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H-mode transition and E_r formation analysis of NSTX based on the gyrocenter shift*

K.C. Lee[1], R.E. Bell[2] , C.W. Domier[1], B.P. LeBlanc[2], S.A. Sabbagh[3], H.K. Park[4], N.C. Luhmann, Jr.[1], R. Kaita[2], and the NSTX Research Team

[1]UC Davis, [2]PPPL, [3]Columbia University, [4]POSTECH

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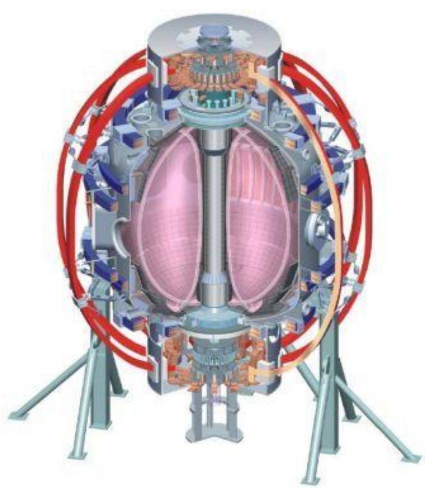

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Abstract of [K.C. Lee, PPCF, 51, 065023, 2009]

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)

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

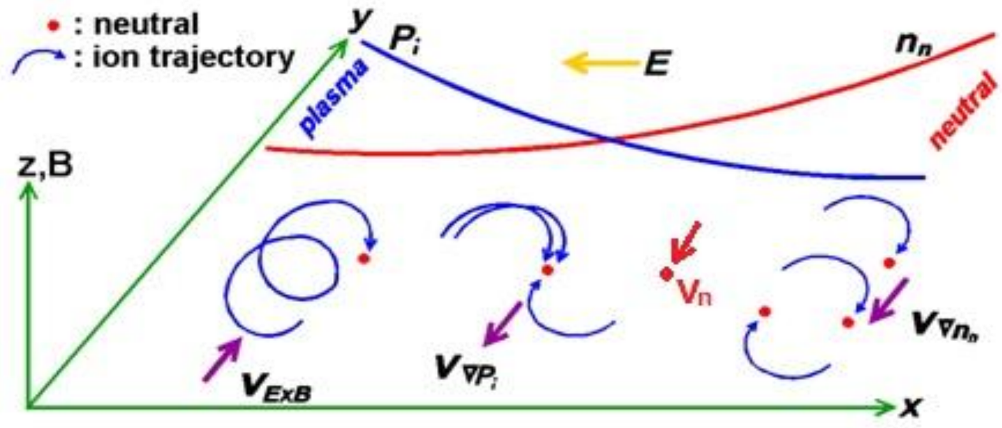
↓

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

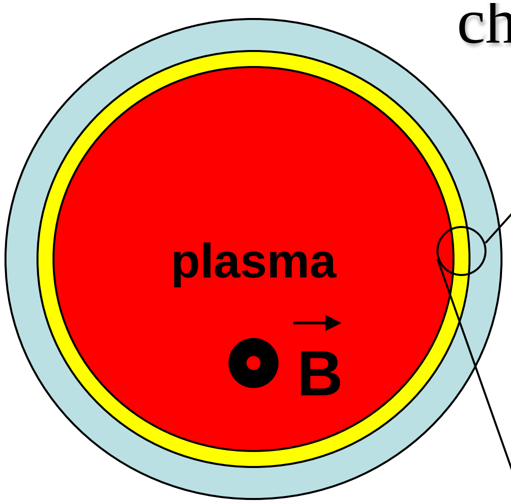
turbulence diffusion by GCS

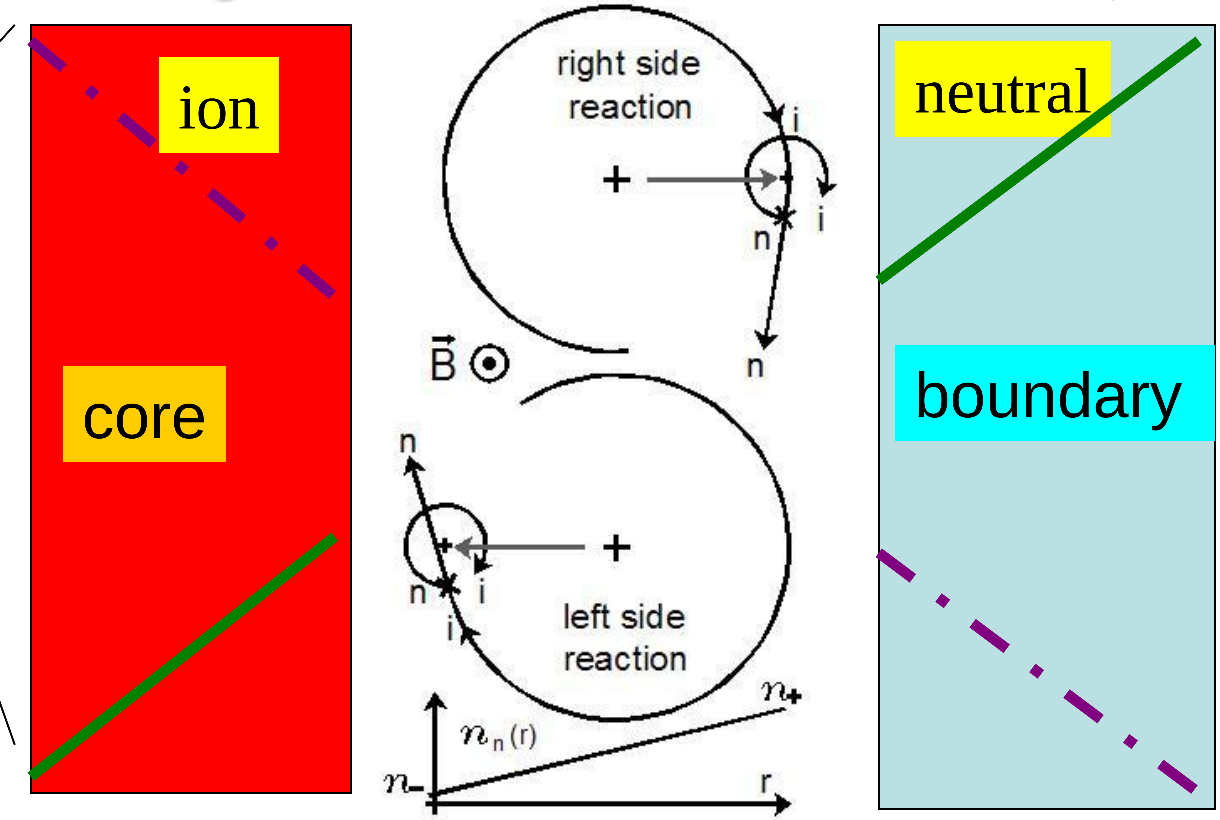
H-mode transition by GCS

Gyrocenter shift due to charge exchange



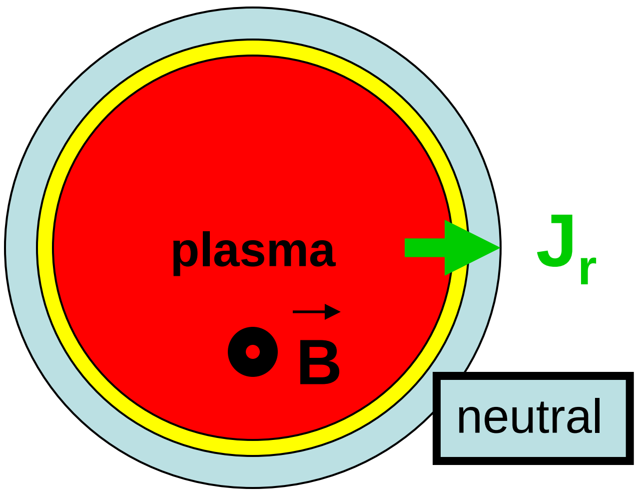
charge exchange reaction rate of an ion; $\nu_{i-n} = \sigma_{cx} \upsilon_i n_n$





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

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



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

neutral velocity

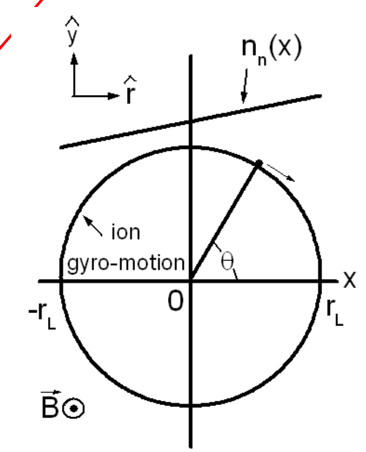
$$J_r^{GCS} = \frac{n_i \sigma_{cx} \upsilon_{i\perp} n_n}{B} m_i \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} - \upsilon_n + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n} \right)$$

v*

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

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

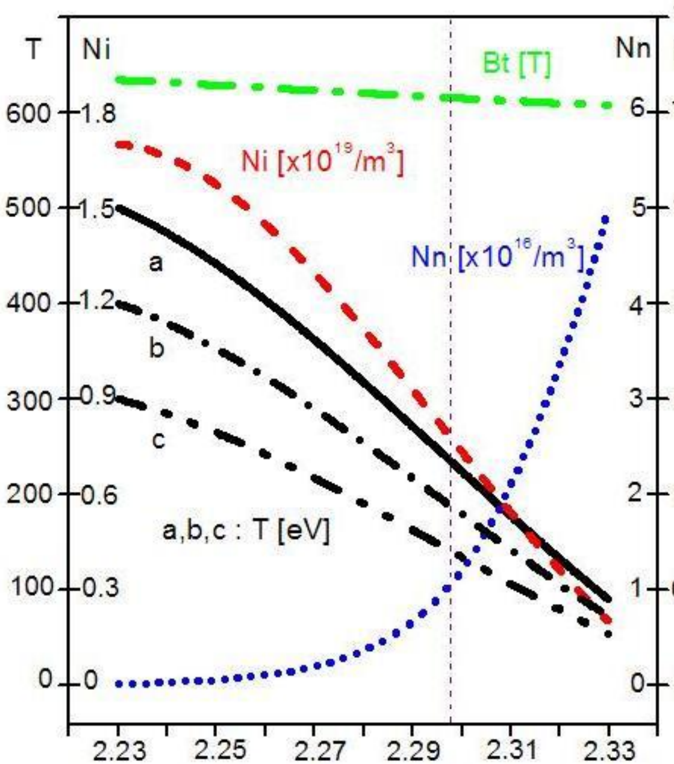
ExB drift is in opposite direction
=> return current (E_r saturation)



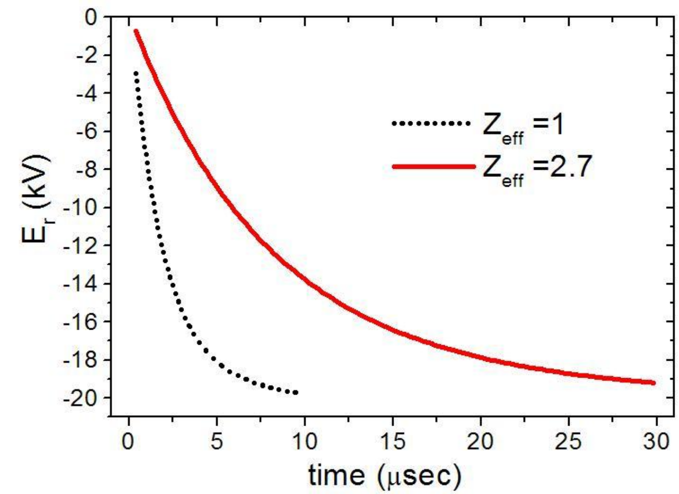
$$\upsilon_{av}^{*} = \frac{\sigma_{cx}\upsilon_{i\perp}\oint \vec{\upsilon}_{i\perp}(\theta) n_n(\theta) d\theta}{\sigma_{cx}\upsilon_{i\perp}\oint n_n(\theta) d\theta} = \frac{1}{2} r_{Li}\upsilon_{i\perp}\frac{1}{n_n}\frac{\partial n_n}{\partial r}$$

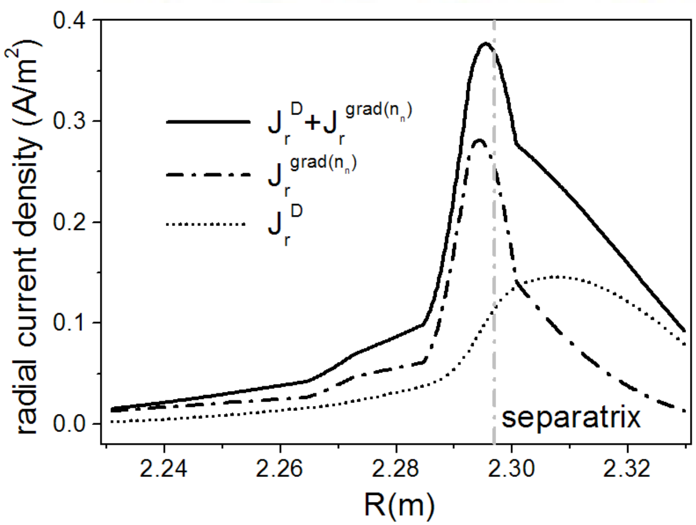
DIII-D example E_r calculation

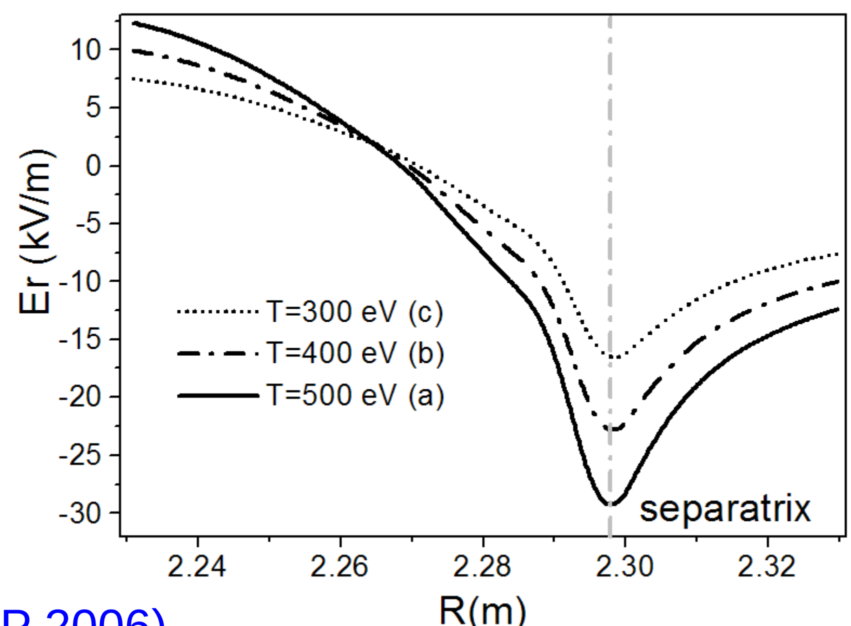
$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n} \right)$$



(Carreras, etc., PoP 98')



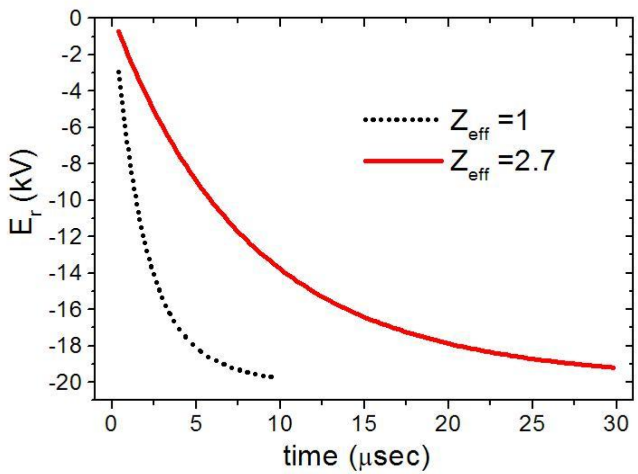




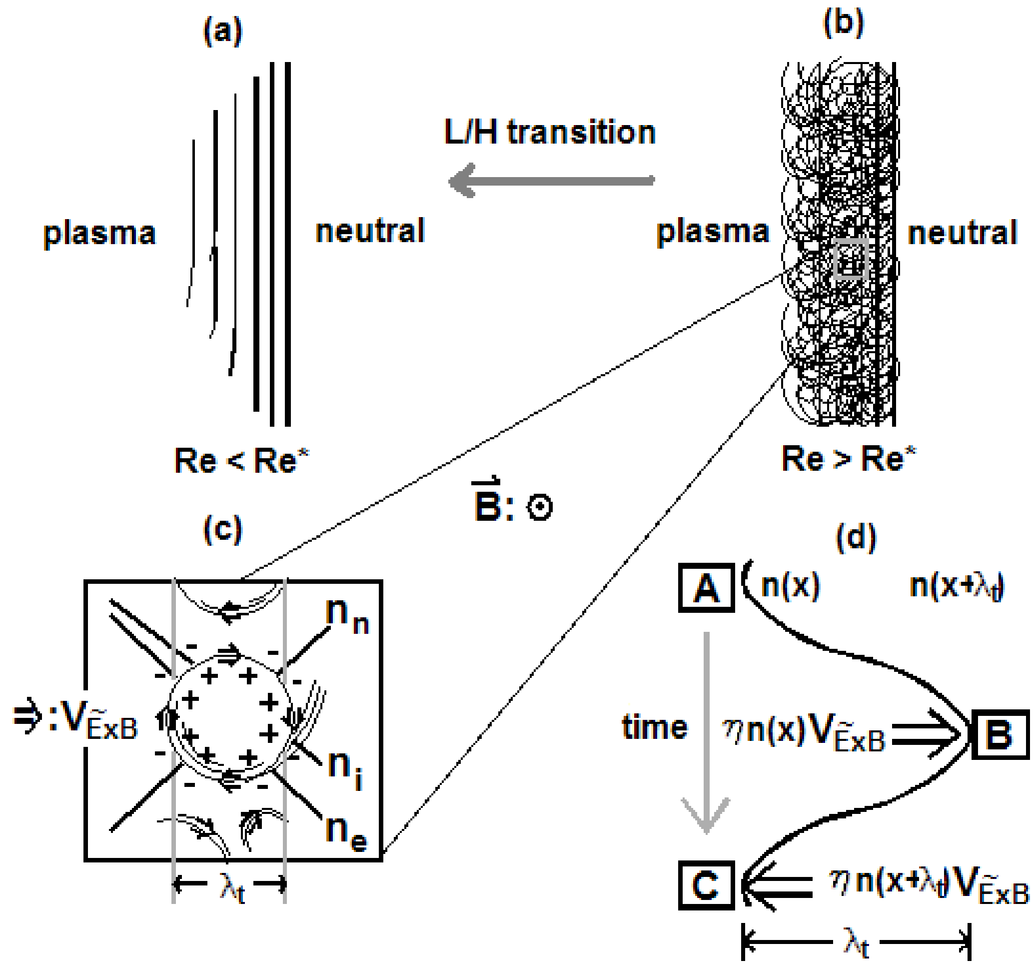
(Lee, PoP 2006)

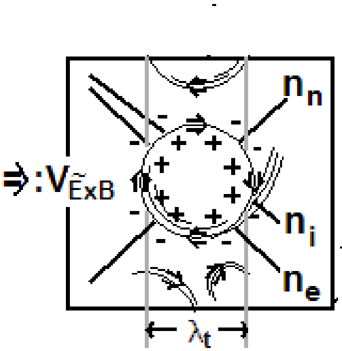
$$J_r^{GCS} = e n_i \frac{r_{Li}}{\lambda_{i-n}} \left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n}\right)$$

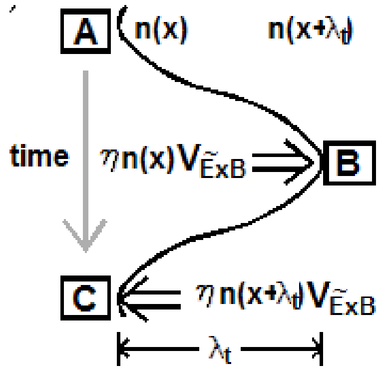
Turbulence induced diffusion and E_r saturation condition of GCS



- ► 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 (particle & charge)
- 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}***

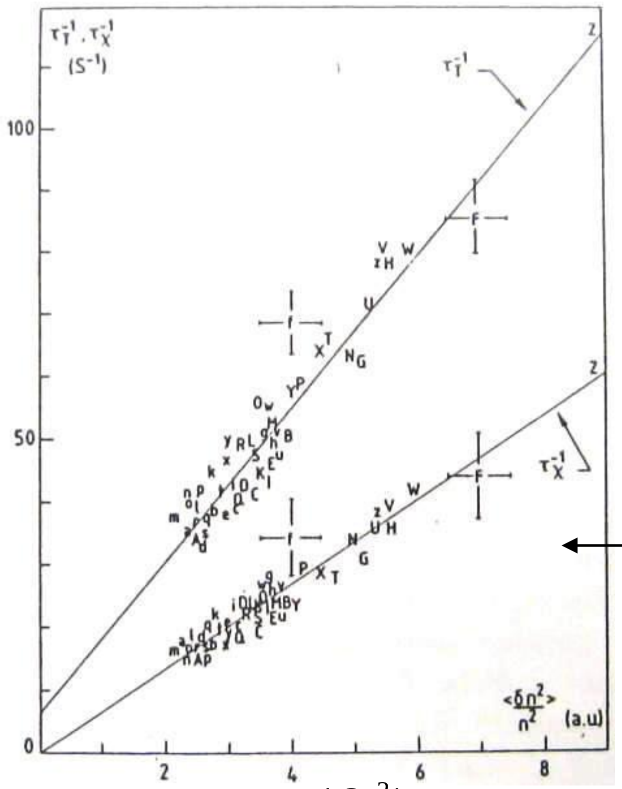
Turbulence induced diffusion coefficient

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

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

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

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



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

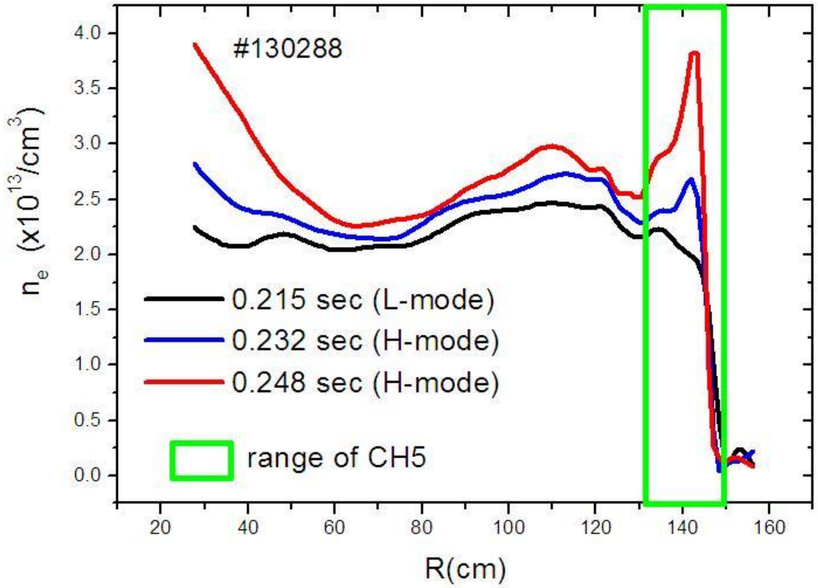
- ► $\propto \frac{1}{B_T}$ and similar to Bohm diffusion : $\propto \frac{kT_e}{eB}$
- ► proportional to η^2: in agreement with experiments
- ← [TFR group, Nuclear Fusion (1986)]
- ► characteristics close to “anomalous” diffusion

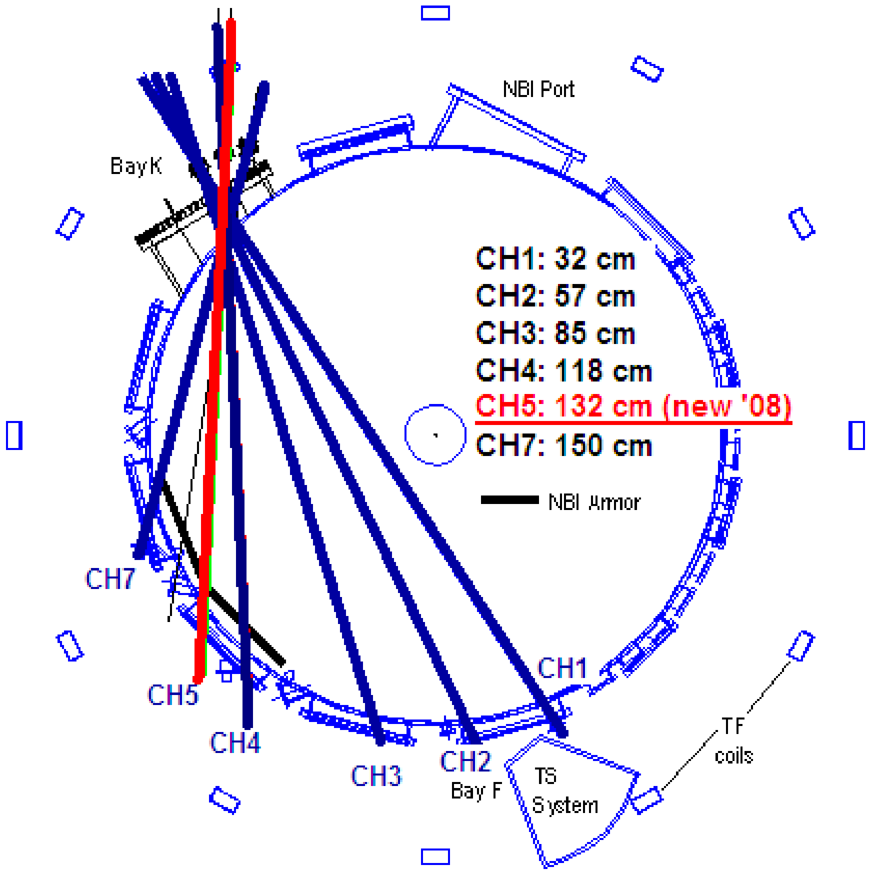
$\frac{\tilde{n}}{n}$ Measurement (FIReTIP) vs. Confinement (EFIT)

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

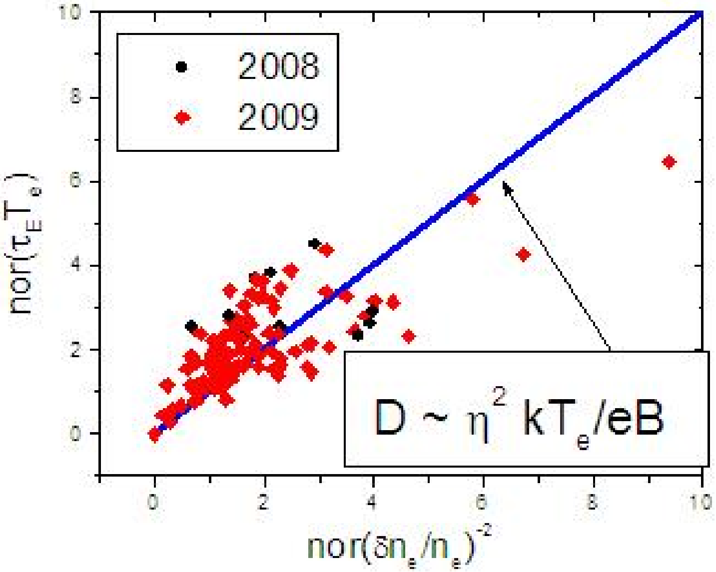
$\tau_E \sim 1/D$

Thomson Scattering

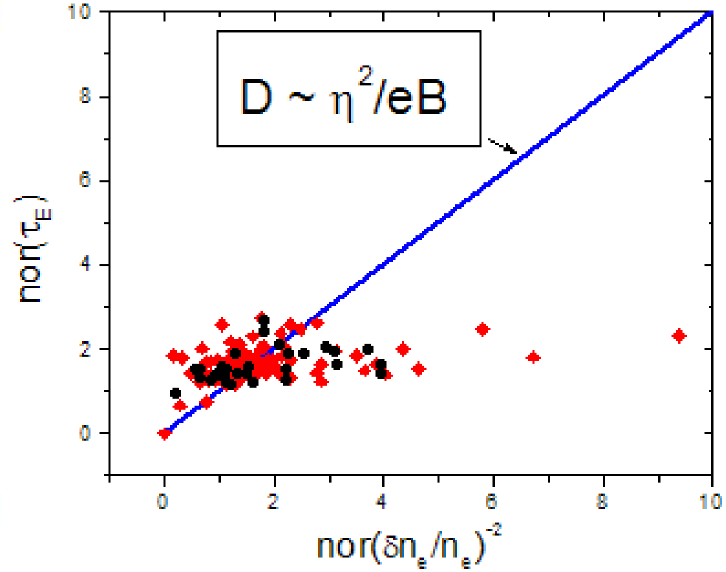




t_E with η^2 : including T_e effect



t_E with η^2 : no T_e effect

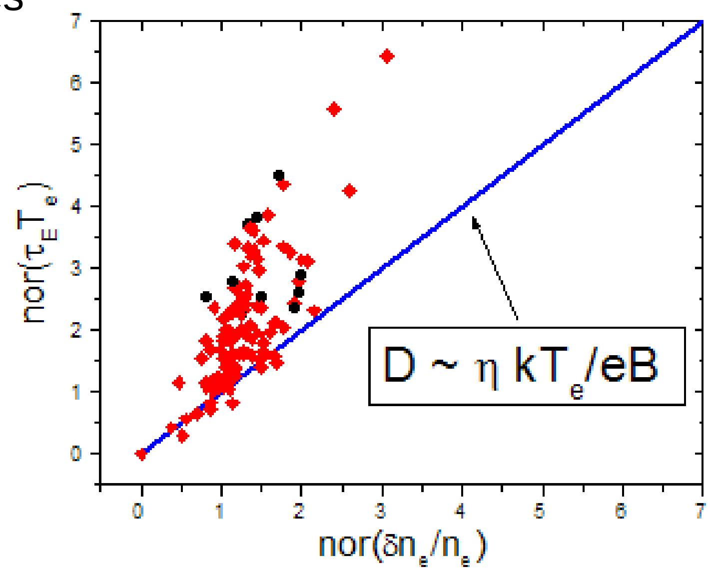


2008
+2009
Data
NSTX

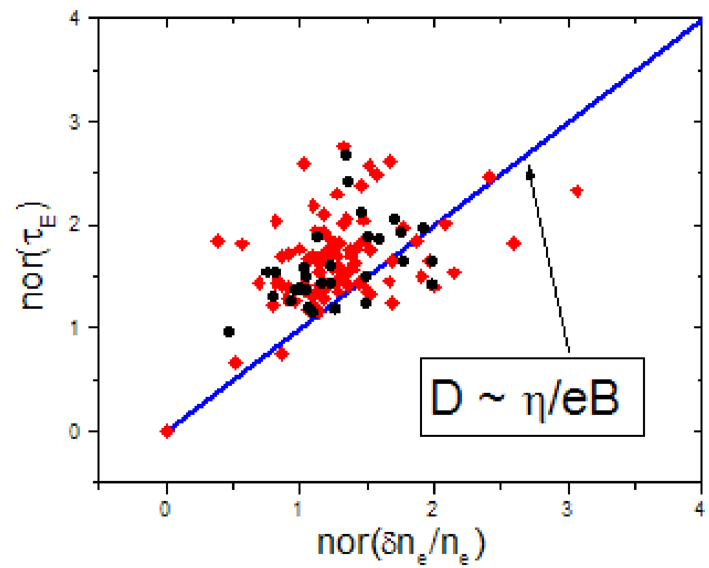
$$D = \frac{2}{\pi}\eta^2 \frac{kT_e}{eB}$$

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

t_E with η : including T_e effect



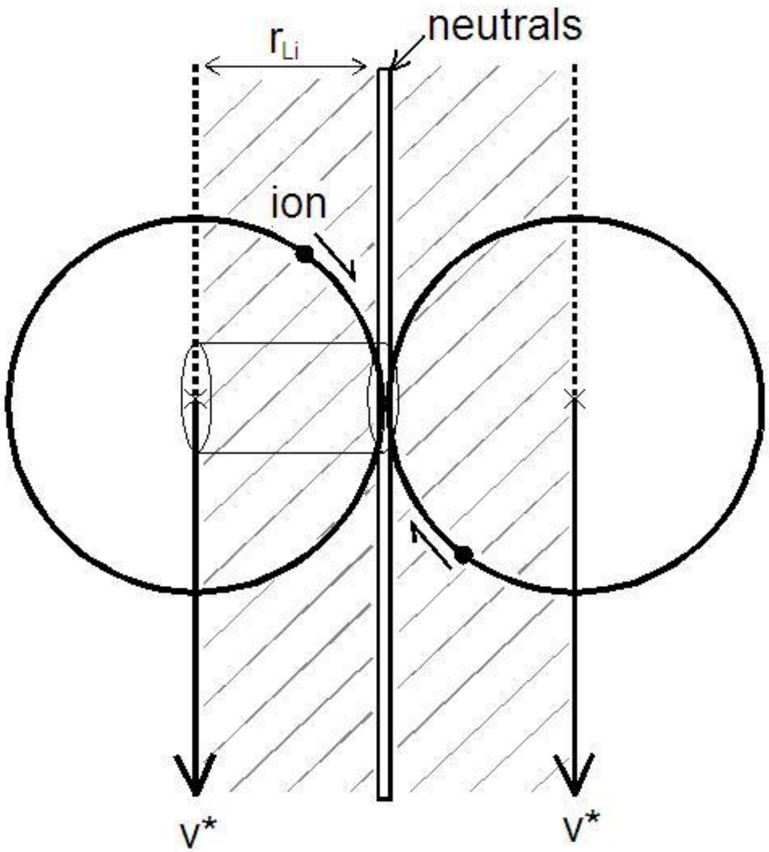
t_E with η : no T_e effect



Turbulence

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

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



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 ↗

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

⬇

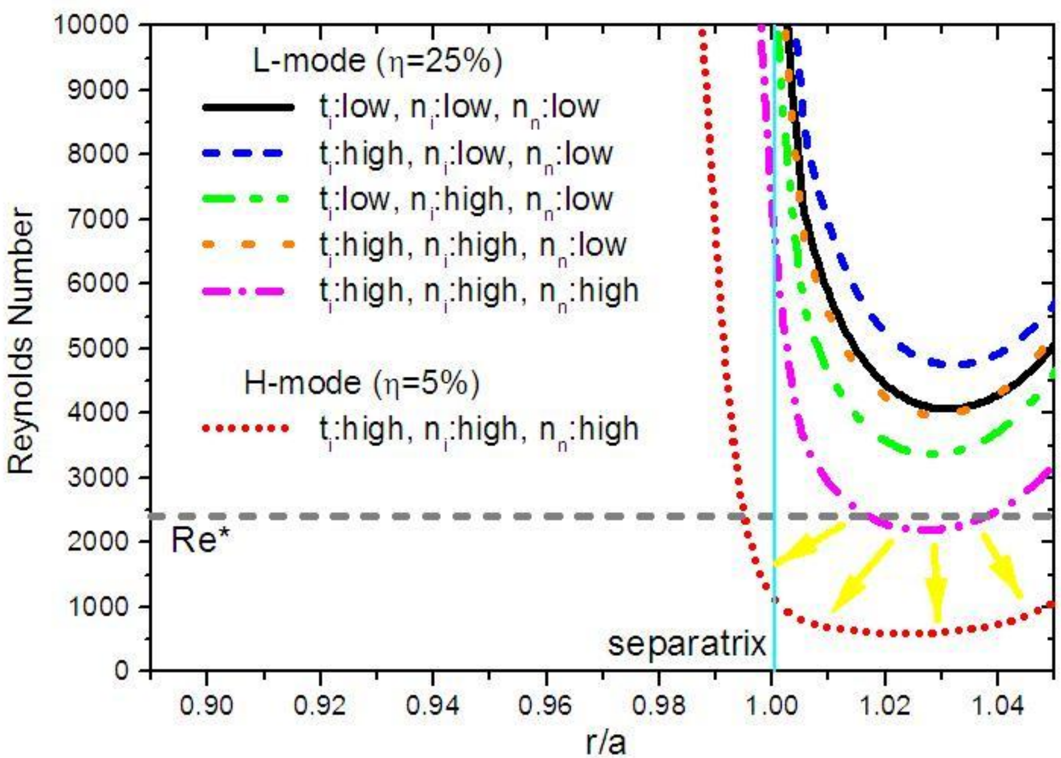
(saturation condition : $J_r^{GCS} = D \nabla \rho$)

⬇

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



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

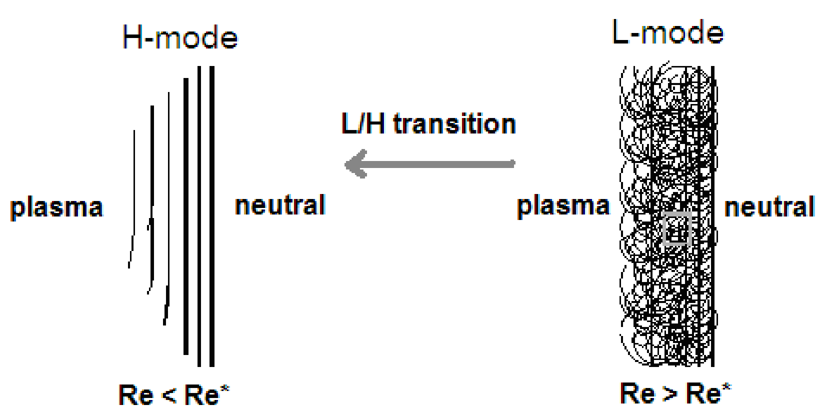
► Re > Re* : turbulent flow
Re < Re* : laminar flow

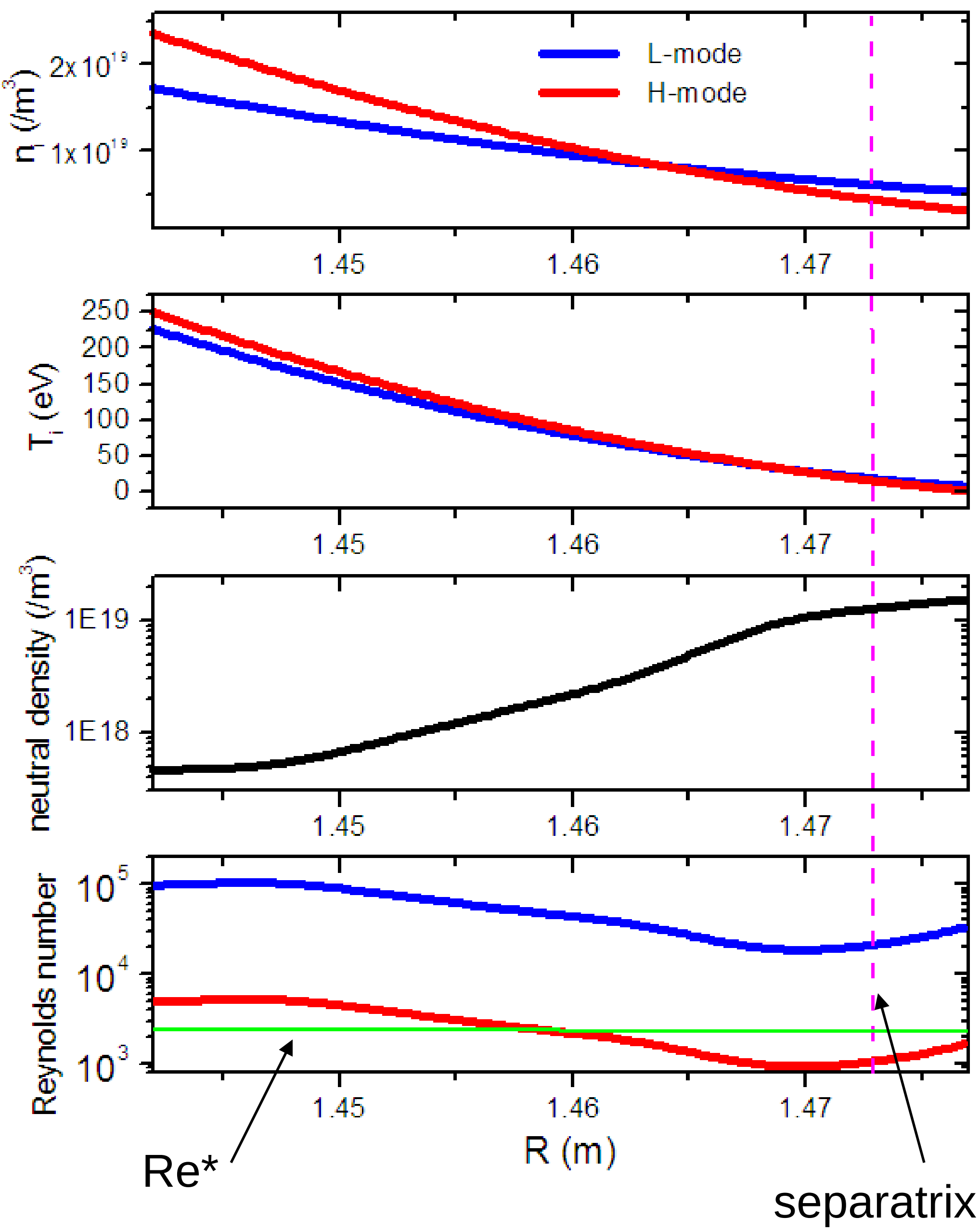
(Re*~2400)

► 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





Reynolds number study for NSTX

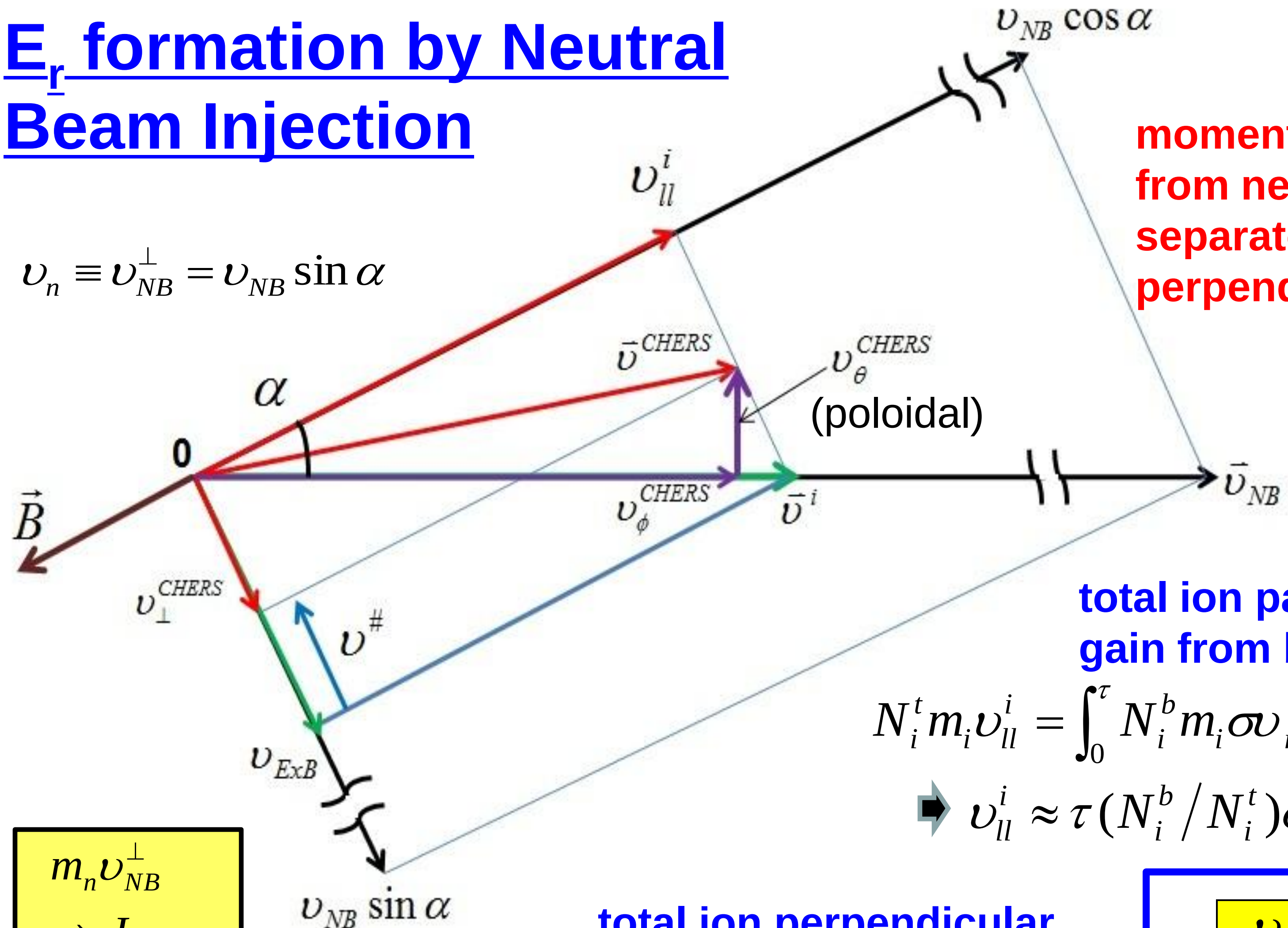
- **similar case of #135042 (T_e, n_e)**
- neutral density profile is assumed based on the measurement of SOL region : assumed same for L-mode and H-mode for convenience
- Reynolds number calculated from

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

- 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)

E_r formation by Neutral Beam Injection

$$\upsilon_n \equiv \upsilon_{NB}^{\perp} = \upsilon_{NB} \sin\alpha$$



momentum transfers from neutral to ion separately for parallel and perpendicular component

total ion parallel momentum gain from beam neutrals :

$$N_i^t m_i \upsilon_{ll}^i = \int_0^{\tau} N_i^b m_i \sigma \upsilon_r n_{NB} \upsilon_{NB} \cos\alpha \cdot dt$$

$$\Rightarrow \upsilon_{ll}^i \approx \tau (N_i^b / N_i^t) \sigma \upsilon_r n_{NB} \upsilon_{NB} \cos\alpha$$

$$m_n \upsilon_{NB}^{\perp}$$
$$\Rightarrow J_r$$
$$\Rightarrow E_r$$
$$\Rightarrow \upsilon_{ExB}$$
$$\Rightarrow m_i \upsilon_{ExB}$$

total ion perpendicular momentum gain :

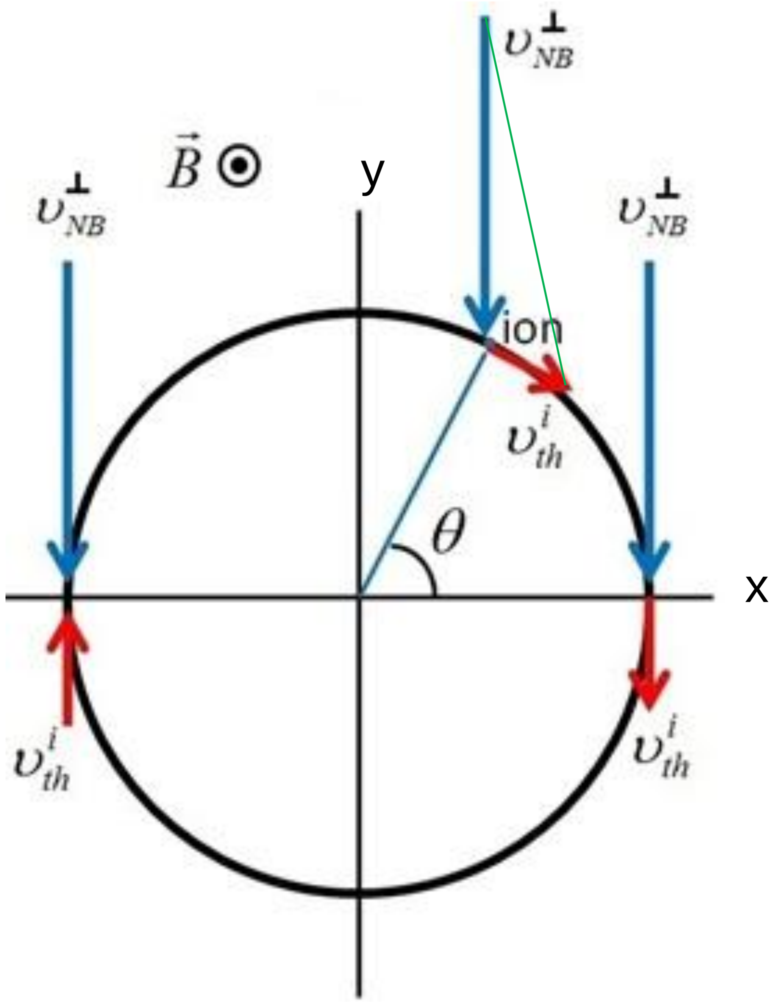
$$N_i^t m_i \upsilon_{ExB} = \int_0^{\tau} N_i^b m_i \sigma \upsilon_r n_{NB} \upsilon_{NB} \sin\alpha \cdot dt$$

$$\Rightarrow \upsilon_{ExB} \approx \tau (N_i^b / N_i^t) \sigma \upsilon_r n_{NB} \upsilon_{NB} \sin\alpha$$

$$\upsilon_{ExB} / \upsilon_{ll}^i = \tan\alpha$$

So υ_{θ} measurement (CHERS) should be small **BUT**

Net poloidal velocity on CHERS measurement



probability of ion-neutral collision is proportional to $\upsilon_r = \left| \vec{\upsilon}_{th}^{i} - \vec{\upsilon}_{NB}^{\perp} \right|$

$$\vec{\upsilon}_{th}^{i} = -\upsilon_{th}^{i} \cos\theta \cdot \hat{y} + \upsilon_{th}^{i} \sin\theta \cdot \hat{x}$$

$$\vec{\upsilon}_{NB}^{\perp} = -\upsilon_{NB}^{\perp} \cdot \hat{y}$$

collision probability at left side is higher than collision probability at right side

so there is net ion poloidal velocity (v#) for CHERS measurement in addition to the pressure gradient term from conventional force balance equation, which is:

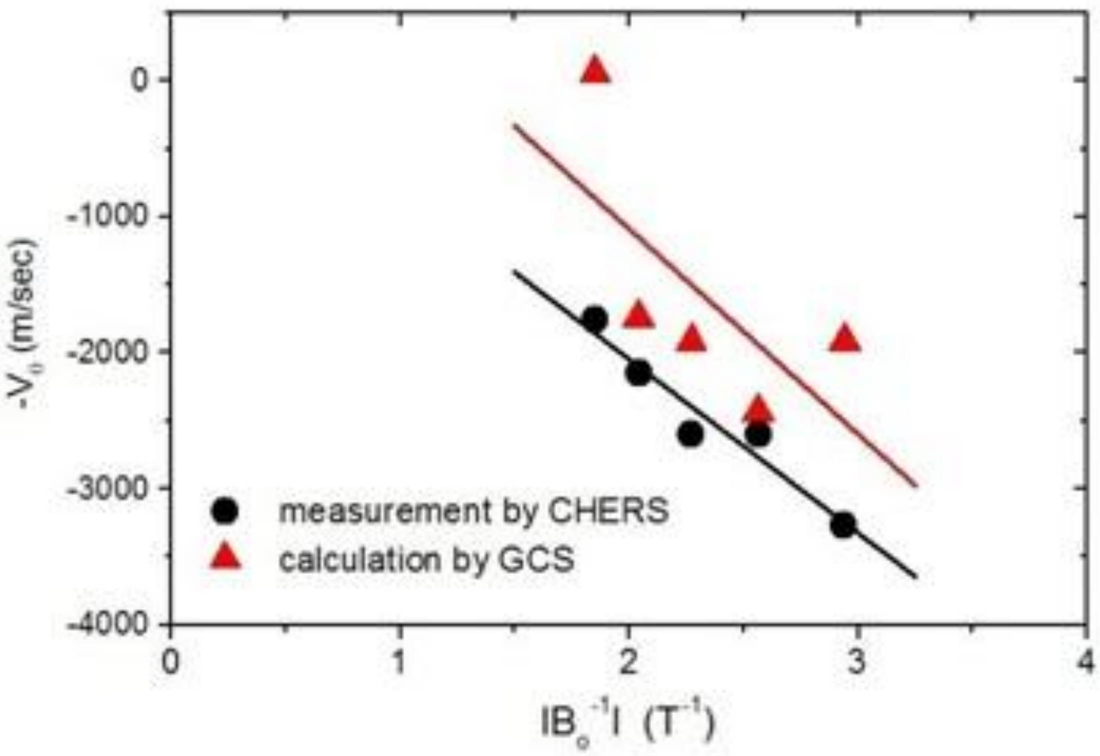
$$\int_0^{2\pi} \vec{\upsilon}_{th}^{i} \upsilon_r \, d\theta \Big/ \int_0^{2\pi} \upsilon_r d\theta \approx \frac{{\upsilon_{th}^{i}}^{2}}{2(\upsilon_{NB}^{\perp} - \upsilon_{th}^{i})}$$

when $\upsilon_{th}^{i} / \upsilon_{NB} << 1$

$$\upsilon\# = \frac{\nabla P_C}{ZeBn_c} + \frac{{\upsilon_{th}^{C}}^{2}}{2(\upsilon_{NB}^{\perp} - \upsilon_{th}^{C})}$$

and $\upsilon_{\theta}^{CHERS} = \upsilon\# \cos\alpha$

Comparison of poloidal velocity by CHERS measurement with the calculation (GCS) on NSTX



► data points were taken for the average of radius range from 137cm to 141 cm with toroidal magnetic field scanning

► calculation shows approximately 50% discrepancy with measurement

► there are many factors disregarded in the calculations such as net velocity from neutral density gradient and difference between main ion velocity and carbon velocity.

► however this result is better agreement than neoclassical simulations which show 260% ~ 330% discrepancy [R.E.Bell etc., PoP, 2010]

Conclusions

gyrocenter shift at boundary

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

turbulence diffusion

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

Reynolds number of ion-neutral collision :

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

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

- 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

- Perpendicular component of momentum transfer from neutral beam by ion-neutral collision forms radial electric field at core region

- There is net perpendicular velocity proportional to ion temperature for CHERS measurement

- Gyrocenter shift is reliable theory for fusion plasma analysis

Abstract

The radial current generated by the ion-neutral momentum exchange has been analyzed to be responsible for the radial electric field (E_r), the turbulence transport, and the low confinement mode (L-mode) to high confinement mode (H-mode) transitions on the edge of tokamak plasmas. In this analysis of gyrocenter shift the plasma pressure gradient, the neutral density gradient and the neutral velocity are the major driving mechanism of the radial current and the electric field is formed as the source of the return current to make an equilibrium condition. When there is turbulence the small scale ExB eddies induce the cross-field transport. Finally the origin of turbulence is interpreted that it comes from the friction between the plasma and the neutrals so that the Reynolds number determines the state between laminar flow (H-mode) and turbulent flow (L-mode). The confinement time of the national spherical torus experiment (NSTX) is compared with the density fluctuation level to verify the turbulence induced diffusion coefficient from the theory of gyrocenter shift. The calculation results based on the gyrocenter shift for the poloidal velocity of carbon impurity ions are compared with CHERS measurement of NSTX plasmas. The calculation result agreed within 50% discrepancy which is closer than the results from neoclassical simulation codes.

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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*