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ABSTRACT

The JET neutron emission profile monitor is used to measure the 2.5 MeV and 14 MeV neutron emission line-integrals before and after sawtooth crashes in high d-d neutron yield, hot-ion H-mode plasmas in the Joint European Torus (JET). Deuterium-deuterium (d-d) fusion produces 2.5 MeV neutrons and 1 MeV tritons (t) at nearly equal rates from its two reaction channels. A plasma current of 3 MA is sufficiently high to contain most of the fusion product tritons, which have similar birth orbit gyro-radii and velocity space distributions to the 3.5 MeV α-particles from d-t fusion. By examining neutron emission line-integrals and tomographically-deduced local emissivity profiles, an upper limit of 10% can be placed on the net fraction of fusion product tritons which are displaced from the plasma axis by those sawtooth crashes studied. This is a much smaller net fraction than that typically observed, 35-55%, for displaced injected neutral beam deuterium ions. A study of the response of beam-injected deuterium ions to a sawtooth crash shows that the change in their axial density depends on the pre-crash spatial width of the neutron emissivity profile. The fusion product tritons respond weakly to a crash. This is consistent with the behaviour of the analogous d-d beam-thermal neutrons when extrapolated to the corresponding emissivity spatial width. The implication of these observations is that beam ions and 3.5 MeV α-particles in JET may be relatively resilient to sawtooth crashes, when the spatial width of their density is sufficiently large.

1. INTRODUCTION

1.1 Overview

In an ignited fusion reactor plasma heated by 3.5 MeV α-particles from the d-t fusion reaction, the heating efficiency from the α-particles will depend on their containment while they thermalize. Evidence of a strong redistribution of neutral beam injected ions and thermal ions by sawtooth crashes has been obtained from measurements of global neutron emission (on several tokamaks) including D-III [1], JET [2], TFTR [3], and FT [4] and from measurements [5,6] (on the JET tokamak) of the local neutron emissivity. It has been shown previously [7] that the topology and inversion radius of sawtooth crashes in JET of the 2.5 MeV neutron emissivity is consistent with soft X-ray (SXR) tomography data and with other plasma measurements such as Electron Cyclotron Emission (ECE). The implication of these results is that a similar redistribution of α-particles would occur in an ignited fusion reactor during sawtooth crashes, causing an axial heating reduction.

In this paper, experimental results are presented which show that the spatial distribution of slowing down 1 MeV tritons produced by deuterium-deuterium (d-d) fusion in the JET tokamak is only weakly altered by sawtooth crashes, i.e. by 10% or less of the maximum pre-crash density, for discharges with the highest yields of 2.5 MeV neutrons. The (nearly isotropic) birth distributions and the gyro-radii of 1.0 MeV tritons and 3.5 MeV α-particles are similar. Thus, by analogy the α-particles should be similarly resilient to sawtooth crashes. The triton redistribution is measured indirectly by observing 14 MeV neutrons from fast triton (t) fusion with deuterium plasma ions. The tritons produce 14 MeV neutrons while slowing down in the plasma. After thermalization, their fusion reactivity becomes negligible at the plasma ion temperature, so that their continued presence does not affect the neutron emissivity profiles. The 14 MeV neutron emissivity profile therefore provides an indirect measurement of the spatial distribution of the tritons while in the several hundred keV energy range.

Since the velocity of 200 keV tritons (the energy of maximum t-d reactivity) is similar to that of beam injected deuterons, it is surprising that their response to a sawtooth crash is seemingly different. In this paper, it is shown that, for the types of discharges and sawtooth crashes examined here, the tritons react in a manner that is consistent with the scaling of the beam ion response.

A discussion of the experimental studies at JET and elsewhere is provided in the remainder of Section 1. Then, in Section 2, line-integral 2.5 and 14 MeV neutron emission data from the JET neutron emission profile monitor are presented. To resolve interpretative problems related to statistical errors and time-resolution, detector counts from 14 MeV neutron emission line-integral measurements of several discharges are added, and compared for sampling intervals taken just before and after a crash. Individual discharges are also examined within the limitations imposed by count rates, and tomography is applied to the line-integral neutron emission data to quantify the level of triton redistribution. In Section 3, the effects of sawtooth crashes on the 2.5 MeV neutron emissivity profile are examined as a function of spatial width and beam-thermal contribution to the emissivity. The 14 MeV neutron response, due entirely to (t) beam - (d) thermal fusion, is shown to be consistent with the trends of 2.5 MeV neutron data. In Section 4, the results are discussed and summarized.

1.2 Previous JET Results

It has been reported from JET experiments [2,8-11] that the thermalization and burnup of 1.0 MeV tritons are classical, with a weak diffusion or loss term detectable only for tritons with a thermalization time of more than 1 s. The effect of sawtooth crashes on the fast triton population has been a topic of considerable interest at JET since the first time-resolved burnup measurements were made by Conroy et al. [8]. Essentially no change in the global emission due to a sawtooth crash was observed during several years of tokamak operations, apart from discharges which suffered from rapid impurity influx and deuterium density change immediately after a crash. A model by Conroy [9] assuming that tritons are not redistributed as a result of a sawtooth crash accurately predicts the experimentally measured global burnup for slowing down times of < 1 s. This model uses experimentally measured plasma parameters including sawtoothing temperatures and assumes classical slowing down. This absence of a global effect in a high-current plasma in JET is readily understandable. The expected triton spatial redistribution does not instantly alter the total number of tritons nor their energy distribution. Any sudden change in the (t-d) fusion rate of the fast tritons with thermal deuterium would therefore only be caused if the tritons were redistributed in a region of lower deuterium density. This is unlikely, since the density profiles are relatively flat in the discharges investigated. With this understanding, evidence of redistribution was sought using single collimated lines-of-sight into the plasma. These observations with collimated Si diodes measuring the line-of-sight integrated production rate of 14 MeV neutrons from t-d fusion have shown falls of less than 10% in the central production rate following sawtooth crashes, over a wide range of discharges in JET [9,10].

In order to pursue the study further, the JET neutron emission profile monitor [12], shown schematically in Fig. 1, was employed. The original signal conditioning electronics were carefully tuned to 2.5 MeV neutrons and the recording of 14 MeV neutrons was of secondary importance. It was not possible to identify 14 MeV neutrons unambiguously when the 2.5 MeV neutron signal rate (two orders of magnitude greater than the 14 MeV neutron signal rate) was very high, as occurred during neutral beam heating, owing to signal pile-up and energy window problems. However, the 14 MeV neutrons could be observed just after the beams were turned off. Preliminary measurements by Jarvis et al. [10] of 14 MeV emissivity widths during burnup studies showed no response to sawtooth crashes.

A preliminary examination was made by Conroy et al. [11] of the transfer of fast tritons from the central region to edge regions of the plasma in JET, by adding up the volume-weighted line integrals of 14 MeV neutron emissivity measured with the neutron emission profile monitor. In the 10-channel horizontal camera, the channels viewing the inner region of the plasma (No. 3-8) were added to form a "wide-angle central channel" with improved measurement statistics, and those viewing the edge regions (No. 1-2 and 9-10) were added to form a "wide-angle edge channel". On most discharges, no discernible effect was observed in the "central" channel. In a few, in particular discharge No. 25416 at 12.4 s, the "edge" channel doubled after the sawtooth crash, but from a level very low compared to the axial value. The statistics of the measurements used in discharge No. 25416 are analysed in detail in the next section.

Anderson et al. [13] have used discharge No. 25416 as an illustration of sawtooth theories [13-15] which contend that 1.0 MeV tritons are strongly redistributed by a crash. However, the statistical uncertainties in the 14 MeV neutron data were large for this discharge and their conclusions cannot be supported (see section 2.7).

Observations have been made by Jarvis et al. [16] on losses of 15 MeV protons produced in JET by ^{3}He-d fusion from ICRF accelerated ^{3}He and from d-d fusion product ^{3}He. With ICRF accelerated ^{3}He, there was clear evidence of redistribution. No evidence of redistribution was found with fusion produced ^{3}He ions; however, plasma conditions may not have been favourable for a positive observation.

1.3 Results from other Tokamaks

Qualitative observations of charged particle loss to wall probes have been made in DIII-D [17,18] and TFTR [19-22]. Based upon observations of prompt orbit loss measurements of 15 MeV protons (from ^{3}He-d fusion) to the wall in DIII-D [18], it was claimed that significant (≈15-20%) oscillations were present in the ^{3}He fusion product population. Of this 15-20%, about half was directly attributable to the change in source rate, leaving less than 10% due to the sawtooth redistribution or other causes. Any oscillations in the 14 MeV neutron flux, measured with a Si diode, were obscured by poor counting statistics. Calculated prompt orbit losses in DIII-D for ^{3}He and t fusion products are 5% and 20% respectively, so that internal redistribution could cause a relatively larger loss of these ions in DIII-D than in the higher current plasmas in JET.

Based upon measurements of MeV ion losses to detectors just outside the plasma boundary in 1.8-2.0 MA discharges in TFTR [20], it was observed that sawtooth crashes had little effect on the instantaneous or integrated loss rate of the product ions from d-d fusion. These losses have been discussed by Zweben et al. in [21]. It is claimed that the loss fraction due to a sawtooth crash is only 10^{-4}. The amplitudes of sawtooth crashes in TFTR are typically smaller than in JET.

2. NEUTRON EMISSION MEASUREMENTS AND INTERPRETATION

2.1 Neutron Diagnostics

The main diagnostic employed in what follows is the JET neutron emission profile monitor. A dual pulse-shape discrimination (PSD) system was installed to optimise observation of triton burnup and to improve the accuracy beyond that of preliminary experiments reported earlier by Jarvis et al. in [10]. This doubling of the signal conditioning electronics allowed the 2.5 and 14 MeV signals to be optimised separately. The line-integral emission data from the new system are analysed here with tomographic methods used in the code NEUTOMO [5,6,23] to obtain the 2-D emissivity profiles before and after a sawtooth crash for both the 2.5 and 14 MeV neutrons. The line-integral measurements are normalised to Si diode and fission chamber measurements [6,24].

2.2 Summed Discharges

Because of low neutron count rates, it is difficult to obtain good time resolution for studying the effect of a sawtooth crash on the 14 MeV neutron emissivity (from the 1.0 MeV triton burnup). For this reason, we analyse discharges with the highest rates of d-d fusion, corresponding to the maximum production rates of 1.0 MeV tritons.

To optimise counting statistics, the data from six similar high performance discharges are added together over equal time bins just before and just after a sawtooth crash during a period of high 14 MeV neutron emission. Table I lists, for each discharge chosen, the time of the sawtooth crashes, the amplitudes of the crashes in the 2.5 MeV neutron global emission and in the line-integral 2.5 MeV neutron emission seen by channel 16 of the profile monitor, the peak 14 MeV neutron global rates before the crash, and the times of maximum global 2.5 and 14 MeV neutron emissions.

The above discharges all achieve the hot ion H-mode, and are heated primarily by a total of about 15 MW of deuterium neutral beam injection at 80 and 140 keV, with Nos. 26625 and 26804 having an additional 4-7 MW of ICRF heating. The first four discharges were part of a series made in preparation for the first high power tritium injection experiments in JET, and therefore had high neutron yields. This type of discharge (especially No. 26087 with the highest d-d fusion rate) is described in publications [6,25-29], of which [28] includes detailed time traces of plasma parameters, and [27] includes a discussion of MHD instabilities during sawtooth crashes.

For each of the 18 channels of the neutron profile monitor (channel #11 was rejected because of its excessive gamma ray count rates), the counts of 2.5 MeV and 14 MeV neutrons are summed separately over the six discharges for intervals of 10 ms, 30 ms, 50 ms, and 100 ms, before and after the sawtooth crash.

The slowing down times of the deuterium beams and the d-d produced tritons are shown in Table II, for both fusion reactivity reduction and energy loss. The plasma parameters chosen are for No. 26087, the discharge which most heavily weights the summations. The 140 keV d beams, which represent most of the beam heating power, have a negligible loss of reactivity on the 30 ms time scale. Only the 80 keV d beams lose significant reactivity in 30 ms, and the interval-averaged loss in this case in only 17%. However, the addition of a new source term due to newly injected ions during the analysis interval is significant, certainly on the 100 ms time scale. An accurate analysis of the beam ion redistribution therefore requires analysis times of at most 20 ms after a sawtooth crash. The high d-d fusion rates allow good statistics on a 20 ms time-scale.

For all cases with d-d produced tritons, the losses of reactivity and energy are negligible on a time scale of 100 ms or less. On this time scale, the production of new tritons during the analysis interval after a sawtooth crash will be less than 10% of the total already present. The additional reactivity due to these new tritons is negligible due to the relatively low reactivity (1/4 of maximum) at the birth energy of 1 MeV.

The improved statistics from the summation allows a channel by channel comparison of the count rate before and after a sawtooth crash. Using such a comparison, the uncertainties are entirely due to random counting statistics, and systematic errors are eliminated, since each channel's absolute calibration will not change during the analysis interval. Even if a weak count-rate dependence were present in the calibration, the rate changes are too small to have any effect. The resulting count rates are presented in Fig. 2 for time bin intervals of 100 ms for 14 MeV neutrons. Practically no change has occurred due to the sawtooth crash. The statistical errors in the line-integrals have been reduced to small levels (≈±5%). The 50, 30 and 10 ms data (not shown) also exhibit no significant change due to the crash, except that the error bars and data scatter grow progressively larger due to fewer counts. The channel numbers 1-10 are from the horizontally viewing camera, and channel numbers 12-19 are from the vertically viewing camera. For each measurement, the uncertainty limits are taken to be plus and minus the square root of the number of counts. The calibration procedure for the channels is described in [6]. The calibration of each channel was kept constant throughout this analysis.

The relative change in the profile due to the sawtooth crash is small. Note that although the spatial profile shape of the 14 MeV data in the vertical camera channels is slightly ragged, consistent with a ± 10% systematic uncertainty in the absolute calibration of each channel, this has no effect on analysing the relative changes in time. A χ^2 analysis to determine if the 18 channels are observing the same population distribution indicates that the before and after-crash distributions of the 14 MeV data are not the same, with χ^2=52 for 18 degrees of freedom. It appears that channels viewing the plasma centre, Nos 5,6,7,15,16,17 indicate a small decrease, and that some of the edge viewing channels, Nos. 2,3,8,9 indicate a small increase (No. 12 decreases slightly), corresponding to a relatively weak redistribution of either fast tritons or deuterons, of the order of the size of the error bars, i.e. 10%. From Fig. 2, the full-width half-maximum (FWHM) of the line-integral data measured by the horizontal camera is approximately 5 channels which, on the horizontal midplane, corresponds to 1.0 m.

The t-d fusion reactivity, integrated over the slowing down of fast tritons, is the same for either thermal or beam energy deuterium to within 10%. The fast deuterium ions constitute about 10% of the thermal deuterium ion density. The total counts of 14 MeV neutrons after the crash are within 2% of the total counts before, consistent with little change in the deuterium density and a (weak) redistribution of fast tritons.

In Fig. 3(a-c), the line-integrals for three of the six individual discharges are displayed (on different scales), for 100 ms time bins. The error bars are larger than in Fig. 2, which displays summed data, since there are fewer counts per channel obtained from individual discharges. There is no obvious response to the sawtooth crash in discharges No. 26042, a slight response apparent in No. 26087, and the strongest apparent response in No. 26625. These responses are discussed below.

2.3 Crash at Peak t-d Yield

We next examine discharges where the 2.5 MeV neutron emission is primarily due to d-d beam-thermal fusion, where its response to a sawtooth crash might be expected to be the most similar to that of the 14 MeV neutron emissivity.

The t-d yield tends to reach its maximum at 0.4-0.8 s after the d-d peak yield, due to the slowing down time of a 1.0 MeV triton to the peak of its cross section at 0.2 MeV. The plasmas at this time have lower plasma temperatures and higher Z_{eff} than at the d-d peak yield. The d-d beam-thermal fusion dominates over thermal and beam-beam contributions to the d-d fusion yield. The sawtooth crashes are not influenced by high β effects, since the crashes occur at values far below the stability limit (β_{Troyon}=2.8I_p/aB_t).

Discharge No. 26042 has a sawtooth crash which occurred at 15.944 s after plasma initiation, during the peak of the 14 MeV neutron emission, and 0.5 s after the peak of the 2.5 MeV neutron emission so that the 2.5 MeV neutron emission had decreased by an order of magnitude. In Fig. 4, time traces are shown of a line-integral (traversing the plasma axis) of the 2.5 MeV neutron emission, measured by channel 16 of the profile monitor, the 2.5 and 14 MeV neutron global emission, the axial electron density and temperature, and electron temperature measurements from ECE showing the details of the sawtooth crash on an expanded time scale. The neutral injection power was 13 MW, until it dropped to 6 MW at or just after (0-20 ms) the sawtooth crash. (The time intervals chosen for analysis of the 2.5 MeV neutron data are much less than the beam slowing down time.) The sawtooth crash itself was not of the high beta variety [30-32], and produced a slow heat pulse and a clearly observable inversion major radius of

3.6-3.7 m on the fast measurement of electron temperature. Just before 15.944 s, the electron density and impurity content had increased from their levels at the peak d-d yield. The axial 2.5 MeV neutron emissivity was due primarily to d-d beam-thermal fusion, with only about 20% of the emissivity due to thermal d-d fusion. After the crash, the electron density was approximately unchanged, but the ion temperature fell by about 20%, so the thermal contribution fell by about 50%. Thus, the change in the total due to the change in the thermal fusion contribution was at most 10%. Therefore, any emissivity changes due to the crash were mostly a result of beam ion redistribution.

The response of the 2.5 MeV neutron line-integrals to the crash in discharge No. 26042 is shown in Fig. 5, where the data are integrated for 20 ms before and 20 ms after the crash. An inversion is visible. There was no evident response of the 14 MeV data to the crash, as shown in Fig. 3(a). In Fig. 6, the emissivity profiles deduced by tomography are shown before and after the crash. The axial emissivity of the 2.5 MeV neutrons (calculated by tomography) fell to 55% of its pre-crash value, and inversion major radii at 2.9 m and 3.6 m were observed. There was no observable change in the 2.5 MeV neutron global emission, as measured either by fission chambers or by the integrals of the emissivity profiles (implying a beam-ion redistribution, since there was very little drop in emissivity due to a change in the thermal fusion term). Since there was no density change, the net axial emissivity decrease of 35-45% due predominantly to beam-plasma fusion corresponds also to a 35-45% decrease in the beam ion density on axis.

To demonstrate that it is instrumentally possible to observe a sawtooth crash in 14 MeV neutron emissivity, a discharge is examined in which the 14 MeV neutron emission was due to fusion processes other than triton burnup. As was discussed in [6], both 2.5 MeV and 14 MeV neutron emissivity profiles react similarly to a sawtooth crash in discharge No. 26114, when the sources are deuterium beams on deuterium and tritium ions (the latter originally beam injected, but at the time of observation had thermalized). In Fig. 7, tomographically deduced 14 MeV neutron emissivity profiles are shown for 100 ms intervals before (13.98-14.08 s) and after (14.09-14.19 s) the sawtooth crash. The crash is similar to what is observed with the 2.5 MeV neutrons, thus demonstrating the ability of the neutron emission profile monitor to detect a response to sawtooth crashes in the 14 MeV neutron signals when present. The 14 MeV neutron emissivity profile also shows a strong response to a sawtooth crash when d-t thermal and beam-thermal (in comparable degrees) and beam-

beam (relatively small) fusion are responsible for the neutron production, as in discharge No. 26148 [6], with the triton burnup contribution being negligible.

2.4 Large Crash in 14 MeV Neutron Emissivity

Of the discharges examined, the clearest effect of a sawtooth crash in the 14 MeV neutron emission line-integrals from fusion product tritons is observed due to the crash at 13.635 s in discharge No. 26625. In Fig. 3(c), the 14 MeV neutron emission line-integrals are shown with uncertainty limits, for 100 ms intervals before and after the crash. There is a clear decrease in channels 4,5,6 in the horizontal camera, and 14,16,17 in the vertical camera. However, an examination of the global 14 MeV neutron emission shows no evidence of any sharp response to the sawtooth crash, but rather a smooth decline from 100 ms before to 100 ms after the crash. The ratio of the time integrals of the global emission over the before and after intervals is 1.123. The electron density profiles show a 15-20% decline during this interval. The density profiles are also more rounded than most profiles observed in plasmas in the H-mode. When the 14 MeV line-integrals after the crash shown in Fig. 3(c) are multiplied by 1.123 and compared to the line-integrals before the crash, the profiles become similar within one standard deviation, except for channels 5 and 9. Thus, the data are consistent with no observable redistribution of fusion product tritons. All the change in 14 MeV neutron emissivity can therefore be attributed to a change in deuterium density, with perhaps a small and slow evolution in the fusion product triton density.

2.5 Crash at Highest d-d Yield

Discharge No. 26087 produced the highest d-d fusion rate from JET. In Fig. 8, detailed time traces of neutron rates, axial electron temperature and deuterium density (using Charge Exchange Recombination Spectroscopy - CXRS) are shown just before and after the sawtooth crash at 13.4685 s, which occurred just after the peak (in time) of plasma pressure and 2.5 MeV neutron emissivity, while the plasma was in the hot-ion, H-mode condition. This sawtooth crash has been discussed in [6,27,28], where the SXR data sampled at 200 kHz shows a collapse which lasted 100 s, and extended across the entire plasma. The sawtooth crash occurred at high normalised plasma pressure, β/β_{Troyon}=0.8, and is characterised by a collapse in the central electron temperature as well as the central SXR emissivity. There was less than a 5% increase observed in the electron temperature in outer channels, and heat propagated outwardly very rapidly, as observed in other high beta discharges [30-32]. The electron density profile was relatively flat. The deuterium ion density was more peaked, and showed a fall of about 10% at 50 ms after, compared to 50 ms before, the sawtooth crash.

In Fig. 9, the line-integrals of neutron emissivity from the central plasma regions, as measured by channels (No. 4-8) of the horizontal camera, are plotted for discharge No. 26087 as histograms for 10 successive time intervals of 100 ms each for the 14 MeV neutron data, and for 100 successive time intervals of 10 ms each for the 2.5 MeV neutron data, spanning the time interval 13 s to 14 s containing the sawtooth crash. The maximum counts per time bin are 150 and 1363 for the 14 MeV (100 ms) and 2.5 MeV (10 ms) neutron data, respectively. The line-integral data clearly show a large sawtooth crash in the 2.5 MeV neutron line integrals, but any crash in the 14 MeV neutron line integrals is smaller than the ≈ ±10% level of statistical fluctuation in the data. The full profiles of the 14 MeV neutron line-integral data for 100 ms before and 100 ms after the crash, summed over data acquired every 2.5 ms, are plotted in Fig. 3(b). Comparing the before and after-crash channel distributions, the χ^2 is 26.5, with 18 degrees of freedom, indicating that the profile has changed, but only slightly.

The method of adding volume-weighted line-integrals [11] was applied to this sawtooth crash. At most, a 10-20% increase of 14 MeV neutron emission was observed in the edge channels, and no discernible change occurred in the central channels, within a ±10% fluctuation level at a faster 50 ms sampling rate.

To obtain neutron emissivity profiles from tomography for discharge No. 26087, time-bins just before and just after the crash were chosen to contain ≈100 counts, giving ±10% statistics. In Fig. 10, the 2-D emissivity profiles of the 2.5 MeV neutrons are plotted versus major radius R and height z, (a) for the 2.5 ms time interval 13.4638-13.4663 s just before the sawtooth crash, and (b) for the interval 13.4713-13.4738 s just after the crash. The emissivity in the central region fell to half its peak value, and the profile broadened, while the global emissivity fell by only 13%. Using CXRS measurements of the deuterium density and temperature, the local thermal fusion rate for d-d reactions was calculated to account for about 50% of the measured maximum axial 2.5 MeV neutron emissivity. TRANSP [28] calculations indicate that most of the other 50% is provided by beam-thermal reactions, with a negligible beam-beam contribution. Just after the sawtooth crash, the calculated axial thermal emissivity due to d-d thermal fusion fell to 50% of the value before the crash, so the remainder of the decrease in neutron emissivity is attributable to a redistribution of deuterium beam ions. Allowing for an axial drop of about 10% in the axial deuterium density, the data are consistent with a net decrease of deuterium beam ions at the axis of about 40%.

The time-bin required for analysis of the 14 MeV data in discharge No. 26087 is 100 ms. In Fig. 11, the 2-D emissivity profiles of the 14 MeV neutrons are plotted versus major radius R and height z, (a) for the time interval 13.36-13.46 s just before the sawtooth crash, and (b) for the interval 13.48-13.58 s just after the crash. The axial value of the 14 MeV emissivity fell by about 20%, and the global emission fell by 8%, attributable to the axial deuterium density decrease of about 10%. Therefore, not more than 10% of the high energy tritons at the axis were redistributed by the sawtooth crash.

2.6 Other Discharges

The 14 MeV neutron emission line-integrals, measured by individual camera channels, were examined in discharges No. 25999, 26040, 26076 and 26804 by choosing analysis times just before and just after crashes which occurred near the peak production rate of the 2.5 MeV neutrons . The measured line-integrals of the 14 MeV neutron emissivity showed no sawtooth crash response that significantly exceeded the statistical fluctuations. The neutron counts accumulated during time intervals of 100 ms have statistical error bars of typically ±10%.

2.7 Previously Reported Redistribution

It has been previously reported by Conroy et al. [11] that in discharge No. 25416 at 12.469 s, the "edge" summed channels doubled after the sawtooth crash. This result was used in a paper by Anderson et al. [13] as evidence for a major redistribution of fast tritons. However, this doubling was from a level very low compared to the axial value, and the statistical errors on the count rates are large. To see if a significant redistribution had actually occurred, we analyse the basic counting statistics for discharge No. 25416 in comparison to No. 26087. The detailed 14 MeV neutron line-integral count rates are shown in Table III, for 100 ms intervals for both discharges, before and after the sawtooth crashes. The count rates in No. 25416 have large uncertainty limits. The philosophy of analysis adapted here is that the neutron emission profiles in No. 26087 and 25416 should be similar before and after the crash, since both discharges are in the hot-ion H-mode configuration, and the crashes both occur after 1.4 s of similar beam heating powers. Therefore, No. 26087 is used as a guide for examining the profiles of 25416. Using the count rates in columns A and C of Table III and scaling the No. 26087 data to the same total counts as No. 25416, a χ^2 analysis comparing the two populations gives $\chi^2 = 6.2$ with 17 degrees of freedom, so the two pre-crash distributions are practically identical. Similarly after the crash, comparing columns B and D, $\chi^2 = 18.5$ is obtained. It is therefore not possible to show that the distributions after the crash of the two discharges are different. The net axial decrease of the 14 MeV neutron emissivity in No. 25416 is consistent with that observed in No. 26087. There is a redistribution that is genuine, but minor.

3. RESPONSE OF 2.5 MeV NEUTRON EMISSIVITY PROFILES TO SAWTOOTH CRASHES.

3.1 Discharges and Heating Time

In this section, the response to sawtooth crashes of the 2.5 MeV neutron emissivity profile is examined as a function of its spatial width and of the beam-thermal contribution to the axial emissivity. The 14 MeV neutron response, due entirely to (t) beam - (d) thermal fusion, is shown to be consistent with the trend of 2.5 MeV neutron data.

The discharges examined are Nos. 20981, 25996, 26000, 26023, 26043, 26061, 26064 and 26087. As was the case in the above analysis, they are all hot ion H-modes heated primarily by a total of about 15 MW of deuterium neutral beam injection at 80 and 140 keV. For these discharges, sawtooth crashes were examined in the time interval (t) between 0.0 and 0.8 s after the start of high power beam heating. (The crash in No. 20981, already investigated in [5], illustrates the dramatic change in the 2.5 MeV neutron emissivity profile that can occur due to a sawtooth crash.) During this period, there was a high 2.5 MeV neutron yield, of order 10^{16} n/s, which allowed the use of 10 ms integration times for neutron tomography analysis, just before and just after each sawtooth crash. Each of these discharges has been analysed with TRANSP as part of other investigations [28]. These calculations determined the fractional contribution of beam thermal fusion to the 2.5 MeV neutron emissivity on axis just before the sawtooth crash, defined as (F_{bt}). The ratio F_{bt} varies between 0.26 and 0.69 and tends to increase with heating time, as follows.

For discharges No. 26000 and 26064, with the lowest ratios F_{bt} of 0.25 and 0.33 at Δt values of 0.168 and 0.043 s, the bulk of the 2.5 MeV neutron axial emissivity is due to beam-beam fusion, with less than 2% due to thermal fusion. At later times, the relative beam-beam contribution becomes smaller, and beam-thermal and thermal become more important. The thermal contribution before 0.8 s tends to be smaller than at the peak of the 2.5 MeV neutron yield which occurs later, so the neutron emissivity during the time range 0.0 s<(Δt)<0.8 s is strongly influenced by beam ions.

3.2 Beam-thermal Contributions and FWHM

From tomographic analysis of the emissivity profiles, the Full Width at Half Maximum of the emissivity profile in the midplane ($FWHM_0$) and the axial emissivity (S_0) just before the crash, and ($FWHM_1$) and (S_1) just after the crash, are determined from the 2.5 MeV neutron line-integral measurements. In Fig. 12, the ratios S_1/S_0 are plotted as a function of F_{bt}. The 2.5 MeV neutron data from discharge No. 26042, and the 14 MeV neutron data from discharge No. 26087, discussed above, are also plotted in Fig. 12, with F_{bt} values of 0.8 and 1.0 respectively. The ratio S_1/S_0 increases approximately linearly with F_{bt}, i.e. the amplitude of the crash decreases with increasing beam-thermal fraction. Therefore the fusion product triton behaviour is not anomalous, but rather is an extrapolation of a trend visible in the 2.5 MeV data.

3.3 Interpretation of Crash Amplitude

An explanation of this behaviour can be found in Fig. 13, where the emissivity profile widths $FWHM_0$ and $FWHM_1$ are plotted as a function of F_{bt}. Two results are apparent from these graphs:

1) The FWHM just before the crash is an increasing function of F_{bt}. This broadening is due to at least two factors. When the plasma density increases, which it does with time: a) the beam deposition profile broadens due to reduced penetration; b) the highly peaked beam-beam contribution, proportional to the square of the beam density, decreases due to broader beam deposition and faster beam slowing down.

2) Just after the crash, the FWHM of the emissivity profile is relatively constant and independent of the initial conditions.

The data from No. 26042 still follows the general trend of the 2.5 MeV data in Fig. 13, although the crash occurs long after the peak d-d yield. The FWHM of the 14 MeV data from No. 26087 is the same before and after the crash, and equal to the FWHM of the 2.5 MeV data after the crash. Thus, since the FWHM before was already as great as the FWHM after the crash (the same value for all discharges), very little net change would be expected in the 14 MeV neutron emissivity. There may be a redistribution of individual fusion product tritons as a result of the crash, but the overall distribution is little changed.

The response of the SXR emissivity profiles to the sawtooth crash is similar to that of the 2.5 MeV neutrons. SXR data sampled at 200 kHz is available for the crashes in discharges No. 26000 and 26087, which have the smallest and nearly the largest F_{bt} values, respectively. Data at 1 kHz is also available for the crashes in discharge No. 26023, with intermediate F_{bt} values. The ranges of the FWHM's of the SXR (and 2.5 MeV neutron) emissivity profiles are 0.54-0.92 m (and 0.30-0.75 m) before the sawtooth crash, and 1.08-1.28 m (and 0.98-1.17 m) after the sawtooth crash. The full width in the midplane of the sawtooth crash inversion radius, presumably corresponding to the approximate location of the q=1 surface, is 0.68-0.80 m (and 0.54-0.78 m) for these discharges. The SXR emissivity profile is peaked before the crash in these discharges, and the peak emissivity region moves off-axis and rotates before the crash occurs. Therefore, the topology of the crash in the 2.5 MeV neutron emissivity is similar to that shown by SXR data, but the time-averaging in order to obtain good statistics obscures any fine details.

Beam ion redistribution due to a sawtooth crash is strong for narrow initial widths, as in [5]. For discharges No. 26000 and 26064, with the lowest ratios F_{bt} of 0.25 and 0.33 (the rest of the emissivity is due to beam-beam), the change in the axial beam ion density due to a crash can be calculated. The beam-thermal emissivity is proportional to the beam density, since in these discharges, the change in the thermal ion density at the crash is small. Therefore, the ratio S_1/S_0, (proportional to the ratio of the sums of linear and quadratic beam density terms), determines the change in axial beam ion density. For the two discharges, the ratio of fast ion density after the crash to that before the crash is 0.45±0.05. Thus about half of the beam ions (net) are removed from the axis for these initially narrow profiles.

4. DISCUSSION AND SUMMARY

For most of the discharges analysed here, the 14 MeV neutron emissivity was due solely to beam-thermal fusion of 1.0 MeV tritons slowing down in a deuterium plasma. In these discharges, in response to a sawtooth crash, the net axial density decrease of fusion product tritons is weaker than the decrease of beam injected deuterium, i.e. 10% compared to 35-55%. In previous studies, it was similarly difficult to find a major redistribution of fusion product tritons.

A detailed examination of the response of 2.5 MeV neutron emissivity profiles to sawtooth crashes as a function of heating time, axial beam-thermal contribution, and emissivity peak values and widths shows that: a) the amplitude of the crash in the axial neutron emissivity decreases as the beam-thermal fraction increases; b) the width of the emissivity profile increases as the beam-thermal fraction increases; c) the emissivity width after a crash is independent of initial parameters; d) beam ions are strongly redistributed when the initial spatial width of their density is narrow, but are more weakly redistributed when the initial width is broad.

The 14 MeV data from triton burnup correspond most directly with the 2.5 MeV neutron emission from beam-thermal reactions. An extrapolation of the 2.5 MeV neutron data to a 100% beam-thermal fraction indicates that the expected change in the 14 MeV neutron axial emissivity should be small and the initial width of the emissivity should be the same as the width after the crash. To the extent that beam ions and partially slowed down tritons respond similarly to sawtooth crashes, no large change is to be expected.

If discharge No. 26087 were operated with a deuterium tritium mixture, the width of the α-particle population would be comparable to that of the fusion product tritons in a deuterium plasma. The above observations on 1.0 MeV tritons imply that α-particle heating in such JET plasmas (or in fusion reactors) may not be impaired by sawtooth crashes of the types studied here, provided the production profile of α-particles is sufficiently wide.

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TABLE I. SAWTOOTH CRASH DATA FROM THE JET NEUTRON PROFILE MONITOR FOR SELECTED DISCHARGES

JET Discharge Number	Sawtooth Crash Time (s)	Amplitude of Crash in 2.5 MeV Neutron Global Rate	Amplitude of Crash in 2.5 MeV Neutron Monitor Channel 16	Peak 14 MeV Neutron Global Rate (10^{14} n/s)	Time of Peak 2.5 MeV Neutron Global Rate (s)	Time of Peak 14 MeV Neutron Global Rate (s)
25999	15.735	15%	33%	2.9	15.5-15.7	16.0-16.2
26042	15.944	0%•	15%	2.4	15.4-15.5	15.8-16.0
26076	13.808	20%	25%	3.5	13.4-13.6	13.9-14.1
26087	13.469	20%	31%	8.0	13.3-13.4	13.7-13.9
26625	13.635	20%	42%	5.5	13.1-13.2	13.4-13.6
26804	14.089	7%	30%	4.0	14.0-14.1	14.4-14.5

• Even though no sawtooth crash is evident from the global neutron rate, a large crash is observed on the electron temperature and neutron emission profiles. See Section 2.3.

TABLE II. REACTIVITY RATIOS AND SLOWING DOWN TIMES
FOR BEAM IONS AND d-d FUSION TRITONS
IN DISCHARGE No. 26087 AFTER THE SAWTOOTH CRASH AT 13.469 s
(At t~13.500 s: T_i=8 keV; T_e=9 keV; n_{eo}=5x1019 m^{-3}; Z_{eff}=2.5)

	Beam Injected E=140 keV d on d Plasma (P=11 MW)	Beam Injected E=80 keV d on d Plasma (P=4MW)	d-d Fusion Produced E=1.0 MeV t on d plasma	Partially slowed-down E=200 keV t on d plasma
Beam-Thermal Reactivity σv(t=0) at Initial Energy E(t=0 ms)	$1.12x10^{-23}$ m^3s^{-1}	$4.8x10^{-24}$ m^3s^{-1}	$3.20x10^{-22}$ m^3s^{-1}	$1.35x10^{-21}$ m^3s^{-1}
Ratio σv(t=30 ms)to σv(t=0)	0.83	0.66	1.09	1.00
Ratio σv(t=100 ms) to σv(t=0)	0.44	0.00	1.03	0.91
Time to slow down to 80% of σv(t=0)	33 ms	17 ms	reactivity initially increases	138 ms
Time to slow down to exp (-1) of σv(t=0)	116 ms	58 ms	reactivity initially increases	228 ms
Time to slow down to exp(-1) of Initial Energy	150 ms	77 ms	690 ms	213 ms
Time to slow down to $1.5T_i$=12 keV	201 ms	97 ms	1260 ms	290 ms

TABLE III.

14 MeV NEUTRON COUNTS IN TIME INTERVALS:

(A,B: before and after MHD crash at 13.469 s in #26087);

(C,D: before and after MHD crash at 12.406 s in #25416);

AND NORMALISATION FACTORS

Shot #	26087	26087	25416	25416
Time Interval	-0.1→0.0s	0.0→0.1s	-0.1→0.0s	0.0→0.1s
	A	B	C	D
Channel #				
1	67	57	5	17
2	83	113	15	51
3	63	67	18	23
4	87	87	28	27
5	118	124	40	18
6	163	131	61	33
7	118	108	12	15
8	86	93	22	23
9	121	148	24	22
10	85	75	10	26
11	---	---	---	---
12	125	93	31	46
13	312	282	68	106
14	134	134	36	45
15	219	175	53	52
16	173	150	31	18
17	151	147	39	28
18	77	70	29	32
19	19	17	6	14
Total Counts	2201	2071	528	596

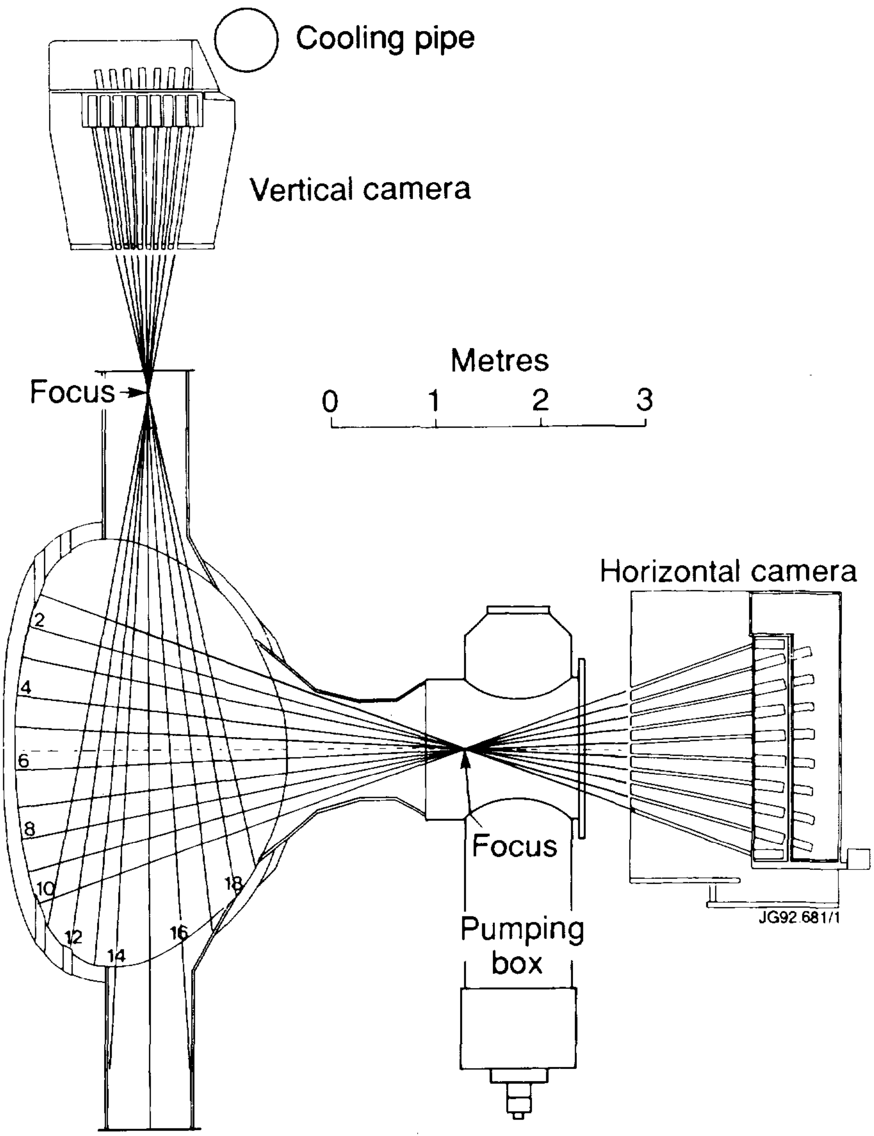


Fig. 1. The JET neutron emission profile monitor is drawn schematically, showing the lines-of-sight. It consists of two fan-shaped multi-collimator cameras using NE-213 scintillators.

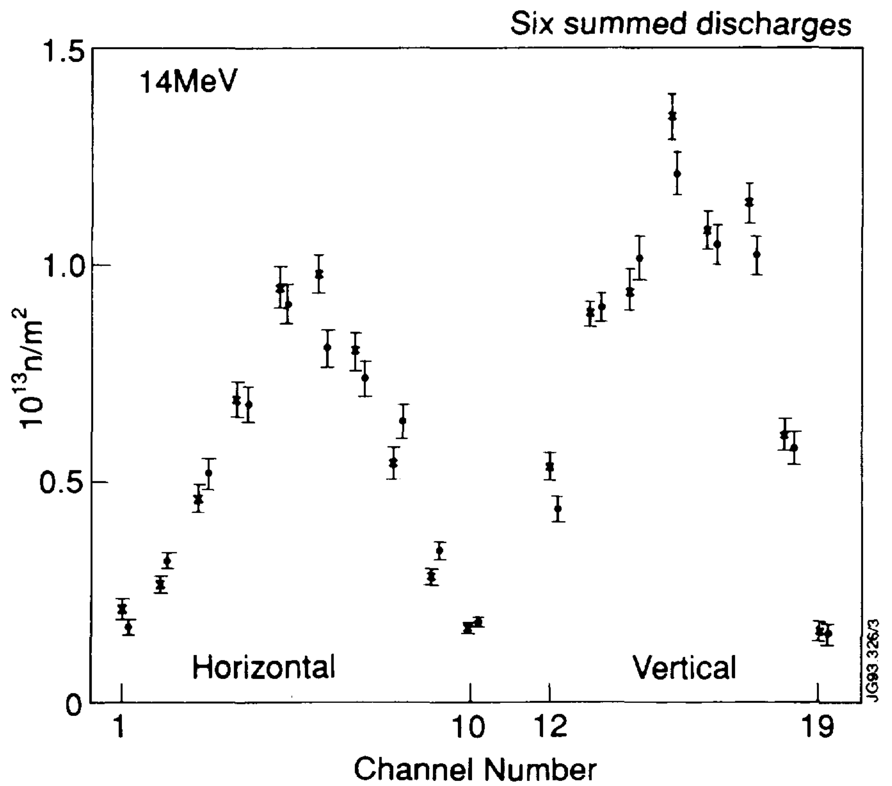


Fig. 2. 14 MeV neutron emission line-integrals summed over six discharges for 100 ms before (x) and 100 ms after (•) a sawtooth crash in each discharge.

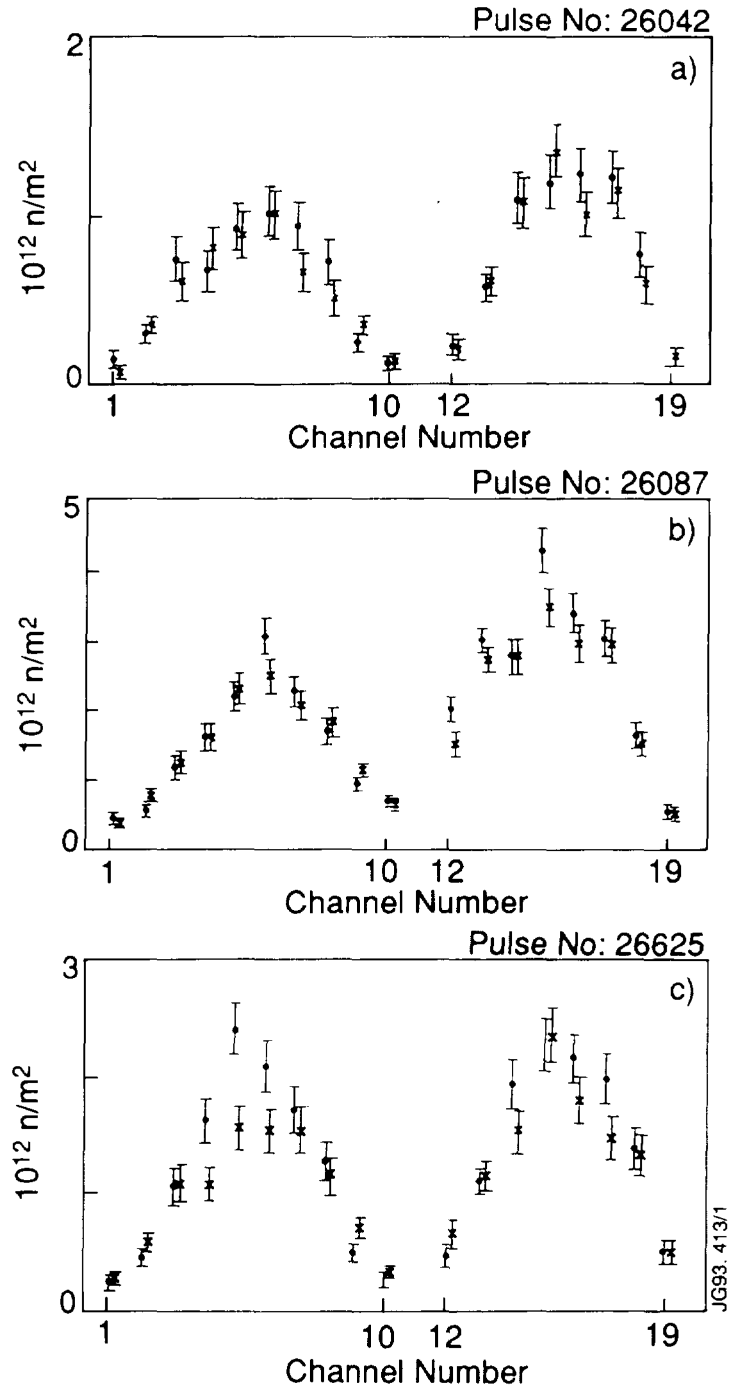


Fig. 3. 14 MeV neutron emission line-integrals for 100 ms before (x) and 100 ms after (•) a sawtooth crash discharge Nos: a) 26042, b) 26087, c) 26625.

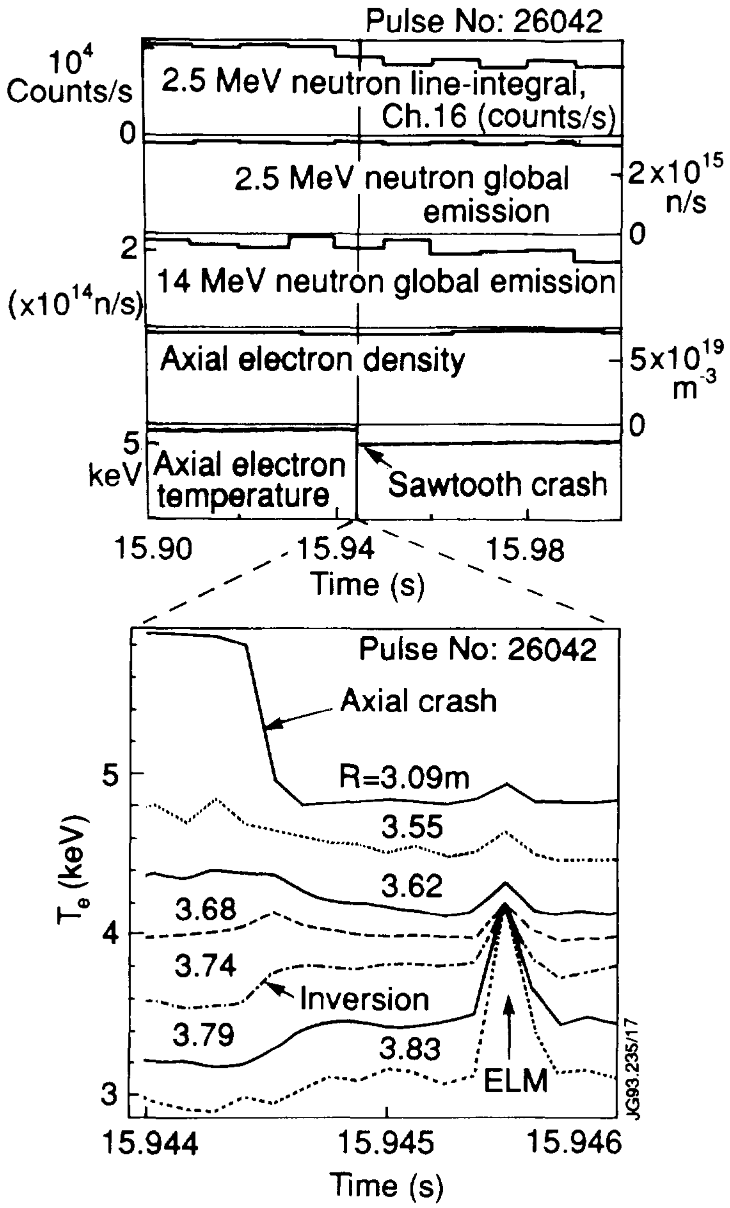


Fig. 4. Time traces showing a line-integral (traversing the plasma axis) of the 2.5 MeV neutron emission, measured by channel 16 of the profile monitor, the 2.5 and 14 MeV neutron global emission, the axial electron density and temperature, and electron temperature measurements from ECE showing the details of the sawtooth crash on an expanded time scale, for discharge No. 26042.

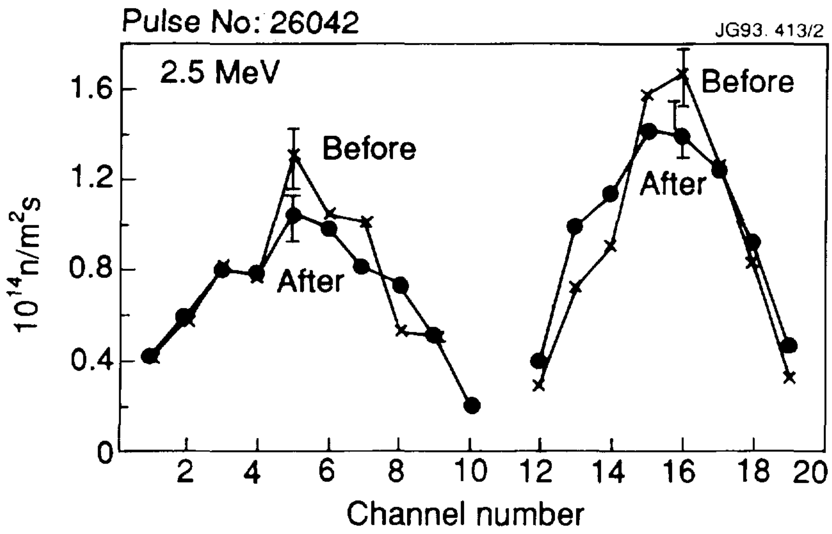
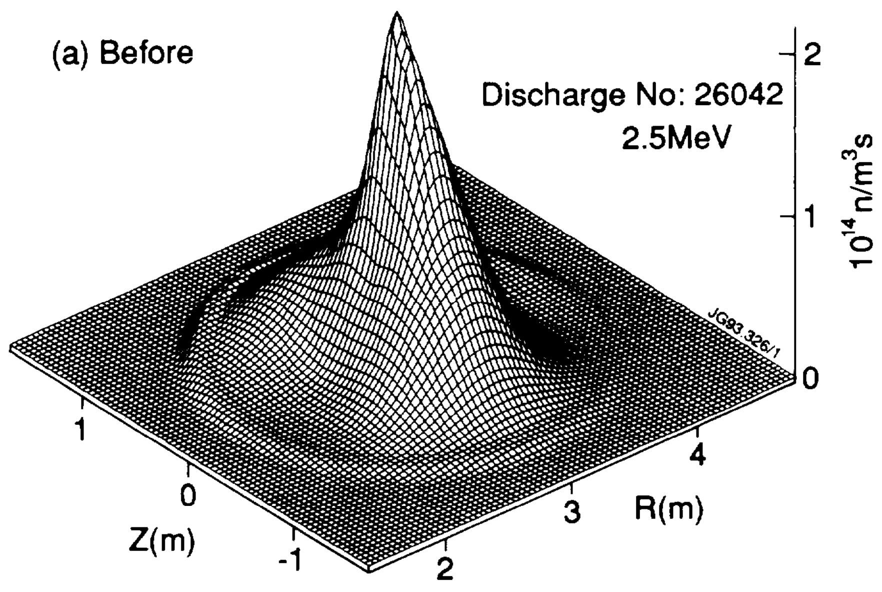
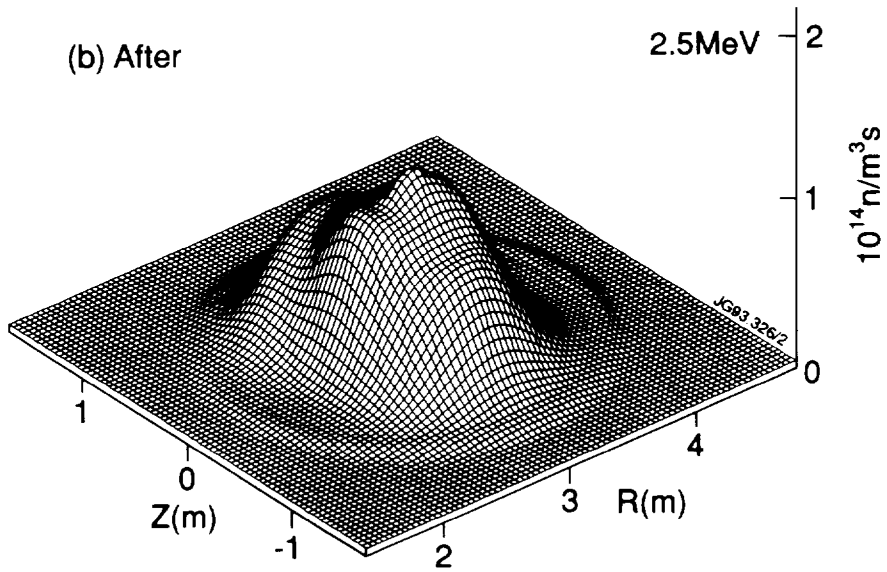


Fig. 5. Discharge No. 26042, Line-integral 2.5 MeV neutron emission rate during 20 ms intervals before (x) and after (•) the sawtooth crash at 15.945 s.


(a) Before
Discharge No: 26042
2.5MeV
10^{14}n/m^{3}s
2
1
0
JG93.326/1
1
0
Z(m)
-1
2
3
4
R(m)


(b) After
2.5MeV
10^{14}n/m^{3}s
2
1
0
JG93.326/2
1
0
Z(m)
-1
2
3
4
R(m)

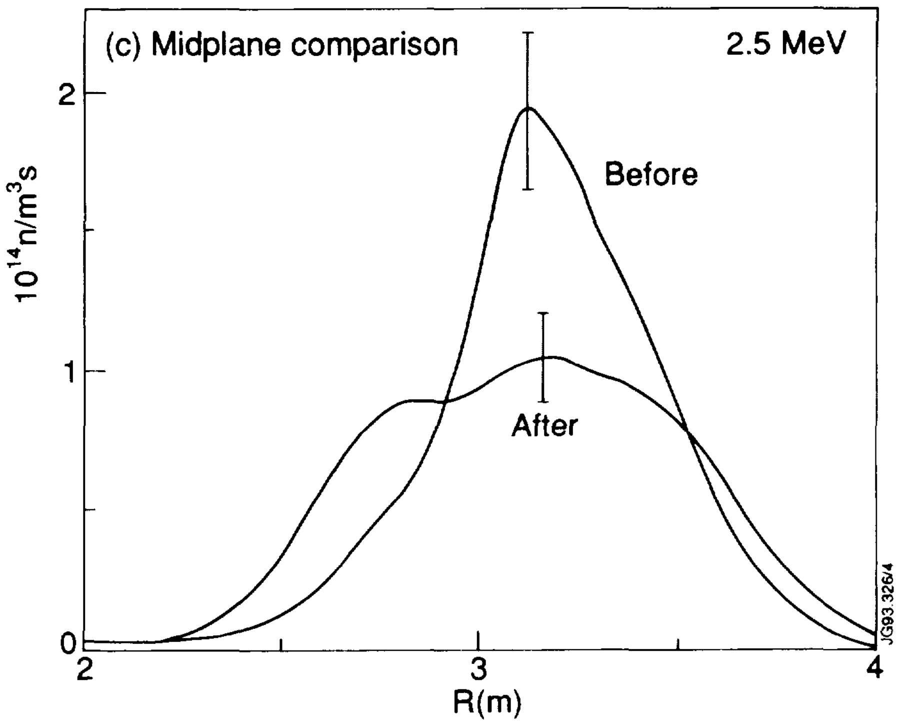


Fig. 6. The 2-D emissivity profiles of the 2.5 MeV neutrons are plotted versus major radius R and height z for (a) the time interval 15.92-15.94 s just before the sawtooth crash, and (b) the interval 15.95-15.97 s just after the crash in discharge No. 26042.

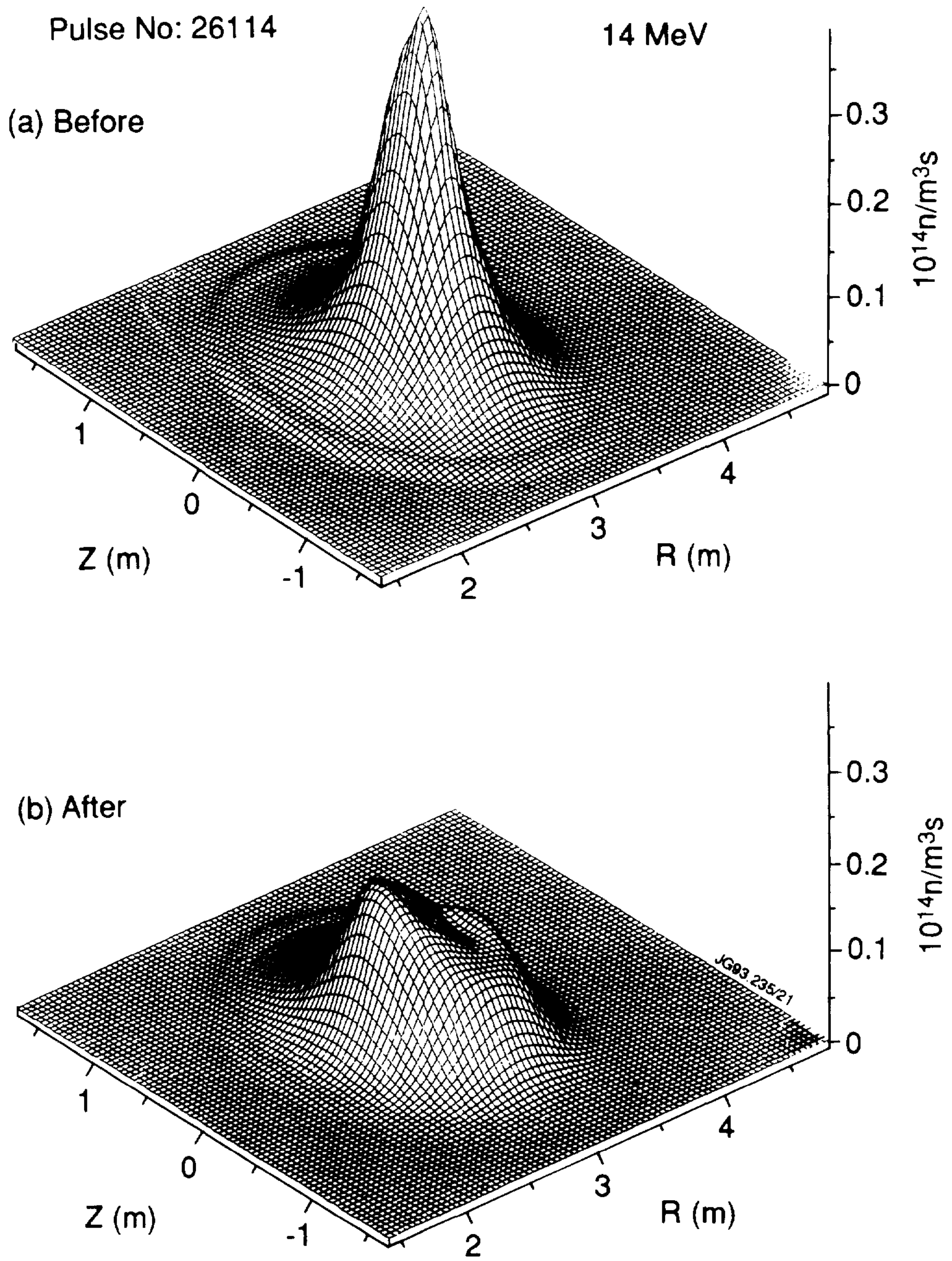


Fig. 7. The 2-D emissivity profiles of the 14 MeV neutrons are plotted versus major radius R and height z for (a) the time interval 13.98-14.08 s just before the sawtooth crash, and (b) the interval 14.09-14.19 s just after the crash in discharge No. 26114.

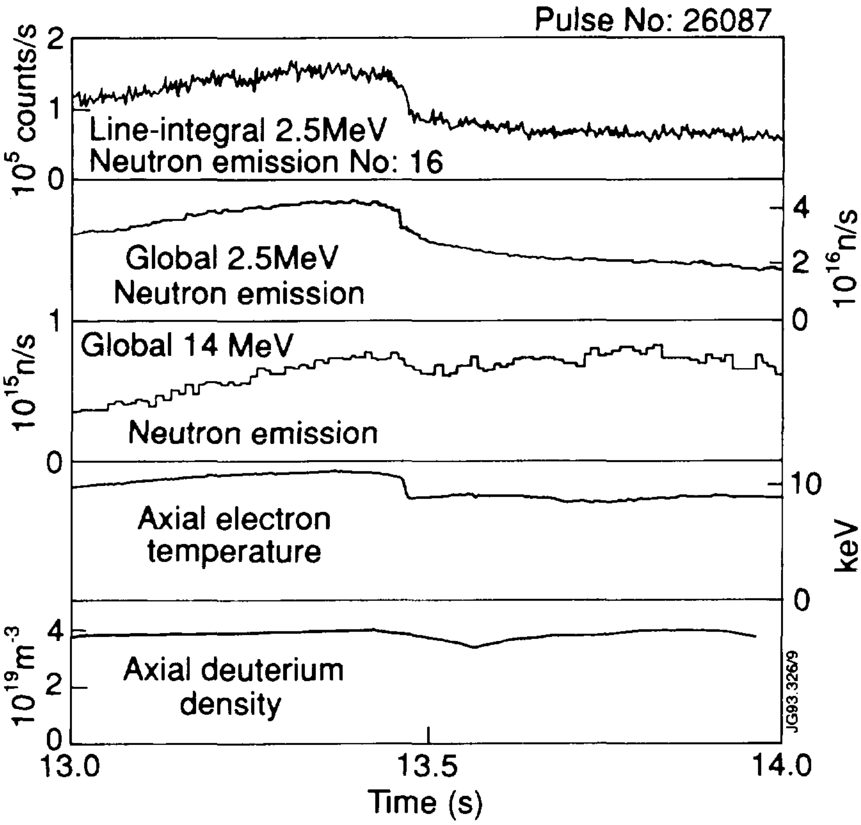


Fig. 8. Time traces for discharge No. 26087 at times near the sawtooth crash at 13.469 s for a centrally viewing line-integral of the 2.5 MeV neutron emission, camera channel No. 16, the global 2.5 and 14 MeV neutron emission, axial electron temperature, and the axial deuterium density.

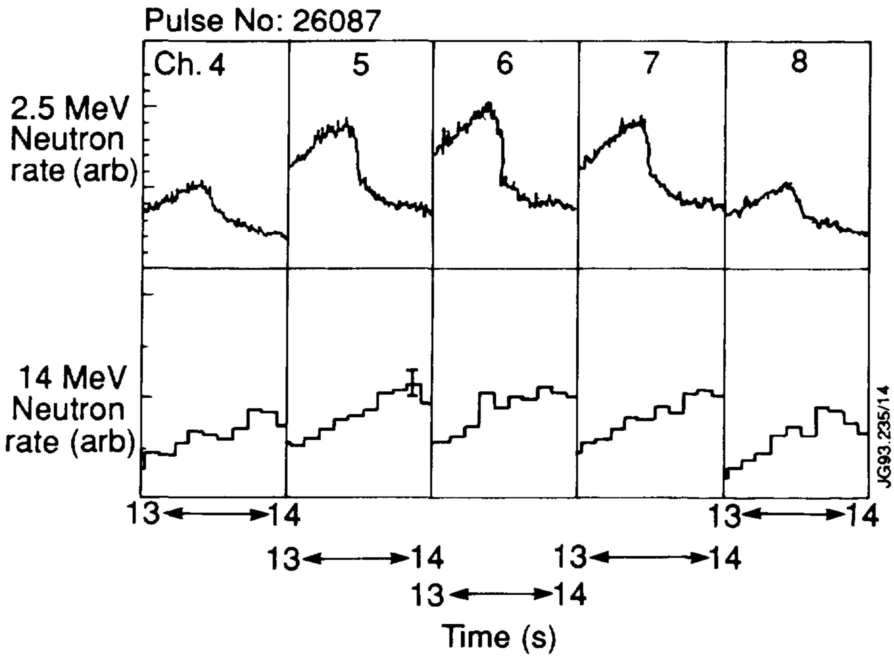


Fig. 9. The neutron emission line-integrals of channels 4-8 of the horizontally viewing camera are plotted as histograms for 100 successive time intervals of 10 ms each for the 2.5 MeV neutron data, and for 10 successive time intervals of 100 ms each for the 14 MeV neutron data, each frame spanning the time interval 13 s to 14 s which contained a sawtooth crash in discharge No. 26087 at 13.469 s.

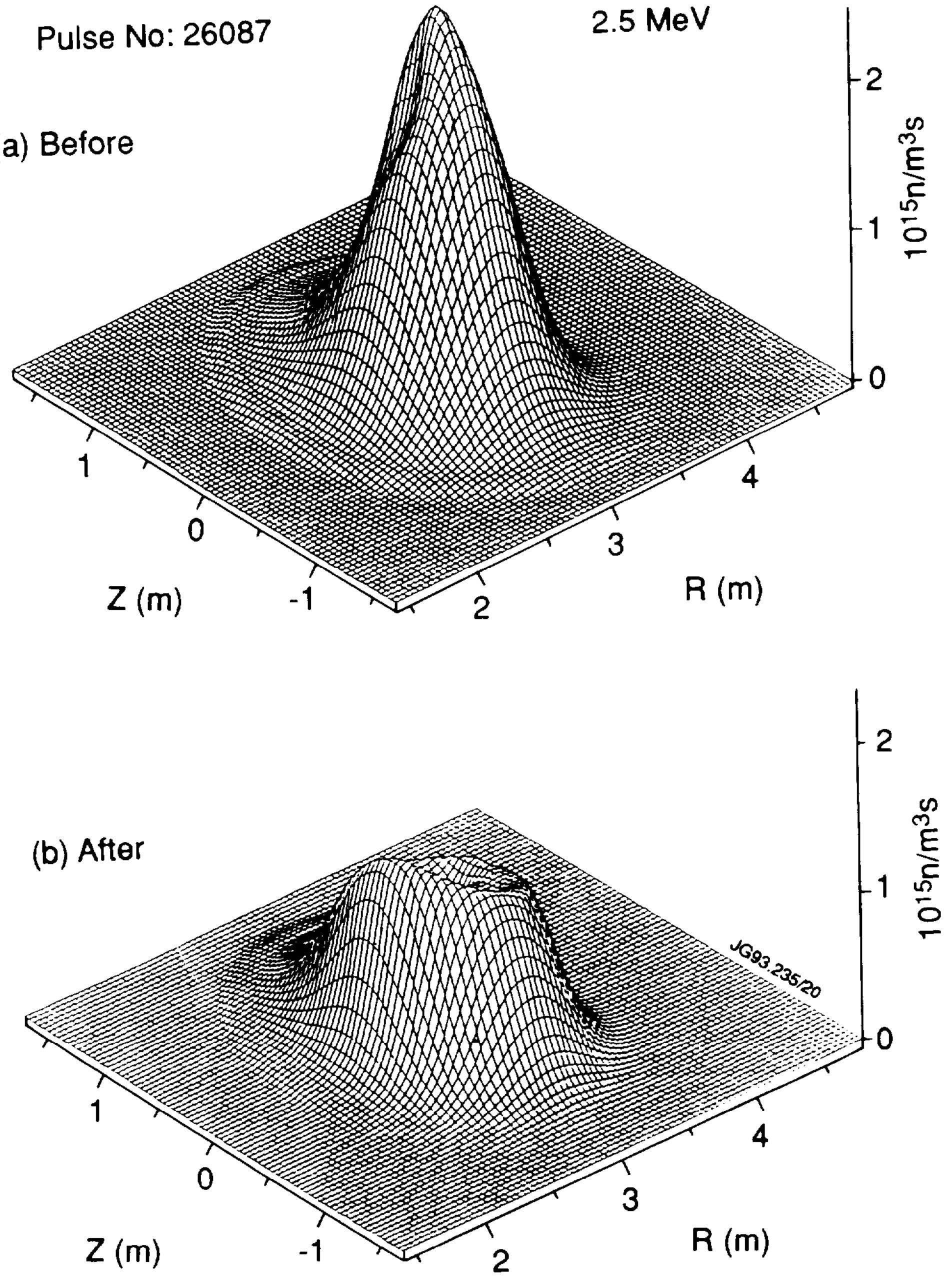


Fig. 10. The 2-D emissivity profiles of the 2.5 MeV neutrons are plotted versus major radius R and height z for (a) the time interval 13.4638-13.4663 s just before the sawtooth crash, and (b) the interval 13.4712-13.4738 s just after the crash in discharge No. 26087.

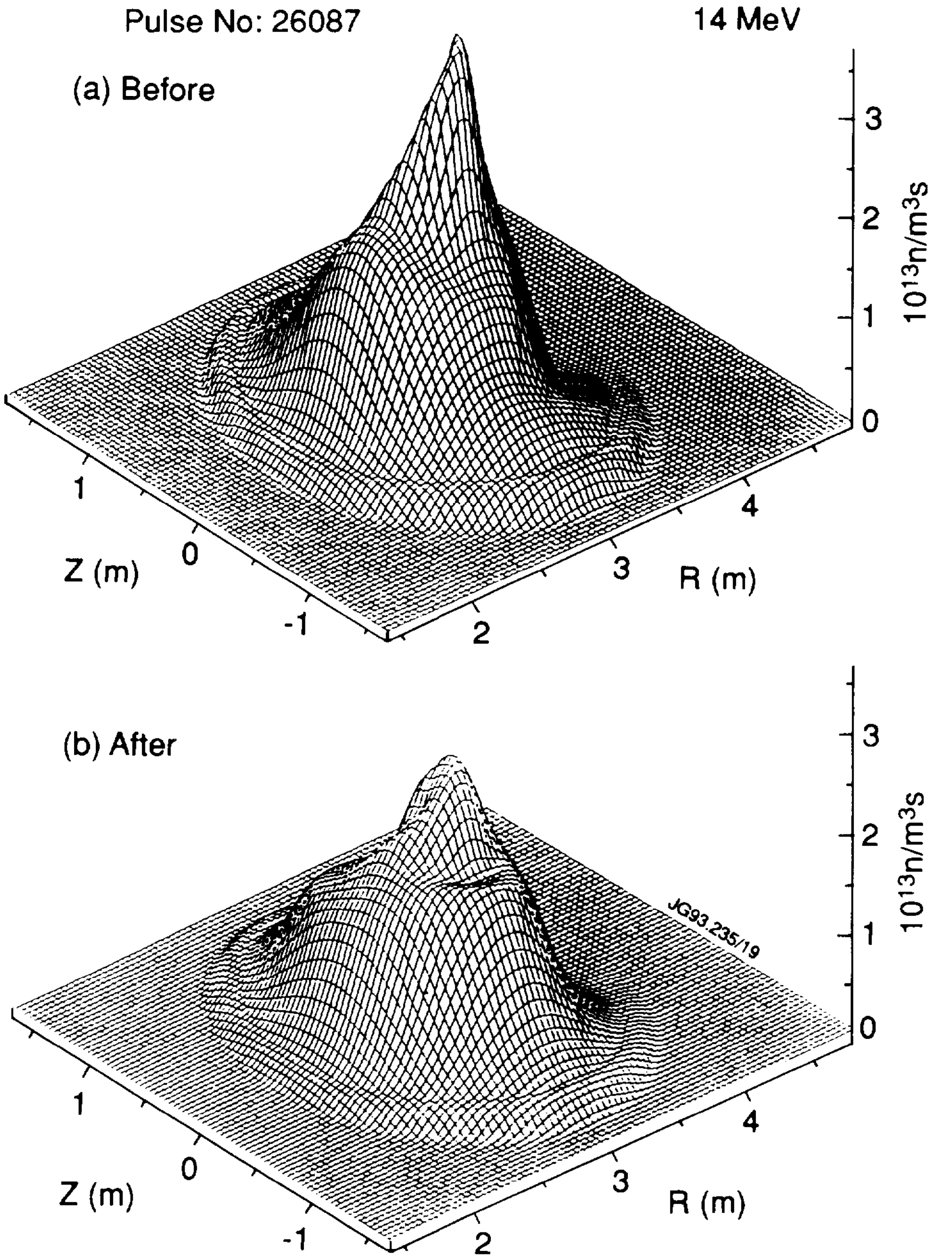


Fig. 11. The 2-D emissivity profiles of the 14 MeV neutrons are plotted versus major radius R and height z for (a) the time interval 13.36-13.46 s just before the sawtooth crash, and (b) the interval 13.48-13.58 s just after the crash in discharge No. 26087.

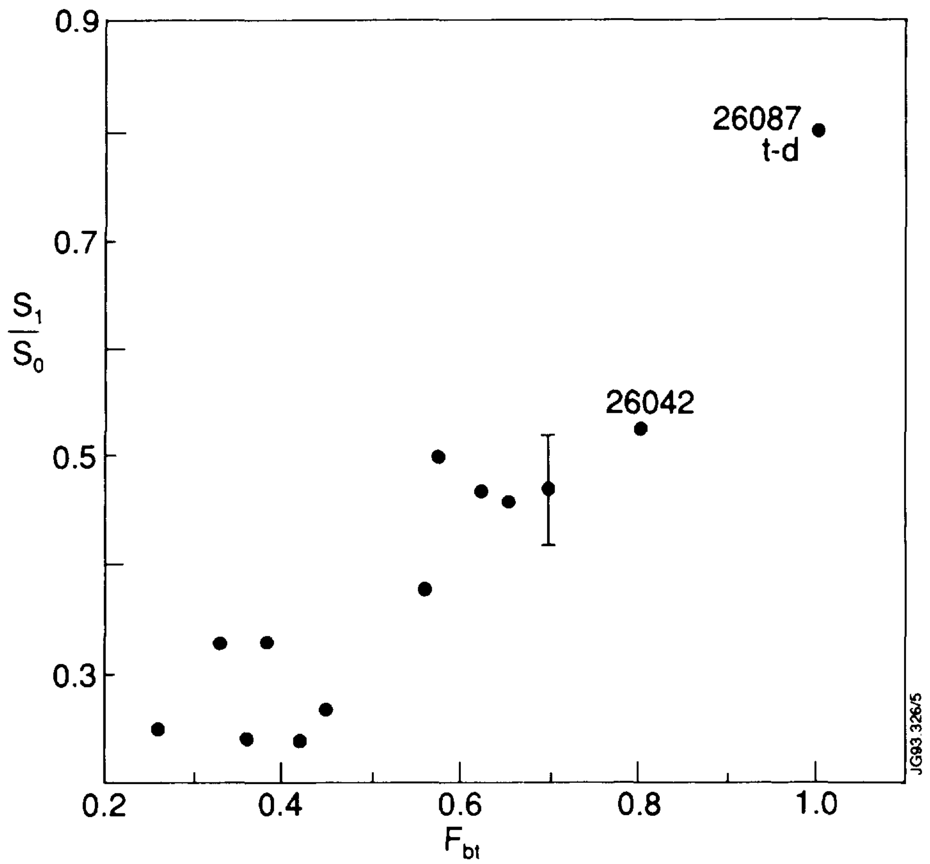


Fig. 12. The ratio of the axial emissivity (S_1) just after the crash to (S_0) just before the crash, versus the fractional contribution of beam thermal fusion to the 2.5 MeV neutron emissivity on axis just before the sawtooth crash, defined as F_{bt}. The 2.5 MeV neutron data from discharge No. 26042, and the 14 MeV neutron data from discharge No. 26087 are shown for F_{bt} values of 0.8 and 1.0 respectively.

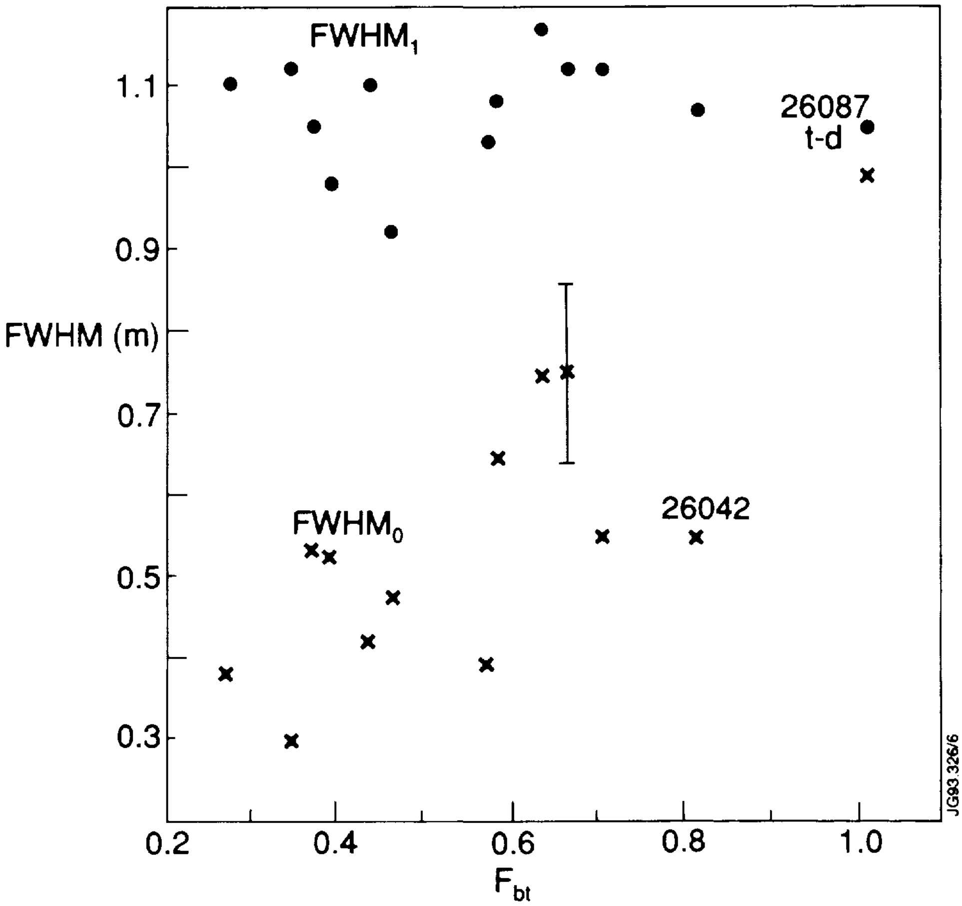


Fig. 13. The Full Width Half Maximum of the emissivity profile in the midplane ($FWHM_0$) just before the crash (x), and ($FWHM_1$) just after the crash (•), versus the fractional contribution of beam thermal fusion divided by the total calculated 2.5 MeV neutron emissivity from d-d fusion on axis just before the sawtooth crash (F_{bt}). The 2.5 MeV neutron data from discharge No. 26042, and the 14 MeV neutron data from discharge No. 26087 are shown for F_{bt} values of 0.8 and 1.0 respectively.