Ten Years of Experience in Integrated Control of the Multi-Megawatt ECW system on the TCV Tokamak

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Abstract: The ECW system on the TCV tokamak consists of six gyrotrons (82.7GHz/0.5MW/2s) used for X2 and electron Bernstein wave (EBW) ECH/ECCD with individual low-field-side launchers. Three additional gyrotrons (118GHz/0.5MW/2s) are used for X3-ECH in a top-launch configuration to provide central heating of high-density plasmas, at nearly 3 times the cutoff density of X2 (cutoff at ne = 4.2 $10^{19}m^{-3}$). The first two X2 gyrotrons were put into operation in April and November of 1996 with one more following in June, 1997. The full complement of 6 X2 gyrotrons operated simultaneously in TCV in December, 1999. With the acceptance of the X3 launcher with 3 X3 gyrotrons in October, 2003, the full power of 9 gyrotrons (4.2MW injected) was available for experiments. From its inception the ECW system has been designed to allow the highest possible degree of automation, integration and flexibility in the experimental program. Each of the X2 and X3 subsystems is routinely individually operated by one person. Only a modest integration effort would be required to permit 9 gyrotron operation by one operator. This high level of automation in the system allows the operator to adapt to changes in the experimental program "on the fly" while maintaining a high success rate. An added benefit is that it allows the physicists to bring their expertise in EC-wave physics to bear on the day-to-day experimental programs to which they would otherwise be associated purely as gyrotron operators. The modularity of the system, the universality of the plant control, the ease with which the control can be modified and improved, and finally the close collaboration between technicians, engineers and physicists have each been crucial to the successes of adaptable, user-friendly, multi-megawatt, EC operation on TCV.

1. Introduction

The ITER electron cyclotron heating and current drive system is considered a "day-one" system. Present planning is for 24, 1MW, 170GHz, CW gyrotrons, 3, 1MW, 127Gz, 10s, startup gyrotrons, their associated superconducting magnets, transmission lines and launching antennas. The system is assumed to work reliably, when requested, and in an integrated way with the overall plant control. Present EC systems, worldwide, are generally regarded by many tokamak physicists to be unreliable, sporadically available and labour intensive. To the extent that they are integrated in the overall plant control, it is due only to the vigilance of a team of "gyrotron operators". On TCV this team is usually represented by a single gyrotron operator in the control room to run the entire system and prepare the shots. This paper reports the reasons for this low-manpower successful operation of the world's highest power, highly-flexible, plant-integrated, EC system.

The paper is organised as follows: Section 2 provides background statistics on the operation of the system over the past 10 years – from the first single X2 gyrotron use through March 2007. Section 3 discusses the integration of the EC system into the plant control of the TCV tokamak. This is followed by a critical view of the strengths and weaknesses of the system as implemented (Section 4) and finally some conclusions specifically related to the expectations of the ITER control and data acquisition system on the EC system.

2. EC system statistics

TCV has a 2 frequency EC system comprised of *a)* 9, 500 kW, 2 s, lateral-output gyrotrons, *b)* 9 evacuated matching optics units (MOUs) containing 2, flat, grating-polarizer mirrors each (12 – remotely controlled) and focussing mirrors, *c)* 9, windowless, 63.5 mm diameter, HE_{11}, corrugated-Al, evacuated waveguides, *d)* 9 high power microwave switches with two integral vacuum gate-valves one on each output leg, *e)* 9, 500 kW, 2 s, calorimetric, stainless-steel, RF loads (SPINNER/GA transmission line) and *f)* 7, moveable, feedback-controlled, independent launching antennas (CRPP) – 6 for the second harmonic heating/current-drive system (GYCOM-NN, 82.7GHz, “X2”) with access from the outboard side of the tokamak; and one for the three beams of the third harmonic heating system (THALES, 118GHz, “X3”). In addition to the RF systems, there are the requisite regulated high-voltage power supplies (3, RHVPS THOMCAST PSMs – one for each cluster of 3 gyrotrons); modulation anode power supplies (3 JEMA – one for each triode electron gun of the X3 gyrotrons); 9 superconducting magnets (6 OXFORD + 3 ACCEL each with LHe manual refill, LN_2 automatic refill); 30 independent vacuum pumping stations and 10 water pumps of various capacities. These systems are all described within the VISTA Vsystem plant control software by ~10,000 active database channels, equivalent is size to the rest of the tokamak database.

The TCV EC system was conceptualized in 1991-1992 and the design finalized between 1993 and 1995 with minor modifications and upgrades made continuously since. The equipment was available for use in TCV in stages from April 1996 (1st X2 gyrotron) through October 2003 (final X3 configuration). The first shot into TCV with X2 power was 11036 with one gyrotron during 0.1s in October 1996. In December 1999 (shot 17257) a demonstration discharge was made with a 5ms pulse from all 6 X2 gyrotrons into the plasma. X3 was used for the first time with power from one gyrotron injected through an X2 transmission line and launcher in May 2000 (shot 18565) and from a 2nd gyrotron through the X3 launcher on the top of the machine in December 2001 (shot 21370). Finally, all X3 gyrotrons were installed in their top launch configuration and fired simultaneously into TCV shot 25582 in September 2003. As of this date, the complete EC system was installed.

System availability for TCV is defined as the number of shots for which ECH was requested by the experimental program. This is indicated by the decision to acquire data traces related to the EC system. From 1st January 2000 through 2nd March 2007 (most recent operation), 17165 shots were recorded in the TCV database (this includes all shots: machine-hardware test shots without plasma, failed plasma breakdown, etc.). During the same period, 5518 requests for the X2 system and 989 requests for the X3 system were recorded (this excludes hardware test shots which use a separate data tree and are performed at the start of each day). This corresponds to a lower-bound estimate of 32.1% and 5.8% use for each frequency, respectively. As with most tokamaks, TCV’s program is divided into campaigns. These typically last, roughly, one year. Planning for these campaigns is done with a knowledge of the known (or projected) installation status of equipment, including the EC system. The result is that ECH is not requested (in the sense defined above) if it is already known to be unavailable; for example if the tubes are being repaired.

If we consider any *repaired* gyrotron to be “new”, then we have had 5 of 12 X2 gyrotrons broken; the longest running tube is still in operation after 9.7 years and the shortest lived tube broke after only 4 months. Similarly, we have had 2 of 4 X3 gyrotrons returned for repairs; one is still in operation after 6.3 years and the shortest lived was 2.8 years old when it broke. In all cases, except one, the tubes broke at a time when no high voltage was being applied. The X2 gyrotrons suffered problems with the filaments or vacuum; whereas, the X3 tubes failed at the window brazing. Two of the X2 failures (shortest lived tubes) were caused by lapses in quality control (QC). The X3 tubes use cryogenic (liquid nitrogen cooled) sapphire windows and this appears to be a less robust technology. Generally, gyrotron lifetime data has a large scatter.

Small numbers of series gyrotrons have been produced. Due to the lack of a standard methodology (of questionable usefulness even for tubes with larger productions, see ref. [1]) it is difficult to predict lifetimes. Nevertheless, without large improvements in QC and the use of proven technologies, several gyrotrons must be expected to fail during the ITER lifetime. The fastest turn-around time for repair was 6 months but was more typically 15 months. Factory turn-around times are claimed to be a minimum of 3 months, so the majority of the total turn-around time is due to shipping, administration complications, personnel and acceptance test coordination and lack of urgency on the part of the experimental program. It is assumed that ITER will carefully coordinate resources to minimize turn-around time as the EC system is considered crucial to the success of the program. Nevertheless, on TCV we have one spare X2 tube in storage which has been used to replace broken tubes, allowing the experimental program to continue after a 2 week hiatus for installation, conditioning, MOU mirror changes and realignment and power calibration. On-site, accepted, spare parts (specficially gyrotrons) would provide a great benefit to the ITER EC system.

3. ECH control system (ECHCS)

VISTA Vsystem live database software was chosen for the overall control of the tokamak plant [2]. Tools are provided to visualise and change the equipment status (meters, levels, alarm lights, buttons, switches, etc.) within Vdraw windows (e.g. GUIs). As the EC system is a subsystem of TCV, it was required to fit within this framework. All TCV subsystems are required to provide redundant levels (2) of hardwired protection for personnel safety and to be designed to be self protecting. For example, the high power microwave switches are governed by a local state machine programmed into the PLC of their control slave. The gate-valves on the output legs of the switch are part of the personnel safety system – an open position causes a fibre-optic trip to the RHVPSs of the gyrotrons to prevent power generation. Additionally, any command can be sent to the slave either locally (front panel buttons) or by the plant control software (programs, Vdraw buttons, etc.) but will be rejected by the state machine if the operation would endanger the equipment (e.g. open an evacuated transmission line to atmospheric pressure).

When each subsystem is delivered to TCV, the Vsystem software channels have been defined and are tested. These are then included into the overall plant as required. This means that any user has access to all plant data at any time. At the time of a TCV shot, a “snapshot” of the plant data is written to the MDS+ database for that shot, in addition to all the acquired traces that have been uploaded. The MDS tree also contains many additional branches and nodes which provide a description of how the equipment is to be used (e.g. limits of permitted settings) or interpreted (e.g. calibration values to convert requested powers to reference waveforms for the RHVPS). These nodes are part of the “model” shot, which contains all the pre-shot feed forward design values for the next shot. When a shot is performed, the model is copied to the shot data so that a record of the actual system status (calibration, etc.) is thus recorded.

Prior to February 1999, the gyrotrons (of which there were only 3) were run manually. Each preparatory action and non-safety check was made by a designated gyrotron operator in parallel to the more automated TCV shot cycle (for example, loading of all feed forward waveforms to the appropriate function generators). This was inherently slow and/or led to operator errors. After that date, an ECH state machine was written in a simple MATLAB script of ~250 lines, controlled by a Vdraw visualization window. By entering a given state, the gyrotron operator is now able to execute an easily written and adaptable MATLAB script which mimics the operations previously carried out manually. Most importantly, all of the manual operator checks have now been automated to minimize errors.

Finally, a simplified MATLAB GUI (named ECHCS) was created, in July 2001, to assist in the preparation of the shot design for the experiments. It allows the gyrotron operator to download the necessary equilibrium data from a target shot. If ECH was used for the shot, the EC data from the *model* of that shot can also be loaded, or alternatively, the EC *measured* data for that shot (permitting and exact repeat of the shot if the measured and model data happen to differ). The desired feed forward time traces of the power from each gyrotron and the angles of the launchers can be entered and plotted. A single time is selected within the time trace at which the intersection of the beam and the equilibrium reconstruction will be calculated and from which data the polarizations required for each beam are determined. The polarization ellipse angles are displayed as are the required rotation angles for each MOU polarizer grating (based on the calibration data stored in the MDS tree). Lastly, as gyrotrons can fire power into either the calorimetric loads or the tokamak at each shot, this choice is made in the GUI. To aid in determining the desired angles, menu access to the TCV TORAY ray-tracing interface provides fast, single-ray ray tracing for that data which is entered in the ECHCS GUI. Many limit checks on the preparation data are performed, as the data is entered, to ensure allowed values. Summary plotting of all time traces facilitates cross-checking with the session leader that the experiment has been properly prepared. Once satisfied with the setup, the data is stored to the model shot with the click of a button. The EC state machine then uses the model data to perform the required actions on the equipment when the appropriate state is entered.

4. Strengths and weakness in the TCV system

Strengths of the present system include, *a)* the use of a common, standardized live database for TCV and all it's subsystems, including EC, *b)* all systems are safe and largely protected against operator error, *c)* gyrotron towers are interchangeable – at least for the same make of gyrotron, *d*) the operating system (Vsystem) during on-site acceptance testing and TCV operation are identical, thereby ensuring de-bugged during testing, *e)* the MDS database provides a self-description of the equipment to the TCV plant – TCV knows what the gyrotrons are and what they can do via this database, *f)* the database is modular, expandable and accessible to all users and software – useful for data processing as it removes all "hidden" or "private" constants from analysis programs, *g)* the EC state machine is nearly generic with simple states applicable to any TCV subsystem, *h)* the automation of tasks can be done by the gyrotron operators as sufficient experience is gained to permit this, *i)* automation upgrades can be done "on-the-fly" during operation so that the software is immediately tested, while still maintaining a high success rate for the experiments, *j)* a motivated operator can be trained to solve 9 out of 10 problems encountered with equipment and shot preparation within about 1 month, and *k)* at present only 1 (at most 2) gyrotron operator(s) is (are) required for X2 (X2+X3) operation.

There are 3 main weaknesses of the TCV control system. First, acceptance tests must be carried out with the same equipment used during TCV operations. In particular, any given RHVPS powers 3 gyrotrons and testing occupies one of these. Although it has been attempted, it has been found extremely impractical to attempt acceptance testing and operations at the same time. Some acceptance tests rely on security actions carried out by trained experts. Both TCV and factory experts are understandably cautious and concerned during testing and the increased vigilance required for simultaneous TCV and acceptance testing was deemed dis-advantageous by both parties. Based on the 16 on-site acceptances for TCV, 2-4 weeks are required to complete them, depending on the behaviour of the individual tubes.

Second, the X2 gyrotrons need re-conditioning after an internal arc, the equipment does not provide detection of an internal arc in the way originally expected. This requires a re-thinking and implementation of the conditioning automation and has not yet been carried out due to manpower constraints. Given the system complexity, ITER must expect to have to deal with similar misunderstandings and/or shortcomings.

Thire, the launchers have been found to have maximum and minimum angle limits which are not fully documented in the MDS database as they depend on the angles themselves. (One degree of freedom is used during the shot and has limits, while the other degree-of-freedom is constant during a shot. The limits depend on this second angle. This was not foreseen.) More importantly, these limits can change over time depending on TCV conditions. The reasons for this behaviour have not been identified. We suspect that the machine disruption history may play a role. The automatic identification of the present angle limits and automated updating of the MDS equipment description has not yet been implemented. Without this information, the shot preparation software cannot warn the session leader that requested operating parameters are unattainable. At present, the experience of the gyrotron operator assures the communication of this information. While this is clearly a weakness, in practice the presence of the gyrotron operator often allows successful completion of the experimental program due to the problem solving capabilities inherent in humans which are lacking in software.

5. Conclusions

ITER CODAQ will require a full description of procured plant systems (e.g. the EC system) via a database structure similar to that implemented on TCV. The measurements, trips, alarms, actuators, etc. will be defined in a contract between ITER and the Domestic Agency at an early stage, after negotiations. Once fixed, the terms of the contract will define a provided *socket* into which the supplied *plug* must fit. ITER CODAQ will make available tools (generic state machine, example database tree, etc.) to aid in the preparation of the *plug* and will require that the entire data structure be used (and thereby tested) at the time of the factory tests. While these tool concepts are also implemented at TCV, this will be a new venture for factory testing. Success will depend critically on communication and the commitment of appropriate resources to the process at an early stage. Acting as the European Gyrotron Test Facility, CRPP has begun to implement this work under present EFDA contracts.

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6. References

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