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RF CONDITIONING OF 120 KW CW 1.3 GHz HIGHPOWER COUPLERS FOR THE bERLinPro ENERGY RECOVERY LINAC*

A. Neumann†, W. Anders, A. Frahm, F. Goebel, A. Heugel, S. Klauke, J. Knobloch, M. Schuster, Y. Tamashevich
Helmholtz Zentrum Berlin, 12489 Berlin, Germany

Abstract

This year, the commissioning of the 50 MeV, 100 mA bERLinPro Energy Recovery Linac test facility [1] will resume. For the Booster cryo-module of the injector line, operated with three modified 1.3 GHz Cornell style 2-cell SRF cavities, a new type of power coupler was developed, based on KEK's C-ERL injector coupler. Modifications were made for a stronger coupling and lower emittance diluting coupler tip variant, a so-called Golf Tee shape and the cooling concept was redesigned based on KEK's first experiences. For the final stage, the injector needs to deliver a low emittance beam of 100 mA average beam current at 6.5 MeV. That results in a traveling and continuous wave forward power requirement of up to 120 kW for each coupler of the twin setup feeding one Booster cavity. In this contribution we will give a short overview of the RF design and its impact on the beam's emittance, give an overview of the conditioning teststand and the results achieved with the first pairs of couplers.

INTRODUCTION

For the bERLinPro ERL [1] the Booster module housing three two cell SRF cavities needs to accelerate the beam from about 2.3 MeV of the SRF photo-injector [2] to 6.5 MeV, whereas the first cavity will be used in zero-crossing mode to allow bunch shortening for the injection into the merger/recirculator section. See Figure 1 for an overview of the coupler-coldstring assembly. Besides transmitting in total 420 kW power to the beam, the acceleration process in the Booster needs to preserve the low beam emittance from the photo-injector. Thus, a coupler design had to be optimized in withstanding the high thermal load by this power level and also minimize any influence on the beam by transverse field components of the geometry variation caused by the coupler arrangement to the field symmetry.

Figure 2 depicts a schematic of the coupler design and how it is attached to the cavity. To minimize the power load per coupler and to mitigate kicks by the field distorted by the coupler as well as emittance increase, two couplers power one cavity. The coupler design is a modification of the C-ERL injector cryo-module coupler [3] and features a single window, fixed coupling and avoids such any bellows exposed to RF. Mechanical variations during e.g. cool-down are compensated by the doorknob part itself and bellows outside the module in the waveguides. Cooling is provided by 5 K and 80 K helium heat intercepts. The major heat transfer is by water cooling of the inner conductor, the outer conductor of the warm part, the doorknob section and the ceramic window by a copper sleeve. More information on the RF and mechanical design can be found here [4] and here [5, 6]. The antenna tip is designed such, that at full

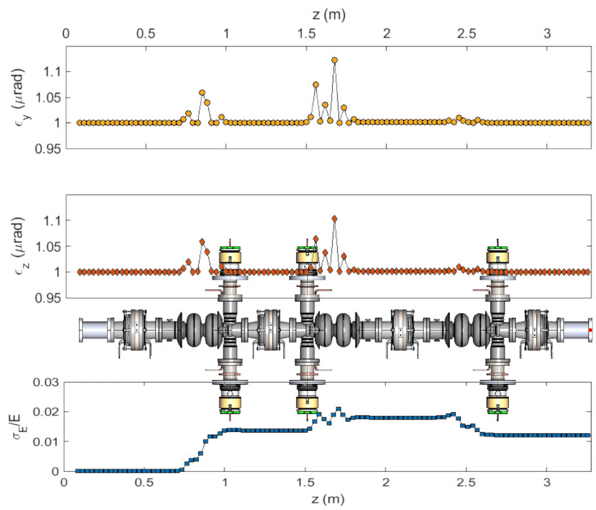

Figure 1: Booster SRF injector cold string layout with attached coupler cold parts and SiC HOM loads between adjacent cavities and exit beam tube. The three plots show the relative energy spread (bottom) and transverse normalized emittance for both planes without space charge calculated by 3DS CST PIC tracking. The emittance increases by 0.3% in both planes is caused by coupler kicks due to port variations as measured with a CMM tool.

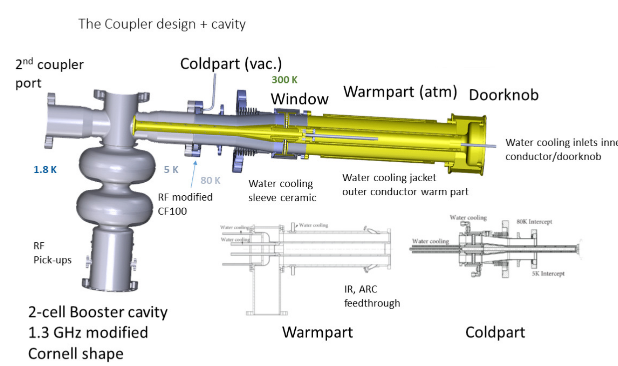

Figure 2: Schematic overview of the bERLinPro Booster injector coupler. The insert gives an better view on the water cooling channels and the diagnostic port observing the ceramic window.

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† Axel.Neumann@helmholtz-berlin.de

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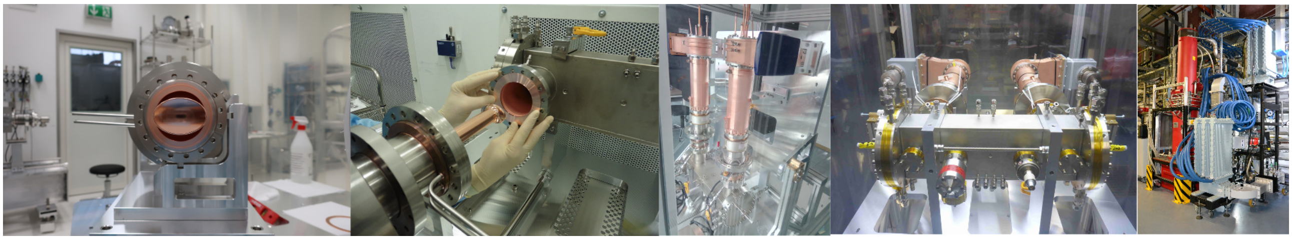

Figure 3: Overview of the steps taken from cleanroom assembly to final setup at test location of the conditioning set up and the CPI 270 kW klyston to operate the coupler teststand.

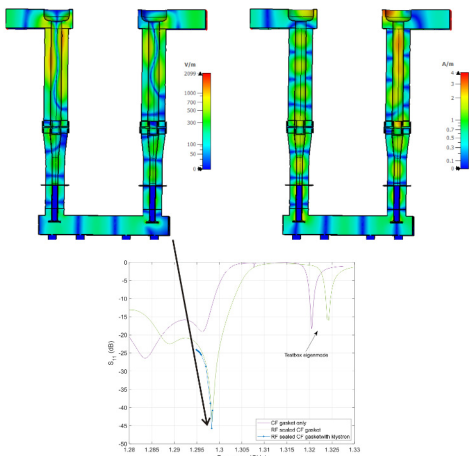

Figure 4: Top row displays the traveling wave field distribution for absolute electric (left) and magnetic field component (right) solved by 3DS CST FD solver normalized to 0.5 W_{rms} input power. The lower plot depicts the S_{11} scattering parameter of the testbox with a pair of couplers mounted with normal CF gasket at the 5K port, RF sealed CF gasket (both measured by VNA) and the same using the Klystron as power source.

beam current, the tip needs to be flush with the beam tube to achieve the desired coupling value.

For the first stage of the ERL, the SRF photo-injector will be limited by power coupler and thus deliver at target beam energy of 2.3 MeV up to 6 mA. Hence, it was decided, to assemble the Booster module with the power couplers retracted by a distance ring of 20 mm thickness to increase the loaded Q for optimum coupling for the lower average current goal, which will also significantly decrease the power consumption of the facility in the first years. Table 1 shows an overview of the operation parameters of the Booster for both stages. The power couplers can thereby be conditioned to a more relaxed target level, but still one coupler pair will be powered to the full design range of 120 kW to demonstrate the capabilities for the future upgrade. In total eight couplers were fabricated, whereas the cold part was produced by Canon Electron Tubes and Devices, while the warm part by FMB Berlin. In this paper, an overview of the conditioning process is given and some example data from the first coupler tests with the first two pairs being installed on the teststand.

Table 1: Parameters of the 1.3 GHz SRF Booster Cavities Operated On-crest and in Zero-crossing Mode for 100 mA and 6 mA of First Stage SRF Gun Operation [2]

Parameter	**at 100 mA**	**at 6 mA**
Loaded Q	$1.05 \cdot 10^5$	$1.74 \cdot 10^6$
$f_{1/2}$	6.2 kHz	374 Hz
V_{acc}	0.56, 2.1 MV	0.56, 2.1 MV
E_0 (MV/m)	4.833, 19	4.833, 19
Φ_{acc}	-90, 0 deg	-90, 0 deg
Penetration depth	2 mm	−18 mm
$P_{forward}$ TW	3.4, 220 kW	0.2, 13.8 kW
$P_{forward}$ SW	3.4, 54 kW	0.2, 3.45 kW

CONDITIONING SETUP

To condition the couplers to target power level in traveling and standing wave regime a dedicated RF testbox has been designed and built. It allows room temperature tests up to 150 kW of a coupler pair and comes with extensive diagnostics based on expectations of coupled thermal-RF simulations, but also observations done in the past at KEK. All critical points are measured temperature wise by PT-100 sensors, all water flow channels are measured including the inlet and outlet temperatures. This allows to calculate power deposited in the different cooling channels. For that reason, each channel for the conditioning is controlled by a separate set of flow meter and temperature sensor. In addition to external monitoring with an IR camera, each ceramic's temperature is measured with an Raytek IR sensor. Also, each coupler is equipped with a light fiber ARC detector and an electron pick-up similar to XFEL couplers [7]. Alternatively, both ports observing the ceramic window can be equipped with ARC detectors to allow for coincidence measurements in case of a too frequent triggering by random events. Peak power meters are installed on directional couplers attached to the teststand to obtain forward and reflected signal at the input upstream coupler and the power level transmitted by the 2[nd] downstream coupler. From assembly to conditioning, the following steps are taken:

- Cleaning of all parts prior to cleanroom transfer
- Cleaning of parts being assembled in cleanroom

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- ISO 4-5 cleanroom assembly of coupler coldpart to testbox, pumping and leak check
- Vertical transport of setup to testing location inside enclosed carrier system
- Shift to horizontal conditioning position inside carrier
- 120 °C baking of the vacuum part, including the coupler cold part
- Assembly of warm part, cooling water lines, doorknob transition in local cleanroom
- Connection of cooling water and final diagnostics
- Check of S-parameters of the setup by vector network analyzer (see 4)
- Connection of RF waveguides, low power tests with klystron, check power balance
- Conditioning starts at 40 Hz and 1 ‰ with 250 kW klystron from CPI limited to 150 kW output.

Figure 3 gives an impression of the different assembly steps from cleanroom to the set up at the test location in the bERLinPro accelerator hall. Figure 4 displays the electric and magnetic field distribution as calculated by CST frequency domain solver [8] for a traveling wave operation in the upper row, whereas the lower row depicts measured S_{11} scattering parameter using standard conflat gasket by VNA as installed during the very first conditioning trials compared to the same parameter measured with VNA with newly designed RF sealed conflat gaskets, as well as some data points taken with the klystron powering the set up. The working point is given by the minimum still being within the klystron bandwidth, that further tuning was not required. It should be noted, that under cold conditions at the cavity, the lower part will have a modified geometry due to shrinkage and thus further conditioning with the cavity might be mandatory, even though it should be better avoided with SRF resonators. The conditioning procedure follows a proposal by [9]. A simplified scheme of the setup at HZB is given in Figure 5.

- The conditioning starts at short pulses at a duty cycle of e.g. 1 ‰, just below any possible formation of multipacting behavior.
- The power is increased in small steps to an intermediate target level, where it is kept for a while.
- From here on, the power is ramped down in the same step width and time intervall as the ramping up was performed.
- During conditioning all diagnostic signals which prevent powering the teststand by an interlock signal are continously monitored and would trigger a switch off of the RF signal from the frequency synthesizer and also interrupt the pre-amplifier of the klystron.

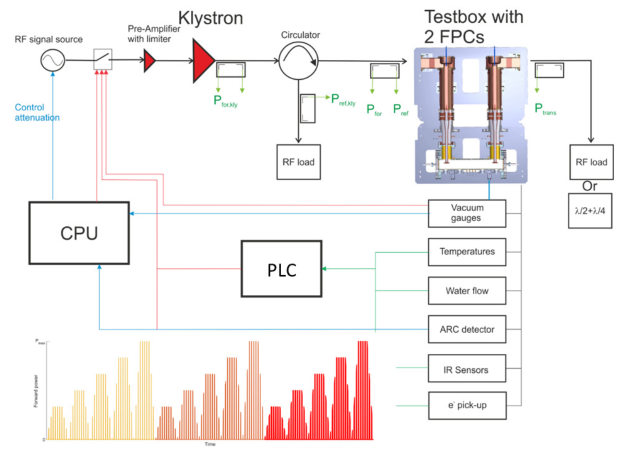

Figure 5: Scheme of the conditioning procedure: The pulse width, denoted by color code, is increased from a set of power ramps to the following. For each power level a ramping up and back down is performed. Depending on vacuum condition and without any other interlock, the power can also be kept constant, decreased or will be completely shut off.

- The current power level during conditioning is mainly controlled by the programmed ramp, but can be anytime depending on the vacuum level kept constant, decreased by a larger step or completely shut off, still with the goal to finalize the curve of the full ramp.

The choice of vacuum level and useful power step width without abandoning the success of the RF conditioning, but also avoiding a too long turnaround time of a pair of couplers, is a result of experience and trials with the first prototype or pre-series couplers. Interlock reacts at $5 \cdot 10^{-6}$ mbar.

COUPLER CONDITIONING RESULTS

To commission the conditioning teststand, the pre-series pair was installed. Because of delayed availability, the couplers were still mounted with standard conflat flanges. During regular conditioning, the normal CF gaskets were exchanged with RF optimized versions closing the gap and decreasing the measured S_{11} parameter from −25 dB to −35 dB. The teststand with the first pre-series was baked once more to 120 °C after CF gasket exchange and commissioning in pulsed mode went quite smooth with only few interlock events by vacuum activity up to 90 kW at 40 Hz and 10 % duty cycle (see Figure 6).

No excessive heating was observed and thus conditioning resumed with the lower target value for phase 1 operation of bERLinPro to reach 40 kW forward power in CW traveling wave and about 17 kW in standing wave. Here, first the full cycle from 1 ‰ to CW was completed. The goal was quickly achieved without any events and a heating of the ceramic window of 0.25 K/kW was extracted, which hints at a possible operation of the couplers at the 120 kW target power level. Figure 8 display the power ramps and window heating measured by IR sensors for the pulsed and CW traveling wave

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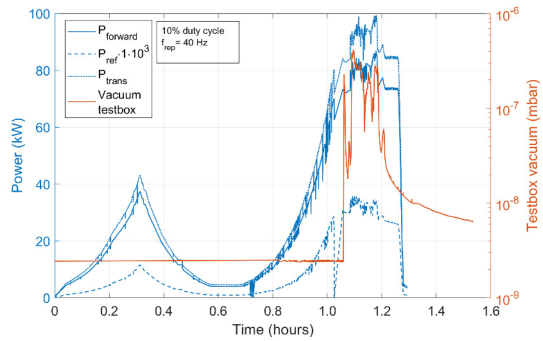

Figure 6: Intermediate result of first condition series with 1st pair reaching about 90 kW forward power at 10 % duty cycle with 40 Hz repetition rate displaying the three power signals and testbox vacuum with time.

conditioning. The results were within the expectations by

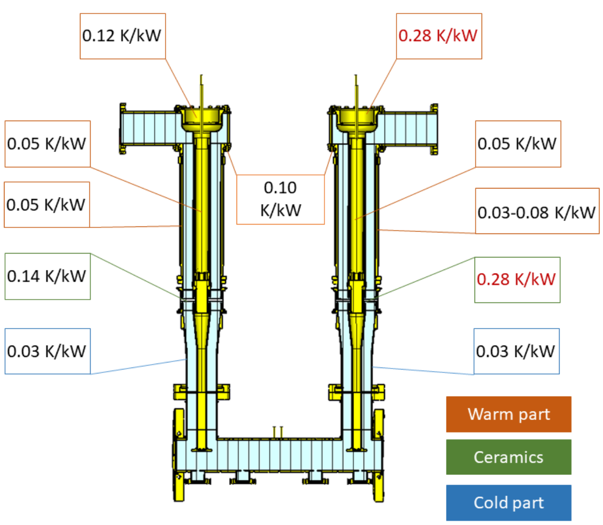

Figure 7: Heating gradients $\Delta T/\Delta P_{\text{forward}}$ with power at various locations as measured in CW TW mode.

coupled RF-thermal simulations and always featured in both TW and SW regime an imbalance between the two couplers regarding heating and thus the field distribution, as is also shown in Figure 4. This feature is eventually caused by the matching of the incoming wave from the rectangular waveguide to the coaxial coupler via ceramic with choke structure and testbox, which is eventually not fully symmetric towards the second coupler by fabrication variations. This was even more visible in SW mode, but here only one data sample with a fixed phase advance was taken. Measurements with variable waveguide propagation length towards the reflective end are necessary to study this. Figure 7 gives an overview of the most dominant temperature rises locations with power level in traveling wave CW mode. Still, the largest gradients of temperature with power are within the expectations and a possible operation of 120 kW seems reachable.

Figure 9 shows a summary of the conditioning of the 2nd pair. Here, we saw a larger imbalance in the ceramic window heating, pointing at a larger mismatch between the installed couplers. However, above some power level some arc event was triggered coming with a large vacuum event, which in addition fired the interlock. After that occurrence, above a threshold of 13 kW the vacuum level increased and the downstream coupler, having a larger temperature gradient with power at the window from the beginning, showed to switch to an exponential increase of that temperature with power.

This hints at some field dependent emission process hitting and thus heating the window. It needs to be checked, whether the window was harmed and eventually some remaining particulate contamination led to this behavior. This coupler will be checked within the cleanroom. Still, both couplers showed below that threshold gradients of 0.2-0.3 K/kW, where the upstream coupler kept the lower value also above that power threshold.

CONCLUSION

The power coupler teststand for the bERLinPro injector was successfully commissioned and two sets of power couplers were conditioned. Table 2 summarizes the current achievements with the requirements by the operation stages. Both pairs fulfill the power requirement for the 6 mA operation of the first stage. The first pair was conditioned to 40 kW CW in traveling wave and 17 kW in standing wave. Also, 95 kW at 10 % was reached in pulsed mode with that pair. The cooling showed no unexpected heating of the coupler beyond the calculated levels, far below the stress limits. The heating of the ceramics by 0.2-0.3 K/kW in CW traveling wave matches the expectation given by the coupled simulations and should allow an operation up to 120 kW with a temperature level of 338 K of the ceramics. The second set showed some increase in vacuum activity above 13 kW along with an exponential increase of the window temperature above this power threshold. This coupler pair will be inspected in the cleanroom for damages or spots on the ceramic to decide the further treatment. Conditioning of the two following pairs should resume after this conference.

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[1] Above 13 kW the temperature with power gradient became exponential for the second pair. All numbers quoted still are for linear fits.

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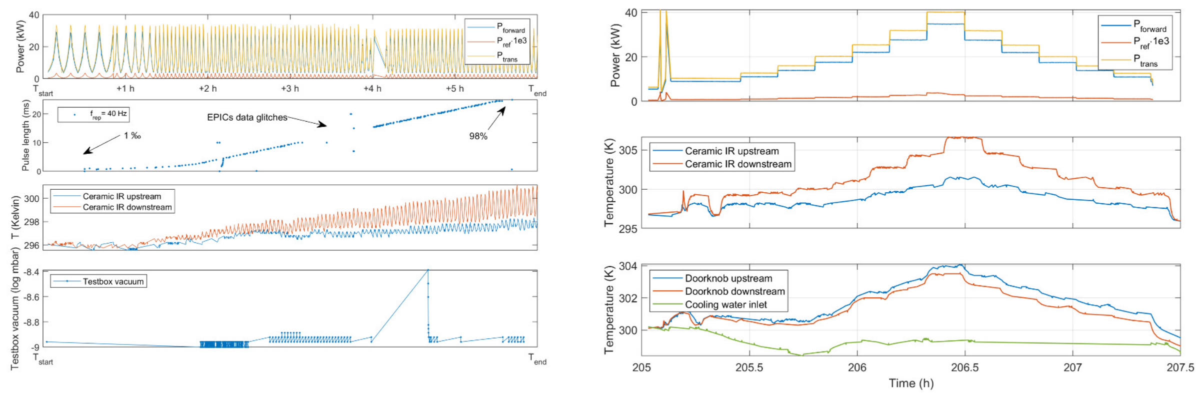

Figure 8: Left column: Power ramps, pulse length, ceramic window heating measured by IR sensor and vacuum level with time for pulsed traveling wave conditioning. Right column: CW power ramps, ceramic heating and doorknob heating with time for the same set up of couplers.

Table 2: Current Status of Coupler Conditioning after Two Pairs

Parameter	at 100 mA	at 6 mA	1st pair	2nd pair
P_{forward} TW	3.4, 220 kW	0.2, 13.8 kW	40 kW, 95 kW (10 %DC)	13 kW, 45 kW (29 %DC)
P_{forward} SW	3.4, 54 kW	0.2, 3.45 kW	17 kW	na
CW TW ceramic heating	-	-	0.14, 0.28 K/kW	0,18, 0.20 (0.35[1]) K/kW
CW SW ceramic heating	-	-	0.35, 0.89 K/kW	na

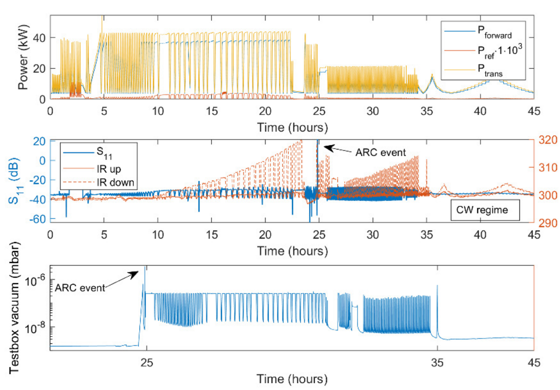

Figure 9: Part of the conditioning series of the 2nd coupler pair displaying peak power, S_{11} parameter, ceramic window temperatur and testbox vacuum with time.

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