Isotopic mass and fast ion effects in JET alpha heating discharges

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Abstract - The alpha heating experiment in the Joint European Torus (JET) 1997 DTE1 campaign is reexamined. At equal times during the rampup phase, central temperatures are linearly correlated with the thermal hydrogenic isotopic mass $< A >$, beam ion pressure, and time of later significant sawteeth. Simulations of high $< A >$ discharges with temperatures reduced to values of those with lower $< A >$ over-predict the observed beam ion parameters so $< A >$ effects alone do not explain better confinement at large $< A >$.

1. Introduction

Alpha heating is essential for practical energy production from DT fusion reactions. Experiments to detect alpha heating were performed in TFTR (1994) [1, 2] and in the JET DTE1 campaign (1997) [3, 4]. The TFTR experiments led to the conclusions that alpha particle heating of electrons was consistent with measurements, and that ion temperature T_i and confinement in the core strongly correlated with the thermal hydrogenic isotopic mass $< A > \equiv (n_{\rm H} + 2n_{\rm D} + 3n_{\rm T})/(n_{\rm H} + n_{\rm D} + n_{\rm T})$ where n_j are the thermal densities of H (trace), D, and T. The $n_{\rm D}$ and $n_{\rm T}$ were varied by varying the T fraction in the neutral beam NB injection and in the gas puffing, and wall conditioning. Early analysis of the JET results led to the conclusions that that isotopic scaling of core parameters were negligible. This paradigm required additional explanations of the observed larger core T_i in DT compared with DD plasmas. Possible mechanisms proposed [4, 5] included fast ion stabilization of turbulence and changes in confinement induced by the presence of alpha particles.

A recent reanalysis [6] of the JET discharges showed that the central temperatures T_e and T_i and stored energy at equal times during the rampup phase correlate well with $< A >$ and that the alpha heating was not clearly demonstrated. This reanalysis showed: 1) the occurrences of large sawtooth crashes set back the increasing temperatures in the core; 2) the time delay δ_{st} between the last "insignificant" sawtooth near the start of NB injection and the time t_{st} of the first large "significant" sawtooth crash scale with both $< A >$ and the tritium beam power fraction $f_{\rm NBT}$; 3) the rates of increase of the core electron stored energy were approximately equal across the scan; but 4) the temperatures and stored energies at equal times correlate approximately with $< A >$; 5) electron energy balance in the core region shows that other electron energy balance terms with considerable uncertainties or magnitudes are comparable to the computed alpha heating rates p_α; and 6) the TT discharge chosen in [3, 4] was incompatible with the others in the scan. The other TT discharge in the scan is a better match and corroborates that the core temperatures increased with $< A >$.

Although the increases of the central temperatures correlate well with $< A >$, this does not establish cause. The total NB heating power was approximately constant (10.5MW), but there were systematic changes in beam parameters as the D and T beam ion mix was changed, as is discussed in section 4. These changed the heating profiles.

Besides T_e and T_i, the core normalized toroidal fast ion pressure β_{fast} is also correlated with $< A >$ and t_{st} for discharges with moderate $< A >$, but T_i tended to saturate, or even roll-over at large β_{fast} (with large $< A > \simeq$3). TRANSP analysis shows that the normalized beam ion pressure β_{bm} is large compared with the analogous alpha particle β_α.

The issue of whether $< A >$ or fast ion effects are the cause of enhanced confinement is significant since enhancement caused by $< A >$ would be inherent in DT reactors. Although β_{bm} is predicted to be small in ITER compared with existing DT experiments, β_α is expected to be much larger [7]. The gradients of β_{bm} and β_α are expected to play important roles stabilizing turbulence. The fast ion pressure also varies as the D and T mix was changed. The goal of this paper is to investigate alternative contributing effects that could cause improved confinement. The delay of the occurrences of significant sawtooth crashes increases with fast ion parameters such as beta.

2. Sawtooth

Sawteeth played an important role regulating the peak temperatures in the alpha heating discharges. The occurrences of the last "insignificant" and first "significant" sawteeth at time t_{st} are shown in Fig. 1. The delay times δ_{st} between these times are listed in in Table 1, along with some other parameters. Six of the nine discharges are the scan considered in [3, 4]. Eight of them were studied in [6]. The last, incompatible discharge, 43011 is excluded from the scaling studies here since it is incompatible. These increases with increasing f_{NBT} and $< A >$-2 as shown in Fig. 2.

Physics mechanisms for suppression of significant sawteeth were studied in [8]. The evolutions of central plasma and fast ion parameters were compared near the times of first significant sawteeth to identify causes of sawtooth suppression. The core electron density increased to t_{st} for all the discharges whereas T_e increased for the low $< A >$ ones and decreased for most of the high $< A >$ ones. The toroidal rotation and T_i decreased for most. Various core fast ion parameters decreased to t_{st}. The core beam ion density and the beam and fusion ion toroidal beta near t_{st} are shown in figure Fig. 3, where the timing of each discharge is shifted to the time of one of the DD discharges. The core beam densities and β_{bm} decrease to t_{st}. The alpha beta increases, but their values are relatively small. The increasing core electron density reduced the slowing down times. These results indicate that high β_{bm} is needed for sawtooth suppression. The critical values increase with T_e and T_i and $< A >$ as discussed below.

3. Isotopic mass and fast ion effects

Correlations of core T_i and T_e with various parameters are studied at three times dictated by t_{st}: 13.6s before the first significant sawtooth and thus is weekly effected by sawteeth; 13.75s after t_{st} of the DD discharges; and 14.0s after t_{st} of the DT discharge with lowest $< A >$ (42870). The peak neutron emission rate $S_{\rm n}$ and p_α occurred around 14.0-14.3s. The core electron densities continued to increase past 14.4s. Late times had higher peak parameters, but fewer discharges with comparable conditions. Also MHD became more prevalent at later times. For each of the times, core T_e and Ti are compared versus six parameters. The outlier 43011 is not included, and for the plots versus t_{st}, 42853 is excluded since the NB injection ended before t_{st}. Rough fits are shown for some of the plots.

The plots at 13.6s in Fig. 4 show approximately linear scaling with t_{st}, $< A >$ (taken at 14s since they are approximately constant in time), β_{fast} ($\equiv \beta_{bm}+\beta_\alpha$) and Sn. These parameters are instantaneous. The other parameters, the core alpha density n_α and alpha heating $p_{\alpha e}$ accumulate in time. The scaling is these less clear. The analogous plots at 13.75s in Fig. 5 show stronger scaling than at 13.6s. For instance with $T_i(0) \propto < A >^{1.1}$ and $T_e(0) \propto < A >^{0.5}$. Note that the alpha heating of electrons is relatively ambiguous. The stored energy scales roughly as $W_{\rm tot} \propto < A >^{1.0}$ at 13.75. These are similar to the scaling seen in TFTR supershots.

The plots at 14.0s (with only three comparable discharges) in Fig. 6 show very weak scaling in t_{st} and $< A >$. The dependence of T_i on β_{fast} is decreasing whereas T_e is increasing. The dependence of T_i on $p_{\alpha e}$ is increasing whereas T_e is decreasing.

4. Discussion and conclusions

Although the total heating power was approximately constant, there were systematic changes in beam parameters as the D and T beam ion mix was changed. Studies of TFTR supershots [9] show that core-peaked NB heating is crucial for their high confinement. These changes could have changed the heating profiles significantly. For instance, the voltages and penetrations of D and T bean ions differ. The peakedness (ratio of central to volume-average) of the D beam deposition (ionization) was 10-30 percent higher than for the T beam deposition. The corresponding peakedness of the D-beam ion density tended to shift in time to be 10-30 percent lower than that of for the T beam ion. The average energy of the D and T beam ions in the center were close to 80 and 100 keV respectively. The partition of beam heating power to electrons and ions changed. The changes in beam ion species and energy densities may have changing the turbulence drive and stability. The measured toroidal rotation varied, but the Hahm-Burrell flow shearing rate profiles do not show a clear $< A >$ dependence.

TRANSP simulations were used to explore the possibility that increased β_{bm} with $< A >$ could be explained by the higher temperatures caused by $< A >$ effects. Simulations based on a DT discharge with high $< A >$ (42856) in which T_e and/or T_i were scaled down to the values in DD discharges or the DT discharge with low $< A >$ (42870). The fast ion parameters reduced slightly, but are considerably higher suggesting that high β_{bm} is not a consequence, but beam heating could contribute substantially to high T_e and T_i.

Various aspects of the analysis and modeling would need further study to increase confidence in the simulations. Examples are the alpha heating $p_{\alpha e}$ and $p_{\alpha i}$ and loss terms, for instance effects of MHD. Also the sawtooth model in TRANSP is simplistic and the sawtooth mixing predictions for alpha ions would benefit from further testing. Gyro-kinetic modeling of the heat flows might show that subtle systematic differences in the heating and rotation caused the observed increased energy confinement.

Thee were too few comparable discharges from the JET DTE1 campaign to separate the fast ion and $< A >$ effects, and to demonstrate alpha heating. Future DT experiments are planned for JET after 2018 and ITER after 2034. Alpha heating and isotopic mass experiments in JET would benefit from a more comparable set of discharges, especially including ones with TT NB. Avoiding sawteeth could improve the reproducibility and simplify the modeling. Measurements such as radiation, recycling, and impurity densities would improve the analysis. Separating alpha heating effects from isotopic mass effects are important, especially since isotopic mass enhancements of transport could help make DT fusion energy possible.

One question concerning the extrapolation of isotopic mass effects to ITER and beyond is to what extent do these effects depend on the fast ion density and energy. The beam ion density fractions in TFTR supershots and JET Hot-ion H-mode discharges were much higher than anticipated in ITER, but the alpha densities were considerably lower [10]. Another question is whether the mass scaling depends on a high ratio T_i/T_e. This ratio was relatively high in the TFTR supershots and JET Hot-ion H-mode discharges. Also the toroidal rotation Mach number predicted for ITER is low [10] relative to values seen in high performance TFTR and JET discharges. Thus rotation-induced flow shear could be less favorable in ITER.

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[b]See the author list of "Overview of the JET results in support to ITER" by X. Litaudon *et al.,* to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016).

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Discharge	t_{st} [s]	δ_{st} [s]	$f_{\rm NBT}$	$f_{\rm RcT}$	$\beta_{bm}(0)$ %	$\beta_\alpha(0)$ %	$\beta_{fast}(0)$ %	$< A(0) >$	$p_{\alpha e}(0)$	$n_\alpha(0)$	Notes
40365	13.6638	0.9026	0.0	0.0	0.440	0.000	0.44	1.99	0.00	0.0	a,b
41069	13.6849	1.0492	0.0	0.0	0.360	0.000	0.37	1.99	0.00	0.0	a,b,c
42870	13.7987	0.9515	0.274	0.27	0.440	0.079	0.53	2.27	2.05	3.00	
42856	14.1242	1.4565	0.520	0.58	0.780	0.288	1.07	2.55	4.22	9.90	
42855	14.2657	1.2515	0.528	0.60	0.770	0.260	1.05	2.62	4.42	8.60	d
42847	14.3087	1.4015	0.720	0.72	0.820	0.244	1.06	2.69	3.00	6.95	e,f
42853	14.3342	1.1820	0.530	0.63	0.760	0.239	1.00	2.60	3.92	7.70	g
42840	14.3387	1.6100	1.00	0.86	0.900	0.140	0.94	2.79	1.82	4.00	
43011	14.3972	1.6217	1.00	0.98	0.840	0.045	0.88	2.94	0.62	1.60	b,h

TABLE I: *Hot-ion H-mode alpha heating discharge parameters with similar* $P_{\rm NB}$*,* $I_{\rm p}$*, and* $B_{\rm tor}$ *ranked by increasing time* t_{st} *of the occurrences of the first significant sawtooth crash; time delay between the last insignificant and 1st significant sawtooth crash* δ_t*; fraction T beam to total beam power* $f_{\rm NBT}$*; T alpha line emission fraction in the hydrogenic wall recycling* $f_{\rm RcT}$*; core beta toroidal of the beam* β_{bm}*, alpha ions* β_α*, and their total* β_{fast}*; core hydrogenic isotopic mass* $< A >$*; and the maximum values of alpha parameters in the time window 14.0-14.1s (near the times of maximum* $S_{\rm n}$*): alpha electron heating* $p_{\alpha e}$ *[10 kW/m*^{3}*]; and number of fast alpha ions [10*^{16}*/m*^{3}*]. The values of* δ_t*,* $f_{\rm NBT}$*,* $f_{\rm RcT}$*, and* β_{bm}*,* β_{fast}*, and* $< A(0) >$ *increase approximately with* t_{st}*. The values of* β_α*,* $p_{\alpha e}(0)$*, and* $n_\alpha(0)$ *do not correlate as well with* t_{st}*. Notes: relatively large deviations from the average values: a=low* $I_{\rm p}$*; b=low core toroidal rotation; c=low* $P_{\rm NB}$*; d=NB ended early (at 14.0s); e=high* $P_{\rm NB}$*; f=mode lock, disruption; g=long-duration NB,* $n_{\rm e}$ *increased to 0.8* $\times$ $n_{\rm Gw}$ *with n=1 and 2 MHD 14.2-14.5s, a second peak in* $S_{\rm n}$ *and high* $p_\alpha(0)$ *at end of NB injection; h=high edge* $n_{\rm C}$ *and edge recycling. Discharge 43011 is too dissimilar from the others, and is not used for the scaling plots. A similar table (without 42853) is in Ref. [6].*

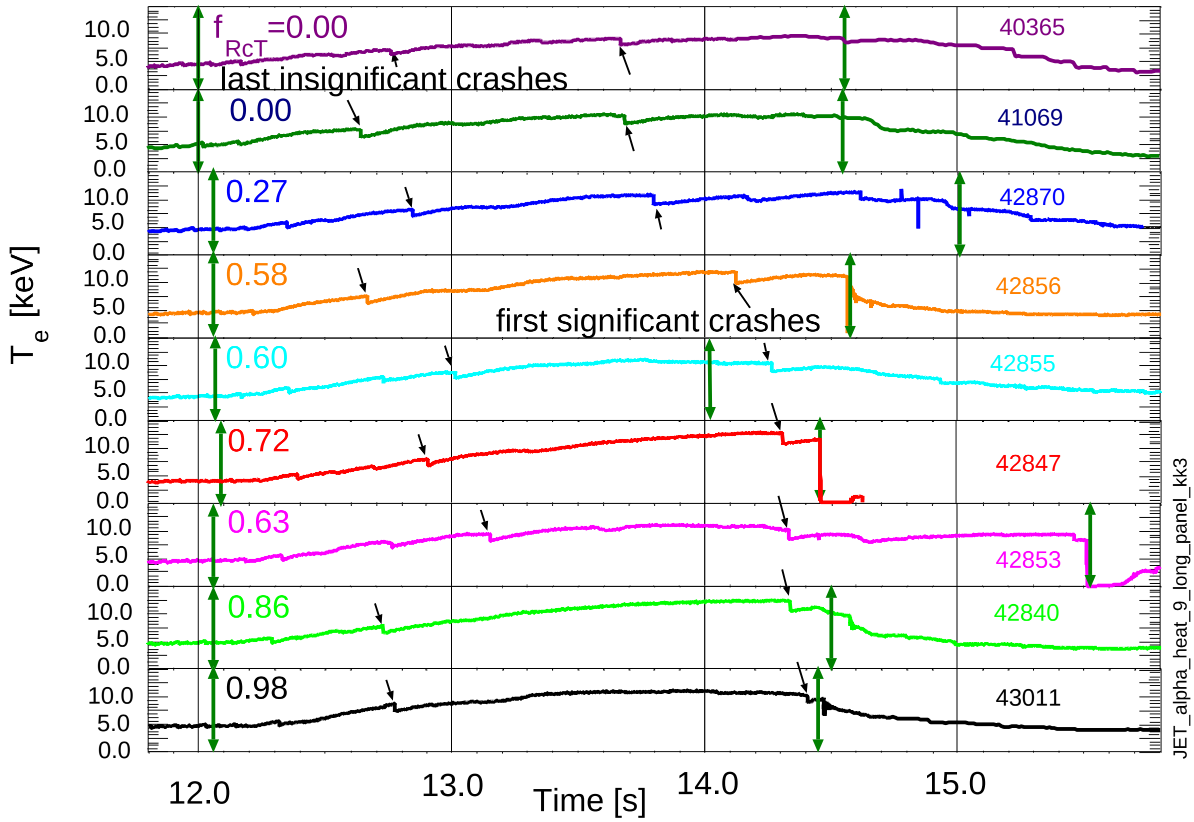

FIG. 1: Waveforms from an ECE channel in the core region showing sawtooth crashes for the alpha heating scan in Table I. Insignificant sawtooth crashes were seen during the first second or so of NB which started around 12.0s. The NB phases are between the vertical double-headed arrows. The discharges are ordered with increasing times of significant sawtooth crashes. The times t_{st} of the first significant sawtooth crashes increased approximately with increasing $f_{\rm RcT}$, $f_{\rm NBT}$ and $< A(0) >$. Some of the discharges show a modest flair-up of $T_e(0)$ after the NB. This is accompanied by a rise of the computed $P_\alpha(0)$. For all the discharges the ELM-free phase ended after the first significant sawtooth.

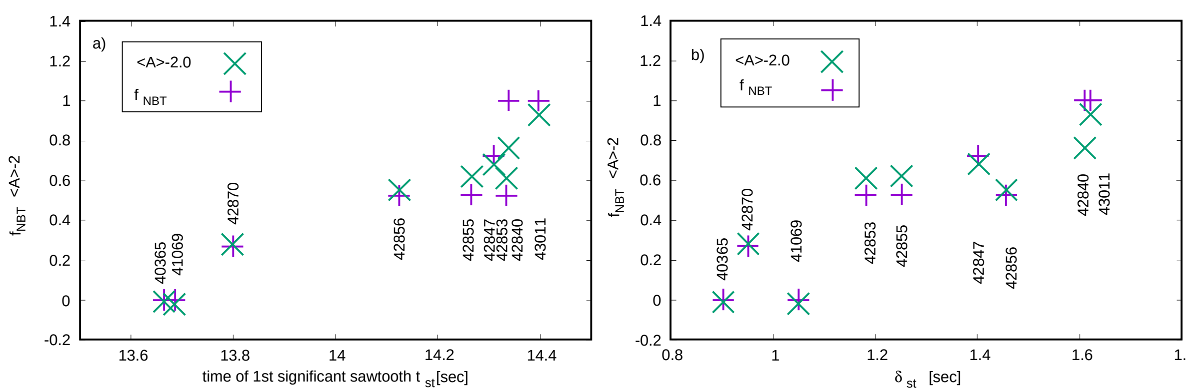

FIG. 2: Tritium beam power fraction and $< A > -2$ vs a) time t_{st} of the first significant sawtooth; b) time difference δ_{st} between the last insignificant sawtooth and t_{st}. This is an upgrade of Figure 11-a) in Ref. [6] with an additional discharge and improved analysis.

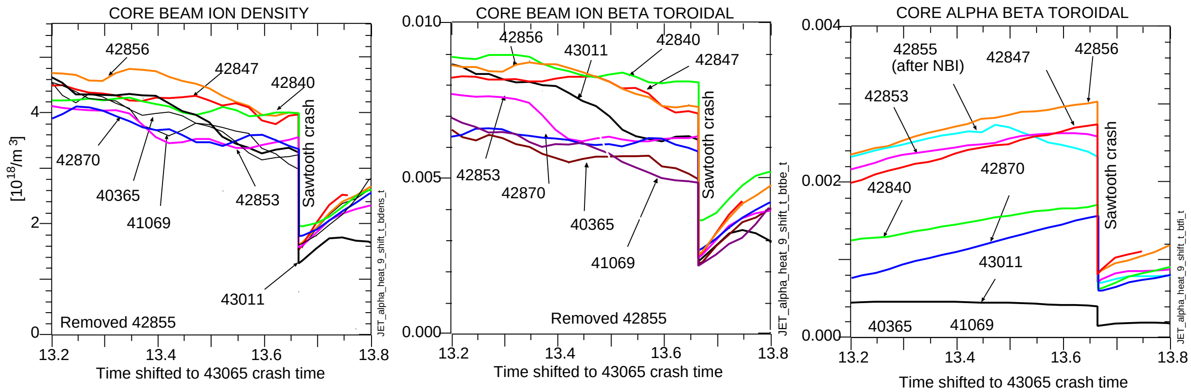

FIG. 3: Central fast ion parameters time-shifted to align the times of their first significant sawtooth crash with that of the DD discharge 40365: a) core total beam ion density (similar trends seen for the D- and T-beam ions separately); b) core total beam normalized toroidal pressure β_{fast} (discharge 42855 is not shown since the first significant sawtooth occurred after termination of beam injection when plasma diagnostic data is less complete); and c) core fast alpha normalized toroidal pressure. The core fast alpha density increases to t_{st}. The decreasing beam pressure was larger than the increasing fast alpha pressure. The discharges with higher core β_{bm} tended to have higher core $< A >$, T_i, and T_e.

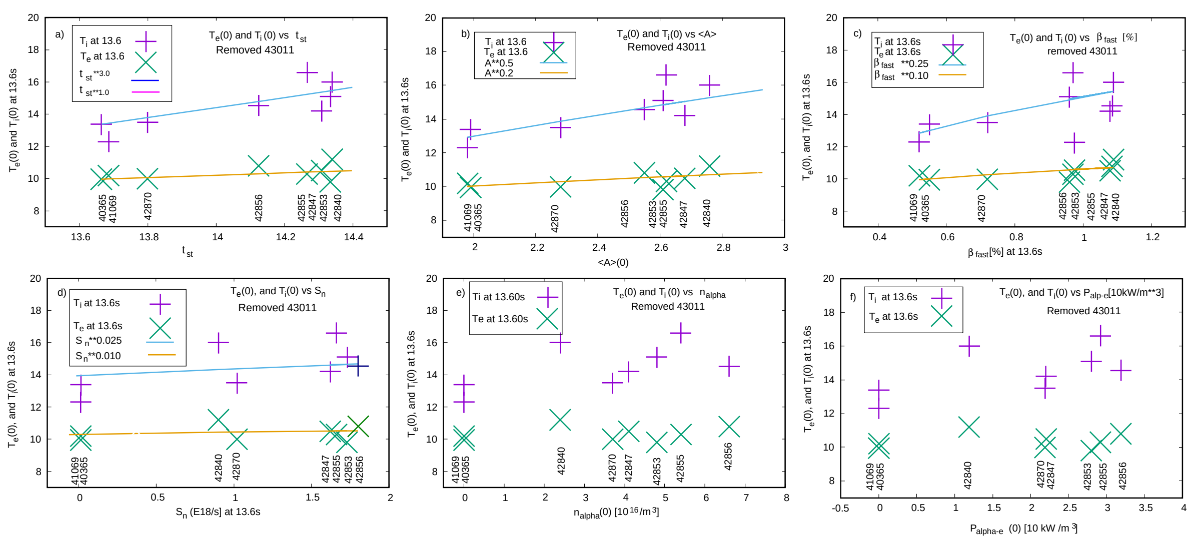

FIG. 4: Central temperatures at 13.6s (before the first significant sawtooth crash t_{st}) with approximate fits normalized to DD discharge values vs: a) time of the first significant sawtooth crash; b) central isotopic mass (at 14.0s); c) central toroidal beta of the fast beam and fusion ions (using β_{bm} instead of β_{fast} gives qualitatively similar results); d) measured neutron emission rate $S_{\rm n}$ $[10^{18}/s]$; e) central fusion alpha density $[10^{16}/m^3]$; and f) central alpha-electron heating rate $p_{\alpha e}$ [10 kW/m^3].

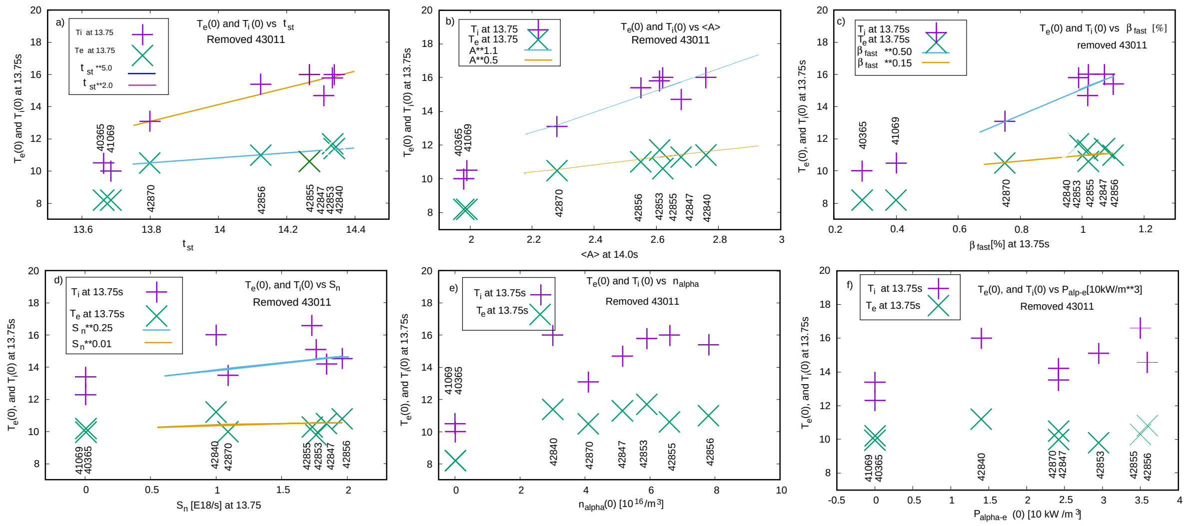

FIG. 5: Plots as in Fig. 4, but at 13.75s (after both DD discharges experienced significant sawtooth crashes); approximate fits normalized to values for the DT discharge 42870 (with f_{NBT}=0.27): The scalings in b) are comparable to the scalings shown in Fig 11-c) and 11-d) of Ref.[6]

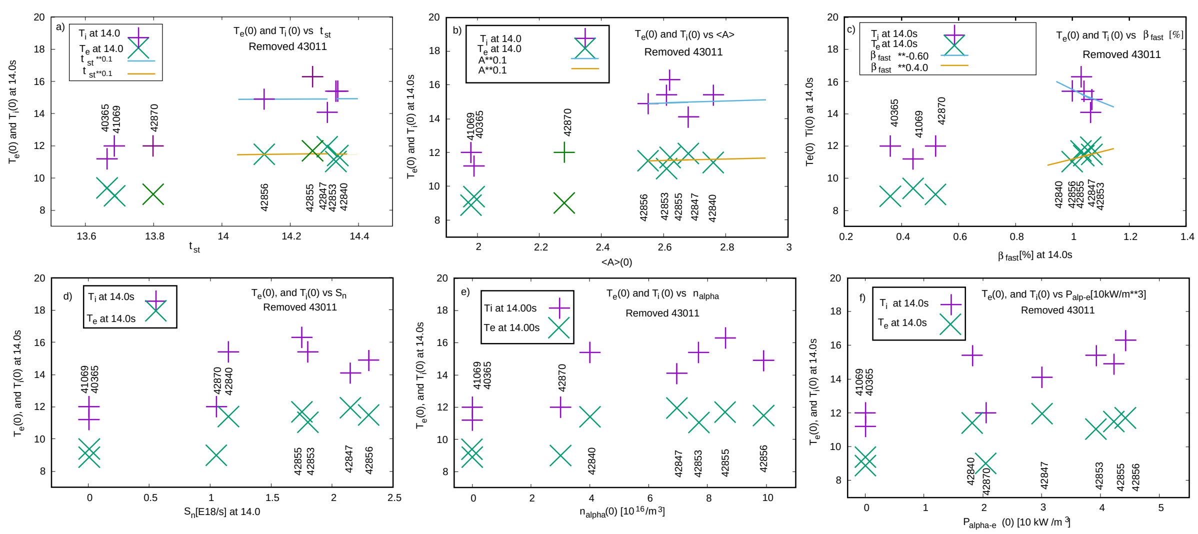

FIG. 6: Plots as in Figs. 4 and 5, but at 14.0s (after the DD and one of the DT discharges experienced their first significant sawtooth crashes); This time is around the times of peak S_{n} and temperatures of the five discharges with later t_{st}. Two of these (42853 and 42855) had decreasing T_e by this time, as seen in Fig. 1 so only three (42847, 42856, and 42840) had comparable conditions.