Development of Improved Lead-copper Split-loop Resonators for the Stony Brook Heavy-Ion Linac*

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Abstract

We describe development efforts to improve the performance of lead-copper β=0.10 split-loop resonators in the Stony Brook heavy-ion linac. The goal is a reliable on-line accelerating field E_a of at least 3.0 MV/m for all 24 installed resonators at 6–8 watts helium dissipation. The best performance to date (3.5 MV/m at 8 watts, with very low field emission) was achieved with a chemically polished copper substrate. Thermometry measurements on several resonators show that in the absence of field emission only about 5% of the total 4.2 K losses occur on the resonator outer housing.

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1 Introduction

The background for the development work on β=0.10 lead-copper split-loop resonators to be described in this paper has been given in the separate overview report [1]. As noted there and previously [2, 3], only a few of the 24 "high-beta" (β=0.10) SLR units installed in 1981–83 reached the 3.0 MV/m design goal accelerating field. With the completion of other linac improvement projects it was therefore decided to investigate the performance limitations of the high-beta with the aim of developing more consistently successful superconducting surfaces. The plan is to use the improved methods to systematically refurbish (replate) all eight modules as opportunities to take them off line arise. To this end module 7 was removed from the linac in early 1993 and its resonators replated and individually tested. The cold tests included sensitive differential thermometry measurements to help fix the origin of the observed resonator losses.

2 Resonator description

The β=0.10 SLR is illustrated and described in Fig. 1 and Table 1 on the next page. The resonator body shown is constructed of OFHC copper parts joined by e-beam welding. The two holes in the outside housing are for a mechanically-variable magnetic coupler [4] and a small electric rf-field probe made from a BNC connector. The coupler is thermally isolated from the resonator by Vespel stand-offs; its temperature is kept at ~100 K by a copper strap to the common liquid nitrogen tank in the cryostat. The hollow resonator loading arms are filled with liquid helium for cooling, while all other parts are cooled by conduction.

Not shown in Fig. 1 are the two OFHC copper end plates with holes for beam entrance and exit. The plates are flat on the inside and have 2 cm long demountable lead-plated beam cut-off tubes on the outside. After all plating operations the end plates are joined to the resonator body with 1.5 mm diameter 50–50 Sn-In wire [5] gaskets. When the end walls are installed the indium is at first strongly compressed to a 50 μm gap, then the torque is partially released to set the correct warm frequency.

As usual with low-beta structures [6] the energy gain of a particle with charge q and velocity β is given by

$$\Delta W = q \cdot L \cdot E_a \cdot T(\beta) \cdot \cos(\phi_s)$$

where L = 22.0 cm is the resonator inside length, E_a is the accelerating gradient, $T(\beta_{\rm opt}) = 1.0$, and ϕ_s is the phase angle between the peak field and the particle arrival time. Thus the energy gain per unit charge can be as much as 0.66 MeV at E_a = 3.0 MV/m, or 0.88 MeV at 4.0 MV/m.

3 Replating program and techniques

Module 7 was picked for the first refurbishing because all three of its resonators had ceased to operate. Inspection showed that one fine-tuner vacuum stepping motor had overheated and failed, depositing a brown film of insulation residues over the inside of the module. Motor failures of this

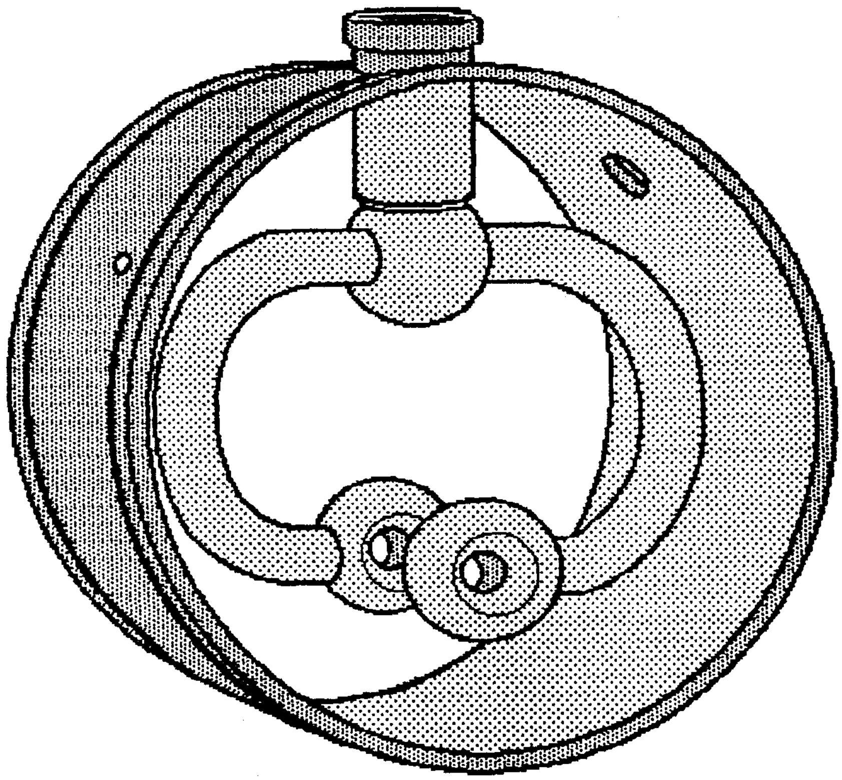

Figure 1: Outline view of the β=0.10 split-loop resonator (SLR) without end covers.

Table 1: Summary of key electrical and mechanical parameters of the high-beta SLR.

Electrical Parameters	
Cold frequency f	150.4 MHz
Optimum velocity β_0	0.105
Energy content U^*	47 mJ
Peak electric field E_s^*	4.3 MV/m
Peak magnetic field H_s^*	105 G
Geometrical factor Γ	25 Ω

$*$ At 1 MV/m accelerating field

Mechanical Parameters	
Housing inside length	22.0 cm
Housing inside diameter	38.2 cm
Housing wall thickness	0.95 cm
Loading arm diameter	3.2 cm
Beam hole diameter	1.9 cm
End wall thickness	0.95 cm

type have been very rare, even with six motors in every cryostat. Of greater concern was evidence that the rf coupling loops in all three resonators had run very hot, damaging the resonators. These loops had been made from hollow copper tubing pieces attached to the transmission lines with soft solder; the solder had melted, depositing many fine solder droplets on the loading arms just inside the coupling holes. Discharge marks and discoloration were also noted around the coupler holes. Based on these observations the coupler probe was redesigned for a solid copper loop with all brazed joints. This construction should be much better able to withstand the reactive tuning power of up to 200 watts present in the line. The new coupler was used for all of the recent cold tests and will be implemented throughout the linac as modules are refurbished.

It was decided to replate all three SLRs the same way except for the preparation of the copper substrates, which would be varied as a test. The plating methods followed the general scheme outlined in Ref. [1]. As usual, the resonator was used as its own plating vessel. A bottom cover of HDPE plastic sloped towards a drain valve at the center, and an HDPE ring at the top edge allowed the plating solution to cover all interior surfaces. The plating anode was a single sheet ~12 cm wide with its two vertical edges shaped into 4 cm diameter cylinders for better plating field uniformity. The anode was thoroughly cleaned then enclosed in a Dynel (polypropylene) bag and suspended midway between the two loading arms. To promote uniformity, a low plating current of 1.0 amps was used (current density = 0.27 mA/cm^2) and the direction of current flow was reversed for 3 seconds out of every 12 seconds. The plating time of 2.5 hours should have given an average thickness of 1.2 μm [7]. The room temperature bath was circulated through a Gelman [8] 0.2 μm disposable filter for several hours before use, but was not circulated during plating.

After plating, the bath was pumped out and the surface rinsed and dried under a nitrogen gas atmosphere as described previously [1]. Two hundred liters of rinse water was used, and the rinsing and drying each took 5–10 minutes. The resonator end plates were plated separately by similar techniques, except for a higher current density of 1 mA/cm^2. Inspection and assembly of the plated parts was done in normal room air in front of a laminar flow hood.

4 Test results

Our surface preparation, plating and test experience is summarized in Table 2. From previous work with quarter-wave resonators it was expected that the Chempolish [9] surface of resonator 7.3 might give the best results, and this proved to be the case. Both the copper surface and the final electroplated lead-tin deposit on R7.3 were very clean and lustrous, similar in appearance to an electropolished metal. Also, close inspection with bright oblique light showed no "fuzz" on the surface characteristic of whisker growth. R7.3 was certainly not visually perfect however. There were a number of drying stains, especially on the lower (during plating) sides of the beam drift tubes, and some pinholes at the rounded end of the stem supporting the loops.

Figure 2 shows the test results for R7.3. This was the first resonator tested although not the first plated. R7.3 had remarkably little field emission. Fields over 3.0 MV/m could be reached almost immediately with only modest x-ray production. Standard helium processing with up to

Table 1. Module 7 plating and test experience.

Plating	Surface Preparation and Appearance	Test Result
7.1 (a)	Stripped and dried, mechanically polished to mirror finish, soaked in "Micro" for 1 hour, rinsed, plated. Plating rejected because of drying stains.	
7.1 (b)	Stripped, rinsed, plated immediately.	3.0 MV/m at 7 W
7.2 (a)	Stripped, rinsed, cleaned with "Perfon," rinsed, plated.	2.0 MV/m at 7 W
7.3	Stripped, rinsed, Chempolished, rinsed, plated (no cleaning agents or abrasives used). Clean, lustrous overall appearance.	3.5 MV/m at 7.5 W
7.2 (b)	Stripped, dried, stains cleaned with 600 emery paper, rinsed, Chempolished, rinsed, dried, stored under N_2. Plating next day failed when residual moisture stripped off lead film.	
7.2 (c)	Stripped, rinsed in open air, plated immediately. Oxide stains on loading arms and walls show through lead.	3.0 MV/m at 7 W

~100 watts of pulsed rf was done for 30 minutes, with little apparent benefit. After processing accelerating fields of 3.0 MV/m, 3.25 MV/m and 3.5 MV/m were recorded at 4.5, 5.5 and 7.5 watts dissipation, respectively (upper Q curve). Stable cw operation at 4.0 MV/m was possible with ~12 watts dissipation; at this field x-rays just outside the cryostat were less than 10 mR/hour. The maximum pulse field in R7.3 was consistently limited to 4.7 MV/m by a thermal breakdown. As the other SLRs tested were limited in the same way it is believed that this field (at which the peak $H_s \simeq 500$ G) corresponds to H_c for the superconductor. The R7.3 Q curve falls off very gradually right up to the limiting field; at 4.6 MV/m 50-watt 50-msec pulses could be applied at 3 pps without breakdown.

The test results for R7.3 are at least as good as the best previous resonator in the Stony Brook linac and also exceed those achieved in an earlier refurbishing [3]. A similar Q curve has however been reported once before by Delayen [10] on an essentially identical β=0.10 SLR built for Oxford University. The Oxford SLR was plated with 1.2 μm of pure lead and employed lead end wall gaskets [11]. The two Q curves do differ in the region above 3.5 MV/m, where the Oxford curve drops off more steeply than the R7.3 curve.

Resonator 7.1 was tested next. Omitting the Chempolish step produced a fine-grained matte (not highly reflective) surface. R7.1 did reach the 3.0 MV/m goal with ~7 watts dissipation. Field emission was not as low as for R7.3 and the Q curve fell off more rapidly. Finally R7.2 performed quite poorly (only ~2 MV/m at 7 watts) on a first test, possibly because of residuals of the abrasive sulfite compound used before plating. The final preparation method (plating immediately after stripping) and test performance were much like those for R7.1.

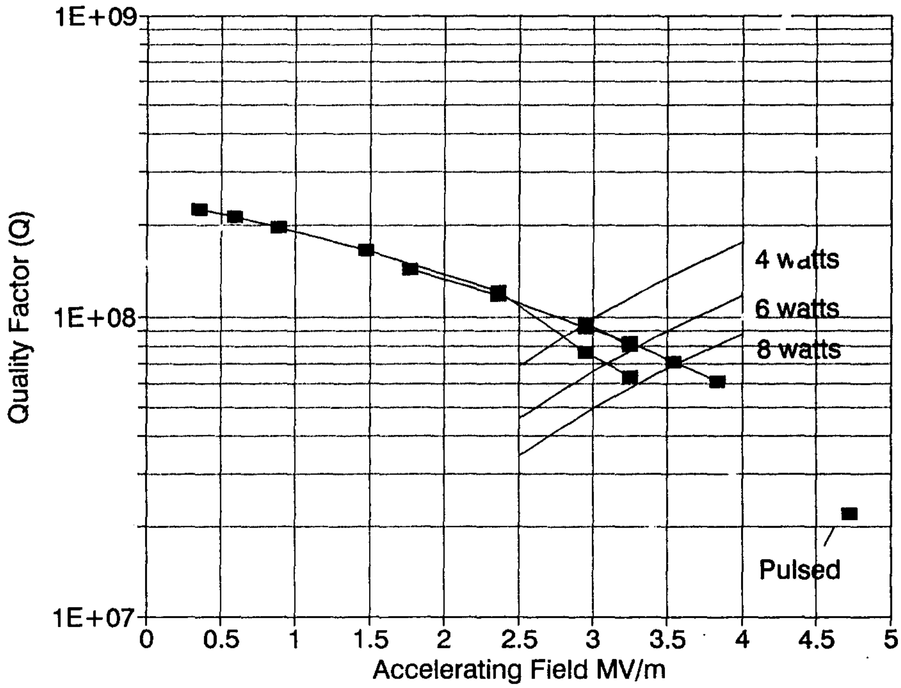

Figure 2: Q-curves for resonator 7.3 before and after brief helium conditioning.

Multipactoring is rarely a problem in the SLR. In our tests the usual low-lying levels were easily eliminated by a few hours of 77 K rf pulse conditioning or by brief Freon processing [1, 12] at room temperature. In every 4 K test, however, an additional unanticipated region of high-field multipactoring appeared between 0.6 and 1.2 MV/m. Fortunately this barrier could always be eliminated by a few hours of 4 K rf processing.

Unlike the situation for some niobium SLRs [13], the Stony Brook lead-copper resonators routinely work as well on-line in the linac as off-line in tests, despite some differences in the two environments (4.5 K on-line *versus* 4.2 K, super-insulation but no magnetic shielding in the linac). This expectation was confirmed when module 7 was installed in September 1993.

5 Millikelvin thermometry

The object of the temperature measurements was to determine the rf power dissipated on the outer resonator housing as a fraction of the total absorbed rf power. This was done by measuring the temperature rise ΔT between rf-off and rf-on conditions at representative sites on the housing. The relation between temperature change and power dissipated was established by separate calibration measurements with test heaters.

The most extensive thermometry studies were done on the third cold test (first test of R7.2), when three heaters were installed and eight diodes could be read out at once. In the other three cold tests (Table 2) similar measurements were made with just the bottom heater and two diodes at the top edges of the two end plates, with similar results.

5.1 Experimental details

Temperatures were measured with Lake Shore DT-470-SD diodes [14], which have a sensitivity of 34 mV/K at 4.2 K. Despite all efforts to make good thermal bonds and to minimize heat leaks the diodes typically read ~1 K higher than the expected 4.2 K voltage. (We had previously calibrated each diode by direct immersion in liquid helium and nitrogen.) These small offsets do not effect the measurements because only on–off temperature changes are relevant. For the diode calibrations and the first two cold tests voltages were read with a microvoltmeter. In the next test, with 8 diodes, the PC-based data acquisition system [15] shown in Fig. 3 was used. Specialized programming was avoided by using a diagnostic program [15] to store 1000 readings (125 per diode) in a file which could later be imported into a spreadsheet program for analysis.

A 12-bit A/D converter normally would not have sufficient resolution to discern the small diode voltage changes. This limitation was overcome by operating at a higher gain with the help of a programmable offset. For example, an offset voltage of 1.5 volts allows signals from 1500 to 1600 millivolts to be read at a gain of 100, for a resolution of 24 μV per bit, corresponding to only 0.7 mK. The subtraction occurs at the differential input of each A/D channel, and the offset voltage is obtained from the on-board D/A converter. The overall range of 100 mV corresponds to several kelvins and is more than adequate.

A second D/A channel was used to provide the 10.0 μA diode currents. The simple passive current sources are adequate in this application because dV/dI is very small. (The voltage change for a 1% current change is equivalent to 8.3 mK at 4.2 K.) Fig. 4 shows the result of a stability test with a room temperature diode. Although individual readings fluctuate by as much as a millivolt, system noise in the low microvolt range can be obtained by averaging many repeated readings.

5.2 Calibration measurements

For the third run test heaters were located on the bottom of the housing and near the center of each end plate. The bottom heater (also used for warmup after tests) consisted of a nominal 50-ohm 10x30 cm Minco [16] thin film heater wrapped in Al foil and held in place with a copper band. The side heaters were small 33-ohm 10-watt encapsulated resistors. Heater resistances were noted to vary somewhat with applied current. Therefore heater powers were calculated from the product of the applied dc voltage and current. Depending on the heater power level, it took one or more minutes for temperatures to reach a steady state, presumably on account of poor internal conductivity in the heaters. Care was taken to allow for this, and for the subsequent cool-down after power was removed. In a few cases where the heater was turned off too soon the final equilibrium value was estimated from fits to the data.

Fig. 5 illustrates the quality of the data. It shows the changing readings (in A/D counts) from the two diodes at the top edges of the end plates as 0.89 watts is applied to the bottom heater.

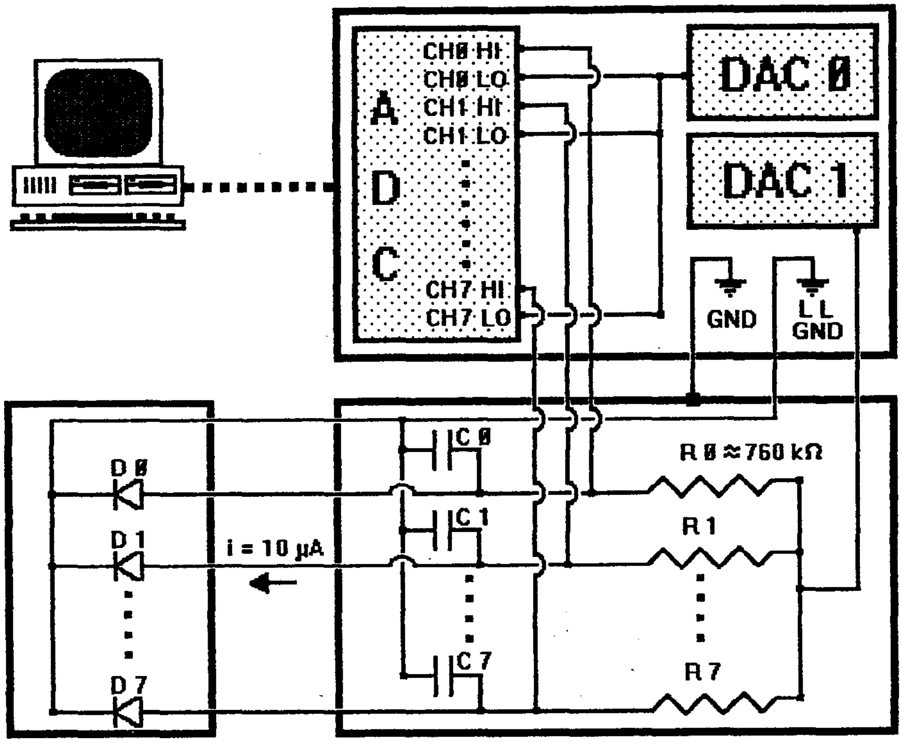

Figure 3: Data acquisition system for the silicon-diode thermometry.

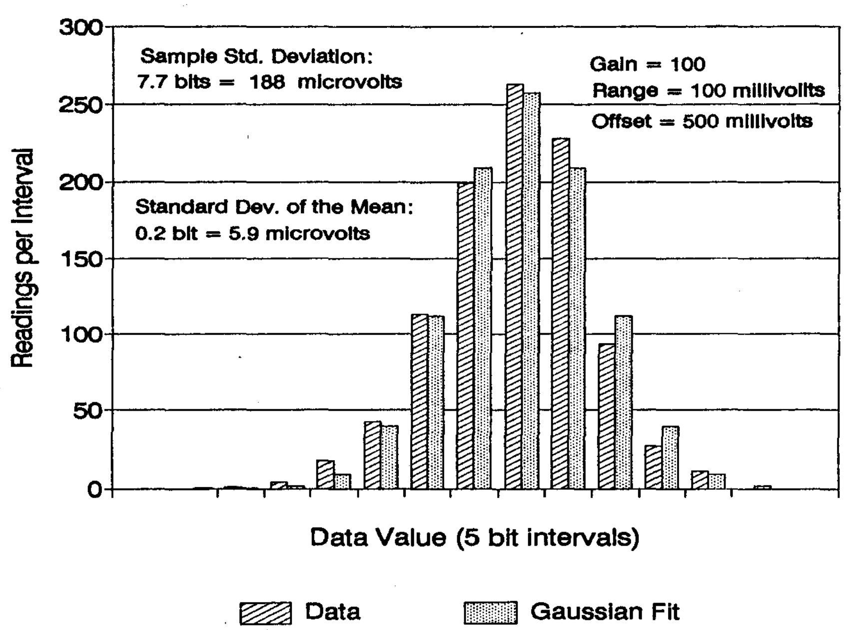

Figure 4: System noise test with a room temperature diode.

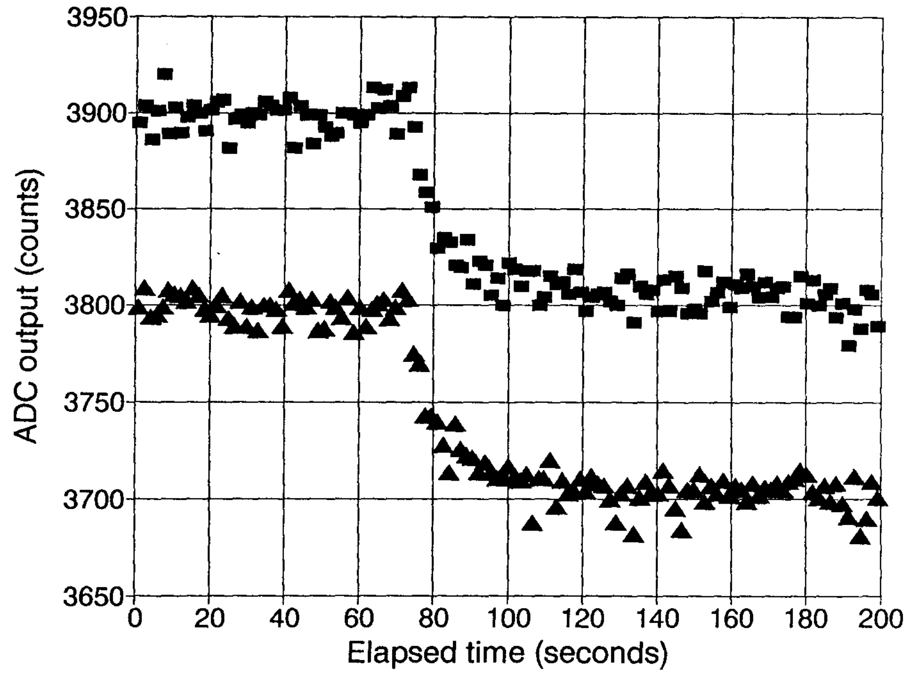

Figure 5: Computer data showing the temperature step of ~60 mK recorded by each of two diodes at the top of the resonator when 0.89 watts is applied to the bottom heater.

Each diode responds with an equal step of ~60 mK, as determined by averaging appropriate plot regions with heater off and on. Temperature steps ΔT thus determined for each diode and each heater were found to depend linearly on heater power out to at least 5 watts. The slope of the linear relation is the desired response factor for a given diode to a particular heater.

Figure 6 shows the 24 derived diode response factors, in units of mK/watt. As expected these tend to be somewhat larger near the heat sources and smaller near the heat sink provided by the liquid helium in the copper support neck, but these variations are less than a factor of two, reflecting the high conductivity of OFHC copper. Confidence in the measurements comes from noting that when the bottom heater is energized diodes at symmetric locations (left/right; coupler/pickup) respond in nearly the same way and that the two side heater patterns are nearly mirror images of each other. The left and right end wall readings do however seem always to be somewhat too low and too high, respectively, for reasons that are not understood.

From Fig. 7 we conclude that the average response of the two diodes at the top edges of the end plates is nearly the same 75 mK/watt for all three heater locations. It follows that these two diodes together are sufficient to measure the integrated rf power dissipated anywhere on the housing.

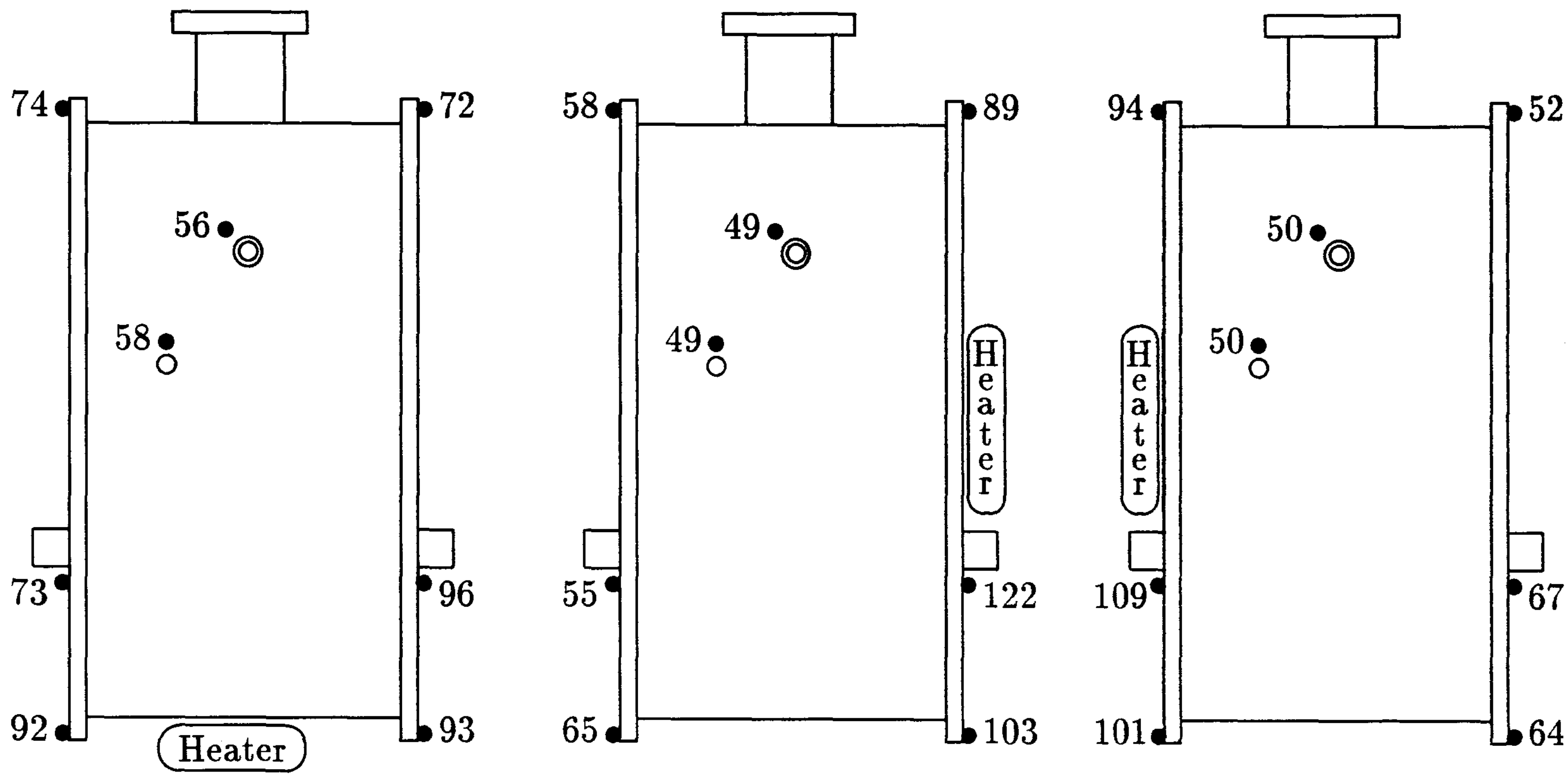

Fig. 6. Summary of measured temperature responses (in millikelvins per watt) as each of the three test heaters on R7.2 is separately activated. The eight thermometers are located at the top and bottom edges of the end plates, near each beam cut-off tube, and near the pickup and coupler holes (which are actually on opposite sides of the resonator housing).

5.3 Rf heating results

With rf power thermal equilibrium occurs within seconds, enabling ΔT's as small as a few millikelvin (corresponding to only tens of milliwatts on the housing) to be reliably determined. As each Q curve was traced out total power (from applied rf power at critical coupling) was compared with the housing power determined from the average reading of the two top diodes using the standard 75 mK/watt calibration factor. Figure 7 shows the outside power fractions $f_{out} = P_{out}/P_{total}$ thus obtained in the first and third cold tests on R7.3 (best resonator) and R7.2 (worst resonator before replating). Fig. 7 has several interesting features:

- In *both* resonators f_{out} is generally quite low, only about 5%, even though the total powers are very different (1.5 W versus 7 W at 2 MV/m) due to the much lower overall Q of R7.2. The 5% figure is consistent within estimated errors with the f_{out} ratio expected for ohmic losses with constant surface resistance R_s (see below). This means that other possible loss mechanisms on the housing must be insignificant.
- For R7.2 there is a sharp rise in f_{out} around 2.5 MV/m due to increasing field emission. (Uniform FE with no other losses would give $f_{out} = 2/6 = 33\%$.) Not shown in the figure, this FE activity later decreased after brief pulse power conditioning (without helium). For example, at the 2.4 MV/m data point shown in the figure x-rays were initially 5.0 mR/hour and the dissipation 12.3 watts. After conditioning the x-rays fell to 0.05 mR/hour, the dissipation dropped to 11.2 watts, and f_{out} became 4.0%. For the 2.6 MV/m data point x-rays fell from 50 mR/hr to 5 mR/hr after conditioning, but unfortunately the temperature measurement was not repeated.
- For R7.3 there is no increase in f_{out} out to almost 4 MV/m, consistent with negligible field emission. (These data were taken after brief pulse and helium conditioning.) The gradual decline in f_{out} with increasing field could be due to the Q droop effect (Section 6).

5.4 77 K measurements

Temperature shifts from both heaters and rf were also measured with R7.2 filled with liquid nitrogen. These measurements were difficult because equilibration times are very long at 77 K and the diode sensitivity is only 1.9 mV/K. The average response factor obtained with the usual two top end wall diodes was 135±15 mK/watt, almost twice the 75 mK/watt 4.2 K value. These two reciprocal conductivity values together with standard conductivity curves [18] imply that the OFHC resonator material has RRR $\simeq$ 200. The rf measurements at 77 K give valuable information on the "partial geometrical coefficient" (the H_s^2 distribution) of the resonator because R_s is constant and large enough to dominate any other loss mechanism. Our result is $f_{out} = (9\pm3)\%$. This value is consistent with the 4 K results (Fig. 7) in the absence of field emission.

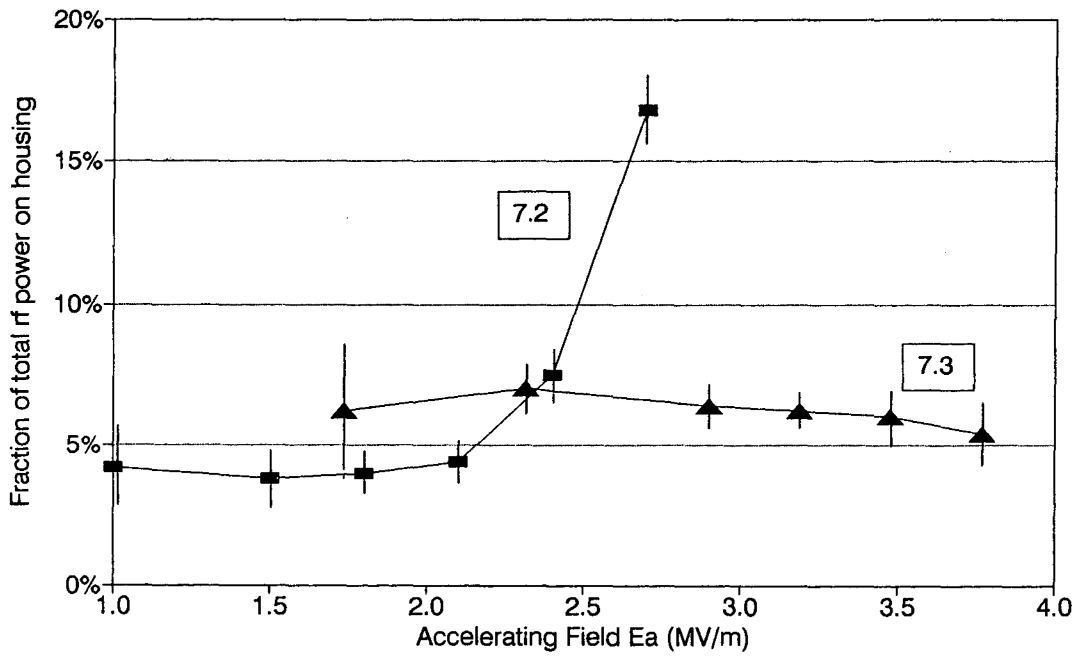

Figure 8: Fraction f_{out} of rf power dissipated on the SLR housing versus field for a "good" resonator (R7.3) and a "lossy" one (R7.2). R7.2 also has strong field emission above 2.4 MV/m.

6 Conclusions

The present work has pointed the way to obtaining superior performance in lead-copper split-loop resonators through two conceptual advances. *First*, our thermometry results show that the several possible sources of losses on the resonator housing are all insignificant, at least in the three resonators tested. Possible loss sources include the demountable end-wall joints, the coupler and pickup penetrations and the beam ports. One corollary is that the complications introduced by a lead or lead-plated copper joint material [10, 3] are not justified. *Second*, the test results with resonator 7.3 demonstrate that field emission is not a fundamental limitation of the high-β SLR out to at least 4.0 MV/m. The microscopically clean and featureless copper substrate obtained with Chempolish [9] seems to be a key factor, but this needs to be confirmed by more tests.

The mechanism that remains is simply resistive losses of the lead superconductor [7] in the high-current loading arms of the SLR. As noted in our summary paper [1], Yogi [17, 7] has shown that these losses tend to increase faster than H_s^2 in thin lead layers, consistent with the steady "droop" in our Q curves. The challenge for the SLR improvement program will be to find a way to minimize or eliminate this droop by optimizing the thickness, composition and crystalline structure of the lead plating on the loading arms, and to do this without unduly compromising the simplicity of the present procedures. Future developments along these lines will hopefully allow Q's of 10^8 or greater at 4.0 MV/m accelerating field (420 Gauss peak surface field).

Acknowledgements

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