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INTRODUCTION

The stored energy in JET discharges is obtained by various methods. Typically, these are found to agree to within ~1MJ. This has important implications for scalings to ITER, which use the confinement time on JET as a key parameter.

1. LEVEL OF CONSISTENCY

Three principal methods of obtaining the stored energy are considered here. In the *diamagnetic method* [1] (energy referred to as W_{dia}), the toroidal flux produced by the plasma is measured and combined with Shafranov integrals obtained from a plasma equilibrium reconstruction or from a boundary extrapolation; in the *MHD method* (W_{MHD}) the pressure profile from an equilibrium reconstruction is integrated; and in the *kinetic method* (W_{kin}) the pressure profile, obtained from density and temperature profile measurements, and mapped over the plasma cross-section with an equilibrium reconstruction, is integrated. This calculation excludes energy carried by fast particles. In order to compare the kinetic method with the other methods, the fast particle energy is calculated from a Monte Carlo simulation of the Fokker-Planck equation [2], and added to the energy from the kinetic method.

An example, comparing energy from the diamagnetic and kinetic methods, is shown in Fig.1. Two versions of the kinetic calculation are shown, one after ($W_{kin\ tot}$) and the other before ($W_{kin\ thermal}$) the addition of fast particle energy, and two versions of the diamagnetic calculation are shown, one in which the Shafranov integrals are obtained from a boundary extrapolation with the XLOC code [3] ($W_{dia\ XLOC}$), and the other from a full equilibrium reconstruction from the EFIT code [4] ($W_{dia\ EFIT}$). Note that the two diamagnetic methods are in good agreement, despite the different approach to obtaining the boundary. The kinetic method gives energies ~1-1.5MJ lower than W_{dia}. The discrepancy is significant even during the ohmic phase (t < 15s), when there are virtually no fast particles, showing that the role of fast particles is not central to the discrepancy. W_{MHD}, also shown, gives an energy ~0.5MJ lower than W_{dia}.

2. INVESTIGATION

The diamagnetic flux from the plasma is a small component of the raw measurement, due to the presence of the large externally applied toroidal field (~5,000 times the desired measurement accuracy), the effects of poloidal vessel eddy currents and thermal expansion of the TF coil (both comparable to the diamagnetic flux), and pick-up of poloidal field due to imperfections in sensor geometry, etc. It is well established that in dry runs with only toroidal field, the residual flux, after all corrections, is small, contributing no more than 250kJ to the energy measurement [5]. Two mechanisms have been identified which could potentially change this situation in the presence of plasma. As discussed below, we consider it unlikely that these are significant on JET:

(i) Pick-up of the poloidal field generated by the plasma due to imperfections of sensor geometry
We note that there are two independent diamagnetic loops on JET, which give consistent energy measurement, even though one of these loops has significant geometric flaws, which result in poloidal field pick-up. The consistency in the energy suggests that the corrections applied to the flux measurements successfully compensate the effects of poloidal field pick-up. Since this indication is based on observation of the difference in energy between the two diamagnetic loops, it does not preclude the possibility of common pick-up from the plasma on both loops, arising from some systematic installation error.

*(ii) Pick-up of poloidal field (principally the vertical field) due to tilting of the toroidal field coils (and hence the diamagnetic loop which is mounted on a toroidal field coil) under the influence of **J**x**B** forces*
To test for this possibility, a dry run was executed with strong toroidal and vertical fields energised simultaneously, in which a tilting force was generated on the TF coil equivalent to ~60% of that in the plasma Pulse No: 52009, as shown in Fig.2. If tilting of the TF coil is to account for the energy discrepancy shown in Fig.1, then a flux pick-up of ~7mWb, about half that needed to account for an energy discrepancy of ~1MJ in Pulse No: 52009, should appear in the dry run, correlated with the vertical field waveform. As seen in Fig.2, there is no such pick-up on the flux signal (after standard corrections). The conclusion, that such pick-up is negligible, is further supported by mechanical modelling of the TF coil (see e.g. [6]), which indicates that the coil stiffness is such as to restrict the resulting flux error to ~0.5mWb.

The effect of the uncertainty in the temperature and density profile measurements on the energy from the kinetic method has also been evaluated. The result is found to be in the range of 200-300kJ. This includes the effects of random, as well as several possible systematic errors (e.g. in the absolute position of the density profile and in it’s peakedness). An example is shown in Fig.3, where the uncertainty in the density and temperature measurements is taken to be the difference in the profiles from different diagnostic techniques, at the extremes of their error bars.

Another possible source of errors is the process of equilibrium reconstruction, involving standard magnetics/diamagnetic measurements, processed by equilibrium codes. Figure 4 shows a plot of the discrepancy between W_{MHD} and W_{DIA} vs. β_{pol}. A trend of increasing discrepancy with decreasing β_{pol} is clearly visible, indicative of errors arising from the equilibrium reconstruction process, when Shafranov integrals and diamagnetism become comparable at low β_{pol}. To test for such errors the parameters of the equilibrium code (EFIT) were varied, with fixed magnetic measurements as input, to study how constraints in the code affected W_{MHD}. In a case with β_p ~ 0.7 (Pulse No: 55935) this variation was found to be ~300kJ. At low β_p the energy increased by 0.5MJ when the measured diamagnetic flux was used as a constraint. These variations are broadly consistent with the trend in Fig.4, which will also be affected by errors in W_{dia} and anisotropies in fast particle energy, e.g. in RF heated plasmas, since W_{dia} is based on perpendicular energy only.

Figure 5 compares the diamagnetic flux calculated from the codes which calculate W_{MHD} (EFIT) and $W_{kin,}$ (TRANSP), with the measured diamagnetic flux. We see that the TRANSP diamagnetic flux is scattered over a wider range than that from EFIT, and is consistently lower, resulting in a larger discrepancy with respect to W_{dia}. TRANSP performs a separate equilibrium calculation, which is used to map the measured profiles. It appears that this processing is more sensitive to data inconsistencies.

DISCUSSION

Several possible sources of error have been identified which could contribute to the discrepancies observed between three calculations of the stored energy, W_{dia}, W_{MHD} and W_{kin}. The errors between W_{dia} and W_{MHD} show the expected characteristics of errors arising from the process of magnetic measurements / equilibrium reconstruction. When profile data are mapped with an equilibrium reconstruction, to calculate W_{kin}, the discrepancy between W_{kin} and W_{dia} appears to be larger than is accounted for by adding the effects of uncertainties in the equilibrium calculation, profile data and the diamagnetic flux. All these would have to add up at their extreme values to reach the observed discrepancy of 1-1.5MJ. This calls for a more detailed error propagation study in the calculation behind W_{kin}.

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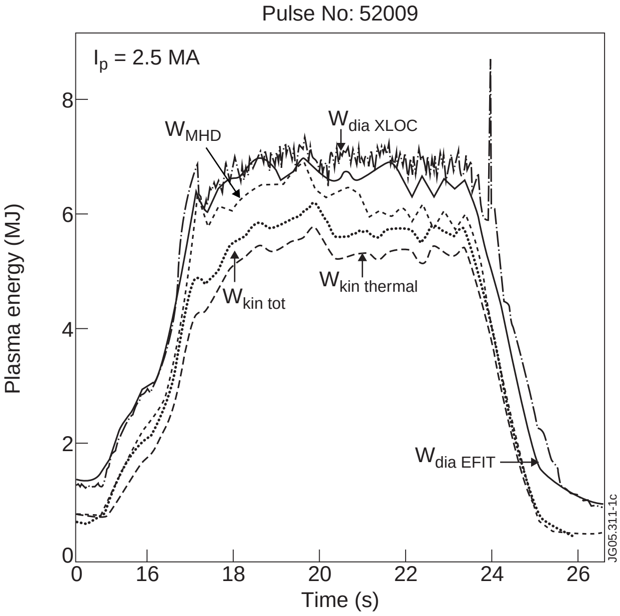

Figure 1: Example of the discrepancy in stored energy calculated by various methods, for Pulse No: 52009.

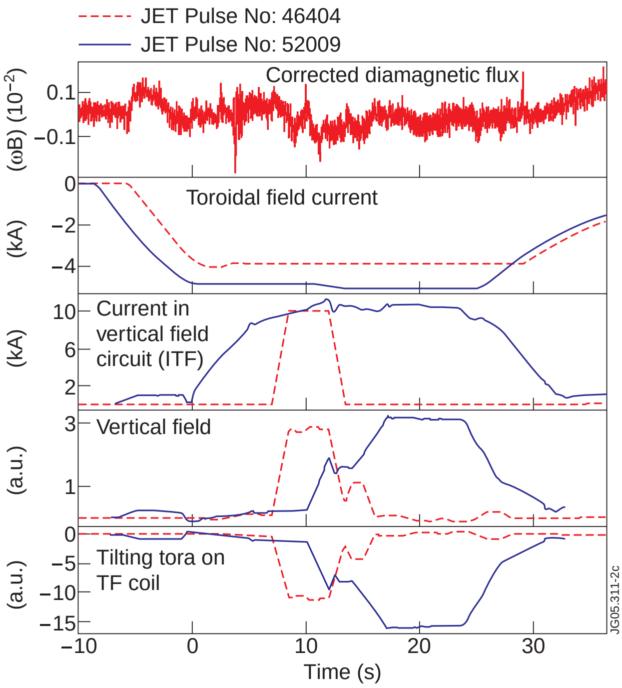

Figure 2: A dry run (in red) with a tilting force on the toroidal field coil equivalent to about 60% of that in the plasma Pulse No: 52009 (in blue). No pick-up of the vertical field is seen on the diamagnetic flux signal in the dry run, after standard corrections.

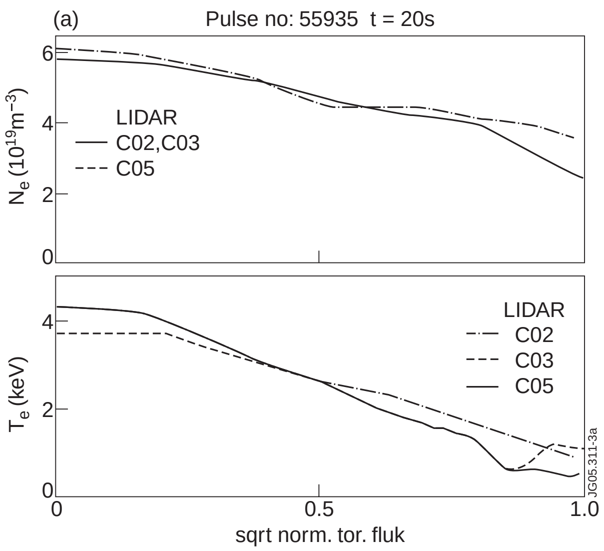

Figure 3(a): Uncertainty in density and temperature profiles used in the kinetic method, determined from measurements made with different diagnostic techniques.

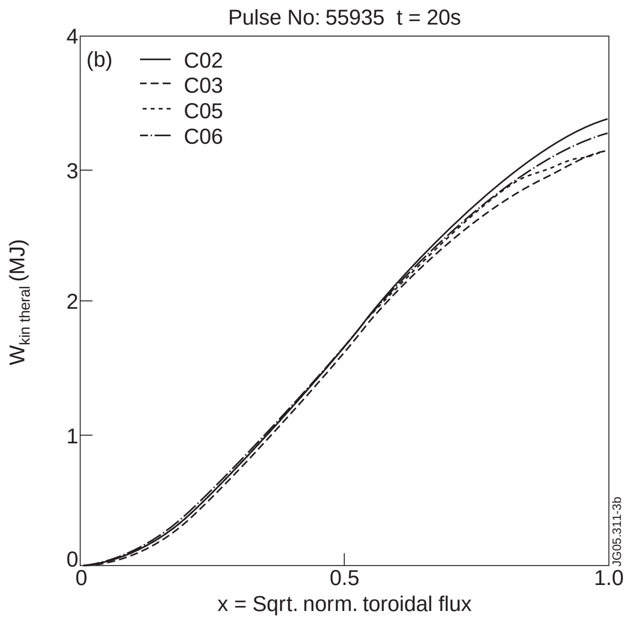

Figure 3(b): Corresponding uncertainty in thermal energy from the kinetic method.

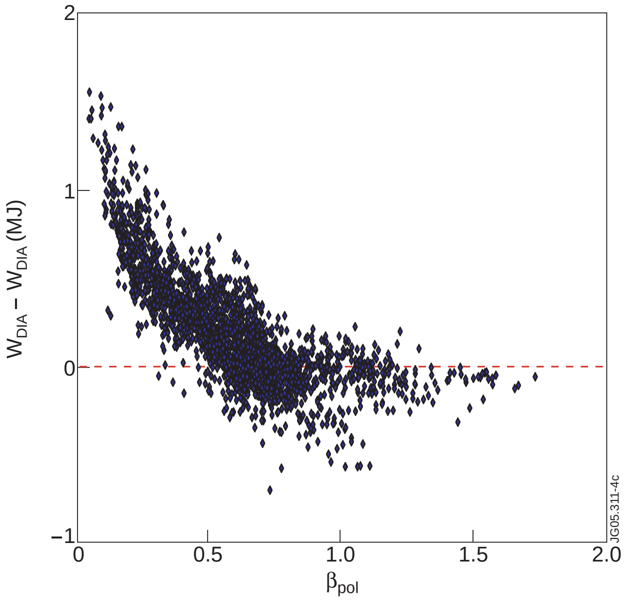

Figure 4: Discrepancy between the diamagnetic method and MHD method as a function of β_{pol}. The trend is consistent with the expected behaviour of equilibrium reconstrection errors.

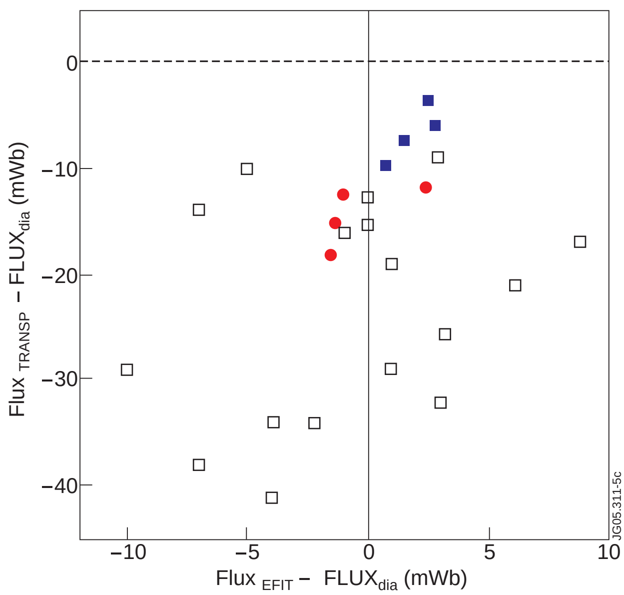

Figure 5: Difference between the diamagnetic flux calculated by the main code behind W_{kin}, and the measured flux, vs. the same quantity using the code behind W_{MHD}. The former has a wider spread and is systematically lower.