SLIDING CONTACTS FOR TUNERS IN HIGH POWER RF RESONATORS

C.B. Bigham, R.J. Burton and J.E. McGregor
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

Summary

A sliding contact configuration has been developed for use in high power rf resonators. The configuration allows a large number of contacts so that each carries only a small current. The tolerance of the contacts to structural inaccuracies is relatively large and the configuration is much less complex than the clamping contact mechanism usually used at high power. The theory, design and material considerations will be discussed and the practical application in the main tuners of the Chalk River Superconducting Cyclotron will be described. Reliable operation has been obtained in the 31-62 MHz frequency range up to 50 A/cm linear current densities. The configuration is clearly capable of considerably higher current densities at these frequencies.

Introduction

Sliding contacts are often useful in situations where mechanical adjustments are required such as in resonant cavity tuning. The tuning shorts of the accelerating structures of superconducting cyclotrons are examples. These shorts must make electrical contact between the inner conductor and the outer conductor of the coaxial tuners. Because resonator voltages are high and tuners relatively small to fit into available space, current densities across the short are higher than the 20 A/cm allowable for the best commercial sliding contacts. Usually, a system of rather complicated clamping contacts has been used for higher currents. This report describes a new configuration of sliding contacts which has operated successfully up to 50 A/cm linear current density at 31 to 62 MHz in the accelerating structure of the Chalk River Superconducting Cyclotron[1]. The tuner is simple, without complex vacuum seals and operable under power. Consideration of the parameters indicates that this contact configuration is capable of considerably higher current densities if required.

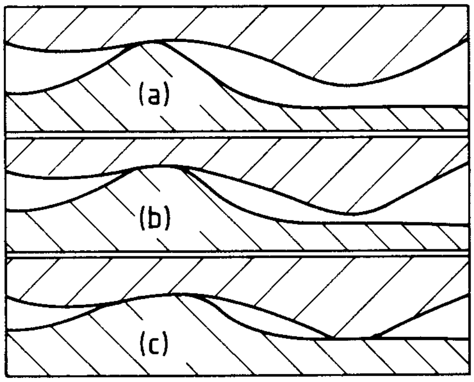

Fig. 1 An illustration of contacting surfaces showing that in small scale, the surfaces are rough. In (a) the initial contact is small. In (b) increased force F deforms the contact, increasing the contacting area and decreasing the resistance. In (c) additional contacts are made, further decreasing the resistance.

Theory

Contact between two conductors brought together will first be at one point only, because on a microscopic scale, the surfaces are rough (Fig. 1(a)). As the force between the contacts is increased, the contact points are deformed with an increase in the contacting area (Fig. 1(b)). Adjacent points may also come into contact adding additional contacting area (Fig. 1(c)). The contacting area will then depend on the force, F, and on the hardness, H, of the conductors or on the softer of the two if they are different.

An electric current between the conductors is constrained to flow through the contacting areas resulting in a contact resistance, R, between the conductors. This contact resistance is given approximately by[2]

$$R \approx \rho \sqrt{H/F} \qquad (1)$$

where ρ is the resistivity of the conductors or the average if they are different.

It has been observed experimentally that sliding copper contacts will operate satisfactorily if loaded to about 1 N. Copper hardness $H = 5 \times 10^8$ N/m^2 and conductivity $\rho = 1.8 \times 10^{-8}$ Ω•m then give $R \approx 0.4$ mΩ for a force of one N between copper contacts.

The current that a contact will carry without damage depends on the temperature at the point of contact. This is given by[3]

$$T \approx \sqrt{T_0^2 + U^2/4L} \qquad (2)$$

where T_0 is the temperature away from the contact,
U is the voltage across the contact, and
$L \approx 2.4 \times 10^{-8}$ in units of $(V/K)^2$.

This simple relationship follows from the relation between thermal and electrical conductivities (the Wiedemann-Franz law) and is shown in Fig. 2 for T_0 = 300 K and 400 K. The copper softening temperature is also shown[3]. This is the temperature at which the strain hardening in the highly stressed contact disappears. Experimentally, as the current is increased the contact resistance is observed to decrease at a fairly well defined voltage across the contact, i.e., the contact area increases because of the softening. This voltage is characteristic of the contact material and is about 120 mV for room temperature copper corresponding to about 460 K as shown in Fig. 2. Sliding contacts must operate below this temperature since the softening could lead to fusion welding.

The softening voltage is approximately the same for all metals of practical interest so the corresponding "softening" current will depend on the resistance of the contact. This is shown in Fig. 3 for a typical copper to copper contact of 0.4 mΩ resistance and a beryllium-copper to copper contact of 1.8 mΩ resistance, i.e., with about the same force on the contact. Conductivity is therefore an important parameter in the choice of material.

CH1996-3/84/0000-0377 $1.00 © 1984 IEEE

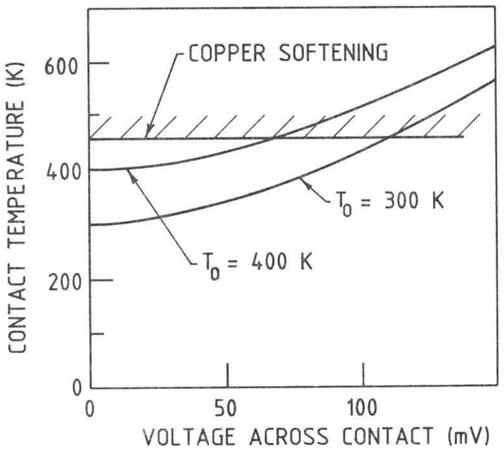

Fig. 2 The contact temperature given by Eqn. (2) for ambient temperatures of 300 K and 400 K as a function of voltage across the contact. The "softening" temperature for copper is also shown and is about 100 mV for an ambient temperature of 300 K.

Practical Constraints

In most high power resonant rf structures, the fixed surface on which the tuner contacts must slide is copper. The most desirable material for the sliding contact is also copper provided the contact force is small enough to be free of excessive wear. More heavily loaded composite contacts in complex configurations have been used but usually result in significant wear and as a consequence limited operating life. Copper of course is a very poor spring material and the penalty for using a good spring material such as Be Cu with 1/4 of the conductivity is large as shown in Fig. 3. It is better therefore to find a configuration that allows the use of one of the less strong copper alloys with higher conductivity.

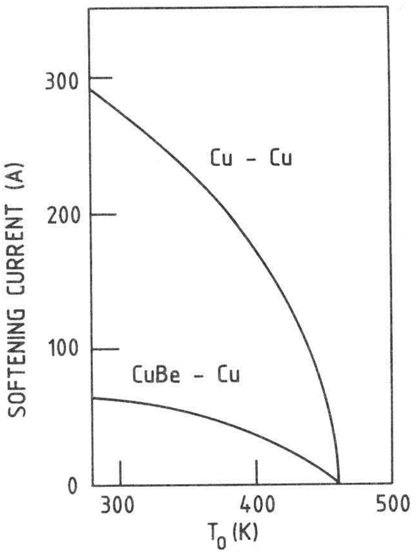

Fig. 3 The current at which softening occurs for Cu on Cu and Cu Be on Cu as a function of the bulk temperature. The "softening" voltage shown in Fig. 2 is about the same for all copper alloys so the corresponding current depends on contact resistance.

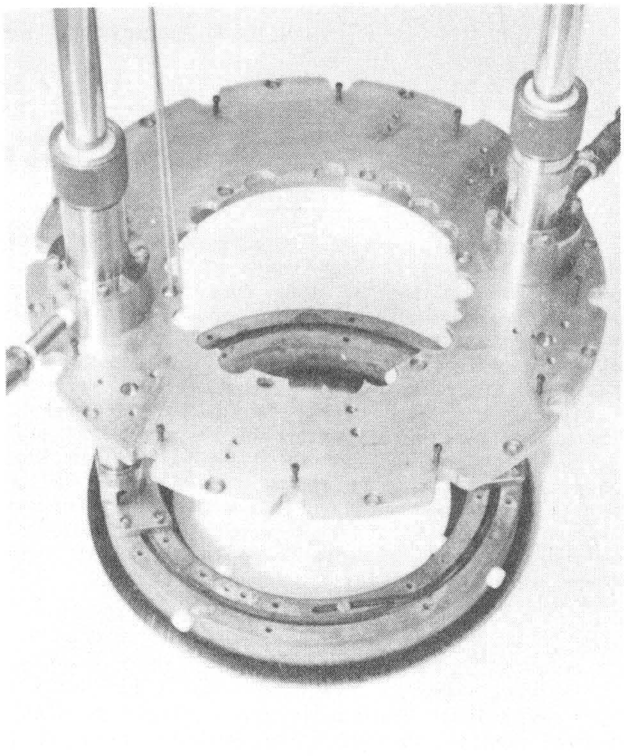

Fig. 4 One of the main tuning shorts in the Chalk River Superconducting Cyclotron rf structure showing the contacts, the tuner end plate, push rods and vacuum seals. The water cooling line is in the central groove.

The Configuration

A configuration that allows a large number of contacts satisfying these constraints is illustrated in Fig. 4. This is a photograph of one of the two main tuning shorts in the Chalk River Superconducting Cyclotron[1] accelerating structure. The contacts are punchings of the shape shown in Fig. 5 mounted at about 30° off the normal with spacers between and all soft soldered in place for good thermal cooling at the base. There are 420 contacts on the outside of the short and 360 on the inside.

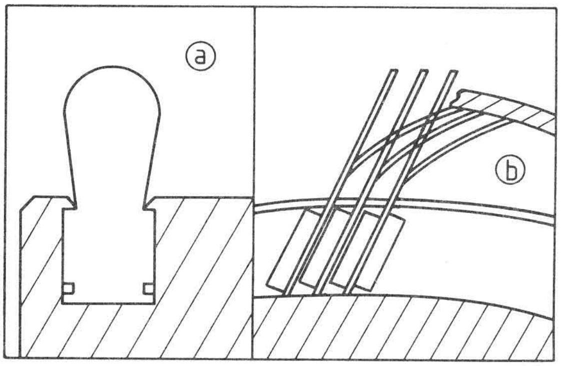

Fig. 5 The contact mounting arrangement used in constructing the short shown in Fig. 4 above. An azimuthal section in shown in (a). A partial plan section indicating the contacts as mounted and as constrained by the outer conductor is shown in (b).

The shape of the contacts shown in Fig. 5 was designed to be made from beryllium copper. The tip was broad to give a large rounded end for sliding over obstructions. However, when deflected, the stress is concentrated near the base. Beryllium copper is strong enough to withstand reasonable contact deflections.

Experimental Results

Several development steps were made in arriving at the arrangement of Fig. 4. In the first tuner short, double rows of contacts were mounted with the slope in opposite directions as shown in Fig. 6. The idea was to balance any azimuthal forces and to provide a backup in case of failure of the first row. Azimuthal forces turned out to be negligible so the double rows are no longer used.

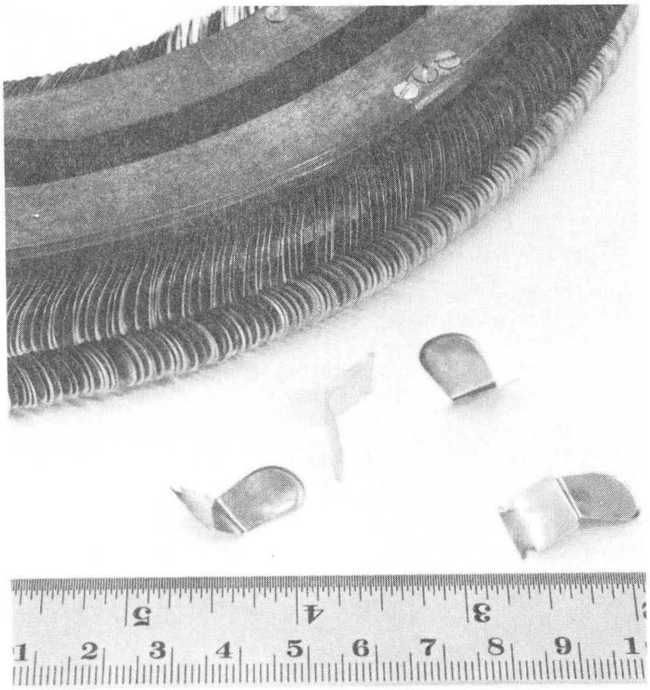

Fig. 6 The first tuning short tried, which had double rows of Cu Be contacts. The contacts were shaped as shown in the foreground and trapped in a slot as indicated in Fig. 7.

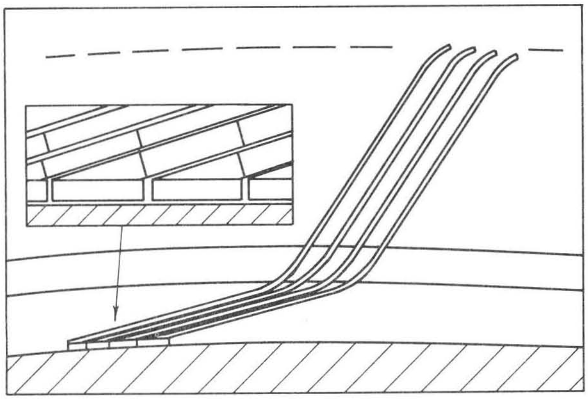

Fig. 7 The mounting method used for the Cu Be contacts shown in Fig. 6. The inset shows how the contacts are spaced by the small tabs on the corner of the base.

The first contacts were "spooned" at the tips as shown in Fig. 6 so that contact was on the side instead of the edge. The spooning limited the pitch because adjacent contacts touched at the tips for too small a spacing. It was found that edge contact worked well both electrically and mechanically and contacts were not spooned.

The first contacts were not soldered at the base. They were trapped in a slot essentially depending on spring loading for contact and cooling as shown in Fig. 7. In practice, a few contacts always worked loose and failed. Subsequently all contacts were soldered at the base.

Figure 8 shows the shape of the contacts when constrained by installation jig rings the same size as the inner and outer conductors of the tuners.

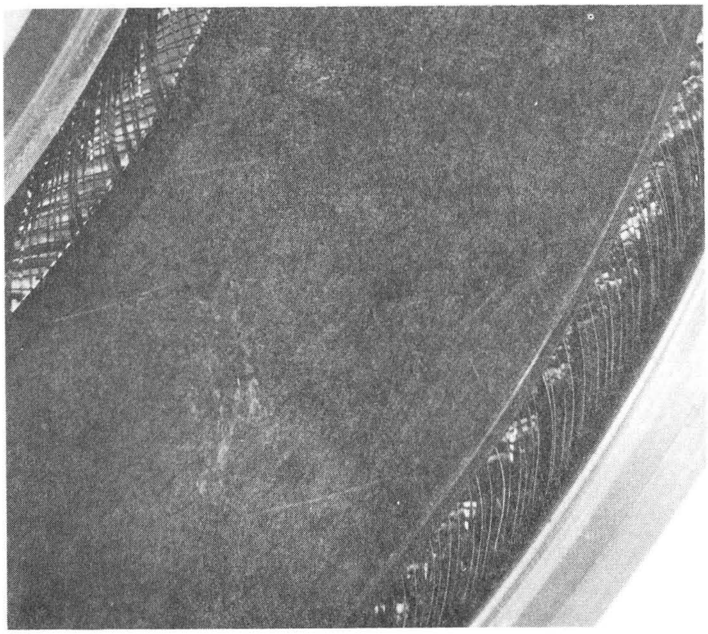

Fig. 8 A section of the double row tuning short of Fig. 6 with installation jig rings in place. These constrain the contacts to their normal shape when contacting the centre conductor and outer conductor.

The first contacts were made from beryllium copper because of its good spring properties. These failed during operation at about 6 A per contact. Later contacts were made from a Cu Ag alloy with conductivity about 90% of pure copper (CDA Alloy No. 155). The thickness was 0.127 mm which seemed near the optimum for this configuration. Measured V-I characteristics at 60 Hz for contacts made of the two materials are shown in Fig. 9, the resistance of the Cu Ag is about 4 times smaller than the Cu Be. At rf frequencies, the resistance is larger because of skin effects but the ratio is about the same. The Cu Ag however is not a very good spring material so the punched contacts were mounted without bending as shown in Fig. 5.

The tuning shorts shown in Fig. 4 have been used in a series of commissioning experiments in the 31 to 62 MHz range up to about 10 A per contact or about 50 A per cm linear current density. There has not been detectable damage or wear in these tests which included one 24 hour run. There was little tuner movement under power so that little experience has been obtained on contact performance with movement at high power.

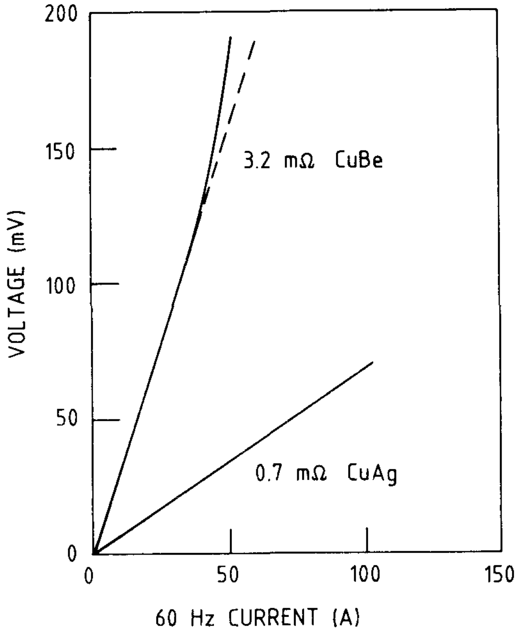

Fig. 9 V-I characteristics for Cu Be and Cu Ag contacts at about 1 N contact force measured at 60 Hz. The measurements were limited to less than 100 A by the test rig transformer. Note that the voltage drop across the contact alone is about half the total so the softening point is out of range at about 240 mV. However, some rise in temperature is indicated by the non-linearity in the Cu Be curve.

Future Developments

There are several possibilities for improving these contacts. The most obvious would be to find the optimum spring contact parameters. An important parameter is the force on the contact, this should be set for the best compromise between wear and resistance. There may also be different optima for operation in air or in vacuum.

The allowable linear current density may of course be increased by decreasing the contact spacing. The limit will depend on the accuracy of construction, i.e., unequal length contacts will set on one another and cause excessive wear. The spacing shown in Fig. 4 could probably be reduced by a factor of three quite safely.

Cooling is very important as was shown in Fig. 3. The ambient surface temperature at the contact must be well below the softening temperature. This may well establish the ultimate current limit for these contacts.

The mounting method shown in Fig. 4 is satisfactory but it was difficult to obtain good solder joints to all contacts. A possible but as yet untested fabrication method is illustrated in Fig. 10. The assembly would be folded from a continuous strip with the pitch determined by the angle of the fold lines. The strip of contacts so formed would then be clamped and soldered into the edge of the tuner with water cooling lines as close as possible.

There may be better material for the contacts. The best tested so far is the Cu Ag alloy used in the tuner shown in Fig. 4. High conductivity is essential and good spring properties are important. Forming properties may also be important in mounting arrangements that require bending or folding. The choice seems to be limited to high conductivity copper either alloyed or dispersion strengthened. Tests are planned on an alumina dispersion strengthened copper called Glidcop*.

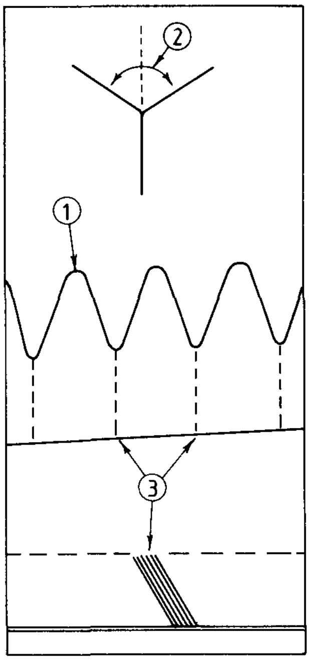

Fig. 10 A method for fabricating contacts by folding a continuous strip. The three steps are (1) cut strip, (2) bend alternate fingers 60° in opposite directions and (3) Z-fold 180° to form continuous array.

Conclusion

A configuration has been developed for sliding contacts on high power rf tuners. These contacts have operated successfully at 50 A/cm linear current density. The important parameters have been discussed and the results indicate that this configuration is capable of considerably larger current densities.

Acknowledgements

We are indebted to J.E. Anderchek, J.F. Weaver, R.J. Bakewell and L.A. Reavie for their expert assistance in fabricating the tuners and to M.A. Trecartin for typing the manuscript.

References

1. J.H. Ormrod, C.B. Bigham, E.A. Heighway, C.R. Hoffmann, J.A. Hulbert and H.R. Schneider, Proc. Ninth Int. Conf. Cyclotrons and Applications, Caen, France, September 1981, p. 159, published by Editions de Physique, Les Ulis, France.

2. Ragnar Holm, Electrical Contacts, Springer-Verlag; New York (1967) 47.

3. Ibid., 64.

---

* Manufactured by SCM Metal Products, Cleveland, Ohio, USA.

CH1996-3/84/0000-0380 $1.00 © 1984 IEEE