EXPERIMENTAL STUDY ON THE SLIDING SHORT CONTACTS AS A RESULT OF A THEORETICAL INVESTIGATION ON THE CHOPPER-500 COAXIAL RESONATOR

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Abstract

In this work we present the experimental study of the sliding short contacts used in the tuneable coaxial resonators, usually employed for particle beam choppering operations. In particular, the case of the Chopper-500 λ/4 coaxial resonator is considered. The frequency tuning is obtained by the movement of a sliding short circuit connecting the inner and outer conductors of the resonator. The current flowing in this sliding short is a limiting factor to the maximum voltage applied to the Chopper electrodes. Starting with the theoretical approach of the evaluation of the maximum current of this short, a simple experimental set-up has been developed to test the RF contacts. The experimental results of these test bench measurements and the simulation by a proper electromagnetic solver, will be provided in this paper.

SLIDING SHORT OF THE RESONATOR

The production of consecutive accelerated bunches with a separation time of 1.5÷2 ns and a width of 500 ps FWHM is the goal of the new chopping beam system for the Superconducting Cyclotron at INFN-LNS in Catania[1]. The frequency range of the Chopper-500 λ/4 resonator is [65, 110] MHz, and the tuning within this interval is obtained by the movement of a sliding short circuit, connecting inner and outer coaxial conductors of the structure. The connection between these coaxials is made by two circular strips of CuBe (Berillium-Copper) finger contacts. A vacuum sealed cylindrical steal tank hosts the whole copper RF cavity. In this environment the short circuit can sustain only current densities lower than a threshold. For higher current values the "softening" temperature for the copper-CuBe junction may be reached and the contact surface may be damaged [2]. The current flowing in this sliding short is therefore a limiting factor of the maximum voltage applied to the Chopper electrodes, and a good estimation for safe working conditions is a max current density of 30 A/cm. It is possible to determine the current flowing in this contact region as a function of the electrodes voltage [2].

Long and strenuous tests have been performed on the sliding shorts from the mechanical point of view. They were done as a specific theoretical study on the single finger contact of the short circuits showed up a possible bottle neck of the entire system [2]. Figure 1 shows the connection between the inner and outer coaxial resonator and a portion of the finger contacts respectively.

Figure 1: the sliding short connection between inner and outer coaxial on the left, the CuBe finger and the spherical copper contacts (9.7 mm diameter) on the right.

THEORETICAL INVESTIGATION

During the first operative test a parallel study was carried out to estimate the maximum power dissipated on the Chopper-500, in terms of the maximum current density on the sliding short [2,3]. In some theoretical investigation the physical behaviour of the Chopper-500 system is described as a bunch shaper (to achieve 500 ps) and beam suppressor (to increase the bunch separation time). The theoretical minimum voltage $V_{M\ req}$ is necessary to obtain the requested Δt_{req} when the beam passes through the Chopper-500 system. We also derived a formula for the current on the sliding short as a function of the $V_{M\,req}$:

$$I_{SHORT} = i V_{M\,req} \sqrt{Y_0^2 + \left(2\pi\, n\, f_{CYCL}\, C_{cap}\right)^2} \approx \quad (1)$$

$$\approx i \frac{m\, d\, y_m\, f_{CYCL} \sqrt{Y_0^2 + \left(2\pi\, n\, f_{CYCL}\, C_{cap}\right)^2}}{q\, \Delta t_{req} \dfrac{l}{\beta\lambda_{CYCL}} \sqrt{\left(\dfrac{a^2}{l^2} + \dfrac{a}{l}\right) \sin^2\left(\dfrac{\pi\, l}{\beta\lambda_{CYCL}} n\right) + \dfrac{1}{4}}}$$

where Y_0 is the characteristic admittance of the coaxial resonator, C_{cap} is the plates capacitance, n is the ratio between the frequency of the sinusoidal voltages driving the Chopper and the Superconducting Cyclotron respectively; m and q are mass and charge of the particles in the beam delivered by the Cyclotron, l = 0.4 m is the length of chopper electrodes in the direction of the beam, a = 3.5 m is the drift length after the plates and 2 y_m is the

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distance between the slits. The Superconducting Cyclotron works in 2nd harmonic and it has a radius at extraction equal to 0.87 m; therefore $\beta\lambda_{CYCL} = 2.733$ m.

The above-mentioned study has been applied to the various beams usually accelerated by the Cyclotron, leading to some tables of optimized conditions for the future use of the Chopper-500 system. The limits due to the threshold for the current flowing in the short circuit, together with the choppering effect on the beam attenuation and the chopping efficiency have been considered. In order to estimate the required input power, the experimental measurements for the cavity R_{SHUNT} have been employed. Tables 1 summarizes some results achieved when the frequency of the sinusoidal signal driving the Cyclotron is 33.7416 MHz, and the accelerated particles have atomic number $A = 58$ and $q = 19$ charge compared to the unit, $V_{min\text{-}500}$ is the voltage to apply for obtaining $\Delta t = 500$ ps and P_i is the related power.

Table 1: $f_{CYCL} = 33.7416$ MHz, $A = 58$, $q = 19$, $y_m = 3.5$ mm; 3 bunches suppressed over 4 – Bunch separation time: 118.548 ns.

f_{CH} [MHz]	n	$V_{min\text{-}500}$ [kV]	P_i [kW]	I_{INNER} [A/cm]	I_{OUTER} [A/cm]
71.7009	2.125	210.390	35.416	67.303	25.239
80.1363	2.375	196.569	33.852	63.787	23.920
88.5717	2.625	186.783	35.347	61.553	23.082
97.0071	2.875	180.207	45.926	60.370	22.639
105.4425	3.125	176.339	50.993	60.106	22.540

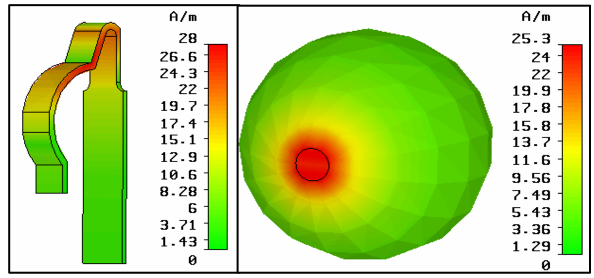
From equation (1) it follows that in order to decrease the current it is possible to operate, under given limits, by reducing the y_m from the typical value of 3.5 mm.

The sliding short circuit

The detailed study carried out on all the accelerated beams of the Superconducting Cyclotron showed that the maximum RF power delivered from the final stage amplifier is theoretically enough to reach the goals of the Chopper-500 system [3], but the shortcoming is the high current on the sliding short. All the simulations and the analyses, also described in Table 1, show an intensity of the total current near the limit of the sliding short. A value reported in more than one study, places 50 A/cm as the upper limit of the finger contact current density [4], but usually the 30 A/cm is used for safe conditions. In order to overcome the limitation due to the use of these finger contacts, another solution employing copper sphere contacts has been used and examined. To this purpose, several electromagnetic 3D simulations have been performed to deal with the study of the problem, by the CST Microwave Studio electromagnetic simulator [5].

In Figure 2 the current distribution on both types of contact is shown at 76 MHz. In the first case, the maximum distribution currents are localized on the finger bending side of the RF contact, while in the second the peak is around the contact regions.

Moreover, a relation between temperature and current can be taken into account to work with the contacts in a safe area. The so-called *copper softening temperature* is the limit of this safe area. This is the temperature at which the strain hardening in the highly stressed contact disappears. As the current increases, the contact resistance decreases. The softening temperature is about 187°C for a room temperature of 20°C [4].



(a) (b)

Figure 2: The current density distribution for a normalized 1 W input power of (a) the Cu-Be finger contact and (b) the copper sphere contact in a 3D electromagnetic simulation at 76 MHz, using the CST Microwave Studio.

RF FINGER CONTACTS TEST BENCH

A simple test bench has been developed to test the finger and spherical contacts. The weak point of the RF contact is the maximum temperature reached when the high frequency signal flows between both sides of the contact itself. With this test bench we focus our attention on the temperature. All the approaches, including our software study, show the increasing temperature to be a consequence of the high current flowing through the sliding shorts. In general, the number of finger contacts are many in this kind of approach, and the intensity current flowing in a single contact is the ratio between the total calculated current and the number of contacts. Let us try to invert this approach. If we reduce the number of finger contacts to one or two, without a proper cooling system, then a small RF power brings the contact near the so-called "copper softening". In Figure 3 the test set block diagram of the system is shown. The same apparatus was also used to test the spherical contacts and the "thru-element" used as a measurement reference.

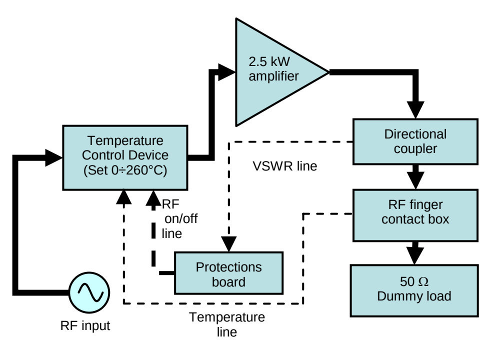


Figure 3: block diagram of the test bench system.

Working principle of the test bench

The tests have been carried out at the maximum power of 1.3 kW CW with a radio frequency of 76 MHz. According to the block diagram the input RF signal reaches the temperature control device. This device contains a voltage controlled amplitude modulator, based on the well-known Mini Circuits PAS-3, a differential amplifier (REF200 plus INA114 Burr Brown semiconductors) and an inverting operational amplifier. The differential stage compares the temperature value from the thermocouple attached to the contact and the set temperature value. The difference between the two signals drives the control gate of the RF modulator according to the maximum sensitivity of 10 mV/°C. The modulated RF signal will be amplified by the 64dB gain, 2.5 kW amplifier. The output amplifier stage, through a directional coupler, is connected with the test box, where the finger contacts are placed to be tested. The output of the box is finally connected with the dummy load. The directional coupler supplies the VSWR, furthermore the attenuated forward and reflected signals are processed inside the protection board to prevent dangerous situations. This simple system is a controlled temperature test set. Once you set the maximum temperature, the system takes the RF contact to the desired temperature automatically.

The contact is hosted inside the test box between two brass bars. Next to the it, a thermocouple (PT-100) reads the reached temperature. An internal view of the test box is shown in the Figure 4.

Figure 4: The internal view of the RF contact test bench.

The small dimension and the elementary hardware of the box allow for a good relantionship between the temperature of the contact and the PT-100 read-out.

Experimental results and measurements

The basic rules of thumb to run the finger contact test bench are resumed below:

- turn the RF power on;
- set the reference temperature;
- increase the power up to 1.3 kW maximum;
- wait until the contact temperature equals the reference one;
- keep away from the copper softening temperature.

In Figure 5 the resume for the measurement with the finger contacts, the spherical contact and the reference thru is displayed. The graph shows an example of "copper softening temperature" reached at the frequency of 76 MHz with 1.3 kW CW maximum. The contacts loose their physical characteristics above 170°C. When the thru is used, a brass bar connecting input and output N-connectors, the temperature gradually increases without the copper softening phenomenon.

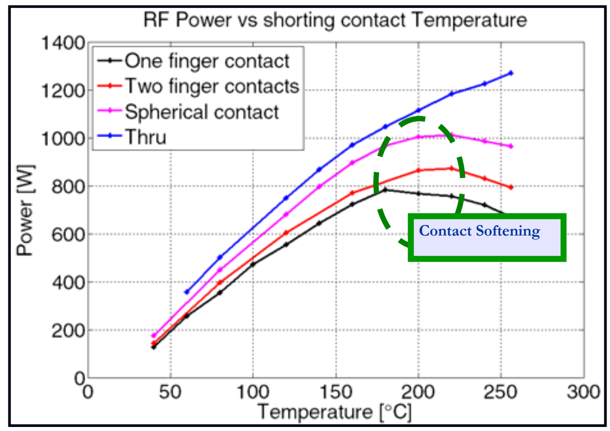


Figure 5: Measurements of the different contacts.

The experience and measurements obtained with this test box can be used for the Chopper-500 apparatus. A thermocouple can be inserted in the final version of the resonator sliding short. We are planning to connect along the circular shape of the inner coaxial of the λ/4 resonator, as near as possible to the finger contacts, more than one PT-100 in order to check the working temperature of the RF contacts. The sliding short of the chopper-500 operates in a vacuum environment; a proper cooling system has been installed and already tested, but the high current can increase the temperature to a dangerous level. The continuous read-out of the heating effect through this simple system can avoid the copper softening. The system can be fixed at a safe, low working temperature far away enough from the softening threshold. This described test bench can easily be used to test all the contact types for this, but also for other future applications.

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