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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

Toroidal field coil current measurements presently available at the JET tokamak (Hall probe, Shunt, Rogowski coil and optical fibre) were investigated over 7 years (2008-2014) in order to explain the radial discrepancy between various electron density and temperature profiles. A difference of 0.81-2.43% was found between the optical fibre measurement and the reference toroidal field coil current based on the Rogowski measurements reducing the radial discrepancy by at least a factor of two between electron density and density profiles respectively. Dedicated pulses were carried out in different power supply configurations indicating a quiescent current flowing in the toroidal field circuit (not measured by the Rogowski coils). This current can be a result of an interaction between the remanence current from the flywheel generator converter and the leakage voltage from the static units supplying current to the toroidal field coils.

1. INTRODUCTION

In tokamak plasmas profile measurements of the electron density (n_e) and temperature (T_e) such as reflectometry and electron cyclotron emission (ECE) rely on magnetic equilibrium reconstruction including precise measurement of the total magnetic field for spatial mapping. A systematic error in the toroidal field measurement (up to 2%) is thought to be the source of radial discrepancy between T_e profiles measured by Thomson scattering and the ECE diagnostics. Furthermore toroidal field corrections of up to 6% are routinely applied to n_e profile measurements of reflectometry to match the line integrated edge densities measured by interferometry.

This study investigates the relationship between the toroidal field coil current measurements available at the JET tokamak and makes a preliminary investigation of its effect on the kinetic profile measurements from reflectometry and the ECE diagnostic.

2. COMPARISON OF TOROIDAL FIELD COIL CURRENT MEASUREMENTS

2.1. TOROIDAL FIELD COILS AT JET

At JET the toroidal magnetic field (B_t) is created by 32 toroidal field (TF) coils capable of creating magnetic fields of up to B_t = 4T. The coils are divided into 16 even and 16 odd coils connected in series respectively forming an even and odd TF circuit. The two circuits are further connected in series and the toroidal field coil current (I_{TF}) in the even and odd circuit can be either equal (normal operation, $I_{TF\_even} = I_{TF\_odd}$) or different (TF ripple mode, $I_{TF\_even} \neq I_{TF\_odd}$).

The TF coils are supplied by a Toroidal Flywheel Generator Converter (TFGC) in series with two Static Units (SUs) fed directly by the UK National Grid as shown in Figure 1. The TFGC is an AC/DC diode converter consisting of two three-phase windings and supplying a total of 960 self-commutating diodes. The SUs are single quadrant three-phase thyristor controlled rectifier converters with freewheeling diodes. The current load required for the TF coils is generally supplied by both the TFGC and the SUs. The TF circuit can however be configured to provide current from one source only with limitation to the TF coil current and thus toroidal magnetic field strength.

2.2. CURRENT MEASUREMENTS

The toroidal magnetic field at R = 2.96m major radius is obtained from the toroidal field coil current measurements based on the solenoid principle as follows:

$$B_t[T] = (k \cdot \mu_0 \cdot N/2\pi \cdot R) \cdot I_{TF}[kA] = 0.0516 \cdot I_{TF}[kA] \tag{1}$$

where k is the relative permeability (≈ 1), μ_0 is the permeability ($\approx 1.2566 \cdot 10^{-6}$) and N is the number of turns (32 coils × 24 turns each = 768 turns). The equivalent toroidal field coil current of the 1.8–3.45T toroidal magnetic field values used in common JET pulses is 35–67kA.

The four coil current measurements available at JET are listed below:

(a) Hall probe: the HALMAR head had been installed in 1982 at the TFGC. It consists of a ferromagnetic core with air gaps and feedback coils and operates on the principle of closed loop magnetic flux nulling. Bus current flowing through the head creates a magnetic field in the core and the magnetic null detectors located in each gap drive amplifiers to supply current to the feedback coils.

(b) Shunts: low resistance precision resistors connected in series in the TF circuit. The current is calculated from the voltage drop across the shunt using Ohm's law. The shunt used in this study is located at the SU.

(c) Rogowski coils: a helical coil of wire encircling the conductor. The voltage induced in the coil is proportional to the rate of change of the current in the conductor in accordance with Faraday's law. An integrator is connected to the Rogowski coil to provide an output proportional to the current. The two Rogowski coils used in this study are located on the even and odd circuit respectively.

(d) Optical fibre: the LKCO (from Dynamp) is based on the Faraday effect. It is described in detail in [1] confirming it to be < 0.1% precise. The optical fibre current measurement has been installed on JET in December 2013 and thus is only available for the last JET campaign.

The reference toroidal field coil current measurement has changed over the years. First the reference had been the Hall probe. In 2005 it has been replaced by a single Rogowski coil measurement which later has been replaced by the average of two Rogowski coil measurements (on the even and odd TF circuit respectively) calibrated to the Hall probe measurement. Thus the present reference toroidal field coil current (I_{TF_ref}) is the following:

$$I_{TF\_ref} = 0.9944 \cdot (I_{Rog\_odd} + I_{Rog\_even}) /2. \tag{2}$$

2.3. COMPARISON OF TOROIDAL FIELD COIL CURRENT MEASUREMENTS

Two methods were used to compare 1) the Rogowski coils on the even and odd TF circuit and 2) the I_{TF_ref} defined in Eq. 2 to the coil currents measured by the Hall probe, shunt and optical fibre.

First, linear regression was performed on each I_{TF} signal pair providing an offset and a slope (often quoted in percentage as (slope-1) · 100) as

$$I_{TF}^{(2)} = \text{offset} + \text{slope} * I_{TF}^{(1)}.$$

In addition, to check for events during the plasma current flattop phase (defined as plasma current being higher than 90% of the maximum plasma current in the pulse) the mean, standard deviation and maximum of the difference of the two I_{TF} signals have been calculated.

Comparison of the Rogowski coil measurements on the even and odd TF circuit for 10400 JET pulses (Pulse No: 72263–Pulse No: 83794) had shown little difference. Only an offset of 13.98 ± 78.7A and slope of 0.023 ± 2.29e-5% was found between the two Rogowski coil measurements.

Comparison of I_{TF_ref} based on the two Rogowski coil measurements (defined in Eq 2.) to the Hall probe and the shunt measurements for the same time period is shown in Figure 2. At zero requested toroidal magnetic field the Hall probe and the shunt, both absolute measurements, indicate a quiescent current in the order of 450–600A (from Hall probe). The Rogowski coils cannot measure this current as the integrator circuit connected to the Rogowski coils is set to zero at this time. In addition a seasonal drift can be observed on the slope from –0.7 to 0.2% over the course of 5 years (2008-2012). Weather data (incl. temperature and humidity) had been collected at the time of each JET pulse from the Benson airport (closest official meteorology station to the Culham Science Centre, host of the JET tokamak) to find an explanation for the seasonal trend. Similar seasonal trend had been observed on the temperature data, a relation that is not yet fully understood.

After the installation of the new optical fibre measurement in December 2013 the analysis had been performed again for all available JET pulses until end of August 2014 (1759 pulses, Pulse Nos: 85536–87399). The results are shown in Figure 3. All absolute measurements indicate an offset compared to the reference toroidal field current, namely an average of 442A, 570A and 348A and an average slope of 0.53%, 0.025% and –0.808% from the optical fibre, Hall probe and shunt. The Hall probe and the optical fibre show a similar seasonal trend. The maximum difference in the current flattop between the reference toroidal field coil current and the optical fibre measurement is 0.81–2.43% with an average of 1.48%.

2.4 QUIESCENT CURRENT AT ZERO REQUESTED TF COIL CURRENT

Seven dedicated pulses were carried out at JET in various TF power supply configurations in order to narrow down the source of the quiescent current that flows in the TF circuit at zero requested toroidal magnetic field. For these pulses the poloidal field coil currents were set to zero and were without plasma. The results based on the optical fibre measurement are summarized in Table 1. Four different power supply configuration of the TF circuit were tested as follows:

1) SU only (Pulse No: 87585): leakage voltage from the static elements is connected directly across the TF coils resulting in 560A quiescent current.

2) TFGC only (Pulse Nos: 86097, 86157): voltage contribution is only from the TFGC itself (remanence current). There is however a constant voltage drop across both static element's bypass diodes which reduces the voltage applied across the TF coils and hence results in a lower quiescent current.
3) In normal configuration, but with the TFGC excitation breaker opened (Pulse No: 86096): there appears to be an additional voltage contribution to the circuit which is currently not understood.
4) Normal configuration (TFGC+SU, Pulse No: 86093,86095): when voltage is applied equally from all voltage sources, the quiescent current falls half way between FGC only and SU only due to the interaction between the remanence current of the TFGC and leakage voltage of the SUs.

3. EFFECT ON KINETIC PROFILES

3.1. ELECTRON DENSITY PROFILES FROM REFLECTOMETRY

The JET microwave reflectometry system consists of 6 independent fast-sweeping channels covering 4 bands between 44 and 150GHz using orthogonal polarisations. It measures electron density profiles in the X polarization mode from the plasma edge to the core based on: a) the measured phase delay between the reference and the microwave beam reflected back from the plasma, b) the total magnetic field and c) electron temperature profiles (for relativistic effects) obtained from ECE measurements mapped to the line of sight of the reflectometer. The absolute density is related to the frequency calibration and the plasma frequency whereas the radial coordinates rely on magnetic equilibrium reconstruction. The obtained plasma density profiles are commonly shifted inwards, to the magnetic high field side. This is often attributed to an error of the toroidal magnetic field measurement. B_t corrections are thus routinely applied to reflectometer data based on cross-calibration to the edge line integrated density obtained by interferometry.

In the 2014 campaign 1753 time points from 174 JET plasma discharges were investigated with toroidal magnetic field values in the range 1.97-3T. The B_t correction obtained from the cross-calibration of the reflectometry is in the order of 0.98-5.54% (2.73 ± 0.24%). This is a factor of 1.5–2 times higher on average than 1.21–1.8% (1.52 ± 0.013%) suggested by the difference of the new high precision optical fibre measurement and the reference values obtained from the Rogowski measurement. The B_t correction based on the optical fibre measurement shifts the electron density profile towards outward, the correct direction, but is insufficient to explain all the radial discrepancy to other electron density measurements. The residual B_t correction has been studied with forward selection, a statistical model selection method [3] to determine further sources among 16 plasma parameters (incl. plasma current, NBI and ICRH heating power, electron temperature/density, plasma geometry, etc.) showing that the residual B_t correction is mainly related to the toroidal magnetic field.

3.2. ELECTRON TEMPERATURE PROFILES FROM ECE

The ECE based diagnostics measure the electron temperature based on two basic principles. First, electrons gyrate around magnetic field lines, emitting and absorbing EM radiation at the electron cyclotron frequency $\omega_{ce} = neB_{(R)}/m_e$, where B is the total magnetic field and n is the harmonic number. Secondly when the emitted radiation is at black body level, the intensity of the measured radiation can be related to electron temeprature at the location corresponding to the emitting frequency. For plasma conditions at JET, the density and temperature of the bulk plasma are high enough to ensure that the second condition is met for the 2X-mode and the 1O-mode ECE. At JET, the ECE spectrum is measured by both a Michelson interferometer and a heterodyne radiometer [4]. The former is absolutely calibrated, the latter has a higher spatio-temporal resolution. The radiometer comprises of 12 heterodyne receivers, covering a frequency range of 63–207GHz. This provides a wide radial coverage for most of the magnetic fields used at JET ($1.7T < B_t < 4T$). A sub-set of 4–6 receivers is typically selected to obtain optimal profile coverage with 96 available channels (each with 250MHz bandwidth and a channel separation of 1.0–1.5cm). The radiometer measurements are cross-calibrated against the Michelson interferometer. A radial discrepancy between T_e profiles measured by ECE and Thomson scattering diagnostic is a long-standing observation at JET [4] with the ECE profiles shifted inwards. A Bt correction must be applied to the calculation of the ECE radial coordinates in order to match the T_e profiles. It has been shown that the B_t correction required to match the profiles in the pedestal region is insufficient to make the profiles symmetric in flux coordinates in the core [4]. Improved EFIT equilibrium reconstructions including pressure constraints are in progress to evaluate the weight of the two sources of errors.

In the 2014 campaign 1502 time points from 159 JET plasma discharges were investigated over a wide range of magnetic field values (1.69–3.38T). The radial coordinates of the T_e profiles were calculated using both the toroidal magnetic field values obtained from the Rogowski coils (B_t^{ref}, reference) and the optical fibre measurement (B_t^{opt}). The center of the temperature profile was then determined using a Gaussian fit for $Te > 3keV$ and compared to the magnetic axis position obtained from the magnetic equilibrium reconstruction EFIT. The obtained distance between the center of the ECE profile and the magnetic axis is 5.81 ± 0.13cm using B_t^{ref} and 2.53 ± 0.10cm using B_t^{opt}. This shows that the use of the optical fibre measurements shifts the electron temperature profiles by an average of 3cm outwards, reducing the radial discrepancy between the Thomson scattering and ECE electron temperature profiles.

CONCLUSION

Absolute measurements of the toroidal field coil current (optical fibre and Hall probe measurements) show a static current in the order of 400A flowing in the Toroidal Field circuit. Dedicated pulses in various TF power supply configurations indicate that this is likely due to the interaction between the remanence current of the TFGC and leakage voltage applied by the SUs. The total difference between the high precision optical fibre measurement and the reference based on Rogowski coils is of 0.81–2.43%. The use of the optical fibre measurement reduces the radial discrepancy between different electron density and temperature profile diagnostics at JET, but does not eliminate it. Further investigations is under way.

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JET Pulse Number	Flywheel generator	Static Units	Current [A]
Pulse No: 86157	Connected	Bypassed	200A
Pulse No: 86097	Connected	Bypassed	230A
Pulse No: 86096	Connected, but de-excited	Connected	465A
Pulse No: 86095	Connected	Connected	390A
Pulse No: 86093	Connected	Connected	380A
Pulse No: 87585	Disconnected	Connected	560A

Table 1: Quiescent current present at zero requested toroidal field (TF) coil current value in different TF power supply configurations.

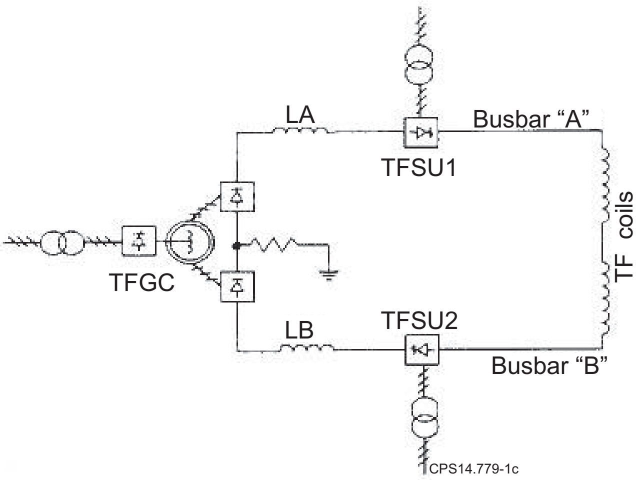

Figure 1: JET toroidal field coil power supply setup.

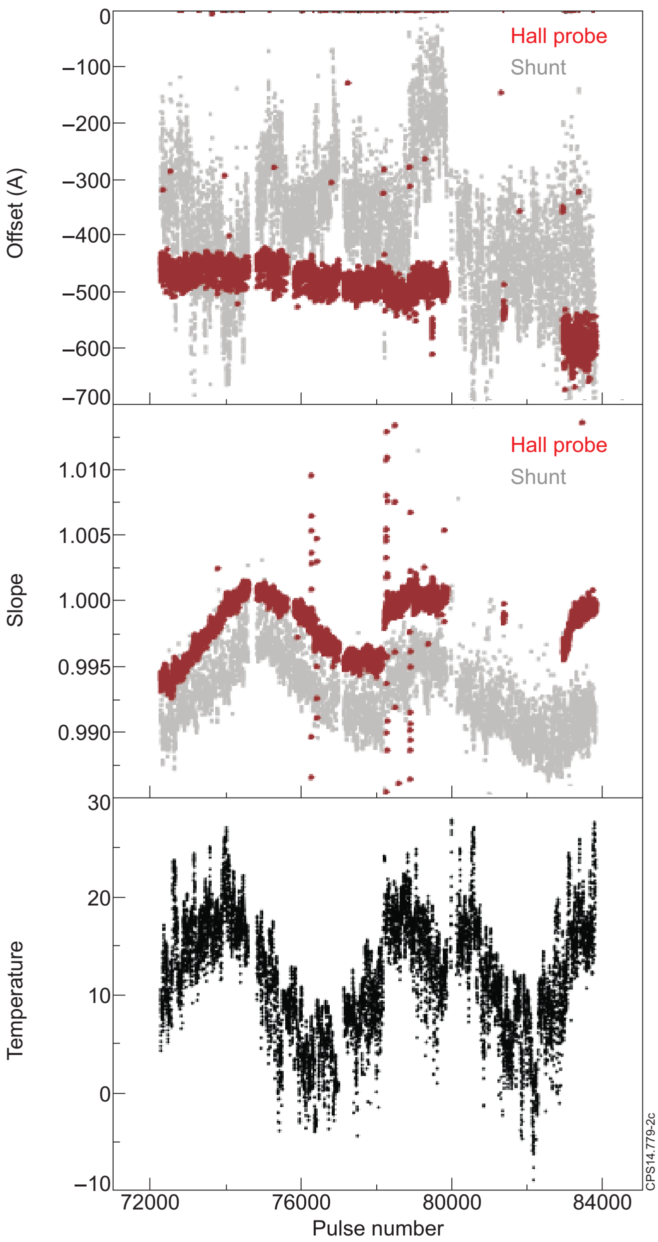

Figure 2: Results from the linear regression applied on the Hall probe and Shunt measurement respectively to the reference TF coil current measurement based on Rogowski coils for the time period 2008 to 2012.

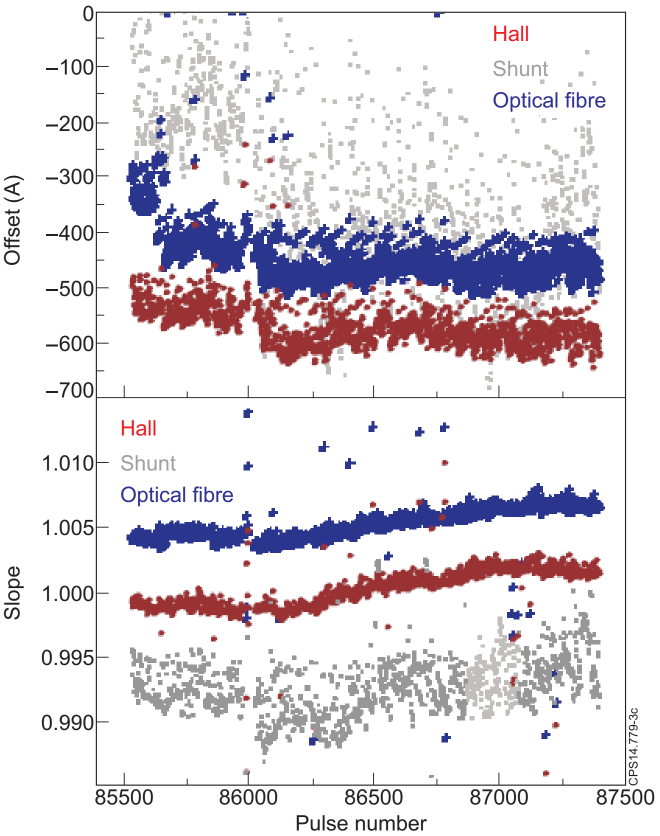

Figure 3: Results from the linear regression applied on the Hall probe, Shunt and optical fibre measurement respectively to the reference TF coil current measurement based on Rogowski coils for the time period December 2013 to August 2014.