Maintenance and preparation of the 3.7 GHz LHCD system for WEST operation

Léna Delpech[a,]*, *Joelle Achard*[a], *Arthur Armitano*[a], *Paul Bienvenu*[a] *and Marc Prou*[a]
[a] CEA, IRFM, F-13108 Saint Paul-lez-Durance, France.

Abstract : The generator for the 3.7 GHz Lower Hybrid Current Drive (LHCD) system on Tore Supra consists of 16 klystrons capable of delivering 600kW/1000s each on plasma. Such a powerful installation needs to be operated on a regular basis in order to preserve the specifications of the klystrons in terms of output power and pulse duration. This has been of particular importance during the long shutdown between the last Tore Supra campaign in 2011 [1] and the start of LHCD experiments on WEST in 2017. The TH2103C klystrons have been operated on matched load once a year during the shutdown. A reduction of 14% of the available RF power for the experimental program is found, which is partly due to the loss of one klystron. Another important aspect of the maintenance procedure is to maintain the knowledge of the operating team at a good level. This paper describes the procedure and tests performed during six years of shut-down. It also summarizes the technical problems encountered and the consequences on the test schedule, and highlights the importance of maintaining such large plants in operating condition during shutdowns.

Keywords: klystron, Lower Hybrid, RF heating system, generator

1. Introduction

The complete refurbishment of the Tore Supra tokamak into WEST tokamak equipped with a divertor dedicated to test Plasma Facing Components (PFC) for ITER, took place from 2011 to 2016 [2]. For the experimental campaigns, Lower Hybrid Current Drive (LHCD) heating system is one of the main heating to maintain long pulse operation and to ensure the power flux on the PFC targets is reached [3] [4]. The LHCD system consists of 16 klystrons TH2103C capable of delivering 600 kW /1000 s each on plasma, powering two launchers at 3.7 GHz [5][6]. To guarantee the reliability of such powerful system, the generator needs to be operated during the shutdowns. Not only the maintenance has allowed keeping the klystrons operational, but also the tests revealed that some parameters of the tubes evolved and sometimes some serious failures appeared. The traceability over the years of the state of the klystrons and the plant is essential as well as to maintain operator's skill maintenance. The tests and target to maintain the plant in good operating condition are described and explained. The paper summarizes the evolution of the 16 klystrons parameters during 6 years of shutdown in section 2 and finally, in section 3, it highlights the main failures the operators had to face.

2. Klystrons maintained in operational conditions

WEST LHCD generator composed of 16 powerful klystrons (700kW/1000s on matched load and 600kW/1000s on plasma) was upgraded in 2009-2010 (Fig 2). Half of the LH generator composed of 8 klystrons was commissioned both on matched load and on plasma with the Full Active Multijunction (FAM) launcher reaching routinely 3.5 MW of coupled power [7]. On the other hand, the 8 klystrons powering the Passive Active Multijunction (PAM) launcher have so far been commissioned on matched load only.

2.1 Klystrons maintenance

A klystron is a linear beam vacuum tube used as a RF amplifier. The klystron TH2103C in operation for WEST creates an electron beam of 21A accelerated under a voltage of -80 kV. The beam interaction with a 3W drive RF power travelling through resonant cavities amplify the drive RF power up to 700 kW in the case of the TH2103C. The vacuum in the tube is maintained by two ion pumps. The klystron and its auxiliaries are housed in a tank filled with 1000 litres of oil to avoid arcs between power cords, connections and material (Fig 1).

The shape of the electron beam travelling in the klystron, from the gun to the collector, is controlled by the means of three focusing coils. The settings of the focusing coil currents control the RF output power. Cavity temperatures and RF losses measured in the klystron as well as outgassing of the klystron can be the sign of abnormal interactions between the electron beam and the internal parts of the klystron itself. Also after a long period of shutdown, the pressure in the klystrons can increase as soon as the filament is heated or the electron beam and RF power is on. An interlock, on the ion pumps current level > 15 µA, prevents the electron beam to propagate to avoid an arc and then the destruction of the klystron.

* *Corresponding author*
Email adress : lena.delpech@cea.fr

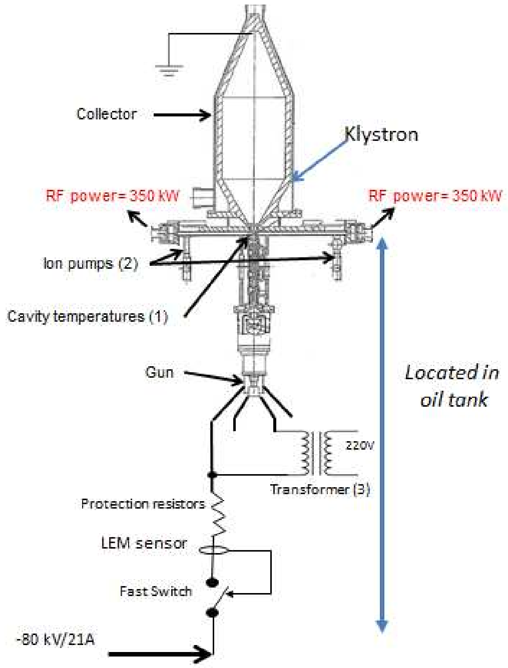

Fig 1 : One klystron and its auxiliaries installed in the LH generator (oil tank)

It is crucial to restart the klystrons quite often to check that the focusing coil currents are adapted to deliver the nominal RF power, to check cavity temperatures and RF losses and also to maintain the klystron operational and avoid over pressure. The criterion of the achievement of three shots of 550 kW/300s on matched load for each klystron was defined to provide 4.4MW of RF power for each launcher. Since 2013, the klystrons have been tested with the following steps :

- Start the klystron in diode mode (no RF power), up to the electron beam nominal value -74kV/21A. Check the vacuum conditioning and the perveance, as defined by $p = \dfrac{I_{beam}}{(V_{Cathode})^{\frac{3}{2}}}$ (I_{beam}= electron beam current, $V_{cathode}$ = accelerating voltage of the electron beam)
- Increase RF input power gradually while checking the cavity temperatures, RF losses, vacuum conditioning, klystron gain (dB) and efficiency (%). Comparison to the data obtained during the factory acceptance tests (Fig 3)
- Three shots at a RF power equal to 550kW/300s with no breakdown

Due to LH plant specifications, the klystrons cannot pulse simultaneously on matched load and three days for each are necessary to reach the target of 550 kW/300 s. The frequency of the klystron tests on matched load was led by the manpower available, the time necessary to operate the plant and also the shutdown for modifications or maintenance of the LH generator itself, the subsystems as HVPS or the cooling loop. Each klystron was tested at least once per year. From 2013, a specific annual report per year depicting the maintenance of the generator including: the klystron results and settings, the failures the operator has to face and the actions for the next year has been made available.

Fig 2 : Half of the generator powering the FAM launcher

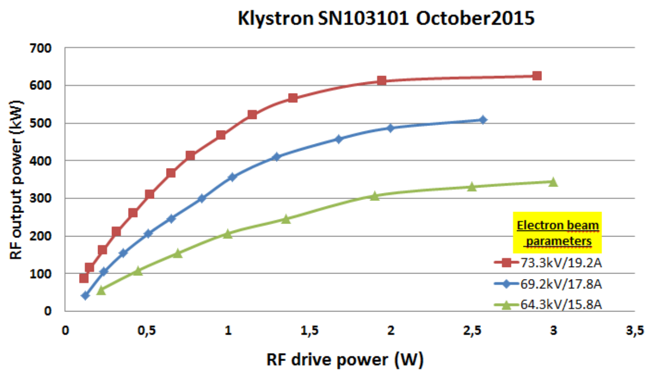

Fig 3 : Klystron Serial Number 103101, specifications that are checked during the tests. Evolution of the RF output power vs RF drive power and High Voltage power supply.

2.2 Evolutions of klystron parameters

Eighteen klystrons (16 for the LH generator and 2 spares) have been commissioned on matched load on the CEA test bed in 2009-2010. A first overview of the RF power available for plasma operation after the installation and commissioning of 16 klystrons in the generator (2011), shows a decrease of 20% compared with the total RF power reached on the CEA test bed. Some limits are due to the generator constraints and the fact that 4 klystrons share the same High Voltage power supply. After 6 years of shutdown some klystrons have evolved and the trend is a decreasing RF output power as shown in Fig 4 (decrease of 10% in 2017 compared with the value in 2011).

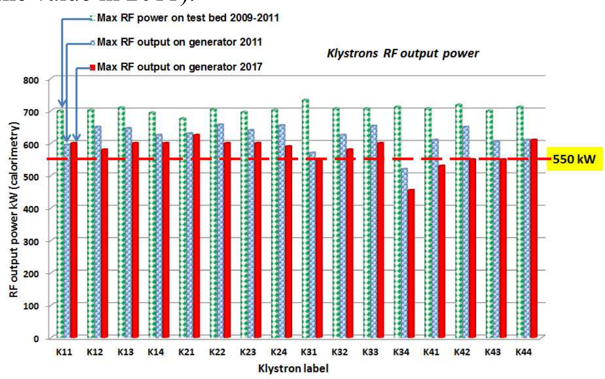

Fig 4 : Evolution of the RF output power of the 16 klystrons of the LH generator from 2010 to 2017

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During the shutdown, the objective of 550 kW/300 s has been achieved for all the klystrons expect for the ones labelled K34 and K41. In particular, the efficiency of klystron K34 is very low (27%) compared to the value obtained during the factory acceptance test and on the CEA test (45%) Fig 4. Two cavity temperatures are monitored and protected with an interlock at 200°C in case of abnormal conditions (Fig 1). The values of the two temperatures are usually in the same range depending of the RF power except for the klystron K34. It has to be noted that a strong dissymmetry was found as illustrated on Fig 5a and Fig 5b for two different sets of current values in the focusing coils. The currents were optimized to decrease the temperature in the cavity 1 (Fig5 (b)) and the three shots at 450kW/300s were performed. Neither the dissymmetry nor the degradation of the RF performances of the klystron can be explained by a special event or failure and no sign of outgassing during its operation occurred. The klystron will be replaced if the efficiency drops below 25% to maintain the RF power available for the PAM launcher at the required value.

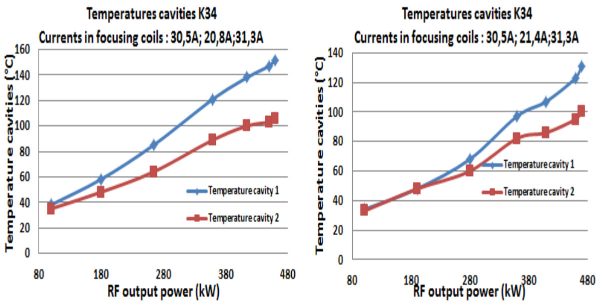

Fig 5(a) Fig 5(b)

Fig 5 Strong dissymmetry on temperature cavities in K34 measured (see Fig 1) with two different settings in the focusing coils

For the klystron K41, the focusing coils will be optimized to increase its gain in a near future. It has not been done due to lack of time.

3. Six years of shutdown: overview of the LH generator maintenance and failures

To increase the generator reliability, several LH subsystems have been replaced such as RF amplifiers, power supplies to heat klystron filaments and filament transformers inside oil tanks. During the period of replacement of the material or modification of the Programmable Logic Controller (PLC), the LH plant was not available for testing the klystrons on matched load.
As it is shown in Fig 1 and 2, the klystrons operating at a nominal value of -74kV/21A, are housed in an oil tank to avoid arcs between power cords, connections and material. Such voltages render crucial the choice of the material and the arrangement of the connections to avoid arcs in the tank. Also the dielectric strength of the oil is controlled every three years or in case of arc in the tank. A solid state switch to protect the klystron, a transformer to heat the filament, protection resistors and a LEM sensor to measure the electron beam current are connected with a cable compatible with oil and is 80 kV isolated. In case of a problem on the latter, to expertise the default and to repair, it is necessary to remove the oil, and in some cases to remove the klystron with a minimum of 5 days for the LH generator shutdown.

3.1 Replacement of eight transformers in oil tanks

The LH generator was upgraded when the klystrons TH2103A were replaced by klystrons TH2103C. This upgrade was performed in two phases. In 2009, a first phase dedicated to the replacement of the 8 klystrons, powering the FAM launcher, with the transformers to heat the klystron filament with new specification: 90kV/750VA. The second phase took place in 2010 for the 8 klystrons connected to the PAM launcher.
A new transformer (Transfo Industrie), made with resin was improved during 6 months on the CEA test bed. The choice of Transfo Industrie material was led by the compact size of the component. Eight transformers were installed in the LH generator in 2009 while the CEA test bed was still in operation. While the upgrade was ending, breakdowns occurred with the test bed transformer for HV > 5 kV due to arcs between the transformer's secondary and the screen. Following an expertise of the transformer, it was found that the fabrication process with the resin had created bubbles in the insulator. After a long period of operation, this part of the transformer being submitted to high electric fields, a slow process of degradation had created a crack as seen in Fig 6. As soon as the crack appeared the insulation was reduced from 80kV to 5 kV. The operation with the transformer was no longer possible. The problem was identified but facing the uncertainty that the transformers installed in the LH generator tanks suffer from the same defect, and because the replacement of the transformers for the klystrons powering the FAM required eight months of the transmitter shutdown, the replacement of the transformers took place in 2015 . The commissioning of the klystrons with Transfo Industrie transformers and the first experimental campaign in 2011 was performed successfully with 3.8MW/5s of LH power coupled to the plasma.

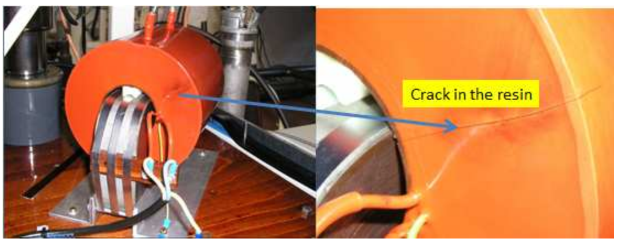

Fig 6 : Transformer Transfo Industrie 90 kV/750 VA

The replacement of the 8 transformers took place during the long shutdown in 2015. Six months were necessary to change the transformers including moving the klystrons and their auxiliaries. Following the hardware modifications, the commissionning of the 8 klystrons on

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matched load with the objective of 550kW/300s, was achieved in April 2016.
For the upgrade of the klystrons powering the PAM launcher in 2010, 8 transformers fabricated by ATESYS company were choosen.

3.2 Arcing in oil tank

Two major failures, that needed a deep analysis and heavy interventions in the oil tank, occurred on the klystron K33 in June 2015 and klystron K13 in January 2016 after the replacement of the 8 transformers. The signs of fault were similar : arcs for HV > 60 kV. The diagnostic was difficult as the arcs took place in the oil tanks. To avoid damaging the klystrons and also for the safety of the operators, a HV power supply 100kV/4mA was used to test the HV insulation. For klystron K33, the expertise took a long time because for each modification the oil was removed from the tank, then a inspection in the oil tank with a difficult access did not permitted to locate the defect easily, the tank was refilled with oil and the HV insulation test was performed. This operation was repeated 6 times before the operator identified the fault. The defect was located on the HV cable connecting the limiting resistors the tube to the transformer as seen in Fig 7. It is the same process as the transformer : a slow degradation of the conductor insulation. The cable was changed and the klystron was commissioned on matched load.

Fig 7 : HV cable defect

For klystron K13, the same defect appeared on the insulator of the cable and the arc occurred between the cable and the current transducer made by LEM to measure the electron beam current. The cable was replaced and the klystron commissioned again.
It is not foreseen for now, to replace all the HV cables of the 16 klystrons : it is not obvious all the cables have the same defects. The replacement of all the cables, the commissioning of the klystrons would take 16 months.

3.3 Klystron failures

The LH generator is equipped with 16 klystrons. Two spares TH2103C are stored and pumped with ion pumps and can replace a faulty klystron in the generator. These klystrons were commissioned on the CEA test bed in 2010 and are stored since then. A long period of conditioning will be needed to reach the 550kW/300s RF power with these two klystrons. As discussed in section 2.2, if the efficiency of klystron K34 decreases below 25%, this klystron will be replaced during a long shutdown. To change a klystron the estimated time is one month including the hardware and the conditioning of the tube on match load. During this period, the LH generator is shutdown.
In March 2017, while the LH generator was in shutdown (no circulation of the cooling water, the filaments were cold and no HV applied on the tubes), the pressure increased suddenly in the klystron K13. The current values measured by the ion pumps are recorded even when the generator is shutdown. The water analysis shows pH parameters in the range of klystron specifications. The klystron will be sent back in 2017 to Thales Electron Devices for expertise and will be repaired if possible. This klystron was replaced by a spare which will be commissioned after WEST experimental campaign in 2017.
These overview of a such powerful installation equipped with 16 klystrons is not exhaustive and only faults or maintenance having a major impact on the shutdown of the generator for maintenance are reported.

Conclusion

The LHCD system is mandatory for sustaining long pulse operation in WEST and essential for testing the PFC-technology for ITER in the framework of the WEST project. The generator, with 7.8 MW of available RF power after the loss of K13 (2017), was maintained during 6 years of shutdown to be operational on request. Taking into account all the constraints, manpower, schedule and shutdown of the plant to change auxiliaries (RF amplifiers, filament power supply…), all of the 16 klystrons were tested at least once a year. It also highlights the fact that, maintaining such plant operational upon request, requires constant work. Another important aspect is to keep operator's skill maintenance at the right level to deliver a reliable plant for experimental sessions. Following a 6 year shutdown, and thanks to a regular maintenance, all klystrons pulsed with RF power from 50 kW to 200 kW on vacuum (10 ms pulses) after only six days of conditioning on vacuum in May 2017, rendering the LHCD generator ready for WEST plasma operation.

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