SARAF PHASE-I HWR COUPLER COOLING DESIGN

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Abstract

The Soreq Applied Research Accelerator Facility (SARAF) design is based on a 40 MeV 5 mA light ions superconducting RF linac. Phase I of SARAF delivers up to 2 mA CW proton beam in an energy range of 1.5-4.5 MeV. The maximum beam power that we have reached is 4.5 kW. The warming of the SARAF linac RF couplers is currently the main limiting factor for reaching higher CW beam power. The coupler cooling configuration was optimized by increasing the cold window copper braid and adding a copper braid to the top end, using CST Multiphysics and ANSYS steady state and transient solvers. The study was conducted for the heat load generated by the surface currents of a matched 4 kW forward CW power, simulated by the CST MWS FD solver. Multipacting is a known potential heat source that overheats the coupler in the vicinity of the cold window. The coupler overheat phenomena was experimentally studied as a function of a DC bias voltage. It was found that a 900 V bias reduces significantly the heating rate. As a result we expect that the beam power could be significantly increased. The long overheat period implies that optimization of the coupler heat leads is still needed.

THE COUPLER OVERHEATING

Phase I of the Soreq Applied Research Accelerator Facility (SARAF) proton/deuteron linac is currently operational at Soreq Nuclear Research Center [1]. Phase-I of the linac has been built in order to study and prove novel acceleration technologies for intense CW beams. It includes a Prototype Superconducting Module (PSM) that hosts six superconducting Half Wave Resonators (HWR) designed and built by RI [2].

During beam operation with the PSM, the warming of the RF couplers is the main limiting factor to deliver high RF power to the beam [1]. The coupler was designed for applying 850 kV to a 4 mA ion beam. The warming effect differs for different couplers (Fig. 1). These couplers are built with a warm window at 300 K and a cold window designed to be at ~70 K during operation (Fig. 2). In order to prevent thermal stress on the cold window, its maximum temperature during operation was limited to 130 K. This limit is not derived from thermal analysis but is rather a good practice value. The worst coupler reaches 130 K at 1 mA and 425 kV (Fig. 1). The potential heat sources along the coupler are two; surface currents due to RF power and the multipacting phenomena. In this work we present a detailed thermal analysis, which demonstrates that cold window overheating due to surface currents could be reduced by increasing the heat leads thermal conductance, and an experimental study to reduce the multipacting load by adding a DC bias on the RF line.

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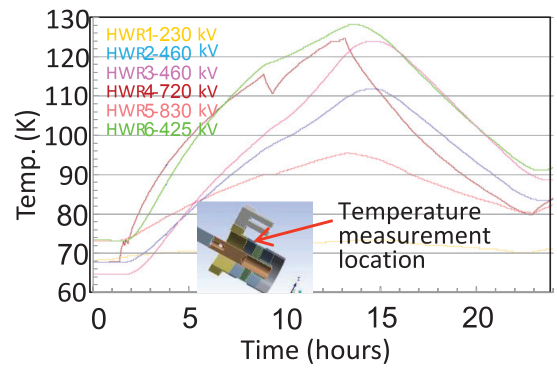

Figure 1: PSM HWRs couplers cold windows temperatures, measured during 0.2 mA beam operation.

COUPLER THERMAL ANALYSIS

One of the leading approaches in a coupler design for a superconducting cavity is to subdivide the coupler into vacuum and thermal zones [3]. The room temperature ceramic window separates between the atmospheric ambient pressure and the cryostat shielding at 10^{-6}-10^{-7} torr. The coupler coaxial outer and inner conductors are thermally isolated from the ambient temperature by thin, 10 μm copper plated, stainless steel bellows. The coupler intermediate 1 m long thermal zone is bound by the top bellows and the bottom outer conductor bellows connected to the 4.2 K superconducting cavity outer conductor. The coupler inner conductor ends with a few-mm antenna penetration into the cavity. The intermediate zone is intercepted at the cold window by a copper block, connected via a copper braid to the surrounding ~60 K thermal shield (Fig. 2). The intermediate zone, including the inner conductor antenna, will approach the thermal shield temperature if the generated heat load along the coupler is efficiently evacuated by copper braids to the thermal shield (assuming that multipacting phenomena are avoided along the coupler).

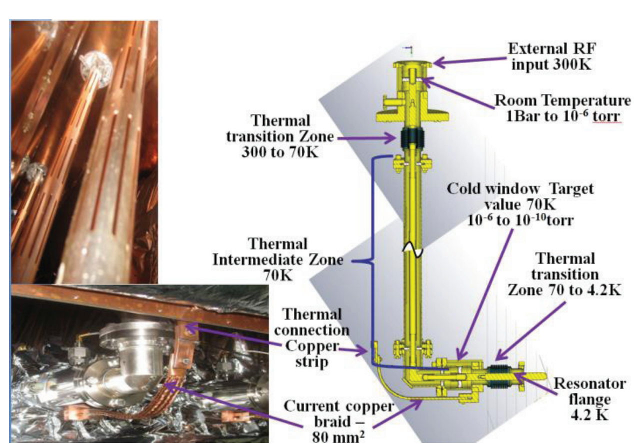

Figure 2: The SARAF PSM coupler thermal zones [2].

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COLD WINDOW PRE ANALYSIS

A former thermal simulation [4] assumed: (1) The heat source (upper bound value 30 W) is generated from the inner conductor antenna. (2) The resistance of the copper braid thermal lead that evacuates the generated heat to the thermal shield is negligible. The copper block is the heat sink at 70 K (Fig. 3 top). Moving the heat sink towards the thermal shield and including the copper braid in the simulation significantly increased the cold window temperature (Fig. 3 bottom). A detailed RF/thermal co-simulation including a study of the optimal copper braid cooling configuration is needed.

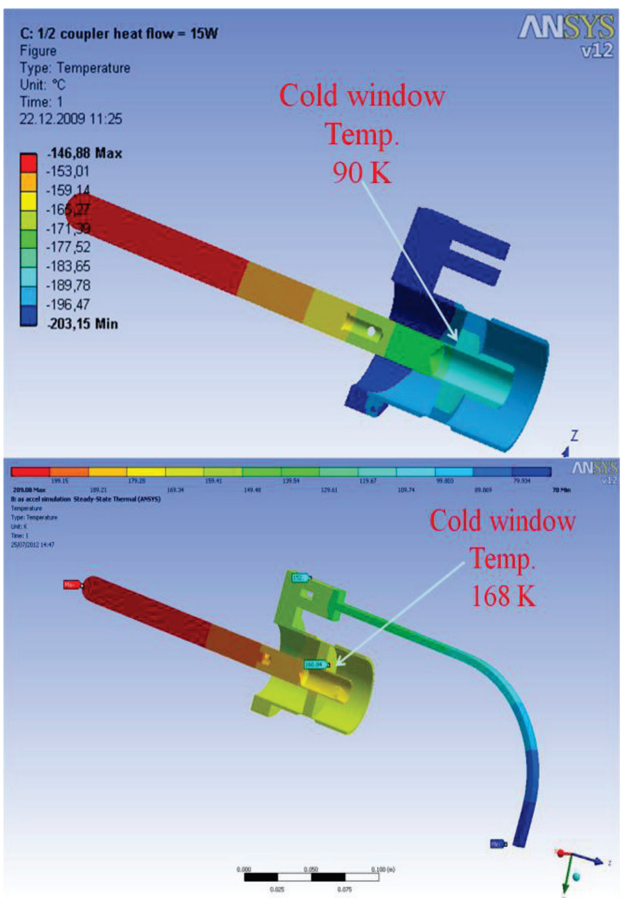

Figure 3: The cold window temperature maps without (top) and with (bottom) the copper braid, for 30 W generated uniformly on the coupler antenna.

A DETAILED THERMAL ANALYSIS

In this work few cooling configurations were analysed to find an optimized one. Direct cooling of the cold window with the available 60 K He gas could be a good technique [3], but the complicated implementation might require disassembling the cold mass. The cooling configurations were limited to those that would not require opening of the PSM internal beam line that is at $<10^{-10}$ mbar vacuum pressure. Utilizing copper braids enables the high flexibility needed for the PSM alignment and displacements while cooling to 4.2 K.

Three cooling configurations based on copper braids were studied for a 4 kW RF forward power with CST MWS FD [5]. The temperature map for the selected configuration is shown in Fig. 4. Table 1 summarizes the variations between the three configurations.

Configuration A- Increasing the cold window current copper braid cross section by a factor of six, the temperature gradient on the copper braid decreased to 13 K (assuming linear correlation between temperature gradient along the copper braid and the copper braid area, implies that in the current copper braid the expected temperature gradient is 78 K). Local cooling of the upper intermediate zone towards 70 K is necessary to reduce the heat load in this section.

Configuration B- Adding a clamp to cool the coupler top end, the external and inner conductor temperatures of the coupler under the upper bellows were reduced to 70 K and 208 K, respectively. Further temperatures reduction is expected due to lower electrical resistivity and higher thermal conductivity.

Configuration C- Increasing the cold window current copper braid cross section by a factor of three (instead of six) while keeping the clamp to cool the coupler top end results in only a slight average temperature rise with respect to Configuration B (approximately 5 K) along the whole coupler, which leads us to select this configuration.

We recalculated configuration C using electrical and thermal conductivity values according to local calculated temperatures, and refining the heat load mesh factor. The results include a higher heat load factor, but there is still a lower temperature gradient along the cold window between the outer conductor and the inner conductor and a higher heat flow through the top end cooling clamp.

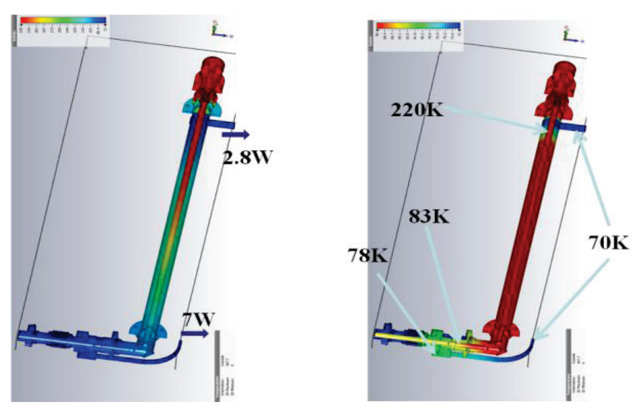

Figure 4: Configuration C. Left: Heat loads. Right: Temperatures.

Table 1: Intermediate Zone Temperatures for the Three Configurations.

configuration		A		B		C	
region		(K)	(W)	(K)	(W)	(K)	(W)
warm	inner	235		208		220	
	outer	180	0	70	1.5	70	2.8
cold	inner	95		86		83	
	outer	82	8	76	7	78	7

THERMAL ANALYSIS OF THE SELECTED CONFIGURATION

A layout of the selected configuration copper braids heat leads is shown in Fig. 5. We explored various contact interface materials (IM) for the copper braids heat leads based on [6]. We applied ANSYS [7] simulations to study the expected temperature gradients along the heat leads contacts as a function of each selected IM (Fig. 6).

Three cases of interface contacts were explored: (1) no IM, (2) Apiezon N, (3) Indium. In Fig. 7 we can see the temperature map results for case 3.

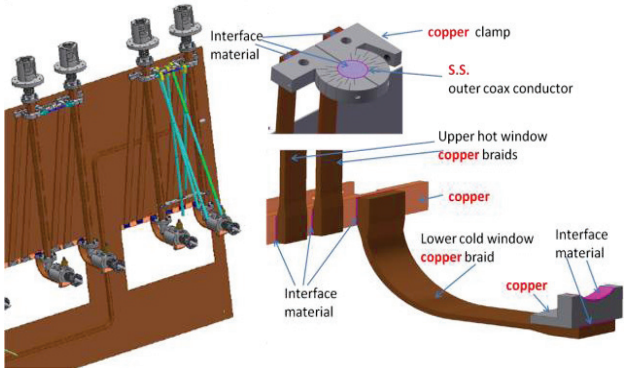

Figure 5: A layout of the copper braids heat leads and detailed views of the interface contacts.

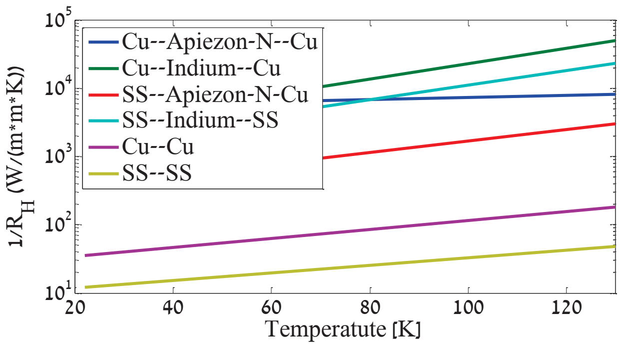

Figure 6: Heat conductance of the considered contacts as a function of temperature based on [6].

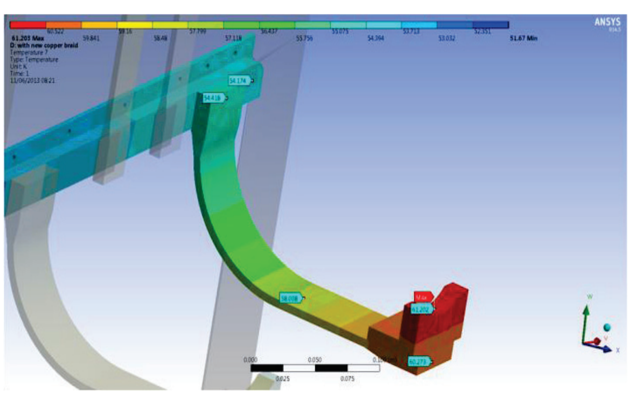

Figure 7: Temperature map of the cold window copper braid, including the IM contacts.

The resulted total ΔT along the cold window heat lead, including its IMs and one contact IM ΔT for all three cases, is presented in Table 2. The addition of both Indium and Apiezon N between the contact surfaces results in an improvement of an order of magnitude over the no-IM case.

Table 2: Cold Window Heat Lead ΔT (K)

Case	Total ΔT	One contact IM ΔT
1 (no IM)	102	33
2 (Apiezon N)	12.5	1.2
3 (Indium)	11.2	0.6

THERMAL TRANSIENT TEST OF THE CURRENT COLD WINDOW

The cold window outer conductor is cooled with a copper block connected via a copper braid to a thermal shield cooled by the He gas loop. We tested (Fig. 8) and simulated by ANSYS the cold window temperature transients initiated by 20 K steps of the thermal shield He gas loop. The measured cooling time constant is an order of magnitude longer than the simulated one, implying that the current heat lead configuration thermal conductivity is smaller than our simulation assumptions. Alternatively, farther distance between the measuring point and the cold window, 6-8 cm towards the coupler warm zone, may cause the same behaviour. Further study is needed.

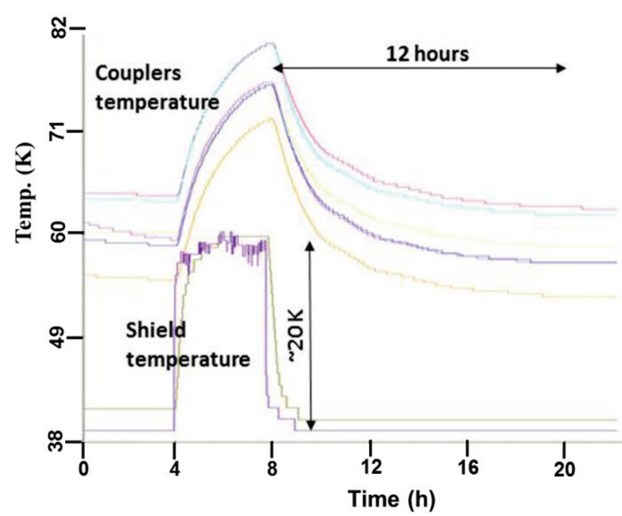

Figure 8: Cold window temperature as a function of time following 20 K upward and downward step changes in the thermal shield He gas loop.

DEVELOPMENT OF A BIAS "T"

The most practical method to suppress multipacting discharge is to apply a DC bias to the inner conductor [3]. A bias "T" was designed to stop the multipacting phenomena (Fig. 9). The Bias "T" was tested with a 4 kW RF amplifier on a 50 ohm, 10 kW dummy load resistor (without DC). Then it was installed on the room temperature coupler window at the PSM top lead (Fig. 10). By applying a 900 V bias voltage, the cold window

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temperature rise gradient is reduced significantly (Fig. 11). The temperature rise time gradient as function of cavity voltage is shown in Fig. 12.

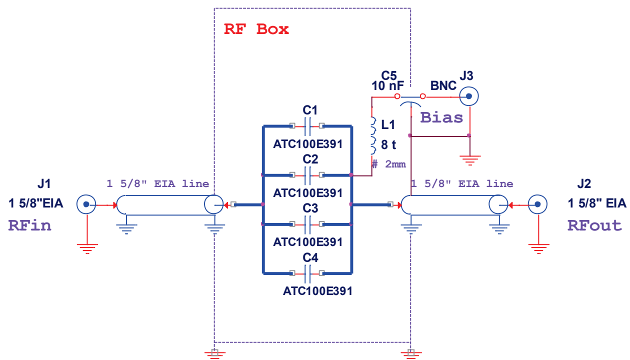

Figure 9: Electrical diagram of the 4 kW BIAS "T".

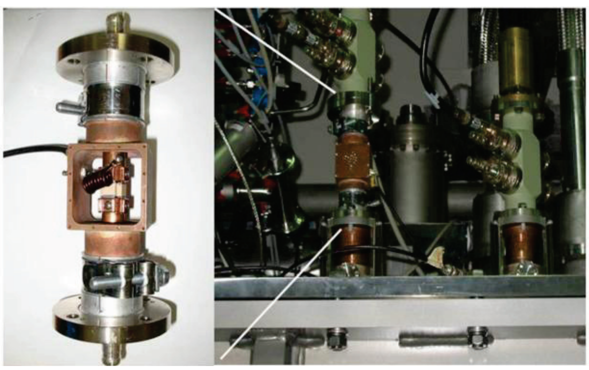

Figure 10: Left: the bias T prototype, Right: As installed on the ambient coupler window at the PSM top lead.

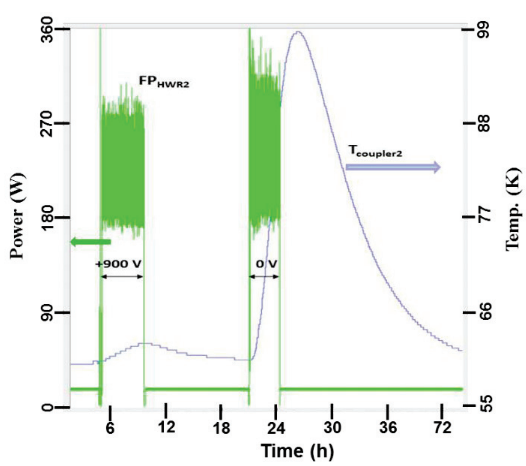

Figure 11: The cold window temperature rise time gradient with/without a 900 V bias voltage.

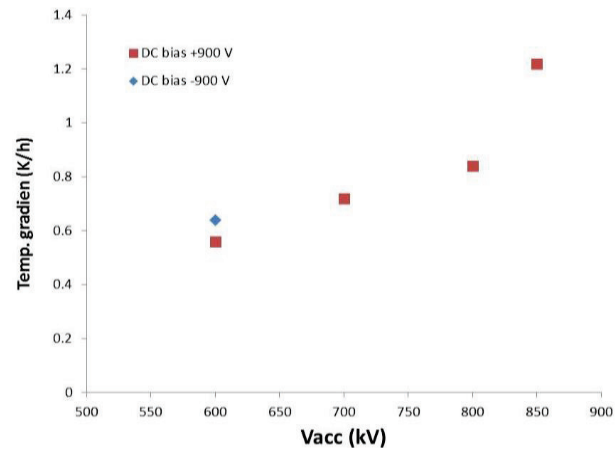

Figure 12: The temperature rise gradient as a function of the cavity voltage.

SUMMARY

Based on realistic RF/thermal simulations, a cooling configuration for the coupler's two 70 K long intermediate zone ends was selected. Applying a bias voltage on the internal conductor to eliminate multipacting reduced the temperature increasing rate significantly. The integral solution including both improvements is expected to enable the coupler operation at the specified 4 kW forward power.

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