TRANSP Users Group Meeting, 23rd March 2015, PPPL, USA

EUROfusion

TRANSP applications to JET plasmas

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JET

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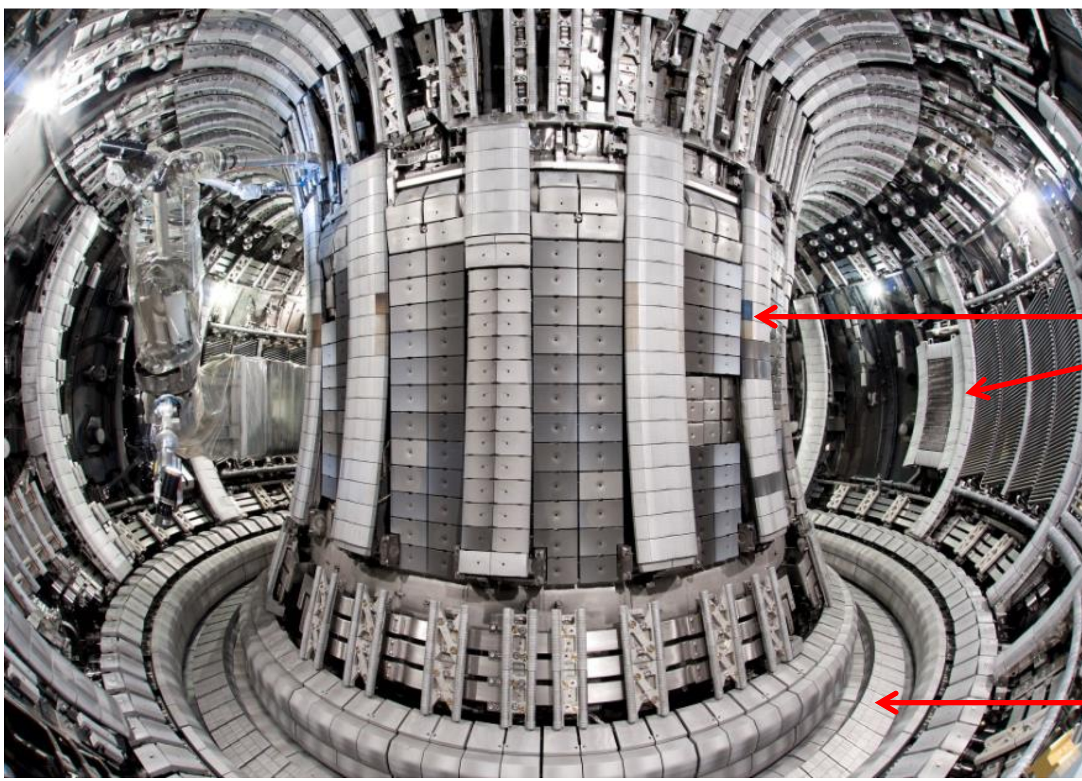
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ITER-like Wall at JET

- The internal wall at JET has been changed in 2010 to conduct dedicated studies for ITER i.e. **Be first wall and W divertor**
- The main subjects of current JET research are to
  1. exploit the ITER-Like Wall to develop robust operation scenarios for ITER.
  2. demonstrate an acceptable core W concentration for the foreseen ITER regimes.
  3. investigate the interaction between plasma and ITER-like wall



<JET ITER-Like Wall>

Beryllium

Tungsten

Content

1. TRANSP applications
    1) Comparative core confinement analysis in ILW and CW
    2) Effects of heating power on confinement
    3) ICRH deposition to avoid W accumulation
2. Future plans
    1) Neutron deficit issue
    2) DT campaign in 2017
    3) Suggestions

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1. TRANSPP applications
   1) Comparative core confinement analysis in ILW and CW
      → Hyun-Tae Kim et al, accepted to PPCF, 2015
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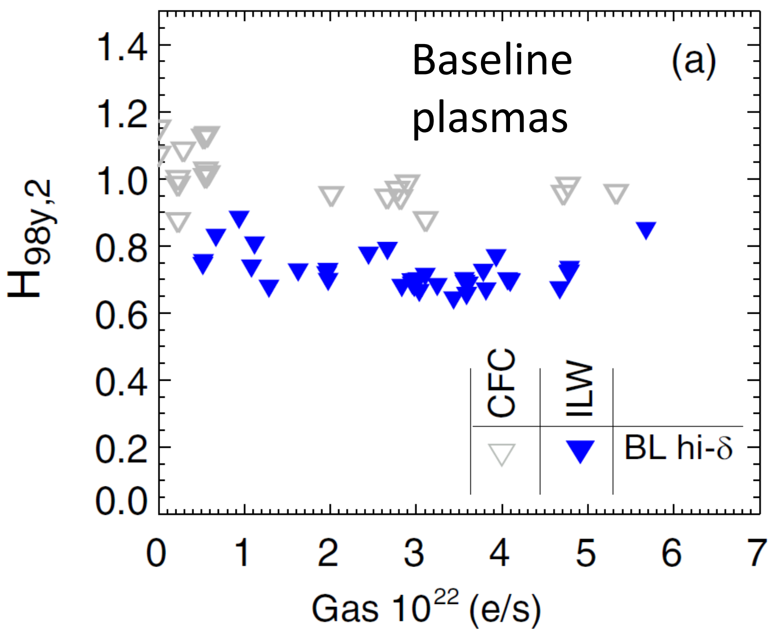
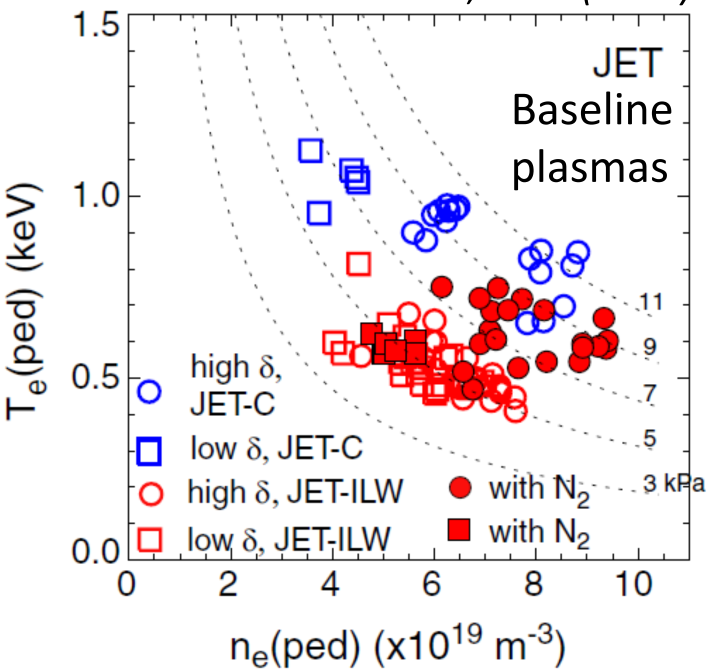
Energy confinement issues in baseline JET plasmas with ITER-Like Wall

M. Beurskens et al, *NF (2014)*

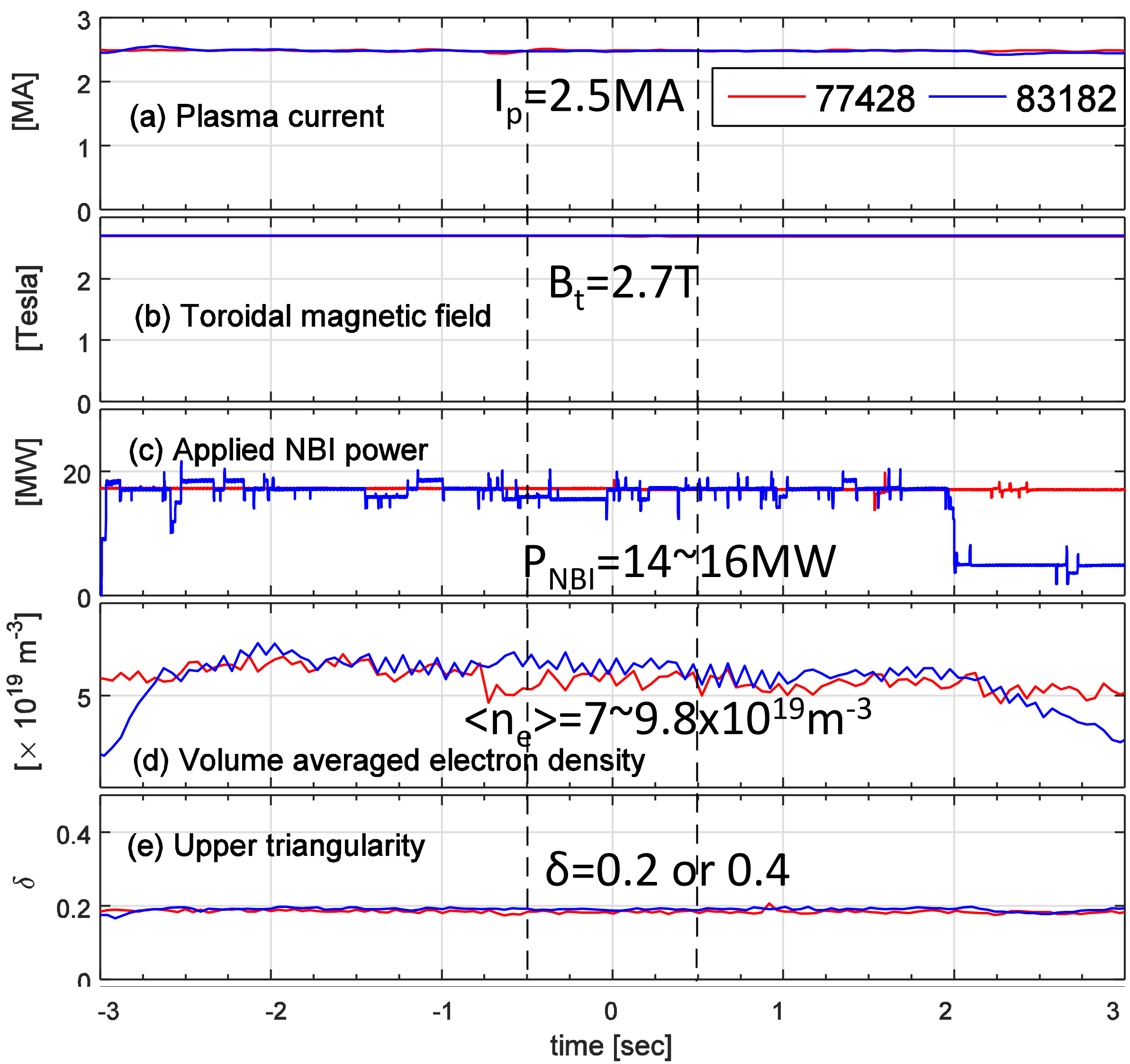


M. Beurskens et al, *PPCF (2013)*



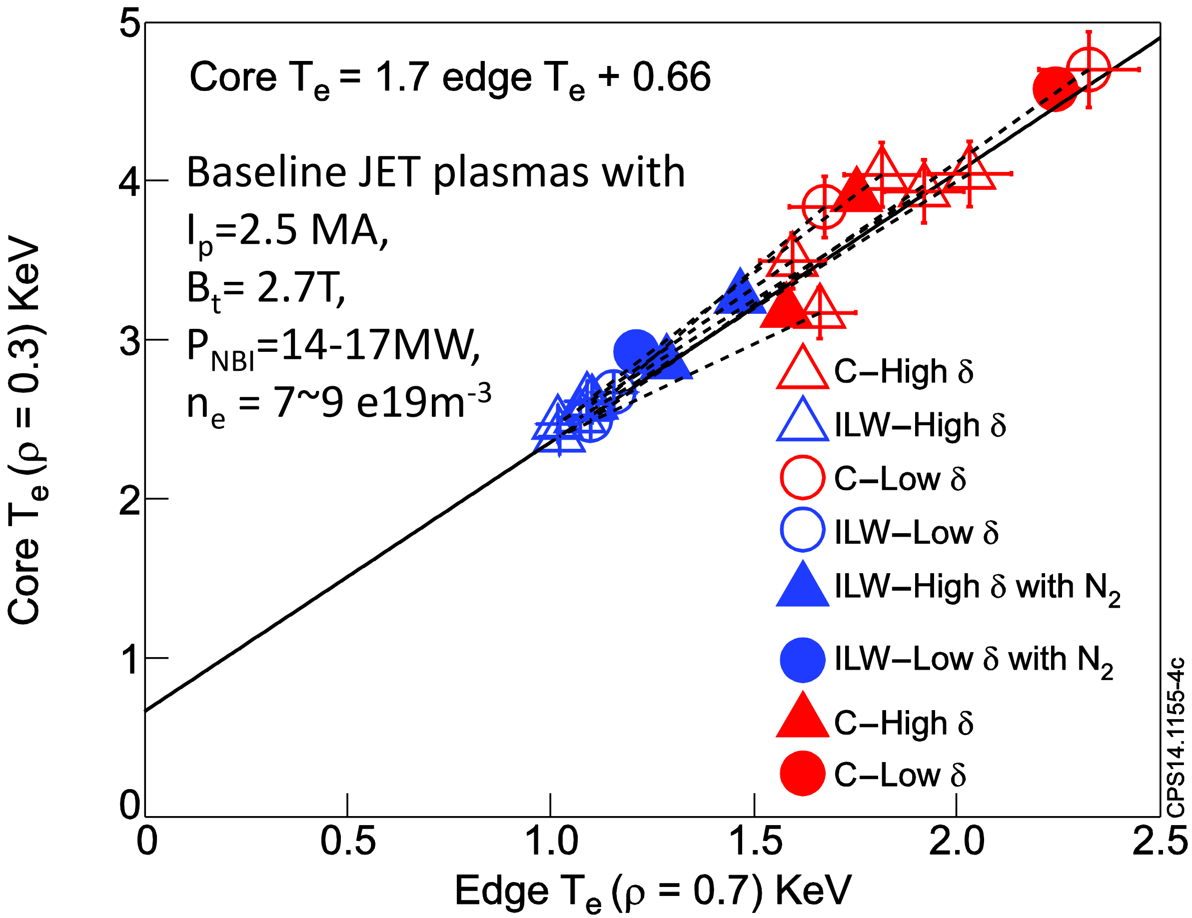
- Global confinement in ILW baseline (β_N=1.5-2) plasmas is degraded.
- Edge T_e in ILW plasmas is decreased compared to C wall plasmas, and this leads to a decrease in core T_e.
- **Is the core confinement also changed in baseline plasmas with ILW?**

Counterpart discharge pairs for comparative analysis between JET-ILW and JET-CW



- **Database for Comparative analysis between ILW and CW**
- **Selected to match 'engineering' variables (i.e. I_p, B_ϕ, P_{NBI}, $\langle n_e \rangle$, q_{95} , and δ) by T. Koskela.**
- 10 pairs of Baseline (β_N =1.5~2) high n_e H-mode
- 3 shots of N_2 seeded ILW discharges

Core T_e and edge T_e are well correlated with a linear fit



slope of fitting line

$$\sim \frac{\text{core } T_e(\rho=0.3)}{\text{edge } T_e(\rho=0.7)}$$

$\equiv$ T_e peaking

core $T_e \propto$ edge T_e

$\Rightarrow$ T_e peaking weakly depends on edge T_e

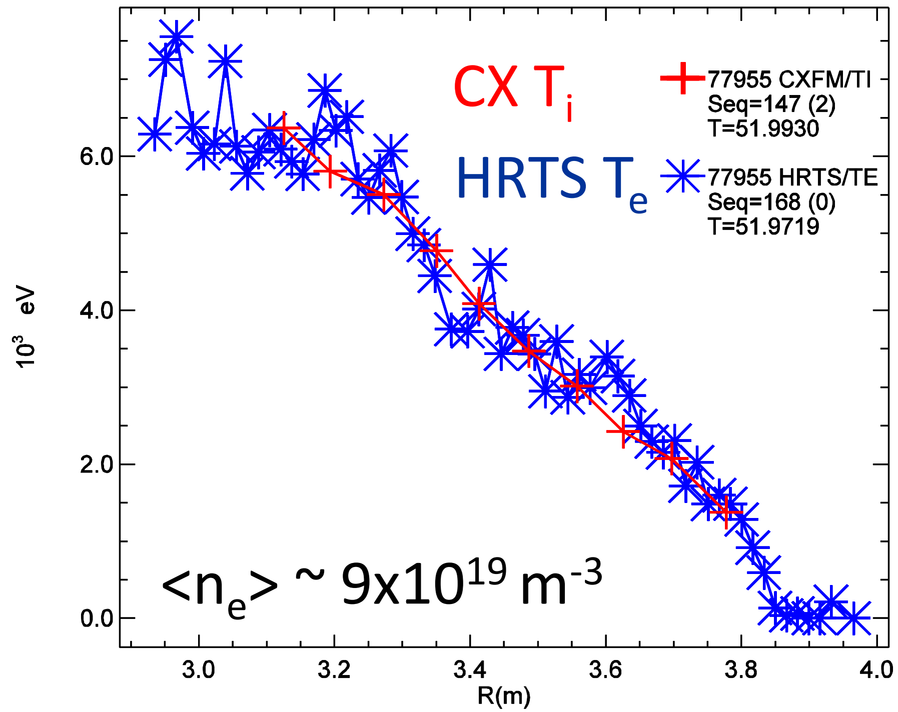
- Both ILW and CW data are well aligned to the same linear fit.
- N_2 seeding moves the profiles towards the CW counterparts, along the same linear fit.

Input and assumptions in TRANSP

- T_e = HRTS
- n_e = HRTS
- T_i=T_e (reasonable for high n_e)
- Z_{eff} = Visible Bremsstrahlung

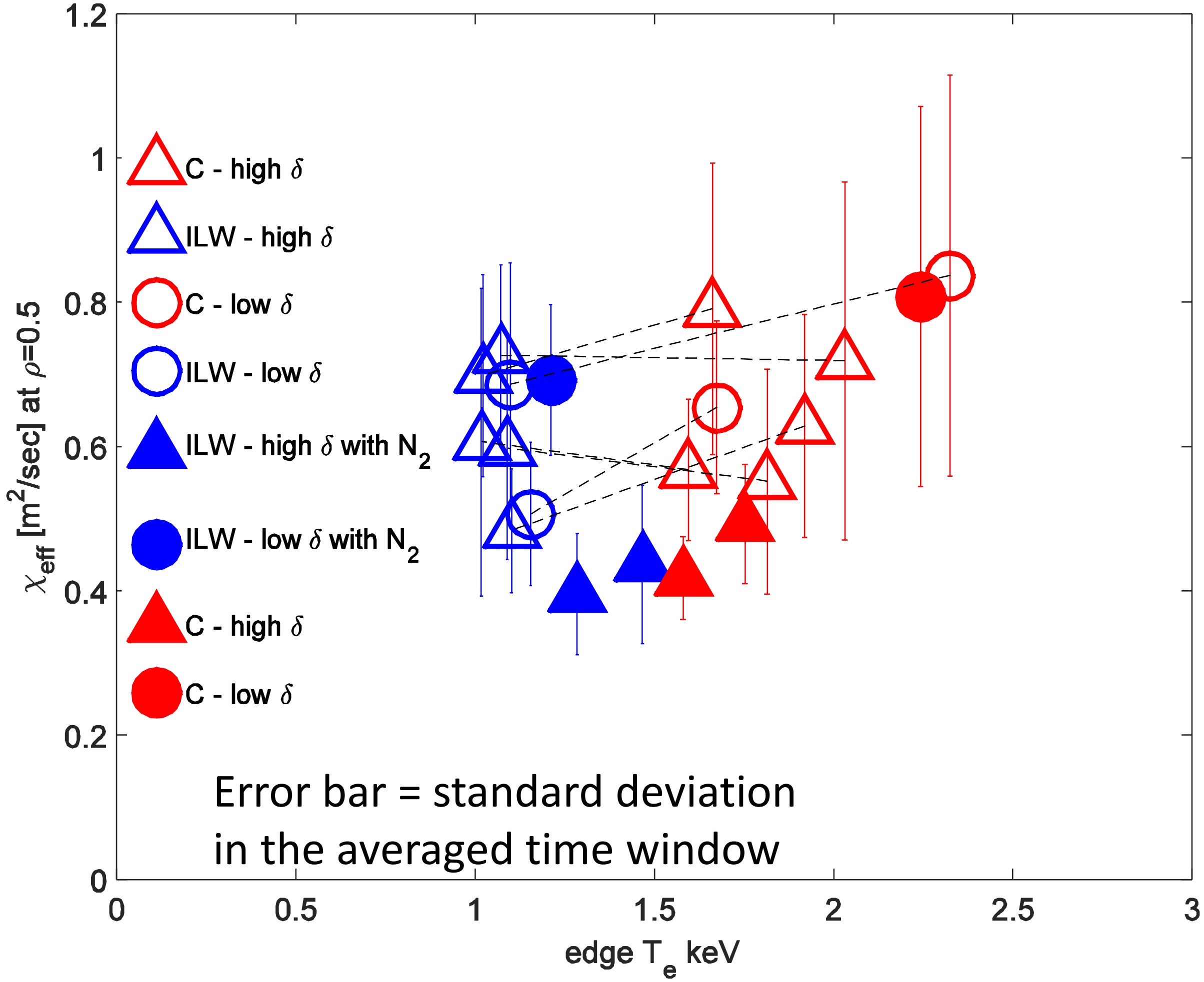
i.e. NZEFMOD=2 and NLZFIN=.T

- ICRH = TORIC
- NBI = NUBEAM



- Bulk Radiation = Bolometry measurement
- D plasma with C or Be impurity
- q profile = EFIT/q i.e. NQMODA=4
- Equilibrium = TRANSP equilibrium solver (TEQ) i.e. LEVGEO=11

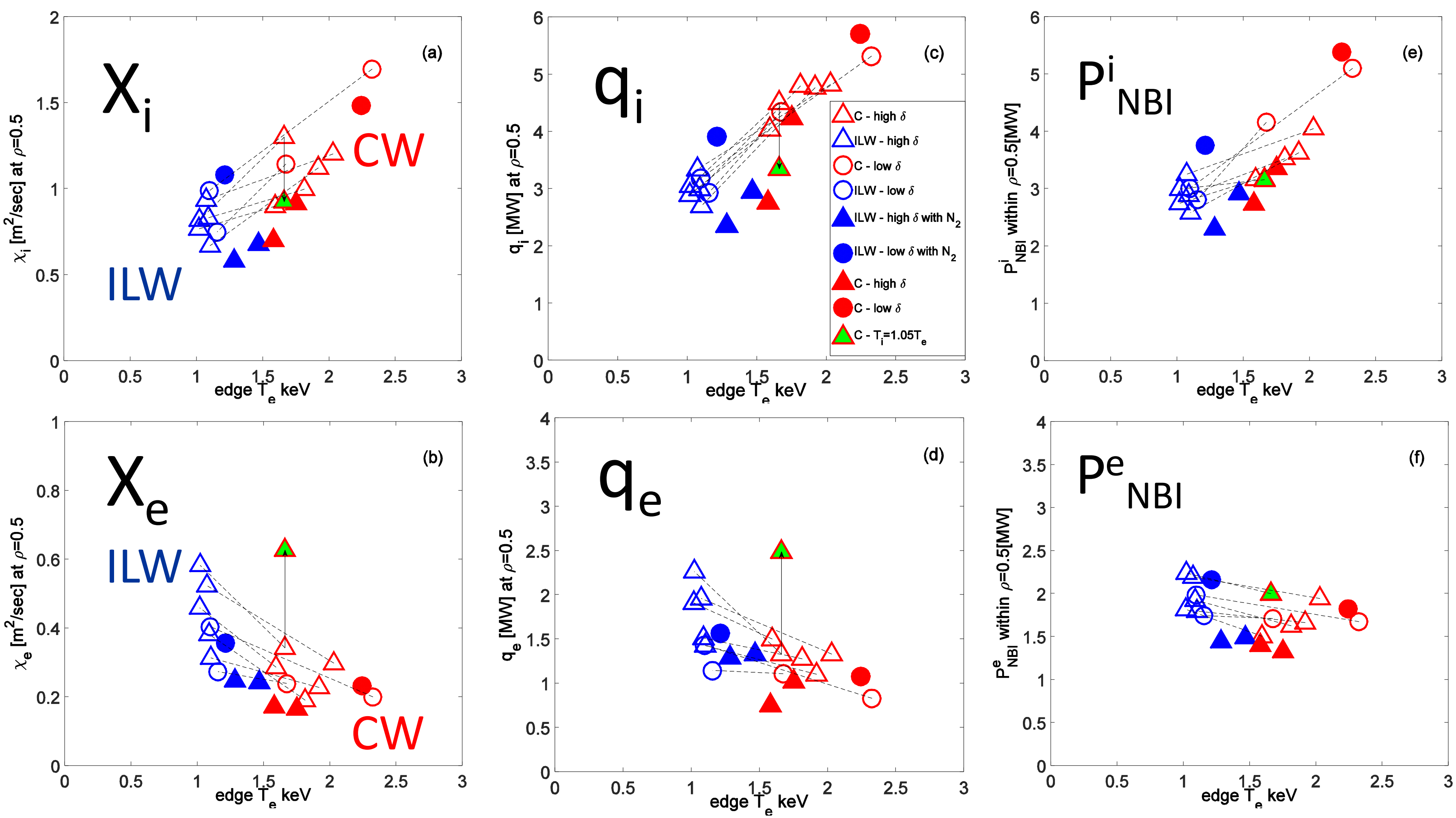
Effective core heat conductivities at ρ=0.5 are not decreased in JET-ILW, compared to the CW counterparts.



$$q_e = -\chi_e n_e \frac{\partial T_e}{\partial r},\ q_i = -\chi_i n_i \frac{\partial T_i}{\partial r}$$

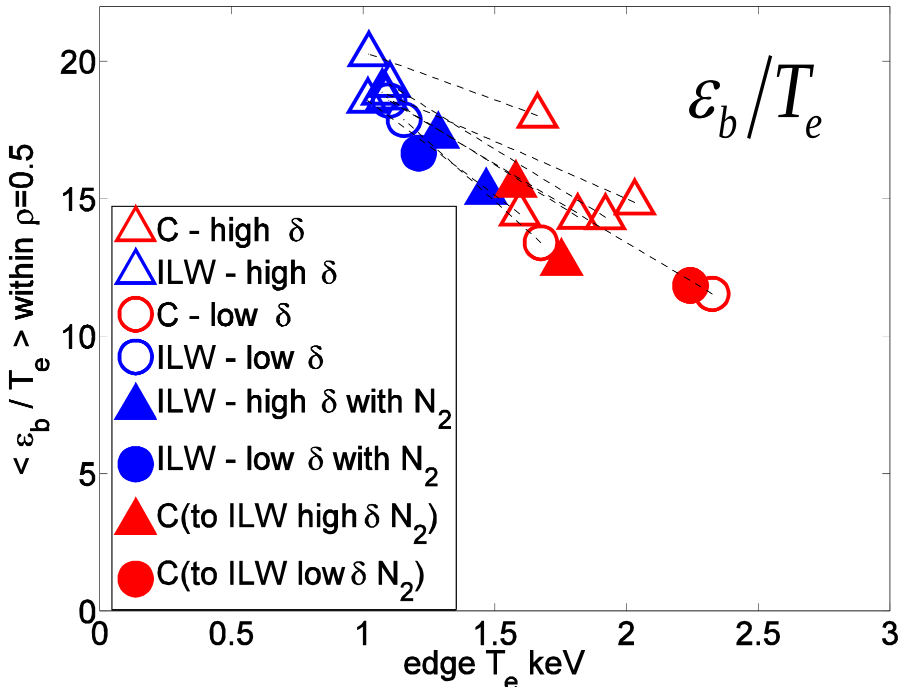
$$\Rightarrow q_e + q_i = -\chi_{eff}\,(n_e \frac{\partial T_e}{\partial r} + n_i \frac{\partial T_i}{\partial r})$$

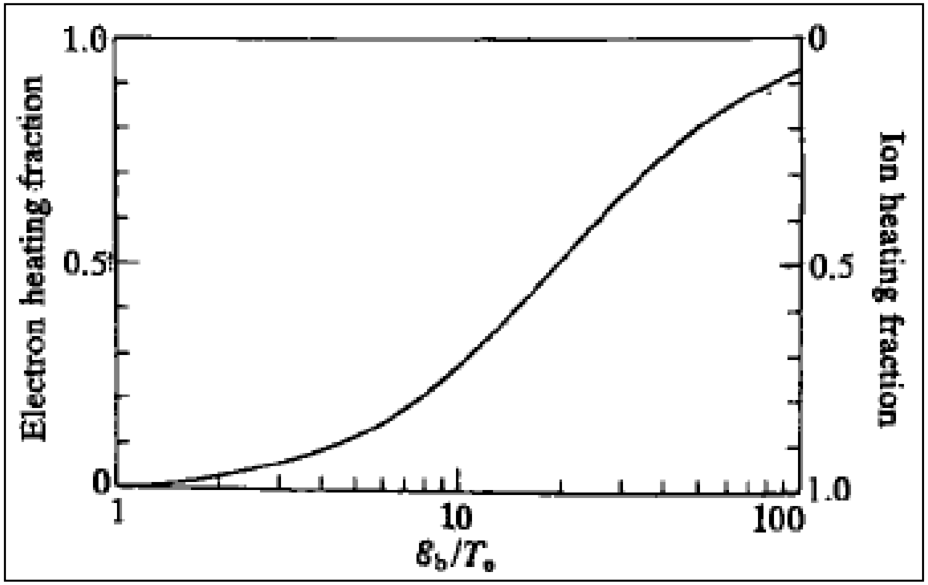
Core (ρ=0.5) confinement in JET-ILW: $X_i\downarrow$ and $X_e\uparrow$



- The transport change of electron and ion in JET-ILW results from the change of NBI heat deposition.

NBI power deposition depends on T_e profile.



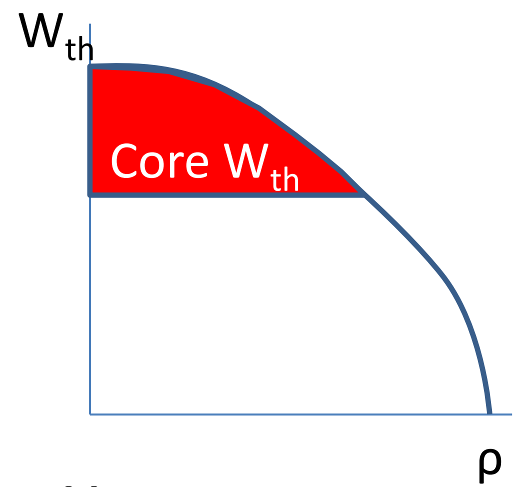


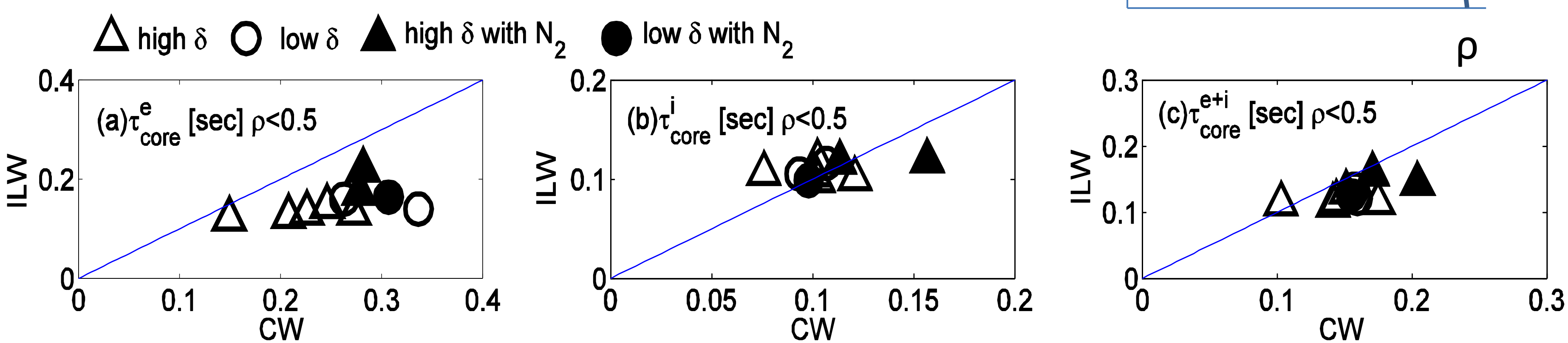
J. Wesson, *TOKAMAKS*

- The higher ε_b / T_e, the higher fraction of electron heating (and the lower fraction of ion heating).
- Beam energy is almost similar for all discharges i.e. about 50KeV
- Lower core T_e in ILW results in smaller core P^i_{NBI} and higher core P^e_{NBI}.

Core energy confinement time

$$\tau_{core} = \text{core } W_{th} \,/\, P_{heat}$$





- The changed core NBI heating fraction to electrons and ions in JET-ILW (i.e. **higher P^e_{heat} and lower P^i_{heat}**) leads to **reduced τ^e_{core} and similar τ^i_{core}**, compared to CW counterparts.
- **Total core energy confinement time τ^{e+i}_{core} is slightly reduced** in JET-ILW.

Conclusion – TRANSP application 1

- Comparative analysis of **ILW versus CW** (baseline high n_e H-mode)
- HRTS T_e profile analysis finds
  - T_e profile peaking is found to be similar, and weakly dependent on edge T_e
  - When ILW discharges are seeded with N_2, core and edge T_e both increase maintaining a similar T_e peaking.
- TRANSP analysis shows that
  - Effective heat conductivities X_{eff} in the core (ρ=0.5) in JET-ILW is not changed.
  - X_e and q_e are higher, and X_i and q_i lower in the core in JET-ILW.
  - This is consistent with the higher P^e_{NBI} and the lower P^i_{NBI} in JET-ILW where core T_e is lower.
  - The overall core energy confinement time is similar or slightly reduced in JET-ILW compared to C-wall counterparts.
- It is likely that high T_e, comparable to that in CW counterparts, would be achieved if the edge T_e is recovered in JET-ILW.
- Hyun-Tae Kim et al, accepted to PPCF, 2015

Content

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   2) Effects of heating power on confinement
   → C. Challis, IAEA Fusion Energy Conference, 2014, EX/9-3
   → C. Challis, NF submitted 2015
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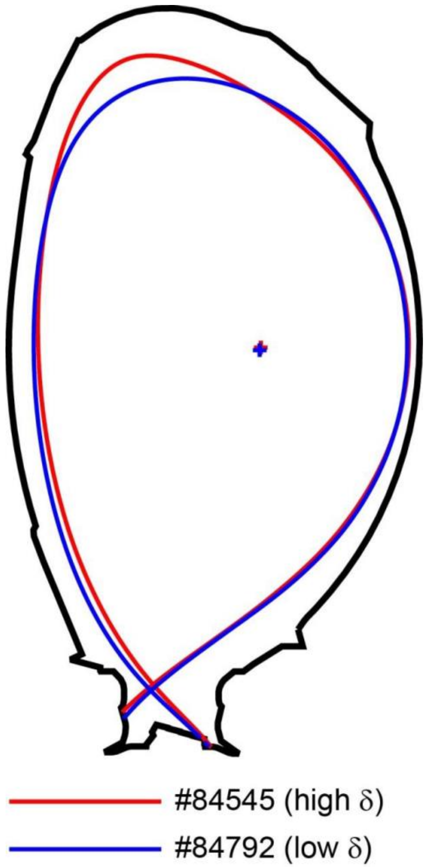
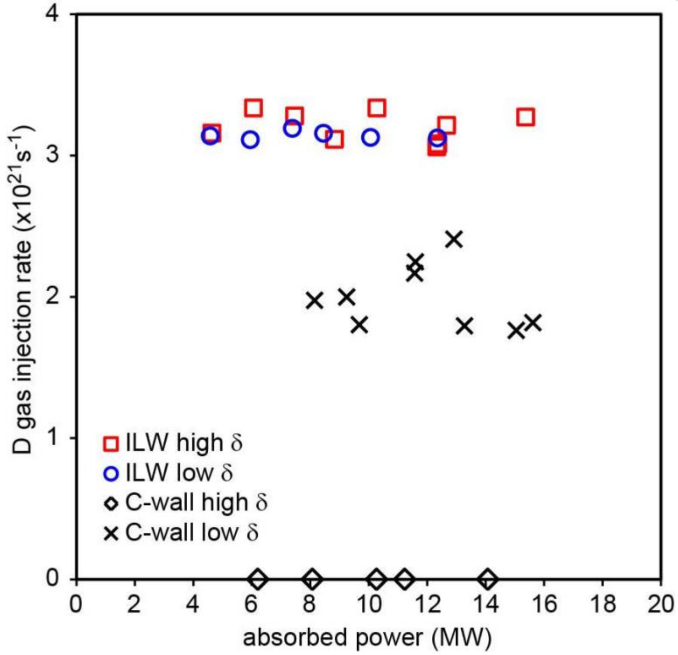
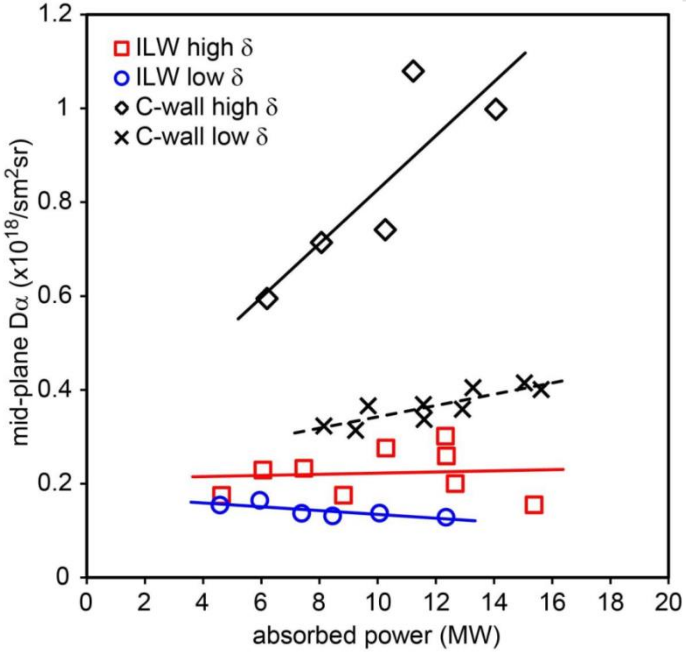
Four cases for heating power scan study







- To avoid W accumulation in core, high D gas injection rate is required for JET-ILW compared to JET-CW.
- Even without any D gas injection, C-wall high δ has the highest D_α in the database.
- D_α increases with absorbed power, only in C-wall high δ.
- <u>D neutrals might play a key role in confinement? [1]</u>
- **Heating Power (=Ohmic + NBI) scan for four cases**

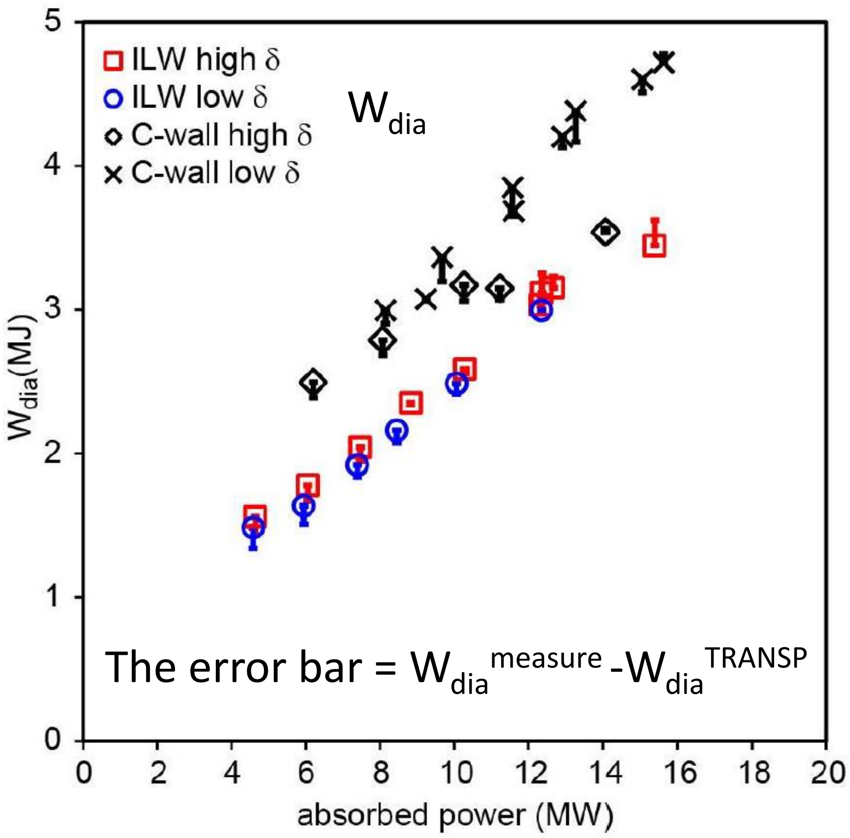
1. **CW or ILW**
2. **low δ or high δ**

[1]Joffrin EPS 2014 & Joffrin IAEA 2014

Input and assumptions in TRANSP

- T_e = HRTS or LIDAR (C-wall low δ)
- n_e = HRTS or LIDAR (C-wall low δ)
- T_i= Charge Exchange Radiation measurement
- D plasma with C or Be impurity
- Z_{eff} = Visible Bremsstrahlung i.e. NZEFMOD=2 and NLZFIN=.T
- NBI = NUBEAM
- Bulk Radiation = Bolometry measurement
- q profile = EFIT/q i.e. NQMODA=4
- Equilibrium = TRANSP equilibrium solver (TEQ) i.e. LEVGEO=11

Data consistency check : $W_{dia} = \frac{3}{2}\int (p_{th\perp} + p_{fast\perp})dV$



$$W_{dia}^{measure} \equiv \text{ measured } \mathrm{W_{dia}} \text{ by diamagnetic loop}$$

$$= \frac{3}{8}\mu_0 R_0 I_p^2 \beta_p \quad \text{where}$$

$$\beta_p = \frac{1}{\mu_0 R_0 I_p^2}\int B_p^2 \vec{r}\cdot d\vec{S} + \frac{1}{\mu_0 R_0 I_p^2}\int B_p^2 \vec{R}\cdot d\vec{S}\left(1 - \frac{R_T}{R_0}\right) + \frac{8\pi B_0 \Delta\phi}{\mu_0^2 I_p^2}$$

$\Delta\phi =$ diamagnetic flux

$B_0 =$ toroidal magnetic field on axis

$R_0 =$ major radius of vacuum vessel centre

$R_T =$ major radius of current centre

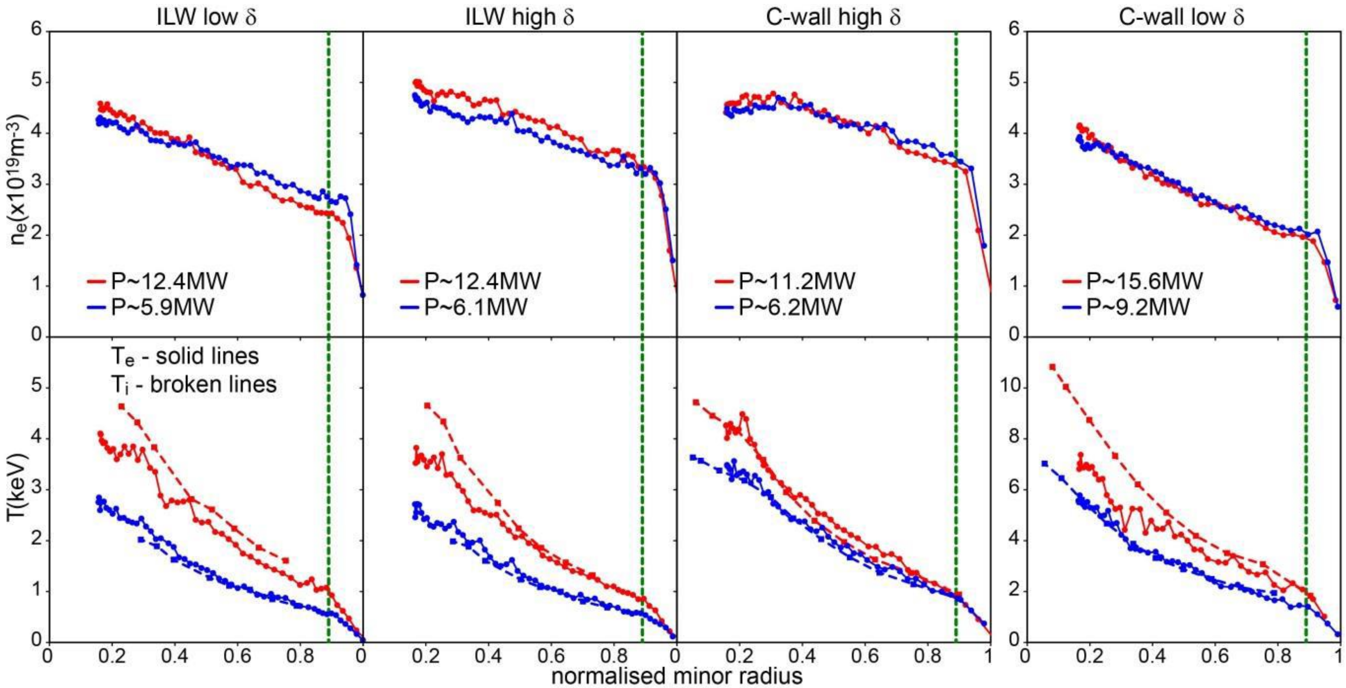
$$\mathrm{W}_{dia}^{TRANSP} \equiv \text{Synthetic } \mathrm{W_{dia}} \text{ in TRANSP}$$

$$= \frac{3}{2}\int (n_e T_e + n_i T_i)\,\mathrm{dV} + \frac{3}{2}\mathrm{p}_{\mathrm{Fast},\perp}$$

Based on the good agreement i.e. $W_{dia}^{measure} \approx W_{dia}^{TRANSP}$,
TRANSP results are used for the following analysis.

Weaker confinement degradation with P_{heat} than

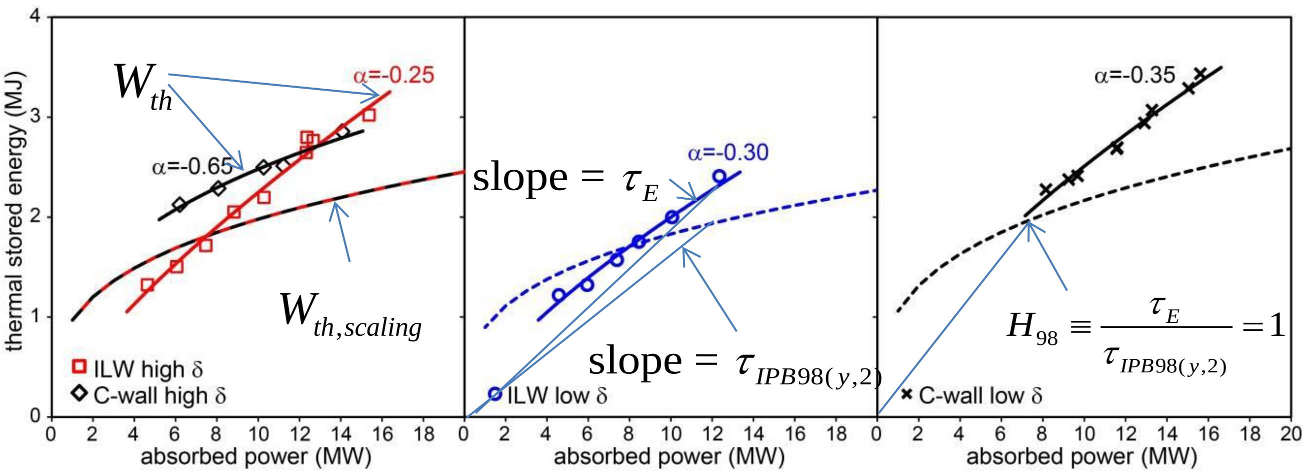
$$\tau_{IPB98(y,2)} = 0.05621 I_P^{0.93} B_T^{0.15} P_{heat}^{-0.69} n_e^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78}$$



Heating power scan (i.e. plasma parameters maintained except heating power) for the four cases shows an increase in

1. Pedestal temperature
2. Core T_i/T_e
3. $H_{98}(=\tau_E/\ \tau_{IPB98(y,2)}) > 1$

at higher heating power. However, exceptional case appears for C-wall high δ.



Measured W_{th}

$$= \tau_E P_{heat} \propto P_{heat}^{1+\alpha}$$

Calculated $W_{th,scaling}$

$$= \tau_{IPB98(y,2)} P_{heat} \propto P_{heat}^{0.31}$$

where $\tau_{IPB98(y,2)} \propto P_{heat}^{-0.69}$

Conclusion – TRANSP application 2

- Power degradation of confinement was weak in both of the ILW configurations and the C-wall low δ plasmas, much weaker than the $IPB_{98(y,2)}$, resulting in elevated H_{98} only at high power and, therefore, high $\beta_{N.}$
- This is consistent with the general observation of higher H_{98} in high β_N 'hybrid' plasmas compared with the low β_N 'baseline' plasmas in these configurations.
- However, the high δ C-wall plasmas show elevated H_{98} over a wide power range with strong, $IPB_{98(y,2)}$-like, power degradation. This exceptional case appears to have been affected by a source of neutral particles in the main chamber.
- C. Challis et al, submitted to NF, 2015
- C. Challis, IAEA Fusion Energy Conference, 2014, EX/9-3

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   → C Giroud 2015 PPCF 57 035004
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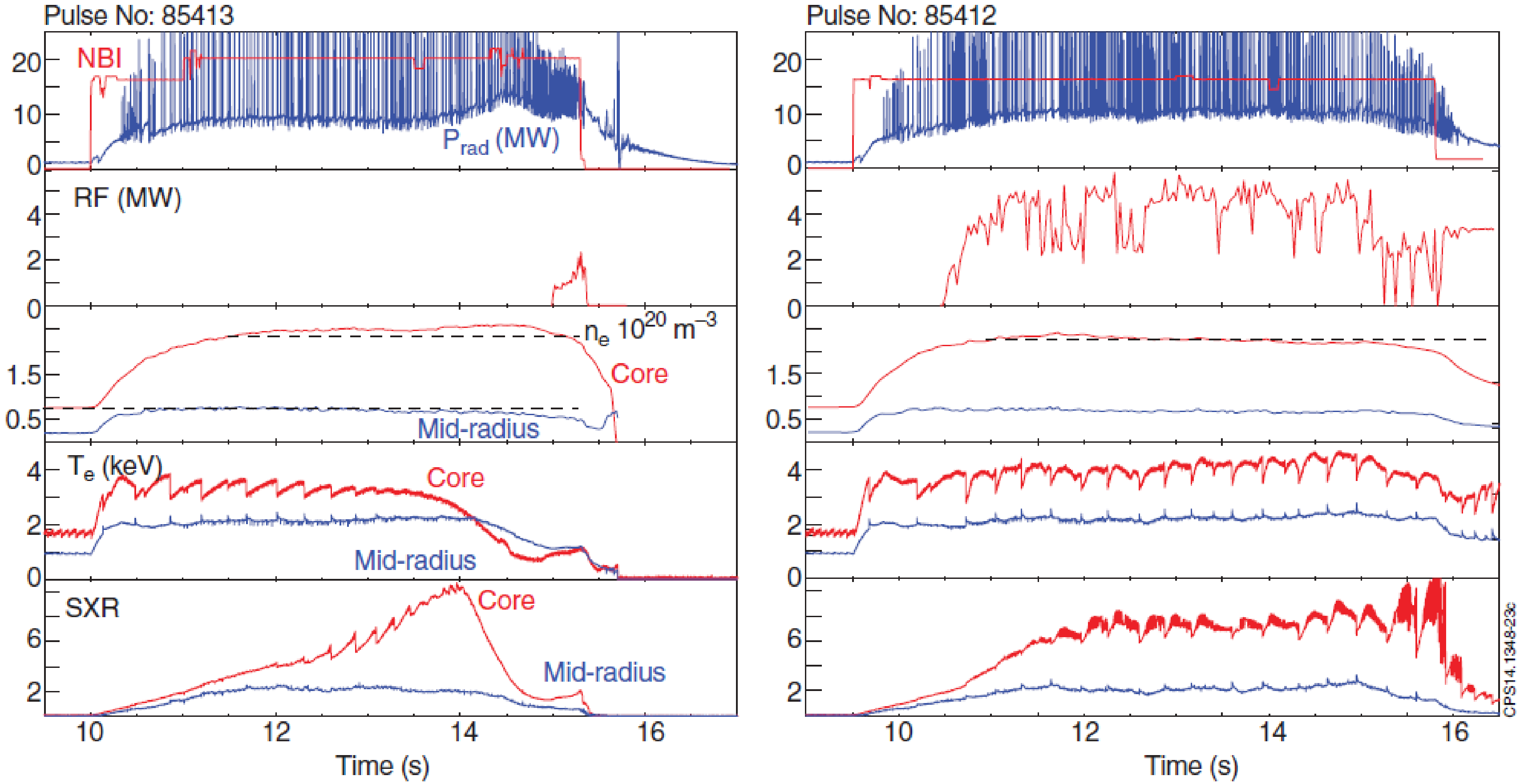
Disruption due to core W accumulation



- n_e peaking → W peaking → core T_e cooling → ST amplitude reduced → W expelling reduced

  ↳ dramatic cooling → disruption!

- ICRH is required to prevent n_e peaking for stationary condition in JET-ILW

Input and assumptions in TRANSP

- T_e = HRTS
- n_e = HRTS
- $T_i = T_e$
- D plasma with Be and N impurity i.e NLZSIM=.T

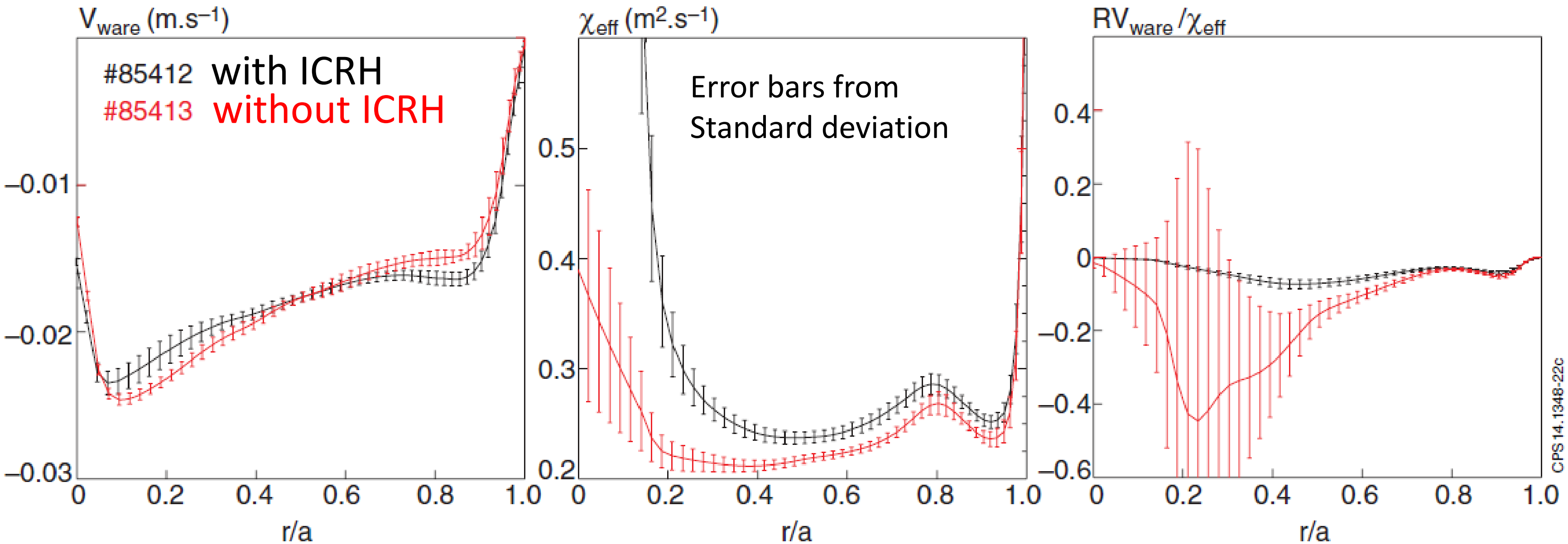
n_{Be} = 1% of n_e and n_N = CX measurement .

- Z_{eff} is calculated by impurity input data i.e. NZEFMOD=10,
- NBI = NUBEAM, ICRH=TORIC with 3% H minority (similar profile with n_e)
- Bulk Radiation = Bolometry measurement
- q profile = Poloidal Field Diffusion equation solved to calculate $E_{\parallel}$,

and in turn V_{ware} i.e. NQMODA=1

- Equilibrium = TRANSP equilibrium solver (TEQ) i.e. LEVGEO=11

ICRH increases particle diffusion, and reduces central W peaking.



$$\text{W peaking} \quad \propto -R\frac{\partial n_e}{n_e \partial r} + 0.5\frac{\partial T_e}{T_e \partial r} \begin{cases} \text{if <0, hollow } n_W \text{ profile} \\ \text{if >0, central W peaking} \end{cases}$$

[1] C. Angioni 2009 PPCF 51 124017

$$\Gamma_e = \underbrace{-D_n \frac{\partial n_e}{\partial r}}_{outward\ \text{diffusion}} + \underbrace{n_e V_{conv}}_{inward\ \text{convection}} \qquad \text{i.e. } V_{conv} < 0$$

$$1.\ \Gamma_e = 0 \text{ for steady state, } 2.\ V_{conv} \approx V_{ware} (\propto \frac{E_{||}}{B_p}) \text{ for high } n_e (> 0.8 n_{GW}), 3.\ \chi_{eff} \approx D_n$$

$$-\frac{\partial n_e}{n_e \partial r} = -\frac{V_{conv}}{D_n} \approx -\frac{V_{ware}}{\chi_{eff}}$$

[2] J. Stober 2001 PPCF 43 A39-53

Conclusion – TRANSP application 3

- N-seeded high δ in JET-ILW is not stationary and can result in disruption due to W accumulation in the core.
- According to Neoclassical theory, W peaking is proportional to n_e peaking.
- n_e peaking can be reduced by core deposition of ICRH, which increases outward n_e diffusion without significant change of inward ware pinch.
- C. Giroud 2015 PPCF 57 035004

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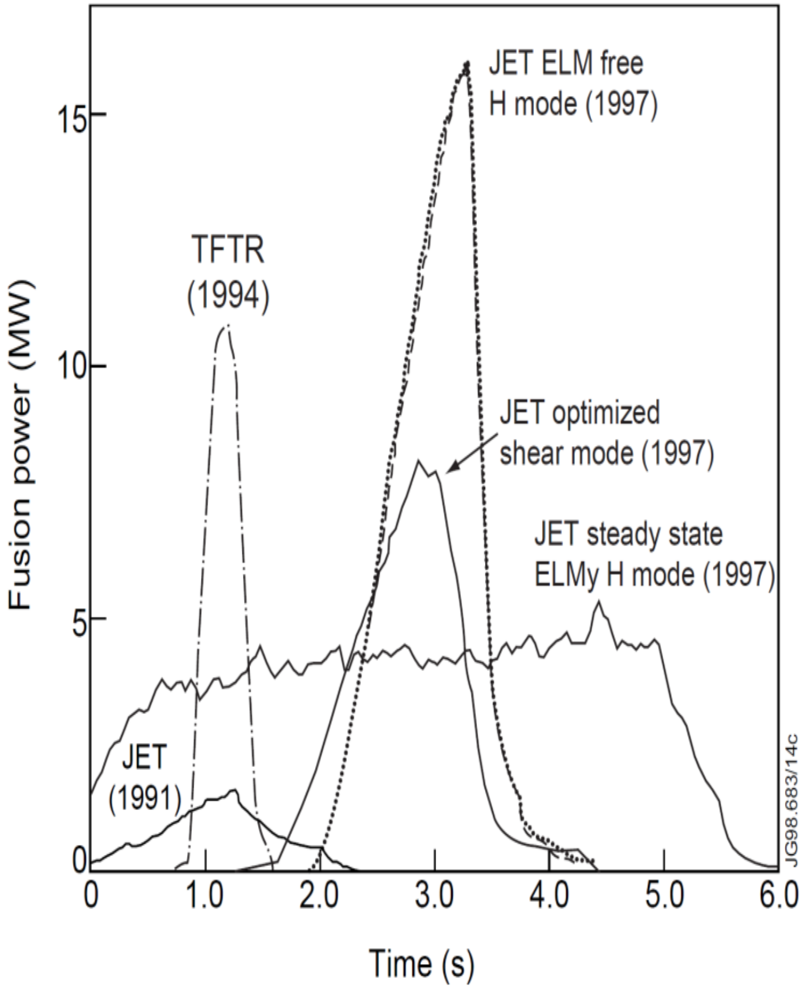
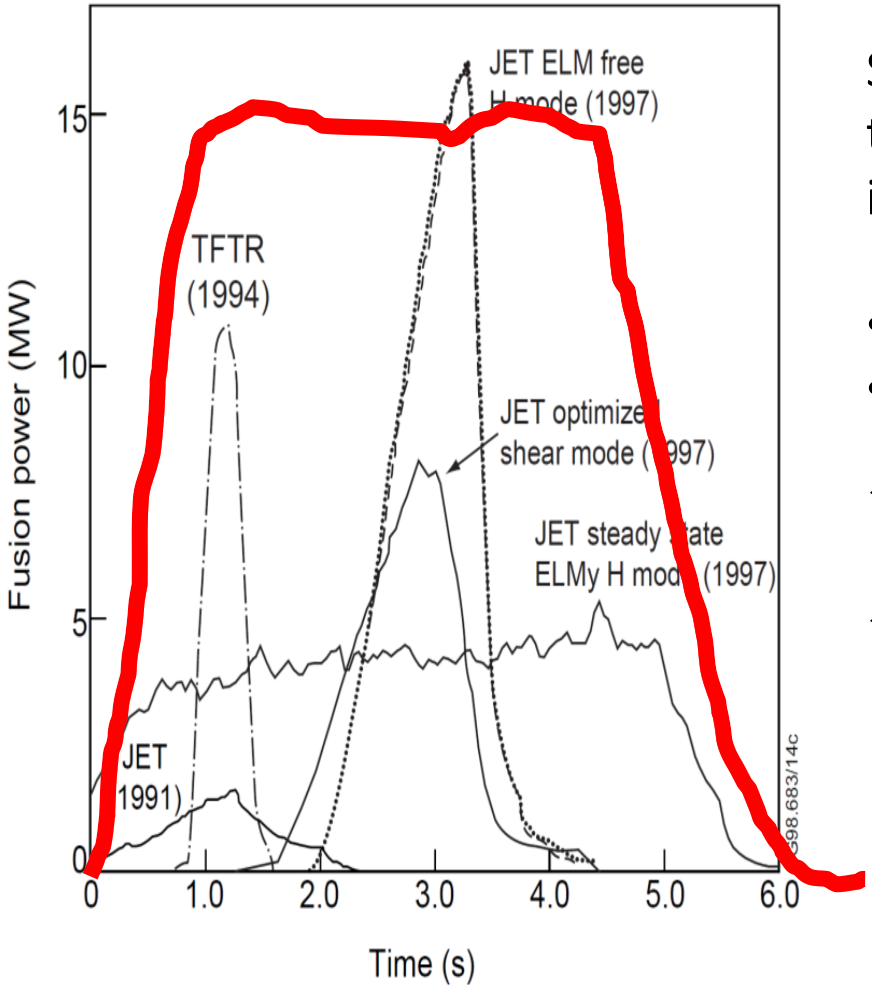
JET DT campaign with ITER-like wall is planned in 2017!



Since 1997 DT campaign,
the heating power at JET has been improved a lot!

- P_{NBI}= 20MW → 34MW
- P_{ICRH}= 3MW → 6MW

JET DT campaign with ITER-like wall is planned in 2017!



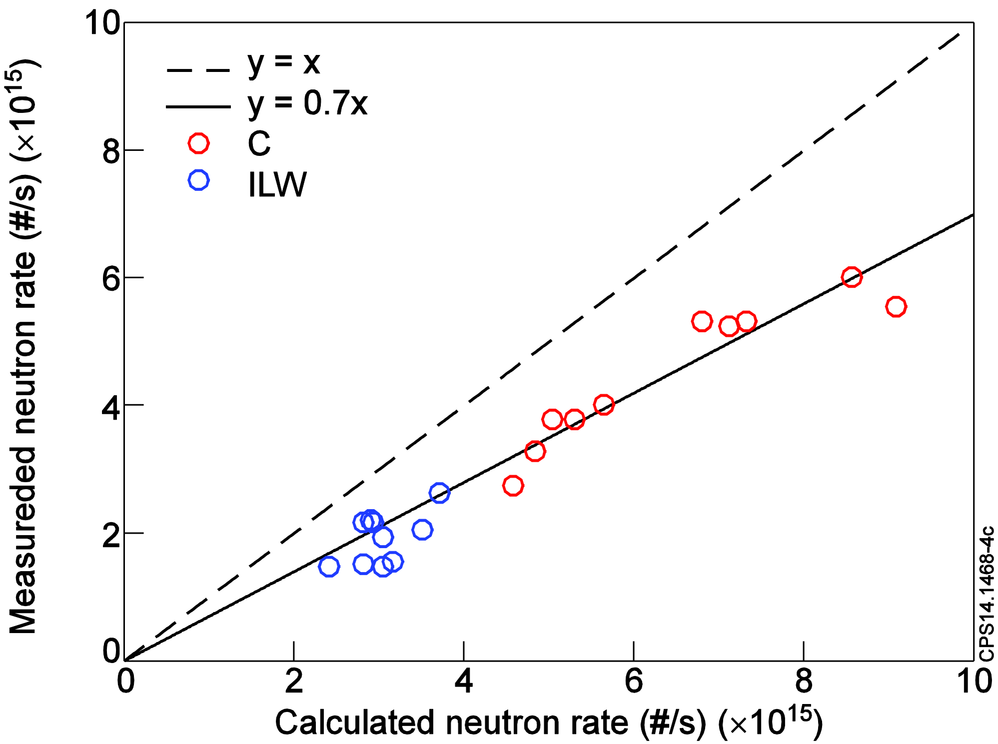
Since 1997 DT campaign,
the heating power at JET has been improved a lot!

- P_{NBI}= 20MW → 34MW
- P_{ICRH}= 3MW → 6MW

✓ **15MW of fusion power for 5 sec?**

✓ **TRANSP will play a key role in 2017 DT campaign**

Neutron rate calculation in TRANSP



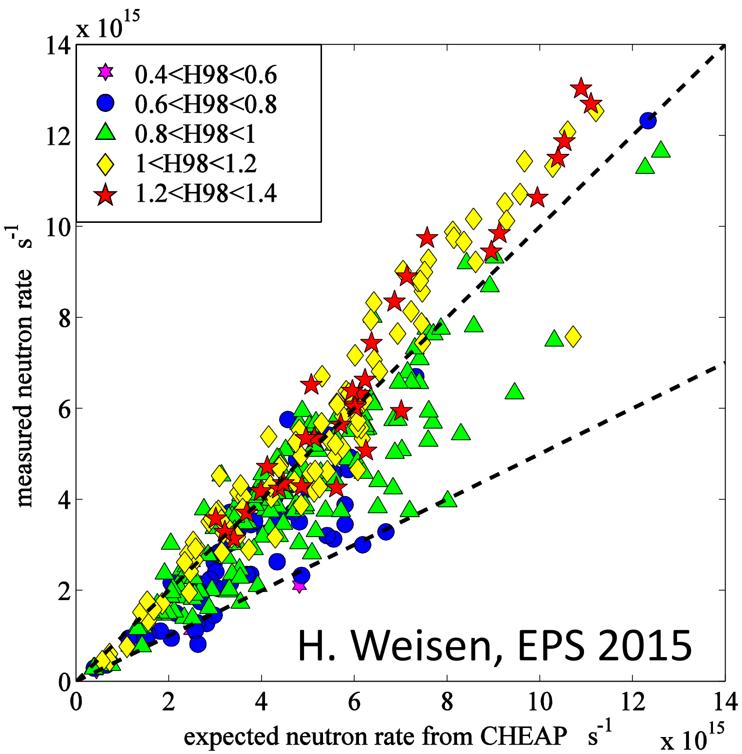
- Baseline JET plasmas with
- ✓ I_p=2.5 MA,
- ✓ B_t= 2.7 T,
- ✓ P_{NBI}=14-17 MW,
- ✓ n_e = 7~9 e19 m^{-3}

- The TRANSP database shows that TRANSP-calculated neutron rate is higher than the values measured by fission chamber
  i.e. **Measured neutron rate < Calculated neutron rate**
- Note, the deficit fraction is consistent i.e. (≈30%) in the database where key plasma parameters i.e. I_p , B_t, P_{NBI}, n_e are constrained.

Neutron deficit issue in a large database of JET plasmas

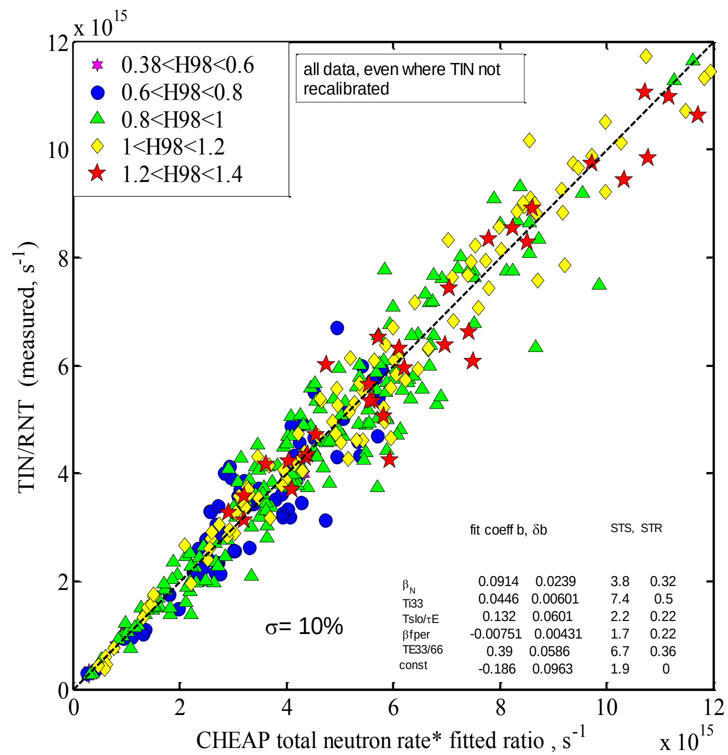
- **Measured < Calculated** (by CHEAP i.e. without fast ion orbits and beam-beam neutrons)
- Good agreement within 10%, using a multi-parameter regression fit with ‘plasma parameters’. This shows that the ‘deficit’ is a matter of physics (rather than random factors)
- If anomalous fast ion transport is not modelled, the neutron rate is over calculated in TRANSP (for high n_e JET plasmas in Yuri Baranov, PPCF 2009, 51 4 044004)

measured neutron rate



Predicted neutron rate

measured neutron rate



Predicted neutron rate * fit

Future work with TRANSP at JET

- Investigation on neutron deficit in measurement
- Reprocessing the TRANSP runs in 1997 DT campaign

- **<u>Interpretative simulations of 2017 JET DT campaign</u>**

Suggestions from JET TRANSP users

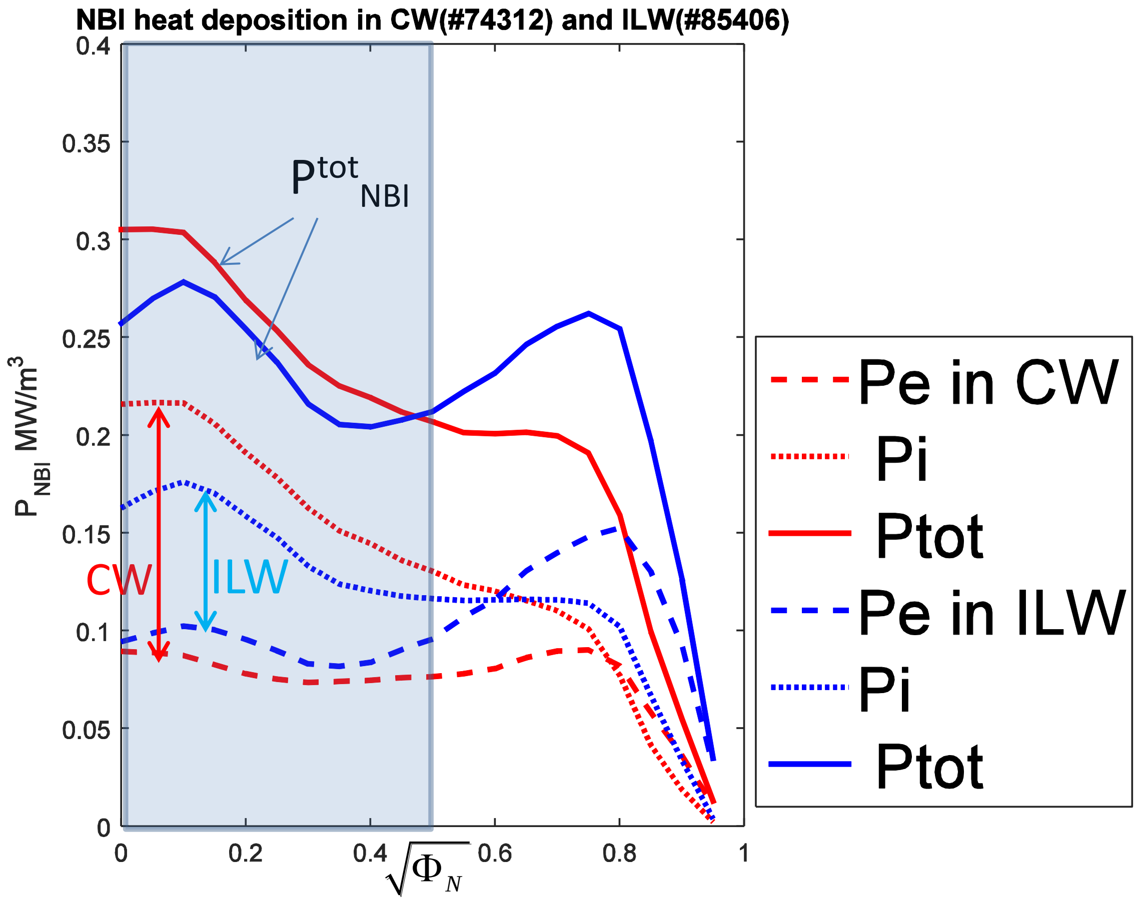
- Interaction between RF and fast ions i.e. TORIC and NUBEAM.
- FI diffusion coefficient as a function of time and radius i.e. $D_{FI}(t,rho)$
- TRANSP runs for a large database
- More synthetic diagnostics data? e.g. MSE, gamma ray

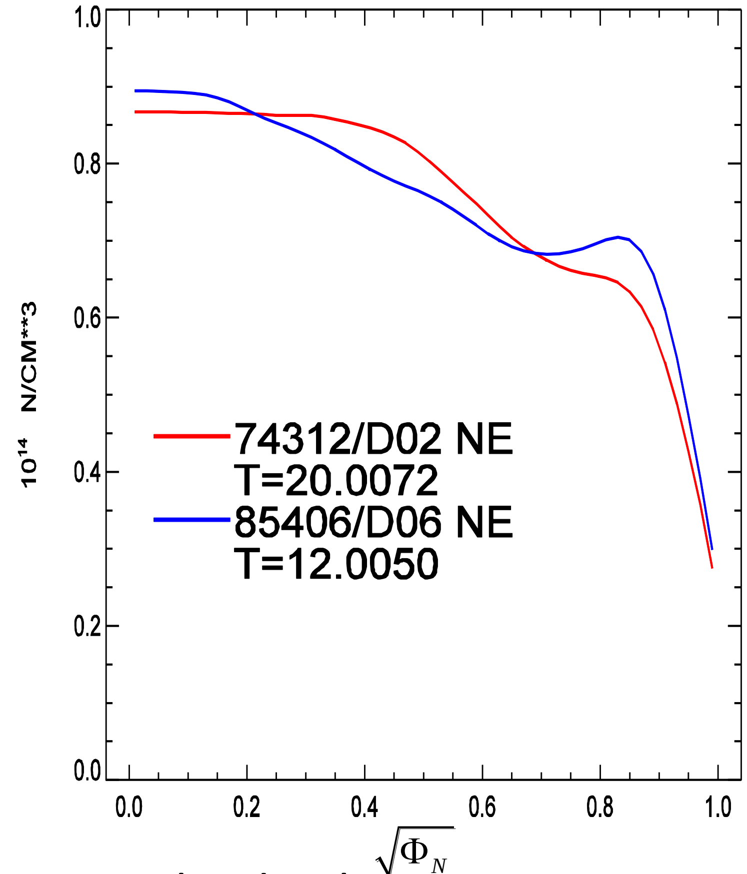
Main conclusion

- **TRANSP is one of the key tools to conduct dedicated studies with ITER-like wall**, as shown by the recent TRANSP applications at JET,
  1. Comparative core confinement analysis in ILW and CW
  2. Effects of heating power on confinement
  3. ICRH deposition to avoid W accumulation
- There are further TRANSP applications not addressed in this talk

  e.g. 1. input data preparation for gyrokinetic code and MHD stability codes, 2. data consistency tests, 3. current diffusion simulations, 4. predictive transport modelling with theory-base transport models, and etc.
- **JET DT campaign is planned in 2017, so the role of TRANSP will be even more important!**
  1. Investigation on neutron deficit
  2. Reprocessing the TRANSP runs in 1997 DT campaign
  3. **Interpretative simulations of 2017 DT campaign**
- hyun.kim@ccfe.ac.uk

NBI power deposition profile



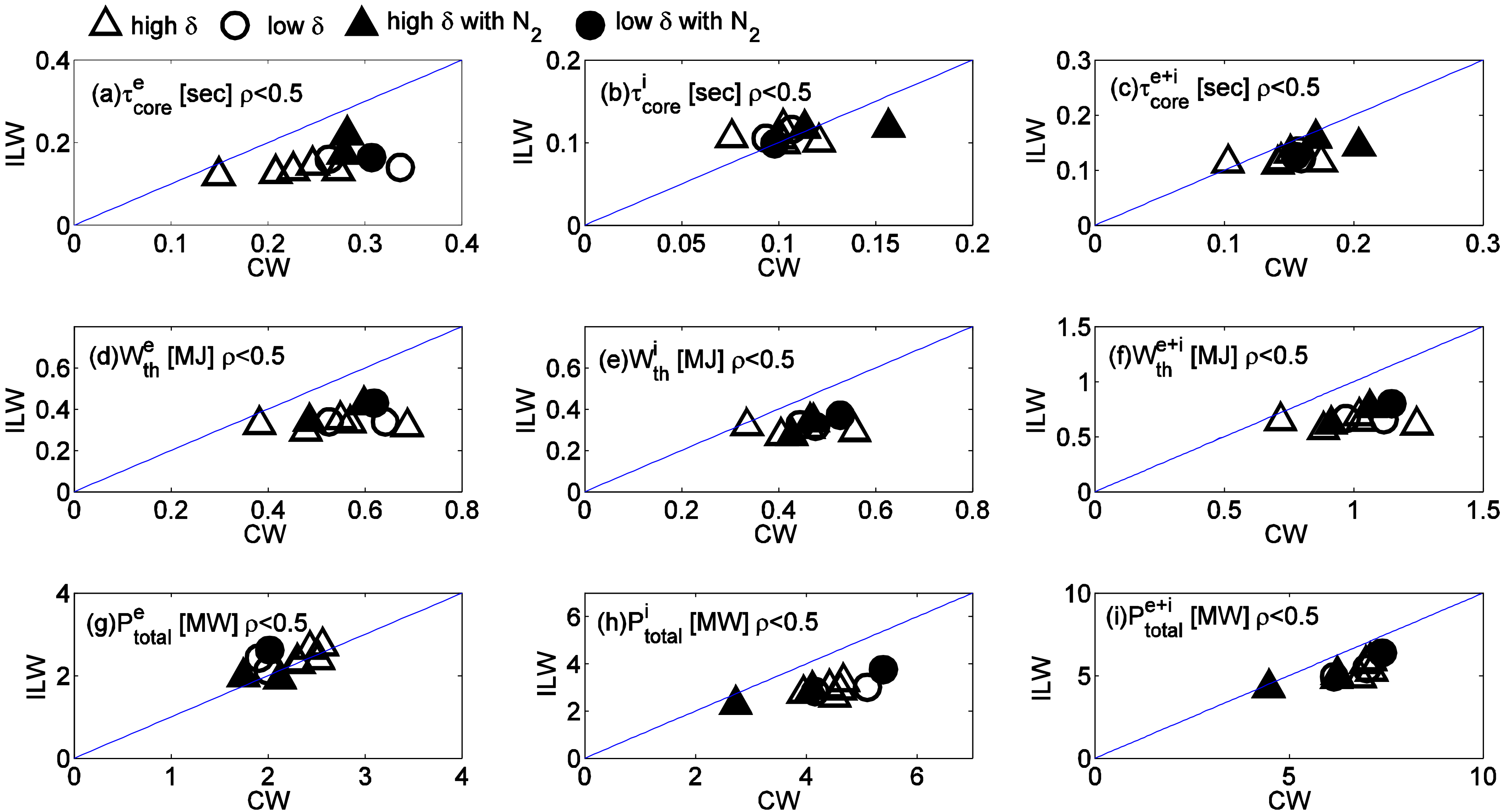


JET-ILW discharges have, compared to CW counterparts in the database,

- Smaller core P^{tot}_{NBI} due to the higher edge deposition resulting from higher $n_{e,ped}$
- **Smaller difference between core P^{e}_{NBI} and core P^{i}_{NBI}**

  i.e. Higher core P^{e}_{NBI} and lower core P^{i}_{NBI} than JET-CW

Core energy confinement time (= W_{th}/P_{total})



- Total core energy confinement time in JET-ILW is similar or slightly reduced with JET-CW.