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REPORT ON THE DESIGN OF JT-4

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JT－4 Group

日本原子力研究所
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The present status of design of JT-4 tokamak is described. The objectives of JT-4 are shown graphically and the main parameters are tabulated.

JT-4 is a tokamak of non-circular (ellipse or D-shape) plasma cross section with axisymmetric divertors at top and bottom of the plasma column. The principal purpose of JT-4 is to obtain high plasma beta values, desirably exceeding 5 % , by strong secondary plasma heating and by impurities elimination. The experimental results obtained with JT-4 are essential in the design of future tokamaks and tokamak reactors with high efficiency and at reasonable cost.

Keywords: JT-4 Tokamak, Non-Circular Cross Section, Axisymmetric Divertor, High-Beta Plasma, Design

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JT－4の調整設計

（JT－4設計報告・11）

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52年度に実施した調整設計の結果を中心にして，非円形断面トーラス試験装置（JT－4）の現在までの設計をまとめた。

JT－4は，非円形断面のトカマク装置であり，上下に軸対称ダイバータを設けている。主な研究目標はプラズマのベータ値を増すことであり，ベータ値を5％以上とすることを目標としている。JT－4で得られる高ベータ化トカマクの実験結果およびプラズマ制御技術は，将来のトカマク装置を経済的に製作する為に必要なものである。

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1. Introduction

JT-4 is a tokamak device with a plasma column of non-circular cross section and two axisymmetric divertors at the top and bottom of the plasma column. The basic purpose of JT-4 is to obtain experimental results about the improvement of efficiency of tokamaks or the design of small-sized low cost tokamaks. It is required that the results obtained in JT-4 should be extraporatable to future large tokamaks, and consequently the size, the plasma temperature and the energy confinement time should not be too small.

The position of the JT-4 program in the development of the tokamak reactor is shown in Fig.1. JT-4 is planned to connect the reactor region and the present plasma region, and locates at the middle of two regions on the confinement time scale. On the scale of beta value, JT-4 is planned to attain more than 4 % which is the minimum beta value required for economical reactor, and possibly more than 5 %.

The actual objectives of JT-4 program are the experimental investigation of 1) the effect of non-circular plasma cross section on attaining higher beta values and 2) the effect of divertor on reducing impurity contents and on controlling plasma density.

The purposes and the design of JT-4 were examined at an official committee (The Nuclear Fusion Council) in 1977. And a special subcommittee of JT-4 also began its work on cooperative study work with universities.

Following the preliminary design carried out in FY 1975,(1)(2) the engineering studies and the test of critical components were done in FY 1976. A design of the whole system (officially called as the design adjustment) were carried out in FY 1977 laying emphasis on the cost reduction. The construction and the operation are expected to start in FY 1979 and 1983, respectively.

The outline of the design done in FY 1977 is described in the following.

2. System of JT-4

The main parameters and the bird's eye view of JT-4 are shown in Table 1 and Fig.2, respectively. The JT-4 machine consists of the vacuum vessel containing divertor coils and other auxiliary components, the toroidal field coils, the poloidal field coils and base plate structure. Around the machine, the vacuum pumping system, the diagnostic devices and the secondary plasma heating devices are set. There are several subsystems included in the JT-4 to supply electric power, cooling water, etc. to the machine components, to control the whole system and to process the plasma data. The component subsystems of JT-4 are shown in Fig.3, where the solid lines show the flow of electric power. The pulsive power with large peak power for the coils and the secondary plasma heating is supplied by large motor generators of JT-60. The secondary cooling water and the emergency power are also supplied by JT-60 system.

The cross section of the main part of JT-4 machine is shown in Fig.4. There are two divertor chambers and six divertor coils at the top and the bottom of the vacuum vessel. The details of the vacuum vessel are described in 3.2. The poloidal field coils are set around the vacuum vessel. Most of the poloidal field coils are supported by the vessel. There are 18 D-shaped toroidal field coils surrounding the poloidal field coils and the vacuum vessel. The toroidal field coils are splittable into upper and lower halves. It is not necessary to joint the poloidal field coils in a narrow space. Thus the difficulties in the coil joint of the poloidal field coils where high insulation voltage is required are avoided, and high reliability is obtained in the poloidal field coils and in the vacuum vessel. The difficulties of the machine design are concentrated on the splittable toroidal field coils which are described in 3.3.

There is a wide variation in the shape of the plasma cross section which is achieved by changing the tap connection of the shaping field coil. One of the plasma equilibrium calculation results is shown in Fig.5. The design of the poloidal field coils is described in 3.2 and 4.2.

The basic specifications of JT-4 are: 1) high vacuum condition in the vacuum vessel, i.e. up to 5 x 10^{-9} Torr of vacuum pressure, 2) 30 kG at R = 1.4 m, 3) plasma current of up to 1 MA, 4) discharge time of 2 sec and 5) number of operation of 100,000 at full power of 30 kG and additional 100,000 times for low power operations. The spaces for the diagnostic devices and the secondary plasma heating devices are given at the beginning of the design and considerable efforts are paid to adjust the space requirements. The characteristics of the negative spikes are given as one of the design specifications for electromagnetic forces of the vacuum vessel; the plasma current of 1 MA diminishes with a time constant of 1 ms without changing its position.

The time interval between discharge determined by the capacity of the JT-60 motor generator is 10 minutes when both JT-4 and JT-60 are operating alternately. There is a close relation between JT-4 and JT-60 as described above, care was taken to adjust the design of both machines, especially in the design of the control systems.

3. Deign of Machine

3.1 Vacuum vessel and its auxiliary components

The vacuum vessel and its auxiliary components are composed of

- i) vacuum vessel
- ii) liner plates
- iii) limiters
- iv) divertor plates
- v) N-coils
- vi) installed detectors
- vii) pumping system
- viii) baking system and cooling system.

Liner plates, limiters, divertor plates, N-coils and installed detectors are placed in the vacuum vessel. Parameters of the vacuum vessel and its auxiliary components are given in Table 2. The picture of the vacuum vessel is shown in Fig.6.

i) Vacuum vessel

Principal design requirements for the vacuum vessel are to (1) maintain a base pressure of 5×10^{-9} Torr or less, and support a continuous 1 atmosphere pressure load, (2) be bakable to a temperature of 250 °C, (3) have a resistance of 2 milliohms or more, and (4) withstand electromagnetic force.

Figs.7 and 8 show a cross-sectional view and a development of the vacuum vessel, respectively. The vessel is composed of two thick plate sections and two bellows sections. The bellows section has a double vacuum structure with a thick outer wall. The bellows is only required to keep a high vacuum. It is designed on the basis of the engineering

ii) Liner plates

Liner plates are attached to the inner surface of the vacuum vessel to protect the vessel wall, bellows and installed detectors. Liner material is SUS316L except bellows linear of Mo. Stainless liners are 5 mm thick square plates of 100 mm x 100 mm. The maximum allowable thermal input from the plasma is 50 W/cm^2 x 1 sec at an interval of 10 min and a temperature rise is 64 °C. The stress due to a electromagnetic force and the thermal stress are 6.9 kg/mm^2 and 14.2 kg/mm^2, respectively.

N-coil casings are protected by N-coil linears shown in Fig.7. N-coil liners are composed of curved SUS316L plates and Mo bars on them so as to endure a large heat flux.

iii) Limiters

Two types of limiters are used, fixed limiters and movable limiters. Fixed limiters are placed on the inner surface of the vacuum vessel in the toroidal direction as shown in Fig.7. Curved Mo plates of 10 mm thick is used as limiter head. The allowable thermal input is 2 MW x 1sec and the maximum temperature is 798 °C, which is lower than the recrystallization temperature of Mo. The thermal stress is 21 kg/mm^2.

Fig.10 shows a cross-sectional view of the movable limiter. Two movable limiters are inserted into the vessel through movable limiter ports. They are manually operated and the stroke is 400 mm. The life of the vacuum-tight bellows is over 2000 cycles. Limiter heads are curved Mo plates 10 mm thick and insulated from the vessel. The thermal input is 0.6 MW x 1 sec. Limiter heads are cooled by oil cooling boxes behind them.

iv) Divertor plates

In the divertor room, there are divertor plates which neutralize the diverted plasma particles and absorb the heat flux. The divertor plates are made of curved Mo plates of 10 mm thick and insulated from the vessel. The torelable heat flux is 1.2 kW/cm^2 and the maximum temperature is 996 °C. They are cooled by oil channels.

v) N-coils

N-coils consist of N1-coils, N2-coils and N3-coils as shown in Fig.7. Their casing has several bellows sections to prevent the thermal stress and to give an electric resistance of 20 milliohms or more

There are 8 support structures for each N-coil and the coil position is adjustable in radial and vertical directions. Support structures are slidable in the radial direction to prevent the thermal stress. Supports have oil cooling channels for the removal of the thermal input of N-coil liners.

vi) Installed sensers

Several types of sensers are installed in the vacuum vessel. For the measurement of the electromagnetic properties of the plasma, one-turn coils, Rogowski coils and magnetic probes are placed behind liner plates. For monitoring mechanical conditions of the vessel and inner components, thermocouples and strain gauges are used. Thermocouples detect temperatures of liner plates, fixed and movable limiters, divertor plates and the vessel wall. Strain gauges are placed on the vessel where high stress will be at work.

vii) Pumping system

The vacuum vessel is pumped through 2 pumping ports. The main pumps are turbomolecular pumps and the effective pumping speed at vessel pumping study and the test of critical components made in FY 1976.(4) The bellows convolutions are shown in Fig.9. They are 0.6 mm thick and made of Hastelloy-X by welding. There are 44 convolutions per bellows assembly. Each convolution is made to a pitch of 3.4 mm with a convolution height of 46 mm. The stacked length of one bellows convolution assembly is 150 mm. The combination of two bellows sections yields an electrical resistance of 2 milliohms.

The thick wall outside the bellows is required to (1) maintain a pressure of 76 Torr or less in the outer vacuum region, (2) be bakable, (3) have electrical insulation in the toroidal direction and (4) withstand various mechanical loads, especially a electromagnetic force produced by saddle currents in thick plate sections. In order to meet above requirements the outer wall is separated by a vacuum-tight insulator with a key structure, as shown in Fig.9. The shear stress due to the electromagnetic force is 1.6 kg/mm^2 at the key.

The thick plate sections are made of 30 mm thick plate of SUS316L. There are 241 port appendages; 104 diagnostics ports, 6 neutral beam injection ports, 2 vacuum pumping ports, 40 divertor pumping ports, 7 gas injection ports, 2 movable limiter ports, etc.

The vessel is supported at the midplane by toroidal field coils. 7 support structures are connected to ports and thick plate sections. They have a slide mechanism to prevent the stress due to the thermal exantion of the vessel. They endure the weight of the vessel and poloidal field coils, several types of electromagnetic forces, earthquake, etc. The primary stress intensity on the vessel at the support structure is 5.8 kg/mm^2 and the primary and secondary stress intensity is 21 kg/mm^2.

apertures is 2000 l/s (N_2). This system is insulated from the vessel and bakable at a temperature of 160 °C. In addition to this, the divertor room is pumped by the divertor pumping system. The outer vacuum region of the double vacuum system of the vessel is pumped with rotary pumps and maintained at a pressure below 76 Torr.

viii) Baking system and primary cooling system

To heat the vessel and inner components up to a temperature of 250 °C in 20 hr, oil piping is placed on them. Oil piping also removes the heat deposited in the vessel, limiters, divertor plates and N-coil liners. The heating power is 370 kW and the cooling power is 225.5 kW. The total flow rate is 30 m^3/hr.

There are thermal insulation layers on the heating oil pipes and water cooling pipings in them. The vacuum vessel cooling system, the toroidal field coil cooling system and the poloidal field coil cooling system compose the primary cooling system. The total flow rate is 333 m^3/hr.

3.2 Poloidal field coils

The poloidal field coil (PF coil) system consists of two independent coil systems, the primary coil of a current transformer (OH-coil) and the equilibrium field coils (EF-coils). The latter is composed of six species of poloidal coil;

i) divertor coil	(D-coil)
ii) shaping coil	(S-coil)
iii) vertical field coil	(V-coil)
iv) quadrupole field coil	(Q-coil)
v) position control coil	(C-coil)
vi) horizontal field coil	(H-coil)

The OH-, S-, V-, H-, and a part of Q-coil are located between the toroidal field coil bore and the vacuum vessel, while the rest inside the vacuum vessel (these coils are named N-coil) for the purpose of controlling the plasma position and shape rapidly.

In FY 1977, a design adjustment of PF coil system was made on the basis of the detailed engineering design made in 1976. As a result, a partial change of coil configuration was made. The general view of the coil positions and the specifications of PF coils are shown in Fig.11 and Table 3, respectively.

Each turn of the PF coils is made of water cooled rectangular hollow-copper conductors. The copper alloy is 0.2 % silver bearing copper. To insulate the turns from each other and to provide for structural integrity of the PF coils, the turns are wrapped with fiberglass reinforced plastics (FRP) and impregnated with epoxy. The insulation scheme is two levels of protection. First, a 10 mm thick layer of FRP is placed between turns and structure and between the OH-coil and the EF-coils. This gives the turns the capability to withstand a turn-to-ground potential. Second, each turn is wrapped with a 3 mm thick layer of FRP tape, which gives a turn-to-turn withstand capability. To support the PF coils, they are divided to eleven blocks. Each block have a stainless steel can, which is supported by the vacuum vessel.

The maximum hoop stress due to the electromagnetic force is approximately 3.9 kg/mm^2 in the OH-coil, 3.8 kg/mm^2 in the Ef-coils outside the vacuum vessel, and 1.29 kg/mm^2 in the N-coil. The maximum axial compressive force in the double-winding solenoid of the OH-coil is about 43 ton, resulting in a maximum compressive stress of 0.35 kg/mm^2. The maximum thermal stress in the conductor is less than 4.5 kg/mm^2.

The maximum error field produced by feeder lines and return windings is less than 50 gauss in the plasma region.

3.3 Toroidal field coils

The splittable toroidal field coils were taken as the design principle of JT-4 in order to avoid the splittable poloidal field coils. It is because the available work space for the poloidal coils between the TF coils and the vacuum vessel is too narrow and deep, and there are about 260 turns of PF coils which would have to be jointed if the TF coils were not splittable. The insulation voltage of TF coils is much smaller than that of PF coils, and the insulation problem in the coil joints can be avoided.

The design of the splittable TF coils is one of the key points in the JT-4 design, and a great deal of efforts have been made on the TF coils design. The points of the deisgn are; 1) the strong electromagnetic force, 2) the thermal stress, 3) the cooling, and 5) the assembly and disassembly.

In the preliminary design of FY 1975, many ideas are proposed and investigated analytically. In FY 1976, the properties of the joint structure were examined experimentally using $\frac{1}{2} \sim \frac{1}{4}$ scaled models. The best structure was selected with the mechanical strength in the stress fatigue test. The joint structure of FY 1976 is strong enough to support the whole electromagnetic force without any other support structure as casing, but the length of the joint section is too long and some problems were left to be solved in the structure of cooling pipes of the joint section and in the assembling procedure.

In FY 1977, another deisgn was investigated in which the assembly problem is solved. The electromagnetic force is supported with both the copper conductors and the casing. In this design, the conductors push the outer conductors or the casing, and attension was paid on the stress of the insulator between copper conductors or casing. The allowable maximum stress on the insulator is ~6 kg/mm^2 of compression or ~1 kg/mm^2 of shear.

The present design of TF coils is shown in Fig.12 and Table 4, and the picture of the joint structure are shown in Fig.13.

The joint structure are made of Cr-Cu and most of the coil is made of Ag-Cu. The main part of the coil and the joint structure is connected by either teeth structure or welding.

About 1/3 of the electromagnetic tensile force at the straight section of the torus center is supported by the stainless steel casing and the average tensile stress of the copper is only 2.5 kg/mm^2. The maximum value is 2.7 kg/mm^2 of the outermost turn. The local maximum tensile stress is high because of the stress concentration at the joint structure, and the maximum stress is 15.8 kg/mm^2, while the tensile strength of Cr-Cu is more than 40 kg/mm^2. The maximum stress of the casing is 8.4 kg/mm^2 which is the value limited by total tensile stretch of 0.5 mm. The maximum compression stress of the insulator is 5.3 kg/mm^2 by the inward cetripetal force and 4.9 kg/mm^2 by thermal compression.

The thermalanalysis are also carried out and the maximum temperature is 96 °C at the joint structure. The contact resistance of the joint is about 1.3 μΩ for a joint.

3.4 Layouts

The floor plans of the JT-4 main building is shown in Fig.14. The machine of JT-4 locates at the center of the experiment room. The machine body stands on a support pillar. There are four floors in the experiment room; basement, second basement, ground floor and upper floor. Most of the main devices are placed on the ground floor. The north half is used for the neutral beam injectors and the south half for the diagnostic devices. On the upper floor, the power supplies of the NBI and one of the vacuum pumping devices are placed. The basemant and the second basement are used mainly for auxiliary devices as cooling, electric power feeder lines, etc. The upper floor is removable to use the 100 ton crane.

3.5 Diagnostic Ports

There are 241 ports on the vacuum vessel and 104 of them are for diagnostic use. The details of the diagnostic ports are shown in Table 5. The 'A' ports are used to observe vertically the inner and outer periphery of the plasma cross section at four different major radius. Through 'M_1' and 'M_2' ports, the main plasma near $Z = 0$ can be observed horizontally. 'M_3' and 'K' ports are usedfor measurement of the outer plasma near the 'null point' of the separatrix surfaces. 'D_1' ports can be used as divertor room acsess ports.

The cross sections of the vacuum vessel at the ports are shown in Fig.15. The layouts of the ports are shown in Fig.8. 'l', 'P' and 'B' denote ports for movable limiters, vacuum pumping systems and neutral beam injectors, respectively.

4. Design of Power Supplies

4.1 Toroidal field coil power supply

The electric power for the toroidal field coils is supplied by motor generator of the JT-60. The coil current of JT-4 is about twice larger than that of JT-60. The power from the motor generator is supplied as high voltage (about ~10 kV) ac, and the power supply of JT-4 consists of power transformers with variable voltage taps and rectifier diodes. The one line diagram of the toroidal field coil power supply is shown in Fig.16. The value and waveform of the current during pulse are controlled by the motor generator (i.e. the current control of the field winding). Although the time constants of the toroidal field coils of JT-4 and JT-60 are different (4.4 sec and 25 sec, respectively), current waveform can be controlled without changing any hardware of the motor generator system as stown in Fig.17.

There is an additional small SCR power supply for continuous operation at 3 kG for the cleaning discharge. The SCR supply is connected to the power network.

4.2 Poloidal field coil power supply

The JT-4 poloidal field coil power supply provides electric power for the following constituents or subsystems; (1) the ohmic heating system which induces a plasma current of up to 1.0 MA and maintains it for about 2 seconds, (ii) the plasma maintaining field system which controls the plasma equilibrium position and shape. The system consists of six poloidal field coils shown in 3.2.

In FY 1977, the detailed engineering design of the poloidal field coil power supply was made. The basic design concept is to constitute the poloidal field coil power supply by a single set of motor generator for the JT-60 which is followed by thyristor controlled rectifier stages for respective coil. The design purposes are to determine the detailed electric circuits and to settle the performance and specifications of the major components of the poloidal field power supply to meet the required operation sequences and conditions. The specifications of the poloidal field power supply are given in Table 6 and the one line diagram of the poloidal field coil power supply is shown in Fig.18. The peak working output dc power is about 140 MW.

4.2.1 Ohmic heating power supply[10)]

The basic design requirements for the ohmic heating power supply under I_p = 1 MA operation are; (i) a total magnetic flux variation of 5 volt-sec., and (ii) a minimum one-turn voltage of 100 volt at the beginning of the plasma discharge.

The high peak voltage and power required to initiate the plasma discharge in JT-4 will be obtained with an inductive energy storage. In this system, the OH-coil functions as an inductive energy storage coil. Prior to the discharge, an external power supply is used to establish a dc bias current, $I_{OH} \simeq 45$ kA, in the OH-coil. At the desired instant, an interrupter switch is used to transfer the OH-coil current from the power supply to a high impedance RC network. The resulting RLC oscillation generates an initial peak voltage of up to 10 kV across the OH-coil, inducing a rapid build up of plasma current. Eventually, the capacitance in the RC network reverses the OH-coil current, and auxiliary switching is used to reconnect the power supply with reversed polarity to further increase the reversed current up to -50 kA to sustain the plasma current flattop ($I_p \simeq 1$ MA) during 2 seconds.

A candidate for the interrupter switch in JT-4 is a solid state (Thyristor) circuit breaker which interrupts a current of 45 kA with recovering voltage of 12 kV. The capacitor bank has a nominal capacitance of 0.6 F with a peak working voltage of 1.6 kV.

4.2.2 Power supplies for equilibrium field coils

In JT-4, the external magnetic field required for the toroidal equilibrium, (B_v, n), is applied by six EF-coils shown in 3.2. S-coil induces the dominant portion of the equilibrium field by controlling of its current and/or changing its connection. V- and Q-coil produce the small field, (δB_v, δn), to adjust the major radius and shape of an equilibrium plasma. By varing the flux values of these three coils and the D-coil, either circular, elliptical, or D-shaped configuration with the magnetic limiter can be achieved. For $q_{limiter} = 3$, typical plasma current is about 0.55 MA for a circular discharge, 1.0 MA for a 1.7 : 1 ellipse at $B_t = 3.0$ T. C- and H-coil produce the horizontal magnetic field to control the vertical position of an equilibrium plasma.

Each of these EF-coils is connected to a thyristor controlled rectifier system, and, prior to the discharge, each current is programed to sustain the plasma equilibrium position and shape. Additionally the V-, Q- and C-coil current are controlled by feedback method. The specification of the EF-coil power supply is given in Table 6.

4.3 Plasma position and shape control

In JT-4, the plasma position and shape are controlled by feedback system of V-, Q- and C-coil currents. Axisymmetric mode involving overall vertical displacement of plasma column of an elliptic discharge is the most troublesome problem in JT-4. C-coil and its feedback loop are set in order to suppress this mode.

In FY 1977, the soft- and the hard-ware analysis on feedback system were separately made. The former is a transient response analysis of feedback loop to survey some optimal coefficients of the control device by using a simulation code developed in JT-60 project. The latter is a design of the thyristor rectifier system of which specifications are shown in Table 6. The results through these analyses are given in Table 7.

4.4 Power distribution system

The continuous electric power for relatively small power devices are distributed to each device through the power distribution system.

The total power for the distribution system is 9 MVA, which is divided into 2.4 MVA for the toroidal field coil continuous operation, 2.5 MVA for the secondary heating system and 4 MVA for the other small devices as control, cooling pumps, vacuum pumps, etc. The power for the diagnostic systems is over estimated to be 1.7 MVA, which may be reduced to 0.7 MVA.

The large pulsive power for the toroidal and the poloidal field coils and for the secondary heating system is not included in the power distribution system. They are supplied by motor generators of JT-60 as described before.

5. Control system

The problems encountered in the deisgn of the control system are suvayed. The details of the design are left for future because the details of the actual design of the whole system is necessary to the design of the control system. The signals and the informations which should be interchanged between JT-4 and JT-60 are listed up. The main factors in the design of the control system are the adjustment between JT-4 and JT-60, the timing system and the man-machine communications. The positions of the consoles and the control panels are shown in Fig.19.

6. Diagnostics and data aquisition system

The diagnostic system will have to yield as much experimental information as possible during a discharge. The data aquisition system must be consistent with the requirement and be able to handle up to 700 thousand words per discharge.

The proposed diagnostics are listed in Table 8. Most of these diagnostics are in operation for JFT-2, DIVA or under development for JT-60 project.

Magnetic probes are designed to be compact cartridge type because it is needed to set up as many probes as possible in vacuum vessel for measuring magnetic flux of JT-4 plasma with non-circular cross section.

All diagnostic signals will be conditioned to conform to the levels established for the CAMAC interface of the aquisition system. CAMAC equipments will be located in the room next to the experimental areas. Approximately 50 crates will be used for JT-4 diagnostics.

All data will be processed in the diagnostic computers which are placed in the control room. The diagnostic computer system is shown in Fig.20. It is possible to store one shot data in each CAMAC crate and one day data in the diagnostic computer and permanently in magnetic tapes.

All data of diagnostics will be presented in the graphic display on the consoles. Experimentalists can set up diagnostic parameters and monitor every experimental devices from the central and local consoles in the control room.

7. Auxiliary system design

7.1 Gas supply system

There are 6 fast acting gas valves and a slow valve in JT-4. The diagram of the gas injection system is shown in Fig.21. The fast valves are divided into two groups; 4 valves for initial gas supply just before the discharge and 2 valves for additional gas injection during discharge. The piezo-electric valves are used as the fast acting valves. The slow valve is used for continuous gas supply or nitrogen gas filling before opening of vessel. The waveforms of the gas pulse of each fast acting valve can be controlled independently by a gas supply control computer. The gas species of the three groups of the valves are either of 8 gas species; hydrogen, deuterium, helium, nitrogen, carbon dioxide, methane, oxygen, and argon. The pressure of the supplied gas or that of the gas resavoir is automatically controlled.

7.2 Preionization system

The J x B gun is designed as a preionization system in the JT-4 design adjustment. The gun itself is same as that used in JFT-2a. The objectives of the design is to know whether there is any problem in the control, power supply or space for the device.

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Table 1 JT-4 main parameters

Major Radius	1.45 m
Minor Cross Section Half Width	
Vertical (b)	0.68 m
Horizontal (a)	0.4 - 0.45 m
Ellipticity (b/a)	1.0 - 1.7
Toroidal Field	30 kG
Flattop	2 sec
Maximum Plasma Current	1.0 MA
NBI Heating Power	6 MW

Table 2 Parameters of the vacuum vessel and its auxiliary components

Vessel shape	Ref. Fig.3.2.1
Vessel material	SUS 316L Hastelloy-X (bellows)
Maximum radius	2010 mm
Minimum radius	950 mm
Height	2665 mm
Width	1060 mm
Thickness	30 mm 0.6 mm (bellows)
Vessel weight	35 ton
Electrical resistance	≥ 2 mΩ
Baking temperature	250 °C 160 °C (ports)
Vessel Volume	24 m^3
Vessel surface area	553 m^2
Internal pressure	$\leq 5 \times 10^{-9}$ Torr
Maximum He leak rate	5×10^{-8} Torr.ℓ/s
Outgassing rate	$\leq 5 \times 10^{-12}$ Torr.ℓ/s·cm^2
Pumping speed (N_2)	2000 ℓ/s
Heating medium	oil
Heating medium flow rate	29.6 m^3/hr
Cooling medium	water
Cooling medium flow rate	87×10^3 kg/hr

Table 3 Poloidal field coils specifications

Parameter		OH	D	S	V	Q	C	H
Ampere turns (MA)		± 4.8	± 0.4	± 1.98	± 0.27	± 0.36	± 0.06	± 0.12
Total turns		96	16	132	12	16	4	8
Max. current (KA)		50	50	30	45	45	30	30
RI^2 (MW)		27.75	7.88	23.85	7.47	10.83	2.18	3.82
$1/2\ LI^2$ (MJ)		6.43	0.47	3.87	0.31	0.38	0.09	0.12
Time const. (msec)		580	134	400	93	82	87	74
Max. current density (A/mm^2)		37.3	22.5	31.0	46.5	46.5	22.5	31.0
Max. permissible square wave pulse length (sec)		3.0	3.0	3.0	3.0	3.0	3.0	3.0
Max. temperature rise (°C)		26	10	18	41	41	10	18
Working voltage (KV)	ground	29	4.8	34	3.6	4.8	1.2	2.4
	turn-to-turn	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Others		$\Delta\phi \sim 5.0$ V·s		$B_z \sim 3000$ G $n=-2.1 \sim 1.0$	$\delta B_z \sim 725$ G	$\delta n \cdot B_z$ ~ 0.194 T	$B_R \sim 215$ G	$B_R \sim 200$ G

Table 4 Toroidal field coil parameters

Toroidal Field (R = 1.4 m)	30 kG
Ampere Turns	21 MAT
Number of Coils	18
Turns per Coil	10
Length of a Turn	~10 m
Area of Cross Section at Center	11700 cm^2
Average Current Density at Center (with space factor : 0.75)	24 A/mm^2
Resistance (75 °C without Feeder Bars)	9.1 m
Inductance	40 mH
Time Constant	4.4 sec
Stored Energy	274 MJ
Flattop Current	117 kA
Flattop Voltage	1065 V
Flattop Power	125 MW
Voltage between Turns	5.8 V
Rise Time (Forcing 130 %)	4.8 sec
Equivalent Square Wave Width	6.8 sec

Table 5 JT-4 Diagnostic Ports

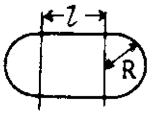
kind	number	shape and dimension	comment
A	42	ϕ 60	vertical access
D_1	4	l=150, R=75 	diverter room
K	5	ϕ 100	outer plasma
M_1	5	l = 400, R = 100	main plasma
M_2	2	ϕ 360	main plasma
M_3	30	ϕ 100	null point investigation
M_2'	2	600 × 500, 600 × 400	Thomson scattering
M_4	8	ϕ 140, ϕ 100 (one)	Thomson scattering
S_1, S_2	6		laser beam injection, damping
Total	104		

Table 6 Rectifier system specifications

		OH	D	S	V	Q	C	H
coil	inductance (μH)	5145	373	8357	301	376	195	273
	resistance at 75° (mΩ)	10.3	3.15	26.5	3.67	5.35	2.42	4.24
	max. voltage & current (V-KA)	800 - 50	344 - 50	3020 - 30	620 - 40	920 - 45	462 - 30	178 - 30
	peak power (MW)	40	14	35	18	32	8	4
rectifier	phase	12-phase in all rectifiers						
	connection	3φ bridge	double 3φ star	3 φ bridge				double 3φ star
	rating (V-KA)	945 - 50	380 - 50	3260 - 50	690 - 40	1210 - 45	700 - 30	200 - 30
transformer capacity (MVA)		29 × 2	10.6 × 2	54 × 2	15.3 × 2	31 × 2	12 × 4	3.12 × 2
others (Method of control)		PR (+FB)	PR	PR	PR + FB	PR + FB	anti-parallel rectifier set PR + FB	PR

PR : preprogram control
FB : feedback control

Table 7 Feedback control specifications

	V	Q	C
Object of control	$\|\delta R_p\| \leq 5$ cm	$\|\delta\kappa\| \lesssim 0.05$	$\|\delta Z_p\| \lesssim 3$ cm
Control field	$\delta B_V \sim \pm 300$ G	$\delta n \sim \pm 0.8/B_V(T)$	$B_R \sim \pm 215$ G
Control current	$\sim \pm 17$ KA	$\sim \pm 22.5$ KA	$\sim \pm 30$ KA
Current response time 0 - 10 KA	10 msec	8.3 msec	5 msec

Table 8 JT-4 diagnostic systems

Diagnostic Name	Brief Description of Purpose
Voltage Loops	one-turn voltage around toroidal direction
Rogowski Loops	plasma current
Magnetic Probe Coils	plasma position and shape, gross fluctuation
4 mm μ-wave Interferometers	electron density of initial breakdown
2 mm μ-wave Interferometers	electron density
Submillimeter-wave Interferometers	electron density
Thomson scattering	electron temperature and density
FIR Spectrometers	cyclotron radiations
Visible Spectrometers	hydrogen and impurity content
V.U.V Spectrometers	impurity content
Ultra-soft X-ray Spectrometers	impurity, power radiated, ion temperature
X-ray Pulse Height Analysis	electron temperature, electron velocity distribution, impurity concentration
Soft X-ray Detectors	internal plasma fluctuation
Hard X-ray Detectors	runaway electron effects
Neutral Particle Detectors	ion temperature
Neutron Counters	neutron flux
Boundary Layer Analysis 1)	total power loss to limiter or wall, etc.
Wall Surface Analysis 2)	examine wall surface effects
TV and Camera System	view inside vacuum vessel during pulse

1) Bolometers, thermocouples, ion gauges, mass analyser, etc.
2) Auger electron spectroscopy, secondary ion mass analyser, etc.

Figure Captions

Fig. 1 Objective of JT-4 Program

JT-4 connects the present tokamak plasma region and the reactor plasma region, and JT-4 is expected to exceed the menimum beta value of 4 %.

Fig. 2 Bird's eye view of JT-4

The front half is for the diagnostics and the rear half for the secondary plasma heating (NBI).

Fig. 3 Subsystems of JT-4

The systems shown in the left column belong to JT-60. They are used by both JT-4 and JT-60. The subsystems are called as 'system' in this report.

Fig. 4 Cross section of JT-4 machine

The outer square shows the support structure (can) of the toroidal field coil. The machine is symmetric as to the horizontal midplane (Z=0).

Fig. 5 One example of equilibrium calculations

The thick solid curve shows the sepsrstrix magnetic surface.

Fig. 6 Picture of the vacuum vessel

The vacuum vessel consists of two thick plate half circle sectors with a number of ports for the diagnostics and the secondary plasma heating, and two bellows sections.

Fig. 7 Cross section of the vacuum vessel

Limiters, liner plates, divertor coils (N1-N3 coils) and divertor plates are contained in the vessel.

Fig. 8 Development of the vacuum vessel

Fig. 9 Cross section of the bellows section

Thin plate welded bellows and double vacuum structure are used to obtain high electric resistance in a small space. The bellows section is shown as a blank at the center.

Fig.10 Movable limiter

The limiter head of curved molybdenum plate is cooled by cooling oil through cooling box. The position of the head is moved by screw handle shown at the right.

Fig.11 Positions of the poloidal field coils

blank -- ohmic heating coils
numbered -- shaping coils (S coils)
D -- divertor coils
V -- vertical field coils (V coils)
Q -- qudrapole field coils (Q coils)
C -- vertical position feedback control coils (C coils)
H -- horizontal field coils (H coils)

Fig.12 Toroidal field coil

They are splittable into upper and lower halves and joited as shown in the figure.

Fig.13 Joint structure of the toroidal field coil

Two expanding pins are used as the mechanical joint of the copper conductors. Three stud bolts are used to give contact pressure.

Fig.14 Layout around the JT-4 machine

Fig.15 Cross section of the diagnostic ports

Fig.16 One line diagram of the toroidal field coil power supply

The large power is supplied by motor generator (MG) of JT-60 system. A small thyrister power supply is applied for the discharge cleaning operation.

Fig.17 Waveform of the toroidal field coil current

The current can be controlled by the field winding circuit of the motor generator.

Fig.18 One line diagram of the poloidal field coil power supply

Fig.19 Layout of the control and diagnostic room
The right half is for the diagnostic consoles and the left half for the control consoles.

Fig.20 Diagnostic computer system configuration

Fig.21 Gas injection system

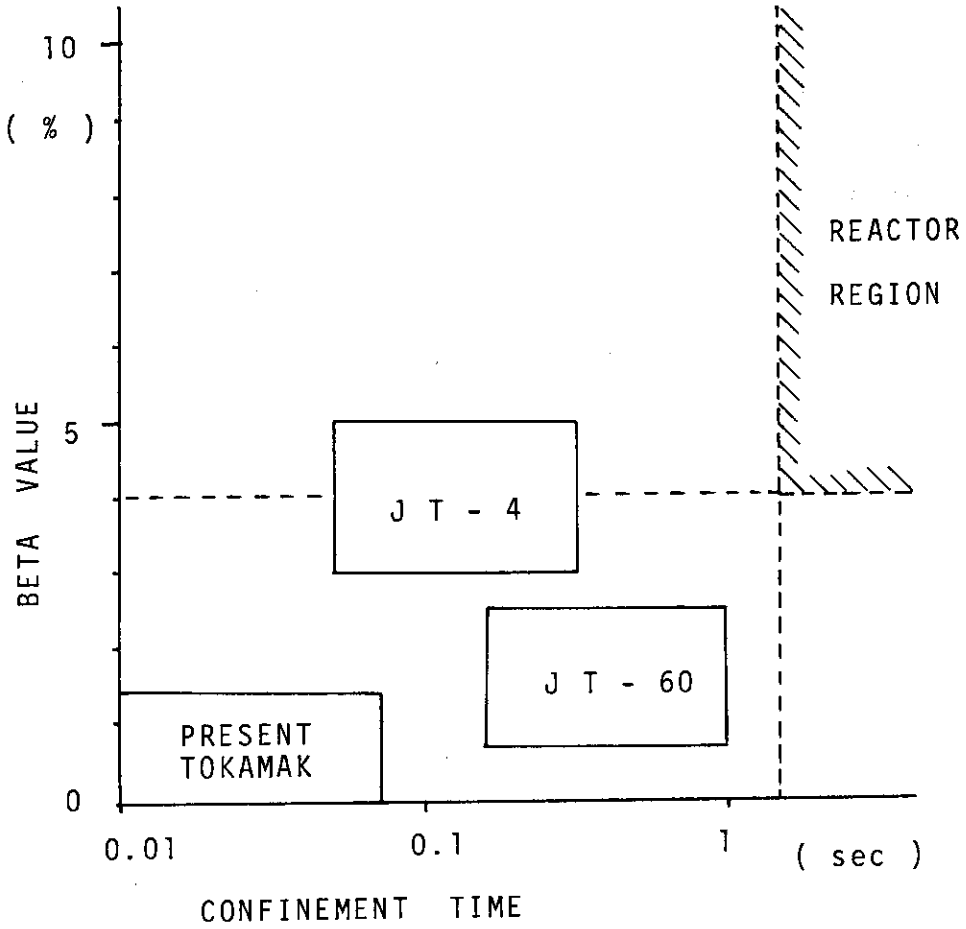

10
(%)
5
0
BETA VALUE
REACTOR
REGION
J T - 4
J T - 60
PRESENT
TOKAMAK
0.01
0.1
1
(sec)
CONFINEMENT TIME

Fig. 1

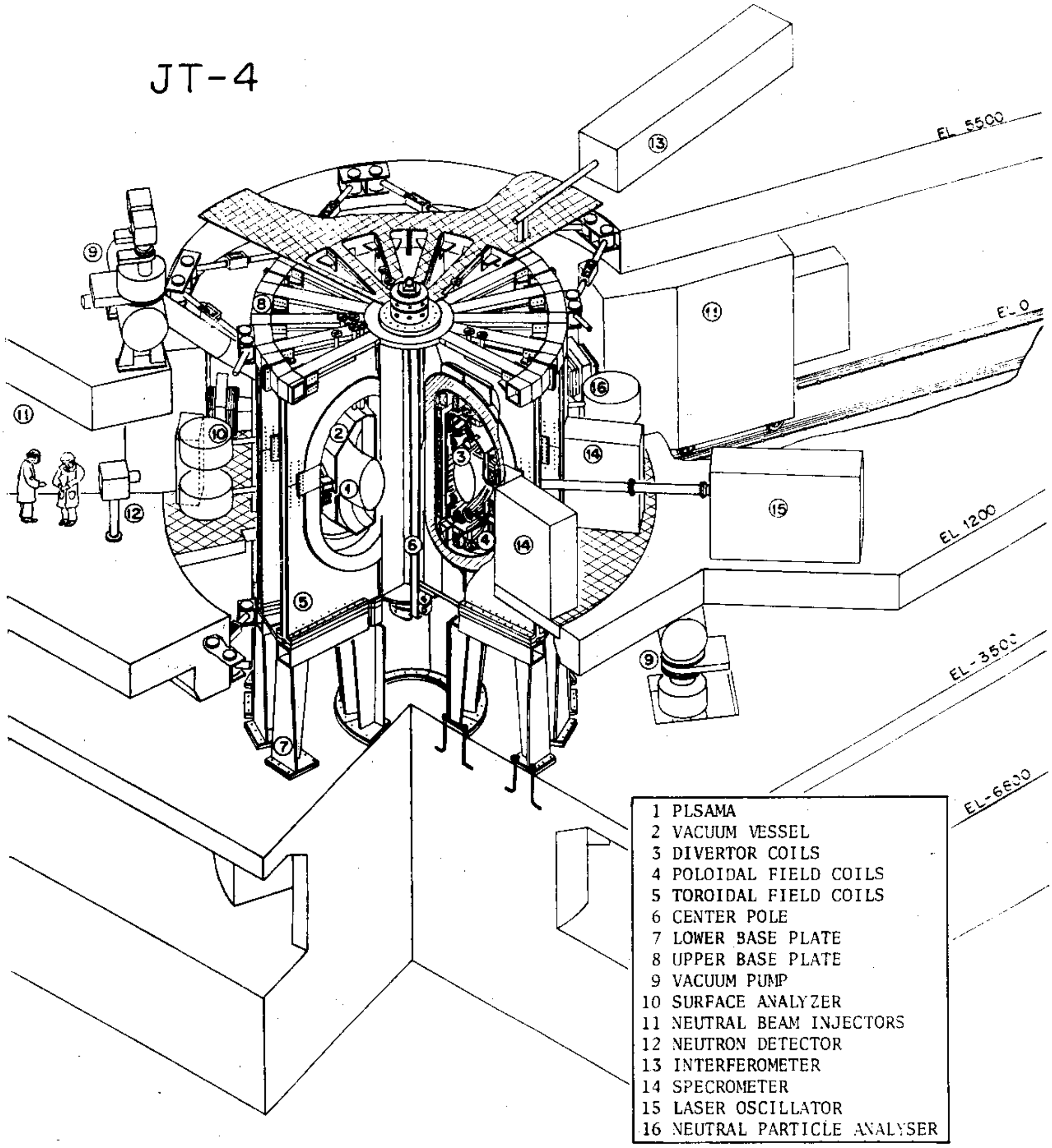

JT-4
⑬
EL 5500
⑨
⑪
EL 0
⑧
⑯
⑪
⑩
②
③
⑭
①
⑫
⑮
⑥
④
⑭
EL 1200
⑤
⑨
EL -3500
⑦
EL -6800
1 PLSAMA
2 VACUUM VESSEL
3 DIVERTOR COILS
4 POLOIDAL FIELD COILS
5 TOROIDAL FIELD COILS
6 CENTER POLE
7 LOWER BASE PLATE
8 UPPER BASE PLATE
9 VACUUM PUMP
10 SURFACE ANALYZER
11 NEUTRAL BEAM INJECTORS
12 NEUTRON DETECTOR
13 INTERFEROMETER
14 SPECROMETER
15 LASER OSCILLATOR
16 NEUTRAL PARTICLE ANALYSER

Fig. 2

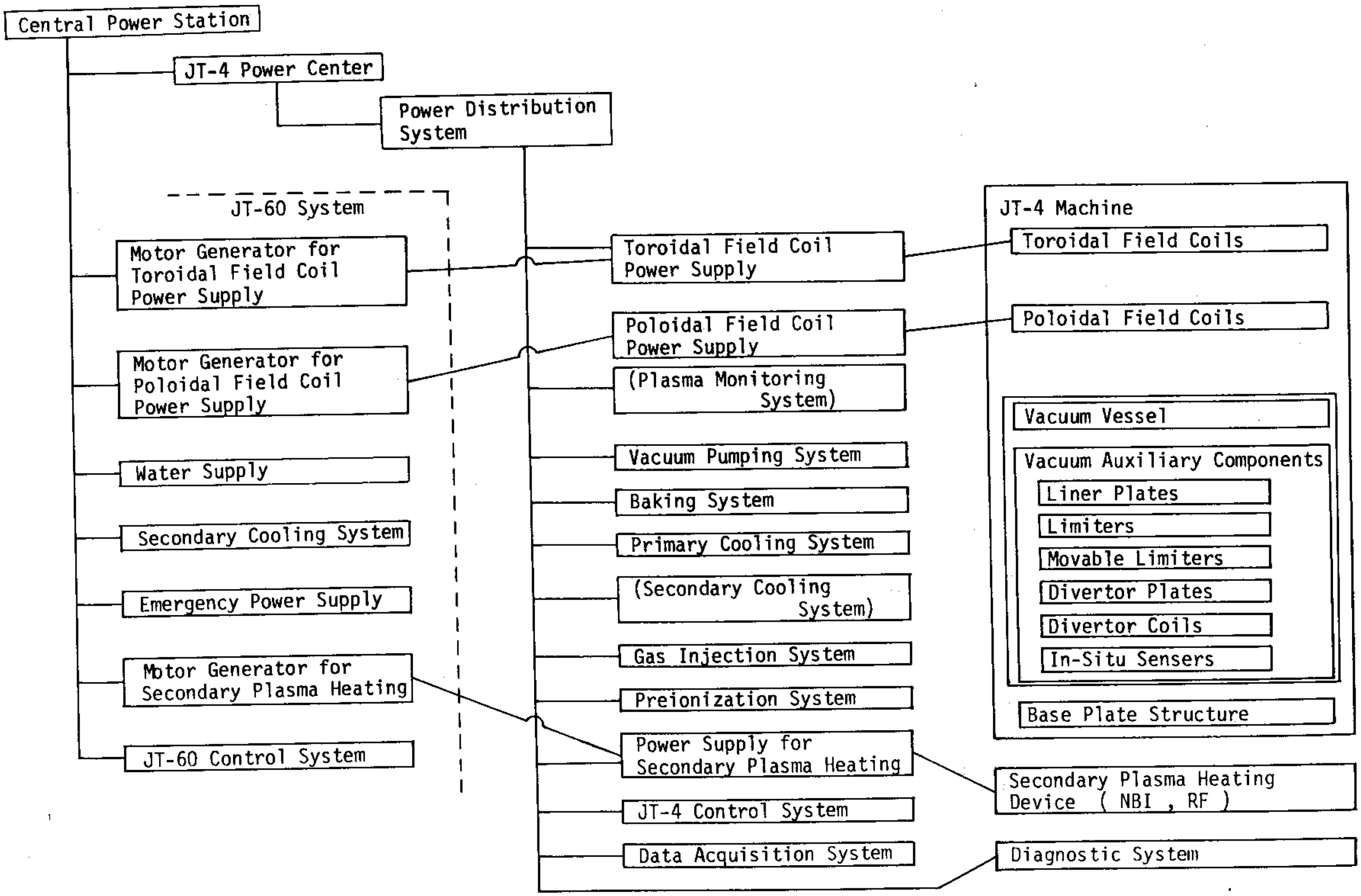

Central Power Station
JT-4 Power Center
Power Distribution System
JT-60 System
Motor Generator for Toroidal Field Coil Power Supply
Motor Generator for Poloidal Field Coil Power Supply
Water Supply
Secondary Cooling System
Emergency Power Supply
Motor Generator for Secondary Plasma Heating
JT-60 Control System
Toroidal Field Coil Power Supply
Poloidal Field Coil Power Supply
(Plasma Monitoring System)
Vacuum Pumping System
Baking System
Primary Cooling System
(Secondary Cooling System)
Gas Injection System
Preionization System
Power Supply for Secondary Plasma Heating
JT-4 Control System
Data Acquisition System
JT-4 Machine
Toroidal Field Coils
Poloidal Field Coils
Vacuum Vessel
Vacuum Auxiliary Components
Liner Plates
Limiters
Movable Limiters
Divertor Plates
Divertor Coils
In-Situ Sensers
Base Plate Structure
Secondary Plasma Heating Device (NBI , RF)
Diagnostic System

Fig. 3

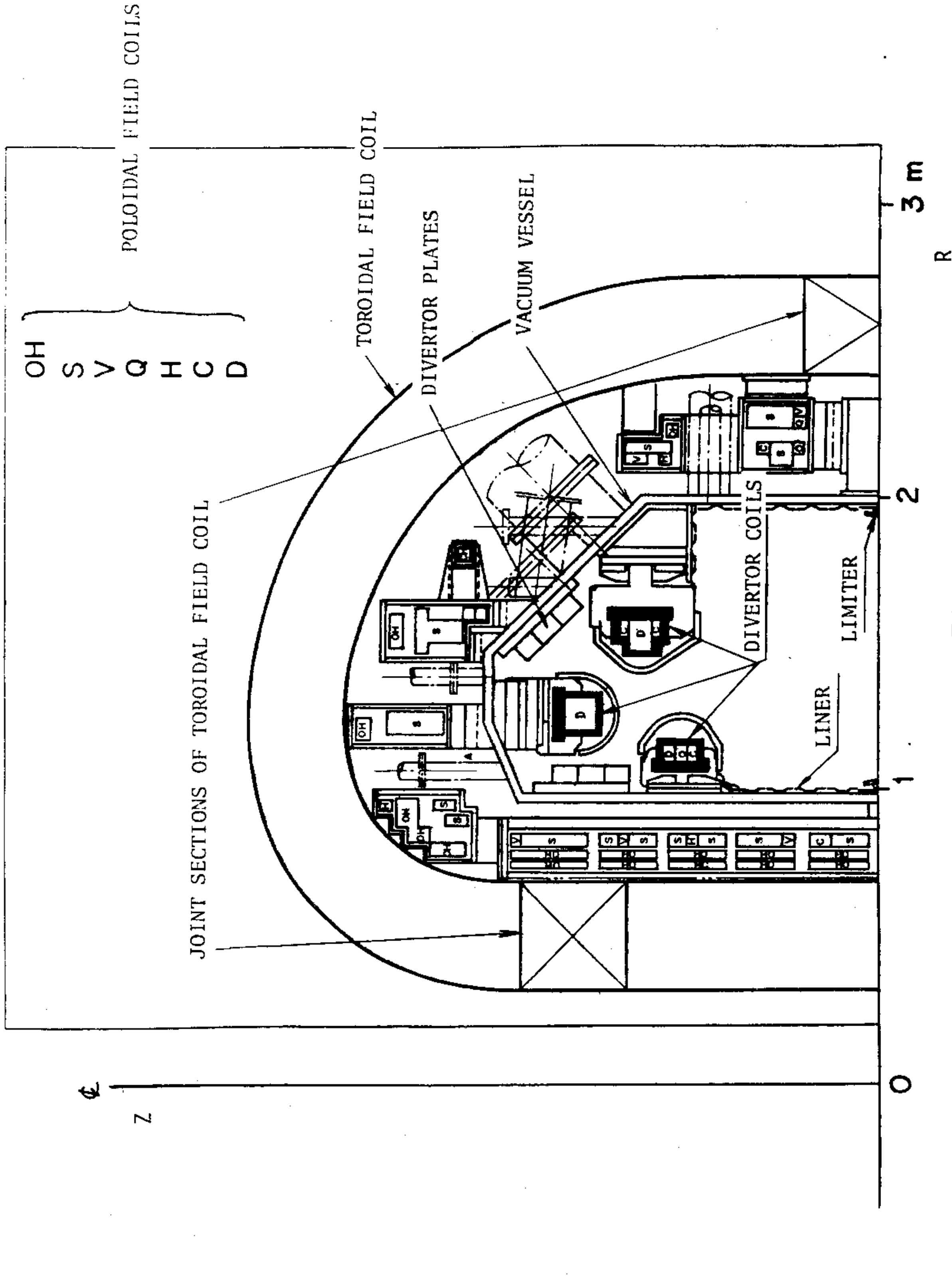

POLOIDAL FIELD COILS
OH
S
V
Q
H
C
D
TOROIDAL FIELD COIL
DIVERTOR PLATES
VACUUM VESSEL
JOINT SECTIONS OF TOROIDAL FIELD COIL
DIVERTOR COILS
LIMITER
LINER
3 m
2
1
0
R
Z
℄

Fig. 4

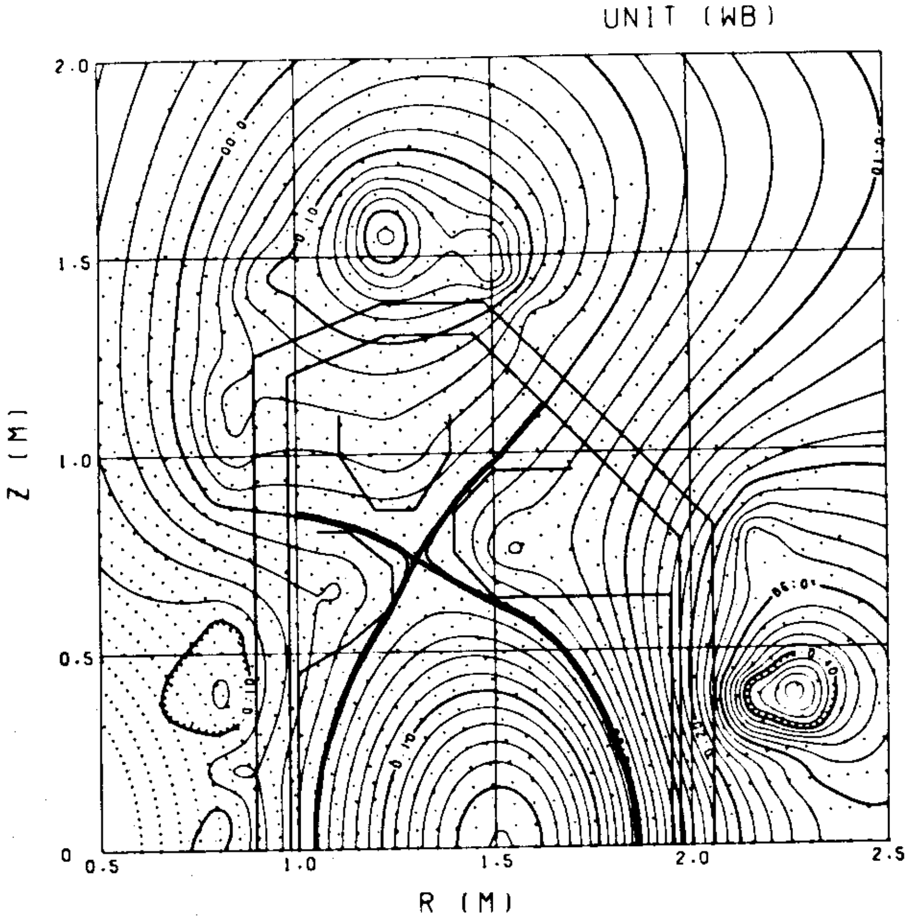

UNIT (WB)
2.0
1.5
1.0
0.5
0
Z (M)
0.5
1.0
1.5
2.0
2.5
R (M)
0.00
0.10
0.10
0.10
0.10
0.10
a

Fig. 5

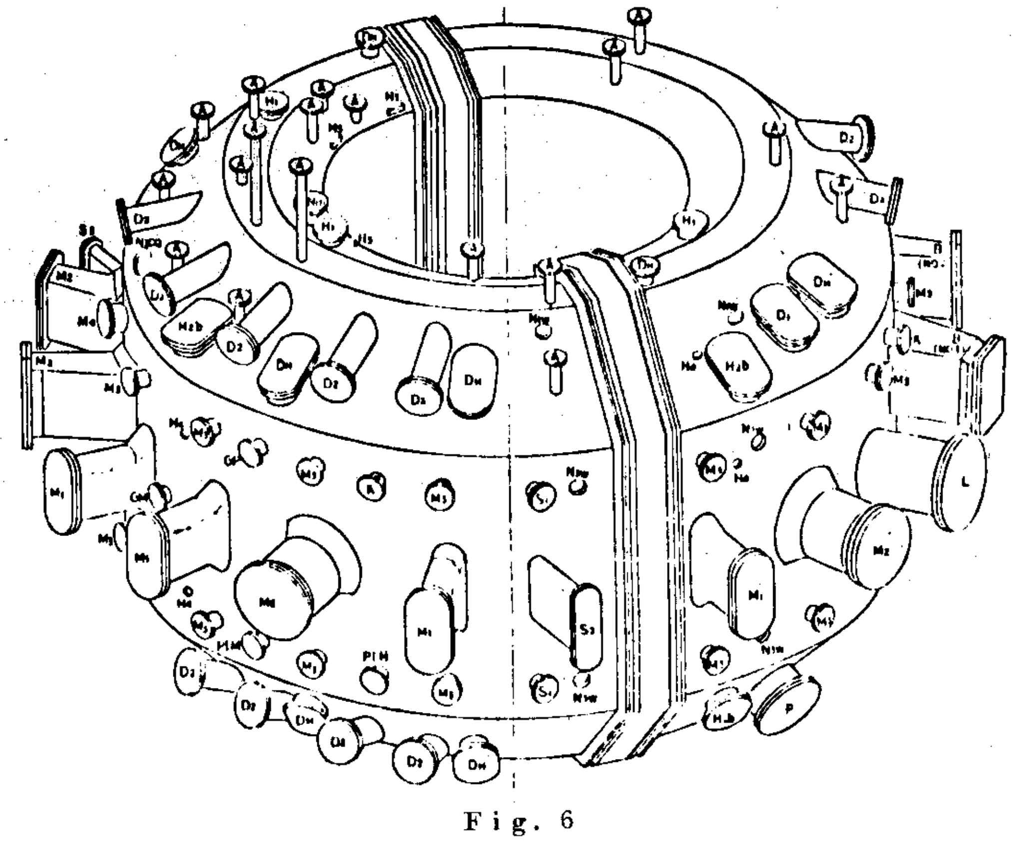

A
Dn
D2
H1
H2b
M1
M2
M3
M4
S1
S2
L
P
PIH
Nw

Fig. 6

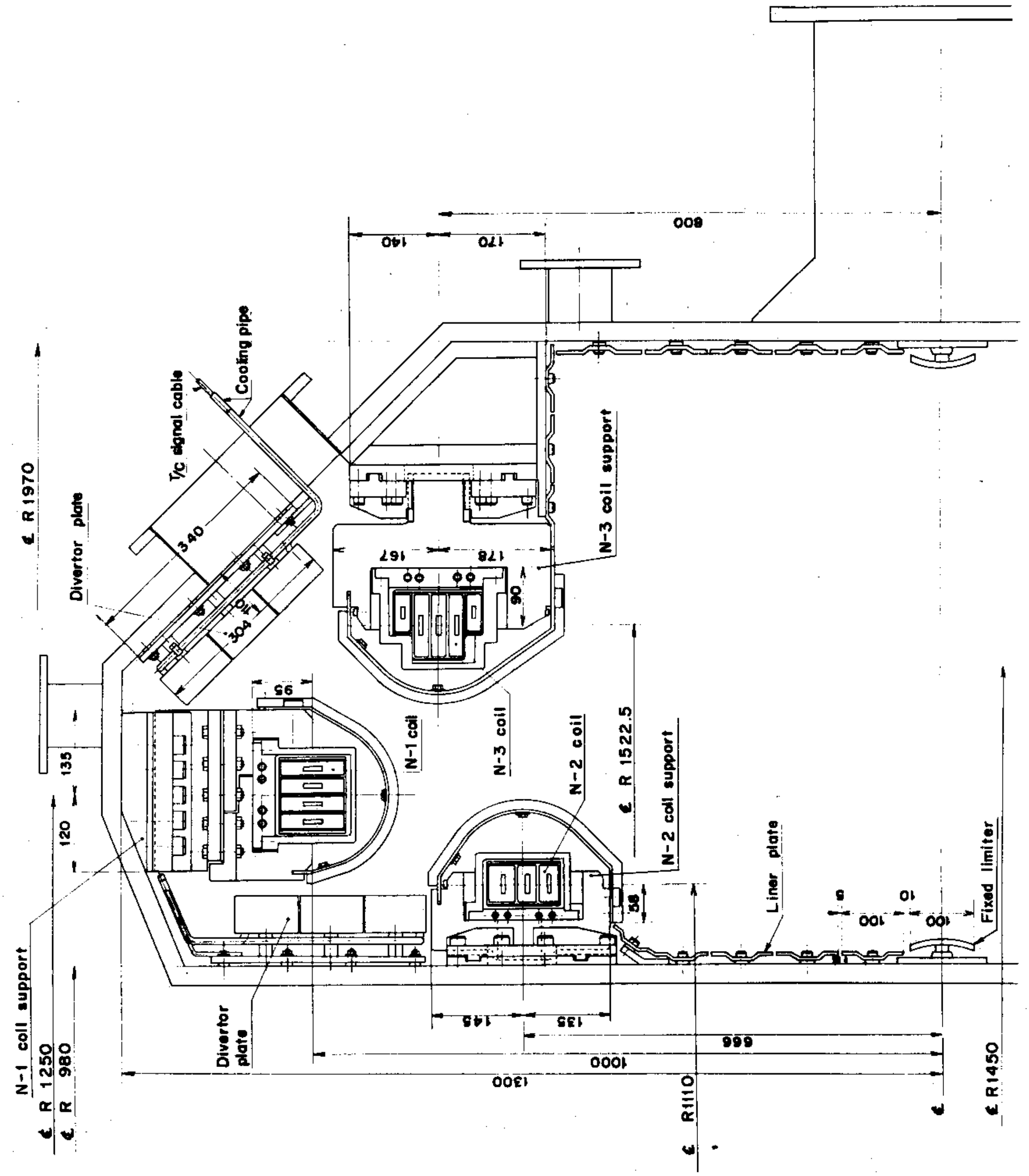

Cooling pipe
T/C signal cable
℄ R 1970
Divertor plate
340
110
304
95
135
120
N-1 coil
N-3 coil
N-2 coil
℄ R 1522.5
N-2 coil support
N-3 coil support
167
178
90
140
170
600
Liner plate
58
5
10
100
100
Fixed limiter
145
135
666
1000
1300
N-1 coil support
℄ R 1250
℄ R 980
Divertor plate
℄ R1110
℄
℄ R1450

Fig. 7

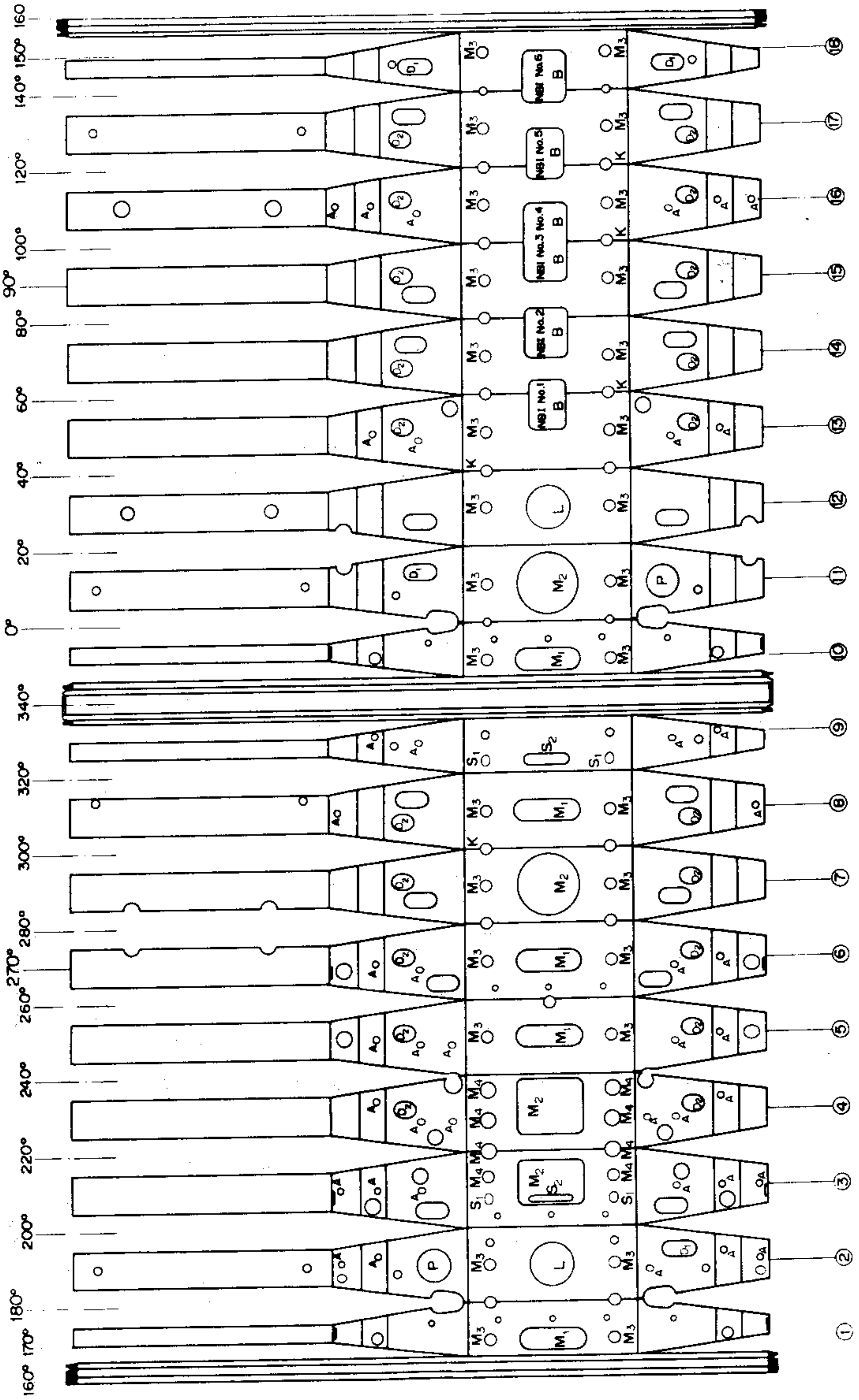

160
150°
140°
120°
100°
90°
80°
60°
40°
20°
0°
340°
320°
300°
280°
270°
260°
240°
220°
200°
180°
170°
160°
⑱
⑰
⑯
⑮
⑭
⑬
⑫
⑪
⑩
⑨
⑧
⑦
⑥
⑤
④
③
②
①
NBI No.6
NBI No.5
NBI No.3
NBI No.4
NBI No.2
NBI No.1
B
M3
M1
M2
M4
L
P
K
S1
S2
D1
D2
A

Fig. 8

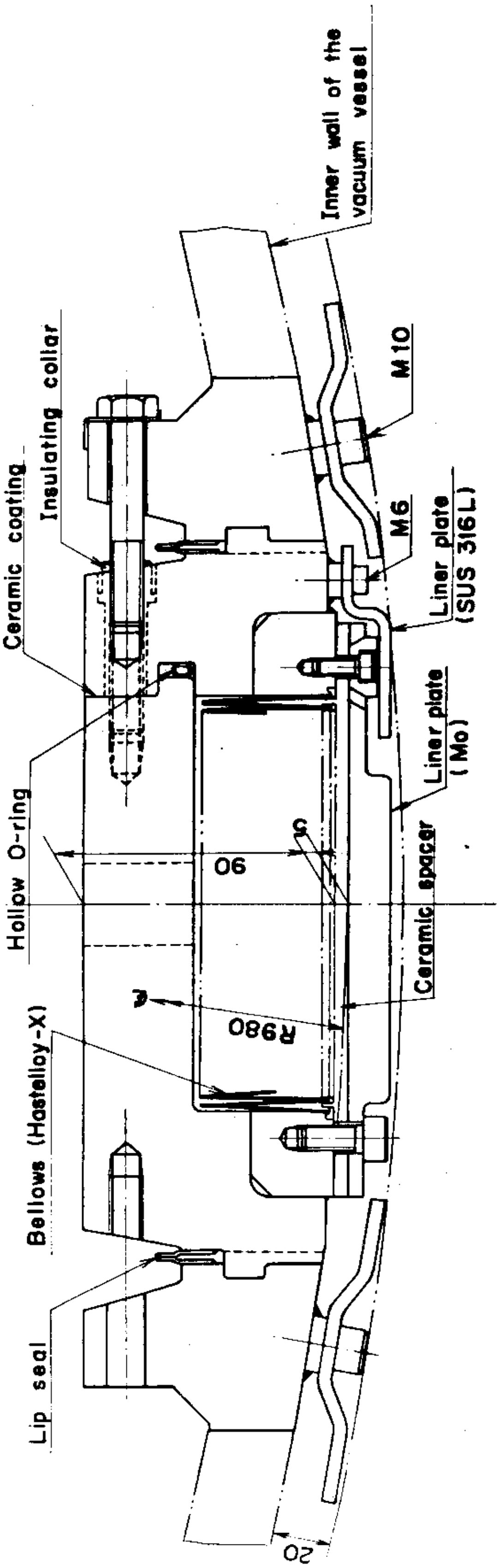

Inner wall of the vacuum vessel
M10
M6
Liner plate (SUS 316L)
Liner plate (Mo)
Ceramic spacer
Insulating collar
Ceramic coating
Hollow O-ring
Bellows (Hastelloy-X)
Lip seal
90
5
R980
20

Fig. 9

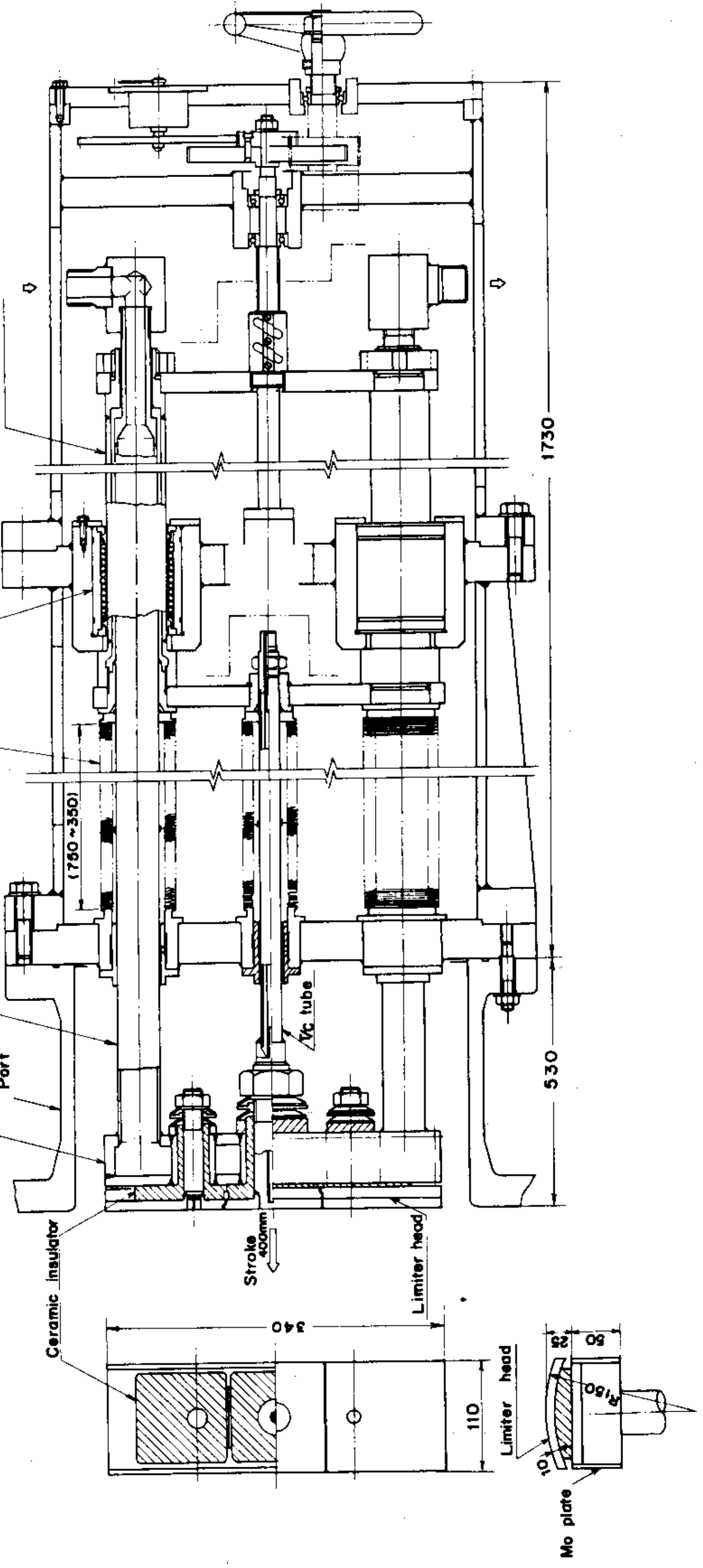

Guide shaft
Linear motion bearing
Welded bellows seal
(750~350)
Cooling pipe
Cooling box
Port
Ceramic insulator
Stroke 400mm
Vc tube
Limiter head
1730
530
340
110
Limiter head
Mo plate
25
50
R150
10

Fig. 10

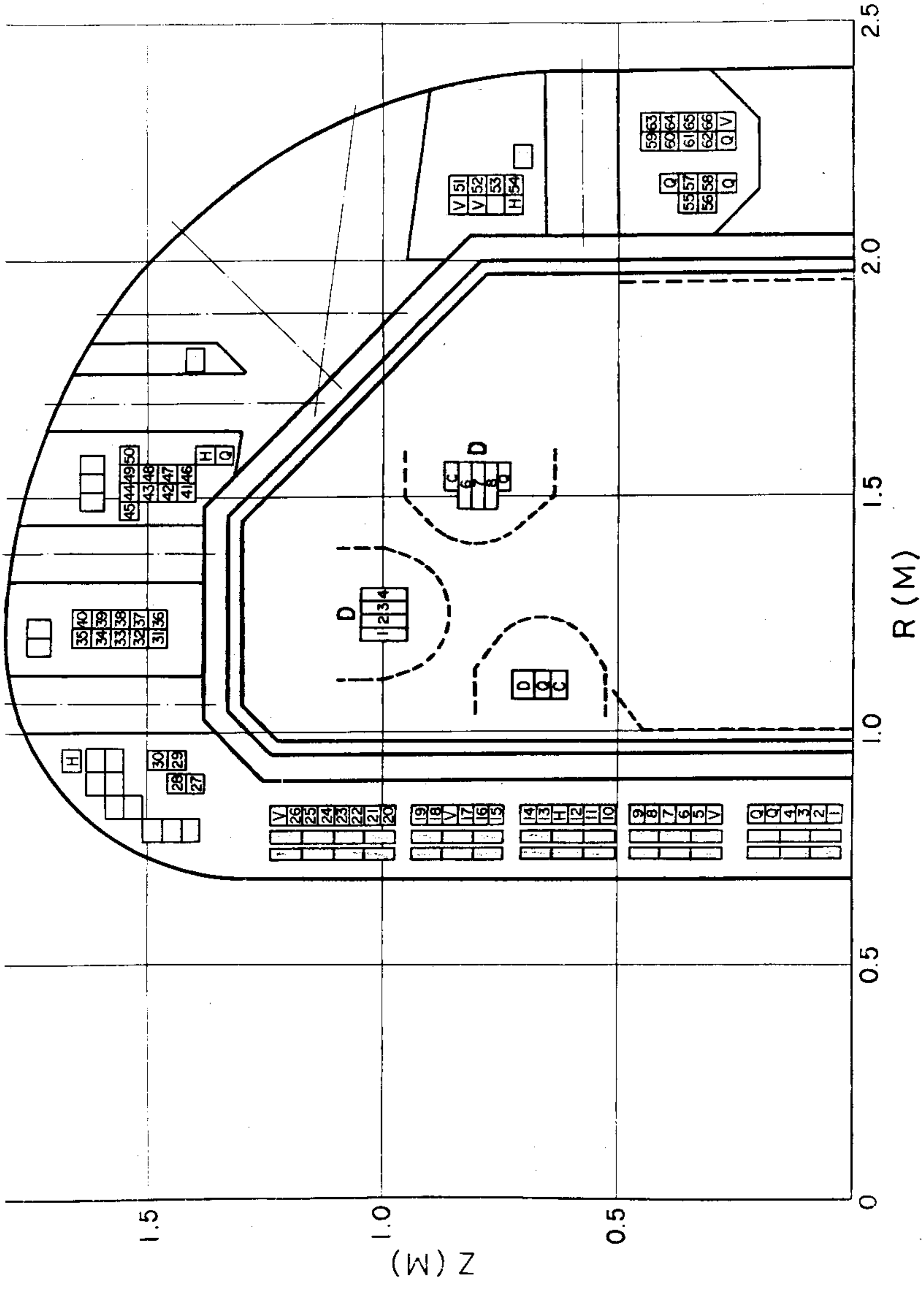


Fig. 11

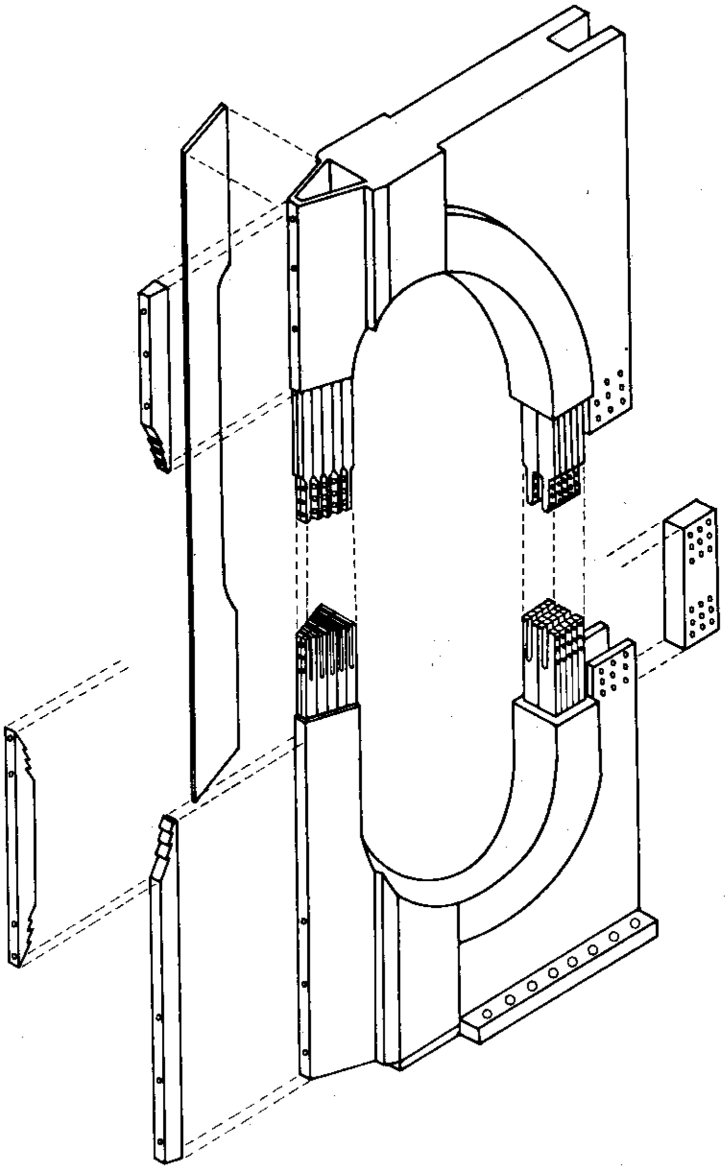


Fig. 12

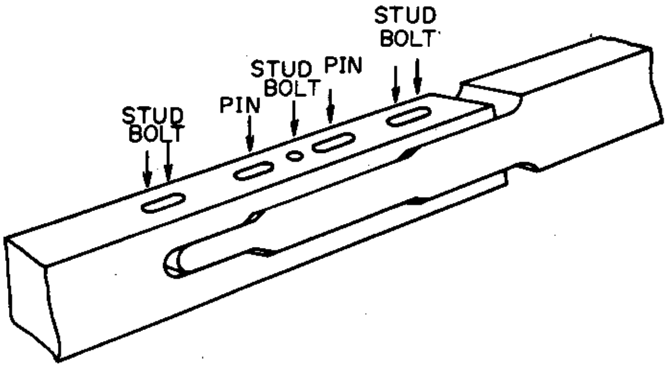


Fig. 13

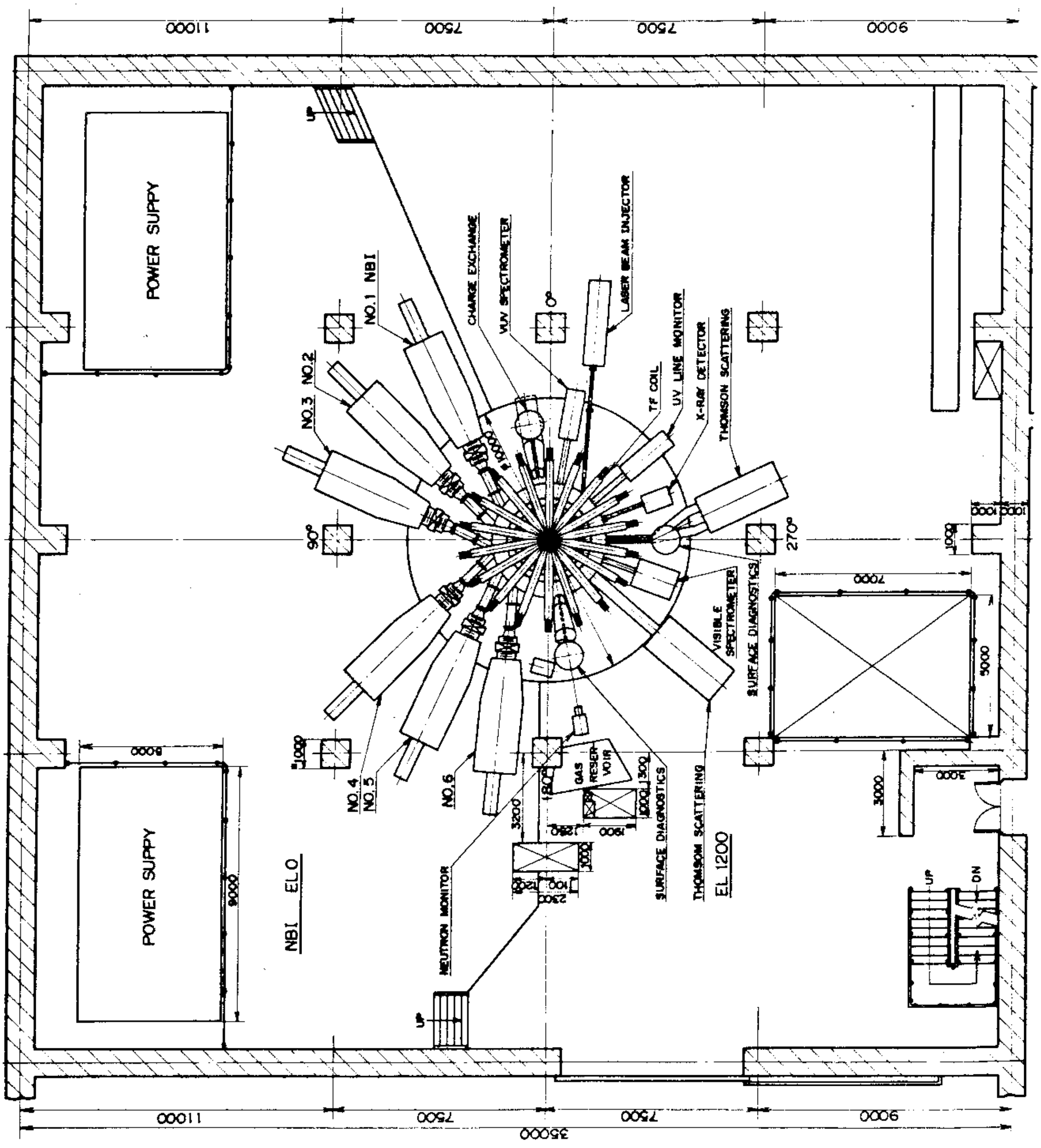

POWER SUPPY
POWER SUPPY
NO.1 NBI
NO.2
NO.3
NO.4
NO.5
NO.6
CHARGE EXCHANGE
VUV SPECTROMETER
LASER BEAM INJECTOR
TF COIL
UV LINE MONITOR
X-RAY DETECTOR
THOMSON SCATTERING
VISIBLE SPECTROMETER
SURFACE DIAGNOSTICS
GAS RESERVOIR
SURFACE DIAGNOSTICS
THOMSON SCATTERING
NEUTRON MONITOR
NBI ELO
EL 1200
0°
90°
270°
UP
UP
UP
DN
11000
7500
7500
9000
35000
7000
5000
3000
9000
6000

Fig. 14

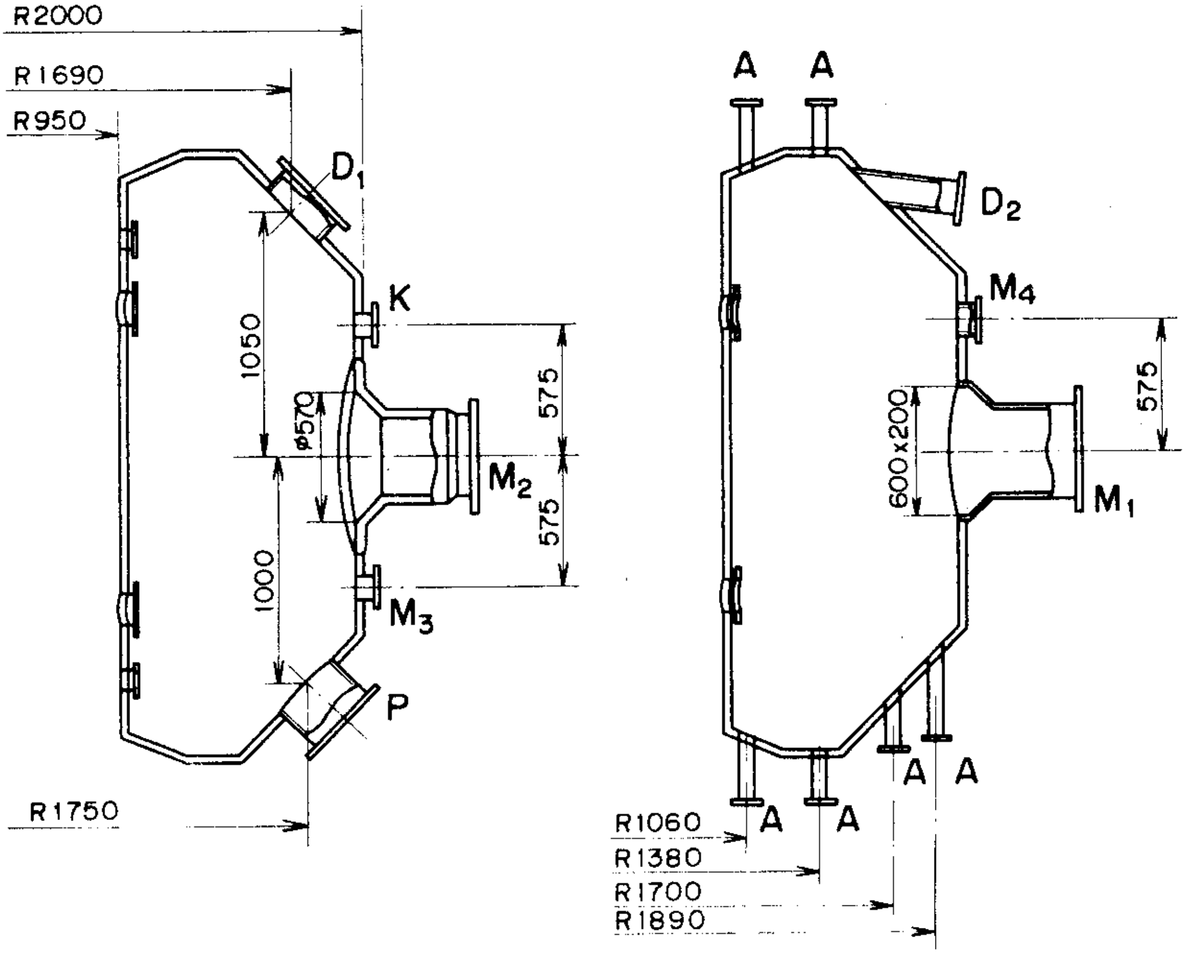

R2000
R1690
R950
D1
K
1050
φ570
575
M2
575
1000
M3
P
R1750
A
A
D2
M4
575
600x200
M1
A
A
A
A
R1060
R1380
R1700
R1890

Fig. 15

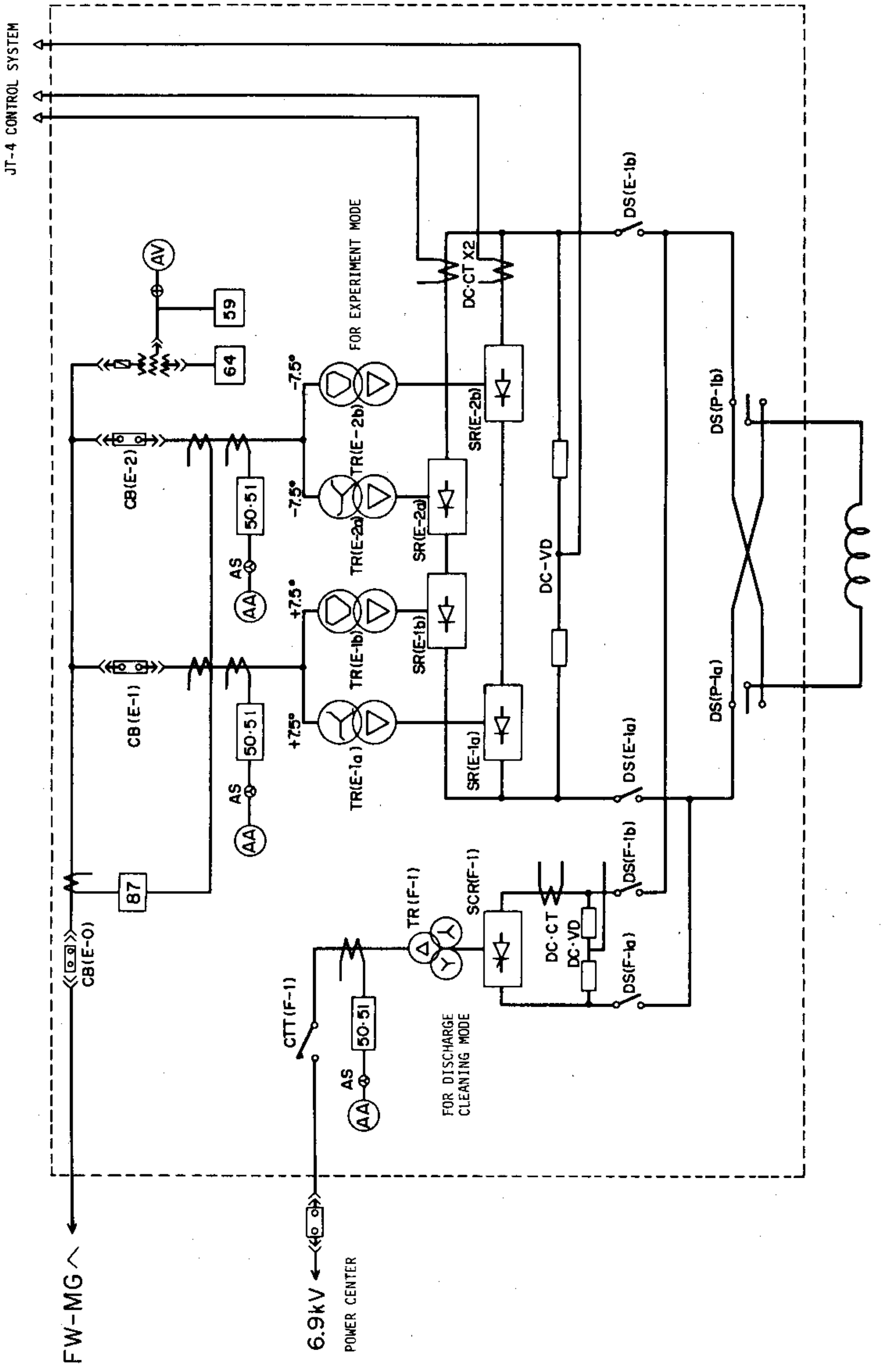

JT-4 CONTROL SYSTEM
AV
59
64
FOR EXPERIMENT MODE
DC·CT X2
DS(E-1b)
CB(E-2)
50·51
AS
AA
-7.5°
TR(E-2b)
SR(E-2b)
TR(E-2a)
SR(E-2a)
DC-VD
+7.5°
TR(E-1b)
SR(E-1b)
CB(E-1)
TR(E-1a)
SR(E-1a)
DS(E-1a)
DS(P-1b)
DS(P-1a)
TOROIDAL FIELD COILS
87
CB(E-0)
TR(F-1)
SCR(F-1)
DC·CT
DC·VD
DS(F-1b)
DS(F-1a)
CTT(F-1)
FOR DISCHARGE CLEANING MODE
FW-MG へ
6.9kV
POWER CENTER

Fig. 16

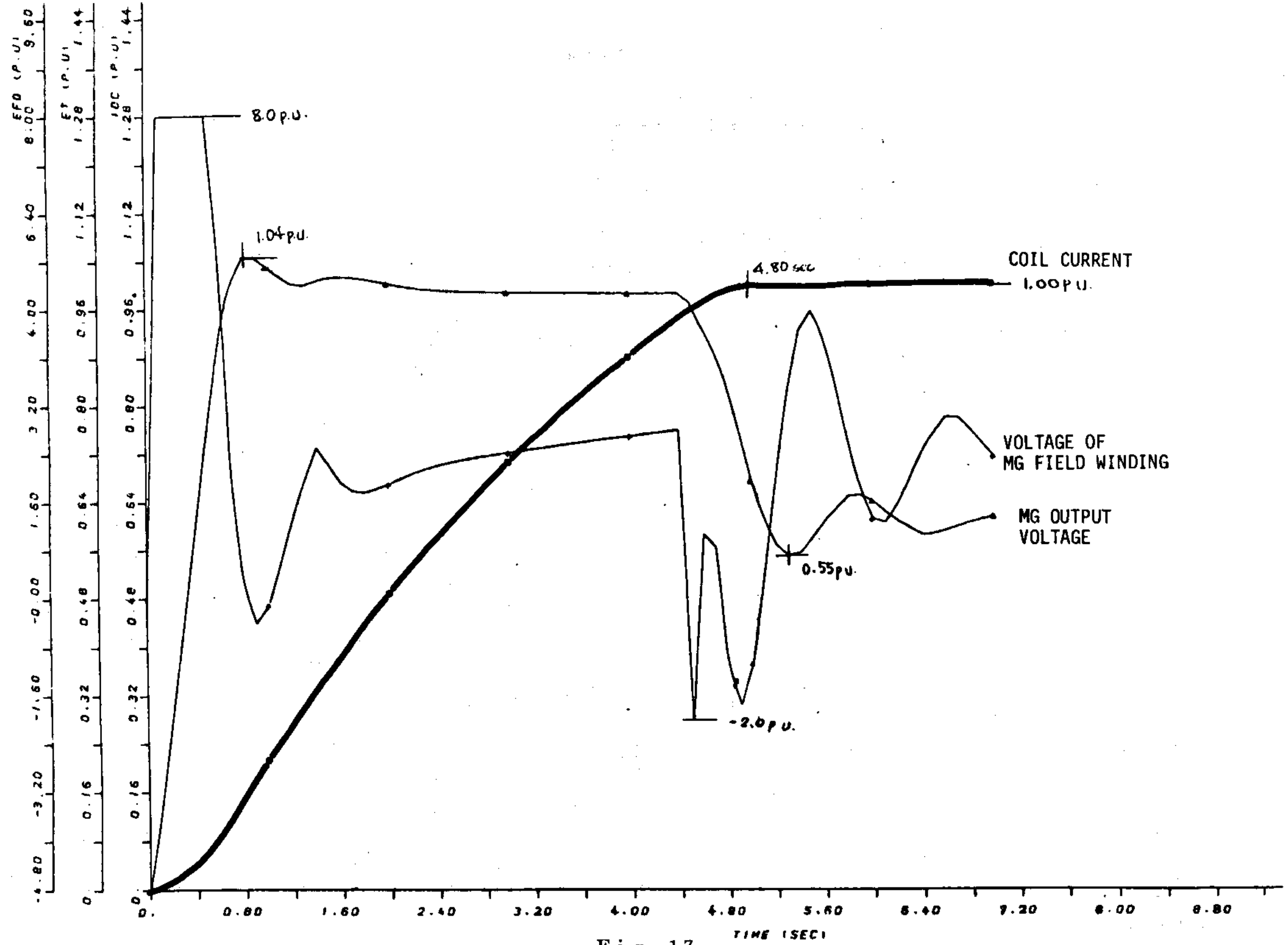

EFD (P.U)
-4.80
-3.20
-1.60
-0.00
1.60
3.20
4.00
6.40
8.00
9.60
ET (P.U)
0
0.16
0.32
0.48
0.64
0.80
0.96
1.12
1.28
1.44
IDC (P.U)
0
0.16
0.32
0.48
0.64
0.80
0.96
1.12
1.28
1.44
0.
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
8.80
TIME (SEC)
8.0p.u.
1.04p.u.
4.80sec
COIL CURRENT
1.00p.u.
VOLTAGE OF
MG FIELD WINDING
MG OUTPUT
VOLTAGE
0.55p.u.
-2.6p.u.

Fig. 17

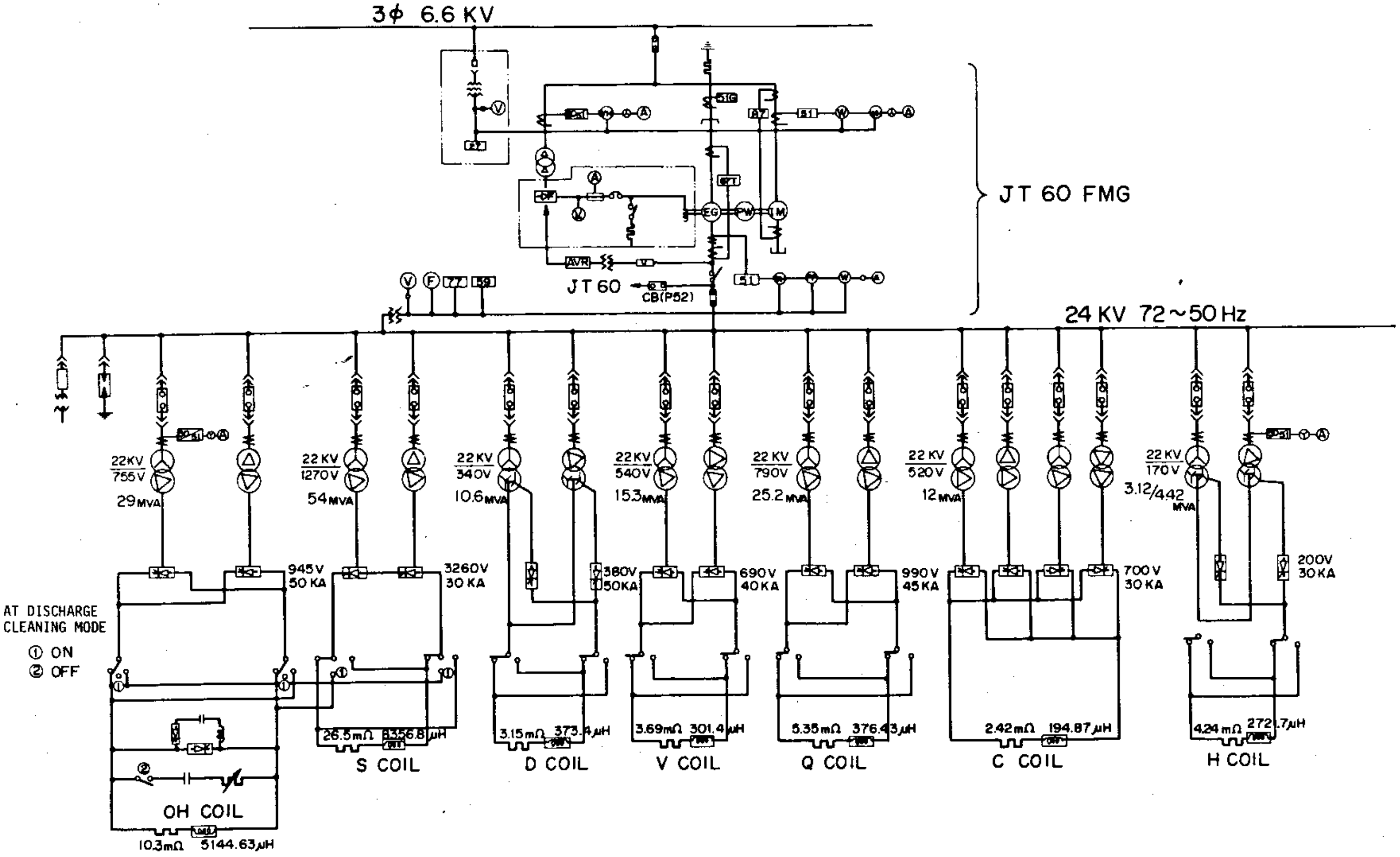

3φ 6.6 KV
JT 60 FMG
JT 60
CB(P52)
AVR
24 KV 72~50 Hz
22KV/755V
29MVA
22KV/1270V
54MVA
22KV/340V
10.6MVA
22KV/540V
15.3MVA
22KV/790V
25.2MVA
22KV/520V
12MVA
22KV/170V
3.12/4.42 MVA
945V 50 KA
3260V 30 KA
380V 50KA
690V 40KA
990V 45KA
700V 30KA
200V 30KA
AT DISCHARGE CLEANING MODE
① ON
② OFF
OH COIL
10.3mΩ
5144.63μH
26.5mΩ
8356.8μH
S COIL
3.15mΩ
373.4μH
D COIL
3.69mΩ
301.4μH
V COIL
5.35mΩ
376.43μH
Q COIL
2.42mΩ
194.87μH
C COIL
4.24mΩ
272.7μH
H COIL

Fig. 18

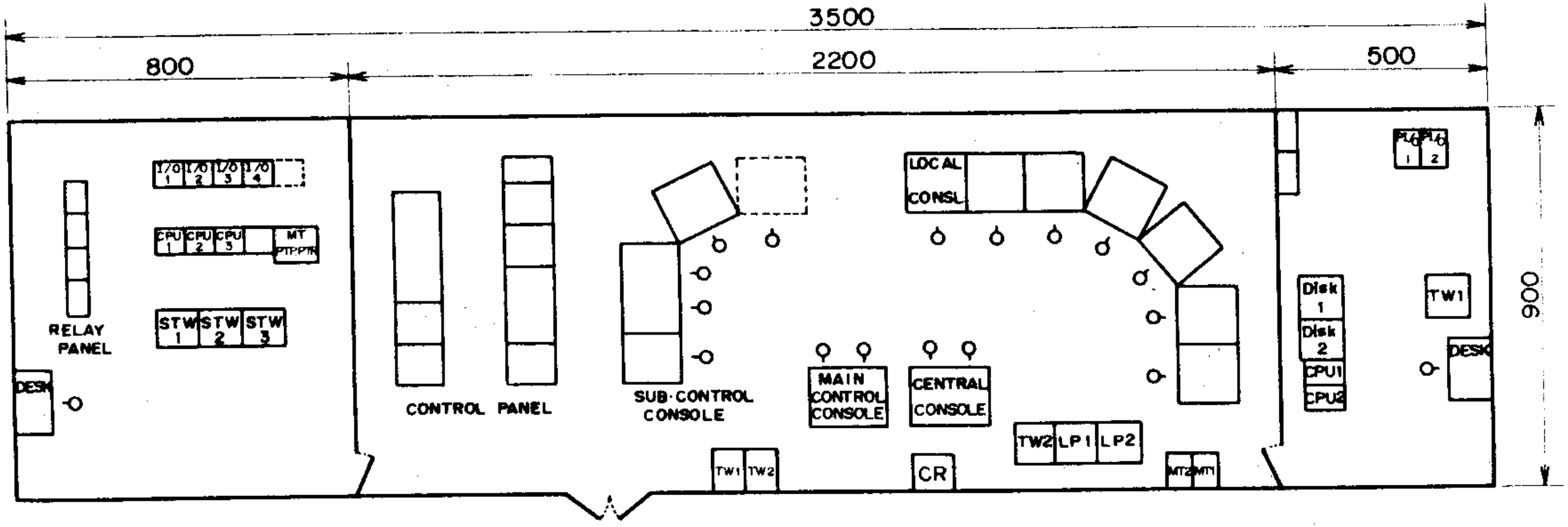

3500
800
2200
500
900
I/O 1
I/O 2
I/O 3
I/O 4
CPU 1
CPU 2
CPU 3
MT
PTPTR
STW 1
STW 2
STW 3
RELAY PANEL
DESK
CONTROL PANEL
SUB·CONTROL CONSOLE
MAIN CONTROL CONSOLE
CENTRAL CONSOLE
LOCAL CONSL
TW1
TW2
CR
TW2
LP1
LP2
MT2
MT1
PI/O 1
PI/O 2
Disk 1
Disk 2
CPU1
CPU2
TW1
DESK

Fig. 19

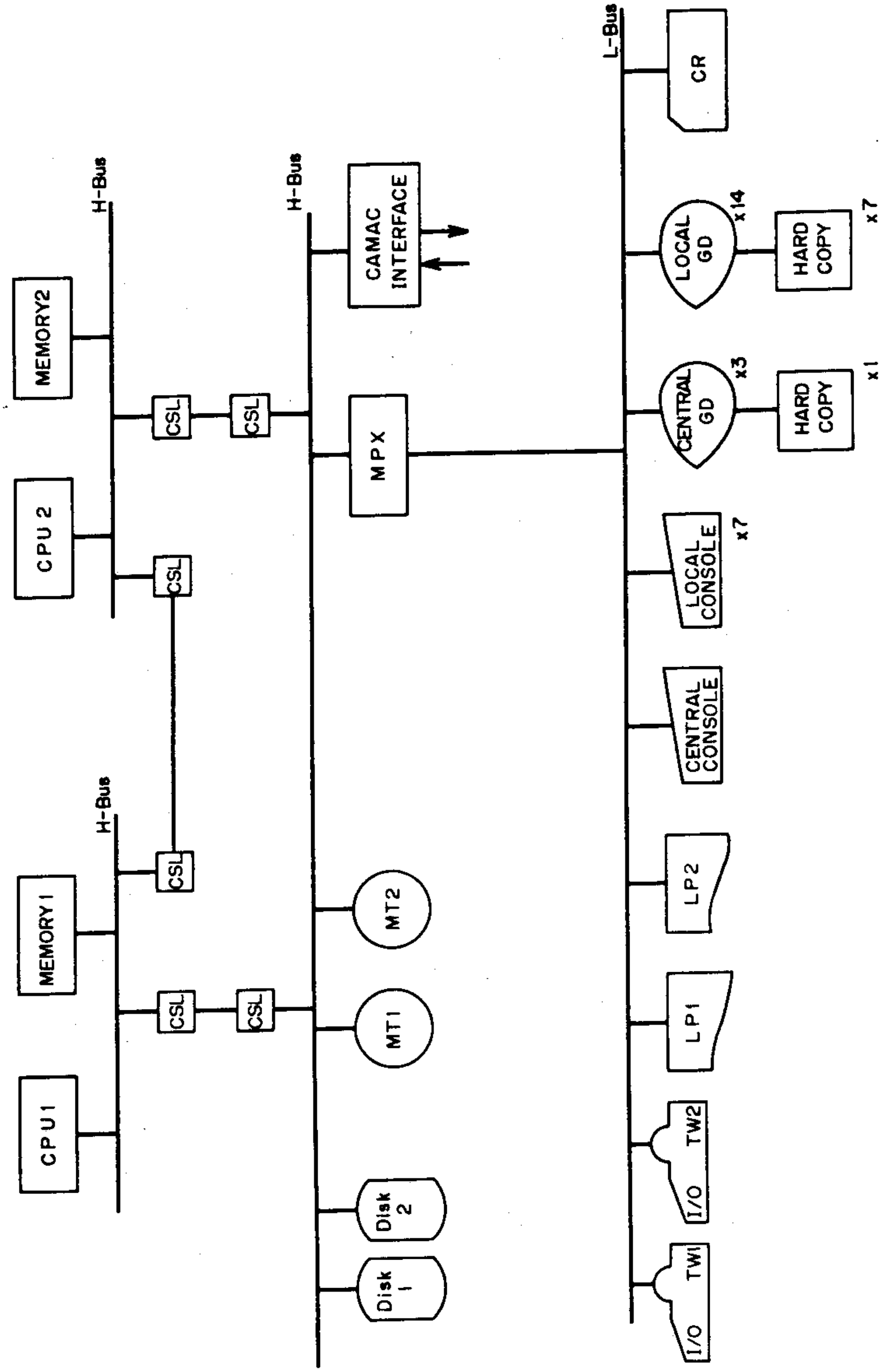

H-Bus
MEMORY2
CPU 2
CSL
CSL
CSL
H-Bus
CAMAC INTERFACE
MPX
H-Bus
MEMORY1
CPU1
CSL
CSL
CSL
MT2
MT1
Disk 2
Disk 1
L-Bus
CR
LOCAL GD
x14
HARD COPY
x7
CENTRAL GD
x3
HARD COPY
x1
LOCAL CONSOLE
x7
CENTRAL CONSOLE
LP2
LP1
TW2
I/O
TW1
I/O

Fig. 20

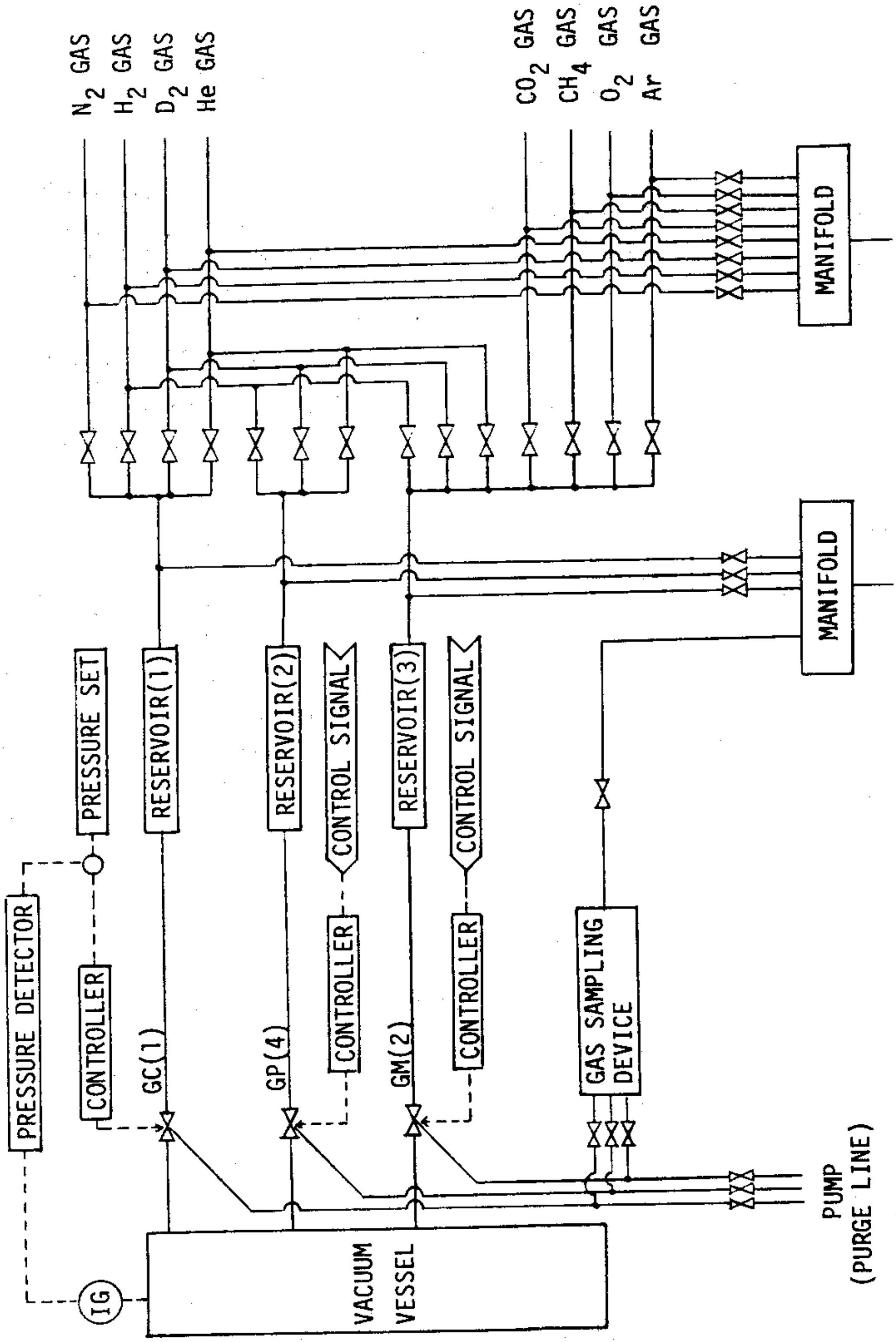

N_2 GAS
H_2 GAS
D_2 GAS
He GAS
CO_2 GAS
CH_4 GAS
O_2 GAS
Ar GAS
MANIFOLD
PUMP
MANIFOLD
PUMP
PRESSURE SET
RESERVOIR(1)
RESERVOIR(2)
CONTROL SIGNAL
RESERVOIR(3)
CONTROL SIGNAL
PRESSURE DETECTOR
CONTROLLER
GC(1)
GP(4)
CONTROLLER
GM(2)
CONTROLLER
GAS SAMPLING DEVICE
PUMP (PURGE LINE)
IG
VACUUM VESSEL

Fig. 21