

Metal Impurity Transport Control in JET H-mode Plasmas with Central *ICRH*

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12 See Appendix of F. Romanelli et al., Proc. 22nd IAEA Fusion Energy Conf. 2008, Geneva, Switzerland

- We need to fully understand the behaviour of impurities in reactor relevant plasmas as in ITER and Demo plasma dilution in the core will be a figure of merit (including fusion ashes).
- Also, as for many other parameters, impurities will need an active control system to guarantee stationarity of plasma conditions

- Source mechanisms and transport across SOL and pedestal important but beyond the scope of this work, **focused on core aspects**.
- For impurities in the core what really matters is the relationship between $D_{\text{impurities}}$, D_{fuel} and $\chi_{e,i}$, since the relevant parameter is dilution.

Here we concentrate on $D_{\text{impurities}}$

To measure impurity transport one powerful means is to **create impurity density perturbations as with laser ablation**. Modelling of the transient evolutions of the appropriate signals provides an estimate of the transport coefficients.

Model based on 1D continuity equation with $\Gamma = -D\nabla n + vn$

+ accurate atomic physics to describe all of the ionization stages.

$$-\frac{\nabla n_z}{n_z} = \frac{v}{D}$$

↓

Peaking factor

>0
peaked profiles

<0
hollow profiles

• **Turbulence and impurity radial transport**

- *Curvature pinch (Perp Dynamics)* : inward ~~$f(Z)$~~
- *Parallel Compressibility* : Outward for TEM
Inward for ITG $\sim Z/A$
- *Thermodiffusion* : Inward for TEM $\sim 1/Z \rightarrow$ lower for high Z impurities
Outward for ITG

- Curvature pinch changes sign with **magnetic shear** (Futatani)
- **Rotation and shear rotation** inward for TEM and Outward for ITG (Camenen)
- **Centrifugal and Coriolis forces** : outward advection (Clements/ Romanelli)
- **Electromagnetic effects** $\sim 10\%$ of electrostatic ones (Hein)
- **RF induced ponderomotive forces** - affect similarly D and v (Nordman)
- **High Impurity concentration**: significant in case of TEM (Fulop/ Moradi)

• **Neoclassical radial transport**

• $v_{neo} / D_{neo} = Z_i \cdot (1/n \cdot dn/dr - H \cdot 1/T \cdot dT/dr)$; H approx 1

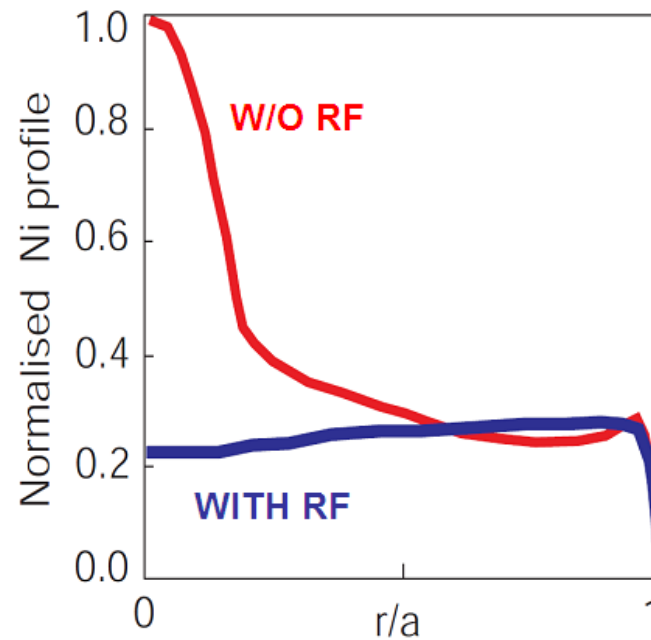
RF (electron heating) pump out effect observed in several other experiments:

C-mod, DIII-D, JT-60, TCV

and also in non axisymmetric devices (W7-AS)

...but only few example of successful explanation of radial flow reversal from
the theory - AUG : TEM (Angioni et al. PPCF 2007)

JET discharges 58143 and 58142



*M.E. Puiatti et al
PoP 13 2006*

Steady state Ni profiles, calculated from exp v and D

Similar results obtained also in high density JET discharges

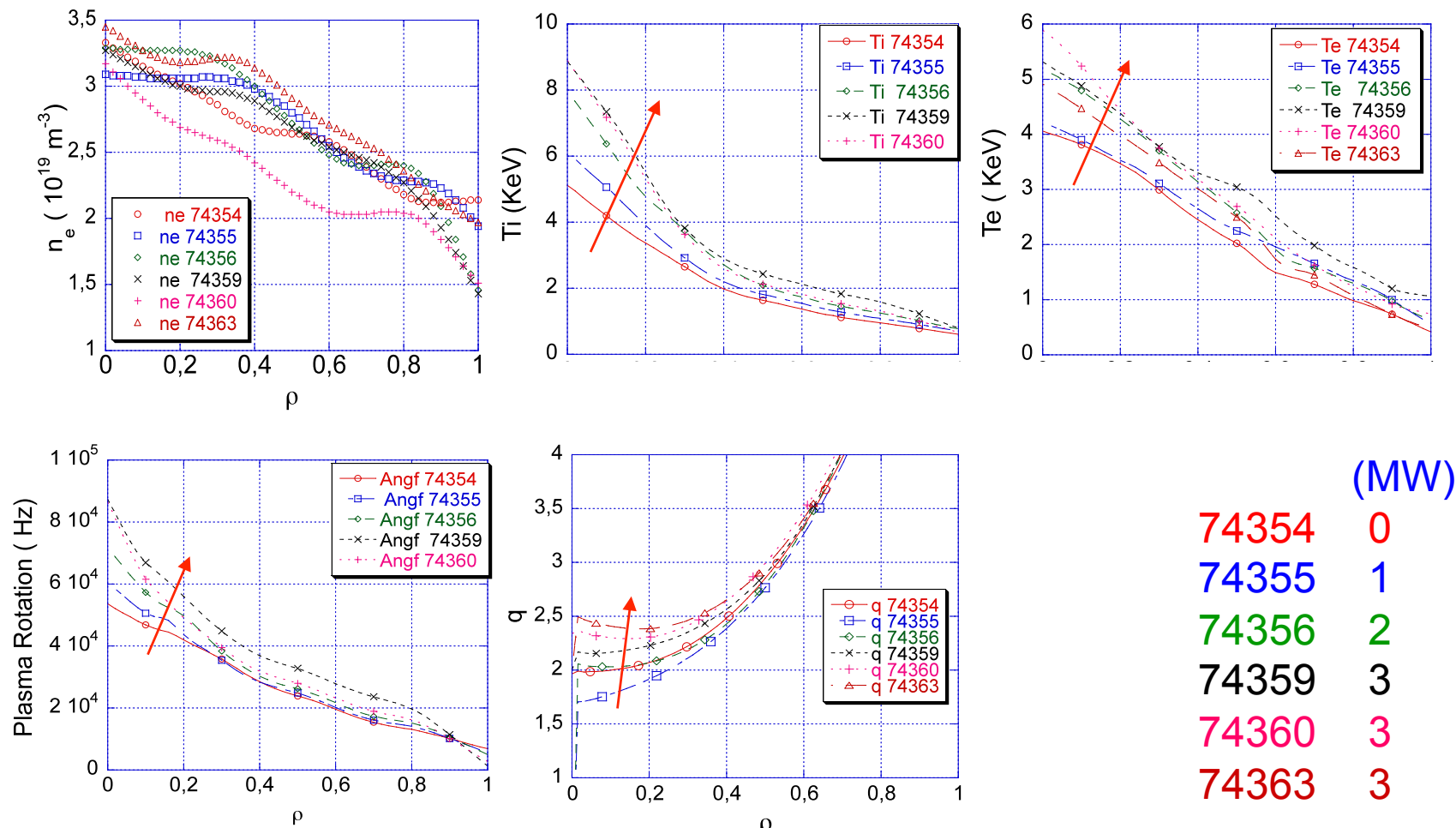
M.E. Puiatti et al .Plas. Phys.Contr. Fus. 44(2002)1863

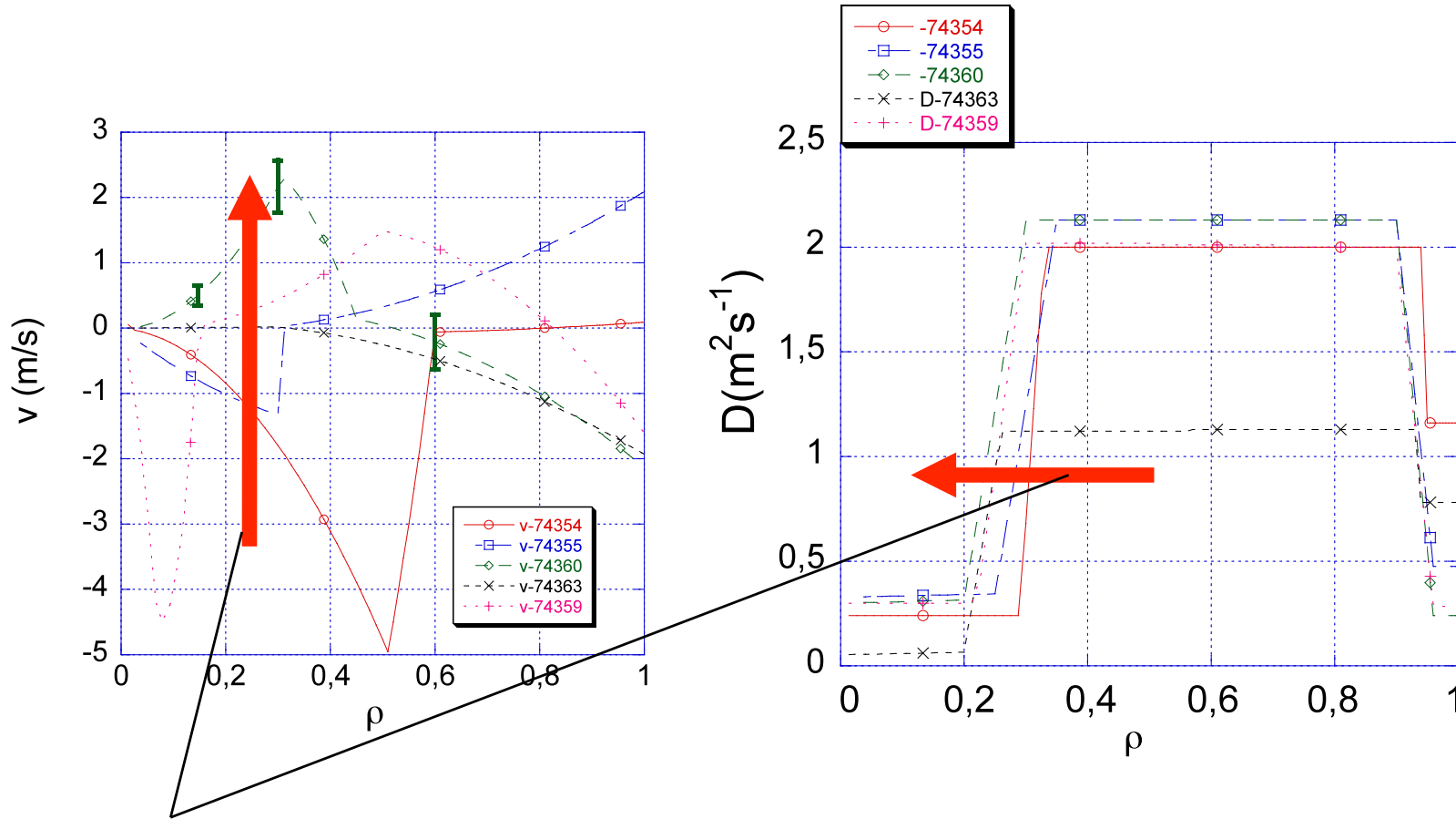
A series of dedicated H mode discharges with a RF power scan + LBO of Ni and Mo have been performed on JET to systematically analyze the effect of Central RF heating

Main feature:

- ICRH heating: H minority, 5% concentration to heat electrons
- low collisionality ($\nu_{\text{eff}} < 0.2$)
- about 12 MW NBI
- high central q to avoid sawteeth
- no total power (NBI + RF) conservation \rightarrow effect of the RF scan on q , T_e , T_i , ω profiles
- no significant MHD activity

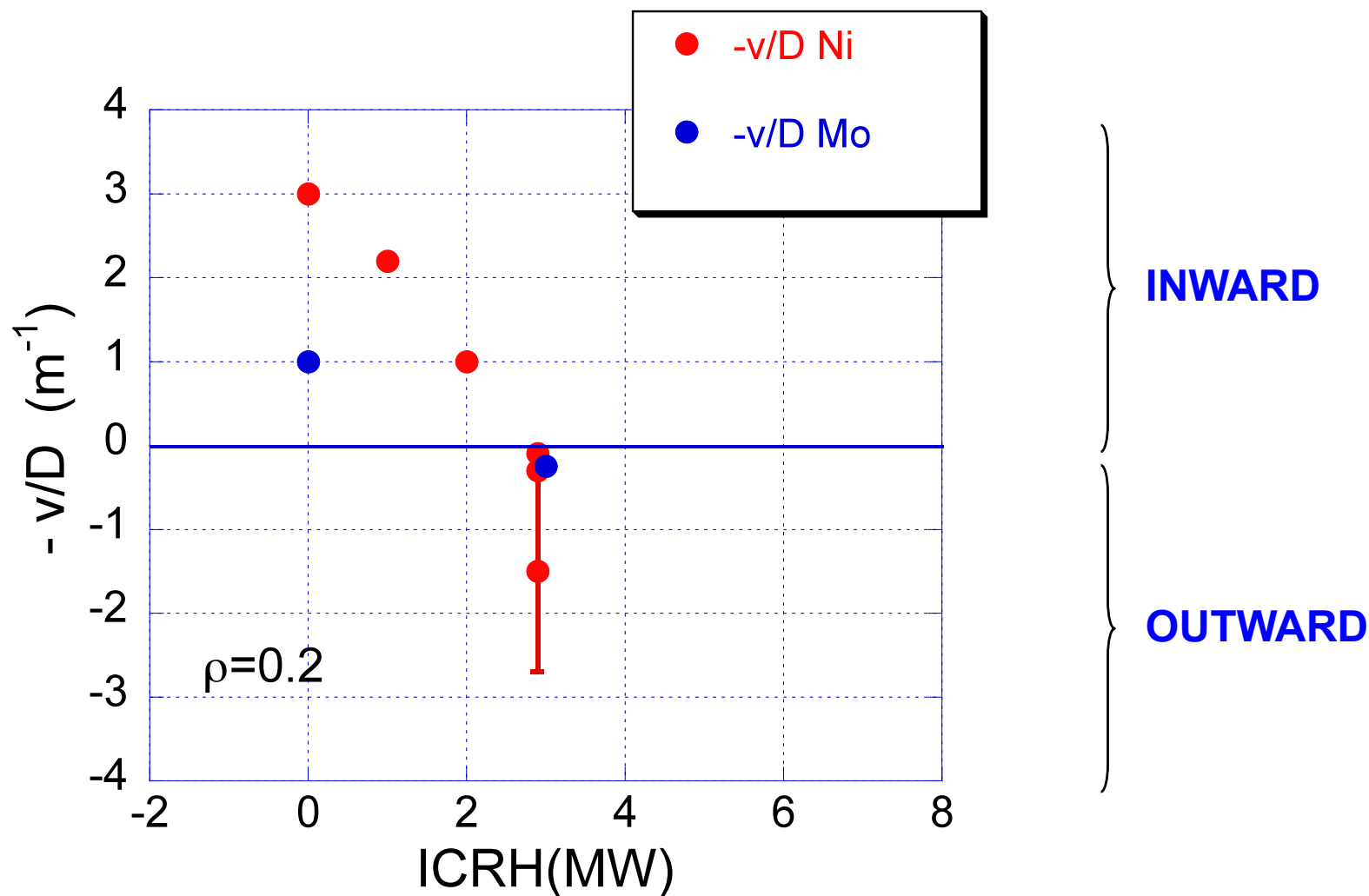
The RF power modifies the target plasma affecting mostly Ti , Te , bulk toroidal rotation and q

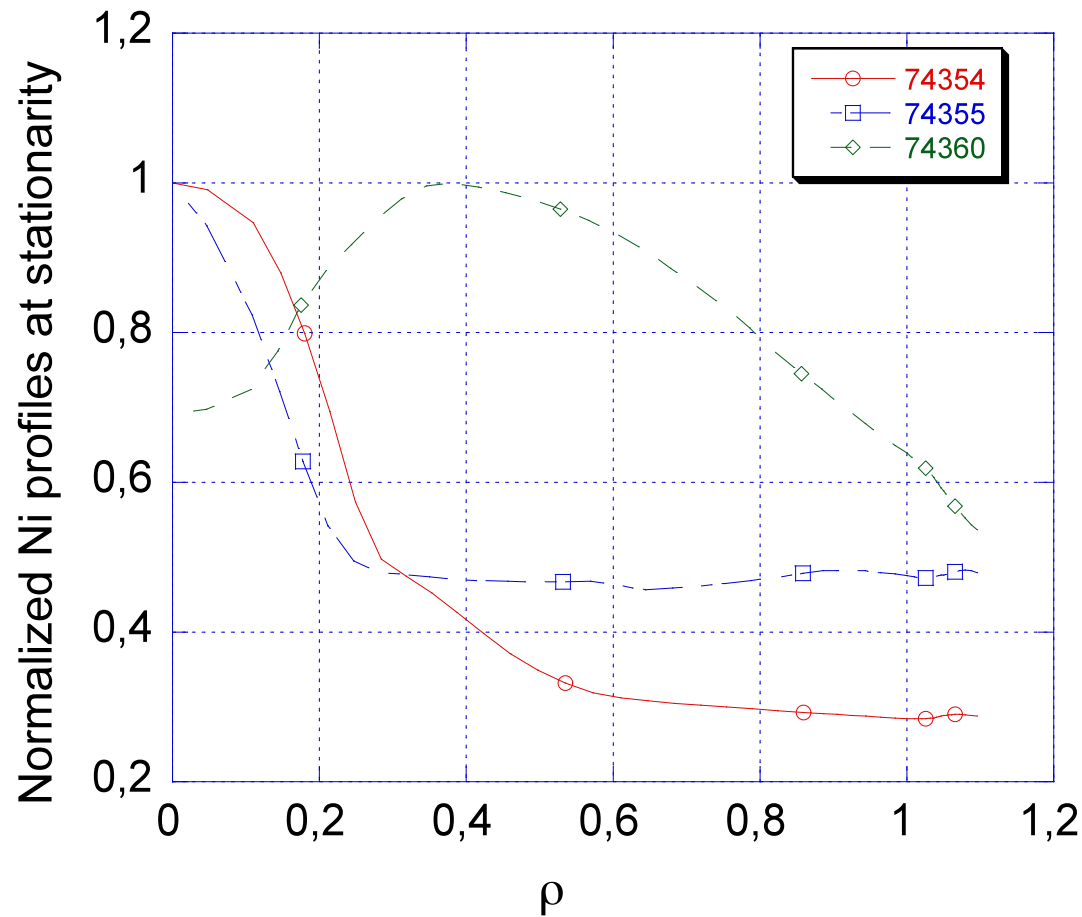




ICRH power

Average between $\rho = 0.2$ and $\rho = 0.3$

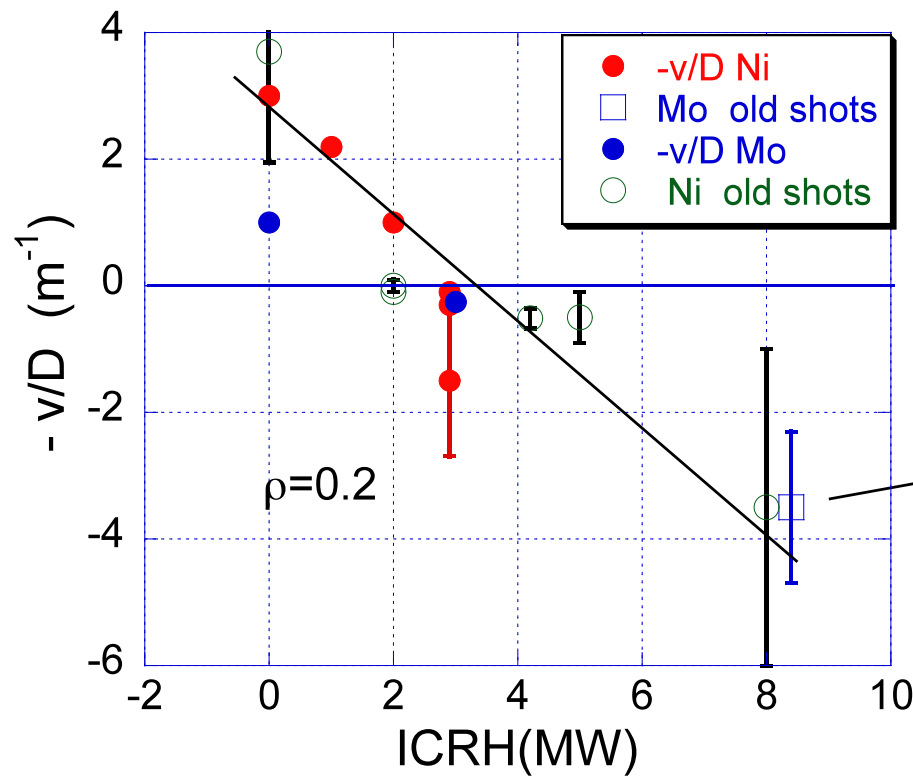




3 MW ICRH

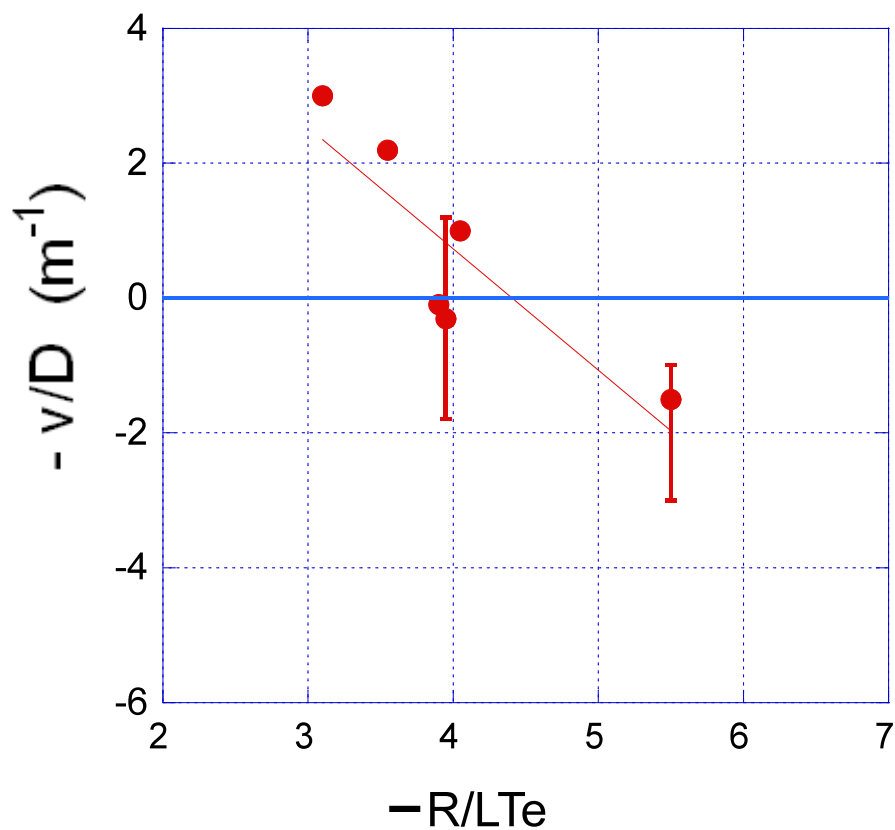
1 MW ICRH

NO ICRH



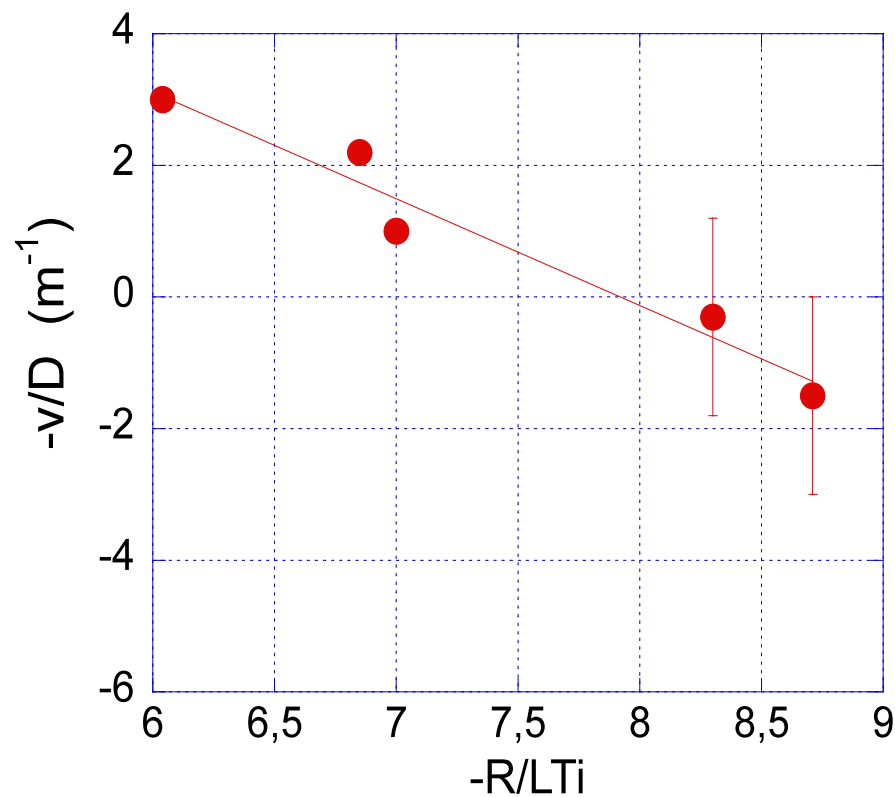
68383 – marginal H mode
Low collisionality,
Similar triangularity
and elongation

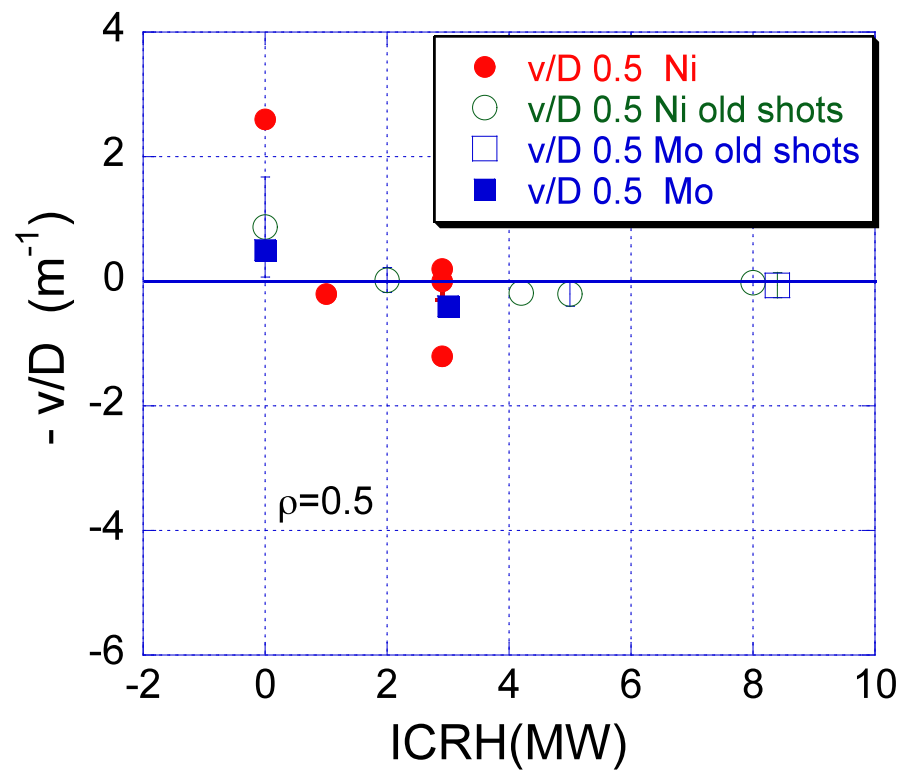
Average between $\rho = 0.2$ and $\rho = 0.3$

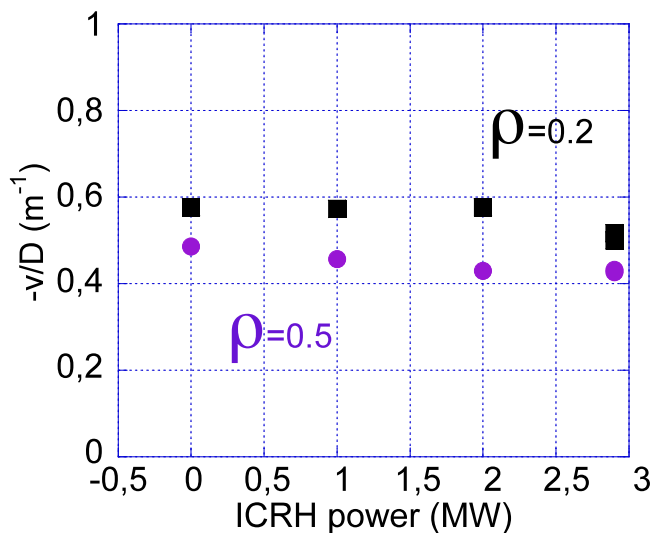


Average between $\rho = 0.2$ and $\rho = 0.3$

Neoclassical effect?







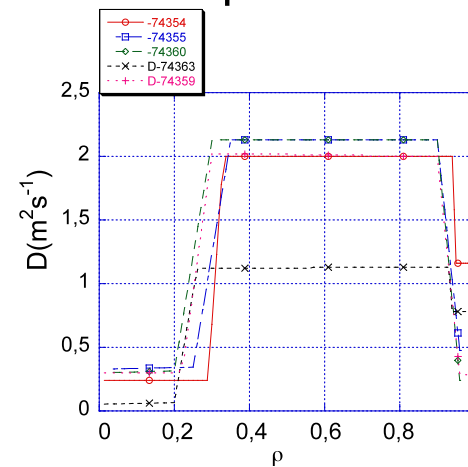
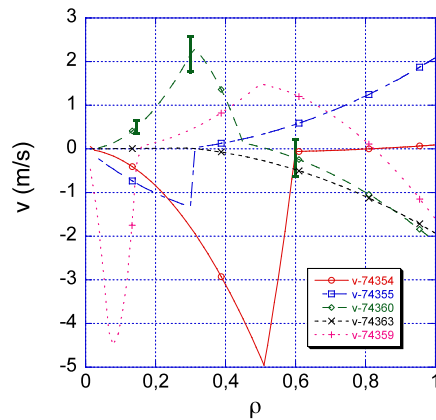
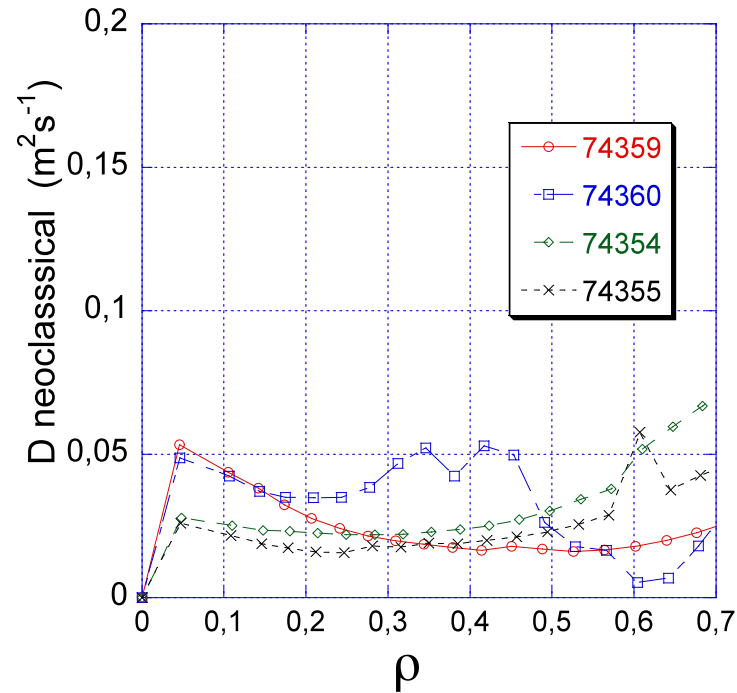
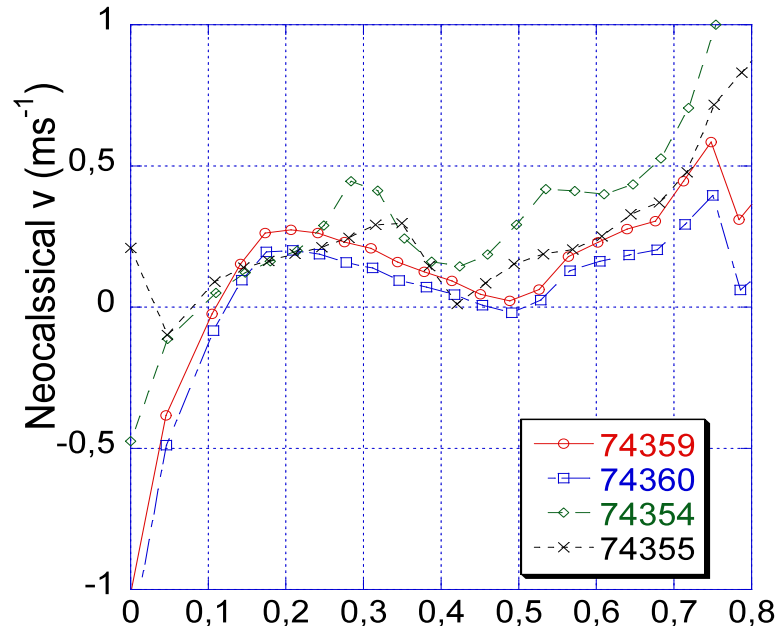
GS2 (linear, electrostatic) analysis shows trends in the right direction, but never provides an inversion of v/D (which may occur for ITG \rightarrow TEM dominant mode transition, obtainable for instance with much lower T_i gradients than in JET experiments - see e.g. Angioni et al. PPCF 49, 2007);

Tested also the addition of a hot H species (to simulate energetic ion tails after ICRH injection).

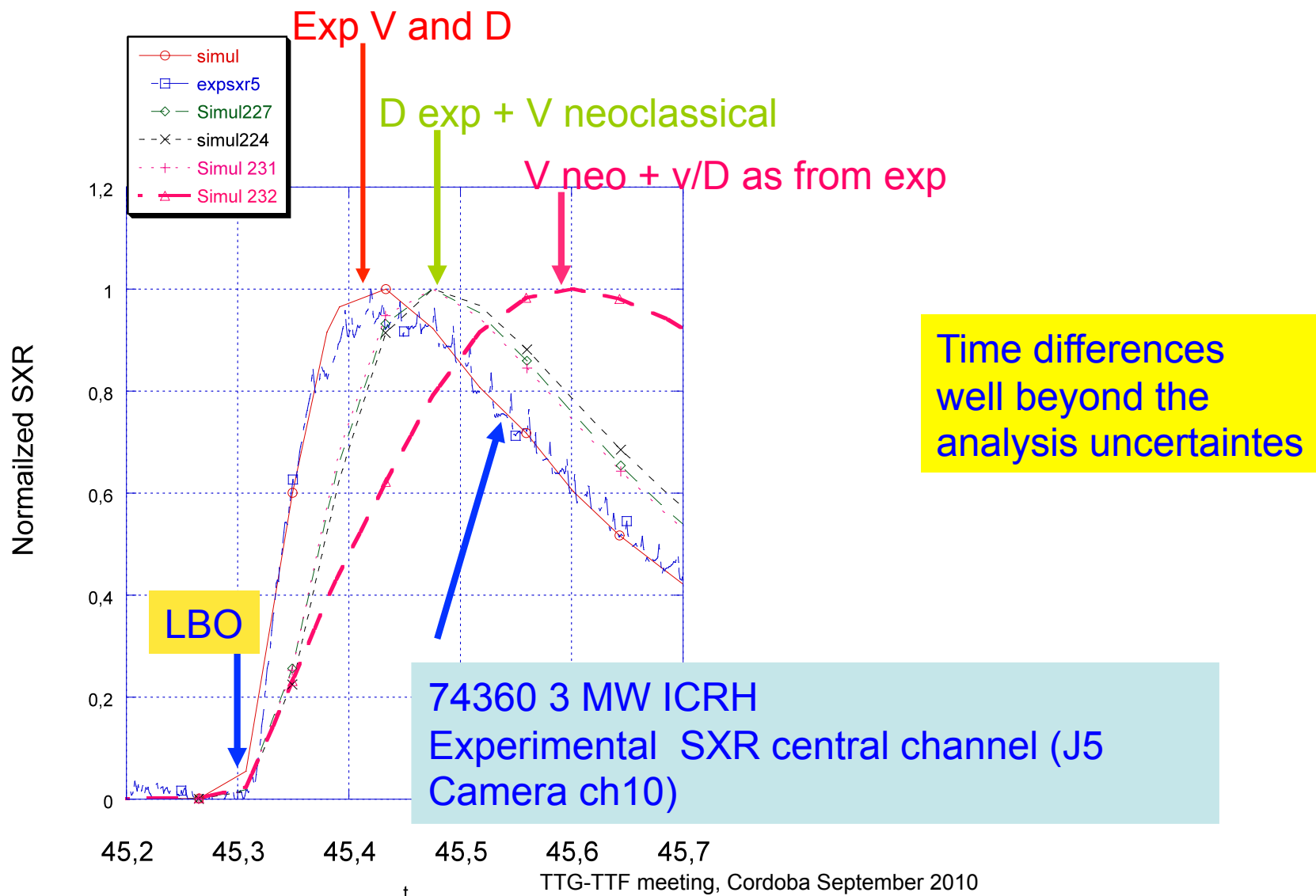
The impressive good correlation between v/D and R/LT_i suggest a strong neoclassical contribution

$$v_{neo} / D_{neo} = Z_i \cdot (1/n \cdot dn/dr - H \cdot 1/T \cdot dT/dr) ; \quad H \text{ approx } 1$$

Flat density profiles and peaked ion temperature profiles screen impurities out

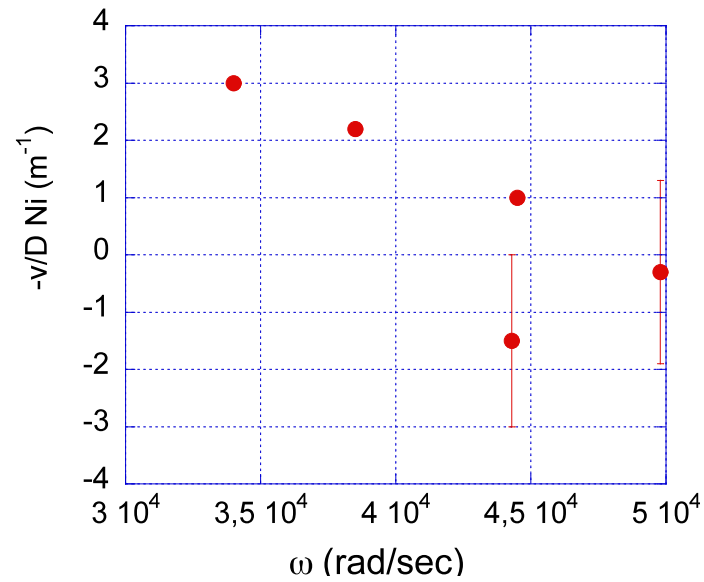
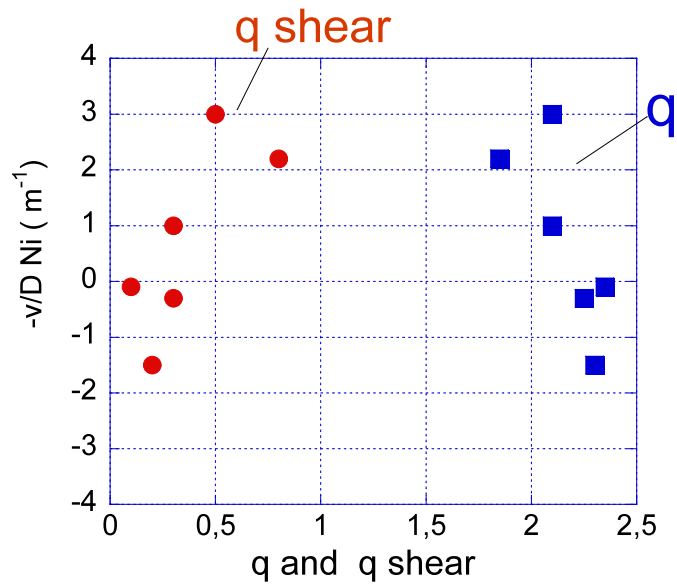


Simulation of SXR emission with various combinations of transport parameters

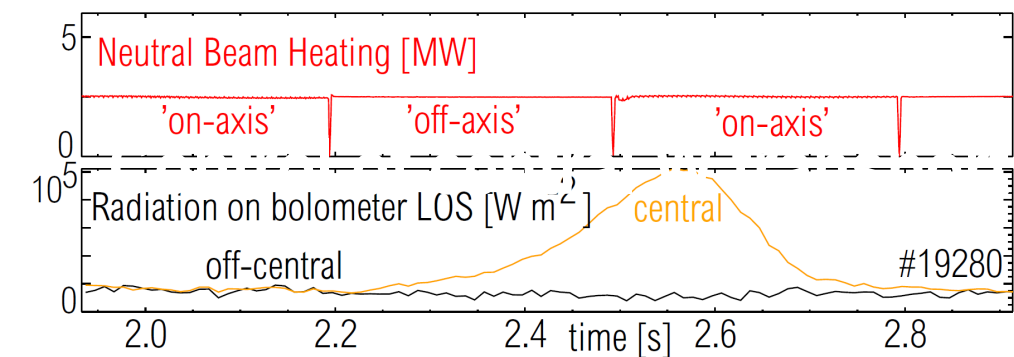


- Ni and Mo feature peaked profiles in JET H mode plasmas at low collisionality without sawtooth activity
- Ni and Mo profiles may be made flat-hollow by applying 2-3 MW ICRH
- Impurity pump out has not been explained by turbulence calculations by GS2
(too large R/L_{Ti} to get outward turbulent flux)
- Very good correlation between v/D (Ni) and R/L_{Ti} , however absolute neoclassical values do not fit the experiment

$\rho = 0.2 - 0.3$



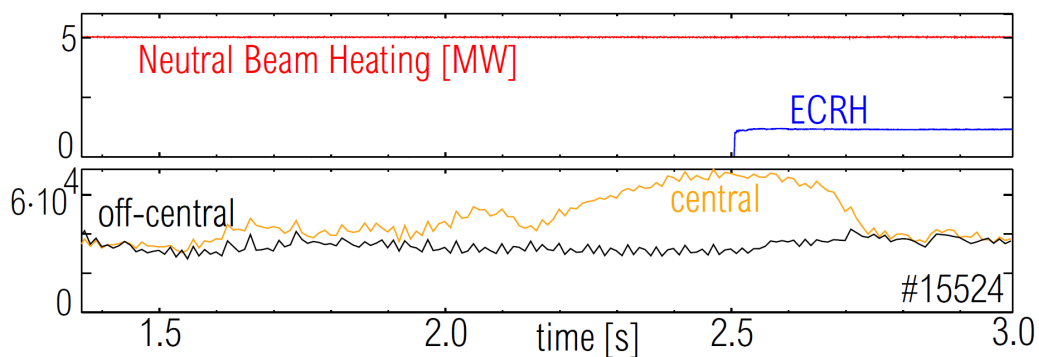
Toroidal rotation



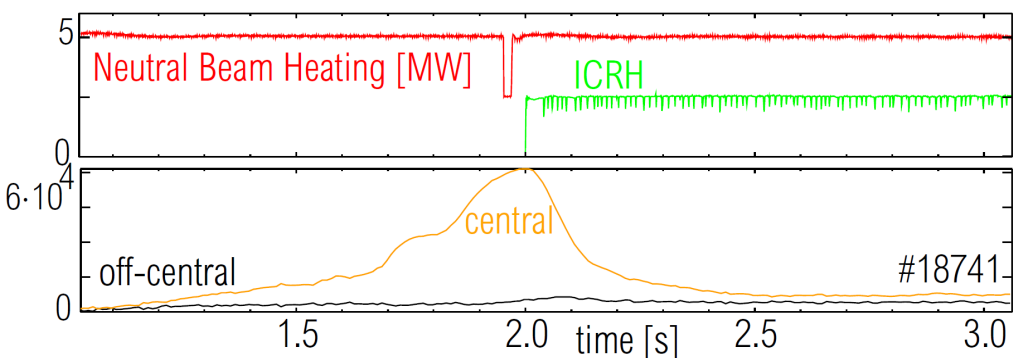
NBI

AUG

(Courtesy of T. Pütterich, EFPW 2009, Hungary)



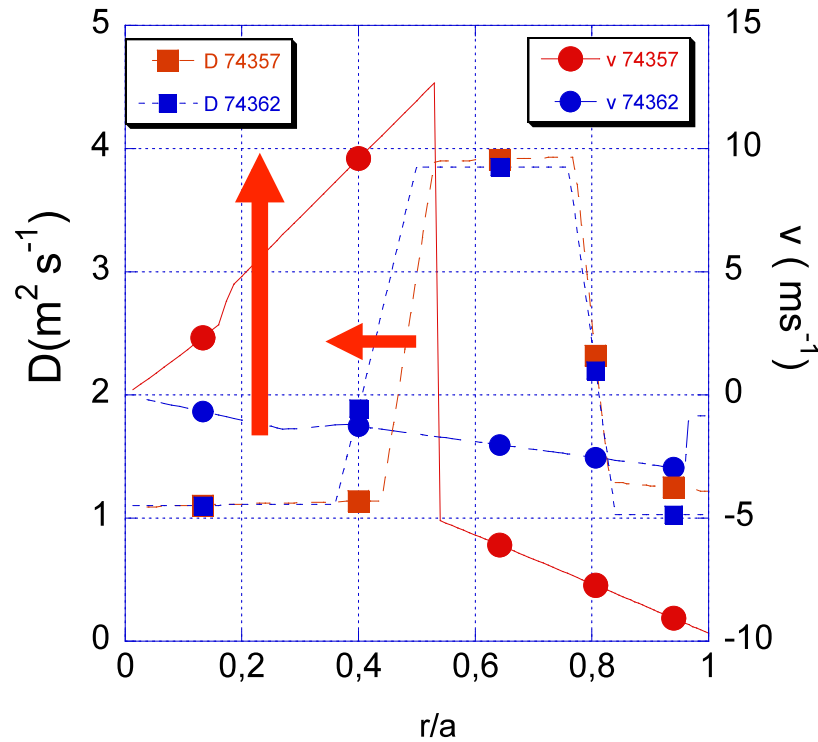
ECRH



ICRH

RF (electron heating) pump out effect observed in several other experiments:

C-mod, DIII-D, JT-60, TCV and also in non axisymmetric devices (W7-AS)



74357 NO ICRH

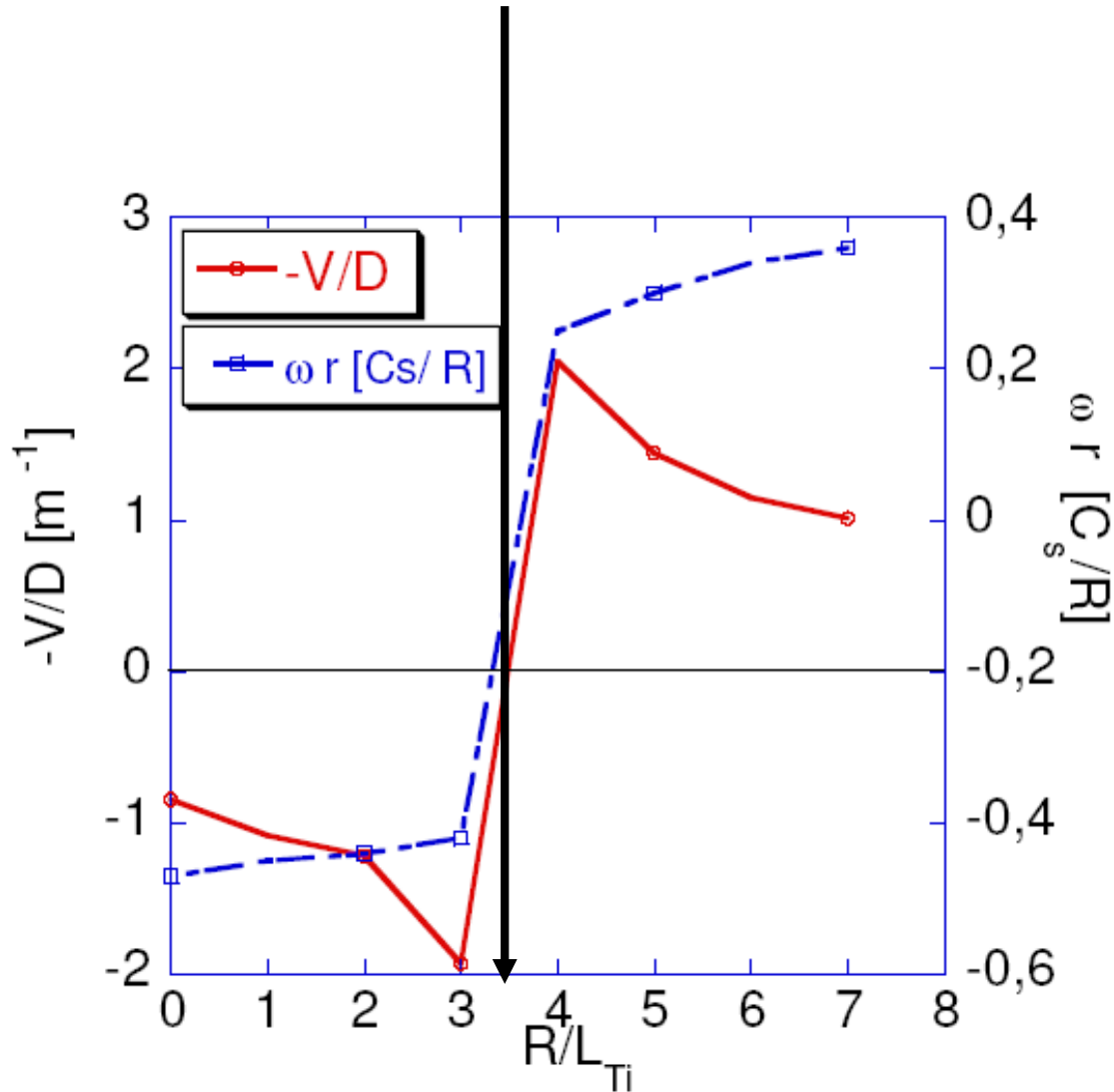
74362 3 MW ICRH

ICRH power

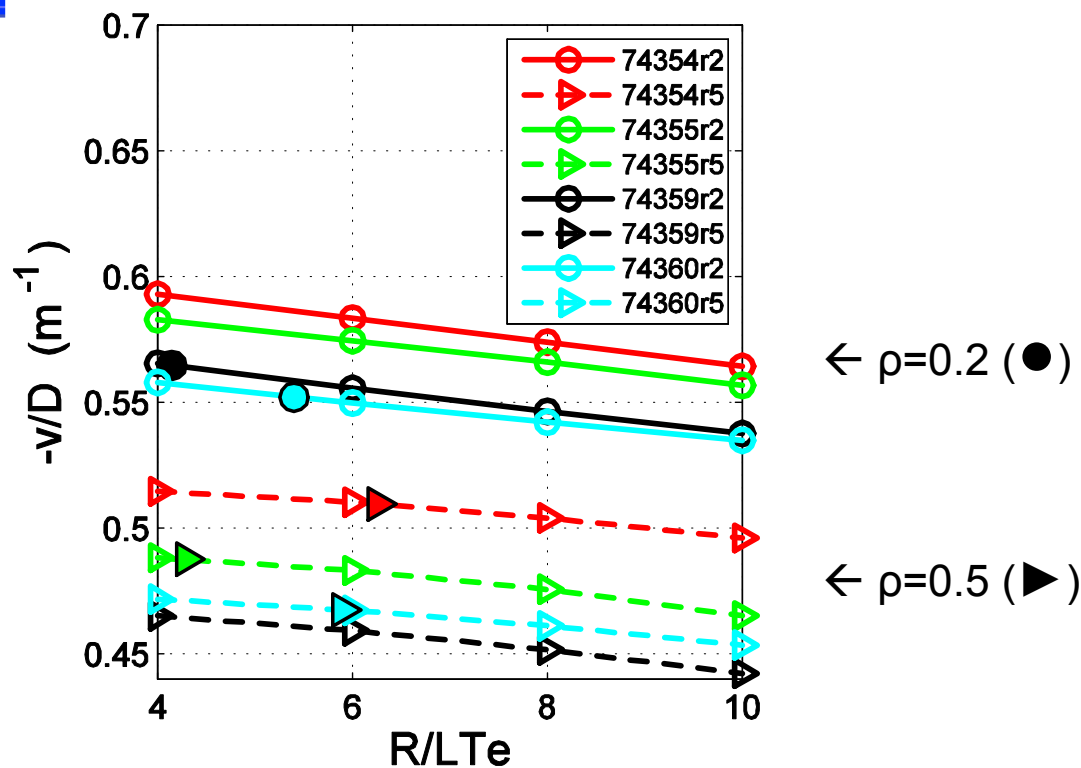
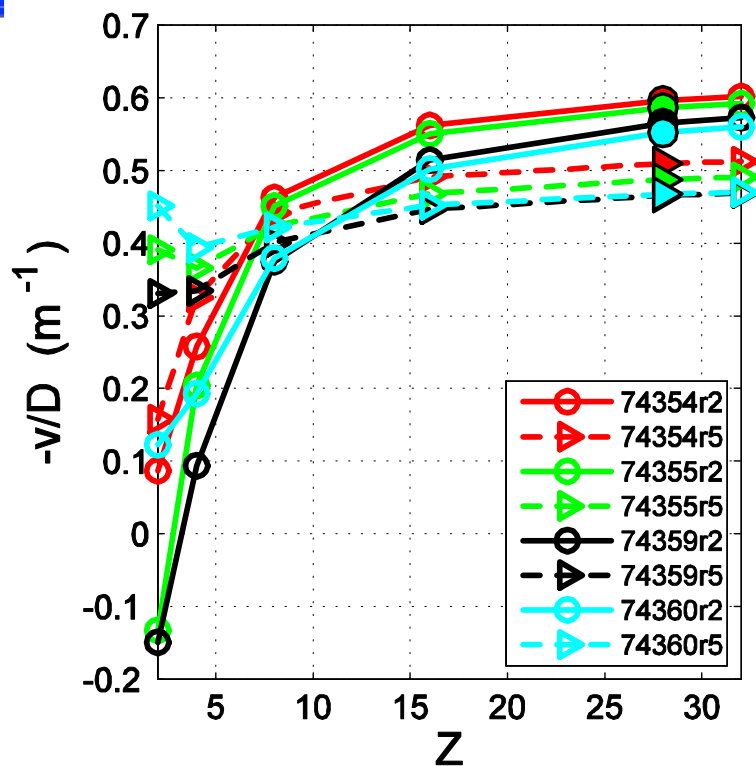
For the experimental ne and Te profiles of #68383 at $r=0.35$, $R/L_{Ti} < 3$ would be necessary for the flow inversion.



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L Carraro, C Angoni et al
EPS 2007 Warsaw



- GS2 (linear, electrostatic) scan analysis shows trends in the right direction, but never provides an inversion of v/D (which it can be for ITG \rightarrow TEM dominant mode transition reachable, for instance, for much lower Ti gradients - see e.g. Angioni et al. PPCF 49, 2007);

- Tested the addition of a hot H species (to simulate energetic ion tails after ICRH injection). The nature of turbulence remains ITG-dominated: the dominant mode frequency only slightly decreases for increasing beam energies, it never changes sign.

Shots 53548 , 53015 **WITH ICRH**:
convection may become outward

- Core diffusion decreases
- Core convection also decreases and may become outward

NO ICRH

Shot 52136: Strong
inward convection

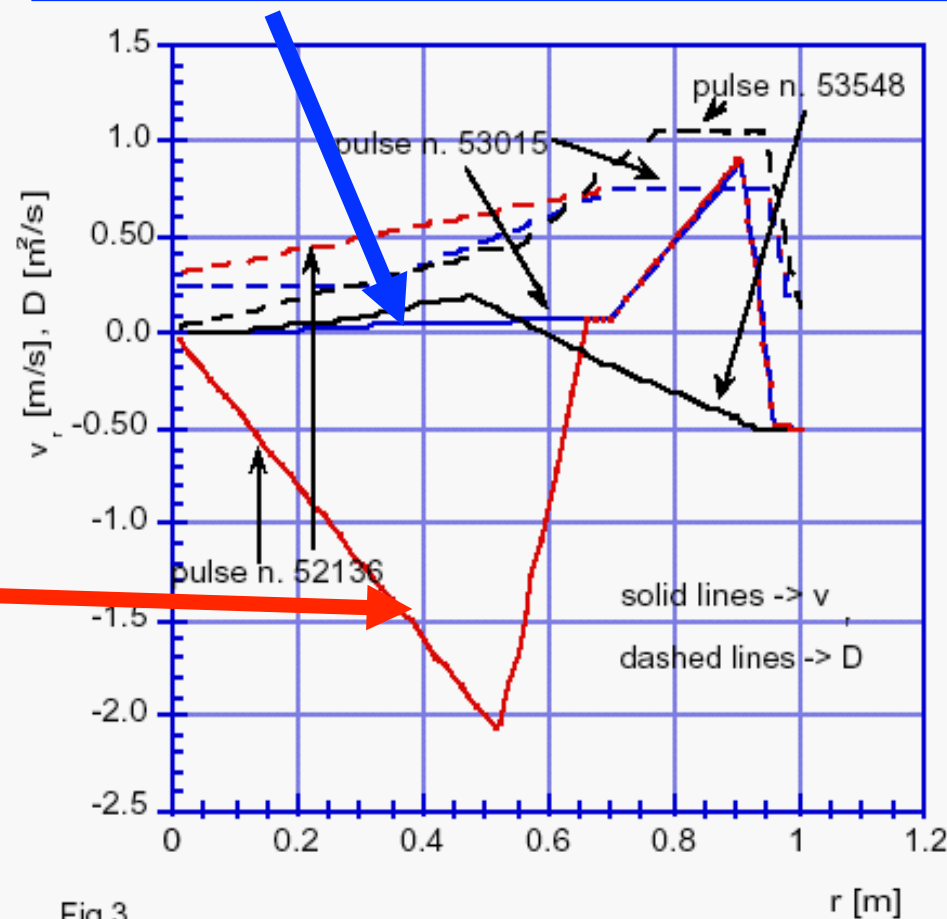
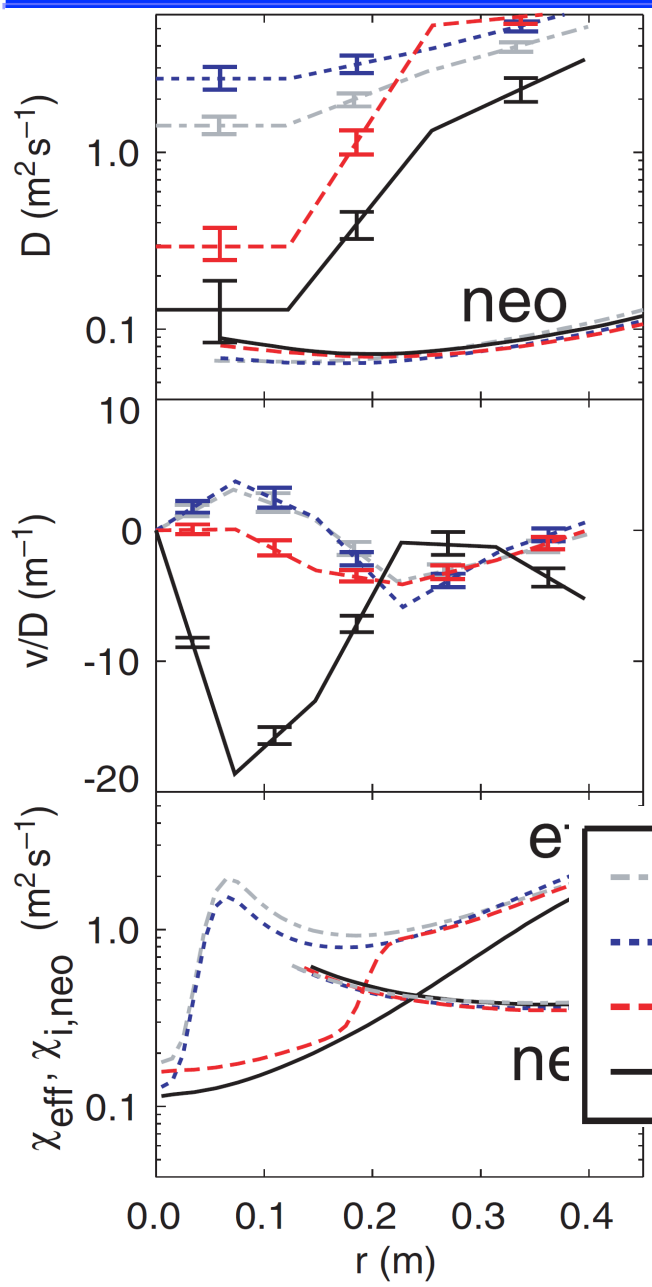
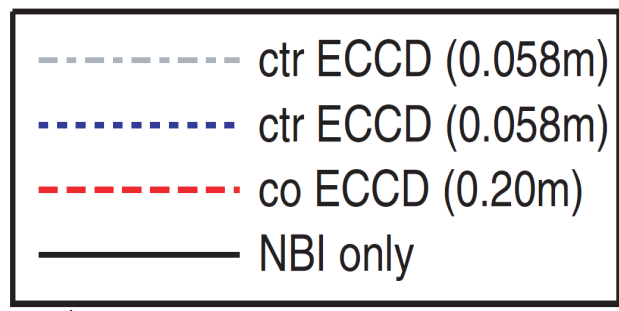


Fig.3



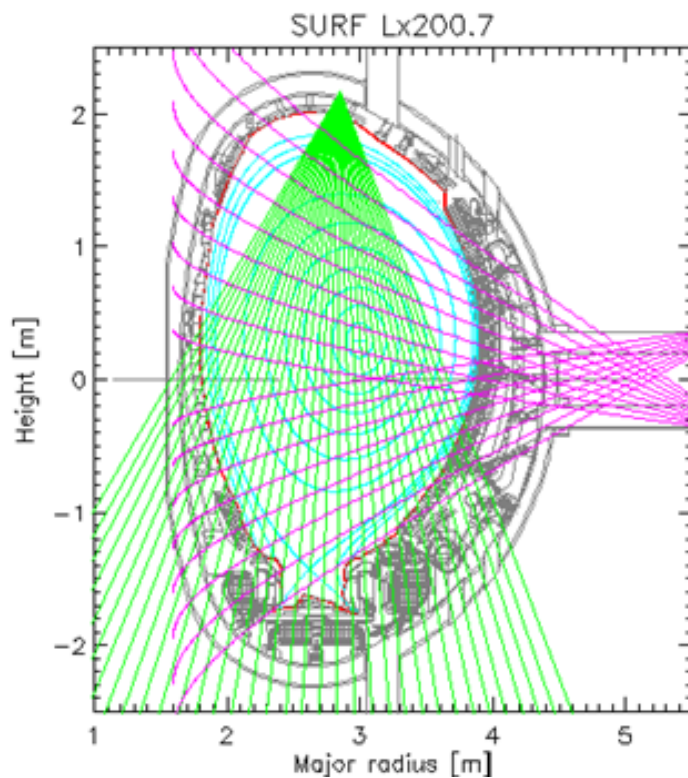
- Turbulent transport in center small, dependent on heating
- Central ECH increases diffusion and reduces inward pinch
- Outward convection with ECH real?
- Effect of ICRH similar but less pronounced

Dux et al., PPCF 45, 2003



Courtesy of T. Pütterich @ EFPW 2009, Hungary²⁷

TTG-TTF meeting, Cordoba September 2010



Soft-X rays: a vertical camera with
34 l-o-s (250 μ filter)

and

a horizontal camera with 17
channels (350 μ filter).