CALORIMETRIC POWER MEASUREMENTS IN X-BAND HIGH POWER RF

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Abstract

With the aim to test prototype accelerating structures for CLIC at high-gradient, new klystron-based, X-band high power test stands are being built at CERN. These tests stands are referred to as Xboxes with Xbox1 and Xbox2 being already operational. Stainless steel loads are placed in the end of the Xbox-1 system to absorb the remaining power which comes out of the accelerating structure. Power information is important and needs to be measured precisely. A new power measuring method based on calorimetry is proposed independent from RF measurements subject to frequent calibration. The principles of the method and simulations are presented and the results of actual experimentation are used to validate the method. The results show calorimetric measurement is feasible method and have a good precision at this power level.

INTRODUCTION

X-boxes are X-band klystron-based high power test stands at CERN. They provide a peak power on the 50~100 MW range which generates a field gradient of about 100 MV/m in the prototype structures for the CLIC project [1]. The flexible and instrumented test stands provide important data for fundamental high-gradient studies including not only initial energy version of CLIC study but also X-band based XFEL linacs and medical linacs [2]. Xbox-1 has now been operated for over two years with the goal of conditioning and operating CLIC prototype accelerating structures. The preliminary results can be found in [3].

Stainless steel RF loads are placed in the end of Xbox-1 to absorb the remaining power which comes out of the testing structures. Power information is important for the data processing in operation and needs to be measured precisely. In order to achieve this goal, a new power measuring method based on calorimetry is proposed independent from RF measurements subject to frequent calibration.

This report describes the concept and principles of the calorimetric power measuring method. Simulation works and experimental set-up are also presented. The calorimetric power measuring experiment was done during the new CPI klystron's commissioning in Xbox-1 in 2014. The experimental results are used to validate the method and show that calorimetric measurement is a feasible method with good precision at this power level.

CONCEPT OF CALORIMETRIC POWER MEASUREMENT

The RF power coming out of the accelerating structures in Xbox-1 is fed into stainless steel RF loads. RF power was transformed into heat energy which will be taken away by the water cooling system in the load. In ideal situation, the RF input power should be equal as the heat energy taken away by the cooling water. The heat energy can be expressed as follows:

$$P = c \cdot \dot{m} \cdot \Delta T . \qquad (1)$$

P is the heat power absorbed by the cooling water. c is the specific heat capacity of water. $\dot{m}$ is the total mass flow rate of the water cooling system. ΔT is the temperature difference between input flow and output flow. The quantities $\dot{m}$ and ΔT can be measured by flowmeters which are attached to the water cooling system of the RF load. We can obtain input RF power by measuring these parameters in experiment and calculating heat power by the formula above. In order to avoid heat dissipation into ambient environment and improve measurement's accuracy, the loads are covered by heat insulation jackets.

SIMULATION OF THE LOAD

Before carrying out the experimental study of calorimetric power measurement, simulations of the RF load are needed for knowing electromagnetic and thermal properties of the system.

Basic Information of the Load

The stainless steel RF load used in Xbox-1 is double-band SS430 dry RF load, as shown in Fig. 1. The load is designed to be working at frequencies of 11.994 GHz and 11.424 GHz respectively [4]. It is made of magnetic stainless steel SS430 and consists of five functional parts which are shown in Fig. 2.

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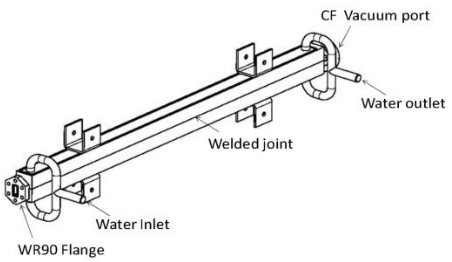

Figure 1: CERN double band SS430 dry RF load.

Figure 2 is one quarter of the whole load. The inside regular part has a corrugation shape's surface where RF wall current is efficiently damped.

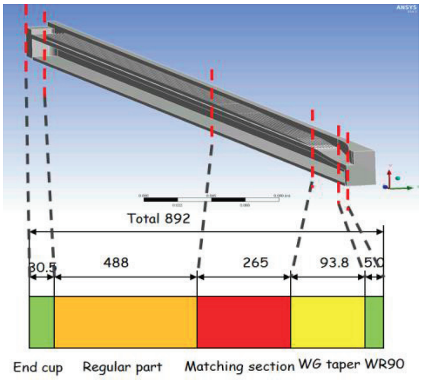

Figure 2: Five functional sections of the load.

Electromagnetic and Thermal Simulation

In order to understand the calorimetric properties of the RF load, electromagnetic and thermal simulations are carried out as the preparatory work.

The model in HFSS and magnetic field are plotted in Fig. 3, which shows that the magnetic field is highest in the matching part. In this simulation we feed 1 W into one quarter load at 11.99424 GHz. The heat generated by the electromagnetic field is proportional to the square of magnetic field. Hence, the matching part will be hottest part of the load.

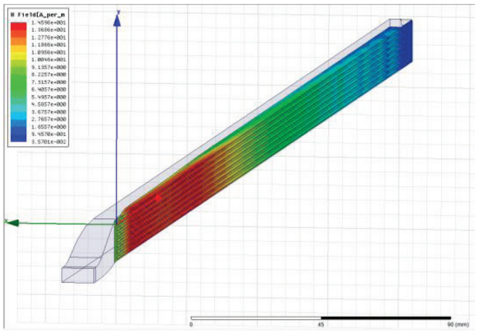

Figure 3: Magnetic field of the load in HFSS.

Thermal simulation is done by coupling HFSS and ANSYS. The surface loss results from electromagnetic field simulation in HFSS are exported into ANSYS to calculate the heat distribution of the load. In order to simulate the water cooling system of the load, we need to know the convection coefficient of the flow. According to the empirical formula from fluid dynamics, convection coefficient is obtained by calculating Reynolds number and Prandtl number of the flow [5]. The full thermal simulation can be done after applying the convection coefficient of the flow in ANSYS model.

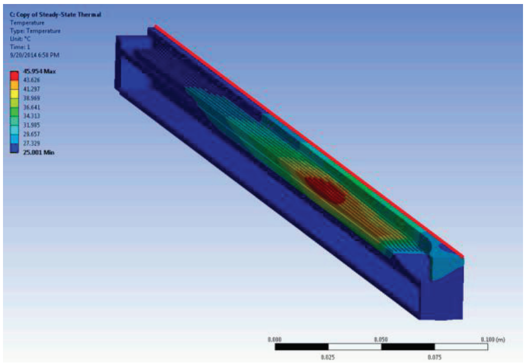

Figure 4: Temperature distribution of the load in ANSYS.

The temperature distribution of the load is shown in Fig. 4. We feed input power of 117 W to one quarter of the load and apply an input flow of 11.9 L/min with 25 degree in this simulation. This power level and flow rate are quite similar to the real situation in the operation. As expected, the matching part of the load is the highest part. Temperature sensors are set along the welding joint line which is the red line in Fig. 4 in the calorimetric power measurement to verify this simulation. This will be shown later.

CALORIMETRIC POWER MEASURING EXPERIMENT

Calorimetric power measurement was done during new CPI klystron's commissioning in Xbox-1 from Jun. 18, 2014 to Jun. 23, 2014. In the end the output peak power reached almost 23 MW with a pulse width of 1μs.

Experimental Set-up

For the klystron commissioning, a load assembly consisting of two X-band high power loads and one directional coupler is connected to the modulator and klystron in Xbox-1, as shown in Fig. 5. Temperature sensors and the heat insulation jacket are placed on the loads and flowmeters are added to the water cooling system of the loads.

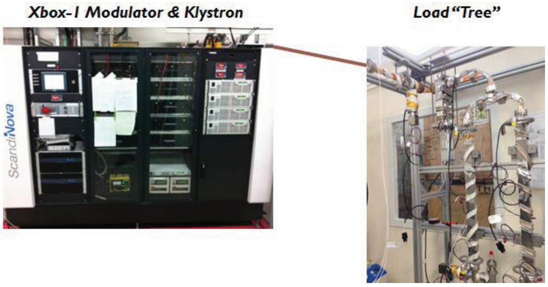

Figure 5: Experimental set-up in Xbox-1.

Experimental Results Analysis

The input power to the loads is measured by directional couplers system and calorimetry system, respectively. The RF measurements based on directional couplers system recorded input peak power and pulse width. Calorimetric power measurements recorded temperature difference between input and output flow and flow rate. Both of these sets of data can give the average power fed into the load, as shown in Fig. 6.

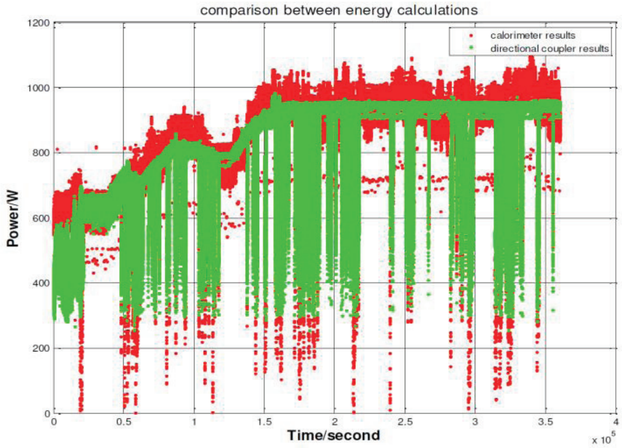

Figure 6: Average power comparison between RF measurements and calorimetric power measurements.

The two results have a good consistency with each other. The low peaks in Fig. 6 are caused by the breakdown events in the commissioning of the new klystron. Input power stops and will rise again after a few tens of seconds when breakdown happens. Calorimetric results fit with directional coupler's results in steady state. There is only less than 7% difference between the two results, as shown in Fig. 7. Due to the cooling water thermal inertia, a time delay is observed when power is ramping due to breakdown. With an average power of 938 W and a flow rate of 11.9L/min, the time delay is about 50 seconds. It causes big difference compared with directional coupler results.

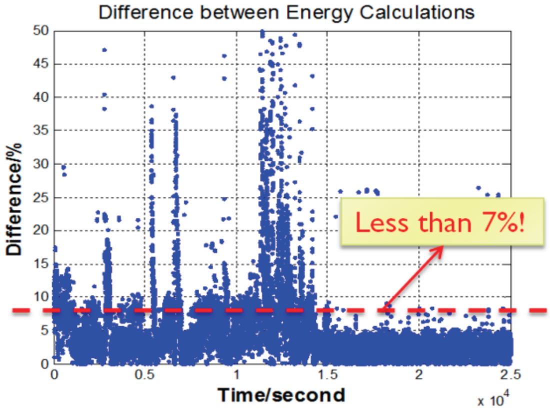

Figure 7: Difference between two power measurements in Jun. 22, 2014's 8 hours' operation.

Five temperature sensors are placed along the welding joint line of the load inside the heat insulation jacket. The experimental results are used to compare with the simulation results. ANSYS results of the temperature distribution along the welding joint line and temperature sensors' results are shown in Fig. 8. Both of the simulation and experiment are using 938 W input power and 11.9 L/min, 25 degree flow. Experimental results fit well with ANSYS simulation which validates the simulation.

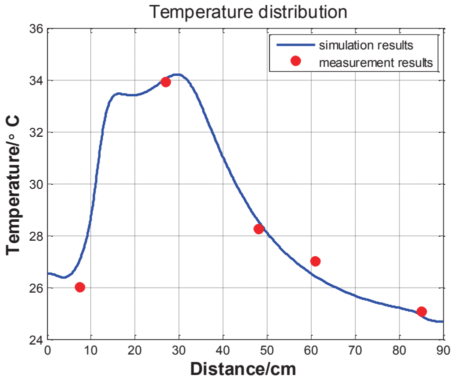

Figure 8: Simulation results of temperature distribution along the welding joint line and experimental results.

The flowmeter used in the experiment has an error of 3% in accuracy and 2% in repeatability, which may be the major contribution to the observed error. Using more precise flowmeters can improve experimental results. More careful calibrations also need to be carried out for the flowmeters.

CONCLUSION

In this work, a new power measuring method based on calorimetry is proposed independent from RF measurements subject to frequent calibration. Calorimetric power measurement experiment has been done to verify this measuring method. The results show calorimetric measurement is feasible method and have a good precision at this power level.

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