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MEASUREMENT OF MICROWAVE PROPERTIES OF X-BAND ACCELERATING STRUCTURE UNDER PULSED HIGH-POWER OPERATION AT LIQUID NITROGEN TEMPERATURE

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Abstract

After required chemical treatments a disk-loading structure was operated at liquid nitrogen temperature with X-band magnetron as an RF source. The peak RF pulse power was variable from 150 to 300 kW and the average power was altered by changing the pulse repetition rate between 1400 and 2800 pps. Measurements on this structure both at low and at high power indicated the Q factor of 6800 at room temperature, which increased to 17000 at liquid nitrogen temperature — an enhancement factor greater then 2,5 in good agreement with theory.

INTRODUCTION

There are several applied applications of linear accelerators where the space available for the accelerating structure and the RF source is limited, or where there is a limitation on the RF power available. The efficiency of guide structure made of conventional materials can be increased by reducing its operating temperature and increasing its operating frequency.

The advantages of superconducting materials application in particle accelerators have been limited by the cost of constructing and operating the refrigerating systems necessary to maintain the low temperature required. In addition, at temperatures very close to the critical temperature T_c, the surface resistance of superconductors would strongly depend on temperature T, which results in variation of the linac characteristics due to the fluctuations or drifts of the cryogenic refrigerator temperature. On the contrary, the surface resistance of all normal metals is nearly independent of tamperature in the anomalous skin-effect domain.

In the past, the microwave surface resistivity of copper and aluminium was carefully measured both at room and liquid nitrogen, hydrogen and helium temperatures [1,2]. Using appropriate surface treatment technology, the theoretical value of surface resistance was experimentally obtained at low power and cryogenic temperatures in microwave structures of complicated shape. However, the Q-factor of S-band accelerating structures at liquid nitrogen temperature decreases with peak RF power [3].

In order to evaluate the advantages and problems associated with a system operating at liquid nitrogen temperature, an investigation was undertaken with the following objectives: first, to establish the feasibility of operating an accelerator structure at 77 K, and, second, to determine what advantages might be realized with respect to size or power input reauirements. We report here experimental results which show the increasing of Q-factor by cooling X-band accelerator cavity working at 9,35 GHz from T = 293 K to T = 77 K, these result being compared to the theoretical value.

RF SURFACE RESISTANCE OF COPPER AT LOW TEMPERATURE

For RF currents, the surface resistance decreases first as $\sigma^{-1/2}$ (σ — conductivity of metal) by lowering the temperature until a certain limit and at relatively low frequencies. But at very low temperatures and very high frequencies, RF field amplitude changes rapidly in space along an electron mean free path l, and during the time t between two successive collisions. For both reasons Ohm's low can no longer be applied.

The surface resistance of normal metals in anomalous skin effect domain can be obtained by using the Dingle's expressions. This fomulas can be used at all temperatures and microwave frequencies, considering both specular and diffuse electron reflection at the metal surface, but neglecting relaxation. At frequencies less than 35 GHz, the influence of relaxation effect on R_S may be neglected [1].

The temperature dependence of copper enhancement factor $K_R(T) = R(293\ K)/R_S(T)$ can be seen on figure 1. The frequency dependence of K_R can be seen on figure 2. The curves were obtained by computation of Dingle formulas [4] (for specular and diffuse electron reflection) at 9,35 GHz (fig.1) and at 77 K (fig.2). The experimental points of K_R (fig.2) for different kinds of cavity

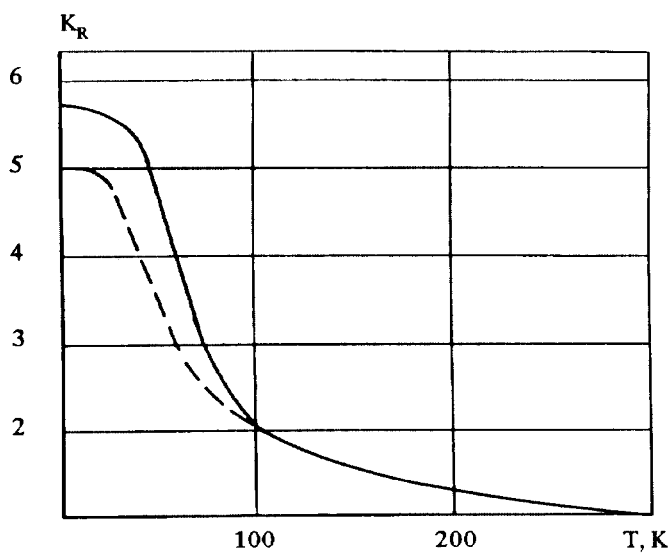

Fig. 1. Temperature dependence of enhancement factor K_R for OFHC copper at 9.35 GHz.
——— *specular reflection*
— — — *diffuse reflection*

surface treatments shows, that for the enhancement factor value at low temperatures in good agreement with theary to be obtained chemical (or electrochemical) polishing and finally annealing in hydrogen atmosphere must be used. The best results were achieved by using copper single crystals [1] or OFHC copper with 1% of yttrium [5]. According to this results the enhancement factor of 2,8 can be obtained at nitrogen temperature and X-band frequences.

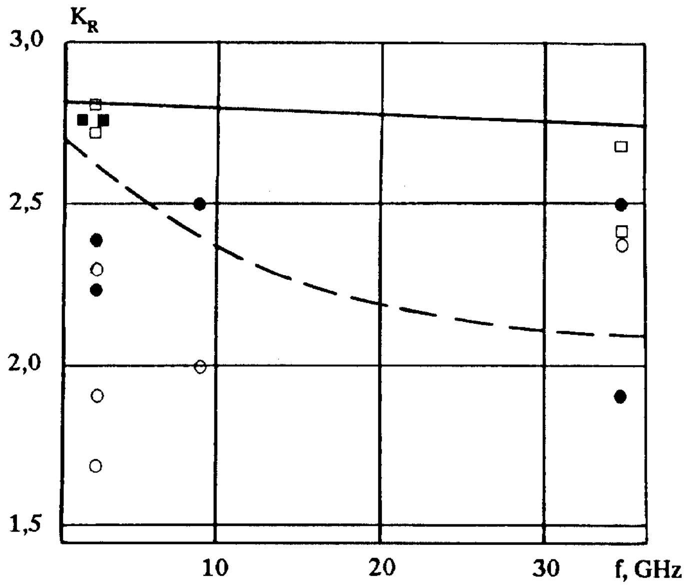

Fig. 2. Frequency depedence of enhancement factor K_R for OFHC copper at 77 K.
1) computed
——— *specular reflection*
— — — *diffuse reflection*
2) experimental
○ — *before chemical treatment*
● — *after chemical treatment*
■ — *after electrochemical treatment*
□ — *after annealing in hidrogen*

Q-FACTOR MEASUREMENT METHOD, EXPERIMENTAL SET UP AND RESULTS

For high-power tests a 12-cell disk-loading cavity was constructed. The length was chosen $L = 4\lambda g$ at 9,35 GHz. This cavity was operated in standing wave of $2\pi/3$ mode. It was fitted with standard 28,5*12,6 mm^2 rectangular waveguide input, which includes a section made out of thin walled stainless steel to minimize the thermal losses. Dispite the relatively poor conductivity of stainless steel, the insertion losses are less than 0,5 dB in this section. A cavity was made out of oxygen-free high-conductivity copper with a purity of 99.99%. A chemical polishing in a 1/3 H_3PO_4 * 1/3 HNO_3 * 1/3 CH_3COOH during a few minutes at a room temperature is sufficient for obtaining mirror like surfaces.

The cavity was cooled down in a cryostat filled up with liquid nitrogen, the working temperature being 77 K. The cavity with its supporting waveguide was pumped down to a low pressure (less than 10^{-6} Pa) to avoid gas condensation on the walls during the cooling process.

At low power the unloaded quality factor Q_0 was obtained by an impedance measurement method both at room andnitrogen temperatures. It is known, that the external quality factor Q_l depends only on the coupling; it remains constant if the coupling is not modified. At low temperatures and high power unloaded quality factor $Q_0(T)$ can be obtained by measuring the input VSWR [3]. In practice, it is, however rather difficult to measure this value with error required when there are reflections in supporting waveguid.

Unloaded quality factor at low temperature can be obtained from the relation:

$$Q_0(T) = \frac{Q_0(T_0)}{1 - Q_0(T_0)\,[\,Q_l^{-1}(T_0) - Q_l^{-1}(T)]}$$

where $Q_0(T_0)$, $Q_l(T_0)$ are unloaded and loaded quality factor respectively at temperature T_0 (T_0 = 293 K for this case); $Q_0(T)$, $Q_l(T)$ — the same parameters at nitrogen temperature. At high power $Q_l(T)$ can be obtaind by a decrement measurement method.

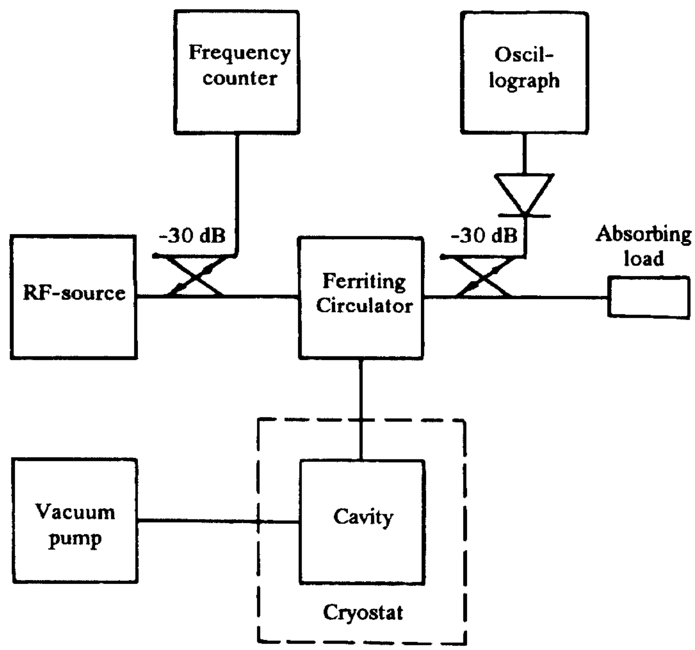

Fig. 3. Electron set up for high power operation.

Table 1.

Calculated and experimental resonator parameters

Parameters	T=293 K	T=77 K
Calculated Parameters		
Stored Energy per Cavity for 1MV/m, J	4,2*10^5	4,2*10^5
Power Loss per Cavity for 1 MV/m, W	316	113
Unloaded Q-Factor	7850	22000
Shunt Impedance, MOh/m	57	160
E_p/E_0	1,52	1,52
Experimental Results		
Resonant Frequency, MHz	9379,8	9348,0
Unloaded Q-Factor	6800	17000
Coupling Factor	0,62	1,53
Enhancement Factor	—	2,5

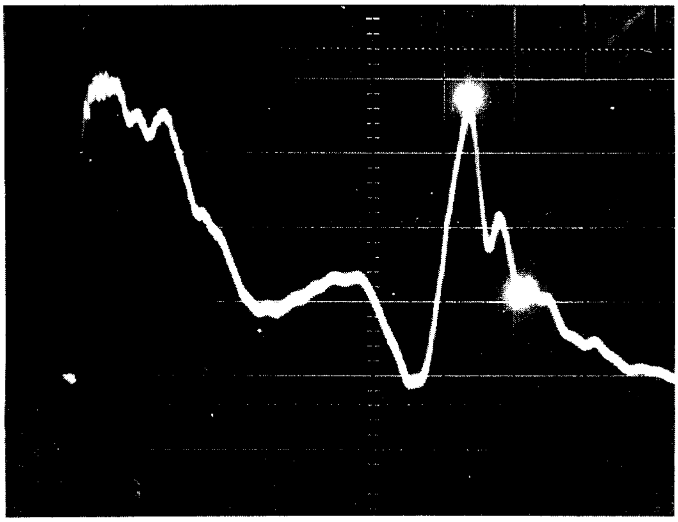

Fig. 4. Oscillogram of RF pulse reflected from the cavity at T=293 K. Scale — 100 ns/cm.

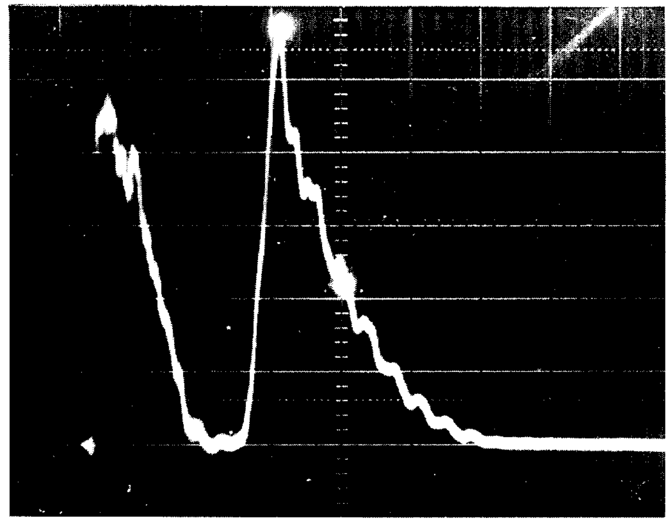

Fig. 5. Oscillogram of RF pulse reflected from the cavity at T=77 K. Scale — 200 ns/cm.

The electron set-up for high power operation is shown in figure 3. The peak RF pulse power from the X-band magnetron was variable from 150 to 300 kW by changing the anode voltage. The average power was altered by varying the pulse repetition rate between 1400 and 2800 pps. The RF pulse width was equal to 0,5μs. The tests were carried out on $\pi/2$ and $2\pi/3$ mode. The frequency was measured by electronic frequency counter.

Calculated and experimental results are shown in table 1. In figure 4 and figure 5 the oscillograms of rf pulse reflected from the cavity at resonant frequency are shown at T=293 K (fig.4) and T=77 K (fig.5). At low and at high power as well the same value of unloaded quality factor was obtained. The accelerating field for 300 kW at T = 77 K is equal about 50 MV/m.

CONCLUSION

The anomalous skin effect should be taken into account for computation the surface rasistance of an X-band cavity at nitrogen temperature.

Using appropriate surface treatment techinques to the cavity fabricated out of OFHC copper, the theoretical value of Q-factor can be obtained at cryogenic temperature.

The enhancement factor of X-band accelerator cavity (after chemical polishing) at nitrogen temperature was equal 2,5 both at low and at high power.

No decreasing of the Q-factor at T= 77 K was observed at high power. The maximum accelerating field was approximately equal 50 MV/m.

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