CONFERENCE PRE-PRINT

THE WENDELSTEIN 7-X ECRH PLANT - EXPERIENCE WITH RELIABLE LONG PULSE OPERATION OF A MULTI MW GYROTRON INSTALLATION

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Abstract

Wendelstein 7-X (W7-X) is a steady state capable optimized stellarator aiming to demonstrate continuous wave (cw) operation at reactor relevant plasma parameters. Electron cyclotron resonance heating (ECRH) is the only available heating system for cw operation up to 30 min. The ECRH plant at W7-X is a world wide unique setup where long pulse operation with up to 12 gyrotrons of the MW class is demonstrated for the first time. In the past years, we continuously increased the reliability of individual gyrotrons by implementing automatic recovery mechanisms to resume operation in case of a failure. We continued this route by improving our fast arc detection system. Furthermore, we focused on the overall performance of the ECRH plant, i.e. the total available heating power in the plasma vessel. A feedback controller keeping the total ECRH power constant by increasing the individual gyrotron power in case of a trip was implemented. With all these measures in place a record energy turnaround of 1.8 GJ was achieved in the last operational phase OP2.3 of W7-X.

1. INTRODUCTION

W7-X is a steady-state capable optimized stellarator. The main heating system is electron cyclotron resonance heating (ECRH) with currently 11 gyrotrons operating at 140 GHz. In the design phase of W7-X a 10MW ECRH plant with 10 Gyrotrons with a nominal output power of 1MW cw was planned [1] and also realized. Fig. 1 shows a top view of the ECRH plant including the transmission line and the stellarator itself. A first of its kind quasi-optical transmission line is used to transmit the power into the plasma vessel. In 2024 an upgraded gyrotron with nominally 1.5 MW based on the original 1MW gyrotron design was installed at W7-X. This prototype tube reached a maximum power of 1.3 MW. Taking transmission losses of about 6 % and the spread of the actually achieved power of individual gyrotrons into account ($\sim 0.6 \ldots 1$ MW) up to 8.5 MW heating power are available in the plasma vessel.

For commissioning and tests of gyrotrons two steady state capable water test loads are installed. One for each row of gyrotrons. Only one beam at a time can be directed into the water load by adjusting the position of two mirrors. Long pulse operation of multiple gyrotrons in parallel is thus only possible with a target plasma in W7-X as a load. For this reason, the identification of hidden issues in the transmission line operated at full microwave power was complicated until W7-X was equipped with a fully water cooled divertor and first

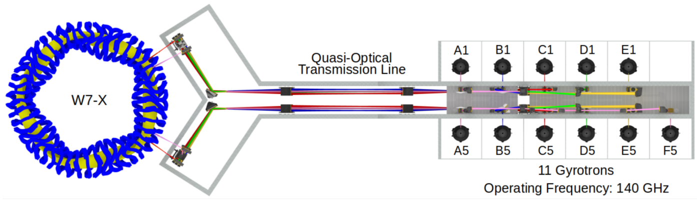

FIG. 1. Top view of the ECRH plant at W7-X including transmission line and the stellarator. The gyrotrons are arranged in two rows of up to 6 tubes each.

wall. Bringing sufficient power reliably into the plasma is an ongoing process where we regularly hit new boundaries. In the past years we continuously increased the reliability of the plant and thus the actually available heating power for W7-X. The control system was continuously upgraded to enable an automated recovery after failures like a mode loss [2] or arcs on the transmission line. In section 2 we report on our latest experience with a fast arc detection system based on a comparison of power measured at the beginning and the end of the transmission line. On the route to reactor relevant stationary plasma operation it is crucial to provide the required heating power continuously. A key lesson learned from the first experimental campaigns of W7-X is on the one hand that in most cases after a gyrotron tripped, operation can be resumed on a time scale of seconds. On the other hand gyrotrons operate more reliable at reduced power levels of 80...90 % of the maximum achievable power. At W7-X the power of all gyrotrons can be modulated continuously between 25...100 % by controlling the acceleration voltage. We recently introduced a feedback controller as part of the gyrotron control system which stabilizes the total heating power by controlling the acceleration voltage of individual gyrotrons. Each gyrotron receives a power set point from the central W7-X control system. The total power controller is a PI controller which determines a power correction factor for all gyrotrons from the difference between the total power set point and the actual power. When a gyrotron trips, the power of the remaining gyrotrons is increased until the tripped gyrotron resumes operation. Details on the controller are presented in sec. 4 and first experience in a plasma program with ~ 1.8 GJ energy turnauround are presented in section 5. The challenge when restarting gyrotrons on time scales of seconds is keeping the beam current constant. Stable gyrotron operation is only possible when the beam current can be stabilized in a narrow band around the optimum current. In section 3 we report on a control scheme to stabilize the beam current by actively boosting the cathode heater current.

2. FAST ARC DETECTION

Arcing on the transmission line has been an issue since the first operational phase of W7-X. The situation has already been improved by several measures, mostly by installing air dryers in order to reduce the probability of arcing. Another measure was the development of a fast arc detection system allowing for an automatic recovery of operation after an arc [3]. The system is based on a comparison of the RF power measured at the beginning and the end of the transmission line for each beam. Grating couplers on the first ("M1") and last ("M14") mirror are used to redirect a fraction of the beam to a RF detector diode. Both signals are compared on a STM32 based microcontroller board. The M1 power signal has already been installed during the commissioning phase of each gyrotron. The signal is our absolutely calibrated output power measurement. During OP2.2/2.3 the M14 measurement was installed step by step for all gyrotrons. In case of an arc, a sudden drop of the signal at M14 is expected since the beam is reflected at the arc if it is generated somewhere between M1 and M14. By triggering a HV ramp down when such a drop is detected, it is possible to stop an arc before it is fully developed. If an arc is stopped quick enough, i.e. on time scales < 0.1 ms, an automatic restart of the gyrotron is in many cases possible. Fig. 2 (l.h.s.) shows an example of a very quickly detected arc. The power measured at M14 is shown together with an expected value derived from The M1 signal. The time when the expected power drops to zero is when the gyrotron is switched off. There was only a delay of $40\ \mu$s between the drop of the actual M14 power and switching off the gyrotron. The arc detection algorithm triggers if the actual signal drops below 50 % of the expected signal

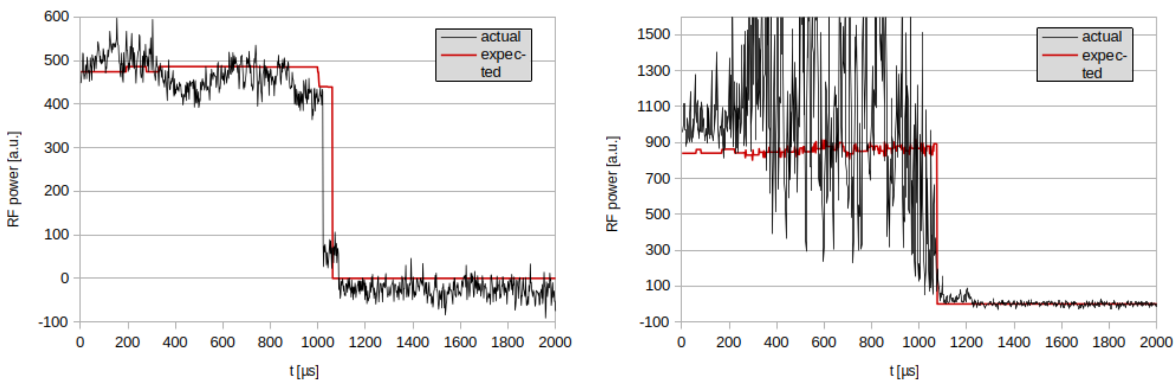

FIG. 2. Actual and expected power at the end of the transmission line measured by the arc detection system. (l.h.s.) An arc causes a sudden drop of power at M14 triggering a very fast shutdown of the gyrotron. (r.h.s.) An arc causes heavy oscillations of the power at M14 due to multiple reflections and stray radiation entering the diagnostic box. The gyrotron shutdown is delayed.

level for 5 samples in a row, i.e. for 10 μs. However, this simple criterion turned out to be insufficient to detect arcs reliably. The detection system at M14 is a part of the open quasi-optical transmission line. It is not only sensitive to the power beam redirected from the M14 mirror but also to stray radiation. An arc occurring close to the M14 detector causes a strong increase of stray radiation in the vicinity due to multiple reflections on metallic surfaces. This is usually observed as strong fluctuations in the output voltage of the M14 detector diode. Fig. 2 (r.h.s.) shows an example where for ~ 1 ms before switching off the gyrotron very strong fluctuation on time scales of the sampling rate are observed. The arc detection algorithm resets itself in that case because the signal drops below the detection threshold only for individual samples. We observed many cases, where an arc could fully develop before it was detected. The envisaged advantage of the arc detection by a fast power measurement instead of optical arc detection system was therefore not visible. We still had problems conducting further experiments once an arc had fully developed due to a polluted atmosphere which strongly increases the likelihood for further arcs. The approach to overcome this problem is to adapt the detection algorithm to react on the AC component of the signal. The new version will react on a sudden increase in the amplitude of a high pass filtered signal. In order to test the new algorithm before the next W7-X campaign, we will install another detector in the vicinity of our test load outside the beam. In this region, the signal level usually goes to zero because the microwave radiation generally propagates into the load where it is nearly fully absorbed. However, in case of an arc the beam is reflected leading to similar fluctuations as shown here. So, the AC component of the signal should be representative for signals from M14. Installing the diagnostic close to the test load has many advantages. On the one hand, test load operation is possible at almost any time and we can try different algorithms well in advance before they are really required for reliable plasma heating. On the other hand we use the test load among others to gain experience with long pulse operation of gyrotrons. This is quite difficult with plasma operation taking into account the limited experiment time foreseen for long pulse operation. Arcing in or near the test load is a similar problem as arcing near the torus. With an upgraded arc detection system we hope to improve the reliability also for test load operation. This would allow us to focus more on issues related to the gyrotron reliability.

3. BOOSTING SCHEME FOR CATHODE HEATER

The automatic recovery mechanisms implemented in our control system react on relatively short time scales compared to the energy confinement time of the plasma. In case of arcs we attempt to resume operation after 100 ms. However, not all possible failures allow an immediate automatic restart of the gyrotron. There will always be failures which require manual intervention or at least an assessment by an operator to decide if it is reasonable to restart the gyrotron. The longer a discharge lasts and the more tubes are operated in parallel, the more likely it is for such failures to occur. We made a series of experiments in order to find out at which time scales it is possible to restart a gyrotron. The critical point here is keeping the beam current sufficiently stable. The beam current in a gyrotron typically suffers an exponential decay after applying the acceleration voltage caused by cathode cooling due to electron emission. This is partly compensated by actively boosting the cathode heater current. We apply a feed forward boosting scheme which stabilizes the beam current after $\sim 10\ldots15$ s. An indirectly heated thermionic cathode used in gyrotrons is a highly inert system that requires the application of a boosting scheme,

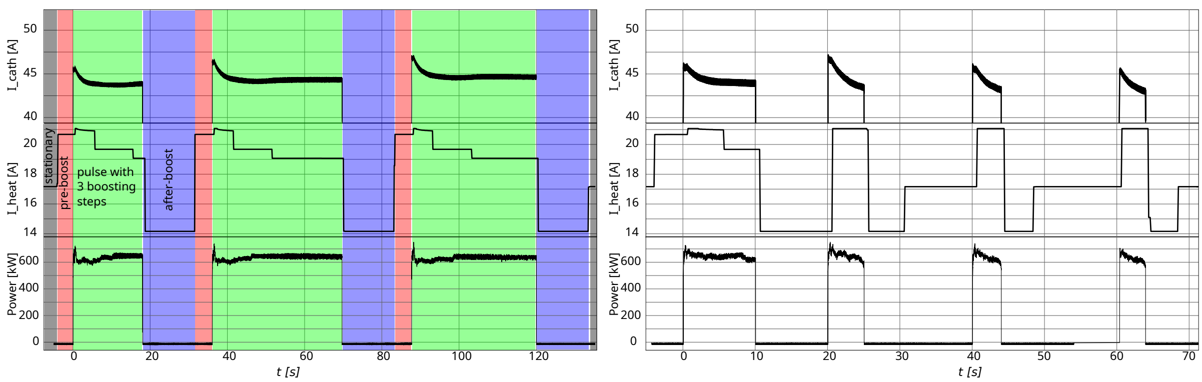

FIG. 3. Time traces of cathode heater current (black), beam current (blue) and RF output power (red) during long pulse operation with provoked interruptions and restarts. Different boosting schemes for the cathode heater current were tested. (l.h.s.) When a gyrotron stops operation, it is only restarted after going through a full cycle of after- and pre-boosing I_{heat}. Shaded regions mark the different phases of the boosting cycle. (r.h.s.) The pre-boost phase is ommitted before restarting the gyrotron leading to unstable regimes because the beam current drops too quickly.

in which the heating power is temporarily increased 5 s before applying high voltage to the gyrotron (pre-boost). Fig. 3 (l.h.s.) shows the typical scheme applied to the heater current in black together with the beam current in blue. After 15 s of operation we keep the heater current constant. The exact height of the boosting steps are determined experimentally for each gyrotron. On the other hand, after switching off the gyrotron there is some surplus energy stored in the cathode heater leading to a kind of memory effect when operation is resumed too quickly. In order to be able to restart a gyrotron as quickly as possible, a negative boosting scheme is applied to the heater after switching off the high voltage by reducing the heater current for a few seconds compared to the stationary value (after-boost). Fig. 3 shows expriements where we provoked gyrotron trips during long pulse operation and manually restarted after a trip. We compared different schemes for the heater current during the down time of the gyrotron. On the l.h.s. the full cycle of after- and pre-boost is gone through before restarting the gyrotron. One can see, that the beam current stabilizes at the normal operating point at ~ 45 A when the gyrotron is restarted applying this boosting scheme. On the r.h.s. of fig. 3 we tried to shorten the time to restart by omitting the pre-boost phase. Here, already after the first restart one can see a much stronger decay of the beam current than with pre-boosting. The second trip in this case was not provoked but was a real mode loss due to a too low beam current which could not be recovered automatically. The same holds for the second and third restart. In further experiments we found that stable operation after a restart is only possible with a break of > 20 s going through the full after- and pre-boost cycle or if the restart occurs in < 3 s with only a short after-boost period. The necessity for a relatively long pre-boost phase of 5 s compared to plasma relevant time scales like confinement times has important consequences on any attempt to compensate a loss of heating power. A tripped gyrotron cannot be immediately replaced by a spare gyrotron.

4. TOTAL POWER FEEDBACK CONTROL

For high performance plasma operation in W7-X the total ECRH power going into the plasma is crucial to sustain plasma parameters. At W7-X the loss of a gyrotron means a loss of ~ 10 % heating power. Therefore we developed a new feedback control scheme to stabilize the total heating power. Operation with a feedback controlled total power is only relevant for long pulse operation starting from ~ 60 s discharge length. Any automatic restart of a gyrotron can happen at time scales which are not critical for the plasma performance. Only when a manual intervention is necessary we loose power for periods in the order of some 10 s as described in sec. 3. As mentioned above, a lost gyrotron cannot be immediately replaced by a spare one on time scales at which the plasma will not suffer. Therefore we follow a different approach to keep the total heating power reliably at a constant level. The gyrotron output power scales almost linarly with the acceleration voltage. At W7-X we calibrated the gyrotron power w.r.t. the acceleration voltage using calorimetric measurements in the long pulse calorimetric load. Thus we determined a linear scaling for each gyrotron. The HV supplies for our gyrotrons operate in principle as amplifiers. Both cathode and body supply receive a digital set point signal from an FPGA based gyrotron controller. This allows an arbitrary waveform modulation of the acceleration voltage with a bandwidth in the order of a few kHz. Standard operation of gyrotrons during plasma operation of W7-X is that each gyrotron controller receives a power setpoint from the central W7-X control system. The gyrotron controller determines the required acceleration voltage and generates the set points for the HV supplies. We used the flexibility of this system to add a feedback controller on top of this feed forward control scheme. The idea is to increase the power of all running gyrotrons slightly when power is lost due to an interlock. A software based controller is implemented on a RaspberryPi platform running a real-time OS. It communicates via Ethernet with

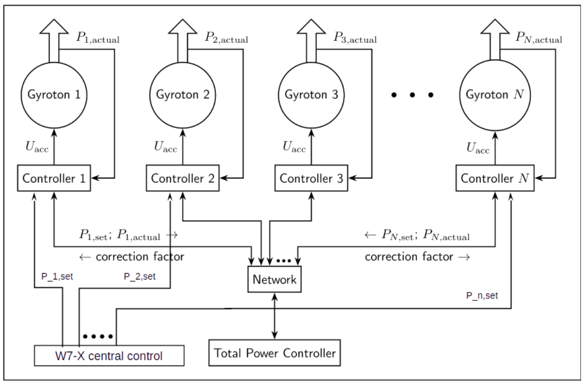

FIG. 4. Schematic overview of the communication paths used to realize total power stabilization. The W7-X central control send power set points to all gyrotron controllers. They generate set points for the high voltage supplies and measure the actual power. The total power controller communicates with the gyrotron controllers via ethernet (UDP). It receives actual power and set point, and sends back a correction factor for the power set point.

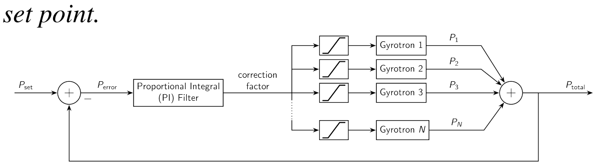

FIG. 5. Feedback control loop implemented in the total power controller.

all FPGA based gyrotron controllers. Fig. 4 shows an overview of the communication paths in our control scheme. The total power controller receives the actual measured power of each gyrotron as well as the power set point. On the total power controller the sum of all actual powers and set points are calculated and enter a PI filter. The filter determines a correction factor which is then sent back to the gyrotron controllers. The correction factor is multiplied by the nominal power set point before calculating the acceleration voltage. Ideally the correction factor would be 1 which means that the actual power equals the set point. When the actual power is too low, the PI filter increases the correction factor equally for all gyrotrons causing an increase of the acceleration voltage. Fig. 5 shows the closed control loop. In order to prevent additional faults when the corrected power set point exceeds the maximum power of a gyrotron, the acceleration voltage is limited in the gyrotron controller to an individual maximum value for each gyrotron.

A drawback of this technique is of course the necessity to operate the gyrotrons below their maximum power. In order to compensate the loss of two gyrotrons at a time a margin of 20 % is required. Hence only 80 % of the available total power are available for plasma heating. However, this requirement is in line with the necessity to operate the gyrotrons with the output power reduced by $10 \ldots 20$ %. We learned in the past experimental campaigns that gyrotrons operate more reliable at reduced power.

5. PERFORMANCE DURING OP 2.2/2.3

The overall performance of ECRH at W7-X was continuously increased over the last years. With all the measures in place that increase the individual gyrotron reliability they could be operated at higher power without increasing the risk of losing power during an experiment program. More than 14000 individual gyrotron pulses were requested in OP2.2/2.3 in 2400 W7-X experiment programs. 94 % of all gyrotron pulses ran through as planned without failure. This is only a relatively small increase compared to OP2.1 where we had a success rate of 92.4 %. However, it went together with a further increase in the mean power per pulse for each gyrotron. Fig. 6 shows a histogram of the mean power per pulse comparing the last operational phases of W7-X. In OP2.1 the gyrotrons were mostly operated a reduced power of ~ 600 kW. In OP2.2/2.3 we operated an increasing fraction of pulses at > 750 kW. Among the milestones to be achieved in the last experimental campaigns of W7-X (OP2.2/2.3) was to extend the energy turnaround to 2 GJ [4]. Fig. 7 shows the closest we got to achieving this goal. We achieved an energy turnaround of 1.8 GJ in an experiment program with 4.9 MW cw ECRH power for 360 s. The total power controller was used to stabilize the heating power. The plasma was in a detached divertor regime with a

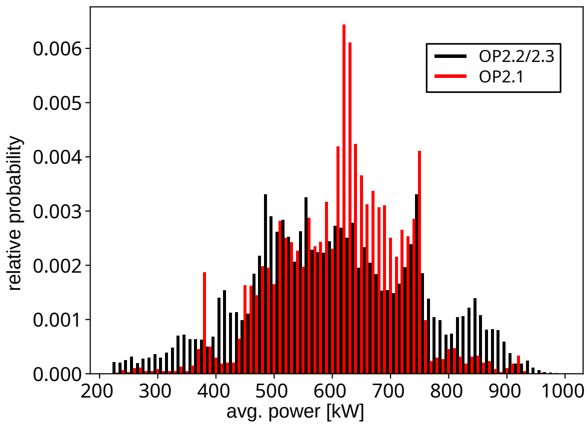

FIG. 6. Probability distribution of the average power of individual gyrotrons during a pulse. The last two experimental campaigns are compared.

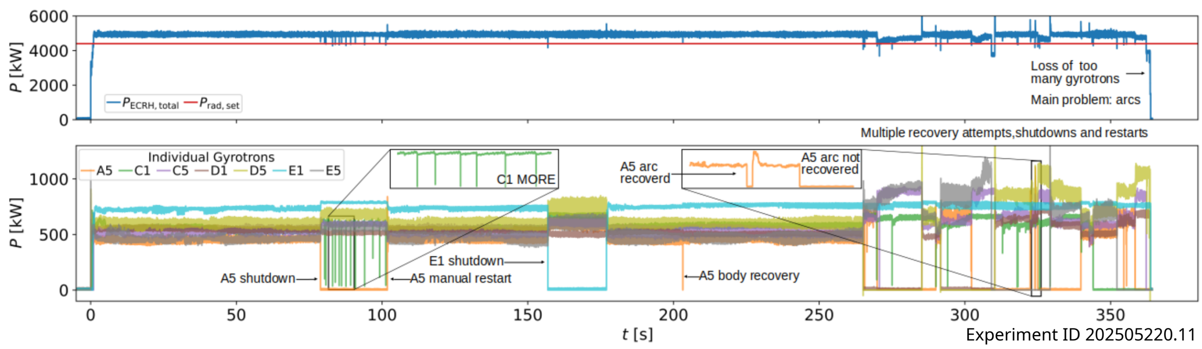

FIG. 7. Time traces of total (top) and individual (bottom) gyrotron power in an experiment program with 5MW ECRH power for 360s. ECRH power was feedback controlled using the total power controller. Several gyrotron dropouts can be seen which were compensated by increasing the power of the remaining gyrotrons. Starting from 270 s power could not be kept constant any more because too many gryrotrons failed due to arcing.

high radiation fraction to keep the divertor load low. The central W7-X control used a separate feedback system to control the radiated power P_{rad}. As shown in fig. 7, the P_{rad} set point was at 4.2 MW leaving only little marging for a loss of heating power. The lower plot in fig. 7 shows the power of individual gyrotrons. Despite several gyrotron dropouts the total power could be kept constant for 270 s. Until that point, gyrotron A5 and E1 tripped once each and were restarted after the boosting cycle explained in sec. 3. The power controller increased the power of all remaining gyrotrons during that phases. The short spikes in the individual power traces show interventions of our automatic recovery mechanisms. Starting from 270 s arcing becomes a significant problem. We had multiple gyrotron dropouts due to arcs on the critical section of the transmission line close to the torus window. They were partly caught by the M14 arc detection as shown by the example of a successful arc recovery for the A5 gyrotron. However, shortly after restarting the gyrotron the next arc occured causing a shutdown of the gyrotron requiring a manual restart. But even after the manual restart after 20 s the next arcs occured nearly immediately. The phenomenon of massive arcing problems after about $5\ \mathrm{min.}$ of high power operation was observed in all long pulse experiments attempts we made in OP2.3. This is a major problem which has to be solved for future campaigns of W7-X. It is assumed to be a thermal effect. The atmosphere in the critical area of the transmission line heats up during long pulse operation which may increase the likelihood for arcing. We are planning to overcome this problem by installing further air conditionig systems that inject very cold air in the critical area during long pulse operation.

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