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The Error Field Correction Coils on the JET Machine

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ABSTRACT

The non axisymmetric magnetic field, naturally present in every tokamak, constraints the machine operational space. A set of dedicated "Error Field Correction Coils" (EFCC) is proposed for JET, which will replace the unreliable existing "saddle coils". The new coils are specified to compensate the main harmonic contribution to error field induced modes. The EFCC structural design comprises a cable coil wound in a metallic casing supported on the JET iron magnetic circuit. Existing power supplies will drive the coils. The EFCC are expected to be installed in 2001 JET shutdown.

1. INTRODUCTION

Error fields are concern for tokamak operation, as they can induce locked modes which lead to disruptions. Error fields are naturally present in all tokamaks and are a particular issue for large devices such as ITER, extrapolations indicating low tolerances ($\delta B/B \sim 10^{-4}$), and some form of error correction is a likely requirement [1, 2].

Experimentally, the resonant m=2, n=1 ('2,1') error field is found to be most likely to induce locked modes, although it is found that other harmonics (the 3,1 and 1,1) also play a significant role [2, 3].

Scans of error field sensitivity have been made on JET using a set of in-vessel "saddle coils" [4]. Amplitude of the natural error field was measured. Compensation of this with the "saddle coils" enabled removal of error field modes, resulting in lower density access and largely preventing error field induced disruptions.

The JET "saddle coils" have suffered many hardware failures, most severely with frequent in-vessel earth leaks. To continue the above studies, the building of a set of ex-vessel "Error Field Correction Coils" (EFCC) was proposed. Design work was commenced under the JET Joint Undertaking, and installation is now planned as part of the JET-EFDA enhancement scheme in the 2001 machine shutdown. The progress of the design is presented below.

2. DESIGN SPECIFICATIONS

The design of the EFCC for JET is based on two basic requirements. Firstly, a minimum of two degrees of freedom must to be guaranteed, allowing for compensation in both amplitude and phase of the (2,1) harmonic of the error field. Secondly, amplitude and spectrum of the magnetic field by the proposed coils have to be adequate for error field compensation on JET. There is not a stringent requirement on bandwidth instead: error field experiments are run in DC. External poloidal currents subject however to a structural limit to the frequency arising from the vessel screening effect, with a time constant of about 25ms.

Specification of field amplitude is given in terms of maximum value of the (2,1) harmonic at the q=2 resonant surface. The new coils are required to produce a field at least as large as the one now provided by the "Saddle Coils" (SC):

$$B_{21}^{EFCC}(q=2) \geq B_{21}^{SC}(q=2) \approx 7 \cdot 10^{-4}\,T \quad (1)$$

Further requirements on relative importance of sideband harmonics exist:

$$B_{11} << 7 \cdot B_{21} \quad (2)$$

$$B_{31} << 1.2 \cdot B_{21} \quad (3)$$

If the above conditions are satisfied the (2,1) field becomes the main contribution to the penetration process.

Power supply considerations also have a significant impact on the design, if planned to use the present Disruption Feedback Amplifier System (DFAS) to power the new coils. The DFAS is composed of four identical units, DFAS1 to DFAS4 [5]. DFAS3 and DFAS4 currently feed the in-vessel "saddle coils", whereas DFAS1 and DFAS2 are spare and candidate to drive the EFCC. The maximum single turn coil current in EFCC is specified to match maximum DFAS current of 3kA. Also the coil thermal rating is specified according to the DFAS I^2t of $9 \cdot 10^6 A^2 \cdot s$ with a duty cycle of 600s. Such limit is satisfactory for experimental purposes and also in view of routine compensation of the error field during JET pulses.

3. THE COIL SYSTEM

The amount of equipment around the machine made finding a route for the windings by far the most difficult task in the design of the EFCC. Work focused on a scenario envisaging four equatorial coils and only after prolonged efforts, as proved by the abundance of twists and bends in the final shape of the coil, an acceptable routing was defined (fig.1).

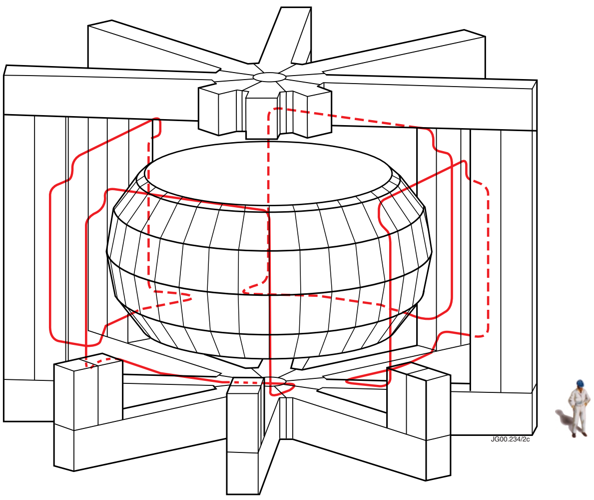

Figure 1: layout of the EFCC system. The eight limbs of the JET iron magnetic circuit are also shown.

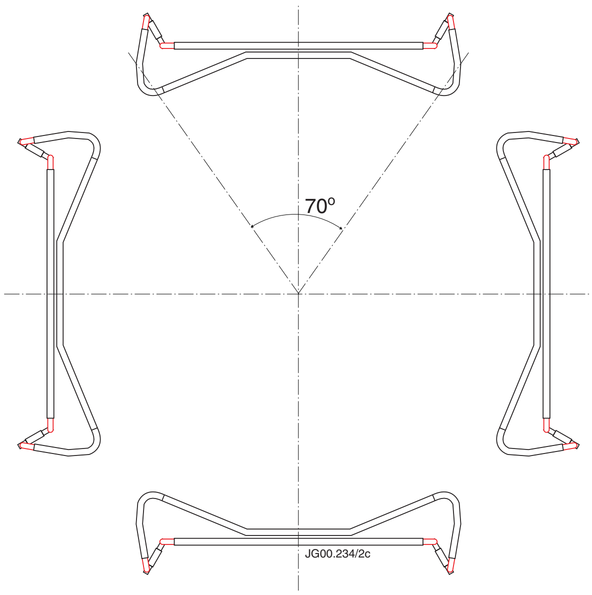

Figure 2: top view of the EFCC.

The coils are all identical and their shape is approximately square, with a dimension of about 6m. Along the winding the radial distance from the centre of the machine varies from 5.3m to 7m. The coil vertical position, but for a 50mm displacement, is symmetrical about the equatorial plane of the machine. Each coil spans a toroidal angle of 70∞ and the system is arranged with four-fold symmetry (Figure 2).

Assuming toroidally opposite currents in toroidally opposite coils for n=1 fields, Fourier components of the resulting magnetic field were computed by means of an analytical model (Table 1). Coil specifications on relative importance of sidebands harmonics (equations (2) and (3)) are met.

Table 1: summary of the EFCC.

Number of coils	4
Number of turns per coil	16
Single turn length [m]	30
B_{21} field at q=2 [10^{-4} T/kAt]	0.179
B_{31} field at q=2 [10^{-4} T/kAt]	0.0417
B_{11} field at q=2 [10^{-4} T/kAt]	0.458
Maximum single turn current [kA]	3
Thermal rating [A2· s/s]	9· 10^6/600
Section of conductor [mm^2]	150
Coil DC resistance [mΩ]	60
Coil inductance [mH]	10

In terms of amplitude of the B_{21} harmonic, at least 7/0.179 kAt=39kAt must be available. As the maximum single turn current is determined by the DFAS at 3kA, not fewer than 39kAt/3kA=13turns are required. 16 turns were chosen for each EFCC winding, to obtain some margin on the minimum field requirement and to rationalise the mechanical layout of coil conductors in a four by four arrangement.

4. COIL CONSTRUCTION

Adoption of a fully impregnated copper winding was deterred by both technical (i.e. very tortuous shape of the coil) and financial reasons. Flexible cable was chosen instead, and a cable cross-sectional area of 150mm^2 was selected based on current carrying capacity and coil resistance considerations.

In the EFCC region the magnetic field due to nearby poloidal field coils and to plasma itself can be as high as 0.4T, determining on the winding a mechanical load up to around 2tonne/m. A metallic box was therefore designed to enclose the conductors. Such casing is not continuous along the winding but is rather composed of a series of straight sections separated by gaps up to

0.6m long, corresponding to the bends of the winding. On site tests confirmed expected forces are well within the cables mechanical capabilities. Stress arising on the casing from electromagnetic load was analysed by a finite element model. Maximum axial stress for the top horizontal section reaches 30MPa, far below the 250MPa static limit.

Selected 150mm^2 cable has an overall diameter of 22.60mm and a corresponding insulation rating of 2.6kV. Additional packing material around the winding, in the form of rubber sheets, is desirable to upgrade coil insulation to ground to 5kV (thus matching the DFAS insulation rating) and to compensate for tolerance on box and cable dimensions. Internal cross section of the casing is square with a dimension of 101.6mm, sufficient to accommodate the sixteen turns winding and the packing material. Box construction consists in 15.9mm thick aluminium plates bolted together (Figure 3).

Winding of the coil, requiring one of the four sides of the box to work as a removable lid, is the reason for a bolted construction: U-shape channels will be installed on the machine first, the coil wound in situ and finally the lid screwed onto it. The whole process of installation will be hampered by problematic access to the machine. Junction boxes designed in the middle gap of each vertical section of the casing (Figure 4), for a total of thirty-two junctions per coil, will make winding of the coil manageable. Their location corresponds to the equatorial plane of the machine where on average the inversion of the polarity of the poloidal radial field takes place, thus minimising electromagnetic load on the joints.

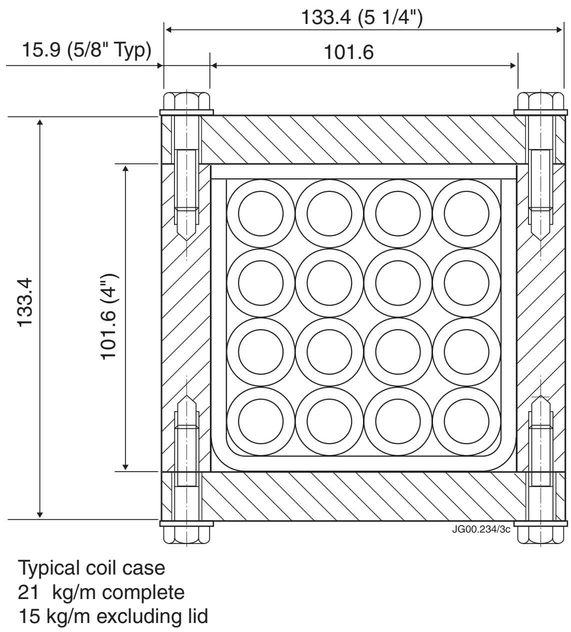

Figure 3: cross section of the EFCC casing.

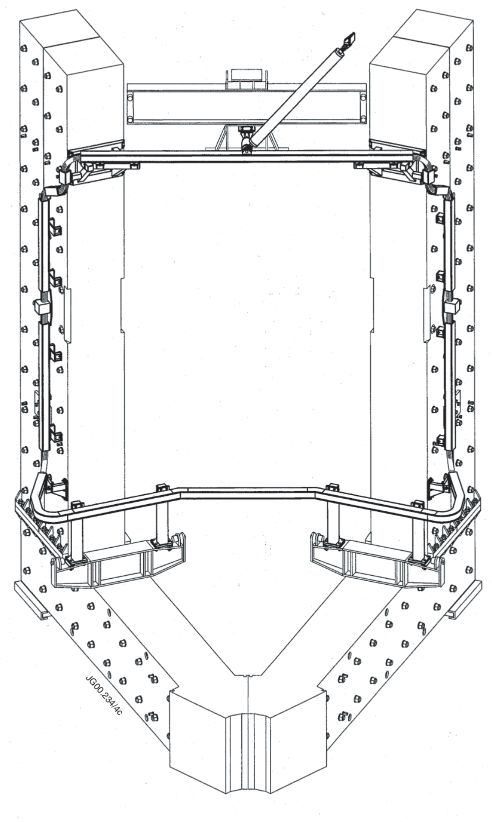

Figure 4: structure of typical "error field correction coil".

The coil casing is supported on the limbs of the JET iron magnetic circuit by mild steel brackets. Those, together with cable winding and aluminium casing are the structural components of the coil (Figure 4).

Figure 4 also shows two clamping tubes in the middle of the top horizontal section of the casing, the longest one. Including those stainless steel features brings the lowest natural frequency of the coil from about 50 up to about 120Hz.

The EFCC will be cooled by natural air. A 2D finite element model of the casing investigated the thermal behaviour of the coil. At full performance ($9{\cdot}10^6 A^2{\cdot}s$ pulses every 600s for 16 hours a day) the conductors will reach a maximum temperature of about 50°, which poses no concern for POLYRAD insulation rated up to 125°. Moreover, when a more realistic duty cycle of 1200s is considered maximum temperature of the conductors drops down to 35°.

5. CONCLUSIONS

The design of the EFCC is nearly complete. Their main features are summarised in Table 1.

The coils are expected to be installed in 2001 JET shutdown. They will make a valuable contribution to physics studies of areas such as error field modes and neo-classical tearing modes.

AKNOWLEDGEMENTS

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