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EXPERIENCE WITH ELECTRICAL CONTACT SYSTEMS FOR RADIO FREQUENCIES AT NAC

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During the past 15 years a number of different electrical contact systems were designed and put into use for the radio-frequency resonators of the 200 MeV cyclotron facility at NAC. All systems operate under vacuum conditions. Detail of their design principles and relative performance is discussed. Retractable, sliding, rolling and static contact systems are described. Conducting and contact materials, welding and soldering connections and finger retracting mechanisms are evaluated. A test cell was developed to compare radio-frequency heating of different conducting materials and designs under vacuum.

1 Conducting Material used for Contact Systems

Hardened beryllium-copper is usually used for contact fingers, owing to its excellent spring property. For most of our systems we preferred Glidcop AL-20, which is a dispersion-strengthened copper with 0.2% Aluminium-oxide, that became commercially available in 1980. It has electrical and thermal conductivity close to that of pure copper and spring properties similar to unhardened beryllium-copper. At the same radio-frequency current, the temperature rise for AL-20 copper is nine times lower than for beryllium-copper with similar dimensions. It is also an easier and safer material to work with. Most contact fingers were made from rolled strip, 150 mm wide and 0.15 to 0.5 mm thick. No temperature hardening is possible and it has good high temperature characteristics. Work hardening does not occur as with pure copper. In some cases additional force was used to ensure contact. Liners of the resonator chambers were made from OFHC copper sheet and the coaxial resonator-conductors were electro-formed. Contact buttons for retractable fingers were made from silver and for sliding contact from silver-graphite.

2 Retractable Contact Systems for Frequency Changes

2.1 Short-Circuiting Plates for the two Injector Cyclotrons

The short-circuiting plates of the two quarter-wave coaxial resonators for both injector cyclotrons connect the 200 mm diameter inner conductor to the 700 mm diameter outer conductor and have an adjustment range of 4500 mm. The frequency range is 8.5 to 27.5 MHz and the maximum peak current 2700 A. A short-circuiting plate consists of 9 identical sectors mounted on a support ring which can be split for installation or removal. Each sector has 5 fingers, with 2 silver contacts each that make contact on the inner conductor and 10 similar fingers for contact with the outer. Each contact finger is 30 mm long and is made from 0.25 mm thick AL-20 copper. As shown in figure 1, the fingers are soft-soldered to a 3 mm thick water-cooled copper section 68 mm long, which in turn is connected with soft-solder to the 3 mm thick copper annular ring by five AL-20 copper strips, each 0.25 mm thick, 15 mm wide and 25 mm long, which form a hinge. Contact pressure is obtained from air-pressure operated bellows and is applied by a pressure-limiting plunger to the central point behind the two 6 mm diameter contact

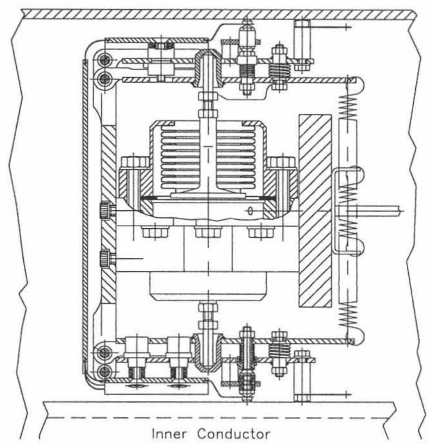

Figure 1: Short-circuiting plate system of the injector resonators.

buttons for each finger. The pressure per contact is 300 g on the inner and 150 g on the outer. The maximum current density on the inner is 30 A(RMS)/cm. Contact withdrawal is done by spring force produced by tension springs and the 5 mm diameter cooling-pipe loops of each sector. The characteristics of the fingers and contacts are compared in table 1. The relatively long 120 mm length from the hinge to the contacts, results in power loss of 3 kW per resonator at maximum frequency, but enables the fingers to be retracted by more than 5 mm. During the 70000 operational hours in the past ten years these contact-finger systems of the resonators for the first injector has given excellent service. During its first year of operation, the second injector has performed similarly.

2.2 Short-circuiting Plates for the 200 MeV SSC

The four short-circuiting plates, of the two half-wave coaxial resonators of the separated-sector cyclotron, connect each 500 mm diameter inner conductor to its 1280 mm diameter outer conductor and have an adjustment range of 3000 mm. The frequency range is 12.5 to 27.5 MHz and the maximum peak current 8000 A. Both inner and outer conductors were manufactured by electro-forming with integral cooling channels. After machining, the dimensional accuracy was better than 0.2 mm. The inner was adjusted to be concentric with the outer along its entire length to better than 0.5 mm. The

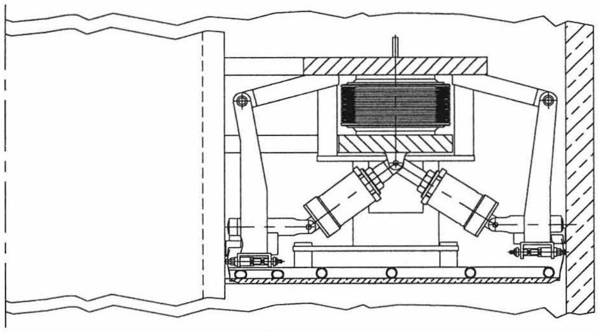

Figure 2: Short-circuiting plate system of the SSC resonators.

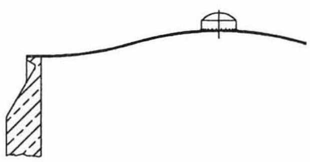

Figure 3: Contact finger of figure 2, showing the profile for welding.

contact fingers of the short-circuiting plates therefore need only slight retraction to enable repositioning for frequency changes. Each plate is guided by 12 wheels rolling on the inner conductor. The contact fingers were made from 0.25 mm thick AL-20 copper. Force-limiting plungers apply controlled pressure to the two 6 mm diameter silver contact buttons on each finger. Six bellows per short-circuiting plate provide the force which is linked to the fingers as indicated in figure 2. Spring force is used to give positive withdrawal of each finger. Thus the flexibility of the finger material is used to the limit, to have the fingers as short as possible. Detail of the fingers is given in table 1. The inner fingers are 23 mm long, from the contacts to the point where they are welded to the 6 mm thick annular copper plate. The inner edge of this plate is machined to enable welding attachment of the thin fingers, as shown in figure 3. Each finger is 14 mm wide and is retracted 3 mm. The pressure per contact is 600 g. The maximum current density on the inner conductor is 36 A(RMS)/cm. The equivalent length of the outer fingers is 33 mm and they are welded to the outer edge of the annular plate in a similar way. The performance of the short-circuiting plate mechanism and the contact fingers has been excellent since installation 9 years ago. At present frequency is changed five times per week.

2.3 Capacitor System for the 200 MeV SSC

A capacitor system for each resonator of the separated-sector cyclotron consist of two copper boxes of 4 by 1 m trapezoidal area and 0.4 m deep. They are required to extend the frequency range from 12.5 down to 6 MHz. The vertical adjustment range is 380 mm. Retractable contact fingers are used along the four straight sides and detail is shown in figure 4. AL-20 copper sheet, 0.5 mm thick, was used to manufacture the fingers in 150 mm long sections, with each finger 10 mm wide and 40 mm long to the contact point. A domed protrusion was pressed out on each finger to give a defined contact point, rather than soldering a silver contact button on. The fingers were then silver plated. In this case the spring property of the AL-20 copper generate the contact pressure of 250 g. The fingers are clamped to the copper lining of the resonator chamber. A long rod with an attached flat bar is rotated to release a row of contact fingers by pulling back on the extended end of each finger. The position tolerance for proper contact is 2 mm. The maximum current density is 15 A(RMS)/cm. Performance of these fingers has been excellent since installation. The capacitors are seldom adjusted as most operation occurs above 12.5 MHz, but the fingers always carry current.

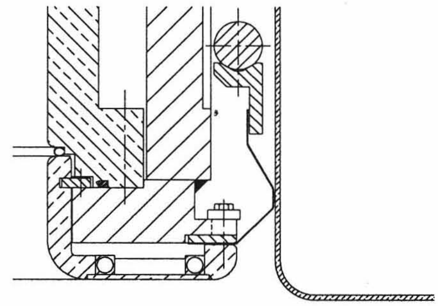

Figure 4: Contact fingers for the SSC capacitors.

3 Contact Systems using Sliding Contact

3.1 Contact System used in the Beamline Bunchers

Two identical resonators are used for bunching in the transfer beamlines. They operate in quarter-wave mode and use capacitive tuning for the 17 to 55 MHz range. Two symmetrically positioned rectangular capacitor boxes, each with an area of 400 by 600 mm and depth of 200 mm, are used per resonator. Sliding contact is used on the four sides of each box, using fingers as shown in figure 5. They are punched from 0.15 mm thick AL-20 copper. The fingers are stacked on a flattened cooling pipe. With the use of spacers five contacts per cm are obtained. The maximum current is 2 A(RMS) per finger and the contact force 30 g. The cooling pipes press the fingers against the walls of the copper chamber and keep them in a fixed position. The copper box slides easily over the other ends of the fingers in a direction parallel to the flat surface of the fingers. Care has to be taken while installing a capacitor box between the contact fingers. Frequency changes occur four or five times per week and the sliding range is 180 mm. Performance of the first buncher

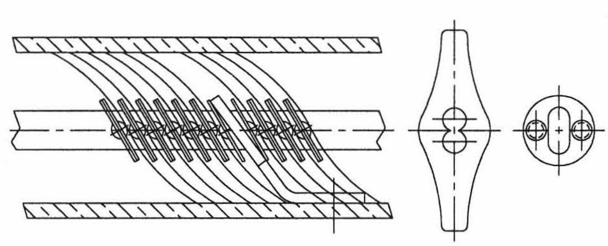

Figure 5: Sliding contact-fingers for the beamline bunchers.

during the past eight years has been excellent, with no contact failures or significant wear having occurred.

3.2 Contact Systems for Coupling Capacitors

Each resonator requires an adjustable coupling capacitor and for most of these, in our facility, we have used sliding contacts, either with silver-graphite buttons or AL-20 fingers. Current densities are low at 2 to 5 A(RMS)/cm and no problems were experienced.

4 Systems where Frequent Movement Occur

4.1 Contact System with Rolling Action

Each resonator of the injector cyclotrons needs a fine-tuning system with a substantial control range owing to ion source repositioning. It has to operate often owing to frequent discharges at certain times. The system is shown in figure 6. It is symmetrical in the vertical direction, with only the bottom half shown. A 12 mm diameter copper roller, 250 mm long, is held between two sets of contact-fingers which are made from 0.35 mm thick silver-plated beryllium-copper. They are formed so that the roller cannot roll out at either end of the fingers. Each of the 5 mm wide and 35 mm long fingers supply 300 g contact force. For correct operation the fingers on opposite sides of a roller must be parallel. The one set, shown at the top, is clamped to the 80 mm high by 250 mm long capacitor plate. The other set is clamped to a sub frame which allows alignment of the roller fingers, as well as the row of standard contact fingers, that make contact with the copper block which is mounted on the copper liner of the chamber. The range of travel of the capacitor plate is 70 mm. The performance of the rolling contact systems on both injector cyclotrons has been excellent at current densities of up to 2 A(RMS)/cm.

4.2 System using Copper Braid

The requirements for the fine-tuning capacitors of the resonators for the separated-sector cyclotron are similar to those of the injectors. A tuning plate is 300 mm high and 600 mm wide, with 100 mm as minimum distance to the chamber wall. An adjustment range of 150 mm is required. Strips of copper braid, with 3 by 25 mm cross-section and 300 mm long, were clamped to the liner of the chamber and the top and bottom of a plate (giving 24 braid strips per side). All original braid is still in use after 9 years, but the maximum current density of 5 A(RMS)/cm experienced, is considered close to the maximum for this type of system. It is an easy and cost effective system for contact with a moveable capacitor plate, if suitable space is available.

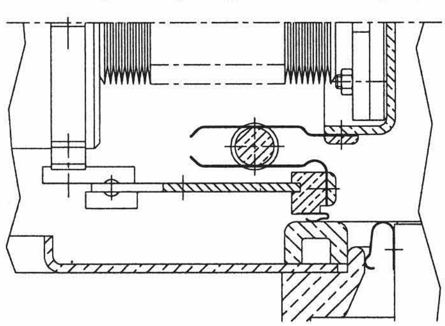

Figure 6: Rolling contact for tuning of the injector resonators.

5 Static Contact Systems

5.1 Between a Circular Pole Liner and Chamber Liner

The circular line of contact, between the copper pole liners and the copper liner of the chamber, of each injector cyclotron, is made by contact fingers, as shown at the right-hand bottom of figure 6. The original fingers were made from 0.35 mm thick silver-plated beryllium-copper. Each finger is 4 mm wide, in 150 mm long sections which are clamped to the pole liner. After two years of operation a section of these fingers failed during tests at high power, as a result of slight mechanical damage during original installation. This showed that the fingers were operating close to their limit. All fingers were replaced by sections with the same dimensions, but consisting of two layers. The inner layer was made from 0.25 mm thick beryllium-copper, with a layer made from 0.35 mm thick AL-20 copper fitting closely over it. The inner gives the larger spring force and resilience, while the outer provides good conductivity. No silver plating was used and these fingers have given excellent service during the past 8 years.

5.2 Soft-soldered Beryllium-Copper Fingers

For contact between the copper liners of the resonator chambers of the separated-sector cyclotron, standard beryllium-copper contact fingers were originally soft-soldered to the 3 mm thick vertical liners. The fingers press against the 3 mm thick horizontal liners, as shown in figure 7(a), making contact along a straight line. Current densities up to 14 A(RMS)/cm occur. Performance of these fingers was not satisfactory in the long term. Overheating softens the solder at maximum power. In addition mechanical shock or excessive pressure at the corner of the fingers break the soft-solder joint. In 1989, after two years of operation, the fingers of the West resonator were replaced. When the top part of the resonator was removed, the fault was aggravated by mechanical shock. The fingers of the East resonator were replaced in 1994, when half of the total 20 m length was found to be faulty. Even at that stage, arc-over at the smallest gaps enabled stable operation, after thermal stabilization, without damage to the liners.

5.3 Contact Strips pushed into Position

The problem described in the section 5.2 , was solved by using contact strips which can be pushed into position if the gap between the liners is in the range of 0.3 to 2.0 mm. The shape of each contact strip is shown in figure 7(b). It is manufactured from 0.15 mm thick AL-20 copper. Each unit is 152 mm long and 20 mm wide. A 4 by 7 mm slot at each end provides inside corners which can be bent upwards, to

Table 1: Comparison of the contact finger characteristics, at maximum power, of the different contact systems at NAC.

Location and Type	Thickness (mm)	Width (mm)	Length (mm)	Material	A(RMS) / (cm)	Force g / Contact	Contacts / (cm)	Gram / A(RMS)	A(RMS) / Contact
Injector s/c inner (retracting)	0.25	15	30	AL-20	30	300	1.4	14	21
Injector s/c outer (retracting)	0.25	17	30	AL-20	15	150	1.2	14	10
SSC s/c inner (retracting)	0.25	14	23	AL-20	36	600	1.4	23	26
SSC s/c outer (retracting)	0.25	14	33	AL-20	15	235	1.4	22	11
SSC capacitor (retracting)	0.5	10	40	AL-20	15	250	1	17	15
Buncher (sliding)	0.15	5–14	2 × 20	AL-20	10	27	5	14	2
Injector tune (rolling)	0.35	6	50	Be-Cu	2	300	2	300	1
Injector (static)	0.35	5	25	AL-20 + Be-Cu	15	300	2	67	8
SSC (static)	0.15	150	10	AL-20	15	100/cm	continuous	100	

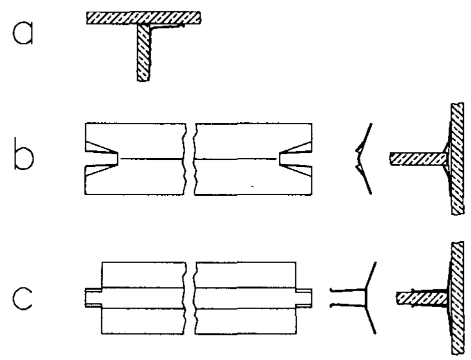

Figure 7: Three types of static contact systems used in the SSC resonators.

give locating lips that keep it clipped in position after installation, as shown on the right. Two small holes on one side enable easy installation, using a hand-held installation tool with two short pins and a retaining clip. These strips can be installed without having to remove the soldered contact fingers. A resonator is large enough that all gaps between the liners can be reached by a person moving about on the inner delta, after gaining entry by removal of the top capacitor unit. The East resonator has not yet been fully opened since original installation 9 years ago and the replacement contact strips were installed in the top and bottom gaps of the liners during January 1994. The performance of these strips has been excellent. The current-density limit of this type of contact strip has been found to be 250 A(RMS)/cm at 50 Hz in air and is expected to be at least 50 A(RMS)/cm as used in our resonators. When the top part of the West resonator was removed in 1989, a slightly different contact strip, as shown in figure 7(c) was made and installed for the top gap before closing the resonator. A clip, which is formed at each end, allows a contact strip to be held in position on the top edge of the vertical liners. The area of each strip is the same as above but a double bend is made and 0.2 mm thick AL-20 copper is used. The current capability is even higher than above and no problems were experienced.

5.4 Clamped C-ring for Contact

A commercially available sealing ring is used for contact between the copper flange of the outer cylinders of the SSC resonators and the copper ring welded to the horizontal liners of the chamber. A silver-plated Inconel sealing ring with a 6.35 mm C-type cross-section and 1290 mm ID., is used as shown on the left side of figure 4. Machining of both mating surfaces is required for proper contact. Performance since installation has been faultless at current densities up to 15 A(RMS)/cm.

6 Testing of Material and Contact-Finger Designs

A test cell was constructed to evaluate different contact-finger designs and conducting material, under vacuum, at radio frequencies. It was installed in the 40 mm diameter coaxial cable between a 20 kW power amplifier and its dummy load. The standard insulators at each end of the cell was made vacuum tight with Viton O-rings. The tested fingers were installed in a gap made in the inner conductor. Two ports were used on the outer conductor, one for evacuation and the other for observation of the reversible temperature-sensitive paint on the finger. The power level at which the paint changed was used for evaluation and comparison. Current up to 20 A(RMS) was available.

A standard microwave oven was used to compare and evaluate insulating materials, by heating a sample or an insulator for 1 minute (together with a glass of water) and then measuring or sensing the temperature rise.

7 Conclusions

Table 1 gives a comparison of the different contact systems in use at our facility. Some problems were experienced with beryllium-copper fingers at current densities above 10 A(RMS)/cm. Fingers made from dispersion-strengthened copper (AL-20) performed very well at current densities up to 36 A(RMS)/cm. Clamping or welding of fingers was found more reliable than soft-soldering. For current densities in excess of 50 A(RMS)/cm it may be necessary to use spheres for contact , as in the resonators of the Milan superconducting cyclotron. For silver button contacts 15 g/A is a safe minimum pressure. Detail of the resonators at NAC were described at previous cyclotron conferences (1975, 1984, 1986, and 1989).