Delta(dw_i(0)/dt)_{off} + [w_i(0)/\Delta(1/\tau_{Ei})]_{off}\} = P_{EGi}(0) \sim 10\ kW/m^3$

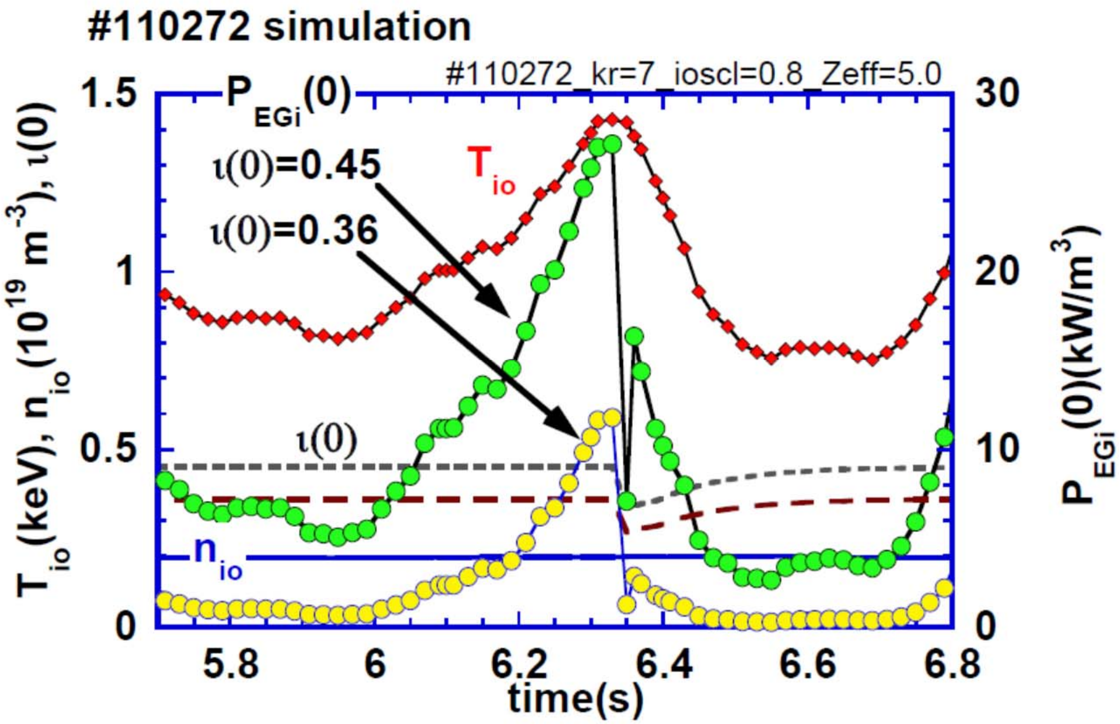
- -

$dw_i(0)/dt + w_i(0)/\tau_{Ei} = P_{NBi}(0) + P_{ei}(0) + P_{EGi}(0)$

where $\tau_{Ei}=\tau_{Ei-bfr}\sqrt{\frac{P_{NBi}(0)_{bfr}+Pei(0)_{bfr}}{P_{NBi}(0)+Pei(0)+P_{EGi}(0)}}$, $\tau_{Ei\text{-}bfr} = 0.05$ **s (just before T_{io}-rise)**

$P_{EGi}(0)$ is iteratively estimated.

Estimation of Bulk ion heating power density by EGAM damping



- **EGAM energy density:**

$$W_G = \frac{1}{2} m_i n_i \frac{(k_r\ \phi_{G-rms})^2}{B^2}$$

- **Ion heating power density:**

$$P_{EGi} = 2\gamma_{dEG} W_G$$

[1]M. Sasaki et al., PPCF 2011

[2]H. Sugama & T.H. Watanabe, PoP 2006

Using exp. data (T_{io} and T_{eo}, B=1.375 T, n_{io}~ 0.20 (or 0.24) x10^{19} m^{-3}, k_r= 7 m^{-1} and $\phi_{G-rms}(0)$ = 1.3 kV) for ι(0)=0.45 or 0.36:=>EGAM damping rate γ_{dEG}~0.8 or 1.9x10^5 s^{-1}

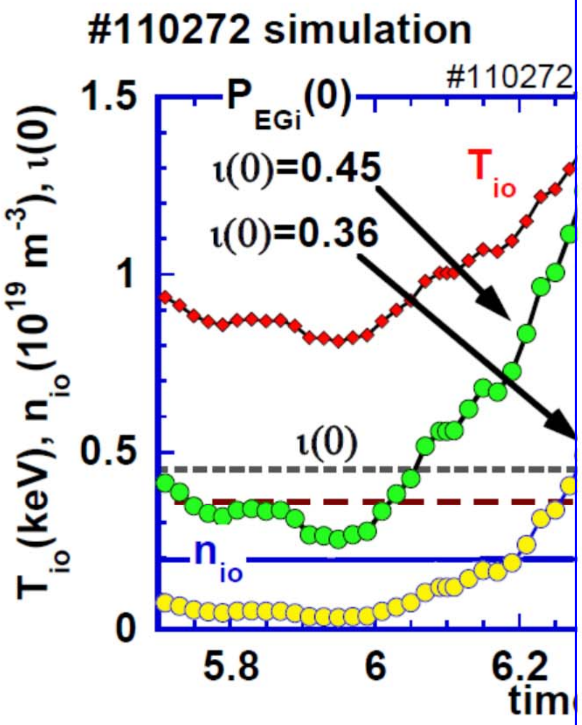
=> $P_{EGi}(0)$ at the end of T_{io}-rise ~ 12 & 27 kW/m^3

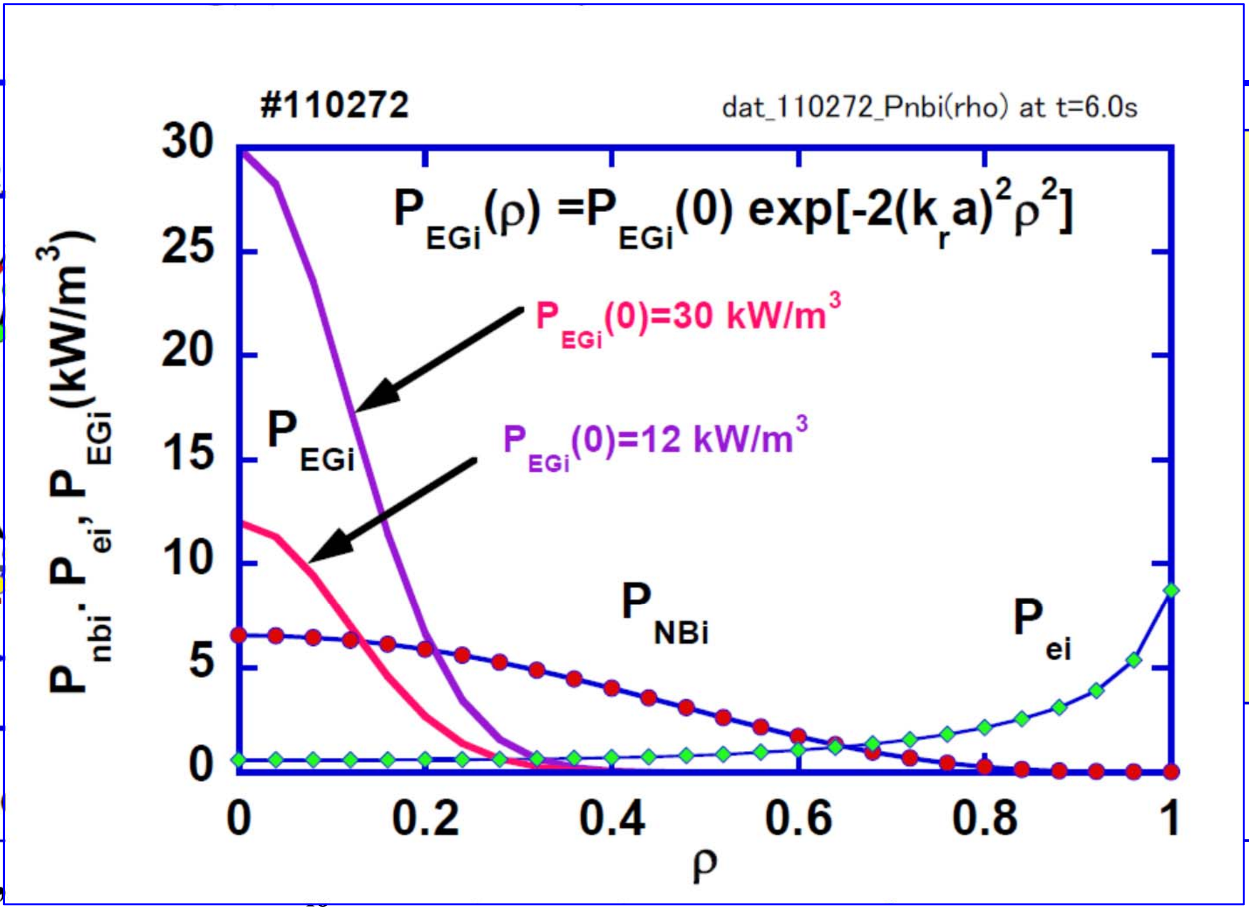
- **Very peaked ion heating power density profile ∝ ϕ^2_{G-rms} , Δ_{dep}~0.17<a>**
- **Expected EGAM growth rate γ_h ~ ω_{EG} ~ 10^5 s^{-1} under dominant beam pressure [3]:**

<P_h>/<P_{th}>~5 , $P_h(0)/P_{th}(0)$~12-16 and n_h/n_i ~ 0.2-0.3

[3] G.Y. Fu, PRL 2008

Estimation of Bulk ion heating power density





Using exp. data (T_{io} and T_{eo},

$\phi_{G-rms}(0)$ = 1.3 kV) for $\iota(0)$=0.45 or 0.36:=>EGAM damping rate γ_{dEG}~0.8 or 1.9x10^5 s^{-1}

=> $P_{EGi}(0)$ at the end of T_{io}-rise ~ 12 & 27 kW/m^3

- Very peaked ion heating power density profile ∝ ϕ_{G-rms}^2 , Δ_{dep}~0.17<a>
- Expected EGAM growth rate $\gamma_h \sim \omega_{EG} \sim 10^5$ s^{-1} under dominant beam pressure [3]:

$<P_h>/<P_{th}>$~5 , $P_h(0)/P_{th}(0)$~12-16 and n_h/n_i ~ 0.2-0.3

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Summary and Future Prospect

◆ Spontaneous T_i –rise in the core region $r/a \lesssim 0.5$ during the phase of $\iota_{min} < 1/3$.

◆EGAM frequency in LHD:=> $f_{EGAM} \approx \frac{1}{2\pi R}\sqrt{T_e/m_i} \approx (0.6\text{-}0.7) f_{GAM-GK}(0)$

◆Monotonic increase of EGAM fluctuations in higher $<n_e>$ RS-plasma without T_{io}-rise

Clear reduction of EGAM fluctuations during the T_{io}-rise in lower $<n_e>$ shots

No suppression but slight increase in micro turbulence during the T_{io}-rise.

=> Additional bulk ion heating power(~ 10 kW/m^3) at the end of T_{io}-rise

Expected bulk ion heating power by ion LD of EGAM at ρ~0 is ~10 to 30 kW/m^3.

◆Termination of T_{io}-rise by “ sudden drop in EGAM & RSAE frequencies”

<= caused by MHD equilibrium change due to RSAE-induced EP-pressure profile

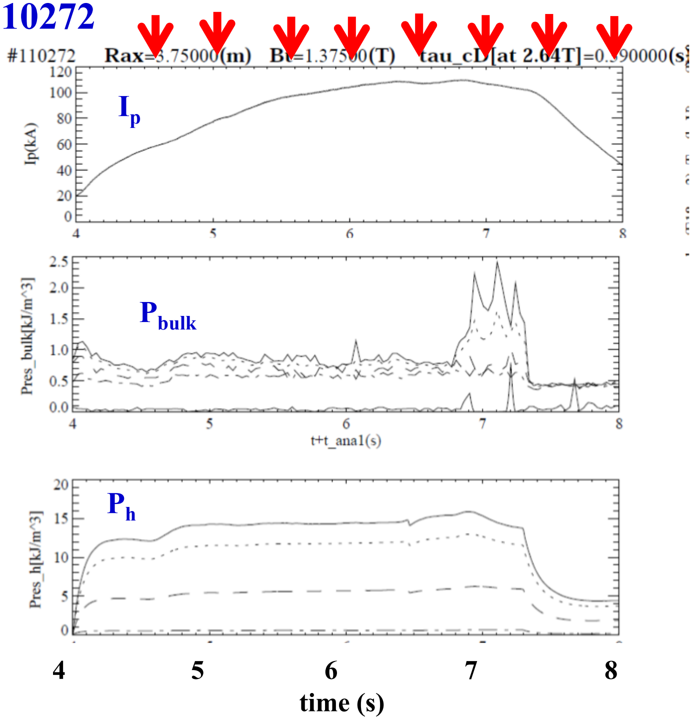
◆T_{io}-rise observed in LHD RS plasmas is thought to be the first experimental observation of energy channeling from beam ions to bulk ions via EGAM.

◆Careful control of ι-profile by ECH/ECCD and other techniques is required for further enhancing bulk ion heating through maximizing EGAM activity and minimizing RSAEs.

Annex

An Example of 3D Equilibria of an LHD RS Plasma

#110272

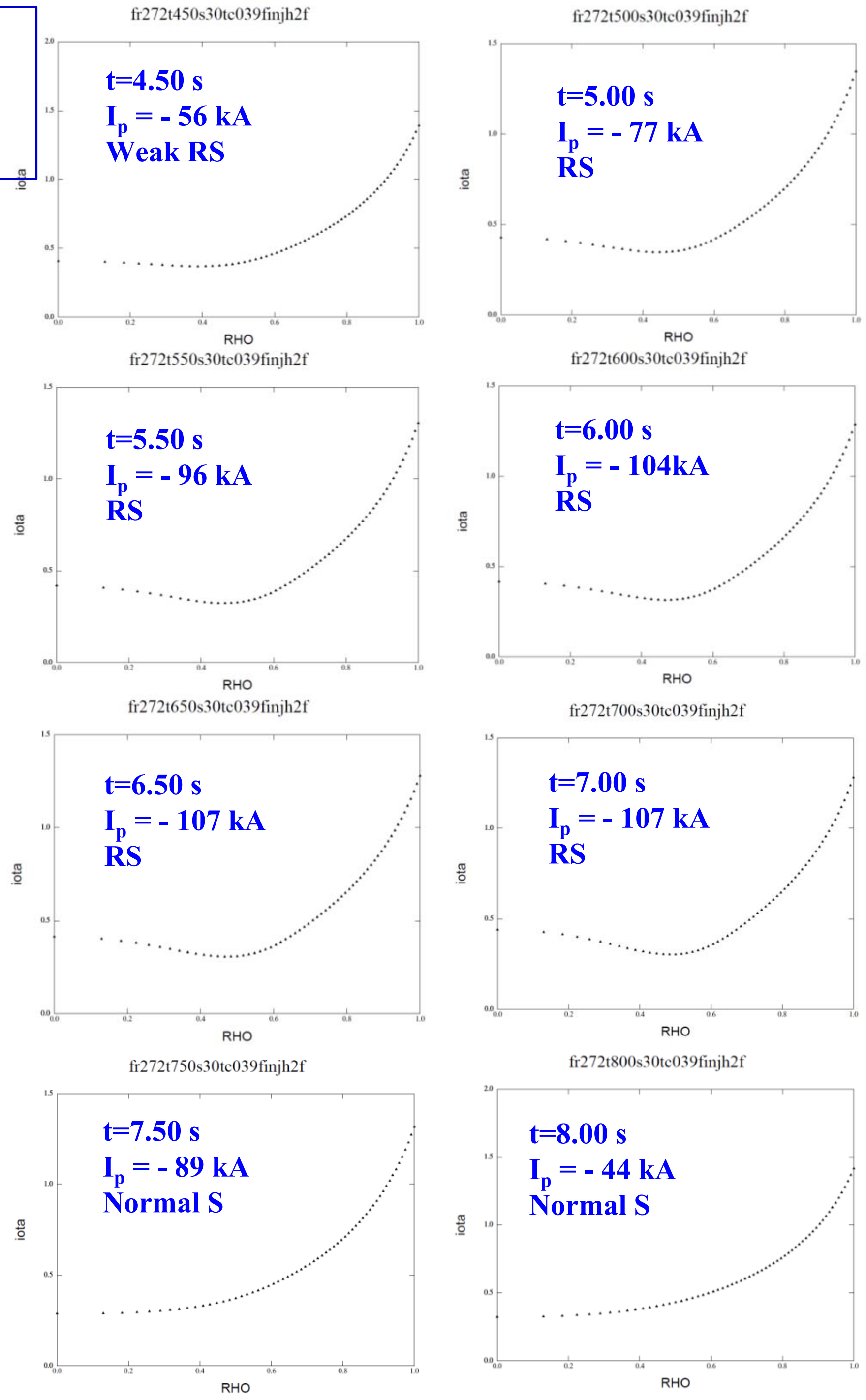


When P_h and ctr-I_p increase up to high level, RS-configuration is formed due to enhanced Shafranov shift.

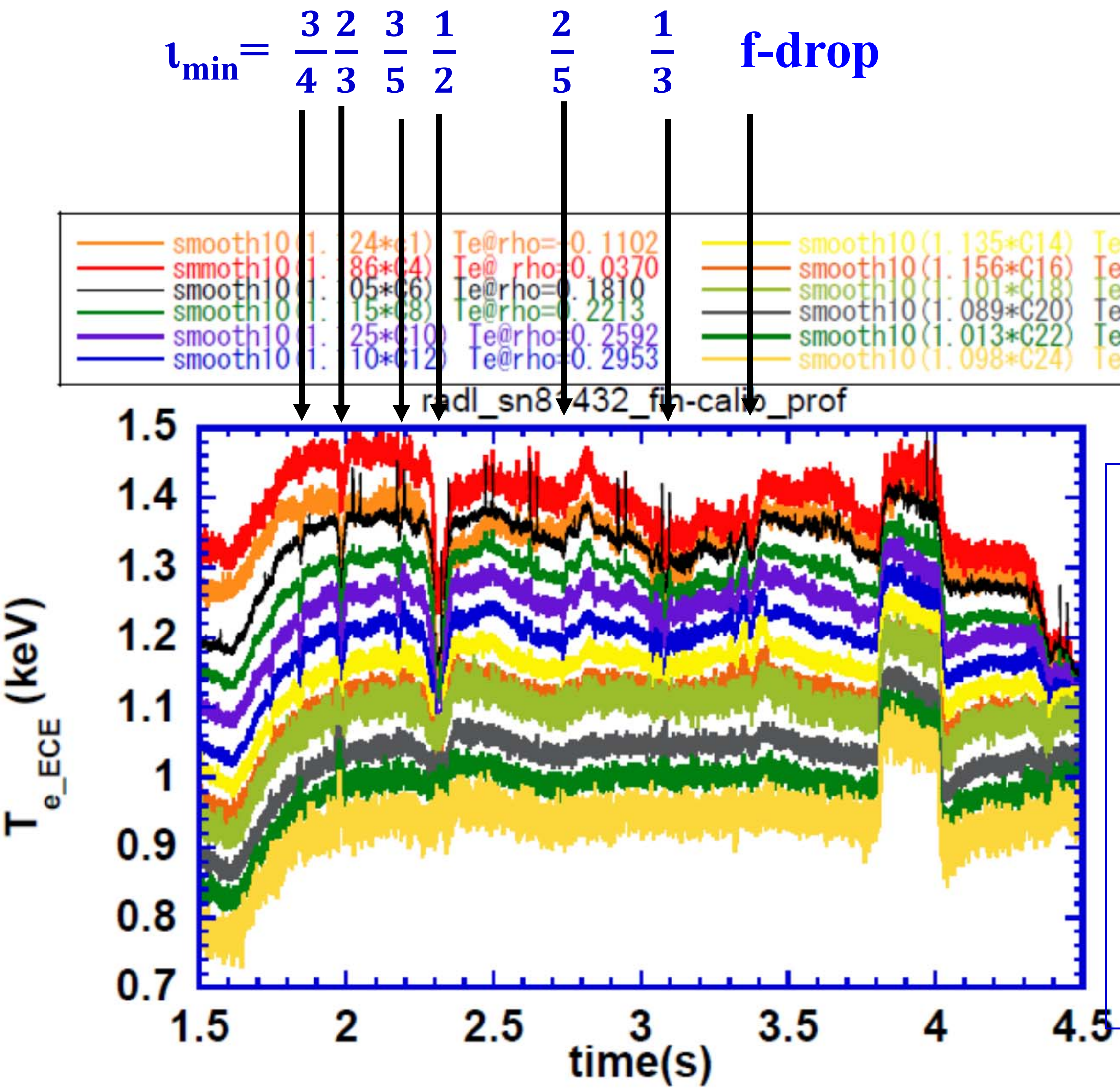
$P_{tot}=P_e + P_i + P_h$, $P_h >> P_{bulk}= P_e + P_i$

RSAE in RS configuration sensitively reflect time evolution of the ι-profile.

Assumption: $P_{abs}/P_o=(1-x^2)^3$, $j_{tor}=j_o(1+x^2)$



T_{e_ECE} Profile Behaviors at the moment ι_{min} passes through various rational values



- T_{e_ECE} shows sharp drops when ι_{min} passes various rational values, i.e., 3/4, 2/3, 3/5, 1/2, 2/5 and 1/3.
- At the end of T_{io}-rise phase, characteristic oscillations near the plasma center appear, which may be induced by oscillation of magnetic axis.