STUDY OF LCLS-II FUNDAMENTAL POWER COUPLER HEATING IN HTS INTEGRATED CAVITY TESTS*

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Abstract

LCLS-II coupler based on modified design of TTF3 coupler for higher average power was assembled on high Q cavity and tested at HTS as part of integrated cavity test program. Couplers were thermally connected to thermal shields and equipped with diagnostics to control temperature in different locations and provide information about cryogenic heat loads at 2 K, 5 K and 80 K. Three dressed cavities with power couplers were tested in HTS at full specified RF power. Results are summarized in this paper and cross-checked with simulation.

INTRODUCTION

The LCLS_II 4 GeV superconducting linac is based on XFEL technology intensively developed over the last couple of decades [1]. A major difference however is that LCLS-II operates in the CW regime, whereas the XFEL/ILC operate in pulsed mode. This required modifications to or complete re-design of some of the basic components: cavity, helium vessel, tuner, power coupler and other cryomodule (CM) parts in order to accommodate the much higher cryogenic loads expected in the CW regime.

The major modifications of the power coupler for LCLS_II project include reduction of the antenna length by 8.5mm to provide required Qext=4.e7, increase in the thickness of copper plating on the inner conductor warm section and reduce length of bellows to reduce coupler temperature [2].

To minimize the risks to the project all technical solutions and new designs have to be prototyped and tested in a cryomodule. Testing was focused on the most critical components and technical solutions, and performed in the Horizontal Test Stand cryostat (HTS) under conditions approximating the final CM configuration. An integrated cavity test was the last stage of the design verification program. In this test a nitrogen doped cavity previously qualified in a vertical cryostat, was dressed and fully assembled with all components (fundamental power coupler, two_ layer magnetic shielding, XFEL-type feedthroughs, end_ lever tuner). All components were previously individually tested in the HTS with cavities, but not as a complete integrated system. One major goal of this integrated test was to demonstrate that high Q_0 values demonstrated in vertical test can be preserved even when additional sources of heating from the power coupler and tuner and potential additional external magnetic fields from auxiliary components are present [3,4]. Other important studies related to design verification are: thermal performance and power handling of the fundamental power coupler (FPC), heating of HOM couplers and tuner components, tuner performance, sensitivity to microphonics, and frequency control. Data from this test program allows component design to be verified and certain other aspects of CM design (e.g., component thermal anchoring) to be finalized.

TEST PREPARATION

Each dressed cavity (AES021, AES027 and AES028) before installation in HTS was tested in a vertical test stand (VTS) without HOM feedthroughs. HOM feedthroughs and coupler cold section were later installed in a clean room. There was no cleaning work for the cavity during and after coupler installation.

The tuner was installed with a pre-determined cavity compression/frequency offset. Two layers of magnetic shield and magnetic shield end caps were installed on the cavity. Additional MetGlas® foil, a thin and flexible magnetic shield alloy, was used to cover the majority of the remaining openings in the magnetic shields. All fields were found to be less than 5mG.

The warm section of the power coupler was assembled on the cavity after it was installed in the HTS. A portable clean room was used to eliminate particle contamination. The cavity and coupler were actively evacuated during testing. The cryostat insulating space was evacuated to 1 x 10^{-6} Torr, and leak checked, before cooldown commenced.

Thermal Straps

Thermal straps were attached to the cavity beam pipes next to the end flanges. The two HOM feedthroughs were also thermally strapped. These thermal straps were then connected to the 2K two phase helium pipe when the cavity was installed in the HTS cryostat. Apiezon® grease was used to ensure good thermal conduction between the copper fixtures and the clamping surfaces.

The power coupler 5K thermal intercept is a specialized design utilizing high purity alumina and OFHC copper. The coupler 50 K thermal shield flange was connected to the cryostat's 80K thermal shield using two commercially procured high purity copper braids. The other two braids connected the 5K coupler intercept to the 5K thermal shield of HTS. These copper braids were extended by adding two straps made of pure aluminium (AL5N, each 95mm long, with a cross section of 125mm^2).

Diagnostics

In order to extract as much performance information as possible for this integrated test, the cavity and coupler were extensively instrumented with thermometers. A total of 17 RTDs were mounted onto the cavity itself, including 6 - inside the helium vessel on the cavity cells, 4 - on the cavity beam pipes and 6 - on each of the HOM assemblies. A total of 4 fluxgate sensors were mounted on the cavity: 2 - inside the helium vessel on the walls of cell #1, to detect the axial

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and tangential field components. The other two sensors were mounted on the beam pipes, to measure axial field components outside of the magnetically shielded volume. This combination of sensors allowed measurements of ambient magnetic field on the cavity walls before, during, and after the superconducting transition, providing an estimate of the effectiveness of both magnetic shielding and flux expulsion during cooldown.

The fundamental power coupler equipped with 15 thermal sensors: Cernox, platinum, and IR (infrared) sensors, to measure and monitor coupler temperatures (see Fig.1). These sensors have been attached to the 5K, 80K, and 300K sections of the coupler and thermal braids. The IR sensors monitored the warm window and warm inner conductor temperature. In addition, the coupler is equipped with electron pickups to measure electron activity at the cold and warm sections/windows that may be present due to multipacting or RF breakdown. The maximum temperature detected by infrared sensor on the inner conductor of the warm section of the coupler was about 400 K (130C) at 4kW of the rf power for all tested coupler

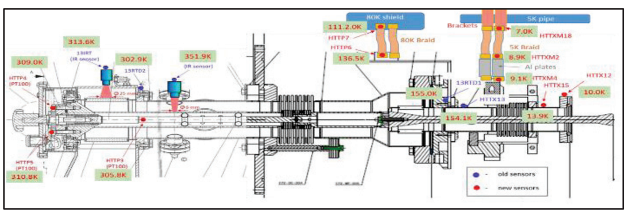

Figure 1: power coupler temperature diagnostics. Temperature map is shown for 4 kW of power measured for AES028 cavity "ON-resonance" in integrated test.

COUPLER RF POWER CONDITIONING

Power conditioning was initially performed at room temperature before cool down of the HTS. The maximum 6kW of RF power was applied. During conditioning the pressure in warm section of coupler was kept below interlock limit to 6.10^{-7} Torr, while RF power was increased gradually from 4.5 to 6 kW. Total processing time was ~ 10 hours, a minimal time to reach equilibrium temperature distribution, but not enough to stabilize coupler vacuum. Typical temperature distribution recorded at different locations along the coupler and braids are shown in Figure 2. There was no breakdowns or multipacting activities observed during the coupler conditioning at room temperature.

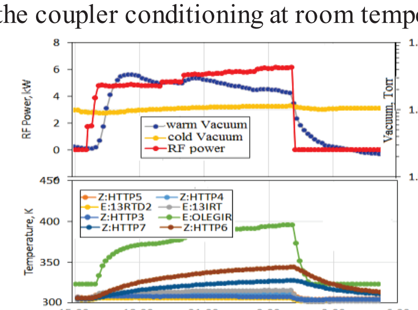

Figure 2: Power coupler warm conditioning. Upper plot shows RF power (red); vacuum in warm (blue) and cold (yellow) sections. Temperatures at different locations vs. RF power is shown in the bottom plot.

During RF power processing of the cavity AES021 the cryostat was open to air to provide better cooling conditions, but in later tests (cavity AES028 and AES027) the room temperature conditioning was done with insulating vacuum in the cryostat. Time constant for last two tests was similar to AES021 test.

Result of COMSOL simulation of the power coupler at room temperature for 6kW in standing wave regime is shown in Figure 3. Phase of reflection is defined from modeling of cavity with Q0=1.e4, boundary conditions are set as measured in coupler test in HTS. Assumptions are the following: 1) for copper plating: thickness is 10um on outer conductor and 100um on inner conductor, RRR=50, surface roughness 0-20%; 2) for ceramic: dielectric constant ε=9.8, tanδ=3e-4. Simulated power flux to 70K zone (CF100 flange) is in the range 18.7 to 20.9 W (depends on surface roughness) is consistent with measured results: 18.6W for cavity AES027 and 19.5W for the cavity AES028. Power was recalculated from differential temperature on copper braid and known thermal conductivity of braids used in tests. In conclusion, the measured temperature on inner conductor and power flux to CF100 flange are in good agreement with simulations.

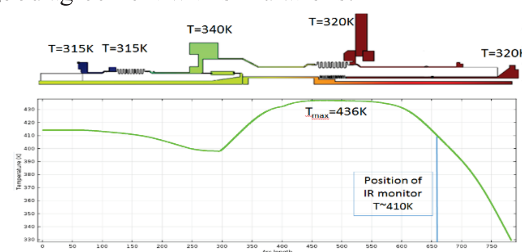

Figure 3: Temperature map and distribution along inner conductor of power coupler for room temperature power conditioning at 6kW.

COUPLER PERFORMANCE

After cool-down of the cavity to a nominal temperature of 2K, coupler conditioning continued with the cavity OFF-resonance. In this regime power dissipation and temperature in the coupler was lower compared to the cavity ON-resonance, as predicted in simulations. In earlier tests the coupler was conditioned up to 6 kW, but in latest integrated tests the RF power was limited by 4 kW.

Finally, the coupler was tested with the cavity "ON-resonance" with maximum 4kW of forward power, which produces the same heat load as the LCLS-II most stringent requirements at 0.3mA beam current operation: 6.4 kW forward power with 1.6kW reflected power (total 8kW) and a Q_{ext} of 4 x 10^7. Figure 4 shows the result of 1.5 days of coupler tests at different levels of rf power. The plot presents input power, vacuum and temperatures in warm and cold parts of the coupler (naming of sensors are shown in Figure 1).

The longest temperature time constant is for data measured at 80K zone defined big mass of the components here.

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Temperature measurements have been recorded at different power levels (1, 2, 3 and 4 kW) for cavity "OFF" and "ON" resonance. In some cases we start from higher power (6kW) to accelerate heating process and then switched to the tested power level, when temperature was close to equilibrium value.

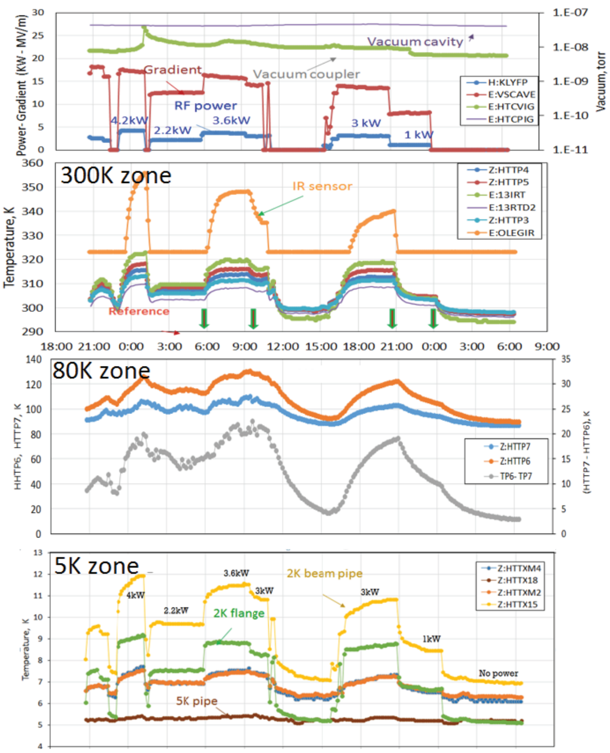

Figure 4: Coupler tested at different RF powers with cavity ON-resonance. Top plot shows RF power, accelerating gradient and vacuum in warm section of FPC. Bottom plots show temperature on warm and cold sections of coupler.

80K Zone: Temperatures and Heat Flux

Results from three integrated tests (AES021, AES028 and AES027) are summarized in plots in Figure 5 for the cavity "ON" and "OFF" resonance. The highest temperature is measured at CF100 flange, the lowest two curves show temperature on the copper braid (source and sink ends). One can see that in case of cavity "OFF- resonance" coupler heating is lower. Measurements are more reliable when done at least one week after cool-down, when temperature of HTS components was stabilized.

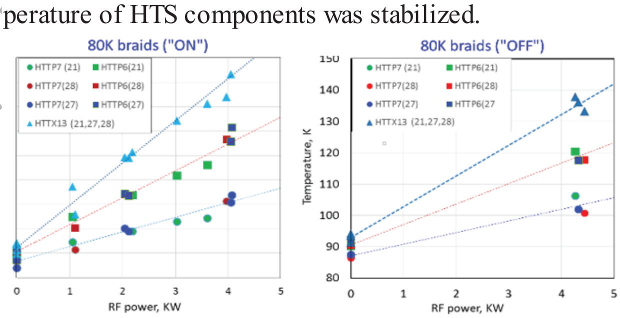

Figure5: Temperature vs. RF power measured at the 80K intercept zone with the cavity ON-resonance (left) and OFF-resonance (right).

Differential temperature on the copper braid for the cavity "ON" and "OFF" resonance is shown in Figure 6 (left). From data and calibrated thermal conductivity of the braids the heat flux going to 80K shield was estimated and plotted on the right. Simulated heat flux to 80K shield is 27W at 4kW power (cavity on-resonance) is in a good agreement with measurements. Based on test results, the design of the coupler thermal connection in cryomodule was finalized.

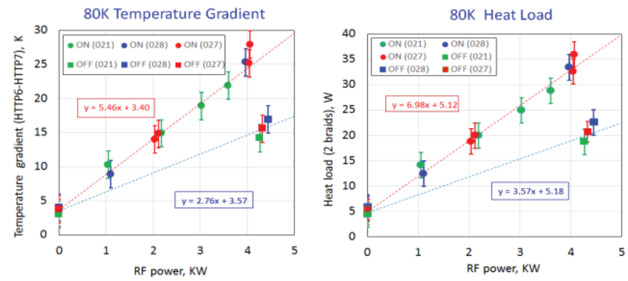

Figure 6: 80K intercept zone: Temperature gradient on the copper braid (left) and calculated heat load (right) vs. RF power for the cavity ON-resonance (circles) and OFF resonance (boxes).

5K Zone: Temperature and Heat Flux

Typical temperature distribution at 4kW rf power at 5K zone is shown in Figure 1 for the cavity "ON-resonance". Temperature gradient on the chain of copper braids and calculated heat load are shown in Figure 7 for the cavity "ON" and "OFF" resonance conditions. All braid were calibrated in temperature range from 4K to 300K.

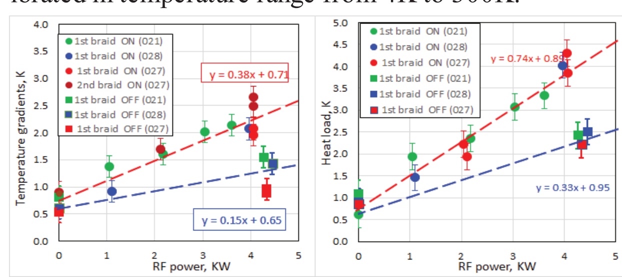

Figure 7: 5K zone: Temperature gradient on the braid (left) and recalculated heat load (right) vs. RF power.

CONCLUSION

The first integrated test at FNAL of a nitrogen doped high-Q cavity demonstrated that the cavity, assembled with all auxiliary components will not degrade cavity performance if done properly. Power coupler heating and performance in tests closely matches expectations.

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