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Garching, 5 to 10 December 2010

Parallel flows in the EAST plasma edge

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Outline

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1. Motivation: rotation boundary condition
2. Flow boundary condition in the SOL of Ohmic plasmas
3. A inversed shear structure in the parallel flow near the edge of Ohmic plasmas
4. Co-current toroidal rotation induced by LHCD
5. Summary

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Motivation

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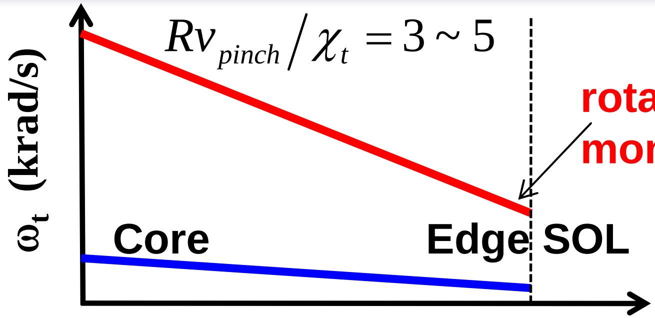

rotation boundary condition ?
momentum sources and sinks at the plasma edge

1. Rotation is important not only for migration in SOL but also for stability, confinement and access to the H-mode.
2. The NBI power is not high enough to drive significant rotation in ITER due to the high injection energy needed for the beam to penetrate deep into the plasma. Thus, there has been a growing interest in the 'intrinsic rotation' in tokamak plasmas.
3. Recent experiments indicate that a toroidal momentum pinch is necessary to explain the measured momentum transport. While it seems relatively robust that rotation profiles will be peaked in ITER thanks to the pinch term, its absolute value remains very challenging to predict with the present knowledge of momentum sources and sinks at the plasma edge, and the uncertainties in the rotation boundary condition.

Two fast reciprocating Langmuir probe systems

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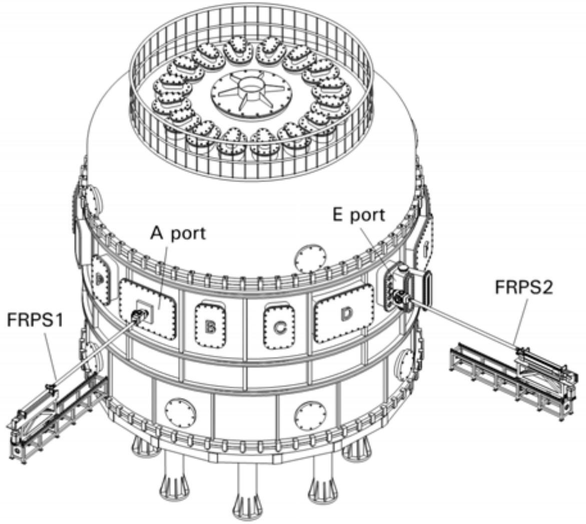
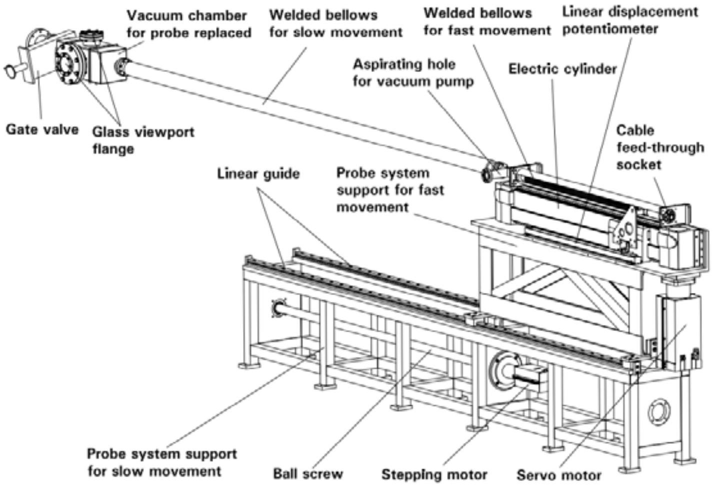
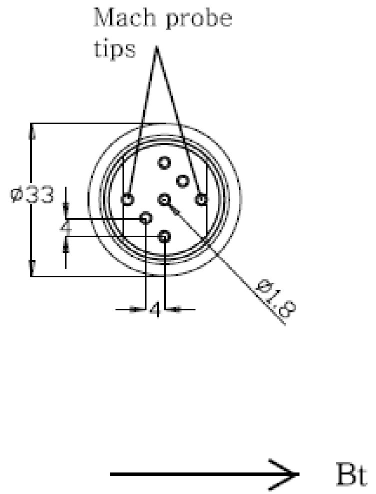
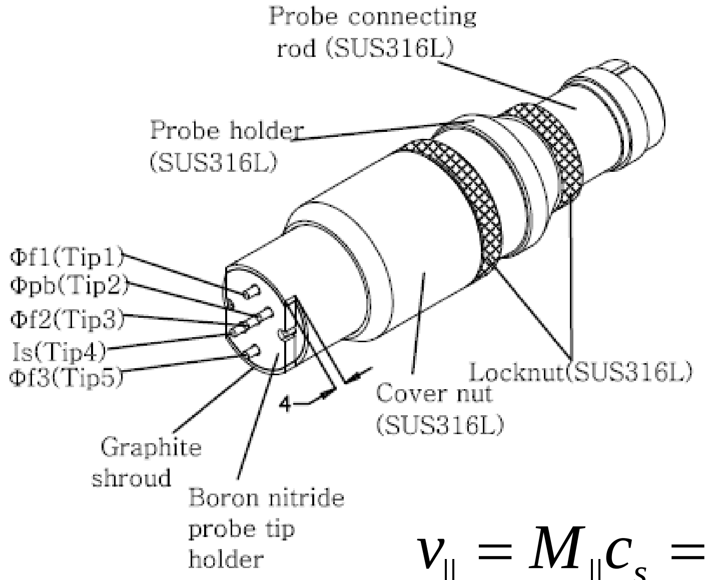




The layout of Langmuir-Mach probe arrays

(a)

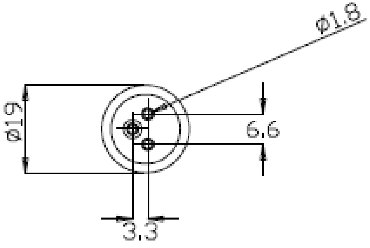


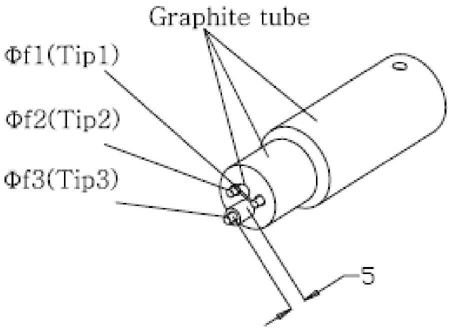


Unit: mm

$$v_{\parallel} = M_{\parallel} c_s = 0.4 c_s \ln\left(I_{up} / I_{down}\right)$$

(b)





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SOL $V_{||}$ on the outer midplane was found close to the P-S flow

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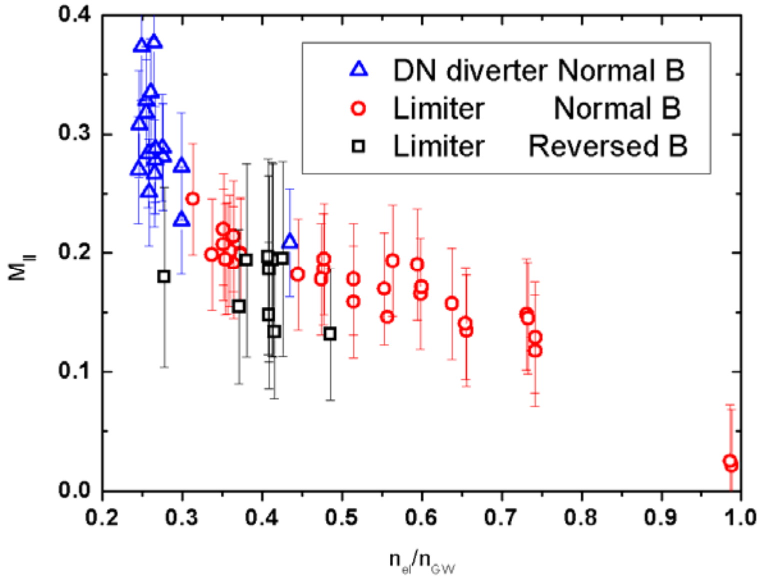

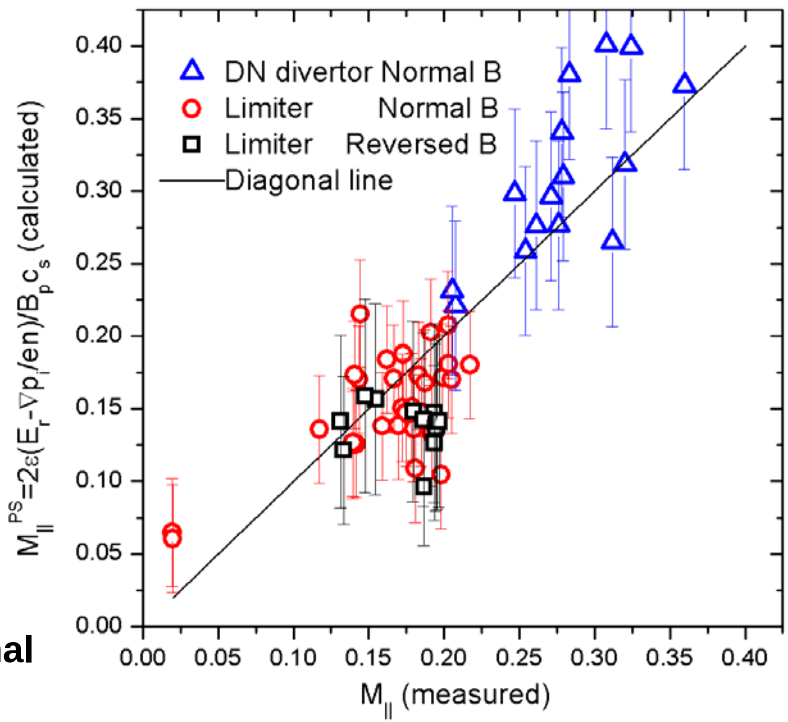

v_t remain in the cocurrent direction for normal and reversed *B*

Comparison of the Pfirsch-Schlüter flow vs. the measured flow shows remarkable agreement.

$$v_{\parallel}^{PS} = 2\varepsilon\left(E_r - \partial_r p_i / en\right) / B_p$$

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A inversed shear structure in the parallel flow was observed in divertor and limiter configurations

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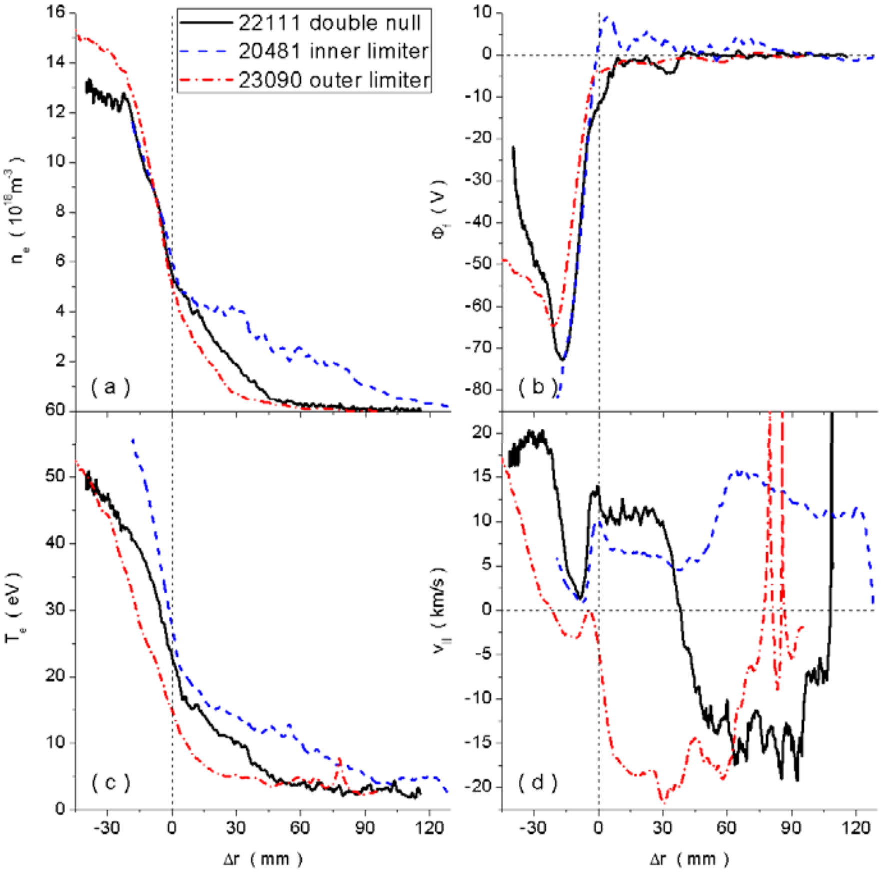
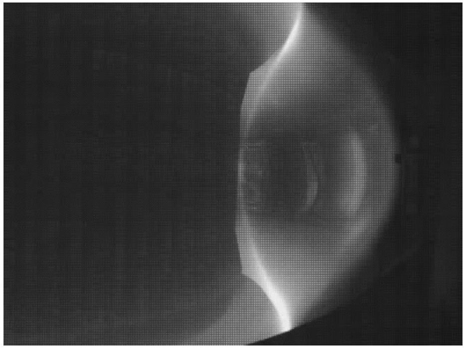
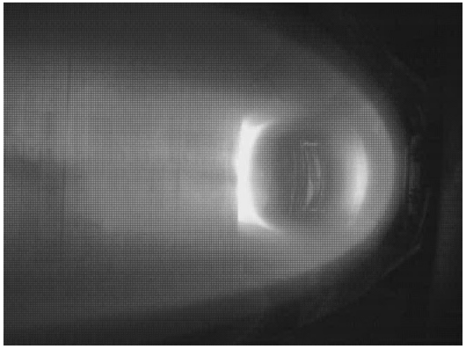


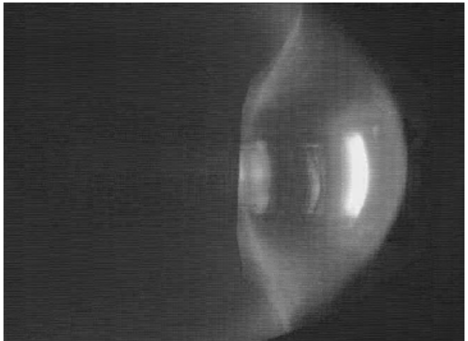
22111 Double null



20481 Inner limiter



23090 Outer limiter



Inversed shear of v_t at the H-mode edge transport barriers

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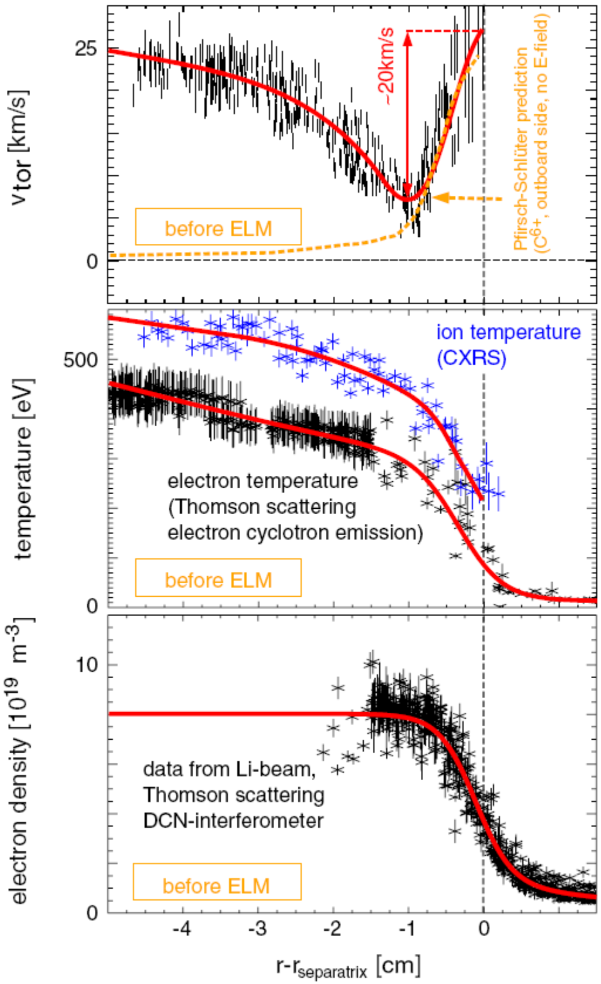
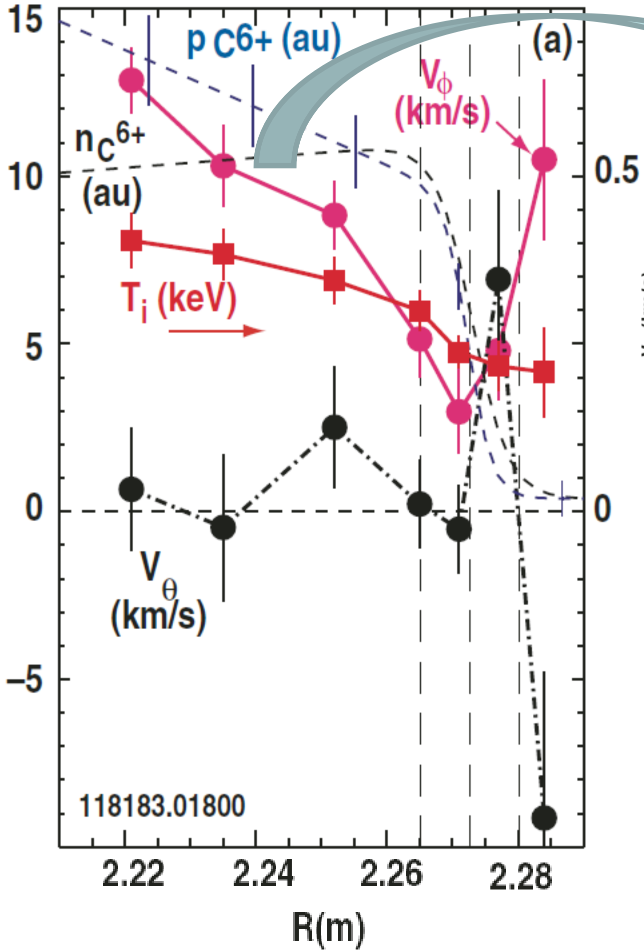
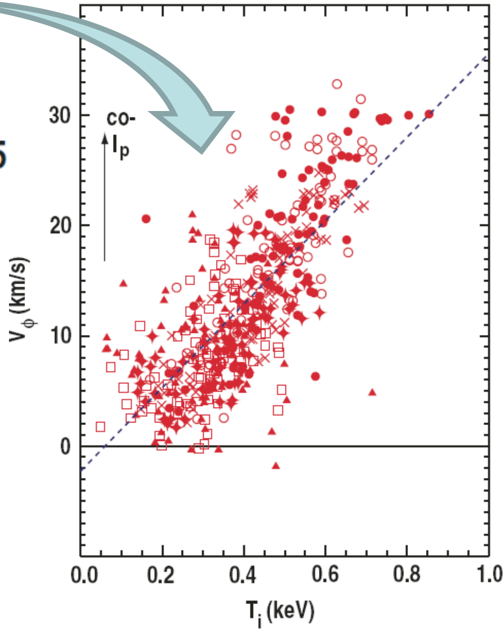
ASDEX-U 2009



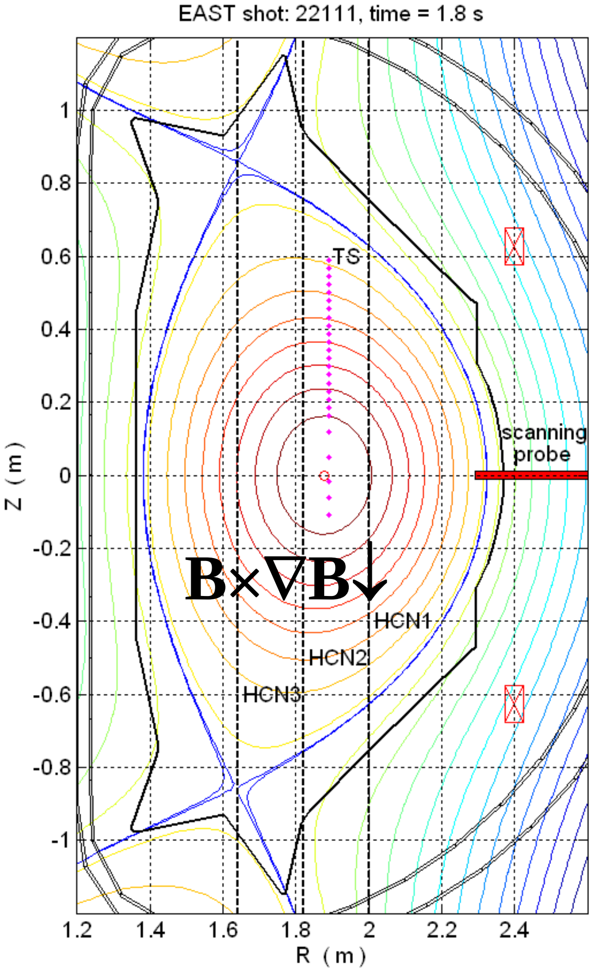
DIII-D 2009





$v_t \propto T_i$

Typical shot #22111 balanced double null Ohmic L-mode



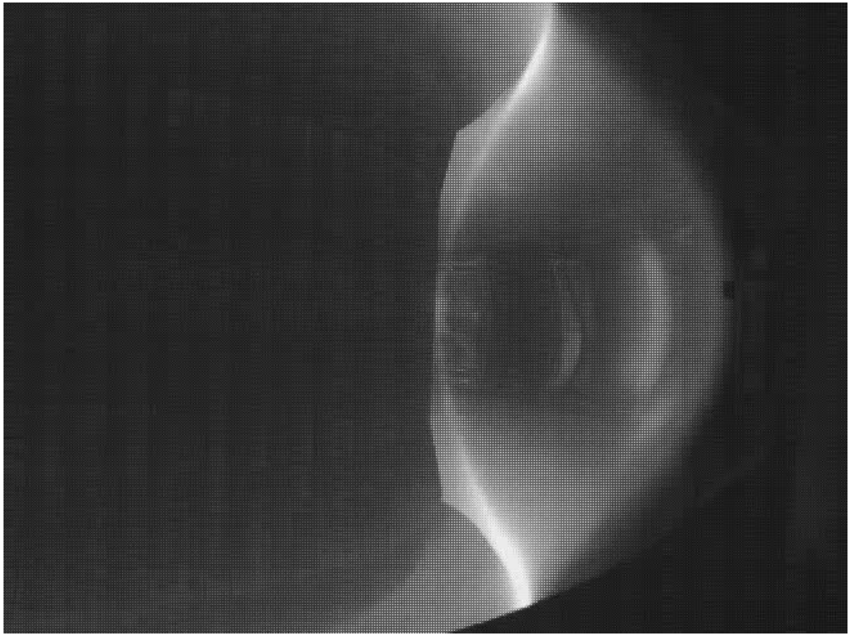
I_p = 250 kA, B_0 = 1.8 T, B_p(edge) = 0.1 T

R_0 = 1.88 m, a = 0.45 m, κ = 1.7

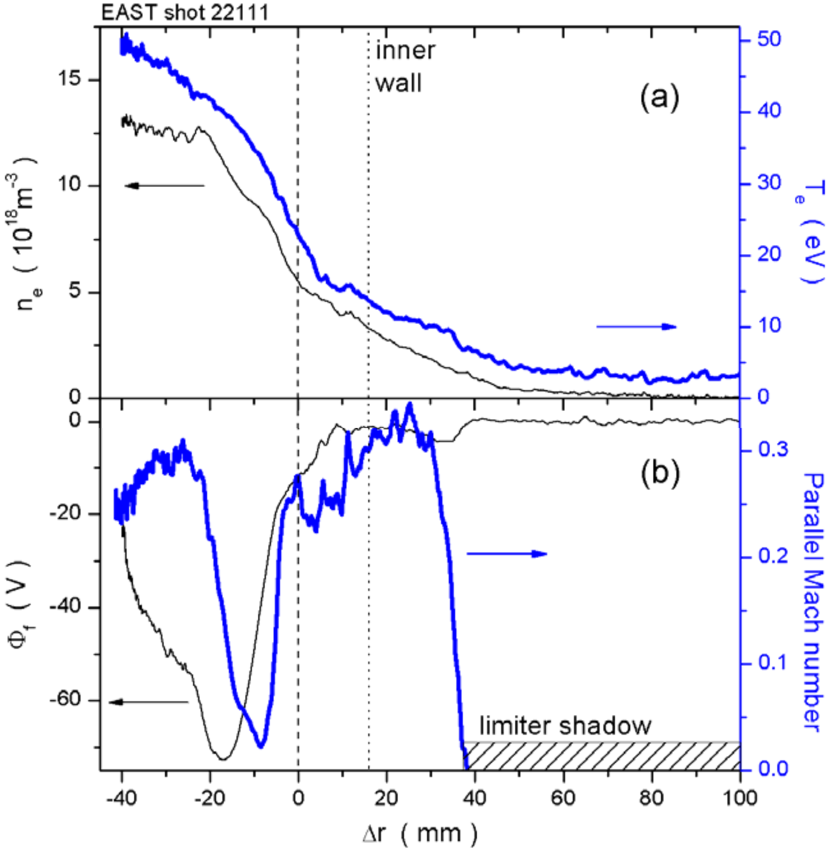
q_{95} ~ 10, W_{ohm} ~ 200 kW

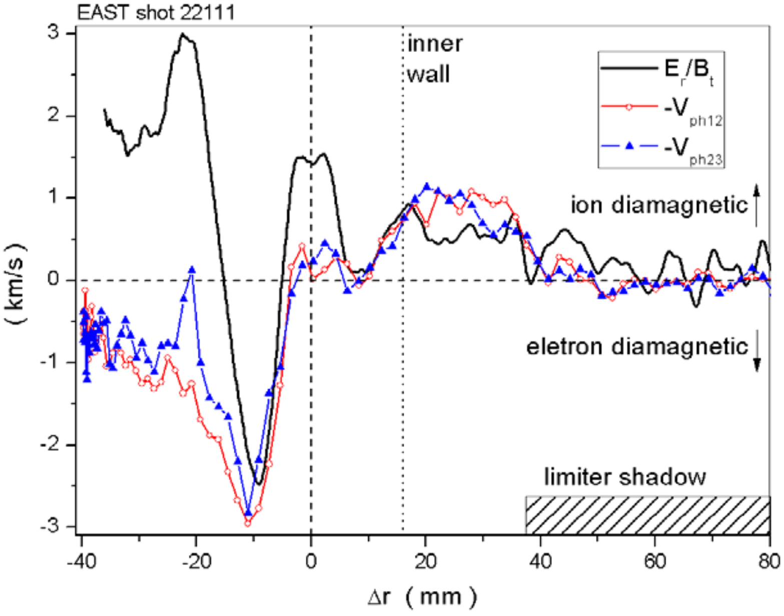
n_{e0} ~ $1.5\times10^{19}m^{-3}$, T_{e0} ~ 500 eV

B_t clockwise, I_p counterclockwise



Situated at the same location of a dip structure in E_r





E_r is calculated as the radial gradient of the plasma potential $\Phi_p = 2.8T_e + \Phi_f$

Neoclassical ‘offset’ $v_{||}$ is much larger than the measured $v_{||}$

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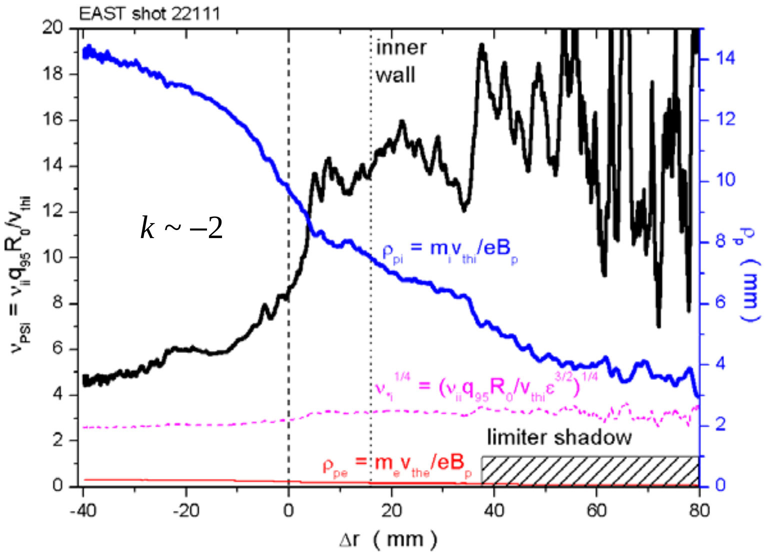
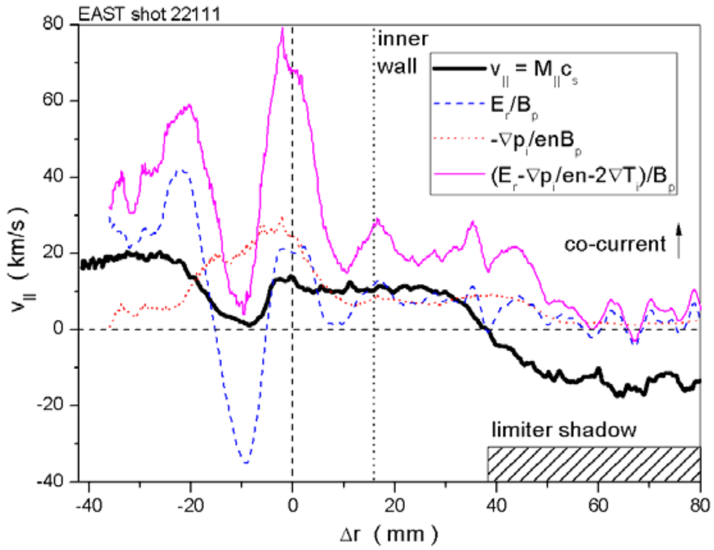


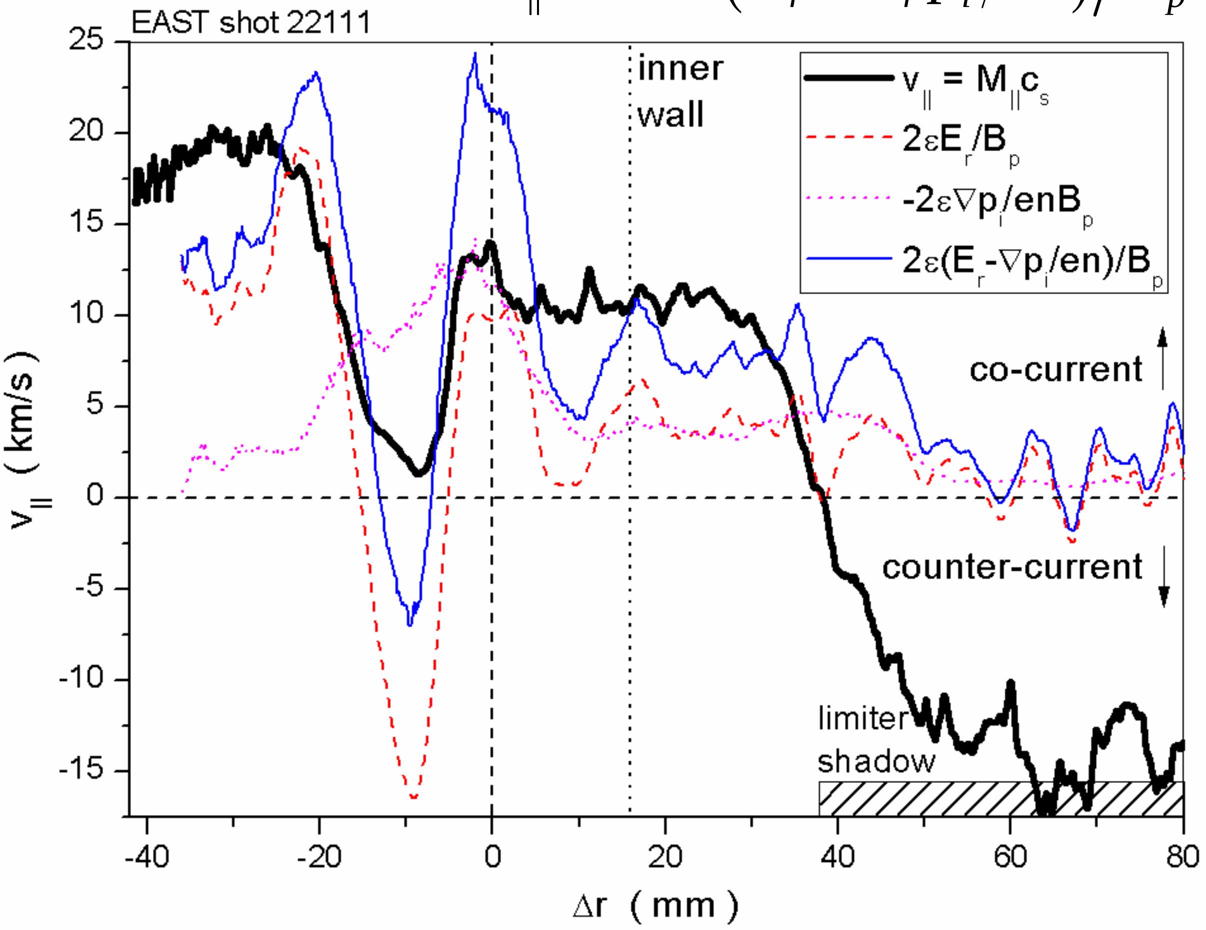


Neoclassical ‘offset’ $$v_{||}^{Neo} \cong \left(E_r - \partial_r p_i / en + k \partial_r T_i / e\right) / B_p$$

The distance from this dip to the separatrix is ~1cm, which is close to the poloidal ion gyroradius and the banana orbit width of thermal ions.

The measured flow was at the same level of the P-S flow

$$v_{\|}^{PS} = 2\varepsilon\left(E_r - \partial_r p_i / en\right) / B_p$$



Toroidal momentum balance near the edge

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Momentum equation **Ampère's law**

$$\partial_t\left\langle m_i n v_t R\right\rangle-\varepsilon_0\partial_t\left\langle \mathbf{E}\cdot\nabla\psi\right\rangle=\mathrm{T}_t=\left\langle \mathbf{J}_f\cdot\nabla\psi\right\rangle=-\left(\varepsilon_\perp+\varepsilon_0\right)\partial_t\left\langle \mathbf{E}\cdot\nabla\psi\right\rangle$$

$$J_f=J_{CX}+J_{RS}+J_{CV}+J_{IOL}+J_{Neo}+\tilde{J}_B+J_{other}$$

$$\mathrm{T}_{tRS}=\left\langle J_{RS}RB_p\right\rangle\sim\alpha_{ballooning}R_0B_pB_0^{-1}m_inr^{-1}\partial_r\left(r\Pi_{RS}\right)$$

Turbulent Reynolds stress

$$\mathrm{T}_{tCV}=\left\langle J_{CV}RB_p\right\rangle\sim-\left(1+2q^2\right)R_0B_pB^{-2}\eta_{i\perp}\partial_r^2E_r$$

Collisional perpendicular viscosity

$$\mathrm{T}_{tIOL}=\left\langle J_{IOL}RB_p\right\rangle\sim R_0B_pGen\nu_{ii}\rho_{pi}\left(\nu_{*i}^{1/4}+\left|X\right|\right)^{-1}\exp\left[-\left(\nu_{*i}^{1/4}+\left|X\right|\right)^2\right]$$

Ion orbit loss (Shaing’s model)

$$\mathrm{T}_{tCX}=\left\langle J_{CX}RB_p\right\rangle\sim-\nu_{i0}m_inR_0\left\langle v_t\right\rangle$$

Charge exchange neutral friction

$$\mathrm{T}_{tNeo}=\left\langle J_{Neo}RB_p\right\rangle\sim 2D_i\rho_{pi}^{-2}m_inR_0\left(U_\parallel^{Neo}-U_\parallel\right)\operatorname{Im}Z$$

Neoclassical viscosity

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1) Turbulent Reynolds stress

2) Collisional perpendicular shear viscosity

3) Ion orbit loss

4) Charge-exchange neutral friction

5) Neoclassical viscosity

An estimation on toroidal torques near the edge

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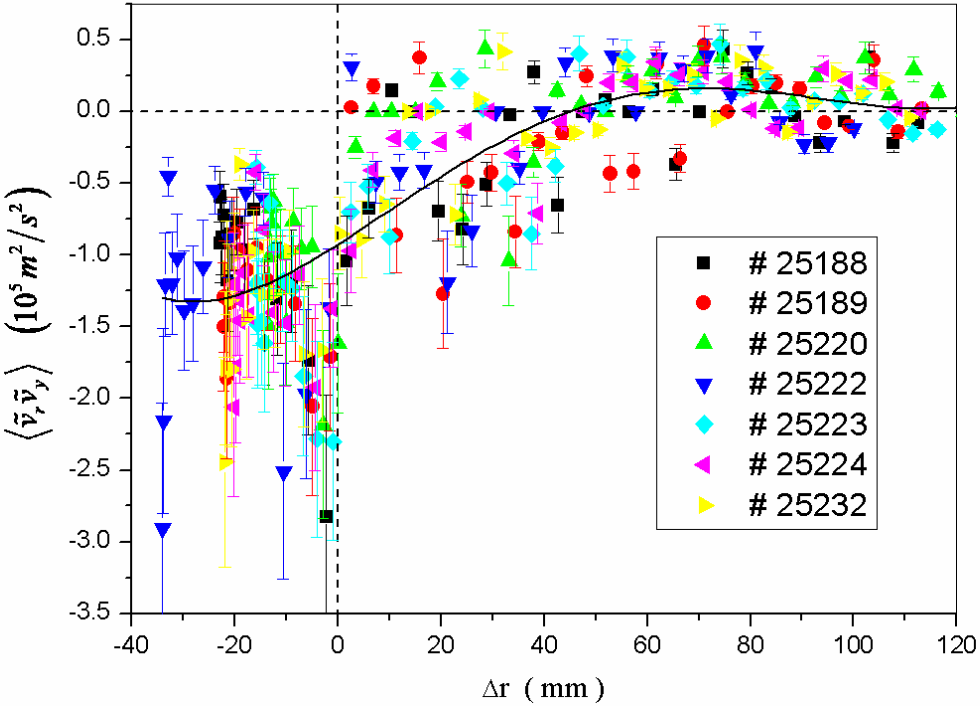
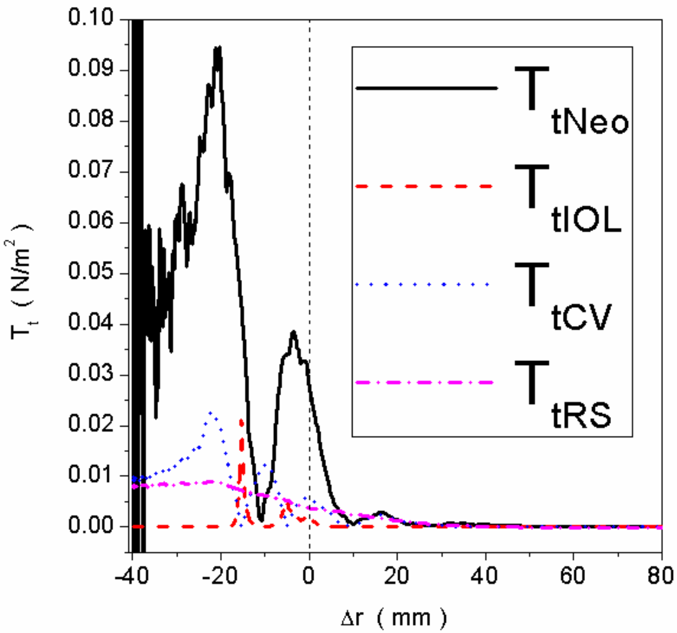
$$\mathrm{T}_{tRS} = \left\langle J_{RS} R B_p \right\rangle \sim \alpha_{ballooning} R_0 B_p B_0^{-1} m_i n r^{-1} \partial_r \left(r \Pi_{RS} \right)$$

$$\mathrm{T}_{tCV} = \left\langle J_{CV} R B_p \right\rangle \sim -\left(1+2q^2\right) R_0 B_p B^{-2} \eta_{i\perp} \partial_r^2 E_r$$

$$\mathrm{T}_{tIOL} = \left\langle J_{IOL} R B_p \right\rangle \sim R_0 B_p Gen \nu_{ii} \rho_{pi} \left(\nu_{*i}^{1/4} + |X| \right)^{-1} \exp\left[-\left(\nu_{*i}^{1/4} + |X| \right)^2 \right]$$





1) Turbulent Reynolds stress

2) Collisional perpendicular shear viscosity

3) Ion orbit loss

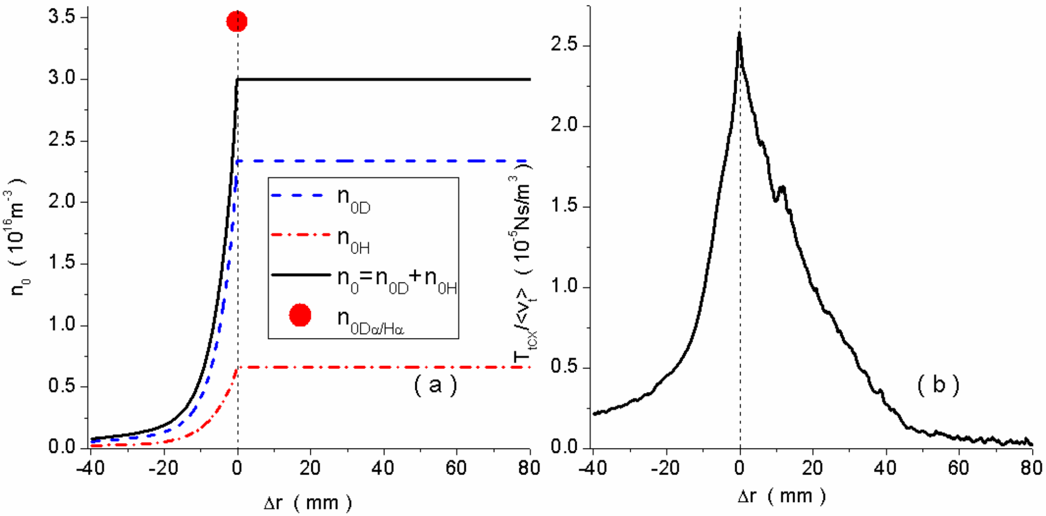
4) **Charge-exchange neutral friction**

5) Neoclassical viscosity

Charge-exchange neutral friction

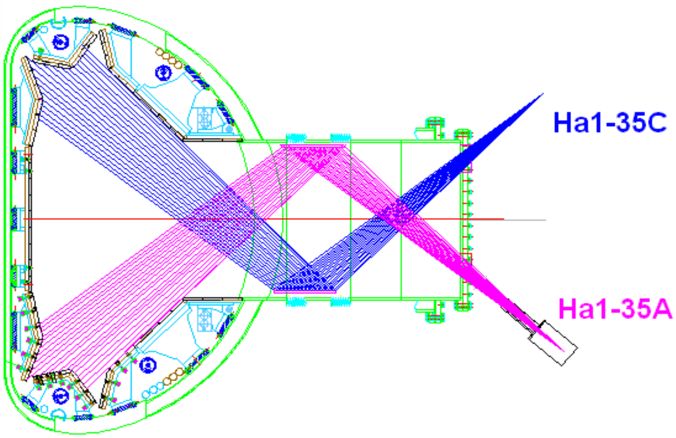
Neutral density was calculated using TRANSP/FRANTIC code validated against the Dα/Hα emission intensity measurements

$$T_{tCX} = \left\langle J_{CX} R B_p \right\rangle \sim -\nu_{i0} m_i n R_0 \left\langle v_t \right\rangle = -n_0 \left\langle \sigma v_i \right\rangle_{CX} m_i n R_0 \left\langle v_t \right\rangle$$



Dα/Hα photodiode arrays (PDAs)

$$I_{D\alpha} = n_e n_0 \left\langle \sigma v_e \right\rangle_{EXC}$$



1) Turbulent Reynolds stress

2) Collisional perpendicular shear viscosity

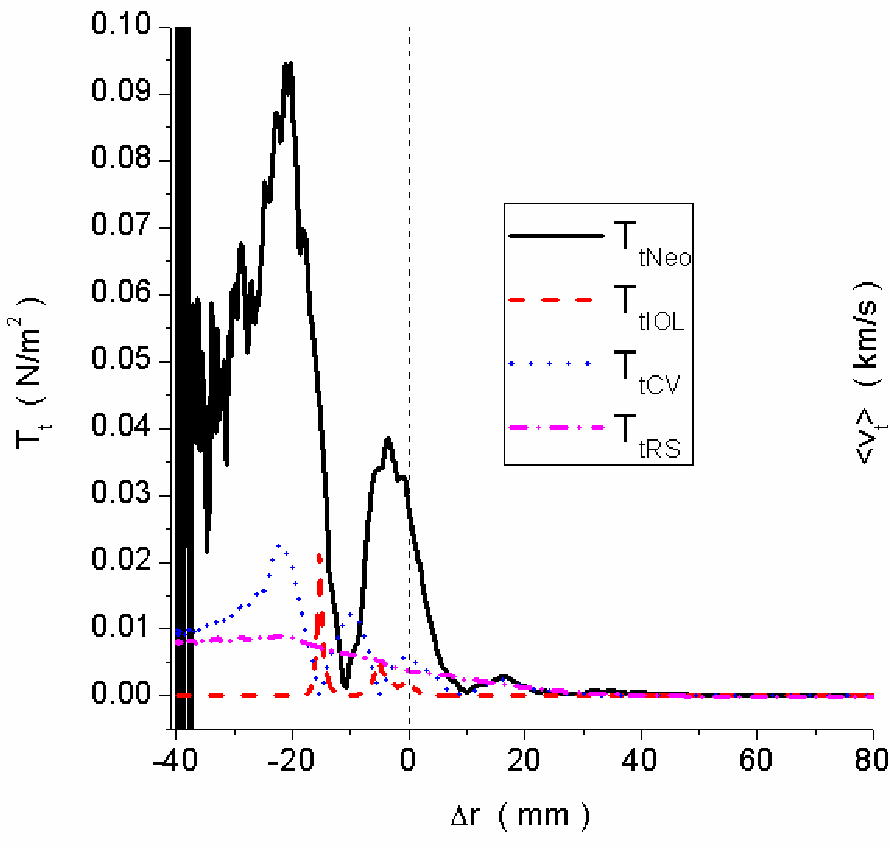
3) Ion orbit loss

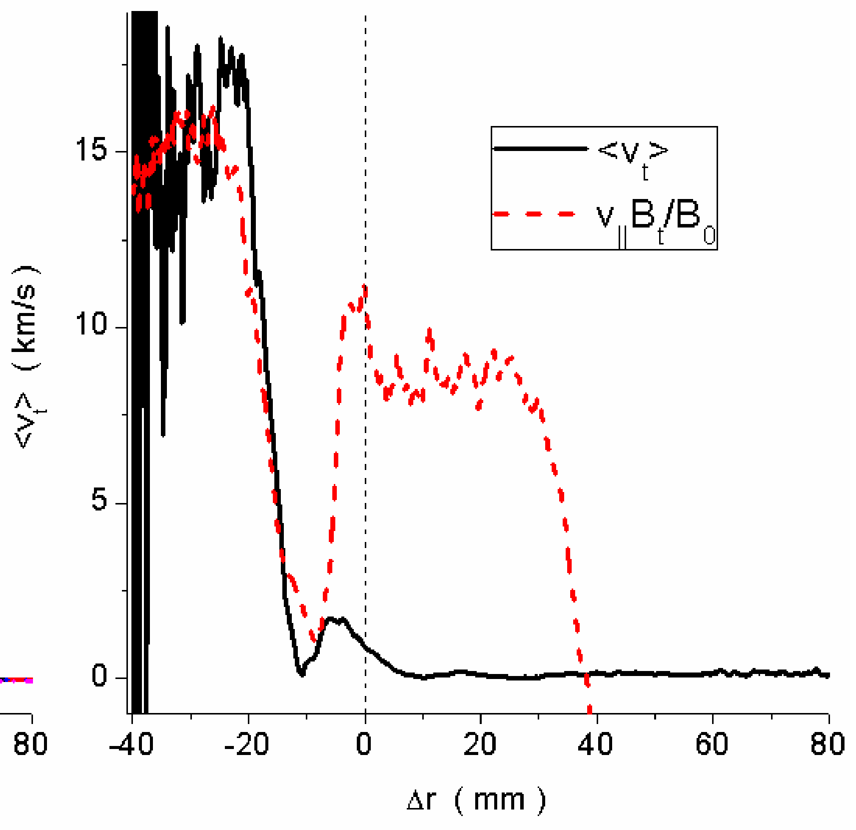
4) Charge-exchange neutral friction

5) Neoclassical viscosity

Neoclassical viscosity

$$T_{tNeo} = \left\langle J_{Neo} R B_p \right\rangle \sim 2 D_i \rho_{pi}^{-2} m_i n R_0 \left(U_{\parallel}^{Neo} - U_{\parallel} \right) \operatorname{Im} Z$$





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Plasma core rotations were measured by high-resolution Imaging X-ray crystal spectrometer

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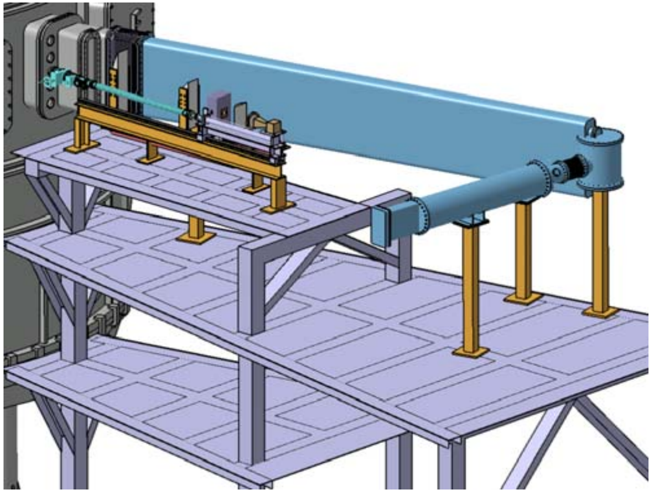
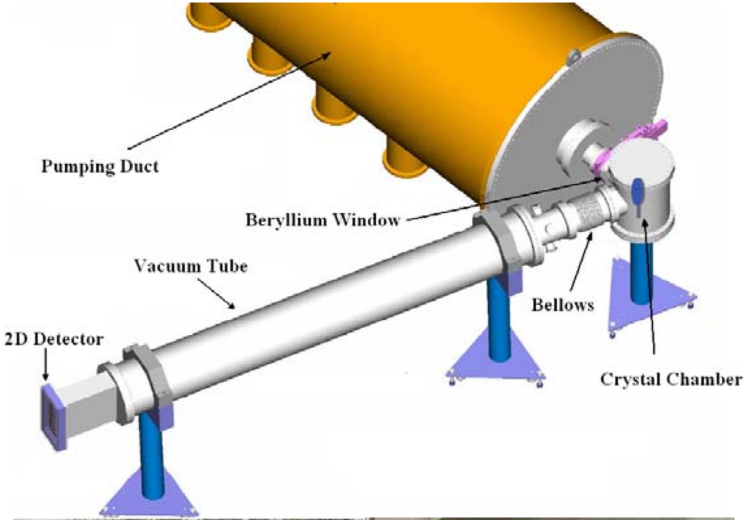
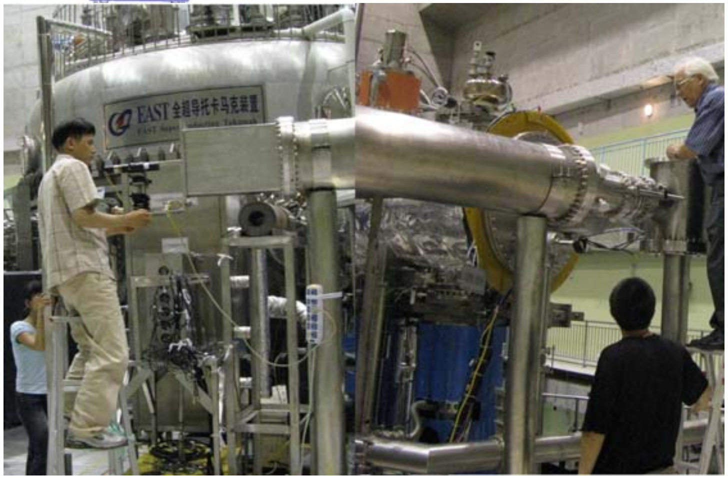
Toloiral rotation

Poroidal rotation







Co-current toroidal rotation ~30 km/s induced by LHCD in DN divertor configuration

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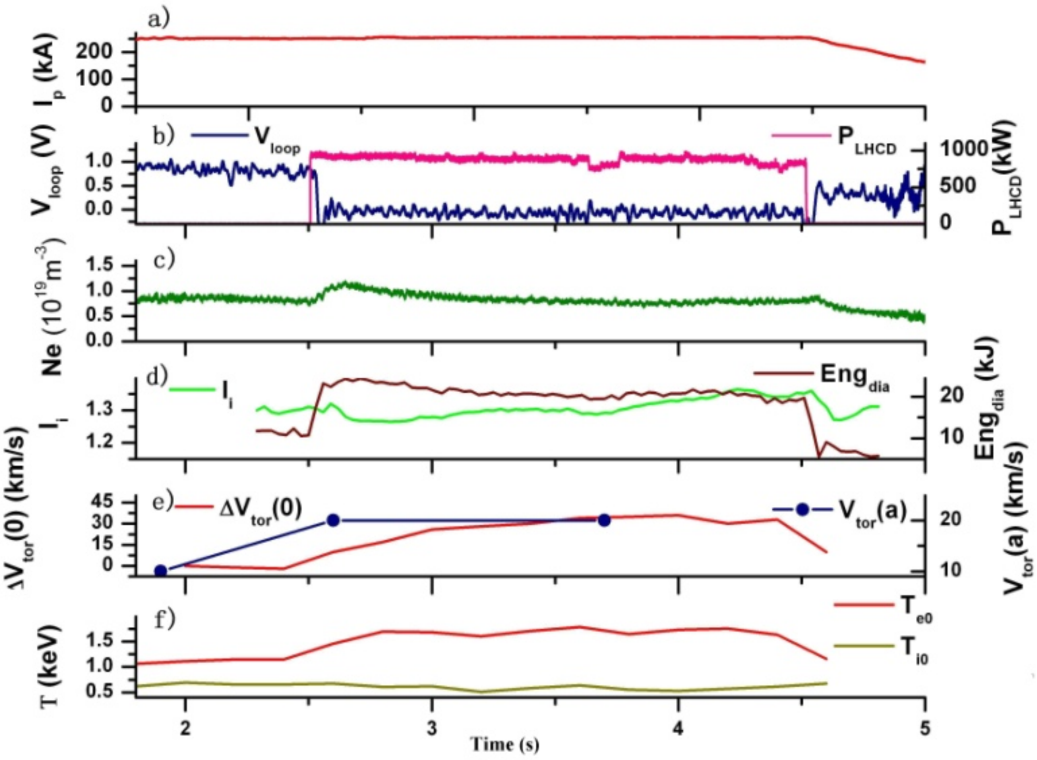

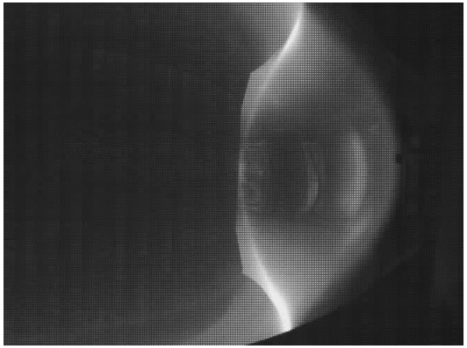

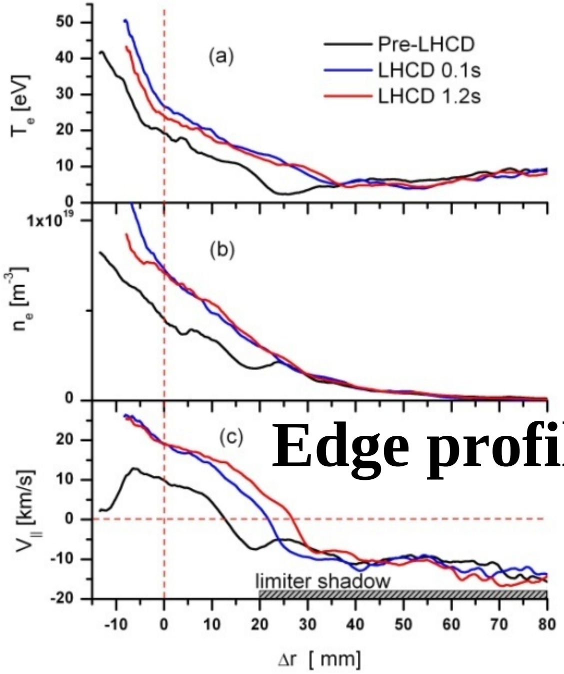

Edge profiles

Comparison between divertor and limiter configurations

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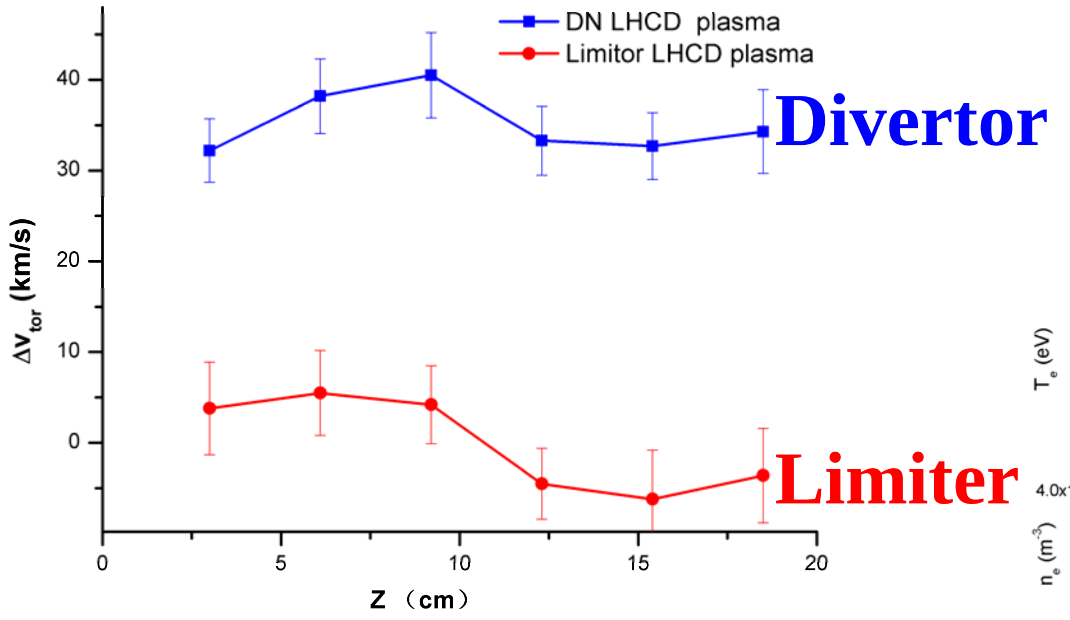
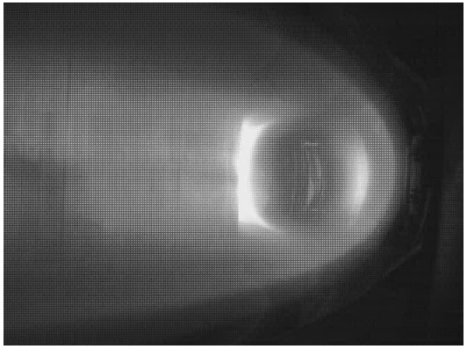
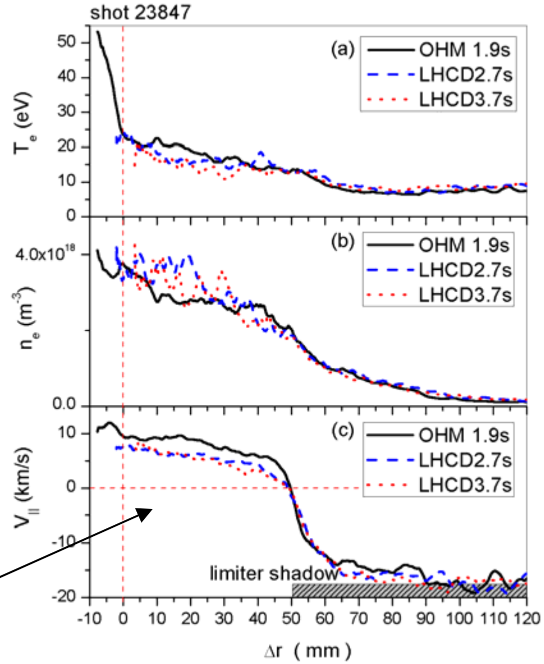




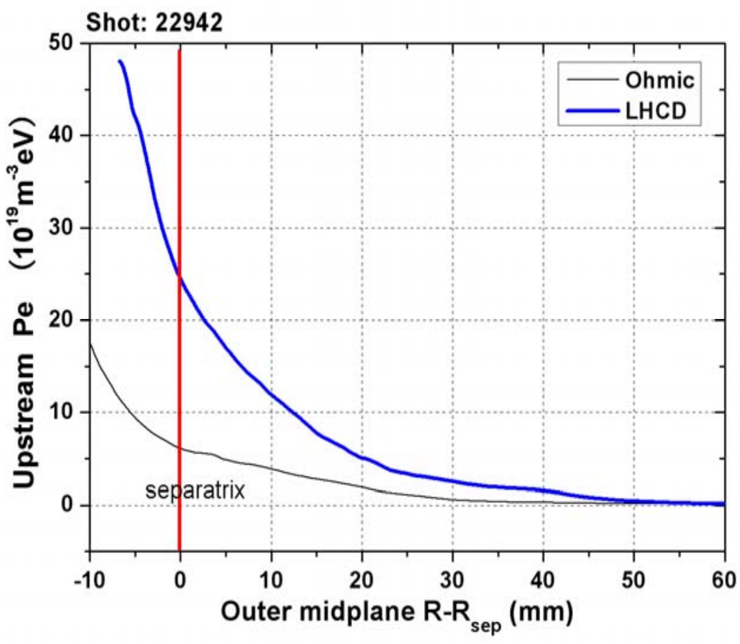


Edge profiles

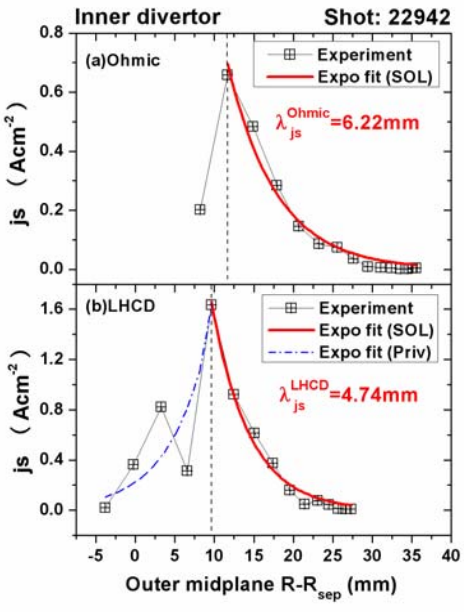
Flow change in SOL was consistent with the P-S flow change

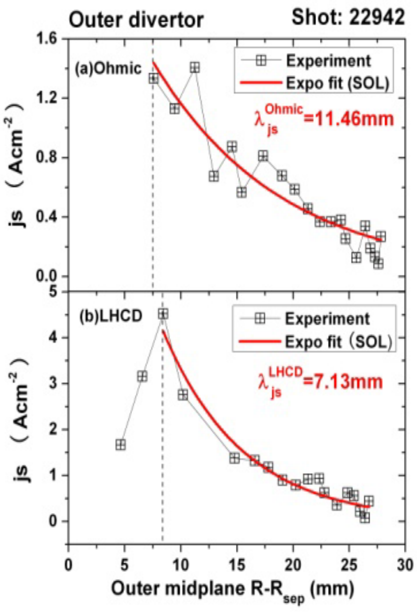
$$v_{\parallel}^{PS} = 2\varepsilon\left(E_r - \partial_r p_i / en\right)/B_p$$

Comparison of upstream p_e profiles between Ohmic and LHCD plasmas

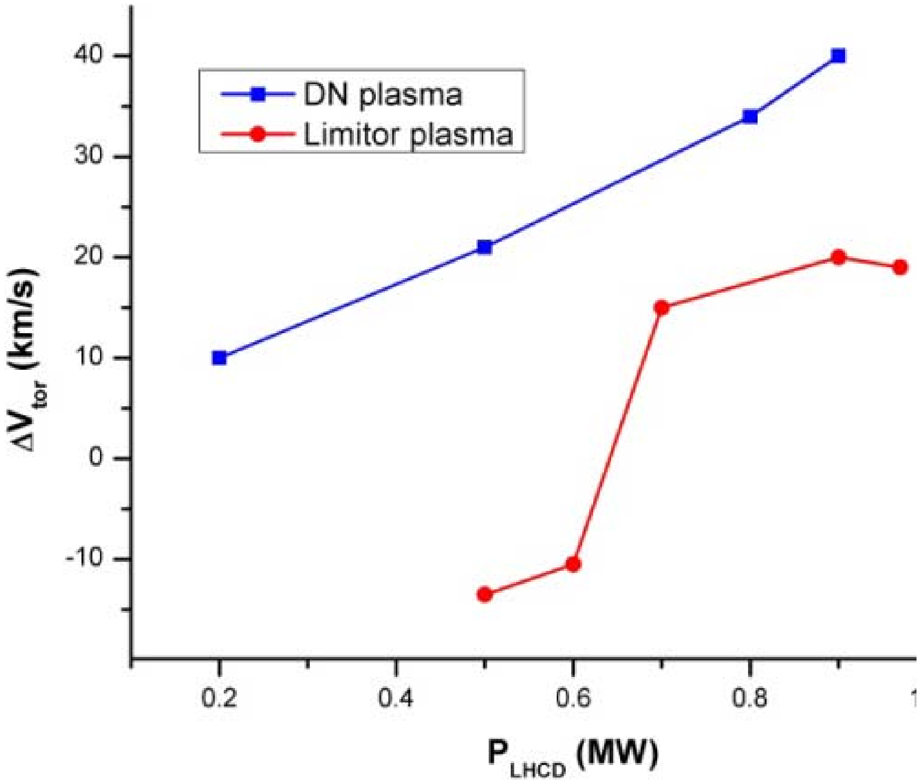


Comparison of target I_s profiles between Ohmic and LHCD plasmas





Parameter dependences for rotation in the core

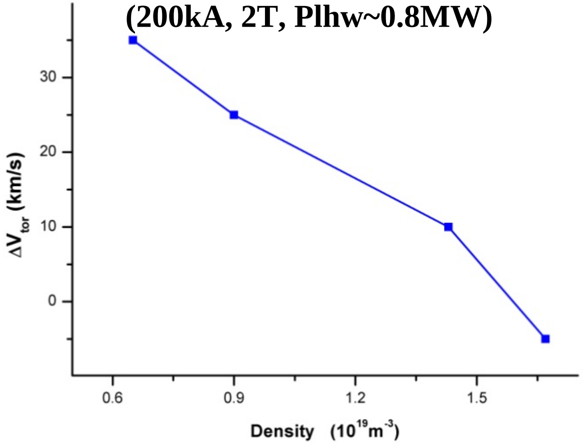


LHCD power dependence for DN divertor and limiter plasmas

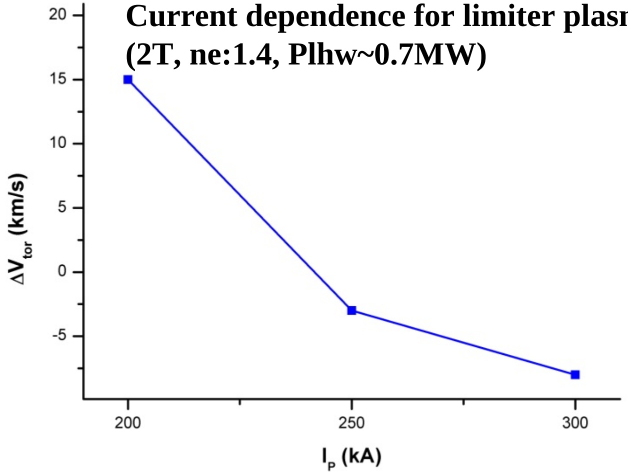
(250kA, 2T,ne,0.9~1.0)

Density dependence for limiter plasmas

(200kA, 2T, Plhw~0.8MW)



Current dependence for limiter plasmas
(2T, ne:1.4, Plhw~0.7MW)



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Parallel flows in the EAST plasma edge

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- SOL $V_{||}$ on the outer midplane was found close to the P-S flow velocity under different situations. It remains in the co-current direction for normal and reversed *B* directions.
- At about 1 cm inside the separatrix a local minimum in $V_{||}$ was observed, from where a co-current rotation increased towards the plasma center and towards the separatrix. The radial width of the $V_{||}$ dip was 1~2 cm, situated at the same location of a dip structure in E_r and steep gradients in n_e and T_e profiles. It was observed in both divertor and limiter configurations.
- In the involved parameter regime it was found that the neutral friction was the dominant damping force and the neoclassical viscosity was the dominant driving force.
- LHCD has been shown to induce a co-current increment in toroidal rotation of up to 40km/s in the plasma core region and 10km/s in the edge under DN divertor configuration, but not under limiter configuration.
- This modification of toroidal rotation develops on different time scales. For the edge the time scale is no more than 100 ms, but for the core the time scale is around 1 s. The modification of toroidal rotation in the edge was found correlated with the change of the P-S flow.
- These results are potentially important for the understanding of boundary conditions for the intrinsic toroidal momentum in tokamak plasmas.

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Thanks for your attention !