Observation of core ion energy increase caused by the Landau damping of MHD wave in the periphery of LHD plasma

K.Ida[1,2], T.Kobayashi[1,2], M.Yoshinuma[1], K.Nagaoka[1,3], K.Ogawa[1,2], T.Tokuzawa[1,2], H.Nuga[1] & Y.Kato

[1] National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[2] The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan.
[3] Graduate School of Science, Nagoya University, Nagoya, Aichi 464-8602, Japan.
[4] Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan.

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Outline

1. Introduction : How to heat ions in the burning plasma?

2. Landau and transit-time damping observed in LHD

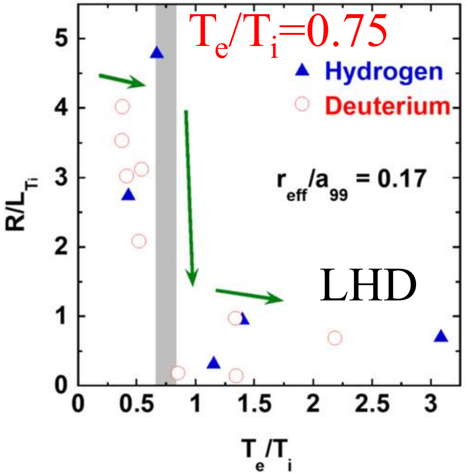
3. Partial flattening of ion velocity distribution function f(v) measured with 10 kHz fast charge exchange spectroscopy

4. Observation of increase of kinetic energy $\int v^2 f(v)\, dv$

5. Phase-space dynamics

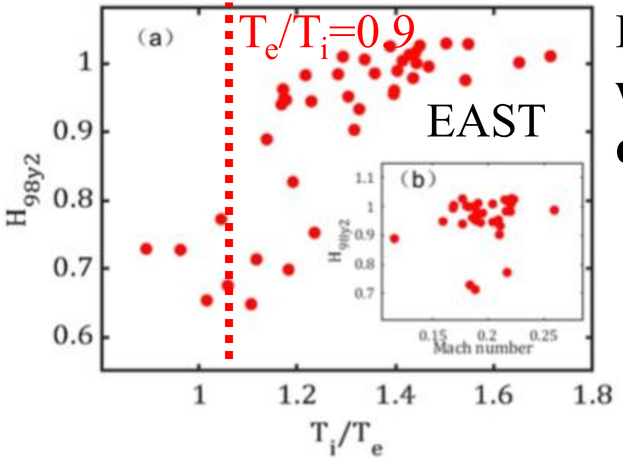
6. Summary

Direct ion heating is necessary in the burning plasma



ITB disappear when the T_e/T_i ratio exceeds 0.75

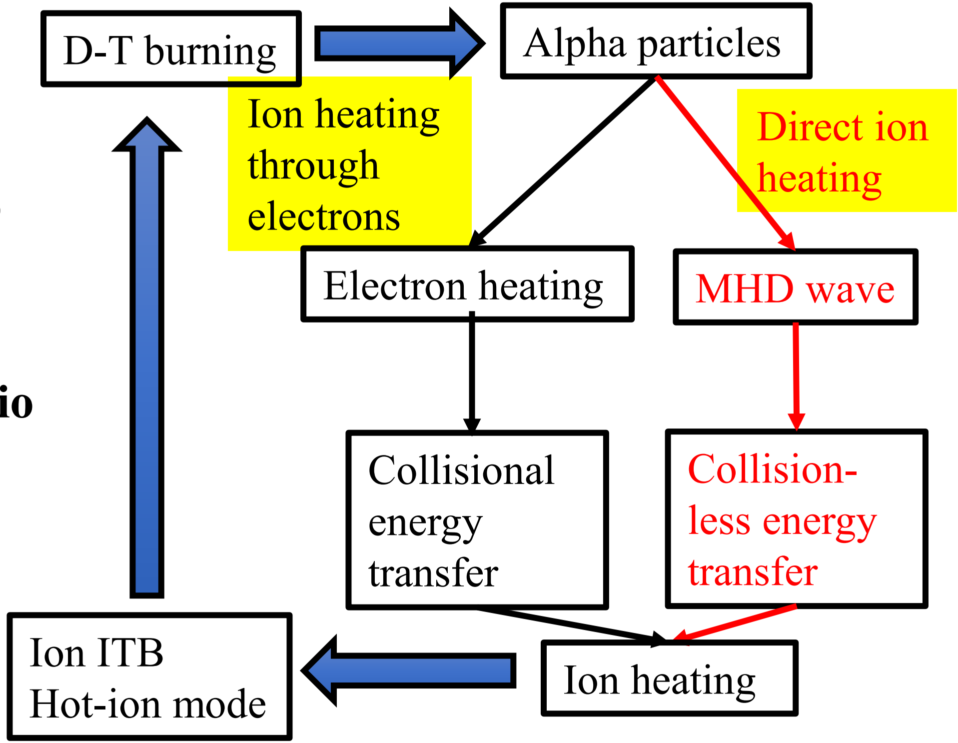
M. Osakabe, et al, Nucl. Fusion 62, 042019 (2022)



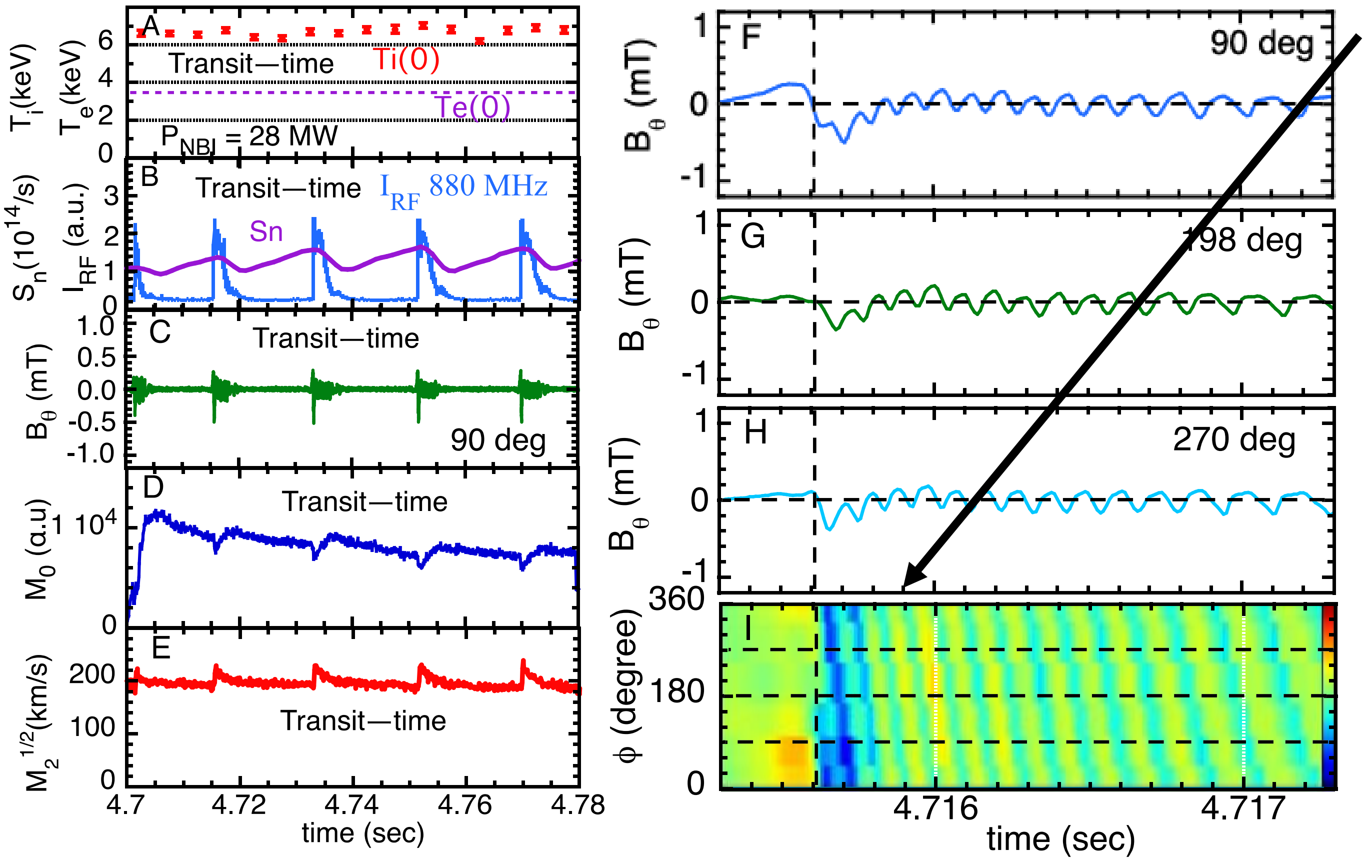
H factor drops when T_e/T_i ratio exceeds 0.9

Y.E. He et al., Nucl. Fusion 64 076064 (2024)

The critical value of T_e/T_i ratio below 1 suggest the importance of direct ion heating to sustain the hot-ion mode in the burning plasma.



Discharge with transit-time damping



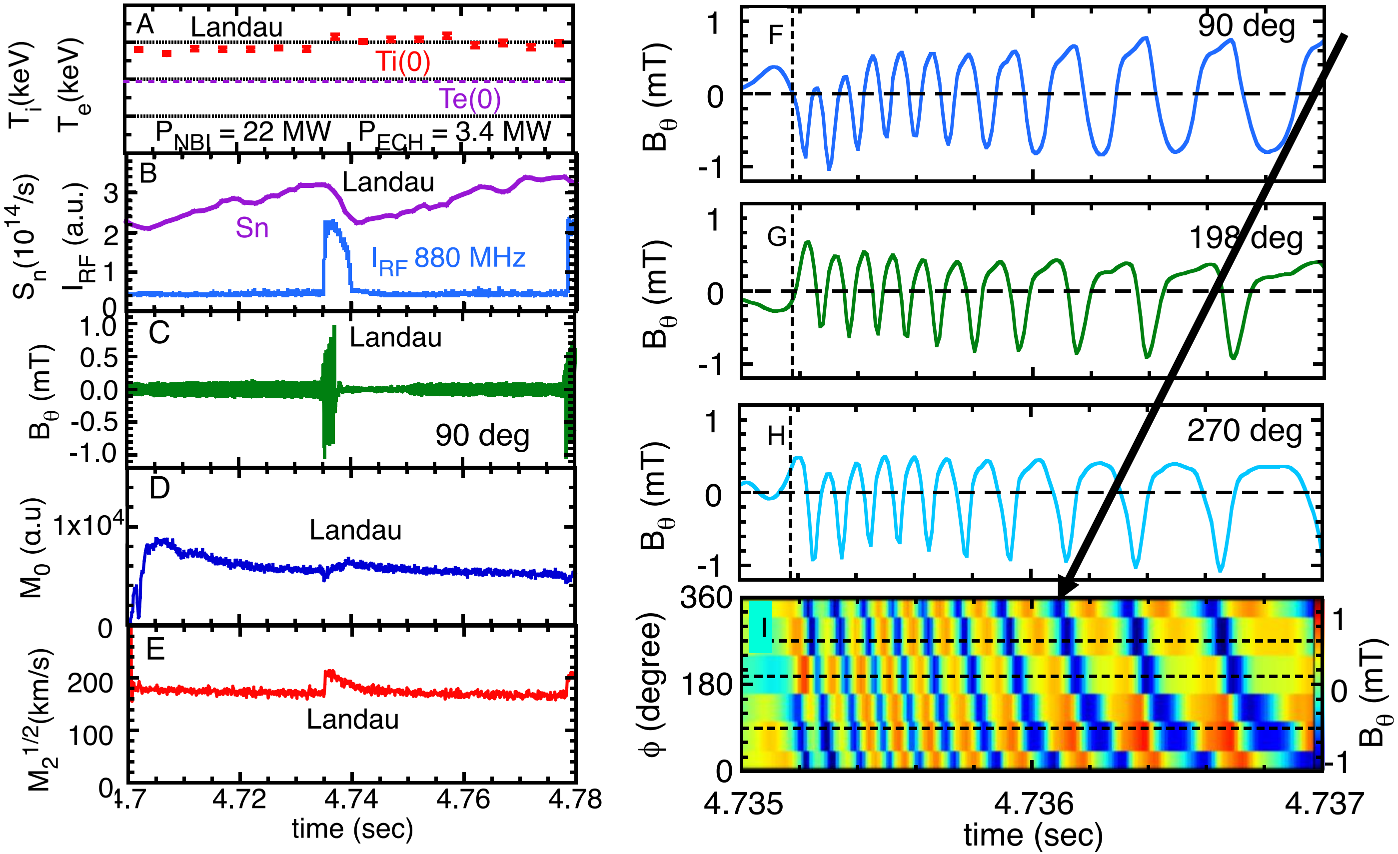
Transit-time damping is characterized by a very short magnetic field perturbation at the onset of the MHD burst.

The wave packet is short and comparable to one-cycle oscillation (solitary wave).

The toroidal mode number is 1

The increase of effective thermal velocity $M_2^{1/2}$ is transient 3~4 ms.

Discharge with Landau damping



Landau damping is characterized by a magnetic field perturbation lasting more than 2 ms with frequency chirping down.

The wave packet is more 10 cycles.

The toroidal mode number is 1

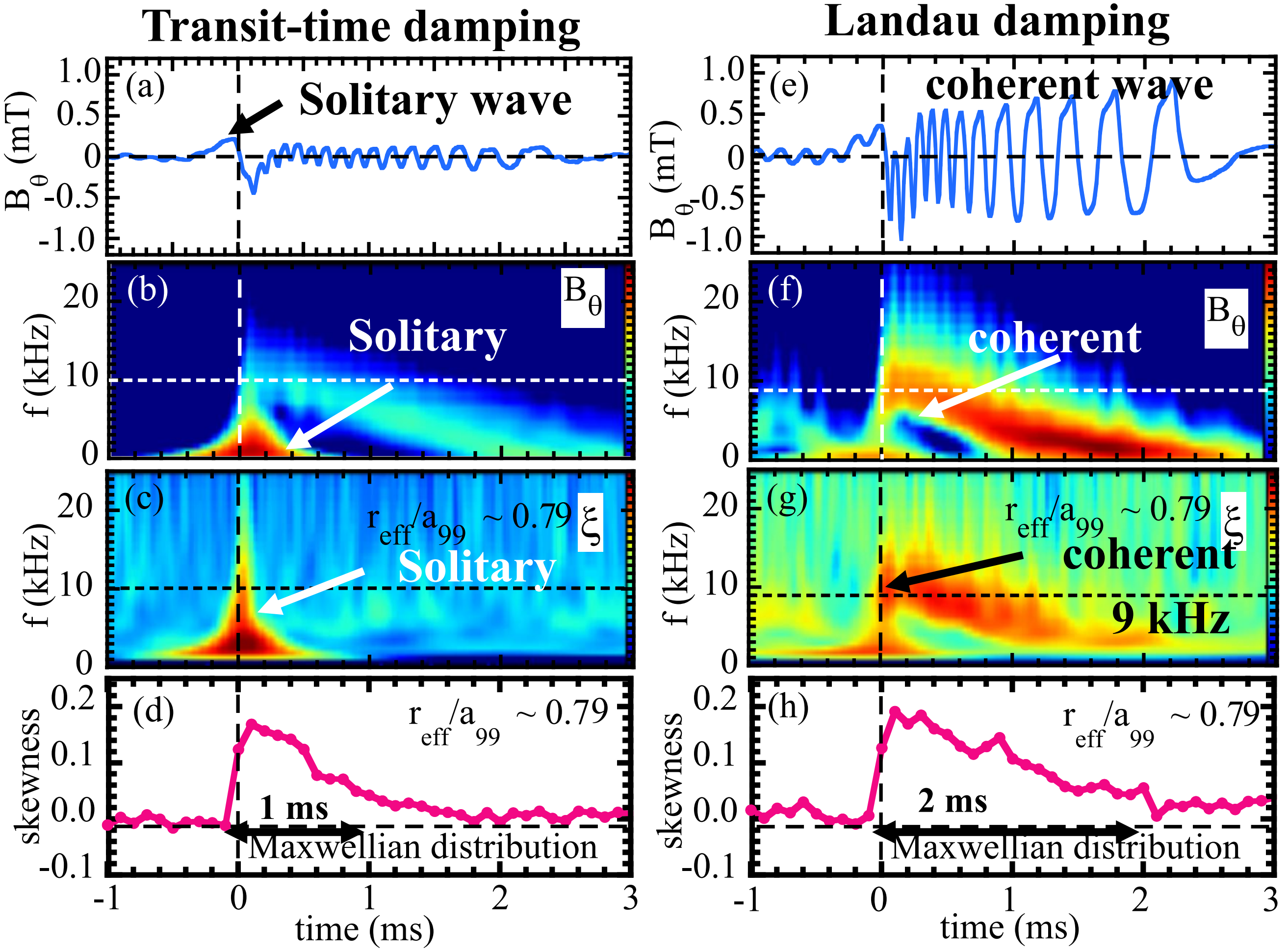
The increase of effective thermal velocity $M_2^{1/2}$ is transient but longer 5~6 ms.

Landau damping of solitary wave and coherent wave are observed

FFT spectrum of magnetic fluctuation (B_θ) shows chirping down

Displacement of isothermal surface (ξ) is observed at $r_{eff}/a_{99} = 0.8$ (resonance location)

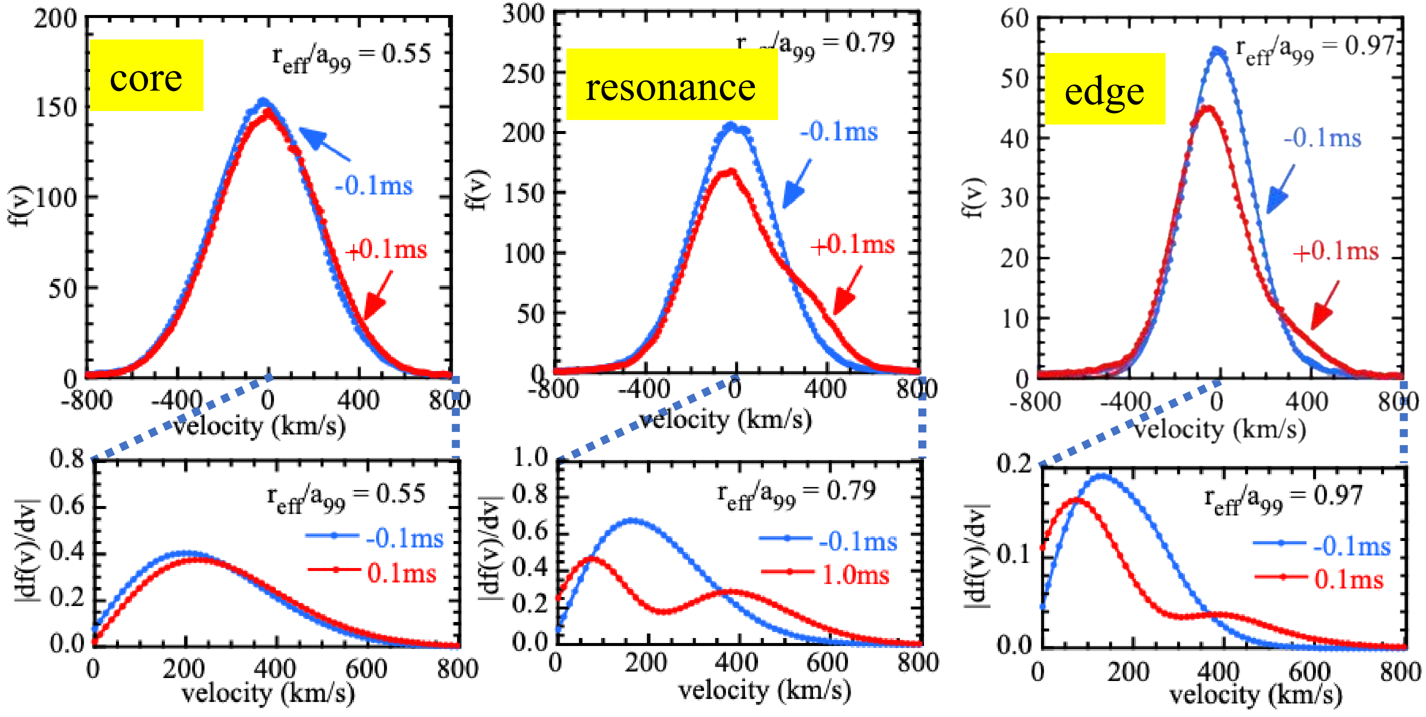
Finite skewness of ion velocity indicates distortion from Maxwellian distribution



Dynamics of ion velocity distribution function f(v) measured with fast charge exchange spectroscopy (10kHz)

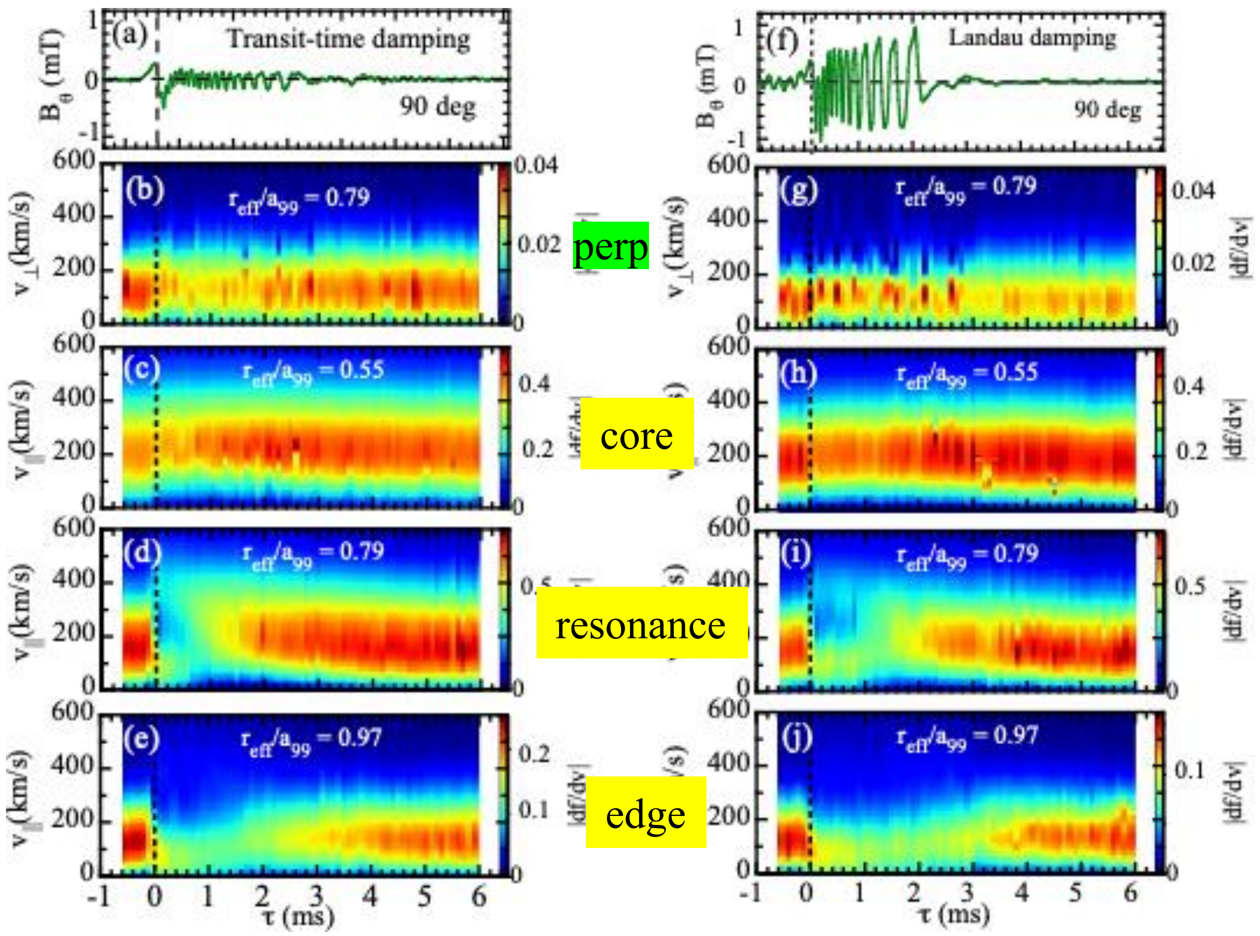
Ion velocity distributed function is well fitted with Gaussian + derivative of a hyperbolic tangent function as $f(v) = f_0(v) + \delta f(v) = a_0 * \exp(-(v-v_0)^2/\sigma_0^2) + a_1 * (1-\tanh^2((v-v_1)/\sigma_1))$

Gaussian profile deformation



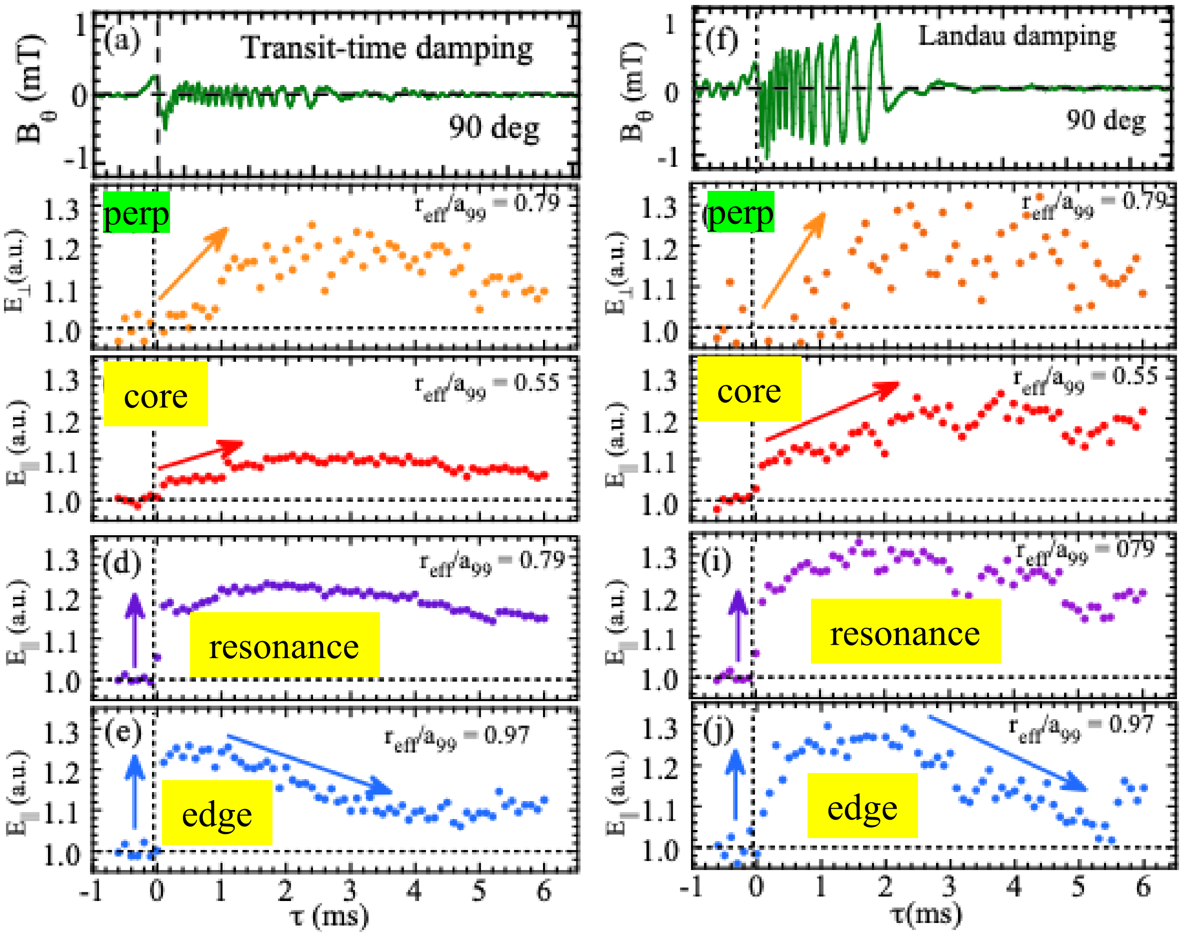
- **The flattening of f(v) is detected as the drop of |df(v)/dv|**
- **The flattening of f(v) are evidences for the Landau and time-transit damping**
- **These damping occurs at the resonance and edge not in the plasma core ($r_{eff}/a_{99} = 0.55$)**

Time evolution of gradient of velocity distribution function df(v)/dv



- The fattening of f(v) disappears within the ion-ion collision time scale of 1 – 1.5 ms at the resonance location and edge.
- The time period of f(v) flattening is longer in the discharge with Landau damping where the magnetic perturbation is larger
- There is no f(v) flattening in the plasma core (r_{eff}/a_{99} = 0.55)

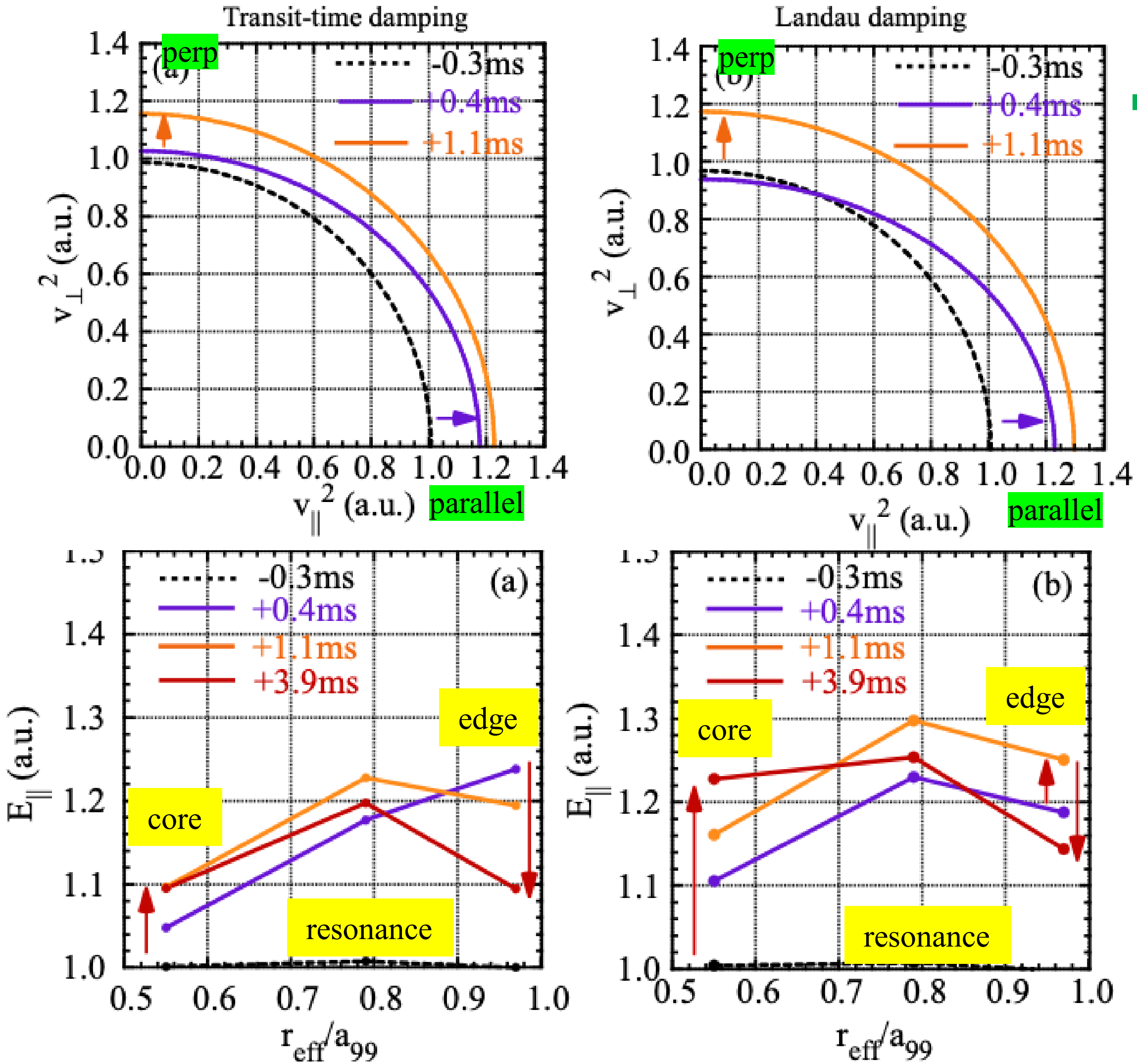
Increase of kinetic energy is 20 – 30%



- **Kinetic energy $E = \int v^2 f(v) dv$ is evaluated from the f(v) measured.**
- **At the resonance and plasma edge, (r_{eff}/a_{99} = 0.79 and 0.97) : kinetic energy jump (increase rapidly) at the onset of MHD burst within 0.1ms**
- **At plasma core (r_{eff}/a_{99} = 0.55) : kinetic energy keeps increasing after the onset of MHD burst**

The 20% increase of kinetic energy is observed in the plasma core, while the transit-time and Landau damping occur near the plasma periphery.

Phase space Dynamics



Dynamics in velocity space

- **Acceleration of parallel velocity is observed within 0.4 ms immediately after the onset of MHD burst.**
- **Thermalization is seen in the time scale of ion-ion collision time scale (~ 1ms).**

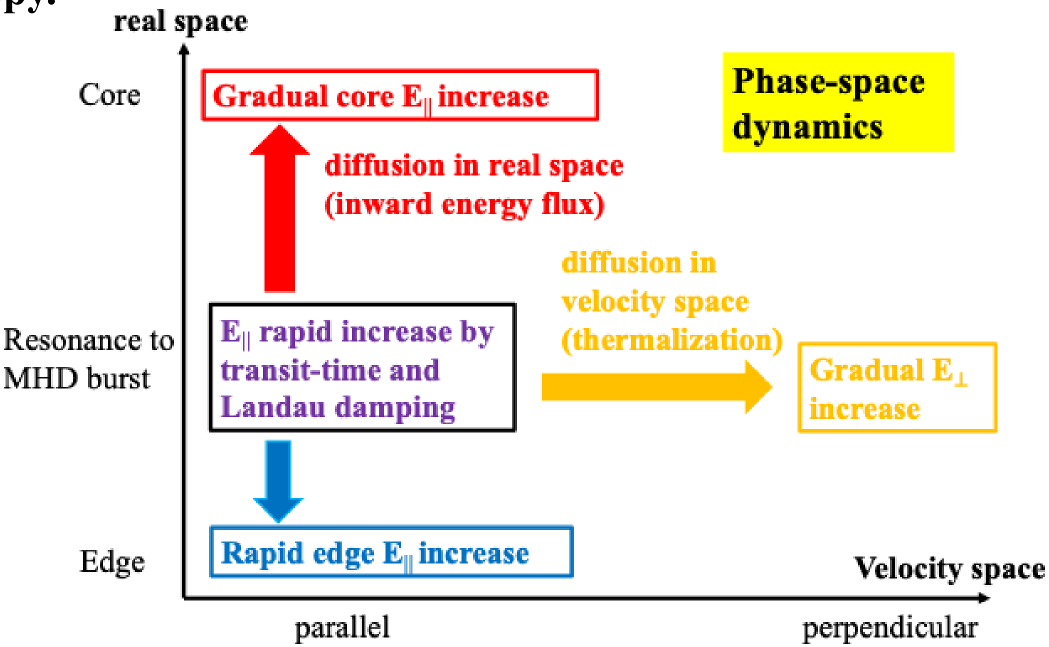
Dynamics in real space

- **Energy increase is most significan at the resonance**
- **Gradual increase is observed in the core**
- **Kinetic energy at the plasma edge decreases.**

Conclusion

The increase of ion kinetic energy in the core due to the Landau and transit-time damping of energetic-particle driven MHD wave near the plasma periphery is observed in the Large Helical Device using fast charge exchange spectroscopy.

- **Kinetic energy $E = \int v^2 f(v) dv$ is evaluated from the ion velocity distribution function f(v) measured with the 10kHz fast charge exchange spectroscopy.**
- **Kinetic energy jump (increase rapidly) at the onset of MHD burst within 0.1ms at the resonance and edge**
- **Kinetic energy keeps increasing and reaches 120% after the onset of MHD burst in the plasma core**



This experiment demonstrates that the wave-particle interaction, such as Landau and transit-time damping of EP-driven MHD wave, can be a candidate for the ion heating scenario in the burning plasma, where no direct ion heating by alpha particles is expected.

Backup

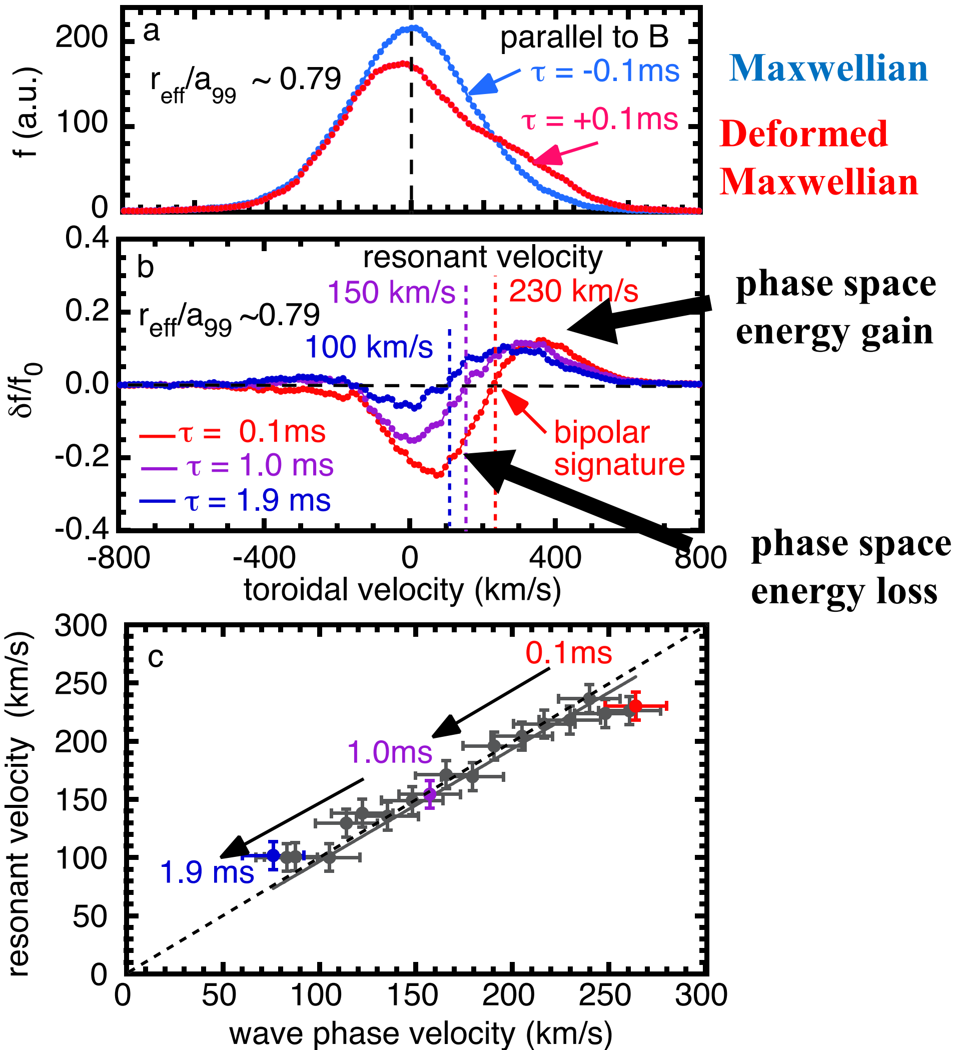
Deformation of ion velocity distribution (Bipolar signature) is observed in laboratory plasma

Bipolar signature of phase space energy gain and phase space energy loss is clearly observed at $r_{eff}/a_{99} = 0.79$.

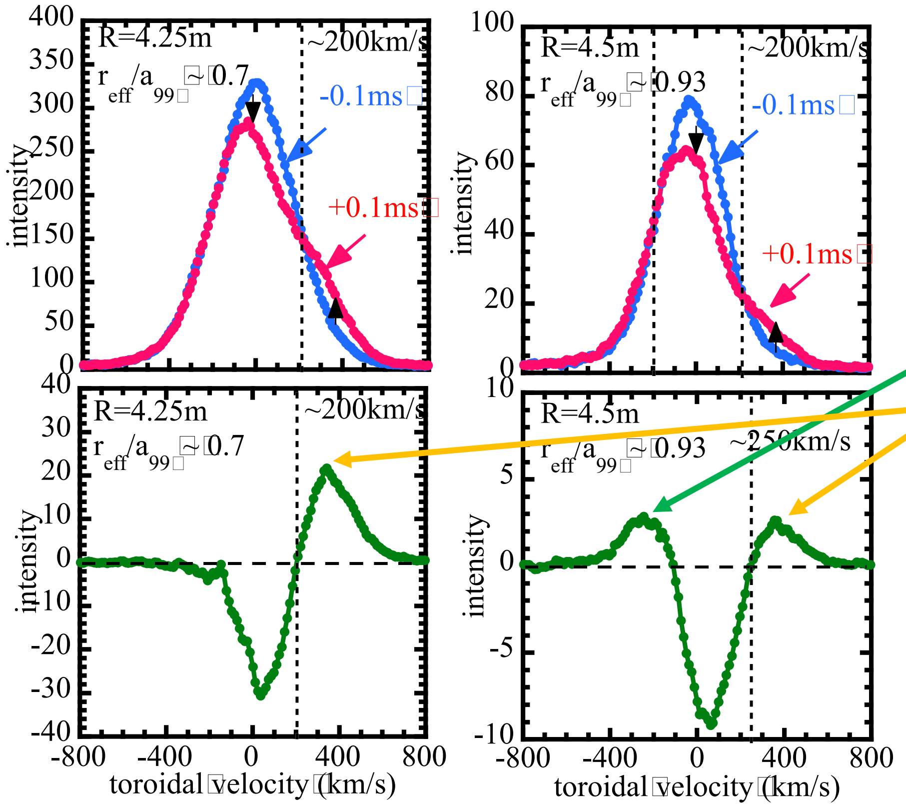
Phase space energy gain > energy loss
→ Net energy flow is wave to particle

The toroidal velocity of pivot point is the resonant velocity of wave-particle interaction

Resonant velocity decreases from 240 km/s to 100 km/s, which is consistent with the chirping down of wave frequency from 9 kHz to 4 kHz Good agreement of two velocities.



Improvement from the previous analysis



In the previous analysis

The difference in the velocity distribution function between before and after the onset of MHD burst $\delta f(v,t) = f(v,t) - f(v, t_0)$ is analyzed. ($t_0 < 0$)

It is difficult to distinguish the flattening of f(v) and shift of f(v) in δf(v,t), for the case at the plasma boundary (R=4.5m)

Positive peak due to shift of f(v)

Positive peak due to flattening of f(v)

1. Gradient of velocity distribution function df(v,t)/dv is derived from the f(v) measured.

   $\delta f(v,t) \Rightarrow df(v,t)/dv$

2. Kinetic energy $E = \int v^2 f(v)\, dv$ is evaluated as well as zero cross velocity v_0 where $\delta f(v_0,t) = 0$ is derived from the f(v) measured.

v_0 for $\delta f(v_0,t) = 0 \Rightarrow E = \int v^2 f(v)$

Energy flow from energetic particle to bulk ions

Collisionless energy transfer from energetic particles to carbon impurity is observed as simultaneous increase of stored carbon energy and decrease of stored beam energy at the onset of MHD burst within s.00 micro-seconds