Study of boundary diffusion via density fluctuation measurement using the FIReTIP system on NSTX*

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Abstract

The Far Infra Red Tangential Interferometry/Polarimetry (FIReTIP) system on the National Spherical Torus Experiment (NSTX) measured boundary density fluctuations with upgraded time resolution up to 3.3 MHz in 2009. The density fluctuation level compared with the energy confinement from EFIT showed agreement with the turbulence induced diffusion coefficient which was recently introduced [1]. According to the gyrocenter shift theory, the plasma diffusion at the boundary is dependent on the density fluctuation level and the density fluctuation level is dependent on the Reynolds number of the poloidal ion gyrocenter drift arising from collisions with boundary neutrals. FIReTIP density fluctuation data are also compared with various plasma parameters which determine the Reynolds number such as the radial electric field and plasma temperature in the vicinity of separatrix for the study of the L\H transition mechanism.

[1] K. C. Lee, Plasma Phys. Control. Fusion, Vol. 51, 065023 (2009)

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Abstract of [K.C. Lee, PPCF, 51, 065023, 2009]

momentum exchange of ion-neutral collision (charge exchange)
is an important source of radial current → explanation of E_r formation

turbulence mixture of plasma and neutral forms microscopic $\tilde{E}xB$ flow
$\tilde{E}xB$ flow : cross field circulation → explanation of turbulence diffusion

poloidal flow (velocity: v*) of ion induces friction with stationary neutrals
high v* → high Reynolds number → turbulence → L-mode
low v* → low Reynolds number → laminar flow → H-mode

poloidal momentum balance (Wagner, PPCF 2007)

$$0 = j_r B / n_i - m_i \mu_\theta \upsilon_{\theta i} - \underline{m_i \nu_n \upsilon_{\theta i}} + m_i \partial/\partial r (\langle \tilde{\upsilon}_{ri} \cdot \tilde{\upsilon}_{\theta i} \rangle)$$

↓

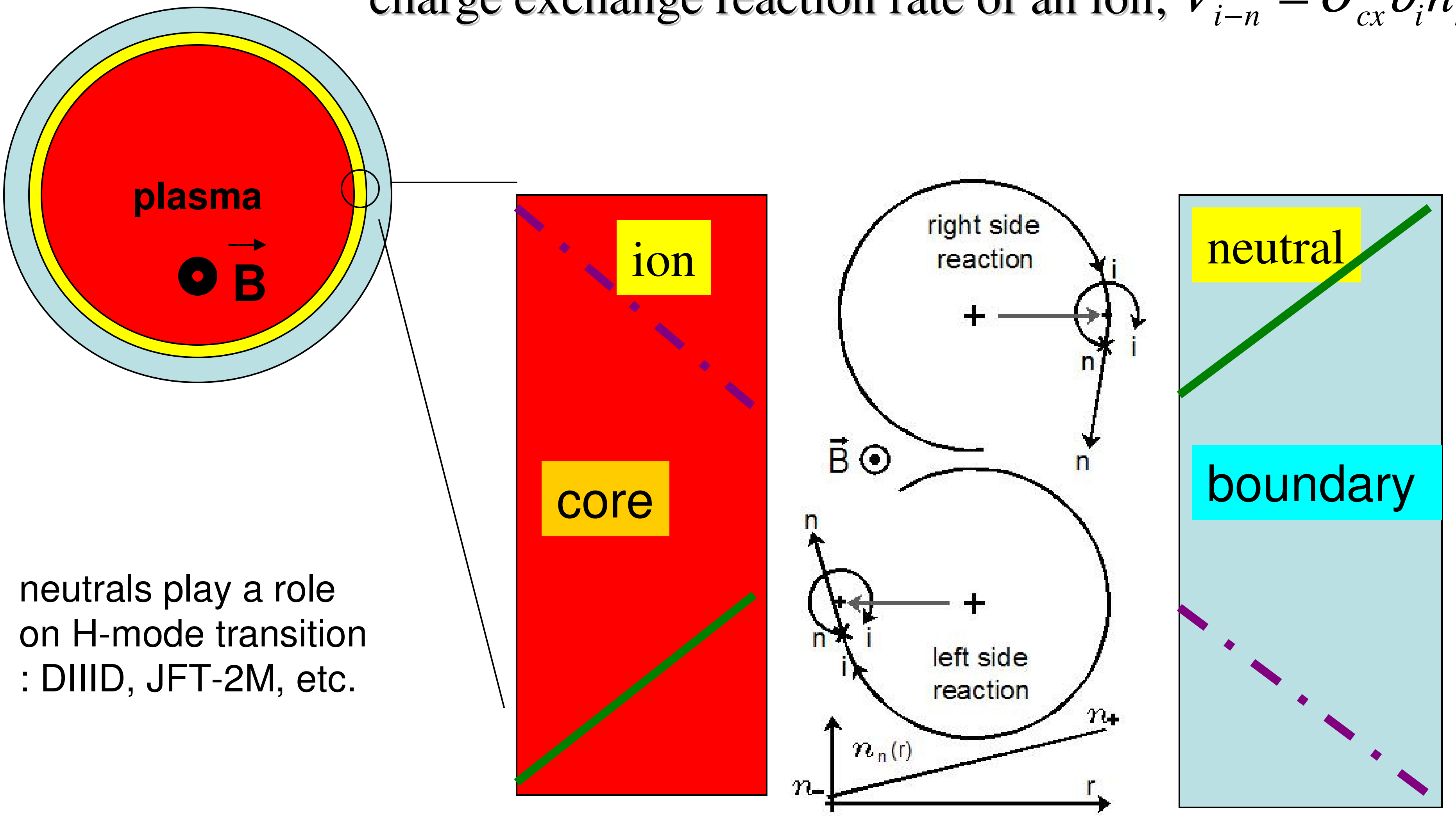
E_r formation: Gyro-Center Shift (GCS)
(Lee, PoP 2006)

turbulence diffusion by GCS

H-mode transition by GCS

Gyrocenter shift due to charge exchange

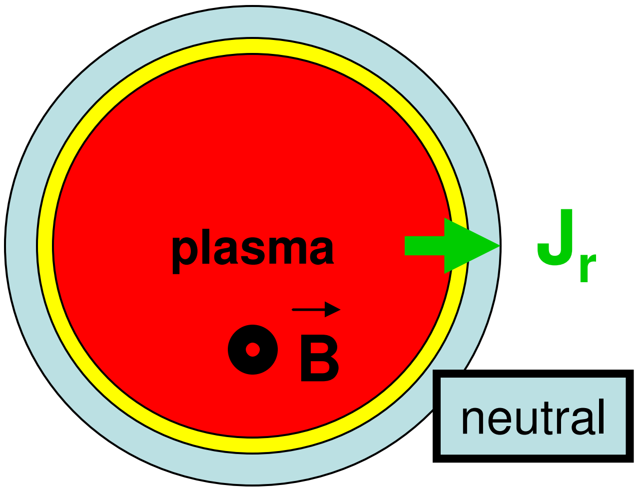
charge exchange reaction rate of an ion; $\nu_{i-n} = \sigma_{cx} v_i n_n$



neutrals play a role
on H-mode transition
: DIIID, JFT-2M, etc.

Introduction to gyrocenter shift

momentum exchange of ion-neutral collisions → J_r
(charge exchange / elastic scattering)



$$J \times B = n_i \nu_{i-n} S_i^m$$

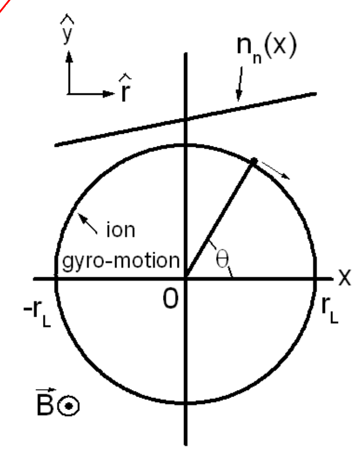
$$J_r^{GCS} = \frac{n_i \sigma_{cx} v_{i\perp} n_n}{B} m_i \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n}\right)$$

v*

$$v_{E\times B} = \frac{E}{B}$$

$$v_D = -\frac{1}{eBn_i}\frac{\partial P_i}{\partial r}$$

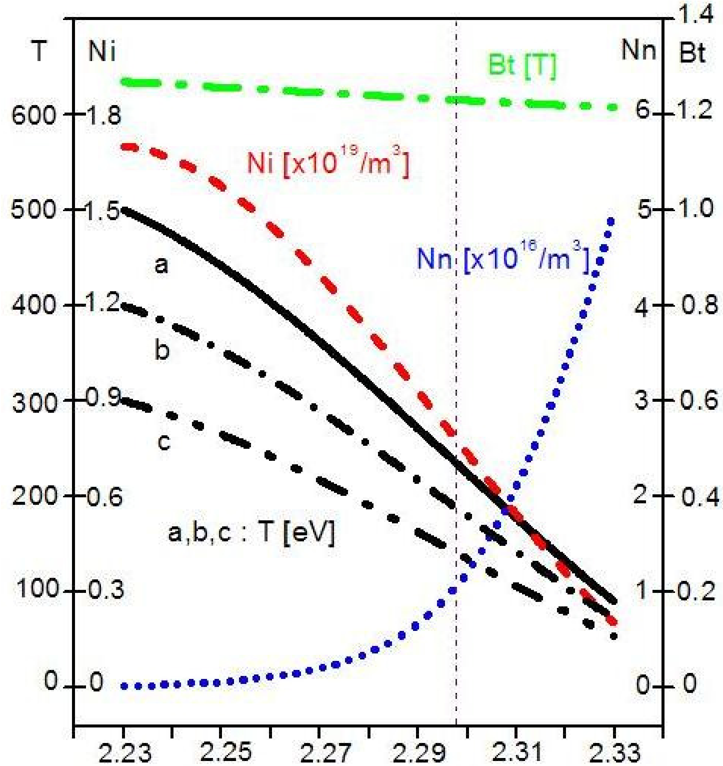
ExB drift is in opposite direction
=> return current (E_r saturation)



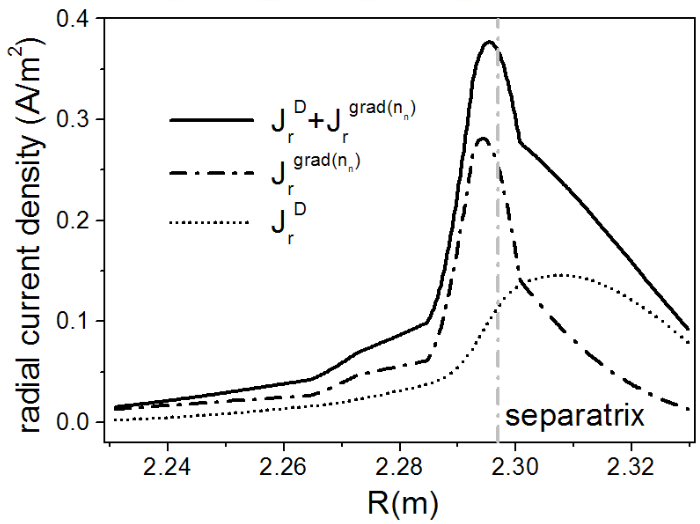
$$v_{av}^* = \frac{\sigma_{cx} v_{i\perp} \oint \vec{v}_{i\perp}(\theta) n_n(\theta) d\theta}{\sigma_{cx} v_{i\perp} \oint n_n(\theta) d\theta} = \frac{1}{2} r_{Li} v_{i\perp} \frac{1}{n_n}\frac{\partial n_n}{\partial r}$$

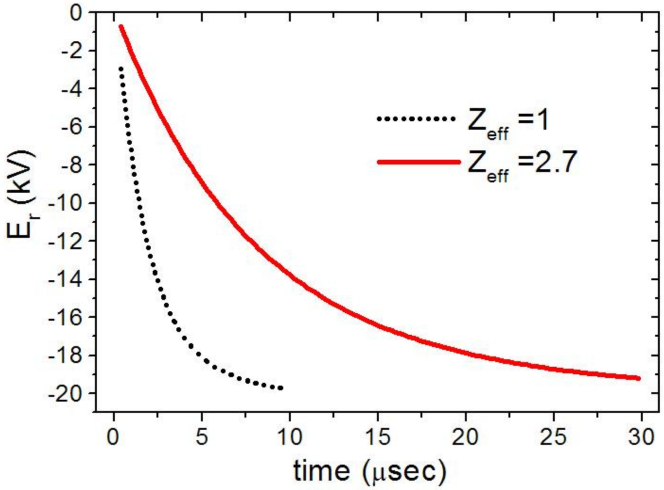
DIII-D example E_r calculation

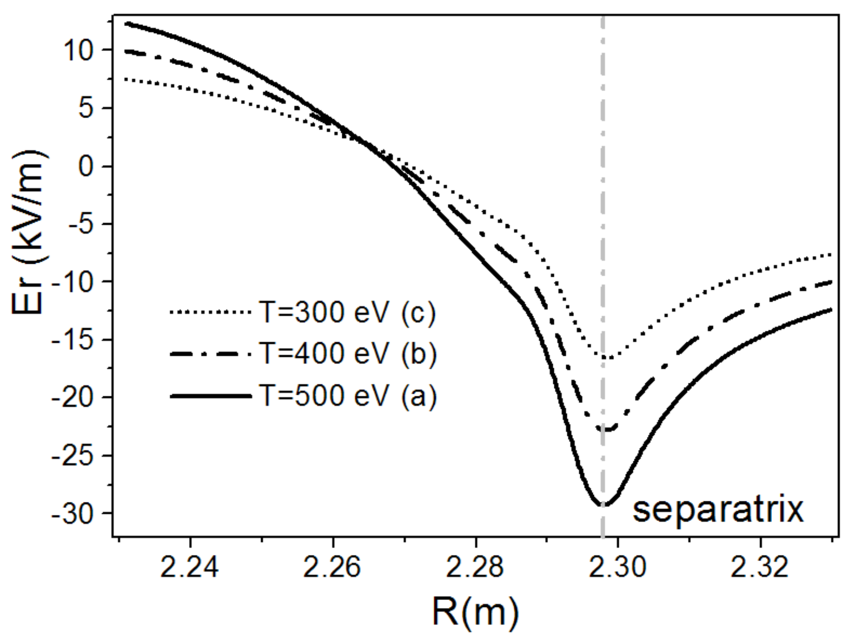
$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB} \frac{\nabla P_i}{n_i} + \frac{kT_i}{eB} \frac{\nabla n_n}{n_n} \right)$$



(Carreras, etc., PoP 98')

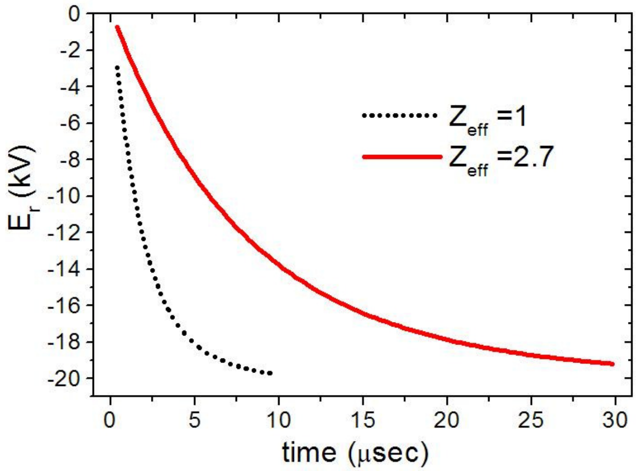






Turbulence induced diffusion and E_r saturation condition of GCS

$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB} \frac{\nabla P_i}{n_i} + \frac{kT_i}{eB} \frac{\nabla n_n}{n_n} \right)$$

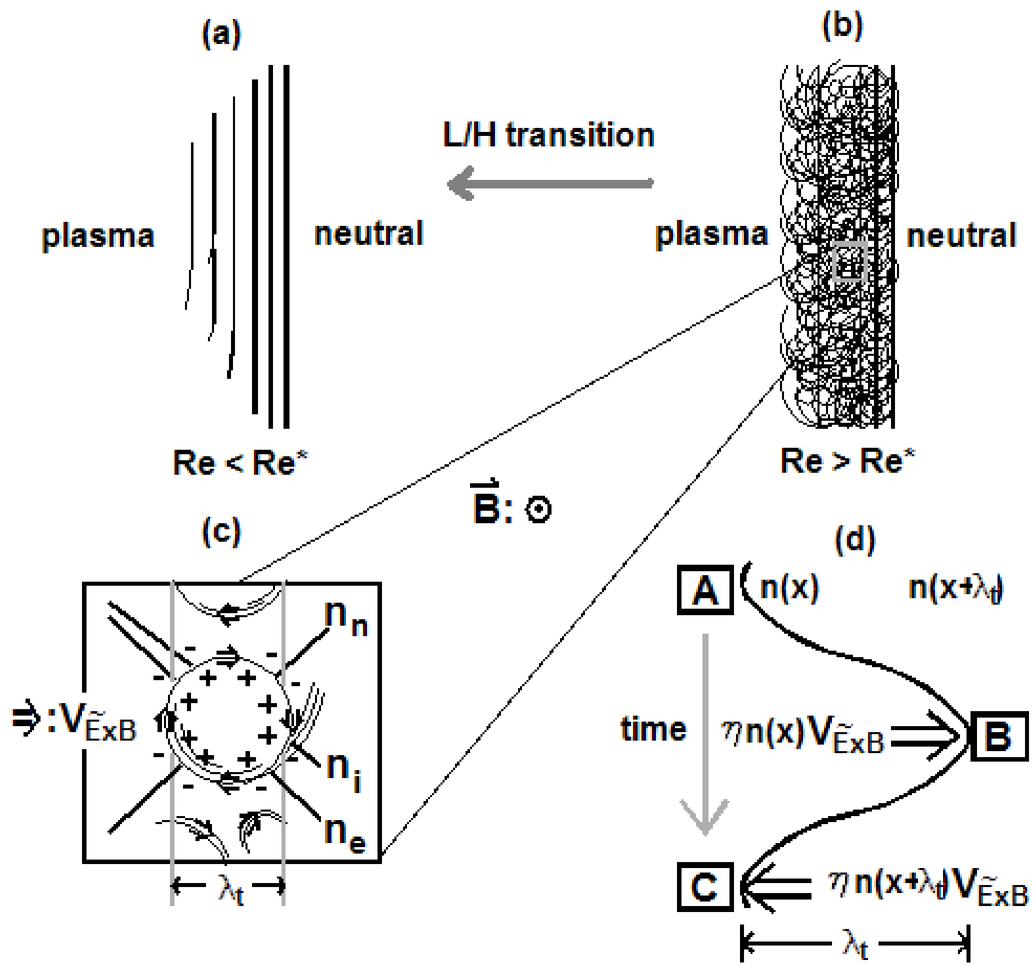


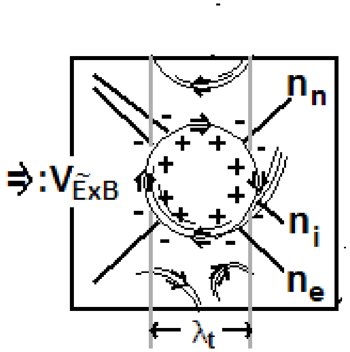
► J_r and E_r saturate before J_r=0

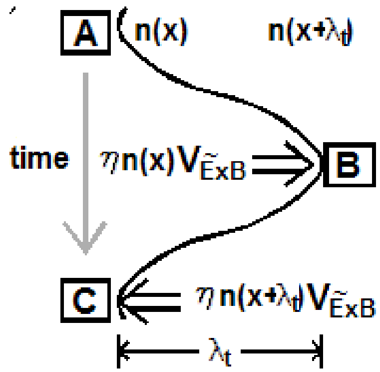
► E_r saturates when ion movement is same as electron movement (ambipolar electric field => classical diffusion)

► only for ideal case of no density fluctuation

► turbulence induces real condition of E_r saturation







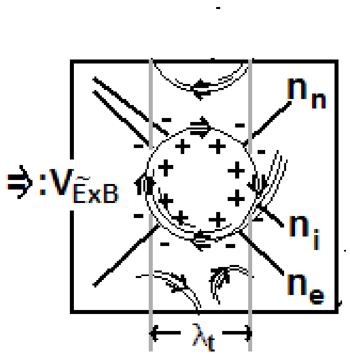
Turbulence induced diffusion of particles

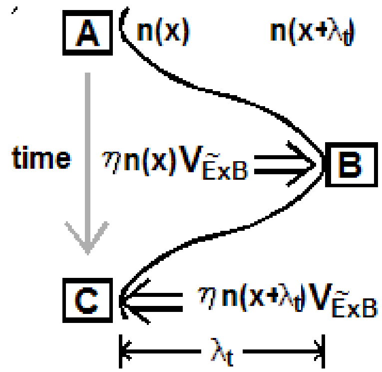
$$\eta \equiv \frac{\tilde{n}}{n}, \quad n' \equiv \frac{\partial n}{\partial x} < 0$$

	x	$x+\lambda_t$
[A]	$n_{i,e}(x) \equiv n_{i,e}$	$n_{i,e}(x+\lambda_t) = n_{i,e} + \lambda_t n'_{i,e}$
[B]	$n_{i,e} - \eta n_{i,e}$	$n_{i,e} + \lambda_t n'_{i,e} + \eta n_{i,e}$
[C]	$n_{i,e} - \cancel{\eta n_{i,e}} + \cancel{\eta n_{i,e}} + \eta\lambda_t n'_{i,e} + \cancel{\eta^2} n_{i,e}$ $\approx n_{i,e} + \eta\lambda_t n'_{i,e} = n_{i,e}(x) + \eta\lambda_t n'_{i,e}$	$n_{i,e} + \lambda_t n'_{i,e} + \cancel{\eta n_{i,e}} - \cancel{\eta n_{i,e}} - \eta\lambda_t n'_{i,e} - \cancel{\eta^2} n_{i,e}$ $\approx n_{i,e} + \lambda_t n'_{i,e} - \eta\lambda_t n'_{i,e} = n_{i,e}(x+\lambda_t) - \eta\lambda_t n'_{i,e}$

► net movement of one cycle is $\eta\lambda_t \nabla n$: same result from L-R-L and R-L-R cycles

► diffusion takes place from high density region to low density region





Turbulence induced diffusion of charge

$$\eta \equiv \frac{\tilde{n}}{n}, \quad n' \equiv \frac{\partial n}{\partial x} < 0$$

	x	$x+\lambda_t$
[A]	$\rho(x) = e(n_i - n_e) \equiv \rho$	$\rho(x+\lambda_t) = \rho + \lambda_t e(n_i' - n_e')$
[B]	$\rho - \eta\rho$	$\rho + \lambda_t e(n_i' - n_e') + \eta\rho$
[C]	$\rho(x) + \eta\lambda_t e(n_i' - n_e')$	$\rho(x+\lambda_t) - \eta\lambda_t e(n_i' - n_e')$

- ► turbulence induced ion and electron diffusion : $\eta\lambda_t\nabla n$
- ► turbulence induced charge diffusion : $-\eta\lambda_t\nabla\rho$
  - ▶ ions and electrons move toward boundary => ***diffusion***
  - ▶ charge (ρ) moves toward core => ***dilution current =>*** ***Saturation by J^{GCS}***

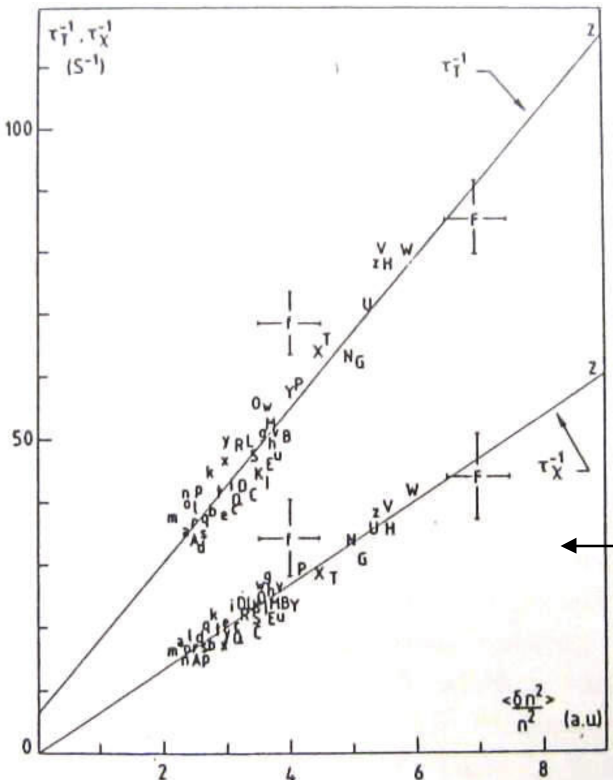
Turbulence induced diffusion coefficient

$$\Gamma = \partial n \cdot \tilde{\upsilon} \quad \rightarrow \quad D = \frac{\eta}{\pi}\frac{\tilde{E}\lambda_t}{B} \quad \rightarrow \quad D = \frac{2}{\pi}\eta^2\frac{kT_e}{eB}$$

$$\partial n \leftarrow \eta\lambda_t\nabla n \qquad \tilde{\upsilon} \leftarrow \frac{1}{\pi}\frac{\tilde{E}}{B}$$

$\tilde{E}\lambda_t \approx 2\eta\frac{kT_e}{e} \leftarrow \left(\frac{e\tilde{\phi}_t}{kT_e} \approx \frac{\tilde{n}_e}{n_e}\right.$: Boltzmann relation, $\left.\tilde{\phi}_t \approx \tilde{E}\frac{\lambda_t}{2}\right)$

$$D = \frac{2}{\pi}\eta^2\frac{kT_e}{eB}$$



$$\frac{\langle \delta n^2 \rangle}{n^2}$$

► $\propto \frac{1}{B_T}$ and similar to Bohm diffusion : $\propto \frac{kT_e}{eB}$

► proportional to η^2: in agreement with experiments

← [TFR group, Nuclear Fusion (1986)]

► characteristics close to “anomalous” diffusion

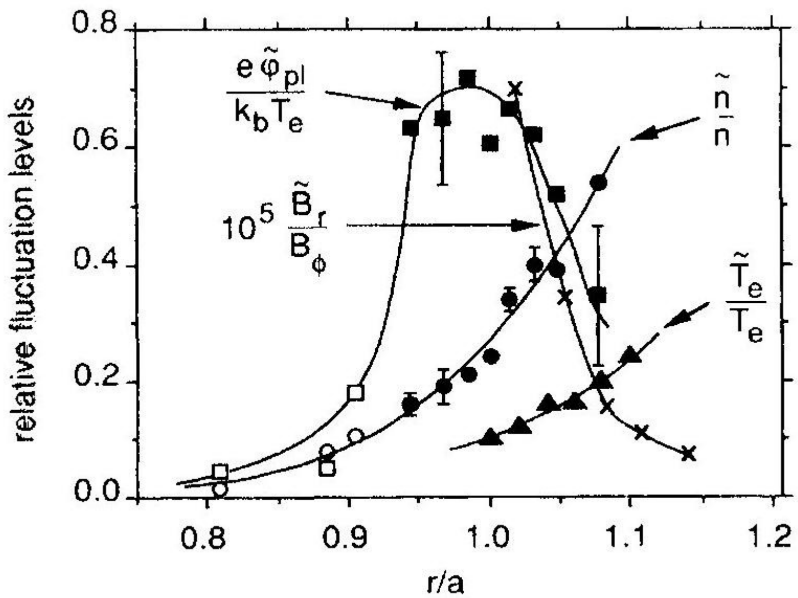
Modified Boltzmann relation

$$F = J_i^{GCS} \times B = m_i n_i \nu_{i-n} \left(\frac{\tilde{E}}{B} - \frac{1}{eB} \frac{\nabla P_i}{n_i} + \frac{kT_i}{eB} \frac{\nabla n_n}{n_n} \right) \approx 0$$

$$\frac{e\tilde{\phi}_t}{kT_e} \approx \frac{\tilde{n}_e}{n_e}$$

$$e\tilde{E} - kT_i \frac{\nabla n_i}{n_i} + kT_i \frac{\nabla n_n}{n_n} \approx 0$$

$$\left(-\frac{\nabla n_n}{n_n} \approx \frac{1}{L_{\tilde{n}}} \right)$$



[Ritz, TEXT, 1989]

$$\frac{e\tilde{E}}{kT_i} - \frac{1}{L_{\tilde{n}}} = \frac{\nabla n_i}{n_i}$$

$$\frac{\tilde{n}}{n} = \frac{e\tilde{E}\lambda_t}{2kT_i} - \frac{\lambda_t}{2L_{\tilde{n}}}$$

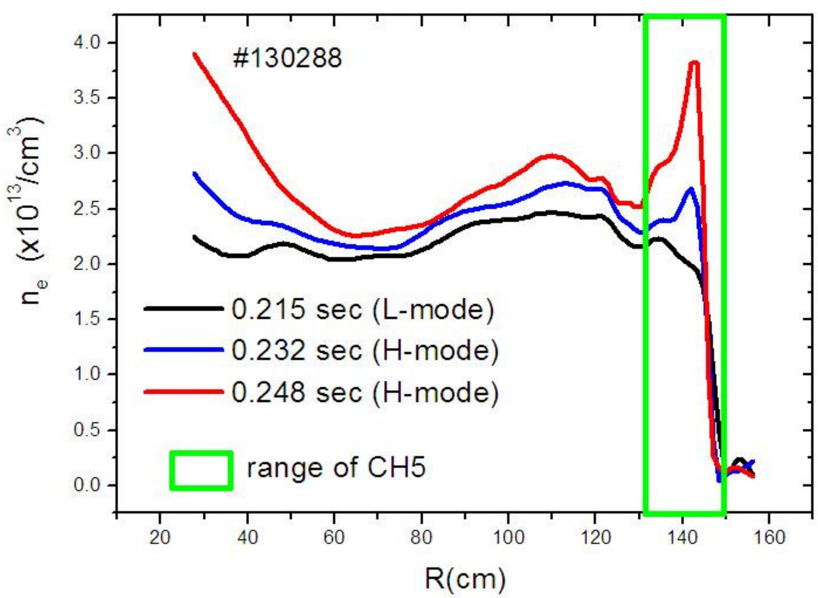
$$D = \frac{2}{\pi}\eta\left(\eta + \frac{\lambda_t}{2L_{\tilde{n}}}\right)\frac{kT_i}{eB}$$

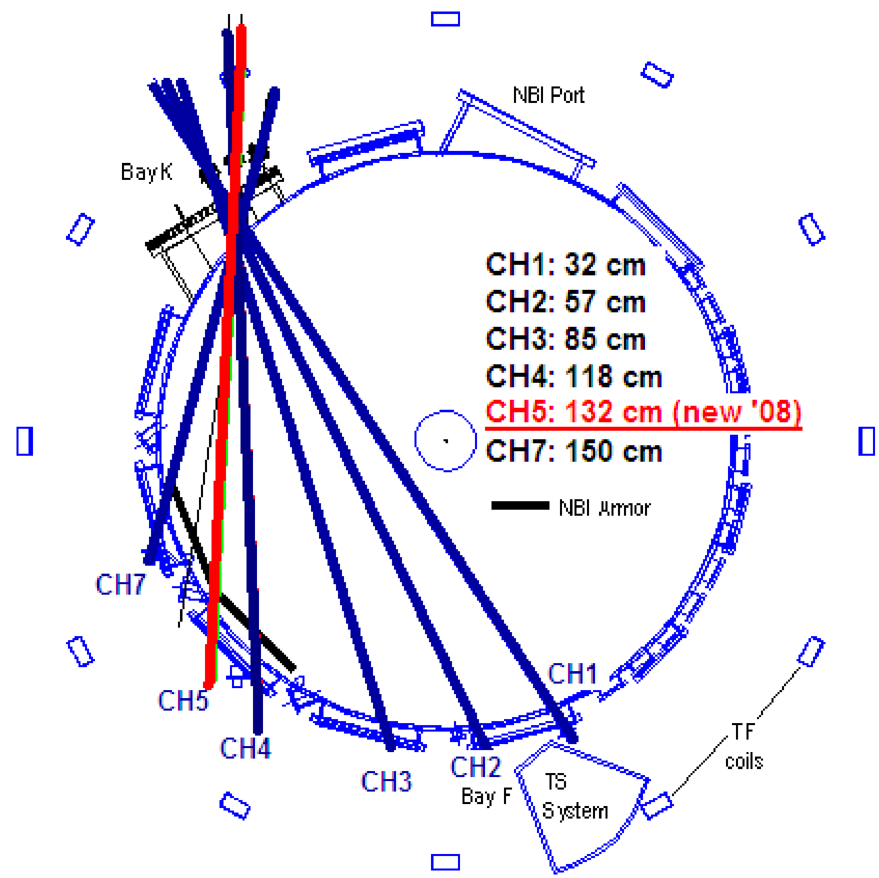
$\frac{\tilde{n}}{n}$ Measurement (FIReTIP) vs. Confinement (EFIT)

$$D = \frac{2}{\pi}\eta^2 \frac{kT_e}{eB}, \qquad \eta \equiv \frac{\tilde{n}}{n}$$

$\tau_E \sim 1/D$

Thomson Scattering



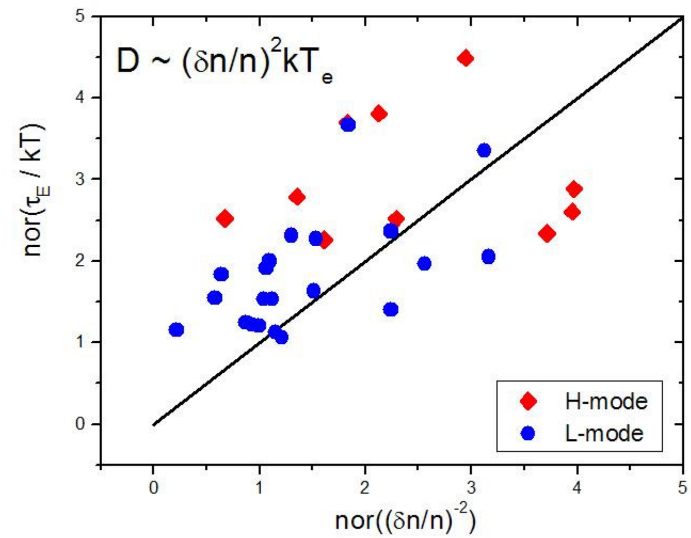


2008 Data NSTX

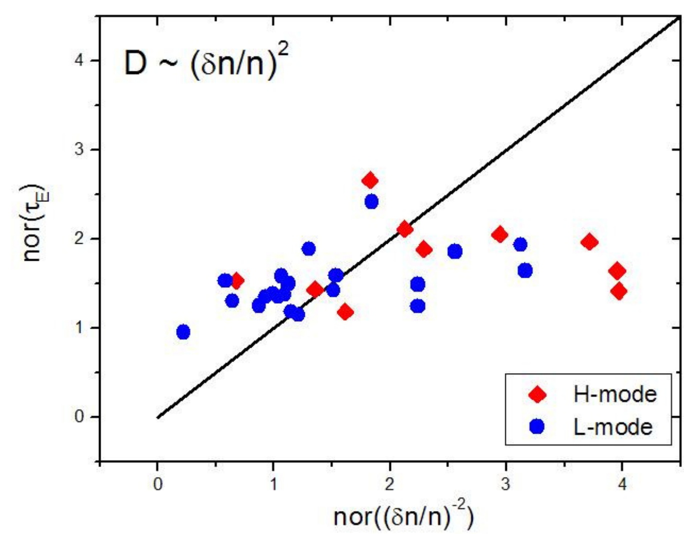
$$D = \frac{2}{\pi}\eta^2 \frac{kT_e}{eB}$$

nor(f)≡ f(t)/f(t_0)
t, t_0: different times in a same shot

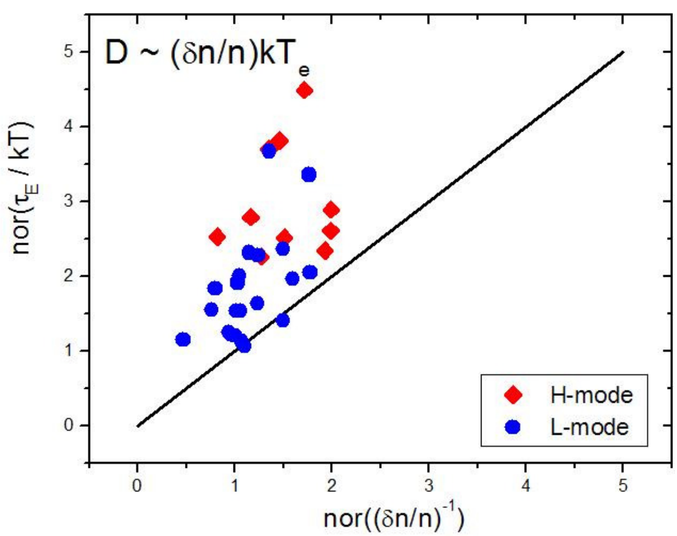
τ_E with η^2 : including T_e effect



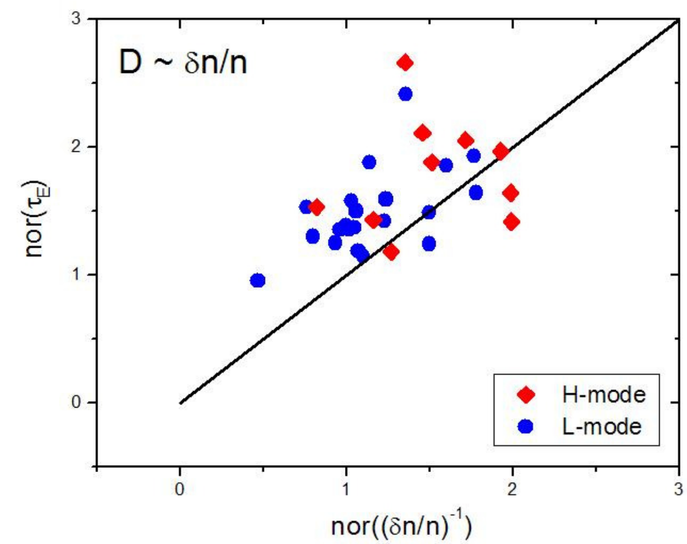
τ_E with η^2 : no T_e effect



τ_E with η : including T_e effect



τ_E with η : no T_e effect

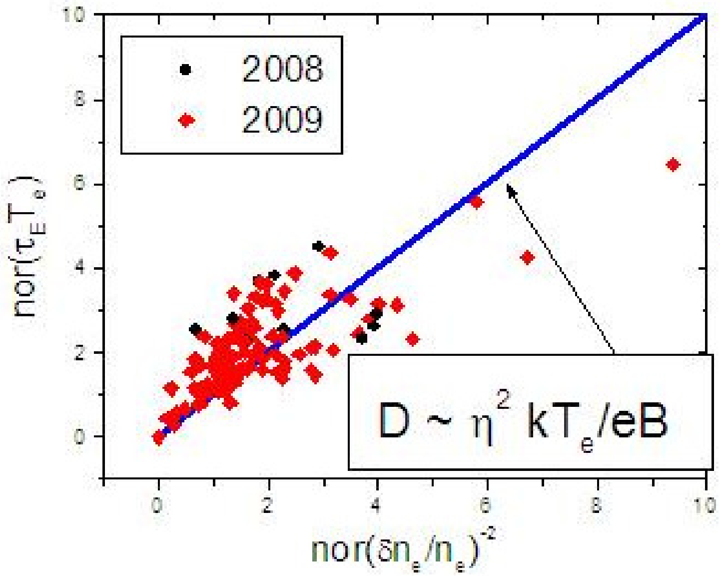


2008
+2009
Data
NSTX

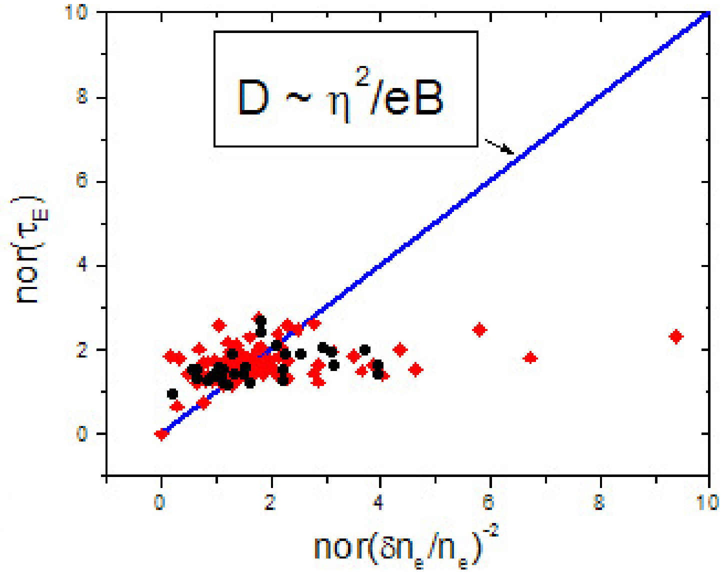
$$D = \frac{2}{\pi}\eta^2 \frac{kT_e}{eB}$$

$nor(f) \equiv f(t)/f(t_0)$
t, t_0: different times in a same shot

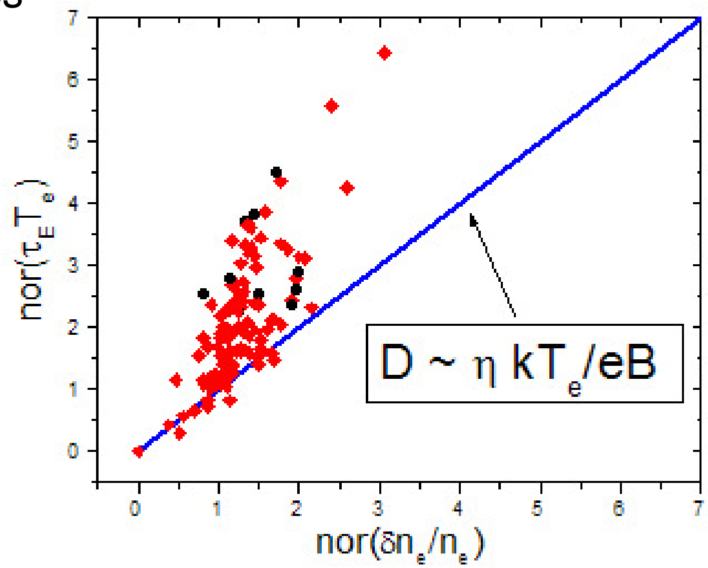
τ_E with η^2 : including T_e effect



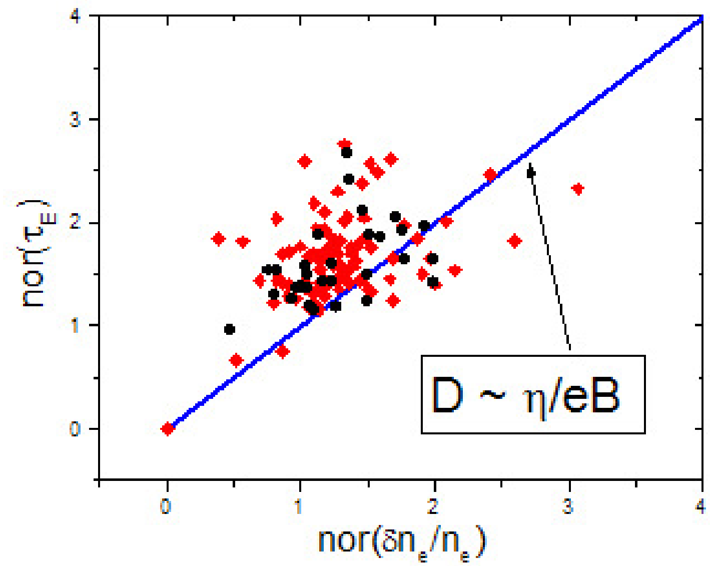
τ_E with η^2 : no T_e effect



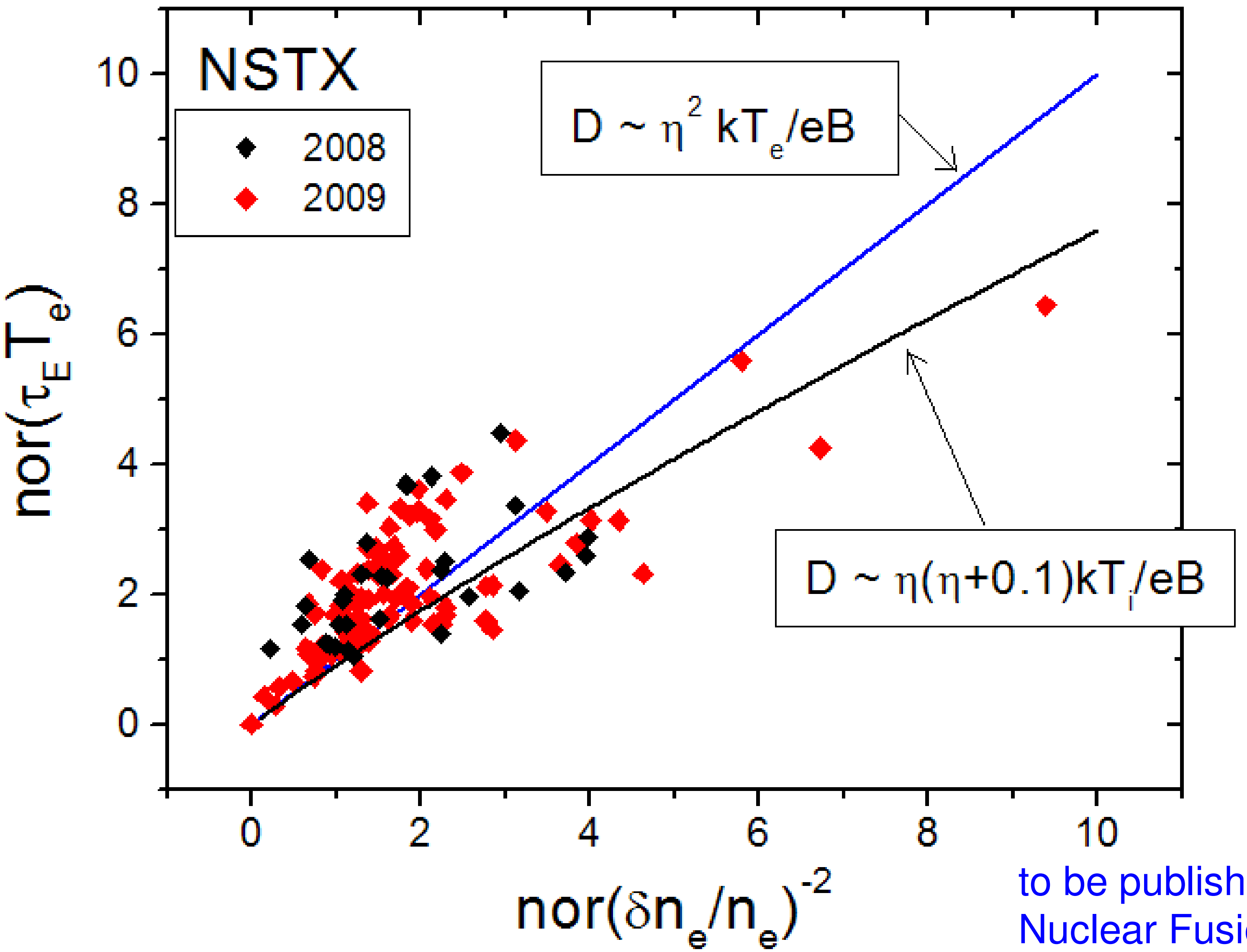
τ_E with η : including T_e effect



τ_E with η : no T_e effect



$$D = \frac{2}{\pi}\eta^2 \frac{kT_e}{eB}, \quad \text{or} \quad D = \frac{2}{\pi}\eta(\eta + \frac{\lambda_t}{2L_{\tilde{n}}})\frac{kT_i}{eB} \quad ?$$



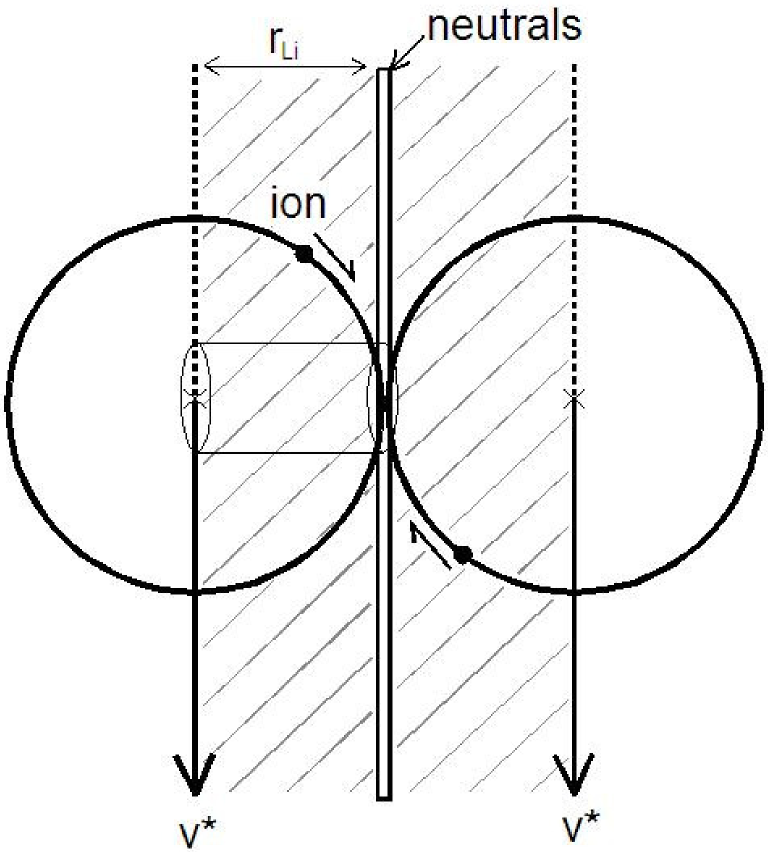
to be published
Nuclear Fusion (2009)

Turbulence

- ions and electrons move toward boundary => ***diffusion***
- charge (ρ) moves toward core => ***dilution current =>*** ***saturation condition***

$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n} \right)$$

v*



Inertia force

$$\mathrm{Re} \equiv \frac{n_i m_i \upsilon^{*2} / r_{Li}}{n_i m_i \nu_{i-n} \upsilon^*} = \frac{eB}{kT_i} \lambda_{i-n} \upsilon^*$$

viscosity force

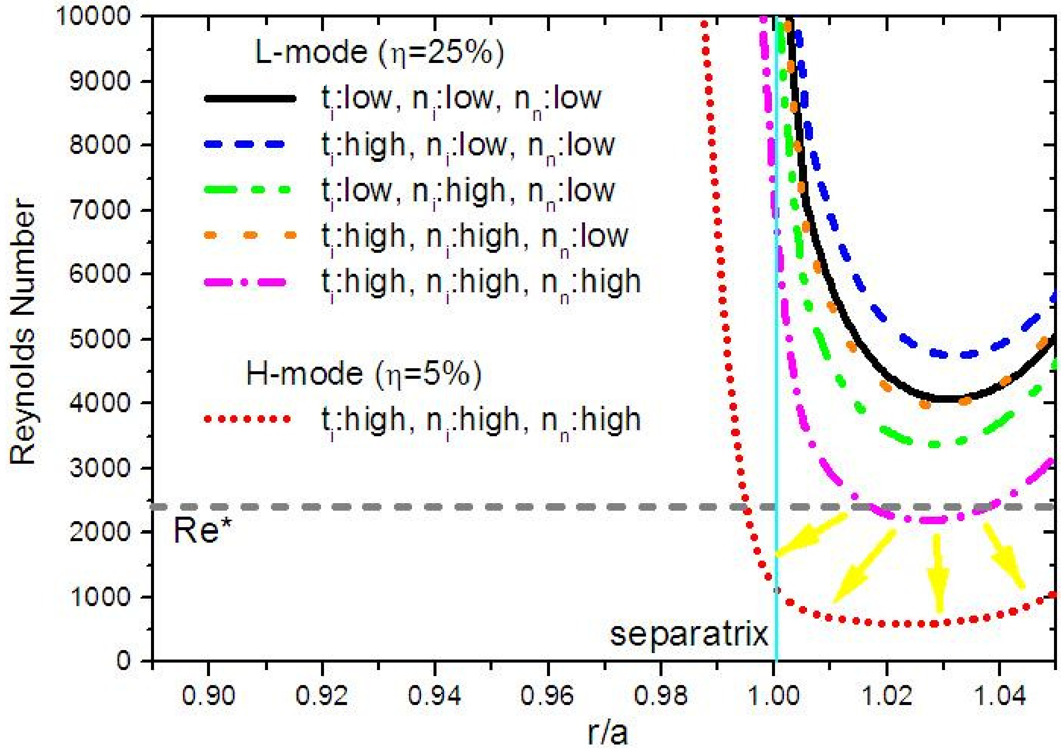
$$\mathrm{Re} = \frac{eB}{kT_i} \lambda_{i-n} \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n} \right)$$

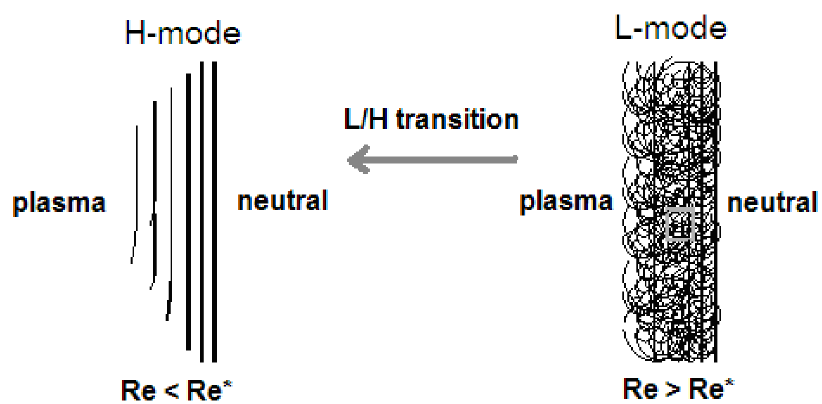
(saturation condition : $J_r^{GCS} = D \nabla \rho$)

Reynolds number of ion-neutral collision

$$\mathrm{Re} = \frac{2}{\pi} \eta^2 \frac{B}{m_i n_i (\sigma_{i-n} n_n)^2 \upsilon_\perp} \nabla \rho$$

L/H transition by critical Reynolds number





$$Re = \frac{2}{\pi}\eta^2 \frac{B}{m_i n_i (\sigma_{i-n} n_n)^2 \upsilon_\perp} \nabla\rho$$

- ► Re > Re* : turbulent flow
  Re < Re* : laminar flow

  (Re*~2400)

- ► turbulent flow (L-mode): high η
  laminar flow (H-mode): low η

- ► plasma heating & neutrals
  => Reynolds number
  => L/H power threshold

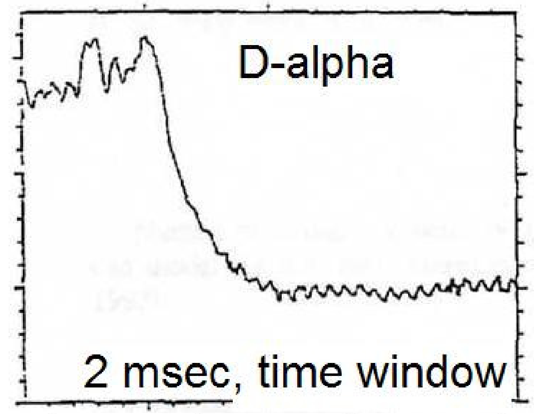
- ► P_{th} dependence on
  neutral density , **isotopes**
  => agrees with experiments

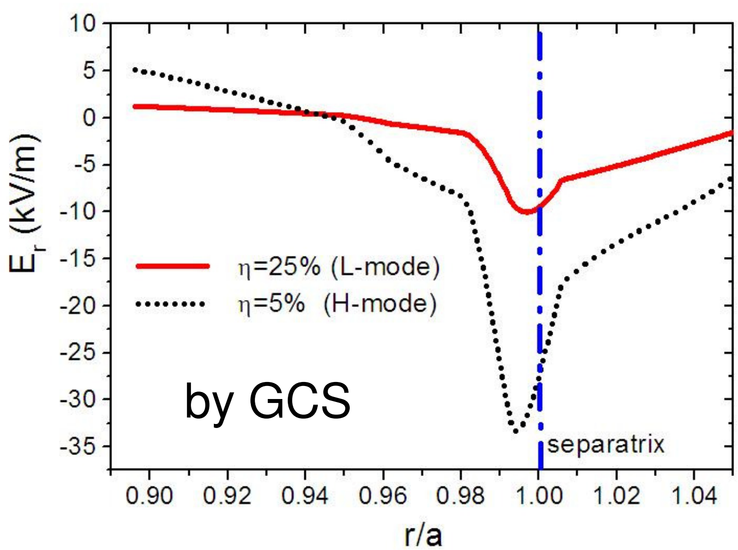
fast and slow changes of H-mode transition

$$\mathrm{Re} = \frac{2}{\pi}\eta^2 \frac{B}{m_i n_i (\sigma_{i-n} n_n)^2 \upsilon_\perp} \nabla \rho$$

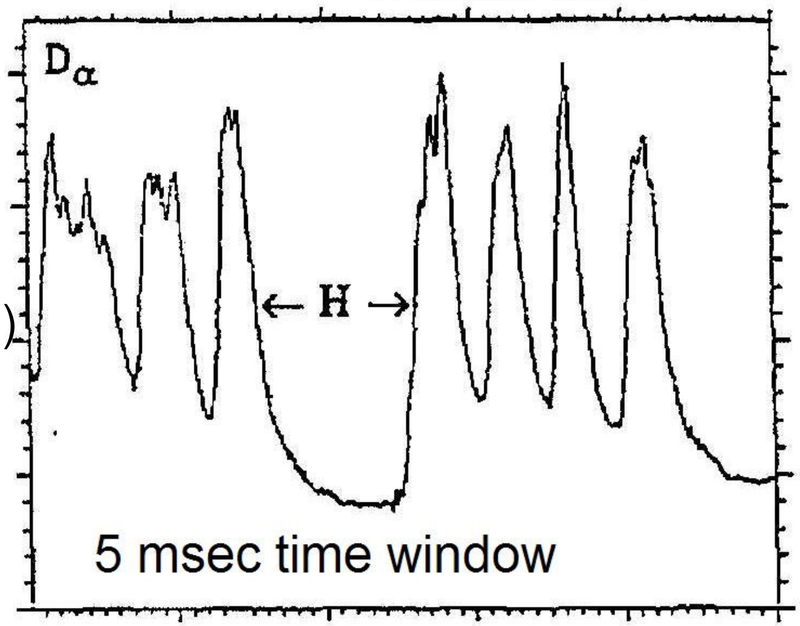
		L-mode	H-mode
fast change (~50 μsec)	η v*(η) E_r	high high low	low => Re ↓ low => Re ↓ high => Re ↑ (deeper saturation)
slow change (~ msec)	$\nabla P, \nabla n_n$ E_r	low low	high ⌉ => Re ↑ High ⌋ back transition

clear H-mode





dithering H-mode, (Holzhauer, etc,PPCF,94') ASDEX

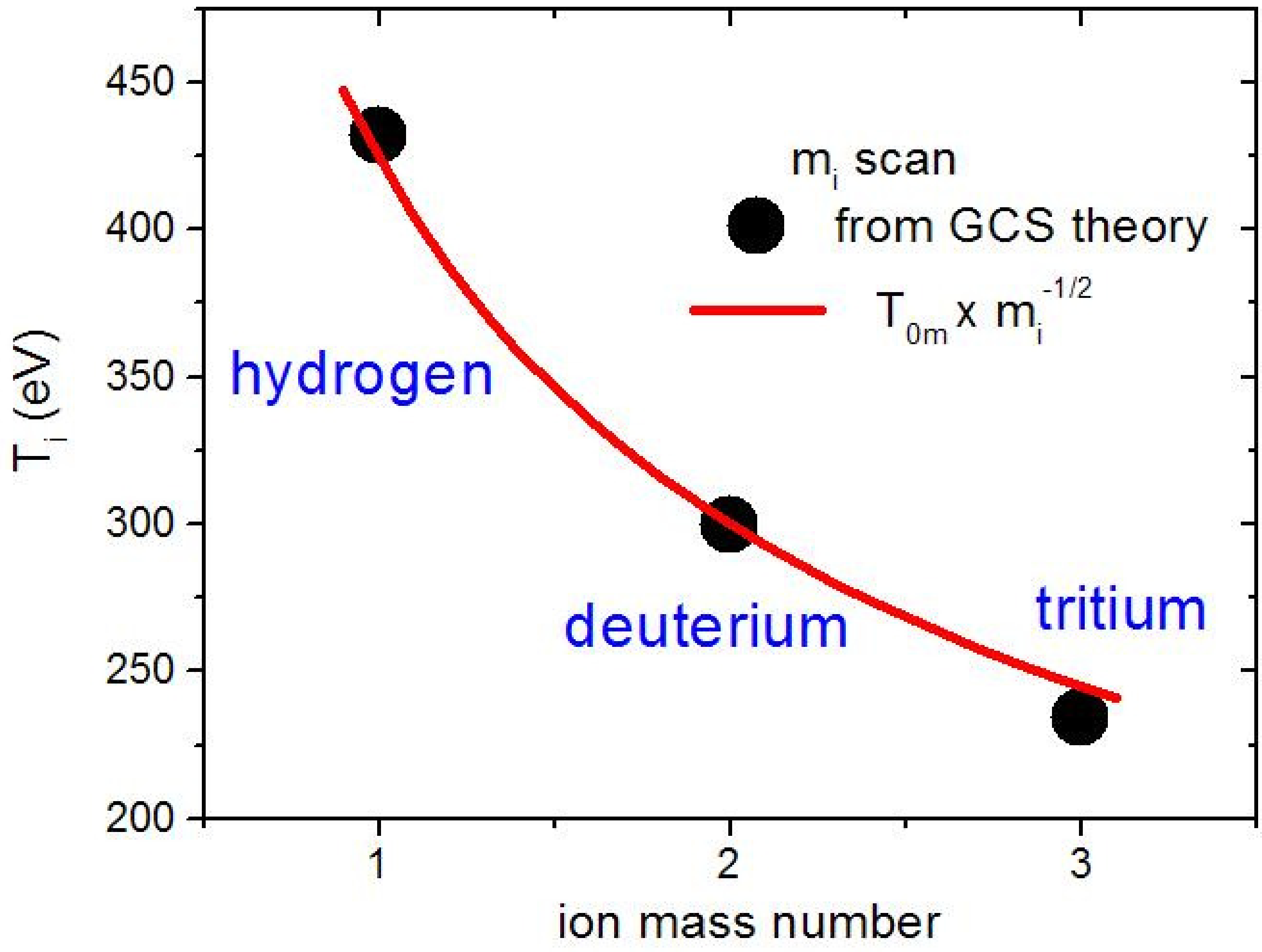


Isotopes difference in H-mode access by GCS

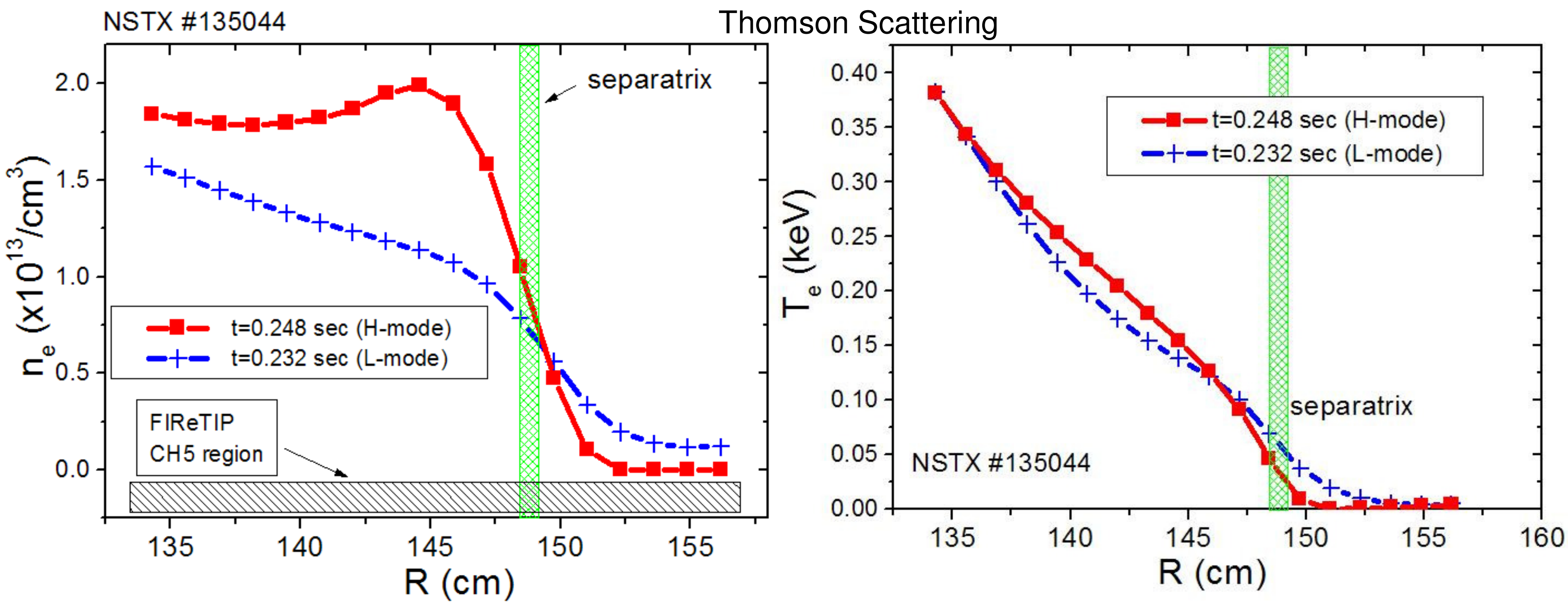
$$\mathrm{Re} = \frac{2}{\pi}\eta^2 \frac{B}{m_i n_i (\sigma_{i-n} n_n)^2 \upsilon_\perp} \nabla\rho$$

(Re -> Re*~2400)

Required T_i for Re*



Analysis of T_e & n_e profile changes at L/H transition

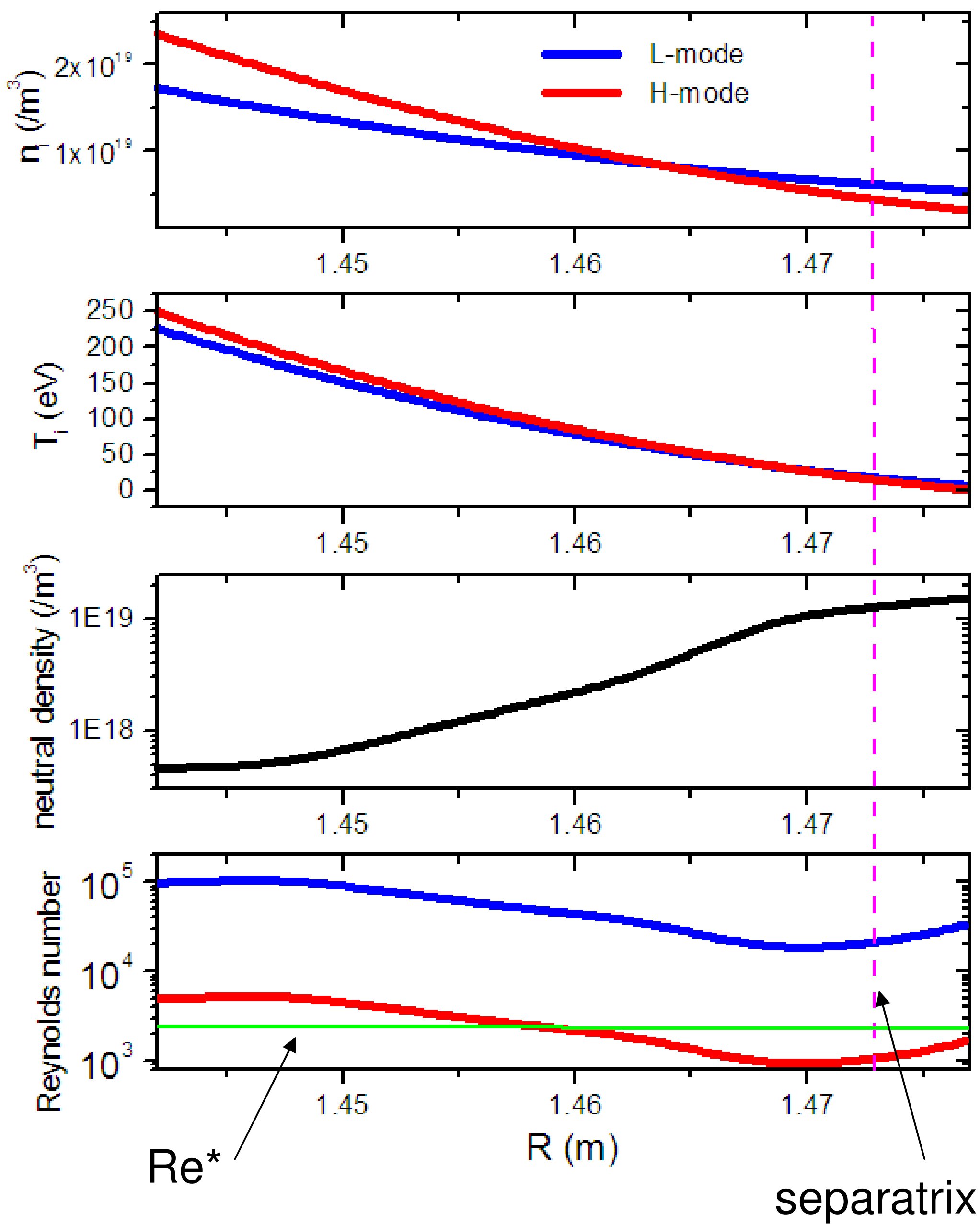


● after L/H transition n_e profile significantly steepens but T_e profile remains unchanged

<= confinement increase by reduction of turbulence diffusion (convective transport)

● around separatrix T_e even decreases after transition <= cooling by neutrals

: keeping H-mode with decreased T_e <= H-mode bifurcation not by T_e but Re



Reynolds number study for NSTX

- **similar case of #135042 (T_e, n_e)**
- neutral density profile is assumed based on the measurement of SOL region : assumed same for L-mode and H-mode for convenience
- Reynolds number calculated from

$$\mathrm{Re} = \frac{eB}{kT_i}\lambda_{i-n}\upsilon^*$$

- typical values of v* are assumed;
  L-mode : v* ~1000 m/sec
  H-mode : v* ~ 50 m/sec
- Reynolds number calculation of H-mode case results below Re* (laminar)

gyrocenter shift

$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB} \frac{\nabla P_i}{n_i} + \frac{kT_i}{eB} \frac{\nabla n_n}{n_n} \right)$$

turbulence diffusion

$$D = \frac{2}{\pi} \eta^2 \frac{kT_e}{eB}$$

Reynolds number of ion-neutral collision

$$\mathrm{Re} = \frac{2}{\pi} \eta^2 \frac{B}{m_i n_i (\sigma_{i-n} n_n)^2 \upsilon_\perp} \nabla \rho$$

Conclusions & future work

● **NSTX FIReTIP density fluctuation measurement showed agreement with GCS theory for the EFIT confinement time dependence on density fluctuation**

: lower density fluctuation case close to Diffusion by conventional Boltzmann relation
higher density fluctuation case close to Diffusion by modified Boltzmann relation

● if the typical values of v* are assumed as L-mode :~1000 m/sec and H-mode : ~50m/sec, calculated Reynolds numbers for NSTX #135042 crosses the critical Reynolds number

● NSTX Reynolds number study with measured E_r profile will be performed when poloidal CHERS is available

● NSTX Reynolds number study with poloidal flow velocity from GPI data is available