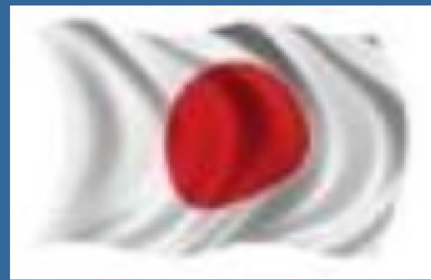
Impact of density and heating power on impurity confinement in W7-AS

Rainer Burhenn

Max-Planck-Institut für Plasmaphysik, EURATOM-Ass., Greifswald, Germany

- with additional references to results of LHD, TJ-II -

For comparison and identification of similarities and problems …



... with additional references to the interesting results of LHD, CHS and TJ-II

Impurity transport in W7-AS I 1

I. Dependence of impurity confinement time on plasma parameters:

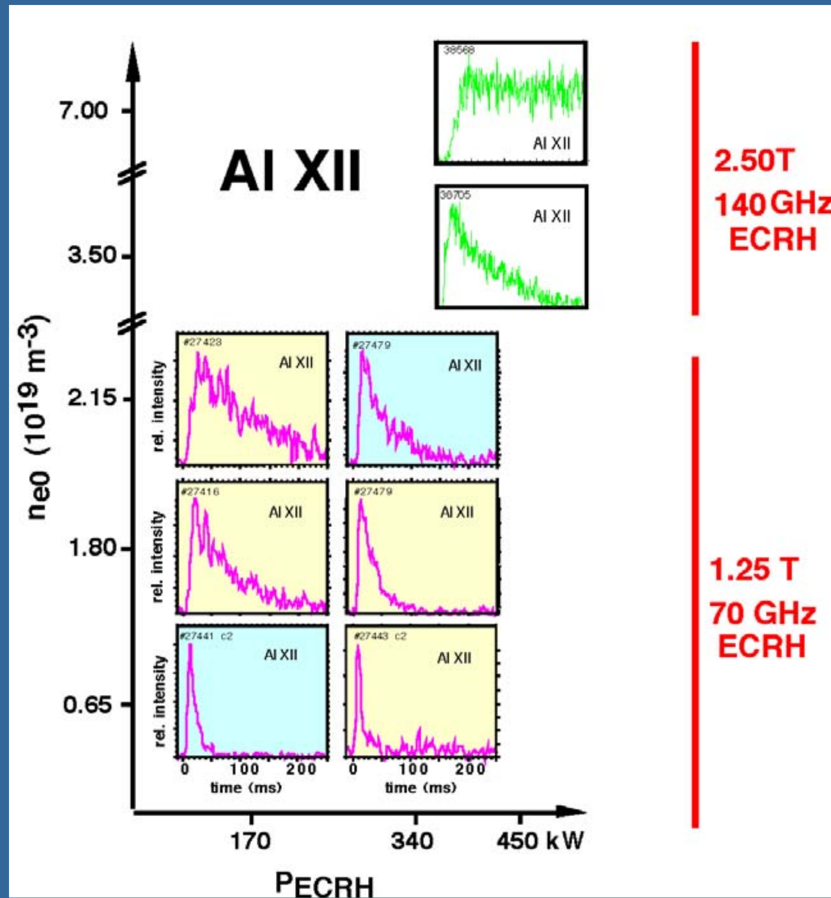
(ECRH plasmas, < 5×10^{19} m^{-3})

$\tau_{Al} \propto a_p^{2.4}\, n_e^{1.2} / P_{ECRH}^{0.8}$

but also …

$\tau_E \propto a_p^{\mathbf{2.2}}\, n_e^{\mathbf{0.5}} / P_{ECRH}^{\mathbf{0.6}}$

$D_p \propto n_e^{\mathbf{-1.2}}\; P_{ECRH}$



Similar scalings for I,p,e: indication for turbulent transport ?

I. Dependence of impurity confinement time on plasma para

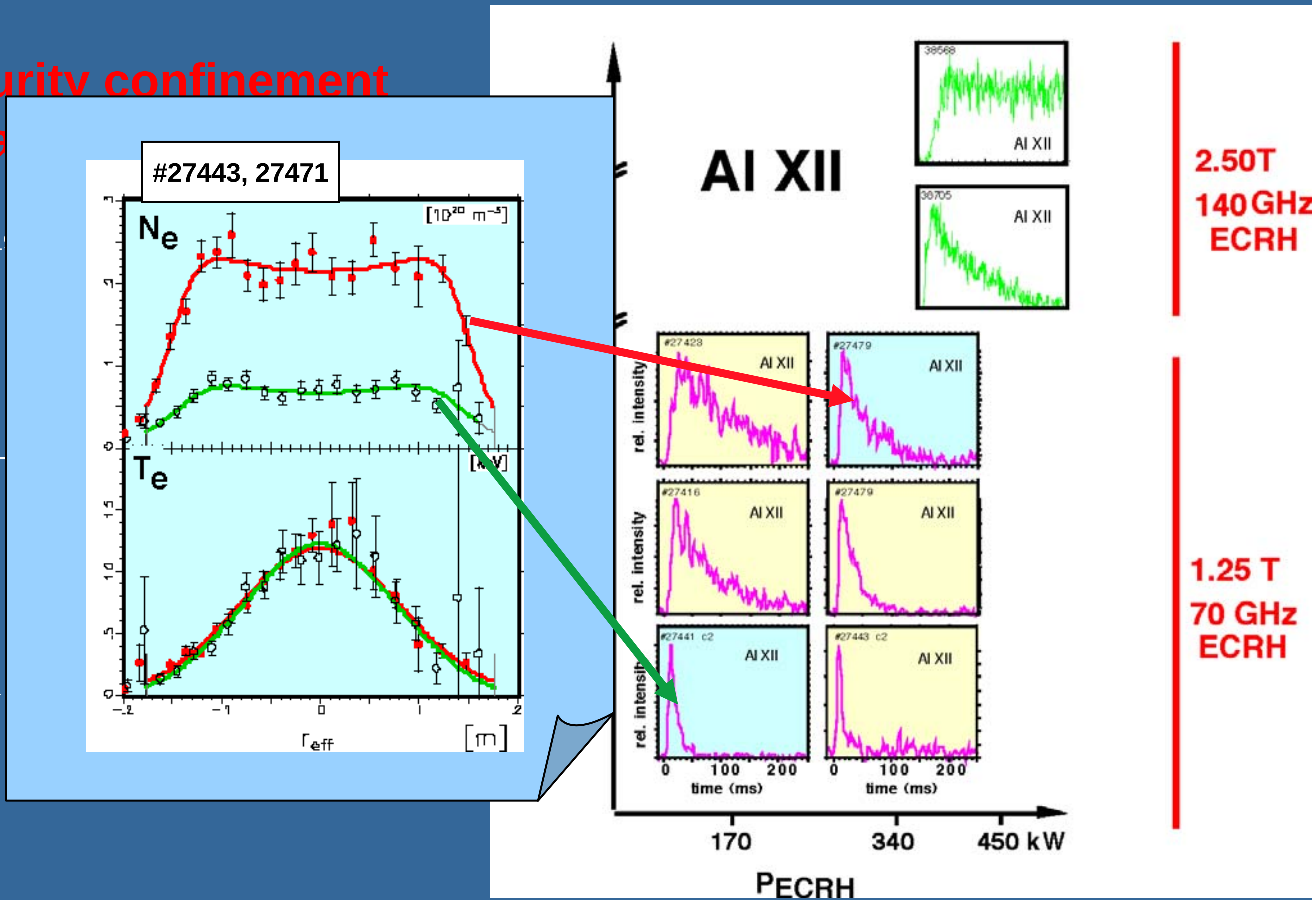
(ECRH plasmas, < 5x10[1]

$\tau_{Al} \propto a_p^{2.4}\, n_e^{1.2} / P_{ECRH}$

but also …

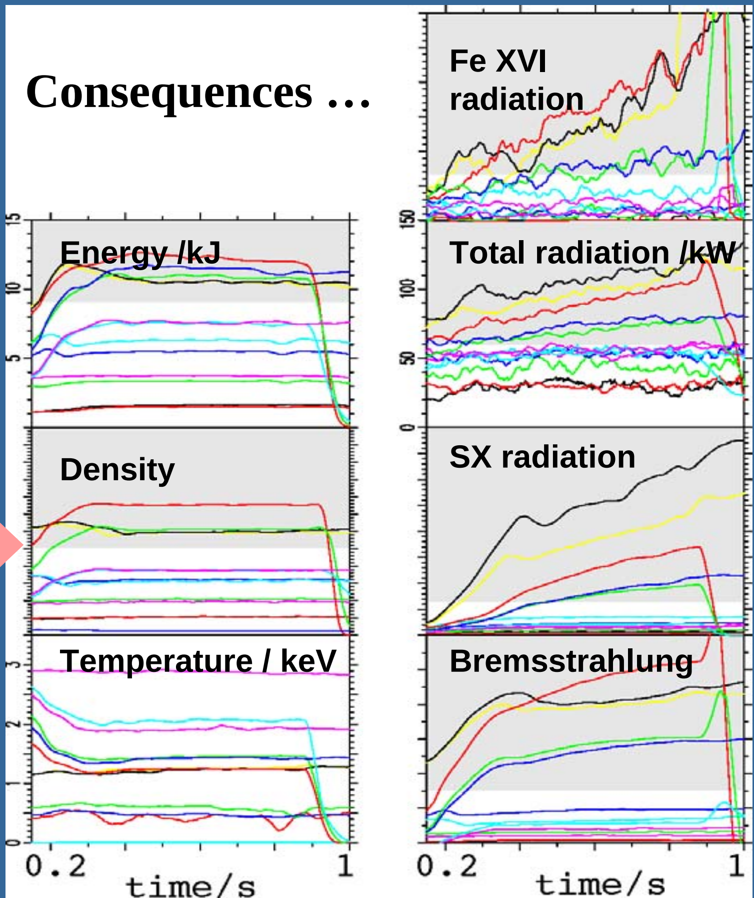
$\tau_E \propto a_p^{2.2}\, n_e^{0.5} / P_{ECR}$

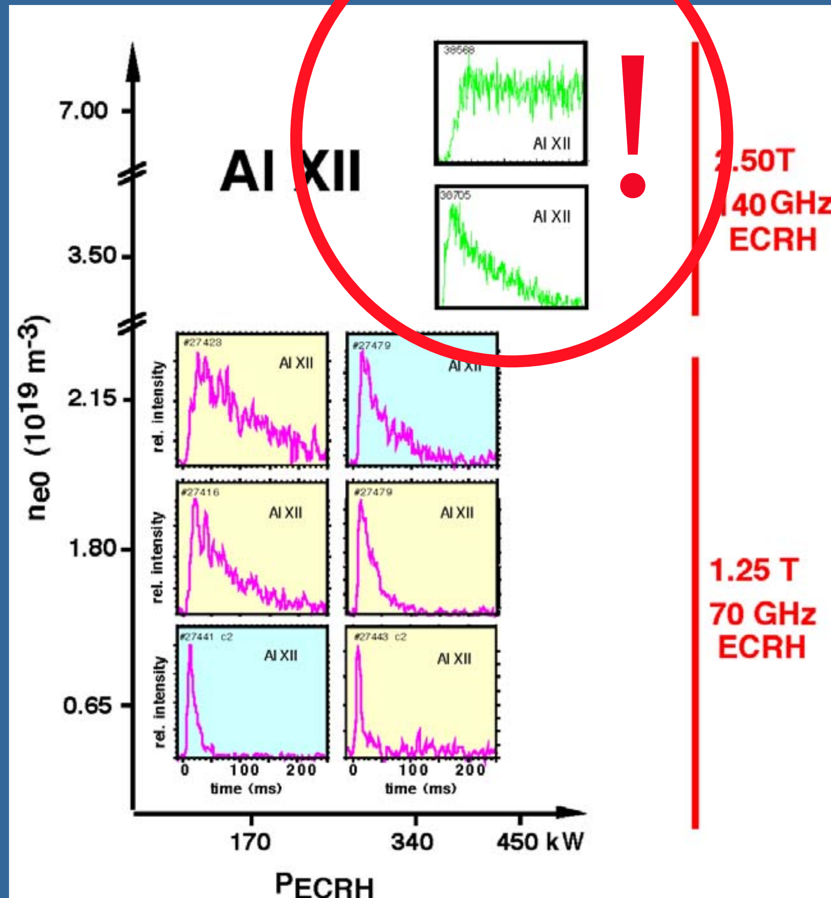
$D_p \propto n_e^{-1.2}\, P_{ECRH}$



No temperature effect !
Similar rel. n_e gradients > similar amb. E_r ? (T_i not available !)

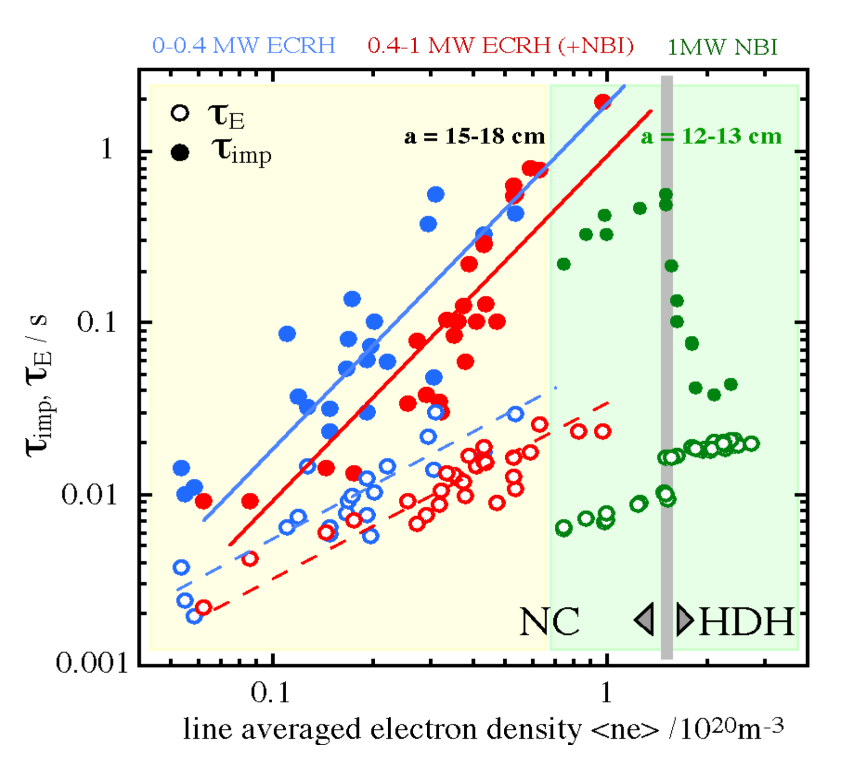
$n_e(0)$=
5 x 10^{19} m^{-3}





At low density: stationary discharges
At high density: rise of radiation losses

Impurity transport in W7-AS I



NC : „normal“ confinement - and very elmy H-mode

HDH: **H**igh **D**ensity **H**-mode High performace ELM-free H-mode

Low density ECRH plasmas:

… stationary operation

High density ECRH plasmas:

… accumulation

… energy degradation by radiation losses

Even higher density (NBI plasmas):

... loss of density control

... strong accumulation

... energy degradation

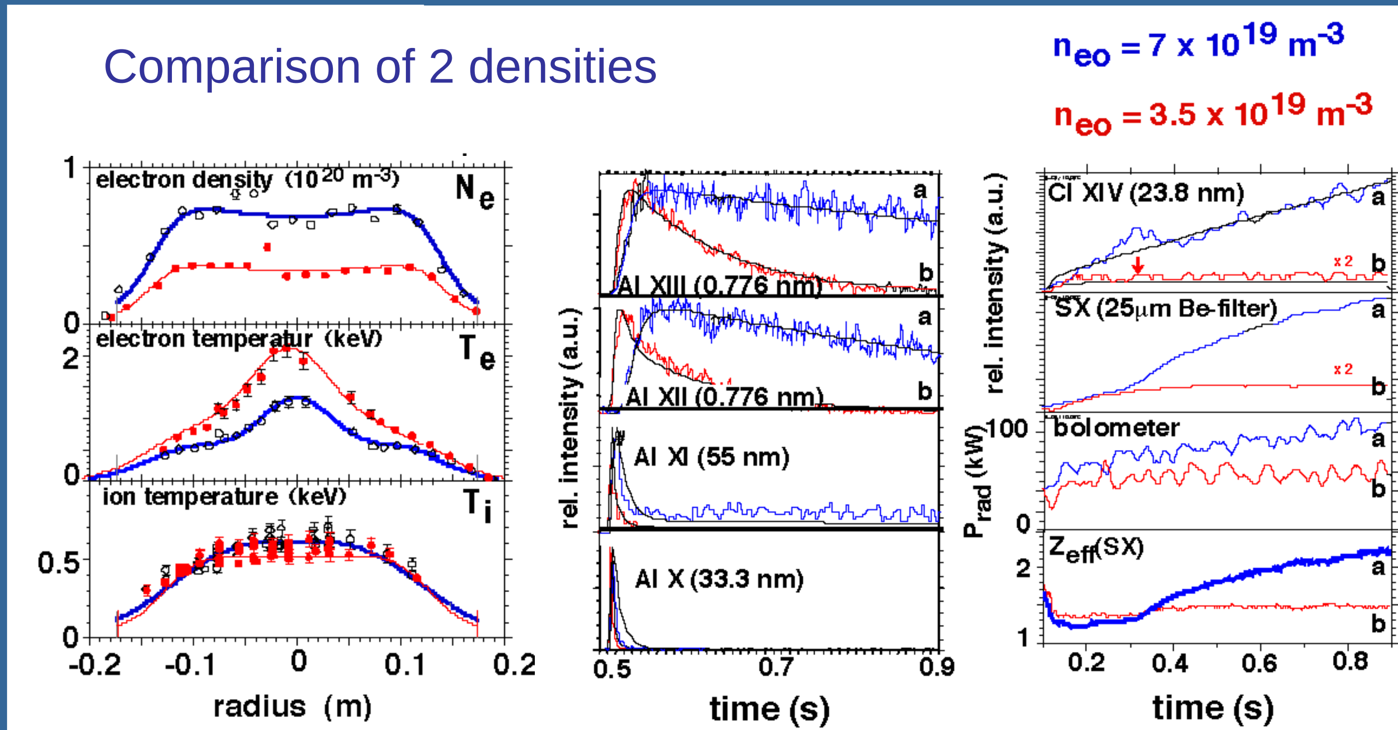
… often radiation collapse

(Highest density NBI plasmas (HDH):

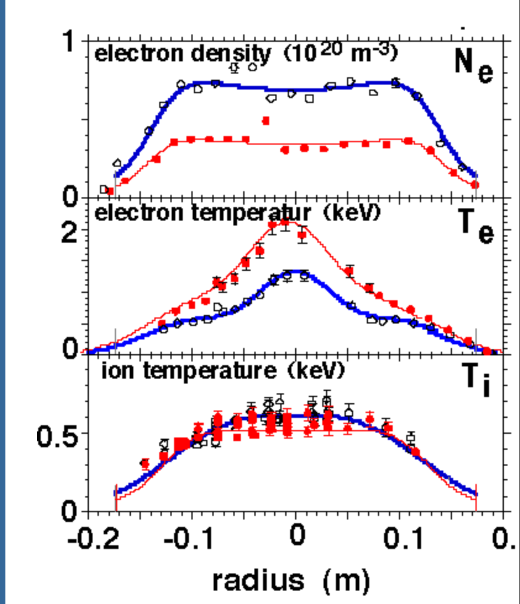
… stationary operation)

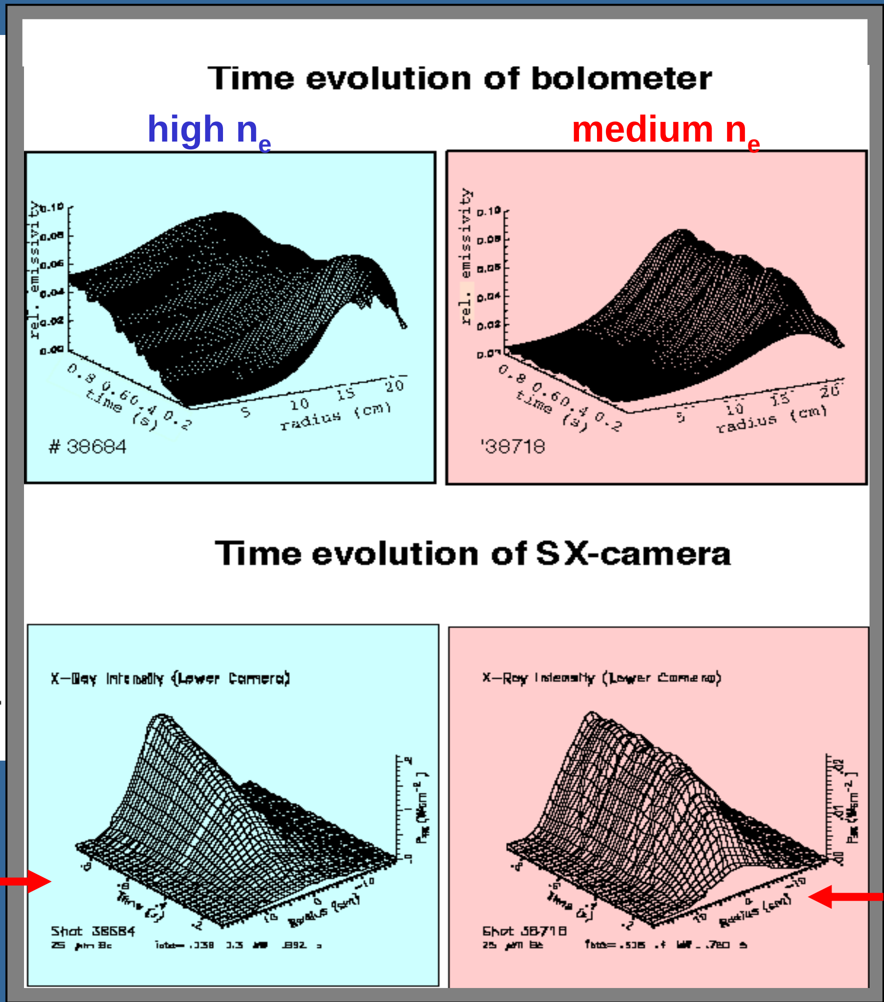
Mechanism for density dependence ? Convection (different ambipolar E_r) ?

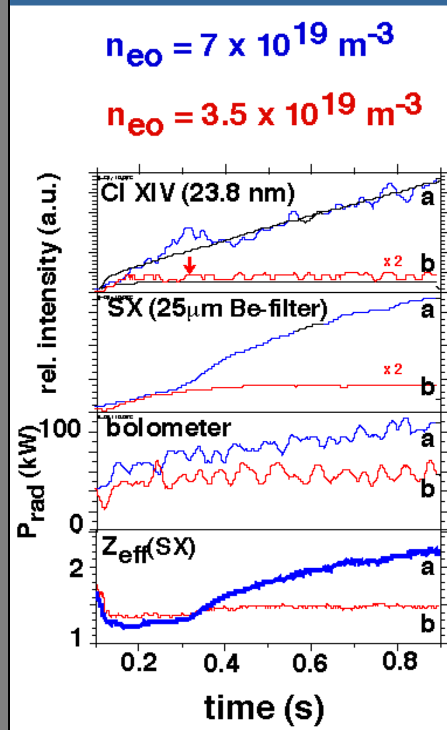
ECRH plasmas at
2 different densities:



Evolution of local emissivity (SX, Bolo) of intrinsic impurities:







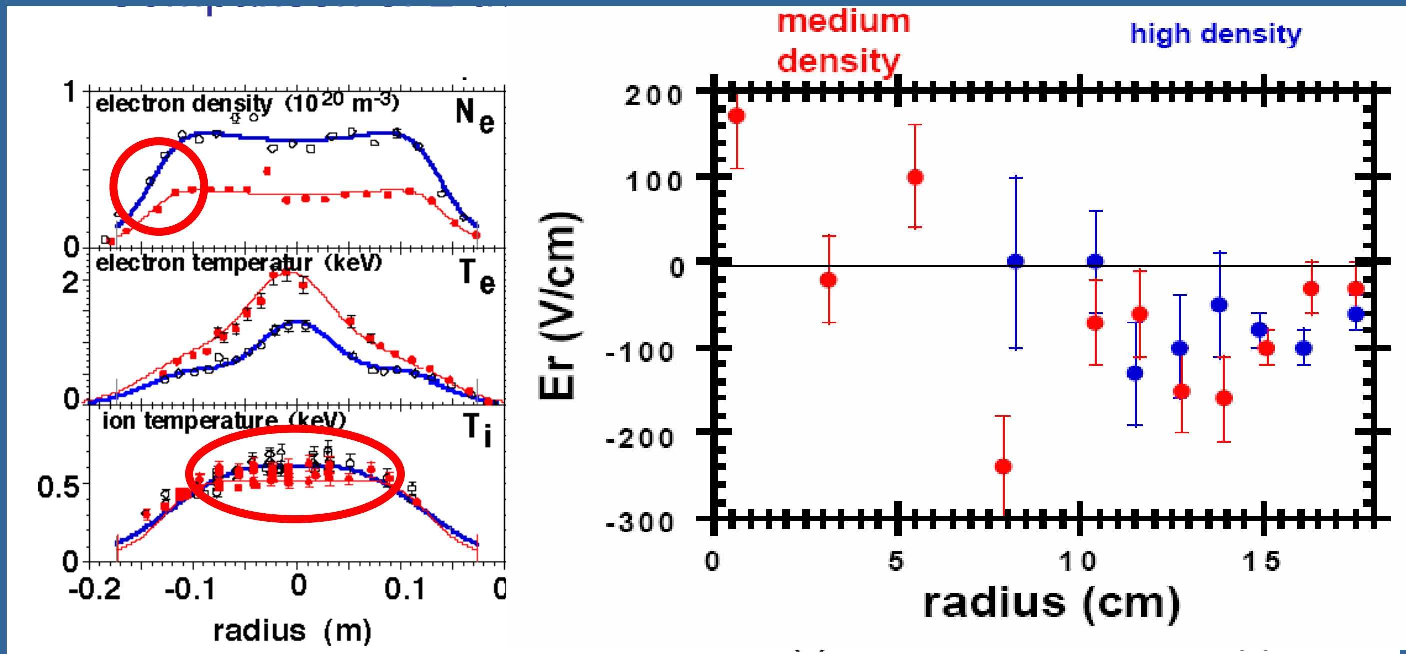
Long equilibrium time:
Peaking of imp. profiles

Short equilibrium time:
Immediately stationary

Mechanism for density dependence ? Convection (different ambipolar E_r) ?

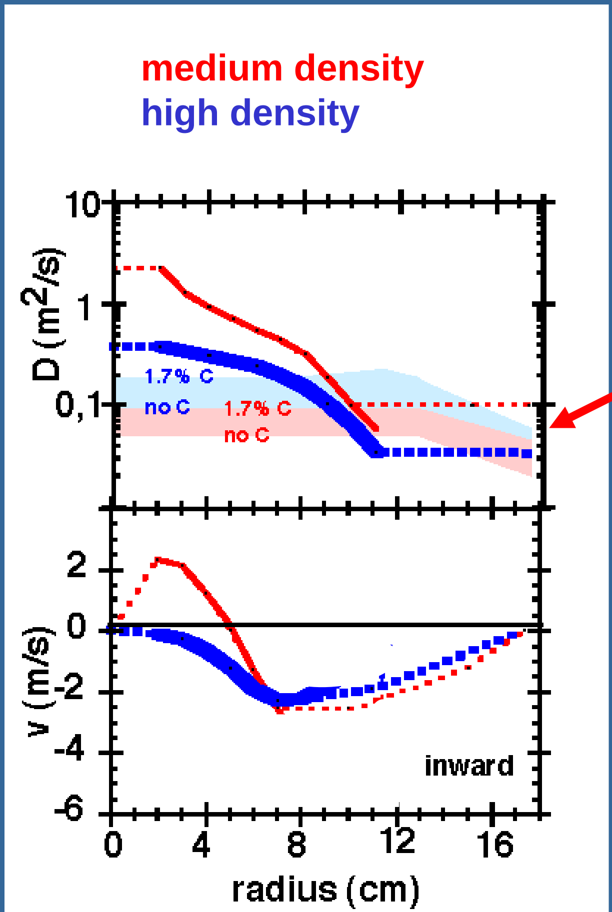
Similar n_e-profiles
No indication for different E_r

Accumulation due to slightly more peaked T_i-profiles ?



No indication for E_r as a different driving force for accumulation

Local transport coefficients – experiment and prediction
(SITAR, for axissymmetric devices only)



main difference is in D

In particular at the edge

***large uncertainties**, but …*
minor differences in v

Local transport coefficients – experiment and prediction

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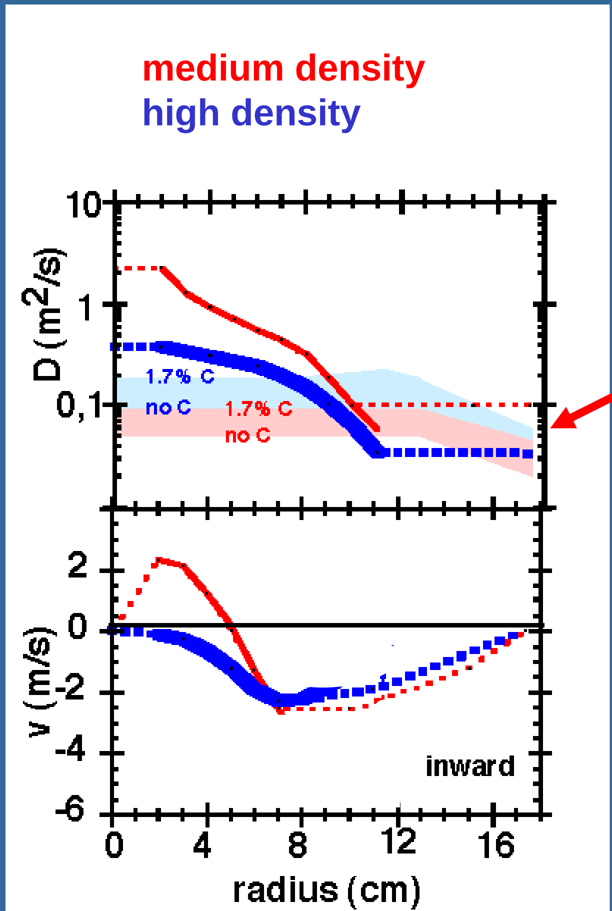


main difference is in D

In particular at the

large uncertaintie

minor differences i

Peaked D(r)-profiles !?

compared to

hollow ones at

Tokamaks and <u>CHS (!)</u>

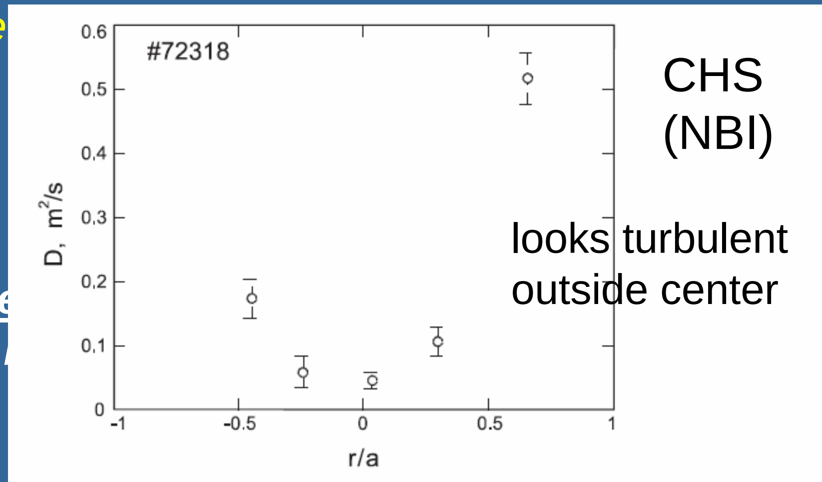
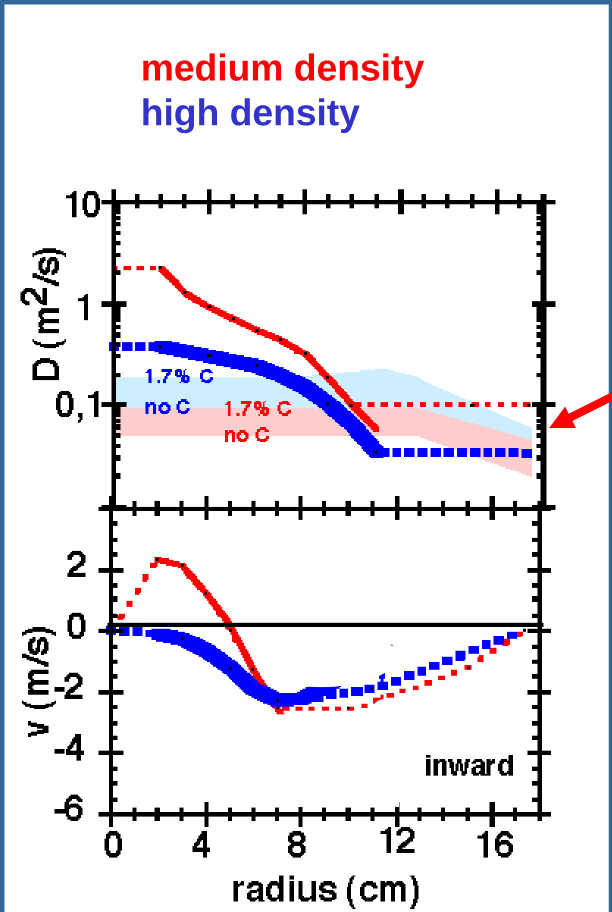


Figure 4. Diffusion coefficient *D* at different radial positions calculated from the signals of Li III intensity in the case of CHS.

Sudo et al., Plasma Phys. Control. Fusion 44 (2002) 129-135

Local transport coefficients – experiment and prediction
(SITAR, for axissymmetric devices only)



main difference is in D

In particular at the edge

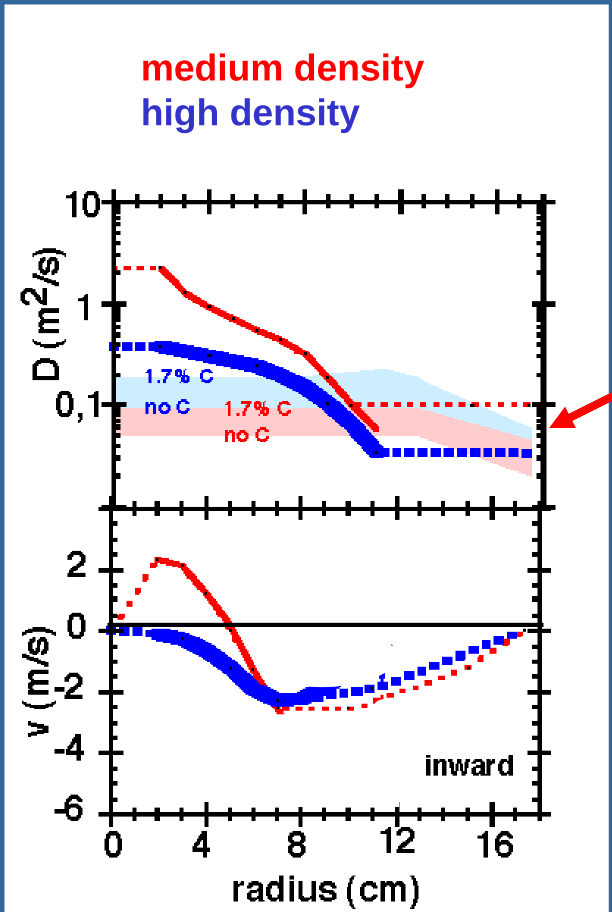
large uncertainties, but …
minor differences in v

So far …

…no indication for different MHD activity

…no indication for different fluctuation behavior

Local transport coefficients – experiment and prediction
(SITAR, for axissymmetric devices only)



main difference is in D

In particular at the edge

large uncertainties, but …
minor differences in v

Conclusion:

Different to tokamaks: Peaked D(r) profiles

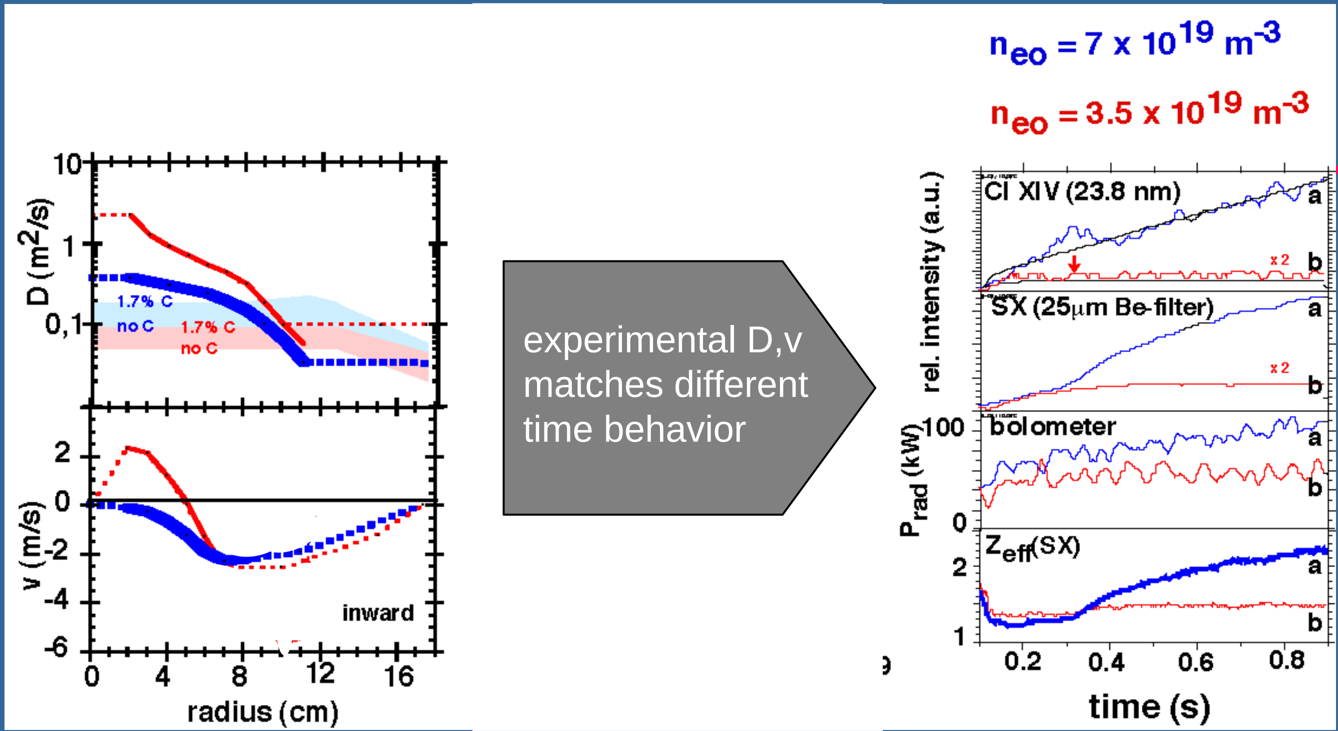
Reduction of D $\propto 1/n_e$ mainly responsible for different impurity behavior

Increasingly turbulent towards low density

Discrepancy with axis-symmetric neoclassical D at the plasma edge

Impurity transport in W7-AS I

Consequences for high density case:



Predicted stationarity at 1.7s

Final level depends on source:

small sources >> acceptable level (<40%)

wall conditioning!

 # Increase at high density is transport phenomenon (rate determined by D,v)

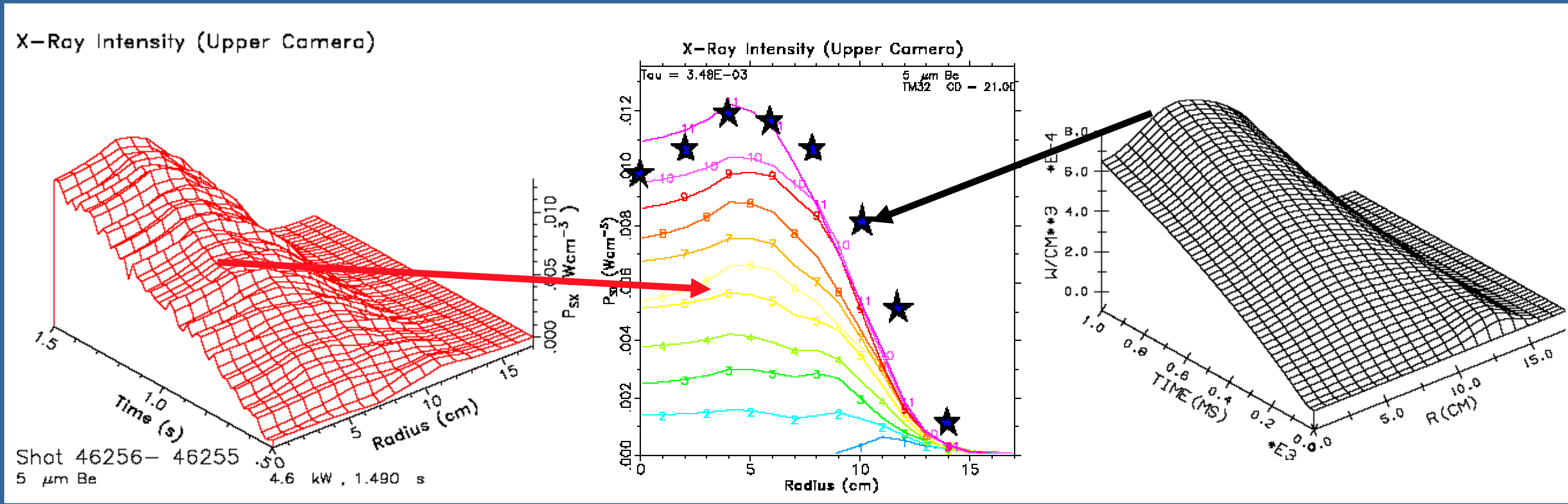
 # Must not automatically lead to radiation collapse if sources are kept small !

Impurity transport in W7-AS I

Check of experimental D(r), v(r) profiles for high density case:

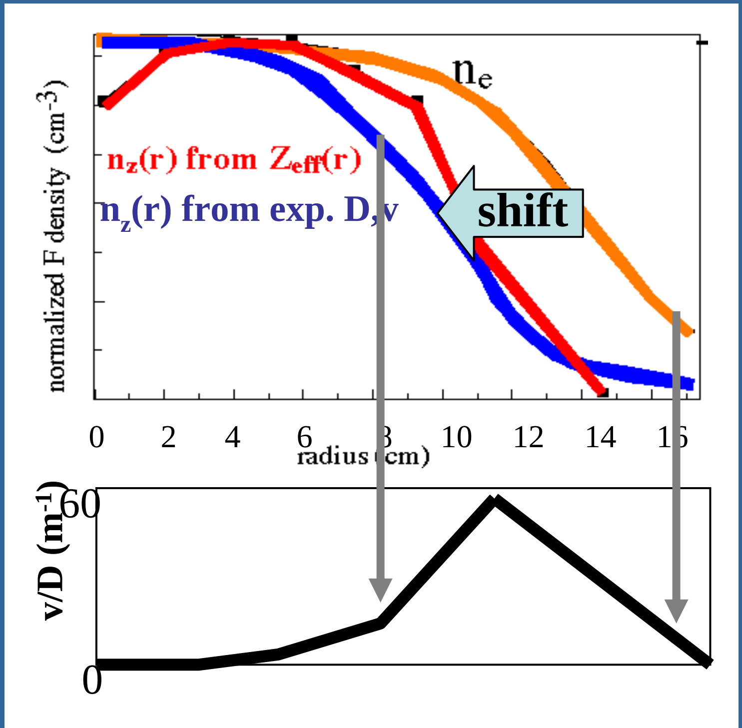
 # Experiment: constant fluorine source

Experimental and predicted (experimental D,v values) Soft-X evolution:



Increase of radiation due to transport - not to transient sources

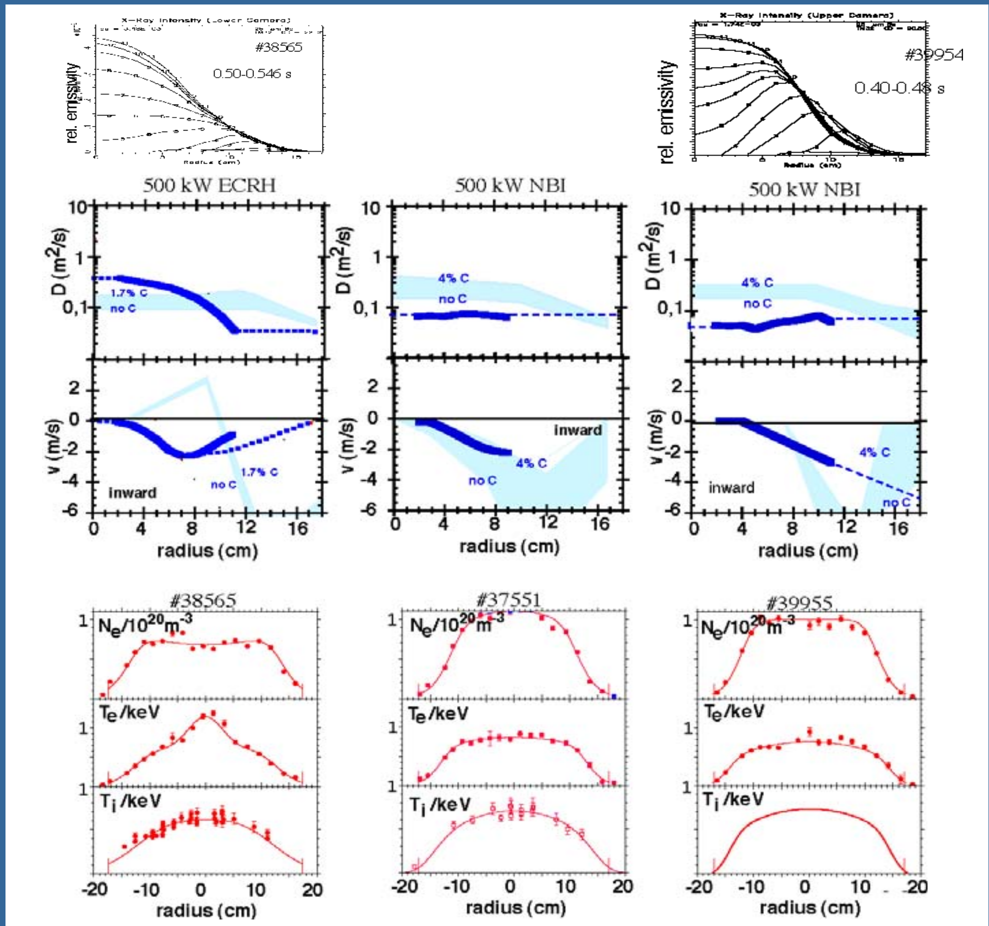
Fluorine density $n_z(r)$ peaked with respect to $n_e(r)$ for high density case:



Observed shift qualitatively in agreement with large experimental v/D

>>> *accumulation phenomenon*

Impurity transport in W7-AS III



NBI: flat D profiles

ECRH: peaked D profiles

Pridictions for axisymmetric device

Discrepancy due to neglection of stellarator features?

Consideration of 3D stellarator effects

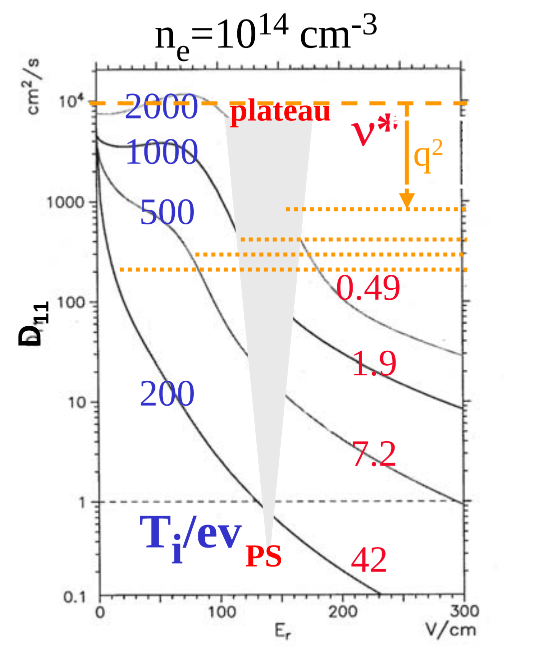
Impurity flux:

$$\Gamma_Z \cong -n_Z D_{11}^Z \left\{ \frac{n_Z'}{n_Z} - Z\left(\frac{n_i'}{n_i} + \frac{D_{12}^i}{D_{11}^i}\frac{T_i'}{T_i} \right) \right\} \approx -D n_Z' + n_Z v_{conv}$$

-1/2 for tokamaks
>0 for stellarators

H. Maassberg, C.Beidler

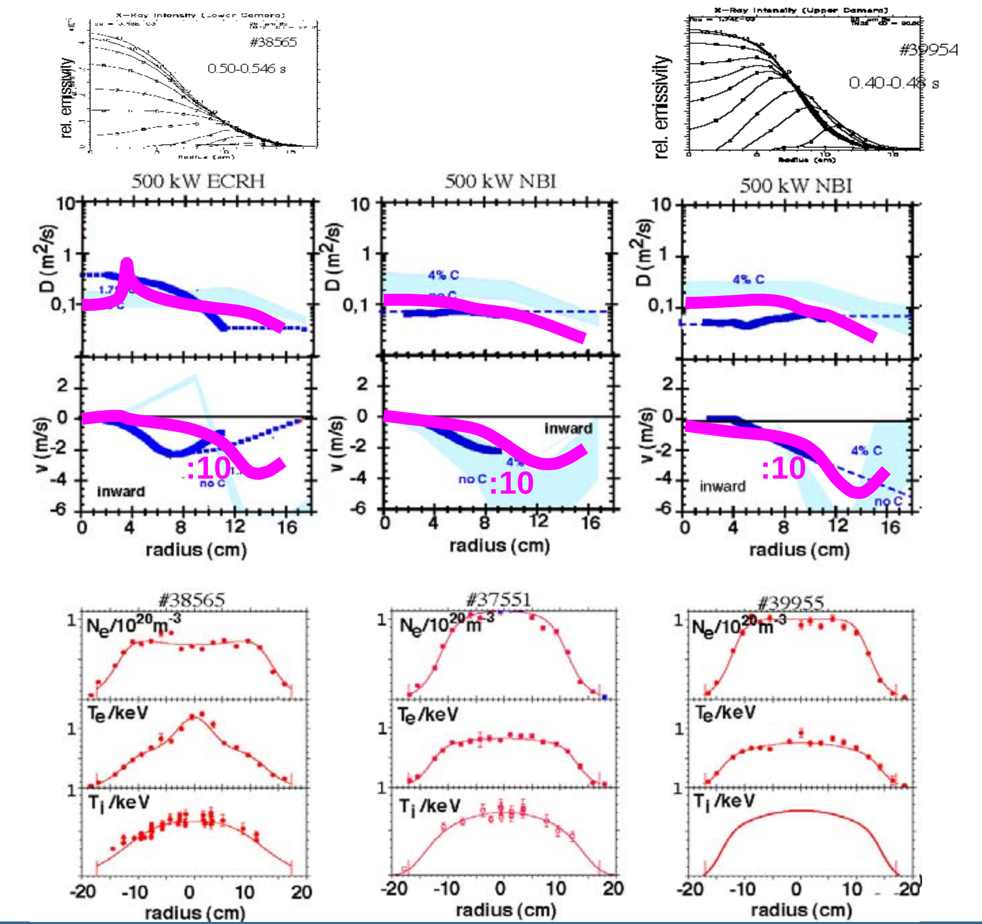
Diffusion coefficient $D^Z(E_r)$ (Al XIII)



Radial electric field E_r

Consequence: positive temperature coefficient >> no T_i screening

Impurity transport in W7-AS III



NBI: flat D profiles

ECRH: peaked D profiles

Pridictions for axisymmetric device

→ *discrepancy*

„non-axisymmetric“ neoclassical D seem to match experiment better …

… but not v.

>> even stronger accumulation expected - but not observed !!

Impurity transport in TJ-II

very low densities - very low ECRH power

Density dependence of global τ_I

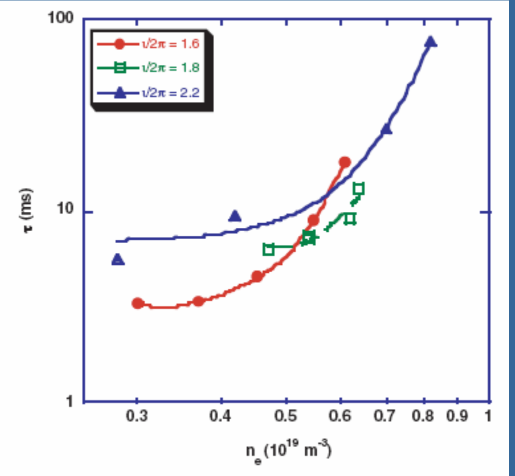


Figure 8. Impurity (Si) confinement time versus plasma density for three different magnetic configurations.

Density dependence of local D

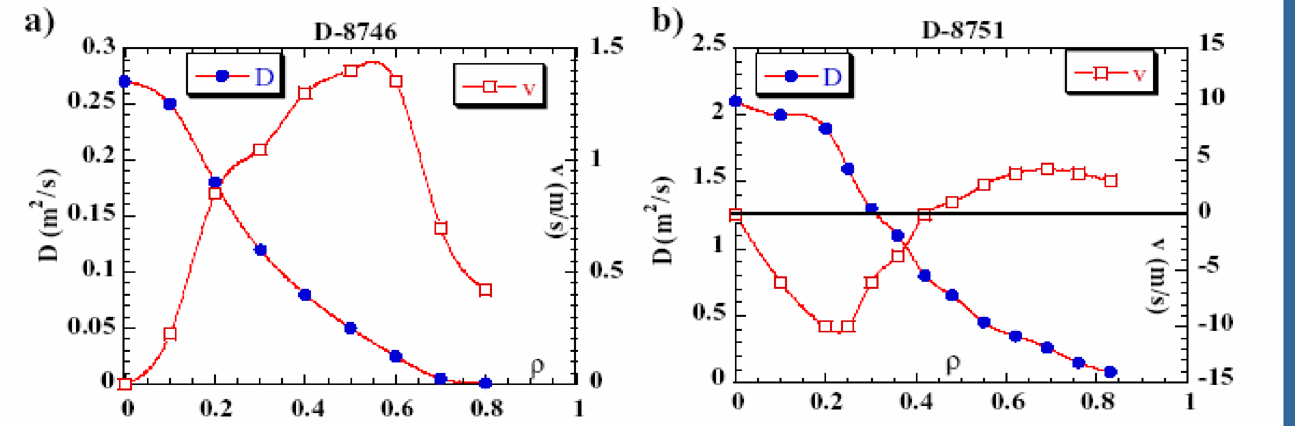


Fig. 2. The spatial dependence of the diffusion convective velocity for two discharges from a density scan: a) a discharge with $n_e = 0.61 \times 10^{19}$ m^{-3}; b) a discharge with $n_e = 0.3 \times 10^{19}$ m^{-3}.

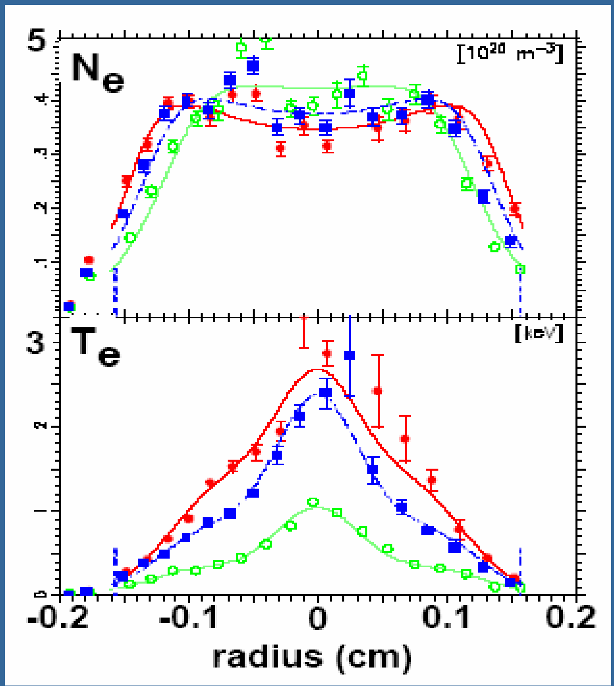
Hidalgo et al., Nucl. Fus. 45 (2005), S266-275

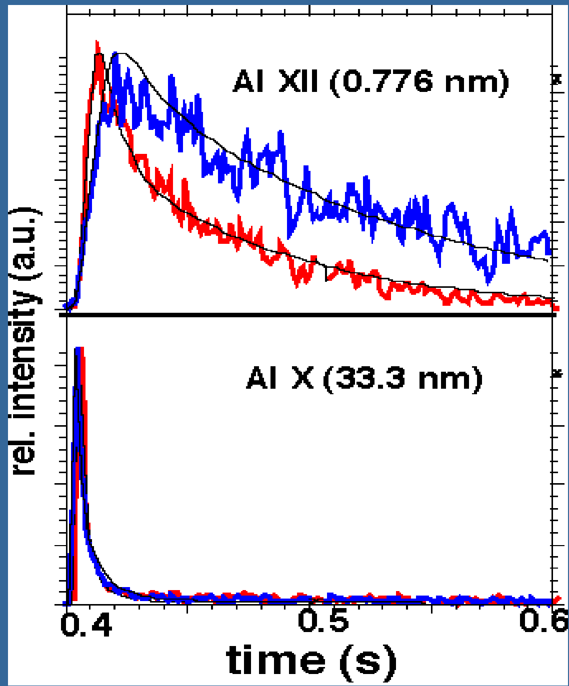
Zurro et al., Rev. Sci. Instrum., 75(10), 2004, . 45 (2005), 4231-4233

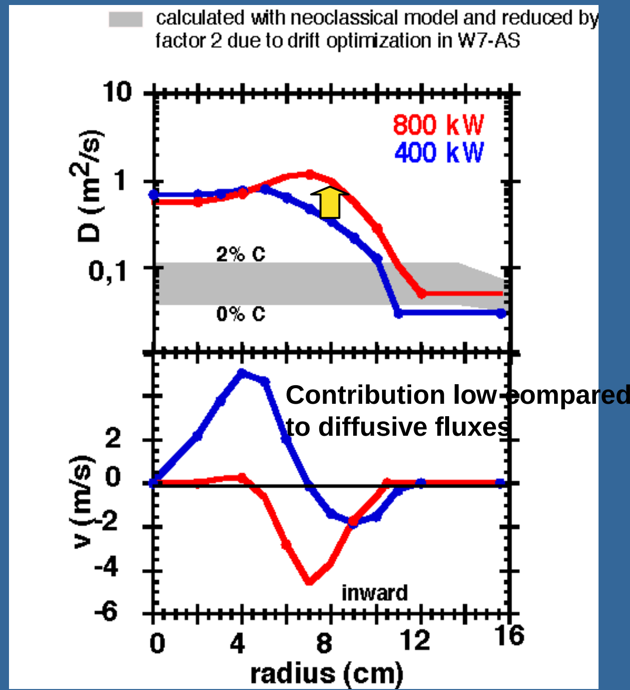
Trend very similar to W7-AS – clear change of D $\propto 1/n_e$ and also v
peaked D(r) profiles

II. Dependence of impurity confinement time on ECRH power:

P_{ECRH} = 800 kW (#37920), 400 kW (#37909)







Enhancement of D ∝ P_{ECRH} mainly responsible for confinement degradation

Impurity transport in TJ-II

very low densities - very low ECRH power

Power dependence of global τ_I

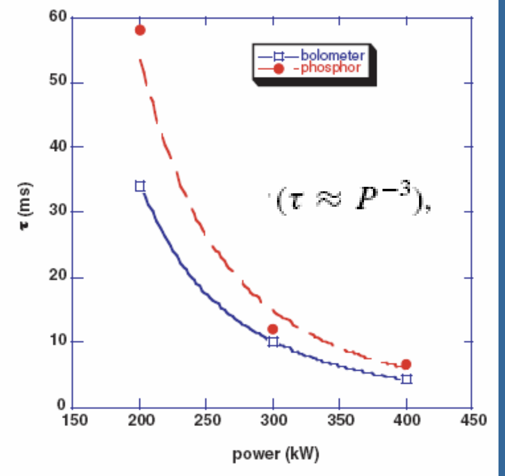


Figure 9. Influence of ECRH heating on impurity (Si) confinement time.

Power dependence of local D

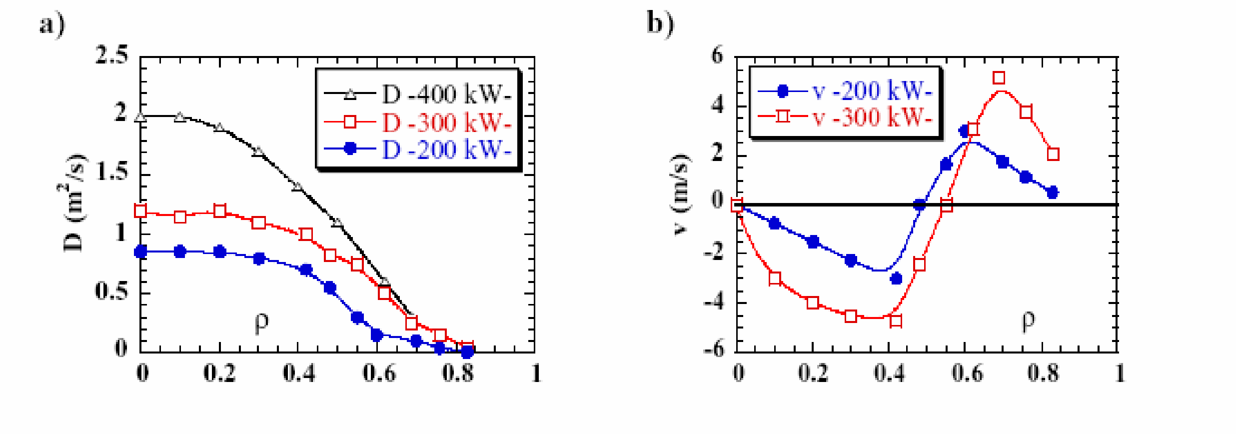


Fig. 3. Spatial dependence of: a) diffusion coefficient, and b) convective velocity for discharges with different injected power.

Hidalgo et al., Nucl. Fus. 45 (2005), S266-275

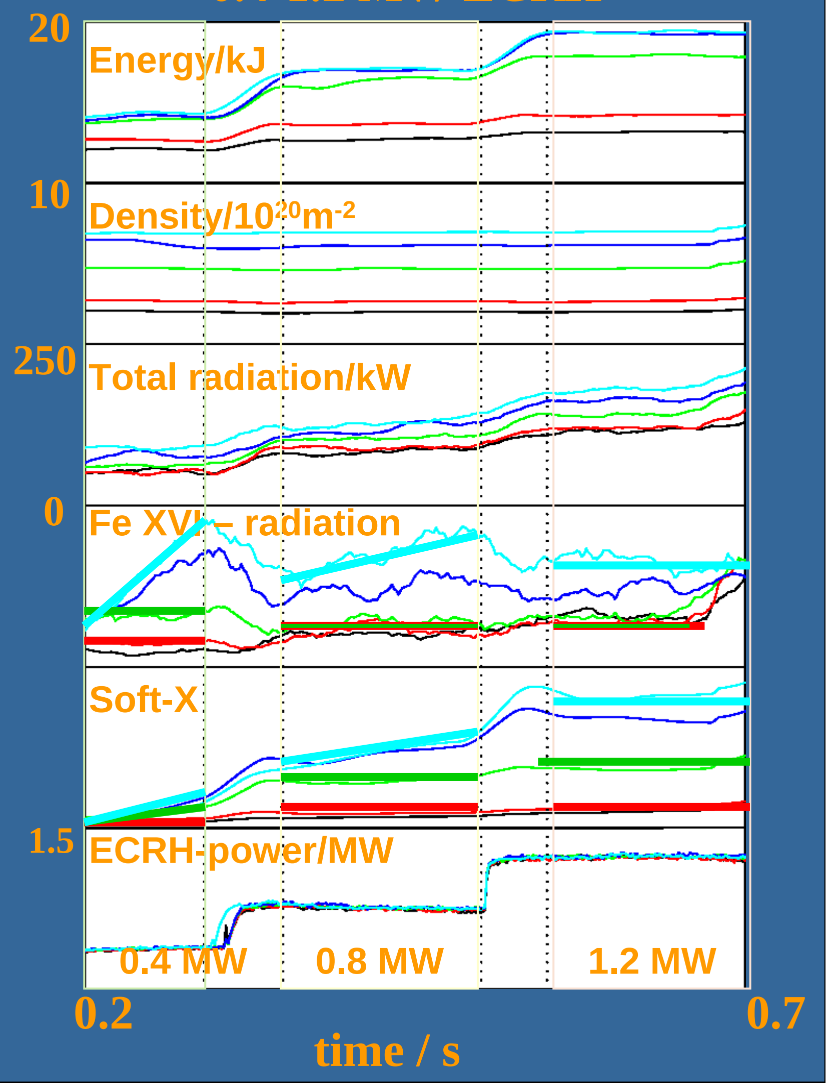
Zurro et al., Rev. Sci. Instrum., 75(10), 2004, . 45 (2005), 4231-4233

Trend very similar to W7-AS – clear change of D $\propto 1/P_{ECRH}$ and also v
peaked D(r) profiles (due to heating mechanism?
>> turbulent?)

Way to stationary high density W7-AS plasmas:

- # Low impurity sources (wall conditioning)
- # HDH regime
- # ELM activity
- # Utilization of power degradation >>

0.4-1.2 MW ECRH



Impurity transport in LHD I

Density window for accumulation in LHD :

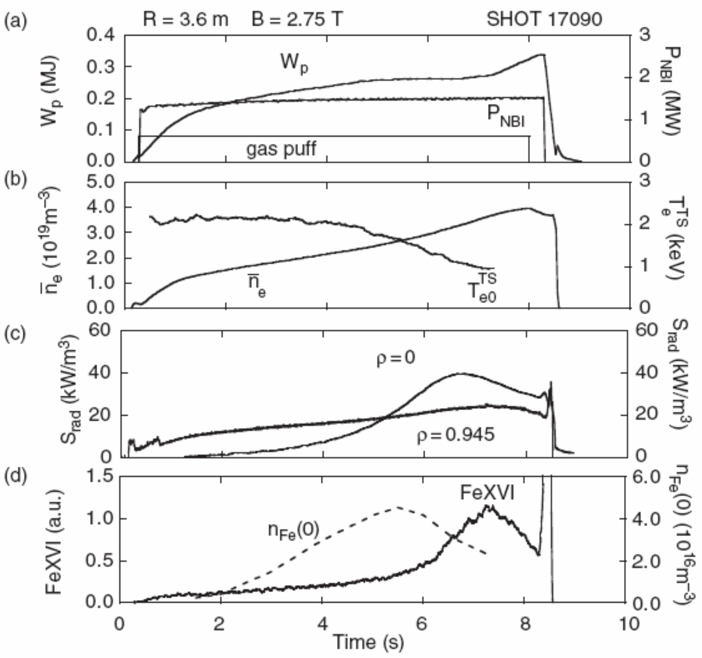


Figure 6. Time evolution of plasma parameters and the central iron density in a density ramp-up discharge (shot 17090). The plasma density increases with time by constant gas puffing. The central iron density was estimated with the impurity transport code MIST.

Y. Nakamura et al., Plasma Phys. Control. Fusion 44 (2002) 2121-2134

Impurity transport in LHD I

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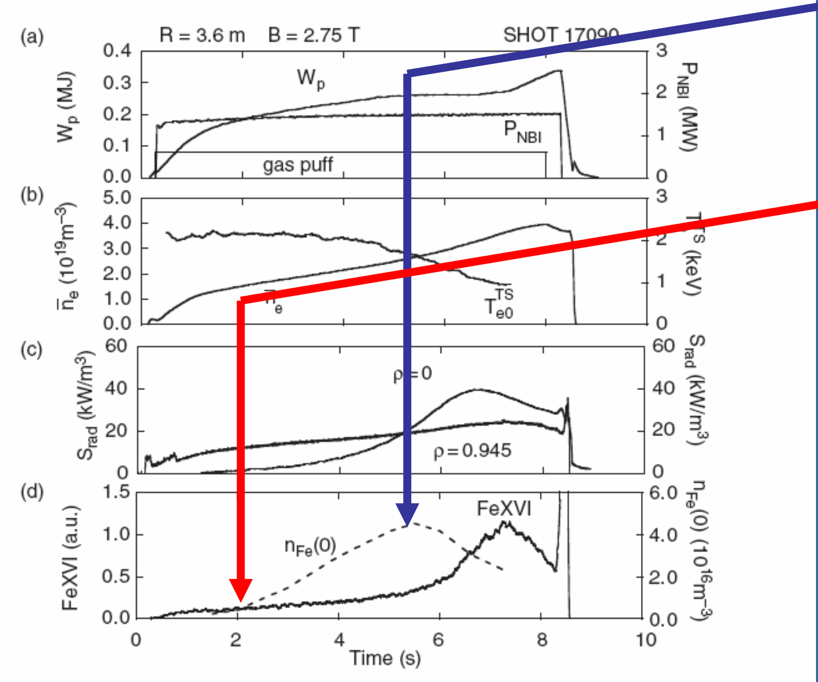

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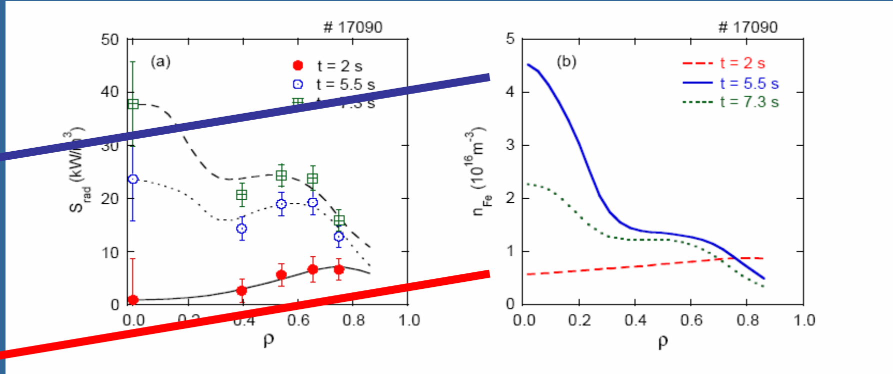


Fig. 11 Profiles of (a) radiation and (b) iron density at each time (t = 2, 5.5, 7.3 s) for the discharge in Fig. 10. The lines in the radiation profiles indicate the fitting curves calculated from the impurity transport code MIST.

Y. Nakamura et al. ISW 2002, No. OIV:5

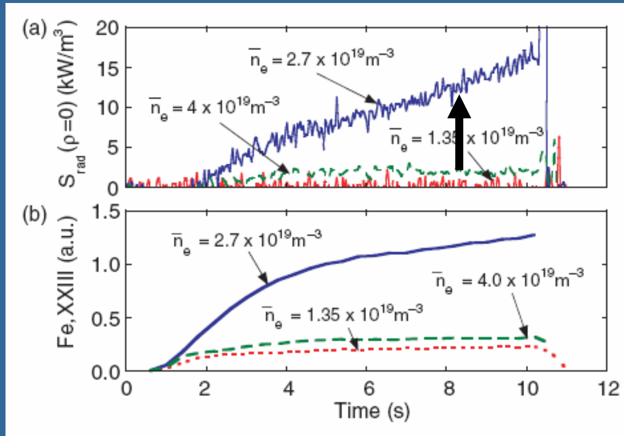
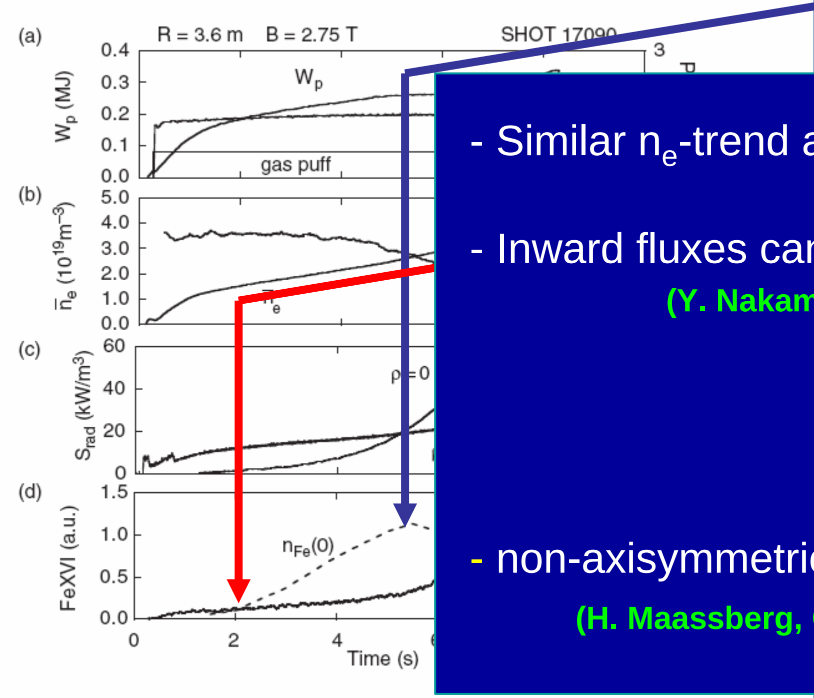


Figure 9. Time evolution of (*a*) central radiation and (*b*) Fe XXIII emission for discharges with constant densities. Remarkable increases are observed only for the discharge with $2.7 \times 10^{19}\ m^{-3}$.

Y. Nakamura et al., Nucl. Fusion 43 (2003) 219-227

Impurity transport in LHD I

Density window for accumulation in LHD :



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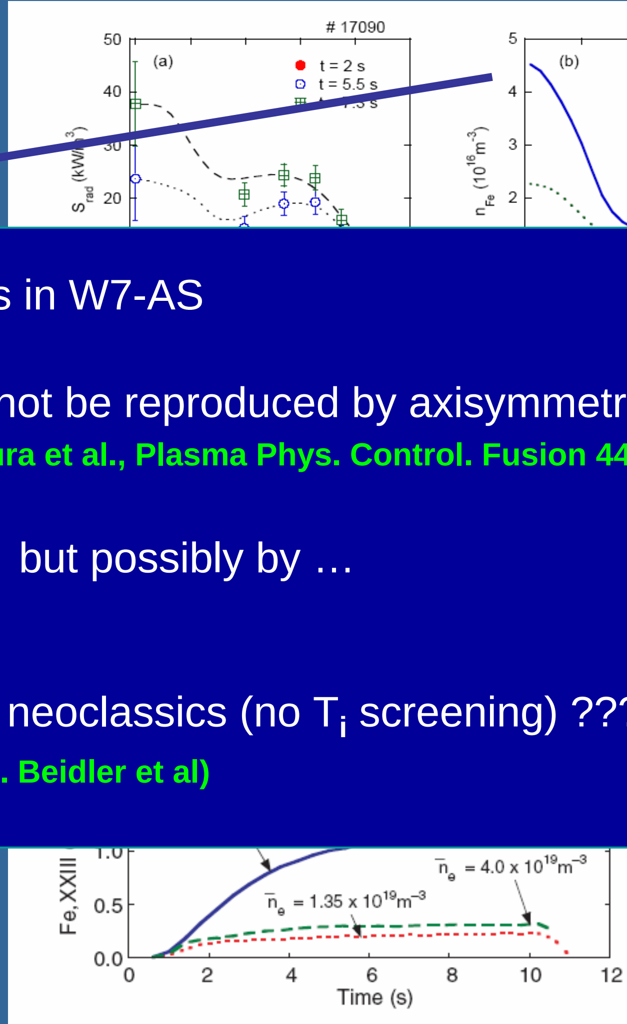

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- Similar n_e-trend as in W7-AS

- Inward fluxes cannot be reproduced by axisymmetric neoclassics
  (Y. Nakamura et al., Plasma Phys. Control. Fusion 44 (2002) 2121-2134)

  but possibly by …

- non-axisymmetric neoclassics (no T_i screening) ???
  (H. Maassberg, C. Beidler et al)

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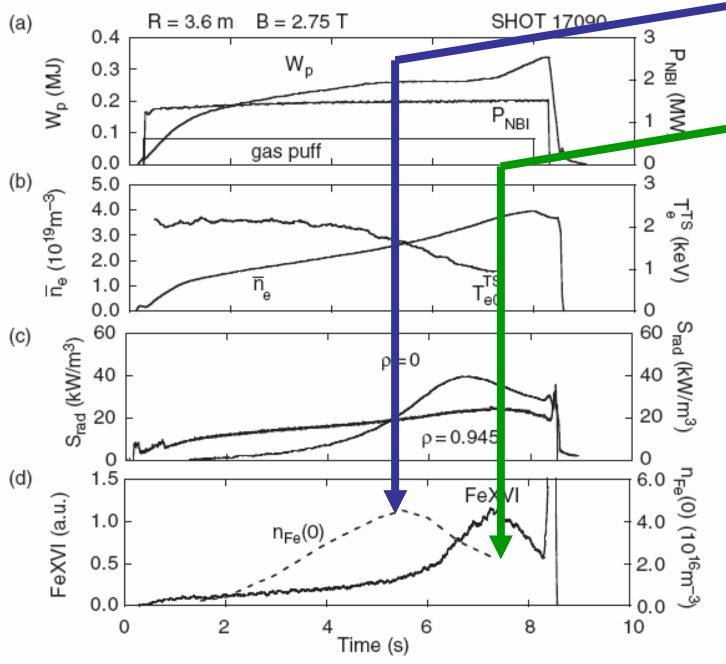
43
(2003) 219-227

Flush-out at high density in LHD :



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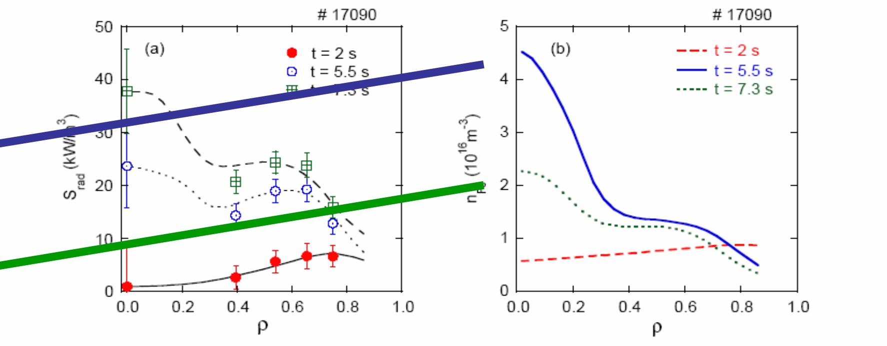

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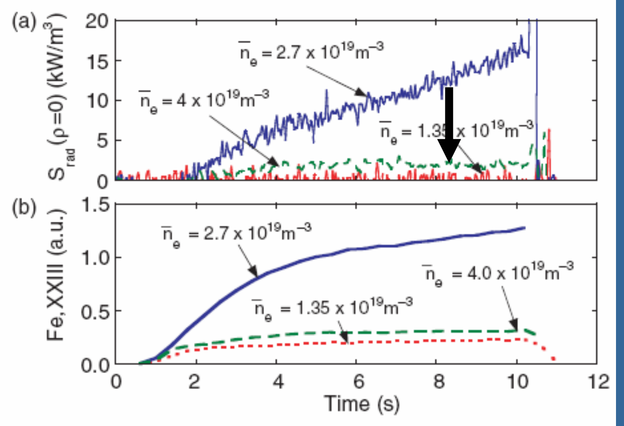

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Impurity transport in LHD I

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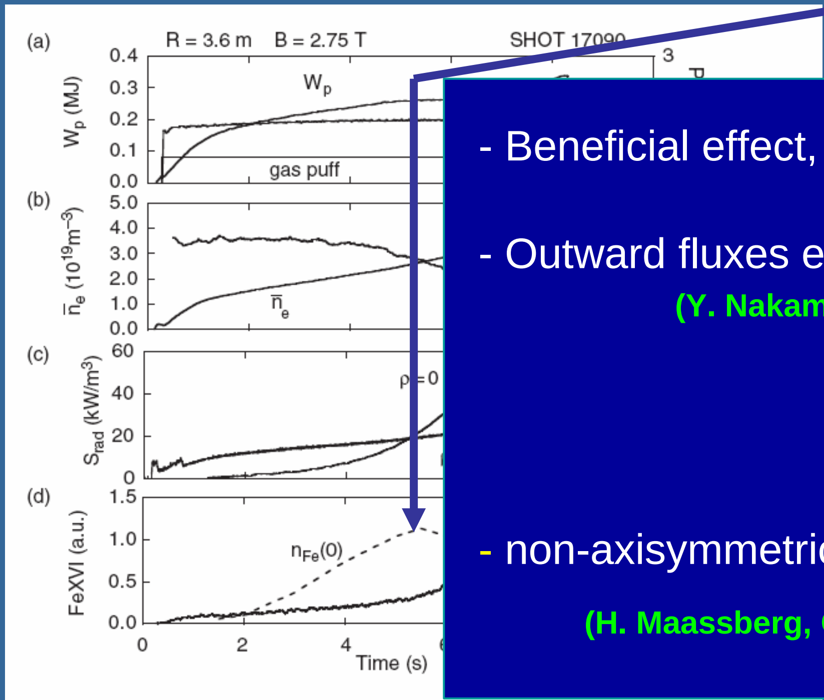

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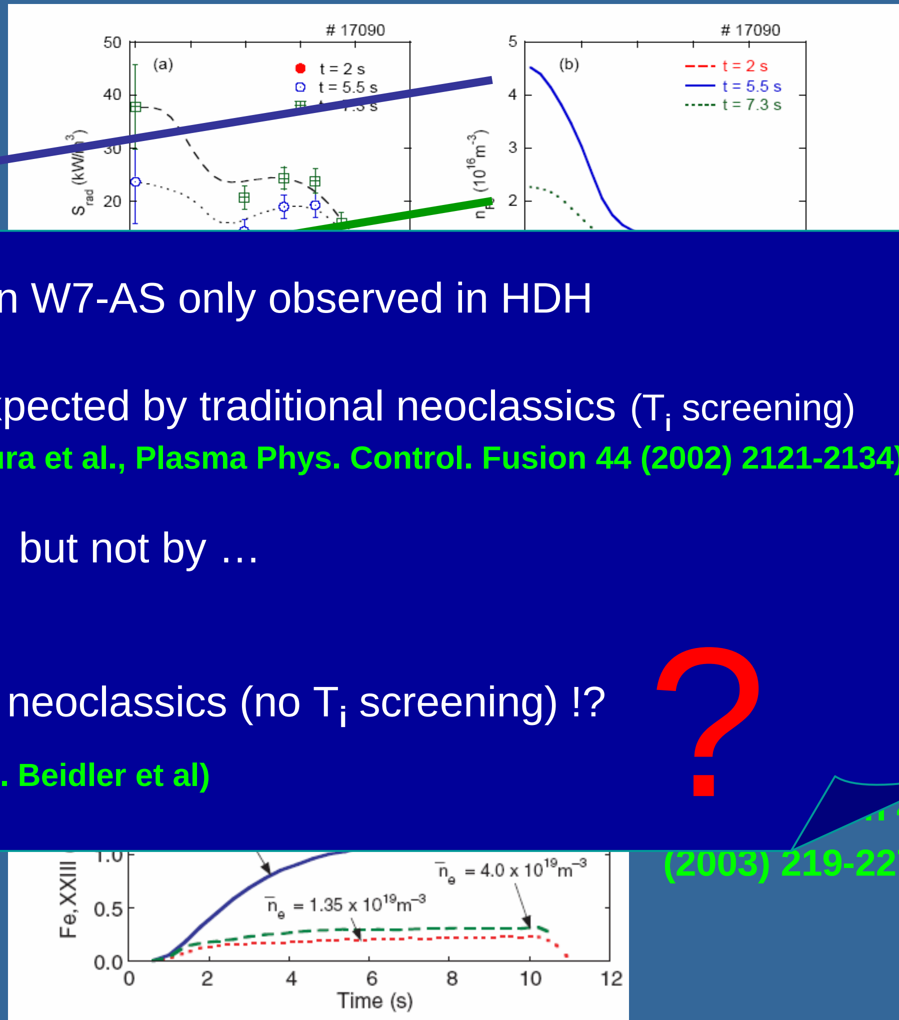

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- Beneficial effect, in W7-AS only observed in HDH

- Outward fluxes expected by traditional neoclassics (T_i screening)

(Y. Nakamura et al., Plasma Phys. Control. Fusion 44 (2002) 2121-2134)

but not by …

- non-axisymmetric neoclassics (no T_i screening) !?

(H. Maassberg, C. Beidler et al)

?

…l., …43 (2003) 219-227

Impurity transport in LHD I

Reason for accumulation in LHD :

… long impurity confinement times

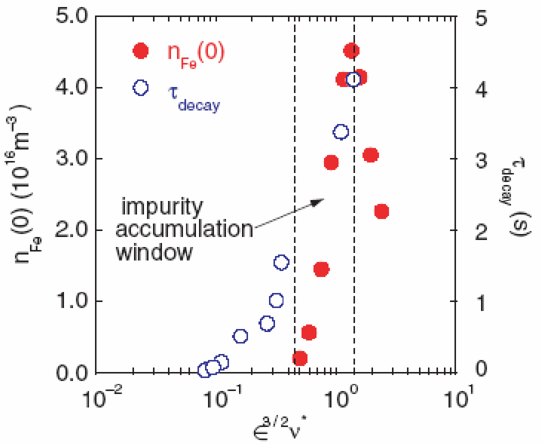


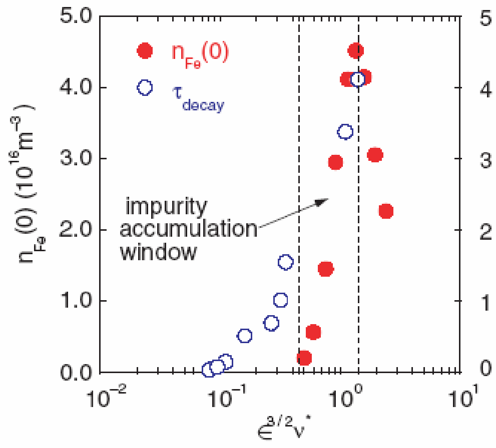
Figure 12. Decay time of TiKα emission as a function of normalized collision frequency for impurity ions. The central iron density (●) in a density ramp-up discharge is also indicated to compare the collisionality with that in the impurity accumulation window.

Y. Nakamura et al. ISW 2002, No. OIV:5

Impurity transport in LHD I 

Reason for accumulation in LHD :

Impurity confinement time:



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Ambipolar field E_r

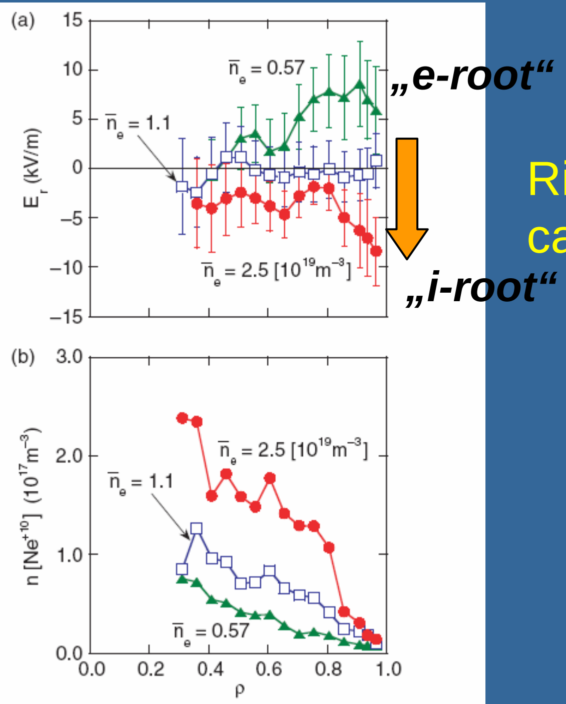


Figure 13. Radial profiles of (*a*) radial electric field and (*b*) fully ionized neon density for the discharges with a pulsed neon gas injection. The radial electric field is measured in the midplane at a position where the plasma is vertically elongated. The electric field changes from positive to negative with increasing electron density. The neon density increases monotonically as the density is increased.

Rising E_r seems to cause „accumulation“

Y. Nakamura et al., Nucl. Fusion 43 (2003) 219-227

Reason for purification beyond the accumulation window in LHD ? :

Impurity confinement time:

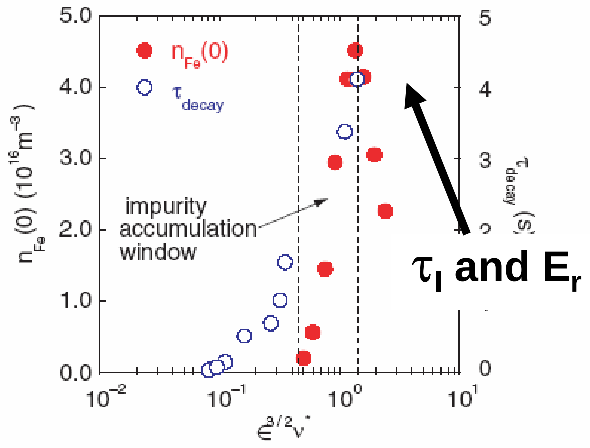
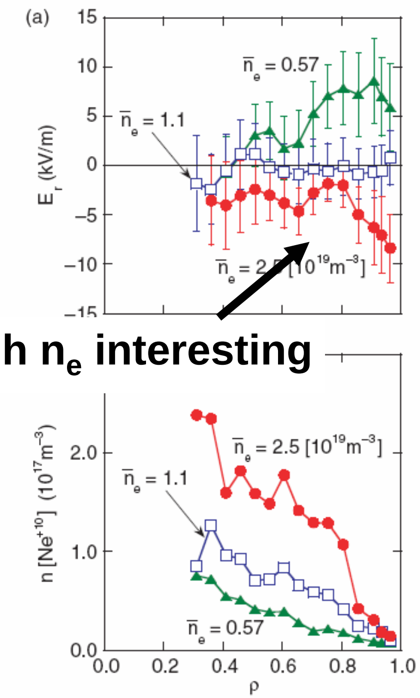


Figure 12. Decay time of TiKα emission as a function of normalized collision frequency for impurity ions. The central iron density (●) in a density ramp-up discharge is also indicated to compare the collisionality with that in the impurity accumulation window.

Y. Nakamura et al. ISW 2002, No. OIV:5

Ambipolar field E_r



τ_I and E_r at high n_e interesting

Figure 13. Radial profiles of (*a*) radial electric field and (*b*) fully ionized neon density for the discharges with a pulsed neon gas injection. The radial electric field is measured in the midplane at a position where the plasma is vertically elongated. The electric field changes from positive to negative with increasing electron density. The neon density increases monotonically as the density is increased.

Assumption:

If τ_I and E_r would still be rising (?) …

… then „purifucation“ window means:

… decrease of influx but still **long impurity confinement** ?

If „yes“ :

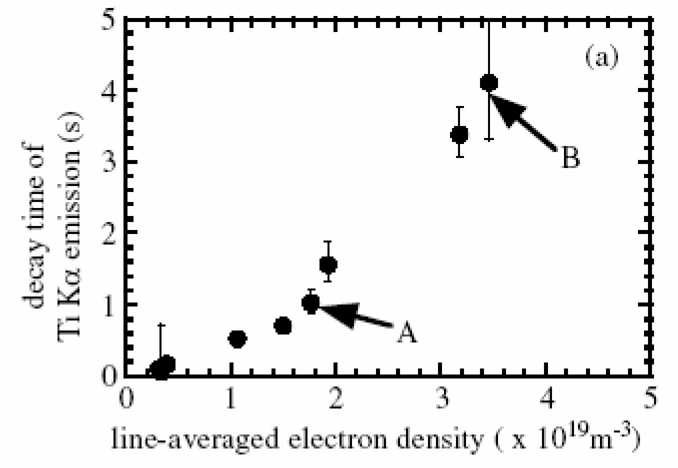
Similar to processes in HDH ??

(Y. Feng et al., …..)

Y. Nakamura et al., Nucl. Fusion 43 (2003) 219-227

Impurity transport in LHD I

Do the following experiments indicate increasing confinement at high density ?



N.Tamura et al.,
Plasma Phys. Contr. Fusion 45 (2003) 27-41

Morita et al., Plasma Science & Technology, Vol. 8, No.1, 2006

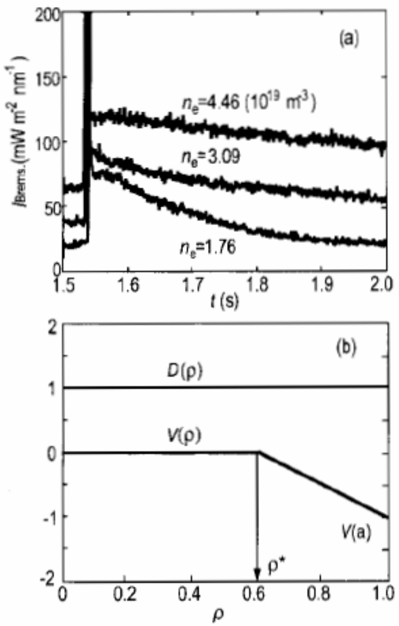


Fig.2 (a) Time traces of visilbe bremsstrahlung after carbon pellet injection and (b) models of diffusion coefficient and inward velocity profiles

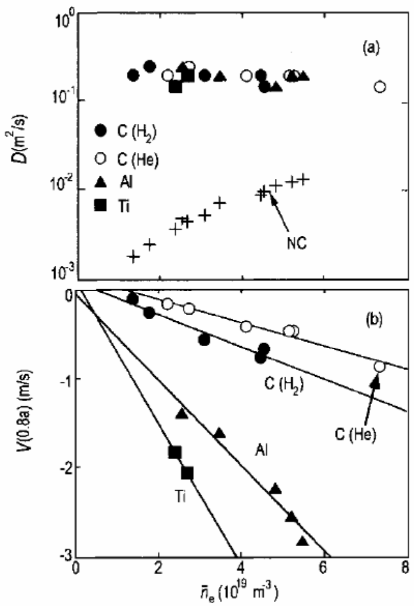
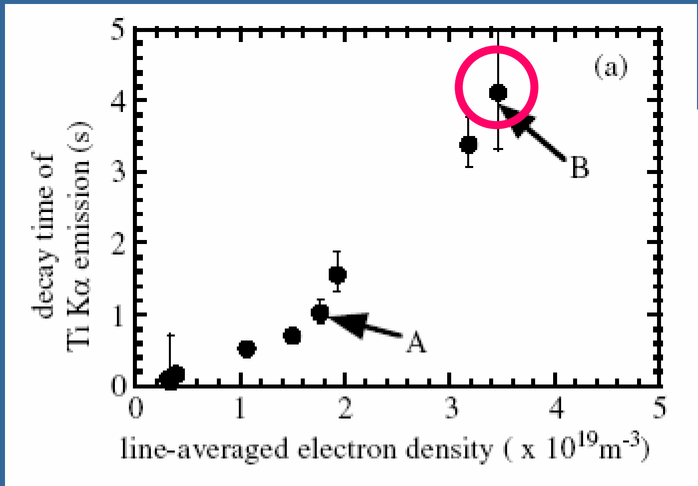


Fig.3 (a) Diffusion coefficients and (b) inward velocities as a function of line-averaged electron density. Points denoted with crosses mean neoclassical values

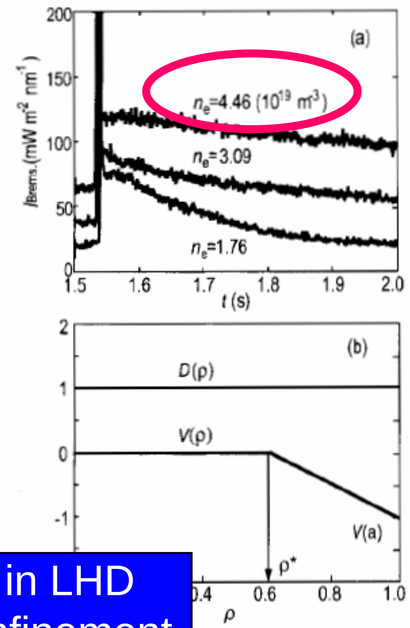
Impurity transport in LHD I

Do the following experiments indicate increasing confinement at high density ?



N.Tamura et al.,
Plasma Phys. Contr. Fusion 45 (2003) 27-41

Morita et al., Plasma Science & Technology, Vol. 8, No.1, 2006



isilbe bremsstrahlung after car-
) models of diffusion coefficient

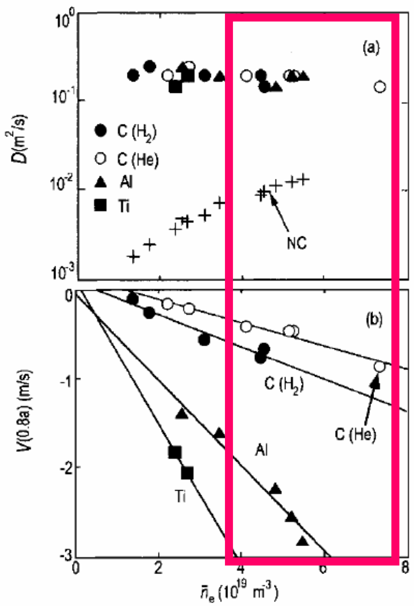


Fig.3 (a) Diffusion coefficients and (b) inward velocities as a function of line-averaged electron density. Points denoted with crosses mean neoclassical values

If „Yes“ >>> similar n_e-dependence in LHD as W7-AS, TJ-II at least for core confinement

D_{exp} >> D_{neo}, turbulent transport in LHD (even at high density) ?

Summary: *Similarities - Differences*

- statements for discussion -

- Indications for anomalous/turbulent transport at low and medium density *(TJ-II, W7-AS, LHD, CHS)*

- Tendency to approach neoclassics at high density *(LHD, W7-AS(HDH))*

- Improvement of impurity core confinement with density *(TJ-II, W7-AS, LHD (high n_e?))*

- What is mainly responsible for confinement „improvement“ ? :

CHS: diffusive fluxes
W7-AS: D, (v)
TJ-II: D, v
*LHD: v, i.e. E**r** - not D*

Summary: *Similarities - Differences* *cont'd*

- statements for discussion -

- Indications for anomalous/turbulent transport increasing with heating power (TJ-II, W7-AS)

- Impact of heating method on local turbulence profile ? :

ECRH:	*TJ-II*	*>*	*peaked D profile*
	W7-AS	*>*	*peaked D profile*
NBI:	*W7-AS*	*>*	*flat D profile*
	CHS	*>*	*hollow D profile*

- Mechanisms of purification at high density similar/different in W7-AS and LHD ?

- Many features are qualitatively
  … consistent with traditional neoclassics - but not quantitatively
  … not consistent with traditional neoclassics

>> Need for nonaxisymm. neoclassics ?

Thank you!

Data base and some key questions

A] Data collection in DB for scaling:

τ_{imp} (B,n,T,P,i, maximum E_r, heating system…)
D,v or D(r) ,v(r) at e.g. 2 radial positions, maximum E_r … where available

B] For physics understanding of transport better:

dedicated discharges for comparison which are well documented
(τ_{imp}, local D,v or with profiles of n_e,T_e,T_i,E_r, P_{heat}, ….)

Basis for understanding:

1) Consideration of stellarator specific features in the neoclassical model
(3-D magnetic topology, gradB-drift, D(E,Z, ν*) >> no analytical solution for ambipolarity,..)

>> strong impact: e.g. no T_i-screening

2) Where is the plasma describable with a neoclassical model
and where is it anomalous/turbulent   >> key: D(r)

3) E_r diagnostic very important for comparison of experimental v with neoclassical model