Design and performance of an inter-pulse cooled calorimeter for low power measurements

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Abstract

In the neutral beam system a calorimeter plays a significant role for the beam diagnostic. Accurate knowledge of the beam properties are important for beam handling and injection into Tokamaks. In order to measure the beam power delivered by the ion source an inter-pulse cooled calorimeter is installed at the BATMAN Testbed. Two-dimensional beam profiles are determined from the thermal response of the thermocouples, placed on the back of the calorimeter. Additionally, the integral energy absorbed by the calorimeter is measured by water calorimetry. To get an accurate measurement heat diffusion out of the individual calorimeter blocks has to be minimised during the pulse. On the other hand the calorimeter has to be cooled down between pulses. The final design of the calorimeter presented in this paper is the result of some simulation and optimisation iterations done with the help of the Finite Element Code ANSYS.

Contents

1. Introduction

A negative-ion-based neutral beam injector (NBI) is one of the promising candidates for heating and current drive in future large fusion machines due to the high neutralization efficiency of the negative ions. In the ITER-FEAT design [1], 33.3MW, 1 MeV D^0 beams will be injected to plasma using two NBI modules. The key component in NBI is a beam source, producing a 40A of ion current for 1000 s at 20mA/cm^2 current density over 2000 cm^2 extraction area. Presently the ITER reference design is based on filamented arc sources which have met these requirements in the past. The main drawback of the filamented arc sources is the limited lifetime of the filaments which have to be remotely replaced twice a year.

An alternative to the arc sources is the radio frequency heated source which is currently being developed at IPP Garching within the framework of an EFDA contract. Apart from lower costs and simplicity, this kind of source does not need regular maintenance periods. However, the current density being extracted from RF source is still a 20 % below the ITER requirements.

All neutral beam systems use a calorimeter in order to measure the power delivered by the ion source. In positive ion based systems the maximum power density is about 25 MW/m^2 which requires active cooling. In contrast, the maximum power density at the IPP negative ion testbeds is about 6 MW/m^2 normal to the beam axis. These testbeds run presently with 20 kV beam energy for less than 10s, mainly due to limits in the power supplies - resulting in power densities of some 100 kW/m^2. Under these conditions an inter-pulse cooled calorimeter is sufficient. Here the total power Q deposited on the calorimeter can be measured by water calorimetry and the current density j, which we are interested in, can be obtained easily by

$$j = \frac{Q}{U \times t_{on} \times A}, \qquad (1)$$

U being the beam energy, t_{on} the beam-on time, and A the extraction area. Here we assume that all particles hitting the calorimeter have the same energy. In order to get reproducible results and not to overheat the calorimeter, the heat should be removed by water cooling between the pulses within - typically a few minutes.

The formula above gives the current density delivered by the source if the whole beam hits the calorimeter. But this is not always the case due to the limited size of a calorimeter. Hence some information about the beam profile is required in order to estimate the amount of the beam not being intercepted by the calorimeter. Hence, the calorimeter must ‘freeze’ the temperature profile a certain time after the beam has stopped. This contradicts to the requirement above for heat removal, i.e. the cooling down time, should be rather fast: in this case the temperature profile is distorted by the heat transport taking place already during the pulse.

Accurate measurements of the properties of the particle beams is important for beam handling and injection into Tokamaks . Beam alignment, divergence and power density distribution are critical parameters which affect the overall injection efficiency.
Common techniques used for high power beam diagnostics are inertial and water calorimetry [2], where the power density is determined from the thermal response of copper blocks or cooling fluids.
This paper describes a design of a calorimeter which is able to perform beam diagnostic according to the techniques described above. It fulfils also both requirements: good heat removal and a frozen temperature profile. The temperature profile is measured by thermocouples inserted in small thermally insulated parts of the calorimeter, whereas the larger part of the calorimeter is cooled down very efficiently within minutes and the total beam energy is measured via water calorimetry.

2. Experimental set-up

A schematic drawing of the BATMAN (**BA**varian **T**est **MA**chine for **N**egative Ions) Testbed is shown in Fig.1. For details see Ref. [3]. Briefly, the plasma is generated in the so-called driver by radio frequency (1 MHz), with a RF power of typically 100 kW, and expands into the main source chamber towards the extraction system (Fig.2). The extraction system consists of three grids with 44 holes each arranged in an area of 15x15 cm^2. The diameters of the holes vary from grid to grid between 11 and 14 mm. In order to remove the co-extracted electrons, the second grid is equipped with permanent magnets forcing the electrons into special designed pockets. In order to keep the electron power into these pockets low, the acceleration is done in two stages: in the first stage the extraction voltage is some kV; the final acceleration up to about 20 kV is then done in the second stage. The total net extraction area of the grid system is 67 cm^2. The highest current density achieved up to now is 26 mA/cm^2 in hydrogen and 16 mA/cm^2 in deuterium.

The divergence of the beam is 1.5-4°. This means that the beam half width in 1.7 m distance is 0.06 - 0.1 m and may be even larger for larger divergences. The calorimeter is placed in a distance of 1.7 m from the extraction area. In order to catch most of the beam the dimension of the calorimeter was set to 0.6 x 0.6 m^2.

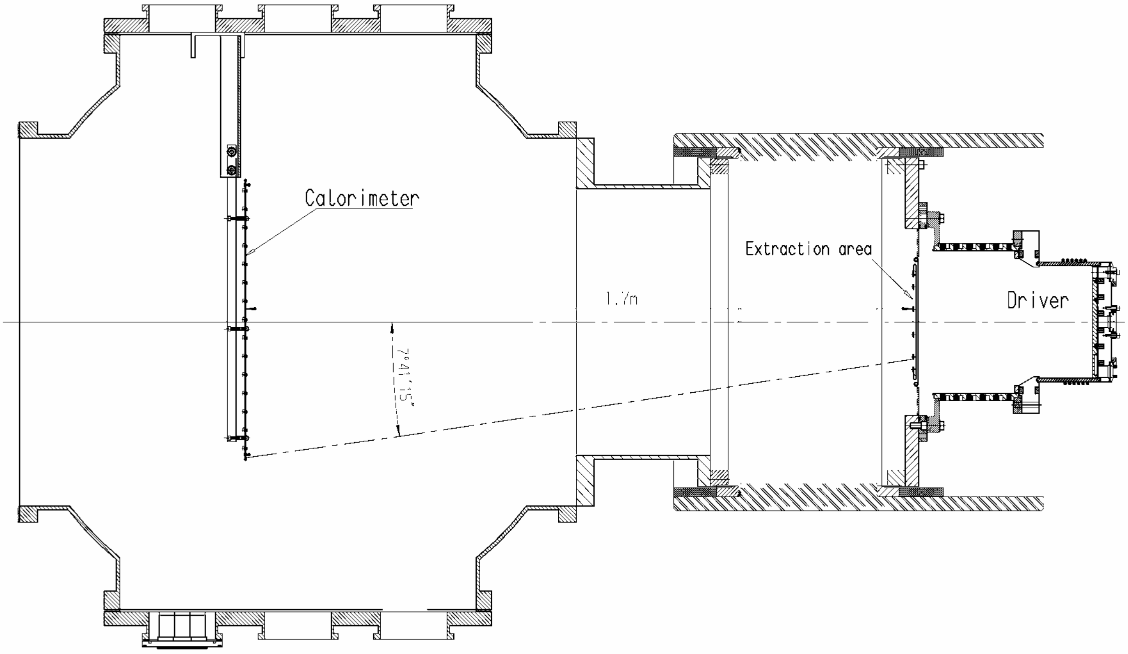

Figure 1: Schematic drawing of BATMAN Testbed. The calorimeter is installed in a distance of 1.7 m.

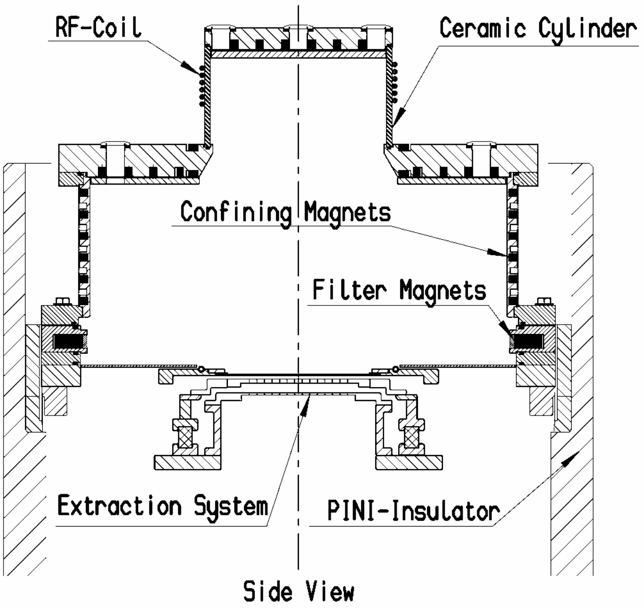

Figure 2: RF Source with three-grid extraction system for negative ions

3. Design

The energy that the calorimeter has to remove ranges between typically 80kJ and 400 kJ in the case of the best values of the source development, i.e. a 2.5 A H^- pulse with 20 kV beam energy for 8 s. However, the design of the calorimeter should also allow to measure low power beam pulses with sufficient accuracy.

The calorimeter described in this paper presents the latest design used in the BATMAN Testbed.

Fig.3 shows a drawing of the present calorimeter. The calorimeter itself is made out of oxygen-free-high-conductivity (OFHC) copper, according to DIN 40 500. Its material properties are shown in Table 1 (see part Calculation).

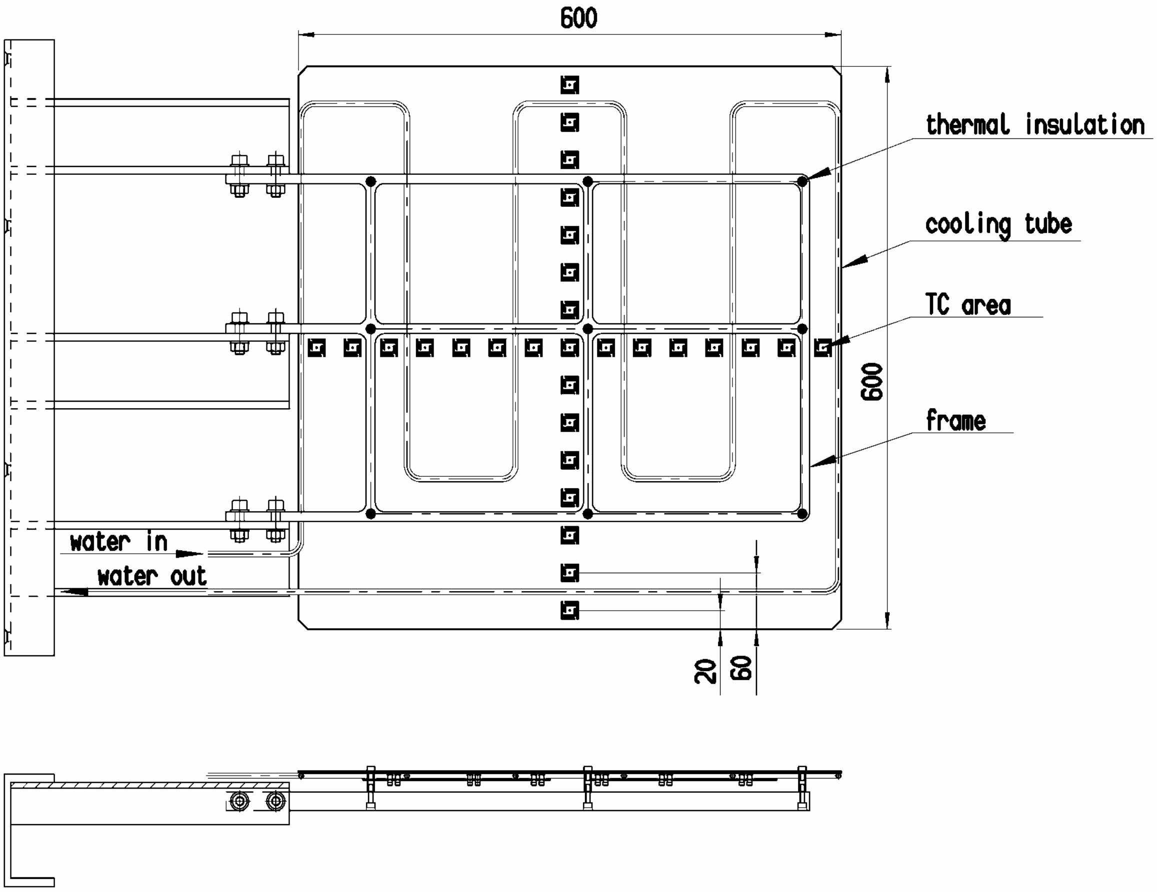

Figure 3: Design of the calorimeter. It is a 600x600mm, 2 mm thick plate, made of copper. The distance between two TC areas is 40 mm. A copper tube with inner diameter of 4mm is brazed on the back of the calorimeter. The direction of the water flow is shown by arrows.

From the past experience and from the results of trajectory calculations it was expected that the heat print of the beam should be well fitted on a calorimeter with dimensions of 600x600mm. A plate thickness of 2 mm is chosen in order to get a significant temperature rise during the pulse. On the back side of the plate a 6x1 mm copper tube is brazed. Water flows through the tube in order to take the heat away. The flow rate of the water is 0.092 kg/s and the inlet pressure is 0.2 MPa. The plate is mounted on a frame via nine thermally insulated bolts which do not significantly influence the heat conductance.

For beam profile measurements a vertical and horizontal line of thermocouples are arranged on the back of the plate. In order to perform accurate local calorimetric measurements not influenced by the cooling effect of the water pipe, the thermocouples are brazed in 29 open slots, later referred to as TC area, in 1.5 mm depth into the plate with a braze which can withstand a maximum temperature of about 450 °C. The slots are cut by water jet in a special meander profile forming a thermal barrier between the central part of the TC area of 1cm^2 and the rest of the plate which is cooled quicker. The thermocouples are placed 40mm away from each other.

This design makes possible to freeze the temperature of the TC area until the end of the pulse and at the same time to provide enough cooling during the pause between two pulses.

Figure 4 shows the TC area in detail. The thermal insulation is achieved by four L-shaped slots cut through the copper. Each slot has a width of 1 mm. The central insulated zone within the inner L's has an area of 1cm^2. The heat is only removed by small connections to the main calorimeters; the heat conductivity is large enough to cool the TC area down between the beam pulses, but it is low enough, that the temperature rise during the pulse and hence the maximum temperature after the pulse is only marginally affected by heat conduction.

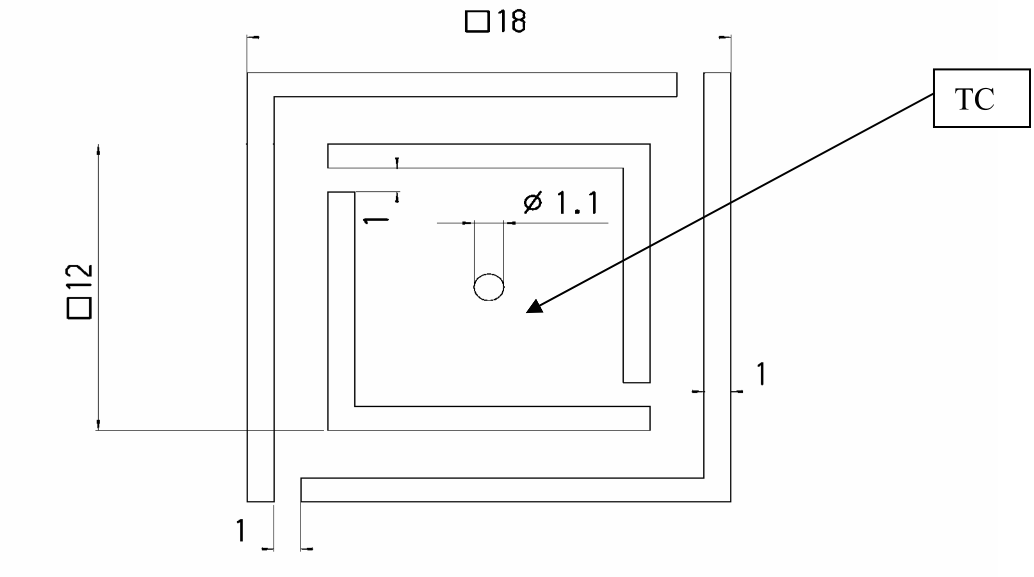

Figure 4: Magnified TC area. Thermocouples are brazed in the middle of the TC area in 1.5 mm depth with a braze, withstanding a temperature of 450 – 500 °C.

Figures 5 shows the effect of the thermal insulation. The temperature distribution inside and outside the TC area in the centre of the calorimeter, immediately after the termination of a beam pulse with duration of 3.65 s and a power densities corresponding to experiment N 15336 . The total beam energy was 44 kJ. Heat conduction takes place in the small connections, but the central temperature remains unchanged.

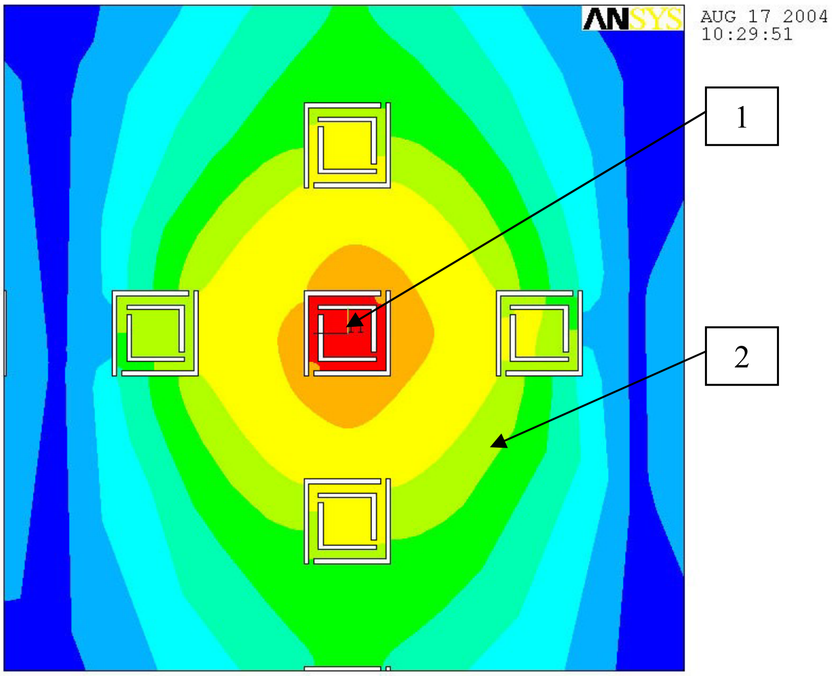

Figure 5: Temperature distribution over the central TC area immediately after the termination of a beam pulse with a duration of 3.65 s. The peak temperature in Pos.1. is about 180° C and in Pos.2 is about 122°C.

Different pipe models (meander, spiral) having various tube spacing were considered and numerically calculated in order to choose the best one, shown in Fig.3, which ensures not only that the heat is removed within a few minutes, i.e. between the beam pulses, in the case of maximum energy impact, but also that the water temperature rise is sufficient for low energy pulses.

4. Numerical simulation

The thermal behaviour of the calorimeter subjected to heat load and the fluid analysis of the cooling water are simulated by using the Finite Element Method Code ANSYS [5]. For obtaining the heat transfer coefficient of the water, used as one of the input data for the ANSYS simulation , the code EUPITER [6] is used.

Transient thermal analyses were performed due to the time variation of the temperature and heat flow.

4.1. Input data

In our case as input data are taken into account the heat fluxes (heat flow per unit area), initial temperature, heat transfer coefficient, flow rate and pressure of the water. The thermal analysis is non-linear because the material properties depend on temperature. Nonlinearities are converged at each time step by one or more equilibrium iteration (Newton-Raphson method).

Table 1 and Table 2 present the temperature dependent material properties of copper and water, respectively.

Temperature dependent material properties	Units	20°C	100°C	200°C	300°C
Density	Kg/m^3	8900	8860	8820	8780
Specific Heat	J/kgK	385	387	390	420
Thermal conductivity	W/mK	398	391	385	381

Table 1: Material properties of E-Cu.

Temperature dependent material properties	Units	20°C	40°C	60°C
Density	Kg/m^3	998	992	983
Specific Heat	J/kgK	4183	4178	4191
Thermal conductivity	W/mK	0.598	0.627	0.651
Convection coefficient	W/m^{2}K	30650	31760	32800

Table 2: Material properties of water.

4.2. Element types used for the modeling.

SHELL57 is a three-dimensional finite element having in-plane thermal conductivity capability. The element has four nodes with single degree of freedom – temperature, at each node. It may have variable thickness and is applicable to a steady-state or transient thermal analysis.

FLUID116 is a three-dimensional thermal-fluid element, having the ability to conduct heat and transmit fluid between its two primary nodes. Heat flow is due to the conduction within the fluid and the mass transport of the fluid. The element may have two different types of degree of freedom: temperature and/or pressure [7].

4.3. Creating the model geometry.

Finally, the ANSYS model of the calorimeter is shown in Fig.6.

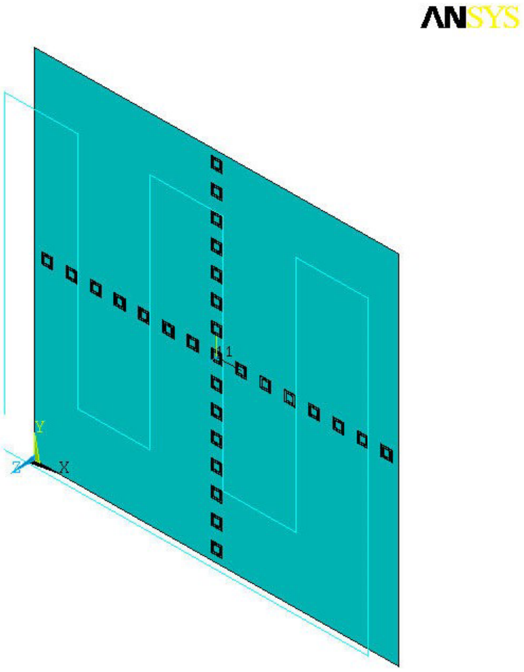

Figure 6. Calorimeter, ANSYS model.

4.4. Simulation and numerical results.

Initial temperature and heat flux distribution over the entire plate are input as loads in the first time step 0-3.65 sec. (duration of the experiment) in the Solution part. In the second time step 3.65 - 90sec. there are no heat loads acting on the plate. In addition, initial temperature of water (22°C), film coefficient of water (see Table 2), flow rate (0.092 kg/s.) and pressure (0.2MPa) are also considered.

The heat flux input for the simulation part corresponding to the BATMAN experiment N 15336 is shown in Fig.7. The peak of the heat flux profile was set at the center of the calorimeter.

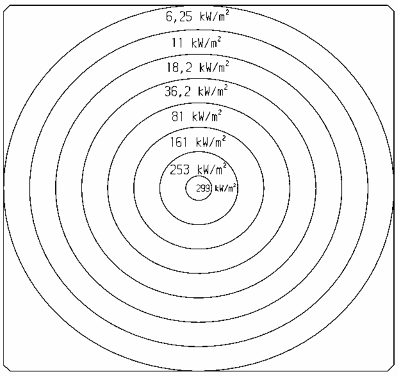

Figure 7: Schematic drawing of the distribution of heat flux over the entire calorimeter.

In Fig.8 and 9 are shown two pictures from the program ANSYS, illustrating the temperature distribution immediately after the pulse, which in our case is 3.65 s and after the cooling time, 90 s, respectively. In Fig.8 the maximum temperature is 179.7° C, considering a starting temperature of 22° C, and in Fig.9 the calorimeter is already cooled down to the temperature of 23.16° C, which means that after this period of time the plate is almost entirely cooled.

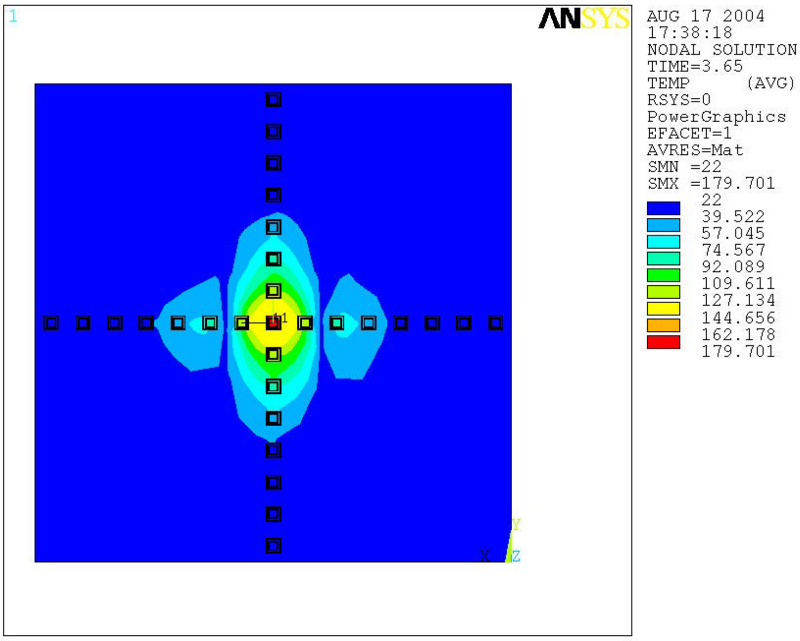

Figure 8: Temperature distribution profile over the entire plate, 3.65 s.

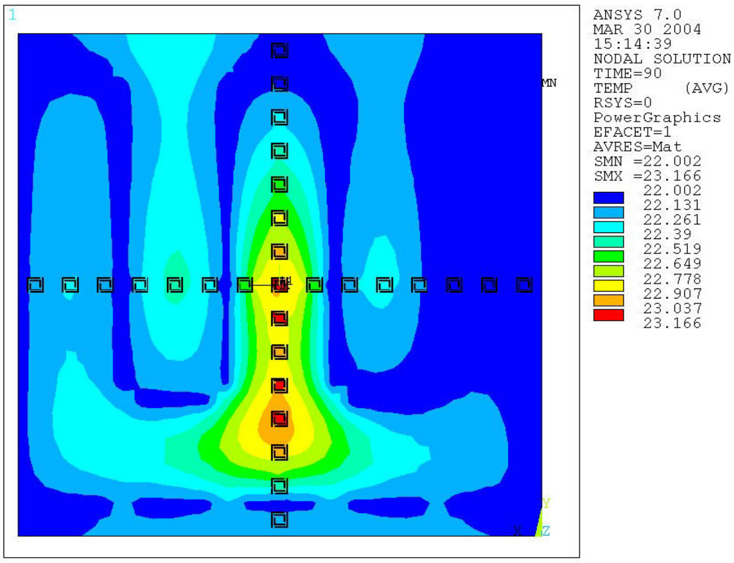

Figure 9: Temperature distribution profile over the entire plate, 90 s.

Fig.10 shows a comparison of the temporal evolution of the temperature in Pos. 1 and 2, already shown in Fig.5.

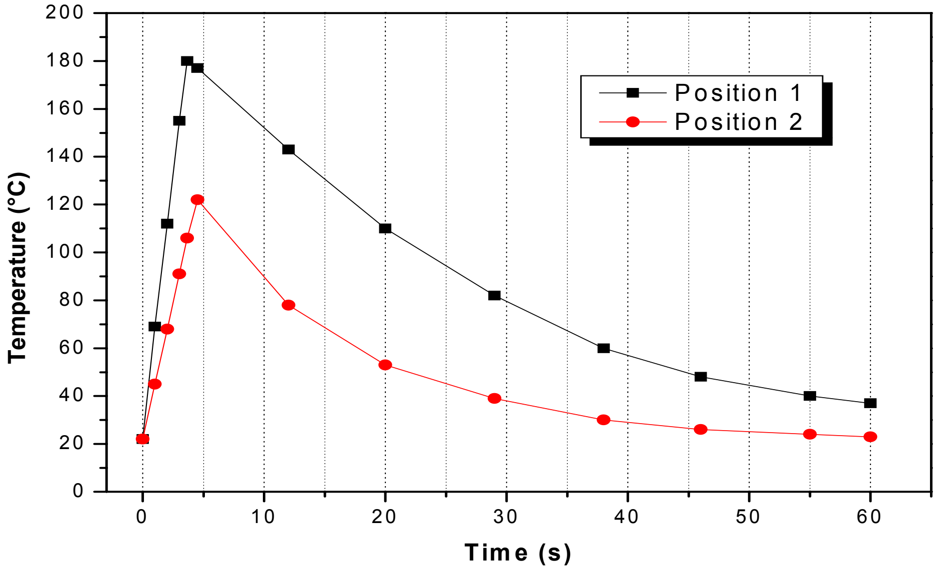

Figure 10: Temperature rise calculated numerically inside and outside the TC area (Pos.1 and 2, see Fig.5). The input data corresponds to the BATMAN experiment N 15336.

The time constant of cooling down according to the numerical calculation is the time reached when the calorimeter is cooled to about 36.8% of the temperature difference. In our case this time is 31.5s and the temperature of the calorimeter in Pos.1 (see Fig.5) has the value of 53.36ºC.

5. Measurements

5.1. Thermocouple measurements

The 2mm thick 600x600 mm copper calorimeter is placed at the beam centre line of the BATMAN Testbed at a distance of 1.7m from the beam source (see Fig.1). The calorimeter is exposed to particle beams with heat flux range between 6 - 300 kW/m^2 and with a pulse length between 1 and 8 s. The surface temperature of the calorimeter can be measured by the thermocouples , as already described under topic Design.

Power density distribution along two lines perpendicular to the beam axis can be calculated by 2D-Gaussian's approximation. The surface temperature distribution reflects the beam power density distribution.

The temperatures resulted from the analysis are compared with the experimental results. The analysed temperatures have reasonable agreement with the experimental one.

The horizontal and vertical temperature profile measured through the centre of the beam immediately after the beam pulse with duration of 3.65s are shown in Fig.11 and Fig.12 , respectively.

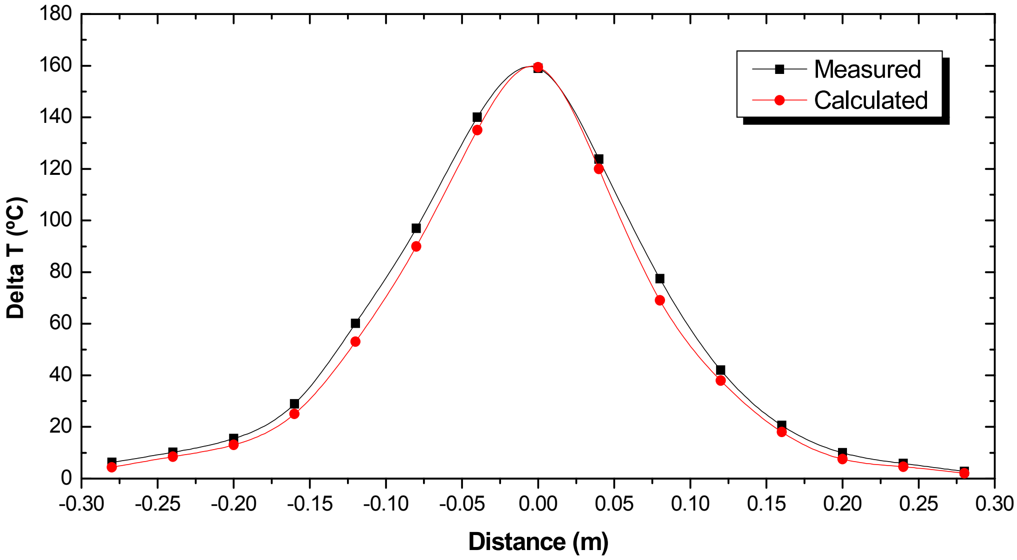

Figure 11: Horizontal temperature profile measured by thermocouples through the centre of the beam and compared to the numerical results done by ANSYS.

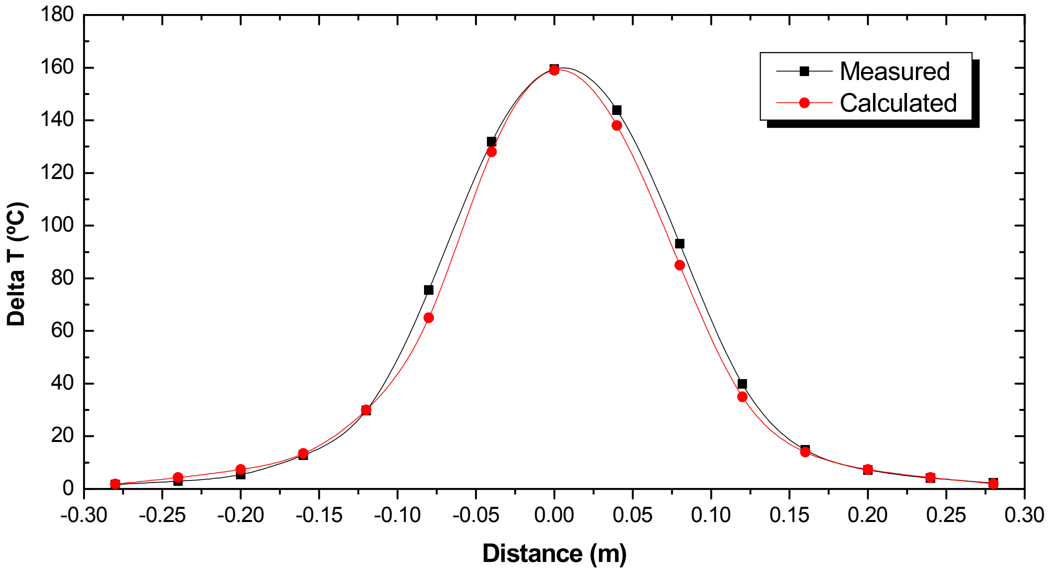

Figure 12: Vertical temperature profile measured by thermocouples through the centre of the beam and compared to the one calculated numerically.

5.2. Power density evaluation

The particle beam power density distribution can be obtained from the surface temperature, measured by the thermocouples [8]. As the thermal properties of the copper are known, it is possible to determine the power density directly from the temperature distribution, already shown in Fig. 11 and Fig.12.

The relationship between the power density and the calorimeter temperature is:

$$E = m . c_p . \Delta T \qquad (2)$$

$$\dot{Q} = \frac{dE}{dt} \qquad (3)$$

$$\dot{q} = \frac{\dot{Q}}{A_s} \qquad (4)$$

where, **t** is the pulse length, **$\Delta T = T - T_0$** (the calorimeter temperature before and after the pulse), **m** is the mass of the copper annulus under consideration, **c_p** is the specific heat of copper, E is the energy in (J), $\dot{Q}$ is the heat flow in (W), and $\dot{q}$ is the heat flux in (W/m^2).

5.3. Water calorimetry

The second approach is the water calorimetry. The water calorimetry is used in this case for measuring the extracted energy by monitoring the temperature rise of the cooling water during a certain period of time (0-90) sec. according to the following formula [9]:

$$Q = \int_0^\infty \dot{m} \,.c_p .\Delta T(t)dt \qquad (5)$$

where, $\dot{m}$ is the mass or flow rate of the fluid, c_p is the specific heat of the water, ΔT is the temperature change, T_{final} - $T_{initial}$' Δt is the time change, $t_n - t_{n-1}$.

The absorbed energy is determined by the time integral of the temperature rise times the water flow [10]. Fig.13 shows the water outlet temperature once calculated numerically and compared to the temperature measured during BATMAN experiment N 15336 .

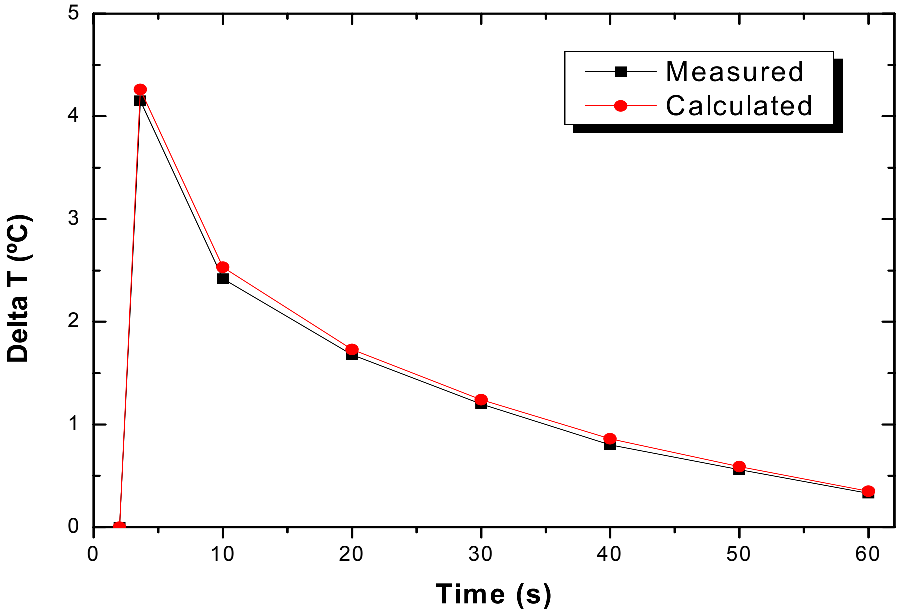

Figure 13: Water outlet temperature presented over the time period 0 - 60s, calculated numerically and compared to the measured one.

The peak water outlet temperature of the measured values is with 0.2° C lower than the one calculated, due to the fact that the measurement takes place on a location about 1 m away from the one , where the calculation is made.
The integral of the water calorimetry curve according to the numerical calculations yields a power 11.45 kW which is in agreement with the total power of 11.29 kW evaluated by the thermocouples.

6. Summary

All neutral beam systems use a calorimeter in order to measure the power delivered by the ion source. An inter-pulse cooled calorimeter has been used in the BATMAN Testbed with the aim of measuring and analysing the extracted beam power. The peak power density is almost 300kW/m^2 concentrated in the central part of the calorimeter and divergence of the beam is 1.5 - 4°. The power density and temperature distribution are measured by the thermocouples, inserted in thermally insulated parts of the calorimeter, and later obtained by the Gaussian's approximation. At the same time the water outlet temperature is integrated over time in order to receive the total energy absorbed from the calorimeter and the largest part of the calorimeter is cooled down very efficiently within minutes.

The calorimeter installed at BATMAN Testbed fulfils both requirements: good heat removal and a frozen temperature profile. All numerical calculations and measurements done with the cooling water calorimetry diagnostic are consistent with the measurements from experiment N 15336 done with the thermocouples within the accuracy of these experimental systems.

One main drawback of the calorimeter is the limitation in pulse length, in particular on the second calorimeter installed at the MANITU test facility in which soft solder is used for connecting the thermocouples to the back of the calorimeter. In this case the maximum temperature reached should be kept below 300ºC.

More interesting experiments are expected for the water calorimetry system, when higher power densities are applied. The experiments performed show that the water calorimetry is a very useful diagnostic method, which is an integral part of the BATMAN experiments.

Acknowledgement

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References

[1] T.Inoue, E.Di.Pietro, M.Hanada et al., "Conceptual design and integration of a diagnostic neutral beam in ITER, 21st Symposium on Fusion Technology (SOFT-21), Madrid, Spain, September 11-15,200, pp.929-934;

[2] P.Massmann et al., Proceedings of the VII International Conference on High-Power Particle Beams, Karlsruhe, Germany, 1988, p.1449;

[3] P.Frank, B.Heinemann,W.Kraus,F.Probst,E.Speth,O.Vollmer, "Progress of the "BATMAN" RF Source for negative hydrogen ions", Proc. of the 20th Symposium on Fusion Technology, Marseille, France, 7-11 Sept. 1998, pp.429-432;

[5] ANSYS, Swanson Analysis systems Inc., Johnson Road, P.O. Box 65, Housten, PA 15342-0065;

[6] EUPITER 4.21, U. Mszanowski, G.Vieider, I. Smid- NET (April 1996);

[7] Ansys Elements Manuel, ANSYS Release 6.1, March 2002, SAS IP, Inc.

[8] D.Ciric, H.D. Falter, J.G.A. Fanthome, P.Massman and K.N.Mellon, "Beam profile measurement using a unidirectional CFC-target and infrared imaging", Fusion Technology 1994, 1995 Elsevier Science B.V., pp.827-830;

[9] Fundamental Physics Lab 9.99, 13.2.1 Calorimetry, Theory, http://193.175.144.216/ist-physics_lab_course/calori.pdf

[10] T.Richter and H.Vernickel, "The cooling water calorimetry system at ASDEX Upgrade Tokamak", Rev.Sci.Instrum., Vol. 65, No.5, May 1994, pp.1613-1615;