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COST EFFECTIVE PREDICTION OF TEMPERATURE PEAKS DUE TO INTENSIVE NANOSECOND RF HEATING IN PARTICLE ACCELERATOR RESONANT CAVITIES

WYDAJNE SZACOWANIE MAKSYMALNYCH TEMPERATUR WYWOŁANYCH INTENSYWNYM POLEM RF NA ŚCIANKACH KOMÓR PRZYSPIESZAJĄCYCH AKCELERATORA CZĄSTEK ELEMENTARNYCH

A b s t r a c t

Accelerating cavities are thermally loaded due to Joule heat dissipated in a skin layer of internal walls caused by the electromagnetic field present inside the chamber. When cavities are fed with cyclic intensive RF pulses split by idle intervals beside steady-state temperature field, a result of averaged thermal load, one may ask about temporary temperature peaks. The paper presents why straightforward use of transient thermal simulations of a full scale model cannot provide reliable temperature peak estimation. As a remedy a hybrid numerical-analytical approach is proposed.

Keywords: *particle accelerator*, *RF cavity*, *intensive surface heating*

S t r e s z c z e n i e

Przyspieszające komory rezonansowe stosowane w akceleratorach cząstek elementarnych są obciążone termicznie ciepłem generowanym prądami naskórkowymi wywołanymi polem elektromagnetycznym występującym w jej wnętrzu. Ponieważ cykl pracy obejmuje części aktywną i bierną, obok ustalonego pola temperatur wynikającego z czasowego uśrednienia obciążenia można postawić pytanie o wartości chwilowe temperatur. Jak przedstawiono w artykule, pełnowymiarowa analiza nieustalona w tym przypadku nie jest narzędziem właściwym. W zamian zaproponowano odpowiednie mieszane podejście numeryczno-analityczne.

Słowa kluczowe: *akcelerator cząstek*, *komory RF*, *intensywne powierzchniowe obciążenia cieplne*

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List of used symbols

c_p – specific heat [J/kg/K]
f – frequency [Hz]
H – intensity of magnetic field [A/m]
k – thermal conductivity [W/m/K]
q – heat flux load [W/m^2]
R – surfach resistivity [Ω]
δ – skin depth [m]
α – thermal diffusivity [m^2/s]
μ – magnetic permeability [V s/A]
ρ – denisty [kg/m^3]
σ – electric conductivity [1/ Ω]

1. Introduction

To accelerate electrically charged particles Radio Frequency accelerating structures are used. These devices using high power source of microwave produce strong on-axis electric field [1] as shown in Fig. 1.

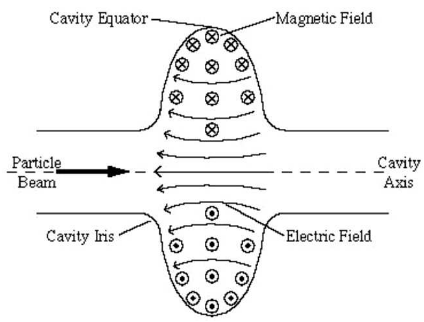

Fig. 1. Accelerating cell of a RF cavity
Rys. 1. Przyspieszająca komora rezonansowa

The electromagnetic field present inside the cavity penetrates the metallic walls. Though very quickly attenuated it causes electric current flow in the thin layer of material that is also called skin. Because of finite conductivity it results in certain level of thermal load that must be evacuated by the cooling system. If not the thermal deterioration of accelerating properties of the device would be a result.

The equivalent heat flux load q applied to the surface of inner walls due to volumetric heat generation in skin layer of depth δ can be evaluated in the following way:

$$q = \frac{1}{2} \cdot R \cdot H^2 \quad (1)$$

where H stands for magnetic field intensity at the surface and R is called surface resistivity and can be evaluated using equation (2):

$$R = \frac{1}{\sigma \cdot \delta}, \tag{2}$$

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}} \tag{3}$$

In the above formulations σ is material property called specific electric conductivity and skin depth δ is determined according to equation (3) with f standing for frequency and μ representing magnetic permeability of metallic walls. Identical formulation tying features of electromagnetic field and surface thermal load can be found in [2].

In case of currently used LHC circular accelerator each of two beam pipes has eight about 0,4 m long accelerating chambers each providing acceleration of 2 MV [3]. High energies of beam are therefore achieved by multiple passes of the accelerating zones which in fact occupy little fraction from the total of 27 km LHC length. Significantly larger amount of space and consumed energy is demanded by magnets needed to bend the beam and keeping it in circular trace. The accelerator of new generation called Compact Linear **C**ollider [1, 4, 5] is conceptually very different from the LHC. Beams of e^+ e^- will be accelerated in two separate straight sections of 21 km length providing 100 MV/m average accelerating electric field gradient. The working frequency of new accelerating structures was chosen to be 12 GHz [5] that means the dimensions of a single cell are much more compact than in case of LHC cavities, while thermal load due to higher accelerating gradients is more intensive.

Differently than LHC accelerating cavities powered by constantly modulated RF source the CLIC structures will be fed with pulse modulated microwaves of higher peak magnitudes. For that reason an effort has been invested into transient simulations to answer what could be the corresponding temperature peaks. Inner surface of cavity exposed on large number of temperature peaks may suffer problems of metal surface fatigue [6].

Prior approval of the current CLIC specification [5] many different accelerating RF structures were evaluated in tests. One of them was HDX11 shown in Fig. 2 designed to operate at 11,424 GHz frequency. The structure assembly consist of four pieces made of copper having cell inner shapes milled in. Overall dimensions of the single quadrant are 45 mm × 45 mm × 150 mm. Its approximate weight is 2,2 kg. Taking into account material properties of copper the penetration skin depth δ = 0,62 μm. That value compared to the overall dimensions is small, therefore replacement of volumetric heat generation with a surface heat flux load is fully justified [7].

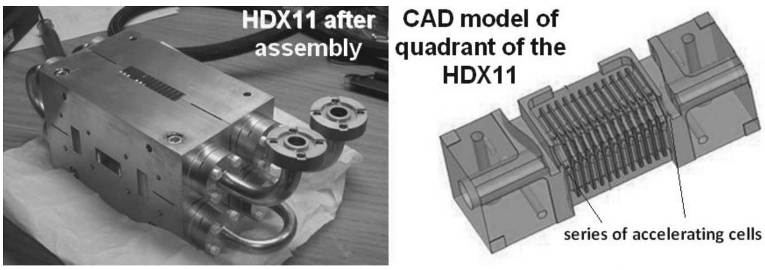

Fig. 2. HDX11 an example of accelerating RF structure
Rys. 2. HDX11 przykład przyspieszającej struktury RF

2. Steady – state thermal simulation

Following equation (1) to evaluate heat flux load a distribution of magnetic field at warmed surface must be known. That information was extracted from results of electromagnetic simulations performed in HFSS software and applied to the finite element model of cavity walls in ANSYS. The data transfer was possible thanks specially prepared interface between these two tools [7]. The overview of results is presented in Fig. 3.

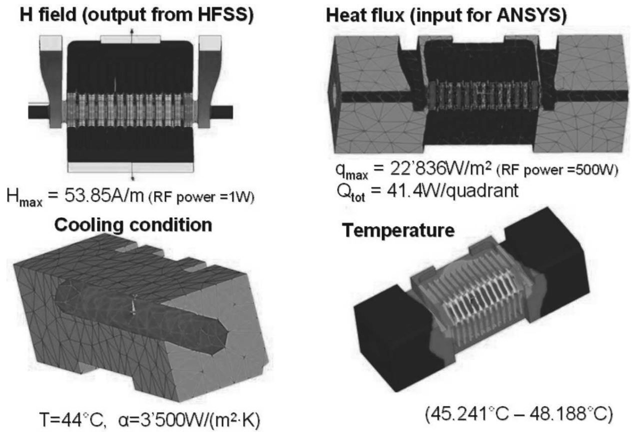

Fig. 3. Overview of steady-state thermal calculations [7]
Rys. 3. Wyniki ustalonych w czasie analiz termicznych [7]

3. Transient thermal simulation

3.1. Full scale model simulation

The 500 W RF load used in steady-state simulations is in fact product of averaging of 70ns strong RF pulse of 100 MW repeated each 14ms. The first transient simulations were performed using same finite element model, with two load steps. During the first 70ns adequately rescaled thermal load was applied to the warmed surface. Over the second load step ending at 14ms the heat flux load was canceled. During the simulation ANSYS was allowed to perform sub-steps on its own.

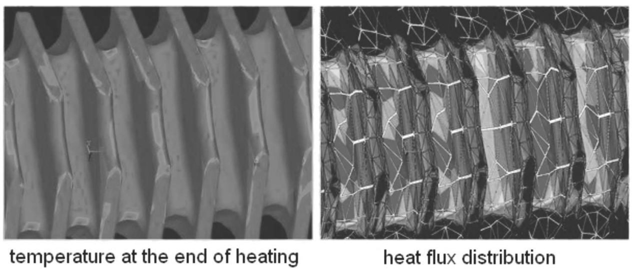

Fig. 4. Mismatch of temperature field and heat flux load in full scale simulation
Rys. 4. Pola temperatur i strumień obciążenia cieplnego w pełnowymiarowej symulacji

Examination of obtained results pretty soon revealed several issues. First of all shape of temperature field was not corresponding to expectations. Occurrence of temperature top peaks was not related with localization of maximum heat flux load as shown in Fig. 4. Furthermore it was also detected that during intensive heating the energy balance in the model is not satisfied. Internal energy grew ~6 times faster than it was expected.

3.2. Thermal diffusivity, characteristic length, transient analysis of a microchip

Explanation of the anomalies described in the previous point appeared to be drastic difference in scales between finite element size and so called characteristic length defined by eq. (4), where α is a parameter called thermal diffusivity and express ratio of thermal conductivity to thermal capacity of the material. In case of copper characteristic length for characteristic time of 10ns and 70ns are 1 μm and 2,8 μm respectively while the element size was as much as three magnitudes of order bigger.

$$L = \sqrt{\alpha \cdot \tau} \tag{4}$$

$$\alpha = \frac{k}{\rho \cdot c_p} \tag{5}$$

To mesh the whole model with elements of appropriate size estimated number of elements would reach level 10^{15}, which is unaffordable value. Therefore series of analyses of only tiny microchip were performed, that one can imagine is cut from warmed surface. In that case the obtained temperature field fits very well to expectations also $L_{70\text{ns}}$ = 2,8 μm characteristic length gives very good estimation of zone affected by temperature rise. Finally the energy balance is accurately satisfied.

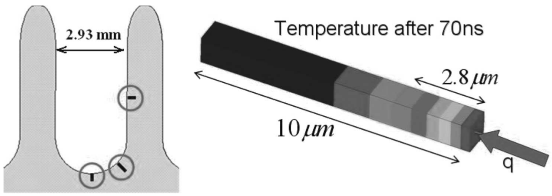

Fig. 5. Temperature field after 70ns heating in microchip of warmed surface [7]
Rys. 5. Pole temperatury w mikro wycinku ogrzewanej powierzchni po 70ns [7]

3.3. Heat flux loaded semi-infinite solid – analytical relationships

With such low penetration of temperature field one may assume that the problem of intensive nanosecond RF heating can be locally considered as semi-infinite solid case. For that situation analytical solution can be found [8, 9]. The temperature can be evaluated according to eq. (6) where temperature depends on time τ and depth coordinate x. Maximum value of temperature will be surely at warmed surface for x = 0 then simplified form (7) is also given.

$$T(x,\tau) = T_0 + \frac{2q\sqrt{\frac{\alpha \cdot \tau}{\pi}}}{k} \exp\left(\frac{-x^2}{4 \cdot \alpha \cdot \tau}\right) - \frac{q \cdot x}{k}\left(1 - erfc\left(\frac{x}{2\sqrt{\alpha \cdot \tau}}\right)\right) \tag{6}$$

$$T(0,\tau) = T_0 + \frac{2q\sqrt{\frac{\alpha \cdot \tau}{\pi}}}{k} \tag{7}$$

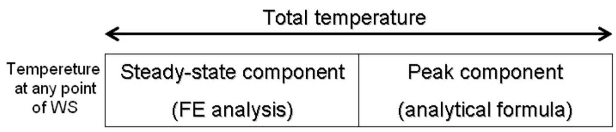

Fig. 6. Evaluation of transient temperature at warmed surface
Rys. 6. Sposób wyznaczenia pola nieustalonych temperatur na powierzchni grzanej

Using equation (7) for lasting 70ns intensive surface heating of copper with maximum rate of heat flux 4,57 GW/m^2 the temperature rise is ~37 K. If use approach proposed in Fig. 6 overall temperatures in model range from 45,3ºC to 81,7ºC.

4. Conclusions

The paper deals with the problem of prediction of temperatures in accelerating cavities of the CLIC accelerator. Due to scheme of its work (pulse modulated RF source) two types of thermal simulations was selected to be considered. Steady-state thermal simulations in order to optimize design of cooling system, whereas transient simulations were expected to deliver information about temperature peaks needed for metal surface fatigue studies. However the research effort invested in transient simulation attempts has brought the author to the conclusion that direct full-scale modeling cannot be considered as reliable source of information in that specific case.

When dealing with transient simulations certain relationships between time and spatial discretization parameters should be satisfied. In parabolic type of the problem the tying parameter is material property called thermal diffusivity. In the analyzed case reliable direct full scale transient simulation was not possible due to unrealistic number of required elements. On the other hand it is shown that reliable prediction of peak temperatures can be done in much smarter way by combining steady-state numerical solution and analytically solved case of thermally loaded semi-infinite solid.

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