Benchmark of local and non-local neoclassical transport calculations in helical configurations

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Background of the work

- **Evaluation of neoclassical transport in stellarator / heliotron devices is important compared to that in tokamaks because of**
  - Relatively large amplitude
  - Strong dependence on radial electric field, especially at low-collisionality
  - Radial electric field estimated from ambipolar condition of NC flux

- **Complexity in solving drift-kinetic equation in helical configurations → mono-energy and local approximation are commonly used (**DKES, GSRAKE, etc.)
  - Reduction of the dimension of DKE to be solved from 5 to 3
  - In some W7AS and LHD ion-root discharges, fairly good agreement has been reported in the particle and energy flux b/w local NC calculations and transport analyses (from deposition profiles) at r/a<0.6. (Dinklage *et al.,* IAEA 2012, Nuclear Fusion 2013)

Purpose of the work

- We further intend to improve the prediction of neoclassical contribution to the total radial fluxes and the E_r profile from ambipolar condition.

- In this work, it is investigated how much does **the non-local, 5D drift-kinetic simulation** (FORTEC-3D code) improve the evaluation of NC transport in the discharges in LHD, W7-AS, and TJ-II, which were precisely studied with local neoclassical transport codes.

- We would like to see in what condition local model is valid, and where the non-local effect becomes important for transport analysis.

Differences in local and non-local NC transport simulations

Drift-kinetic equation for $\delta f(r,\theta,\zeta,v,\xi) = f - f_M$:

$$\frac{\partial \delta f}{\partial t} + \left[(\mathbf{v}_{\|} + \mathbf{v}_{E\times B} + \mathbf{v}_B) \cdot \nabla + \dot{v}\frac{\partial}{\partial v} + \dot{\xi}\frac{\partial}{\partial \xi} \right] \delta f = -\left(\mathbf{v}_B \cdot \frac{\partial}{\partial r} + \dot{v}\frac{\partial}{\partial v} \right) f_M(r,v) + C(\delta f)$$

Here, C(δf) is the collision term, $\xi = v_{\|}/v$, and

$\boldsymbol{v}_B = \left(\frac{\mu}{e}\right)\frac{\boldsymbol{B}\times\nabla B}{B^2} + \left(\frac{mv^2\xi^2}{eB}\right)\boldsymbol{b}\times\boldsymbol{b}\cdot\nabla\boldsymbol{b}$ represents the magnetic drift velocity.

- **Local and mono-energy methods** [Reduced to 3-D (θ,ζ,ξ)]
  - **Simplified collision operator :** Adopt pitch-angle scattering operator
  - **Small-magnetic-drift & mono-energy approximations** :

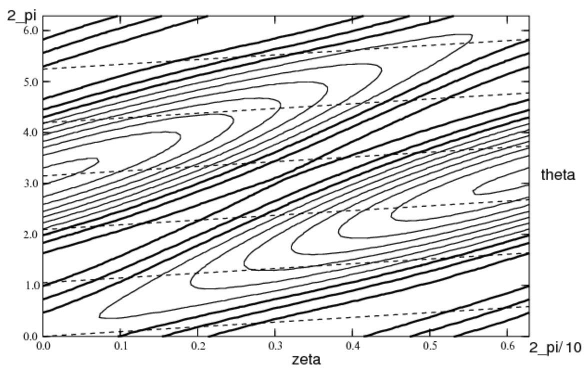
    Neglect the $[\boldsymbol{v}_B \cdot \nabla + \dot{v}(\partial/\partial v)]\delta f$ term ($\dot{v} = e\boldsymbol{v}_B \cdot \boldsymbol{E}_r/mv$)

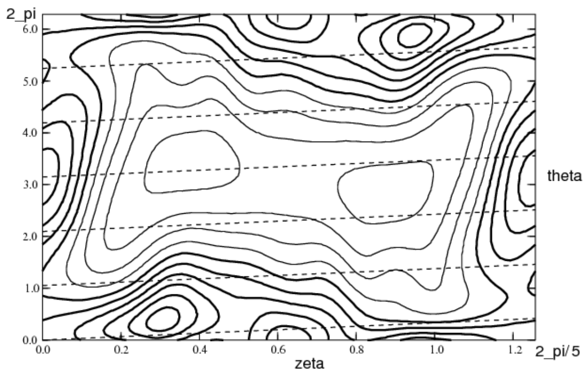
    - **DKES:** Solves the DKE by using the variational principle.
    - **GSRAKE:** Ripple-averaged DKE (both passing and trapped particles). Simplification in the magnetic field spectrum.

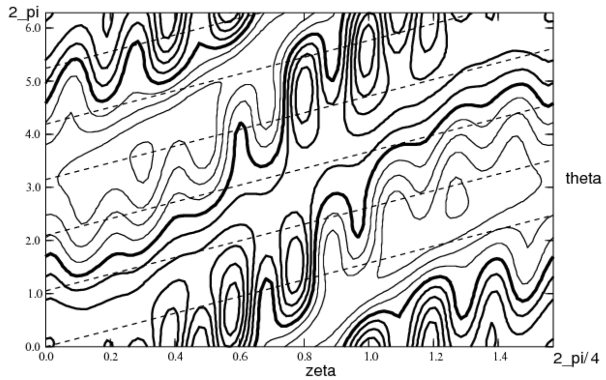
- **Non-local, full-5D method**
  - **FORTEC-3D:** Solve **the full 5-D DKE** as it is, using the δf-PIC method.
  - Exact guiding-center trajectory **including the $[\boldsymbol{v}_B \cdot \nabla + \dot{v}(\partial/\partial v)]\delta f$ term** (what we call **"non-local effect"** here).
  - Pitch-angle & energy scattering collisions with conservation property.

Configuration of target plasmas

B-contour ($@r = 0.85a$)



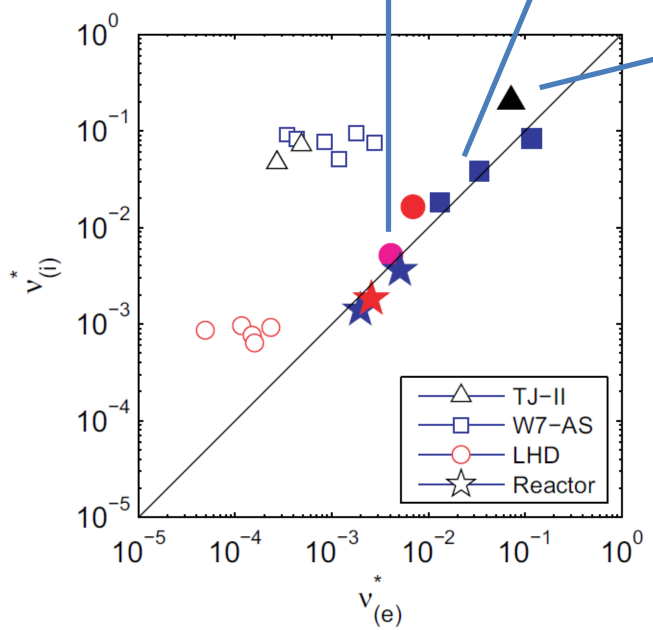




LHD (l=2, N=10 heliotron)
(#109696 t=4.44s)
$1/\nu - \sqrt{\nu}$ regime (near the plateau boundary)

W7-AS (N=5 modular-coil helias)
(#34609, t=0.3s)
Plateau regime (near the $1/\nu$ boundary)

TJ-II (N=4 heliac)
(#19065, t=1.17s)
Plateau regime (near the $1/\nu$ boundary)

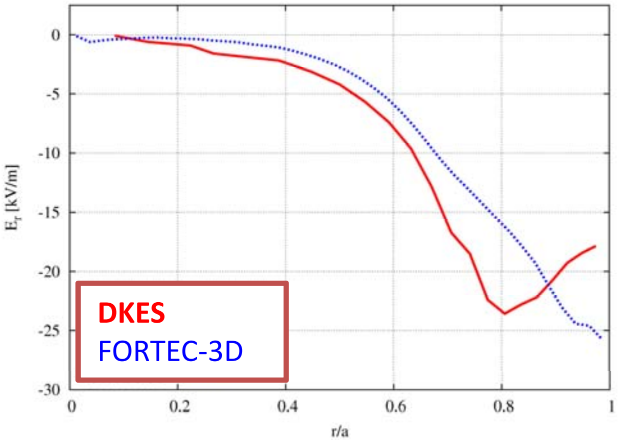


- The target discharges are characterized by $\nu_{*i} \sim \nu_{*e}$, since this situation is relevant to prospect the neoclassical transport in future reactors in stationary operation, $T_i \sim T_e$.
- The ambipolar condition in this condition is expected to be ion-root (negative E_r).

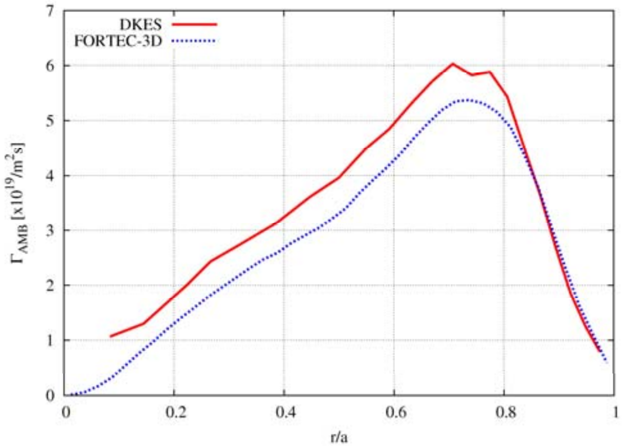
← Ion and electron collisionality of the discharges in the three devices (Dinklage et al., IAEA 2012, NF 2013)

Simulation result : (1) W7-AS (Comparison with DKES)

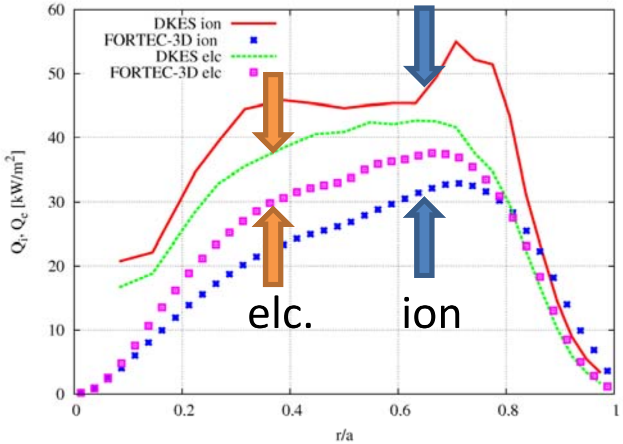
Ambipolar-E_r : E_{amb}



Ambipolar particle flux : Γ_{amb}



Energy flux : $Q_{i,e}(@E_{amb})$



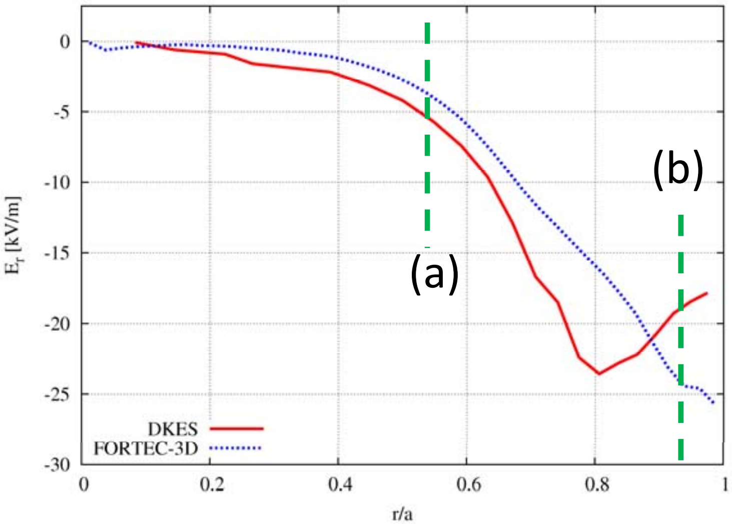
- Ambipolar condition is determined by scanning the E_r profile which satisfies $\Gamma_i(r, E_r) = \Gamma_e(r, E_r)$.

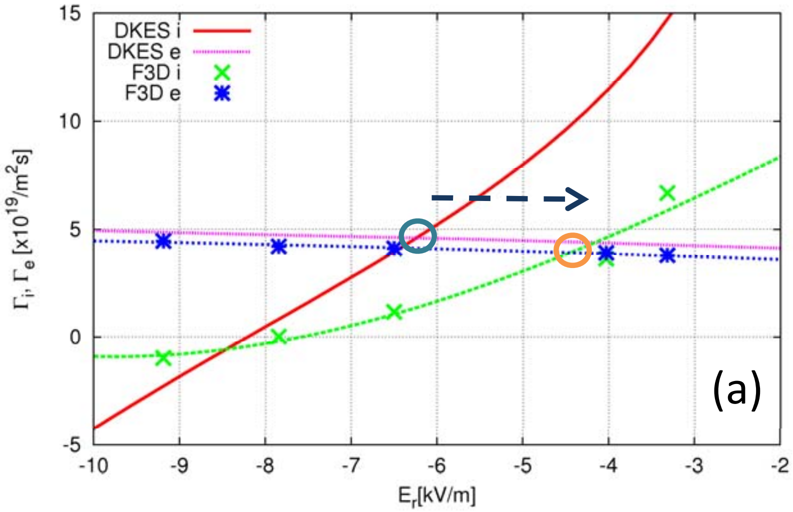
➢ Difference in the E_{amb} b/w local and non-local codes is small in the core region but becomes larger towards the plasma boundary.

➢ On the contrary, difference in Γ_{amb} is small in the entire region.

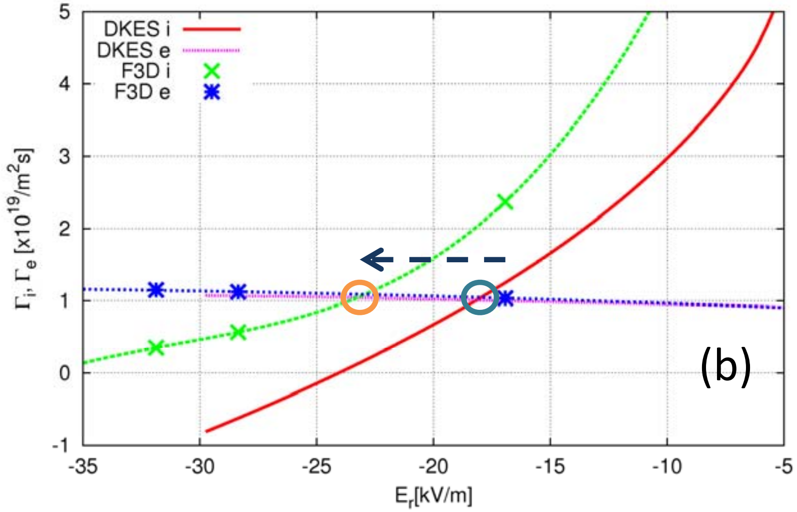
➢ Most significant difference appears in Q_i.

Finite magnetic drift causes the difference in ambipolar-E_r





A) $|E_r| \sim 0$ → Assumption $V_{E\times B} \gg \mathrm{V_B}$ is not good. $V_B \cdot \nabla\theta$ term $\left(\propto \frac{\partial B}{\partial r}\right)$ causes poloidal precession of ripple-trapped particles and prevents $1/\nu$-type large NC flux even without $E \times B$ rotation.



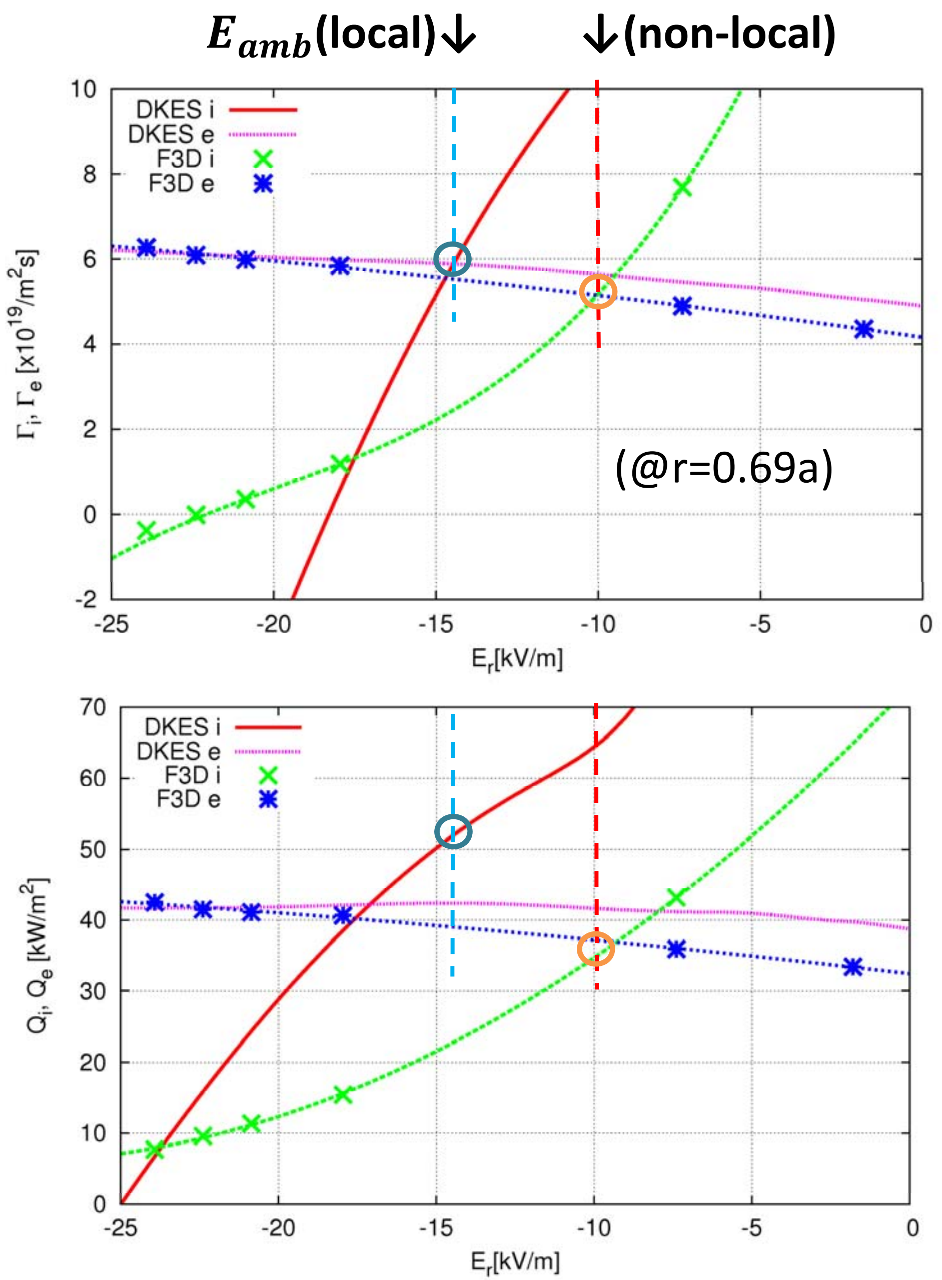
B) $|E_r| \gg 0$ → Assumption $V_{E\times B} \gg \mathrm{V_B}$ is valid. $V_B \cdot \nabla \mathrm{r}$ term $\left(\propto \frac{\partial B}{\partial \theta}\right)$ becomes more effective near the boundary, since magnetic ripple is larger there.
Also, at $\rho > 0.9$, poloidal Mach number is $\cong 1$.
→ Incompressible-$E \times B$ approximation used in DKES is not valid.

Finite magnetic drift can cause large difference in Q_i

- Even if E_{amb} changes, difference in Γ_{amb} is small.

→ because of weak dependence of Γ_e on E_r.

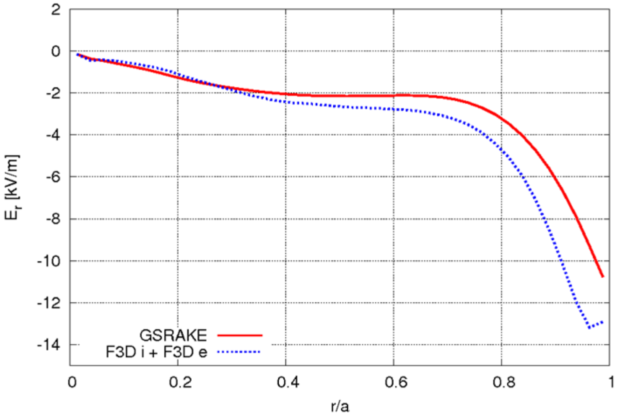
- Not only because of difference in E_{amb} but also the difference in the dependence on E_r causes the large difference in Q_i.



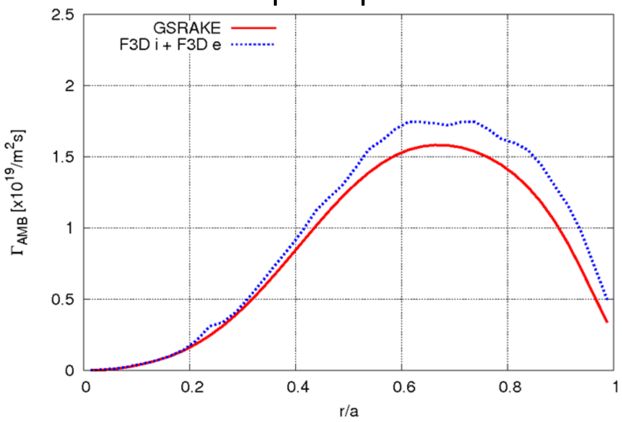
Simulation result : (2) LHD

(Comparison with GSRAKE)

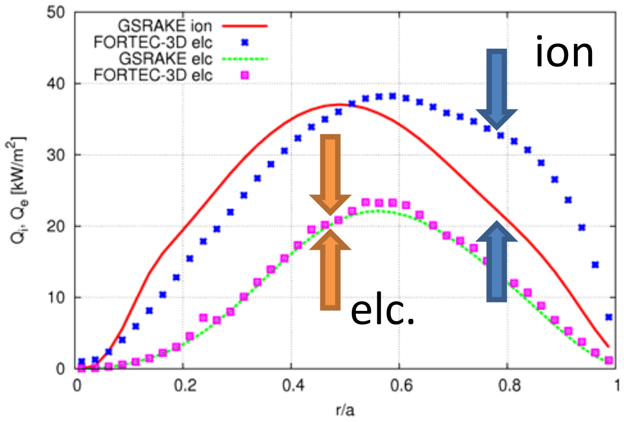
Ambipolar E_r

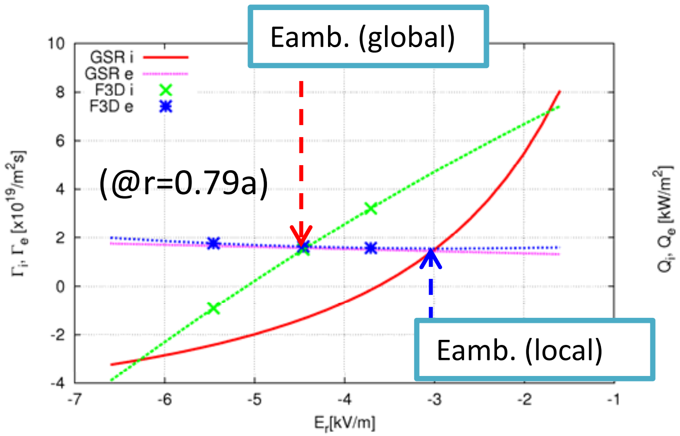


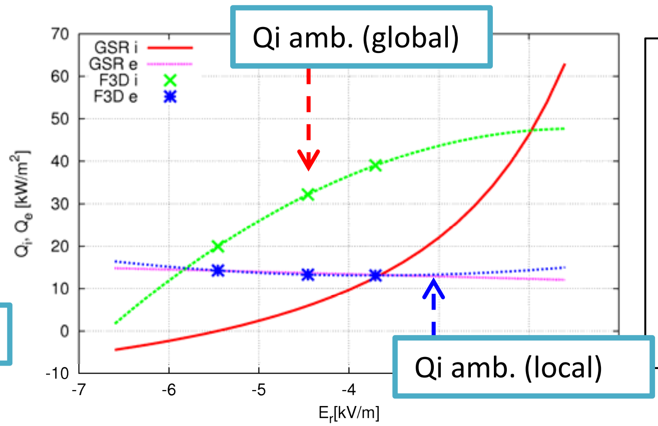
Ambipolar particle flux



Energy flux







- **Local & mono-energy solutions of Γ_i and Q_i tend to be peaky at $E_r \rightarrow 0$** since it neglects $v_{B,r}$ drift which is important at there.

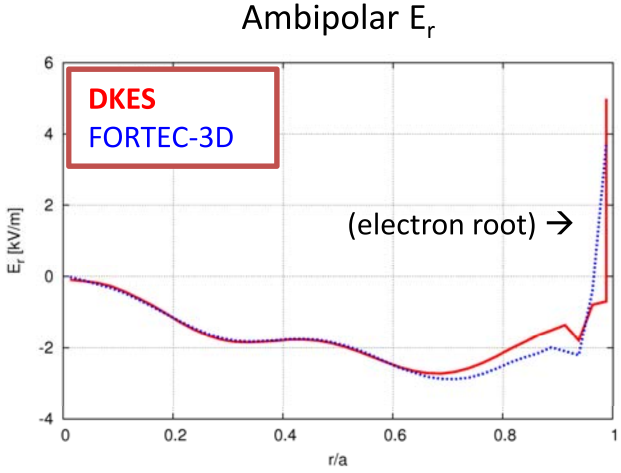
⇒ Results in difference in E_{amb}

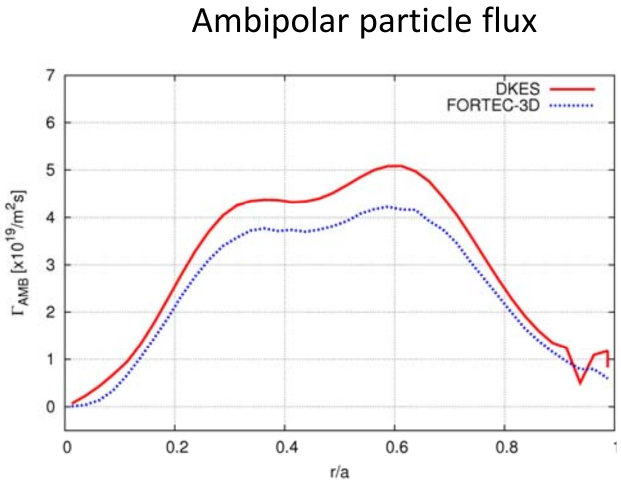
- Since Γ_e and Q_e depend on E_r weakly and zero-orbit-width approximation is valid for electrons, **ambipolar-Γ and Q_e differs only slightly b/w two calculation methods.**

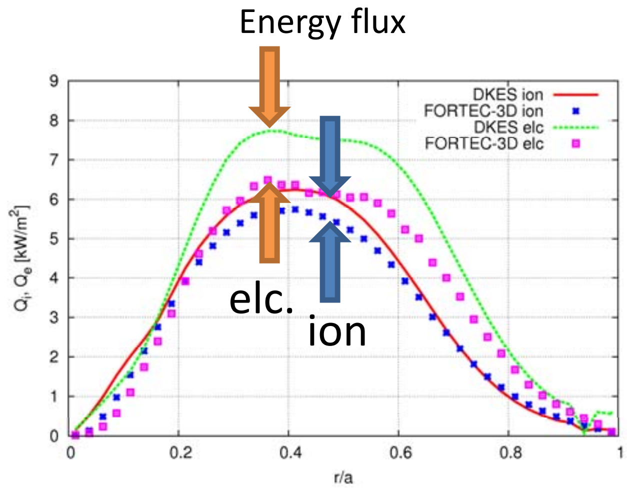
- **Difference in amb-Q_i between local and global calculations are much more significant than that in Q_e.**

⇒ Same tendency as in the W7-AS case

Simulation result : (3) TJ-II (Comparison with DKES)

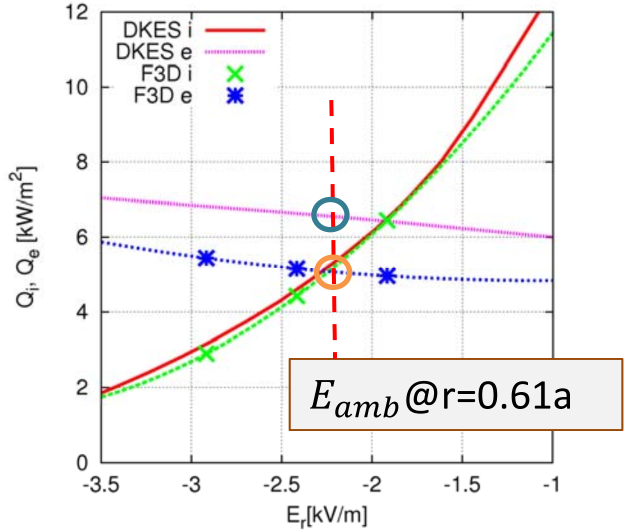




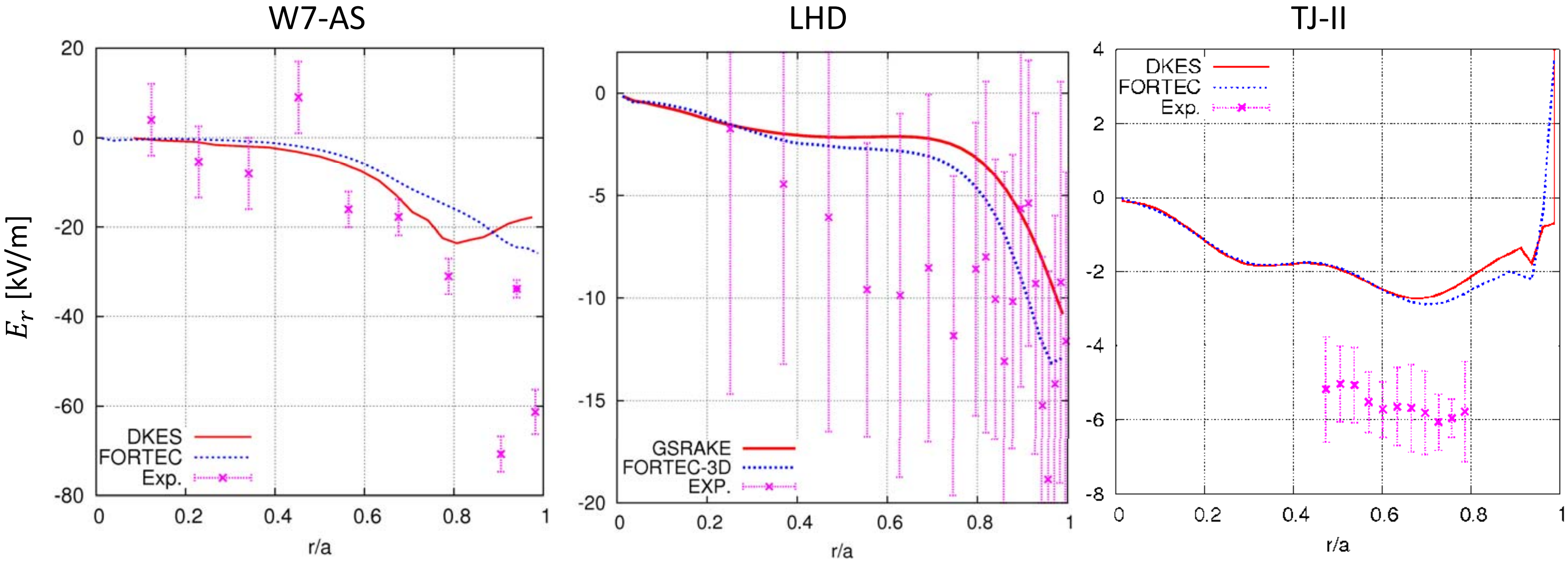


- As the plasma is **most collisional among the 3 cases**, non-local effect is least expected to appear in this case.
- **Ambipolar-E_r coincides well b/w local and non-local simulations**.
- However, **difference b/w two solution is more significant in Q_e than in Q_i**.

✓ Finite $V_B \cdot \nabla\theta$ term, which is not negligible compared to $V_{E\times B} \cdot \nabla\theta$ term for electrons at the ion-root E_r, seems to significantly affect the evaluation of Q_e in the TJ-II configuration.



Comparisons with experimental analysis
(1) Radial electric field



- Measured E_r profile (HIBP or CXRS) < NC ambipolar condition, but reasonable agreement is found in LHD and W7-AS cases.
- For TJ-II case, non-local NC simulation cannot resolve the discrepancy.
- Some unconsidered mechanism of ion particle loss other than the bulk ion NC flux is required to explain the difference.
  - ✓ Loss of fast ions from NBI heating? Impurity ion transport?

Comparisons with experimental analysis
(2) Radial energy flux

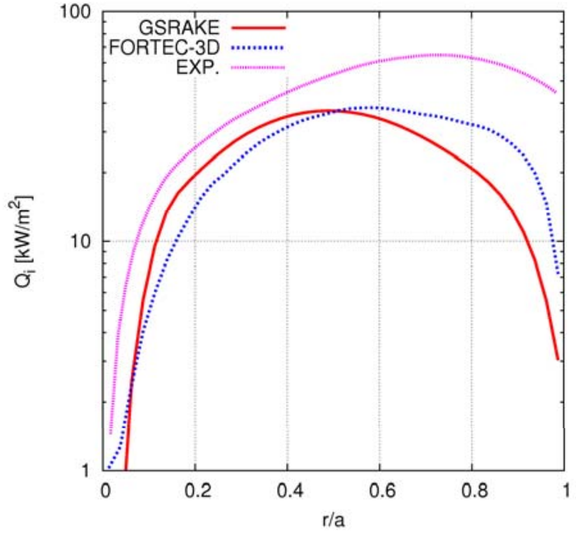
Energy fluxes were analyzed by **TASK3D** or **ASTRA** codes from the heat deposition profile.

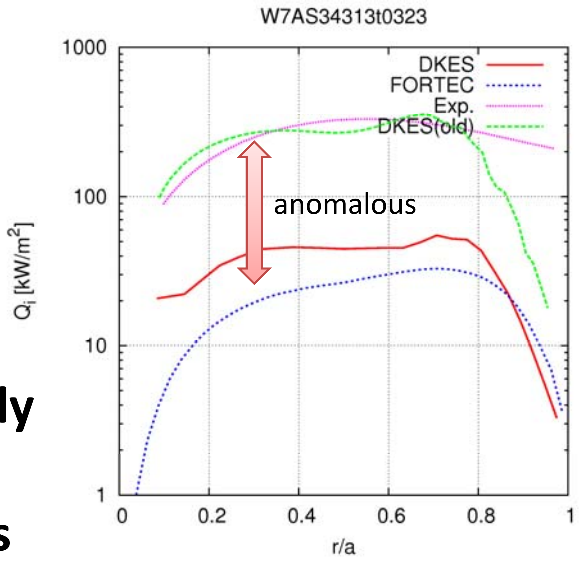
- **In the LHD case,** good agreement of Q_i between local NC flux from GSRAKE and experiment analysis within factor 2 (in the core region) has been reported.
- Non-local NC calculation also changes the estimation of Q_i(NC) at ion-root by factor 2 from the local one.

- **In the W7-AS case,** it is found that previous DKES solution (lower accuracy in the MHD equilibrium and low resolution in solving DKES) differs much from the new DKES and FORTEC-3D solutions, though it agrees better with ASTRA in the core region.
- Contribution of anomalous transport to the energy flux is almost one order larger than that from neoclassical transport, according to the improved calculations.

Improvement of the evaluation of neoclassical Q_i is really important for the quantitative accuracy of transport analysis, especially if the neoclassical energy transport is dominant.

LHD





Summary

- FORTEC-3D non-local neoclassical transport code was applied to LHD, W7-AS and TJ-II to see the difference in the ambipolar NC flux and E_r from those evaluated by the local, mono-energy approximation codes.

- In ion-root plasmas, **the ambipolar $\boldsymbol{E_r}$ profile in these configurations estimated from local & mono-energy codes is similar to that is obtained by non-local simulation.**

- Though E_{amb} profiles are similar between local and non-local NC simulations, the **magnetic drift term**, which is neglected in local NC codes, is found to **alter the $\boldsymbol{Q_i}$ at the ion-root as large as by factor 2**.

- We plan to extend this analysis to more collisionless cases, in which non-local NC calculation is expected to be more important.

backup slides

Procedure to find the ambipolar condition by FORTEC-3D

- FORTEC-3D can solve DKE and the time evolution E_r for only a single particle species at once. **In previous studies, only ion neoclassical transport was solved by FORTEC-3D**, while table of $\Gamma_e(r, E_r)$ was prepared from another local code.
- To determine the ambipolar condition from **both Γ_i and Γ_e by FORTEC-3D** code, the following three steps are used.

1: Run a simulation and solve time evolution of E_r until it reaches a steady state solution.

$$\epsilon_\perp \frac{\partial}{\partial t} E_r = -e\left(Z_i \Gamma_i - \Gamma_e\right)$$

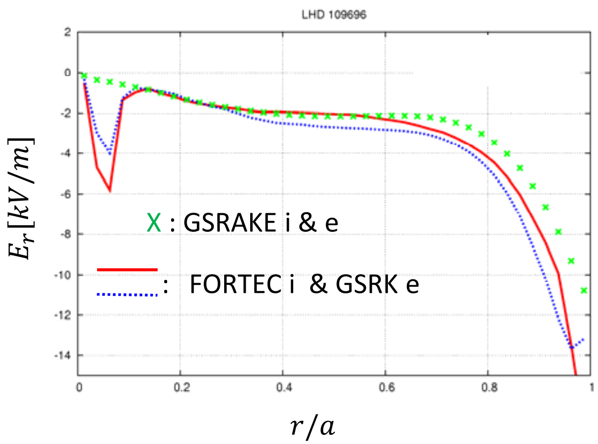
FORTEC-3D　Local code

2: Using three E_r profiles ($E^{(1)}(r), E^{(1)}(\mathrm{r}) \pm \Delta E$), neoclassical fluxes (Γ, Q) for ion and electron are evaluated by FORTEC-3D.
(Note : E_r is time constant here.)

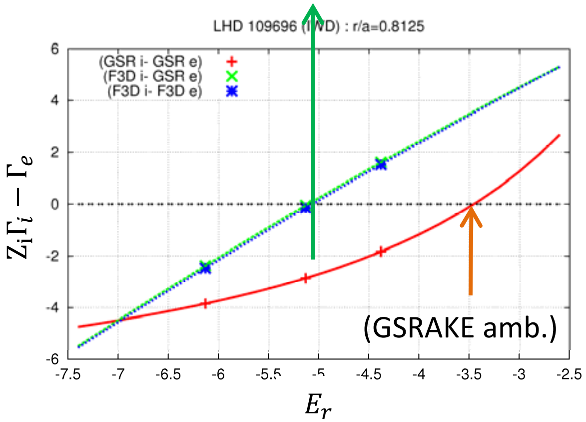
3: From fitting curve of $(\mathrm{Z_i}\Gamma_i - \Gamma_e)\ [E_r]$, determine the ambipolar E_r ($E^{(2)}$). Also, using the fitting curves for Q, estimate energy flux at the ambipolar condition ($Q_i\ (E^{(2)})$, $Q_e(E^{(2)})$).

(Γ, Q) dependence on E_r around $E^{(1)}$.

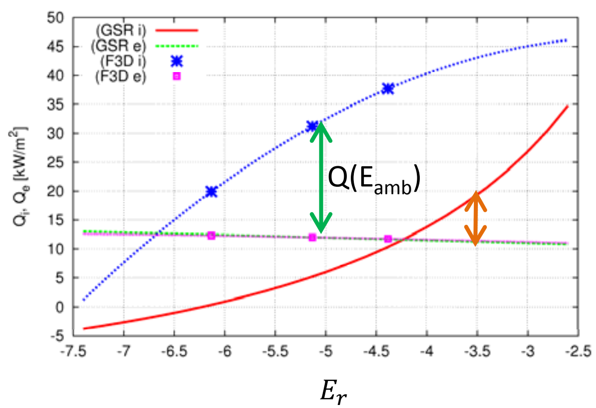
1st guess of amb. $E^{(1)}$



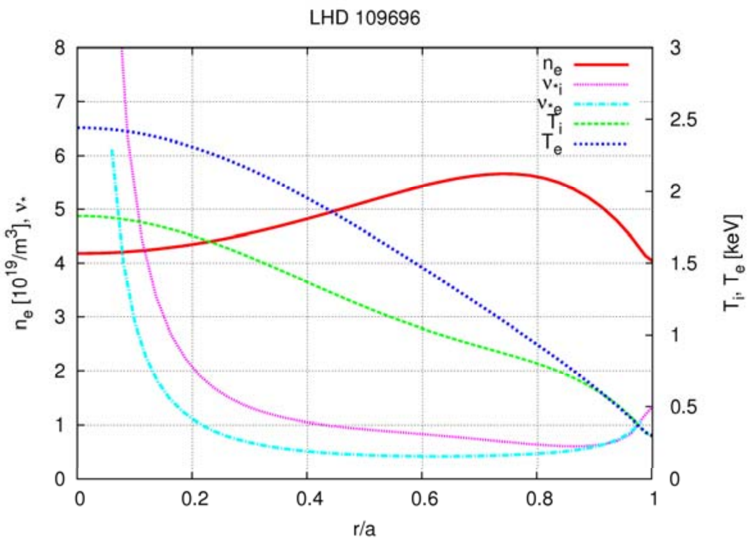
$E^{(2)}$ from FORTEC-3D i&e

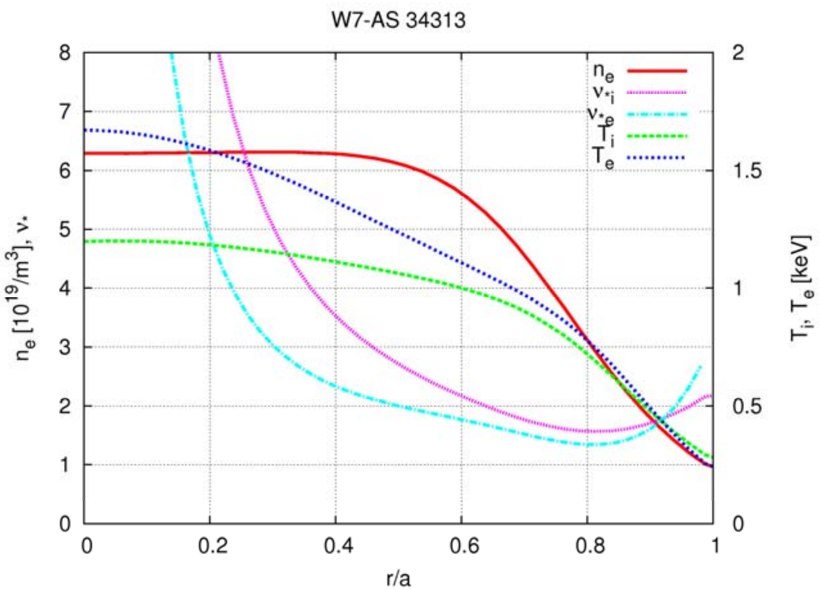


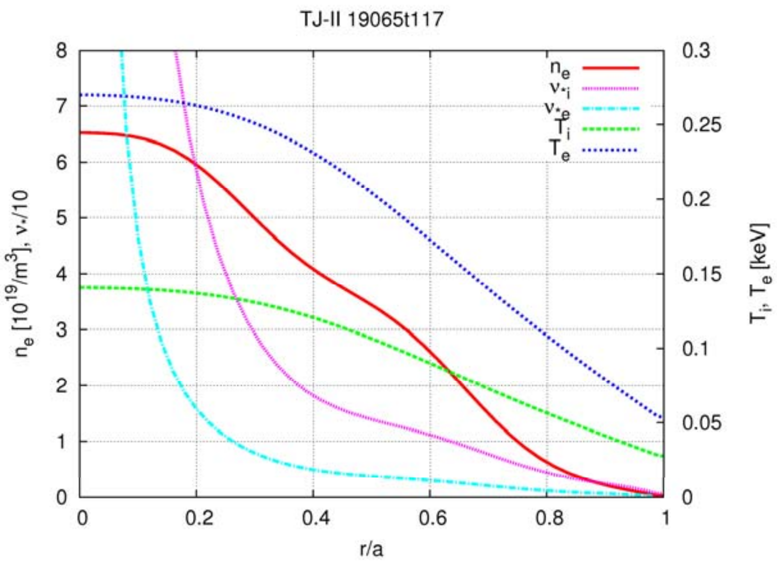
Amb. flux interpolation



density , temperature profiles





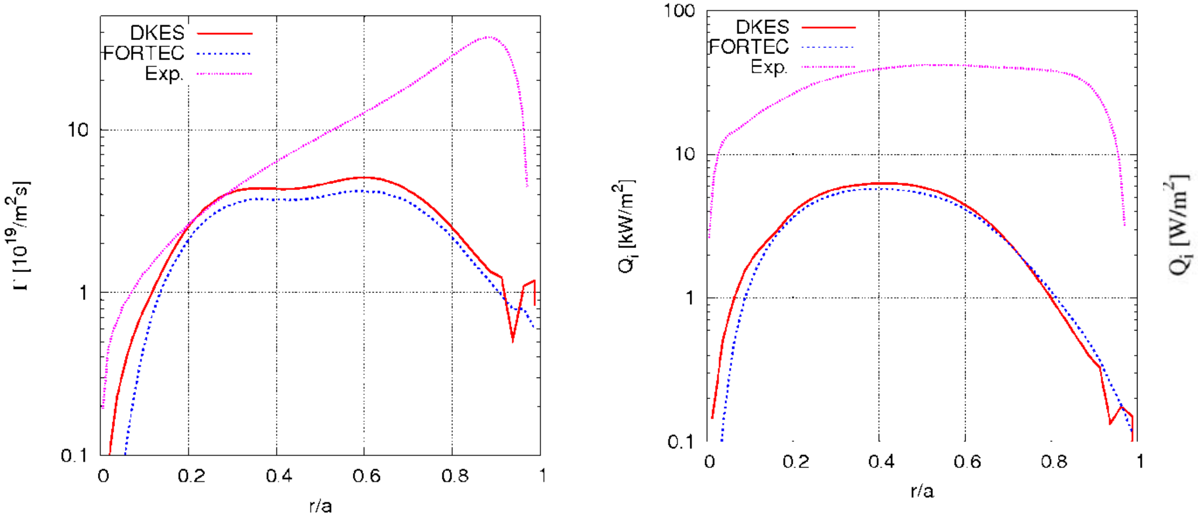


Comparisons with experimental analysis
Radial particle / energy flux in TJ-II

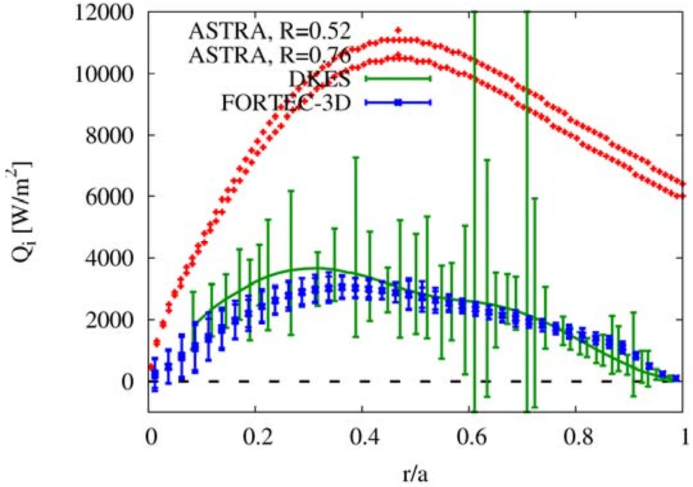
The TJ-II case analyzed here has $10\times$ difference b/w Q_i(NC) and Q_i(Exp.).

However, we also found a case where Q_i(Exp.)$= 2{\sim}3\times Q_i$(NC,local) $\cong Q_i$(NC,non-local)

TJ-II(#19065)



TJ-II(#28263)
(Velasco, P2.077)



Comparisons with experimental analysis
Radial particle / energy flux in W7-AS

- Particle and energy fluxes in the W7-AS discharges was analyzed by ASTRA code considering the particle and heat deposition profiles.