COLD PHOTOCATHODE RF GUN

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Abstract
Heating and thermal expansion in normal conducting RF-guns are the main limitations for achieving a high accelerating gradient and consequently a low emittance beam. Some pure materials show a significant increase in thermal conductivity with a small coefficient of temperature expansion at temperatures around 20 K. Possible materials are Molybdenum, Iridium or Tungsten. However, machining of these materials is very difficult. Therefore we propose a simplified shape for an L-band RF-gun. We expect to achieve a significant increase in gradient for similar RF power as used in the present DESY RF-gun. On the other hand, it would also be possible to increase the duty cycle keeping a moderate gradient. In this report we discuss one possible design of an RF-gun using hard metals and present simulations on thermal properties.

INTRODUCTION

RF-guns are key elements for high brightness beam applications as free electron lasers (FELs). In recent years the interest in high-average-power FELs, which need a high gradient and a high average current in the RF-gun cavity has been growing. High gradients are the domain of normal conducting cavities, while higher duty cycles can be realized with super conducting cavities. In [1] a design of a 1.3 GHz RF-gun, which has a gradient of 60 MV/m and thermal losses of 62 kW with a RF pulse length of 1 ms and a repetition rate of 10 Hz is presented. A sophisticated design of cooling channels is required to remove the heat load from this gun, however, a further improvement of the cooling efficiency with water is not to be expected. Another problem connected with the thermal losses in the gun is the shift of the resonance frequency of the gun due to the thermal expansion of the material during the RF pulse. Many authors reported about a reduction of the thermal losses in cavities by cooling them down to liquid nitrogen temperature. From [2, 3, 4 and 5] the RF losses were reduced in L- band by a factor of 2.4, in X-band by 2.5 and by about 2.7 in an S-band structure. In this paper we propose to cool the RF gun down to a temperature of about 20 K, i.e. about the temperature of liquid hydrogen or liquid neon [6], which could reduce the losses by a factor 6.2.

THERMAL LOSSES

Thermal losses in the thin surface layer of a cavity can be reduced by cooling it to low temperatures, but at the same time the free path length of electrons is inversely proportional to the temperature and at some temperature can be as large as the depth of the skin layer. This effect is known as anomalous skin effect [7 - 9] and limits the rising of the conductivity. From [10] this effect is visible

Table 1:Properties of some pure metals: Cu - RRR = 400, W - RRR = 450, Mo - RRR = 600, Ir - RRR = 450.

Material	T K	ρ Ω·m	λ W/m·K	C_p J/kg·K	α E-6/K
Cu	300	1.72·E-8	384	385	16.5
	20	5·E-11	6000	7	0.42
W	300	5.4·E-8	178	134	4.5
	20	1.2·E-10	1600	~2	~0.08
Mo	300	5.7·E-8	138	251	5.2
	20	8.0·E-11	360	~3.5	~0.07
Ir	300	5.1·E-8	147	134	6.5
	20	1.0·E-10	1900	~3	~0.09

at a temperature of about 40 K for a copper cavity at 11.4 GHz. For L-band cavities we can expect an impact of the anomalous skin effect at temperatures below 20 K. Data of resistance, thermal conductivity, specific heat and expansion factor [11 - 14] of several metals at temperatures of 300 K and 20 K are collected in Table 1.

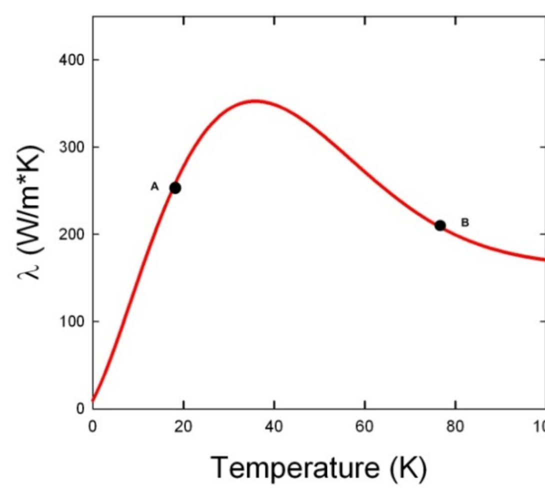

Figure 1: Thermal conductivity of molybdenum: point "A" normal operation, point "B" for cavity conditioning.

The specific heat and the expansion factor drops monotonously when reducing the temperature. The resistance drops also but it saturates at some level, which defines the RRR for this metal. An example of the behaviour of the thermal conductivity for molybdenum is plotted in Fig. 1. The maximal level of the thermal conductivity and the temperature at which the thermal conductivity has a maximum depend on the purity of the metal. The thermal conductivity increases for higher RRR and the maximum moves toward lower temperatures. In case that the thermal layer is much thinner than the cavity walls the surface temperature rise during the RF pulse can be written as:

$$\Delta\text{Ts}\ (\text{t}_0,\tau) = H_p^2 \cdot \sqrt{\frac{\tau\cdot\rho(t)\cdot f\cdot\mu}{\gamma\cdot\lambda(t)\cdot C_p(t)}} \qquad (1)$$

with the magnetic field strength at the cavity surface H_p, the pulse length τ, the electrical resistivity $\rho(t)$, the frequency f, the density γ, the thermal conductivity $\lambda(t)$, the mean specific heat C_p, the magnetic constant μ and the initial cavity temperature t_0 [15]. The temperature rise calculated with Eq. (1) for a copper cavity (RRR=100) at a frequency of 1.3 GHz is shown in Fig. 2.

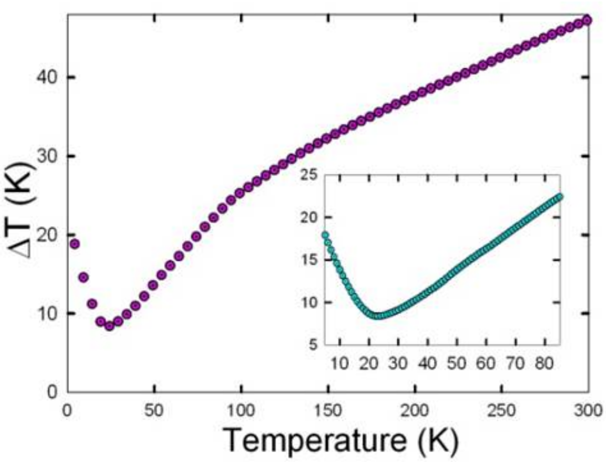

Figure 2: Surface temperature rise after 1 ms RF pulse as a function of initial gun temperature (Gradient 60 MV/m).

GRADIENT AND DARK CURRENT

RF breakdown and dark current are phenomena which limit the maximal gradient in a RF gun. According to the modern theory of RF breakdown in vacuum [16, 17 and 18] the reason of breakdown is an explosion of a micro protrusion on the cavity surfaces. The electrical field strength on the tip of these micro protrusions can be much higher than the average field on the cavity surface and according to the Fowler-Nordheim equation this tip starts to emit an electron current. This current heats the protrusion and its resistance and length increase which raises the temperature and the current again until the tip explodes producing sufficient plasma to trigger a breakdown. The temperature dependence of the heat conductivity at ~20 K counteracts this process (Fig. 1). Several other mechanisms such as Nottingham effect, Thomson effect and electrical field stress should be taking into account too. The investigations of vacuum breakdown and dark current phenomena for different materials in normal and low temperature regions are underway in many laboratories worldwide [16,19,20,22 and 23]. Usually these investigations are done with DC voltage or DC pulsed voltage in vacuum or in a pressurized RF cavity [23]. Fig. 3 shows some properties of pure metals which apparently are key parameters in RF breakdown phenomena. The horizontal order rates the metals according to the maximum DC gradient which was measured in [16] except for Ir which was not tested.

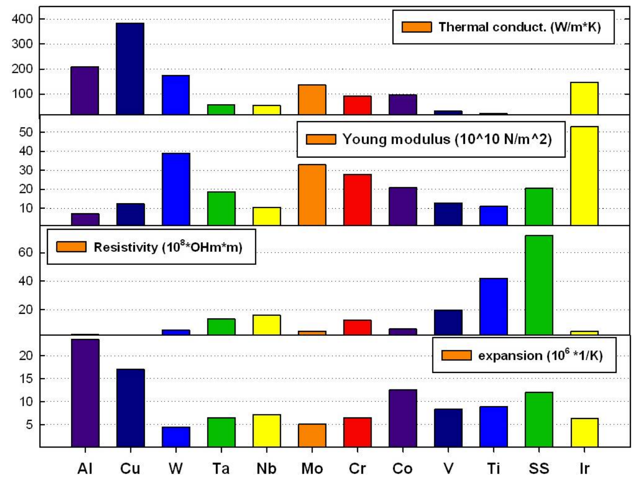

Figure 3: Some physical property of pure metals. The horizontal order ranks the metals according to the maximal gradient achieved in DC voltage test.

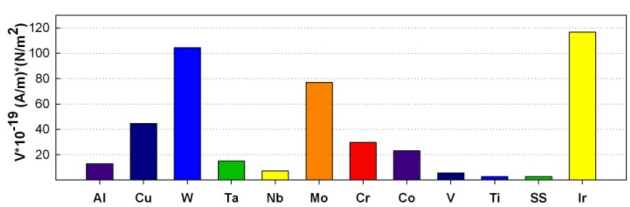

Figure 4: The rankingof metals for RF high gradient.

We propose a new parameter V_m (2) which can be used for ranking materials for RF cavities.

$$V_m = E_Y \cdot \sqrt{\lambda_m / \alpha_m \cdot \rho_m} \qquad (2)$$

where theYoung's module E_Y, the thermal conductivity λ, the thermal expansion factor α and the resistivity ρ.Values of V_m for a temperature of 300 K are shown in Figure 4. It is important that our ranking is not in conflict with the results from [23 - 25] at least for Cu, W and Mo.

CAVITY DESIGN

To keep all advantages due to the extraordinary thermal conductivity of pure copper and the possibility of a high gradient and low dark current which we can expect by using tungsten, molybdenum or iridium, we propose a design of a gun cavity with TM020 mode in the half cell and TM010 mode in the full cell. The electrical field pattern is shown in Figure 5 [26]. Electrical fields on the axis of this cavity are similar to the fields in the DESY RF- gun. Using a TM020 mode in the half cell give us the possibility to make a part of the cathode wall from a different material as the cavity body. For the TM020 mode a circle with zero radial current exists, so that it is possible to make a slit between cathode wall and cavity body. Thus the cathode part of the cavity can be made as a flat disk which can be removed from the cavity. A simple shape is very important because the machining of the hard metals as Mo, W and Ir is difficult. Other advantages of the design are the increased cavity surface which facilitates the cooling and the absence of a photo cathode holder because the Cs2Te film can be coated directly on to the removable part of the cavity.

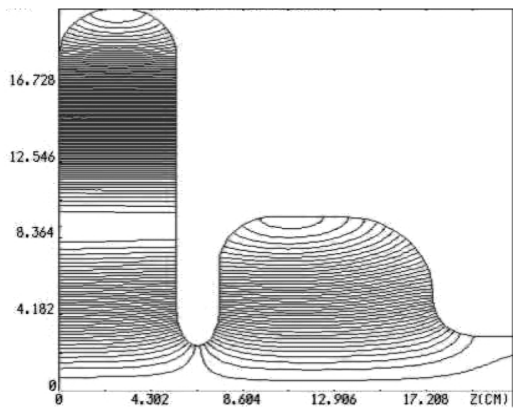

Figure 5: Electrical field lines in the gun cavity with a TM020 mode in the half cell and TM010 mode in the full cell. The vertical axis is the cavity radius;the horizontal axis is the cavity length.

CONCLUSION

The uncommon values of the thermal conductivity and from it appears a growth of thermal skin depth for some metals, such as Cu, Mo, W and Ir in the range of temperatures of approximately 20 Kelvin, will allow us to significantly increase the accelerating gradient and cooling efficiency in the L-band RF gun and to decrease heat losses, frequency shift and dark current.

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