3 TECHNICAL ACHIEVEMENTS OF THE CRPP IN 1999

3.1 TCV tokamak operation

TCV was operated for 8 months in 1999, with a total of 1626 pulses. Operational statistics on a monthly basis are shown in Fig. 3.1.1. Operation was interrupted from July to October for the installation of the ECH launchers of the second cluster of 3 gyrotrons, which doubled the available heating power to 3MW. Several new diagnostics, described below, were also installed or upgraded.

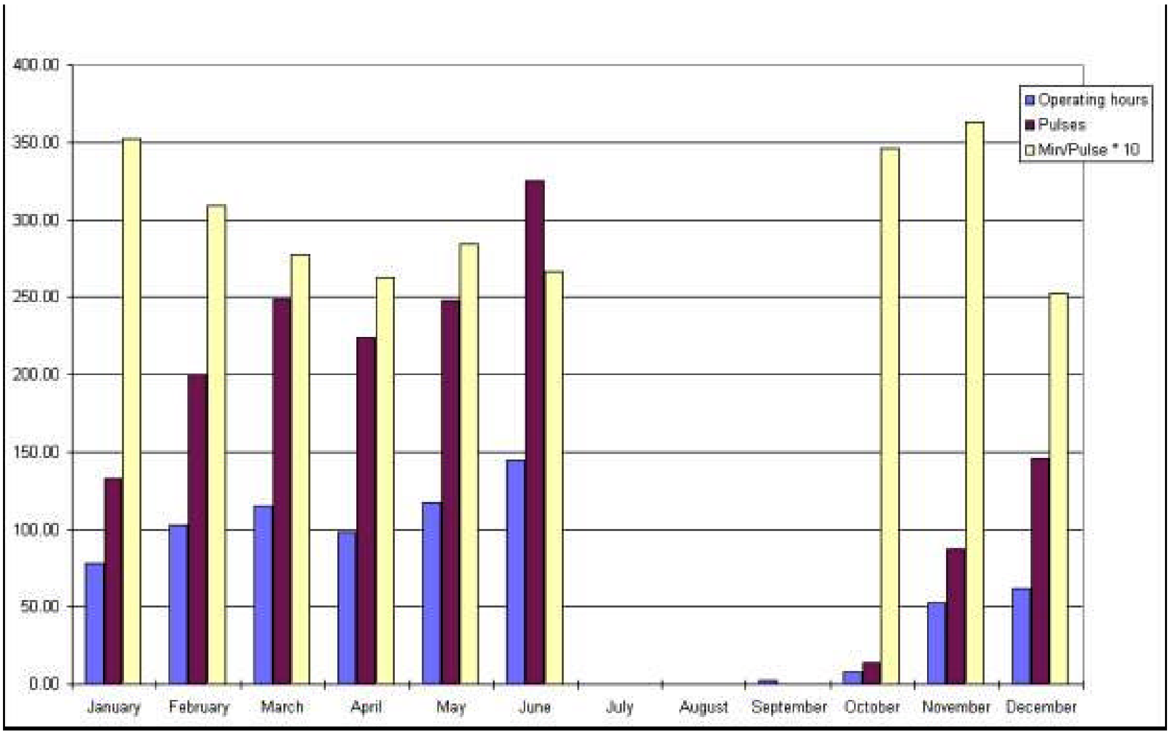

Fig. 3.1.1 ***TCV operation in 1999. Red: Number of pulses per month. Blue: Hours of operation of power system. Yellow: Average time interval between pulses (minutes×10).***

3.2 TCV X2 Electron Cyclotron Wave System

After an extensive experimental campaign with 3 gyrotrons on TCV during 1999, the second cluster of 3 gyrotrons of the second harmonic ECW system (X2) operating at 82.7GHz was commissioned in December 1999. The 118GHz gyrotron tube for heating at the third harmonic in TCV, which is being developed for use on both TCV and Tore Supra, has reached a total energy output of 6.2MJ per pulse, which is the highest value achieved worldwide for a high power gyrotron operating in the frequency range relevant for ECH in tokamaks.

The first cluster of second harmonic gyrotrons has had extensive use at its design specifications of 2.0s pulses at a total of 1.5MW. A total of 364 ECH discharges were fired into TCV plasmas, of which three quarters made use of all three heating sources simultaneously. The implementation of integrated control software has greatly simplified the operation of the full cluster. The flexibility and reliability of the TCV X2-ECW system was instrumental for the success of the 1999 experimental campaign, as detailed in the scientific sections of this report. During the operating period, one of the gyrotrons developed an internal electrical short circuit in the cathode heating filament and was returned to the manufacturer for repair. A replacement gyrotron was installed, aligned and conditioned to its design operating parameters. Standard operation of the 1.5MW cluster resumed after a down time of only three weeks, including changes in the control system imposed by the use of the replacement tube. All mirrors in the matching optic unit (MOU) of each gyrotron of the second cluster have been aligned and motorised. The transmission lines up to the last section before the torus were evacuated and successfully leak tested. The corresponding launchers, which are of an improved design, were assembled and successfully leak tested, prior to their installation on the torus during the 4-month summer shutdown period.

The mobile mirror systems of the first cluster were retro-fitted with ZrO_2 bearings which reduce friction and permit baking of the system to 250˚C. A full upgrade of the first cluster launchers is planned, pending successful operation of the second cluster.

Each of the 6 gyrotron subsystems (gyrotron/MOU/transmission line/launcher) was tested to determine the overall transmission efficiency, the power coupling to the power monitors on each line and the rest positions of all the launcher mirrors. The total power now available into the tokamak is 2.7MW with an average transmission line efficiency of 95%. These tests were followed by vacuum tests of the complete ECH system including reconditioning of the gyrotrons, transmission lines and calorimetric loads. The conditioning tests also provided an opportunity to verify the measurement hardware as well as the control software of all equipment, as required for operation with TCV.

The successful completion of the conditioning allowed the injection of 2.3MW of ECH power into the TCV vessel for a pulse limited to 5ms for machine safety reasons, using all 6 gyrotrons on the last day of operation of December 1999, thereby opening a new era of high power ECH operation on TCV.

3.3 X3 System Development

Prototype Gyrotrons (118GHz/0.5MW): The factory acceptance test of the prototype gyrotron with 5s pulse demonstrated that most of the critical components reach thermal equilibrium well before 5s. The conditioning of the tube showed that at full power the tube vacuum was stabilised after 1s. Extensive measurements of the gyrotron behaviour at this pulse length have shown excellent consistency with the design parameters. The RF beam characteristics in free space propagation after the sapphire window were determined using a phase reconstruction technique based on infrared images taken at four different distances from the window.

Extension of the pulse length beyond 5s was carried out at CEA-Cadarache with a CW high voltage power supply. Due to a magnetic field misalignment during the first tests, the cavity and internal converter sections of this prototype gyrotron were slightly damaged and subsequently did not reach the nominal power level of 500kW. After realigning the magnetic field, a maximum power of 400kW was reached, but, compared with the factory acceptance test, a 50% increase in the cavity- launcher power losses was observed. Despite this setback, the installation of a prototype CW evacuated load allowed an extension of the pulse length from 5s to 15.5s within 5 working days. The total energy in the RF pulse was 6.2MJ and is presently the highest value achieved world-wide for gyrotrons operating in these frequency and power ranges.

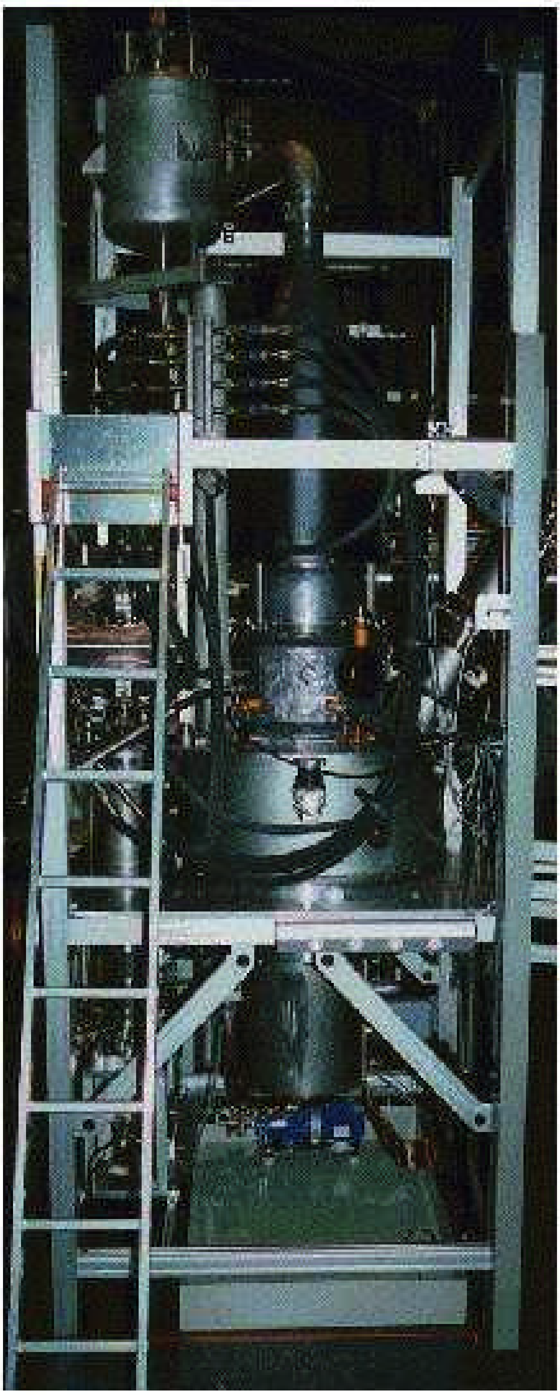

Fig. 3.3.1 Installation of an X3 gyrotron

TCV series gyrotrons: The first two series gyrotron tubes successfully passed the factory and onsite acceptance tests in 1999. During the acceptance test the gyrotrons underwent a rigorous check of their output frequency, output power efficiency and mode purity. An endurance test consisting of 250 pulses during 4 periods of 4 hours each was performed with a duty cycle of 1.5%. The fraction of successful pulses not interrupted by a gyrotron interlock signal was 98%. All interrupted pulses were terminated by a vacuum increase in the tube. Arcs were never the cause of a pulse interruption. No reconditioning was required to recover after an interrupted pulse. The third and last series tube will be delivered and commissioned during summer 2000.

TCV transmission lines: The support structures for the transmission lines, the loads and the pumping system have been designed and manufactured. The installation of the transmission line system will be completed by the end of 2000.

Launcher: The launcher is essentially composed of a single mirror onto which the three 0.5MW beams converge. The combined 1.5MW reflected beam is then vertically injected into the plasma. This mirror has two degrees of freedom for independent control of its radial position and the injection angle in the poloidal plane. A prototype launcher was designed and a mock-up constructed. Preliminary tests on the first prototype identified critical issues that were taken into consideration for the final design of the launcher. This launcher is presently in construction and will be mounted onto TCV by the end of 2000.

X3 Power Supply: Since the three 118GHz X3 gyrotrons are of the triode type, two power sources are required for these tubes. The first power source is used to apply the main potential on the cathode of the gyrotrons and provides the energy needed to generate the microwave power. The second source is used to drive and control this power by applying a potential between the anode and the cathode of the tube. A fully solid state Regulated High Voltage Power Supply (-85kV, 80A) is used to apply the cathode potential to the three gyrotrons. This equipment was installed at the end of 1997. Following an international call for tender, a Spanish company was selected for the design and the delivery of the three independent anode modulators, one for each gyrotron. A fully solid state design was again chosen, based on the "stand alone source" principle (the driving energy is not drawn from the cathode source). The main output parameters of these power supplies are: -5kV/30 kV, 250mA. An output shut-down faster than 10µs is required in the case of arcing in the gyrotron cavity. The first modulator was delivered at the beginning of 1999 for commissioning the first X3 tube. The acceptance tests of the third and final power supply unit were successfully completed in November 1999.

3.4 TCV diagnostics

Diagnostic Neutral Beam: Although TCV is already well equipped with electron diagnostics and will be even more so with the new ECE systems, the only ion temperature diagnostic is a neutral particle analyser inherited from TCA, the previous tokamak operated by CRPP until 1990. Although ions contribute little to the stored energy of intensely heated low density ECH plasmas, they are expected to be important both in measurements of the stored energy and transport in future experiments using third harmonic ECH as well as in Ohmic plasmas at higher densities. In 1997 the CRPP ordered a diagnostic neutral injector (1A equivalent current, 50keV) as a source for active charge exchange recombination spectroscopy (CXS) from the Budker Institute for Nuclear Physics (BINP) in Novosibirsk. The system was delivered in 1999 following acceptance tests at BINP and integrated during the summer shutdown. Two visible Czerny-Turner grating spectrometers equipped with a 2D CCD array have been brought into service for CXS measurements in conjunction with this injector. These CXS spectrometers each have 16 separate viewing chords, which image the neutral beam through a window and a double mirror assembly mounted inside a TCV vacuum port. The CCD camera software has been adapted to allow the acquisition of spectra from all 16 chords with a 100Hz repetition rate. The spectrometers are placed outside the torus hall and are linked to the two camera lenses on the viewport by optical fibres. Final commissioning of the injector and first results are expected early in 2000. At a later stage the injector could also be used for Motional Stark Effect Polarimetry and Beam Emission Spectroscopy.

Electron Cyclotron Emission measurement of electron temperature: ECE is a classic and highly sensitive electron temperature diagnostic used in many tokamaks. Its application to TCV is somewhat complicated by the multiple plasma shapes that are possible and the low magnetic field, which leads to low cut-off densities $\sim 4 \cdot 10^{19} m^{-3}$. With ECH, operation at low densities has become routine, making the construction of an ECE diagnostic a worthwhile investment. The radiometer, designed for high-field side observation, has been nearly completed by a commercial manufacturer, and was due for delivery in October 1999. It features 24 frequency channels in the range 78-115GHz for electron temperature profile measurements over a radial extent of 30cm, using two tile-embedded receiving antennae at the inner wall. With an acquisition frequency of 80kHz the system will allow both high time resolution and high frequency measurements of power deposition, heat transport and MHD activity in ECH plasmas. If necessary, the 24 channels can be grouped to cover a region of about 15cm, either near the edge or near the plasma centre, to increase spatial resolution. Band reject filters at the gyrotron frequencies for receiver protection are under development at the Institute of Radiophysics in Kharkov, Ukraine. Two antennae, at heights of z=0 and z=20 cm for operational flexibility, have been installed in the vessel, with fundamental mode waveguides running behind the inner wall tiles. The ECE signal is relayed from TCV to the radiometer by several meters of oversized waveguide.

AXUV bolometry: An exciting recent development of the semiconductor industry, absolute XUV (AXUV) silicon diodes, has considerable diagnostic potential in fusion plasmas. Thanks to a novel diode architecture these diodes are free of the ~0.5 micrometer Si^+ "dead layer", which makes ordinary Si photodiodes, such as those used for X-ray tomography on TCV, blind to photons with energies in the range 3-1000eV. The most appealing of the diagnostic opportunities offered by these devices is the replacement of the metal film bolometers currently used for total radiation measurements, to achieve higher temporal resolution. Metal film bolometers have inherently low time resolution, low sensitivity and are prone to electromagnetic pick-up, including direct absorption of microwave power from the ECH system. In order to investigate the potential of AXUV devices, three prototype cameras equipped with 16-element AXUV arrays were commissioned on TCV in 1999. The camera design is similar to that of the TCV soft X-ray cameras and features diodes viewing the plasma through a pinhole. The camera interior, with the diodes, is directly connected to the TCV vacuum. Preamplifying electronics at atmospheric pressure are connected to the adjacent diode array by a vacuum feedthrough socket designed at the CRPP. Two of these cameras were installed in the same toroidal sector which houses the existing 5-camera metal foil bolometer system for cross comparisons. The outcome confirmed all our high expectations concerning AXUV bolometric measurements. The prototype system has extraordinary sensitivity and bandwidth, allowing studies of MHD activity using bolometers for the first time. It is insensitive to ECH and is simpler and considerably less expensive than metal foil bolometer systems. In addition, it is insensitive to low energy neutrals emitted from the edge, which can make up to a 60% contribution to the plasma emission, but can severely compromise metal foil bolometric tomography because the plasma is opaque to neutrals.

Langmuir probes: A new array of 34 Langmuir probes was installed during the 1999 summer maintenance period. These probes provide measurements both in limited configurations and at the inner strike zone of diverted discharges.

IR cameras: The existing ageing infrared camera for divertor measurements will be replaced by a new camera based on solid state technology. Orders have been placed for two such devices, one of which will be used to view the central column tiles, providing surveillance during high power ECH experiments.

Reciprocating probe: Within the framework of a collaboration between CRPP and the University of California, San Diego (UCSD), a fast reciprocating probe system is on long term loan to TCV. Installation at the tokamak midplane was completed during the summer shutdown period. The new probe will permit the measurement of radial profiles of electron density and temperature in the plasma edge, allowing comparisons to be made between the divertor and scrape-off layer plasmas during high density detachment experiments. In collaboration with UCSD, measurements are also planned of fluctuations in poloidal electric field, electron temperature and particle flux.

Divertor spectroscopy: The recent progress in the development of two-dimensional spectroscopic observations in the divertor volume of modern tokamaks is driven by the requirement for better understanding of impurity and neutral hydrogen transport in these regions. Experimental and analysis techniques developed at DIII-D, using tangentially viewing CCD cameras, have been adopted at CRPP in collaboration with General Atomics. Using suitable narrow band interference filters, the poloidal distribution of emission from the excitation of neutral deuterium and radiation from carbon impurity ionisation stages (CI, CII, CIII) is being routinely measured using CCD cameras during diverted discharges and the resulting images numerically reconstructed using an efficient inversion algorithm developed at CRPP.

Laser ablation of trace impurities: CRPP has a co-operation with KFKI Budapest on injection of trace impurities into TCV using laser ablation. KFKI has delivered an injection chamber which was mounted onto TCV in October 1998. A ruby laser previously used on TCA and the required relay optics were installed below TCV in 1999. The effect of plasma shaping on the transport of injected impurities such as aluminium will be studied using X-ray and spectroscopic diagnostics during the 2000 operational campaigns.

VUV survey spectrometer: A broadband Vacuum Ultraviolet Spectrometer ("SPRED") with a flat image plane was delivered in 1999. This spectrometer has been adapted to fit under the TCV vacuum vessel to observe the plasma along a vertical chord. It is equipped with two interchangeable ion etched gratings which disperse the incoming light from 140-10nm and 300-10nm onto a flat image plane where a channel plate detector amplifies the signal and converts the signal to visible photons. Design and construction of a 2048 channel electronic readout system are nearing completion at CRPP. This broadband survey instrument will be used for long term continuous monitoring of impurity line radiation from all impurities in the plasma.

3.5 *Data acquisition and handling*

Each TCV discharge in 1999 generated in the range 20-50MB of compressed data. With the advent of new diagnostics this is likely to approach the 100MB mark in 2000.

In order to meet the increased requirements for mass data acquisition, a new line of PC-based acquisition modules was purchased as a custom development. The four modules, of which 2 were delivered in 1999, offer 64 to 128 channels of 16-bit acquisition at a frequency of 200kHz and 2MB of memory per channel. Acquisition will systematically be at 200kHz, although for diagnostics with lower bandwidth requirements the data will be digitally filtered and resampled on the host PC before being dispatched for archiving on the TCV main computer. The increased requirements for data interpretation and simulation will be met by three new computers also purchased at the end of 1999.

3.6 *SULTAN Facility*

SULTAN, the world wide unique high field large bore test facility located in Villigen, was built as a European contribution to the development program for ITER. The facility has primarily been devoted to the qualification of full-size CICC foreseen as potential candidates for use in the CS and the TF coils of the ITER reactor. Fields up to 11T can be imposed onto the vertically inserted CICC-Samples. Within the frame of the ITER full size conductor test programme, several international joint samples were tested in the facility in 1999. The major technical project realised in 1999 was the upgrade of the cryogenic control system.

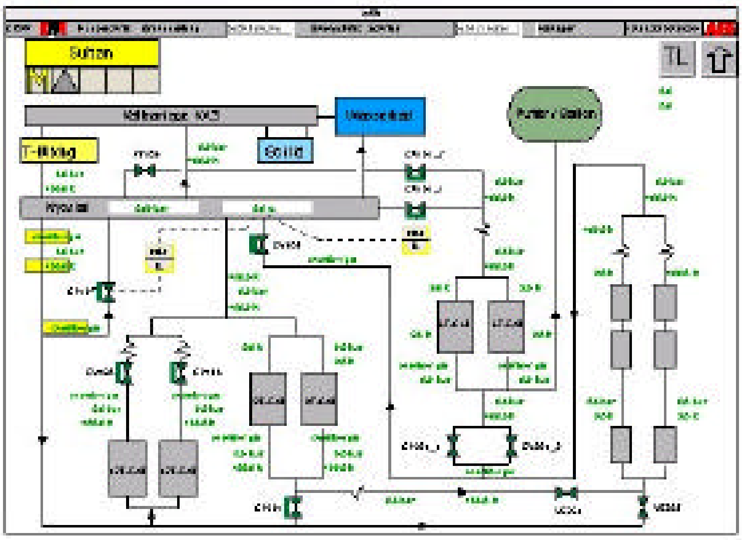

Fig. 3.6.1 ***Screen representation of the SULTAN interactive graphics on the control and visualisation workstation.***

The SULTAN facility consists of a split coil magnet system with a cryogenic cooling circuit, a superconducting 100kA transformer also with it's own cryogenic cooling circuit and a Helium refrigerator connected via transfer lines to the two consumers.

In order to manage the different operation modes for the cryogenic circuits a SPS control system is used. Communication between the equipment and the SPS is via 296 input signals and 136 output signals. A variety of different sensors are implemented, for example, 49 temperatures, 32 pressures, 29 mass flows, 3 Helium levels, 6 vacuum levels, 6 current measurements and about 48 valve feedbacks. About 30 pneumatic driven valves are operated and depending on the actual operation mode 9 different PID controlling cycles are used. Until 1999 the SPS consisted of a Sattcon 31-90 system whereas visualisation of the processes was provided by an AFE monitoring system. In order to avoid 2000 problems a new SPS based on Sattcon 200 series was implemented in 1999. The control and visualisation system is based on Sattline. The programme runs on a workstation PC with Windows NT. Communication between the workstation and the Sattcon 200 controller is via Ethernet. A multiple screen configuration is used to view the cryogenic layout of SULTAN and the transformer simultaneously, as in Fig. 3.6.1 for SULTAN operation. The windows are organised in a multiple layer concept. The alarm system distinguishes between 59 different error sources, whereas each alarm itself is divided into four classes imposing different actions on the system when occurring. During the first facility cool-down, at the end of 1999, the new system proved to be operational and user-friendly.