CW Operation of the TTF-III Input Coupler

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Abstract

Several newly proposed superconducting linacs are designed to use TESLA technology operating CW rather than pulsed for which the system was developed. It must therefore be demonstrated that CW operation is feasible. Here we describe a series of CW tests with the TTF-III power coupler to determine the average power limit. These tests were performed on a coupler test stand both at room temperature at the FZ Rossendorf and under cryogenic operating conditions in BESSY's HoBiCaT[1] facility. An extrapolation of the measurements suggests that the coupler can handle 5 kW CW standing wave. It was also demonstrated that even higher power levels are feasible if the cooling of the inner conductor is modified.

INTRODUCTION

TESLA superconducting radio-frequency (RF) cavities were originally developed for pulsed operation in the TESLA linear collider and X-FEL. In part due to the success of the TESLA Test Facility (TTF) at demonstrating their reliable operation, a number of proposals for CW linac-based light sources are now based on this technology. They include the Cornell Energy-Recovery Linac (ERL), the BESSY Free Electron Laser (BESSY FEL) and the Daresbury Fourth-Generation Light Source (4GLS).

Much of the pulsed TESLA technology can be directly transferred to CW applications. Still, several components to be re-examined. This includes the TTF-III input coupler. It was designed for 1 MW pulsed power but generally is not operated at more than 1.5 kW average-power travelling wave. However, for the future CW projects, where beam loading is small and microphonic detuning dominates the power budget, up to 10 kW *standing wave* (SW) power will be required. Under these conditions, thermal aspects may limit the coupler operation.

To resolve this question, ACCEL Instruments, BESSY, Cornell, DESY and Forschungszentrum Rossendorf agreed to collaborate to test the CW limit of this coupler. The coupler was produced by ACCEL and tested at Rossendorf and BESSY. The Rossendorf tests were limited to room-temperature tests on a test stand supplied by DESY. These tests were expanded upon at BESSY, where tests under cryogenic conditions in the HoBiCaT facility, albeit without a cavity, were performed. In both cases the available transmitter power was limited to 10 kW CW.

* Funded by the BMBF, the Land Berlin and EUROFEL

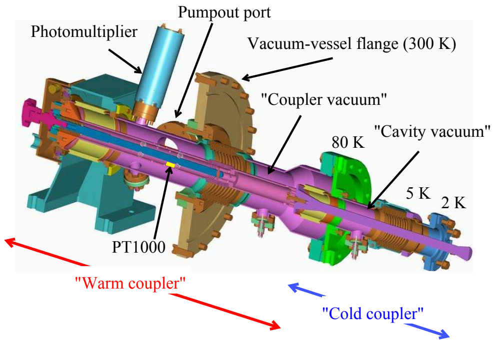


Figure 1: The TTF-III coupler

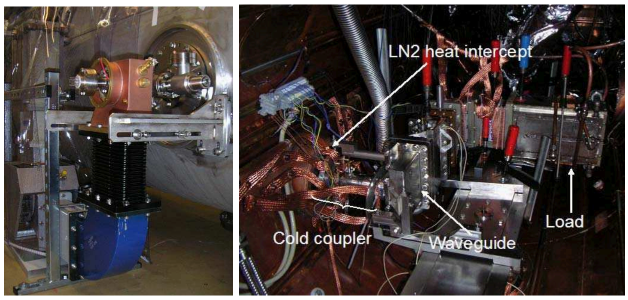
TTF-III COUPLER

Figure 1 depicts the layout of the TTF-III input coupler. It consists of two coaxial parts ("warm" and "cold") and a waveguide-to-coaxial-line transition. The "cold" part attaches to the cavity beam tube and has a common vacuum with the cavity, preserved by a ceramic cylindrical window. The warm part is attached once the cavity is inserted in the cryostat. A second, cylindrical window at the transition from waveguide to coax provides an additional vacuum barrier, the warm coupler segment being pumped through a separate line. Bellows in the coupler permit the coupling strength to be varied and facilitate alignment. The outer and inner conductors (except for the "cold" antenna) are 10-μm and 30-μm copper-plated stainless steel, respectively. Details on the coupler design can be found in [2].

For normal operation in the cryomodule, three heat intercepts exist. The cavity flange is at 2 K, with additional heat intercepts at 5 K and 80 K as shown in Figure 1. These are tied to the 5 K and 80 K heat shields of the TTF module.

The inner conductor is cooled simply by conduction through the cold ceramic and hence is susceptible to strong heating even if the losses are small. A thermal analysis of the design demonstrated that the most critical component (inner conductor bellows) heats by 25 °C per kW of travelling-wave power for room temperature operation. At cryogenic temperatures it is expected that the conductivity of the ceramic improves by about a factor 3–8, so that the coupler should be able to operate at higher power because the inner conductor is cooled better. These simula-

Figure 2: Coupler stand used for warm coupler tests.



(a) (b)

Figure 3: (a) Warm part of the coupler mounted on the outside of HoBiCaT. (b) Cold part of the coupler mounted in HoBiCaT along with the waveguide load. The copper straps are used to cool the 77-K and 2-K points of the coupler to about 100 K.

tions also suggest that the radiative losses play an important role when cooling the inner conductor at power levels above 4 kW travelling-wave (TW) power [3].

EXPERIMENTAL SETUP

Tests at Rossendorf

For the initial room-temperature tests, the coupler was mounted on a single-coupler test stand (Figure 2). A ceramic waveguide window preserves the vacuum in the cold section of the coupler and the waveguide. On the air side, a water-cooled RF load absorbed the transmitted RF power. The coupler was matched to the waveguide by adjusting the penetration for reflectionless operation, so only TW operation was tested. The only cooling provided was cold-water (2.2 °C) cooling of the 70 K flange.

IR sensors monitored via viewports the warm ceramic temperature and that of the warm inner conductor. The tuning rod was removed and a PT1000 temperature sensor was attached inside the inner conductor near the the bellows (see Figure 1). Several PT100 sensors were also mounted on the exterior of the coupler. A CPI klystron provided 10 kW CW RF power.

Tests at BESSY

At BESSY, the waveguide test stand was mounted in the HoBiCaT facility, as shown in Figure 3. Initial warm tests with a matched load were performed to verify the Rossendorf results. For cryogenic tests, HoBiCaT was operated with liquid nitrogen only. Copper bands were attached to the 77 K and 2 K points of the coupler as shown in Figure 3(b) so that the coupler could be cooled. Typically the 77 K point reached an equilibrium temperature of about 120 K. The waveguide ferrite load was also in the HoBiCaT insulation vacuum and kept at room temperature by the water flow that removes the dissipated RF power.

Additional ports were added in the waveguide to improve the pumping of the load by the insulation vacuum. Nevertheless, at power levels above 2 kW the outgassing from the ferrite was so severe that arcing would occur in the load. Thus cold tests were limited to 2 kW TW power.

For SW operation the load was replaced by a short. By adding different waveguide lengths ($\lambda/4$ and $3/8\lambda$) the SW pattern could be shifted to different parts of the coupler.

A simple modification to improve the power limit has been proposed by Cornell [4]. One key aspect is the cooling of the inner conductor with air, a modification that can easily be incorporated in the TTF coupler. To test this scheme the feedthrough at the warm ceramic was removed and a tube was inserted into inner conductor. Room-temperature air was flowed through the tube and allowed to escape through the open feedthrough flange. Since there are small holes in the inner conductor, the entire warm coupler thus was at 1 atm, but most of the air flow was limited to the interior of the inner conductor. The total air-flow rate for these tests was about 20 liter/min.

RESULTS

Figure 4(a) illustrates a typical measurement as the power is being raised in steps. The thermal time constant of the inner conductor is very long (about 50 min), so that the measurements are very time consuming.

Also included in Figure 4(a) is the temperature of the warm ceramic. This ceramic was easily air cooled via two fittings in the waveguide hat, so that its temperature never came close to the recommended maximum value of 80 °C during any of the tests.

Figure 4(b) depicts the temperature rise measured by the PT1000 sensor per kW of RF power as a function of power under various operating conditions.

A comparison of the room temperature tests at Rossendorf and BESSY show that the results are consistent, with a temperature rise ($\Delta T/\Delta P$) of about 29 K/kW, so that at 4 kW the absolut temperature is about 140 °C.

Several observations should be pointed out:

1. No significant difference in $\Delta T/\Delta P$ was observed between warm and cold tests, except that there is an offset temperature of about 25 °C for the inner conductor (T_0 in Figure 4). For the room temperature tests $T_0 = 295$ K

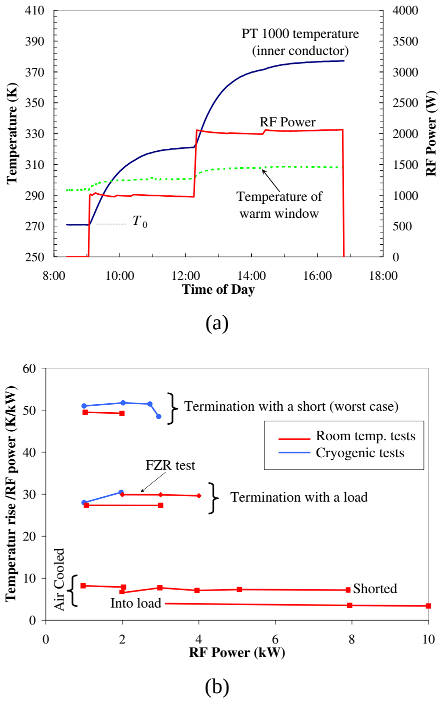


Figure 4: (a) Example of PT1000's temperature versus time. Measurements were made with HoBiCaT cold and the waveguide shorted. (b) Summary of the all tests.

and for the cryogenic tests $T_0 = 270$ K. Thus, the improved thermal conductivity of the ceramic does not appear to cool the inner conductor any better. One reason may be that the warm inner conductor is joined to the cold ceramic by simple compression being exerted by an Allen screw. This "joint" may therefore limit the heat conduction so that improvements in the ceramic's conductivity help little.

2. Values for $\Delta T/\Delta P$ are independent of the power up to 4 kW TW within the measurement accuracy. Thus nonlinear effects, such as radiative cooling, appear not to be of consequence in the investigated power range. Given that the couplers are fired at 400 °C following fabrication, the inner conductor should easily be able to handle temperatures of at least 300 °C, which corresponds to a power level of about 10 kW TW for the cold tests if one extrapolates the curves. Simulations predict that at higher temperatures radiation cooling does actually play a role improving the power limit further.

3. As expected, SW operation increases the heating of the inner conductor, the amount depending on the position of the short. In the worst case the heating nearly doubles. Since low beam-loading machines such as the BESSY FEL will operate mostly SW due to microphonic detuning, the maximum operating power is roughly halved. Thus, in the present coupler configuration SW operation up to 5.5 kW should be possible given the 300 °C temperature limit discussed in 2.

Unfortunately for the cryogenic tests we were unable to apply more than 2 kW TW due to the arcing in the load meantioned above. Similarly, for warm operation (load at 1 atm) we were limited to about 3 kW SW by the vacuum in the warm coupler part which then exceeded 10^{-5} mbar. At this level, the temperature rise was nearly 160 °C and presumably the epoxy of the PT1000 sensor was outgassing heavily.

Because we observed little difference between warm and cold tests, experiments with the air cooled inner conductor were all performed at room temperature. The results are also shown in Figure 4(b). Clearly, the heating drastically reduced and the available klystron power (10 kW) limited the test. For SW operation, the temperature rise is again roughly double that for TW. Klystron interlock trips (reflected power) in this case limited the test to 8 kW. Nevertheless, when extrapolating the curve, one does not reach 300 °C until about 38 kW SW is applied. One should be aware of the fact, though, that other components may limit the operation to a lower power.

For example, the antenna tip is not actively cooled and heats significantly. This was monitored with an infrared sensor (emissivity set to 0.28) and a temperature rise of about 11 °C/kW was observed, which, for room temperature operation, would limit the coupler to about 25 kW SW. Still, this value is sufficient for machines such as the BESSY FEL and the Cornell ERL.

SUMMARY AND OUTLOOK

The extrapolation of the test results suggest that the existing TTF-III coupler can very likely be operated safely up to 10 kW TW and 5 kW SW, although the direct verification is still outstanding. Whether long term operation with a cavity at this power level is possible must also still be demonstrated. For example, outgasing may be an issue due to the elevated coupler temperatures.

A simple cooling scheme of the inner conductor has been demonstrated, which can be incorporated given minor modifications of the warm part of the coupler. As was demonstrated, this improves the power limit to at least 8 kW SW and the extrapolation of the results suggest that even 25-kW SW operation is feasible.

No significant difference between warm and cold operation was observed. Hence we plan to equip the coupler with additional temperature sensors and retest this at room temperature on the coupler test stand to increase the power further. In parallel, the same coupler design will be mounted on a TESLA cavity and tested in HoBiCaT under normal cavity operating conditions. We plan to build a redesigned coupler with the improved air cooling to test this up to 15 kW SW once a 20-kW transmitter comes online at BESSY.

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