EVALUATIONS OF PARAMETERS STABILITY FOR S-BAND RF GUN CAVITY DUE TO EFFECTS OF PULSED RF HEATING

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Abstract

Requirements to high stability of electron beam arrival time in modern FEL facilities transform to requirements of high stability of amplitude and phase of electric field in RF photocathode gun which is used as electron injector. To provide high quality of bunches, gun cavities with high electric and hence magnetic RF fields. Effects, related to pulse RF heating, result in change of the cavity frequency and quality factor during even few µs RF pulse. Cavity deformations due to pulse heating are considered and corresponding cavity detuning are evaluated. Resulting deviations of the phase and amplitude of the RF field in the gun cavity as a function of RF pulse duration are estimated.

INTRODUCTION

Photocathode RF guns are now widely used for generation of short and bright electron beams in modern Free Electron Laser (FEL) facilities. For low repetition rate FEL the guns are usually based on S-band normal conducting RF cavities. Despite of specific requirements to different facilities and details of technical decisions used, design and operating mode of the gun cavities have common, typical patterns. As a typical modern example Fig. 1 illustrates High Repetition Rate Gun (HRRG) photocathode gun designed for the CLARA project, [1]. HRRG 1.5 cell cavity has a coaxial input RF coupler with symmetric feed.

To provide electron bunches with small transverse emittance the gun operate in pulsed mode with a high, of up to ~ 120 MeV/m electric field \( E_c \) at the cathode surface. With a need it results in a high, of ~ 250 kA/m magnetic field at the surface \( H_m \) and the high density of the pulsed RF losses \( P_s \) of up to \( 4.5 \cdot 10^8 \text{ W/m}^2 \). Effects of the pulsed RF heating take place during RF pulse \( \tau \sim (3 \div 6) \mu s \) then the temperature at some parts of the cavity surface \( T_s \) rises up to \((19 \div 30) ^\circ\text{C}\).

One of the critical requirements to the linear accelerator based FEL facilities with laser seeding is high arrival time stability of the electron bunches. Essential impact on the arrival time gives the amplitude and phase of the pulsed RF field in the gun cavity, [2]. Temperature rise of the cavity during RF pulse leads to thermal deformations and change of the cavity parameters. It directly lead to deviations in the amplitude and the phase of the RF field in the cavity.

PROCESS DESCRIPTION

Process of thermal elastic deformations is described by the coupled equations for temperature \( T(r, t) \) and displacements \( \bar{u}(r, t) \) distributions, [3]:

\[
\begin{align*}
\text{div}(\text{grad}T(r, t)) - \frac{\rho_m C_p}{k_c} \frac{\partial T(r, t)}{\partial t} - \frac{\alpha_t E_Y T_0}{3k_c(1-2\nu)} \frac{\partial \text{div} \bar{u}}{\partial t} &= 0, \\
\frac{3(1-\nu)}{(1+\nu)} \text{grad}(\text{div} \bar{u}) - \frac{3(1-2\nu)}{2(1+\nu)} \text{rot} \text{rot} \bar{u} &= -\alpha_t \gamma \frac{\partial^2 \bar{u}}{E_y} - \frac{3(1-2\nu) \rho_m}{\gamma E_y} \frac{\partial^2 \bar{u}}{\partial t^2} = 0, \\
\end{align*}
\]

where \( \rho_m, C_p, k_c, \alpha_t, E_Y \) and \( \nu \) are the density, the specific heat, the heat conductivity, the coefficient of linear thermal expansion, the Young’s modulus and the Poisson ratio, respectively. The first equation in Eq. 1 describes the heat diffusion from the heated surface into the cavity body. This process is well studied and explained in [4] and related references. The pulsed temperature rise \( T_s \) of the surface over the average steady-state value and the heat penetration depth into body \( D_d \) can be estimated as:

\[
T_s = \frac{2P_s \sqrt{\tau}}{\sqrt{\pi k_c \rho_m C_p}}, \quad \alpha_d = \frac{k_c \tau}{\rho_m C_p}, \quad D_d = \sqrt{\alpha_d \tau},
\]

where \( \alpha_d \approx 10^{-4} \text{ m}^2/\text{s} \) is the thermal diffusivity for copper. For the RF pulse duration \( \tau = 1 \mu s, 3 \mu s, 6 \mu s \) and 10 \( \mu s \) the heat penetrates to the depth \( D_d = 10.7 \mu m, 18.5 \mu m, 26.2 \mu m \) and 33.8 \( \mu m \) respectively.

The second equation in Eq. 1 is a typical wave equation for displacements \( \bar{u} \) with source \( \alpha_t \gamma \text{grad}T(r, t) \). Equation describes propagation of longitudinal elastic waves of compression from the source with velocity \( V_t = \)
The procedure has been thoroughly verified on simple models of hollow spherical cavities, which allow analytic solutions for displacements in Eq. 1 in some approximations [3]. For the cost of computing resources and considering only 30 degree sector of simplified model, Fig. 2, the deviations between analytic and numerical results in units of percents was achieved and procedure parameters were fixed for further simulations.

Materials parameters \( \rho_m, C_p, k_c, \alpha_t, E_Y \) and \( \nu \), required for numerical simulations, accepted assuming typically used in cavities construction materials - OFE annealed copper and AISI steel, as listed in [7].

**NUMERICAL RESULTS**

Both rectangular \( (P_l = P_r = \text{const}, 0 \leq t \leq \tau, \text{to compare } T_s \text{ with Eq. } 2) \) and accretive \( (P_l = P_r (1 - e^{-\frac{t}{\tau}})^2, 0 \leq t \leq \tau) \) pulsed load \( P_l \) were considered, where \( \tau \) is the filling time of the cavity. For a short pulse \( \tau \sim (3 \div 6) \mu s \) the accretive shape of the heat load \( P_l \) is essential and two options \( \tau_{c1} = 0.62 \mu s \) and \( \tau_{c2} = 0.76 \mu s \) were considered for comparison.

For rectangular \( P_l \) pulse the estimations based on Eq. 2 for \( T_s \) works fine. All the time, with the precision of \( D_d \), distribution \( T_s \) reflects the surface distribution of \( P_s \). In Fig. 3a maximal surface temperature evolutions \( T_{s_{max}} \) for different \( P_l \) pulses are shown assuming the maximal RF loss density of \( P_{s_{max}} = 4.48 \times 10^8 \text{ W/m}^2 \). Thickness of the hot layer \( \sim D_d \) strongly exceeds the thickness of the RF skin layer \( \delta \sim 0.9 \mu m \) and temperature rise at the surface results in the increasing of the surface resistance and an additional growth of RF losses \( dP \). Large \( T_s \) rise is due to the surface resistance increasing takes place in the cavity parts with high magnetic fields. The effect of losses increasing for pulsed RF heating is more pronounced. As \( T_s \) rise is not that big as compared to absolute surface temperature, time dependence of additional RF losses, illustrated in Fig. 3b, are similar to dynamics of \( T_s \).

For long RF pulse in L-band gun cavities we can consider distribution of displacements as steady-state, neglecting distribution of displacements as steady-state, neglecting...
The deviation \( \delta \) of frequency for cavity surface and related resonance deviation \( Q \) for static and transient approximations (a) and transient deviations in the field amplitude for stationary . Both surface temperature rise and cavity thermal deformations result in changes of own quality factor and cavity resonance frequency even during few microseconds long RF pulse. This report presents results of numerical simulation of both the cavity parameters change and related deviations of the RF field amplitude and phase for typical operating regime.

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REFERENCES


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