EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET Pellet Ablation Studies with ECE and Fast Spectrometer

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*: See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).

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INTRODUCTION:

- Pellet Injection on JET can take place along either high field or low field launch trajectories - trajectories similar to those which would be employed for pellet fuelling of next generation Tokamaks.
- Operation of a new JET high time resolution Pellet Spectrometer (JPS) combined with high time resolution radial profiles measurements of electron cyclotron emission (ECE) provide JET with a new capability to study details of pellet ablation and the redistribution of pellet mass.
- Experiments described here demonstrate in separate initial studies the capability on JET for time resolved measurements, during the pellet ablation process, of both pellet cloud electron density and pellet mass redistribution.
- The cloud electron density is inferred from the Stark broadening of the deuterium spectral lines. Data is available for the high field side launch trajectories which can be viewed by the spectrometer.
- Mass redistribution is inferred from changes in the electron temperature profiles which are themselves inferred from ECE data. This data can be obtained for all JET pellet trajectories.
- Modelling of the pellet ablation and mass redistribution is being done using the Tokamak Simulation Code (TSC).

RESULTS:

High time resolution spectrometer measurements indicate cloud density in the range from ~3 x 10^22 m^-3 to ~3 x 10^23 m^-3 for the H-mode target plasmas studied in these first experiments. Cloud density is found to increase within this range as the pellet penetrates more deeply into the target plasma.
High time resolution radiometer measurements show electron cyclotron emission is not cutoff during pellet events on JET when low density target plasmas are used. Evolution of the temperature profiles during a HFS pellet event indicate a cooling wave can precede the pellet radial motion reducing the electron temperature encountered by the pellet. Interpretation of the cooling wave will require detailed study but redistribution of the pellet mass is likely to play a significant role. Evolution of the temperature profiles during a LFS pellet event indicate no cooling wave precedes the pellet. Rather, cooling of regions behind the pellet during the entire time of the pellet event suggest that mass is redistributed to larger major radius as the pellet is ablated along a LFS trajectory.
TSC modelling of pellet ablation using standard ablation rates dependant on electron density, temperature and pellet size, dN/dt = (8.89x10^15) * Te^5/3 * ne^1/3 * rpel^4/3 [1], reproduce the JET LFS case studied here using temperature and density present prior to pellet injection. For the HFS case modeled here using standard ablation rates however, pre-cooling of the plasma by mass ablated earlier during the pellet event was used. Although pre-cooling as currently implemented in TSC did improve agreement between measured and calculated pellet lifetime, mass redistribution in the HFS case is not yet fully modeled.

NEXT STEPS:

In coming pellet experiments, combined measurements of cloud density and electron temperature are proposed using JPS and ECE instruments simultaneously. Such measurements will be taken over a range of target plasma conditions. The relationship between cloud electron density and the radial extent of the pellet mass redistribution will be examined. In addition, the TSC modelling capability for radial mass redeposition will be further developed and compared with the observed temperature profile evolution and with current redistribution models.

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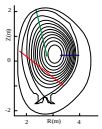
HIGH TIME RESOLUTION JET PELLET SPECTROMETER

Earlier measurements of pellet emission spectra on JET [2] have shown a broadening of the deuterium lines similar to that seen on other Tokamaks [3]. These first measurements integrated the spectrum over the full pellet event. In order to study the event in detail, a new high time resolution JET Pellet Spectrometer (JPS) has been installed. The JPS is a 300mm Czerny-Turner spectrograph. The instrument can acquire multiple spectra during a pellet event with integration time as low as 100microsec. The instrument is capable of viewing both Dalpha and Dbeta lines simultaneously with ~1nm spectral resolution. The instrument can also view these lines individually but not simultaneously with ~0.5nm resolution. During the experiments reported here the Dalpha line was generally observed with 500microsec integration time. Measurements show a broadening of the deuterium emission lines. This broadening is taken to be Stark broadening [4] associated with the high electron density in the low temperature plasma near the pellet. For these initial measurements, the electron density is obtained from the FWHM of the Lorentzian line profiles using the relationship:

ne (m^-3) = (FWHM(nm) - 0.168) / 8.45 x 10^-24 .

The density to width conversion is obtained by simple extrapolation between data sets in the literature at lower and higher density [5] and [6] ignoring any temperature effects. The instrument function is taken into account when determining the line width.



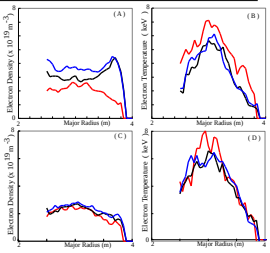
On JET, pellets can be injected along one of several trajectories shown in figure 1. Currently the JPS has direct views of the HFS and VHFS trajectories. During the experiments reported here the HFS trajectory was studied.

Figure 1: JET pellet trajectories.
Black: Horizontal mid-plane trajectory from the Low Field Side (LFS).
Red: High Field Side inner wall launch trajectory (HFS) - pellets injected at mid-plane but aimed below the plasma magnetic axis due to mechanical constraints.
Green: new JET vertical High Field Side trajectory (VHFS) - pellets injected above mid-plane to the high field side of the magnetic axis and directed downward toward the magnetic axis.

PLASMA DETAILS - HIGH TIME RESOLUTION ELECTRON TEMPERATURE MEASUREMENTS

Figure 6:
Approximate electron density profiles prior to and following pellet injection: (A) HFS JPN49676, (C) LFS JPN49675.
Approximate electron temperature profiles prior to and following pellet injection: (B) HFS, (D) LFS.
Timing: **Red**: 45.377sec;
Black: 45.627sec; **Blue**: 45.877sec.

High time resolution measurements of electron temperature were made during pellet injection experiments into TFB plasmas. Both LFS and HFS pellet trajectories were utilized. Two pellets were injected into each target plasma one at ~45.6 sec (5.6sec) and a second at 45.8 sec (5.8sec). Although pellet target plasma densities in these cases are lower than that present in the H-mode case studied with the JET Pellet Spectrometer, target plasma electron temperatures within the region from 3.6 to 3.9m reached by the pellet are roughly comparable. In particular, pre-pellet electron temperature greater than or equal to 2keV is present in all cases.



PLASMA DETAILS - FAST SPECTROMETER MEASUREMENTS

Figure 2 - (A) Approximate electron density profiles prior to pellet injection.
(B) Approximate electron temperature profiles prior to pellet injection.
JET Pulse 55340. **Red**: 57.88sec;
Black: 58.63sec; **Blue**: 60.38sec.

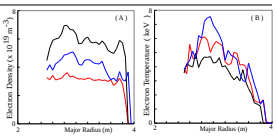
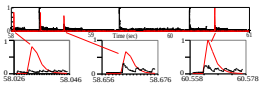


Figure 3: **Black:** Divertor Dalpha emission showing ELM behavior and timing. **Red:** Pellet Dalpha emission showing pellet timing.



Initial spectrometer measurements were made in JET H-mode plasmas heated by combined NBI and RF. Pellets at 58.032, 58.664, 59.954 and 60.564s were observed with the instrument. All pellets were nominal 4mm cylinders injected at ~150m/s along the HFS trajectory. ELM conditions differed for the pellets as shown in the figure. The pellet at 58.032s was injected into plasma with high frequency ELMs of small amplitude. The pellets at 58.66s and at 60.56s triggered a strong ELM on entry into ELM free plasmas. The pellet at 59.954s appeared to be only a fragment.

ELECTRON TEMPERATURE CONTOURS - HIGH FIELD SIDE PELLETS (HFS)

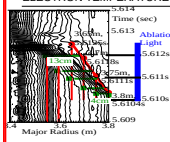
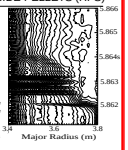


Figure 7 Contours of electron temperature spanning the ~ 3ms period of pellet ablation as indicated by the presence of pellet ablation light. First pellet event - 5.609 sec, JPN 49676, TSC Run B09a.

Figure 8 Contours of electron temperature spanning the period of the second pellet event - 5.862 sec, JPN 49676.

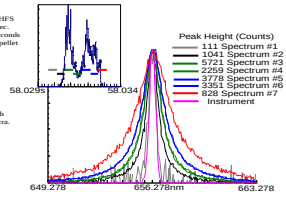
Although the pellet density perturbation is a highly localized event which takes generally ~ 1ms or more (plasma sound speed) to assume a toroidally and poloidally symmetric form, the electron temperature perturbation linked by adiabticity with the pellet densityperturbation is symmetrized in 10's of microseconds (electron thermal conduction time scale) [7].



Pellet mass deposition on a flux surface can therefore be inferred generally from high time resolution measurements of electron temperature. In the experiment reported here, measurements of electron temperature begin at a radial position of 3.8m ~ 0.07m inside the last closed flux surface measured on the horizontal plasma mid-plane. In Figure 7, the **RED** dots locate the nominal pellet in time and space when the HFS trajectory is mapped to the measurement location on the low field side. Compression of flux reduces the effective radial pellet speed below its nominal value of ~100m/s (**BLACK** line) at the actual pellet HFS location. Constant pellet speed is assumed. The **GREEN** squares identify the radius at which a decrease in electron temperature is first observed for each time as the pellet moves along the red track. The separation of the green and red points indicates that a cooling of the plasma occurs in front of the pellet (smaller radius) presumably due to mass redistribution. The radial extent of this redistribution increases from ~0.4 to 0.13m as the pellet moves deeper within the plasma. During this pellet motion the temperature encountered by the pellet increases and the cloud density as measured by the spectrometer in separate discharges also was observed to increase. Figure 8 shows the temperature response to the second pellet. A more extensive early radial perturbation of the temperature is observed in this case when compared with the first pellet. Future simultaneous measurements of line width (spectrometer) and temperature contours (ECE) will examine correlations between variations in the evolution of the temperature profiles and the cloud electron density.

TYPICAL SPECTRAL SEQUENCE OBTAINED DURING A SINGLE PELLET EVENT

Figure 4: Normalized spectra for the HFS pellet injected in JPN55340 at 58.03sec. Spectra are integrated for 500microseconds yielding 7 spectra during the ~3.5ms pellet event. The time of each spectrum is indicated by the colored bars in the figure insert showing the time evolution of the Dalpha light near line center. The relative peak height of each spectrum reflects the time evolution of the line. The normalized instrument function is shown for comparison with the width of the measured pellet spectra.



The spectral time sequence shows an increase in spectral width as the pellet penetrates more deeply into the plasma. This behavior is shown in figure 5 for all three pellet events.

ELECTRON TEMPERATURE CONTOURS LOW FIELD SIDE PELLETS (LFS)

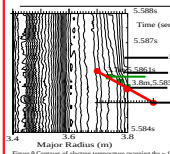


Figure 9 Contours of electron temperature spanning the ~ 1ms period of pellet ablation as indicated by the presence of pellet ablation light. First pellet event - 5.585 sec, JPN49675, TSC Run M04_5.

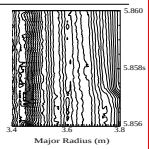


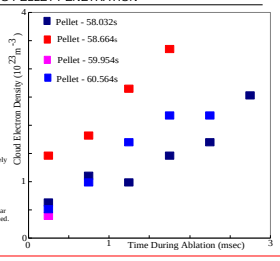
Figure 10: Contours of electron temperature spanning the period of the second pellet event - 5.858 sec.

Measurements of electron temperature begin at a radial position of 3.8m ~ 0.07m inside the last closed flux surface measured on the horizontal plasma mid-plane. In Figure 9, the **RED** dots locate the nominal pellet in time and space. In this case injection is along a radial trajectory located on the plasma mid-plane. The effective radial pellet speed is now 150m/s and that speed is assumed constant. The **GREEN** squares identify the radius at which a decrease in electron temperature is first observed for each time as the pellet moves along the red track. The coincidence of the green and red points indicates that no cooling of the plasma occurs in front of the pellet (smaller radius). Mass redistribution in fact appears to occur to larger major radius as discussed in the next figure. Figure 10 shows the temperature response to the second pellet. A radial perturbation similar to that of the first pellet is seen in this case.

EVOLUTION OF CLOUD ELECTRON DENSITY DURING PELLET PENETRATION

Figure 5: Time evolution of pellet cloud electron density. Density is obtained from measured pellet spectra FWHM. Integration time 500microseconds.

Cloud Density is observed to increase with penetration depth (time). A density of >~ 0.5 x 10^23 m^-3 is established in the lower temperature region at the plasma edge. As the pellet moves deeper into the plasma the cloud density is seen to rise by roughly a factor of 3 to 4 to >~2 x 10^23 m^-3 . Since the pellet life time is some 3ms at a radial speed of ~100m/s the pellet penetration is roughly 30cm. As can be seen roughly from figure 2 over this radial distance on the outside of the plasma electron temperature of the pre-pellet target plasma rises by approximately the same factor from roughly 500eV to 1500 to 2000eV. These pre-pellet temperatures may not actually be encountered by HFS pellets as is discussed in the ECE measurement portion of this poster. None the less, the electron temperature encountered by the pellet does appear to increase even when dilution effects are included.



STATUS OF TOKAMAK SIMULATION CODE (TSC) CALCULATIONS HFS AND LFS PELLET EVENTS AND ELECTRON TEMPERATURE MEASUREMENTS

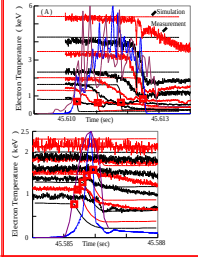


Figure 11: Measured and calculated electron temperature at selected radial positions, (RED and BLACK curves), measured pellet ablation light (BLUE curve) and calculated ablation rate (MAGENTA curve) as a function of time.
(A) - HFS launch pellet - JPN49676, TSC-B09a
(B) - LFS launch pellet - JPN49675, TSC-M04_5

TSC currently uses two empirical models to calculate pellet penetration and mass deposition. In the case of HFS launch ablated pellet mass is deposited in the region immediately surrounding the pellet. A portion of this region is located in front of the pellet. This ablated mass is permitted to adiabatically cool the plasma which the pellet then encounters. Using this model the pellet encounters temperatures below those present in the pre-pellet target plasma and pellet life times and penetration are calculated to be similar to the observed value. Measured temperatures displayed in figure 11 confirm that such a process does occur for HFS injection. The temperatures encountered by the pellet in both the HFS and LFS cases are identified by the RED squares. The time behavior of the measured temperatures however, indicate that the mass deposition occurs over a larger region then is currently incorporated in the TSC calculation. In the case of LFS launch ablated pellet mass is deposited over a region extending from the pellet location outward in the radial direction beyond the last closed flux surface. Mass deposited outside the last closed flux surface is lost from the plasma. No mass is deposited in front of the pellet so no pre-cooling of the pellet target plasma occurs. For pellets which do not penetrate to the plasma core, LFS launch pellet life times and penetration are calculated to be similar to the observed value. By adjusting the impact of the effective volume outside the last closed flux surface the measured radial distribution of the deposited mass can be approximated [7]. In the JET case shown the impact of this outward mass redistribution can be seen in the continued drop of the plasma temperature at radii outside the location of the moving pellet.