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** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22 nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

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ABSTRACT
A study has confirmed the feasibility of designing, fabricating and installing Resonant Magnetic field Perturbation (RMP) coils in JET with the objective of controlling Edge Localized Modes (ELM). A system of two rows of in-vessel coils, above the machine midplane, has been chosen as it not only can investigate the physics of and achieve the empirical criteria for ELM suppression, but also permits variation of the spectra allowing for comparison with other experiments. These coils present several engineering challenges. Conditions in JET necessitate the installation of these coils via remote handling, which will impose weight, dimensional and logistical limitations. And while the encased coils are designed to be conventionally wound and bonded, they will not have the usual benefit of active cooling. Accordingly, coil temperatures are expected to reach 350^{o}C during bakeout as well as during plasma operations. These elevated temperatures are beyond the safe operating limits of conventional OFHC copper and the epoxies that bond and insulate the turns of typical coils. This has necessitated the use of an alternative copper alloy conductor C18150 (CuCrZr). More importantly, an alternative to epoxy had to be found. An R&D program was initiated to find the best available insulating and bonding material. The search included polyimides and ceramic polymers. The scope and status of this R&D program, as well as the critical engineering issues encountered to date are reviewed and discussed.

1. INTRODUCTION
Erosion and damage caused by ELMs is a major hurdle on the route towards achieving magnetic fusion in a reactor scale machine. Scaling predicts that the ELM energy in ITER, if not mitigated, will exceed the acceptable level by a factor of up to 20. Presently, ELM control coils are the only method of completely suppressing ELMs; other methods have only shown mitigation. A system of ELM control coils in JET will provide additional information towards our understanding of ELM control by RMP, and extend the dataset for extrapolation towards ITER like plasmas.

A system of two rows of in-vessel coils has been chosen as it not only can achieve the empirical island overlap (Chirikov parameter) criteria for ELM suppression, but also permits variation of the spectra allowing for comparison with other experiments, including DIII-D, and to investigate the physics of ELM suppression [1]. The two rows of coils are positioned inside the JET vacuum vessel and mounted on the wall above the machine midplane on the low field side as space exists in this region. The lower row has 24 coils, which allows for toroidal mode numbers up to 12 and for fine adjustment of the phasing relative to the upper row of 8 coils.

2. ELM CONTROL COIL DESIGN OVERVIEW
2.1 BACKGROUND
JET is a very mature facility; it was constructed three decades ago and has been modified many times since then. Its long operating history includes periods in which hazardous materials (e.g., beryllium) and deuterium-tritium fuel have been used, leaving a contaminated environment that restricts human access to the machine, especially the interior of the vacuum vessel. Therefore, the existing physical configuration and condition of the JET equipment impose strong constraints which

determine the feasible design envelope for any proposed modification. The strategy for this study was to design the equipment to the limits of the feasible envelope and then evaluate the JET operating space over which that equipment can provide useful physics capability. In order to evaluate the feasibility of an Edge Localized Mode (ELM) control coil system for JET, a pre-conceptual design was developed in 2009 and 2010.

Two basic design decisions were needed early in the study to set the directions for design development. The first was the number and general arrangement of coils including whether to locate them inside or outside the vacuum vessel. The second was the method of cooling the coils.

2.2 COIL CONFIGURATION

Early scoping calculations were performed for representative in-vessel and ex-vessel coil configurations. The attraction of ex-vessel coils is that they would not require remote handling to install. However, due to the crowded conditions around the JET machine, ex-vessel coils would have to be located far from the plasma (>1m) such that they would require very large currents (~1MA) to produce a high-mode-number resonant perturbation at the plasma edge, as required by the criteria. Suppressing the low-mode-number spectral components in the plasma, and providing adequate flexibility, would be very difficult with such a design. Inside the vacuum vessel, the coils can be located within 10cm of the plasma surface and the physics criteria and flexibility goals can be satisfied with reasonable currents (60kA-turns). Feasibility issues associated with equipment removal and installation by remote handling, were judged to be resolvable, based on past success installing wave launchers of comparable complexity. An in-vessel approach was therefore determined to have the better prospects for satisfying project goals.

The coils are mechanically grouped in eight sets, each set consisting of one large and three small coils, straddling adjacent octants and centred on the boundary between them, as shown in Figure 1. The large coil measures 1.5m × 0.3m in overall dimensions, while the small coil measures 0.8m × 0.3m. Each coil will be constructed of wound copper alloy conductor which will be insulated, encapsulated, and encased in a vacuum-tight Inconel 625 enclosure which will be mounted onto structural beams along the vacuum vessel wall.

After several iterations, the basic cross section for each large upper ELM coils is a 48-turn configuration with a 6 radial by 8 poloidal turn cross section (Figure 2). Each turn is capable of handling up to 1.25kA, for a total of 60kA-turns for the coil. Each turn measures 6.35mm × 6.35mm with slightly rounded corners to avoid sharp edges. There is a one millimeter space between turns to allow for kapton film, glass, and the insulating bonding agent. There is a two millimeter space between the coil bundle and the Inconel 625 case to also allow for kapton, glass overwrap and bonding agent. This extra space allows for potential coil offset enabling cleaner welding of the case. Based on structural analysis, the Inconel case will be 4 mm thick. A large coil is estimated to weigh approximately 110kg. The coil cross section typically measures 70mm × 55mm.

All coil lead pairs will be separately brought out of the vessel through feedthroughs in five of the main vertical ports.

2.3 COIL COOLING

The ELM coils must withstand vacuum vessel bakeout at elevated temperatures (350 C) for extended periods, and must operate with the vessel at 200 C. Pulsed coil heat loads due to Joule heating of the conductors and radiation from the plasma must be handled. Cooling by both active and passive means were considered. Both were deemed feasible, but passive cooling was chosen because its risks were judged to be the more manageable [1]. One overriding concern with active cooling was the complexity of installing leak-proof hydraulic fittings via remote handling.

Passive cooling means that the design must rely almost exclusively on radiation to the vacuum vessel walls for removal of pulsed heat loads between pulses. Coil overheating protection is provided by control of the ambient temperature and of the coil current and pulse length. The risk of damage can be mitigated through careful design and control, since adiabatic coil temperature rise can be reliably predicted. The performance and lifetime of insulating materials operating close to manufacturer's limits can be tested via R&D. The consequences of overheating, should it occur, are likely to be confined to the coil system. The coils are limited thermally to a 17-s maximum pulse length at full current (60kA-turns), starting from a pre-pulse temperature of 200^{o}C. For repetitive pulsing, they are limited to 8-s full-current pulses at 30-minute intervals. The operating scenario is illustrated in Figure 3.

2.4 COIL REQUIREMENTS AND CONSTRAINTS

The design envelope for these coils is limited by the following constraints:

Location

As discussed above, a set of four ELM coils shall straddle each of the eight octant joints in the upper regions of the vacuum vessel.

Size

The size of these coils and their assemblies is limited by the dimensions of the port access into the JET vacuum vessel, including accounting for any remote handling and support hardware including manoeuvrability for installation. These limits must also account for any protruding leads.

Remote Handling Compatibility

The Remote Handling (RH) arms, including envisaged end effectors, limit the maximum net load to 170 kg for any individual component. In addition, each assembly must be in compliance with the various geometric limitations encountered by the entire RH operation. This includes temporary coil mounting while the RH arm hardware is changed from lift-related to install-related fixturing. Note that different obstacles and issues can be expected from octant to octant.

Limited support locations and load carrying capacity

The proposed supports for mounting these ELM coils are along beams mounted on the vacuum vessel wall. Additionally, the mechanical loads passed from the coils to the vacuum vessel must be evaluated because these ELM coils will introduce reaction loads to the vessel that it was not originally designed for. Should the load capacity of the vacuum vessel be exceeded, either the coil will need to be redesigned or supported in an alternate manner, or else the 60 kA-turns operating current may need to be reduced. Temporary supports of these coils along the vessel wall need to be fully addressed as part of the remote handling operation, which requires that the coils be held in place while the remote handling arm(s) is re-configured with different tooling.

Thermal environment

As discussed above, passive radiative cooling with some minor conduction cooling through the coil supports are the only anticipated methods of coil cooling. JET guidelines specify that worst case plasma radiation heating peaks at 250kW/m^2. The design will incorporate an Inconel shield protected by beryllium tiles to absorb this heat load, which comes to approximately 238kJ per meter of coil per pulse. The shields will protect the coils from this heat during pulses, leaving the coils to almost exclusively cope with its own Joule self-heating, which, for reference, comes to approximately 750kJ per meter of coil per ten second pulse at 60 kA-turns.

Power supply considerations

In order to be compatible with economical power supply designs, the number of turns for these coils is then determined by the coil current and voltage requirement for a 60kA-turn pulse scenario with 100ms rise and fall times and up to a twenty second flattop. This results in a choice of 48 turns per coil.

Access ports for leads

There is a very limited amount of space available to efficiently run paired leads into the vacuum vessel to power these proposed ELM coils. A comprehensive review of the entire port system resulted in the selection, for purposes of this study, of the main vertical ports for the coil leads.

2.5 MATERIALS

Due to the unique thermal conditions that require performance for repeated extended periods up to 350 C without active cooling, the selection of materials to build these coils is crucial. A detailed survey of a wide range of material options was undertaken and the material choices made as follows:

Coil conductor

Copper-Chrome-Zirconium (CuCrZr – C18150) – Conventional copper will lose its integrity and soften at 350^{o}C. Therefore, another conductor material was sought. Although the material properties of Glidcop are promising, the decision to select CuCrZr was based on the extensive database of material properties available, especially via ITER. While the mechanical properties of ITER grade of CuCrZr are somewhat more conservative than conventional CuCrZr, they are quite ample for the design of the JET ELM coils. Test data also verifies that exposing CuCrZr for extended periods at 350^{o}C will not cause over-aging [2]. All performance limits presented herein are based on CuCrZr conductor.

Coil case & supporting hardware

Inconel 625 – Chosen for its high temperature integrity, high strength, weldability, and experience with JET, Inconel 625 is an ideal choice for the JET ELM coil case and supporting hardware.

Coil insulation

Kapton and glass cloth - each turn of conductor will be wrapped in a bonded layer of Kapton film followed by glass cloth. There is a great deal of experience with both materials for winding coils. These materials provide an extra measure of protection against potential turn-to-turn electrical shorts.

Coil encapsulation / bonding

Polyimide and/or ceramic polymer – There are several commercially available candidate polyimide and ceramic polymer bonding compounds that can be vacuum impregnated in a manner similar to conventional epoxy. Originally developed for aerospace engine components, polyimide has all of the desired specifications and application experience, including bonding components wrapped in glass cloth, that make it well suited for the JET ELM coils. Candidate polyimides will not break down at temperatures lower than 370^{o}C while maintaining an adhesive bond strength of at least 14MPa and a short-beam shear strength of approximately 90MPa. Due to the fusion community's inexperience with polyimides, an R&D program is currently underway to verify manufacturer's performance claims. In parallel, a similar R&D program is being performed on ceramic polymer adhesive resins, which offer similar thermal, but slightly reduced mechanical performance.

2.6 CONSTRUCTION

A key advantage to the manufacturing of these ELM coils is that they do not involve any new or risky technology or techniques. The rectangular racetrack-shaped coil bundles can be wound using conventional practices used for many previously wound coils. There is prior experience winding CuCrZr conductor on a mandrel into shapes similar to these ELM coils. ITER has selected CuCrZr as a high strength conductor option.

The case is manufactured by welding four Inconel plates with full penetration corner welds. One proven process is laser welding. A requirement of the case is that it provides a vacuum boundary between the ELM coil and the inside of the vacuum vessel. This will prevent any potential outgassing from the coil to the vessel and prevent any tritium leaks from the vessel to the coil, thereby keeping the coils from being part of the tritium system. As a further precaution against vacuum leaking, these coils will be actively pumped after they are installed. Once welded closed, the case can be visually inspected, but must be vacuum qualified by a pressurized helium leak check following cyclic heating (to operational temperatures) and cooling of the case. Radiographic inspection of this design would not be practical for these welds. Although the case walls would be toroidally curved, this does not overly complicate the welding and manufacturing process. All of these manufacturing processes have been done before with Inconel 625.

For more efficient and safe welding, the coil bundle could be offset inside the case by adjusting the thickness of the outer insulation layer on each side. Inlets and outlets in the case would be used for the polyimide / ceramic polymer impregnation process, then plugged upon completion. Coil leads will exit each case in pairs. With the exception of gaining experience with the polyimide / ceramic polymer impregnation process, every step of the coil manufacturing process is one that has been successfully done many times before.

3. POLYIMIDE / CERAMIC POLYMER R&D PROGRAM

An R&D program has been initiated whose goal is to reduce the risk that may occur during the fabrication, installation, and operation of the coils so that the design requirements of the coils can be met.

Operating the coils at 350 C is a very challenging requirement. Materials used to date in the fabrication of coils for fusion devices will not meet this extreme temperature. The selection of a polyimide or ceramic polymer that will meet the operating temperature limit will require testing to verify the manufacturer's listed properties. Experience will need to be gained in their use as electrically insulating bonding agents to understand their limits during the fabrication process because the viscosity for these products is higher than the standard epoxies. Issues that will be addressed through the R&D effort will include:

- The wicking properties will have to be tested to verify complete fill during the impregnation process.
- Electrical properties will need to be tested to verify that the insulating properties of the Kapton/glass/resin system at 350 C will maintain its ratings and integrity for long exposures.
- Mechanical testing of the bonded conductors will be done to determine the turn-to-turn shear strength, bond strength, and fatigue testing.
- Welding of the case to minimize distortions and to verify that the weld process does not adversely affect the dry-wound coil bundle.

For these purposes, 0.6 meter long coil bundle samples, with the cross section shown in Figure 2, have been built for the R&D program (Figure 4). Note that the alternating ends of the turns have short Macor spacers that enable accurate turn-to-turn electrical testing of the samples both before and after the application of the bonding agent. These first set of samples, bonded with polyimide or ceramic polymer, will be impregnated, examined then electrically and mechanically tested in Fall 2010. Additional R&D, including case weld samples and scale prototype coil manufacture and testing will follow.

CONCLUSIONS

Initial studies of ELM control coils for JET are scheduled to continue into 2011. Results from the R&D program, currently underway, will add definition to the design and engineering of these coils.

REFERENCES

[1]. JET ELM Coil Study Team, JET ELM Coil Feasibility Study – Final Report (2010).

[2]. Blatchford, P.W., UKAEA Design Report Document ID: CD/MU/PP/423/DB/003-Version 1 (2009).

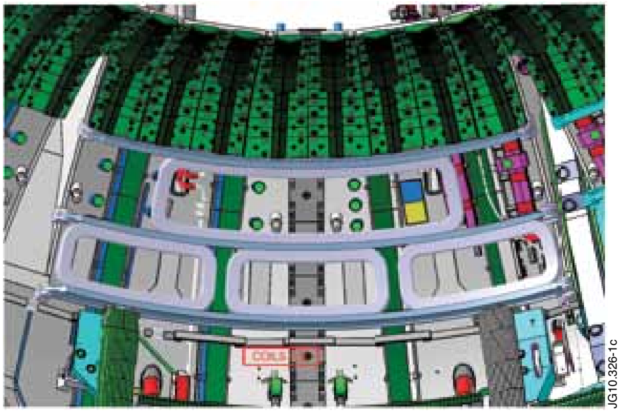

Figure 1: Mechanical layout of a typical set of four ELM control coils positioned on the vacuum vessel wall in a JET octant.

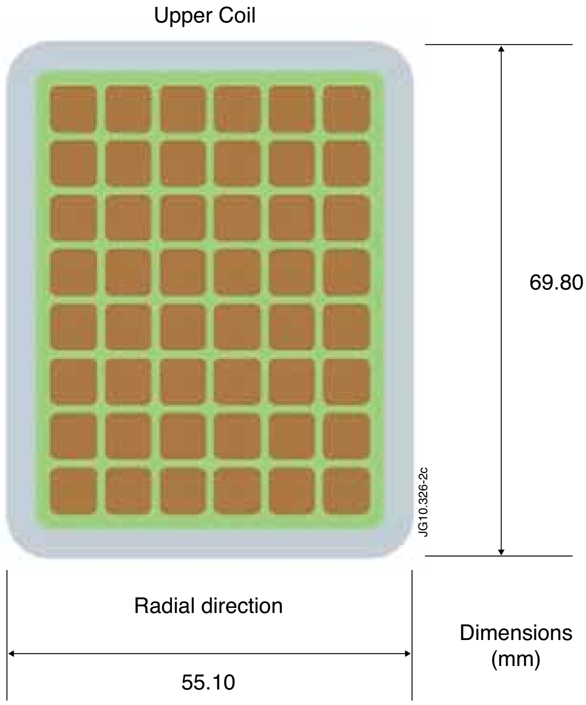

Figure 2: Cross section of a large ELM coil

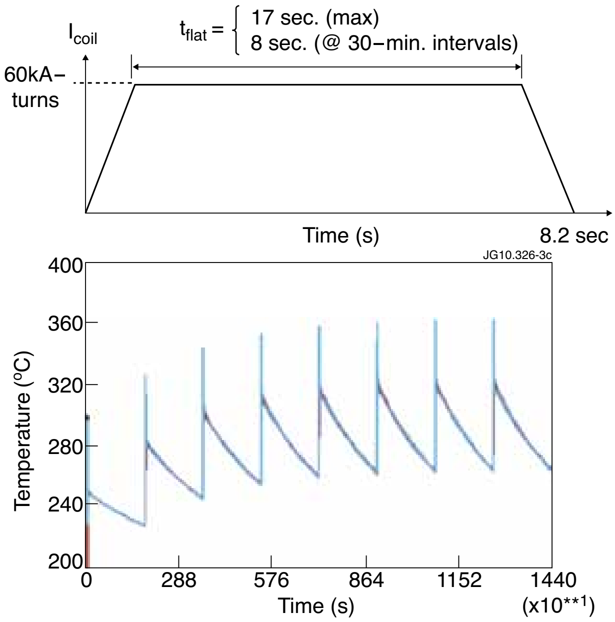

Figure 3: ELM coil pulsed operation scenario. Top: current pulse shape. Bottom: conductor temperature for repetitive pulsing at 30-minute intervals.

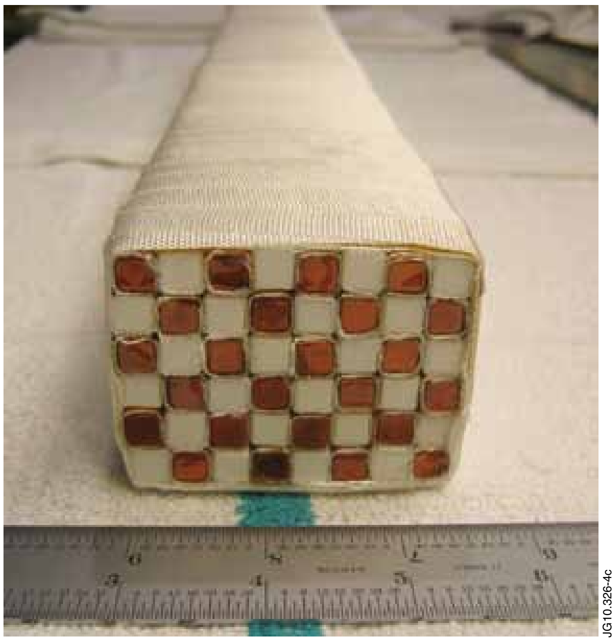

Figure 4: Dry-wound ELM coil R&D test sample, with Macor spacers, prior to impregnation.