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15 MeV Proton Emission from JET Plasmas Exhibiting Sawtooth Behaviour: Results and Interpretation

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Abstract

A proton spectrometer has been installed and operated on JET with the objective of measuring the energy spectrum of 15 MeV protons produced in ^3He -d reactions under conditions of ICRF heating. The proton emission is observed to be briefly but strongly enhanced at the moment of a sawtooth collapse. A convincing explanation is proposed for the proton energy spectrum recorded between sawtooth collapses. The interpretation of the spectra recorded at the collapse itself is more contentious, nevertheless it is clear that a momentary radial drift for the energetic particles is required as well as a significant alteration in pitch angle.

1. Introduction

A general description of the 15 MeV proton measurements has been provided in a previous paper [1]. The purpose of the present study is to explain the observations recorded during ICRF heating of the plasma with ^3He minority ions. The most striking feature of the recorded data is the very strong proton count-rate detected at the moment of collapse of the sawtooth oscillation (Fig. 1). Measurements of the proton energy spectra proved rather more difficult due to excessive count-rates, but a few reliable spectra were obtained and these were found to display some at first sight surprising features for which explanations are proposed.

2. Experimental data

Experiments using the proton spectrometer were conducted on JET during May 1985. The plasma conditions were as listed in Table I, being typical for ICRH heating on axis with minority ^3He ions. With a plasma current of 2.7 MA, even the fastest fusion reaction products are confined to a large extent if they are produced within the central region of the plasma (defined to be within the $q = 1$ flux surface). Under these conditions the only 15 MeV protons which can reach the detector are those originating at a minor radius in excess of $a/3$, well outside the $q = 1$ surface.

In the absence of RF heating, 15 MeV protons can be produced by d- ^3He reactions between ions in the bulk plasma and by ^3He '-d reactions where the ^3He ' is a fast reaction product of a preceding $\text{d} + \text{d} \rightarrow \text{n} + ^3\text{He}'$ reaction. The measured energy spectra (Fig. 2a) are readily explained in terms of prompt loss 15 MeV protons.

For discharges in which low RF heating power was applied (i.e. 0.5–0.8 MW), the count-rate in the detector was similar to that observed during ohmic heating only, except for extra counts which are recorded in bursts as shown in

Fig. 1b. These bursts coincided with the sawtooth collapse and the count-rate decay time was of the order of twenty milliseconds. The corresponding proton spectra, Fig. 2b, were accumulated in 1 sec time bins and therefore encompassed several sawtooth collapses. They display an appreciable broadening (1.2 to 1.8 MeV) and a clear downward shift of approximately 0.3 to 0.6 MeV from the value of 14.6 MeV recorded during the ohmic part of the discharge (Fig. 2a). Spectra of this type were observed over a series of discharges with count rates in the detector varying from 20 to 2000 c s^{-1} . These discharges will be referred to as “Low-RF” in the following discussion.

For discharges with higher RF power (1.0 to 2.0 MW), a very high flux of protons reached the detector. The sawtooth features observed at lower powers were still present, but some infilling now occurred, see Fig. 1c and 1d. At these high RF powers, the sawtooth period becomes appreciable and some spectra accumulated at the start of the RF heating period did not include any sawtooth crashes. Such a spectrum, Fig. 2c, displayed a fairly narrow peak of width 0.6 to 0.8 MeV which was shifted upwards by about 1.8 MeV. Subsequent spectra in the same ICRF heated discharge which included several sawtooth crashes, of which Fig. 2d is typical, can be interpreted as the superposition of the two types mentioned above. Only four discharges were obtained which displayed these features because subsequent discharges were at still higher RF power and count-rate saturation effects were encountered. For convenience, the four discharges will be referred to as “High-RF”.

To summarize, there are two observations to be explained

(i) The appreciable broadening and downwards shift of the 14.6 MeV protons which are detected at the moment of the sawtooth crash, and

(ii) The modest broadening and upward shift characteristic of protons detected between sawtooth crashes.

All the spectra obtained during RF heating exhibit a high level of low energy events due to various background radiations, such as neutrons and gamma-rays, in addition to electronic noise. A new spectrometer incorporating a compensation detector, blind to protons, is now under construction and will be used in an attempt to clarify this situation.

3. Interpretation of the high-RF case

The upward-shift in peak energy observed at the start of the RF heating period can be simulated with a classical model.

It is well known that in the minority heating scheme the power is deposited mainly on the minority species, creating an anisotropic high energy tail with velocities mainly perpendicular to the magnetic field [2]. With increasing power, both

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Table I. Conditions under which the observations were made

Toroidal field	3.1 T
Plasma current	−2.7 MA
Central density	4.2×10^{13} electrons cm^{-3}
Central temperatures	3.2 keV — electrons
(during RF heating)	2.4 keV — ions
Plasma constituents	70% — deuterium, 5% — ^3He
($Z_{\text{eff}} = 3$)	Main impurity: C
Major radius	$R_0 = 3.1$ m
Minor radius	$a = 1.2$ m
Elongation	1.45
ICRF heating (30 MHz)	Resonant for ^3He on axis
RF power	Between 0.4 and 2.0 MW
Typical sawtooth period	100 ms
15 MeV proton slowing down	220 ms
time (15–10 MeV)	
300 keV ^3He slowing down time	45 ms
300 keV fusion weighted slowing	~ 15 ms for 90% of the reaction
down time	probability

density and mean energy of the tail ions increase. We can represent the distribution function of the ^3He ions by a Maxwellian of temperature $T(^3\text{He}) = T(\text{d})$ for the bulk of the population and a perpendicular velocity tail at a higher temperature. To evaluate the importance of this tail, we assume that the RF power absorbed by the tail equals the plasma drag.

Fig. 1. Count rate in the proton detector as a function of time during ^3He minority heating. When the RF power is low ($0.5 \text{ MW} \leq P_{\text{rf}} \leq 0.8 \text{ MW}$) protons reach the detector mainly in bursts at the moment of sawtooth collapse as shown on the lower trace, B. The upper trace is typical for discharges with RF power exceeding 1 MW and has been subdivided into two parts: C and D. During the initial period C the signal is continuous whereas bursts appear to be superimposed during the final period D, which lasts for the major part of the RF heating period.

Fig. 2. Typical proton spectra as measured during an ohmically heated discharge (trace A) and during the periods B, C and D defined in Fig. 1.

In the literature, calculations are usually performed in a dimensionless geometry. A trajectory effect is an essential ingredient for the model used here. Fast particles having nearly perpendicular velocities move on “banana” trajectories with their turning points in the RF resonance layer, as illustrated in Fig. 3. The particles will cross the torus mid-plane with pitch angles of about 70 or 110 degrees, the precise angles being dependent on particle energy, mean radius and direction of travel. The two examples of banana orbits show in Fig. 3 are chosen because they pass the same point P, as well as having turning points which lie in the RF resonance layer. The fusion protons from ^3He –d reactions taking place at the point P and being emitted with any particular pitch angle will possess energies determined by the pitch angle of the parent ^3He ions (74 and 106 degrees in the above examples).

^3He distribution functions have been calculated for each point lying on orbits of protons which can reach the detector (for convenience, one may refer to the line-of-sight of the detector) by evaluating the location of the turning points (if they exist) as a function of velocity and equating the power absorbed in the resonance layer with the plasma drag. The power profile [3] was assumed to be rather peaked both in major radius (the resonance layer being a constant radius line) and in azimuth (due to focusing of the antennae). A typical distribution is shown in Fig. 4a, plotted as a function of pitch angle. Fig. 4b shows the same distribution weighted

Fig. 3. Calculated orbits for ^3He ions being heated in the resonance layer where $V = V_\perp$ and for a 15 MeV proton being born at the reaction point P with a pitch angle such that it can reach the detector. At birth all proton pitch angles are permitted (although with different probabilities due to the high ^3He energies).

with the ^3He -d fusion cross-section. The tail containing less than 1% of all the ^3He particles is responsible for more than 99% of the fusion reactions. The ^3He particles with midplane pitch angles of about 110° clearly do not contribute appreciably to the observed signal. Fig. 5 gives for each midplane radius the calculated fusion rate, the number of particles reaching the detector (see discussion of detector efficiency below), the mean energy in the distribution and the mean energy of the particles involved in fusion reactions. A fusion rate of 10^6 s^{-1} corresponds to a fusion power of $3 \times 10^{-6} \text{ W}$, which is very low compared with the RF power.

A proton energy spectrum was next constructed by summing over the elementary spectra. The elementary spectrum (curve A) presented in Fig. 6 has been derived from the distribution of Fig. 4. It displays peaks at both high (16 MeV) and low (14 MeV) energies and thus reproduces the double peak characteristic of perpendicular distributions for reacting particles and perpendicular observation for fusion products. Only the high energy peak was observed in our measurements.

Calculation of the detector efficiency (i.e. the number of particles observed per fusion event in the plasma) shows that there is a very strong dependence of particle energy in the vicinity of the region of observation. This efficiency is shown in Fig. 7 as a function of midplane radius for three values of proton energy. Only those protons with energies above 15 MeV can reach the detector if emitted within a minor radius of 40 cm. Correcting the spectrum shown in Fig. 6a for the energy dependent efficiency (curve B) transforms it to the final spectrum C.

An integration from $r = 30 \text{ cm}$ (below which the detection efficiency is zero) to $r = 45 \text{ cm}$ yields a proton energy spectrum which, as shown in Fig. 8, is found to be in agreement with the high energy peak observed experimentally. This good fit is obtained for a total power of 900 kW delivered to

Fig. 4. (a) Example of an RF heated ^3He distribution function as calculated in the midplane of the machine. Lines of equal intensity are shown as a function of pitch angle and energy. On adjacent lines the intensity differs by one order of magnitude. (b) Reactivity curves obtained from the distribution function shown above by folding in the ^3He -D ion cross-section.

the ^3He ions, deposited within 20 cm radius and 33 cm azimuth (using Gaussian profiles). The central power is about 0.9 W cm^{-3} . Keeping all parameters constant except for the power, which is halved, drops the count-rate in the detector from nearly 4500 cs^{-1} down to 30 cs^{-1} , which explains the absence of infilling for the "Low-RF" experimental data.

In conclusion, it is established that during RF heating a strong near-perpendicular velocity ion tail with a mean reacting energy of 100 to 300 keV is formed close to the centre of the plasma. This is consistent with observations made in previous experiments [4].

4. Proton emission at the sawtooth collapse

The observation of a high count-rate coincident with the sawtooth collapse implies that either the confined 15 MeV protons from RF-heated ^3He -d fusion reactions or the energetic ^3He ions themselves are in some way being ejected by the collapse from within the $q = 1$ region to the outside where they enter the line of sight of the detector. That the sawtooth behaviour produces a strong effect on the ions in a thermal

Fig. 5. Showing the radial dependences for: (a) ^3He -d fusion reaction rate; (b) Number of protons reaching the detector; (c) Mean energy of ^3He ions divided by bulk ion temperature T_i ; (d) Mean energy of reacting ^3He ions.

plasma is also demonstrated by the fact that the abrupt drop of the neutron flux is much higher than would be expected from a simple thermal cooling of the deuterium [5] and by the observation [6] of bursts of fast (6 keV) particles being ejected in to the outer regions of PDX in coincidence with the sawtooth collapses. Such a radial movement is easily understood on the basis of the recent model of the sawtooth effect proposed by Wesson [7]: during the collapse the magnetic field lines become rearranged, thereby moving the charged particles to the $q = 1$ boundary, and a slow (10–20 ms) reconnection occurs during the early phase of the sawtooth recovery.

It cannot be disputed that the central region of the plasma under conditions of strong RF heating will contain very

Fig. 6. (a) Calculated proton spectrum for the ^3He distribution function shown in Fig. 4(a). (b) Detection efficiency. (c) Spectrum of protons reaching the detector.

Fig. 7. Energy dependent detection efficiency.

energetic ^3He ions and confined 15 MeV protons from ^3He -d reactions. Both types of particle will be ejected by the sawtooth collapse. We are now faced with a choice. The detected protons are either delayed-loss protons hitherto confined or prompt-loss protons produced by the displaced ^3He ions in further reactions whilst slowing down. Quite possibly, both sources contribute.

Fig. 8. (a) Calculated spectrum and (b) measured spectrum of continuously emitted proton (in between sawtooth collapses).

Any serious explanation must be consistent with the observation of a broad width and downwards shift of the proton peak corresponding to the sawtooth collapse, as for the "Low-RF" case. Consider first the ejected RF-heated ^3He ions. In order to produce the observed energy spectrum the parent ^3He ions are required to possess a mean reacting energy of 200 to 250 keV and a mean pitch angle of around 30 to 45 degrees. Larger angles would not be consistent with observation since they would give a larger spectral width and a smaller shift. The heated tail ^3He ions however have pitch angles between 70 and 110 degrees and therefore a change in pitch angle is required. This pitch angle scattering must also take place during radial shift which throws them from the plasma centre into the region seen by the detector (otherwise the energy spectrum would resemble curve A in Fig. 6). The ^3He ions now being at larger radius, although with more parallel velocities, are no longer subject to the RF heating effect and will undergo fusion reactions as they slow down in the plasma on a timescale of 15 ms, which is entirely consistent with the decay of the observed signal. The objection to this hypothesis is the large change in pitch angle. Such an unusual effect of the sawtooth collapse has never before been observed but the main theories of the sawtooth phenomena neither anticipate nor forbid it. Regardless of the possible pitch-angle change, prompt loss protons from ejected ^3He interactions with deuterons must be observed; approximately 0.004% of the ^3He ions will undergo fusion reactions whilst slowing down.

We now turn to the possibility that the protons detected at the sawtooth collapse were previously confined. As the 15 MeV proton slowing down time is several hundreds of milliseconds, the broad width and downwards shift of the observed spectrum is consistent with the energy loss suffered between sawtooth collapses. Since the RF heating maintains the parent ^3He ions at high energies, about 0.05% of them will undergo fusion reactions during a sawtooth period and most (> 50%) of the 15 MeV protons produced will be confined. The potential source of protons is thus one order of magnitude greater than in the case discussed previously. Of course, there must also be a change in pitch angle at the time of the sawtooth collapse because the angle must not be too large if the proton is to be initially confined and must be about 80° after the collapse if it is to reach the detector. The implied pitch-angle change is not nearly so large as was

considered previously. The main objection to this explanation is that the duration of the collapse is less than 1 ms whereas the observed signal has a duration of 10 ms or more. The timescale for the loss of protons which have become unconfined is less than one microsecond. Of course, if the model of Wesson [7] is correct in its essentials, then the magnetic reconnection takes place after the collapse on a timescale of 10–20 ms and it is during this period that the pitch-angle changes would be expected. It is therefore interesting to conjecture that the duration observed for the proton signal is a measure of the reconnection time. Further pitch-angle scattering would take place whilst the remaining confined protons slow down and a continuous, but relatively weak, contribution from this source would be expected.

5. Conclusion

The 15 MeV proton emission from the JET plasma unequivocally demonstrates that the sawtooth collapse has a strong effect on the orbits of the fast confined ions. This takes the form of a combination of a radial shift at the collapse accompanied by a change in pitch-angle possibly during the magnetic reconnection. Both shift and pitch-angle change are not inconsistent with the latest theory of the sawtooth collapse. Similar effects may be expected for the α -particles produced in tokamaks operating near to ignition conditions and would become manifest as non-classical delayed losses.

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