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# Evolution of the bootstrap current profile during the type I ELM cycle of JET-ILW H-mode plasmas

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*\*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

**1. Introduction** The understanding of the physical processes governing the behaviour of the edge pedestal structure is crucial in order to predict the plasma performance in future devices such as ITER. A well-known theory which explains the stability conditions in the pedestal is the peeling-ballooning (P-B) model [1]. In this model the bootstrap current, which can be efficiently driven by the steep pressure gradient at the plasma edge, plays a crucial role: it can stabilise ballooning modes through reduced magnetic shear or drive peeling modes in the edge.

A recent study [2] has shown that the pedestal stability in JET with the new Be/W ITER-like wall (JET-ILW) is consistent with the P-B model in discharges with low D<sub>2</sub> gas rates. However, high D<sub>2</sub> gas rates are required in JET-ILW to increase the ELM frequency in order to achieve core W control over longer time scales [3]. At high gas rate and high beta, pre-ELM pedestals have been shown to be stable to P-B modes, but ELMs still occur experimentally [2].

In order to try to understand the origin of this discrepancy, in this contribution we study the evolution of the calculated edge bootstrap current profile ( $j_{BS}$ ) during the type I ELM cycle. We consider the same dataset of [2], [4], namely power and gas scans, which allow decoupling of effects of  $\beta$  and D<sub>2</sub> gas injection on  $\nabla p_e$ , thus on  $j_{BS}$ .

**2. Bootstrap current calculation** The  $j_{BS}$  is computed with the local neoclassical transport code NEO [5, 6], which solves the drift-kinetic equation with a full linearized Fokker-Planck collision operator including all inter-species collisions. This approach provides a more accurate estimation of  $j_{BS}$  than using the Sauter-formula [7], [8], especially at high collisionality ( $\nu^*$ ), where the Sauter-formula overestimates  $j_{BS}$  (by up to 100 %) compared to NEO [2].

The input for NEO are the plasma equilibrium (from EFIT), the electron ( $T_e$ ) and ion ( $T_i$ ) temperatures and the ion density, which are evaluated from fitted electron kinetic profiles from Thomson scattering (HRTS) measurements assuming equal electron and ion temperatures, constant line averaged  $Z_{eff}$  and Be as the intrinsic impurity. The HRTS profiles collected from a steady time window of the discharge are ELM-synchronised. The ELM cycle is divided into 20 % long intervals, as shown in figure 1. As 100 % corresponds to the ELM crash and 0 %

corresponds to the ELM crash of the preceding ELM cycle, the 0-20 % interval is excluded from the analysis as the profiles in this interval are dominated by the ELM crash. Composite profiles are taken from each 20 % bin and a modified tanh function [9] is fitted to both the electron temperature ( $T_e$ ) and density ( $n_e$ ) profiles. Examples of fitted  $n_e$  and  $T_e$  profiles are shown on figure 2c and 2d, respectively, for JET-ILW discharge #84797 (1.4 MA/1.7 T,  $P_{IN} \approx 4$  MW, low  $\delta$ ,  $\Gamma_D = 2.8 \cdot 10^{21}$  e/s). The time evolution of the  $j_{BS}$  profile through the ELM cycle for this discharge is shown in figure 2a, showing a similar time evolution to  $\nabla p_e$ , as expected.

### 3. Impact of $n_e$ , $T_e$ , $Z_{eff}$ uncertainties on $j_{BS}$ profile

The uncertainty of the  $j_{BS}$  profiles on the input parameters  $n_e$ ,  $T_e$ ,  $Z_{eff}$  has been investigated with NEO. For this purpose, “modulated”  $n_e$  and  $T_e$  profiles are created where each parameter (width,

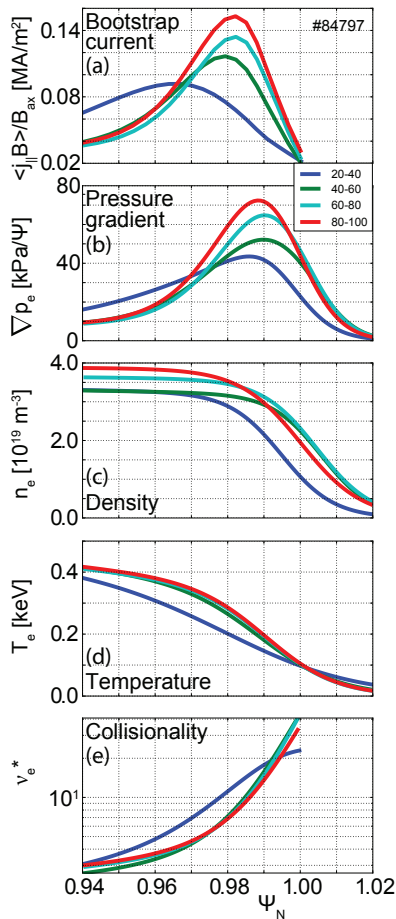


Figure 2: Time evolution of (a)  $j_{BS}$ ; (b)  $\nabla p_e$ ; (c)  $n_e$ ; (d)  $T_e$ ; (e)  $\nu_e^*$  profiles in #84797.

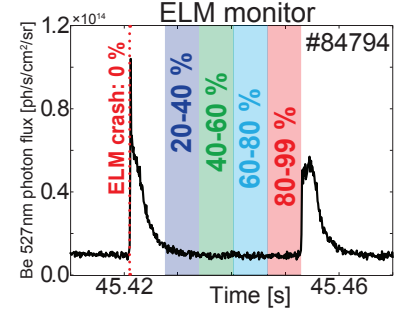


Figure 1: ELM cycle is normalized to a relative time scale (from 0 % to 100 %) and divided into 20 % long intervals.

height, position and slope) is substituted with a Gaussian random number. The mean and variance of the Gaussian random numbers are given by the mean and variance of the parameter estimates of the mtanh fit. The  $j_{BS}$  profile is then calculated several times ( $\sim 50$ ) using different “modulated” profiles. The line averaged  $Z_{eff}$  is varied between the experimental uncertainties of  $\pm 10$  %. The result of the sensitivity analysis is shown in figure 3, where all three parameters ( $n_e$ ,  $T_e$ ,  $Z_{eff}$ ) are modulated within their uncertainties. The percentile of the resulting  $j_{BS}$  profiles gives the  $1\sigma$  and  $2\sigma$  error bars, which are visible in figure 3 in red and blue, respectively. Tests where only one input parameter was “modulated”, have shown that the uncertainty in  $j_{BS}$  is dominated by the uncertainty of the  $T_e$  profiles. This is likely to be due to the higher uncertainty of the  $T_e$  profiles in this dataset. In the following figures the  $1\sigma$  error bars will be used.

### 4. Inter-ELM $j_{BS}$ evolution

The time evolution of the  $j_{BS}$  profiles (see figure 2a) is evaluated for the discharges in the dataset: 1.4 MA/1.7 T, low triangularity,  $P_{sep} = 4 \rightarrow 14$  MW, gas injection rate:  $2.8 \rightarrow 18 \cdot 10^{21}$  e/s,  $\beta_N = 1.2 \rightarrow 2.8$ ,  $f_{ELM} = 12 \rightarrow 120$  Hz. The pedestal pressure varies between  $p_{e,PED} = 1.3 \rightarrow 3$  kPa in the dataset. At a given  $P_{sep}$ ,  $p_{e,PED}$  is reduced with increasing gas rate. The pedestal collisionality ( $\nu_{e,PED}$ ) is mainly driven by the variation in the pedestal top temperature [2] and varies between  $\nu_{e,PED} = 0.3 \rightarrow 4.5$ .

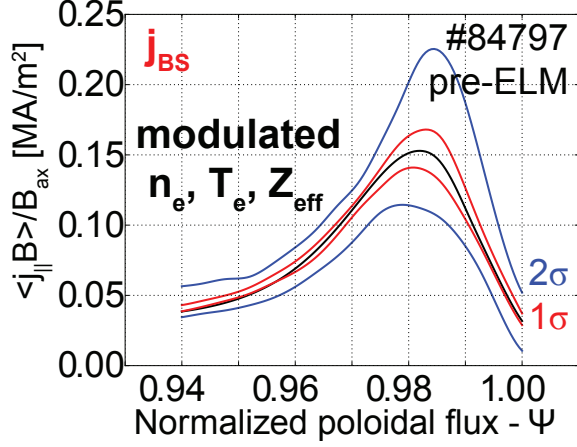


Figure 3:  $1\sigma$  and  $2\sigma$  error bars of the  $j_{BS}$  profile as a result of the sensitivity analysis to  $n_e$ ,  $T_e$  and  $Z_{eff}$ .

It is interesting to compare the inter-ELM  $j_{BS}$  evolution to that of the separate drives of  $\nabla p_e$ , namely the temperature and density gradients, as shown in figure 5, where all values are normalized to the pre-ELM phase. For all shots of the dataset, experimentally we observe that peak  $j_{BS}$ ,  $\nabla p_e$  and  $\nabla T_e$  have always the same time evolution, even if  $\nabla n_e$  may differ in evolution. Figure 5a (low gas) shows a case where  $\nabla n_e$ ,  $\nabla T_e$  and  $\nabla p_e$  evolve similarly. In figure 5b (high gas),  $\nabla n_e$  evolves differently to  $\nabla p_e$  and  $\nabla T_e$ . The latter behaviour is typical regarding the whole dataset, which is likely to be due to that the  $\nabla T_e$  term in  $\nabla p_e$  is higher than the  $\nabla n_e$  term.

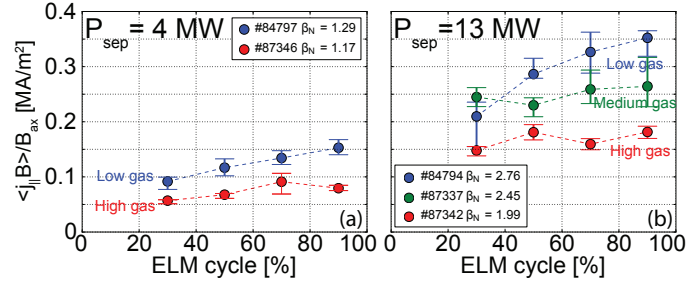


Figure 4:  $j_{BS}$  evolution during the ELM cycle for discharges at low and high gas rates at constant  $P_{sep}$ : (a) lowest power and (b) highest power of the power and gas scans dataset.

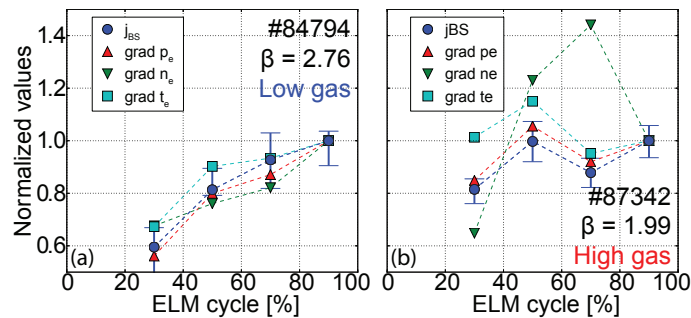


Figure 5: The evolution of peak  $j_{BS}$  and the peak of  $p_e$ ,  $n_e$ ,  $T_e$  gradients at low and high gas at high input power. All values are normalized to the pre-ELM phase.

The evolution of the peak  $j_{BS}$  is shown in figure 4 at constant net power through the separatrix ( $P_{sep}$ ) comparing low vs. high gas rate cases. At low gas injection (where the pre-ELM stability was consistent with the P-B model), the peak  $j_{BS}$  continuously increases during the ELM cycle. At medium and high gas rate (where the pedestals were stable against P-B modes just before the ELM crash) the peak  $j_{BS}$  is roughly constant throughout the ELM cycle. At low power ( $P_{sep} \sim 4$  MW) in figure 4a,  $j_{BS}$  is reduced due to the lower  $T_e$  and thus higher  $v^*$ , but the peak  $j_{BS}$  time evolution at low vs. high gas rate is similar to that at high  $P_{sep}$ .

In this study we have assumed  $j_{BS}$  to evolve in time following the pressure gradient without a delay, that is, ignoring current diffusion in the pedestal region. This assumption can be tested by estimating the resistive time scale for current diffusion in the edge transport barrier:  $\tau_{res} \approx \mu_0 \Delta_{PED}^2 / \eta_{Spitz}$ , where  $\mu_0$  is the vacuum permeability,  $\eta_{Spitz}$  is the Spitzer resistivity and  $\Delta_{PED}$  is the pedestal width of the order of 2 cm.  $\tau_{res}$  is estimated in two cases for low and high  $v^*$  pedestals of the power and gas scan (see table 1). As  $\tau_{ELM} \gg \tau_{res}$ , this simple estimate shows that a significant time delay of the edge current with respect to  $\nabla p_e$  is unlikely. Therefore, it is unlikely that current diffusion in the pedestal could explain the discrepancy with the P-B model reported for high gas, high  $\beta$  discharges in [2].

	$T_{e,PED}$	$\eta_{Spitz} @ \max \nabla T_e$	$v_{e^*} @ \max \nabla T_e$	$\tau_{res}$	$\tau_{ELM}$
Low gas (#84794)	0.9 keV	$2.5 \cdot 10^{-7} \Omega m$	1	$\approx 2$ ms	$\approx 28$ ms
High gas (#87342)	0.6 keV	$3.5 \cdot 10^{-7} \Omega m$	4	$\approx 1.5$ ms	$\approx 8$ ms

Table 1: Estimated resistive timescale of two discharges at the highest power in the power scan at low (low  $v^*$ ) and high gas (high  $v^*$ ).

**5. Conclusions and future work** The present analysis has shown that in JET-ILW type I ELMy H-modes at low gas rate the peak  $j_{BS}$  continuously increases during the ELM cycle. In contrast, with increasing gas rate the peak  $j_{BS}$  tends to saturate during the ELM cycle, in agreement with previous analysis in JET-C [10]. The short resistive time scales for current diffusion in the pedestal indicate that the delay of edge current with respect to the pressure gradient is probably very small, thus it could not explain the ELM trigger. The time evolution of  $j_{BS}$  closely follows that of  $\nabla p_e$  and  $\nabla T_e$ , even if  $\nabla n_e$  may differ in evolution. The uncertainty in the  $j_{BS}$  profiles with respect to  $n_e$ ,  $T_e$  and  $Z_{eff}$  is dominated by the uncertainty in  $T_e$  in this dataset. Future work will include, modelling of the Ohmic current contribution to the total edge current and its comparison with the edge current derived by EFIT reconstructions with kinetic constraints [11]. The impact of  $j_{BS}$  uncertainty on edge stability analysis will be also investigated.

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## References

- [1] P.B. Snyder et al., Physics of Plasmas **9**, 2037 (2002)
- [2] C.F. Maggi et al., Nuclear Fusion **55**, 113031 (2015)
- [3] M.N.A. Beurskens et al., Plasma Physics and Controlled Fusion **55**, 124043 (2013)
- [4] C.D. Challis et al., Nuclear Fusion **55**, 053031 (2015)
- [5] E. Belli et al., Plasma Physics and Controlled Fusion **50**, 095010 (2008)
- [6] E. Belli et al., Plasma Physics and Controlled Fusion **54**, 015015 (2012)
- [7] O. Sauter et al., Physics of Plasmas **6**, 2834 (1999)
- [8] O. Sauter et al., Physics of Plasmas **9**, 5140 (2002)
- [9] R. Scannell et al., Review of Scientific Instruments **82**, 053501 (2011)
- [10] S. Saarelma et al., Nuclear Fusion **53**, 123012 (2013)
- [11] L.C. Appel et al., 33rd EPS Conference on Plasma Physics **30I**, P2.184 (2006)