Comparison of Impurity Transport in Different Magnetic Configurations

Presented by Kieran J. McCarthy[a]

With coauthors

R. Burhenn[b], K. Ida[c], H. Maassberg[b], Y. Nakamura[c], N. Tamura[c]

a) *Laboratorio Nacional de Fusión, Asoc. EURATOM-CIEMAT, Madrid, Spain*

b) *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Greifswald, Germany*

c) *National Institute for Fusion Science, Toki, Japan*

International Stellarator/Heliotron Profile Database

IEA Implementing Agreement for Cooperation in the Development of the Stellarator Concept

17th International Toki Conference on *Physics of Flows and Turbulence in Plasmas* and 16th International Stellaretor/Heliotron Workshop

Outline

Motivation

Introduction

Experimental Observations in Different Configurations

Similarities and Differences

Database requirements

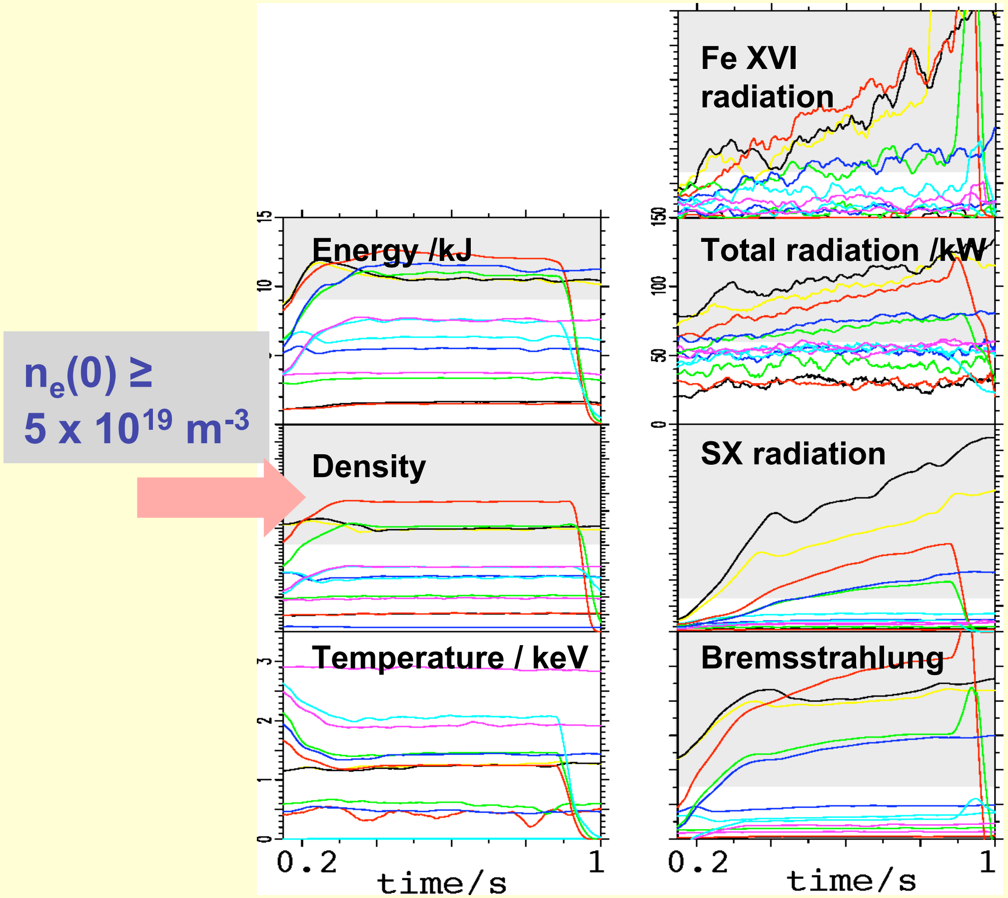
Motivation

Impurities: should they be of concern for stellarators?

- **Impurities acceptable at low concentrations**
  - ➡ **Beneficial (*e.g*. radiative cooling at edge, etc.)**
  - ➡ **Valuable diagnostic tools (e.g. V_r, E_r, etc.)**
- **Avoid core impurity accumulation (high-Z) during improved energy confinement modes**
  - ➡ **Overbalance of equilibrium between radiation losses & heating power**
    - ➡ **Degradation of plasma energy**
      - ➡ **Discharge termination**

W7-AS

An unfavourable impurity confinement dependence on density!



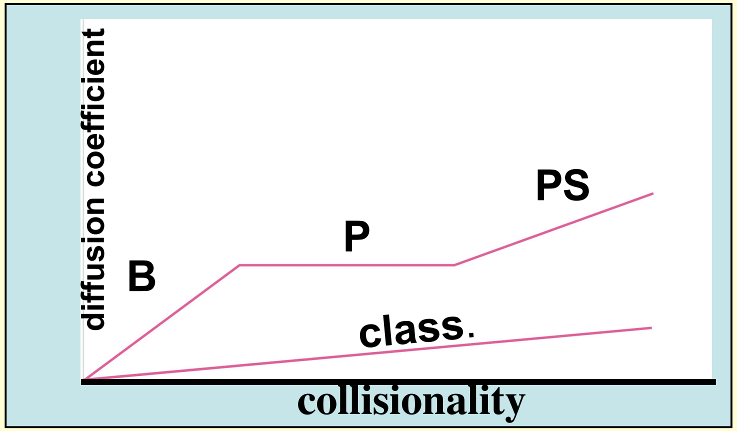
At low densities ➡ Stationary radiation levels

At high densities ➡ Increase of intrinsic impurity radiation

Motivation

How can core impurity accumulation be prevented?

- **Tokamaks**
  - ➡ **Confinement degrading phenomena such as ELMs and sawtooth crashes can be used to flush out impurities.**



With the background plasma is in banana regime

➡ υ **can be outward** ➡ **Temperature screening**
(from axisymetric neoclassics)

Motivation

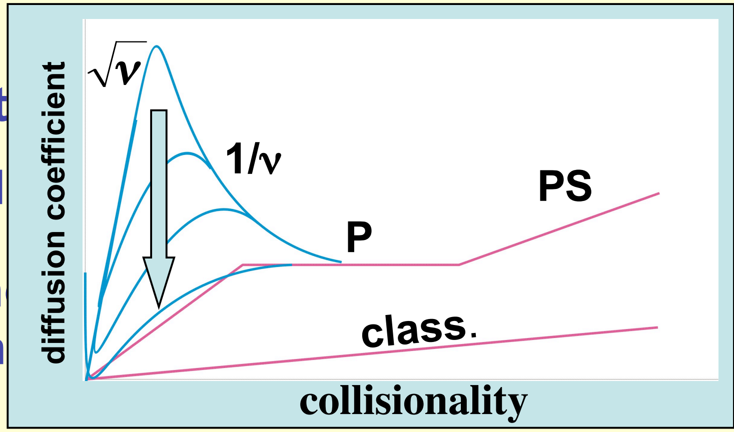
How can core impurity accumulation be prevented?

- **Tokamaks**
  - **Confinement degrading phenomena such as ELMs and sawtooth crashes can be used to flush out impurities. Also temperature screening.**
- **Stellarators**
  - **Current-connected phenomena not an option**
  - **ELMs difficult to produce in a controlled manner**
  - **No principal neoclassical mechanism in standard ion root (only in low n_e +ive electric fields in roots).**
  - **3-dim magnetic topology**
    - **Additional collisionality regimes for the background gas appear in the *lmfp* regions**

Motivation

How can core impurity accumulation be prevented?

- **Tokamaks**
  - **Confinement degrading phenomena such as ELMs and sawtooth crashes can be used to flush out impurities. Also temperature screening.**
- **Stellarators**
  - **Current ... option**
  - **ELMs d ... d manner**
  - **No prin ... standard ion root (only in ... ts).**



  - **3-dim magnetic topology**
    - ⇨ **Additional collisionality regimes for the background gas appear in the *lmfp* regions**

No temperature screening possible in P, ν, 1/ν, $\nu^{0.5}$ (υ is inward)

¿Possible in PS? *Non-axisymmetric neoclassics*

Motivation

How can core impurity accumulation be prevented?

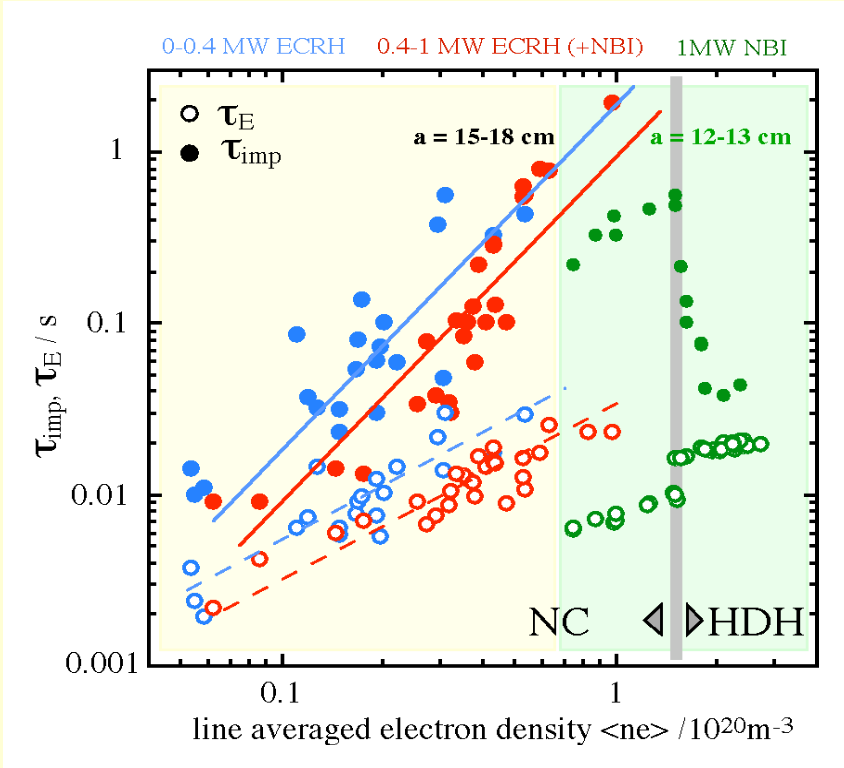
- **Tokamaks**
  - **Confinement degrading phenomena such as ELMs and sawtooth crashes can be used to flush out impurities. Also temperature screening.**
- **Stellarators**
  - **Current-connected phenomena not an option**
  - **ELMs difficult to produce in a controlled manner**
  - **No principal neoclassical mechanism in standard ion root (only in low n_e +ive electric fields in roots).**
  - **3-dim magnetic topology**
    - **Additional collisionality regimes for the background gas appear in the *lmfp* regions**
  - **There is a need to investigate Stellarator specific ways**

Motivation

What can these observations tell us wrt. stellarator pathways?

- **W7-AS**
  - **τ_{imp} scales with density in NC mode!**
  - **Introduction of divertor modules led to HDH-mode**
  - **Significant drop in τ_{imp} observed in HDH mode**

R. Burhenn *et al*, FST 46 (2004) 115



NC : „Normal" Confinement - very elmy H-mode
HDH: **H**igh **D**ensity **H**-mode

Motivation

What can these observations tell us wrt. stellarator pathways?

- **LHD**

  High-Z accumulation in specific density window

  Screening of intrinsic impurities at higher densities

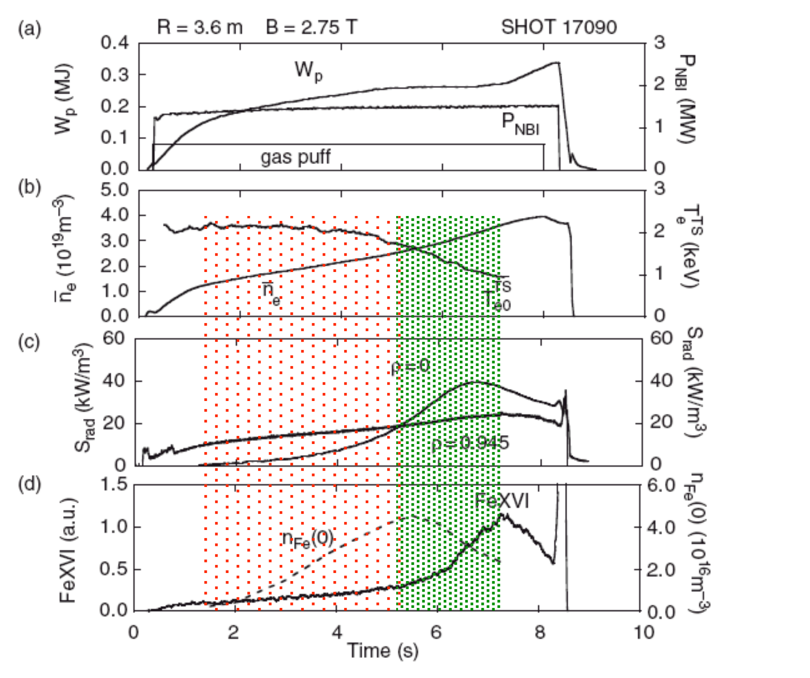


Figure 6. Time evolution of plasma parameters and the central iron density in a density ramp-up discharge (shot 17090). The plasma density increases with time by constant gas puffing. The central iron density was estimated with the impurity transport code MIST.

Y. Nakamura *et al.*, PPCF 44 (2002) 2121

Motivation

Can core impurity accumulation be prevented?

- **Tokamaks**
  - **Confinement degrading phenomena such as ELMs and sawtooth crashes can be used to flush out impurities. Also temperature screening.**
- **Stellarators**
  - **Current-connected phenomena not an option**
  - **ELMs difficult to produce in a controlled manner**
  - **No principal neoclassical mechanism in standard ion root (only in low n_e +ive electric fields in roots).**
  - **Different magnetic topology**
    - **additional transport regimes in *lmfp* regimes**
  - **Stellarator specific ways have been explored**
    - **need a clearer understanding of underlying physics**

Motivation

Is impurity behaviour in stellarators well described by the standard theoretical models for axisymmetric devices?

- **If good agreement with observations**
  - **Transport is understood**
  - **Conclusions can be drawn with respect to further improvements and extrapolations**
- **If poor agreement with observations**
  - **Point to dominance of turbulent/anomalous transport ?**
  - **The need for Stellarator specific transport contributions ?**
  - **Further interpretation becomes difficult!!**
  - **Predictions have to be substituted by measurement.**

Motivation

Introduction

Impurity content

Impurity Transport Analysis

Experimental Observations in Different Configurations

Similarities and Differences

Database requirements

Impurity Content

What mechanisms determine impurity content?

- **Impurity influx from the chamber walls, *etc*.**
  - ➡ **Governed by transport at open magnetic field & retention**

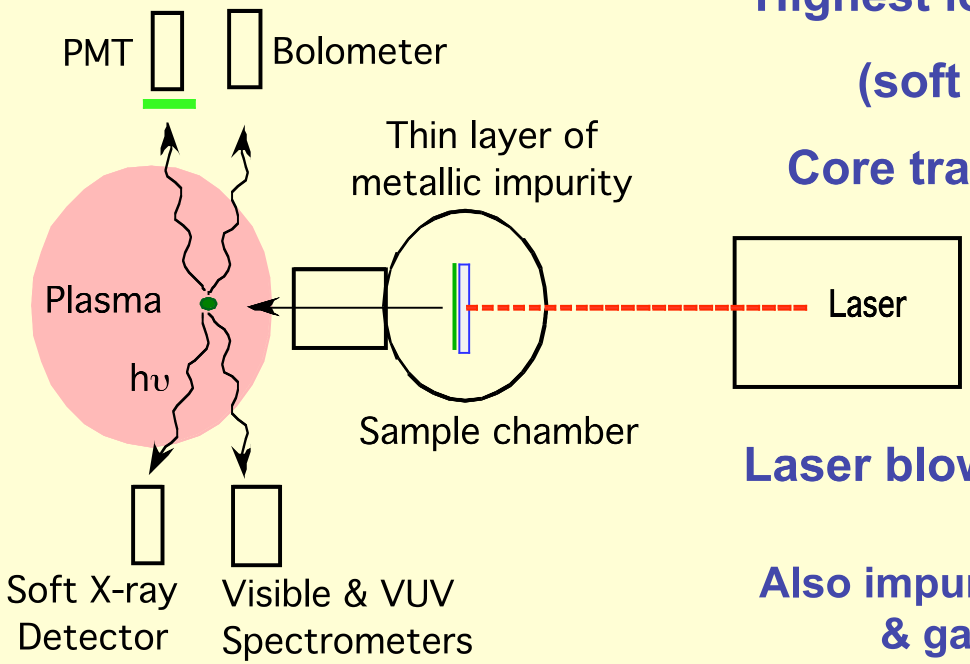
    Feng I-06 & Kobayashi I-07

- **Impurity transport inside closed magnetic surface**
  - ➡ **Diffusive, *D*, and convective, υ, terms**

    υ **driven by T and n gradients & space potential**

Impurity Transport Analysis

◆ Confinement time, τ_{imp} ⇨ Global transport quantity



Highest ionization stages

(soft x-ray, VUV)

Core transport studies

Laser blow-off

Also impurity pellet injection & gas-oscillation

Impurity Transport Analysis

- Confinement time, τ_{imp} ⇨ Global transport quantity
- Local transport quantities
  - Impurity fluxes, Γ, are based on neoclassical and PS transport for axisymmetric devices

$$\Gamma = D \cdot \nabla n + v \cdot n$$

D (r) - diffusion coefficient ($m^2\ s^{-1}$)

υ (r) - convective velocity ($m\ s^{-1}$)

- One-dimensional impurity transport models for axisymetric devices (e.g., SITAR, MIST codes)
  - No stellarator specific transport features implemented

Motivation

Introduction

- Impurity content
- Impurity Transport Analysis

Experimental Observations in Different Configurations

- **W7-AS**
- **TJ-II**
- LHD

→ **Tendencies**

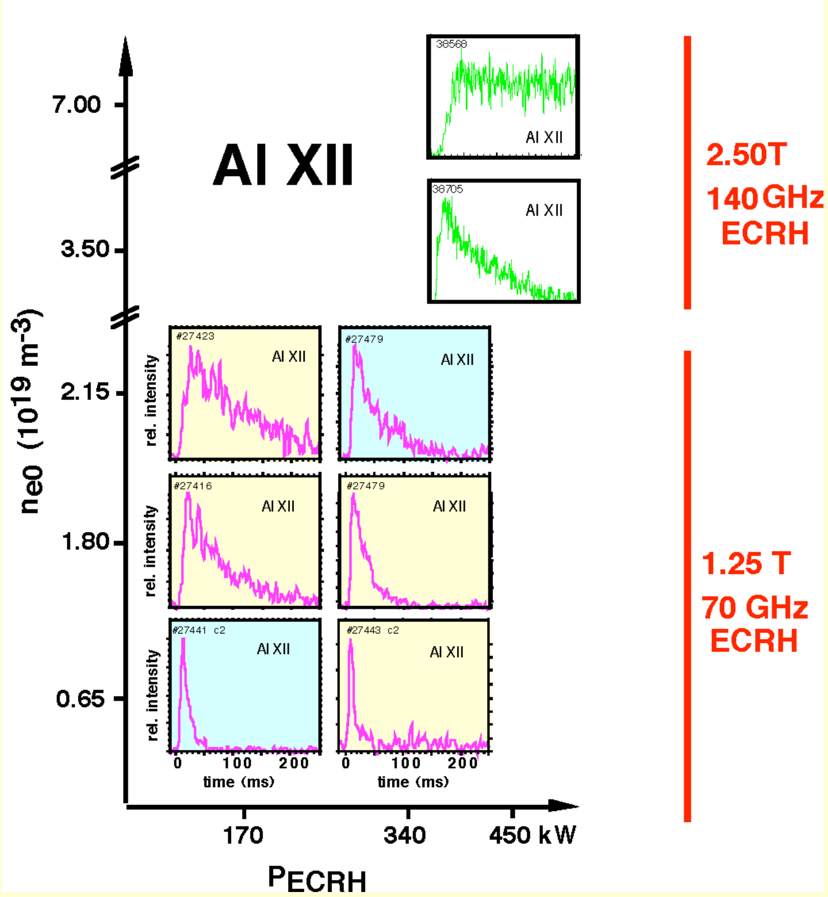
Similarities and Differences

Database requirements

W7-AS

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

(for $n_e(0) < 5 \times 10^{19}\ m^{-3}$)

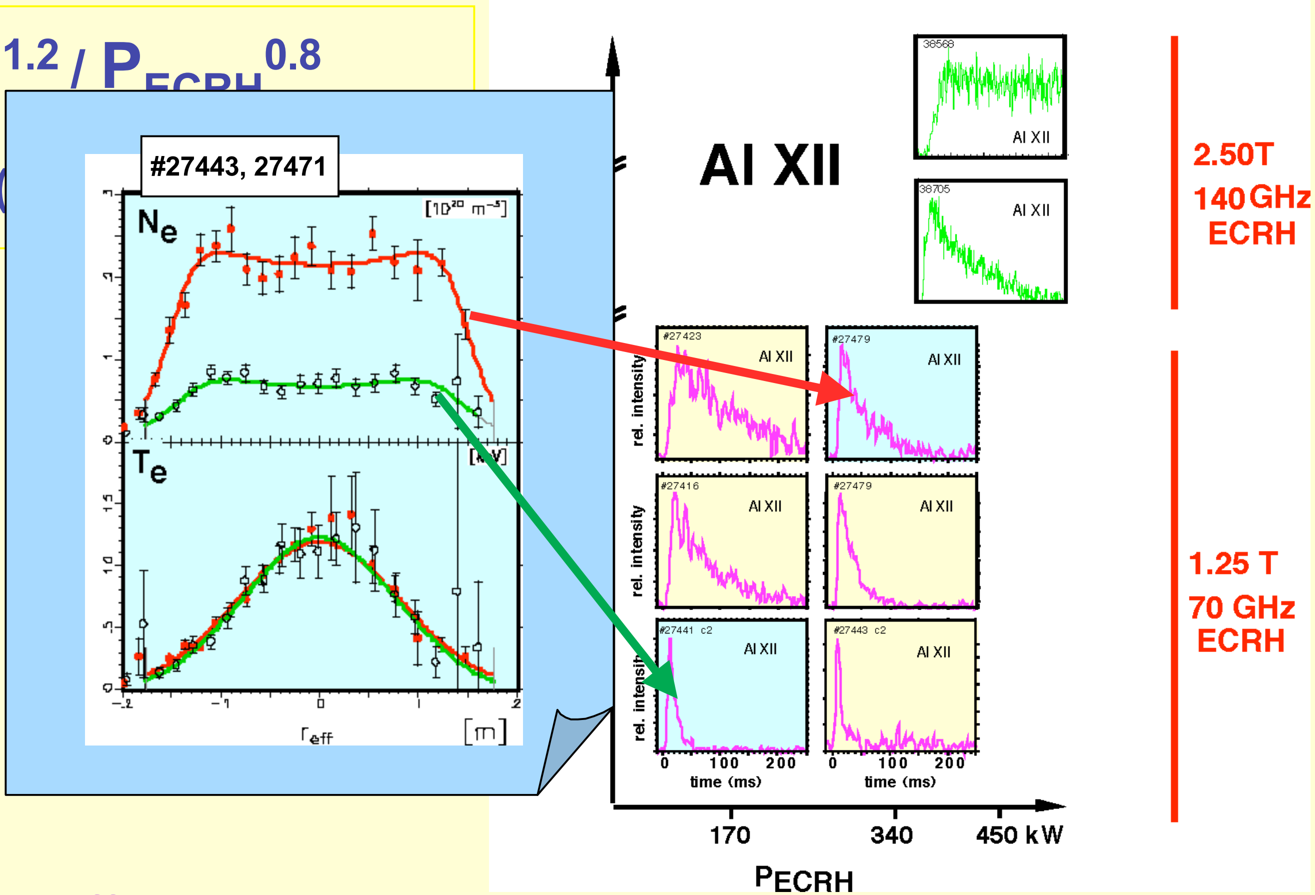


R. Burhenn *et al*,
Proc 22nd EPS (1995) III 145

W7-AS

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

(for n_e(



No T_e effect!
Weak role of B!

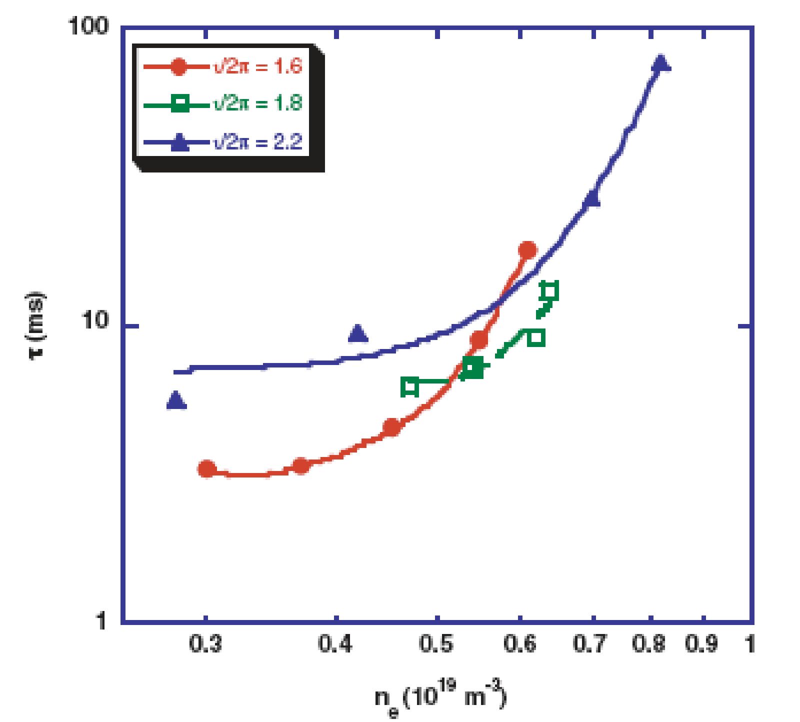
R. Burhenn *et al*,
Proc 22nd EPS (1995) III 145

W7-AS

TJ-II

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

(for $n_e(0) < 5 \times 10^{19}\ m^{-3}$)



z

Similar trend observed in TJ-II for $n_e(0) < 10^{19}\ m^{-3}$

PECRH

Hidalgo *et al.*, Nucl. Fusion 45 (2005) S266

Proc 22nd EPS (1995) III 145

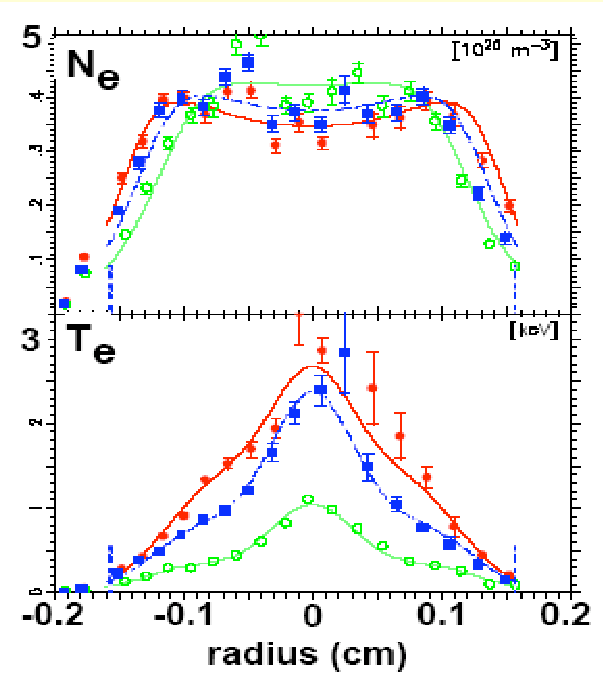
W7-AS

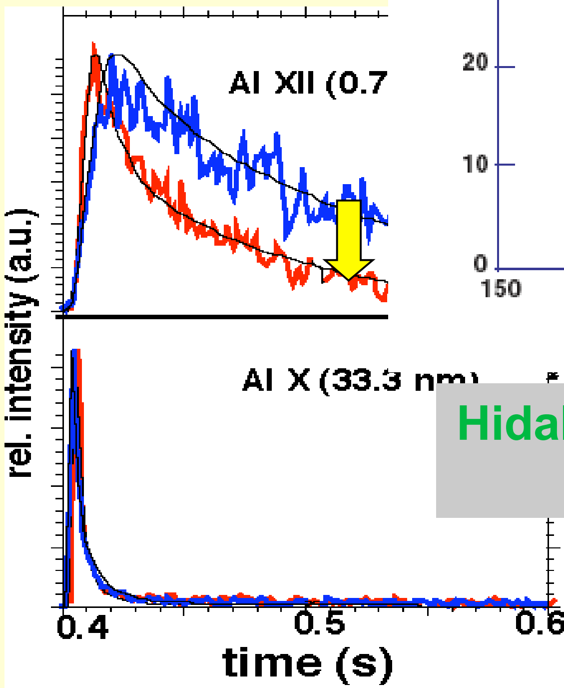
$\tau_{Al} \propto a_p^{2.4}\, n_e^{1.2} / P_{ECRH}^{0.8}$

(for $n_e(0) < 5 \times 10^{19}\ m^{-3}$)

800 kW (#37920)

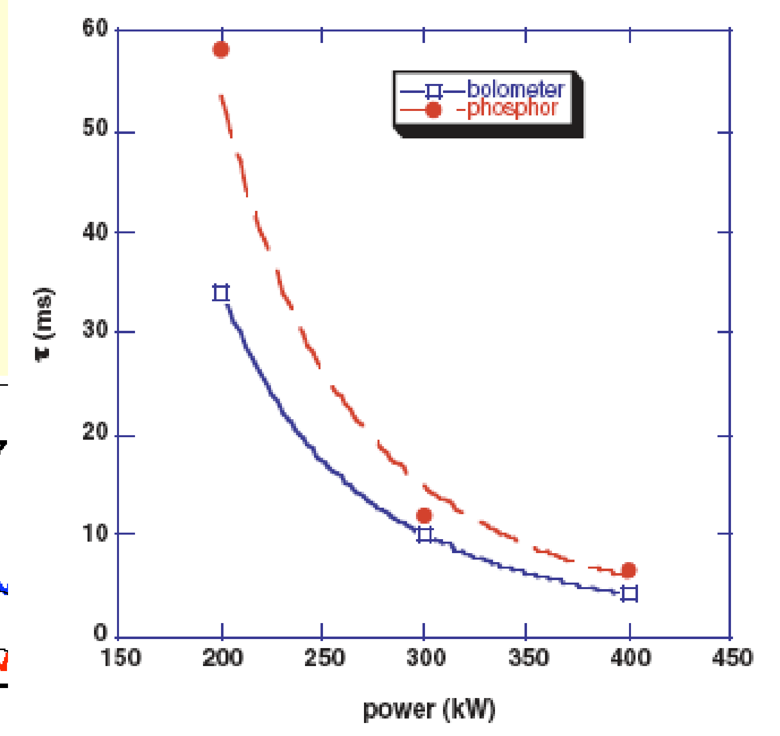
400 kW (#37909)





Burhenn *et al.*, FST 46 (2004) 115

P_{ECRH} dependence in TJ-II



Hidalgo *et al.*, Nucl. Fusion 45 (2005) S266

W7-AS

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

(for $n_e(0) < 5 \times 10^{19}\ m^{-3}$)

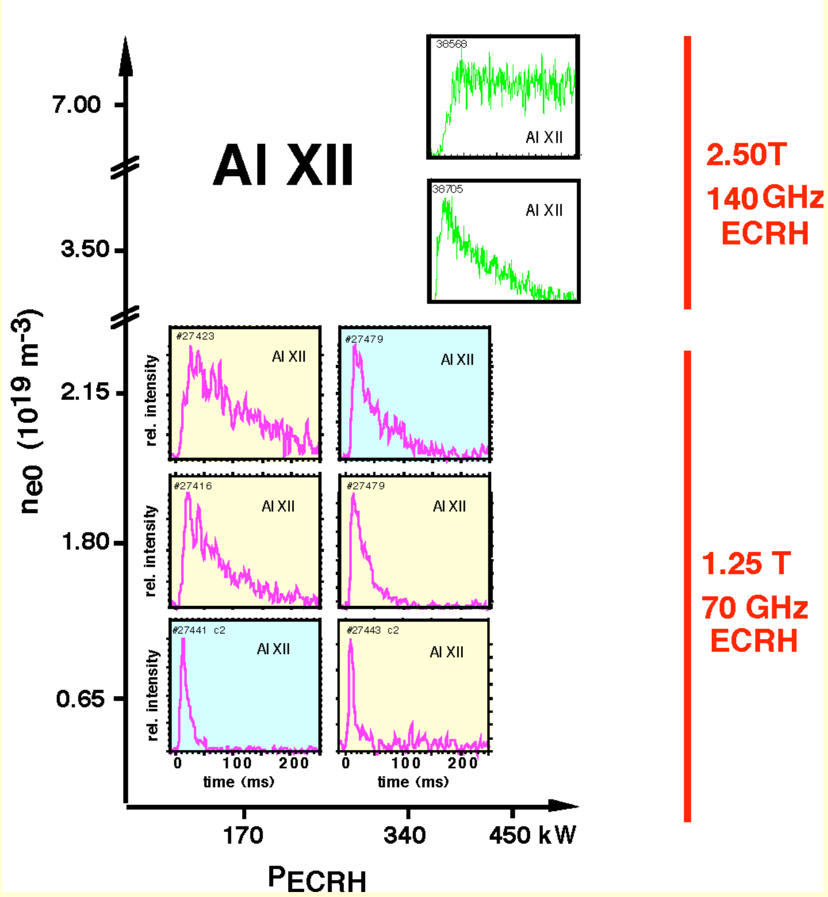
while…

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

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

The observed dependencies are trends not expected for the neoclass and PS transport model

➡ May point to additional impact of turbulent /anomalous transport?



R. Burhenn *et al*,
Proc 22nd EPS (1995) III 145

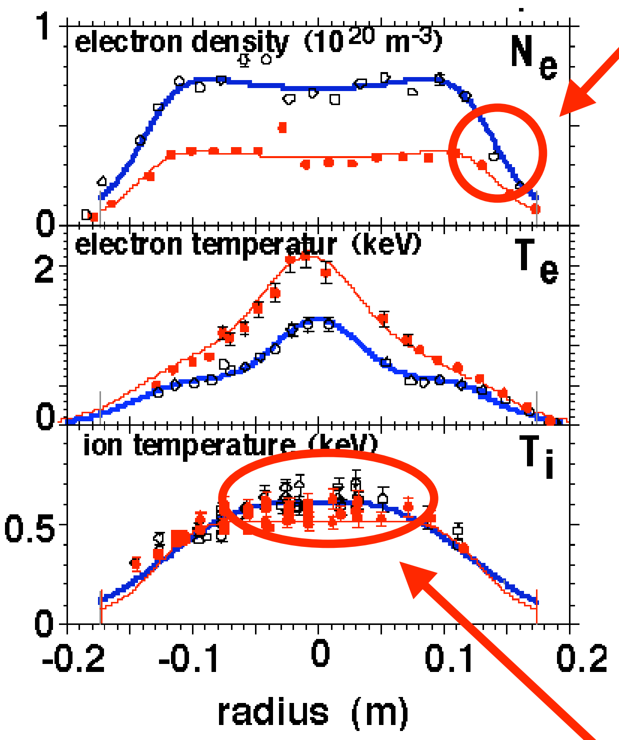
W7-AS What lies behind density dependence?

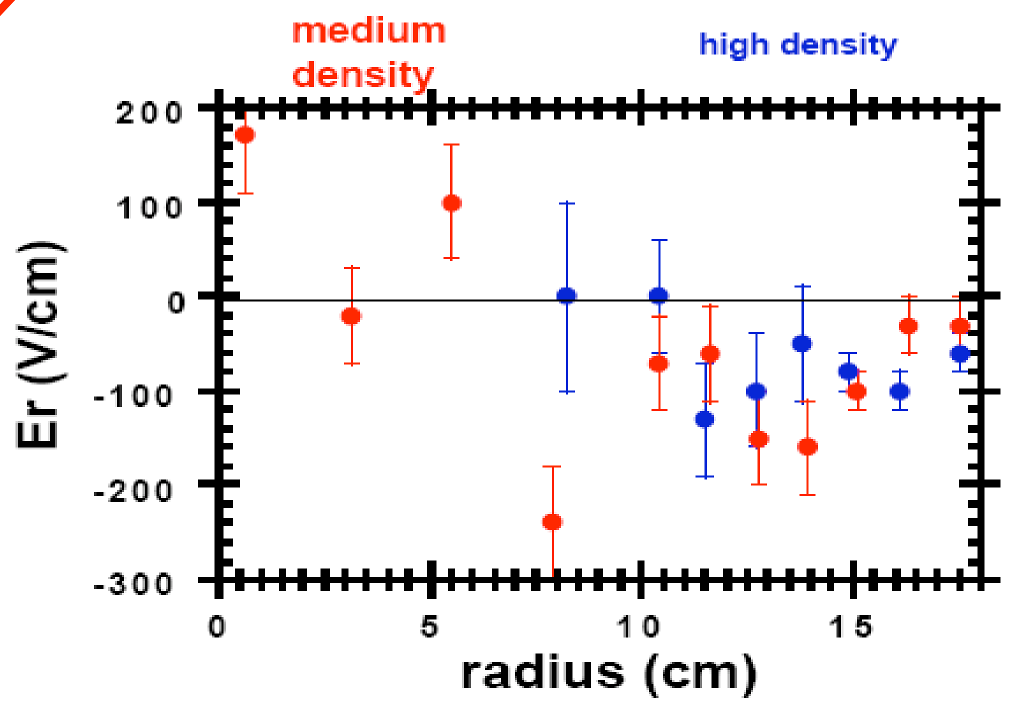
Comparison of ECRH plasmas

n_e profiles similar
⇒ no indication for different E_r

eo = 7 x 10^{19} m^{-3}

eo = 3.5 x 10^{19} m^{-3}



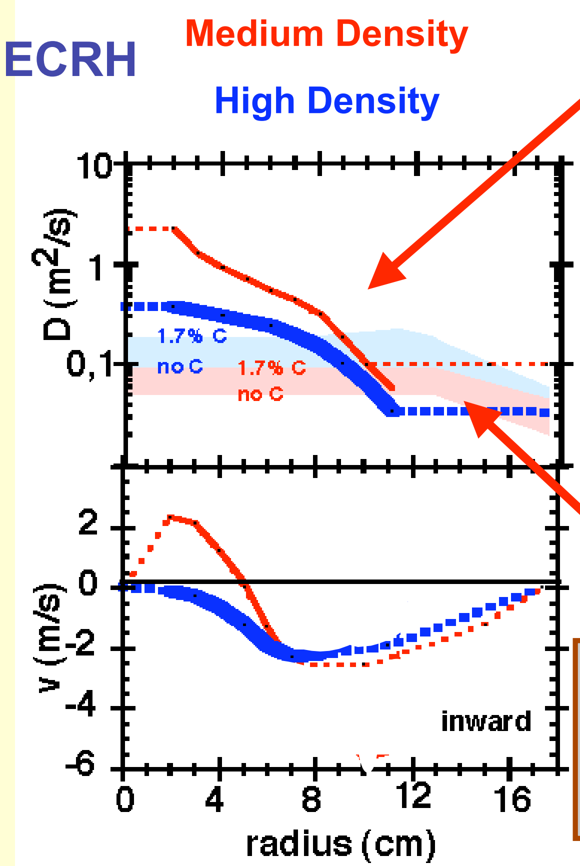


Might accumulation be due to slightly more peaked T_i profile?

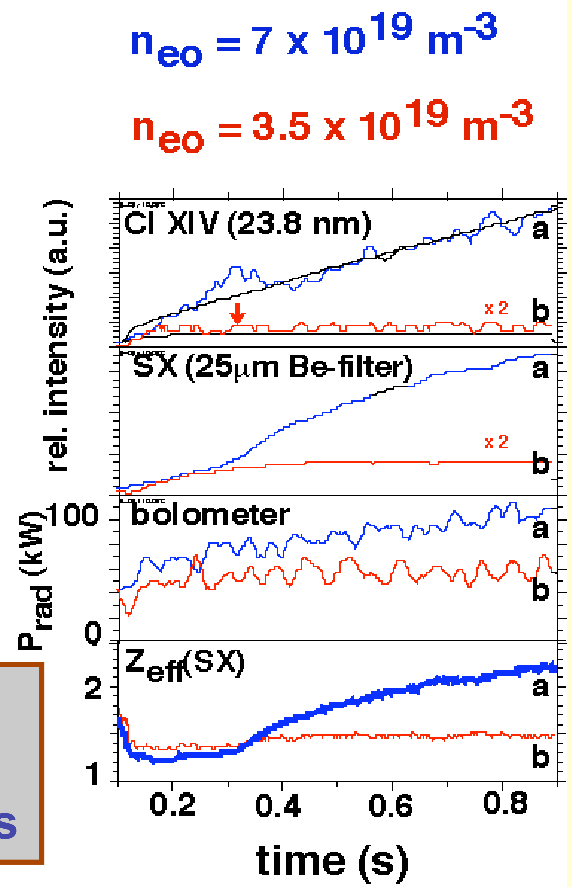
Expect outward υ for grad Ti from axisymmetric neoclassics!

W7-AS What lies behind density dependence?

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



experimental D, v match different time behaviour



Model predictions for different background impurity concentrations

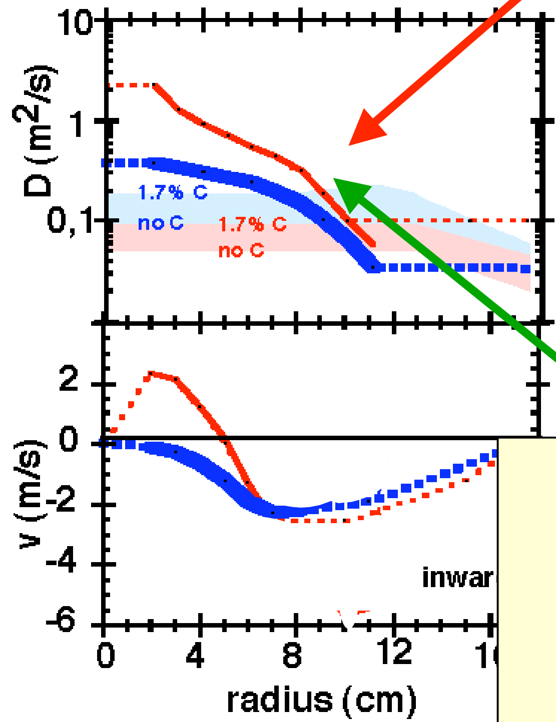
W7-AS What lies behind density dependence?

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

ECRH

Medium Density

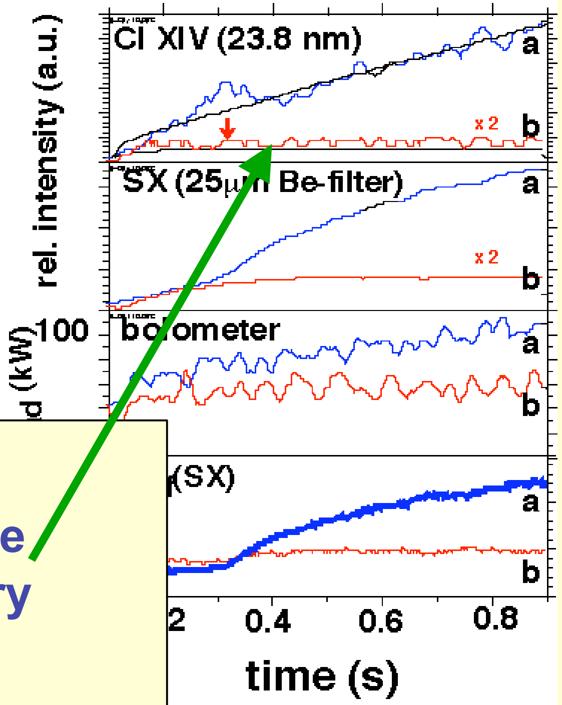
High Density



experimental D, v match different time behaviour

$n_{eo} = 7 \times 10^{19}\ m^{-3}$

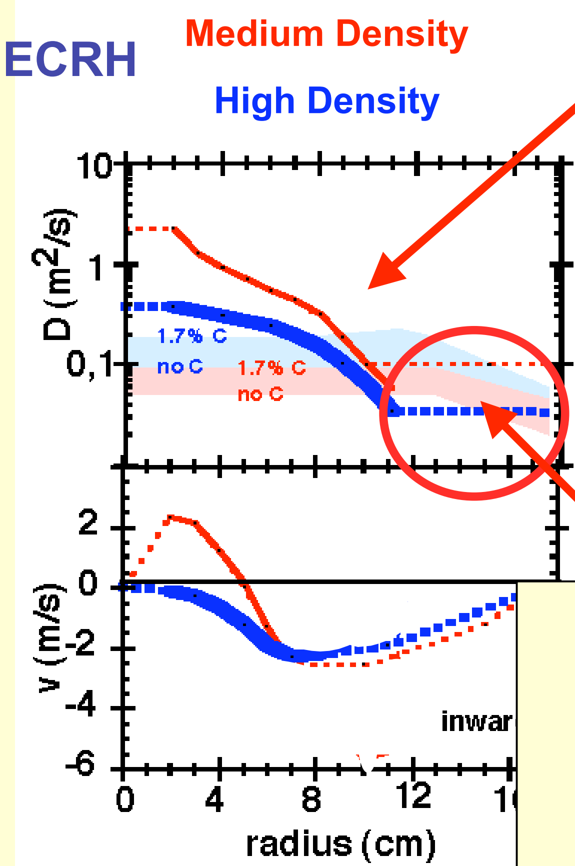
$n_{eo} = 3.5 \times 10^{19}\ m^{-3}$



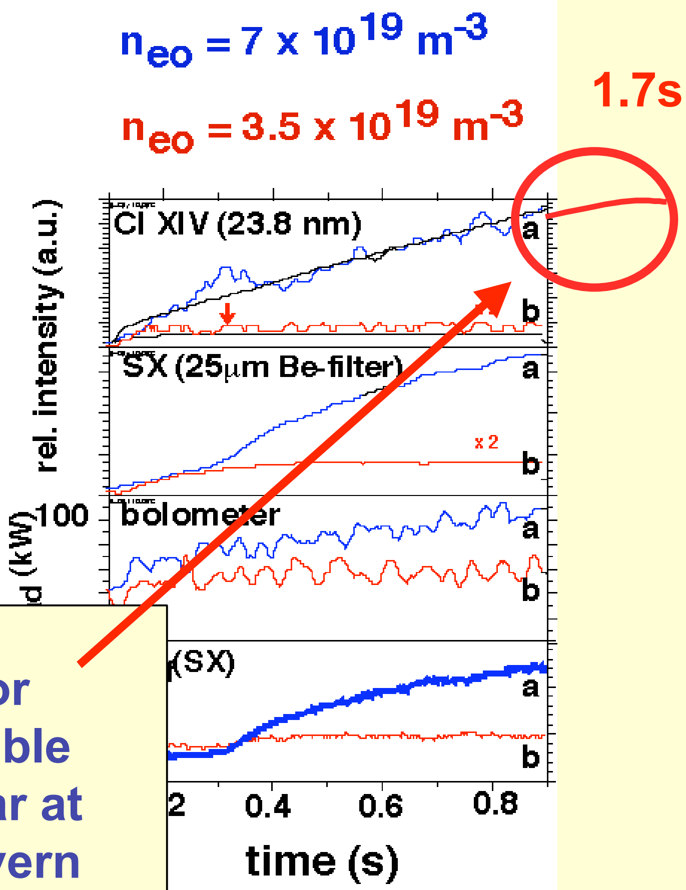
For **Medium Density**, the fast onset of a stationary radiation level is well described by high *D*.

W7-AS What lies behind density dependence?

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



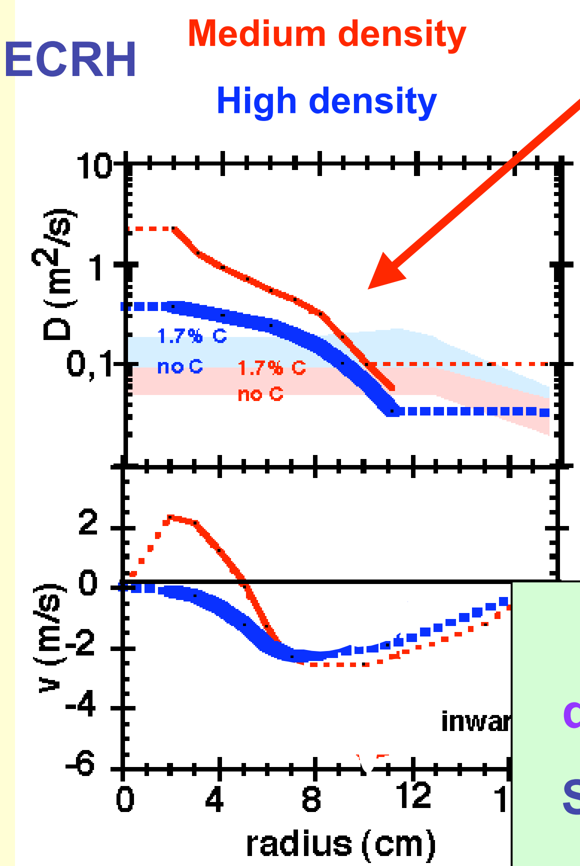
experimental D, v match different time behaviour



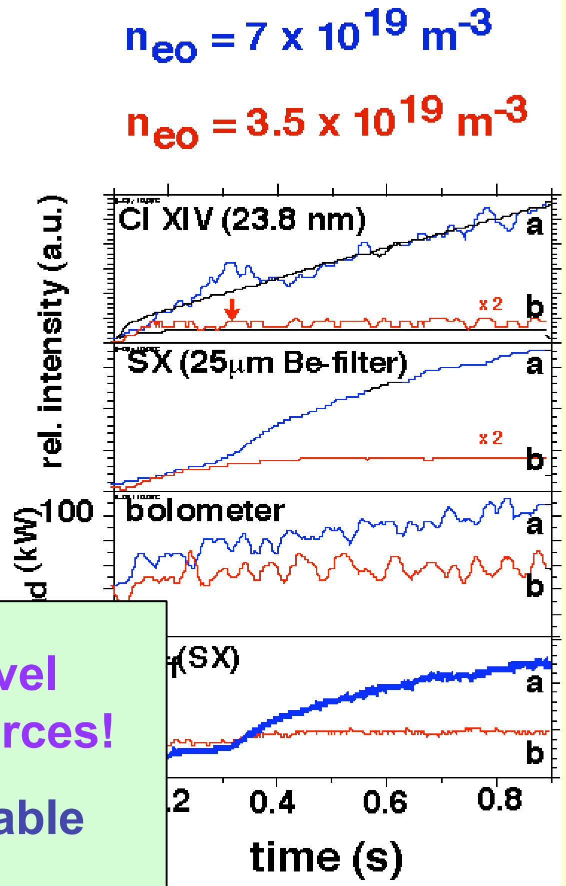
Increasing radiation for **High-Density** is compatible with lower *D,* in particular at edge, where low *D*`s govern time constant for transport.
Reduced impurity influxes cause long timescale.

W7-AS What lies behind density dependence?

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



experimental D, v match different time behaviour



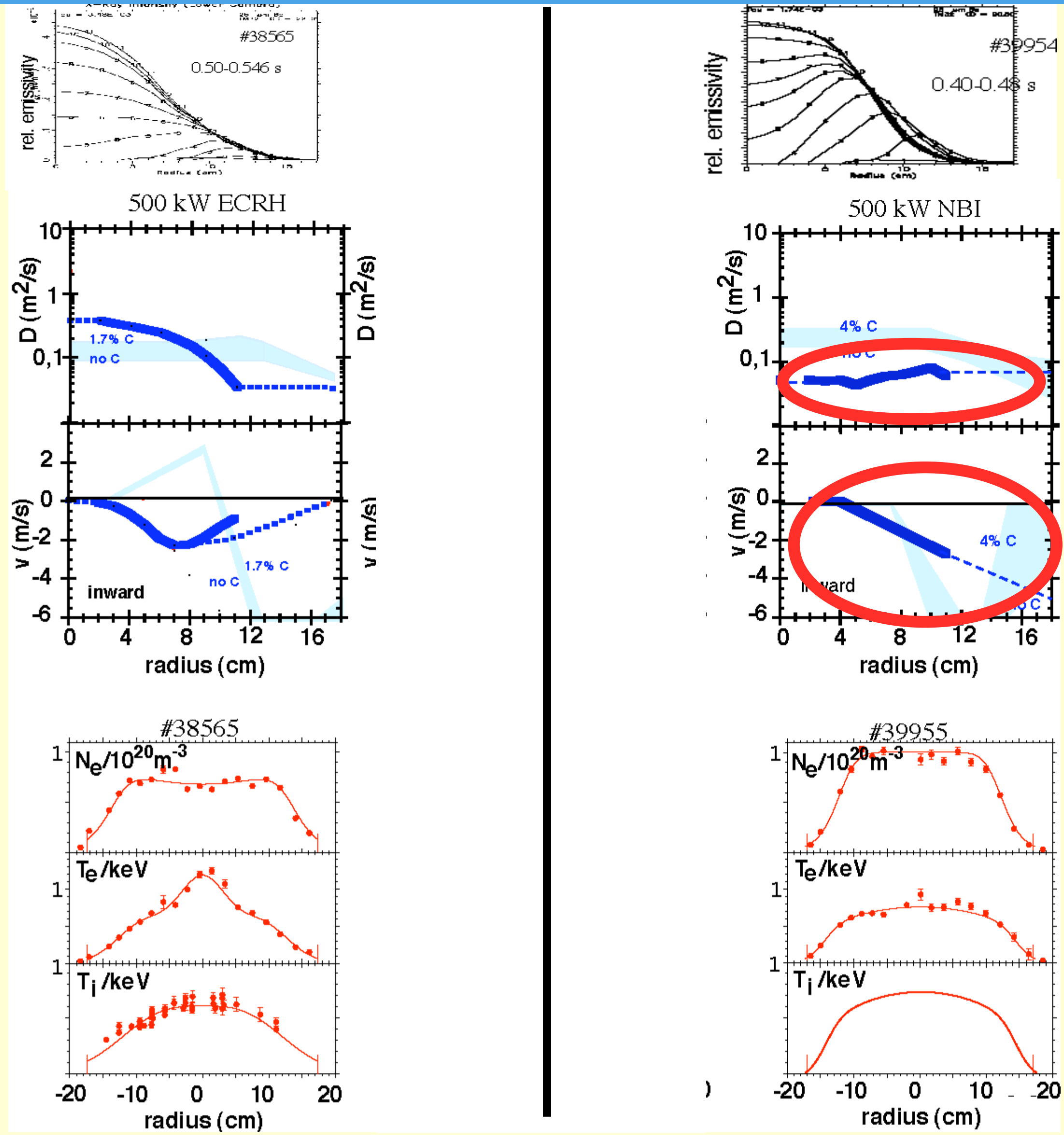
Stationary radiation level depends on impurity sources!

Small sources >> acceptable

Wall conditioning!

W7-AS

ECRH / NBI plasmas comparison with theory

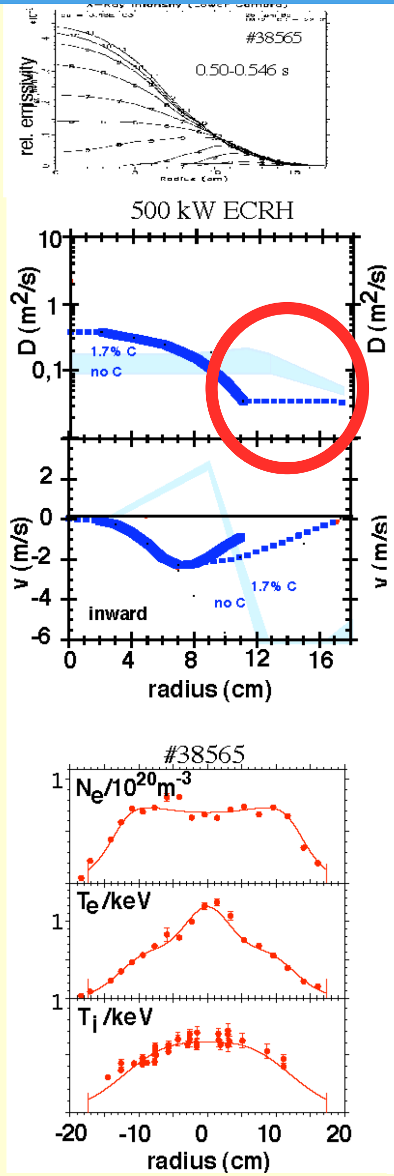


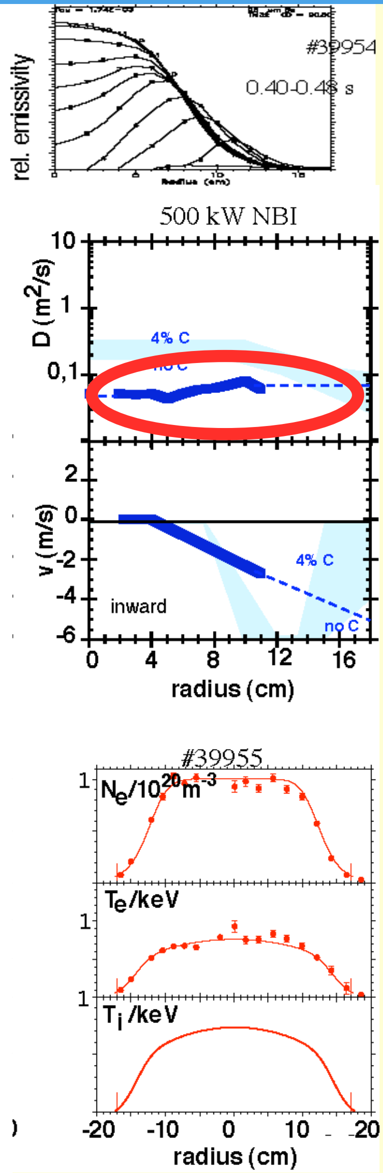
LBO Al injection into ECRH and NBI plasmas + Predictions for axisymmetric device.

Qualitative agreement

R. Burhenn *et al*, FST (2004) 115

W7-AS ECRH / NBI plasmas comparison with theory





LBO Al injection into ECRH and NBI plasmas + Predictions for axisymmetric device.

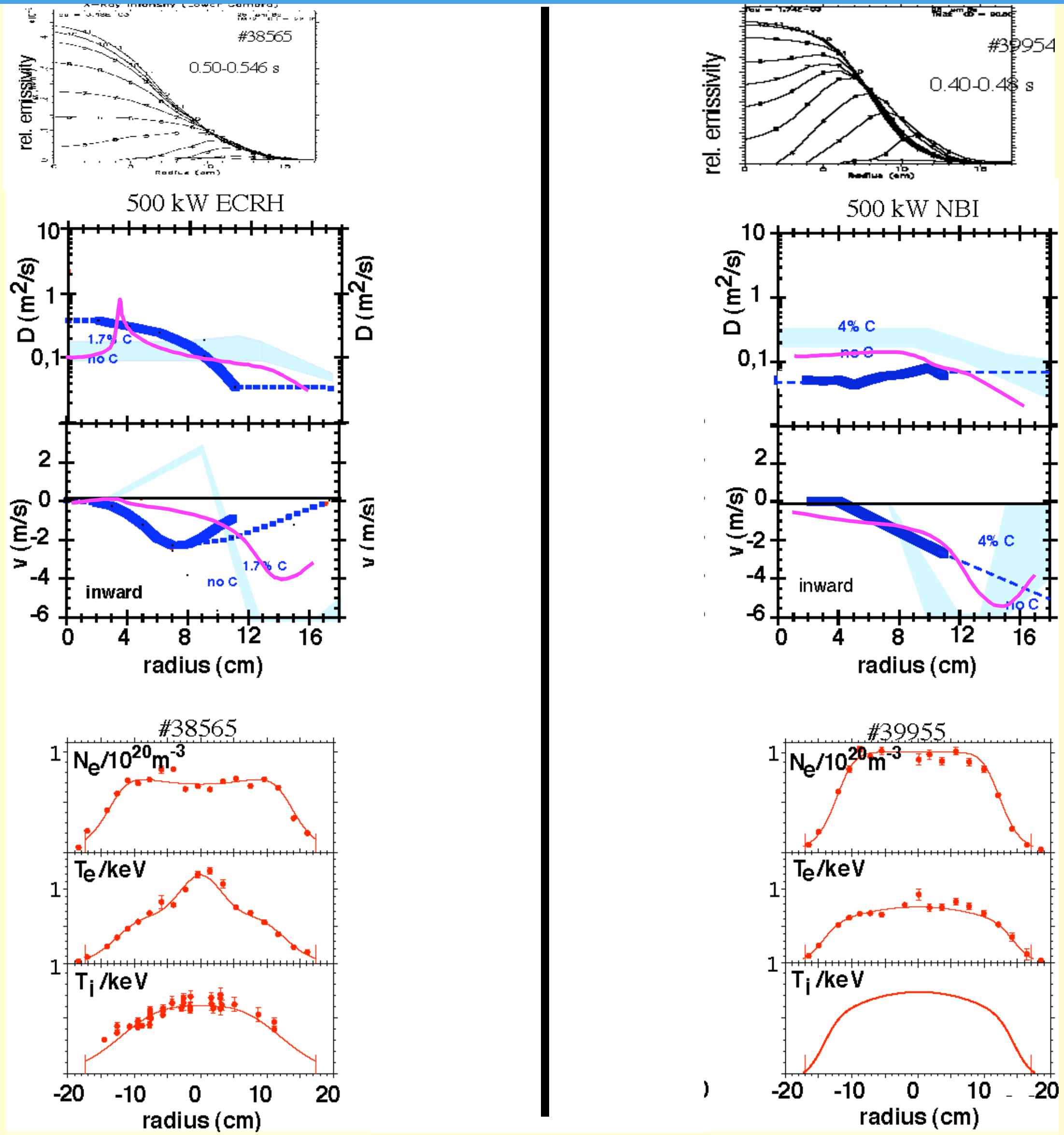
Discrepancy in *D*:

Experimentally derived *D*'… x3–8 times lower (!) than those predicted by model

Is this discrepancy due to neglect of stellarator features?

R. Burhenn *et al*, FST (2004) 115

W7-AS ECRH / NBI plasmas comparison with theory



Model modified with non-axisymmetric terms

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

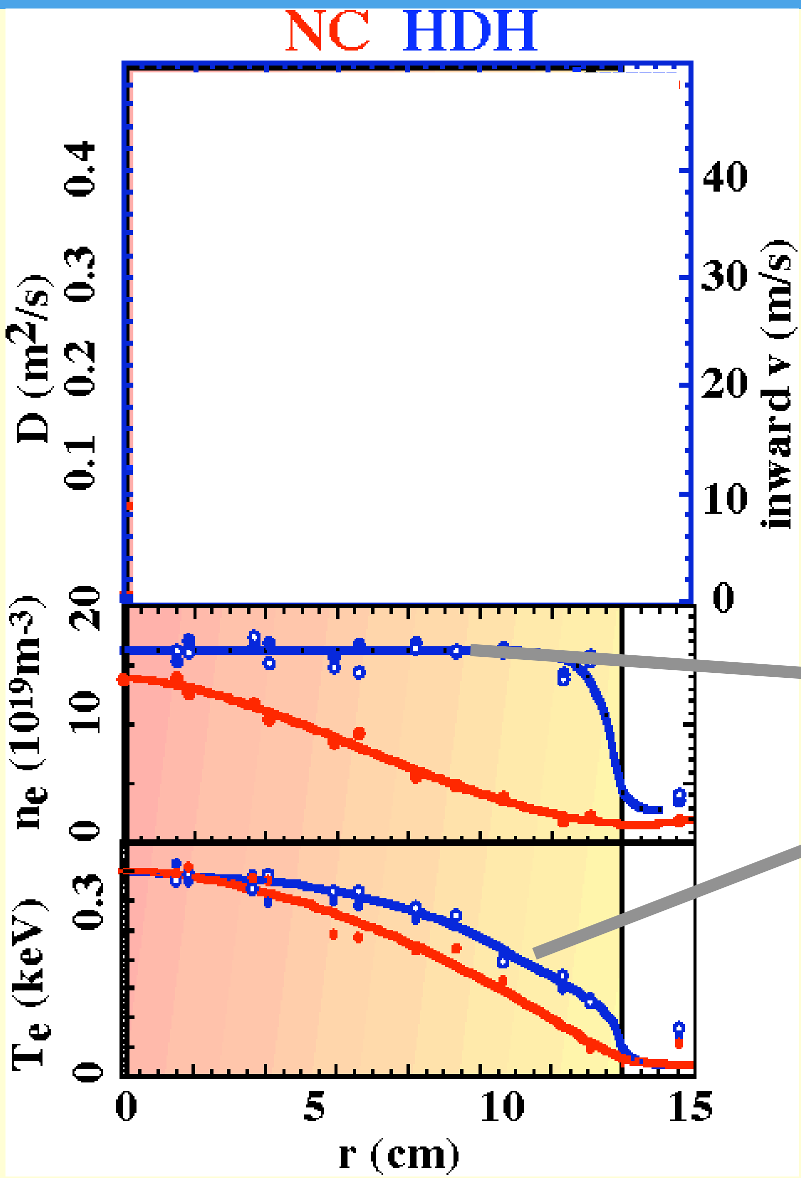
… but not υ …

Stronger accumulation expected

but not observed!

R. Burhenn *et al*, FST (2004) 115

W7-AS HDH mode



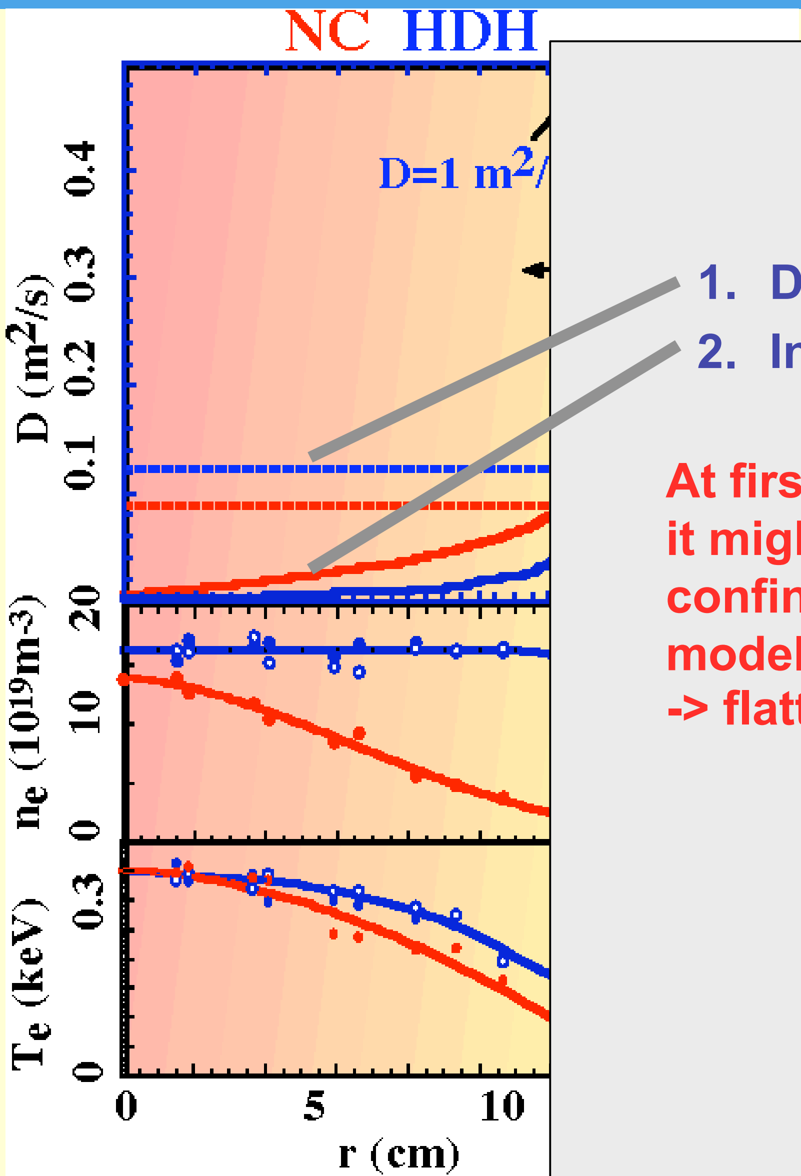
- Island Divertor modules
- Transition from NC to HDH at a power dependent threshold density
- τ_{imp} decreases
- τ_E increases

Density profile flattens

Temperature profile is similar

R. Burhenn *et al*, 30th EPS (2003) 27A

W7-AS HDH mode



For plasma core:

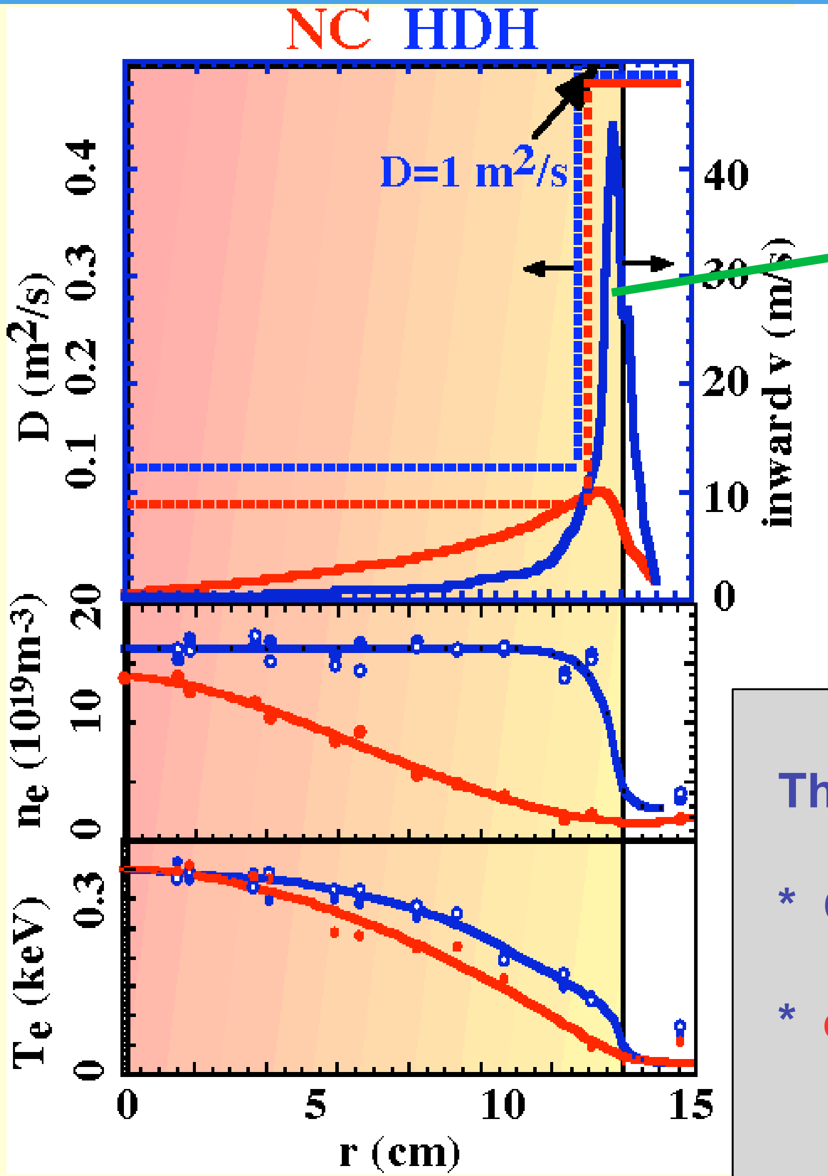
1. **Diffusion coefficients similar**
2. **Inward convective velocity is reduced**

At first glance,
it might appear obvious to explain degraded confinement in terms of the neoclassical/PS model
-> flattening of n_e profile >> reduction of υ_{in}

Not the whole story ...

R. Burhenn *et al*, 30th EPS (2003) 27A

W7-AS HDH mode



Need to consider plasma edge also!!

◆ **Strong increase of v_{in} !** (K. Ida)

➡ **Long confinement time**

rather than

degraded confinement!

Need to compensate with high *D* at edge to achieve the short confinement

This means:

* **Changes of core transport important, but**

* **edge impurity transport essentially determines global confinement!**

R. Burhenn *et al*, 30th EPS (2003) 27A

Motivation

Introduction

- Impurity content
- Impurity Transport Analysis

Experimental Observations in Different Configurations

- W7-AS
- TJ-II
- **LHD** ⇨ **Tendencies**

Similarities and Differences

Database requirements

LHD

Density Ramp-up

Low density

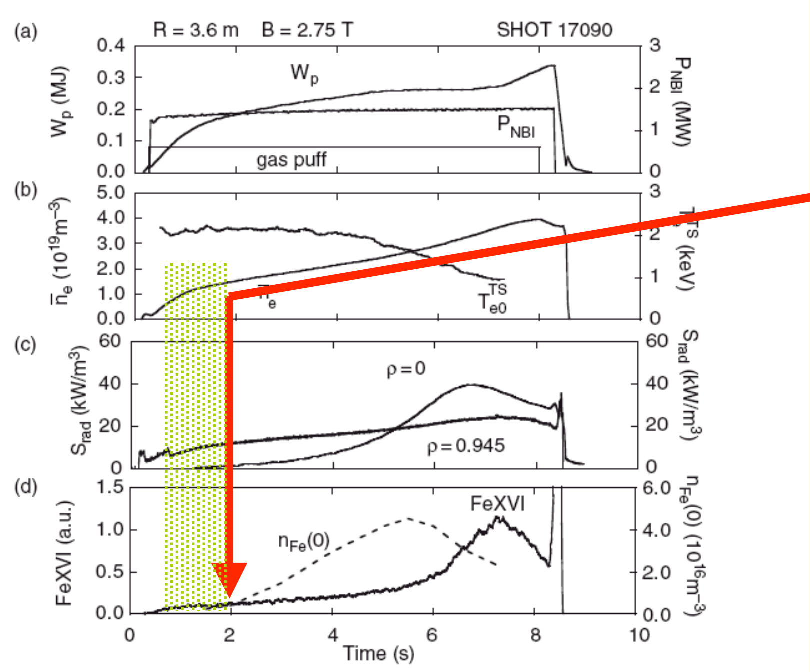


Figure 6. Time evolution of plasma parameters and the central iron density in a density ramp-up discharge (shot 17090). The plasma density increases with time by constant gas puffing. The central iron density was estimated with the impurity transport code MIST.

Y. Nakamura *et al*.,
PPCF 44 (2002) 2121

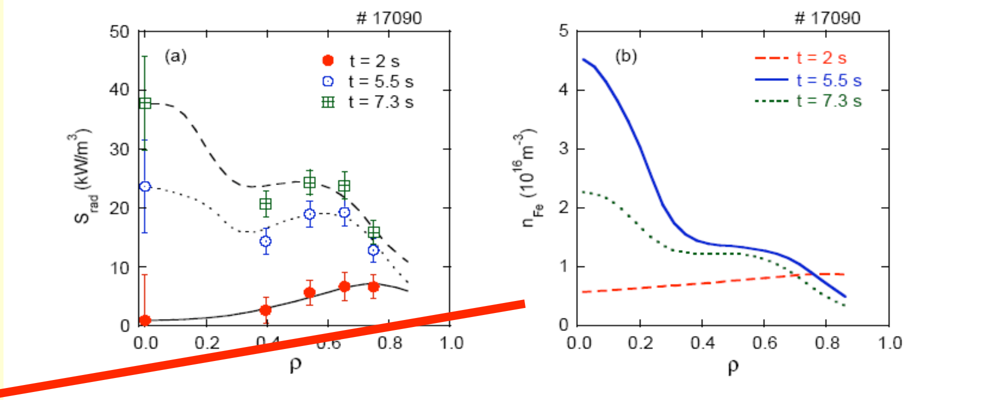


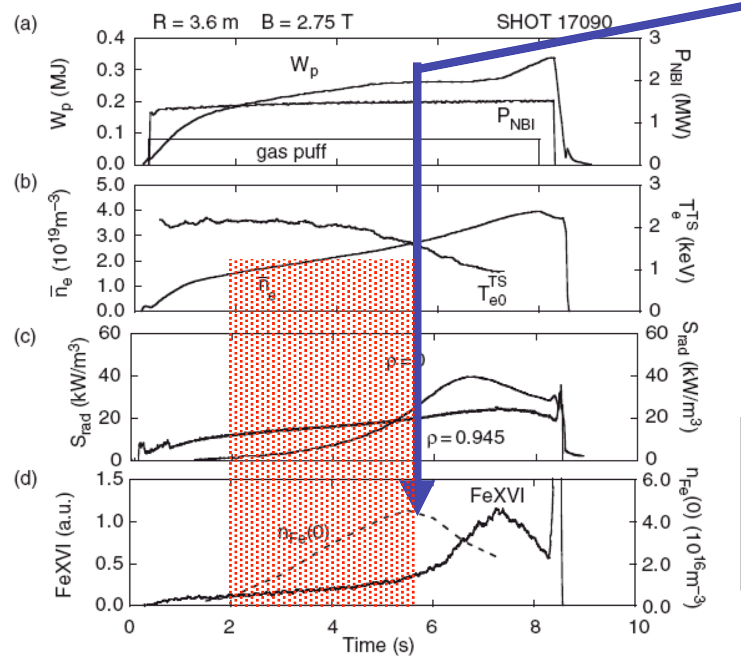
Fig. 11 Profiles of (a) radiation and (b) iron density at each time (t = 2, 5.5, 7.3 s) for the discharge in Fig. 10. The lines in the radiation profiles indicate the fitting curves calculated from the impurity transport code MIST.

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

LHD

Density Ramp-up

Accumulation window at medium density



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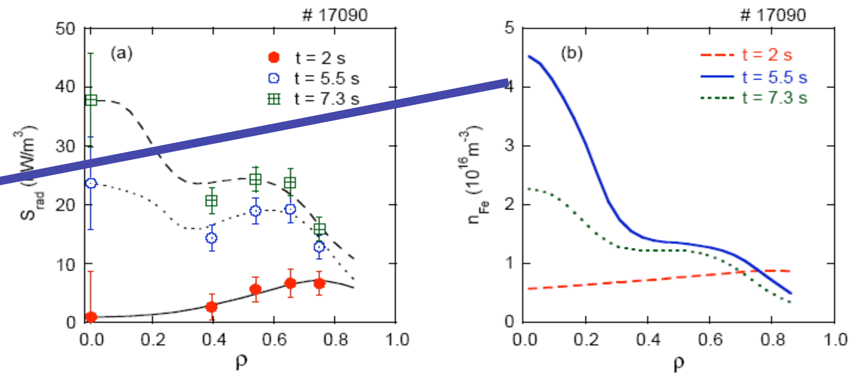
Y. Nakamura *et al.*, PPCF 44 (2002) 2121



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

See accumulation with long time constant!

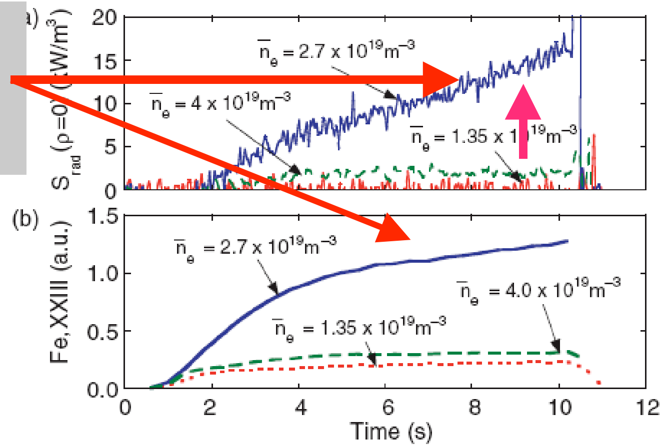


Figure 9. Time evolution of (*a*) central radiation and (*b*) Fe XXIII emission for discharges with constant densities. Remarkable increases are observed only for the discharge with 2.7 × 10^{19} m^{-3}.

Y. Nakamura *et al.*, NF 43 (2003) 219

LHD

Density Ramp-up

Accumulation window at medium density

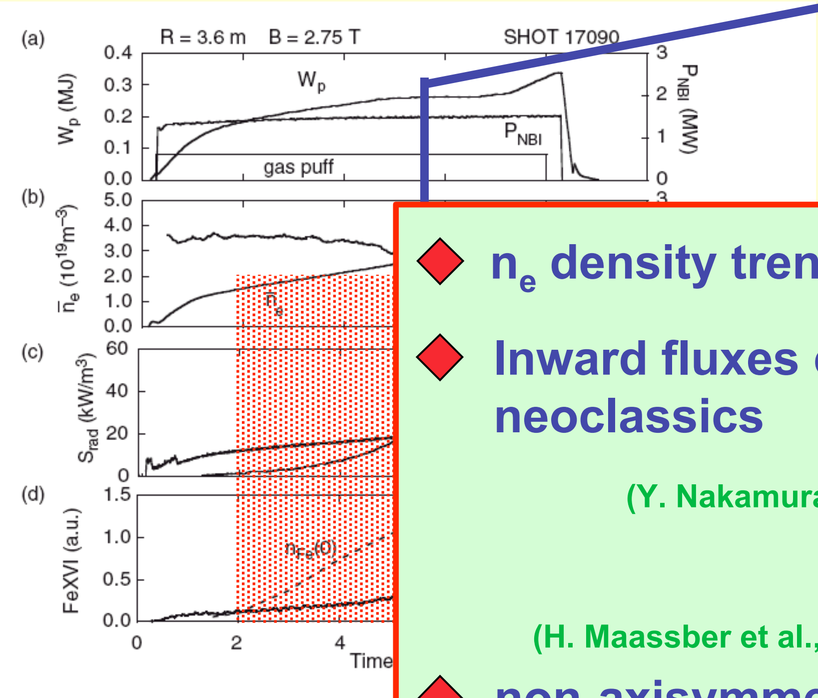
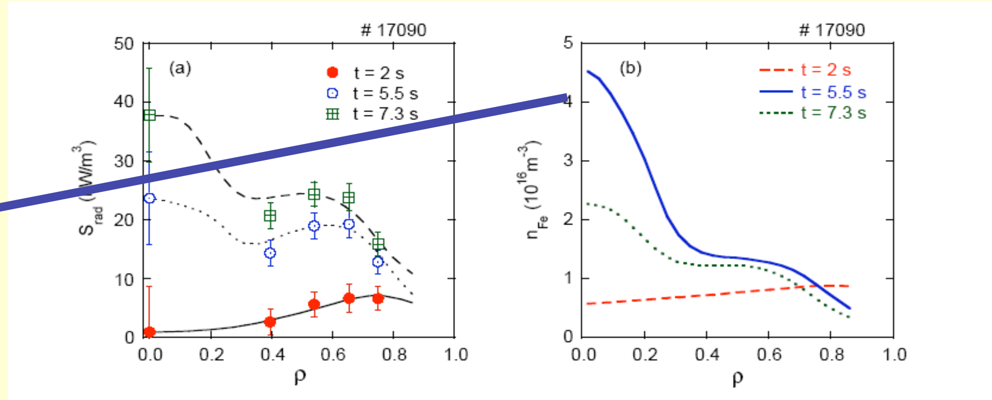


Figure 6. Time evolution of plasma parameter… discharge (shot 17090). The plasma density i… central iron density was estimated with the impurity transport code MIST.



- n_e density trend similar to W7-AS
- Inward fluxes cannot be reproduced by axisymmetric neoclassics

  (Y. Nakamura et al., PPCF 44 (2002) 2121))

  but possibly by …

  (H. Maassber et al., PFCF 41 (1999) 1135)

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

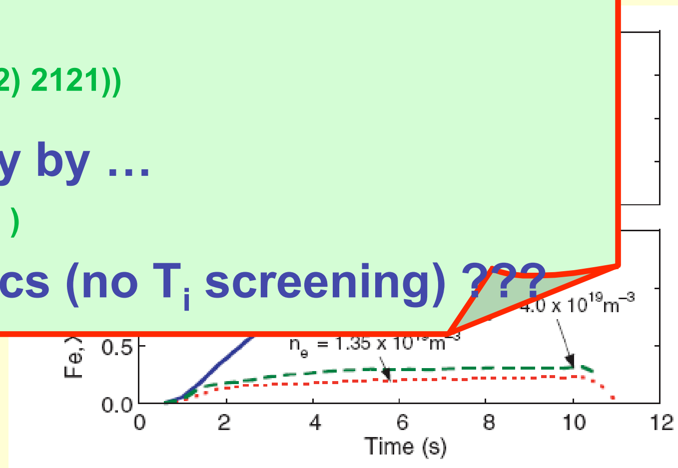


Figure 9. Time evolution of (*a*) central radiation and (*b*) Fe XXIII emission for discharges with constant densities. Remarkable increases are observed only for the discharge with 2.7 × 10^{19} m^{-3}.

Y. Nakamura *et al.*,
PPCF 44 (2002) 2121

Y. Nakamura *et al.*,
NF 43 (2003) 219

LHD

Density Ramp-up

„Flush-out“

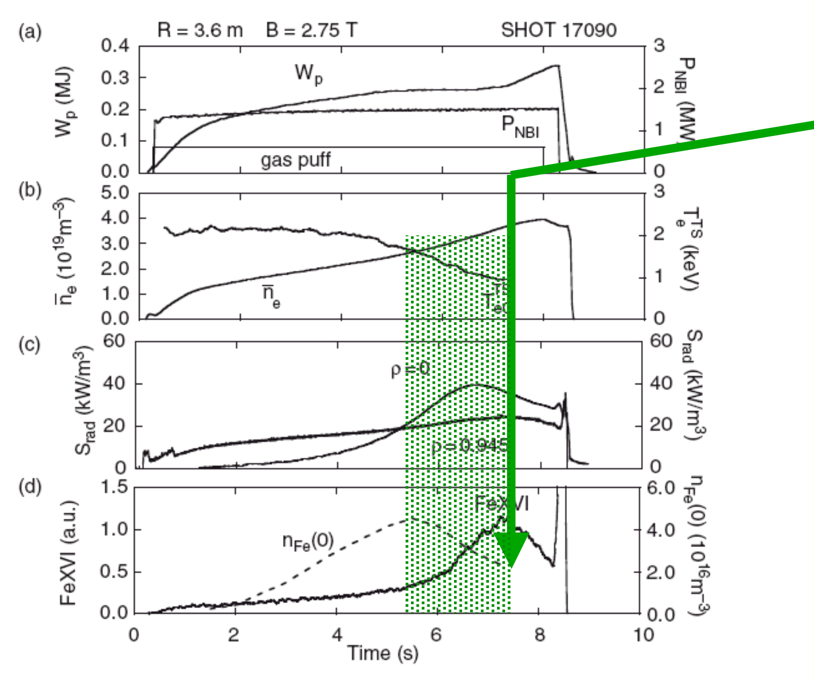


Figure 6. Time evolution of plasma parameters and the central iron density in a density ramp-up discharge (shot 17090). The plasma density increases with time by constant gas puffing. The central iron density was estimated with the impurity transport code MIST.

Y. Nakamura *et al*., PPCF 44 (2002) 2121

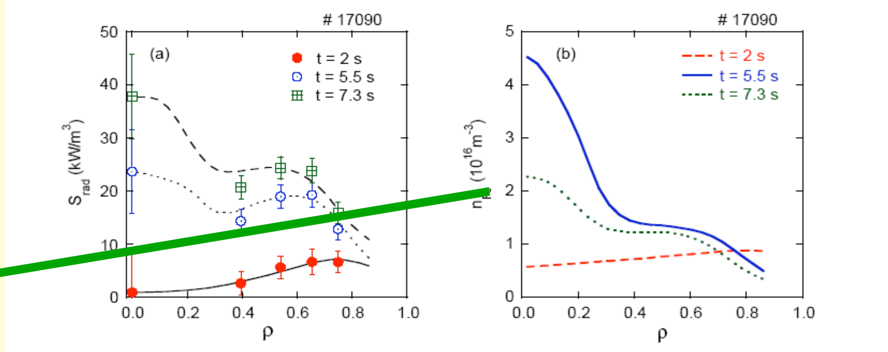
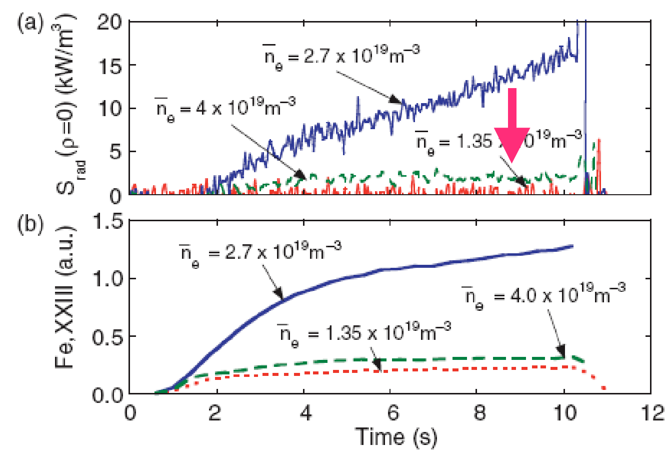


Fig. 11 Profiles of (a) radiation and (b) iron density at each time (t = 2, 5.5, 7.3 s) for the discharge in Fig. 10. The lines in the radiation profiles indicate the fitting curves calculated from the impurity transport code MIST.

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



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Y. Nakamura *et al*., NF 43 (2003) 219

LHD

Density Ramp-up

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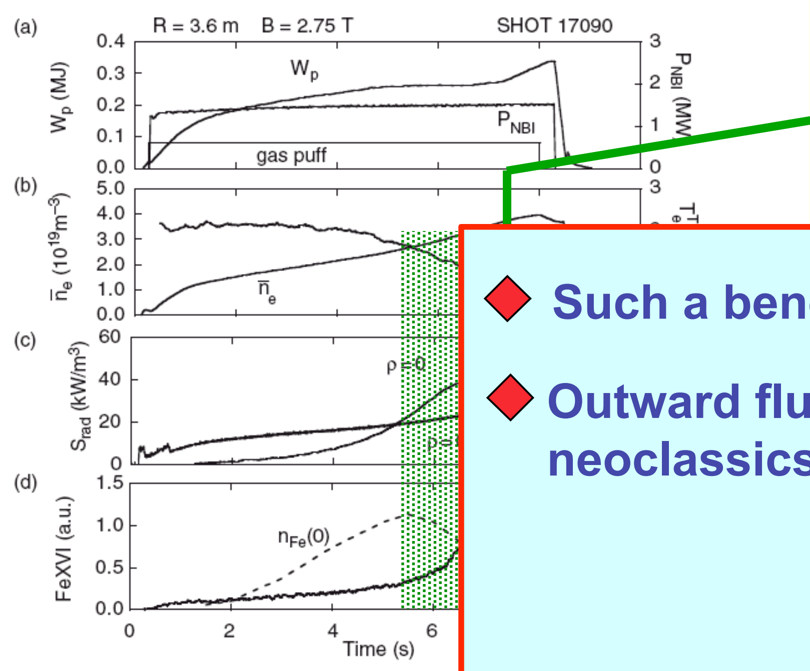
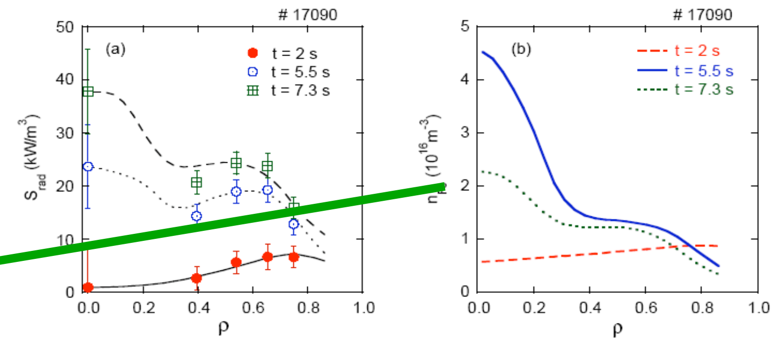


Figure 6. Time evolution of plasma parameters and the discharge (shot 17090). The plasma density increases central iron density was estimated with the impurity tran



- Such a beneficial effect observed only in HDH (W7-AS)
- Outward fluxes are expected from traditional neoclassics (T_i screening)

(Y. Nakamura et al., PPCF 44 (2002) 2121-2134)

but not from …

non-axisymmetric neoclassics (no T_i screening) !?

(H. Maassberg et al., PFCF 41 (1999) 1135)

?

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Y. Nakamura *et*
PPCF 44 (2002) 2121

Y. Nakamura *et al.*,
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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 2.7×10^{19} m^{-3}.

LHD

What are the reason(s) for the accumulation window?

Low collisionality **High collisionality**

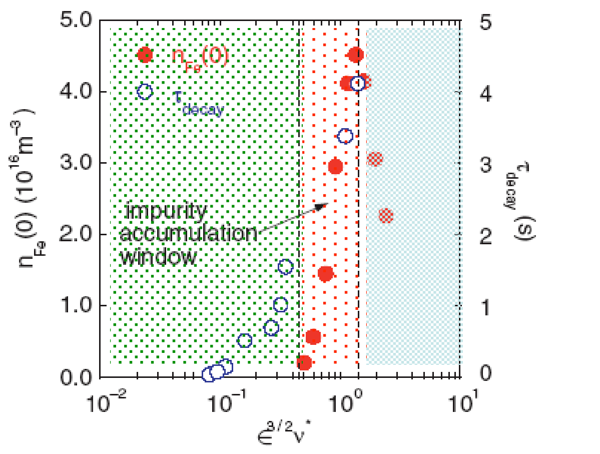


Figure 12. Decay time of TiKα emission as a function of normalized collision frequency for impurity ions. The central iron density (●) in a density ramp-up discharge is also indicated to compare the collisionality with that in the impurity accumulation window.

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

Ambipolar field E_r

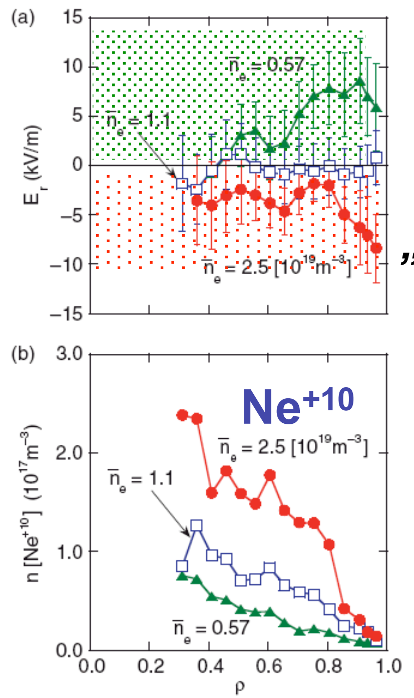


Figure 13. Radial profiles of (*a*) radial electric field and (*b*) fully ionized neon density for the discharges with a pulsed neon gas injection. The radial electric field is measured in the midplane at a position where the plasma is vertically elongated. The electric field changes from positive to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

Y. Nakamura *et al.*, NF 43 (2003) 219

Positive Er in „e-root“

outward flux in core

„i-root“

impurity flux high

Changing E_r seems to cause „accumulation“

May be caused by dominant effect of T grad in PS (n_e flat) “Temperature Screening” effect

LHD

Why purification beyond the accumulation window?

… long impurity confinement times

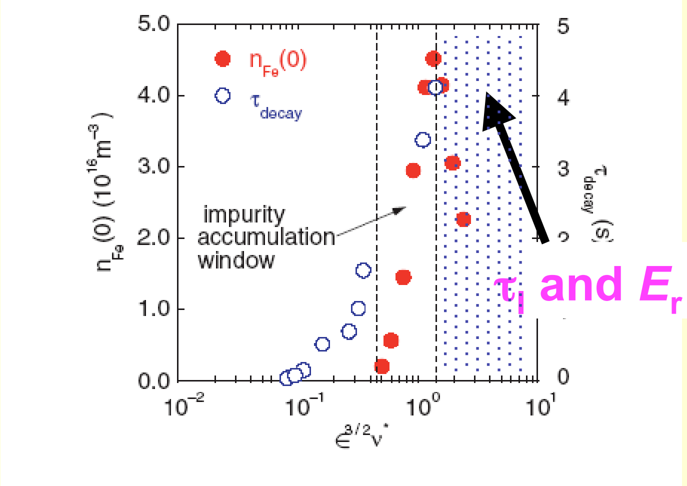
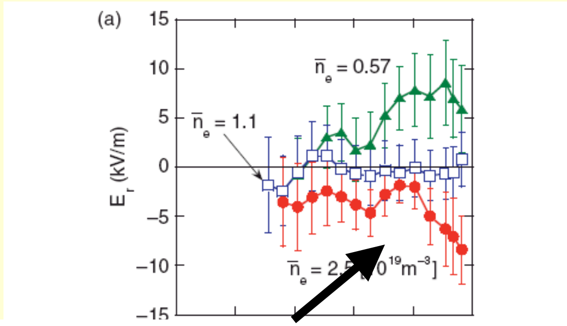


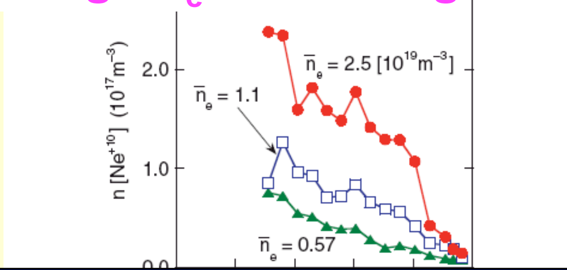
Figure 12. Decay time of TiKα emission as a function of normalized collision frequency for impurity ions. The central iron density (●) in a density ramp-up discharge is also indicated to compare the collisionality with that in the im
window.

Y. Nakamura *et al.*, ISW 2

Ambipolar field E_r



τ_I and E_r at high n_e interesting



Assumption:

If τ_I and E_r would continue to rise (?) …

… then „purifucation“ window means:

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

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

$D_{exp} >> D_{neo}$, cannot be related just to turbulent transport (may need „still to be understood“ non-axisymetric features)

Motivation

Introduction

Impurity content

Impurity Transport Analysis

Experimental Observations in Different Configurations

W7-AS

TJ-II

LHD

Similarities and Differences

Database requirements

Similarities and differences

- **Indications for anomalous/turbulent transport at low and medium densities** ***(TJ-II, W7-AS, LHD)***
- **Tendency to approach neoclassics at high density** ***(LHD, W7-AS)***
- **Improvement of impurity core confinement with density** ***(TJ-II, W7-AS, LHD (high ne))***
- **Impurity screening mechanisms 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 non-axisymmetric neoclassics ?

Motivation

Introduction

Impurity content

Impurity Transport Analysis

Experimental Observations in Different Configurations

W7-AS

TJ-II

LHD

Similarities and Differences

Database requirements

Database requirements

- In DB, data needed for scaling:
  τ_{imp} (B,n,T,P,i, maximum E_r, heating system…)
  D,υ or D(r) ,υ(r) at e.g. 2 radial positions, maximum E_r …
- To achieve a better understanding of physics of transport:
  For comparison need dedicated discharges with well documented
  (τ_{imp}, local D,υ or with profiles of n_e,T_e,T_i,E_r, P_{heat}, ….)
- Basis for understanding:

  1) Consideration of stellarator specific features in 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) When can plasma be described with a neoclassical model
     and when is it anomalous/turbulent >> key: D(r)

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