DISTRIBUTION OF THE RF LOSSES ON THE ELECTRODES OF ACCELERATING STRUCTURE WITH SPATIAL PERIODIC RFQ FOCUSING

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Abstract

The accelerating structure with spatial focusing periodic RFQ focusing is used to accelerate protons up to β=0.25 [1]. The electrodes of this structure have an intricate shape. There are two types of RF power losses: for the RF currents and the field emission (FE) electrons, accelerated in gaps [2]. The values and distributions of the RF losses for the RF currents are determined by the method of the changing surface resistance and by the method of the small perturbation. This RF lossses on the new construction electrodes were decreased about two times. The FE electrons increase the total losses in the cavity about 1.7 times [2] and redistribute the losses on the electrodes. The recommendations for suppression of these electrons are given.

I. INTRODUCTION

The RF power losses heat and deform the accelerating structure elements. The intricate shape of the electrodes of the accelerating structure with spatial periodic RFQ focusing (SPRFQF) fig.1 inhibits the calculations of the values and distributions of the RF losses on the electrodes. The electron load increases and redistributes the RF losses on the electrodes. Here the experimental methods are described to determine the values and distributions of the RF losses for the electron load and the RF currents. The results are needed to decrease the losses and to design the electrode cooling system.

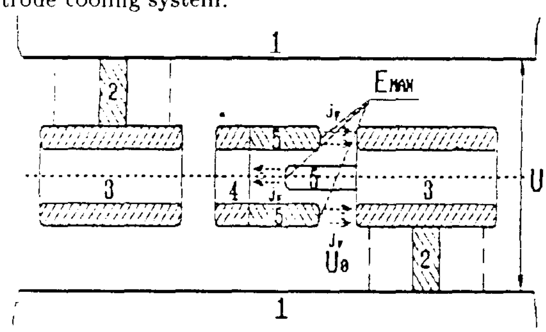

Figure 1. Accelerating period of the SPRFQF structure. 1 – H-cavity; 2 – electrodes holders; 3 – electrodes; 4 – intermediate electrod; 5 – focusing "horns".

II. RF POWER LOSSES FOR THE RF CURRENTS

According to the method of the changing surface resistance [3] the relative RF losses on some i-electrode are

$$\frac{P_i}{P} = \frac{Q_o/Q'_o - 1}{R'_{s_i}/R_{s_i} - 1}, \tag{1}$$

where Q_o and Q'_o are the unloaded Q-factors corresponding to the different surface resistance R_{s_i} and R'_{s_i} of the i-electrode.

The value of the total cavity losses P may be found from the perturbation theorem:

$$P = \frac{2\pi f^2}{Q} \frac{k \int_V \varepsilon E^2 dv}{4\Delta f}, \tag{2}$$

where f is the unperturbated resonant frequency of the cavity, Q is the unloaded Q-factor of the cavity, E is the magnitude of the electric field where the small perturbating body with from-factor k and volume V is located, Δf is the value of the frequency perturbation.

Determination of the value $k \int_v \varepsilon E^2 dv$ is the main problem. The method of experimental determination this value is described in the paper [4]. The method is based on the comparition of the frequency perturbations $\Delta f_{a.p.}$ and Δf_{eq}. $\Delta f_{a.p.}$ corresponds to the location of the perturbating small ball in the field of the accelerating period. Δf_{eq} is measured when this ball is located in the homogeneous field of the equivalent capacitor, where $k = 3$. The electrodes of the accelerating period and equivalent capacitor have been installed in the same H-cavity and have had the same RF voltage.

In this case

$$P = \frac{2\pi^2 f^2}{Q} \varepsilon \frac{\Delta f_{a.p.}}{\Delta f_{eq.}} \frac{a^3}{\Delta f\, d^2} U^2, \tag{3}$$

where Δf is measured at the same point of the accelerating period as $\Delta f_{a.p.}$ but in the real structure, a is the radius of the perturbating small ball, d is the equivalent capacitor gap, U is the H-cavity voltage in the real accelerating structure.

The experiments for founding of the relative RF losses have been made on the special H-cavity which was loaded with the electrodes of five accelerating periods of SPRFQF structure. For realization the equation (1), the elements of the copper Cu electrodes have been covered with zinc Zn in turn. The relative surface resistance for Zn is:

$$\frac{R_{s_{Zn}}}{R_{s_{Cu}}} = \sqrt{\frac{\rho_{Zn}}{\rho_{Cu}}} = 1.863, \tag{4}$$

where ρ_{Z_n} and ρ_{C_u} are resistivity for Zn and Cu.

The thickness of the Zn coat more then $2 \cdot 10^{-5}$ m because the depth of the skin for Zn is

$$\delta_{Zn} = \sqrt{\frac{\rho_{Zn}}{\rho_{Cu}}} = 10^{-5} \text{ m} \tag{5}$$

where $\delta_{Cu} = 0.54 \cdot 10^{-5}$ m is the depth of the skin for Cu for f=148.5 MHz.

According to the results of applicable measurements the total cavity losses are

$$P = 505 \text{ kW} \tag{6}$$

for U=305 kV.

The values and distributions of the RF losses on the electrodes are presented in table 1.

As follows from these results, the electrode holders have a maximum of RF losses. This fact is explained with large RF holder currents. An increase of the cross-section perimeter of the holders allows to decrease this losses:

$$P'_{hol.} = P_{hol.}\frac{\ell}{\ell'} \tag{7}$$

where $P_{hol.}$ and $P'_{hol.}$ are the holder losses with perimeters ℓ and ℓ' accordingly.

Table 1.

Elements / Losses	System of electrodes	Electrodes holders	Focusing "horns"
Relative losses	$8.76 \cdot 10^{-2}$	$6.12 \cdot 10^{-2}$	$0.6 \cdot 10^{-2}$
Magnitude of the losses in pulse, [W]	44238	30906	3030
Magnitude of the losses in pulse per accelerating period, [W]	1301.1	909	89.1
Magnitude of the losses density on the element in pulse [W/m^2]	$7.7 \cdot 10^4$	$1.26 \cdot 10^6$	$2.3 \cdot 10^4$

Practically, the holders with round cross-section have been replaced by the holders with rectangular cross-section. In this case:

$$\frac{\ell}{\ell'} \approx 0.18 \tag{8}$$

and the magnitude of the holders losses was decreased from 30906 W to

$$P'_{hol.} = 5563 \text{ W} . \tag{9}$$

The losses of the electrode system were decreased from 44238 W to

$$P'_{sys.} = 18895 \text{ W} \tag{10}$$

and the total cavity losses form 505000 W to

$$P'_{cav.} = 480000 \text{ W} . \tag{11}$$

The rectangular holders are used in new SPRFQF accelerator. For obtaining the average value of the RF losses the duty factor is used.

III. RF POWER LOSSES FOR FIELD EMISSION (FE) ELECTRONS

The paper [2] shows, that the Q-factor – RF-cavity power relation and the power shortage of RF generators at the SPRFQF accelerator URAL-30 are explained with FE electron load.

It is known, the FE current density for direct current is described by Fowler-Nordheim (FN) equation [5]:

$$j_F = \frac{1.54 \cdot 10^{-6} \ 10^{4.52\Phi^{-0.5}} E^2}{\Phi} e^{-\frac{6.53 \cdot 10^9 \Phi^{1.5}}{E}} = aE^2 e^{-\frac{b}{E}} \tag{12}$$

where E is the externally applied electric field in $\frac{V}{m}$, Φ is the work function of the metal in eV, $\Phi \approx 4.5$ eV for copper.

For reasons of some geometric irreqularity on the electrodes surfaces, the electric field E is enhanced by a factor β_E. Suppose that [5,7]:

$$\beta_E = 100. \tag{13}$$

In the case of RF fields

$$E_{RF} = Ecos\omega t = Ecos\varphi \tag{14}$$

where $\omega = 2\pi f$, f is a radio frequency (RF).

In this case electron field emission has place during a part φ of the RF period and the equation (10) needs to average over the RF period:

$$\bar{j}_F = \frac{a}{\pi}\int_o^{\varphi_1} (\beta_E Ecos\varphi)^2 e^{-\frac{b}{\beta_E cos\varphi}} d\varphi. \tag{15}$$

The value of φ_1 have been found from the condition:

$$\frac{j_F(\varphi_1}{j_F(0)} = 0.1. \tag{16}$$

For (12) and $E = 38 \cdot 10^6 \ \frac{\text{V}}{\text{m}}$ [6]

$$\varphi_1 \approx 26^o. \tag{17}$$

The result of $\bar{j}_F$ calculation is

$$\bar{j}_F \approx \frac{7 \cdot 10^{-12} \ 10^{4.52\Phi^{-0.5}} (\beta_e E)^{2.5}}{\Phi^{1.75}} e^{-\frac{6.53 \cdot 10^9 \ \Phi^{1.5}}{\beta_E E}}. \tag{18}$$

The obtained equation agrees with the same equation [7].

There are two gaps in the period of the SPRFQF structure: accelerating and focusing. It is known, the tips of focusing "horns" have the maximum $E = 38 \cdot 10^6$ V/m [6]. Values of E for other elements of the electrodes are not in excess of $30 \cdot 10^6$ V/m. Therefore the FE currents from this elements smaller by a factor of 10^2 as minimum then the current from the tips of the focusing "horns". These currents may be neglected in comparison with the RF current from the "horns".

RF power losses are explained by the acceleration of the FE electorns between the electrodes and the additional RF currents on the electrodes surfaces.

Power losses for the acceleration of the FE electrons from one "horn" are

$$P_e = \frac{1}{\pi}\int_o^{\varphi_1} j_F(\varphi)U(\varphi)d\varphi \approx \bar{j}_F U_o \tag{19}$$

where U_o is accelerating voltage.

Power losses for the additional current from one "horn" are

$$P_R = \frac{1}{\pi}\int_o^{\varphi_1} j_F^2 \varphi R d\varphi \approx$$

$$\approx \frac{7.7 \cdot 10^{-18} \cdot 10^{9.04\Phi^{-0.5}}(\beta_E E)^{4.5}}{\Phi^{2.75}} e^{-\frac{13.06 \cdot 10^9 \Phi^{1.5}}{\beta_E E}} . \quad (20)$$

The surface resistance may be neglected in comparison with the resistance R=100 Ω, which is included as a component of the intermediate electrod holder for suppression of the higher modes [8].

In accord with the results [2] the equation of power balance is:

$$\frac{P}{P + \Delta P_{e.l.}} \approx 0.6, \quad (21)$$

$$\Delta P_{e.l.} \approx 0.7P \quad (22)$$

where P is the total cavity losses without the electron load (4), $\Delta P_{e.l.}$ are the additional power losses for the electron load.

There are N focusing gaps with four "horns" in each in the accelerating SPRFQF structure. In this case the equation for an effective FE area A_{ef} is:

$$4A_{ef}^2 p_r N + 4A_{ef} p_e N = 0.7P \quad (23)$$

for N=34 and U_o=152.5 kV

$$A_{ef}^2 + 4.2 \cdot 10^{-5} A_{ef} - 1.6 \cdot 10^{-13} = 0, \quad (24)$$

$$A_{ef} \approx 4 \cdot 10^{-9}\ m^2 . \quad (25)$$

The FE current from one "horn" is

$$\bar{I}_F = \bar{j}_F \cdot A_{ef} = 18.2\ mA. \quad (26)$$

The power losses for acceleration of the FE electrons in one focusing gap are:

$$P_e = 4p_e A_{ef} = 11102 \text{ W} \quad (27)$$

on either electrode of this gap:

$$P_{e_1} = 0.5P_e = 5551 \text{ W} . \quad (28)$$

The power losses for R is:

$$P_R = 1.05 \text{ W} . \quad (29)$$

As follows from this results the basic part of the power losses for the FE electrons is the losses for acceleration of the FE electrons.

The electron load increases the total cavity losses from 505 kW to 856 kW. The electrodes losses per period without holders and "horns" increases from 303 W to 11405 W and, correspondingly, the losses density from $2.5 \cdot 10^4$ W/m^2 to $9.4 \cdot 10^5$ W/m^2. The experimental plot of $Q/Q_{max}(E)$ is shown in fig.2. The same calculational plot may be obtained with equation

$$\frac{Q}{Q_{max}} = \frac{1}{1 + \frac{4NA_{ef} \cdot \bar{j}_F \cdot U}{P}} \quad (30)$$

where $\bar{j}_F$ is the current has been found from (19) for corresponding E and U. The curve is presented in fig.2. As plots are closely spaced, the equation (28) may be used for estimate of the electron load effect. As it follows from this plots, the electron load effect disappeares when E decreases from E=380 kV/cm to E'=300 kV/cm. This decrease may be obtained with decrease of the focusing voltage or increase of the curvature radius of the "horn" tip, but this way is undesirable for the partical dynamics.

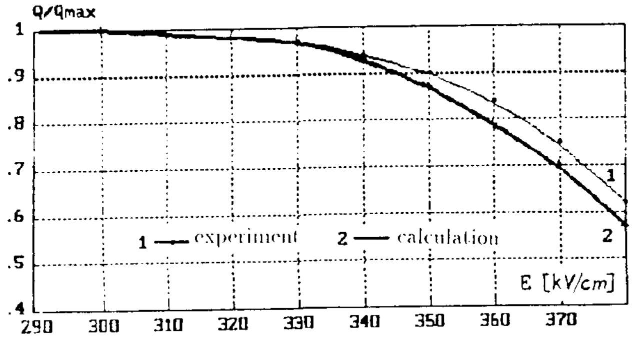

Figure 2. The experimental and calculated relationship Q/Q_{max} as a function of E.

If E is constant, the FE electrons may be depress by the choice of the electrode metal having the work function Φ' such that:

$$\bar{j}_F(\Phi, E') \geqslant \bar{j}_F(\Phi', E). \quad (31)$$

The solution of this equation is

$$\Phi' \geqslant 5.26 \text{ eV} . \quad (32)$$

The work function of platinum Φ_{P_t}=5.32 eV conforms to this condition. The FE current density for the platinum electrodes is

$$\bar{j}_{FP_t} = 2.4 \cdot 10^4 \text{ A/m}^2. \quad (33)$$

The value $\bar{j}_{FP_t}$ smaller about 200 times then the FE current density for the copper electrodes. But the P_t electrodes are very expensive. In this case the P_t coat may be used. When the thickness of this coating is about $5 \cdot 10^{-6}$ m then decreasing of Q-factor is about 3%.

Finally the suppression method of electron load may be found in result of the experimental research which is doing now.

IV. CONCLUSION

In this paper the distribution and value of RF losses on the electrodes of the SPRFQF structure were determined by the experimental methods. The influence of the electron load, causing the increase and redistribution of the losses, was studied. Recommendations for suppression of this electron load were given.

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