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Report

THE DESIGN CONSTRUCTION AND INSTALLATION OF THE HELICAL WINDING FOR THE CLEO STELLARATOR

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ABSTRACT

The CLEO stellarator has a torus 900mm major radius and 166mm minor radius, fitted externally with a 7 field period, ℓ = 3, 120kAT helical winding of 179mm mean radius. The winding and torus have to withstand the large forces produced by the interaction of the current flowing in the winding with the toroidal magnetic field of 2 tesla produced by 24 coils spaced around the torus. To allow the torus to be divided the winding has to be split requiring a total of 240 demountable current-carrying joints at the torus vacuum joint positions.

The design, development, manufacture, installation and operation of the helical winding is discussed.

From the early development stages to installation took four years. When completed this was the largest installation of its type in Europe.

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C O N T E N T S

1. INTRODUCTION

The magnetic confinement of the CLEO stellarator results from a combination of the fields produced by two systems; a toroidal field produced by coils equi-spaced around the torus and a field generated by a helical winding. This field system is illustrated in Fig 1, which is a simplified cross-section of the apparatus.

The helical winding and torus have to withstand forces resulting from the current flowing in the conductors interacting with the toroidal magnetic field. These toroidal field coils have been described previously[1] and are of similar design and construction to those installed in the DITE tokamak assembly.[2]

To permit assembly of the toroidal field coils the torus and helical winding were made in two halves. A major problem in the design and manufacture of the winding is the provision of a high current demountable joint system. When the field coils have been assembled this system is inaccessible, consequently an extensive life testing programme was carried out to ensure that a reliable joint system was installed.

2. LIST OF PARAMETERS

Torus major radius	900.6mm
Torus minor external radius	165.6mm
Torus wall thickness	24.4mm
Plasma minor radius	120.0mm
Helical winding mean radius	179.0mm
Helical winding ratio	7 : 3
Helical winding resistance	50mΩ
Helical winding inductance	1.3mH
Helical winding time constant	26ms
Conductor section	25 x 6mm
Conductor cooling water passage - area	$9mm^2$
Maximum current per conductor	12kA
Maximum conductor joint current density	$11.1kA/cm^2$
Mean joint resistance - per joint	12μΩ
Maximum joint clamping pressure	$27.5MN/m^2$
Toroidal field at 900mm radius	2 tesla
Maximum force on winding per set of 10 conductors	152kN/m

	as designed	as normally operated
Resistive energy input, MJ	5.4	3.3
Inductive energy input, MJ	0.1	0.1
Duration of < 0.2% stabilised pulse, seconds	0.5	0.25
Pulse repetition rate, minutes	< 5.0	∿ 13.0
Measured temperature rise of current joint insert, °C	28.8*	25.5
Calculated temperature rise of current joint insert, °C	36.7	23.8
Calculated temperature rise of conductor, °C	24.0	15.5
Total cooling water flow, ℓ/min	54.5	5.2

* thermocouple connected to water drain connection therefore not a true indication

3. DESIGN FEATURES

Figure 2 shows the winding schematically. It is basically two sets of conductors, connected in series, each carrying maximum ampere turns of 120kAT with a stability better than 0.2% for 0.5 seconds.* The connections to and from a flywheel motor generator are arranged so that the direction of the current flowing in one set is always in opposition to the other positioned adjacent to it on the torus. The polarities of the two sets can be reversed by changing the position of two connecting links. As a similar arrangement is provided for the connections to the toroidal field coils several modes of operation are permitted by changing the connecting links in each system.

Each conductor set spirals seven times round the minor azimuth in going three times round the major azimuth. The total effect is that of a six-start left-hand thread giving a three-fold multipolarity. The field configuration repeats itself seven times in going once round the major azimuth.

To establish the magnetic surfaces it is necessary to position all the conductors producing the magnetic field accurately in space. For the dimensions of this apparatus it, therefore, becomes necessary to form the conductors to within ± 1.5mm of the true azimuthal position and 0.5mm in the radial direction.

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* The winding was designed for maximum pulses of 0.5s duration but is normally used at 0.25s. Figures quoted here refer to the longer pulse condition.

The magnitude of the magnetic force on a set of conductors at a particular point depends upon the helix angle and the value of the toroidal field at that point, as shown in Fig 3, and varies between 71.6 and 152kN/m for a maximum toroidal field of 2 tesla measured at the torus centre. The torus, of 900mm and 166mm major and minor radii respectively, has a wall thickness of 24.4mm to withstand the inward going forces on the conductor set. The outward going forces on the other set are restrained by 24 rings fitted over the winding under the 24 toroidal field coils.

The winding is made from lengths of conductors which are 25mm deep x 6mm wide mounted on edge onto the torus, see Fig 2. To complete one set, 60 lengths are connected in series. The energy input of 5.5MJ is dissipated by water cooling, between pulses, through an elliptical passage 9mm^2 in area formed in the copper by extrusion.

To assemble the toroidal field coils the winding was made in two halves. To connect the two halves a joint system with 240 demountable connections is provided, each connection being capable of carrying a maximum current of 12kA for 0.5s when the joint current density is 11.1kA/cm^2. The joint system was designed to minimise field perturbations and special manufacturing procedures were adopted to ensure correct matching of the piece parts which are of the same helical form as the main conductors.

4. JOINT DESIGN

Figure 4 is an illustration of one joint assembly which has two current carrying faces with a current density of 11.1kA/cm^2.

The connecting components of the assembly are three specially formed pieces; two of which are helically formed short copper strips, with cooling passages and slightly curved joint faces, which are brazed to the ends of the main conductors and are permanently fixed to each torus half. The third component is a helically formed removeable insert piece which bridges the gap between the conductor end pieces. The insert piece, and a part of the conductor end pieces, are wedge-shaped in cross-section to optimise the available space. The inserts are specially profiled to permit assembly from the top as access from the side is impossible because of the proximity of adjacent assemblies. The current carrying faces of the conductor joint ends and insert pieces are clamped together by two stainless steel bands which are tightened by screws threaded into a brass block retained inside the clamping bands. Two bands are necessary as it was found that one single band would not accommodate the helical form of the joint pieces.

A high contact pressure of $27.5 MN/m^2$ is achieved with this clamping system. The clamping screws bear onto countersunk registers in a beryllium copper spring which performs the dual function of spreading the screw pressure onto the copper and also provides a follow-up to maintain the contact pressure even if the clamping system relaxes by as much as 0.25mm. In its free condition this spring has a flat top and a double bevelled base, but when the screws are tightened the bevelled portion deflects until flattened against the top edge of the copper. (The illustration shows the springs in the deflected condition.)

Cooling water is connected to the joint end piece and is directed through two holes into the elliptical passage of the conductor. Having gone 180^o round the torus it passes out of the joint piece, brazed to the other end of the conductor, and into a jumper connection (as shown in Fig 4) into the next conductor to emerge finally at a drain connector which is adjacent to, but displaced 120^o around the minor azimuth from, the supply connection. There are, therefore, 60 parallel water cooling circuits, each of which is monitored and interlocked with the supply generator controls to inhibit pulsing in the event of a blockage.

At the joint faces the current flowing between the joint end and insert has a radial component which generates a localised field which perturbs the main field. To minimise this effect, adjacent assemblies are reversed, as shown in the bottom right hand corner of Fig 4, so that adjacent inward and outward radial current components are compensated.

The joint area is insulated by interleaving 0.1mm thick polyester sheets in such a way that there is a minimum of two thicknesses between the conductors and torus and adjacent conductors.

To withstand outward going forces a specially shaped restraining ring is fitted over the joint insert pieces to minimise the stresses at the reduced sections local to the joint faces.

5. MANUFACTURE

5.1 Introduction

The principal activities in the manufacture of the helical winding are shown in Fig 5.

The winding was produced to the correct helical form with the aid of specially designed jigs and tools. A toroidal cast iron former, made in two halves, of approximately the same dimensions as the stainless steel torus was manufactured for two reasons; firstly to develop a toroidal machining technique which could be adopted to machine the torus; secondly to provide two formers for use in the production of the winding. A toothed jig was used to machine the insert pieces and various other tools were employed, the function of which is described below.

As each of the conducting components is unique, a coding system was used and each component marked accordingly so that on subsequent assembly its position in the winding could be established.

To ensure an accurately fitting winding it was tailored to suit the torus with the joint ends individually cut to lengths to fit their matching conductors. The 120 conductors were cut to a pre-determined length, with an allowance for the joint ends, and hand formed on one half-former. They were next assembled onto the appropriate torus half to measure the actual length of the joint ends required to complete the conductor, the ends being brazed on at a later stage. The joint ends themselves were formed on the second half-former onto which they were subsequently mounted to machine the end profile and the joint faces. After cutting the ends to the prescribed lengths they were joined to the conductors by fluxless brazing.

A major problem with such a complex assembly is to decide how to machine the joint faces. It was considered impossible to machine the faces flat and square to a conductor of helical form, and also require them to fit exactly with the mating faces, without resorting to very intricate machining procedures and the use of complicated jigs. This was resolved by machining the joint faces to cylindrical form; for example, one set of joint ends was internally bored to a specified diameter over a given length, the matching insert pieces being externally turned to the same diameter and length.

5.2 Forming the Conductors - Fig 5(a)

Each of the 120 conductors was cut accurately to a length to suit its unique torus position, allowance being made for the joint end pieces which would be brazed on later. After checking that the cooling passage was clear, the conductors were cleaned and insulated with two different tapes, half-lapping to provide maximum tracking. The first tape applied was an 0.05mm thick self-adhesive polyester, the second an 0.2mm thick polyester tape fibre re-inforced and impregnated with a B-stage epoxy resin. This was cured by heating at 200^{o}C for one hour giving a robust insulated layer sufficiently flexible to allow subsequent forming by hand using simple tools. The insulation was then pin-hole tested and the conductors stored until required.

In parallel with the above work, one half of the machined cast iron toroidal former was prepared. Holes were drilled in it in specific minor and major azimuthal positions calculated so that each formed conductor would fit into its allotted torus position. The former was then mounted on a rotatable manipulator which was enclosed by a platform for ease of access when forming. Into each hole in the former spring pins were driven to locate tapered pegs against which six sets of aluminium strips were formed and fixed. Any burrs and sharp edges on the former and strips were removed and the countersunk fixing holes in the strips filled with epoxy resin.

The conductors were formed to the requisite compound curvature against the aluminium strips. To allow for the fitting of the two co-axial feed connectors, twenty conductors were specially formed. At a specific distance from the end of the former, the conductors were displaced one conductor thicknesss at the connector position. This was arranged by fitting over-sized tapered pegs with a short aluminium strip to the end of the former. The change in the radial attitude of the displaced conductors was made by a hydraulic crimping tool fitted with special die blocks. Two short conductor lengths were formed to and from the connector position for the supply and return connections. (On to the connector ends of these lengths adapator pieces were subsequently brazed on to which the inner and outer connections are fixed.) This assembly is shown in diagrammatic form in Fig 2.

5.3 Determining the Length of the Joint Ends - Fig 5(b)

After vacuum testing, the stainless steel vacuum torus was fitted with tapered pegs in a similar manner to that described above to define the helical path but, in this case, the pins did not penetrate the wall of the torus since it is a vacuum vessel. The pegs were accurately positioned at each restraining ring position. As these are widely spaced, the helical path of the first conductor of each channel was marked for guidance in positioning. The torus was then split and circular surface plates fitted to provide a reference to the centre of each vacuum joint. The halves were next assembled on to the forming manipulators as shown in Fig 6.

The formed conductors were assembled and clamped against the locating pegs.

To achieve the correct radial attitude of the conductors, with adjacent conductors touching at the inner edges on the torus surface and spaced apart at the outer edges, wedge-shaped resin combs were fitted to each group of ten conductors. As there was a slight difference between the calculated and actual fitted lengths, the height from the end of a particular conductor to the surface plate was unique to that conductor. It was necessary to measure this height for every conductor in order that the matching joint ends could be cut to length to ensure an accurate fit. The heights were duly measured and recorded for subsequent reference.

5.4 Preparing the Joint Ends - Fig 5(c)

The blanks for the conductor joint end pieces were machined so that the ends, local to the brazed joint, have the same cross-section as the main conductors. Over the joint area the joint ends are wedge-shaped to provide a joint of optimum width. The water cooling and pipe connector fixing holes were drilled in the blanks prior to forming.

The second half of the cast iron toroidal former was used to form the piece parts. At two positions on the former, helical aluminium strips were fixed to it in the same way as described for the main conductors, so that the formed joint ends simulate the winding form local to both torus vacuum joints. The blanks were hand formed against the strips and former and the completed lengths, of 60 per vacuum joint, placed and clamped on the former about a major radial centre line marked on the former representing the centre of the vacuum joint. A line coincident with this centre line and two lines 82.5mm from, and parallel to it, were scribed on the top edges of the formed blanks. The blanks were then removed and cut into two pieces at the centre line mark.

5.5 Machining the Joint Ends - Fig 5(d)

To have reasonable access when machining the conductor joint end pieces, it was necessary for them to overhang the ends of the former. For this purpose two sets of helical aluminium strips were fitted to the former on which the blanks had been previously formed. They were positioned so that the centre of the vacuum joint, used as a datum, did not lie on the surface of the former but a few centimetres from the ends.

The blanks to have externally machined joint faces were fixed to both ends of the former butting the cut edges against an angled setting plate, fixed to the end, which represents the vacuum joint centre. The plate was then removed and the end profile and joint faces externally machined to a set diameter. An identical procedure was carried out for the blanks with internally machined joint faces.

Figure 7 shows the blanks positioned and clamped on the ends of the former. The farthest blanks have not been machined, the nearest ones are in the process of having their joint faces externally machined. The set of strips used to form the blanks can also be seen in the background on the far side of tneformer.

After machining, the end pieces were individually held at the required angle using the line previously scribed on the top edge, as described in Section 5.4, as a reference and marked off to the length, as recorded in Section 5.3, to suit its matching conductor. The surplus material was then machined off.

5.6 Machining the Joint Insert Pieces

The insert pieces were formed from wedge-shaped blanks in the same way as the joint end pieces. They were machined in a jig in which they were retained in a plate with slots cut in it at varying angles to hold the pieces to the correct helical configuration. The joint faces were then externally machined on one side and internally machined on the other to the same diameter as the joint end pieces.

Figure 8 is a view showing the inserts being machined where the curved form of the joint faces is clearly visible.

5.7 Brazing the Joint Ends to the Conductors - Fig 5(e)

The conductors and joint ends were brazed together using a fluxless brazing technique. A proprietary silver alloy (15% Ag:Cu:P) brazing foil 0.125mm thick, slotted in the region of the water passage, was clamped between the joint faces and the joint area heated by passing a current of 1,400A at 10V through carbon electrodes. The joint was purged with argon through a pipe fixed to the water cooling connection point. Before brazing a batch of conductors and ends, sample strips were brazed together and fractured for examination. (An ultrasonic method was investigated but the complex geometry of the joint and water passages made the oscilloscope trace difficult to interpret.) The individual electrical resistances and water pressure drops of the two components were separately recorded before brazing and compared with those for the jointed conductor.

5.8 Inspection

To ensure that the winding and joint system when finally assembled would fit correctly, the torus halves were connected, with a spacer ring between the vacuum faces, and the completed conductors assembled on to it. The joint inserts, clips and springs were then fitted to complete the joint system, as shown in Fig 9. The joint was next visually examined to assess whether or not the joints fitted correctly and the gaps between non-joining edges measured to ensure that they were spaced apart a distance sufficient for assembly purposes and for flashover not to occur. The winding was then removed, the torus split into two halves and the halves mounted on the manipulator.

5.9 Fitting the Winding to the Torus

The torus halves were carefully examined and any imperfections which could damage the conductor insulation were removed. The surface was cleaned and covered over the winding area by two layers of 0.05mm thick polyester tape. The completed conductors were finally assembled on each half torus, with the spacing combs, and temporarily secured by clamping bands.

The restraining rings, which are in two halves joined together by a tee-shaped key, were assembled over the torus and conductors and fixed to the torus by clips screwed to the locating pegs. The half toroids were rotated in stages to position each ring horizontally in turn (with the exception of those at the ends of the half toroids which were omitted at this stage). The gaps between the winding, torus and rings were filled with an epoxy resin mix using a marble flour filler. To ensure the integrity of the winding it was insulation tested, before filling each ring, to hold off 7kV d.c. for five seconds with the torus connected to earth.

5.10 Connecting the Winding to the Generator

The torus halves and the winding were next joined, as the final installation, and connected to the supply generator to assess their combined electrical characteristics. The number of 12kA-$\frac{1}{2}$ second pulses was restricted to 150 as it was considered inadvisable to proceed further because of the large deflections of the joint system in the absence of the local restraining rings. The joint resistances were monitored throughout the test and these were found to agree closely with those of the life tests.

On completion, the supply cables were disconnected and the torus positioned vertically on to a cross frame to position the remaining four restraining rings for epoxy filling. These had not been filled before as it was considered that this should be done with the joints assembled. Figure 10 shows the assembly being insulation tested at this stage.

The winding joints were removed, the torus split into two halves, blanking plates being fitted to the ends to protect the vacuum faces. The halves were then transported to the site for installation.

6. INSTALLATION

Installation commenced in January 1974. Figure 11 shows a toroidal field coil being lifted over one half of the torus assembly which is mounted on cast aluminium supports fixed to a large concrete plinth. To enable the plinths to be moved together, when connecting the torus halves, they are fitted with rollers locating in hardened steel rails embedded in the experimental hall foundations.

The toroidal field coils were temporarily positioned together as closely as possible to afford maximum access at the vacuum joint positions. The plinths were then moved towards each other to make the torus vacuum joints. After vacuum testing, the helical winding joint area was prepared for assembly of the joint system.

The joint system was assembled in stages making up to twelve connections at each stage. Figure 12 shows one of the insert pieces being assembled. The stages were scheduled to permit the insulation to be tested to hold off inter-turn 2kV d.c. and 7kV d.c. to earth. The design does not enable all the joints to be inter-turn tested.

To be certain that all the clamping screws were correctly tightened they were checked at least twice. After initial installation by craftsmen, the two supervisors each checked the assemblies at one vacuum joint changing over to recheck those at the opposite vacuum joints.

The central keyed restraining rings were fitted over the joint inserts filling the assembly clearances with a thixotropic resin.

The water pipes were next connected and pressure tested. The leads used to measure the joint resistances were connected to the screws which fix the water connection flange to the joint ends. The completed assembly is shown in Fig 13.

The toroidal field coils were repositioned providing access to fit the co-axial supply connections which pass through the plinths to plates on to which are fixed bus bars connecting to the generator.

After completing final checks the winding was pulsed 700 times at 12kA for 0.5 seconds. Joint resistances were monitored and carefully checked for variations but they were found to be constant throughout the test. Cooling water and joint insert temperatures were also monitored and recorded.

The supply connections were removed to reposition the coils as before with maximum access at the vacuum joints. The joint clamping screws were checked and found to be tight at their original torque setting. They were finally checked by the supervising engineer and then locked. The field coils were finally assembled and the toroidal field coils, the helical winding system and auxiliary field systems commissioned.

7. OPERATIONAL EXPERIENCE

The machine was operated between October 1974 and May 1976 both in the stellarator and tokamak modes. The results obtained are given in references [7] and [8]. During this period the opportunity of measuring the movements of the torus and winding under operational conditions was taken, using an optical displacement detector developed by the CLEO group.[9]

Figure 14 shows the displacement of the two vacuum joints when a current of ∿ 12kA is passed through the winding with and without the toroidal field coils energised. For the north joint, the field does not appear to have any pronounced effect, whereas, for the south joint there appears to be a transient increase, possibly due to magnetic forces resulting from the winding current interacting with the toroidal field, of approximately half that due to helical winding resistive heating alone. This movement was higher than anticipated at the design stage and gave rise to vacuum problems at the torus vacuum joints making it necessary to limit the current to 6kA until modifications to the vacuum joint could be made.

Figure 15 shows the radial and azimuthal deflections of one conductor channel measured mid-way between restraining rings where there is minimum support. This shows a complex expansion pattern with rapid expansion in both directions with the channel displaced 0.2mm in the azimuthal direction when it is also 0.2mm above the torus surface.

The operational requirements were reviewed and it was decided that a 0.5s pulse was longer than required and that a ripple free pulse of 12kA for 0.25s, with a repetition rate equivalent to that of the field coils, would meet future experimental conditions.

In May 1976 the machine was shut down to fit improved vacuum joint seal assemblies which would allow the torus to move under the influence of the helical winding expansion forces and hence reduce the conductor movement relative to the torus to negligible values. This provided an opportunity to inspect the current joint surfaces. At this time they had been pulsed 950 times at 12kA for 0.5s and 4,000 times at 6kA for 0.2s. The surfaces were slightly discoloured and, in some cases, were etched and slightly pitted. There were no traces of welding. Since the imperfections were of a minor nature, which could easily be removed by lightly stoning, the current joints were re-assembled with conducting grease as before. The winding was assembled as described previously but this time the winding was pulsed 600 times at 12kA, 0.25s to bed-in the joints.

During December 1976 the winding was commissioned to the toroidal field system. Since this refit the winding has been pulsed at various current settings in varying toroidal fields. Up to the end of 1978 the winding had been pulsed in excess of 7,000 times at various settings since it was first assembled in the test area.

Figure 16 is a view of the completed machine.

ACKNOWLEDGEMENTS

A number of people contributed to the success of this construction and their efforts are hereby acknowledged.

In particular to Messrs Barrow, Coultas, Crossley and Walker who were involved throughout the whole of the project and to Mr J E Partridge and members of the Manufacturing and Installation Group. The advice and assistance of the CLEO Group, Dr Reynolds and Messrs Lees and Shatford were most helpful. Thanks are due to Mr K M Plummer, who had overall responsibility for this work, and Messrs Galloway and Millward and the Generator House staff for their assistance when operating.

JOINT DEVELOPMENT AND LIFE TESTING

A1.1 INTRODUCTION

The design of the current joint assembly was developed by extensive life tests and special procedures were used during installation since it is impossible to maintain or examine the helical winding connections when the water cooling pipes and toroidal field coils have been installed. This is evident from Fig 13, showing the joint assembly as installed in the machine before finally positioning the toroidal field coils.

A1.2 DEVELOPMENT TESTING

To assess whether the current joints were satisfactory, five assemblies were subjected to 19,000, 12kA pulses of 0.5s duration. Approximately half way through this test series the clamping bands, which were then manufactured from beryllium copper tube, fractured seriously damaging the assembly components. Examination showed that the bands failed at a low stress figure of 114.6MN/m^2 over a region where the band was bent to an internal radius of 0.5mm. Increasing this radius to 1.25mm increased the failing stress five-fold. This confirms published information indicating that where beryllium copper parts are dynamically loaded and must have long term reliability, then the fatigue factor has to be carefully assessed and abrupt changes in section avoided.[3][4] The bands were subsequently redesigned and manufactured from stainless steel tubing 0.5mm thick, which when tested failed at higher loads than identical bands of beryllium copper.

A1.3 CLAMP AND SPRING TESTING

The hoop stress of the stainless steel clamping bands was determined by strain gauges and found to be a quarter of the 0.2% proof stress value with the clamping screws tightened to a torque of 1.0Nm which was the setting adopted for the life tests and final installation.

To ensure the reliability of the springs a selective manufacturing procedure followed by a destructive test routine was adopted. The springs were heat treated in batches of 40 and two were taken at random for testing. Using a Hounsfield extensometer each spring was loaded to the maximum deflection condition, with the bevelled edges flat against a test plate, and then unloaded. This was repeated ten times to check for permanent set. They were next broken by bending over a centrally positioned anvil fixed to the test plate. The load-deflection characteristics for the two tests were compared and it was found that, in the worst case, the deflection to flatten the spring was half that required to fracture.

A1.4 LIFE TESTING

To prove the design, five assemblies made to the same standard as the final installation were pulsed 47,000 times. Figure 17 is a view of the assemblies connected to the battery power supply. Also shown is a co-axial supply connector on test, the resulting data being used to determine the final design.

A1.5 JOINT RESISTANCE MONITORING

Throughout the tests, joint resistances were monitored and recorded by UV oscillogram. There was an indication of a decrease in resistance during the first few hundred pulses thereafter remaining reasonably constant. It was considered that this could be attributed to a bedding-in of the joint faces on a macroscopic scale. Since, in the extreme, this might reduce the clamping pressure it was decided that on installation to the torus a bedding-in procedure be adopted. After completion of the winding it would be pulsed 700 times at maximum current conditions, monitoring the joint resistances throughout for any variations. On completion, the tightness of the clamping screws to be checked and the screws locked before proceeding with final assembly of the toroidal field coils.

A1.6 JOINT SURFACE TREATMENT

During the course of this development work the following surface treatments were tested:

(a) proprietary conducting grease
(b) silver plating using the 'Dalic' process
(c) electro plating - gold on silver
(d) 'tinning' with indium
(e) 'tinning' with pure tin
(f) silver coating by an evaporation process in vacuum
(g) gold coating by an evaporation process in vacuum

In addition, some samples were tested with a 0.25mm thick shim of annealed silver between the joint faces but the results did not justify adopting this as a jointing technique, especially as it would have caused assembly problems on the machine.

The various surface plating treatments did not appear to enhance the current carrying characteristics, or inhibit surface deterioration, over that of a machined copper face coated with 'conducting' grease. It would appear that provided the formation of an oxide layer is inhibited and the joint is tightly clamped this treatment is perfectly adequate. This is in accordance with work carried out by Melsom and Booth[5] which indicated that there is a rapid reduction of contact resistance with increasing pressure up to about 17.2MN/m^2. (The lowest contact pressure for the joint system is estimated to be 27.5MN/m^2.)

A1.7 JOINT OVERHEATING TESTS

Two joints were assembled with conducting grease and connected to the power supply and pulsed at varying currents for periods of 1 to 24 seconds, to compare the temperature of the cooled conductors with the uncooled joint insert under different load conditions, and to determine the effect on the joint assembly after gross over-heating. On dismantling, slight pressure was needed to part the joint faces which were in good condition with no signs of arcing or burning.

A1.8 ELECTRO-MECHANICAL PROVING TEST

To prove that the joint system could withstand the forces resulting from the interaction of the current flowing in the system with the toroidal field, an electro-mechanical test rig was constructed. This simulated a set of ten, closely packed, joint assemblies as assembled at the inward facing surface of the torus. Steel beams of equivalent stiffness to the restraining rings of the final assembly were clamped over the conductor ends and the insert pieces. A force was applied by a large air cylinder in synchronisation with a 12kA pulse. The bedding-in procedure adopted for the installation was followed. After retightening and locking the clamping screws, and connecting the air cylinder, the rig was operated for more than 5,000 pulses. The resistance figures were consistent with those of the static life tests. There was no indication of any mechanical defects of the components.

The life and mechanical tests have been reported.[6]

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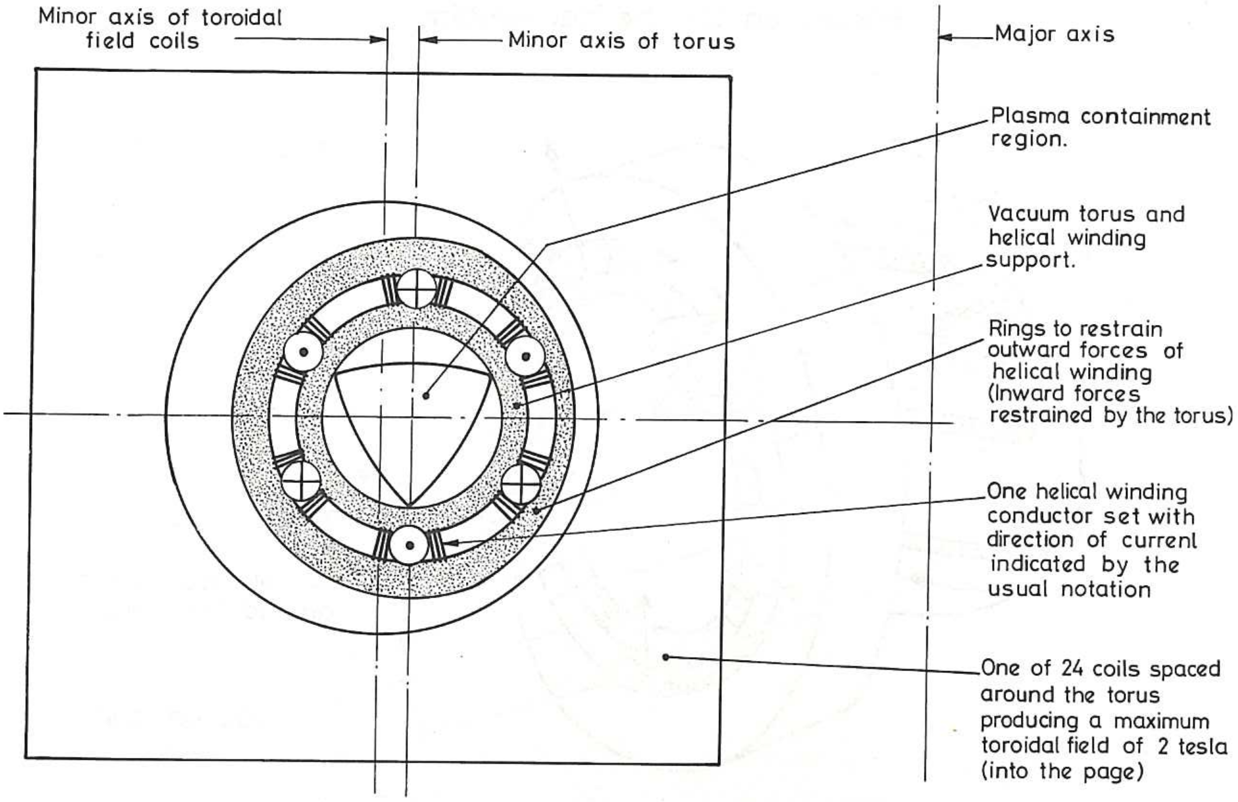

Fig. 1 CLEO – simplified section through minor axis.

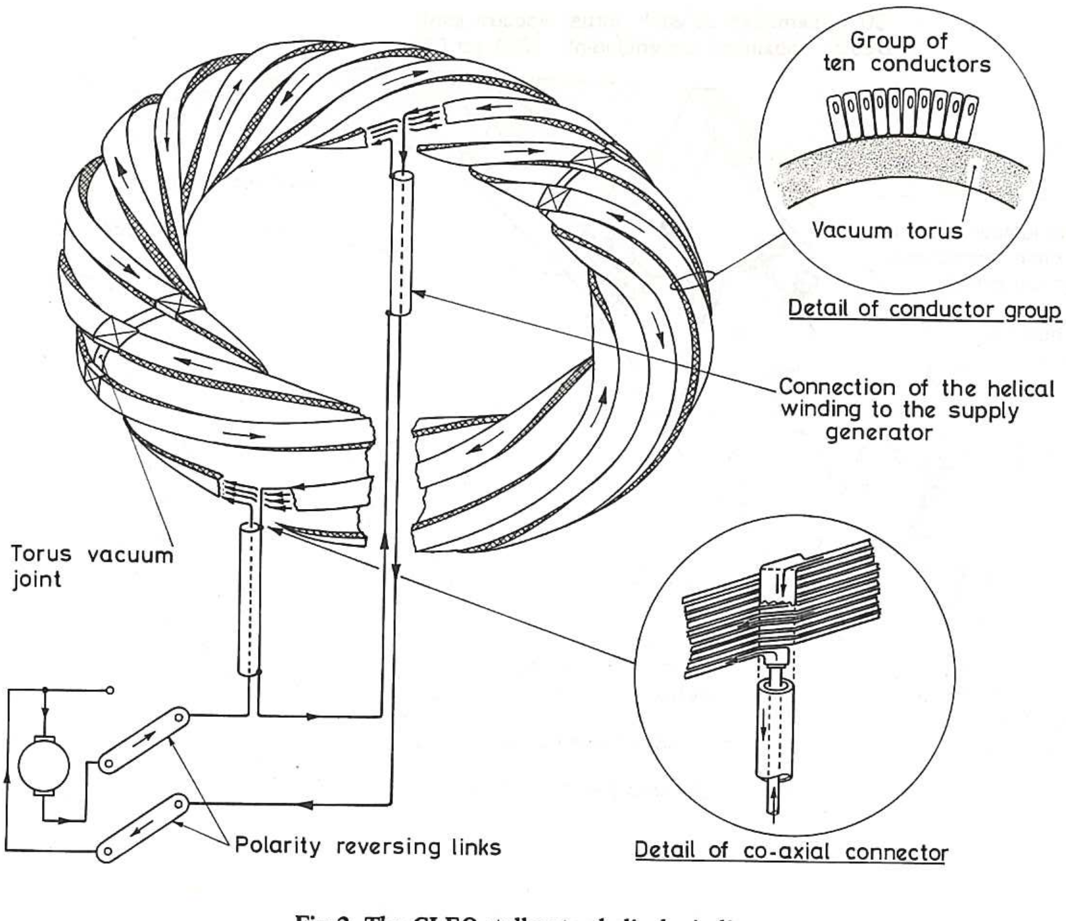

Fig. 2 The CLEO stellarator helical winding.

Forces on the helical winding

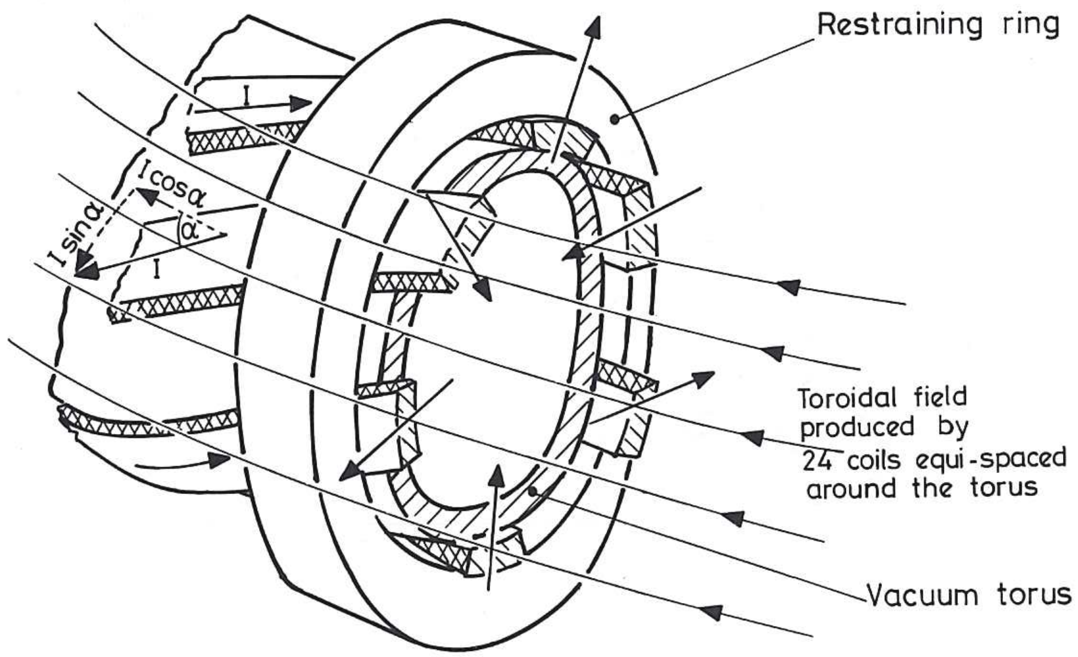

Fig. 3 Forces resulting from the interaction of the I sin α component of the helical winding current with the toroidal field produces inward going forces which react against the torus, and outward going forces which are restrained by rings fitted under each toroidal field coil.

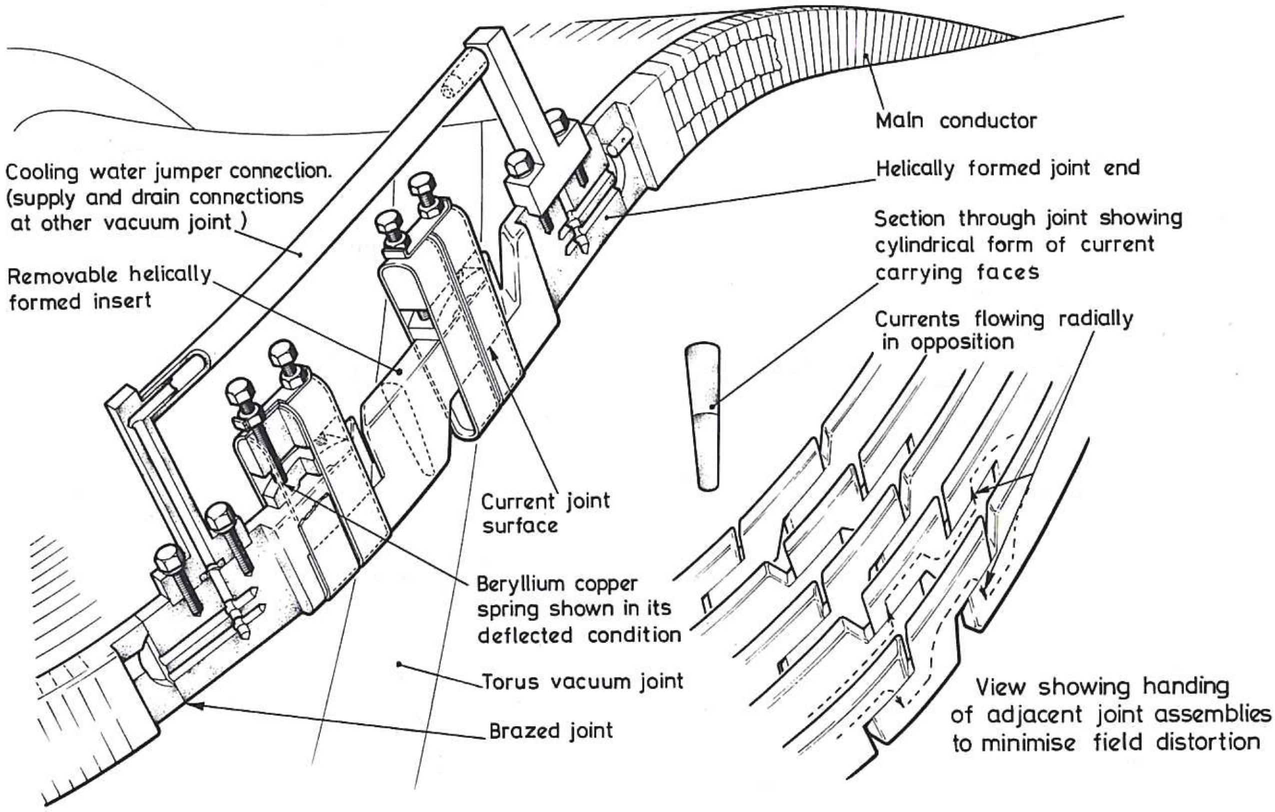

Fig. 4 Helical winding joint assembly.

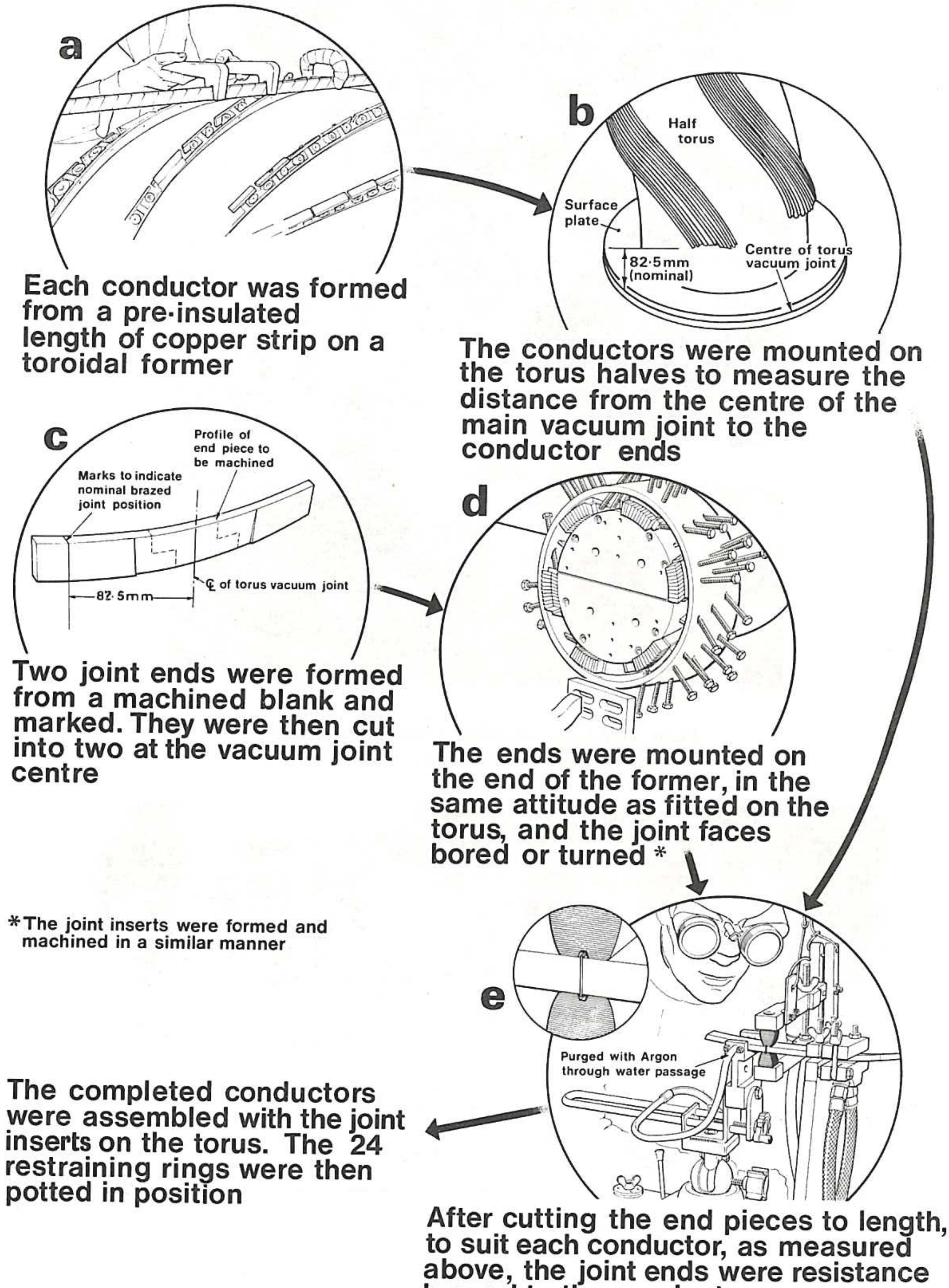

Fig. 5 Manufacture of the CLEO helical winding.

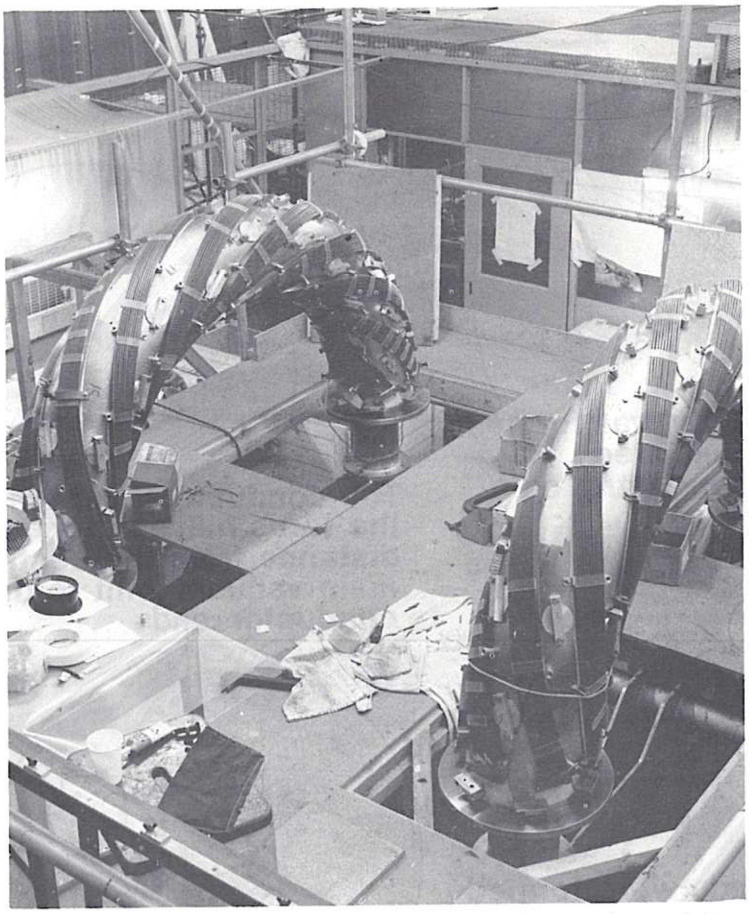

Fig. 6 Trial fitting of helical winding conductors onto the stainless steel vacuum torus.

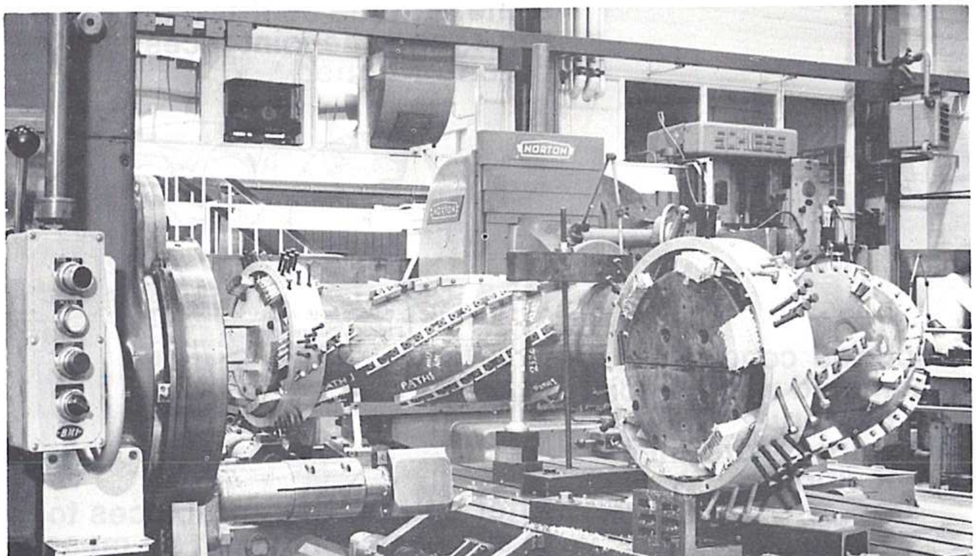

Fig. 7 External machining of joint end-pieces.

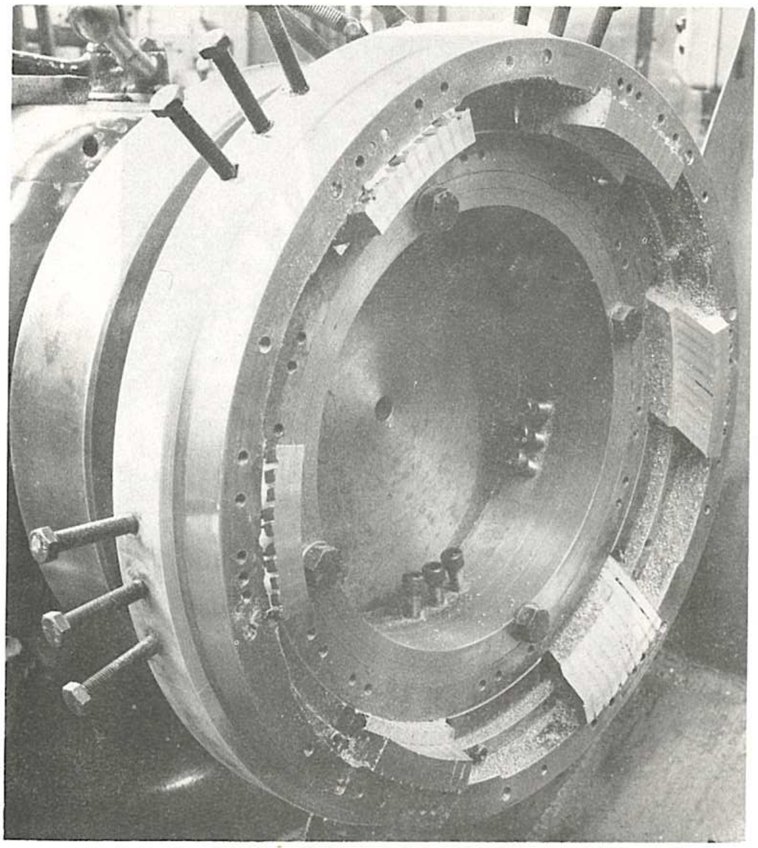

Fig. 8 Joint inserts being machined.

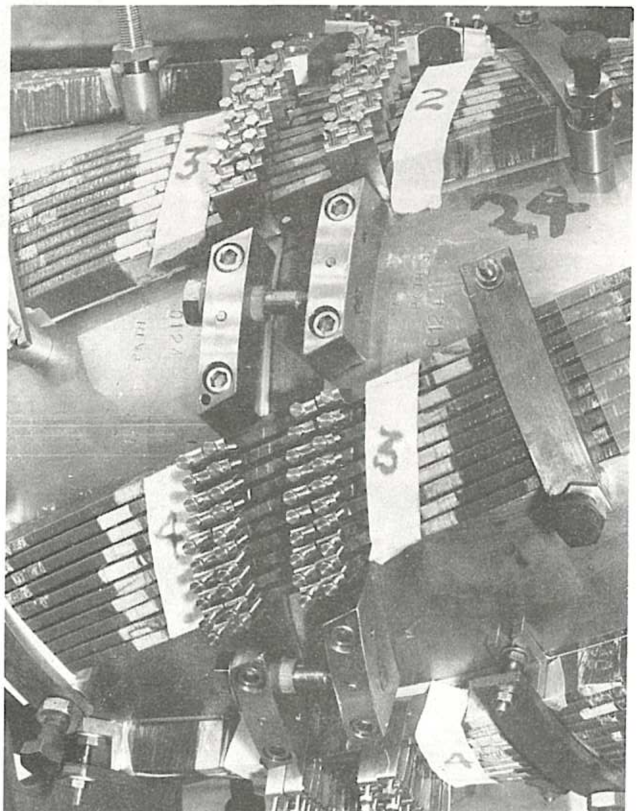

Fig. 9 Trial assembly of conductors and joint-inserts on the stainless steel vacuum vessel.

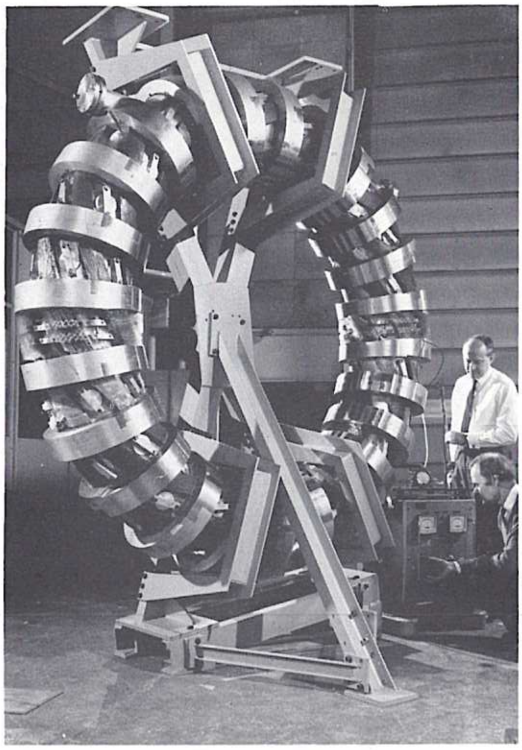

Fig. 10 Insulation testing prior to potting the gaps under the end restraining rings.

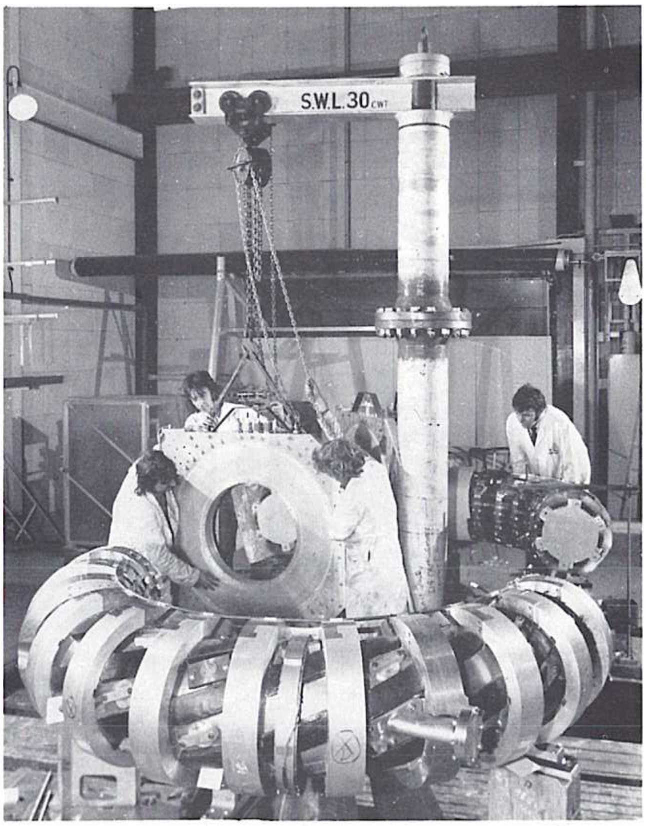

Fig. 11 Installation of main field coils over the vacuum torus and helical winding assembly.

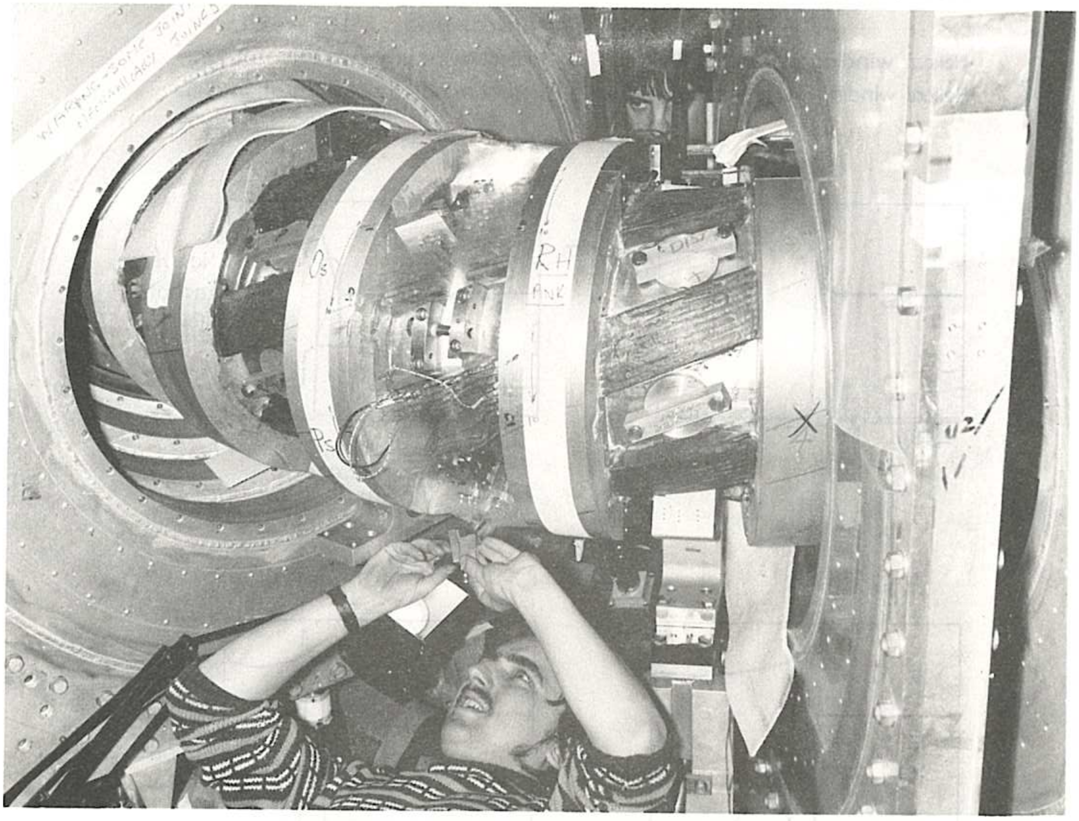

Fig. 12 Installation of joint-inserts in the current joints.

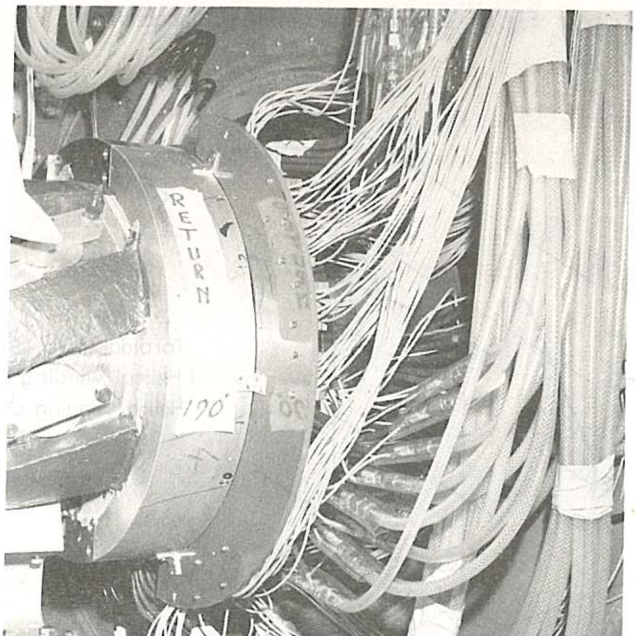

Fig. 13 Helical winding joint area after fitting water and joint resistance monitoring connections.

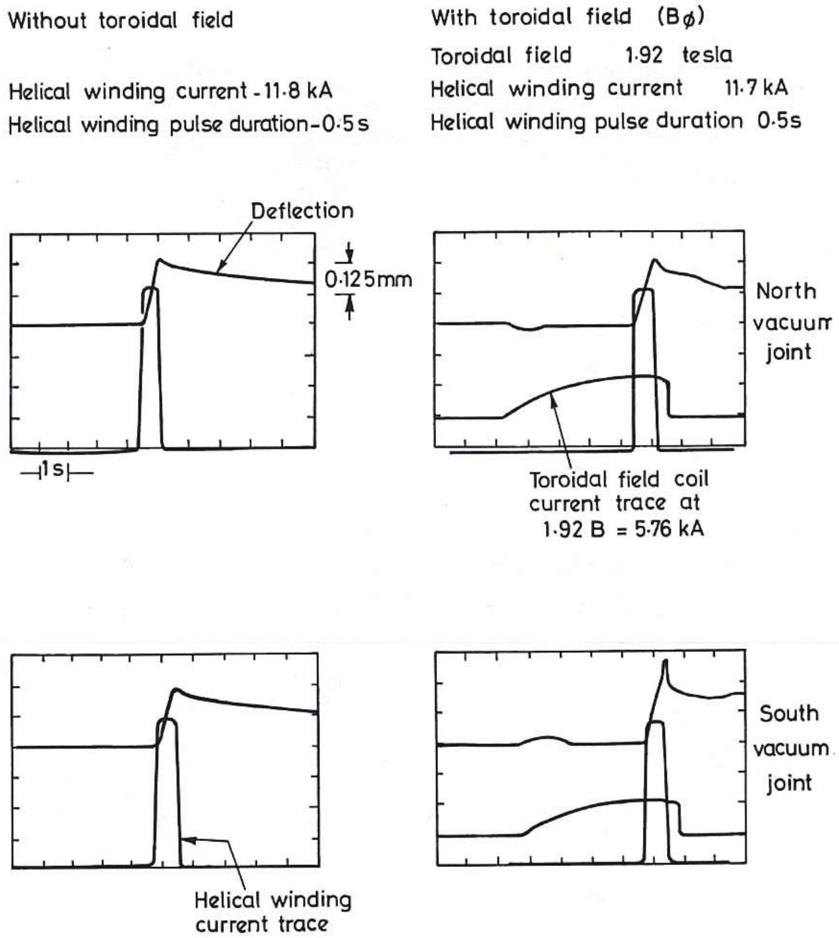

Fig. 14 Torus vacuum joint displacement.

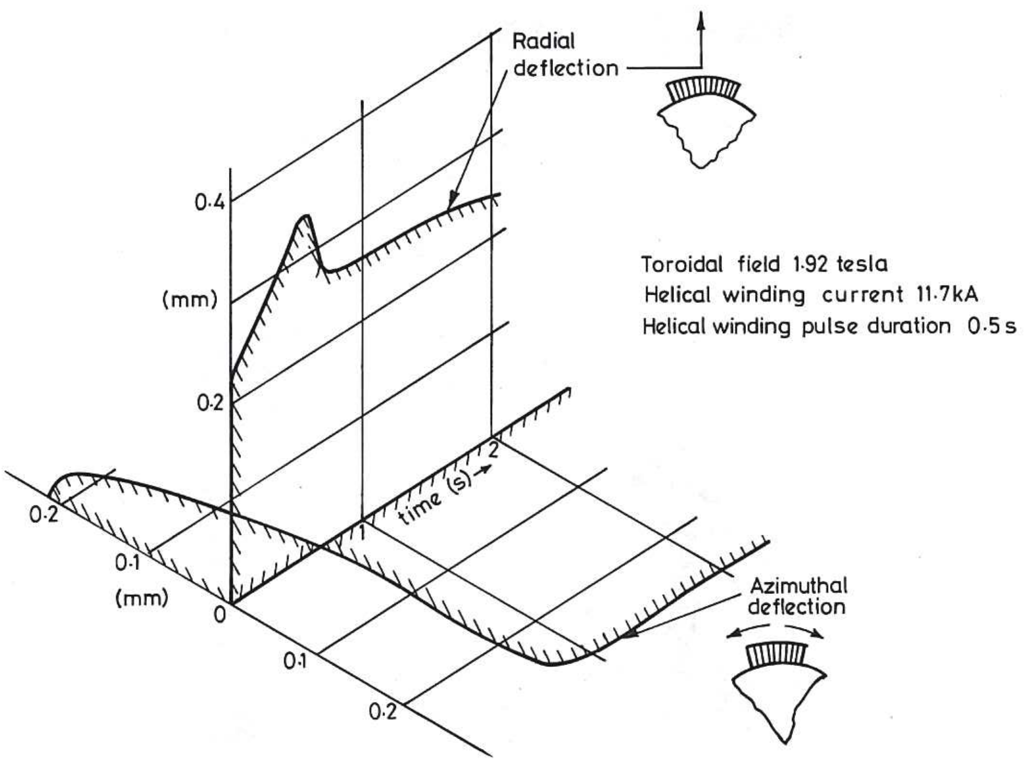

Fig. 15 Radial and azimuthal deflection of one conductor set midway between restraining rings.

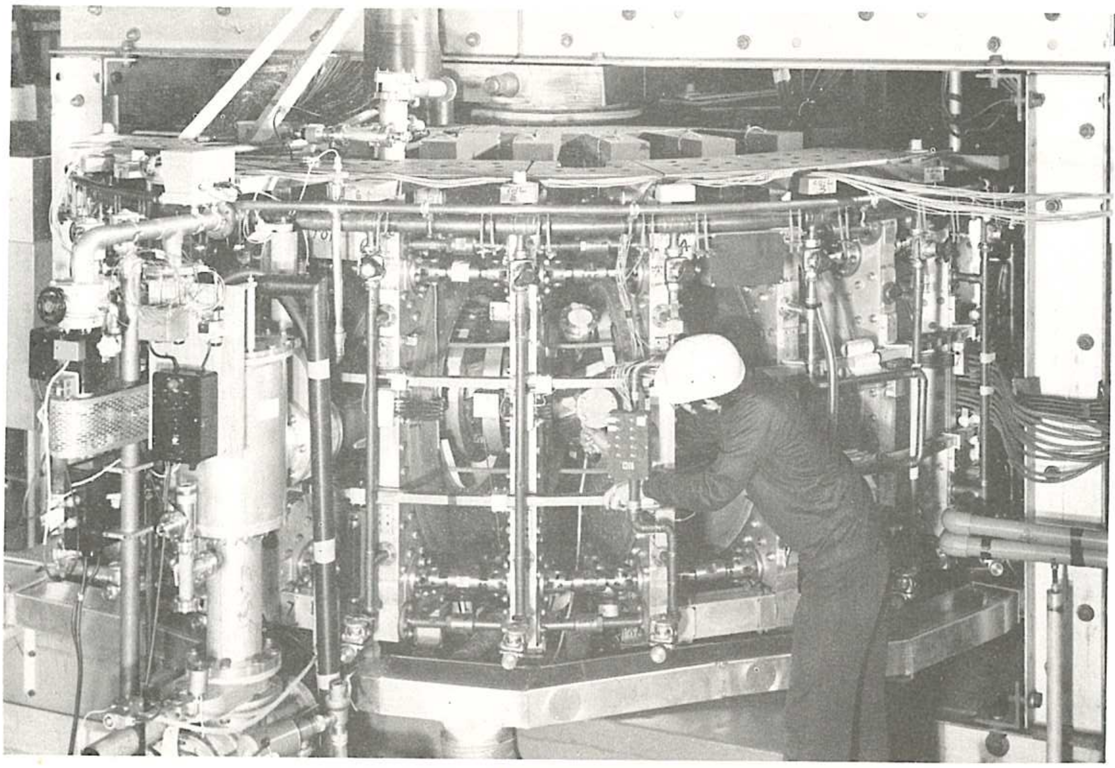

Fig. 16 View of the CLEO machine fully assembled.

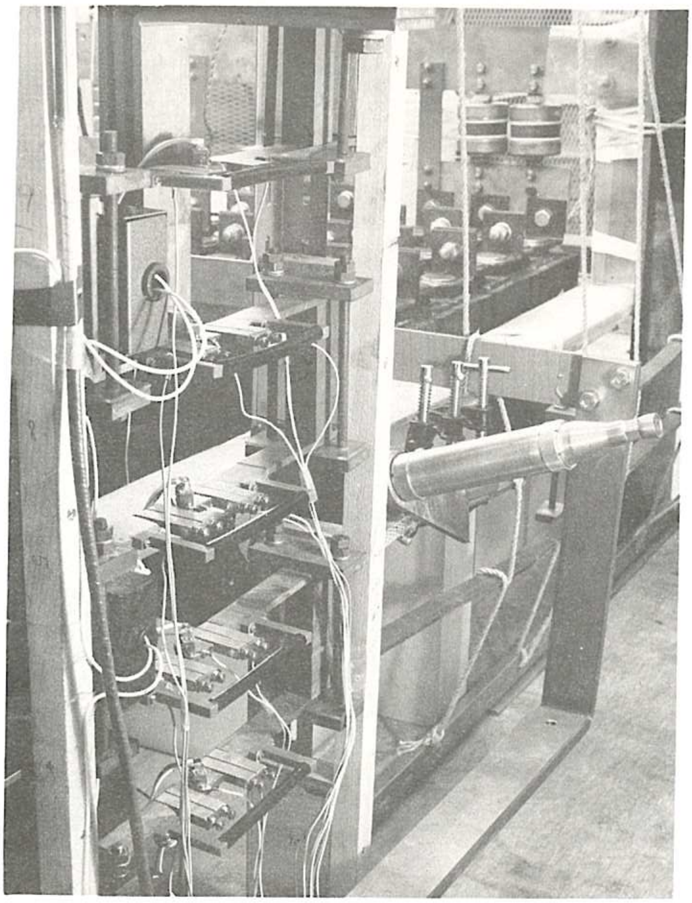

Fig. 17 Current joint test rig.

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