Aditya: The first Indian Tokamak

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Aditya: The first Indian Tokamak

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One of the methods of confining hot fusion plasmas is by use of the toroidal magnetic bottle known as tokamak. Aditya is the first tokamak, designed, fabricated, erected and commissioned by India. It is a moderate field (toroidal field 15 kGauss), medium size (minor radius 25 cm, major radius 75 cm) tokamak which should produce a 250 kA discharge with a peak density 3×10^{13} cm^{-3} and a peak electron temperature of about 5 million degrees. The plasma is generated in a stainless steel vessel evacuated to a base pressure of 10^{-9} torr. The vessel is surrounded by twenty large rectangular toroidal magnetic field coils. An ohmic transformer is placed in the central hole of the torus and is used to induce substantial voltage in the hydrogen gas (typically kept at 10^{-4} torr in the vessel) to cause its breakdown and drive and sustain plasma currents upto 250 kA. Other field coils produce programmed fields necessary for keeping the plasma in equilibrium. Power is supplied to the various magnetic field coils in the form of dc pulses generated by transformer-converter systems controlled by a PDP 11/23 computer. The main source of the power is a 132 kV line connected to the Gujarat Electricity Board power grid system. Plasma parameters are to be measured by a variety of passive and active diagnostics. The data acquisition and control of the entire experiment is carried out using control system based on CAMAC and VAX 11/730 computer. Experiments dealing with plasma disruptions and their feedback control, plasmas with significant current in energetic carriers, etc. are the major directions of the experimental programme. The paper summarises design and development activity leading to the commissioning of Aditya.

1. Introduction

Magnetic confinement of thermonuclear grade plasmas is a major scientific and technological challenge to modern plasma physics. Amongst the various possible magnetic configurations, which have been proposed to confine a plasma, the tokamak is by far the most successful. In fact, several major tokamak experiments in the world are close to demonstrating scientific breakeven conditions in the laboratory. At the same time, our understanding of the collective, far from equilibrium physics phenomena dominating the empirical performance of a tokamak is still rather sketchy. One can learn a great deal about the physical phenomena taking place in a tokamak by a detailed experimental study of moderate sized devices. It is for these reasons that tokamak Aditya, a low-field medium-sized tokamak has been conceived, designed, largely indigenously fabricated and erected at the Institute for Plasma Research, Bhat, Gandhinagar. Aditya is presently undergoing final commissioning tests.

Basically, a tokamak is a toroidal magnetic bottle in which the confining fields are produced by a combination of currents in external coils and currents induced in a plasma. At the heart of the device schematic is a stainless steel vacuum torus which can be evacuated to a base pressure $\sim10^{-9}$ torr and then filled up with the desired gas at $\sim10^{-4}$ torr. A toroidal magnetic field is produced in the vacuum vessel by a number of toroidal field coils surrounding it. Additional magnetic fields giving plasma confinement are produced by induction of a toroidal plasma current in the gas inside the vacuum vessel. This is accomplished with the help of a controlled flux swing of an ohmic transformer whose primary sits in the hole of 'doughnut' (torus); a secondary voltage is induced in the gas, which breaks it down and then drives and sustains the plasma current. The induced plasma current not only generates the confining fields but also resistively heats the plasma to high temperatures. Plasma equilibrium is assured by additional fields created by external vertical field coils which give a $\mathbf{J}\times\mathbf{B}_v$ force opposing the natural hoop force on the toroidal current filament. Power to the various magnetic field coils is supplied by special computer controlled transfromer-converter type power supplies which take an 11 kV, 50 Hz input and convert it into appropriate voltages and pulse shapes required for the experiment. Enormous electromagnetic forces appear on the magnetic field coils because of the large currents flowing through them and the plas-

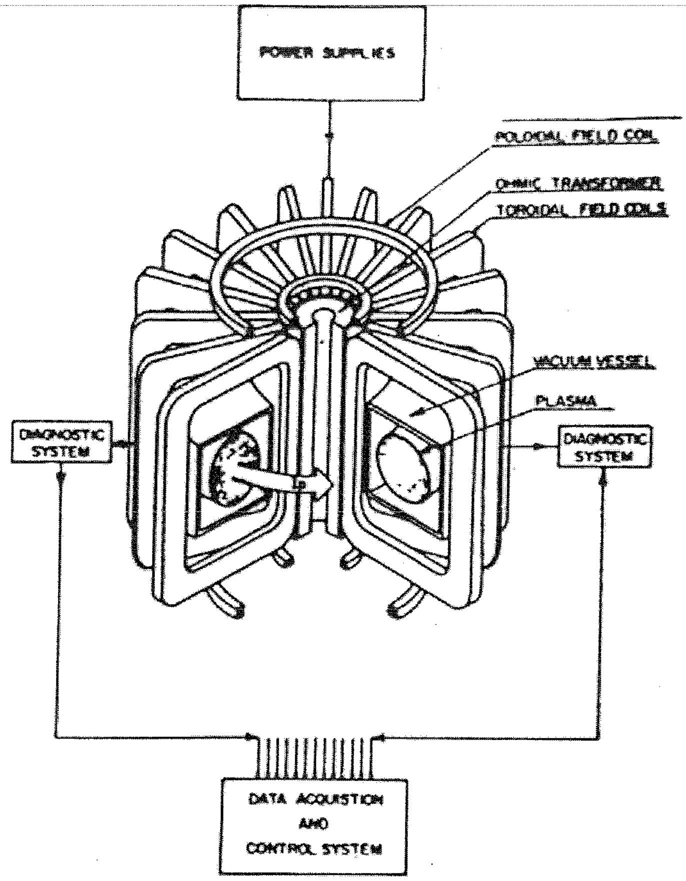


Fig. 1 – Schematic of the tokamak device

ma. The coils, are therefore, restrained by a carefully designed mechanical structure, which also provides an independent support for the vacuum vessel. The entire experiment of plasma production, confinement and heating is a pulsed experiment lasting a few seconds only. It, is therefore, automated, controlled and monitored by a computer system. The plasma performance is diagnosed by a number of passive and active probes (such as microwave interferometer, laser thomson scattering, langmuir probe, etc. with the help of a computerised data acquisition and control system.

The chief scientific objectives of Aditya are (i) investigation of density and current limits of a tokamak with special emphasis on interesting phenomena like MARFES, detached plasma, disruptive instabilities and their control; (ii) study of novel regimes of operation such as those with currents dominantly in energetic current carriers; (iii) investigation and control of edge phenomena, etc. The choice of machine parameters has been guided to a large extent by considerations of simplicity, available indigenous technology and the desire to allow maximum flexibility to accommodate various needs of the proposed experiments. One of the prime considerations was to provide ample access for a large number of diagnostics and have a plasma with reasonable, density, temperature values and sufficient size for good confinement times. The preference, was therefore, towards a large volume low field design rather than towards a high field tokamak. The toroidal field at major radius was thus fixed at 1.5 T and the plasma minor radius chosen to be 25 cm. To optimise energy usage, a tight aspect ratio (major radius/minor radius)=3 was chosen. This then leads to plasma currents ~0.25 Mega amps. The basic parameters of the plasma created in the device can be deduced with the help of available empirical scaling laws. Some of these estimated parameters are listed in Table 1 alongwith the basic machine parameters. Figs 2 and 3 give the top and cross-sectional views of Aditya.

Table 1 – Aditya design parameters

1. Plasma major radius	R (m)	: 0.75
2. Plasma minor radius	a (m)	: 0.25
3. Toroidal Field at Plasma	B_T (Tesla)	: 1.5
4. Safety factor	$q(a)$	: 2.5
5. Plasma Current	I_p (MA)	: 0.25
6. Electron Temperature	T_e (keV)	: 0.5
7. Ion Temperature	T_i (keV)	: 0.2
8. Energy Confinement time	τ_E (ms)	: ~5
9. Pulse duration time	τ (s)	: 0.3

The basic plan of the paper is as follows. Sections 2 to 6 give detailed descriptions of the five major subsystems of tokamak Aditya, viz. the vacuum system (Sec. 2), the magnetic field coils and supporting mechanical structures (Sec. 3), the pulsed power supply system (Sec. 4), the diagnostics (Sec. 5) and the data acquisition and control system (Sec. 6). Since this is an issue devoted to instrumentation, the emphasis in this paper is on

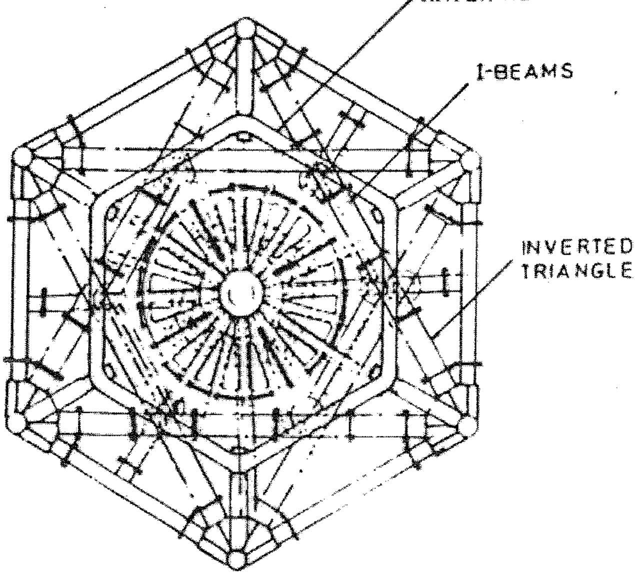


Fig. 2 – Top view of Aditya Tokamak

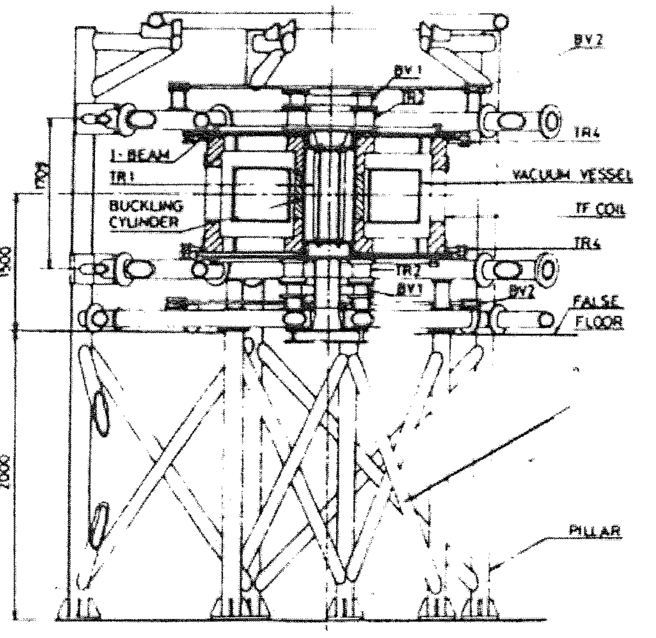


Fig. 3 – Cross-sectional view of Aditya Tokamak

technical aspects of design and fabrication of tokamak Aditya rather than on the physics studies that are to be conducted with its help. Sec. 7 briefly discusses erection and commissioning of tokamak Aditya and the last Section highlights some of the future directions in which the system will be upgraded in the coming years.

2 Vacuum System

The major components of the vacuum system are the vacuum vessel, pumping system, gas feed system, limiters and the vacuum diagnostics. This Section describes these sybsystems and two important aspects involved in the design and running of Aditya vacuum system namely the seal-joint concept and the conditioning of vacuum vessel wall.

2.1 Vacuum Vessel

The primary requirement of the vacuum vessel is that it should be non-magnetic, ultrahigh vacuum compatible and should not give out impurities during a plasma discharge. The vacuum vessel is a torus of major radius 75 cm with a square cross-section of side 60 cm. The wall thickness of the top and bottom flat sections is 20 mm and the inner and outer curved sections is 10 mm. A number of port extensions are provided in the vessel for pumping, plasma diagnostics, injection of particle beams, etc. The vessel is made out of SS 304 L material and assembled in four quadrants. Toroidal (electrical) discontinuity is provided at two of the four quadrant joints to allow fast poloidal magnetic field penetration into the vessel.

The vessel is subjected to a compressive force when it is evacuated. A detailed stress analysis using a finite element code showed that the local stresses at the vessel body and the corners are below tolerable limits and that the maximum deflection of about 1 mm occurs on the flat section of the vessel. Besides this static force the vessel wall and joints are subjected to dynamic forces when eddy currents are produced by time varying magnetic fields permeating through electrically conducting wall structure. These time-varying magnetic fields occur during (i) establishment or turning off of toroidal magnetic field inside the vessel; (ii) application of poloidal field for start up of discharge and ohmic heating; (iii) application of vertical magnetic field for providing equilibrium for the plasma ; (iv) shifts in the position of plasma column and sudden disruption of plasma current. Under worst conditions, these forces can be about 5×10^4 Newtons and the displacement about 0.4 mm. Clamping of the vessel for avoiding vertical and horizontal displacement is, therefore, done.

2.2 Pumping System

The pumping system is expected to withstand a heavy transient gas load, usually hydrogen, during the high power discharge in addition to the need to maintain an ultrahigh vacuum under normal conditions of low outgassings from the vacuum vessel's inner surface. Aditya will be mainly pumped by two turbo-molecular pumps each having a pumping capacity of 2000 liters per second for air and backed by two rotary pumps of 60 cubic meters per hour pumping speed. As an aid to the above pumping lines especially during discharge cleaning, two cryopumps will be used to pump out the gas inside the vessel. Each has a pumping capacity of about 10,000 liters per second for water vapour and condensible hydrocarbons. The cryo cooled surfaces will get saturated after a few hours of operation and have to be then regenerated. For this purpose, two regeneration pumping lines are provided. The four vacuum pumping lines are joined to vessel through 25 cm diameter electro-pneumatically operated gate valves. A low vacuum line runs to evacuate all the interspaces between double viton 'O' rings. A schematic of the pumping system is given in Fig. 4 and the various gas loads of the system and pumping system parameters are given in Table 2.

2.3 Wall Conditioning

The plasma-wall interaction results in a release of impurities from the wall as well as recycling of the parent species[2]. These phenomena are very important and generally very serious if they are not controlled due to the following reasons. The presence of low-Z impurities results in a cold

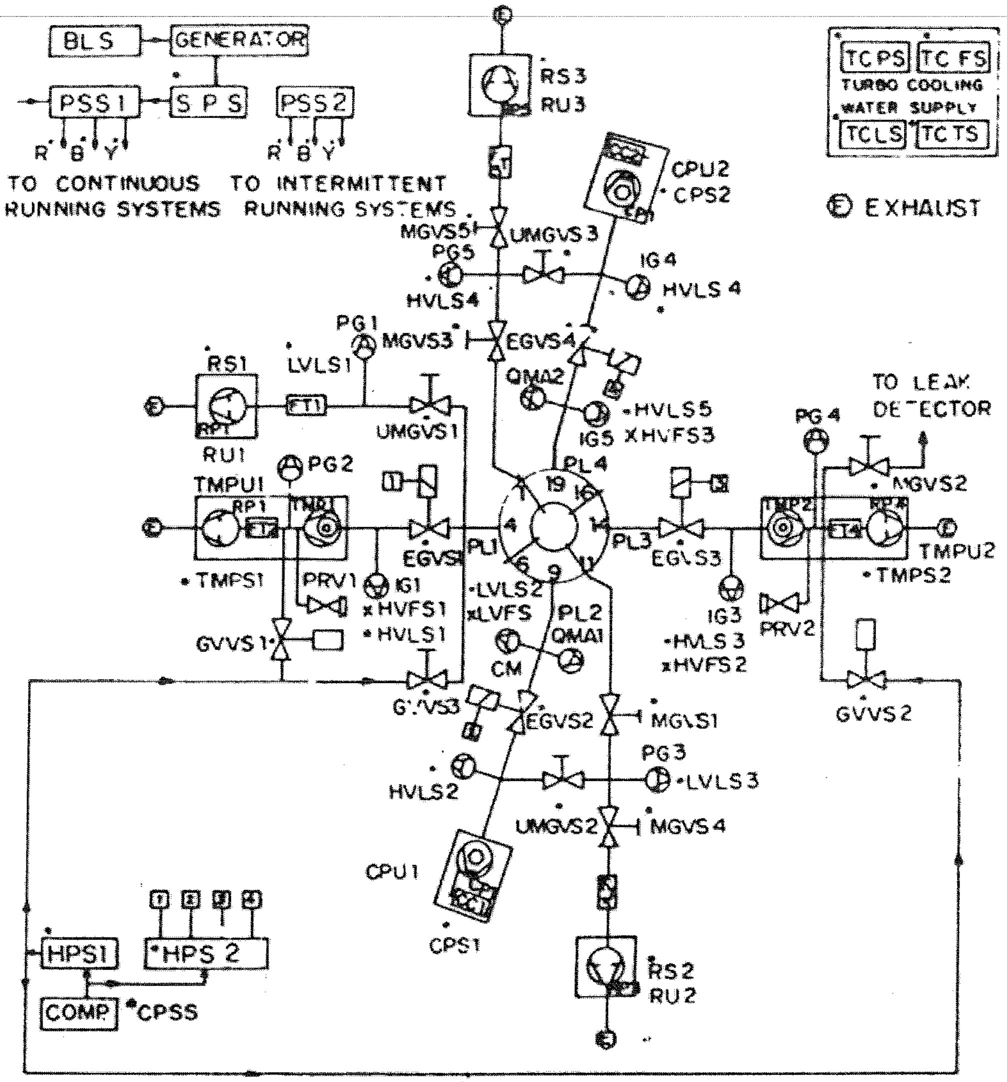


Fig. 4 — A schematic of the vacuum system. Detailed descriptions of units and sensors are given in Ref.(1)

Table 2 — Parameters of pumping system

Pumping speed	$\sim 4000\ \mathrm{l\,s^{-1}}$
Gas load	
Normal pumping	$\sim 2\times10^{-6}$ Torr $\mathrm{l\,s^{-1}}$
Discharge cleaning	~ 2 Torr $\mathrm{l\,s^{-1}}$
Tokamak operation	~ 0.2 Torr $\mathrm{l\,s^{-1}}$
Pumping time constant	
Turbomolecular pumps	
for air nitrogen	~ 1 s
for hydrogen	~ 0.5 s
Turbomolecular & cryo pumps	
for hydrogen	~ 0.8 s
for water & hydrocarbons	~ 0.2 s
Pump down time (from atmosphere to 10^{-6} Torr)	~ 5 h
Cryo regeneration time	~ 5 h
Ultimate vacuum in the vessel (after baking and discharge cleaning)	$\sim 10^{-9}$ Torr

boundary plasma which sets a limit to the operating plasma density due to onset of disruption. If the high-Z impurities are present they radiate away the energy, cooling the plasma. Also it is desirable to have an effective recycling coefficient of less than unity for most modes of tokamak operation so that the plasma density can be controlled by the amount of extra gas pulsed into the torus. The pretreatment procedures are very significantly different for a tokamak device from a conventional UHV system. The various wall treatment procedures for impurity control are: (i) cleaning with mild hydrochloric acid, (ii) detergent cleaning, (iii) electropolishing, (iv) mild alkali treatment, (v) cleaning with distilled water, (vi) blow drying, (vii) ultrasonic cleaning, (viii) baking, (ix) discharge cleaning and (x) special wall preparation. Processes listed in (i) to (vi) are performed prior to assembly of the component in the vacuum system. In the following sections, we discuss the important processes.

2.3.1 *Electropolishing and ultrasonic cleaning*— Removal of microscopic non-uniformities and reduction of outgassing rate are the major motivations behind electropolishing the various components to be used in ultrahighvacuum systems[3]. The anodic process involved in electropolishing leads to a smooth surface. The prescribed electropolishing parameters for tokamak Aditya are summarised in Table 3a. For the large size vessel quadrants, the normal approach demanded a need of a very high current, steady state power supply (20V, 25 kA) and posed the problem of a large increase in temperature rise of electrolyte. To avoid these two problems, a significantly different approach was adopted. Based on tests conducted, a small area moving cathode was made to sweep over the different parts of the vessel's inner surface at a rate of one cycle per minute using a motor and limit switches. The electropolishing operation of a quadrant of the vessel took approximately six hours instead of the normal fifteen minutes but greatly reduced the heating problem.

The ultrasonic cleaning process involving both agitation and cavitation is used for removing the contaminant films on the components to be used in ultrahigh vacuum[4]. Frequency in the range of 20 kHz is ideal for cleaning non-delicate substance like stainless steel. 1,1,1-Trichloroethane is chosen as the wetting agent from the point of UHV compatibility. PZT transducers are used as ultrasonic source. The relevant parameters for ultrasonic cleaning are summarised in Table 3b.

Table 3 – Parameters for wall conditioning

(a) Electropolishing	
Solution	Orthophosphoric acid (64%) Sulphuric acid (12%) Demineralised water (24%)
Temperature of operation	~27°C
Voltage	4-8 V
Current density	~0.2 A/cm^2
Time of treatment	~15 min
(b) Ultrasonic cleaning	
Transducer	PZT type immersible
Power density	~1 W/cm^2
Operating frequency	20 ± 3 kHz
Solution	1,1,1-trichloroethane
(c) Baking	
Temperature of baking	~100°C
Mass of the vessel	~3000 kG
Total power required	~32 kW
Temperature rise time	~2-4 hr
(c) Glow discharge cleaning	
Current density	~20 μA/cm^2
Electron temperature	~5 eV
Anode voltage	350-400 V
Discharge power	~2 kW
Wall temperature	~100°C
Magnetic field	zero or very low (< 100 G)
(e) Pulsed discharge cleaning	
Ion dose rate	10^{16}-10^{18} cm^{-2} s^{-1}
Plasma density	~10^{11} cm^{-3}
Electron temperature	~5 eV
Toroidal field	≤ 1000 G
Discharge power	~10 kW
H_2O dissociation time	~5 ms
Cleaning pulse width	~1 ms
Repetition rate	~10 pulses/s

2.3.2 *Baking*—Baking of the vessel increases the wall outgassing rate and enables to reach the ultimate vacuum in a shorter time. Heating of the vessel using wound tapes (heating element enclosed in a fibreglass coverings) was preferred to resistive heating by passing current through the vacuum vessel wall. Relevant parameters for baking the vessel are given in Table 3c. During the tokamak operation, the baking power supplies will remain totally disconnected from the heating tapes leaving them open to avoid closed conducting loops around the vessel. Baking of the vessel will also be performed during the discharge cleaning processes to increase the rate of removal of wall impurities.

2.3.3 *Discharge cleaning*—Discharge cleaning is an indispensable prerequisite for obtaining plasmas with low impurity content as well as for achieving a low desorption rate from vacuum vessel wall in a tokamak device. It essentially reduces the impurity reservoir on the surface of wall which exists in the form of a thin layer, rich in compounds of oxygen and carbon[5-9]. During discharge cleaning, the desorbed impurity atoms form volatile compounds (gases) like H_2O, CH_4, C_2H_6, etc. and get pumped out of the vacuum system. The discharge cleaning scheme is based on the creation of atomic hydrogen which induce the formation of these volatile gases. In Aditya, a combination of glow discharge cleaning and low temperature pulsed discharge cleaning will be used. The parameters of the two discharge cleaning operations are summarised in Tables 3d & e. Fig. 5 is the schematic of one of the two glow discharge cleaning electrode introduced into the vessel. The electrode is retractable using the UHV flexible bellows.

2.3.4 *Special wall preparation methods*—The technique of impurity control by gettering is adopted in a few tokamaks. Covering the significant portion of the inner surface of the tokamak with an evaporated titanium has been found to dramatically improve the basic plasma parameters and the plasma impurity content. The reduction of the oxygen concentration in tokamak plasma and hydrogen recycling from wall are the prime motivations for the consideration of a gettering scheme for Aditya. However, recent experiments have shown that carbonisation of the wall—essentially coating the vessel wall with a thin film of carbon (diamond), both low-Z materials, improve

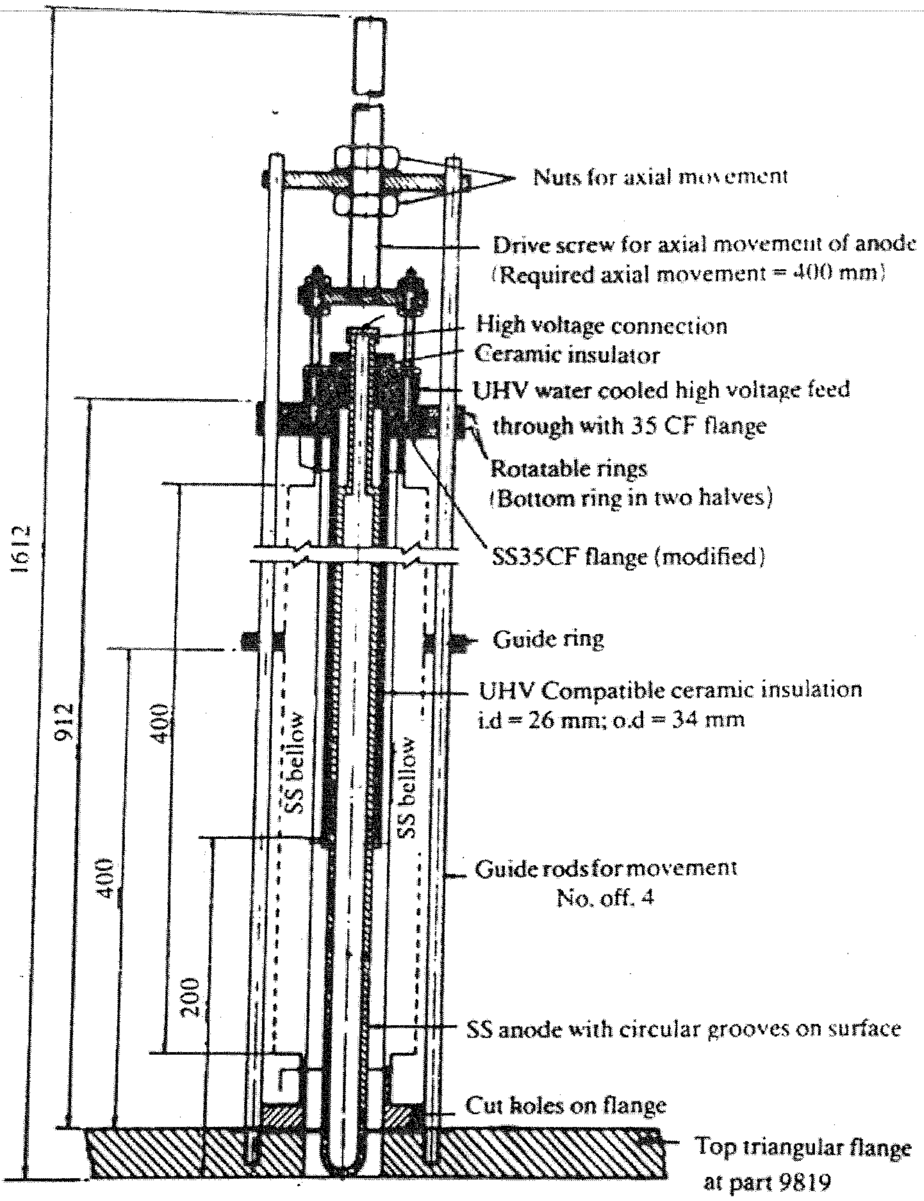


Fig. 5 – A schematic of the glow discharge cleaning anode

the performance of the discharge and reduce the impurity levels. Provisions are made in Aditya for coating carbon by discharge cleaning process performed with a mixture of hydrogen and methane.

2.4 Seals and Joints

Closed copper wire seal is chosen for all the non-standard circular and non-circular joints with flat flanges. Some salient features of this sealing concept are given in Fig. 6. Restrictively, indium wire seal has been used where there are limitations of tightening. At those locations where electrical insulation is required, we have used a double viton 'O' ring joint with the interspace pumped to a vacuum of about 10^{-3} torr. The interspace pumping together with the in-situ baking of viton reduces the outgassing rate by two orders of magnitude from viton.

2.5 Gas Feed System

The Gas feed scheme involves the injection of working gas (generally hydrogen) from a constant pressure reservoir through servo-operated gas leak valves for large rate but slow response filling and through four piezo electric valves for fast response filling. The gas feed system takes care of the fuelling needs of the tokamak device during glow discharge cleaning, pulse discharge cleaning and tokamak operation phases. In the tokamak operation, there are three stages of gas filling: (i) Pre-filling of torus to a specific pressure prior to the initiation of a tokamak shot, (ii) Pre-programmed gas feed for building up of the plasma density and (iii) active feedback control of the gas input to maintain a constant plasma density in the plateau regime. A schematic of the gas feed system is shown in Fig. 7. High purity hydrogen (< 5 ppm) is used as the working gas.

2.6 Limiter

In a tokamak, the limiter is the first material

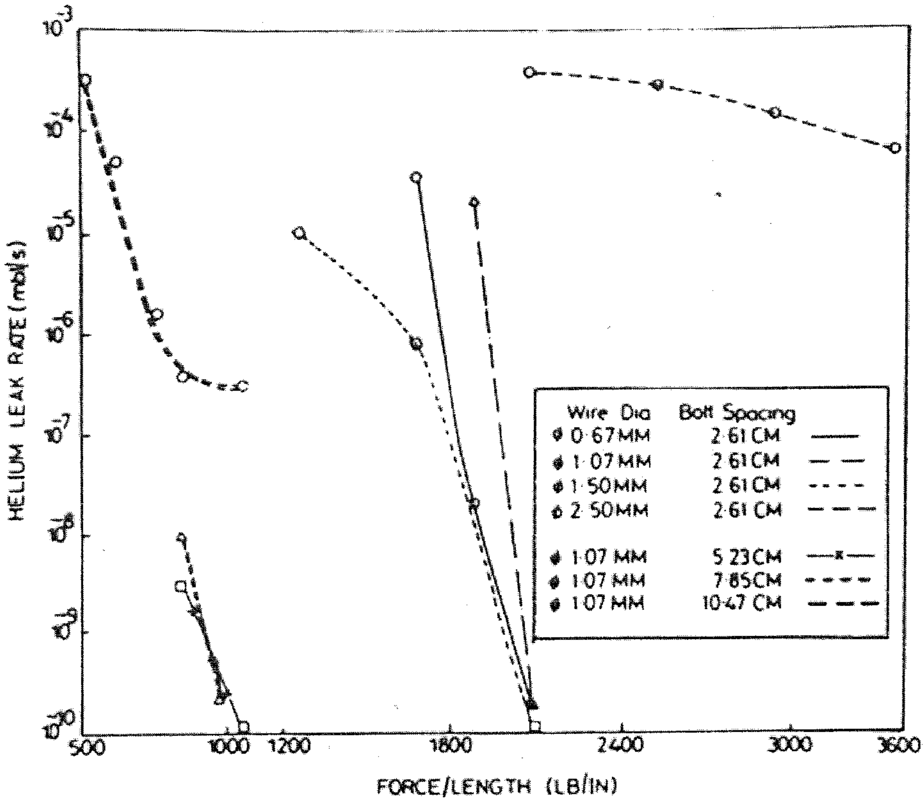


Fig. 6 – Performance of the wire seal joint: Helium leak rate as a function of torque applied on tightening flanges

surface to come into contact with the hot plasma and hence the heat and particle fluxes per unit area falling on the limiter face far exceed that falling on any part of the wall of the tokamak[10,11]. Based on the consideration of impurity generation and heat load withstanding capability, graphite has been chosen as the limiter material for Aditya. Fig. 8 is a plot of particle and heat load to the limiter as a function of the distance from the edge of the limiter for various scrape-off lengths and different shapes. A semi-circular profile for the limiter edge has been chosen from the point of optimum operation. However, the heat loads to the limiter during disruption is quite large as compared to the loads during normal discharges. Repetitive discharges with disruption or runaway phenomena can cause serious damage to the limiter.

Aditya will have two safety limiters, a poloidal limiter and four segmented movable limiters. The locations of the limiters are shown in Fig. 2.

2.6.1 *Safety limiter*—The poloidal view of limiter alongwith the mounting details is shown in Fig. 9. Each safety limiter contains fourteen carbon tiles mounted on two semicircular rings which are joined using alumina ceramic mounts. The safety limiter generally does not receive significant particle or heat load (only the working limiter—poloidal or movable does). In fact, it receives less than 10% of the total energy. It is designed to take the full load in the event of failure of the working limiter to protect the vessel and the components in the shadow of it. The estimated rise of the temperature of the safety limiter is 12°C, if the plasma dissipates its entire energy on it.

2.6.2 *Poloidal limiter*—The poloidal limiter consists of two semi-circular stainless steel rings joined at the midplane of the vessel using ceramic insulators. The insulation between the top and bottom halves of the limiter is to avoid the large electromagnetic forces on it due to the interaction of poloidal currents with the strong toroidal magnetic field. 16 Pieces of shaped carbon tiles are mounted on the ring which face the plasma boundary defining a radius of 25 cm. The poloidal limiter structure is similar to the safety limiter and is mechanically fixed to the vessel at the four corners of the vessel.

2.6.3 *Movable limiter*—Four segmented movable limiters have been designed for Aditya. The top, bottom and outer segments are operated from respective ports using bellows. The inner segment is operated from the top and bottom ports of the adjoining port location. The inner, top and bottom can move from a radius of 20 to 25 cm while the outer can move from 20 to 35 cm. Each segment contains 10 tiles, five facing the ion side and five electron side. Figs 10 and 11 give the details of movable limiters of Aditya. The surface temperature can increase to about 1000°C. All the

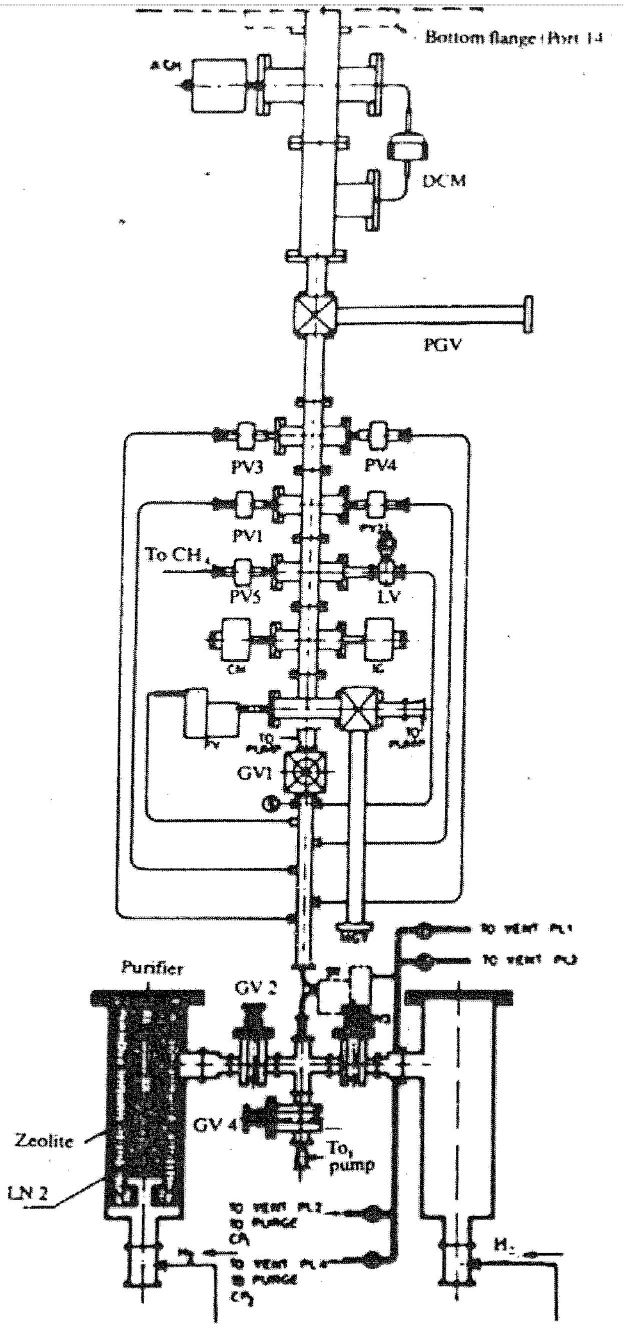


Fig. 7 – A schematic of the gas feed system

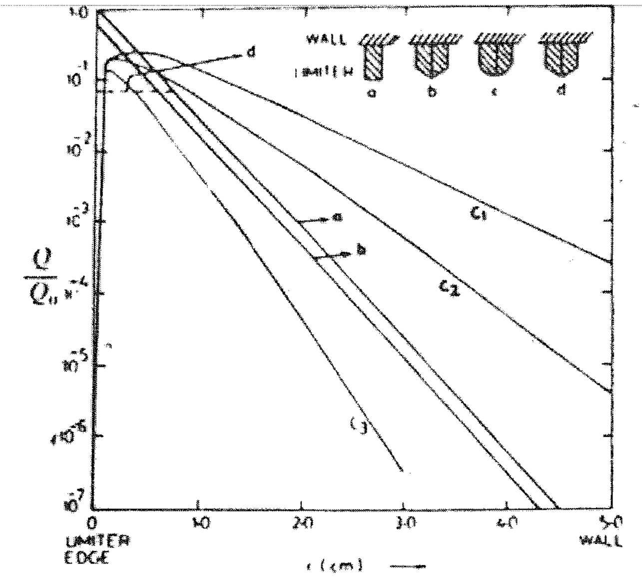


Fig. 8 – Load on the limiter surface

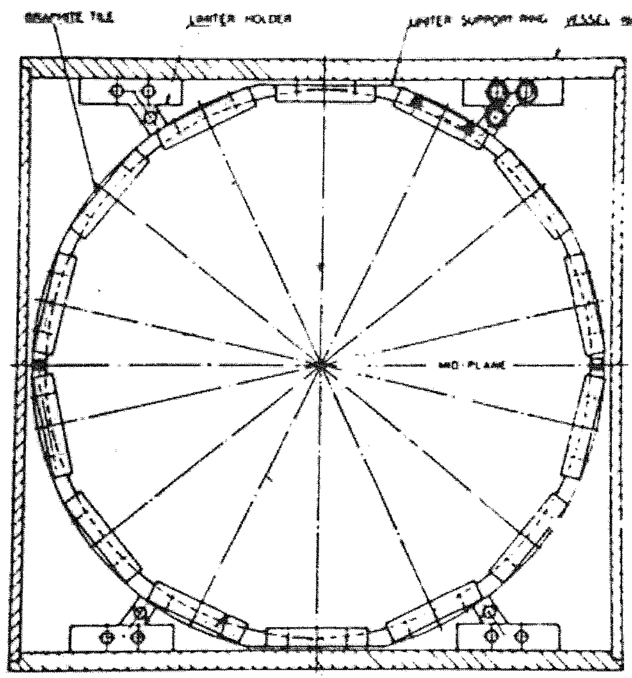


Fig. 9 – Poloidal view of the safety limiter

stainless steel parts of the limiter are electropolished and ultrasonically cleaned. The carbon tiles have been baked at a temperature of 1000°C for 48 hr in vacuum prior to installation in Aditya vessel.

2.7 Vacuum Diagnostics

Background vacuum in the vessel, impurity concentrations and operating gas pressure are primary measurements made by the vacuum diagnostic units. Besides, specific vacuum sensors are placed for vacuum control purposes. Gas flow measurements are made for plasma diagnostic measurements of particle balance. The placement of the Bayard-Alpert type hot-cathode ionisation gauge in the magnetic field environment is a crucial problem because its sensitivity is a strong function of magnetic field value and direction with respect to the gauge electrodes. A very limited use of this will be made during the presence of magnetic fields in tokamak. The capacitance manometers which basically give an output proportional to the kinetic pressure will be used for measurements in the presence of magnetic field. Table 4 presents a list of vacuum diagnostics deployed in Aditya. Fig. 4 gives the locations of the various diagnostics.

3 Magnetic Field Coils and Structure

Tokamak Aditya employs three principal sets of

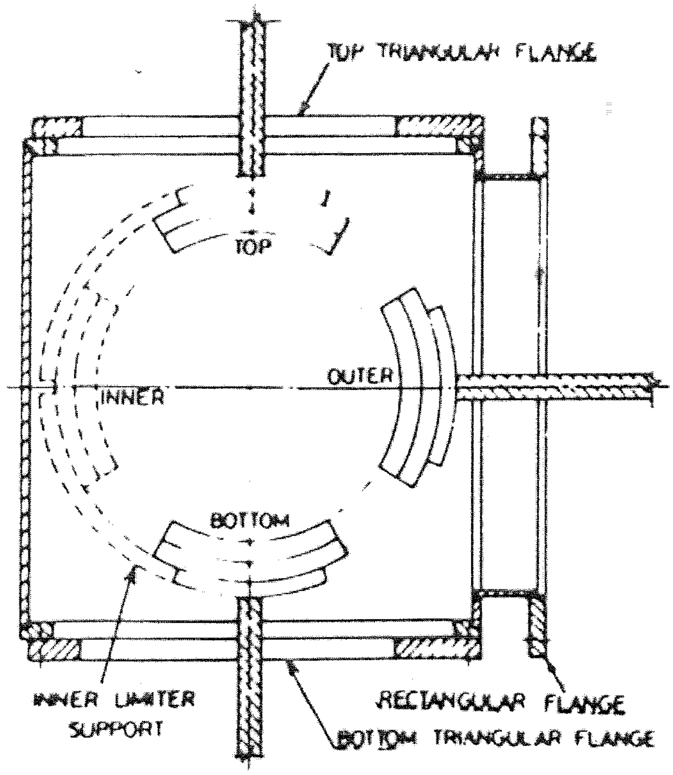


Fig. 10 – A schematic of movable limiters

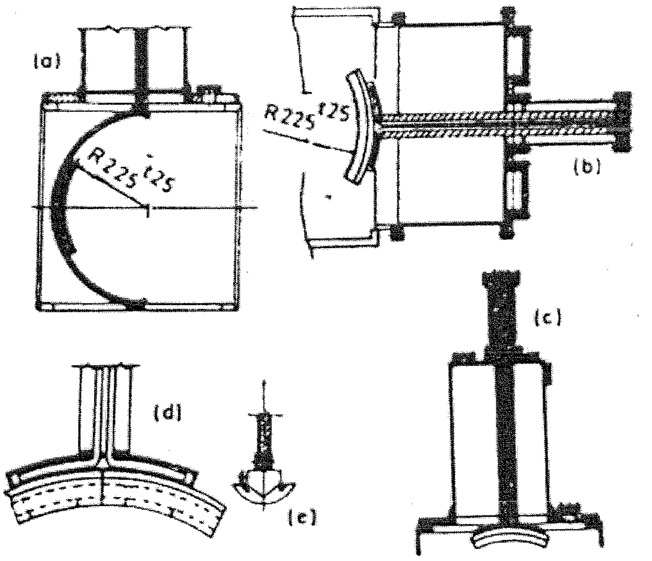


Fig. 11 – Details of the movable limiters – (a) inner; (b) outer; (c) top/bottom; (d) & (e) toroidal and cross-sectional view of the carbon tiles mounted on the limiter holder

magnetic field coils, the TF coils, the TR coils, and the BV coils. The TF coils produce the main toroidal field, the ohmic transformer formed by TR coils produces the transformer flux required to produce the plasma and drive current through it, and the BV coils provide the vertical or equilibrium field that maintains plasma in equilibrium position during the course of a discharge. In addition a set of feedback coils are used to control the plasma position. The magnetic field coils system for Aditya is schematically shown in Fig. 12. The coils have been designed using magnetic field code BARC[12] adopted to run on PDP and VAX computers.

3.1 Toroidal Magnetic Field Coils

The TF coils for Aditya have been designed to produce a magnetic field of 1.5 Tesla at the plasma centre with provision to increase the field to 2.2 Tesla at a later date. The field is produced by 20 numbers of TF coils, each having 6 turns with a current of 50 kA through each of the turns. The field ripple at plasma edge is reduced to $<2.5\%$ by off-centering the coils relative to plasma by 6.5 cm. The coils are of picture frame type having rectangular cross-section. The dimensions and the electric parameters of the TF coils are given in Table 5. In order to facilitate the vacuum vessel assembly each coil is demountable, and each turn is made up of two [sections. Detailed stress analysis showed need to provide generous rounding-off of the corners to prevent large stresses at the corners. The corners of the inner [sections have been given a radius of 9.5 cm while those in the outer [sections have a radius of 8 cm. An inter-turn insulation of 1 mm is provided. The TF coils are cooled by passing chilled water through the cooling tube embedded in and soldered to the sections of each turn. A sketch of the TF coil is given in Fig. 13.

Table 4 – List of vacuum diagnostics

No.	Parameter	Range	Device	Relevance
1	Base pressure	10^{-9}-760 Torr	BA gauge, capacitance manometers	Vacuum system performance
2	Leak rate	10^{-9}-10^{-6} Torr l s^{-1}	Helium mass spectrometric leak detector	″
3	Fill pressure	10^{-6}-10^{-4} Torr	Capacitance manometer	Particle balance
4	Flow rate	10^{-3}-1 Torr l s^{-1}	″	″
5	Partial pressure	10^{-10}-10^{-4} Torr	Quadrupole mass analyser	Impurity level, discharge cleaning performance, outgassing.
6	Vacuum level	Pre-set values	Capacitance manometers, BA gauge, pirani gauge	Level and failure sensors for control

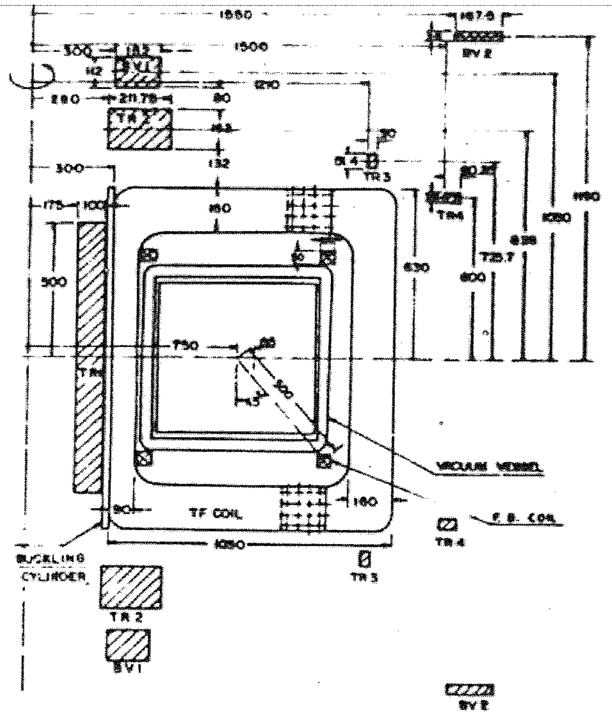


Fig. 12 – A schematic of the magnetic field coils

3.2 Ohmic Transformer

The primary purpose of the ohmic transformer is to initiate the plasma discharge, drive the plasma current to its peak value and maintain it at the peak value for a desired duration. The plasma current forms a single turn secondary of the ohmic transformer in which the primary must induce voltage to drive and sustain plasma current. For Aditya, the peak plasma current is 250 kA and this together with the requirements of breakdown and a flat top duration of 300-500 ms need a total flux swing of about 1.2 V-s in the ohmic transformer. In order to reduce the stresses in the transformer, the ohmic transformer is swung symmetrically from −0.6 V-s to +0.6 V-s and the transformer is, therefore, designed for a maximum flux storage of 0.6 V-s. Large peak voltages ($\approx$ 10-15 kV) are likely to be induced across the transformer during the gas break down phase. The ohmic transformer, while, providing adequate flux linkage to the plasma loop has to be such as to produce a minimum field (< 10 Gauss) near the plasma centre and keep the magnetic field values in the plasma region below 100 Gauss with field increasing away from the centre, in order to ensure the gas breakdown.

The ohmic transformer for Aditya consists of a central solenoid TR1, which produces the required flux and three additional pairs of compensating coils (TR2, TR3 and TR4) in order to minimise the field within the plasma region. The solenoid TR1 is placed in the central bore (Fig. 12) and produces a peak field of 3.2 Tesla within the bore to store a flux of 0.6 V-s. A total of 3.4 MA-turns over 1000 cm^2 are required which is achieved by having 174 turns in TR1 and passing a peak current of 20 kA. Two hollow copper conductors of (1.5 × 1.7) cm^2 cross-section, with 6.4 mm diameter central hole in each, in parallel are used to give an effective cross-section of 4.46 cm^2. The parameters of the coils forming the oh-

Table 5 – Parameters of TF coils

			Design
1.	Width		
	(a) coil	(mm)	1030.0
	(b) inner vertical leg	(mm)	90.0
	(c) outer vertical leg	(mm)	160.0
	(d) horizontal legs	(mm)	160.0
2.	Length	(mm)	1260.0
3.	Radial aperture	(mm)	780.0
4.	Vertical aperture	(mm)	940.0
5.	Thickness of a turn	(mm)	12.5
6.	Inter turn insulation	(mm)	1.0
7.	Resistance:		
	(a) per turn	(μΩ)	42.0
	(b) total	(mΩ)	5.0
8.	Inductance	(mH)	4.0
9.	Max. stored energy	(MJ)	5.0
10.	Peak current	(kA)	50.0
11.	Peak power		
	(a) dissipative	(MW)	12.5
	(b) inductive	(MVAR)	3.0

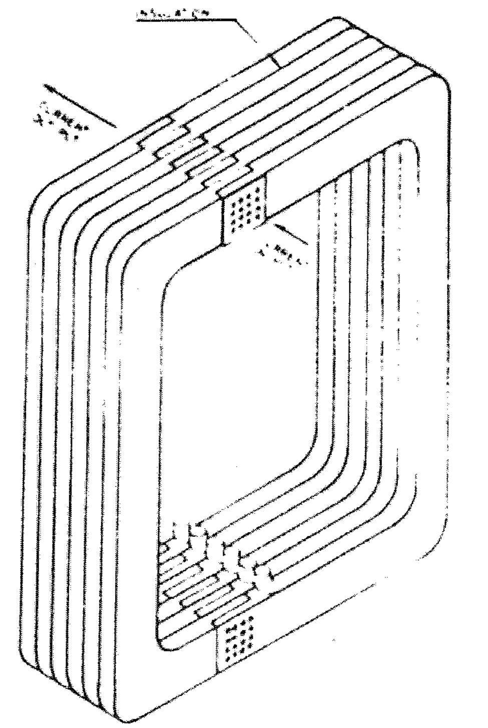


Fig. 13 – A sketch of the toroidal field coil

mic transformer are given in Table 6. The contours of the expected field within the plasma due to the ohmic coils are shown in Fig. 14.

3.3 Vertical Field Coils

To balance the forces resulting from the magnetic and thermal plasma pressures, a vertical field is required. The vertical field B_v required for Aditya is estimated to be 0.4 Tesla per MA of plasma current. A peak vertical field of 0.1 Tesla at the plasma centre is, therefore, required. Further, for stability of plasma against motion in horizontal and vertical directions, the spatial variation of the vertical field should be such that

$$0 \leqslant n \leqslant \left\{1.5 - \frac{l_i - 2}{l_i(l_i + 1)}\right\}$$

with

$$n = (-R/B_v)(dB_v/dR)$$

R being the radial distance from major axis at which the field is B_v. The vertical field for Aditya is generated by means of two pairs of the vertical field coils (BV1 and BV2) each pair consisting of coils placed symmetrically about the mid-plane of the tokamak. The coil parameters are tabulated in Table 6. The coil positions and the ampere-turns in the coil are adjusted such that the field index n lies between 0.4 and 1.2. The inductance matrix of poloidal coils and plasma is given in Table 7.

3.4 Feedback Coils for Position Control

Equilibrium of the toroidal plasma current is provided by means of a vertical field and the vertical position of the plasma is controlled by the index of the vertical field. The main vertical field is programmed to be proportional to the plasma current. The programmed vertical field could differ from the required field due to changes in internal inductance and other parameters of plasma or sudden change in plasma current. In order to compensate for these errors, it is proposed to provide a system of feedback coils placed around the vacuum vessel (Fig. 12) to compensate for error fields upto 100 Gauss. The feedback coils consist of two pairs of coils placed around plasma. Each of the pairs ~~carriers~~ carries current which is equal to and opposite in direction to that in other pair, the absolute direction depending upon the instantaneous position of the plasma, such that the currents cause a force on plasma towards the plasma centre. The parameters of the feedback coils are given in Table 8.

Ca

3.5 Fabrication of the Coils

3.5.1 *TF coils*—The [sections are cut from ETP 3/4 hard copper plate by band saw and ma-

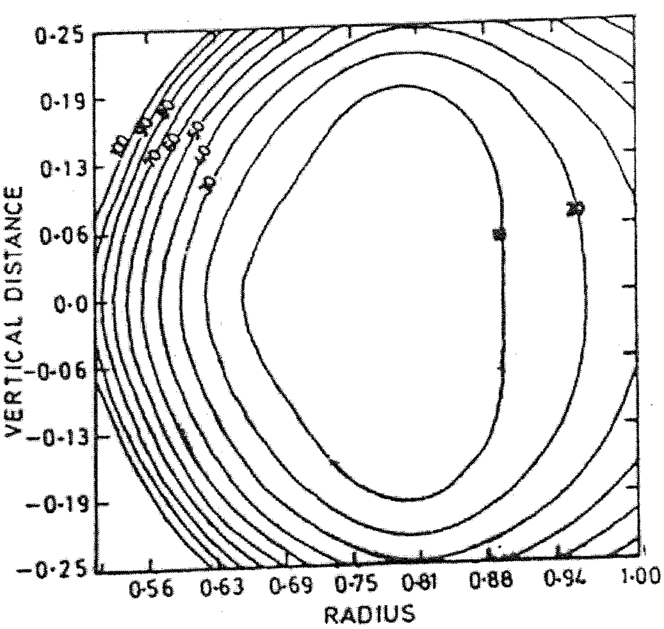


Fig. 14—Contours of the magnetic field within the plasma due to Ohmic coils

Table 6 – Parameters of poloidal coils

Parameter	TR1	TR2	TR3	TR4	BV1	BV2
1. No. of coils	1	2	2	2	2	2
2. Turns/coil	174	56	3	4	60	22
3. Type (Layers/pancakes)	L	P	P	P	P	P
4. No. of layers-pancakes	6	8	3	2	6	2
5. Inner radius (cm)	17.5	28.0	121.0	150.0	30	155
6. Outer radius (cm)	27.5	49.0	124.0	156.0	45.2	171
7. Distance (cm) of coil centre from mid-plane	0.0	± 83.8	± 72.5	± 60.0	± 105	± 119
8. Vertical width (cm)	100	15	3.6	6.04	11.2	3.6
9. Inductance/coil (mH)	5.6	2.2	0.1	0.25	4.0	4.4
10. Resistance/coil (mΩ)	9.4	5.3	0.9	1.5	11.0	17.6

Table 7 – Inductance matrix for poloidal coils and plasma (values in mH)

Coil	TR coils	BV coils	Plasma
TR coils	12.2	4.06	34.7E-03
BV coils	4.06	17.7	23.8E-03
Plasma	34.7E-03	23.8E-03	1.39E-03

Table 8 – Parameters of the feedback coils

1.	No. of turns per coil	4
2.	Inductance of the coils (μH)	256
3.	Resistance of the coils (mΩ)	25
4.	Peak current (kA)	2.5
5.	Peak voltage (V)	200

chined by a plano-miller to achieve the desired shape. Cooling tubes are embedded in the machined grooves and soldered using eutectic solder (63 Sn-37 Pb). B-stage epoxy impregnated fibre glass system has been used as inter-turn insulator. 1 mm thick pre-pregs of this insulator (G-10)have been bonded to copper by suitable pressure cum heat curing method. The insulator bonding is preceded by surface preparation involving chemical cleaning and grit blasting of the copper surface and application of CIBA DZ-80 premier to the surface, to ensure high strength bond. The six sections of each half of a coil along with the interleaving insulation, are wrapped together with epoxy impregnated fibre glass tape and consolidated by heat cum pressure curing. The two consolidated halves are then joined together with the help of stainless-steel bolts dressed in insulation to form a single coil.

3.5.2 *Poloidal coils*—OFHC copper conductors of the cross-section described above, were used for the fabrication of poloidal (TR and BV) coils. While two conductors in parallel were used for TR coils only single conductor was used for BV coils. The conductor was obtained wound on wooden drums capable of withstanding pulling force of 5000 kg. These drums were mounted on suitable mounts with appropriate locking arrangements and the conductor was tension stretched. The straightened conductor was cleaned chemically, grit blasted and dried with dry nitrogen. Immediately afterwards one half lap layer of 0.2 mm thick epoxy mica paper tape was wrapped followed by 0.13 mm thick glass tape. In case of TR coils, this insulation was applied to a group of two conductors while for BV coils only a single conductor was used. The TR1 coil was fabricated by winding the insulated conductor on glass epoxy former. Inter layer insulation consisting of four layers of 0.25 mm thick Nomex paper was used in this case. TR2, TR3, TR4 and BV coils are of pancake type and were formed by winding on a winding former, which was removed after the coils were consolidated. A thin coat of silicon release agent was applied to the winding former for this purpose, which was mounted on a turn table. The insulated conductor was wound on this former in the form of a spiral. After the requisite number of turns, the ends were secured and nipples brazed to the conductor ends. Each pancake was cured individually by passing super saturated steam (160°C) through the conductors. Individual pancakes of a coil were then assembled by providing inter-pancake insulation and insulation packing. Epoxy red gel paint was applied on all bonding surfaces before putting the insulation. The entire assembly was then coated with epoxy red gel and one half lap layer of 0.13 mm thick glass fibre woven tape was wrapped. The coils were finish painted with two coats of epoxy red gel and allowed to dry for 24 hr before testing. After testing for the inter-pancake insulation, the pancake leads were brazed to make series connections.

3.6 Supporting Structure

3.6.1 *Design requirements*—The two main subsystems of the tokamak, namely the magnetic field coil systems and the vacuum vessel with its accessories are independently supported on a mechanical supporting system, primarily fabricated out of stainless steel components. During design and fabrication of the supporting structure, following requirements were kept in mind: (a) the structure must be able to withstand the forces acting on the coils, static and dynamic loads appearing at the time of the experiment; (b) it should provide adequate support to TF coils to relieve any stress concentrations which might arise due to various forces acting on the coils; (c) it should allow for proper positioning and alignment of various coils to the desired accuracies; (d) it should allow easy access to the radial, top and bottom ports on the vacuum vessel; (e) the support should allow for the assembly and disassembly of the demountable section of the TF coils; (f) provide support to the vacuum vessel which is independent of the TF coil support and allows accurate positioning of the vessel; (g) material used have to be non-magnetic and electrical discontinuity within the structure in the toroidal direction has to be maintained.

3.6.2 *Forces on the coils*—The TF coils experience forces (Figs 15a and b) due to the interaction of the current flowing through the coils and the field existing in the tokamak. The in-plane forces result from the interaction of the current with toroidal field. The difference in the in-plane forces at the inner vertical leg and outer vertical leg causes a net radial centering force on each coil, the magnitude of the force being $3.55 \times 10^5 (B/1.5)^2$ N/m per coil. In addition the TF coils experience out of plane forces due to interaction of TF current with the poloidal and the vertical fields. These forces tend to topple the coil and have to be taken into consideration in the design of the supporting structure. These forces have both radial and vertical variations and reverse at mid plane. Displacement, bending moments and stresses in the TF coil due to in-plane forces have been estimated using the model given by Hoffmann and Noterdaem[13]. The estimated stresses due to in-plane forces, for the case of coil supported against a elastic support from buckling cylinder placed in the inner bore are $\leqslant 0.85 \times 10^8$ N/m^2 for a 2.0 cm thick stainless steel buckling cylinder or a 2.2 cm thick FRP buckling cylinder. The out-of-plane forces produce the bending stresses in the copper and shear stresses in the insulation between the neighbouring turns of the coil. The coil is subjected to a maximum overturning moment of $\approx 4.0 \times 10^4$ N-m due to these forces. The TF coils, thus need to be supported against the centering force arising from in-plane forces and against the overturning moment arising from out-of-plane forces.

The forces on the poloidal (TR and BV) coils are: (a) radial hoop force (f_r) tending to expand the circular coil elements and (b) the vertical force (f_z) directed towards the mid-plane of the machine. In addition there are forces of attraction between the individual turns of the coils, the integration of which lead to forces of collapse on the winding. Due to the in-plane forces the conductors in the poloidal field coils (TR and BV) are subjected to radial stress and circumferential tangential stress due to the interaction of current with poloidal field. These stresses are maximum at the inner radius of the respective coils and are well below the yield strength of the material. Thus the poloidal coils have to be supported only against the vertical force directed towards the mid-plane.

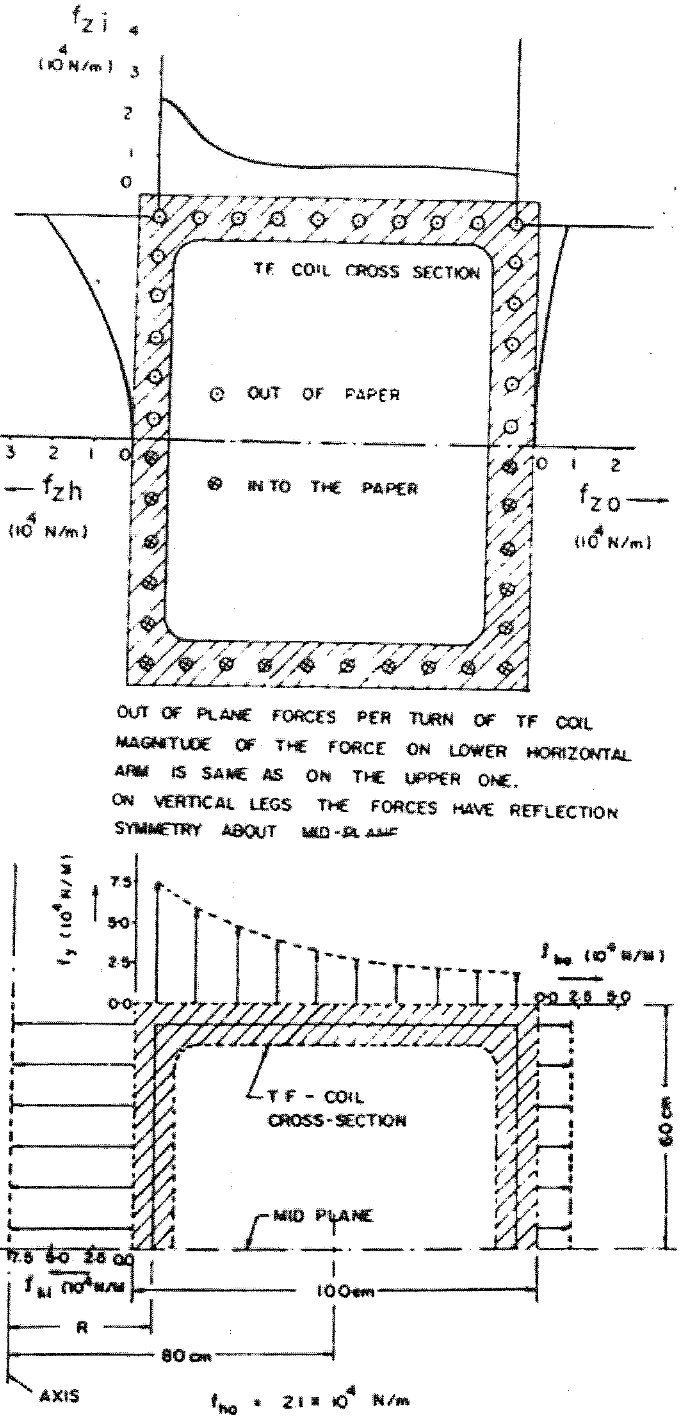


Fig. 15(A&B)—Forces on the TF coils

3.6.3 *Structure description*—An overview of supporting structure for the coils and the vacuum vessel is shown in Fig. 3. The supporting structure has been mainly fabricated out of vertical pillars and radial members at different radial and vertical locations. This allows integration of the whole structure. The vertical pillars are placed at three radial locations. The central support for the auxiliary and main OH coil is built on the inner pillars. The outer, middle and the supporting member on the inner columns are connected by radial members. Each set of pillars are connected by cross members at different heights to restrict their movements against the out of plane forces.

TF coils are sandwiched between the I-beams mounted on the top and the bottom inverted triangle as shownin Fig. 2. The coils are supported against the centering force by the buckling cylinder placed concentrically outside the central transformer. The support against the out-of-plane forces is provided by the wedges (Fig. 16). The vacuum vessel is supported on the four independent columns. The support built on these columns restrict radial and vertical motion of the vacuum vessel and is not effected by the vibrations on the main structure due to the dynamic forces acting during the operation of the machine. The whole structure is grouted to the pit floor with the help of special grouting cement Shrinkomp-H. The deflections of the structural members do not exceed few hundreds of microns at any place. The vertical and ohmic heating coils are directly supported from the radial structural members. The damping distances are optimized to reduce the radial and vertical motion to within allowable limits.

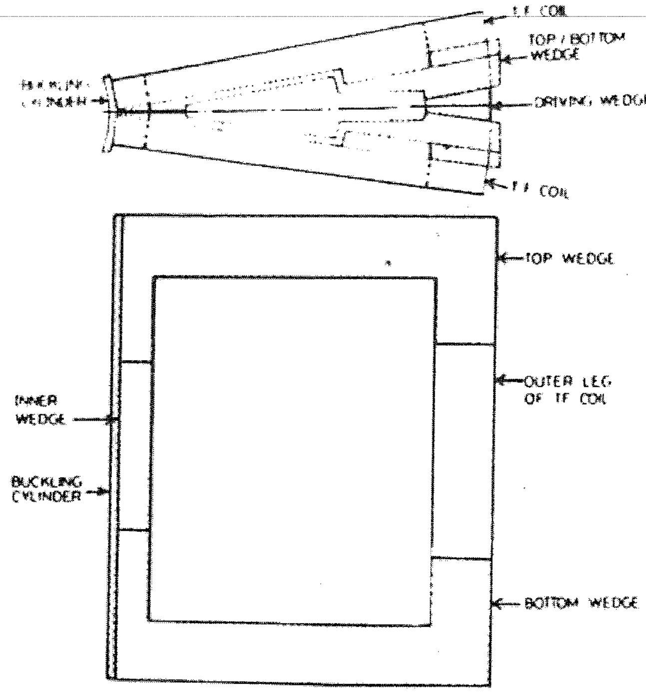


Fig. 16 – Top view of the wedge separating the TF coils

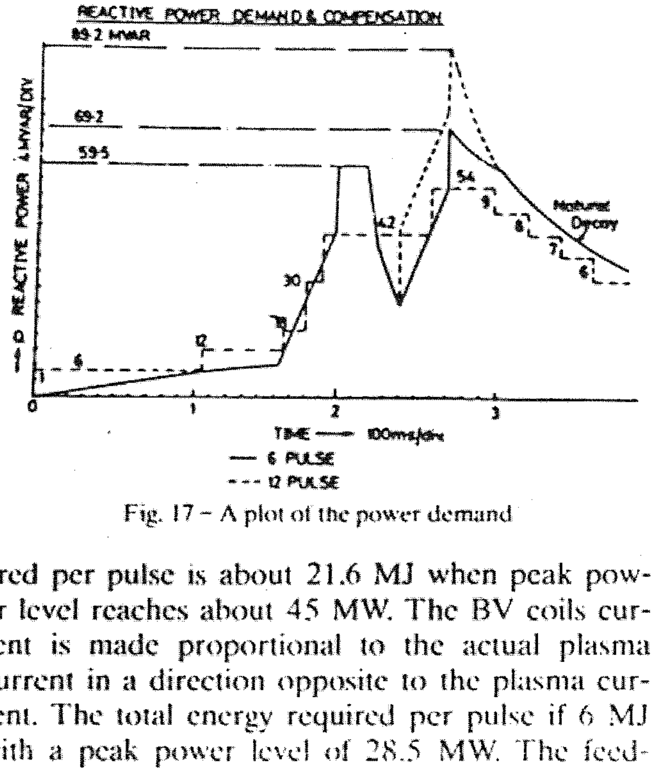


Fig. 17 – A plot of the power demand

4 Aditya Pulsed Power System

The main function of the Aditya pulsed power system (APPS) is to extract electrical energy from the Gujarat Electricity Board (GEB) grid and to generate the current pulses of specified shapes, amplitude and duration. APPS consists of two major sub-systems namely the 132 kV/11 kV substation including the reactive power compensation system and the DC system comprising of the line commuted converters, pulse shaping units and the control instrumentation.

4.1 Power and Energy Requirements for the Magnetic Coils

The electrical loads of the tokamak are the magnetic field coils which are subjected to pulsed operation. For Aditya coils, the operation cycle is 5 s "ON" period and 300 s "OFF" period. Due to the high peak power and energy requirements of each of the coils per pulse, the overall demand for all loads exceeds a peak power level of 50 MW per pulse, drawing more than 60 MJ per pulse when run to full capacity. The TF coils require 5 MJ of stored energy to produce 1.5 Tesla field with a current of 50 kA. The total energy delivered per pulse amounts to 23.5 MJ at a peak power of 15.5 MW. The TR coils carry a peak current of 20 kA. To produce a desired plasma loop voltage and current, an active waveshaping circuit is connected between the dc power converter and the TR coils. The total energy delivered per pulse is about 21.6 MJ when peak power level reaches about 45 MW. The BV coils current is made proportional to the actual plasma current in a direction opposite to the plasma current. The total energy required per pulse if 6 MJ with a peak power level of 28.5 MW. The feedback coils carry current whose direction and magnitude are controlled by the actual plasma position. The coils are fed from a transistor chopper amplifier operated from a dc converter and required to supply peak current of ± 2.5 kA at 180 V. The power demand in MW, MVA and MVAR is shown in Fig. 17.

4.2 Power Sources

The above requirements call for high energy density, high power density sources. The conventional techniques like capacitors, batteries, inductors, etc. are therefore, either less suitable or relatively expansive. Present fusion research facilities use either direct grid power or flywheel-motor-generator sets or both. For Aditya, as all the power requirements can be solely met with grid power alone, all the coils are fed from the power drawn from a 132 kV high tension line. This line is connected to the GEB grid at Ranasan sub-station, requiring a 7 km long single circuit overhead line. When such a direct grid loading is opted for, the capital investment is reduced to only a few major equipments such as incoming circuit breaker and a step down power transformer.

4.2.1 *Substation and reactive power compensation*—The combined schematics of the substitution and the reactive power compensation is shown in Fig. 18 and the operating parameters of the substation components are given in Table9. The incoming 132 kV is stepped down to 11 kV by a 60 MVA (peak) oil natural-air natural cooled, two-winding transformer designed for pulsed duty operation with 5 s on time and 300 s off period. On-load tap changing facility is available for load and line regulation of the 11 kV bus voltage. The nominal impedence of the transformer being 9.24%, it is suitable for fault current limiting of the harmonic overvoltages generated by the dc power converters. The peak power demand is limited to 50 MVA (for 1 s by local capacitive compensation for the reactive power drawn by the coil loads. The capacitor banks are tuned with series reactors to absorb

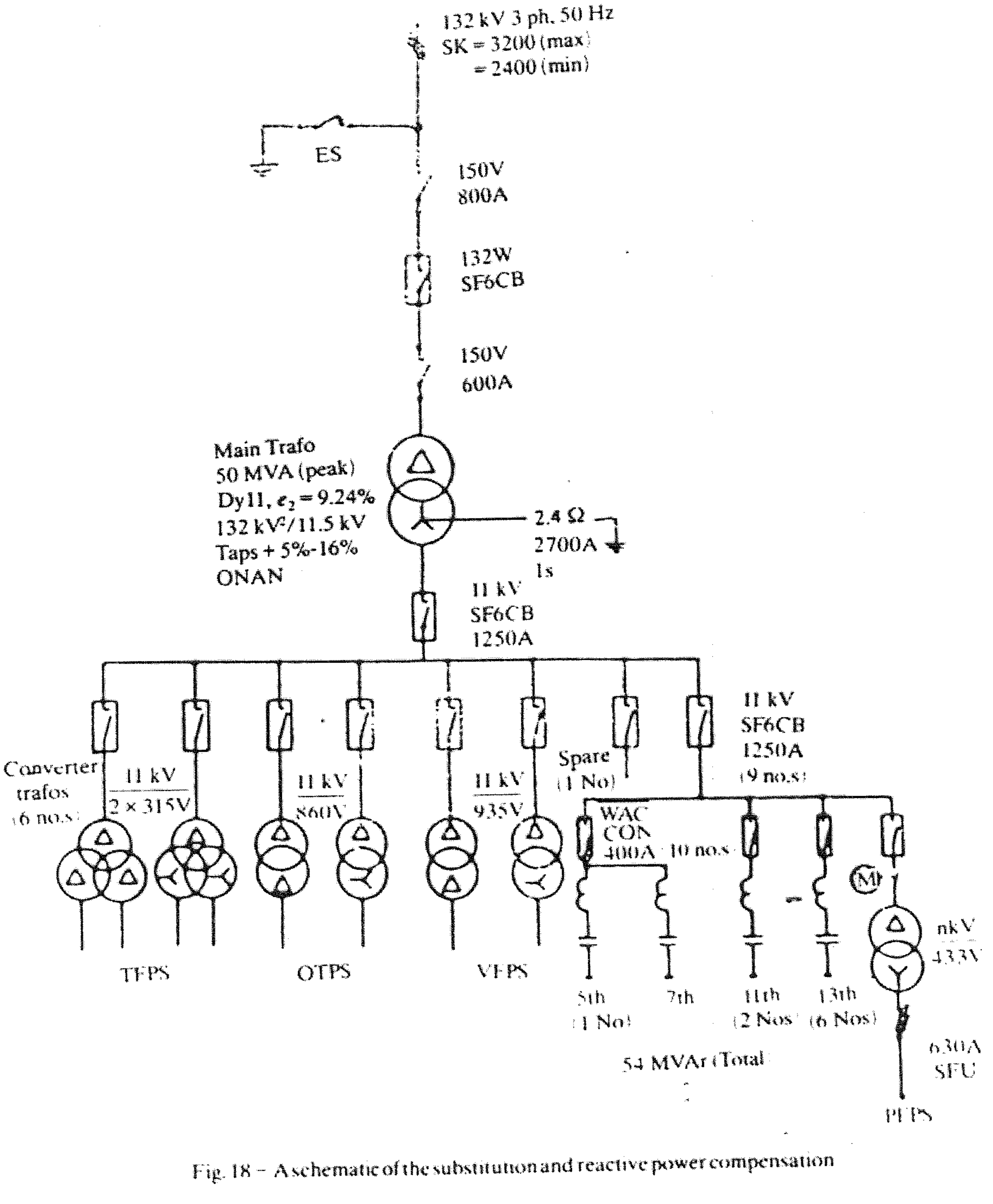


Fig. 18 — A schematic of the substitution and reactive power compensation

Table 9 – Main data for the components of the 132 kV/11 kV substation and reactive power compensation yard

Equipment	Voltage (kV)	No.	Power rating (MVA)		Breaking time (ms)
Step-down transformer	132/11	1	50	(pulsed)	–
			5	(cont.)	
Isolators*	132	2	200	(cont.)	–
SF_6 circuit	132	1	5700	(breaking)	60
			457.3	(cont.)	
Circuit breakers**	11	9	500	(breaking)	60-70
			23.8	(cont.)	
Vacuum contactors***	12	10	66.5	(breaking)	25-40
			10.5	(cont.)	

*One with earth switch.
**For converter feeders. ***For capacitor banks rated for 300 switching/hr.

Table 10 – Data for reactive power compensation harmonic filter banks

Harmonic No. (frequency)	Capacitance (μF) (unit/ph)	Reactor (mH)	current (mA)	KVAR unit/bank
5th (one bank)	109.26	3.713	70.72	152.63/4121
(250 Hz)	(8/ph)			
7th (one bank)	48.66	4.326	50.00	135.60/2034
(350 Hz)	(5/ph)			
11th (two banks)	158.00	0.5878	12.00	153.80/6000
(550 Hz)	(13/ph)			
13th (six banks)	158.00	0.3445	52.00	153.80/6000
(650 Hz)	(13/ph)			

Duty cycle: 3 sec 'ON', 300 sec 'OFF'.
Reactive power capacity: 54000 kVAr at 11 kV, 3ϕ, 50 Hz.
Maximum voltage rise: 11.819 kV

harmonic currents generated by converter operation. The main transformer is normally energised by the circuit breaker only for the period of tokamak operation and is shut down at the end of the day. The capacitor banks (Table 10) are switched dynamically during the shot pulse period by a preprogrammed timing sequence. The transformer and the compensation banks are provided with all standard and recommended protection accessories (Fig. 19), mainly for the overcurrent, transformer differential current, earth faults, transformer internal faults and for overvoltages and unbalance voltage in the capacitor bank.

4.2.2 *dc High current power supplies*—The magnetic field coils are energised by an independent ac-dc converter system. The overall schematic diagram of the dc supplies is shown in Fig. 20. The main data for the converters is given in Table 11. Following is a brief discription of the main features of the supplies.

The TF power supply (TFPS) is designed to supply 50 kA at 294 volts for 1 s with a current rise phase of 2 s and a fall time of 2 s. The supply consists of two 6-pulse thyristor convertor bridges connected in parallel through an interphase transformer to limit the circulating current

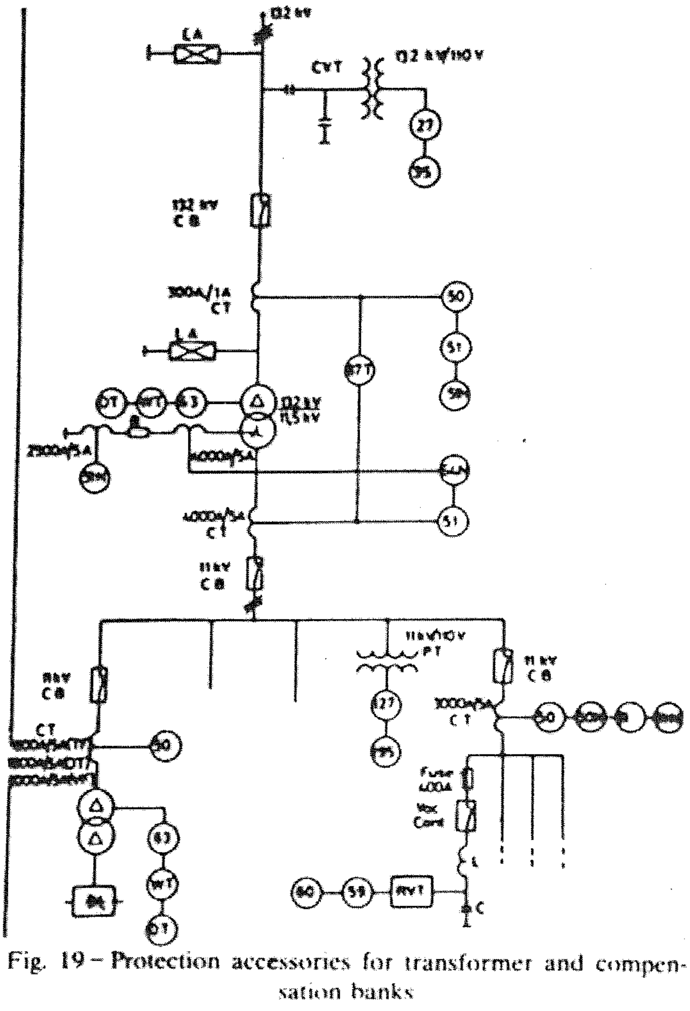
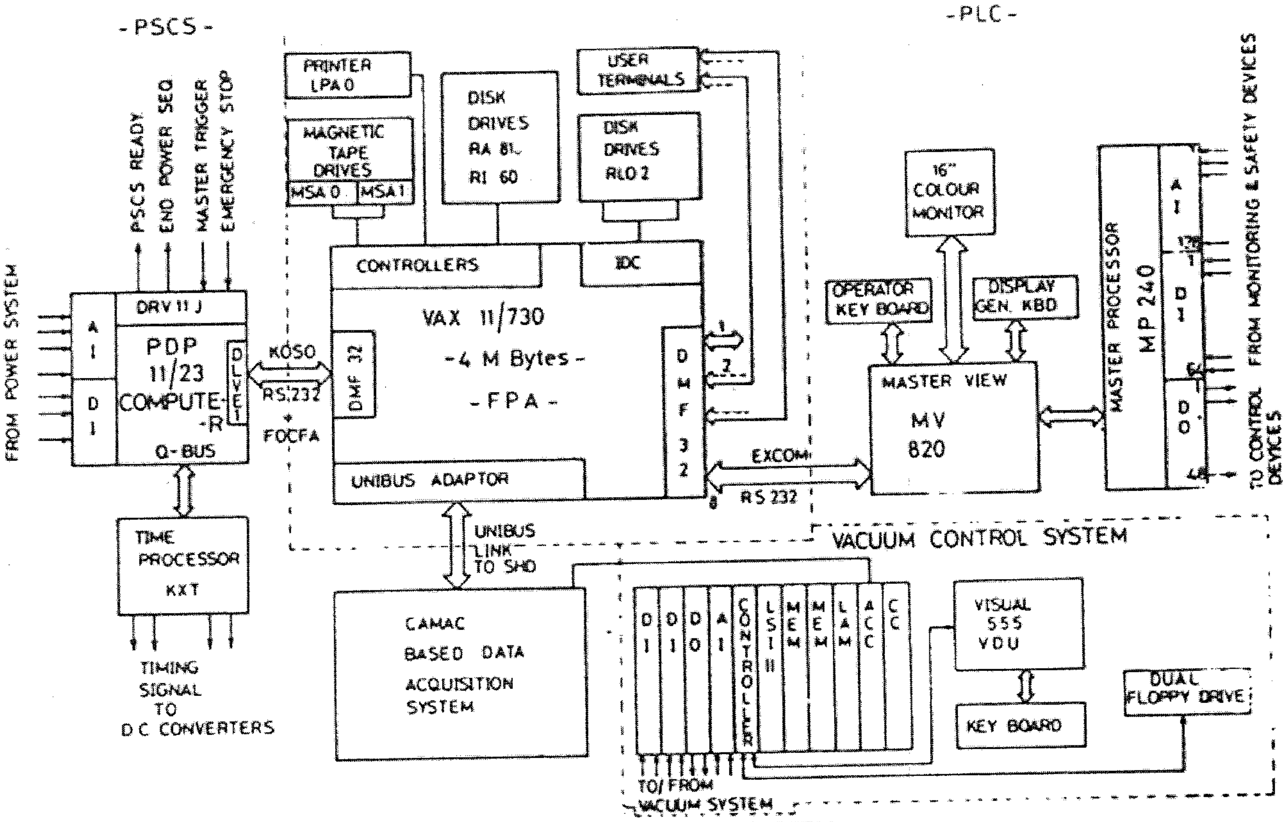


Fig. 19 – Protection accessories for transformer and compensation banks



ADITYA DATA ACQUSITION & CONTROL SYSTEM
(ADACS)

Fig. 20 – A schematic of the DC power supplies

Table 11 – Main data for converter unit

Parameters	TFPS	OTPS	VFPS
dc output:			
voltage (kV)	0.38	2.0	2.4
current (kA)	50.0	±20.0	12.5
Converter data:			
Thyristor type	AEG T1900N2000 (1900A, 2kV)	– AEG T1580N3400 → (1580A, 3.4 kV)	
No. of thyristors	96	96	36
bridge arrangement	4 subunits in parallel 4 bridges in parallel each, 12 pulse	4 subunits (2 in series each direction), 4 bridges in parallel, 12 pulse	2 subunits in series 3 bridges in parallel each 12 pulse
Thyristor cooling	———	Air Natural	———
thyrister protection	Fuse 2000A600V	Fuse 2000A1000V	Fuse 1800A1000V
		Over temp.,AC overvoltage damping	
Transformers data:			
Voltage rating	11kV/2 × 315V	11kV/880V	11kV/935V
No. of units	2	2	2
Cooling	ONAN	ONAN	ONAN
Vector groups	Dd0/Dy1	Dd0/Dy1	Dd0/Dy1
Freewheeling thyrister data:			
No. of thyristers	6	4	6
Arrangement	———	2 in series	———
	———	3 in parallel	———

arising due to the differences in the output dc voltages in the two converter units. The converters are fed by converter transformers connected to 11 kV bus. The converters are controlled to regulate peak coil current within ± 1% of the set value as well as for differences in the transformer ac currents to ensure equal current sharing.

The ohmic transformer power supply (OTPS) for TR coils is designed to supply 20 kA magnetisation current to the TR coils, to reverse the current to − 20 kA in a pre-programmed way within 300 ms and to bring the current to zero in a controlled way after this. The OTPS consists of two series connected 6 pulse converters for both forward and reverse directions. The converters are fed from two converter transformers connected to 11 kV bus. The peak current of 20 kA is reached with 2 kV dc voltage of the converter. The current is then commuted through a selected resistor to develop the loop voltage required for gas breakdown. The commutation is achieved by opening the vacuum circuit breaker using a precharged commutation capacitor switched with ignitors. A peak loop voltage of 50 V can be achieved for initiating gas breakdown. The loop voltage is further controlled to control the plasma current rise by switching resistors and finally a reverse converter to provide opposite magnetisation of the coils. At an appropriate time, the current transition takes place from the forward converter (operating in inverting mode) to the reverse converters through an auxillary current-zero circulating current converter. In this period, plasma current reaches the peak value and a flat top plasma current is maintained. After the current-zero in the TR coils, the reverse converter takes the TR current to − 20 kA and maintains it for 300 ms when the plasma current falls from 250 kA to zero. The reverse converter then goes in the inverting mode of operation thereby bringing the TR current to zero in a controlled manner.

The vertical field power supply (VFPS) for the BV coils is designed to supply a peak current of 12.5 kA for the maximum pulse duration of 600 ms with a repetition time of 5 min. The current in BV coils is required to be raised proportional to plasma current. A 2.4 kV, 12 pulse converter (consisting of two series connected 6-pulse converters) is provided for this purpose. In order to raise the current at fast rate in the plasma current rise phase, a 4 kV pre-charged capacitor is switched in series with the converter. During the plasma current flat top phase, the reactive power drawn by the converter is reduced by bypassing one of the 8-pulse converter units.

The position feedback power supply (PFPS) is designed to supply a maximum of ±2.5 kA of current for a period of 1 s with a repeating rate of once in 5 min. In order to achieve a fast, bi-directional control of the plasma position, a four-quadra-antichopper with a chopping frequency in the range of 3 to 5 kHz is employed to feed the feedback coils. The transistorised chopper is powered mainly from a dc link capacitor, which in turn is charged by a 8-pulse, 180 V bridge rectifier. The power supply incorporates the control system which uses the actual plasma position as input to track the plasma to the reference position.

4.3 Power Supply Protection and Control

APPS is a complex, multicomponent system distributed over a large area and interconnected by cables and busbars. The magnetic field coils are expensive and difficult to access and replace in case of damage. Adequate protection has, therefore, been built into APPS. Protection for overcurrents and overcurrents on both ac and dc sides, thyristor commutation failures, and failure of the auxiliary sources are provided for all the converters. Additionally the current waveshaping components are provided with protection for VCB opening faults, ignitron firing faults and overvoltages on the capacitors and the resistors.

5 Diagnostics

Since the purpose of Aditya is to provide fundamental information on plasma equilibrium, stability and confinement, a moderately high emphasis is placed on diagnostics of the plasma. Development and setting up of standard diagnostics to give information on the plasma quality and to ensure tokamak performance formed the first phase of development of diagnostics. Even these diagnostics are of advanced physics and technology. Future developments include Faraday rotation, pulse height analysis of soft and hard x-ray photons, crystal spectrometry, fibre-optics current probe, visible light tomography and electron cyclotron emission spectroscopy. In the following sections, some details of the diagnostics already deployed are presented.

5.1 X-ray Tomography

Soft x-ray emission from tokamak plasma is dependent on various plasma parameters, viz. temperature, density and impurities. This information can be analysed and related to properties such as electron temperature, plasma position, shape, impurity distribution and magnetohydrodynamic

(MHD) instability phenomena[14-16]. The x-ray tomography system consists of 3 pin-hole cameras placed around the machine to view a poloidal cross-section. Each camera consists of an array of 20 soft x-ray detectors (Ortec Inc. with active area of 50 sq. mm and depletion depth of 100 μ). The hardware consists basically of an isolating gate-valve, a circular aperture pin-hole covered with beryllium foil, to avoid any charge-exchanged neutral and ultraviolet light reaching the detector, a bellow to absorb any vibration being transmitted to the detector array (Fig. 21). The system is electrically insulated from the main vessel and maintained at a pressure of 10^{-5} torr to avoid absorption of x-rays in air. The data acquired from each detector is proportional to the line integral of the volume emission along the viewing chord. These data have to be inverted to get emissivity. A software package is developed to carry out the Abel-inversion and to plot equal emissivity contours.

5.2 Electromagnetic Measurements

Loops of wire or coils of different configuration perform very useful measurements. Details of diagnostics we have deployed are given below.

5.2.1 *Rogowski coil*—Rogowski coil is used for measuring the total plasma current[17-19]. The knowledge of current in tokamak along with the knowledge of loop voltage will provide information about the input power as well as resistivity. This information is also important for controlling the power supply. The former for Rogowski coil winding is made up of fibre glass with square cross-section of 4×10^{-4} m^{-2} and length 0.64 m. The windings (4600 turns) of teflon insulated copper wire and fibre glass former can sustain upto 150°C of baking temperature of vessel. The whole Rogowski is shielded using 0.25 mm copper foil and the signal is taken out through a shielded twisted pair cable to reduce the pick up

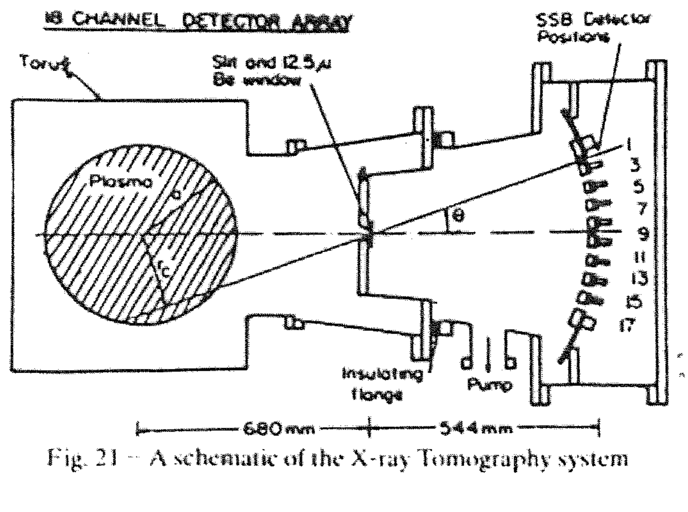


Fig. 21 — A schematic of the X-ray Tomography system

from any stray field. Each Rogowski is rigidly fixed to the vacuum vessel by a SS304 structure. It has flat frequency and phase response upto 1 KHz and is capable of measuring 250 KA of plasma current with a resolution of 1KA. We have deployed 4 Rogowski Coils.

5.2.2 *Loop voltage*—Loop voltage measurement provides information about power input in the plasma, and approximate measurement of plasma temperature in the presence of current information[17,18,20]. It consists of single loop of wire. This loop is placed along the vessel wall in toroidal direction which forms the single turn secondary to the ohmic transformer and measures the voltage induced inside the vessel. To provide redundancy, 13 loops are deployed, distributed at different poloidal locations. All the loops are passing through guiding tubes which are maintaining loop position. The central wire of a shielded coaxial cable RG188 A/U is used as a loop whereas the outer shield is used as an electrostatic shield. The signal is taken through the twisted shield pair cable. The insulation material used is teflon. The maximum loop voltage obtained till now is 42 V (Fig. 22).

5.2.3 *Magnetic probe*—The studies of some of the instabilities such as kind and tearing modes and disruptions in the tokamak plasma are performed through MHD oscillation measurements[21,22]. These oscillations have frequency between 1-20 kHz and amplitude B/B_0 varying between 10^{-4} and 10^{-2}. In Aditya, there are three garlands of 32, 16, 16 Mirnov coils (a short sole-

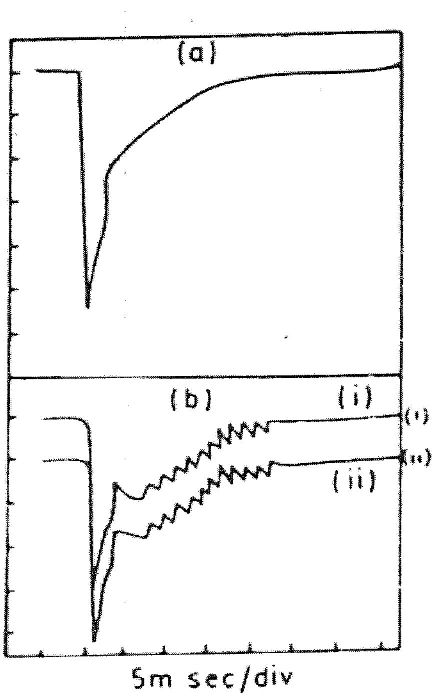


Fig. 22 — A Trace of loop voltage [(a) 2500 V/div, primary flux = 0.35 V-s; (b) 5 V/div, induced flux = 0.3 V-s; (a) Voltage applied in OT; (b)(i) induced loop voltage in loop 3 and (ii) in loop 10]

noid) placed at different toroidal locations and distributed at equal angular separations in poloidal direction. In addition, several single probes are placed in the toroidal direction. This set-up is able to measure poloidal mode number 16 and toroidal mode number 3. Each Mirnov coil has 3×10^{-4} m^2 area and 100 numbers of turns. It has a flat frequency response upto 50 kHz. They are placed inside the vacuum vessel in evacuated housings made up of SS 304L material. The signal from these probes is taken out through 52 pin ultrahigh vacuum feed throughs from top and bottom ports. All the Mirnov coil signals are amplified and noise filtered before they are acquired on a data acquisition system.

5.2.4 *Plasma position measurements*—Two schemes are used for plasma shift measurement[23-25]. The first method requires the measurement of difference of poloidal flux near inside and outside wall along with flux in vertical direction. The second method is new and it involves the measurement of difference signal on the top and bottom of the plasma column along with the horizontal flux with two different loops subtending different solid angles on the vacuum vessel centre. We use four pick-up coils positioned at 45° from the equatorial plane in poloidal direction to measure the flux difference at required positions. The coils are made up of three rectangular loops of cross sectional area 630 cm^{-2} with one turn loop. Two loops are placed at different toroidal but at the same radial position, vertically subtending different solid angles on vessel centre. They measure horizontal component of the field. These loops are made on a fibre glass former and have a copper foil shield. The radial loops have a crossing of wires at middle and effectively form two loops. A schematic diagram of magnetic probes and loops is shown in Fig. 23.

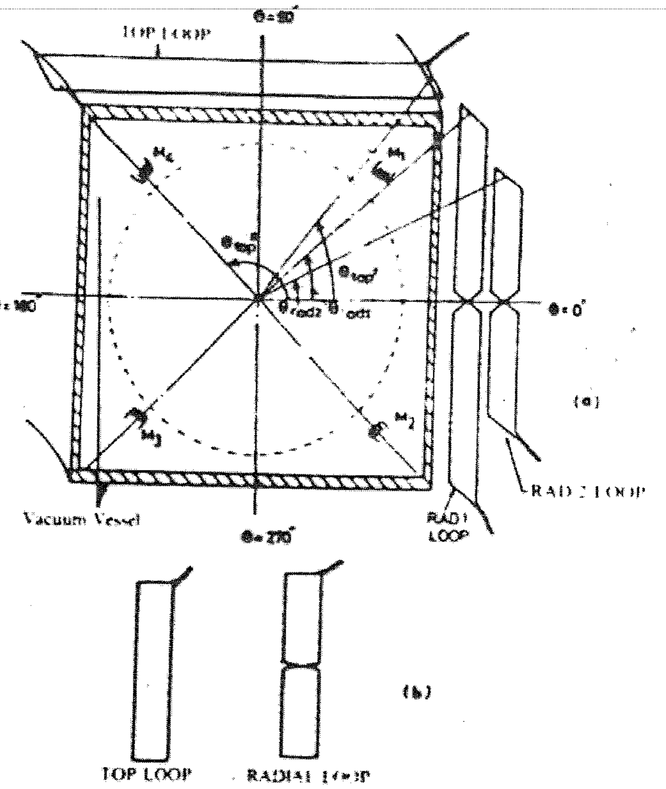
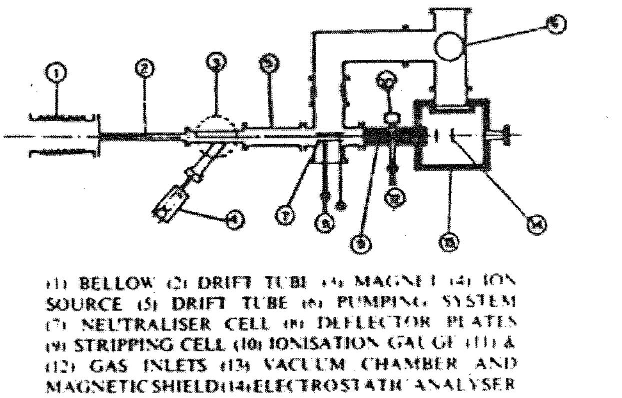


Fig. 23 – A schematic of the Magnetic probes and Loops



(1) BELLOW (2) DRIFT TUBE (3) MAGNET (4) ION SOURCE (5) DRIFT TUBE (6) PUMPING SYSTEM (7) NEUTRALISER CELL (8) DEFLECTOR PLATES (9) STRIPPING CELL (10) IONISATION GAUGE (11) & (12) GAS INLETS (13) VACUUM CHAMBER AND MAGNETIC SHIELD (14) ELECTROSTATIC ANALYSER

Fig. 24 – The experimental arrangement for ion temperature diagnostics

5.3 Ion Temperature Measurement

Hot plasma ions of hydrogen of the plasma suffer charge exchange collisions with neutral hydrogen atoms and molecules. This gives rise to a population of hot neutrals. These hot neutral atoms have the same temperature as plasma and ions can come out of the confining fields[26]. A measurement of energy distribution of these charge exchange neutrals would thus give us ion temperature. Our diagnostic measurement of ion temperature is based upon this principle. The experimental arrangement for ion temperature measurement is shown schematically in the Fig. 24. Charge-exchange system is connected to Aditya through a gate valve, a UHV transition and a bellow. Stripping cell consists of 0.4 cm diameter and 20 cm long hole made in soft iron. This is filled with H_2 gas at a pressure of a few mtorr. The hydrogen atoms passing through the stripping cell is ionized with an efficiency depending on particle energy and operating pressure[27,28] which is stabilized by a feedback control system. The resulting ions are energy analysed in a parallel plate analyzer having ten exit channels. The ions are detected by channeltrons used in counting mode. The pumping system, consisting of a diffstak (3000 l/s for hydrogen) pumps the stripping cell differentially and maintains the pressure in the system at 10^{-6} torr. The vacuum chamber and stripping cell are made of soft iron in order to shield the ions from stray magnetic fields. An ion source developed and fabricated here provides a calibration beam of hydrogen ions upto 5 keV and a few microamperes. The signals from channeltrons are discriminated against noise, counted and stored in a memory module. These counts are then corrected for system efficiency and plotted against energy to yield ion temperature.

5.4 Thomson Scattering

Electrons can scatter electromagnetic radiation. The radiation is Doppler broadened by temperature of the electrons. So the most straight forward and accurate method of measuring the electron temperature of high temperature plasma is incoherent scattering (Thomson scattering) of a ruby laser light[29-32]. Ruby laser Thomson scattering system consists of a 10 Joule Q-switched ruby laser and 1 meter, 10 channel polychromator to measure the electron temperature (50 to 500 eV) and density (3×10^{12} cm^{-3} to 10^{13} cm^{-8}) profiles. Fig. 25 shows the general view of Thomson scattering system. The profile will be measured on shot to shot basis. The density measurement will be calibrated by Rayleigh and Raman scattering. Ruby laser, focussing optics, beam diverting mirror, vertical lens translator assembly, collection optics polychromator and detectors are all mounted on a single rigid trolly structure so that the critical optical alignment is maintained for long duration. The radial (+18 cm to −12 cm) profile of electron temperature and density is obtained by moving the trolly along the major radius of tokamak structure horizontally on wheels on rails and vertical profile (−18 cm to +15 cm) by moving objective lens by means of vertical lens translator assembly up and down. Single trolly structure also helps in alignment between incident and collection optics and calibration of detection system. The laser beam is focussed by 150cm focal length lens at the center of plasma and beam is diverted up by a mirror placed at 45°C to the direction of laser. A set of three stainless steel plates, has knife edge ground circular hole of diameter such that they do not scrape the main beam. They are placed inside the vacuum vessel to reduce the stray light scattered from input optics and vacuum window. There are eleven holes in each plate, with center to center distance of 3 cm. At a distance of 150 cm from the center of plasma a beam dump, consisting of glass filters inclined at the Brewster angle, is placed. The laser beam comes to beam dump through a set of three knife edge baffles. The collection optics for scattered signal consists of objective lens (achromatic lens, $f=60$ cm, diameter = 6.5 cm) which moves up and down by vertical lens translator and two relay lens and one field lens. This optics images scattering volume with unity magnification on to the entrance slit of 1 meter polychromator (minuteman, reciprocal linear dispersion = 8 Å/mm with 1200 g/mm grating). The profile of dispersed scattering signal is recorded by a multichannel detection system which consists of fiber bundle array. Each channel, which corresponds to 20 Å of wavelength of scattered signal, transmits light to a photomultiplier tube. The signal from PMT is processed before it is fed to a 12 channel ADC. ADC are gated two times, once to measure scattered light and next time to measure plasma background light for the same duration as for scattered light.

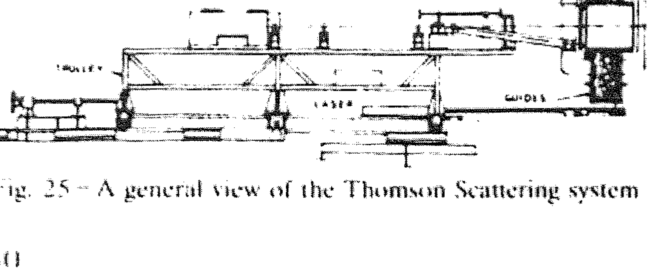


Fig. 25 – A general view of the Thomson Scattering system

5.5 Interferometer

The most common method to measure electron density profile is based on the variation of the plasma refractive index. The technique most commonly used in microwave interferometry measures phase difference between the propagation of electromagnetic waves along two paths of equal length, one thorough the plasma and the second through vacuum. Based on this principle, we have constructed a 7-channel interferometer to measure electron density profile.

5.5.1 *Multichannel interferometer*—A seven chord 100 GHz interferometer is used to measure the radial density profile of plasma where each chord is separated by a distance of 70 mm at the median plane of plasma. A schematic of interferometer is shown in Fig. 26. A 10.5 W extended interaction oscillator (EIO) at 100 GHz is used to give seven pairs (channels)of power by using power dividers. To find the radial electron density profile unambiguously, the EIO source is frequency modulated by a scheme which allows to generate sine and cosine waves at the output of the phase detector alternatively[33-36]. Plumbing components include 23.5 m K-band oversized waveguides, waveguide transitions, variable attenuators and phase shifters. Horns transmit and receive power through high grade bakeable glass ceramic lenses fitted on the cover flange. These lenses act as vacuum windows as well. The phase detectors are made of H-plane Tees, detectors and detector mounts. The output of detector is amplified be-

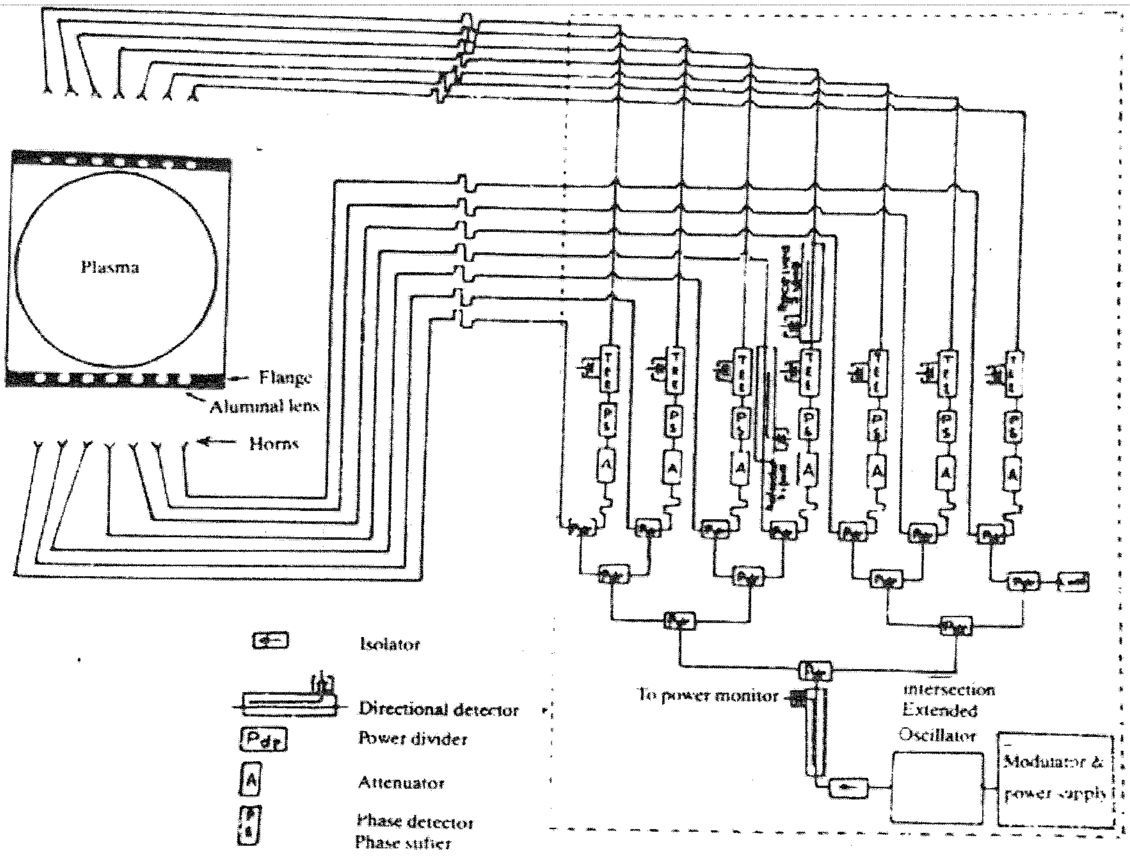


Fig. 26 – A schematic of the microwave interferometer

fore digitization. The digitized signal contains phase information and thus the integrated density.

5.52 *Single channel interferometer*– A single channel conventional microwave interferometer at 136 GHz (which has a critical density of 2.29×10^{14} cm^{-3}) is also used to measure the central chord plasma density by fringe counting method[37]. This will be used for feedback loop of the circuit used for keeping the plasma in an equilibrium position.

5.6 Laser Induced Fluorescence

A scrape-off layer (SOL) plasma is a transition region between the plasma core and wall system of a tokamak. It has a complicated structure and complex constitution and has sharp gradients in electron temperature and density. So we need to employ diagnostic techniques capable of providing a high spatial resolution. We have chosen the techniques capable of providing a high spatial resolution. We have chosen the techniques based on low energy particle beams and laser-induced fluorescence to measure electron density and temperature of SOL. The techniques of low energy (~ 5 eV) neutral atomic beam and laser induced fluorescence[38-41] will be used to measure electron density (10^{11}-10^{13} cm^{-3}) and electron temperature (1-100 eV). Fig. 27 shows the general view of this diagnostic. The neutral beam consists of Li and Al atoms which are produced by laser induced evaporation.

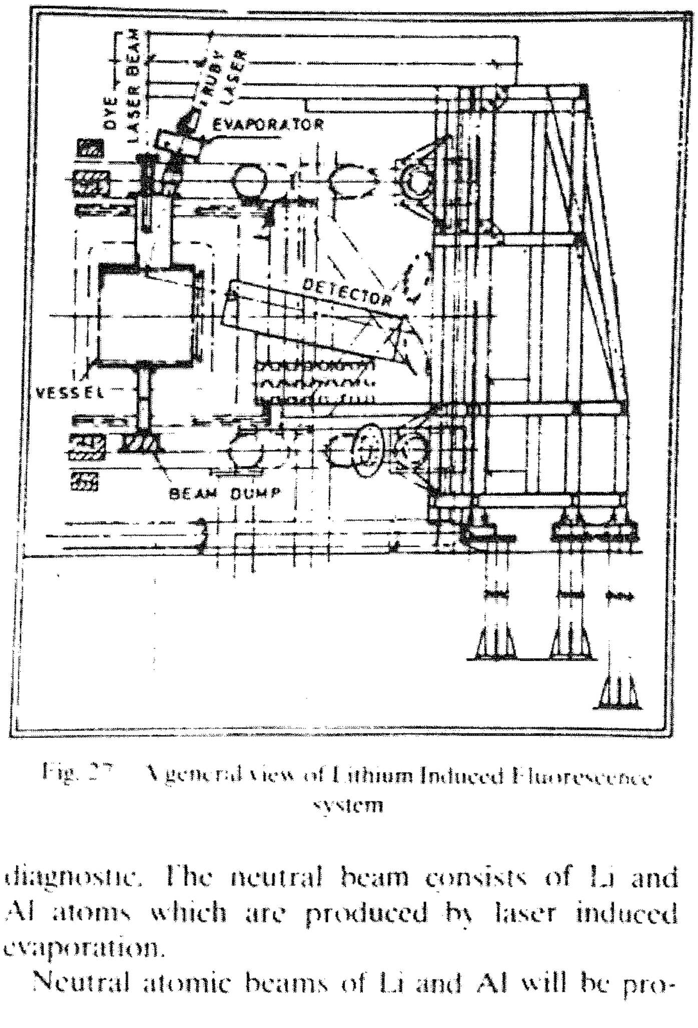


Fig. 27 – A general view of Lithium Induced Fluorescence system

Neutral atomic beams of Li and Al will be produced by laser induced evaporation of vacuum deposited thin films of Al and Li of thickness 0.5 m each on glass slide. A Q-switched ruby laser of about 1.5 J energy with pulse period of 20 ns will be focused by lens on the target from the rear through the glass on to the target for the purpose of evaporation. In order to obtain more number of shots from one target, glass slide will have size of $6\times6\times0.1$ cm and exposed area of 5×5 cm. The target will be moved on a designed translator along two axis inside a vacuum chamber at base pressure of 10^{-9} torr by means of UHV standard remote controlled feed through. The beam source will be optimized on test stand for optimum density and beam energy.

Two flash lamp pump dye lasers with output power of 6.4 kW cm^2 and 20 kW/cm^2, pulse duration of 500 ns and pulse width of 1.5 Å will be used to pump upper excited state of resonance line of Li(2-2po at $\lambda=6708$ Å) and Al (2po-2c at $\lambda=3082$ Å) to a saturation parameter of 160 and 5 for the purpose of measuring local neutral atomic density of Li and Al. We can obtain good signal-to-noise ratio of fluorescence excited by laser and electron impact excitation for plasma upto 8 cm radially in spatial resolution of 0.5 cm. Excited fluorescence will be detected perpendicular to laser by a multichannel detection system consisting of the interference filters and an array of photomultiplier tubes.

5.7 UV and Visible Spectroscopy

The major constituent of plasma (i.e. hydrogen) and the minor constituents (i.e. impurities like carbon, oxygen, iron, etc. present in a typical tokamak plasma) have their emission lines in the wavelength region extending from a few tens of Angstroms in the vacuum ultraviolet (VUV) to a few thousands of Angstroms in the visible. Apart from these line emissions, there is also a continuum due to bremsstrahlung and ion-electron recombination processes. Hence the emission spectroscopy in this region is a rich source of information about the plasma parameters (from absolute, line intensity measurements). These parameters include the number density of species, the electron temperature, the ion temperature, the time evolution and spatial distribution of these parameters.

For Aditya, three spectrometers have been acquired. A visible (VIS) spectrometer (1/2 m focal length, resolution 0.2Ao, 3000-7000Ao), a normal incidence (NIM) monochromator (1 m focal length, resolution of 0.1Ao, 1100-3500Ao) and a grazing incidence (GIM) monochromator (1/2 m focal length, resolution 0.3Å, 50-700 Å). These spectrometers will be used for measurement of many impurity lines and thus for obtaining an estimate of the densities of these impurities. The continuum intensity measured at 5Å, a region free from line emissions, will be used to estimate Z_{eff}. As the impurities in the tokamak plasma are in their highly ionised states, most of their strong emissions are in the VUV. The radiation from the plasma is transported to the spectrometers by a grazing-angle reflection at gold plated mirrors. By controlled tilting of the mirrors under vacuum different chords of the plasma cross-section can be scanned. To protect the integrity of the ultrahigh vacuum of the tokamak chamber, safety features like pressure activated relays and gate valve have been incorporated into the design. Adequate magnetic and radiation shielding for the photomultiplier tubes have been provided for. Absolute intensity measurements of OVI (150, 3834 Å), NV (209, 4604 Å), and CIV (312, 5812 Å) lines and monitoring their time evolution are the initial activities planned.

5.8 Bolometer Camera

For writing a power balance equation, every conceivable energy input and loss must be accounted for and heating rates and cooling rates must be compatible with equilibrium temperatures and densities. Basically we have to measure power losses due to radiation and particles from the plasma. This can be done by deploying sensitive bolometers. The objective of bolometric diagnostic on Aditya is to make temporally and spatially resolved measurements of impurity radiations in a broad spectral range. A bolometer camera is designed to measure radiated power in a spectral range of 2 Å to 5000 Å with a spatial and temporal resolutions of 2 cm and 10 ms respectively. A bolometer element consists of a uniform absorber layer of gold deposited on one side of a kapton foil (thickness = 7.5 μm) and a resistor pattern (R = 4.7 kΩ) deposited on its reverse side. The rise in the temperature of the resistor layer is $\Delta T = 1.3\times10^{-2}$°C assuming an incident power of 1 mW/cm^2 and integration time of 10 ms which leads to resistance change of $\Delta R = 280$ mΩ. This resistance change, related to the power to be measured, can be measured electronically using a bridge circuit. The Aditya bolometers consists of two such foils (or elements) in a common housing fixed one behind the other (Fig. 28). The front foil receives radiation from the plasma. The rear foil is shielded from the radiation and is used in the reference arm of the circuit.

The bolometer camera basically consists of an

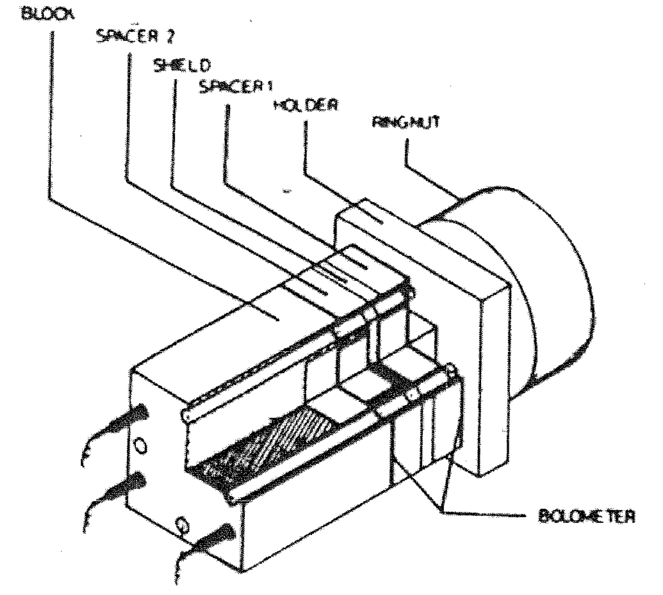


Fig. 28 – A schematic of the Bolometer camera

extension frustrum which is connected with the vacuum vessel. A gate valve on top of the extension frustrum isolates the rest of the camera from the vacuum vessel. A pin-hole flange is connected with the gate valve on one side and a bellows on the other side. The bellow is connected to the camera box (frustrum) which houses the bolometers. The camera box is evacuated to 10^{-6} Torr by a diffusion pump. Eleven double-foil bolometers fixed on a support plate (radius of curvature = 450 mm) are used for measuring radiated power integrated along an observation chord. The chord integrated power (W/cm^2) is then Abel-inverted to obtain local emissivity (W/cm^3) of the plasma in the appropriate spectral range.

5.9 Langmuir Probe Diagnostics

Another diagnostic for measurement of electron density and electron temperature of SOL plasma consists of a simple metal plate exposed to the plasma to collect electron and ion current. This is called Langmuir probe. We are using a number of these probes and its varient called a triple-probe.

The Langmuir probe diagnostic has capability of measuring floating electric potential, electron density and temperature. their fluctuations, and Mach numbers in the scrape-off layer plasma. The probe consists of a graphite tip which is tightly held in contact with a conductor by a cylindrical nut-bolt arrangement made up of machinable ceramic. The ceramic tube is covered by a stainless steel tube and tightly held by a threaded button which goes into a dent made on the ceramic tube. These probes are supported at the flanges on the vacuum vessel and can be inserted and taken out without disturbing the port flanges. Four such probes, separated by 90° allows us to measure electron density and electric field in vertical and horizontal direction. Aditya has one triple probe which allows continuous measurement of electron temperature. We have deployed a movable Langmuir Probe as well. Future development in this area consists of deploying a poloidal garland to yield complete information on poloidal variation of edge plasma parameters.

6 Aditya Data Acquisition and Control System (ADACS)

Tokamak Aditya is operated in a pulsed mode, with 5 sec ON and 5 min OFF period repetitively. To establish a systematic, reliable and safe operation for such duty cycle, complete automation of control, protection and data logging is essential. Aditya, therefore, operates under the control of ADACS, which performs following major tasks:

(i) to monitor and control various sub-systems, and display their status,
(ii) to control the vacuum pressure, gas feed, and various magnetic field during the discharge,
(iii) to provide interlocks, exercise limits on the monitored parameters and initiate partial/complete shutdown in case of the failures or interrupts,
(iv) to provide countdown and initiate various sub-systems for shot, and carry out the shot,
(v) to acquire plasma diagnostics and engineering data during the shot,
(vi) to process part of the data in real time and send feedback signals for plasma control,
(vii) to analyse priority data and display the same to the operator for next shot decisions, and
(viii) to provide necessary mechanism for storage, archiving and retrieval of the data acquired during the shots.

An overview of the ADACS is given in Fig. 29. The control and monitoring functions are distributed between a VAX 11/730 computer, a Programmable Logic Controller (PLC), a LSI 11/23 microcomputer and a PDP 11/23+ computer with the VAX 11/730 computer linked to all other controllers and acting as a master controller. VAX 11/730 computer system is equipped with 4 Mbytes of memory, two RL02 20 MByte disk drives, one RA60 400 MByte disk drive and one RA81 456 Mbyte winchester disk, two CYPHER magnetic tape drives, floating point accelerator, Printronix line printer, a number of alpha/graphic terminals and graphic hardcopy printer. The PLC, procured from M/s ASEA Ltd., con-

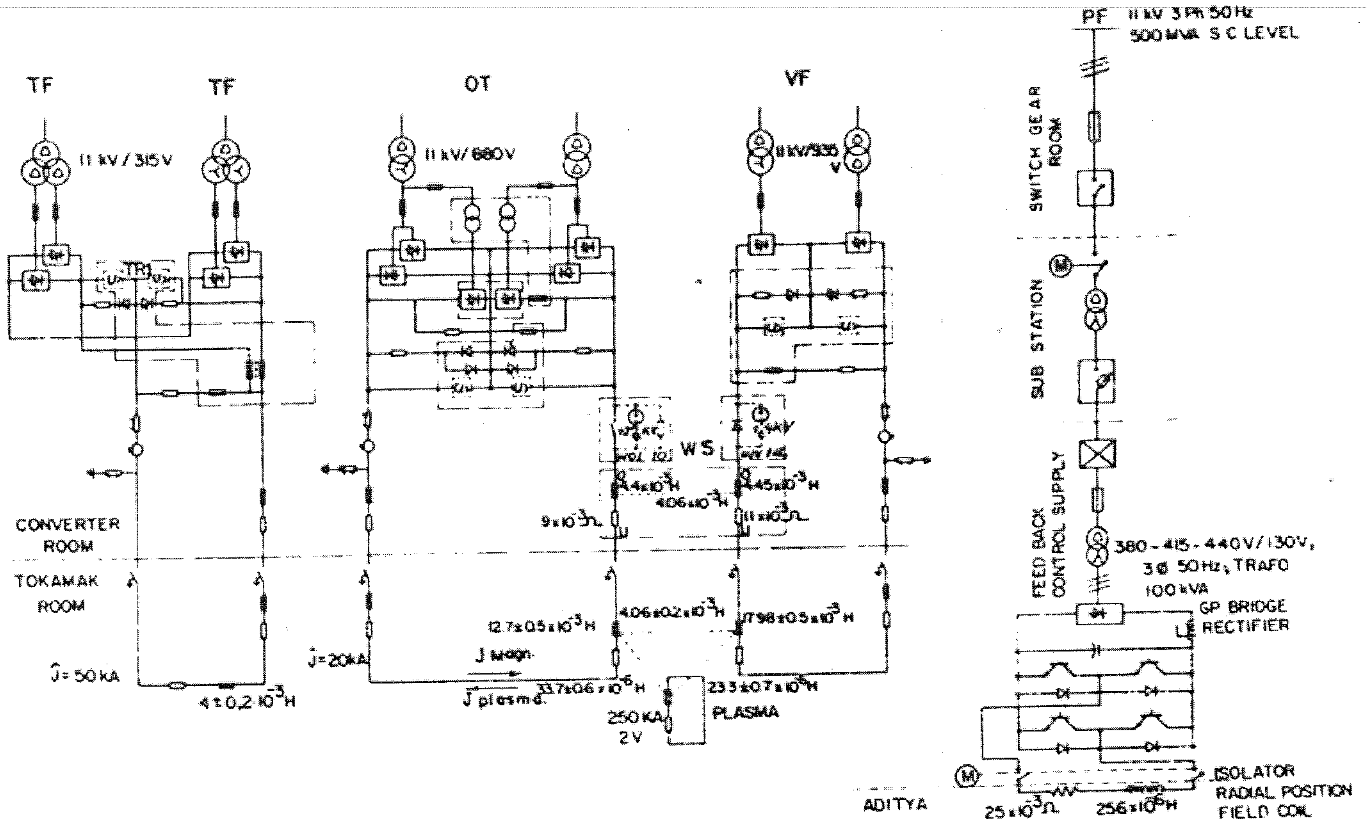


Fig. 29 – An overview of the ADACS

sists of a programmable controller (ASEA Master Piece 240), a Man-Machine communication computer (Master View 820), Input/output modules (Digital & Analog) and System & Application software. The Master Piece 240, can be configured to suit process specific requirements of control and monitoring. Logic elements like OR, AND, NOR, NOT, TIMER, COUNTER, SHIFTING etc. are available as PC-elements. For data handling functions like ADD, SUB, MUL, DIV, ABS, LOG, EXP, COM etc. are available for operation on integer as well as real numbers. It can be programmed with the help of a programming unit. ASEA Master View 820 enables the operator to monitor and exercise control over the system and process concerned, and supports two keyboards, event reporting printer, hard copy unit, 16" colour monitor and external computer communication link. The system is capable of containing maximum of 86 processes arranged in a hierarchy and 20 trend displays. The processes can be either static or dynamic. Input/output modules constitute third major part of PLC. There are 128 analog channels, 64 digital inputs and 48 digital outputs. The analog module accepts 4 to 20 mA current or 0 to 10 volt inputs coming from various transducers. The digital modules have built in 8 bit microprocessors with interrupting facility for fast response. The digital output modules are capable of driving 24 volt DC and 230 Volt AC devices. The status and measurement data of all 112 digital signals and 128 analog signals is presented to operator on 16" colour monitor on demand. The presentation of analog data is dynamic & directly in engineering units on the process pictures at pre-defined locations. Trend curves can also be generated for 240 data points and presented to operator on demand through dialogue. Similarly status of any digital signal can be presented to operator through dialogue on process picture or individually as object display along with the set limits. The violation of set limits or change in status is event listed with time tag and brought to the notice of operator for information and acknowledgement. The PLC is linked to VAX 11/730 through RS232 port and EXCOM software protocol. Any information related to parameters being monitored can be accessed by VAX 11/730 from the data base of PLC through this link. The system is expandable to cater for the future expansion needs. The sub-systems of ADACS are described below.

6.1 Data Acquisition Sub-system (DAS)

The DAS acquires the real time data for various plasma and machine parameters, archives the data along with other essential information and provides for retrieval, analysis and display of the shot data on demand. Ready status of the DAS is conveyed to the main control system for interlocking./The DAS is designed to provide various selectable sampling rates, allow for data acquisition in different selectable time slots, record post and pre-trigger samples, provide a large number of channels, have expandability, interchangability and modularity of the hardware and allow for time synchronisation for pulsed experiments. Computer Automated Measurements And Control (CAMAC) concept has been adopted to meet these requirements. The hardware, shown schematically in Fig. 30), consists of (a) Serial Highway Driver (SHD), Kinetic Systems' 2050, connected to VAX 11/730 computer, (b) CAMAC crates containing digitizers and memory modules, for real time data acquisition, (c) serial crate controllers, timers and LAM encoders for software control of digitizers, (d) trigger modules, digital input and output modules for control and monitoring interfaces and dataway display modules for quick look at Dataway status. The analog signals coming from various diagnostics are passed through signal conditioners and opto-isolators and sent to the digitizers. The digitizers are software/hardware setable for appropriate sampling rate and memory length depending upon the frequency of interest and viewing time interval during plasma discharge. The time synchronisation between the plasma discharge and acquisition is achieved with the help of appropriate trigger signal derived from control process and timer modules. Before the discharge all the digitizers and timer modules are armed for acquisition and the digitizers acquire data as pre-trigger & post-trigger samples when stop trigger is applied/ During the interval between successive discharge the local memory of digitizer is read by computer through the SHD and the data is stored on hard disk for immediate & future processing. All digitizers, memory and time delay generator modules are CAMAC compatible and reside in a various CAMAC crates. Crates provide the physical mounting, the power, and dataway connections to modules. The dataway provides interconnection between modules and crate controller. The crate controllers, residing in the right most slots of each crate, provide hardware link between the other modules and the external highway. All the CAMAC crates containing CAMAC modules are connected on serial highway which is driven by the SHD. The SHD is a interfacing device between VAX 11/730 and CAMAC crate controller and is connected via UNIBUS and mapped into the I/O address space of VAX 11/730. It is operated in byte serial mode for faster data transfer rate of 1 MB/Sec. The interfacing L-2 crate controllers in crates decode the message received from SHD. If it is addressed to a particular crate controller than that controller executes the command and puts appropriate response or data in reply. If the command is not addressed to the crate it passes the message to next crate. The L-2 crate controller is capable of accepting a bit serial or byte serial data, addressing the modules and transfering data and commands to modules, monitoring the interrupt lines Look-At-Me (LAM) and also supporting bypass and loop collapse. The digitizers presently used for various diagnostics are listed in Table 12 along with their characteristics. Any other CAMAC compatible digitizer could, however, be used. The details of allocation of digitizers and selection of sampling rates for various diagnostics are given in Table 13.

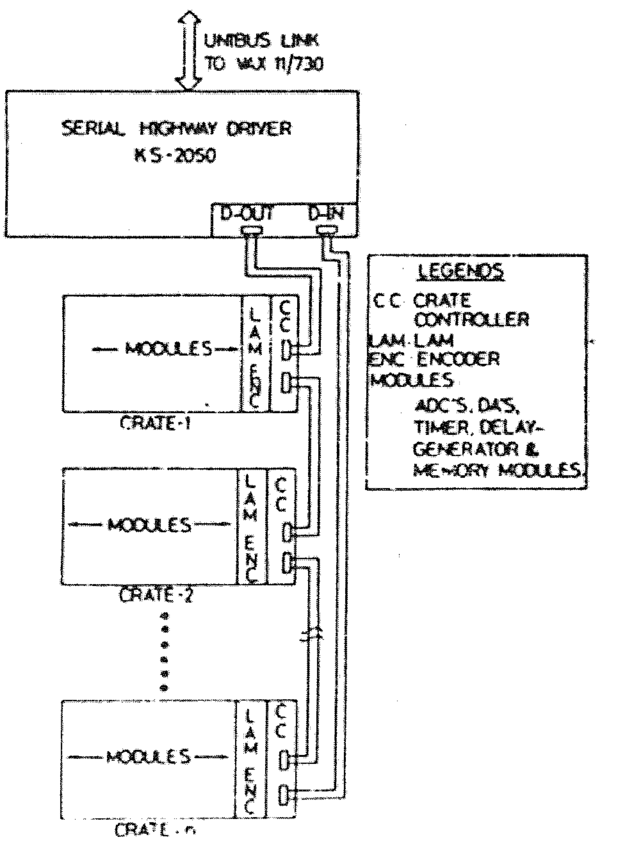


Fig. 30 A schematic of the DAS hardware

The DAS software is adopted from the software packages developed at ORNL, USA and at IPP, KFA, Julich, West Germany for tokamak TEXTOR.

The CAMAC software obtained from ORNL is a general purpose software to interface Serial parallel Camac Highway drivers to VAX computers and includes *system level software* (Device Driver and ACP) & *user lever software* (CAMLIB, CTS & CCL). The software from IPP uses CAMAC software and enables the user to define, set & access any CAMAC module for acquisition and

Table 12 – Parameters of digitisers used with ADACS

Modules	No. of channels	Sampling time	Memory	Input impedence	Input range	Bits	B.W.
LS2264	8	0.25 μS to 25 μS	External Max. 4 × 32 kB	50 Ω	± 256 mV	8	1 MHz
LS8212/8	8	25 μS to 5 μS	External Max. 4 × 32 kB	1 MΩ	10 V	12	50 kHz
LS8212/32	32	-do-	-do-	-do-	-do-	12	50 kHz
LS2256	1	50 μS to 5 μS	Internal 1024 bytes	50 Ω	512 mV	8	30 MHz

Table 13 – Data acquisition channels

Diagnostics	No. of channels (mS)	Acquire time (μS)	Sampling time	Data channel	Total data (k bytes)	Modules
Loop voltage	5	400	100	4	20	IS8212/8[1]
Rogowskii	2	400	100	4	8	LS8212/8[1]
Soft X-ray	2	400	100	4	8	LS8212/8[1]
Soft X-ray	16	400	25	16	256	2 × LS2264[3]
Mag. probes	32	40-100	25	4	128	4 × LS2264[1]
Mag. probes	2	2	2	1	27	LS2256
UV spec.	2	400	25	16	32	LS8212/8[1]
μ-Wave int.	4	400	25	16	64	LS8212/8[2]
Lang. probes	10	400	1000	0.4	4	LS8212/32[1]
Bolometers	20	400	1000	0.4	8	LS8212/32[1]
Limiter	10	400	1000	0.4	4	LS8212/32[1]
Charge ex.	8	400	counter	2	16	LS8590[4]
Displacement	8	400	100	4	32	LS8212/8[1]
Total			141		552	

1: One memory module 8800 to be used with each ADC. 2: Two memory modules 8800 to be used with each ADC. 3: Four memory modules 8800 to be used with each ADC. 4: One memory module to be used with 8 channel counter.

control of the process. Three main modules are included viz. DLG, the Dialog Topology Supervisor, ACQ, the Acquire process and RTR, containing retrieval routines. System level software includes a highway (serial/parallel) device driver, allowing SHD to be treated as computer peripheral, and a CAMAC Ancillary Process (ACP) which provide support for LAM management and CAMAC crate control function. The user level software includes a library of CAMAC I/O procedures (CAMLIB), which provides convenient user-access to the functionality of the CAMAC device driver and/or the ACP, and a CAMAC Topology Supervisor to privileged I/O functions performed by the CAMAC device driver and/or ACP such as defining logical to physical module equivalences and performing crate control functions. CCL supports a DCL like command language to enable a user to control the CAMAC modules either interactively or utilizing command procedures. The program DLG maintains a database of system module names and their *module control blocks* (MCB). Each of the module used in the acquisition task is assigned a logical name which translates to a SYSTEM logical name and ultimately to a PHYSICAL name in terms of the crate number and station number at which the module is located. Further for multichannel modules each channel is given a logical name. Any of the modules and the channels within the modules can be made online/offline for any shot through DLG. Other operational parameters can be set for all the modules and their channels through DLG acquisition task ACQUIRE. The data acquisition process ACQ is used for the acquisition of data by the modules and for storing the data in files. The logical program flow of ACQ is controlled through DLG which provides the actual configuration of all modules tobe included for acquisition. In practice there can be a number of data acquisition processes for various diagnostics or groups of diagnostics. The ACQ timing is controlled by two external hardware triggers. The first trigger, the start trigger, indicates that thenext shot is about to begin, and activates the ACQ processes. Upon receipt of the second trigger, the stop trigger, the data acquisition modules obtain the pre- and post-trigger samples and then stop sampling. All the data are then read and are put into corresponding files (one file for each ACQ process) and the files are closed and made available for the user access through retrieval (RTR) routines. The RTR software consists of a set of subroutines whichprovide an easy access to the shot data stored in various files by ACQ processors. A user program can incorporate calls to retrieval routines to get data for a given shot and a channel.

6.2 Vacuum Control System (VCS)

The VCS ensures reliable and effective functioning of the vacuum system for achieving UHV conditions in the vacuum vessel. It enables conditional startup/shutdown of the pumping system, monitors the vacuum system interlocks, initiates appropriate action on fault conditions, and indicates the status of the vacuum system. The pressure data is logged at regular intervals and Residual gas analyser (RGA) data can be acquired on command from the operator. The VCS is based on CAMAC system and command from the operator. The VCS is based on CAMAC system and utilises LST 11/23 microcomputer, with 64 kB memory, floppy disk controller, quad serial port and real time clock, housed in a CAMAC crate. Other modules in the crate include 24 bit change of state input modules, 24 bit output registers, ADC and DAC modules, Auxillary crate controller for LST 11/23 computer and L2 type controller for interfacing with main serial highway linked to VAX 11/730 computer. The peripherals are Dual floppy drive RX02, Visual 550 Alpha-Graphic console cum operator terminal and 180 cps Data South dot matrix printer. The system software include RT11 operating system, foreground-background monitor, fortran IV compiler, CAMAC driver and fortran collable CAMAC subroutines. The application software displays vacuum process panel on the monitor screen and runs two processes TURN & MONITOR in foreground background mode. The process TURN displays sensor status, enables interactive DIALOG mode, checks the validity of the DIALOG command, calls and displays error condition (if any) and enables conditional turning on/off of any device. The process MONITOR monitors status of all devices and performs follow up action as per predefined conditions. The VCS links to the main control system through hardwired VACUUM-READY/Failure signals. Designed to run 24 hours a day the VCS runs on a uninterrupted power system with battery and diesel generator backup.

6.3 Power Supply Control Sub-system (PSCS)

The PSCS monitors the power system, generating ready/fault status displays the power system status, runs the power supplies as per the input data, acquires the current and voltage data in various coils during the shot, calculates the power consumption during the shot, displays the selected data on request and transfers the selected data to VAX 11/730 computer. The PSCS hardware consists of a PDP 11/23 + computer system, a VT240 console/operator terminal, a time processor (KXT-11) on PDP Q-bus and PLCs controlling individual convertors. Peripherals include a dual floppy disk drive, a winchester disk, and a console printer. For analog outputs the PSCS has a combination of DMA interface with D/A converter and time multiplexed scanner unit. For analog inputs similar arrangement with A/D-converter exists. In addition for supervision of hardware alarms and test points three interfaces with 64 programmable I/O lines are available 16 of which can be used in interrupt mode. The operating system is RSX-11 M and application software allows the PSCS to operate inone of the following four modes:

(1) full power supply control without connection to main control system (*Stand Alone Mode*).
(2) full power supply control under commands from main control system (*Slave Mode*),
(3) mode for display of all control or monitored data, transfer of data to VAX 11/730, and data file management (*Data Mode*), and
(4) individual monitoring and control of all the process I/O signals (*Test Mode*).

The PSCS is linked with optical cable to VAX via an asynchronous serial interface (RS232 port) and communication software (*KOSO*) on both sides allows to and fro data/command transfer. The PSCS is further linked to main control system through four hard wired signals. It sends 'System Ready' and 'End of Power' sequence signals to the main control and accepts 'Master Trigger' and 'Emergency Shut' signals from it. The PSCS provides for safe operation of the power system and checks for faults at four levels taking appropriate action in each case. The fault levels and actions initiated at each level are listed in Table 14.

6.4 Machine Monitoring Sub-system (MMS)

The MMS aims at continuous measurement of critical parameters and conditions necessary forthe Tokamak operation (other than those of power supplies and vacuum system, which are separately monitored as described above) and take fast and automatic control measures. Several critical parameters, like temperature on the surface of the coils, temperature and flow rates of water in the cooling paths of the coils, earth faults in coils,

Table 14 – Protection levels for PSCS

Level	Faults	Actions initiated
1 Major fault	Feeder overcurrent Feeder shortcircuit Converter door open Tokamak door open Emergency off in main signal panel Main CB off during shot 132 kV line failure (to indiv. conv.)	Trip of main CB. Fly wheel all converters. Trip all individual CB. Singla to main control
2 Major fault in one power supply	Emergency off in aux panels Indiv. CB off during shot Pulse failure during shot/test phase Transformer Buchholz/oil temp/oil level trips Converter thyrister fuse/overtemperature Flywheeling I-WT or surge diverter current Earthfault of coils	Trip pair of CB. Signal to main control "converters not ready" till faults cleared (to rest of converters) put to level 3
3 "Stop" signal	Hardwired stop from tokamak/control room Aux. conv. fuse Flat top not reached Charging unit failure Vac. C.B. not cleared	Impulses at $\alpha = 90°$ Block waveshaping Close safety switch Charging unit OFF Cap. discharge ON Signal to main control "converter ready" for next shot
4 Warning	Converter burden fuse Aux. conv. fuse Charging unit failure transformer Buchholz/oil temp/oil level warning	Pulses blocked for the *next* shot till all warning signals off Signal to main control "converter *not* ready"

Table 15 – Aditya monitoring system

Sr. No.	Critical conditions	Measurement	Sensor
1	Overheating of field coils due to cooling system	Temperature of coil insulation and that of cooling water type	RTDs (surface & insertion)
2	Failure of cooling system	Flow rate monitoring or limitcheck meters or flow switch	Venturi flow
3	Buckling cylinder failure	Displacements of the cylinder	Linear potentiometer
4	High stresses in structural members	Strains (linear bending & torsional)	Strain gauges
5	Shorting of coil turns leading to decrease and assymmetry in the magnetic field	Voltage drop across each coil	Voltage divider & comparator

displacement of the coils and structure members and strains on the structural members, are measured. Table 15 summarises the critical conditions, measurements required and type of sensors used. The physical parameters are converted to electric signal using appropriate sensors and the output is converted to industrial standard 4 to 20 mA loop or 0 to 10 volt signal. The signal is fed to PLC which is then used to monitor, generate alarms, and take appropriate action if the parameters exceed the pre-defined limit.

6.5 Diagnostics & Gas Feed Control System (DGCS)

The DGCS caters to the needs of, on line controls required for certain diagnostics, monitoring the ready status of the diagnostics for a shot, giving start-of-shot signals to some diagnostics, initial and pre-programmed gas feed for the shot and dynamic density control using feedback gas feed control. Pressures in various diagnostics and the vacuum vessel are monitored to generate conditions of opening gate valves connecting the diagnostics-systems to the vacuum vessel. Ready status of essential diagnostics and the vacuum vessel pressure and impurity levels, are interlocked for Master Trigger signal and status of other diagnostics is recorded. Analog and digital inputs and digital outputs of the PLC are used for this purpose where appropriate logic resides.

6.6 Personnel Monitoring & Safety Subsystem (PMSS)

The PMSS consists of various door-interlocks controlling personnel entry in the Tokamak hall. Digital inputs to the PLC check for the No-Entry conditions before allowing start-of-shot. Closed circuit TV cameras allow operator a view of the hall. Emergency stop switches installed in the hall, power room, the power control room and the main control room provide for shot abort during an emergency.

7 Assembly & Commissioning

In this section, we shall describe the assembly of various subsystems into forming the complete machine and highlight some problems of integration and their solution. We shall also summarise the performance tests conducted during the course of commissioning and modification and alteration of the device in cases where the performance fell short of design objectives. The machine is installed in a $60' \times 60'$ high ceiling hall with a $30' \times 30'$ pit at the centre containing a raised foundation on which the machine is assembled. The hall contains facilities like a 5 ton EOT crane. The North-side annexe houses the AC-DC converters as well as the power protection and control systems including the PDP11/23 computers. The South-side room houses the main control room on the upper floor and a support room below. The cooling water system is housed in a basement on the east-side with interconnecting plumbing.

The erection sequence followed a 'vertically up, radially out concept arrived at after studying the integration problem. The critical requirements during the mechanical assembly stage were the intercomponent electrical insulation, structural rigidity and the overall mechanical positioning accuracy of all members supporting the magnetic field coils. The radial I beams which support the TF coils gave severe assembly problems in meeting the required angular accuracies as well as overall planarity. Another problem area was the joints between the members of the top and bottom inverted triangles and the outer columns; wherever necessary, proper matching was achieved by insitu cutting of welded flanges and re-winding.

After completion of the first phase of assembly of all magnetic field coils, the vacuum fields were mapped using dc magnetic field and an accurate Hall probe. The TF coil system passed this test successfully and met the design objectives. However it was found that there was an over compensation of the return flux of the TR-1 coils by the other TR coils resulting in a net vertical field beyond tolerable limits. After considering various options it was decided to install a set of compensating coils near TR-4 coils to correct the field error. This coil was would insitu with multicore flexible cables.

The TF coil outer C's were then dismantled and the vacuum vessel valves installed in the toroidal cavity formed by the inner C's. The vacuum vessel half-tori were integrated and secured to the vessel supports against toroidal and radial displacements. For the TF coil reintegration, special tools were designed and used for the accurate radial and vertical matching of the two C's. The insulation in the multiple lap joints between the two C's was found to be quite delicate and great care had to be exercised in preventing damage to them during integration.

The power system had by this time been independently installed and commissioned on dummy loads which had the same electrical characteristics as the TR and VF coils. A purely resistive dummy load used for Tf system commissioning resulted in mechanical damage Tf bus and interphase transformer which had to be replaced. DC bus system connecting the power system with the loads were also installed and tested.

In the beginning of the TF power tests electrical grounding problem arose which were diagnosed to be due to excessive coil movement. Subsequently the TF coils were radially compressed and the compression rings fastened tightly to produce adequate precompression. With this, the TF coils were powered upto a peak current of 35 kA. The radial displacements were in the sub-millimeter range and are within design limits. During this test a problem of unbalance in the X and Y converter was detected at currents above 30 kA which was corrected by adjusting regulation. A typical data for TF current is given in Fig. 31.

The ohmic coil testing phase also revealed problems which were not fully anticipated. Although the coils had been pretested at the manufacturing stage for electrical insulation, the proximity of the coils to mechanical supports and the coil movement under energization resulted in electrical grounding faults. Subsequently an extensive procedure of impulse voltage test was con-

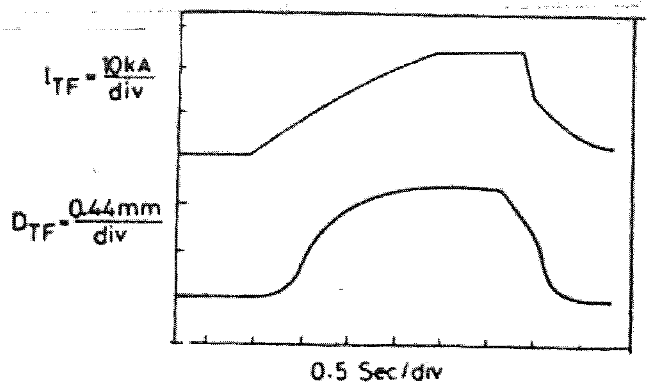


Fig. 31 – A time profile of TF current and corresponding displacement of a TF coil taken during commissioning tests

ducted at various levels on sets of coils and the insulation strengthened at critical points. After this the coils were operated through the magnetization, current interruption and negative current phase with the primary objective of realizing more than 40v loop voltage.

The VF coil tests were successfully conducted upto 8 kA and the combined operation of VF and TF coils did not give rise to out of plane coil displacements within measurable limits. As abundant precaution, however a few sets of radial I beams were constrained against toroidal movement by supports welded in-situ. The coil cooling system was then commissioned successfully to generate the required flow rate. The vacuum vessel commissioning is progressing satisfactorily and is expected to achieve the design vacuum.

8 Integrated Operation

For purpose of taking a shot the Aditya operation can be divided into following phases: the preparation phase, pre-shot phase, shot phase and post-shot phase. The preparation phase includes carrying out machine integrity tests, getting various subsystems in ready status, putting on the input power for convertors, configuring the data acquisition system and loading the same. In each pre-shot phase system readiness is checked and operator initiates the start-shot pulse. This pulse initiates the gas fill, conditionally opens gate valves, initializes the DAS, sends data to PSCS on VAX-PSCS link and awaits OK from PSCS, Vacuum system and Gate valves. PSCS follows following sequence of operation after receiving shot data from VAX 11/730:

(i) The validity of the data set is checked, and if a valid data set is received the steering data for the converters is calculated. In case of invalid data a message is sent to this effect to the VAX and PSCS awaits new data set.

(ii) On completion of the calculation of the steering data the required values of the capacitor and the resistor of the OTPS wave shaping circuit are displayed which PSCS operator is required to set and acknowledge.

(iii) A dynamic hardware test is optionally initiated and on successful completion of the test PSCS issues a 'SYSTEM READY' hardwired signal to main control. The PSCS then awaits hardwired 'MASTER TRIGGER' from the main control.

An auto/operator initiated 'MASTER TRIGGER' follows starting the shot-phase consisting of the power-up sequence and data acquisition in local memories. The power-up sequence carried out by the PSCS includes powering up of various power supplies as per the time sequence defined by the input data by outputing the reference values of the currents to respective controllers, time critical switchings of the waveshaping circuit elements and continuous data acquisition. On completion of the shot, the PSCS issues 'END OF POWER-UP SEQUENCE' hardwired signal when measured values of the currents in the coils are zero. During the POWER-UP phase fatal faults or operator initiated 'EMERGENCY STOP' abort the shot and the current in the coils forced to zero. Less severe faults disable the 'NEXT SHOT' and need to be cleared before next shot can be taken.

The post shot-phase involves the data scan from the memories, archiving of the data, shutting off the gas feed and the gate valves described above can be carried out under the master-control of either VAX 11/730 or the PLC.

9 Discussion

It is perhaps evident from the above sections that the design, fabrication, erection and commissioning of tokamak Aditya posed a major technological challenge to Indian scientists and the Indian industry. The successful completion of the project was achieved with the involvement of various agencies and organisations. The basic conceptual design was carried out by IPR scientists and engineers in close collaboration with Tata Consulting Engineers, Bombay. Special advice in this phase was also provided by Scientists from BARC, VSSC and SAC. Table 16 lists the various industries which participated in the fabrication of major subsystems of Aditya.

In the next few years, we shall be carrying out a number of plasma experiments on Aditya to elucidate the physical mechanisms responsible for the phenomena listed under the major scientific objectives in the Section 1. This will involve development of a number of specialised and novel diagnostics to monitor the various plasma characteristics. In addition, efforts will be made to extend the plasma parameter space of

Table 16 – List of participated agencies

Subsystem components	Agency for fabrication
1. Vacuum vessel	Larson & Toubro, Bombay
2. Pumping system, seals etc.	IPR
3. Machining of copper	Laxmi Vijay Iron & Brass Works
4. Coil insulations	BHEL, Bhopal
5. Cooling system	Blue Star, Ahmedabad
6. Mechanical structure	Godrej Ltd., Bombay
7. Buckling cylinder	Dakle, Washi
8. Power supplies	NGEF (Bangalore) & AEG (West Germany)—Collaboration
9. 132 KV substation	Hindustan Brown Boveri, Baroda
10. Diagnostics	IPR
11. Data acquisition & control	IPR
12. PLC	ASEA Ltd.

The project supervision was carried out by IPR with the assistance of TCE.

Aditya by using auxiliary heating techniques to augment the Ohmic heating. It is well known that externally launched radio-frequency waves at characteristic plasma frequencies can be used to increase the electron and ion temperatures. Certain types of waves (e.g. lower hybrid waves) can also be used to pull tails on the electron velocity distribution, thereby generating novel regimes of operation where current is dominantly carried by energetic carriers. Our present plans for RF plasma heating are to use Ion Bernstein Waves in the frequency range 20-40 MHz to carry out plasma heating and lower hybrid waves in the frequency range 2-6 GHz to do the novel regime experiments. Typical power levels ⩽1 MW in pulses 50-100 ms long will be required for these experiments. The MHz power is launched with special antennae kept in the limiter shadow inside the vacuum vessel whereas the GHz power is typically launched with phased wave-guides attached to the vacuum vessel.

Another major area of technology that we shall be investing in, during the coming years will be that of inductive energy storage systems useful for carrying out pulsed power experiments. As discussed in the text, the pulsed power for the present generation of Aditya experiments is directly coming from the GEB grid. However, for future experiments much longer requirements of pulsed power will arise and direct pulsing of the electricity grid isnot practical. For this purpose, we shall install flywheel motor generator sets with an ultimate energy capability ⩽1 Giga Joule.

Such flywheel systems draw power from the electricity grid on a continuous basis at a slow rate and store it in the rotational energy of the flywheel. A sudden braking of the flywheel motion is then used to deliver pulsed power to the plasma experiment. Such combined use of inductive storage systems and power pulsing of the electricity grid is routinely used in fusion laboratories around the world.

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