Transition between isotope-mixing and non-mixing states in hydrogen- deuterium mixture plasmas in the Large Helical Device (EX-6-2)

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OUTLINE

1 Introduction : isotope-mixing and non-mixing

2 Key diagnostics for this study (How to measure isotope density and turbulence)

3 Parameter dependence and regime for mixing and non-mixing state
   3-1 Characteristics of isotope mixing and non-mixing states
   3-2 Impact of plasma collisionality, Te/Ti ratio and density gradient

4 Control of mixing and non-mixing state by H/D pellet injection

5 Summary

Introduction

In the gyro-kinetic simulation, two states of isotope particle transport can be expected in the isotope mixture plasmas, where isotope species has a freedom in the quasi-neutral condition.

ITG dominant state Di > De (large ion particle transport)

→ Radial density profile of different isotope species becomes identical regardless of isotope source location (Isotope mixing)

TEM dominant state De > Di (small ion particle transport)

→ Radial density profile of different isotope species becomes different depending on isotope source location (Isotope non-mixing)

reference: C.Bourdelle et. al., Nucl. Fusion 58 (2018) 076028

crucial issue in D-T plasma.

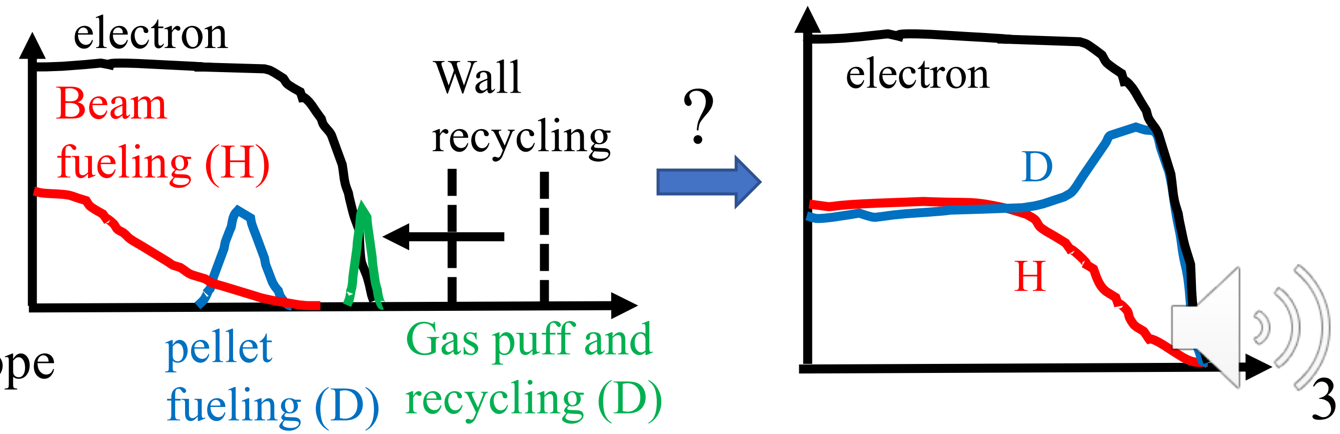
The isotope source location is controlled by

1 core H/D beam fueling

2 edge H/D pellet fueling

3 SOL H/D wall recycling

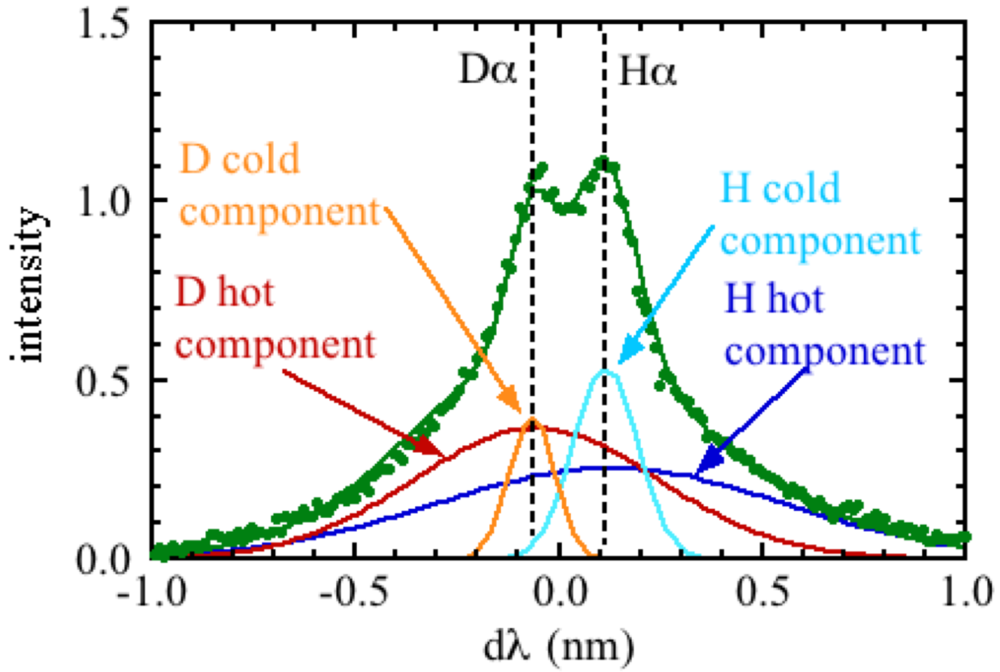
to study the relation between isotope mixing and turbulence



Isotope ratio inside plasma is measured with bulk charge exchange spectroscopy

The charge exchange lines are fitted with four Gaussians (H, D cold and hot components) by reducing the free parameters from12 to 5

$$I(\lambda) = \sum_{i}^{4}\left[A^{i}\exp\left(-\frac{(\lambda-\lambda_0^i-\lambda_s^i)^2}{(\lambda_w^i)^2+(\lambda_{\rm ins})^2}\right)\right].$$



Fitting parameters

$A^{H\text{-}cold}$, $A^{D\text{-}cold}$, $A^{H\text{-}hot}$, $A^{D\text{-}hot}$, $\lambda_w^{H\text{-}hot}$, $\lambda_w^{D\text{-}hot}$ $(T_i^H = T_i^D)$

Given from spectrum at NBI-off

$\lambda_w^{H\text{-}cold}$, $\lambda_w^{D\text{-}cold}$, $\lambda_s^{H\text{-}cold}$, $\lambda_s^{D\text{-}cold}$

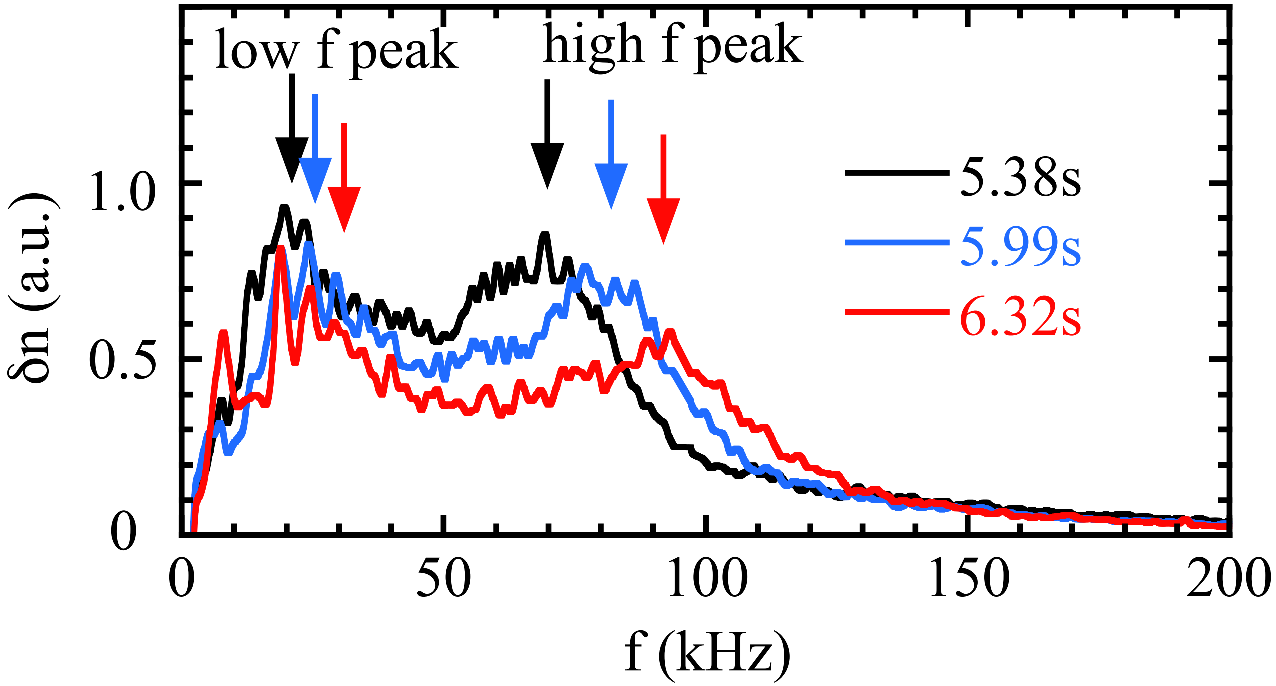
Derived from carbon charge exchange spectroscopy with taking account of energy dependence of charge exchange cross sec[tio]n

$\lambda_s^{H\text{-}hot}$, $\lambda_s^{D\text{-}hot}$:

Turbulence states are measured with phase contrast imaging

Example of frequency spectrum of density turbulence measured phase contrast imaging (PCI)

There are two peaks of turbulence spectrum observed.



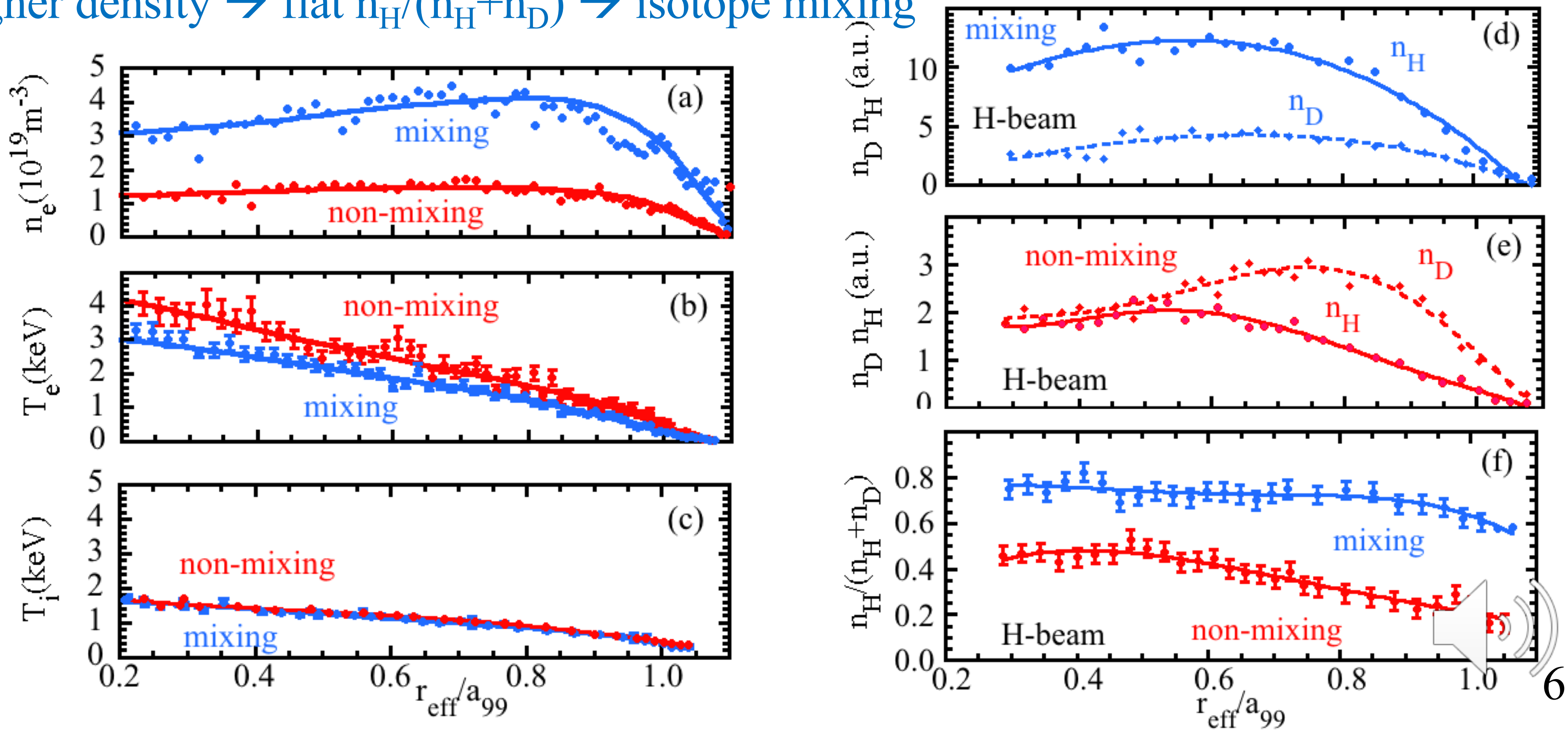
Depending on the parameter regime, only low frequency peak or high frequency peak appears.

For example
Low density ECH plasma
→ high f peak (60 ~ 90 kHz)
high density NBI plasma
→ low f peak (~20kHz)

Density dependence of isotope mixing and non-mixing transition

Lower density → peaked $n_H/(n_H+n_D)$ → isotope non-mixing

Higher density → flat $n_H/(n_H+n_D)$ → isotope mixing

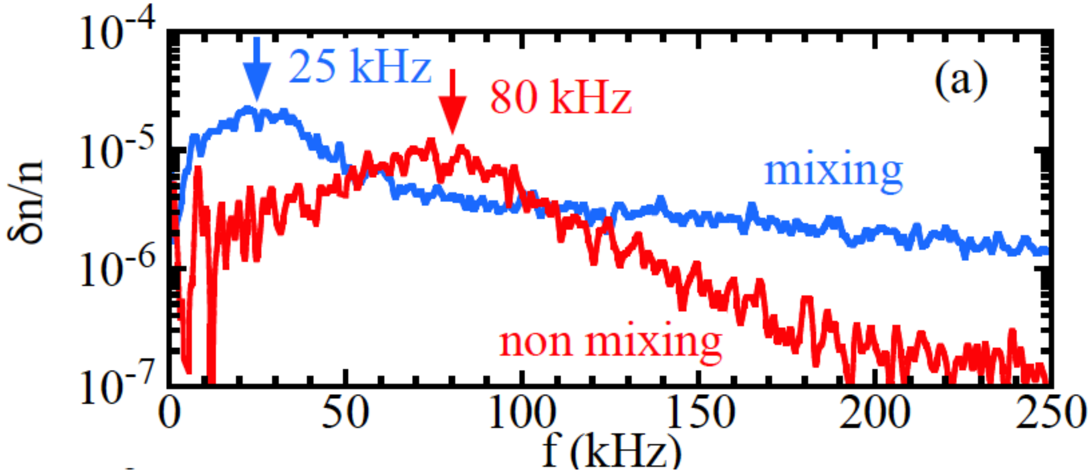


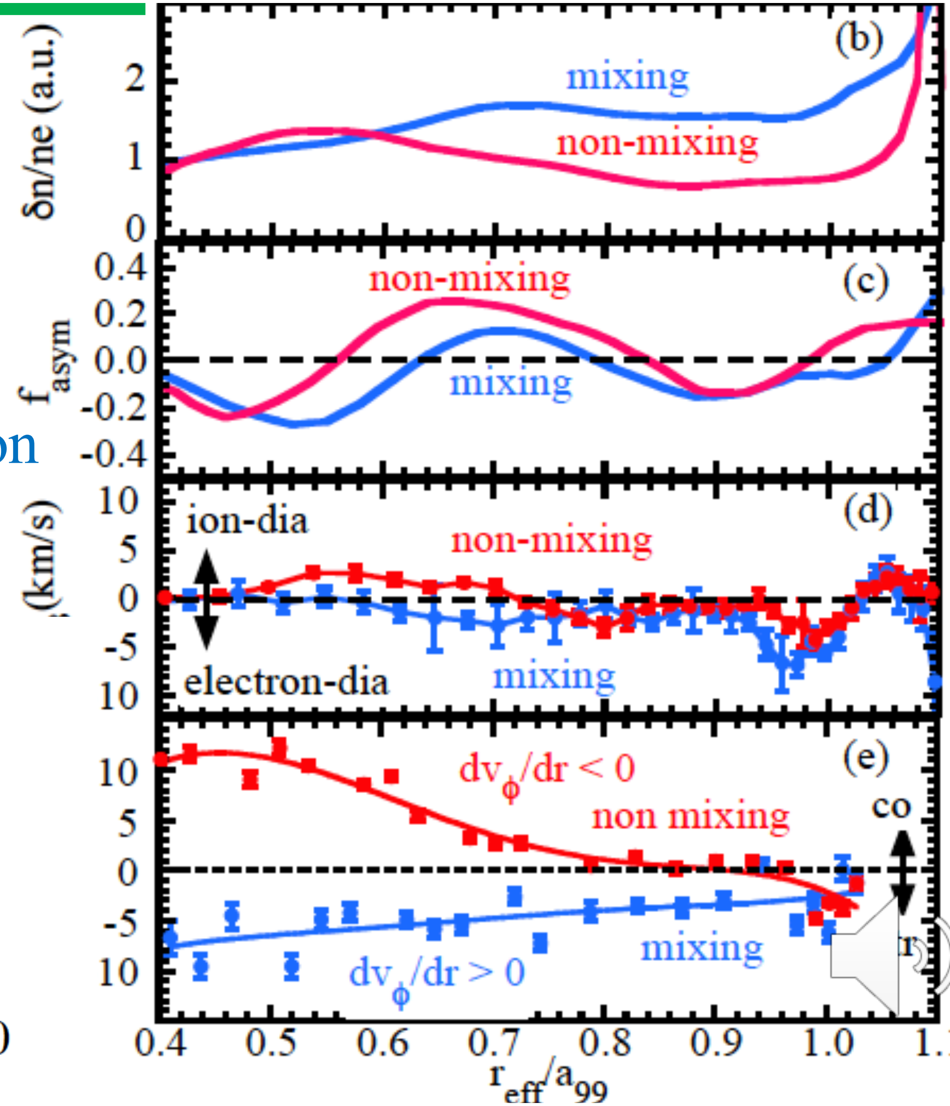
Characteristics of density fluctuation

isotope non-mixing
- fluctuation peak 80 kHz
- intrinsic toroidal flow in co-direction

isotope mixing
- fluctuation peak 25 kHz
- intrinsic toroidal flow in counter-direction

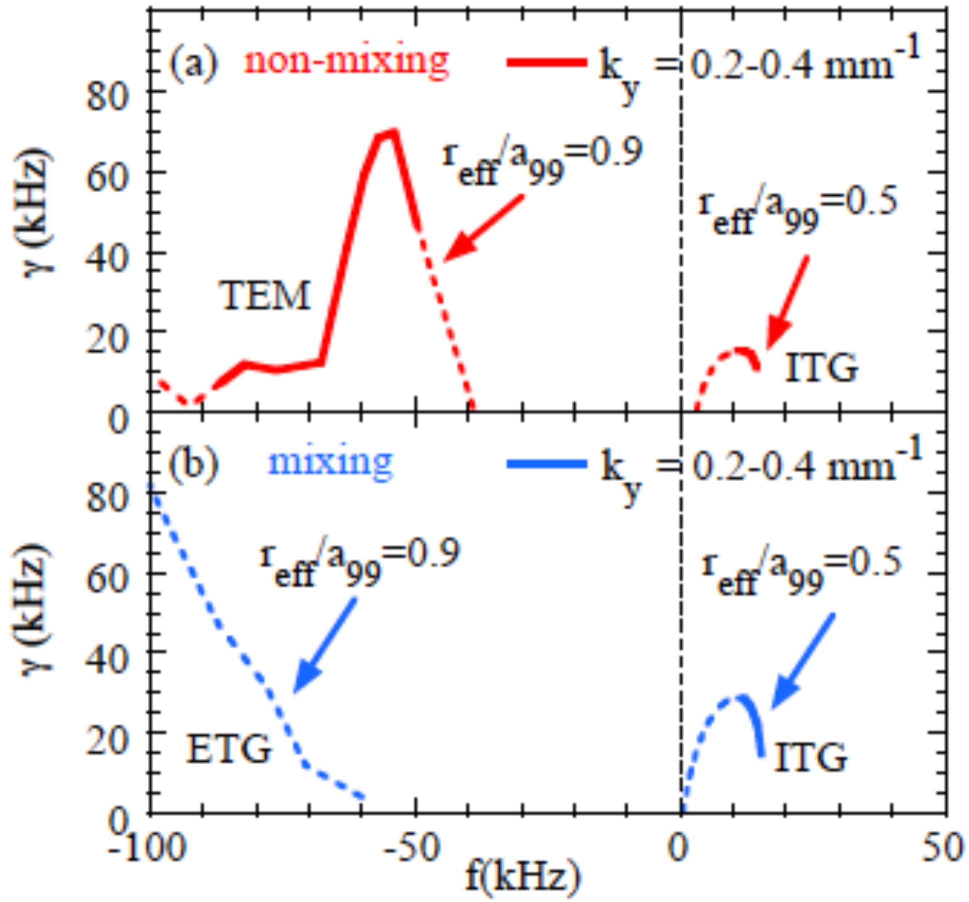
ExB flow velocities are similar





Growth rate of turbulence predicted by gyrokinetic simulation code is consistent with the observations

Growth rate calculated by gyrokinetic simulation GKV



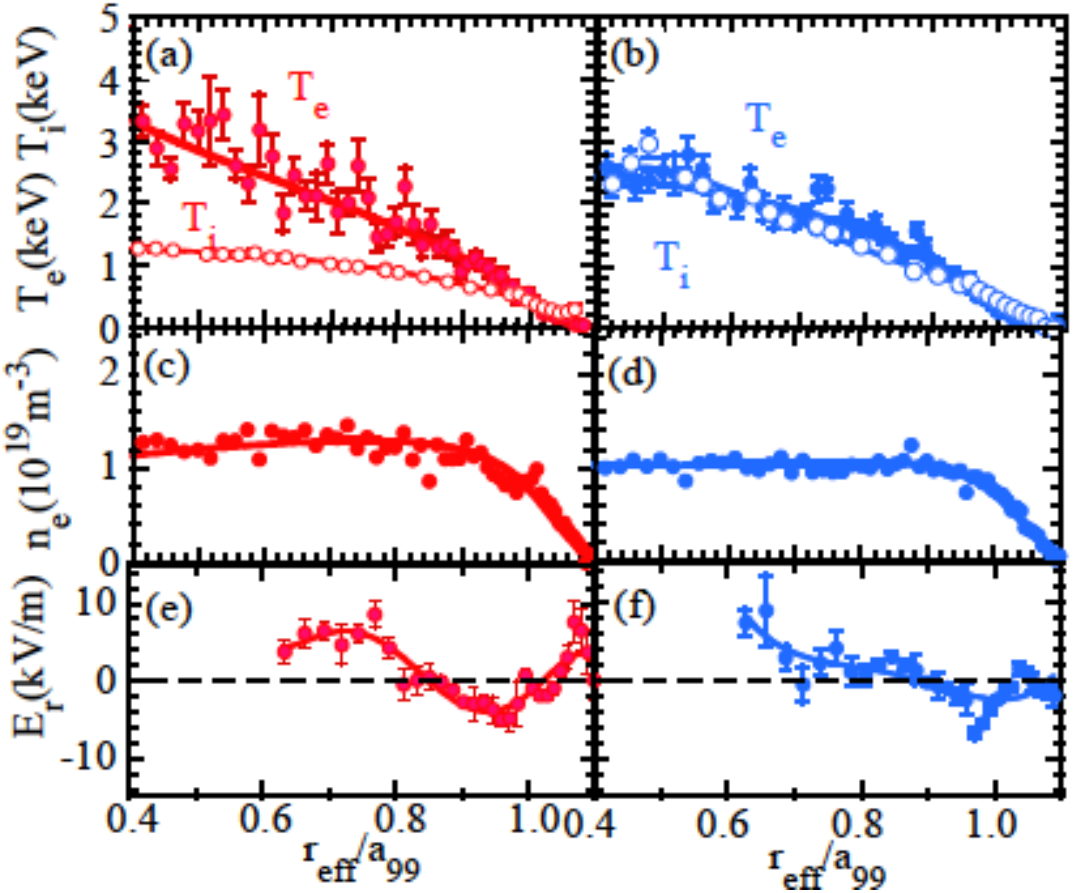
Core → ITG
Edge → TEM or ETG
due to steeper density gradient

TEM → f = 50 - 85 kHz
ITG → f = 10 - 20 kHz

Isotope non-mixing state
higher Te/Ti → TEM destabilized

Isotope mixing state
Lower Te/Ti → TEM stabilized
→ ETG destabilized

Impact of Te/Ti ratio on isotope mixing and non-mixing

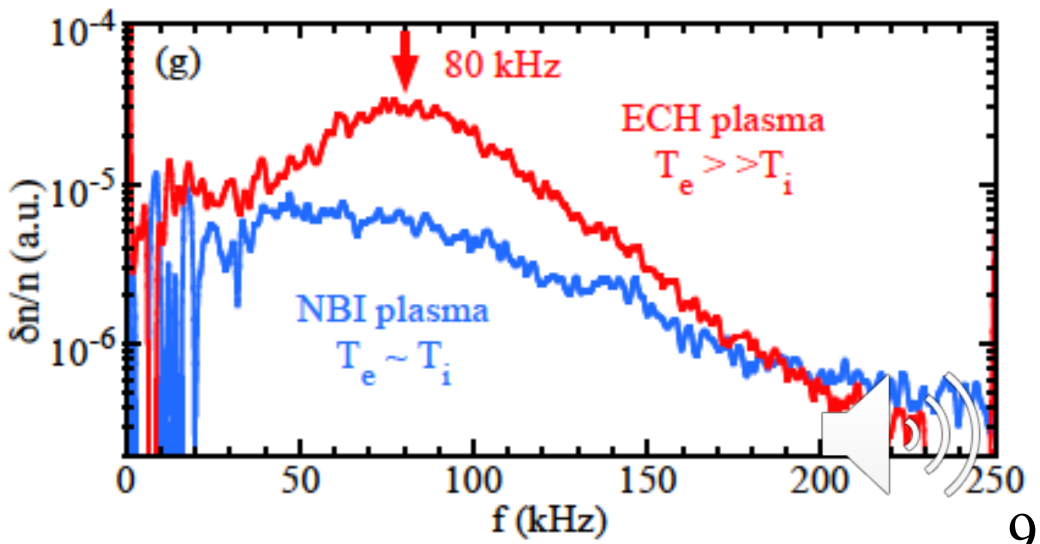


ECH plasma → Te/Ti >1

→ 80 kHz fluctuation peak clearly appears

NBI plasma → Te/Ti ~ 1

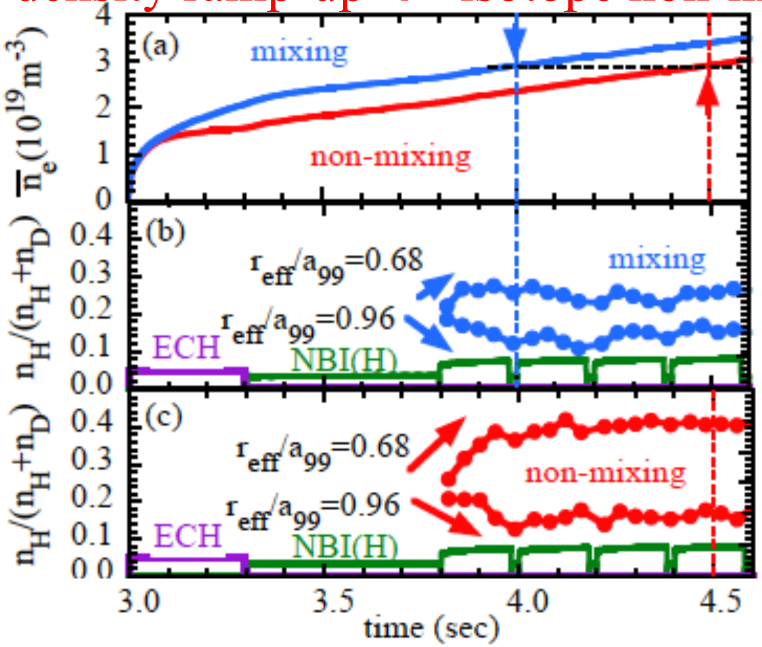
→ 80 kHz fluctuation peak disappears

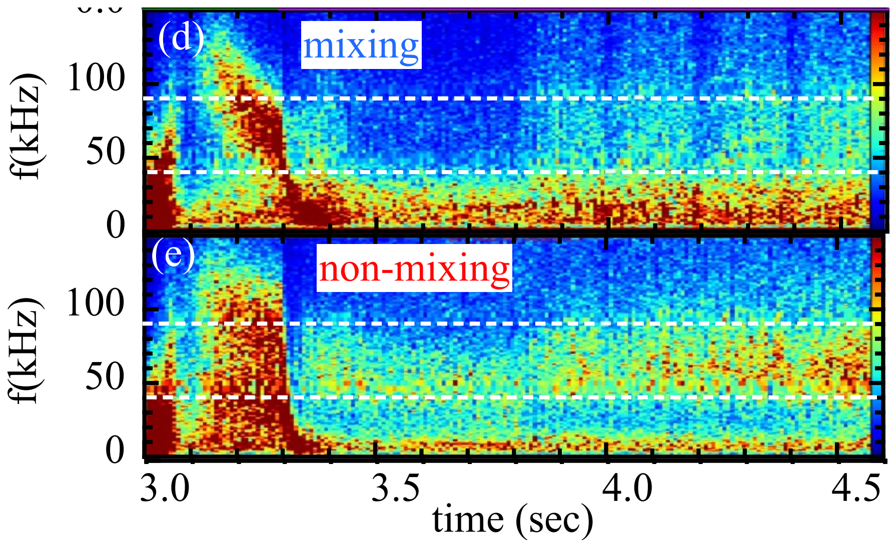


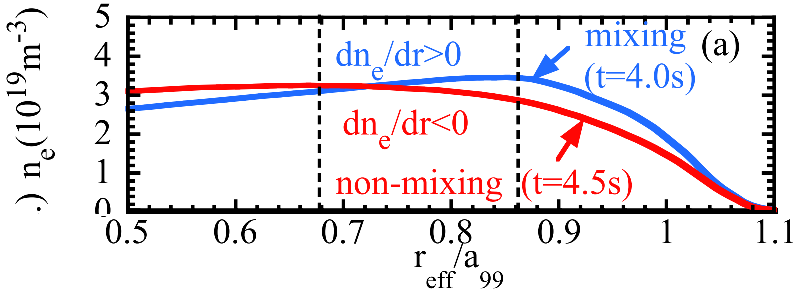
Impact of density gradient on isotope mixing and non-mixing

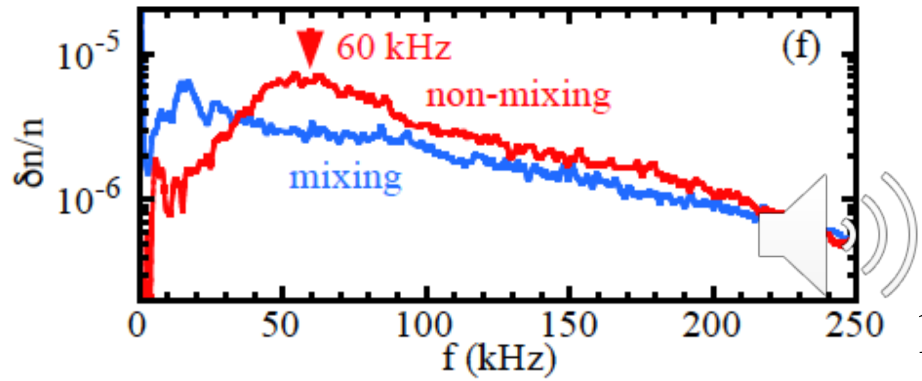
Faster density ramp-up → isotope mixing → No 60 kHz fluctuation peak is observed

Slower density ramp-up → isotope non-mixing → 60 kHz fluctuation peak appears

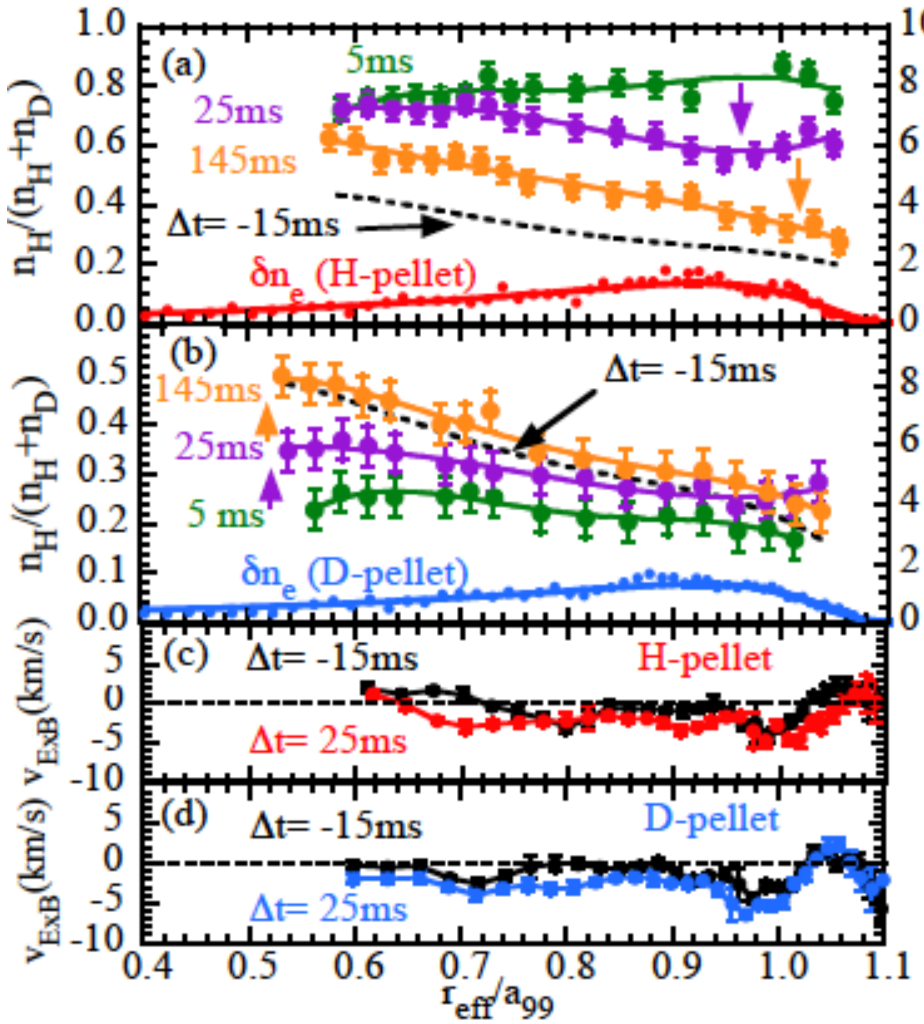






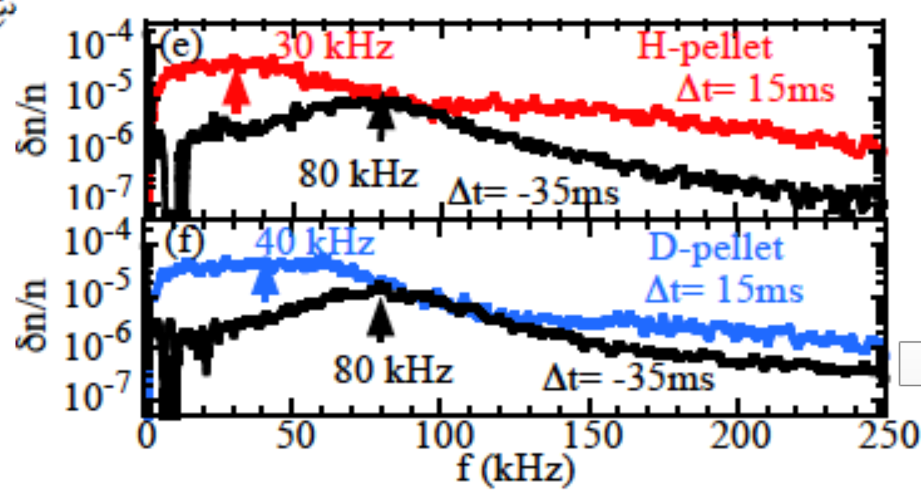


Control of mixing and non-mixing state by H/D pellet injection

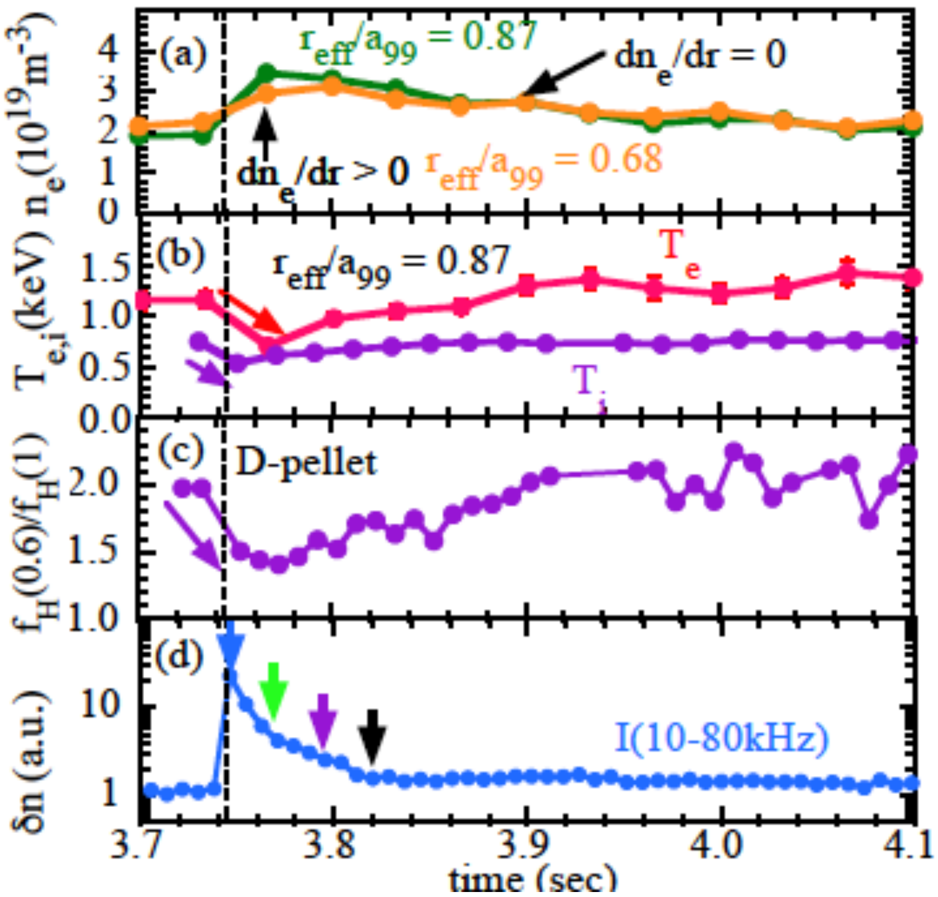


After H-pellet injection
→ Flattening of $n_H/(n_H+n_D)$ profile → mixing
→ 80 kHz fluctuation peak disappears
After D-pellet injection
→ Flattening of $n_H/(n_H+n_D)$ profile → mixing
→ 80 kHz fluctuation peak disappears

ExB flow velocities are almost unchanged



Mixing state after pellet injection is transient

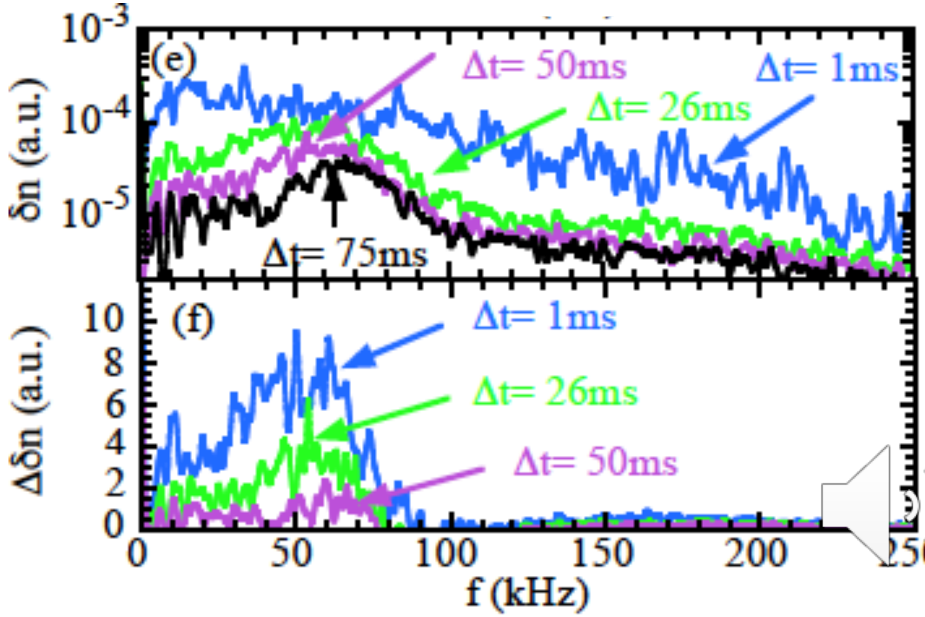


After pellet injection

→ Increase of fluctuation is transient (< 50 ms)

→ The peaking of H-fraction $n_H/(n_H+n_D)$ starts after the decay of density fluctuation

→ Time scale of H-fraction peaking is > 100ms as expected by the beam fueling rate



Summary

Parameter regime for isotope non-mixing and mixing are investigated
Characteristics of density fluctuation in the non-mixing and mixing state are clarified.

Parameters	Non-mixing state	Mixing state
Isotope density ratio	Non-uniform	Uniform
Electron density	$< 2\text{–}3 \times 10^{19}\ \mathrm{m}^{-3}$	$> 2\text{–}3 \times 10^{19}\ \mathrm{m}^{-3}$
Density gradient	$dn_e/dr \leq 0$	$dn_e/dr > 0$
T_e/T_i ratio	Large ($>$1–2)	Small ($<$1–2)
Peak frequency	60–90 kHz	20–40 kHz
Intrinsic toroidal flow	Co-direction	Counter-direction

Stability of micro-instability (linear growth rate) is studied using gyrokinetic code GKV
Strong correlation between TEM and non-mixing state is suggested

	Non-mixing state	Mixing state
Edge $r_{\mathrm{eff}}/a_{99} = 0.9$	TEM destabilized	TEM stabilized
Core $r_{\mathrm{eff}}/a_{99} = 0.5$	ITG destabilized	ITG destabilized