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JT-60 PROJECT

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Abstract

JT-60 project is presented in this paper for the accelerator physisist and engineers. JT-60 is a large Tokamak, nuclear fusion experimental device aiming at achieving break-even plasma conditions. A brief description is presented about each of the major components of which JT-60 constitutes. The time progress of the designing, construction, commissioning and experiment is also described.

1. Introduction

JT-60 is one of the three large Tokamaks in operation in the world for the nuclear fusion reactor development with objectives of achieving break even plasma conditions. Tokamak is the most prominent device for the plasma confinement, which can aim at obtaining high temperature plasma with moderate density, according to the empirical scaling law based on the experimental results with the medium size Tokamak. The basic program of JT-60 development was originally laid out in July 1975 in the Second Phase Basic Plan for Fusion Energy Development by Atomic Energy Commission (AEC): The objectives of JT-60 is not only to achieve break even plasma conditions in a Tokamak device but also to provide an integrated evaluation of Tokamak plasma physics and fusion technologies. In this sense, JT-60 was constructed for the extension of the plasma physics understanding of Tokamak confinement as well as the development of fusion engineering and technologies. Tokamak is, in principle, explained as a kind of betatron accelerators in the meaning of application of the induction voltage for the electron current drive. The electron current is used for plasma ohmic heating and for plasma confinement rather than obtaining high energy of electron beam.

Following the conceptional design and the preliminary design study in 1973 and 1974, the preconstruction design and the engineering development were carried out in 1975-1976. The contruction was actually initiated in April 1978 and was completed in April 1985. JT-60 was operated in April-June 1985 for its ohmic heating experiments. The supplementary heating devices and most of plasma diagnostics instruments were then installed in a later period of the year. During the two years of 1986 and 1987, JT-60 has been operated with high performance of tokamak machine, heating devices and diagnostics, to obtain the experimental results for the break even plasma condition, that is, $n\,\tau_E = 2 \sim 6 \times 10^{19}\ \mathrm{m}^{-3}$ and $T=5\sim10$ keV which correspond to a DT energy gain of $Q=1$. In this paper, taking into consideration of the interest of the accelerator physists and engineers, JT-60 is overviewed firstly in the next section. The time schedule of JT-60 construction and experiment executed, is described subsequently. Concluding remarks are given in the final section.

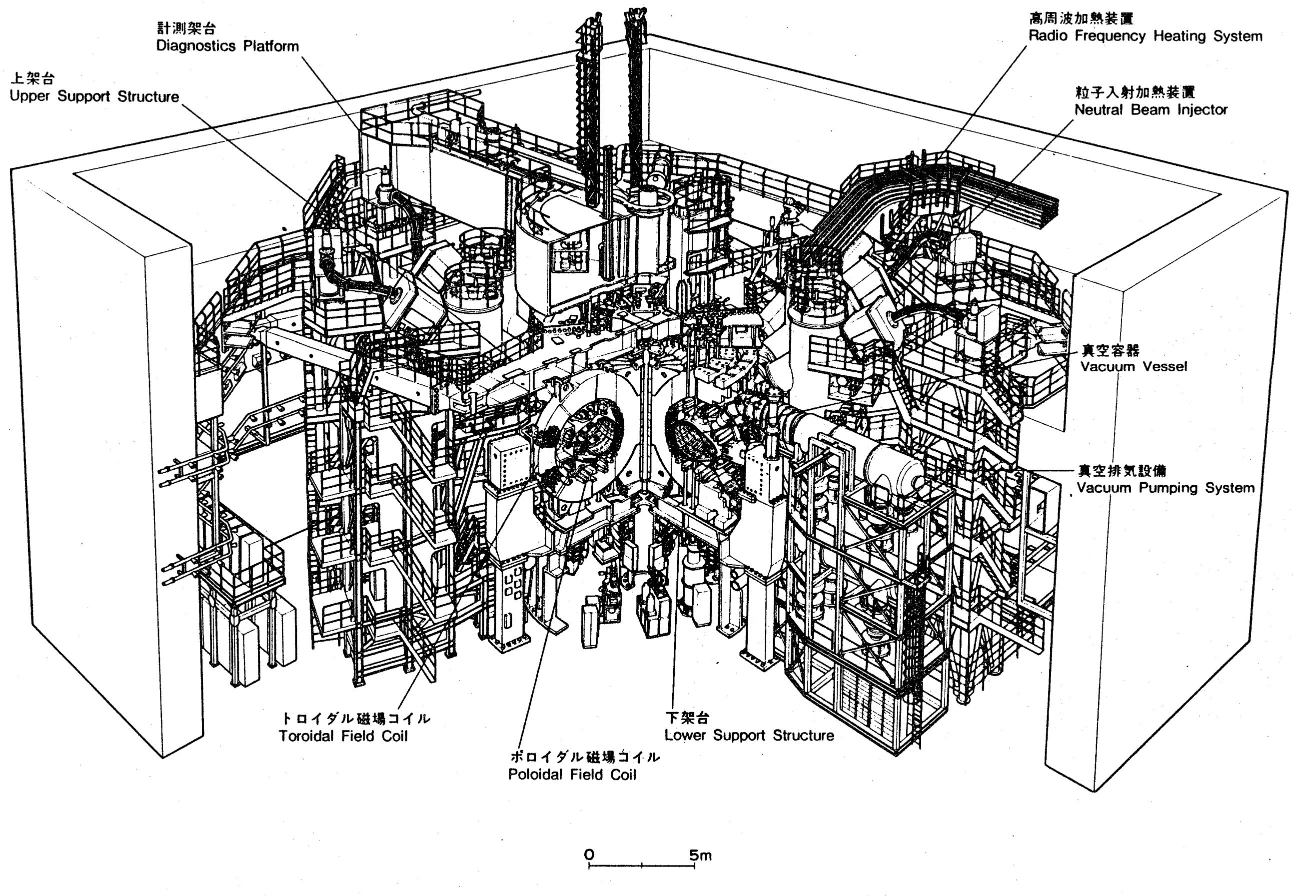

Fig. 1 Bird's-eye-view of JT-60

2. Over View of JT-60

Major components of JT-60 are JT-60 device, heating devices and diagnostic equipments. These devices are installed in the experimental building, power supply buildings and control building, all of which are mutually connected with big under-ground duct. JT-60 device constitutes of three subsystems, the tokamak machine, the power supplies and the control system. Heating devices which heats further the ohmically heated plasma and increases the plasma temperature up to the several keV, are composed of the neutral beam heating system (NBI) and the radiofrequency heating system (RF). Various kind of diagnostics equipments are needed to measure the high temperature plasma in the research area of the large tokamak experiment as well as in the area of the plasma physics in order to understand the plasma characteristics and to operate the tokamak safely.

Table 1
Major parameters of JT-60

	JT-60	
	Material Limiter mode	Magnetic limiter mode
Plasma major radius (m)	3.0	3.2
Plasma minor radius (m)	0.95	0.9
Axial toroidal field (T)	4.5	4.2
Plasma current (MA)	2.7	2.1
Flux swing (V·s)	25.5	25.5
Discharge duration (s)	5–10	5–10
Poloidal beta	2.5	1.5 (2.5)

JT-60 device

The tokamak machine

The tokamak machine is shown schematically in Fig. 1, and the major parameter are summarized in Table 1. The plasma is produced in the vacuum chamber made of Inconel 625 and combined with alternately welded rigid rings and bellows. This structure ensures loop resistance of the vacuum chamber 1.3 mΩ. The inner surface of the vacuum chamber, which is shown in Fig. 2 was initially covered with molybdenum limiters and molybdenum or Inconel liners coated by titanium carbide with thickness of 20 μm. At present, however, a part of limiters and liners are replaced with carbon graphite, taking account of the latest progress in the tokamak experiment. The vacuum vessel is bakable at a temperature beyond 300°C.

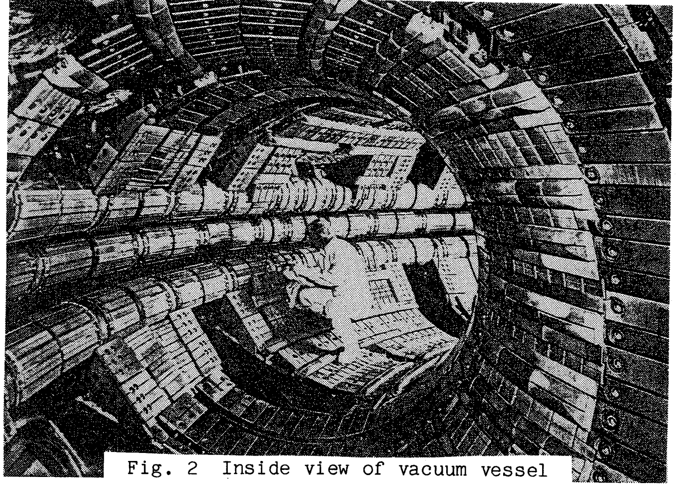

Fig. 2 Inside view of vacuum vessel

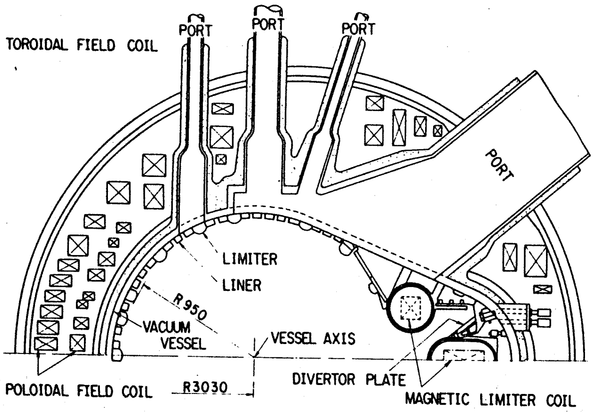

Fig. 3 Cross-sectional view of tokamak machine

Inside and outside of the vacuum chamber as shown in Fig. 3, the poloidal field coils are wound, which consist of five kinds of coils with different functions: the ohmic heating to induce the plasma current, the vertical field (the dipole field) and the horizontal field to control plasma position, and quadrupole field and the magnetic limiter field to control plasma shape and positional stability. The flux swing of the ohmic heating is 26 volt-sec and the loop voltage can be induced up to 300 V at maximum. The vertical field coils correspond to the bending magnet for controlling the particle orbit in the accelerator physics and the characteristics of the quarupole field coils can be defined by the intenisty and the n-index, $n = -R/B_z(\partial B_z/\partial R)$, similarly to the betatron accelerator field. The eighteen toroidal field coils are placed outside the poloidal coils and can produce 4.5 Tesla at maximum on the vessel axis (R=3.03m).

The Power supplies

An operational scenario of JT-60 discharge is shown in Fig. 4. At the flat top of the toroidal field coil current, the ohmic heating coil current is interrupted rapidly. Hydrogen gas prefilled in the vacuum chamber with gas puffing, discharges by the induced voltage of the current interruption. In the flat top phase of plasma current, plasma parameters are extended by additional heating. The discharge duration is 10 second and its nominal duty cycle is 10 minutes.

A large pulsed electric power is required to energize the toroidal field coil, the poloidal field coils and heating devices. The JT-60 power supplies need an power of over 1000 MW during the plasma discharge, which is supplied through the three motor generator systems and the network power line. JT-60 receives a peak electric power of 200 MW for operation of the entire JT-60 from the power network of the electric power company of 275 kV, 50 Hz. The largest pulse load is the toroidal field system which requires 160 MW directly from the power network line of 275 kV. The second major load is the three motor generator system. JT-60 power line is shown in Fig. 5. The toroidal field power supply is composed of the flywheel motor generator system of 215 MVA and the power network of 275 kV the latter of which is used for the forcing voltage of the toroidal coil current, and they can generate the peak power of 400 MVA as a whole. The toroidal field coils can be energized up to 9 GJ through the rectifier circuit of the power supply during one-cycle operation. The poloidal field supply excites the coils, with an AC generator of 500 MVA. Each poloidal field coil is powered independently, the current and voltage waveform of which are regulated with the respective thyristor banks with the direct digital controllers equipped in the CAMAC crates. The NBI and RF heating devices are powered with a 400 MVA flywheel motor generator which can release the energy of 2.6 GJ during a pulse operation of 10 second. The power supply for heating devices is characterized by its low impedance for output voltage regulation and special design effort was paid to the stability of the AC voltage on the common bus of two heating devices.

The control system

The control system of JT-60 is called as Zenkei. As JT-60 consists of more than twenty large independent subsystems, which in the experiment,

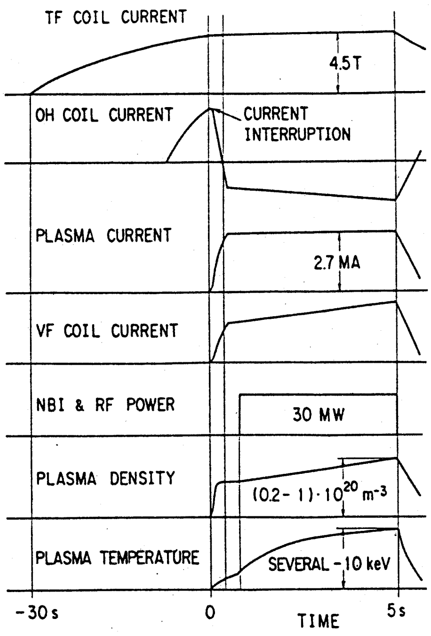

Fig. 4 JT-60 operational profiles

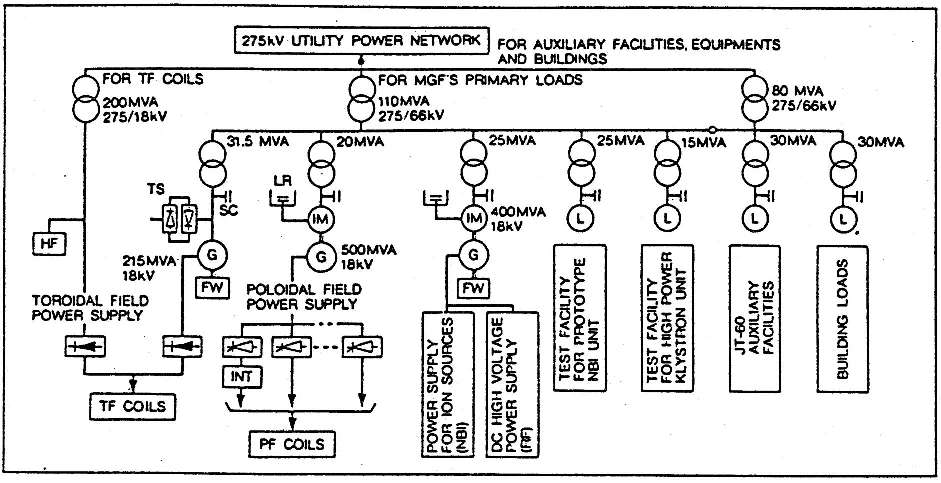

Fig. 5 Schematic of power distribution system

should be organized into one system and be operated simultaneously, Zenkei was paid by special attention to the high performance and reliability. Moreover, Zenkei should be adaptable flexibly to the various operation modes without losing reliability and it also should be coped with new operational demands. For the correspondence to these requirements, Zenkei is fully computerilized except a hard-wired safety interlock system and it is composed of 7 minicomputers and relavant electronic devices including CAMAC highways. Zenkei computers are connected with the communication crates equipped with microcomputers. Each of Zenkei computers is dedicated to its own function such as plant support, discharge control, real time control and feed-back control, and is connected with several kinds of CAMAC highways through communication crates to the subsystem controllers, that is, device CAMAC. The number of the CAMAC crates reaches up to 300 crates including plasma diagnostics CAMAC. The plasma control scheme with real time control computers and feed back control ones is shown in Fig. 6.

Heating devices

Neutral beam injection system

The 14 neutral particle injectors are installed around the JT-60 vacuum chamber and generated the hydrogen beam of 20 MW in total. Two beamline units are illustrated in Fig. 7. The neutral beam with the energy of 75 keV penetrates into the plasma and heats it. Each injector consists of a beamline unit mounted with ion sources and a neutralizer cell, and a power supply for the ion sources. For a whole NBI system, a liquid helium and liquid nitrogen cryogenic system for beamline cryopumps, a cooling system for heat dump materials, an auxiliary pumping system and the control system are provided. A schematic drawing of the ion source is shown in Fig. 8, as an example of the high current proton source developed. A plasma source is a rectangular bucket-type source with a backstream electron beam dump inside. The ion is extracted from the plasma source and is accelerated up to 75 keV through the plasma grid and the gradient grid. These grids are made of molybdenum to improve thermal properties and are cooled with water to cope with high heat loading. The performances of heating devices are listed in Table 2.

Radio frequency heating system

The radio frequency (RF) heating system has two kinds of heating method, that is, the lower hybrid heating (LHRF) and the ion cyclotron heating (ICRF), the specification of the RF heating system is listed also in Table 2. The LHRF system is composed of three units, each of which consists of 8 MW klystron amplifiers, wave guide transmission and the launching structure mounted on the JT-60 vacuum vessel. High

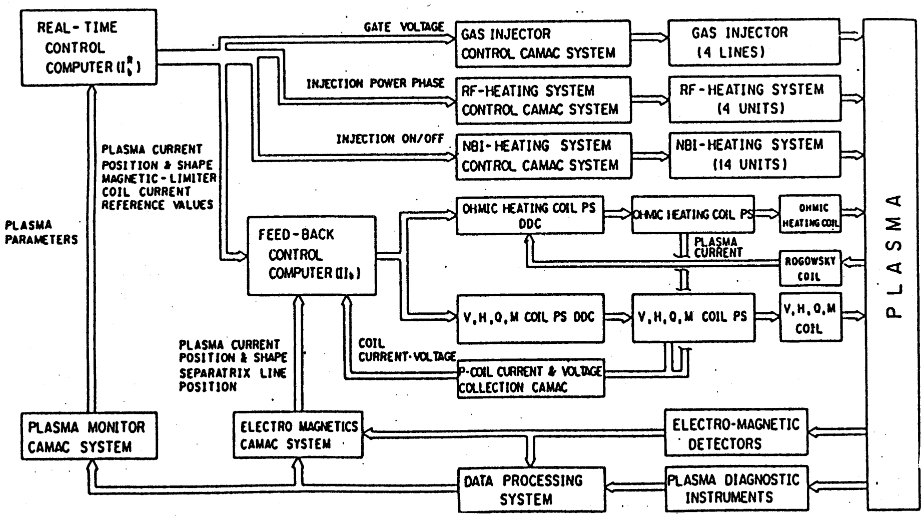

Fig. 6 Real-time plasma control loops

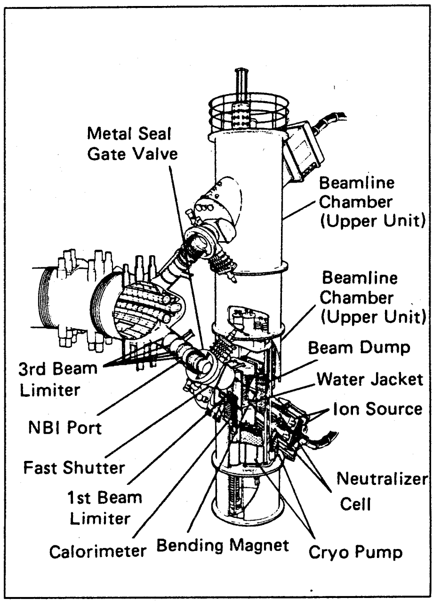

Fig. 7 Beamline unit of the neutral beam injection system

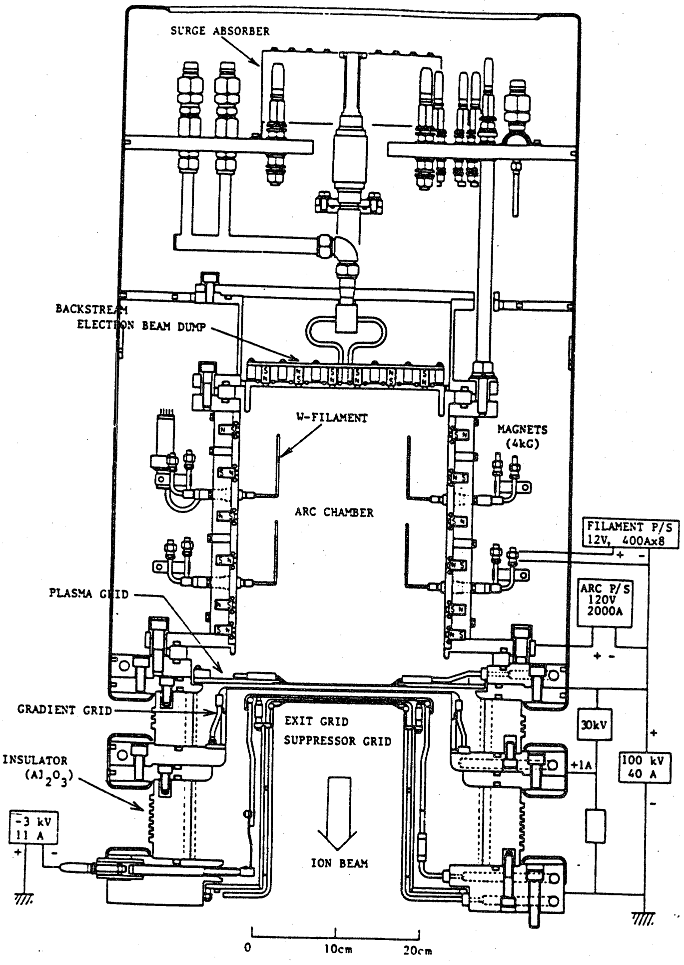

Fig. 8 A schematic of the ion source for JT-60 NBI

power klystrons are driven with the chains of low power amplifiers and solid state amplifiers which are connected cautiously each other with microwave circuits, namely, phase shifters, attenuators and wave guide couplers. The wave launcher is the essential and important part of LHRF to feed the output power from the klystrons into the JT-60 plasma. A cross-section view of the launcher is illustrated in Fig. 9. In the ICRF system, eight tetrode amplifiers are used, each of which generate 1 MW in 120 MHz wave for pulse duration of 10 second with 10 minutes interval. ICRF launcher is 2×2 loop array antenna as shown in Fig. 10, with which toroidal and poloidal wave numbers are controlled.

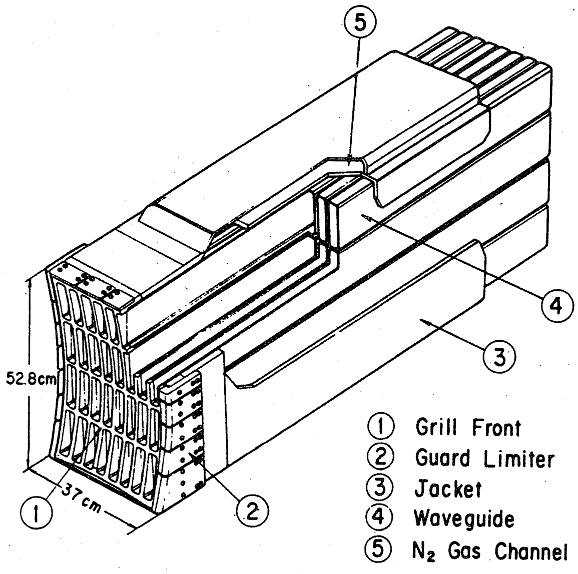

Fig. 9 Cross-sectional overview of the LHRF launcher in JT-60

Table 2
Performances of heating devices

a. Neutral beam injector system

Beam energy	75 keV (50–100 keV)
Neutral beam power	20 MW
Ion beam power	72 MW
Pulse length	10 s
Number of injectors	14

b. Radio-frequency heating system

	Lower hybrid system	Ion cyclotron system
Frequency	1.7–2.3 GHz	110–130 MHz
Number of units	3	1
RF power	24 MW	6 MW
Pulse length	10 s	10 s
Final tube	Klystron (24 tubes)	Tetrodes (8 tubes)
Coupling system	Wave guide array	Loop array

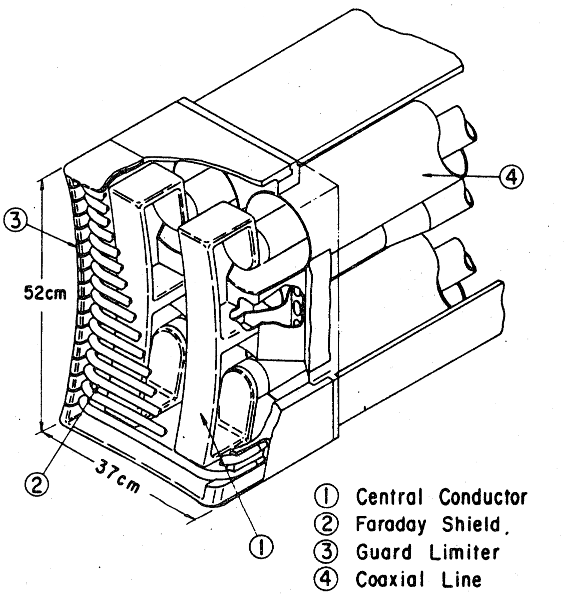

Fig. 10 Structure of the 2×2 phased loop antenna array of JT-60

Diagnostic System

Various measurements of the plasma parameters are needed not only for obtaining the break-even plasma but also for researching the characteristics of the break-even plasma. The electron and ion temperature, the plasma density, the plasma position and shape, the plasma current, the particle loss, the radiation loss, and the impurity contents should be measured from the viewpoint of time behaviour and spatial distribution. 23 different kinds of diagnostics were constructed and each diagnostics is able to obtain useful data with high resolution in time and space simultaneously and also to transfer the data quickly within a few milliseconds in the online feed back loop and within a few minutes in the shot-by-shot feed back loop. So, in the JT-60 diagnostics system, the data processing system is provided seperated from the machine control computer, Zenkei. Taking account of the design consideration JT-60 diagnostics system is sorted out into eight groups, including the data processing system and diagnostics supporting system as shown.

The total installation of JT-60 diagnostics system around JT-60 vacuum chamber is illustrated in Fig. 11. The electron density is measured by mm and sub-mm wave interferometers. The CH_3OH sub-mm wave (119μm) laser has been selected and developed to measure the electron density. The optical passage length is monitored by a He-Ne laser interferometer to get the phase difference caused by plasma. The electron temperature is measured both by a electron cyclotron emission measuring system and a Thomson scattering system with a multipulse laser. The power of cyclotron radiation from the plasma is fourier analyzed in the Michelson-type interferometer, which provide the profile of the electron temperature with time resolution of 15 ms. The electron temperature from the Michelson-type interferometer is calibrated by the Thomson scattering measurement.

The information about the ion temperature in the plasma can be obtained mainly by active beam scattering apparatus and charge exchange neutral particle energy analysers. The principle of the active beam scattering method is based on the energy broadening analysis of neutral particles, which are injected into plasma and scattered by plasma ions. A drawing of the system is shown in Fig. 12. For the measurement, Helium ions with 200 keV energy, 3.5 A current and 0.1 sec duration are converted to helium neutral atoms by the change exchange neutralizer, and 0.6 A neutral helium beam is injected into the plasma.

The charge exchange neutral particle energy analyser detects the neutral atoms which are produced in the plasma by a charge exchange reaction between plasma ions and neutral atoms, and by recombination of plasma ions and electrons. These particles convey the information about the ion temperature distribution.

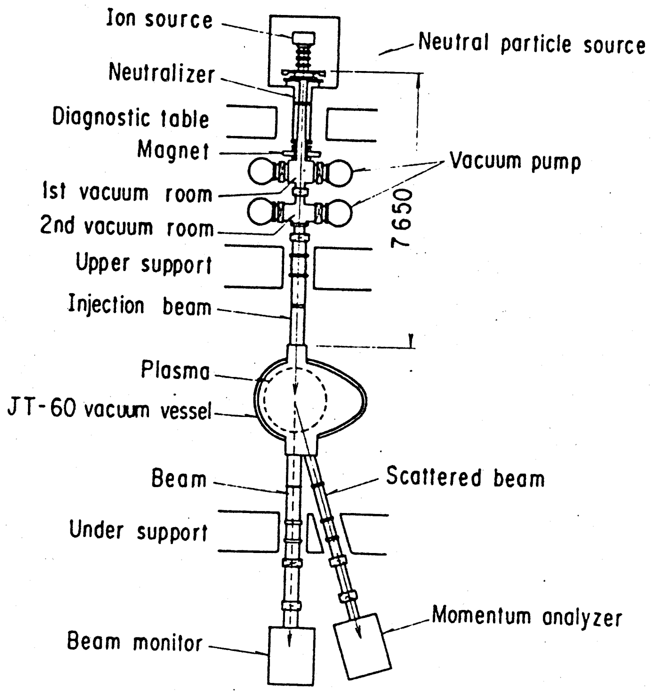

Fig. 12 Active beam sattering system

It is important to diagnose the behaviour of impurity ions in the JT-60 plasma. The impurity measuring system covers fully the spectrum region from X-ray to visible light. In order to measure the spatial resolved impurity lines, a small-size unit

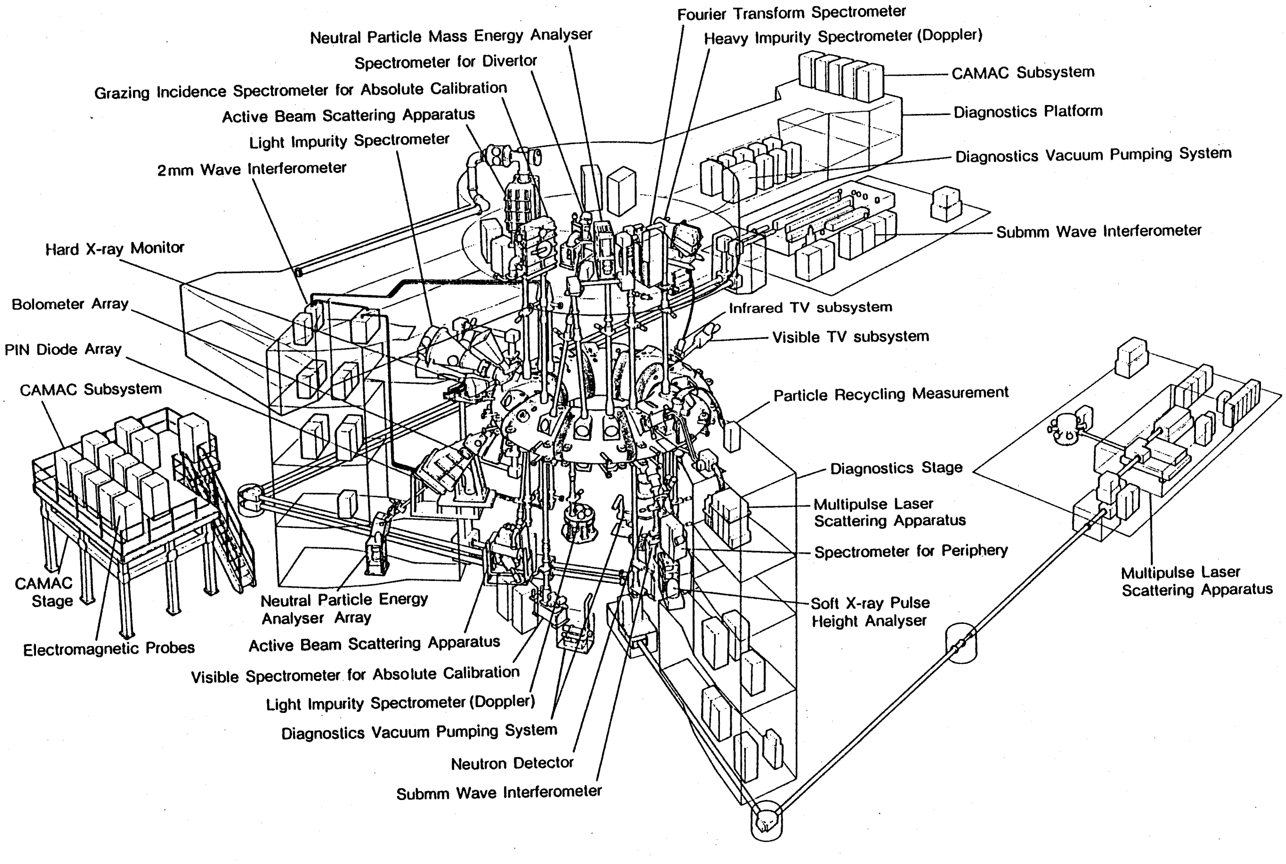

Fig. 11 JT-60 diagnostics system

type of the grazing incidence spectrometers has been developed and installed on a shelf to analyse the spatial distribution of the impurity lines. In the unit type spectrometer, spectral lines are imaged by the holographic grating on the flat plane where the array detector is placed. The temperature of the impurity ions can be measured by the Doppler broadening of the impurity lines. The radiation flux is measured by a germanium detector with a high counting rate pulse height analyzer. The radiation profile is obtained by a PIN diode array and a bolometer array. The peripheral plasma and wall surface are viewed by visible TV cameras, IR-TV cameras, probes, thermocouples and gas analysers.

Data obtained in diagnostics instruments is transfered through three different ways to data processing system which consists of a real-time processor, an intershot processor with a CAMAC system and a mass data recorder (MDR). The 50 million word of data (2 Bytes/word) are obtained by the diagnostics at one discharge, and some data are processed immediately and presented as a graphes on the CRT's in the control room for the operators who pepare the conditions of the next discharge and for the diagnosticians in the diagnostics room.

The major part of data is stored in the mass data recorder which has the recording capability of 30 input channels, 4 Mb per second for each channel simultaneously. The intershot processor is a general purpose large computer to store and process data so that the sophisticated analysis is rapidly performed using a large mount of the stored data.

3. Construction, Commissioning and Experiment

Schedule of JT-60 Project

JT-60 project schudule is summarized in Fig. 13. After the conceptual design, the preliminary design study, the preconstruction design study and engineering development which are conducted from 1973 to 1976, the construction of the tokamak machine was actually started in April 1978. Thereafter, major components of the JT-60 were conducted to the contract with the industries year after year successively. JAERI procured a new site for the fusion energy development in Naka-machi, Ibarak-ken in october 1978. The transportation of the tokamak machine started to the Naka-site on April of 1982, after completion of the experimental building. Assembling and installation work continued day and night for about 22 months. Installation of the tokamak machine was completed in october 1984. In the final stage of construction, the integrated system test were performed for commissioning of JT-60 device from June 1984 and lasted for ten months. Based on these successful test results, JT-60 entered the phase of the initial ohmic heating discharge from April to June 1985. Heating devices and most of diagnostics equipments were installed during July to December 1985, and the test operation of the heating devices and the extensive experiment were carried out in 1986. Heating experiment for obtaining the break even plasma condition has been performed and the successful results is expected to get at the earliest possible time.

4. Conclusion

This paper described JT-60 device, heating devices and diagnostics equipments as well as the project schedule of construction, commissioning and experiment. The results of ohmic heating and supplementally heating experiment will be reported at the Accelerator Science Seminar.

Acknowledgements

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Reference

[1] The special issue for JT-60 engineering aspects; Fusion Engineering and Design 5 (1987) 1.

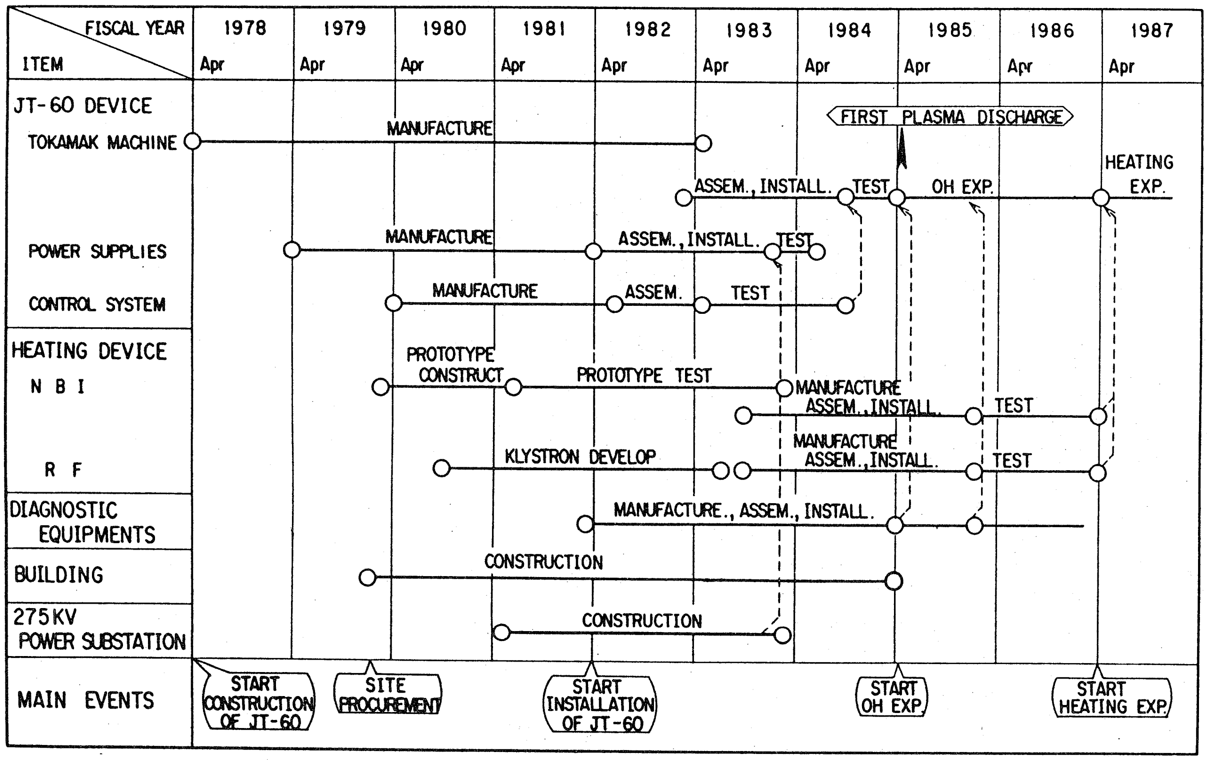

Fig. 13. JT-60 project schedule