HIGH SENSITIVITY CALORIMETER FOR MEASURING WAKEFIELDS ENERGY EXCITED BY A TRAIN OF ELECTRON BUNCHES

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The special calorimeter for measuring total energy of HF-wakefields excited in plasma or dielectric by relativistic electron bunches has been elaborated. Simple by design calorimeter operates in the energy range from 0.02 J up to 780 J. Water is used as an absorbing material. For measuring irradiated water volume change the capacitive ferroceramic sensor was applied. Sensor sensitivity is 8.7 pF/J that two orders exceeds sensitivity of capacitor-sensor used in our experiments before. The calorimeter is not sensitive to nonuniformity of radiation field, and its response on HF-radiation is high enough. Calorimeter design allows along with measuring radiation energy simultaneously controlling the current of bunches sequence.

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1. INTRODUCTION

For measuring the total pulsed energy of HF-radiation excited by a train of electron bunches in plasma or dielectric structure [1-3] calorimeter is needed that could work in a wide frequency band and a considerable range of measured energies. Requirements to such calorimeter become even more rigid at measuring a frequency spectrum of radiation [4], because for this purpose calorimeter sensitivity should be higher (0.01-0.03 J). Besides the fast response of the calorimeter to change of absorbed energy and simplicity of operation are desirable. From our point of view all these requirements are fulfilled by the calorimeter with capacitive ferroceramic sensor that is represented in this work. Due to high permittivity the ferroceramic sensor allows increasing essentially the sensitivity of the calorimeter and at most simplifying its design.

A lot of calorimeters described earlier [5-9] allow to measure energy of HF-radiation in a range from several mJ up to kJ over the frequency range from one GHz up to several hundreds GHz. Most frequently used working substance is a solid absorber (metal ceramics, resistive textile, graphite plates) [5-7], and a measurand is the increase of temperature that is measured, by thermo-batteries, thermistors, wire-wound resistors. The shortages of such calorimeters are their time delay and non-isothermality. It is especially essential at large volumes of working substance and non-uniformity of radiation fields in various points of the calorimeter. Very likely these shortages in the even greater measure are proper in flow calorimeters [8] which working substance is water, as a rule. In the work [9] a broadband HF-calorimeter of large square (1200 cm^2) is described which working substance is ethanol (C_2H_6O) and a measurand is increase of its volume. The calorimeter is not sensitive to non-uniformity of heating of ethanol. However it is intended for measuring energy of a plane wave and is settled down outside of the HF-oscillator.

In the work [10] the simple calorimeter for measuring the total energy of pulsed and continuous HF-radiation is described. Measured energy of HF-radiation is in the range from 0.5 J up to 6 кJ. The calorimeter is placed in the circular waveguide. The absorptance of energy of HF-radiation in the range of 3-60 GHz is not worse of 0.9. The calorimeter is not sensitive to nonuniformity of the radiation field over volume of working substance, and its response to HF-radiation is practically instantaneous. But its shortage is rather low sensitivity ≈0,025 pF/J, that makes difficult measuring, especially at low energy of HF-radiation.

The idea of sensor sensitivity increasing concludes to the enhancement of accuracy of volume change ΔV measuring. For this goal the coaxial condenser with high permittivity ε was used that provides perceptible its capacity change at small water volume change.

2. CALORIMETER DESIGN

The design of the proposed calorimeter is similar to that realized in [10] but it has a capacitive ferroceramic sensor that is more sensitive and simpler in work. The scheme of the calorimeter is pictured in Fig. 1.

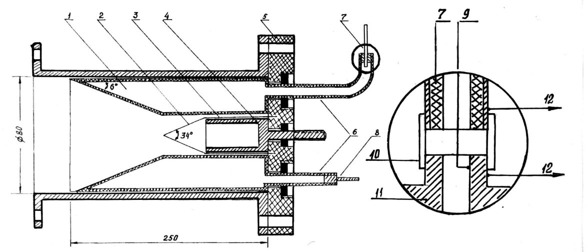

Fig. 1. Scheme of calorimeter:
1-absorbing section, 2-reflecting cone, 3-connecting pipe from stainless steel, 4-Faraday cap, 5-ebonite flange, 6-glass branch tubes, 7-ferroceramic tube, 8-piston for regulation of water level, 9-copper conductor, 10-connecting dielectric tube, 11-copper tube, 12-to device for capacity measuring

The absorbing section *1* is a matched load. It represents a cylinder of diameter 75 mm and length 250 mm with a conic interior surface and a hole along the axis. Walls of the absorbing section are manufactured from quartz glass of thickness 1 mm. The section is filled by water. Its volume is 606.5 cm^3. For improving of HF-radiation absorption in a wide frequency band, the metal cone *2* manufactured from titanium foil of thickness 50μ is located inside absorbing section. Such foil is "transparent" for relativistic electron beam.

Behind titanium foil a Faraday cap *3* is arranged. Such placing allows simplifying researches of dielectric wakefield generator, avoiding the problem of deflection of relativistic electron beam on the walls of generator encasement at measuring output HF-energy. The foil cone is fastened on a segment of stainless steel tube *4* in which there are holes for pumping of Faraday cap volume. It serves as a thermal screen too.

Absorbing section and Faraday cap are fastened on ebonite flange *5* through which two glass branch tubes *6* from the absorbing section are brought out. At the exit of one of them measuring ferroceramic tube *7* is mounted. Inside ferroceramic tube the non-insulated copper conductor *9* of thickness 0.1 mm is extended, providing contact to device for capacity measuring. Such arrangement results in linearity of measuring. The second glass branch tube is ended by an adjusting piston for regulation of water level. From it also the wires of the warmer placed inside the absorbing section are also brought out. At breaks in-process, and also if fast performance of repeated measuring is necessary the initial level of water in the measuring tube is reestablished with the help of the adjusting piston. Outlet of the calorimeter, the measuring tube and the adjusting piston were located for thermo-insulation in the foam plastic casing of thickness 15 mm.

3. PRINCIPLE OF OPERATION

Measurand is the increase of volume of the water, caused by a thermal expansion at HF-energy absorption. The increase of water volume ΔV is equal:

$$\Delta V = V_0 \alpha_0 \Delta T, \qquad (1)$$

where V_0 is initial volume of water, α_0 is coefficient of volume expansion at initial temperature, ΔT is change of temperature of water which is proportional to the value of the absorbed energy ΔW:

$$\Delta T = \frac{\Delta W}{m c_0} = \frac{\Delta W}{V_0 \rho_0 c_0}, \qquad (2)$$

where m is mass of water, ρ_0 – a denseness and c_0 – specific heat of water at initial temperature. Substituting value ΔT from (2) in (1), we shall obtain the expression for the increase of water volume ΔV in dependence on absorbed HF-energy ΔW:

$$\Delta V = \frac{\alpha_0 \Delta W}{\rho_0 c_0}. \qquad (3)$$

The increase of water volume is proportional to absorbed energy ΔW and also does not depend on initial volume of water and distribution of the absorbed energy over water volume. From (3) the ratio of change of water volume to the absorbed energy is equal $\Delta V / \Delta W \approx 0{,}048$ mm^3/J.

For solving the main problem of measuring of the increase of water volume the sensor was used which basic element is ferroceramic tube with inner diameter a=1,8mm and a working length l=11 mm was used. In ferroceramic tube the increase of water volume transforms in the increase of length of water column. The tube from ferroceramic condenser KT-1 was taken with admissible change of capacity at 20 in the temperature interval -60 - +85° less than 10 % (group H10). The conductive coating of interior surface of the condenser was carefully etched.

The length of water column in ferroceramic tube was determined by the value of the capacity formed by water inside tube and the conductive coating on the outside of tube. Change of capacity was determined from relation

$$\Delta C = 2\pi\varepsilon\varepsilon_0 \Delta l / \ln(b/a) \qquad (4)$$

where $\Delta l = \Delta V / \pi a^2 / 4$ is change of length of water column in the tube, b is outer diameter of the tube. As the ferroelectric ceramics has large permittivity (in our case permittivity $\varepsilon \approx 3100$), capacitive sensitivity of the sensor was $\Delta C / \Delta l \approx 620$ pF/mm.

4. DIELECTRIC WAKEFIELD ENERGY MEASUREMENTS

Calorimeter was designed so that it can be mounted directly into dielectric waveguide to envelop the total generated HF-energy. Energy sensitivity of the sensor at using water as a working substance is $\Delta C/\Delta W \approx 8{,}7$ pF/J that is 350 times higher than sensitivity of the usual capacitive sensor proposed in [10.] Minimum registered energy is determined by minimum measured change of capacity. At accuracy of measuring of capacity by our device ΔC_{min} =0.1 pF the minimum registered energy of HF-radiation is $W_{min} \leq 0{,}02$ J.

Permittivity of ferroelectric ceramics strongly depends on temperature, therefore both good stabilization of initial temperature of the calorimeter and its careful calibration is necessary. Stabilization of initial temperature was achieved by the continuous heating water preliminary heated to the temperature above ambient temperature. Needed heating should provide zero velocity of change of water volume and therefore the velocity of change of initial capacity of the sensor.

The maximum energy registered by the calorimeter is proportional to the total length of ferroceramic tube. At the length of the tube 11mm taken from ferroceramic condenser KT-1 (maximum capacity at full filling by water ~ 6800 pF) maximum measured energy makes $W_{max} \approx 785$ J. The increase of length of measuring tube twice reduces in increase of maximum measured energy up to 1,5 kJ. At absorption of such energy the temperature of water in the calorimeter on the average increases on 0.6 ^{0}K that ensures the constancy of its specific heat of water, coefficient of volume expansion, etc. The increase of maximum measured energy due to increase of length of the tube is not desirable because of increase of hydrostatical pressure The upper limit of measured energy can be increased considerably when having used a measuring tube of greater diameter, though with sensitivity decreasing.

Precise measuring capacity of ferroceramic sensor is a complicated problem. Firstly, it is necessary to exclude heating of water in the sensor during measuring. In our case measuring of capacity was performed by multimeter DT9208A at frequency 1MHz with amplitude of oscillations 0.02 V in pulsed mode (τ_{pulse} = 1ms) that did not lead to essential heating of water in sensor. Secondly, measuring of capacity by measuring of its capacitive resistance is correct under condition $R_w<<(2\pi fC)^{-1}$ where R_w is active resistance of water in sensor, f is frequency on which measurement is being performed. In our case the value $(2\pi fC)^{-1}$ changes from 105 Ω (at C_{min}=10 pF) up to ≈150 Ω (at C_{max}=6800 pF). If distilled water is used then R_w is in limits 103 – 104 Ω that allows to use water at measuring with a low level of energy. In other cases it is necessary to use preliminary obtained calibration curve of the absorbed energy determination from the measured value of capacity or to reduce active resistance of the sensor by adding in water of a small amount of copper vitriol to make it conducting. In the third, it is necessary to prevent formation water film on an interior surface ferroceramic sensor by wiping with glycerine before performance of measurements.

Calibration of the calorimeter was carried out both with the help of magnetron oscillator with pulsed power 200 kW and with heater located inside the absorbing section and having resistance 8 Ω. Both methods have shown good agreement of the calculated and measured values of absorbed energy

Calorimeter has been used for measuring energy of wakefields excited in cylindrical dielectric waveguide (length 70cm, inner and outer diameters 2.2 cm and 8.4 cm, correspondingly, ε=2.1) by a sequence of relativistic electron bunches, obtained at linear electron accelerator "Almaz-2" with REB parameters: energy 4 MeV, pulsed current 0.5 A, pulse duration 2 μs, modulation frequency 2805 MHz (so one pulse consists of $6\cdot10^3$ cylindrical electron bunches of diameter 1cm and length 1.7cm), repetitive frequency 3 Hz. Experimental results concludes to measured wakefields energy 0.4 J excited by one pulse of 4 J.

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КАЛОРИМЕТР ВЫСОКОЙ ЧУВСТВИТЕЛЬНОСТИ ДЛЯ ИЗМЕРЕНИЯ ЭНЕРГИИ КИЛЬВАТЕРНЫХ ПОЛЕЙ, ВОЗБУЖДАЕМЫХ ПОСЛЕДОВАТЕЛЬНОСТЬЮ ЭЛЕКТРОННЫХ СГУСТКОВ

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Разработан специальный калориметр для измерения полной энергии СВЧ–кильватерных полей, возбуждаемых в плазме или диэлектрике релятивистскими электронными сгустками. Простой по конструкции калориметр работает в диапазоне энергий 0,02-780 Дж. В качестве поглощающего материала использована вода. Для измерения изменения ее объема применен емкостной сегнетокерамический датчик, чувствительность которого составляет 8,7 пФ/Дж, что на два порядка превышает чувствительность применявшихся ранее емкостных датчиков.

КАЛОРИМЕТР ВИСОКОЇ ЧУТЛИВОСТІ ДЛЯ ВИМІРУ ЕНЕРГІЇ КІЛЬВАТЕРНИХ ПОЛІВ, ЗБУДЖУВАНИХ ПОСЛІДОВНІСТЮ ЕЛЕКТРОННИХ ЗГУСТКІВ

В.О. Кисельов, А.Ф. Лінник, М.І. Онищенко, В.В. Усков

Розроблено спеціальний калориметр для виміру енергії НВЧ–кільватерних полів, збуджуваних в плазмі або діелектрику релятивістськими електронними згустками. Простий по конструкції калориметр працює в діапазоні енергій 0,02-780 Дж. Як поглинаючий матеріал використана вода. Зміна її об'єму вимірюється ємнісним

сегнетокерамічним датчиком, чутливість якого складає 8,7 пФ/Дж, що на два порядки перевищує чутливість ємнісних датчиків, які використовувались раніше.