Heavy Impurity Transport in the Core of JET Plasmas

M Valisa

C Angioni[2], R. Bilato[2], F J Casson[5], L Lauro Taroni[5], P Mantica[3], T Pütterich[2], M Baruzzo[1], P Belo[4], E. Belli[2], I Coffey[6], P Drewelow[2], C Giroud[5], N Hawkes[5], T Hender[5], T Koskela[7], E Lerche[8], C Maggi[2], J Mlynar[9], M O'Mullane[10], T. Odstrcil[2], M Puiatti[1], M Reinke[11], M Romanelli[5] and JET contributors*

JET, Culham Science Centre, Abingdon, OX14 3DB, UK

1-Consorzio RFX, Padova, Italy, 2-Max Planck Institut fur Plasmaphysik, Garching, Germany, 3 -Istituto di Fisica del Plasma, CNR, Milano, Italy, 4Instituto de Plasmas e Fusao Nuclear, IST, Lisbon, Portugal, 5CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK, 6Queen's University, Belfast, UK, 7 Aalto University, Tekes, P.O.Box 14100, FIN-00076 Aalto, Finland, 8LPP-ERM-KMS , TEC partner, Brussels, Belgium, 9 IPP.CR, Institute of Plasma Physics AS CR, Prague, Czech Republic, 10 Department of Physics, University of Strathclyde, Glasgow UK, 11Department of Physics, University of York, UK.

**See the Appendix of F. Romanelli et al., Proceedings of this conference*

Outline

- **Introduction**

- **The analysis tools**

- **Results**

- In both standard H-mode and hybrid scenarios, the path towards W accumulation is determined by the inward neoclassical convection due to density peaking of the main plasma.

- ICRH helps hampering W accumulation in the core of standard H-mode plasmas.

- **Summary and conclusion**

Motivation1: W concentration must be contained

- JET is studying the impact of a ITER-like wall on the plasma: Be wall and W divertor.

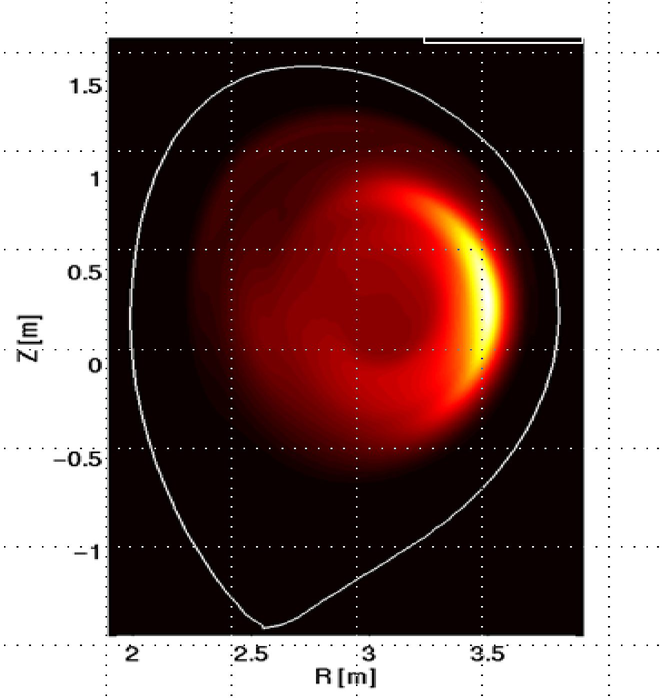
- (W: Z=74 , 193 amu; the W cooling rate remains high over a large range of Te *T Putterich et al Nucl. Fusion 50 (2010) 025012*

- W concentration in a reactor must be kept around 10^{-5}, its production minimized and core accumulation avoided.

Motivation 2: W complex behaviour must be understood

W density distribution is often highly asymmetric

as observed for heavy impurities in many experiments



This sets requirements on the modelling tools, which must include:

- 2 dimensional description for both neoclassical and turbulent transport.
- Description of the poloidal structure of the equibrium electric potential in presence of centrifugal forces and auxiliary heating.

L C Ingesson, H Chen, P Helander, et al. PPCF42, 161 (2000).
M L Reinke, I H Hutchinson, J E Rice, et al.. PPCF54, 045004 (2012).

Analysis tools

Analysis tools / theory

Integrating the parallel force balance equation:

Toroidal rotation frequency

$$n(r,\theta) = n_0(r)\ \exp\left\{-\frac{Ze\Phi(r,\theta)}{T(r)} + \frac{m\Omega^2(r)}{2T(r)}\left(R(r,\theta)^2 - R_0(r)^2\right)\right\}$$

Poloidal angle

Major radius

the electrostatic potential

must include all possible mechanisms affecting it: in our case centrifugal effects and anisotropy heating of minority species with ICRH

Bilato Maj Angioni, NF 54, 072003 (2014)

Analysis tools / theory

- Goal of modelling is to compute the flux surface averaged particle fluxes

$$\Gamma = -D\frac{dn}{dr} + Vn,$$

- Different time scales → compute turb. and neocl. coefficients separately

$$\frac{R\Gamma_W}{n_W} = -(D_{W\,NEO} + D_{W\,GKW})\frac{R}{L_{nW}} + (RV_{W\,NEO} + RV_{W\,GKW}),$$ at equilibrium

- Reduce sensitivity of turb. transport to gradients using ratios between particle and heat transport channels.

  Normalize turbulent transport to empirical turbulent component of the power balance heat conductivity

$$\frac{R}{L_{nW}} = -\frac{\frac{\chi_{i\,an}}{\chi_{i\,\mathrm{NEO}}}\frac{RV_{W\,\mathrm{GKW}}}{\chi_{i\,\mathrm{GKW}}} + \frac{RV_{W\,\mathrm{NEO}}}{\chi_{i\,\mathrm{NEO}}}}{\frac{\chi_{i\,an}}{\chi_{i\,\mathrm{NEO}}}\frac{D_{W\,\mathrm{GKW}}}{\chi_{i\,\mathrm{GKW}}} + \frac{D_{W\,\mathrm{NEO}}}{\chi_{i\,\mathrm{NEO}}}}$$

$$\chi_{i\,an} = \chi_{i\,PB} - \chi_{i\,NEO}$$

stationary, no impurity source

C. Angioni et al Nuclear Fusion 2014

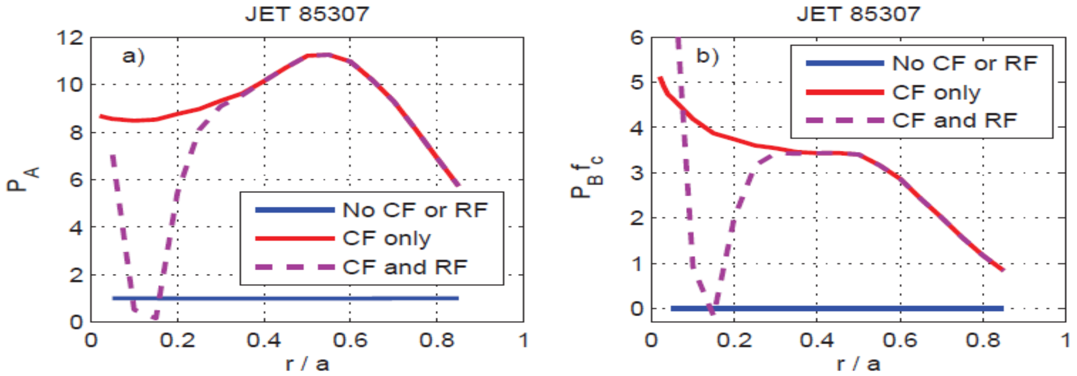
Asymmetries in the electrostaic potential can strongly affect neoclassical transport

Pinch | Screening | Diffusion

$$R\langle \Gamma_z^{\mathrm{neo}} \cdot \nabla r\rangle \propto n_i T_i \nu_{ii} Z \left[P_A \left(-\frac{R}{L_{n_i}} + \frac{1}{2}\frac{R}{L_{T_i}} + \frac{1}{Z}\frac{R}{L_{n_z}} \right) - 0.33 P_B f_c \frac{R}{L_{T_i}} \right]$$

radial transport

fraction of passing particles



Wong PF 87;
M. Romanelli Ottaviani PPCF 98 ;
Angioni and Helander , PPCF 2014
Casson et al tbp on PPCF , http://arxiv.org/abs/1407.1191

Fulop Helander PoP 99;
Belli et al PPCF 2014 F ;

Analysis tools: model vs experiment

Theory

- Neoclassical transport: NEO *Belli PPCF 2008 and 2012*
- Turbulent transport: GKW *Peeters CPC 09, Casson PoP 10*

From the normalized density gradients the impurity densities to be compared with the experiments are derived.

Experiment

- W density recovered from SXR tomography, deconvolving W contributon from Bremmstrahlung due to hydrogen-like particles

T. Putterich et al 2012 IAEA FEC., San Diego, EX/P3–15

- JETTO/SANCO transport code to provide empirical W transport coefficients, and W densities. Based on best matching between synthetic data produced by JETTO and experimental SXR tomography and bolometry.

] Lauro Taroni L et al 1994 21st EPS Conf Montpellier, 1, (1994) 102.

Results

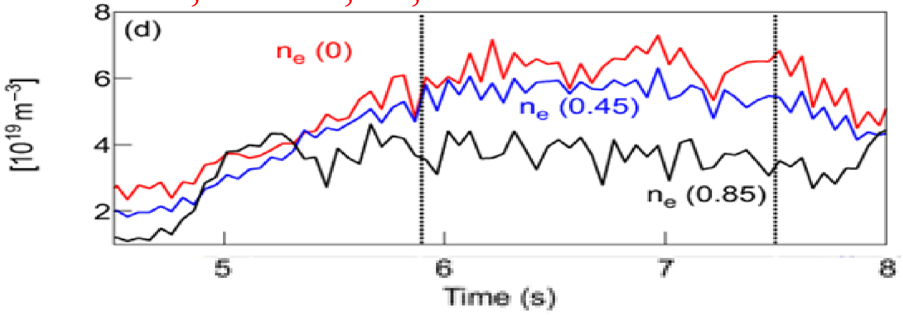
The path to W accumulation follows the electron density evolution: Hybrid

Electron density, initially hollow, evolves towards peaked profiles due to NBI core fuelling and Ware pinch.

P Mantica et al 40th EPS Conf., Helsinky 2013
C Giroud et al 41st EPS Conf, Berlin 2014
Loarte 2013 Nucl. Fusion ***53*** *083031*

Hybrid**

#82722, 1.7 MA, 2T, 16MW NBI



ne time evolution @ three radii: 0, 0.45, 0.8 5 r/a

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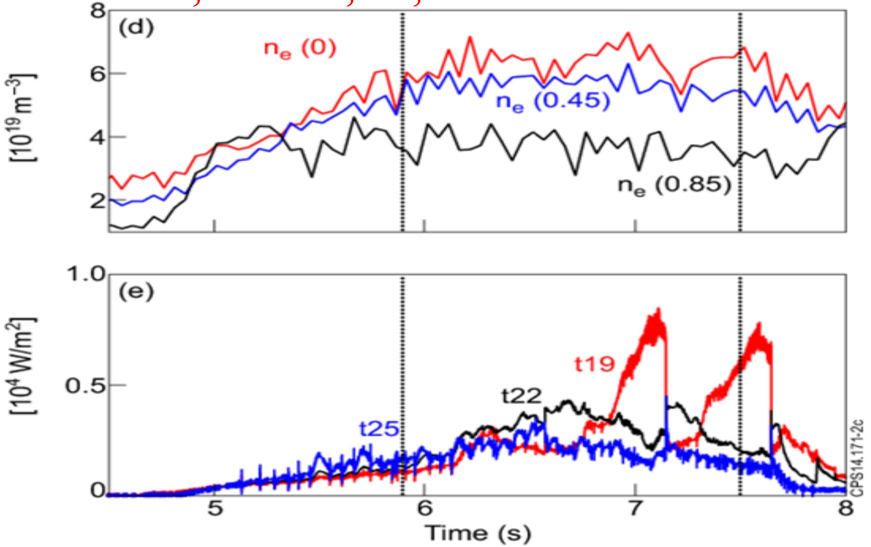

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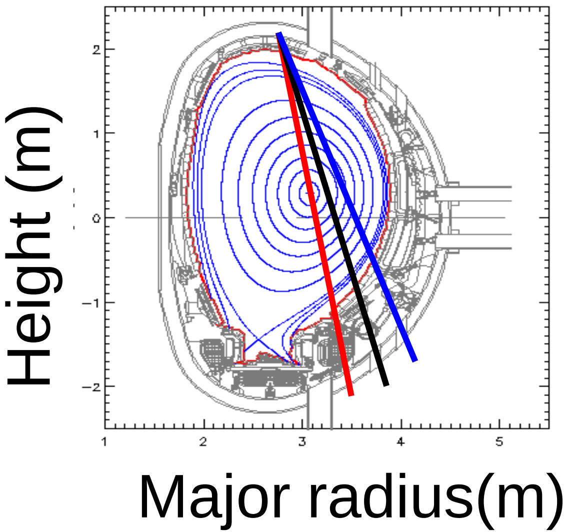
SXR LOS Impact parameters 0, 0.2, 0.35 r/a



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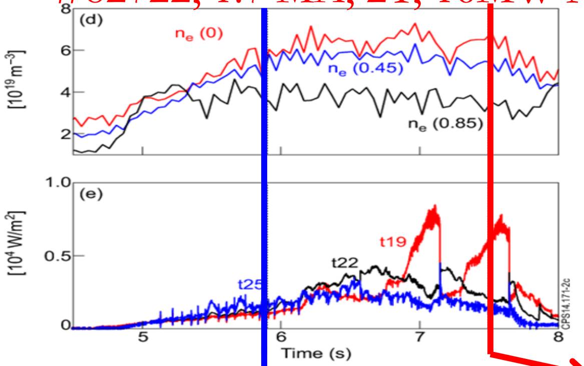

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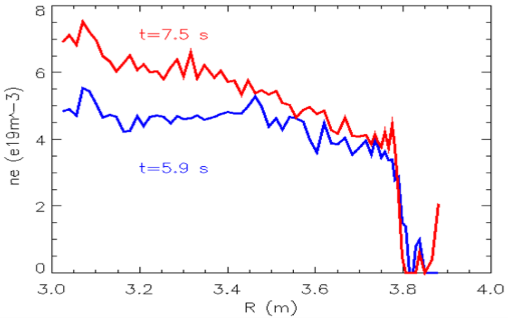

ne profiles at selected times

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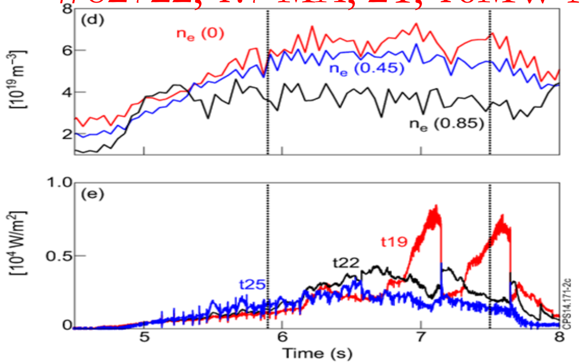

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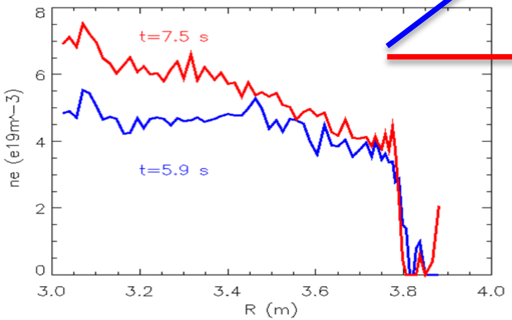
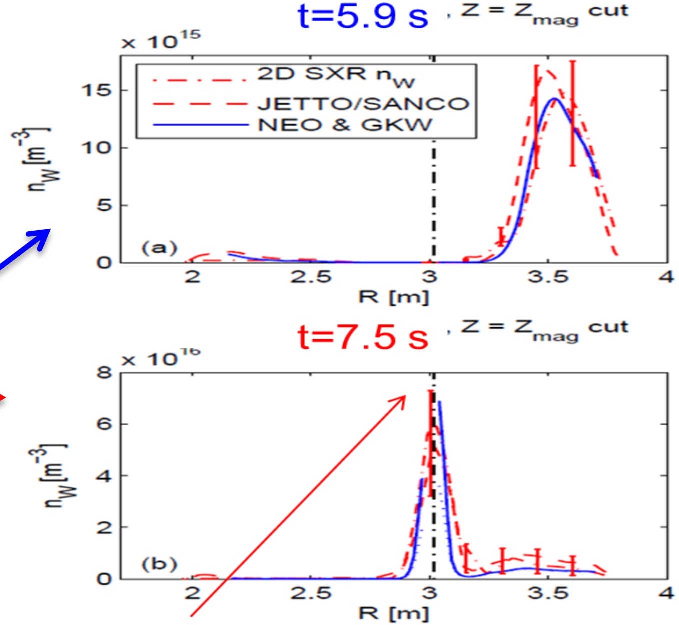


ne profiles at selected times

C. Angioni et al Nuclear Fusion 2014



W concentration ~10-3

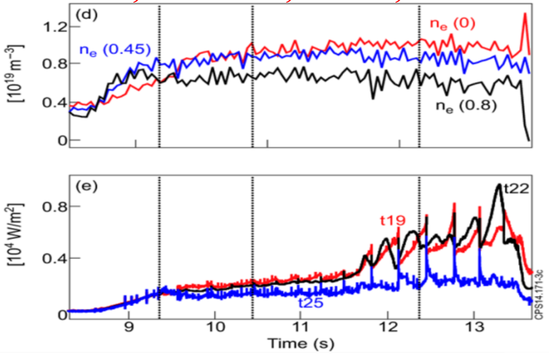
The path to W accumulation follows the electron density evolution: Standard H-mode

Very similar situation for the standard Hmode.

More frequent sawteeth keep the W dynamics lower

Standard H-mode

#83351, 2.75 MA, 2.6 T , 17.5 MW NBI,



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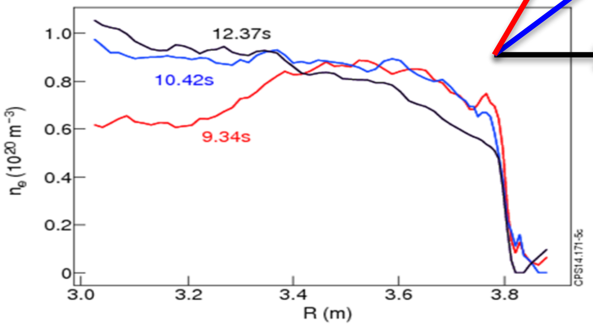
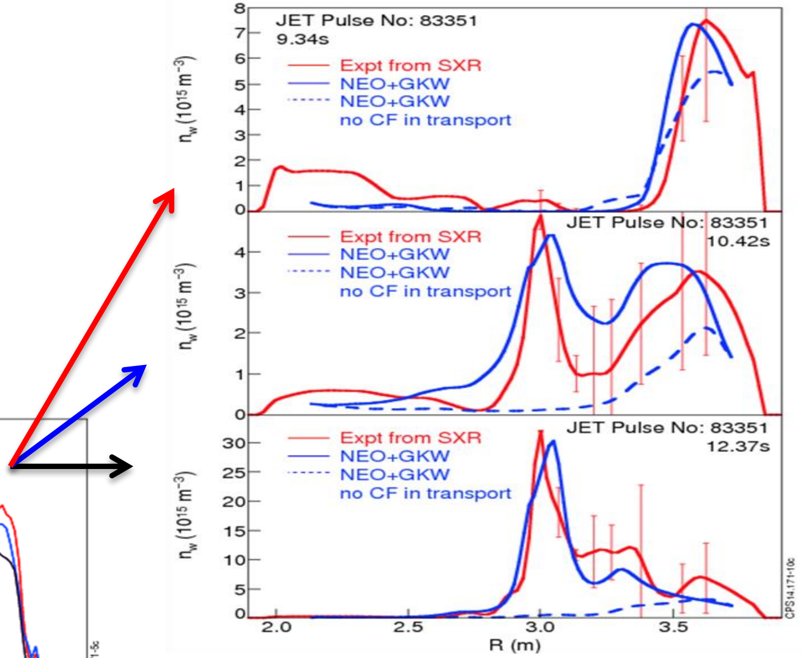




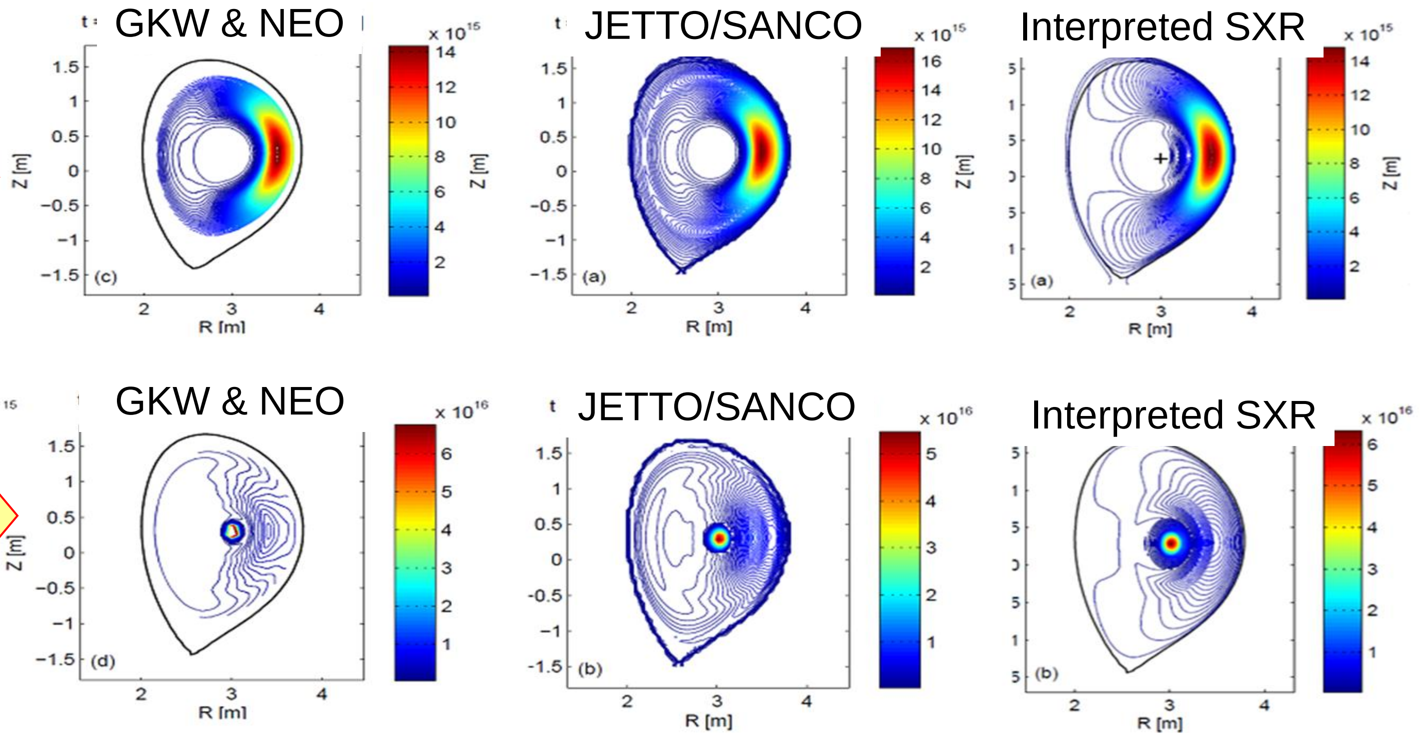
P Mantica et al 41st EPS Conf, 2014 Berlin

Model matches well the experiment

82722 Hybrid

Time slice @ 5.9 s

Time slice @ 7.5 s Center accumulation



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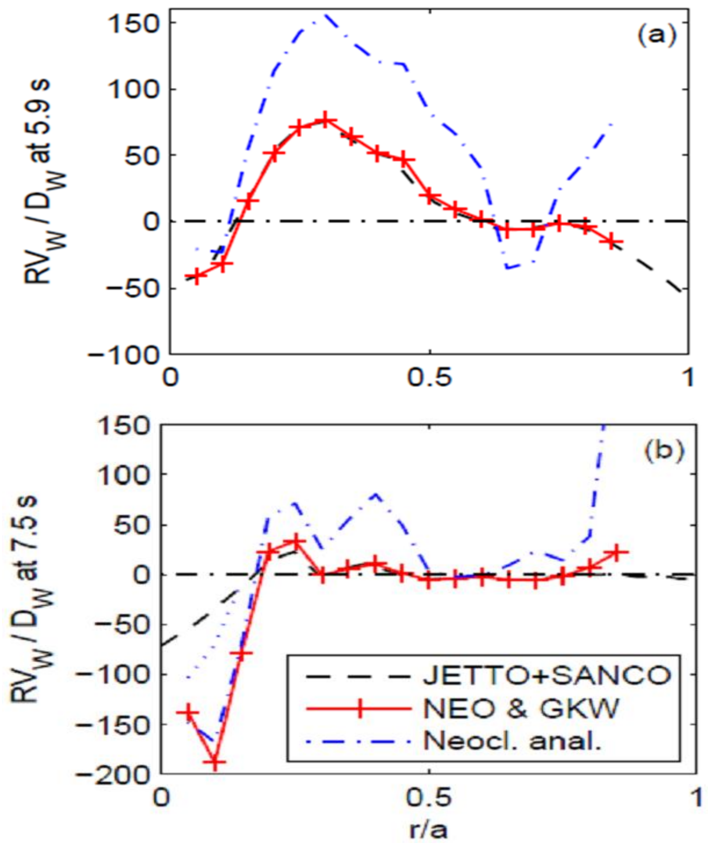
Neoclassical transport dominant

Time slice
@ 5.9 s

Convection to diffusion ratios for W as computed by NEO + GKW and by JETTO/SANCO

Time slice
@ 7.5 s



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MHD and W transport interplay

- MHD modes have complex interplay with W as they affect also the background kinetic profiles and thus the neoclassical transport drive.
- Sawtooth crashes clearly help flushing W out of the core.
- In presence of hollow W densities and peaked main plasma density the onset of an NTM accelerates the accumulation process. They facilitate the drift of W into inner regions where neoclassical inward pinch is particularly strong

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W transport and ICRH in standard H-mode

- Effects on background profiles and indirect impact on neoclassical transport of W

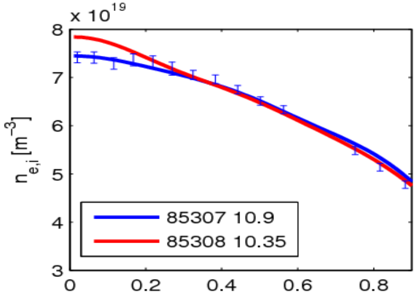
- Direct effects on W transport

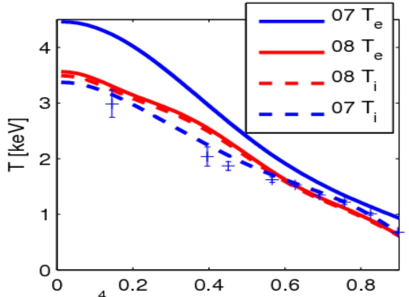
Impact of ICRH on kinetic profiles

85308: 2.5 MA, 2.7 T , 19MW NBI ONLY

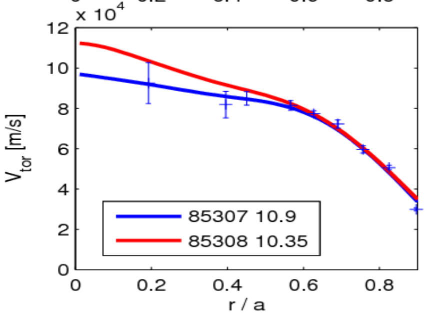
85307: 2.5 MA, 2.7 T , 14.7 MW NBI + 4.5 MW ICRH (H minority)**

Flatter ne





Higher Te
Similar Ti



Lower rotation

r/a r/a r/a

F Casson et al tbp on PPCF , http://arxiv.org/abs/1407.1191

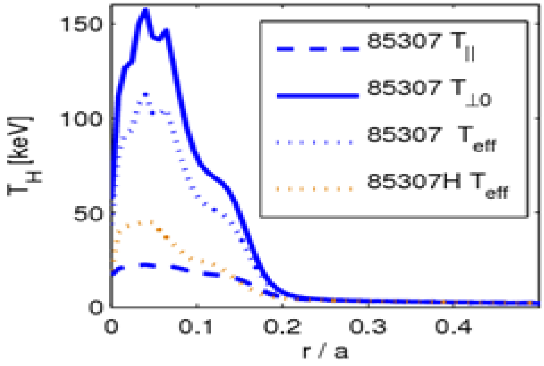
** see E Lerche et al. EX/P5-22.

Direct Impact of ICRH on W transport

In order to match the experiment it is important to add the following mechanisms:

- Thermal screening due to minority species temperature gradients
- Anisotropy heating of minority species

$T_\perp > T_{||}$



F Casson et al tbp on PPCF

$$n(\theta) = n_{R0}\frac{T_\perp(\theta)}{T_{\perp R0}}\exp\left(-\frac{eZ\Phi(\theta)}{T_{||}} + \frac{m\Omega^2(R(\theta)^2 - R_0^2)}{2T_{||}}\right)$$

$$\frac{T_\perp(\theta)}{T_{\perp R0}} = \left[\frac{T_{\perp R0}}{T_{||}} + \left(1 - \frac{T_{\perp R0}}{T_{||}}\right)\frac{B_{R0}}{B(\theta)}\right]^{-1}$$

Bilato Maj Angioni, NF 54, 072003 (2014)

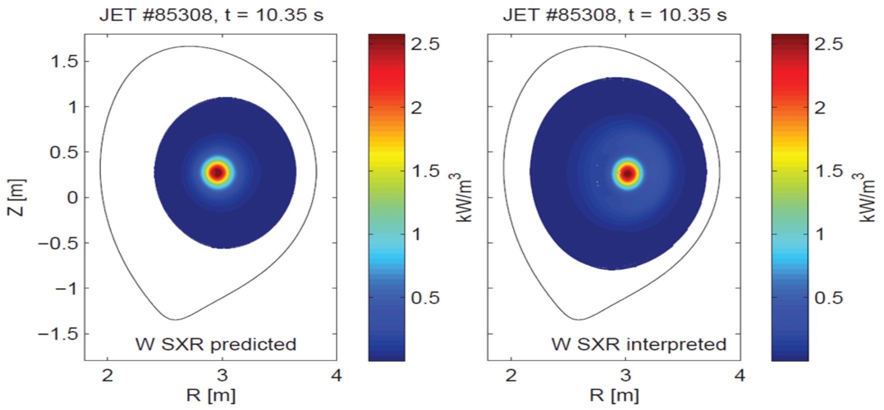
from TORIC & SSPQL

R. Bilato, M. Brambilla, O. Maj, et al., Nucl. Fusion 51, 103034 (2011).

Central ICRH helps avoiding accumulation

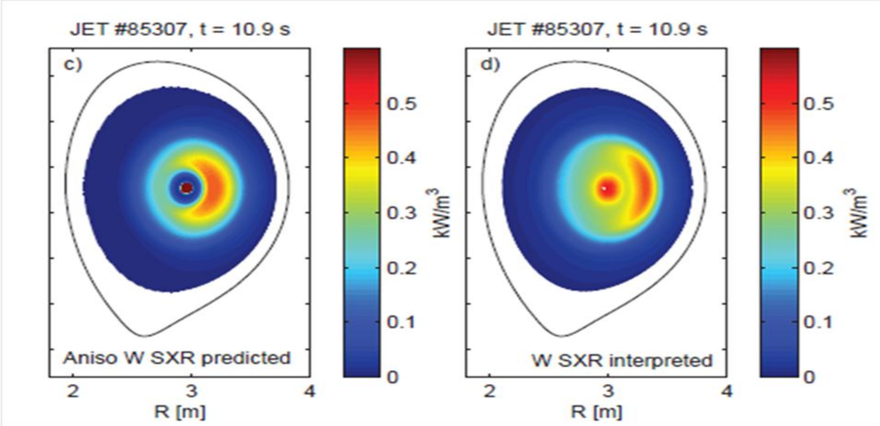
Again successful match between theory-based model and expt

85308: NBI ONLY



Model   Experiment

85307: NBI + ICRH



Model   Experiment

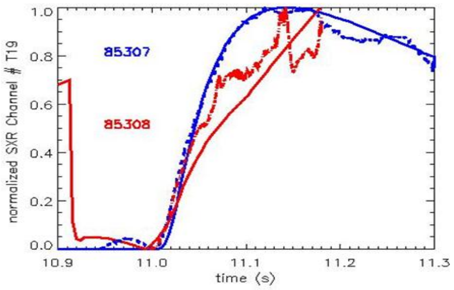
Includes anisotropy
heating of and thermal
screen by minority species

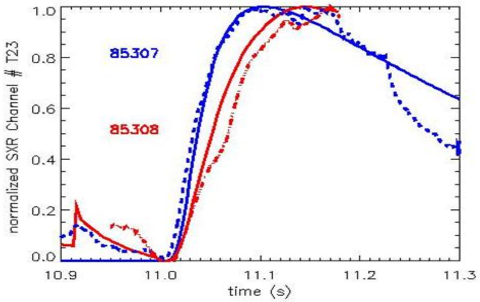
F Casson et al tbp in PPCF , http://arxiv.org/abs/1407.1191
R Bilato M Brambilla, O. Maj et al., Nucl. Fusion 51, 103034 (2011).

ICRH impact on Mo transport

- Analysis of ICRH effects on W confirmed by LBO injections of Mo
- Simulation of Mo LBO with theory-based model coefficients fits well experiment in the two cases with and without ICRH .

85307 (with ICRH) **85308 (NBI only)**





Simulation of two SXR vertical Lines of Sights From central (left) towards the LFS.

ICRH impact on Mo transport

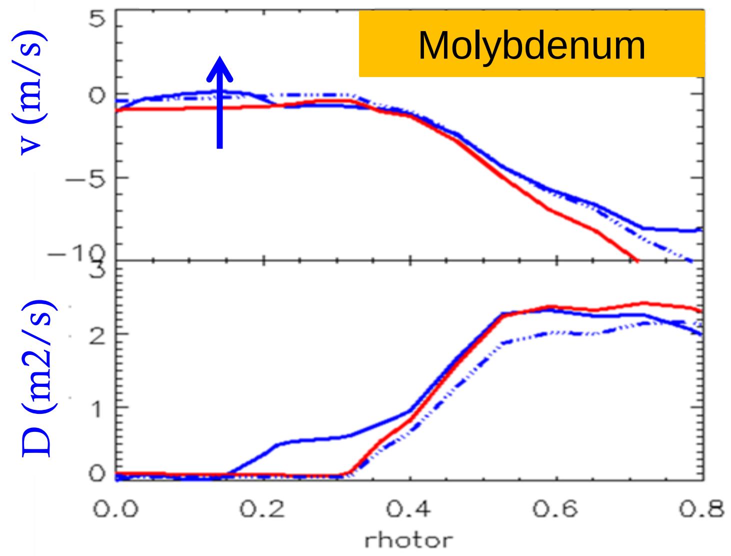
Model-based transport coefficients used in JETTO/SANCO to simulate Mo transient behavior (LBO)

85307 (with ICRH)

85308 (NBI only)

Centrifugal Effects only

CF and fast ion effects

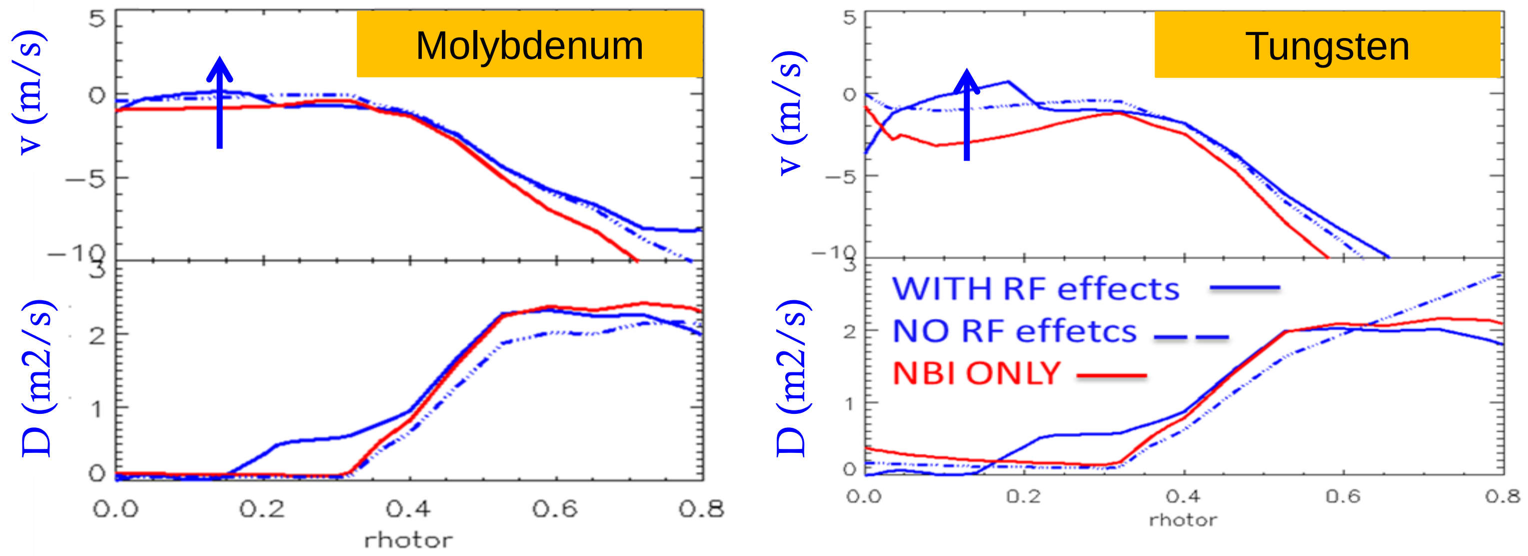


ICRH impact on Mo transport

Model-based transport coefficients used in JETTO/SANCO to simulate Mo transient behavior (LBO)

85307 (with ICRH) — - · - · Centrifugal Effects only; —— CF + fast ion effects

85308 (NBI only) ——



Summary and conclusion

- With advanced theory-based two dimensional transport models the complex behavior of W in the core of JET standard H-mode and hybrid discharges has been understood.

- The sensitivity to neoclassical transport of W is the main reason for its accumulation in JET discharges characterized by peaked density profiles.

- Central ICRH hampers W accumulation affecting the main kinetic profiles and the related neoclassical drive but also modifying directly W transport through thermal screening and anisotropy of heated minority species.