STUDY OF THE THERMOMAGNETIC INSTABILITY FOR SUPERCONDUCTING RF STRUCTURE OF SVAAP ACCELERATOR ON THE BASE OF NB/CU

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Abstract

Recently scientists of the different accelerating centers where SC accelerating structures are used, pay much attention to analysis of conditions of origin of thermomagnetic breakdown [1-4]. Theoretical methods of the analysis thermomagnetic instability analysis of SC accelerating RF structure operation are developed. These methods [1-4] allowed to reveal the limit of the magnetic field on the internal working surface, when there is no thermomagnetic breakdown in the cavity. It is necessary to note that all the works are related to the analysis of the SC cavities only made of Niobium.

Now the project of the SC linear electron accelerator is developed in our Lab. It is known as SVAAP (**S**uperconducting **V**ertical **A**ccelerator for **A**pplied **P**urposes) [5, 6]. in our Lab . SC cavity on the base of Nb/Cu is used [7]. We began develop the technology of the superconducting cavity on the base of Nb/Cu since 1993 [7,8].

1. METHOD OF THE THEORETICAL STUDY FOR CONDITIONS OF THE THERMOMAGNETIC INSTABILITY OCCURRENCE

Fig.1 shows the distribution of the magnetic field among nine cells of the SC cavity for SVAAP.

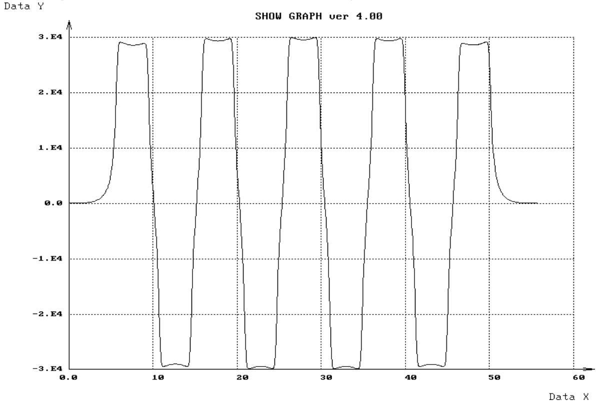

Fig. 1. The diagram of distribution of magnetic intensity along the length accelerating structure according to the program PRUDO.

From this we can draw a conclusion, that the maximal meaning of the magnetic intensity is necessary on equatorial area of a cell of the cavity. On the assumption of this, it is possible to pass to consider only the equatorial area, as an area of the most probable transition from a superconducting state to normal conducting state in the result of the thermomagnetic breakdown. It allows us to proceed from the complicated form of the cavity cell to consideration of a cell as the cylinder with a diameter equal to a diameter of the equator of a cell.

Let's consider the multi -layer cylindrical wall of the cavity (fig. 2) with the inside diameter d1, intermediate diameter d2 and outside diameter d3, with different factors of thermal conductivity of layers λ_1 and λ_2.

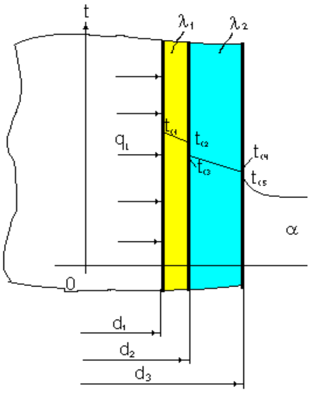

Fig. 2. Heat transfer through the multy -layer cylindrical wall.

As given we have the constant Helium temperature of a bath t_l, factor heat transfer to Helium on an outside wall α, thermal resistance Kapitza on the boundary Nb-Cu R_{k1}, Kapitza thermal resistance on the boundary Nb-He R_{k2} and flow of heat through inside surface q_l. Let us assume that length of a considered cell is big in comparison with thickness of a wall. Then the losses of heat from the butt end of a pipe can be neglected, and at the established thermal mode the same quantity of heat will pass through a wall and will be given back from a wall to the cold liquid.

Hence, it is possible to write:

1. Thermal flow through the Nb film

$$q_l = \frac{\pi(t_{c1} - t_{c2})}{\frac{1}{2\lambda_1}\ln\frac{d_2}{d_1}} \;;$$

2 Thermal flow through the boundary in the in Nb/Cu

$$q_l = \pi\frac{d_2}{R_{k1}}(t_{c2} - t_{c3}) \;;$$

3. Thermal flow through a copper shells

$$q_l = \frac{\pi(t_{c3} - t_{c4})}{\frac{1}{2\lambda_2}\ln\frac{d_3}{d_2}} \;;$$

4. Thermal flow in an inter boundary layer Cu-He.

$$q_l = \pi\frac{d_2}{R_{k2}}(t_{c5} - t_{c4}) \;;$$

5. Flow of heat to the He bath

$$q_l = \alpha\pi d_3(t_{c5} - t_{He}) \;;$$

where R_{k1} and R_{k2} - thermal Kapitza resistance between layers.

After addition of these equations is made , we receive a temperature pressure amount of heat which is passes through a unit of the surfaces of the cavity wall, that we can determine as:

$$Q = k \cdot \Delta\mathrm{T}\,, \qquad (1)$$

where k is a linear factor of a heat transfer [9].

For multi- layer wall

$$k_l = \frac{1}{\left(\frac{1}{2\lambda_1}\ln\frac{d_2}{d_1} + \frac{R_{k1}}{d_2} + \frac{1}{2\lambda_2}\ln\frac{d_3}{d_2} + \frac{R_{k2}}{d_3} + \frac{1}{\alpha d_3}\right)}$$

The magnetic field on the surface of the cavity causes heating, which raises temperature of an internal surface of the RF structure. Thus the certain balance between the reserved energy and the quantity of heat that is passing through a unit of the surfaces of a wall of the cavity is necessary for the steady work of system:

The dissipated RF power is defined as:

$$P = \frac{1}{2}R_s(T)\cdot H^2\,, \qquad (2)$$

where $R_s(T)$ is surface resistance.

For the cavity from Nb/Cu [10]:

$$R_s(T) = A\omega^{-n}\exp\left(-\frac{\Delta}{k_b T}\right) + R_{ocm}\,, \qquad (3)$$

where A is a factor that is a function of variables: the electron velocity on the Fermi surface v_F, electronic density N, length of free run L ($A=10^{-25}$), ω is frequency, Δ - energy gap, k_b - Boltsmann constant ($\frac{\Delta}{k_b} = 15.6$) , $R_{ост}$ - residual surface resistance, $n \approx 2$.

Having equated P from (2) and Q from equation (1), we shall receive the equation of a thermal balance as:

$$\frac{1}{2}R_s(T)H^2 = k\cdot\Delta\mathrm{T} \qquad (4)$$

The received equation can be analysed by the following ways:

If we take $R_s = 2\cdot k\frac{\Delta\mathrm{T}}{H^2}$ (5)

it is possible to receive a critical intensity of a magnetic field that depends on the on temperature of a He bath [11];

If we take $H = \sqrt{\frac{2\cdot k\cdot\Delta\mathrm{T}}{R_s}}$ (6)

we receive a critical intensity of a magnetic field that depends on the temperature of an internal surface of the cavity [8, 11];

Let's consider the given ways in more detail.

The table 1 includes the initial data for the cavity on the base of Nb/Cu for the accelerator SVAAP.

Table 1.

№	The name	meaning
1	Working frequency ω, MHz	2950
2	Thermal transfer to He α, $\frac{W}{m^2\cdot K}$	2500
3	Temperature of the He bath t_h, K	4.2
4	Internal diameter d_1, mm	96.122
5	Intermediate diameter d_2, mm	96.125
6	External diameter d_3, mm	102.125
7	Nb thermal conductivity λ_1, $\frac{W}{m\cdot K}$	80
8	Cu thermal conductivity λ_2, $\frac{W}{m\cdot K}$	200
9	Thermal Kapitza resistance Nb-Cu R_{k1}, $\frac{m^2\cdot K}{W}$	$0.02\cdot t_h^{-3.6}$
10	Thermal Kapitza resistance Cu-He R_{k2}, $\frac{m^2\cdot K}{W}$	$0.02\cdot t_h^{-4.5}$

On the base Table 1 we shall do the calculation of the thermal magnetic instability.

Method 1

We want to find the graphic decision of the system of equations consisting of the transformed equation of thermal balance (5) and the temperature-frequency dependence of surface resistance (4). In the fig. 3 curve 1 is a temperature dependence of the surface resistance according the BKS-theory. Curve 2 corresponds to the meaning of intensity of a magnetic field H=2.5 10^5A/m, curve 2 ' - H=3.8 10^5A/m at T=1.8 K.

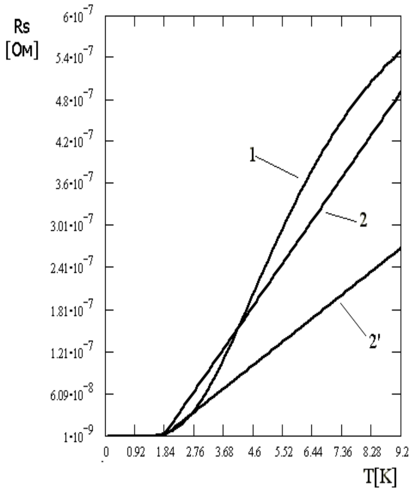

Fig. 3 Graphic decision of the system of equations by method 1 for the cavity made of Nb/Cu.

Other characteristics of cavity, such as a thermal conductivity factor, Kapitza resistance, geometrical sizes are included into parameters of a straight line 2 and 2 .The points of intersection of curve 1 from a straight line 2 and 2 ' give the decision of the equation.

When we have a straight line 2 and the BKS-curve crossing the stable work of RF cavity is possible. In this case all heat selected at dispersion of the RF power on an internal surface of the cavity is allocated in the He bath.

At the increase of magnetic intensity the inclination of line 2 decreases and under certain conditions it reaches a state, when the straight line is pertinent to the BKS-curve. In this case metastable condition of the system is observed and at any deviations of temperature of a wall thermal and thermal magnetic breakdown is possible. This critical inclination enables us to define a critical level of magnetic intensity.

Method 2

A graphic decision of the equation (6) is given in fig.4. The received curve displays the greatest possible theoretical field of magnetic intensity (H_{br}). The given model allows more precisely and visuall analyse the stability of the SC accelerating cavity work at the a working temperature range from 1.8 up to 4.2 K.

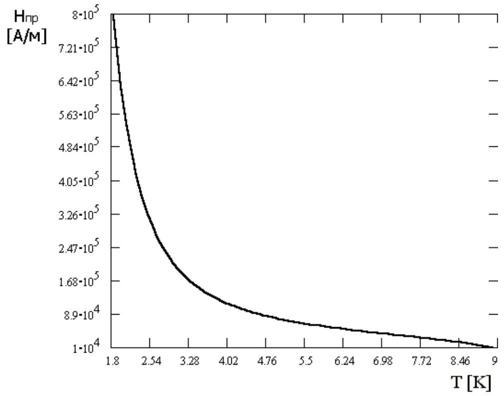

Fig. 4. Diagrams of dependence of intensity of a magnetic field from

It is necessary to note, that the given model in contrast to model described in work [4] allows to take into account such factors, as temperature and BKS frequency dependence of surface resistance of an environmental superconductor, heat transfer between of the cavity wall and the He bath (thermal Kapitza resistance) and factor thermal transfer to He). It is possible to influence these parameters by technological methods of a processing of the cavity surface, that will allow us to come nearer to the theoretical meanings

2. ACCELERATING FIELDS FOR CAVITY ON THE BASE NB/CU

For calculate the accelerating fields the formula is used

$$\frac{P}{L} = \frac{E_{yck}^{2}}{\frac{r_a}{Q_0} \cdot Q_0} , \qquad (7) \; [$$

where L is length of the accelerating structure 12]:,

E_{yck} is accelerating field, $\frac{r_a}{Q_0}$ is the impedance.

Having transformed this expression we shall receive :

For the resonator from Nb/Cu:

$$E_{yck}^{teor\,\max} = \sqrt{\frac{\pi(t_{kp} - t_{He})\frac{r_a}{Q_0} \cdot Q_0}{(\frac{1}{2\lambda_1}\ln\frac{d_2}{d_1} + \frac{R_{k1}}{d_2} + \frac{1}{2\lambda_2}\ln\frac{d_3}{d_2} + \frac{R_{k2}}{d_3} + \frac{1}{\alpha d_3})}} \qquad (8)$$

In fig. 5 the dependence of the maximum accelerating field on the temperature for cavities is represented at different quality factor calculation is made with the geometry and thickness of the layers for accelerating cavity, showed at Fig.6. . The curve 1 corresponds to the cavity with the quality factor $Q_0 = 10^{10}$, curve 2 corresponds to the quality factor $Q_0 = 10^9$.

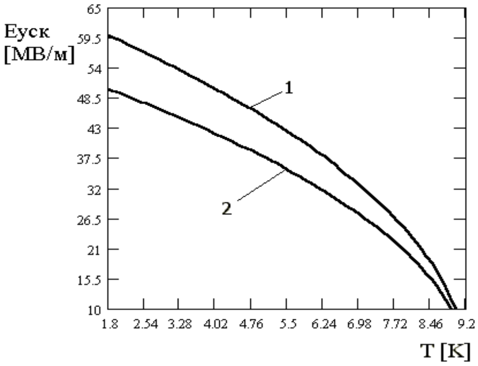

Fig. 5 Diagrams of dependence of an accelerating field versus to the working temperature

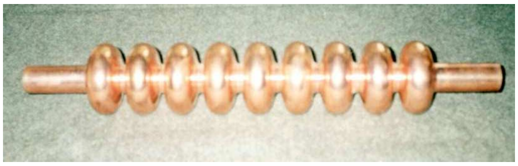

Fig. 6. SC accelerating cavity for SVAAP with thickness of Nb film is 3 μm and thickness of Cu shells is 3mm

3. CONCLUSION

Analysing the received results, it is possible to make the following conclusions:

1. Theoretically the use of SC films in RF accelerating cavities gives us not only economic benefit, but allows to increase accelerating fields.

2. Increasing of copper shell thickness leads to decreasing of the common thermal resistance and allows us increase the hardness of SC accelerating structure.

3. Niobium thermal conductivity in this case does not render significant influence on the maximum accelerating field, at to temperature range 1.8-4.2 K. This influence becomes more significant at temperature close to critical temperature.

4. It is necessary to continue to develop a new technology and special equipment for the accelerating cavities on the base of Nb/Cu.

It is necessary also to note, that in is work the influence of metallurgical and technological defects on critical fields was not taken into account. At present we work at the computation program that allows us to take into account this influence will for cavity on the base of Nb/Cu..

4. ACKNOWLEDGEMENTS

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