JOINT EUROPEAN TORUS

JET–P(91)26

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** See Appendix 1*

Preprint of a paper presented to 12th International Conference on
Magnet Technology, Leningrad, USSR., 24th-28th June 1991

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Abstract. **The JET Tokamak is to be modified to incorporate a divertor. A coil system in the vacuum vessel has been developed, which can produce a range of different divertor plasmas. The divertor coils are of conventional construction and are contained in thin Inconel cases. They will be assembled in the vacuum vessel, welded into their cases and impregnated with epoxy resin.**

I. INTRODUCTION

A new objective for JET is to provide plasma engineering data for future fusion machines. An important part of this will be studies of impurity control and plasma exhaust by means of a pumped divertor [1]. This pumped divertor will consist of divertor coils and pump mounted inside the Jet vacuum vessel.

II. MAGNETIC CONFIGURATION

The divertor magnetic configuration [2] is produced by four in-vessel coils (see Fig. 1). Many different divertor plasmas can be produced with the following properties.

- The separatrix is well clear of the vessel wall or target plates and the field lines from the scrape-off layer fall on the target plates.
- The plasma fills the available vacuum vessel space in order to maximise plasma volume and current and make vertical stabilisation easier.
- The connection length between the separatrix and the target plates is acceptably large.
- The strike zone of the plasma scrape-off layer can be swept across the target plates to reduce local heating effects by varying the ratio of the divertor coil currents.

Two examples of plasmas that can be set up are given below.

- A "fat" plasma can be made using only the "central" divertor coils (D2 and D3). This has a large plasma volume but short connection length.
- A "slim" plasma can be made by adding currents in the "side" divertor coils (D1 and D4). This has a longer connection length but smaller volume.

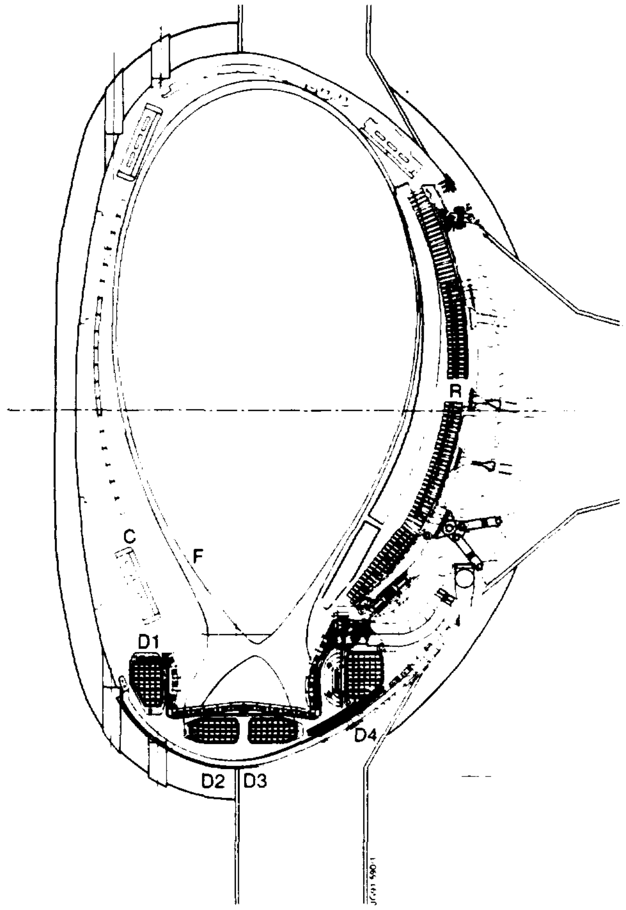

Fig. 1. The JET divertor assembly showing divertor coils (D1, D2, D3, D4), flux surfaces (F), stabiliser coils (C) and RF antenna (R).

The parameters of these plasmas are summarised in Table I.

Table I. Reference plasma parameters

Description	"fat"	"slim"
Plasma current (MA)	6	5
Plasma volume (m^3)	93	78
Connection length (m)	3	7
Safety factor q_{95}	2.3	2.1
Vertical instability growth rate γ (s^{-1})	270	800
Sum of divertor coil currents (MAturn)	0.74	1.8

III. COIL DESIGN

A. Currents and forces

The required coil currents (ampere turns) are determined by plasma equilibria but the coils also have to withstand forces due to vertical instabilities with loss of plasma current. Forces and currents for equilibria and instabilities were calculated using the Proteus code [3] to give the parameters in Table II.

B. Construction

The coils are shown in Fig. 2 and some information on coil construction is given in Table III.

C. Cases and supports

The coils are enclosed in cases made of 1.2 mm thick Inconel 625. Each case is fully welded and encloses the coil, electrical terminals and water connections and is connected to the vacuum vessel by bellows at the base of a lower vertical port. The coils are supported at 32 unequally spaced points. The supports are connected to the coils by clamps encircling the exterior of the cases. Vacuum vessel radial expansion is allowed by hinged parallel links between coil clamps and the support bases, which are welded to the vessel.

Table II. Coil currents, forces and technical data

Coil number		1	2	3	4
Max. current in equilibrium (MAturns)		0.34	0.56	0.56	0.65
Max. force in equilibrium (tonnes)	radial	220	160	-300	-870
	vert.	-10	110	260	290
Max. force in vertical instability (tonnes)	radial	300	170	-330	-980
	vert.	-100	150	340	380
Number of turns		16	15	15	21
Mean radius (m)		2.1	2.5	2.8	3.4
Weight of copper (tonnes)		3.1	3.4	3.9	6.4

Table III. Construction details

Item	Description
conductor material	copper, half hard
conductor cross-section	59 mm x 30.5 mm
cooling hole diameter	17 mm
joints in copper	induction brazed with Silphos shim
insulation material	glass and Kapton tape vacuum impregnated with epoxy resin
insulation thickness	3 mm interturn, 6.5 mm to earth
electrical terminals	2 rigid conductors passing through lower vertical port
voltage per turn	0.5 kV in operation, 1.0 kV test
voltage to ground	15 kV in operation, 30 kV test

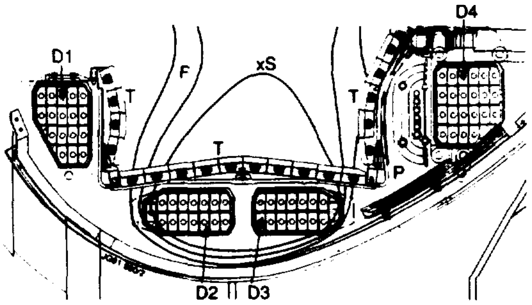

Fig. 2. The divertor coils (D1, D2, D3, D4), flux surfaces (F), separatrix (S), target plates (T) and cryopump (P).

D. Stresses

Stresses in the coils were calculated from the forces given in Table II. These stresses are compared with acceptance test levels in Table IV. It will be seen that the stresses are acceptable. The maximum net force transmitted to the vacuum vessel by the coils is about 1000 tonnes.

E. Cooling

The coil cooling system has been designed for a maximum coil current of 40 kA and a pulse length of 20 seconds. The heating is effectively adiabatic during the pulse and the coils are cooled between pulses. A recirculatory cooling system which limits the temperature difference across the coil to 20°C will be used. As the Jet vacuum vessel may operate at temperatures up to 350°C, the coils will be cooled continuously.

IV. MANUFACTURE

A. Basic method

Final assembly of the coils will take place in the Jet vacuum vessel. Manufacturing methods were assessed in two industrial study contracts. Two basic manufacturing methods were considered, namely;

- winding the coil in the vacuum vessel using a temporary winding table and
- pre-forming the conductor sections into half or third turns at the factory and brazing the conductors together in the vacuum vessel.

Table IV. Stresses in coils

Description of stress	Calculated stress (MPa)	Acceptance level for preproduction tests (MPa)
Von Mises stress in copper, general	75	180 (brazed joint test)
Von Mises stress in copper, at stress concentrations	105	250 (half hard copper)
Shear stress in insulation	4	20

Both methods are feasible but the second has been chosen, because it requires simpler in-vessel equipment and more work can be completed at the factory before delivery.

B. Effects of in-vessel working

Although the construction methods used for these coils are conventional, the fact that the coils are inside the JET vacuum vessel affects manufacturing methods in several ways.

If a coil fails during operation, repair will be impossible and the coil will have to be rebuilt. This would impose a very long delay on the JET programme. If a coil fails after tritium operation of the JET machine is established, then coil rebuilding would be impossible and it is difficult to see how the JET experimental programme could continue. The coils therefore have to be made in such a way that they will not fail. This means that every step of coil manufacture has to be qualified, tested and inspected in the most rigorous way.

Tools for use in the JET vacuum vessel have to be suitably designed for in-vessel conditions. These conditions include entry through ports of limited size, limited lifting equipment, materials to be vacuum compatible and prohibition of the use of hydraulic oil.

The JET vacuum vessel is a radiation and beryllium controlled area. The radiation level will be low (averaging about 7 μSv/hr) so this will impose no restriction on the planned in-vessel working time. The beryllium level will be below that which requires respiratory protection but will require equipment that has been in the vessel to be de-contaminated.

C. Work at the coil contractor's factory

Work at the contractor's factory includes study of manufacture and assembly methods, design of the tools for in-vessel use and development of suitable production processes.

A process that is of particular concern from the reliability point of view is the conductor brazing. A total of 216 brazed joints will be made in the four divertor coils. The brazing process will be conventional (butt joints, induction heating, Silphos shim) but particular attention will be paid to developing a reliable, reproduceable process and non-destructive testing.

Another point of concern is the in-vessel handling and assembly processes, from the points of view of feasibility and speed. Although quality is the prime concern, the in-vessel working time also has to be minimised. The in-vessel procedures have been studied on the JET CAD system but to gain hands-on experiences a full size vacuum vessel simulation will be built and used to study conductor handling and assembly processes.

Production work at the factory includes

1. rolling the conductors to the correct radius to make half or third turns,
2. assembly into a coil to check dimensions and fit and
3. disassembly and application of primer, dry glass and and Kapton insulation to conductors except at the ends.

Finally the coil components and tools will be delivered to the Jet site.

D. Work at JET

The divertor coils are only part of the equipment to be installed for the complete pumped divertor. Due to the restricted space many of these operations have to be carried out in series. To keep the total installation period within reasonable limits the coil assembly time has to be minimised, so

- three shifts per day will be scheduled (2 eight hour shifts for assembly plus a third shift for X raying brazed joints)
- the coils will be built two at a time in parallel (coils 1 and 4 will be assembled and impregnated and then coils 2 and 3).

Figs. 3, 4 and 5 show typical assembly operations and impregnation of the coils.

The main in-vessel operations are;

1. install coil assembly tables, lifting equipment and other tools in vacuum vessel,
2. enter conductors through a horizontal port and store in vessel,
3. assemble conductors on table and braze together to form coil, test and insulate joints after brazing,
4. braze and weld electrical terminals and water pipes,
5. when assembly is complete, apply dry glass tape and Kapton ground insulation,
6. lower coil into coil case, put on case upper half and weld two halves together,
7. evacuate case, heat coil to dry, vacuum impregnate with epoxy resin and heat to cure,
8. lower coil to final position at bottom of vacuum vessel,
9. test electrically and hydraulically.

It is expected to start assembly of the coils in mid 1992 and complete all four coils in about 20 weeks.

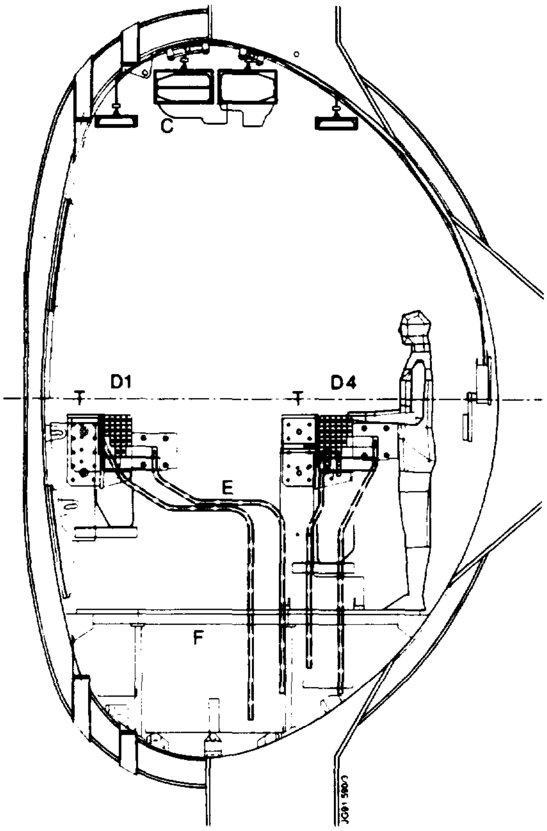

Fig. 3. Assembly of coils 1 and 4 (D1, D4) showing assembly tables (T), temporary floor (F), electrical terminals (E) and cases for coils 2 and 3 (C).

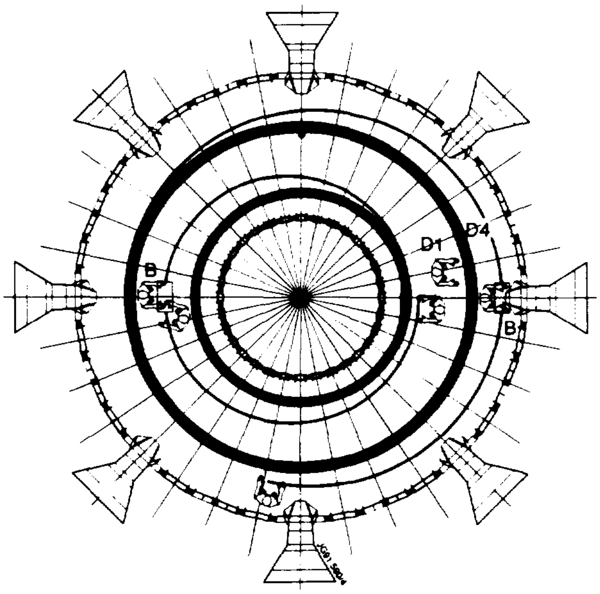

Fig. 4. Plan view of assembly of coils 1 and 4 (D1, D4) showing brazing positions (B).

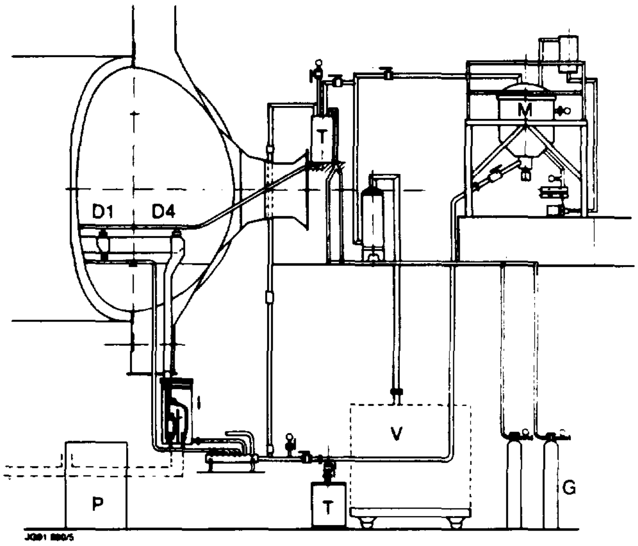

Fig. 5. Layout of vacuum impregnation equipment showing coils (D1, D4), vacuum pump (V), gas supply (G), mixer tank (M), resin tanks (T), air filter (F), impregnation adaptor box (I) and coil heating power supply (P).

IV. CONCLUSIONS

The divertor coil magnetic configuration provides a flexible facility for the investigation of plasmas with a pumped divertor.

Manufacture of the coils inside the vacuum vessel presents many interesting problems, which can be solved to produce satisfactory coils.

ACKNOWLEDGEMENTS

The work described in this paper includes contributions from many colleagues at JET and Ansaldo.

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