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## ABSTRACT.

Impurity behaviour in JET internal transport barrier discharges with reversed shear has been investigated. Metallic impurities accumulate in cases with too strong peaking of the main ion density profile. The accumulation is due to inwardly directed drift velocities inside the ITB radius. The strength of the impurity peaking increases with the impurity charge and is low for the low-Z elements C and Ne. Transport calculations show that the observed behaviour is consistent with dominant neoclassical impurity transport inside the ITB. MHD events in the core flatten the radial profile of the metallic impurity.

## 1. INTRODUCTION

Impurity accumulation occurs when the radial density profile of an impurity evolves a stronger peaking than the profile of the main plasma ion. This is usually observed in the central part of the plasma inside a normalised radius  $r/a < 0.5$ . The high impurity concentration on axis leaves the main plasma impurity content nearly unchanged due to the small affected volume and vice versa the same impurity production at the vessel walls might produce largely different central impurity concentrations. The impurity sources are located in the edge region of the plasma and the equilibrium radial gradient of the impurity density  $n_I$  at radius  $r$  depends only on the ratio of the radial drift velocity  $v$  and the diffusion coefficient  $D$  at this radius:  $(1/n_I)(dn_I/dr) = (v/D)$ . The diffusion coefficient has an anomalous and a neoclassical contribution  $D = D_{an} + D_{neo}$  and the convective transport, which is a necessary condition for impurity accumulation, is assumed to be purely neoclassical with  $v = v_{neo}$ . In a simplified treatment, only collisions of impurity and main ion  $D$  are considered and  $v_{neo}$  is for equal temperatures of both ion species  $T_D = T_I$ .

$$v_{neo} = D_{neo} \frac{Z_I}{Z_D} \left( \frac{1}{n_D} \frac{dn_D}{dr} - H \frac{1}{T_D} \frac{dT_D}{dr} \right) \quad (1)$$

The density gradient term drives an inwardly directed convective flux, while the temperature gradient yields an outwardly directed drift velocity, where the factor  $H$  has typical values  $H = 0.2 - 0.5$ . Thus, the normalised impurity density gradient is

$$\frac{1}{n_I} \frac{dn_I}{dr} = \frac{1}{n_D} \frac{dn_D}{dr} \frac{Z_I}{Z_D} \frac{D_{neo}}{D_{neo} + D_{an}} (1 - H\eta_D) \quad (2)$$

where  $\eta_D$  denotes the ratio of the normalised temperature gradient to the normalised main ion gradient. Eq.2 shows, that impurity accumulation can only occur, if  $D_{an}$  is not too large compared to  $D_{neo}$  for plasmas with peaked ion density gradient at small  $\eta_D$ . In such a situation elements with higher charge number  $Z$  will accumulate stronger than low- $Z$  elements.  $D_{an} < D_{neo}$  is often observed in the central part of the plasma [1], however, sawtooth crashes periodically cause a flattening of the impurity profile. Plasmas with internal transport barrier (ITB) are thus of special concern with respect to impurity accumulation, since possible neoclassical inward convection is not suppressed

by the low anomalous diffusive transport or by the sawtooth instability [2-6]. In low density ITB plasmas, the neoclassical inward drifts for the impurities can be provoked by the central fueling from the NBI heating, which creates peaked deuterium profiles for low Dan. In the following, impurity behaviour for ITB plasmas with reversed shear in JET will be described. Results on He transport investigations are given in [7], Ne transport in plasmas with and without reversed shear is compared in [8]. For monotonic shear ITB plasmas, complementary information on C and Ni can be found in [9] and on Ar in [10].

## 2. DATA ANALYSIS

Two soft X-ray (SXR) cameras with 250 $\mu$ m thick Be filters (detection efficiency >0.1 for photons in the energy range 2.3-15keV) served as the main diagnostic tool. The SXR cameras cover the plasma cross section with 35 vertical and 17 horizontal lines-of-sight and time averaged data with a time resolution of 1ms were used. The measured radiation fluxes along the line-of-sights were unfolded by assuming constant emissivity  $\epsilon_{sxr}$  on flux surfaces. The SXR emission was analysed to gain information about the impurity composition. The dependence of  $\epsilon_{sxr}$  on the impurity density  $n_I$  and the electron density  $n_e$  can be written as

$$\epsilon_{sxr} = \frac{n_e^2}{Z_D} L_D^{sxr} + n_e \sum_I n_I \left( L_I^{sxr} - \frac{Z_I}{Z_D} L_D^{sxr} \right) \quad (3)$$

The first term gives the radiation for zero dilution while the second term contains the radiation caused by each impurity I including the dilution of the main ion D. For the plasma core, the mean charge Z and the total soft X-ray power coefficients  $L^{sxr}$  (including the detection efficiency of the setup) of each element can be calculated using corona ionisation equilibrium and thus are mainly functions of the electron temperature  $T_e$ . The relevant atomic data were taken from the ADAS database [11], while the detection efficiency was calculated from the tabulated coefficients of Henke [12]. Figure 1 gives an example for the unfolding procedure for Pulse No: 53521. The high level of  $\epsilon_{sxr}$  in the plasma centre can not be explained by low-Z impurities (Be-Ne) which mainly cause bremsstrahlung in the core. The strong emission must be due to the line radiation of metallic elements and Ni is assumed to be the predominant metallic impurity. The radiation from low-Z elements is calculated by taking the impurity densities of C and Ne (for discharges with Ne puffing) from CXRS and by increasing the C emission by 50% as an estimate for the contribution from other low-Z elements Be, N and F. Ni densities were calculated from the remaining difference  $\Delta\epsilon_{sxr} = \epsilon_{sxr} - \epsilon_{sxr;lowZ}$ .

## 3. HIGH PERFORMANCE DISCHARGES

The analysed high performance discharges had a current profile with strongly reversed shear and a central 'current hole' at the start time of the main heating power phase [13]. Figure 2 gives the evolution of C, Ne and Ni densities in Pulse No: 51976 [14] with a high performance ITB of 1s duration. Before the formation of the strong barrier, at  $t=45.8$  s, Ti has an almost constant gradient length for the

depicted radial range, and the impurity density profile is hollow or mildly peaked. A strong barrier in  $T_i$ ,  $T_e$  and  $n_e$  forms at  $t$   $T_i$  gradient shifts towards larger radii for the following time slices due to an expansion of the barrier width and due to the increasing Shavranov shift. For the later times, the radial region of the  $T_i$  barrier location is depicted by a vertical light grey bar. Inside that region  $T_i$  becomes  $n_e$  progressively flat. Here,  $n_e$  and the impurity densities develop the strongest gradient and the radial region with increased density gradients is given by a darker grey bar. The impurity peaking increases with the impurity charge  $Z$  and is weakest for C and very strong for  $N_i$ . At  $t = 6.9s$ , the dominant  $Z_{eff}$  contribution is due to Ni and reaches a value of  $\Delta Z_{eff} = 1.5$  for  $Z_{eff} = 3.5$  causing a dilution of  $\Delta n_e / n_e = 6\%$ . Thus, the ni profile has not much reduced peaking compared with  $n_e$ .

The observed impurity accumulation is a pure transport effect due to convective particle flows. The radial transport of C, Ne and Ni has been simulated for Pulse No:51976 with the impurity transport code STRAHL. In Fig.3, various profiles for three time points during the ITB phase  $t = 6.2, 6.6,$  and  $6.8s$  are shown and compared with measurements.  $n_e$  (Fig.3(a)),  $T_i$  (Fig.3(b)), and  $T_e$  profiles were taken from the experiment.  $n_D$  follows from the impurity ion distributions and quasi neutrality. The classical, Pfirsch-Schlüter and banana-plateau contribution of the transport parameters were numerically evaluated by solving the coupled equations for the parallel velocities of a four component plasma (D,C,Ne,Ni) with NEOART [15-17]. using the fractional abundances of the different ion stages from the impurity transport code.  $D_{an}$ , which is assumed to be equal for all species, is set ad hoc. Close to the axis ( $r \leq 0.2m$ ) the poloidal field becomes very low, the orbits of trapped particles are very large and standard neoclassical theory may not be applied. Here, the measured profiles are flat and a high value of  $D_{an} = 1m^2/s$  is used to describe this situation. For  $r > 0.2m$ , the anomalous diffusion coefficient is chosen to be below  $D_{neo}$  with  $D_{an} = 0.02m^2/s$  for radii inside the radius of the ITB and to increase from the ITB radius towards the edge. The radial evolution of the ITB radius is thus reflected in a broadening of the region with low  $D_{an}$  (see Fig.3(c)).

The simulation starts at  $t = 5.8s$  using radially constant impurity density with  $n_C = 5 \times 10^{17} m^{-3}$ ,  $n_{Ne} = 7 \times 10^{16} m^{-3}$ , and  $n_{Ni} = 1.5 \times 10^{16} m^{-3}$ . During the ITB phase, the neoclassical transport becomes increasingly convective with inwardly directed (negative) drift velocities in the radial region with weaker temperature gradient and pronounced electron peaking while in the region with strong temperature gradient  $v_{neo}$  is close to zero or outwardly directed in the case of Ni. For Ne and Ni, the according diffusion coefficients  $D_{neo}$  are shown in Fig.3(c) while the ratio  $v_{neo} / (D_{neo} + D_{an})$  is depicted in Fig.3(d). The plot of  $v_{neo} / D$  demonstrates, that transport is more convective for Ni, the element with higher  $Z$  compared to Ne and stronger peaking is expected for Ni. This can be seen in Fig.3(e) and Fig.3(f), where the simulated density profile of Ni evolves a much stronger peaking than Ne. While the measured Ne densities are well described by the model, there is still not enough peaking of Ni in the simulation. The central density at  $t = 6.8s$  is  $n_{Ni} = 8 \times 10^{16} m^{-3}$ , i.e. 27% below the measured value. An artificial increase of the neoclassical drift of Ni by a constant factor of 1.4 yields a perfect match of measured and simulated profile evolution. When choosing the value of  $D_{an}$  inside the ITB a factor of 5 higher, i.e.  $D_{an} = 0.1 m^2/s$ , the central Ni density rises

only to  $n_{\text{Ni}} = 6.4 \times 10^{16} \text{ m}^{-3}$  at  $t = 6.8\text{s}$  and an increase of the neoclassical drift by a factor of 1.8 is needed to fit the observed Ni peaking. Due to the uncertainties in the choice of  $D_{\text{an}}$  and in the measured gradients, it is difficult to quantify the goodness of the neoclassical transport description, however, there is certainly qualitative agreement between measured impurity evolution and the simulation, which assumes a dominating neoclassical transport.

#### 4. LONG ITB DISCHARGES

In Fig.4 two reversed shear discharges (Pulse No: 53521 in black, Pulse No: 53697 in grey) with long ITB phases are compared [18,19]. The toroidal field is  $B_{\text{T}} = 3.4 \text{ T}$ . During the shown time interval, the plasma current has a constant value of  $I_{\text{P}} = 2 \text{ MA}$  for Pulse No: 53521 and  $I_{\text{P}} = 1.8 \text{ MA}$  for Pulse No: 53697 and in both discharges the plasma is heated with  $\approx 15\text{MW}$  of NBI and 3-5 MW of ICRH. throughout the discharges. The total neutron rate is in the range  $1.0\text{-}1.4 \times 10^{16} \text{ s}^{-1}$ . In Pulse No: 53521, the ITB in the ion channel is sustained for 27 confinement times.

The temperatures  $T_{\text{i}}$  and  $T_{\text{e}}$  and the Ni density  $n_{\text{Ni}}$  close to the plasma centre are shown. Two horizontal interferometer channels (central, and half radius) tion of the electron density profile.  $T_{\text{i}}$  and  $T_{\text{e}}$  are similar in both discharges stronger gradients in Pulse No: 53521. The electron density, however, shows a pronounced and evolves a stronger peaking in Pulse No:53521, where  $n_{\text{Ni}}$  becomes extremely peaked. The correlation between density peaking and Ni peaking can be understood in transport as discussed in the previous section. For Pulse No: 53521 at  $t \approx 10.7\text{s}$ , the accumulated Ni is the dominant  $Z_{\text{eff}}$  contributor with central  $Z_{\text{eff}} = 7$  and the dilution due to Ni is  $\Delta N_{\text{e}}/n_{\text{e}} = 20\%$ . The central SXR emission  $\epsilon_{\text{SXR}} = 0.6 \times 10^5 \text{ Wm}^{-3}$  (see Fig.1) corresponds to a calculated local radiation loss of  $\epsilon = 1.4 \times 10^5 \text{ Wm}^{-3}$ , which is about the central heating power density into the electrons. Thus, the loss of confinement at  $t = 11.1\text{s}$ , which is very strong in the Ni channel, is probably a radiative ollapse. The ITB reforms after this collapse [7], however, there is no information about the further evolution of Ni since SXR data collection stopped. MHD events, which lead to a sawtooth like signature of  $T_{\text{e}}$ , correlate with a decrease of the Ni peaking, which might become very strong as for Pulse No: 53697 at  $t = 10.1 \text{ s}$ , where the central radiation is too low to explain a radiative collapse. Here, a  $n = 1$ -mode is observed, followed by a decrease of central plasma rotation by  $\approx 30\%$  central electron density is lost and the Ni profile becomes flat. Further investigation is needed for these phenomena. Carbon density profiles from CXRS peak only slightly stronger as  $n_{\text{e}}$  and the concentration of C stays almost constant resembling the same Z dependence of impurity transport as in Pulse No: 51976.

#### CONCLUSION

In ITB discharges with reversed shear, Ni accumulates in cases with too strong peaking of the main ion density profile. The accumulation is due to an inward particle pinch inside the ITB. The peaking increases with the impurity charge and is low for the low-Z elements C and Ne. In the very centre, with low  $B_{\text{p}}$ , profiles of  $T_{\text{i}}$ ,  $T_{\text{e}}$ ,  $n_{\text{e}}$  and  $n_{\text{Ni}}$  are flat. The dependence of impurity peaking on impurity



charge is in agreement with dominant neoclassical impurity transport inside the ITB. Using this assumption, transport modeling yields a good description of the Ne evolution, while the calculated Ni peaking  $n_{\text{center}}/n_{\text{edge}}$  is  $\approx 30\%$  too low.

### ACKNOWLEDGEMENT:

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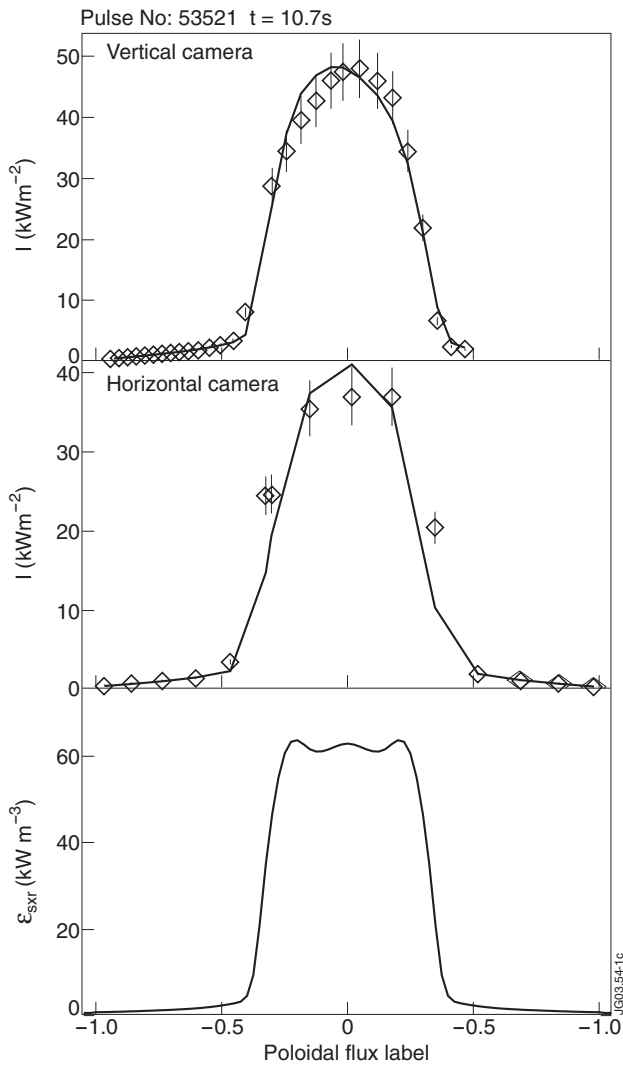


Figure 1: Measured radiation fluxes for two SXR cameras (a,b) and fitted local emissivity(c) for Pulse No: 53521 at  $t=10.7s$ . Calculated radiation fluxes from the fit are shown as a solid line (a,b)

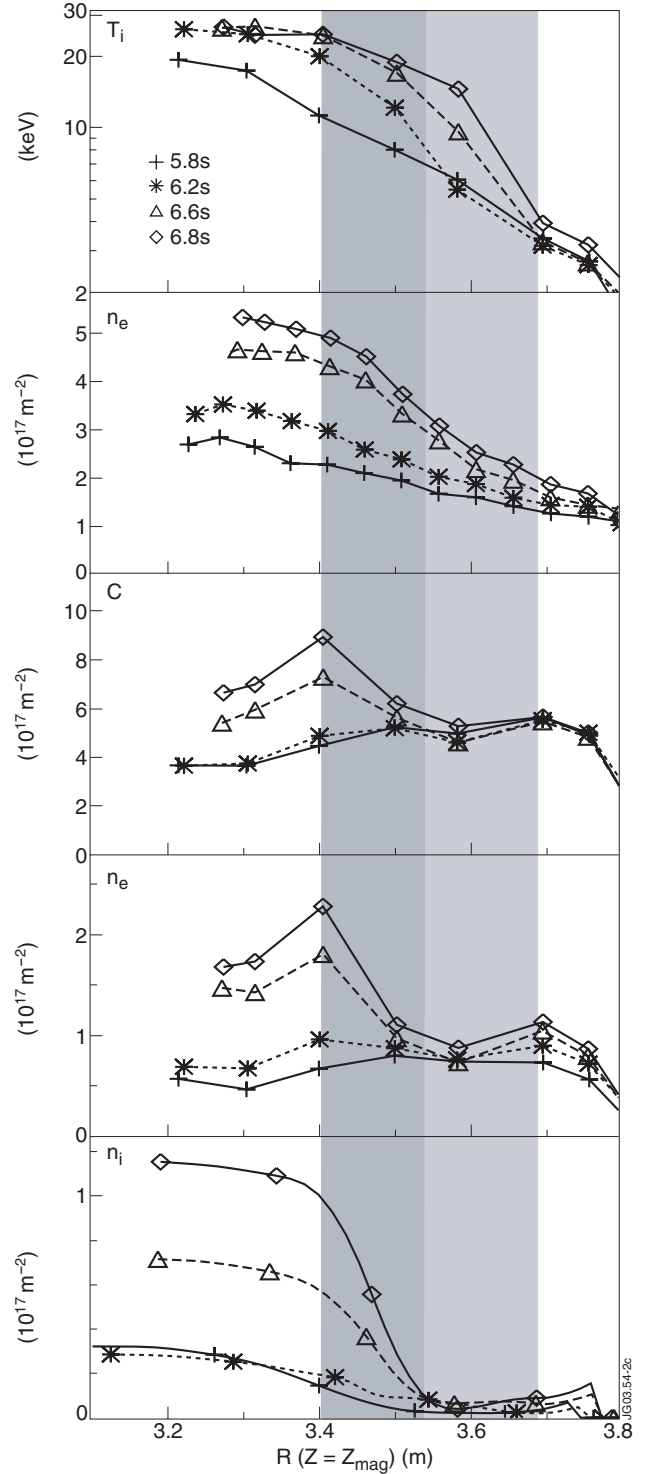


Figure 2: Evolution of the radial profiles of  $T_i$ ,  $n_e$ ,  $n_c$ ,  $n_{Ne}$  and  $n_{Ni}$  for the Pulse No: 51976.

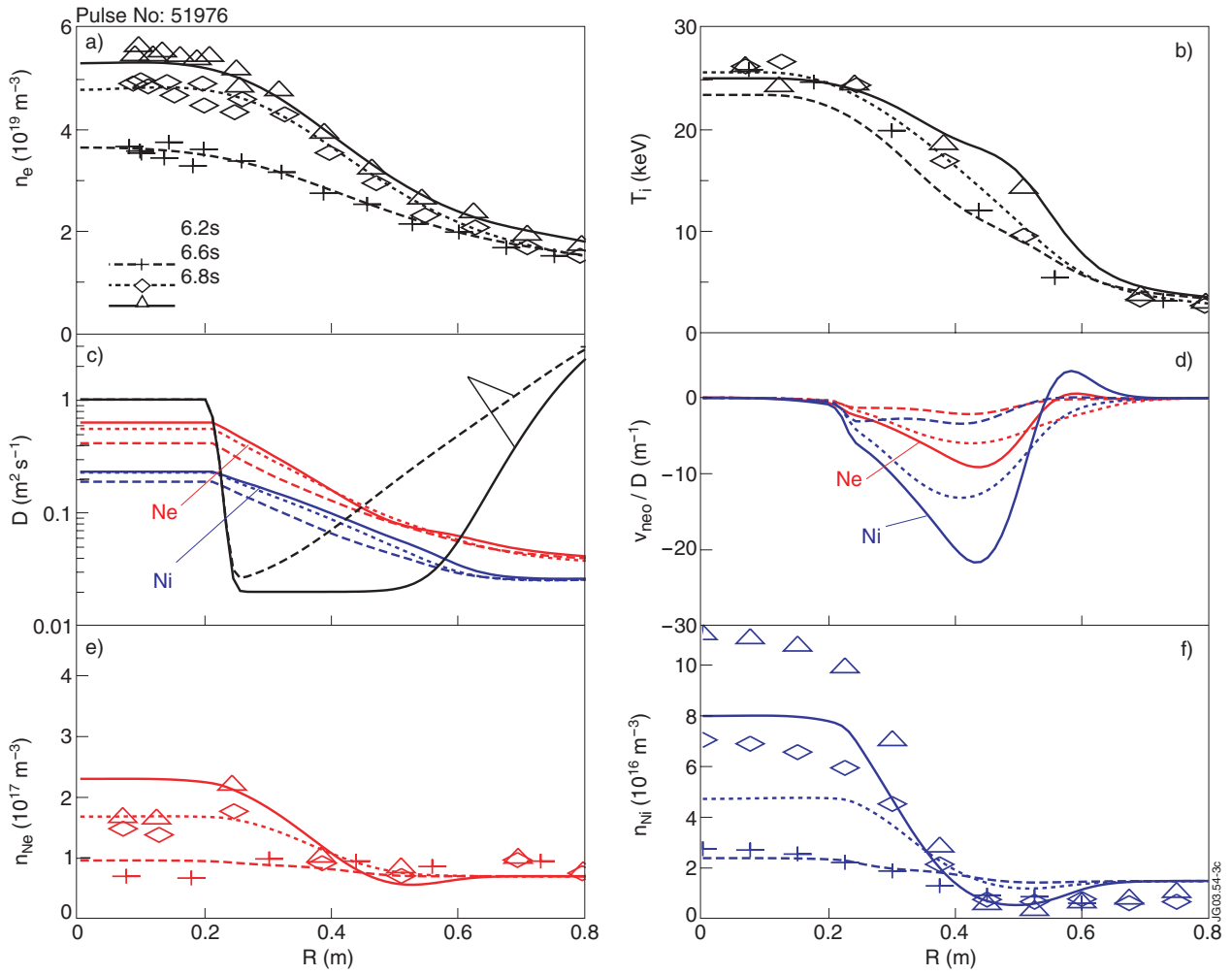


Figure 3: Three radial profiles of  $n_e$ ,  $T_i$ ,  $D_{an}$ ,  $D_{neo}$ ,  $v_{neo} = D$ ,  $n_{Ne}$  and  $n_{Ni}$  from the impurity transport simulation of Pulse No: 51976. The overlaid symbols give experimentally measured profiles.

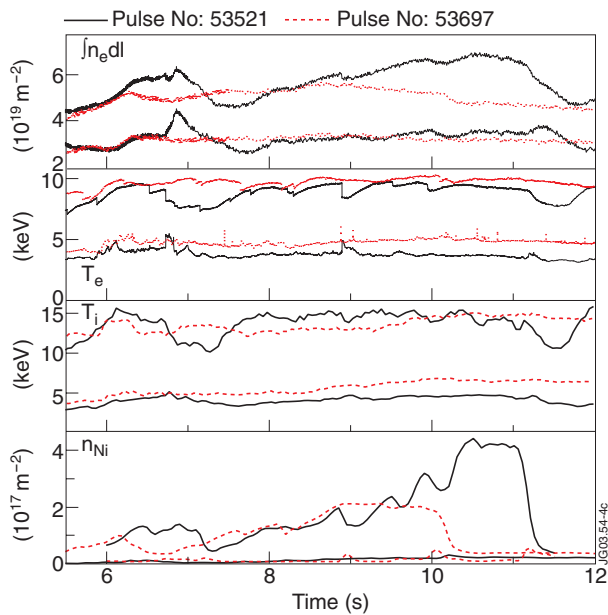


Figure 4: Time traces for  $\int n_e dl$ ,  $T_e$ ,  $T_i$  and  $n_{Ni}$  for two reversed shear discharges (Pulse No: 53521 in black, Pulse No: 53697 in grey) with long ITB phases are compared.