# VERY HIGH PERFORMANCE SLIDING SHORT FOR RF RESONATORS TUNING

C. Pagani, J. Camon* and G. Varisco
University of Milan and Istituto Nazionale di Fisica Nucleare,
Milan, Italy

## Introduction

RF Sliding contacts are necessary or useful in many applications and mainly for tuning power amplifiers and cavity resonators. Just looking at room temperature cyclotrons, a lot of contact types are in use and different sliding shorts were developed according to the RF system requirements. Nevertheless, with the advent of superconducting cyclotrons, new ideas were necessary, because no one of the existing sliding shorts was applicable.

In fact from the preliminary design parameters it was clear that a sliding short capable to carry at least a current density of 50 A/cm was necessary; moreover large mechanical tolerances and small dimensions were envisaged. A demonstration that new ideas were necessary is the completely different structure of the systems developed in the three laboratories involved from the beginning in the design of a superconducting cyclotron[1,2].

This paper describes the Milan design criteria and the solution adopted for the prototype and for the final simplified and improved version, which was able to carry a current density of 200 A/cm at 38 MHz. The tuner is rather simple and can be moved under power, while providing electrical contact between the inner and the outer conductor of the coaxial cavity. Considerations on experimental results indicate that the limits of this sliding contacts system are well above the tested values.

## Design criteria and preliminary tests

The starting point of our analysis was to understand the rationale of conventional contacts limits. From literature and computing we were convinced that for any type of contact the limit is dictated by temperature related problems. This very obvious sentence appears less evident looking at the problem with some detail. Particularly we can try to separate two aspects: the heating at the contact point, produced by the contact resistance, and the heating of the pushing element, due to heat transfer and, eventually, to the current flow.

As an example a sketch of a flat spring contact is shown in Fig. 1, together with an enlarged view of the contact region. The contact resistance, causing the contact point heating, depends on the contact surface, which produces locally a very high current density, i.e. power dissipation and heating. This surface is a function of the pushing force and also of geometrical and hardness characteristics of the two contacting elements, however, it is easy to demonstrate that[3], for contacts working below the softening temperature, a careful optimization can produce just marginal reduction of the contact resistance. Moreover, in high frequency applications, the limit of such a contact type is usually given by the spring softening, which, via a pushing force reduction, brings to a divergent destructive phenomenon. In fact, the spring geometrical parameters are dictated by the force needed and by the mechanical tolerances that the contact system must accept. This gives a very poor thermal conductance for the flow of the heating created by the RF current on one of the spring surfaces. As a consequence, a very simple analysis taking into account just this last phenomenon (i.e. forgetting the contact point heating) is adequate to give a good figure of the current holding capability of most of the contacts of this type and to give a reason of the inverse dependence with respect to the mechanical tolerances accepted by the system[4,5].

From the analysis sketched above, we were convinced that, independently from the influence of possible optimizations, this class of contacts was not adequate for our requirements. This sentence must be probably reviewed after the successful results from Chalk River[2]. In fact, in our opinion, this contact system can be included into the flat spring family, but, the new idea to use many large and vertical springs puts the spring heating limit, caused by the RF current, behind the contact softening limit and the large number of contacts per centimeter allows high current density.

The critical arguments exposed above, together with a set of numbers coming from a mathematical approach, brought us to the idea that a good contact system was possible if we were able to overcome the two principal limitations, namely: the RF heating of the pushing element and the limit temperature at the contact point. In other words, if a contact could work above the softening temperature, being pressed by an ideal thermally and electrically insulated element, its current holding capability would be enormously increased and practically independent from mechanical tolerances.

Figure 2 presents the preliminary sketch of one contact element used for the development of the idea. A metallic sphere is pressed between two cooled surfaces,

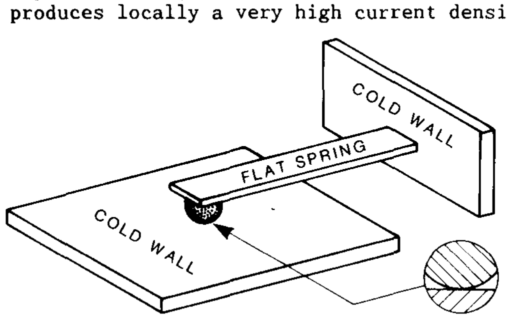


Fig. 1 - Sketch of a flat spring contact.

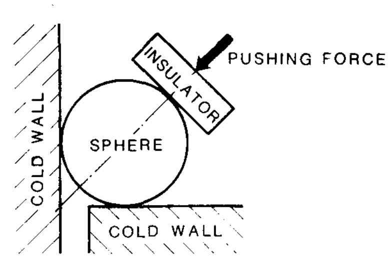


Fig. 2 - Sketch of a ball based contact.

which have to be electrically connected, by a force directed like the bisectors of the angle. The calculation result showed us that a pushing force at the contact points between 1 and 2 kg was adequate to guaranty a thermal equilibrium of the sphere below 200 °C, for a DC current of 1000 A and a 50 MHz current of 100 A (rms). We want to point out that the doubling of the contact points is not critical, because it doubles the overall contact resistance but also the heat exchange from the sphere to the cold walls.

So that we decided to built and test a single sphere (10 mm in diameter) prototype to verify the numerical results, before starting the design of a balls based sliding short. Particularly two perpendicular water cooled copper bars were used, and a silver-graphite sphere was pressed for contact by an insulated helical compression spring, able to give a force between 1 and 2 kg on the contact points. For a reason of simplicity our current generator was the high current 50 Hz transformer of the superconducting coils power supply, current variation being obtained through a Variac on the transformer primary. The experimental results, for a 2 kg pushing force, are presented in Fig. 3 (solid line), where the double contact voltage is given as a function of the current. Few sphere temperatures are also shown. Looking at this curve, it is evident the strong reduction of the contacts resistance as the current increases, its maximum value being in our case limited by the heating of the cables (Φ 20 mm) connecting the transformer to the single sphere prototype. We want to point out that the linear behavior of the system, typical for contact temperature below softening, is limited to very low current values (less than 100 A). With higher currents the system gets a thermal equilibrium through a local softening which, increasing the contact surface, reduces the electrical and thermal contact resistance.

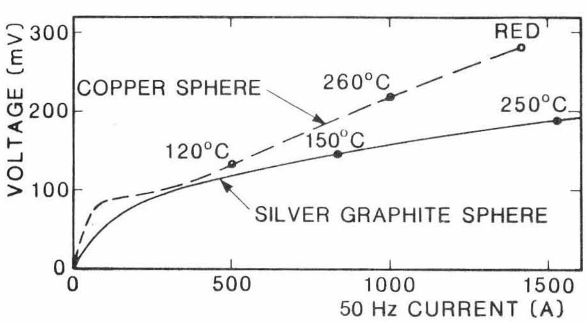


Fig. 3 - Single sphere prototype performances, for the case of a silver-graphite (solid line) and a copper sphere (dashed line).

The curve presented in Fig. 3 is typical for a new silver-graphite sphere and is also well reproducible. Nevertheless, a variation of the contact resistance up to 500 A has been observed for sphere already used at high temperature or slided on the copper surface before the current flow. Above that current value any sphere behaves according to the same curve.

Concerning the balls material silver-graphite behaves better than all the other tested material, having also some crucial peculiarities from sliding and welding prevention point of view. As an example the electrical behavior of a copper sphere is presented in the same Fig. 3 (dotted curve).

## Sliding short circuit prototype

A drawing of the prototype of the balls based sliding short is presented in Fig. 4, while a picture of the short circuit fully assembled on the dummy coaxials support is shown in Fig. 5.

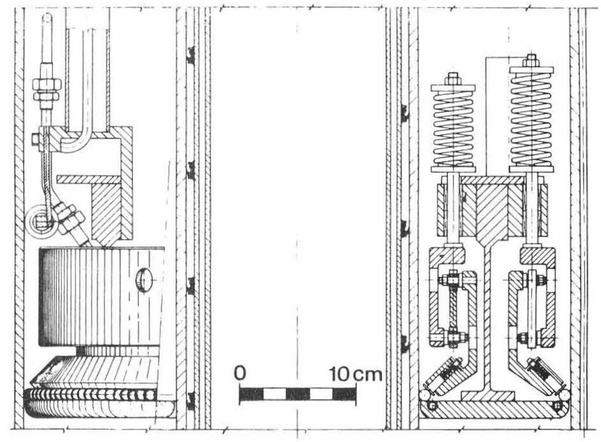


Fig. 4 - Drawing of the prototype of the balls based sliding short circuit.

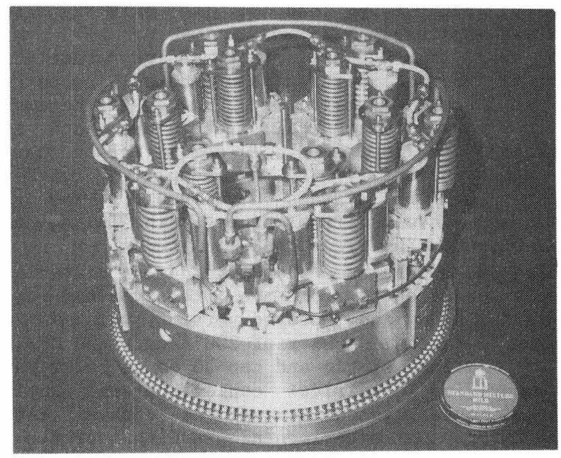

Fig. 5 - Sliding short prototype fully assembled on the dummy coaxials support.

We used 144 spheres for the outer coaxial contact and 63 for the inner, each sphere being pushed with a force of 2 kg by an insulated helical compression spring (see Fig. 4). The thermal and electrical insulation was guaranteed by small steatite and Teflon cylinders, respectively for the inner and the outer contact ring.

This sliding short has been extensively tested, during the Milan RF cavity power tests[7], up to a current density in the inner contact ring of 69 A/cm (rms) at 38 MHz. Damages or anomalous heating have been never observed, also when the short was moved on full power, the force on the contacts being reduced to one kg using the 12 releasing air pistons.

Since some words have been already spent on this short in the last Conference[6], we shall limit the following discussion to the main reasons which convinced us to change its design, even if the power tests showed that it could be completely adequate for current densities much higher than our requirements.

Since we tried to put in this prototype all the options which in principle were interesting to test, as a consequence the resulting item has been very useful to better understand the phenomena related to a balls based sliding short, but it was also too much complex and its assembling very laborious. The starting point for its simplification was that, from preliminary tests, we were convinced that a minimum contact force of one kg was adequate for current carrying and also for sliding, making useless the large springs and air pistons system (see Fig. 4). Another complication, which proved to limit its performances, was the sliding short guiding and self-centering systems. In fact, being the short circuit plate guided by nylon wheels on the outer conductor, most of the eventual eccentricity defects are compensated by the self-centering system of the inner contact ring, which is also forced by the residual force from the outer ring; in other words, the inner contacts, which carry the highest current density, support also most of the pushing force variations, caused by coaxials eccentricity (see Fig. 4). So that, a new design was tried which, taking into account the few envisaged modifications, could reduce the cost, simplify the assembling procedure and increase, if possible, the system performances.

## The new sliding short design

A drawing of the improved final version of the Milan RF cavity sliding tuner is presented in Fig. 6, while a picture of the item fully assembled, in the dummy coaxials support, is shown in Fig. 7. Referring to these figures, a few comments on the sliding short components or performances are given in the following.

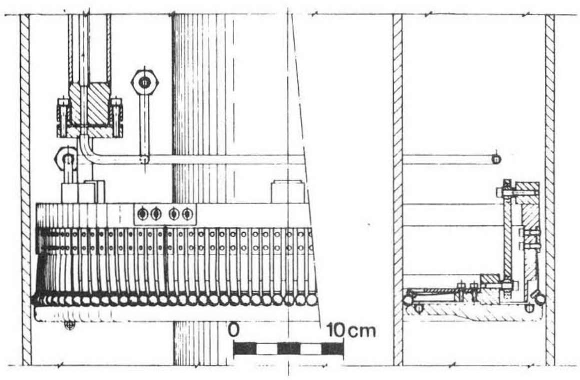


Fig. 6 - Drawing of the improved final version of the Milan RF cavity sliding tuner.

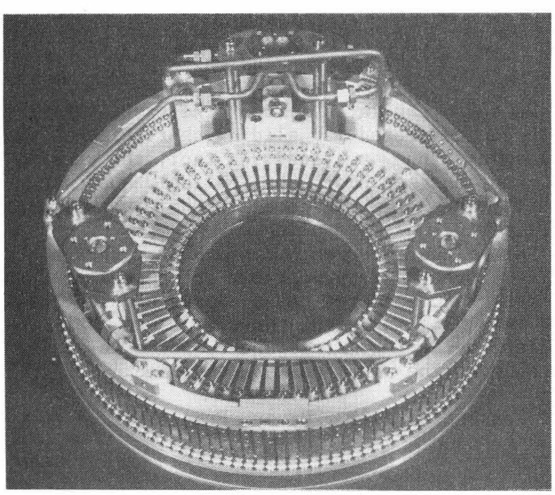

Fig. 7 - Photograph of the Milan K800 cyclotron sliding short fully assembled on the dummy coaxials support.

### Contacting spheres

We conserved the spheres design that was used for the prototype, being close to the optimum for our application. Also their number, which means about one contact per centimeter, was taken constant for the inner and the outer contact ring. Particularly the choice to use for the outer ring much more contacts that needed is dictated by the consideration that their reduction does not effect appreciably the total cost of the item while could produce RF leak problems.

### Pushing elements

The design of these components has been completely changed, how can be seen comparing Fig. 4 and Fig. 6. While in the prototype the pushing elements were small helical compression springs (in series with larger ones which could be released by the 12 already mentioned air pistons), in the new design horizontal and vertical Cu-Be flat springs are used, being this simpler design possible because no force releasing elements are present. The contact force produced by these springs is respectively 1.2 kg ± 15% and 1 kg ± 20% for the inner and the outer spheres, the variation ranges being referred to the maximum allowed tolerances for the coaxial walls position, namely ± 2.5 mm. We want to point out that, from electrical and mechanical experimental results, these value are completely adequate and their quite small variation is mainly due to the self-centering system, which will be described below.

Another important improvement refers to the thermal insulation. In fact in the new design each sphere is guided in its radial movement by an inclined groove in the sliding short plate, while a 3 mm thickness quartz disk, glued on the Cu-Be spring, ensures thermal and electrical insulation. A proper model was built to measure the thermal insulation, being in such a design the glue softening temperature (in our case 130 °C) the limiting parameter for the maximum allowed temperature on the sphere. A conservative factor 3.5 was measured between the temperature increment in the two opposite quartz faces, which means a maximum allowed temperature for the sphere greater than 350 °C.

A blow-up of the inner and the outer contact ring is presented respectively in Fig. 8 and Fig. 9 for a better comprehension of the elements discussed above.

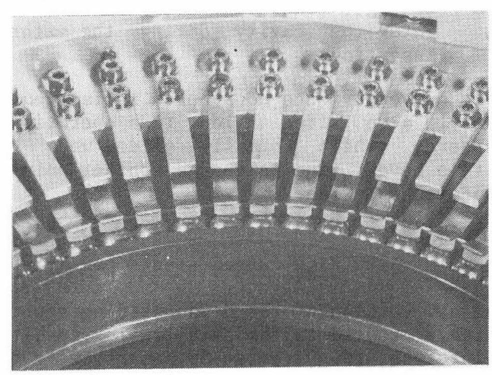

Fig. 8 - Blow-up of the inner contact ring. The horizontal flat springs with the glued quartz disks are shown while pushing the spheres.

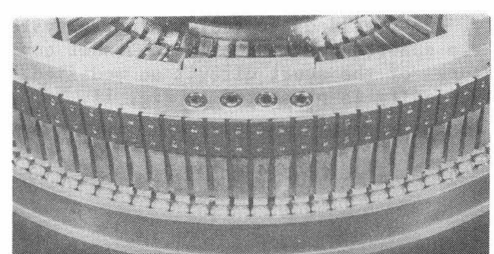

Fig. 9 - Blow-up of the outer contact ring, showing the vertical flat sprigs.

### Self-centering and guiding

In such an item it is very important to include a self-centering and guiding system, since most of the required tolerance comes from an eccentricity defect due to the imperfect straightness of the coaxial copper tubes. Moreover, because the inner contact ring is much more critical (for the higher current density) we decided, as anticipated above, to modify the prototype design. Particularly, the sliding short plate is now mainly centered, with respect to the inner coaxial, by the radial forces created by the internal spheres (the spheres guiding grooves having an inclination of 30°), while the outer contact ring can almost freely find a self-centered position with respect to the outer coaxial.

Assemblage and maintenance

The assembling procedure of the new sliding short is very simple, not only with respect to the prototype. Particularly, once fully assembled and controlled on a proper dummy coaxials support (see Fig. 7), it is split in three sectors for its insertion into the cavity resonator, each section of internal finger springs being removed. Once the three sectors have been recomposed around the inner coaxial and connected to the moving bars (in the region properly opened at the cavity edge[6]), the internal spheres being taken in place by their inclined housings, the three sections of internal springs can be reassembled. Finally the external spheres are inserted with a finger when the short is just inside the outer coaxial, as can be seen in the photograph of Fig. 10.

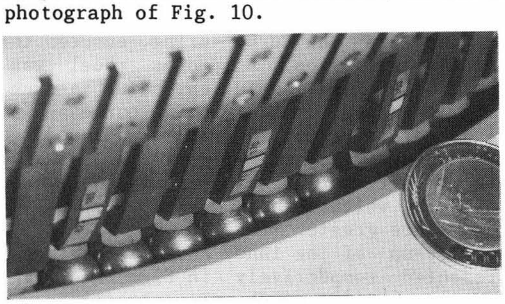

Fig. 10 - Enlarged view of the sliding short assembled into the cavity during the external balls insertion.

From our experience no spheres replacement would be necessary, also after a long time operation. In fact the spheres, which normally slide when the short circuit is moved, tend to change contact point when its area becomes too wide.

## High current tests

The new version of the Milan sliding short has been extensively tested in the same testing conditions than the prototype (69 A/cm at 38 MHz) showing that it is fully adequate for our requirements. Nevertheless, because the flat springs temperature never exceeded 43 °C (from thermal stickers placed on the springs edge) and the cavity was not able to give a higher current density, we decided to test again the system, taking away two spheres over three in the inner contact ring. A picture of the short circuit so modified, assembled into the cavity is presented in Fig. 11.

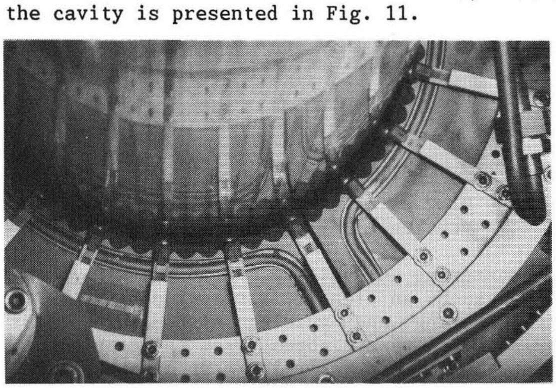

Fig. 11 - Picture of the short circuit inner contacts ring, with one sphere over three left, for high current density test.

Also under these extreme conditions the sliding short behaved very nicely, being moved, at the maximum disposable current (>200 A/sphere at 38 MHz), inside the trimming capacitor range. During this test, the maximum detected springs temperature was 60 °C.

## Final destructive test

Before to stop for ever the sliding short tests, we decided to perform a destructive test, to know what would be the consequences in case of failure. So that, we repeated the last test, reducing the force on one of the internal ring spheres, the system being not protected by photo-transistors on the short circuit region. Finally the unloaded sphere burned, carrying a current of 180 A, with a force on the contacts of about 500 g. A picture of the burned sphere, removed by its position, is presented in Fig. 12.

From this experiment we learned that no damage was supported by the coaxial or by the sliding short plate, being enough to clean the deposited graphite layer. Moreover, also if the glue was no more efficient, it was able to support the quartz disk and the two adjacent contacts could carry the over-current without anomalous heating, how can be seen in Fig. 12, looking at the white color of the thermal stickers.

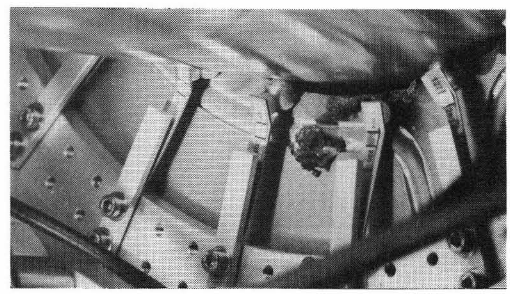

Fig. 12 - Photograph of the melted sphere, removed by its original position, after the final destructive test.

## Conclusions

We are convinced, from the experimental results that we developed a sliding short circuit much more performing than we need. In fact, the present design can, in our opinion, be reliably used for current density up to 250 A/cm at 50 MHz, just improving the short circuit plate cooling.

For higher current density, a design based on smaller spheres is preferable and a contact force of 2 kg must be considered. As a consequence we think that, for very high current density, one has to accept smaller mechanical tolerances and a releasing system for sliding the short must be designed.

* On leave from IN2P3, Orsay, France.

## References


1. P.S. Miller, Proc. 9th Int. Conf. on Cycl., Caen (France) 1981, Les Ed. de Physique, 1981, pag. 191.
2. C.B. Bigham et al., Proc. 10th Int. Conf. on Cycl., East Lansing 1984, IEEE cat. 84CH 1966-3, pag. 377.
3. R. Holm, Electrical Contacts, Ed. Springer-Verlag, pages 45-70.
4. R. Gayraud, Internal report, IN2P3, 78N/1, Orsay.
5. C. Bieth, Proc. 10th Int. Conf. on Cyclotrons, East Lansing 1984, IEEE cat. 84CH 1966-3, pag. 295.
6. C. Pagani, Proc. 10th Int. Conf. on Cyclotrons, East Lansing 1984, IEEE cat. 84CH 1966-3, pag. 305.
7. C. Pagani et al., Full Power Tests of the First RF Cavity for the Milan K800 Cyclotron, this Conf.