Princeton Plasma Physics Laboratory

PPPL-5190

Alpha heating in JET plasmas with sawteeth

R.V. Budny and JET contributors
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

June 2015

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Alpha heating in JET plasmas with sawteeth

R.V. Budny[a] and JET contributors[b]

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

Alpha heating is essential for practical energy production from DT fusion reactions. Experiments to detect alpha heating were performed in TFTR (1994) [1] and in JET (1997) [2]. Measurements of alpha heating were difficult since the alpha heating power p_α was small relative to the external heating $p_{\rm ext}$, and since the experiments were not accurately reproducible. It was difficult to realize comparable DD or TT discharges for comparison. One cause of irreproducibility in the JET discharges was the presence of sawteeth.

This paper studies effects of sawteeth in the discharges featured in [2]. They had $I_{\rm p}$=3.8MA and $B_{\rm tor}$=3.6T, and density 35% of the Greenwald empirical limit. The mix of D and T was varied from discharge to discharge by changing the D and T in the neutral beam injection while maintaining their total powers approximately constant ($P_{\rm NB} \simeq$ 10.3MW). Several of them had global fusion power to heating power ratio $Q_{\rm DT}$=0.7, and core values (defined in [3]) of 1.2. These are near the highest values seen in JET. The fraction of T to total beam power $f_{\rm T}$=$P_{\rm T-NB}$/($P_{\rm NB}$) is an important metric for the scans. Here, one with D-only, three with D and T, and two with T-only NB [2] are used. Summary values are in Table I.

Sawtooth crashes cause rapid drops in the core electron temperature T_e. Minor disruptions also cause rapid crashes, but sawtooth crashes have simultaneous rapid increases in T_e outside the mixing radius (past the radius where the safety factor is unity). Crash times were determined from core electron cyclotron measurements of T$_e$. Examples are shown in Fig. 1-a). The pattern of frequent small sawteeth crashes petering off after the start of NB is typically seen in JET discharges. Even large sawtooth crashes within the first second of NB did not appear to have major effects on the later performance. However, larger crashes occurring later in the phase of stored energy ramp-up did have significant impacts, discussed below. Sawtooth crashes were generally seen in TFTR supershots continuing briefly into the NB phase, but they were usually suppressed later during the NB phase. Effects of the sawtooth crashes in the JET scan can be seen on the total neutron emission rate $S_{\rm n}$ and on the central neutron emission rate $s_{\rm n}(0)$ observed in fits to neutron camera measurements in Fig. 1-b).

The electron density profiles $n_{\rm e}$ were sometimes hollow, as often seen during the JET DT campaign The general trend was for the $n_{\rm e}$ shape to very from peaked for H to flatish for D to increasing peakedness in DT and T H-mode plasmas [4]. For this reason, and also since the heating directly effects the stored energy, it is insightful to focus on the electron and ion energy densities $w_{\rm e}$ and $w_{\rm i}$.

At least in the core, $w_{\rm e}$ and $n_{\rm e}$ increased approximately linearly in time from the start of NB for at least 1.6s. Plots of $w_{\rm e}$ volume-averaged from the magnetic axis to x($\equiv$ square-root of the normalized toroidal flux) = 0.2 in Fig. 1-c) show w_e increasing with approximately the same rate except for abrupt decreases at sawtooth crashes. They do not show a clear trend in $s_n(0)$ or f_T suggesting that p_α is not playing a significant role, perhaps due to systematic changes in confinement or energy loss rates compensating for increased p_α. The values for w_i shown in Fig. 1-d) do show a trend of increasing f_T suggesting that an isotopic effect might be playing a role if 43011 is excluded . This discharge had the most hollow n_e and recycling rates 50% higher than the others. The n_e pedestal was the lowest and the T_i and T_e pedestals the highest in the scan. This discharge was pivotal for the argument against isotopic mass effects in [2].

The T_e profiles also are similar across the scan at the same time, and do not exhibit consistent trends in f_T or $s_n(0)$ up to the times of the first significant sawtooth crash as shown in Figs. 2-a). At later times sawtooth crashes break the tight clustering of rates and the discharges that have not crashed continue to increase at the same growth rates. By 14s a clear separation of T_e and T_i profiles appear with the high $s_n(0)$ shots, still before sawtooth crashes, having the highest T_e and T_i. Profiles of T_i shown in Figs. 2-b) and Figs. 2-d) show greater separation. Central values of T_e shown in [2] just before the last sawtooth crashes did have clear separation with S_n. This separation of T_e can be attributed to the sawtooth crashes and ion-electron coupling p_{ie}. Increased sawtooth period with increasing f_T has been reported [5].

The discharges were modeled using the TRANSP code to study heating and transport. The modeling achieves approximate agreement with S_n and $s_n(0)$, as well as with the EFIT diamagnetic energy indicating that the modeling is approximately accurate. The largest discrepancy between the simulated and measured $s_n(0)$ differed by at most 12% at the peak, indicating that p_α is credible. The sawtooth crashes are modeled assuming Kadomtsev helical mixing of current and fast ions at the observed sawtooth crash times. Sawteeth crashes have been observed to mix fast beam and alpha ions [6]. The core volume-averaged p_α, fast alpha density n_α and pressure β_α also increase approximately linearly in time, except for sharp breaks at sawtooth crashes. At 13.6s the predicted peak core averaged p_α is half the maximum calculated for this scan. In 42856 at 14.1s the peak predicted ratio p_α/p_{ext} is near 0.2.

The electron channel time-integrated the beam fueling and electron heating source rates during the energy ramp-up phase. The rates of increases of the volume-integrated n_e(x) and the volume- and time-integrated NB electron source rates within x are nearly equal. The agreement of rates holds both for the core (x$\simeq$0.2) and larger x, suggesting that the TRANSP beam deposition calculation is accurate and the electron flux is negligible, or that an inward pinch and outward diffusivity transport were canceling each other.

Similarly the volume integrated electron energy $\int_0^1 dV w_e$ increased at a constant rate $\simeq$2MW throughout the ramp-up. TRANSP uses measurements to calculate the heating and loss profiles. The dominant terms for electrons are $p_e \equiv p_{be} + p_\alpha + p_{oh} + p_{ie} - p_{cond_e} - p_{conv_e}$. The radiation emission profile p_{rad} is not available, so TRANSP is used to predict the line, bremsstrahlung, and synchrotron emission. Their total volume-integrated rates scale in time approximately as the measured total emission, but are lower by about a factor of 0.8. The convected and conducted power losses $p_{\mathrm{cond_e}}$ and $p_{\mathrm{conv_e}}$ are TRANSP outputs. To study p_α consider core $\int_0^x dV w_\mathrm{e} \simeq \int_0^x \int_{12}^t dt dV p_\mathrm{e}$ integrated to x=0.2 or 0.3. This is dominated by p_be. During the end of the ramp-up and into the flat-top phases the terms p_oh, p_rad, p_ie, $p_{\mathrm{cond_e}}$, $p_{\mathrm{conv_e}}$, and p_α contribute roughly equally, except for the f_T=0 discharge where p_α is negligible. This makes it is difficult to accurately quantify p_α. The total thermal ion stored energy $\int dV w_\mathrm{i}$ increased at the same rate, also $\simeq$2MW. The dominate terms are: $p_\mathrm{i} \equiv p_\mathrm{bi}$ - p_ie - p_cx -$p_{\mathrm{cond_i}}$ - $p_{\mathrm{conv_i}}$. One large uncertainty is the charge-exchange loss term p_cx which is estimated (from the estimated recycling rate) to be large near the edge. The $p_{\mathrm{cond_i}}$ and $p_{\mathrm{conv_i}}$ terms are large. In the mid-radius region near 13.6s χ_i is around 0.5 m^2/s and χ_e is less.

An important parameter from the modeling is the hydrogenic isotopic mass $< A >$ defined as (n_H+2n_D+3n_T)/(n_H+n_D+n_T). This is calculated from species conservation using the beam neutral ionization rates and the wall recycling and gas fueling rates [7]. The core <A> is dominated by the beam neutral ionization rates. Across the scan $< A > \simeq f_\mathrm{T} + 2$. The time delay δ_t is another important parameter. Values in Table I tend to increase with f_T and $< A >$ as shown in Figs. 3-a). Neither S_n nor p_α are linearly correlated with δ_t as shown in Figs. 3-b). This suggests that increasing core isotopic mass is the cause of longer δ_t, and thus contributing to the higher core T_e and T_i.

In conclusion $< A >$ is strongly correlated with the increase of δ_t, and the delayed crashes allowed T_e and T_i to obtain higher values. At constant time T_i was higher for discharges with higher $< A >$. Thus longer δ_t and p_ie could explain the higher T_e. The computed p_α/p_ext is up to 0.2, but electron power balance in the core shows that multiple terms with uncertainties are comparable to p_α.

Work supported in part by the US DoE contract No. DE-ACO2-76-CHO3073, and carried out within the framework of the EUROfusion Consortium, and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[a] *Princeton University, Princeton, NJ 08543, USA*

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

[1] G.Taylor, J.D.Strachan, R.V.Budny, and D.R.Ernst, Phys. Review Lett. **76** 2722 (1996).

[2] P.R. Thomas, P Andrew, B.Balet, D. Bartlett, J. Bull, B.de Esch, *et al.,* Phys. Review Lett. **80** 5548 (1998)

[3] R.V.Budny, J.G.Cordey, “Core fusion power gain and alpha heating in JET, TFTR, and ITER”, to be submitted

[4] R.V.Budny, D.R. Ernst, T.S.Hahm, D.C.McCune, J.G.Cordey, *et al.,*, Phys of Plasmas, **7** 5038 (2000)

[5] M.F.F. Nave, N.N. Gorelenkov, K.G. McClements, S.J. Allfrey, *et al.,*, Nucl. Fusion **42** 281 (2001)

[6] G McKee, R.Fonck, B.Stratton, R.Bell, R.Budny, C. Bush, B. Grek, *et al.,* Phys. Review Lett. **75** 649 (1995)

[7] R.V.Budny, M.G.Bell, D.K.Mansfield, J.D.Strachan, S.Zweben, *et al.,*, 21st EPS, Montpelier, France (1994)

Discharge	f_T	δ_t [s]	$< A >$ (14.0s)	p_α [10^{-2}MW/m^3]	n_α [$10^{17}/m^3$]
40365	0.0	0.9026	1.99	0.0	0.0
42870	0.27	0.9515	2.24	2.1	0.38
42856	0.52	1.4565	2.55	4.7	1.02
42847	0.88	1.4015	2.49	3.6	0.88
42840	1.00	1.6100	2.77	2.1	0.40
43011	1.00	1.6217	2.91	0.7	0.17

Table 1: f_T, *time delay* δ_t *to 1st significant crash, core (volume-averaged to x=0.2) hydrogenic mass,* p_α *and number of fast alpha ions before the 1st significant crash.*

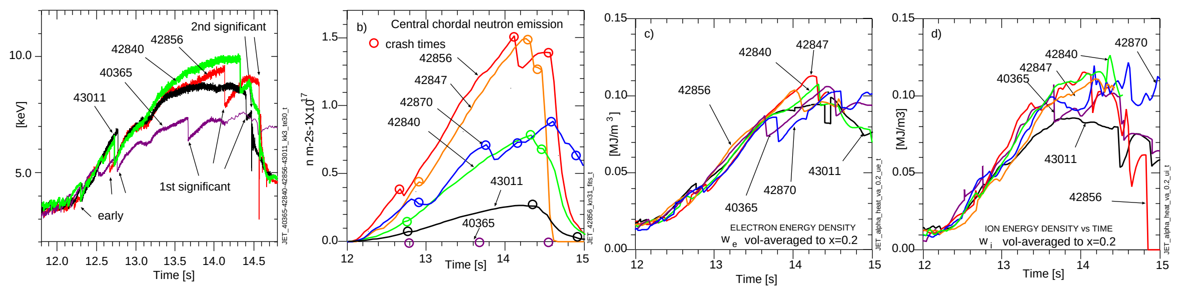

Figure 1: a) Examples of sawtooth / minor disruption crashes in ECE signals of the discharges with f_T = 0.0, 0.52, and 1.0 from the alpha heating scan; significant crashes / minor disruptions seen after 13.6s; b) Sawtooth crash effects in the measured central chordal neutron emission rates; Time evolution of the core volume-averaged c) electron and d) thermal ion energies.

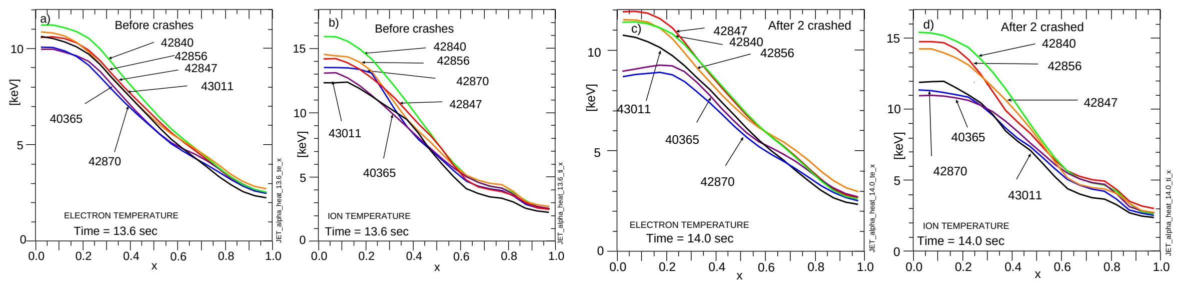

Figure 2: Profiles of T_e and T_i profiles at 13.6s (before the first significant sawtooth crash) and 14.0s (after two of the discharges experienced their first significant sawtooth crash).

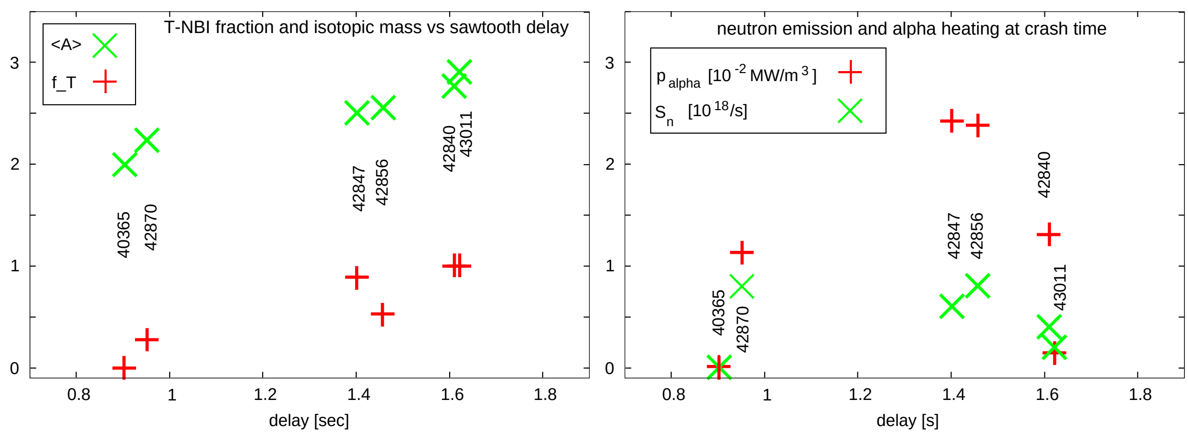

Figure 3: Correlations of delay times to the first significant sawtooth crash with a) core hydrogenic mass and tritium fraction of NB power; b) neutron emission and core alpha heating at the 1st significant crash times.

Princeton Plasma Physics Laboratory
Office of Reports and Publications

Managed by
Princeton University

under contract with the
U.S. Department of Energy
(DE-AC02-09CH11466)

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov