Gyrocenter shift and H-mode transition

K.C. Lee[1], R.E. Bell[2], B.P. LeBlanc[2], R.J. Maqueda[3], D.P. Stotler[2], P.W. Ross[2], D.A. Gates[2], H. Park[2], S.M. Kaye[2], S.J. Zweben[2], M.G. Bell[2], R. Maingi[4], C.E. Bush[4], V.A. Soukhanovskii[5]

1. University of California at Davis
2. PPPL, Princeton University
3. Nova Photonics
4. Oak Ridge National Laboratory
5. Lawrence Livermore National Laboratory

NSTX Research Team

UC DAVIS
DEPARTMENT OF APPLIED SCIENCE

NSTX

Contents

New origin of radial electric field (E_r) formation

- **Motive : H-mode transition analysis developed turbulence suppression by ExB flow**

► **Requires the origin of radial electric field : E_r**

- **Candidates : Non-ambipolar ion losses [Itoh 88']**
  - Different from experiment [Burrell 89']
  Ion orbit loss [Shaing 92'], x-point transport [Chang 02']

► **E_r formation remains beyond the complete understanding**

- **Experimental research results :**

● **E_r has peak of -30~ -50 kV/m at core periphery near from separatrix within 100 μsec transition time [Burrell 94' DIII-D]**

● **Significant (unknown) correlation between the boundary neutrals and H-mode transition threshold [Carreras 98' DIII-D]**

► **Charge exchange with neutrals => regarded as 'friction' in previous works**

Assumptions in the theory of gyrocenter shift

(1) Toroidal and poloidal symmetry except circular gyro-motion of ions (1-dimensional approach in radial direction)

(2) Ionization, recombination and electron involved reactions are neglected (considered charge exchange & elastic scattering)

(3) Semi-steady state

(4) $T_i \sim T_e$

↓

Principle of simplicity

If we can describe E_r by one process, other effects can be considered later

Concept of reaction rate

reaction rate density $[m^{-3}s^{-1}]$ → $R^* = \sigma\Phi n_n$ ← target particle density = neutral density $[m^{-3}]$

cross-section (charge exchange) $[m^2]$

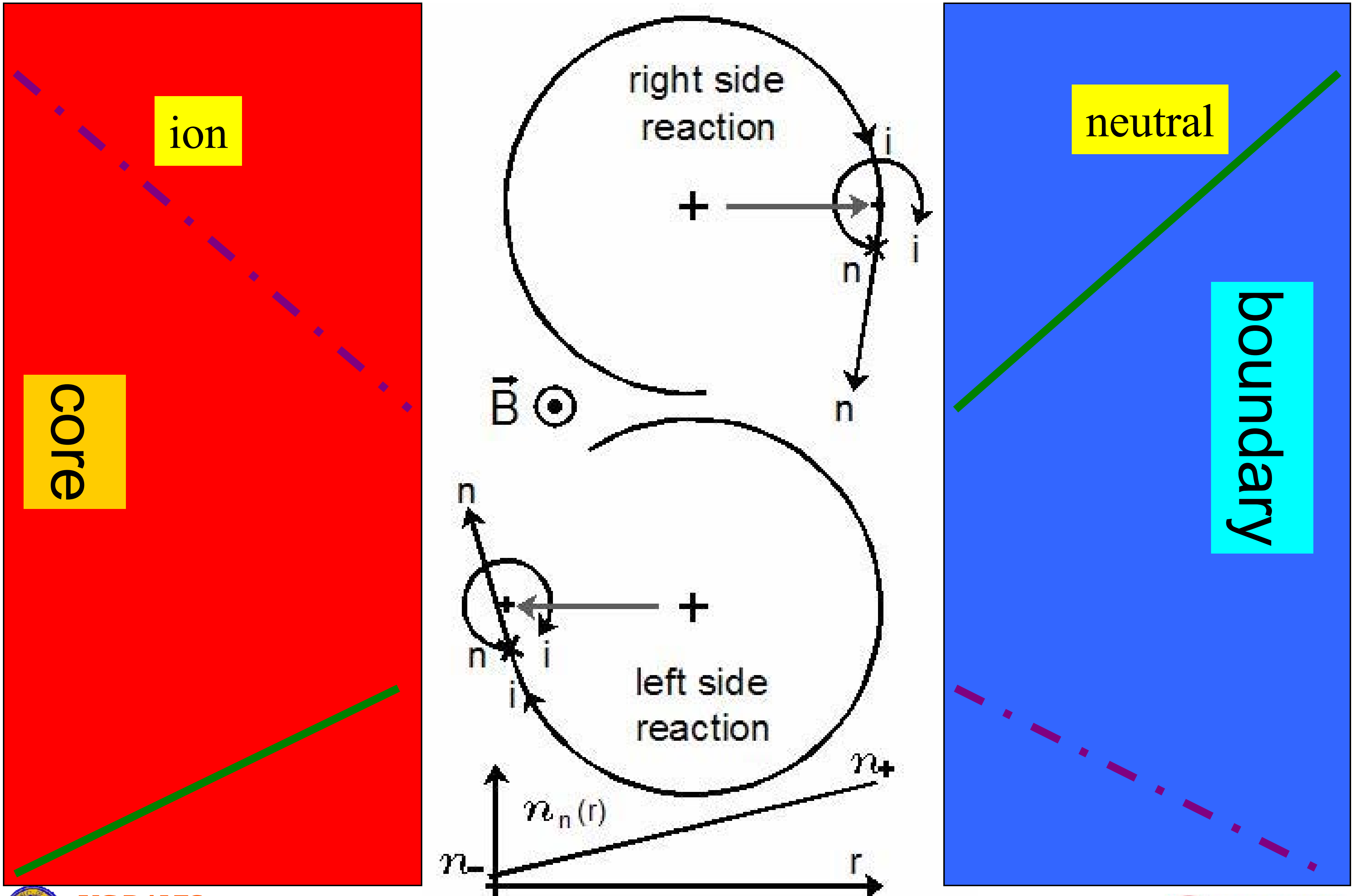
Incident particle flux = $n_i v_i$
(ion density)x(ion velocity)
$[m^{-3}][ms^{-1}] = [m^{-2}s^{-1}]$

Reaction rate per ion (microscopic)

$$R\ [s^{-1}] = \sigma v_i n_n$$

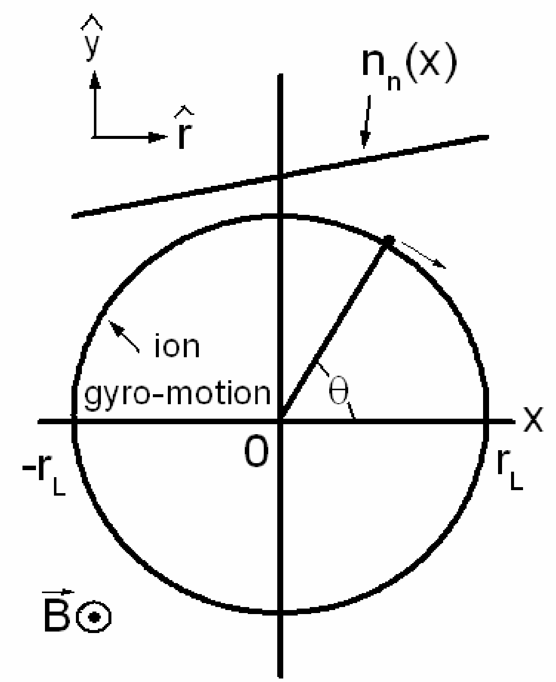
$R\ [s^{-1}]$: **How many reactions to happen per unit time**
$1/R\ [s]$: **Average time to be taken before reaction**

Gyrocenter shift by charge exchange



Gyrocenter shift calculation

average gyrocenter shift over ($-r_L < r < r_L$) per reaction	x	reaction rate of an ion with r_L and gyrocenter at the point	=	average gyrocenter shift rate
$\dfrac{\sigma v_i \oint x n_n(x) d\theta}{\sigma v_i \oint n_n(x) d\theta} = \dfrac{1}{2} r_L{}^2 \dfrac{1}{n_n} \dfrac{\partial n_n}{\partial r}$	x	$\sigma v_i n_n$	=	$\dfrac{1}{2} \sigma v_i r_L{}^2 \dfrac{\partial n_n}{\partial r}$



current density (charge separation)

► **different from plasma neutral friction**

$$J_r^{GCS} = \frac{1}{2} e n_i < \sigma v_i r_L{}^2 > \frac{\partial n_n}{\partial r}$$

$$J_r^{GCS} = \frac{m_i n_i T_i}{q_i B^2} < \sigma v_i > \frac{\partial n_n}{\partial r}$$

by $r_L = \dfrac{m_i v_\perp}{q_i B}$ and $v_\perp = \sqrt{\dfrac{2T_i}{m_i}}$

Gyrocenter shift calculation by fluid picture

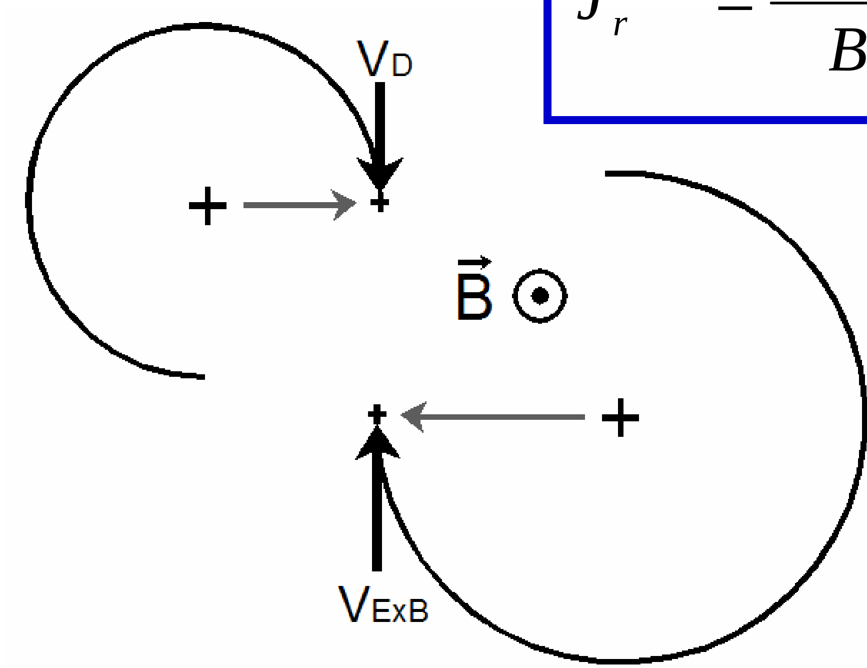
From a fluid equation of motion ; $J \times B = n_i R_{av} S_i^m$

$$v_{av} = \frac{\sigma v_i \oint v n_n(x) d\theta}{\sigma v_i \oint n_n(x) d\theta} = \frac{1}{2} r_L v_\perp \frac{1}{n_n} \frac{\partial n_n}{\partial r}$$

momentum sink by charge exchange

$$S_i^m = m_i v_{av}$$

$$\boxed{J_r^{GCS} = \frac{m_i n_i n_n}{B^2} < \sigma v_i > \left(E - \frac{1}{q_i n_i}\frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n}\frac{\partial n_n}{\partial r}\right)}$$



$$v_{E\times B} = \frac{E}{B} \qquad v_D = -\frac{1}{q_i B n_i}\frac{\partial p_i}{\partial r}$$

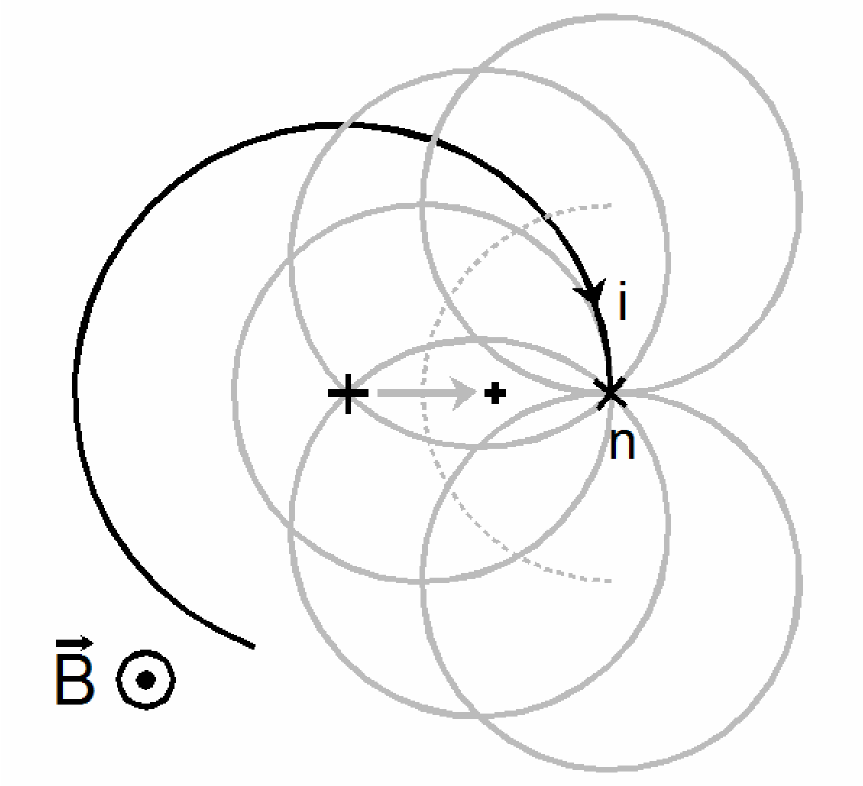
other contributions of v_{av}

(ExB and diamagnetic drifts)

ExB drift is in opposite direction

=> return current (E_r saturation)

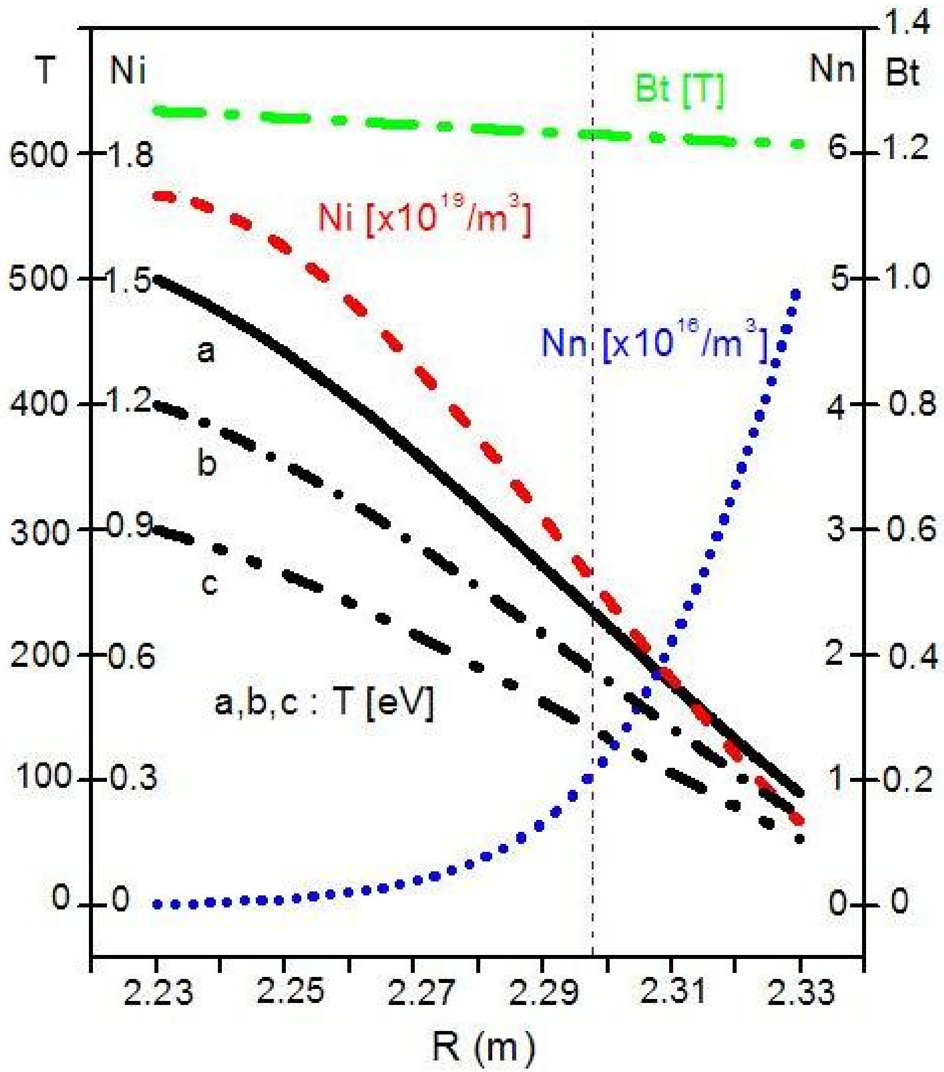
Gyrocenter shift by elastic scattering



- asymmetry between backward scattering and forward scattering
- scattered angle distribution of s-wave scattering from conservation of energy and momentum
- $0.5(\frac{1}{2})\sigma v_i r_L^2 dn_n/dr$ => new coefficient 0.5 is introduced
- only less than 20% due to small cross-section at high temperature

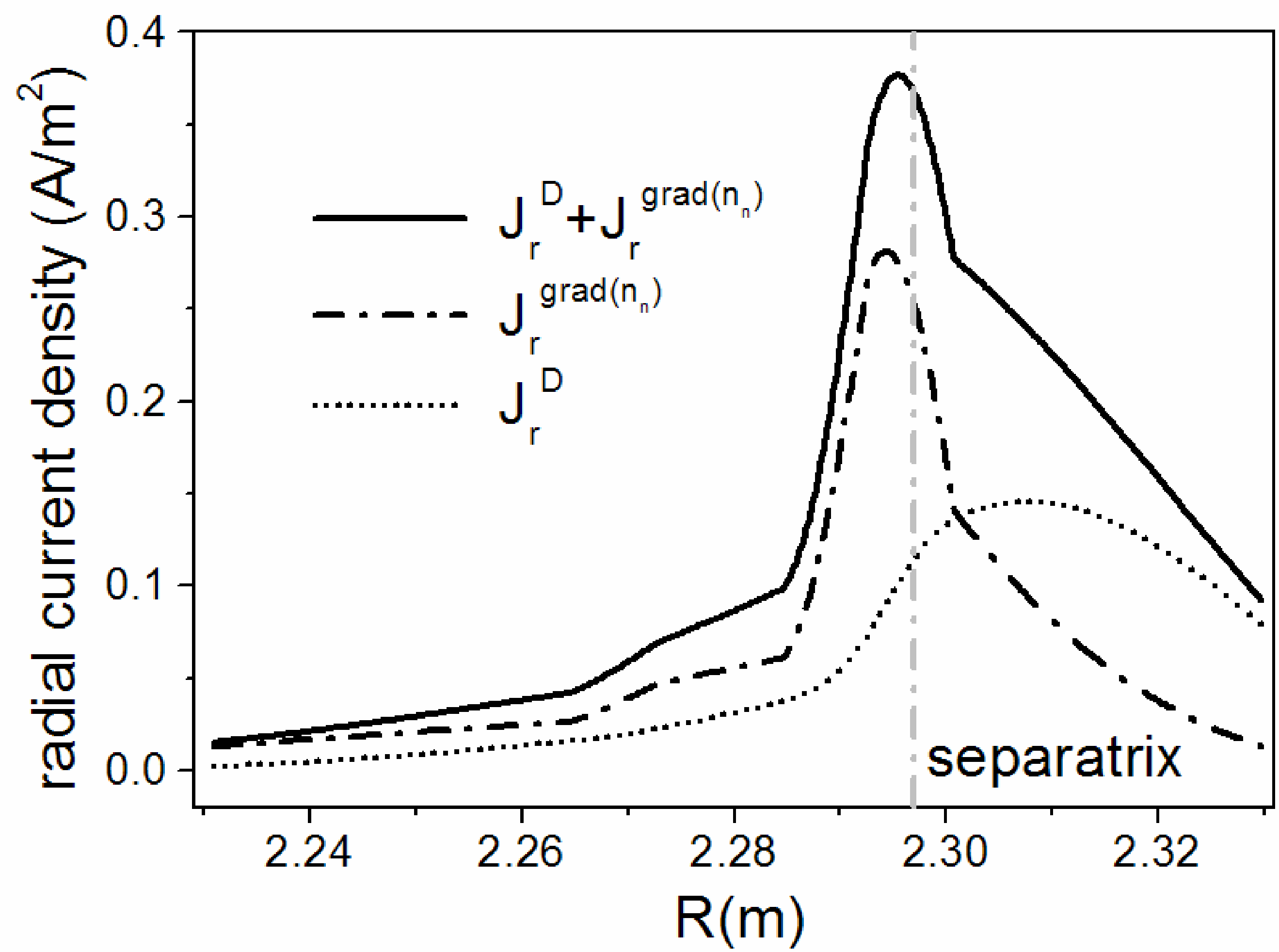
Comparison with experiments (DIII-D)

neutral density from Carreras 98'



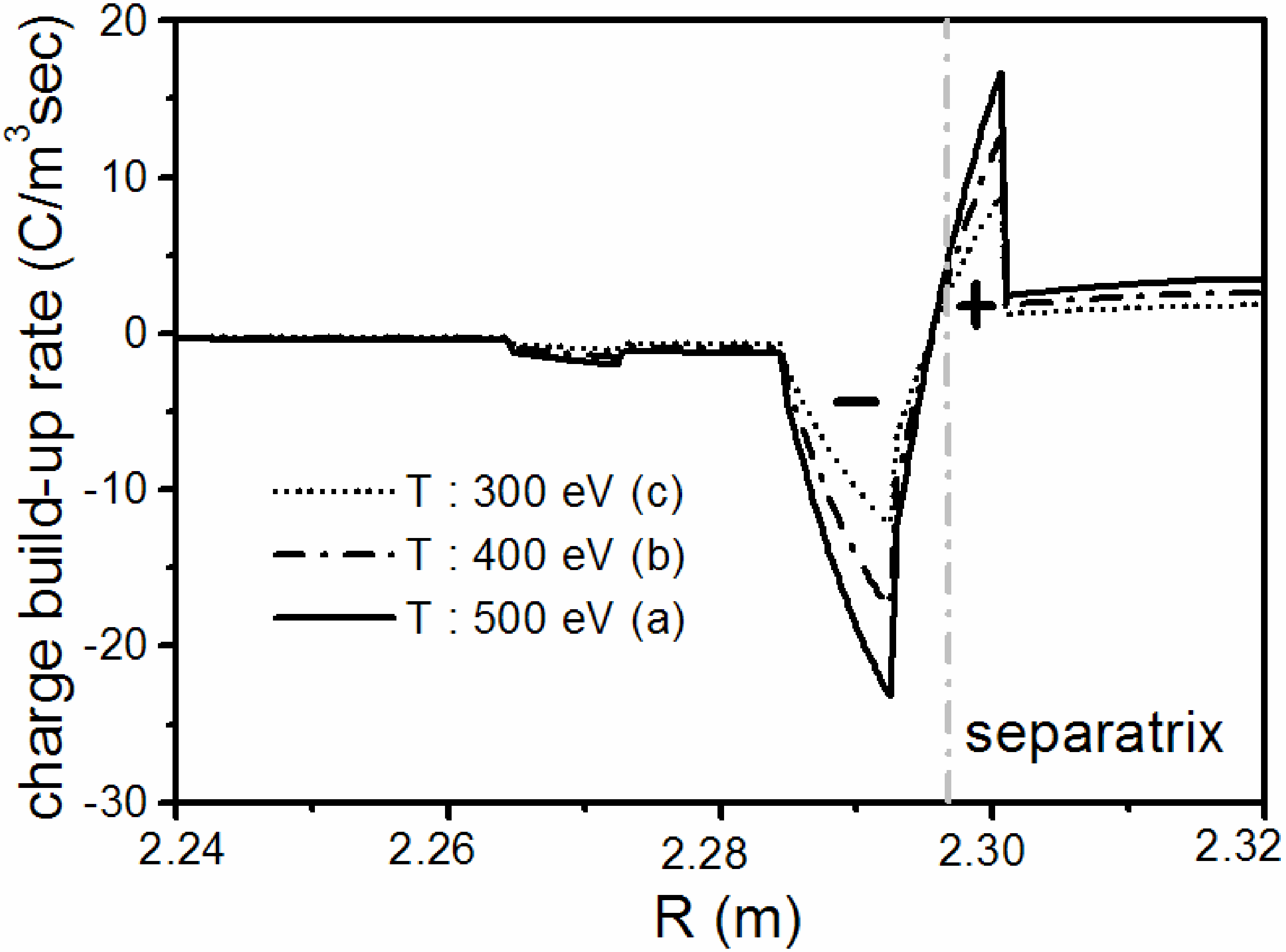
- simulated data for DIII-D
- profiles were made by cubic polynomials except n_n
- n_n has exponential functions decay into core plasma
- separatrix: around R = 2.297m
- calculated for three different temperature profiles; a(500 eV), b(400 eV), c(300 eV)
- cross section data from Thomas & Stacey 97'(±15%)

Result of calculation, J_r (DIII-D)



$$J_r^{GCS} = \frac{m_i n_i n_n}{B^2} < \sigma v_i > (E - \frac{1}{q_i n_i}\frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n}\frac{\partial n_n}{\partial r})$$

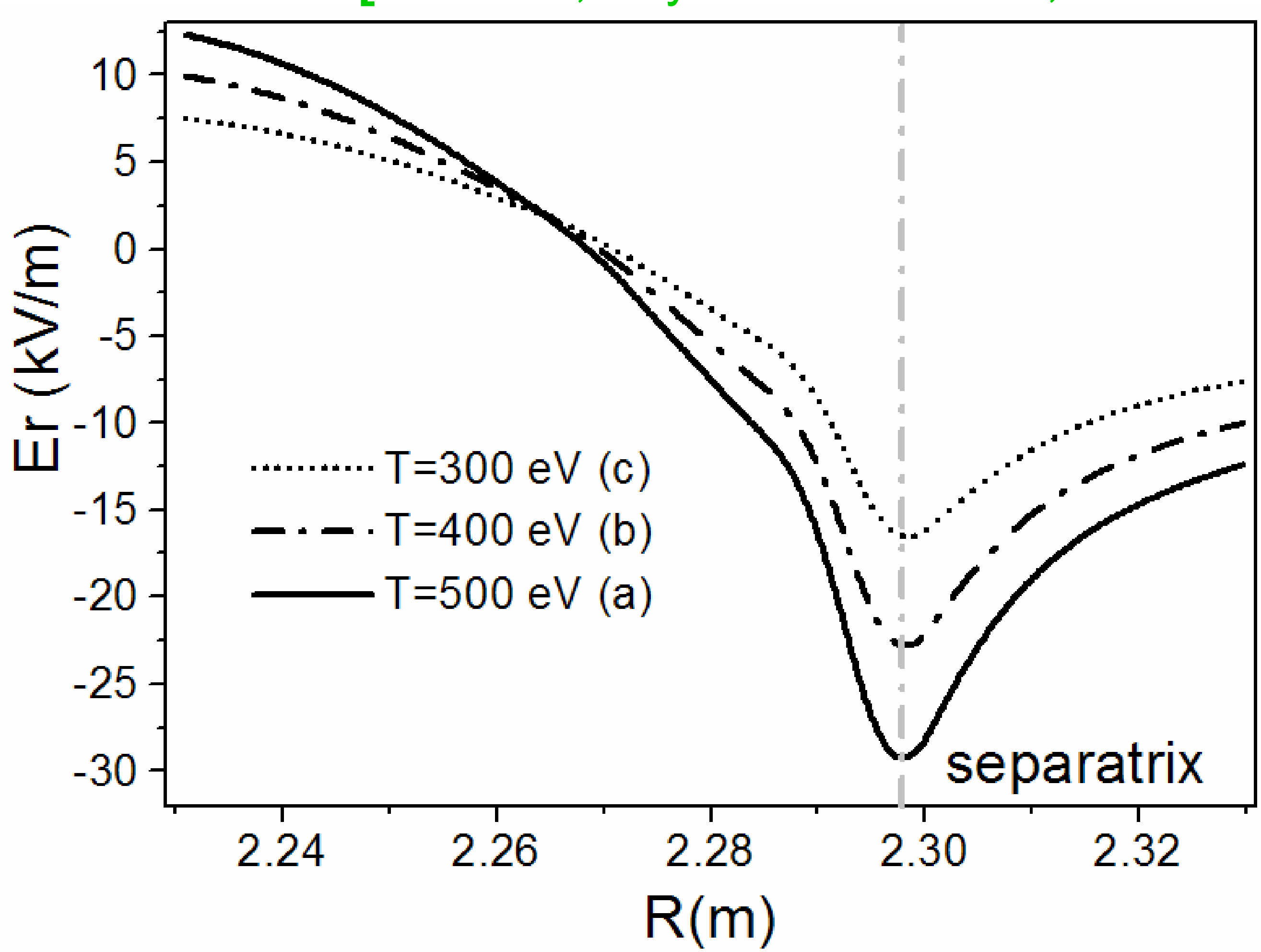
Result of calculation, dρ/dt (DIII-D)



$$\nabla \cdot J_r(r) = -\frac{d\rho}{dt}$$

Saturated profile of radial electric field

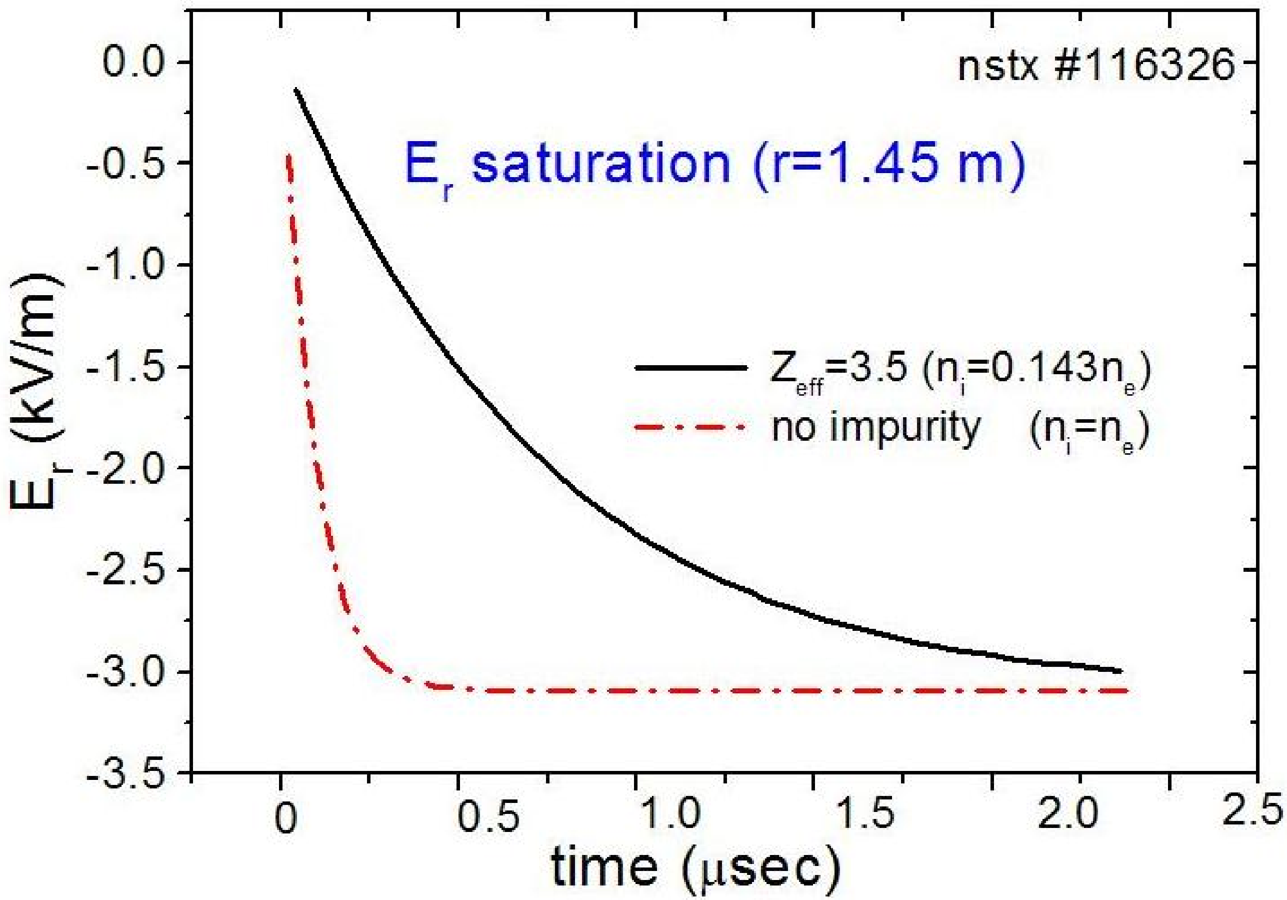
[K.C. Lee, Physics of Plasmas, **13** 062505 (2006)]



► **Profile shape and absolute value are in agreement with experiments [Burrell 94' on DIII-D]**

Cryopump on => high H-mode P_{th}

E_r saturation and effect of impurity



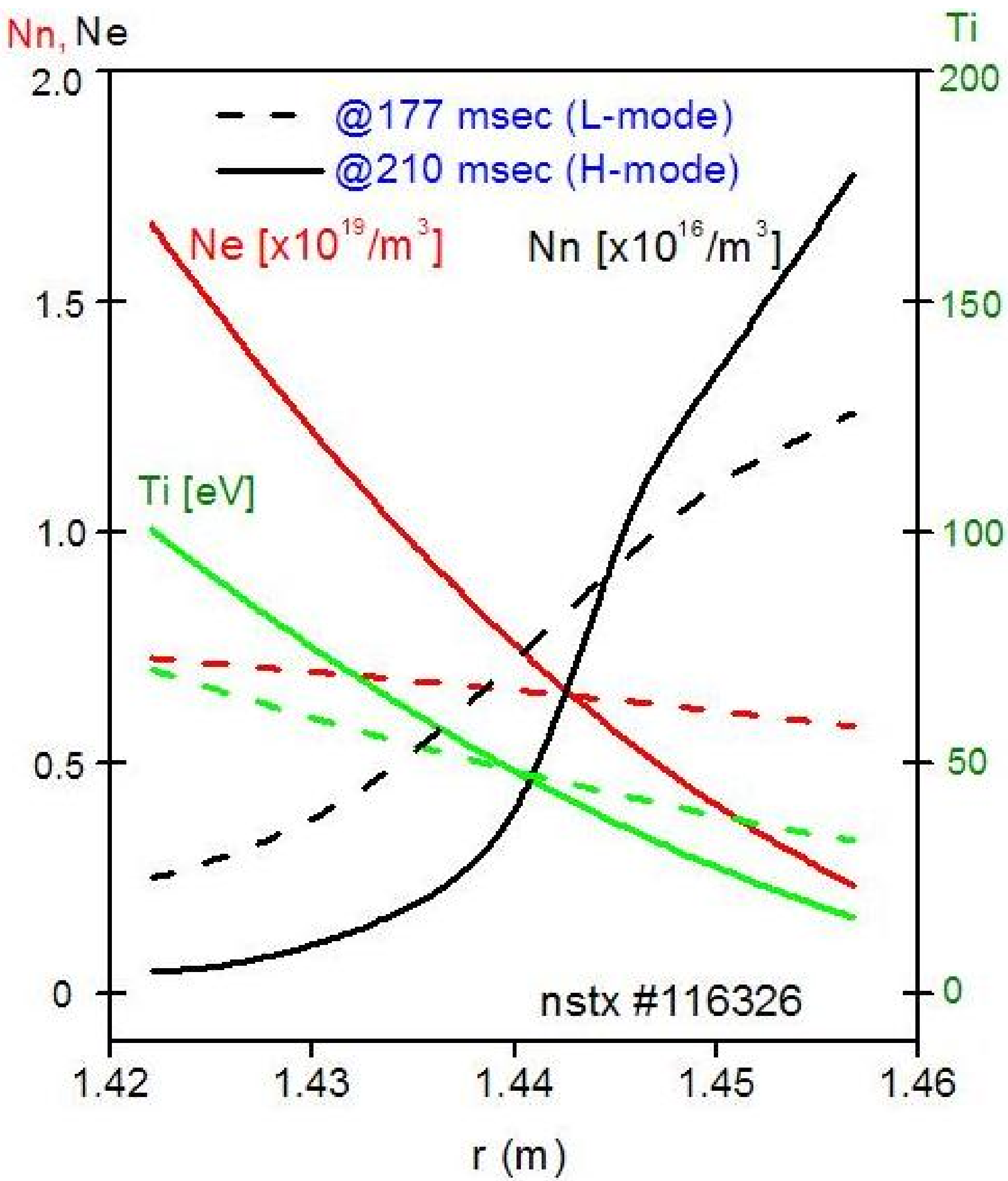
► Calculation starts with zero initial E_r

► Coefficient of J_r changes only saturation time

► gyrocenter shift of impurity is neglected (small cross-section)

$$J_r^{GCS} = \frac{m_i n_i n_n}{B^2} < \sigma v_i > (E - \frac{1}{q_i n_i}\frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n}\frac{\partial n_n}{\partial r})$$

Calculation for NSTX L-mode and H-mode



► **most parameters were measured from #116326 (T.S.)**

► **H-mode neutral density profile is deduced by using DIII-D result [Carreras'98] with separatrix location**

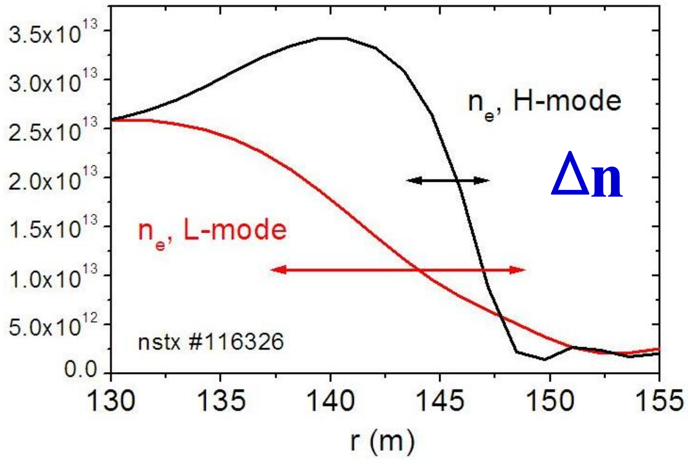
► **L-mode neutral density profile ; 'scale length relation Δn of n_e & n_n' [Groebner'02 DIII-D]**

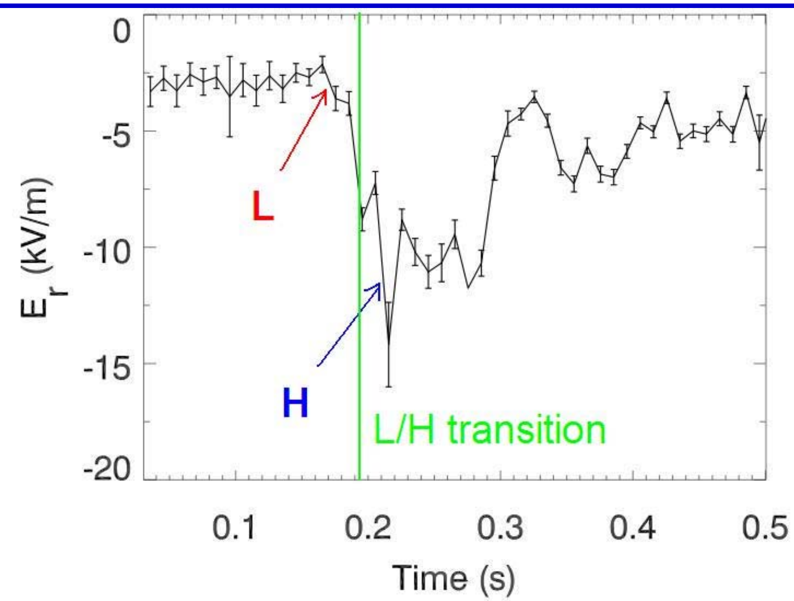
► **sensitive dependence of E_r on separatrix location (~ mm)**

► **impurity included (Z_{eff} = 3.5)**

Calculated radial electric field on NSTX

[Thomson Scattering n_e]

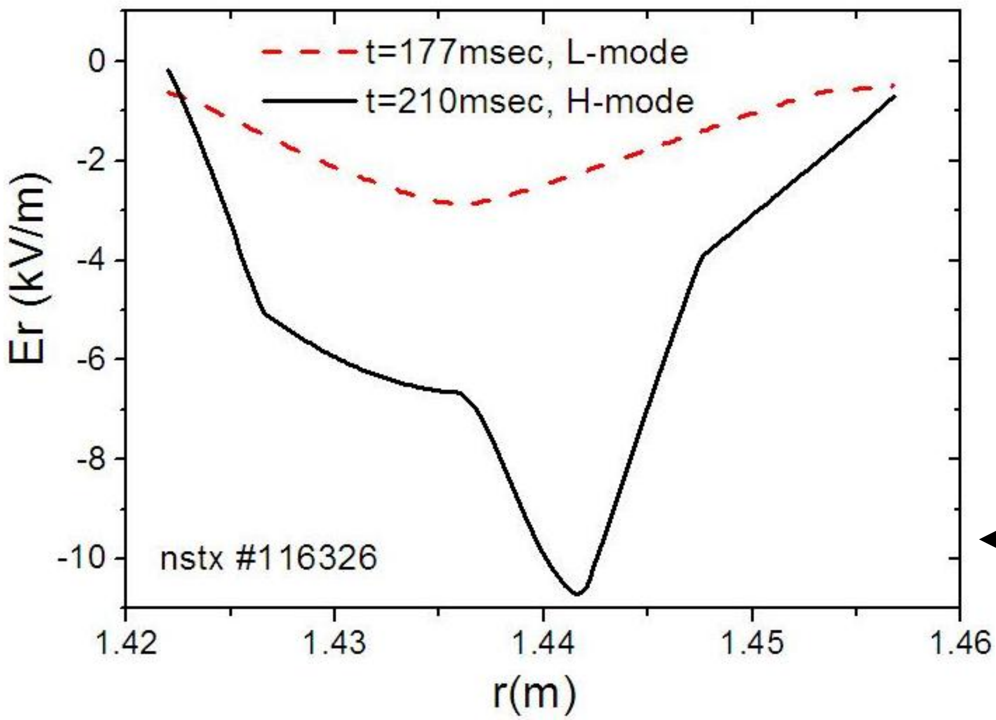




[ERD; edge rotation diagnostic]

► Radial electric field profiles calculated by gyro-center shift theory are compared with ERD measurement

► L-mode characteristic scale lengths (Δn) of n_n & n_e are 3 times larger than H-mode ones



[E_r calculated by gyrocenter shift theory]

NSTX

Discussion on the H-mode transition

- **higher temperature => higher E_r : power threshold of L\H transition**

● a scenario of L\H transition

L-mode (high turbulence, low E_r)

↓

► neutral density gradient → radial current and E_r

► H-mode pedestal → neutral density gradient ↑

(high plasma density blocks neutral penetration)

E_r ↑

(ExB flow)

Δn_n ↑ grad n_n ← grad n_i (pedestal) Δn_i ↑

Turbulence suppression

↓

H-mode (low turbulence, high E_r)

Conclusion

$$J_r^{GCS} = \frac{m_i n_i n_n}{B^2} < \sigma v_i > (E - \frac{1}{q_i n_i}\frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n}\frac{\partial n_n}{\partial r})$$

Gyrocenter shift by charge exchange reaction
=> major source of E_r formation

- **Gyrocenter shift calculation results were compared with DIII-D and NSTX experiments**
- **An H-mode transition scenario was suggested by gyrocenter shift and scale length Δn concepts**
- **Experimental evidences, ex) P_{th} (D < H) <= low V_D, high ∂n_n, high E_r**

Future work

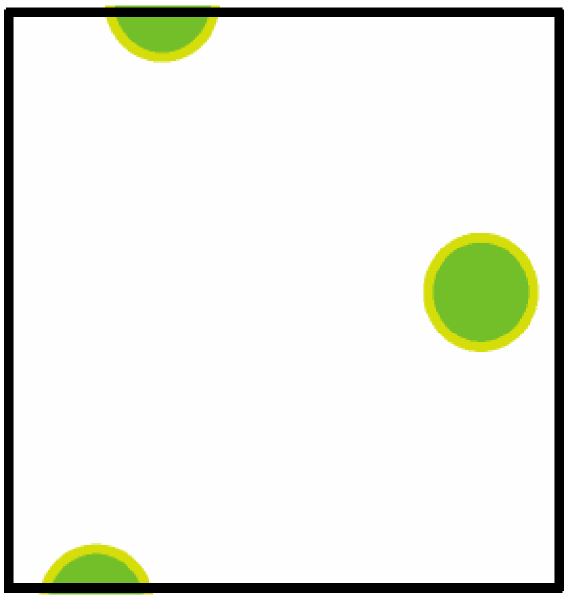
► **Measurement/calculation of neutral profile on NSTX: both GPI and mid-plane D-β emission diagnostics**

► **Studies on poloidal asymmetry and neoclassical effect**

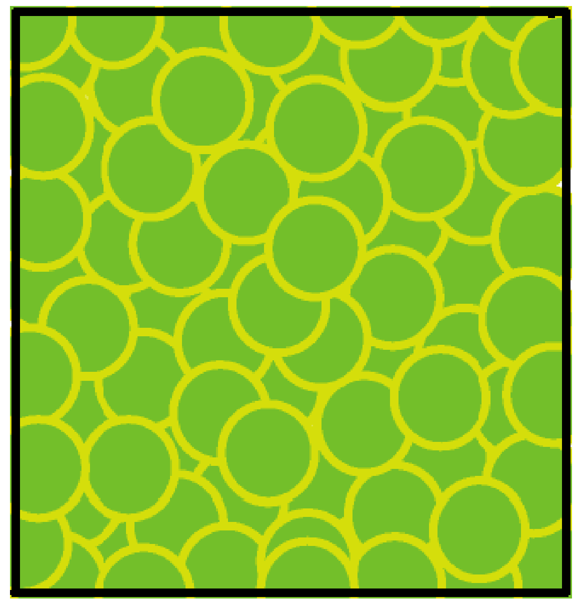
► **Developing a way to optimize the neutral distribution (and H-mode)**

Validity over Quasi-neutrality

- electric potential vanishes away out of Debye shielding : screening effect
- electric potential is effective inside Debye shielding
- when charge build up rate is high enough => all space become field effective
- life time of Debye shielding ≡ τ_D » electron collision time



No. of new charges in $\lambda_D^3\tau_D \ll 1$



No. of new charges in $\lambda_D^3\tau_D \gg 1$

Calculated values in the example of experiment are well above the criterion

Force balance vs. gyrocenter shift

$$q_i n_i (E + v_i \times B) = \frac{\partial p_i}{\partial r}$$

$$J_r^{GCS} = \frac{m_i n_i n_n}{B^2} < \sigma v_i > (E - \frac{1}{q_i n_i} \frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n} \frac{\partial n_n}{\partial r})$$

$$\Rightarrow \quad v_i \times B \approx -\frac{T_i}{q_i n_n} \frac{\partial n_n}{\partial r}$$