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Micro-channel–based high specific power lithium target

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Summary. — A micro-channel–based heat sink has been produced and tested. The device has been developed to be used as a Lithium target for the LENOS (Legnaro Neutron Source) facility and for the production of radioisotope. Nevertheless, applications of such device can span on many areas: cooling of electronic devices, diode laser array, automotive applications etc. The target has been tested using a proton beam of 2.8 MeV energy and delivering total power shots from 100 W to 1500 W with beam spots varying from $5\,\text{mm}^2$ to $19\,\text{mm}^2$. Since the target has been designed to be used with a thin deposit of lithium and since lithium is a low-melting-point material, we have measured that, for such application, a specific power of about $3\,\text{kW/cm}^2$ can be delivered to the target, keeping the maximum surface temperature not exceeding $150\,^\circ$C.

1. – Introduction

Micro-channel targets have been largely considered one of the best solutions to remove high specific power (power per unit area or volume). Since their first discovery in the late' 80s, the efficiency of heat removal of micro-channel targets has been proved and the study of the performance and characterizations of their properties have been widely improved. In [1, 2], we have proposed the application of micro-channels to a high-power target for the LENOS project, where a power density of $4\,\text{kW/cm}^2$ must be dissipated on a thin lithium metal target. Strictly speaking, micro-channels are channels where the cooling fluids flow inside and have sizes of the order of tens of microns. Together with the large value of the convection coefficient (h), the compelling advantage is the low wall thickness of the channels. Usually the power impinging on a tube or channel and the heat transport proceeds thought two separate steps; heat conduction from the outer surface to the inner surface of the channel and convection from the inner surface of the channel to the cooling medium (being it gas or liquid). Having micro-channels means having small wall thickness and thus a strong reduction of the conductive part of heat transport so that the convection part is dominant. Moreover, thanks to the micro-size of the diameter and the cylindrical shape, even with small thickness, the channels are able to sustain high pressure of the cooling medium, which is also necessary in order to accept the large pressure drop along the micro-channels. Micro-channels has a simple relation (following the original paper of [3]): Consider a collection of n parallel channels of length L, embedded in a substrate of the same length L and width W. A coolant flows in each channel, absorbing a constant heat flow (P) per unit length from it walls (the substrate).

At each cross-section along the length of the channel, assuming that the walls are infinitely thermally conductive so that the temperature is uniform around the perimeter, the convective heat-transfer coefficient h is defined as $h = Q/nLp(T_w - T_f)$, where T_w is the wall temperature, T_f is the mean fluid temperature, and p is the cross-sectional perimeter. It is customary to calculate h using dimensionless groups $h = Nu \cdot k_f/D$, where Nu is the Nusselt number, a dimensionless heat transfer coefficient; Nu can be calculated from empirical or semi-empirical formulas containing D, Pr and Re, and different formulas are reported in the literature for different channels shape and size. For micro-channels, Pr and Re stay for: $Pr = \mu Cp/k_f$, the Prandtl number, which is a property of the fluid , the ratio of momentum diffusivity to thermal diffusivity ($Pr = 6.4$ for water at 23 °C); $Re = \nu D\rho/\mu$, the Reynolds number, which account for turbulent or laminar flow. Here D is a characteristic width of the channel, defined as $D = 4$ (cross-sectional area)/(perimeter). The terms μ, k_f, ρ, C_p and ν denote, respectively, the viscosity, thermal conductivity, density, specific heat, and mean velocity of the coolant fluid. From this simple relation, the lower the channel diameter the higher the convection coefficient h, as well as the higher the thermal conductivity of the coolant (k_J) the higher the resulting h: for this reason we proposed to use the micro-channels in conjunction with metal cooling. Because h is proportional to $1/D$, the micro-size of the channels is effective in increasing the convection coefficient and thus the efficiency of heat removal, even though the size and length of the channels must be balanced with respect to the pressure drop, which is proportional to $1/D^2$.

A review paper proposed a general formula for calculating Nu for different channel geometry [3] under the hypothesis of fully developed laminar flow with H1 boundary condition (constant axial wall heat flux with constant peripheral wall temperature). They suggest to use the value of (cross-sectional area)/(perimeter) instead of hydraulic diameter. Moreover, Nu depends on the shape of the channels [4], It appears that elliptical and rectangular channels have the best performance. Nevertheless, the hypothesis under the model is strong and, as stated in the article, the development of a general geometric model for the Nusselt number is complicated or impossible. Hundred of formulas are published to calculate the Nusselt number for different micro-channel geometry and flow regimes Finalizing, the high efficiency of micro-channels is well recognized and the main problems are related to the construction, so a balance between the construction problems, pressure drop and efficiency must be achieved, with the experimental validation of the heat sink the only way to evaluate the performance of the device.

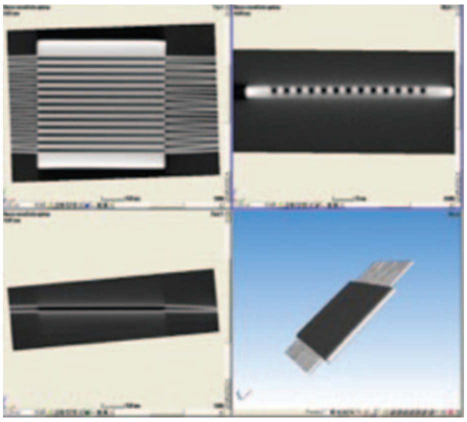

Fig. 1. – 3D tomography of the produced target. The good thermal contact is obtained.

2. – Target construction

From the point of view of the construction, micro-channels are usually obtained by producing square fin in a thermal conductive substrate and the upper part of the finned substrate is closed with a plate, producing micro-channels with different shapes. Channels are then closed by a plate, mechanically couples to transform fins in separated channels. For small sizes, the production is done by etching or growing the channels. The main limitations of such construction is mostly due to the size of the target that can be produced and the needs of avoiding large working pressure, since the covering plate can be bended and, consequently, the micro-channels are no more separated. Moreover, the etching or deposition process is strongly dependent from the material used and coupling of different materials is often problematic. In order to overcome these limitations, a new method for the production of the micro-channels has been patented by INFN [5] and the obtained target has been tested and characterized. Starting from a thin plate of copper (1.2 mm thickness), almost semi cylindrical fins are produced by using an electro erosion machine or a cutter with a small spherical head. In the same way different shapes for the channels can be obtained. Inside the produced fins, small micro-tubes are tightly inserted and interference is produced between the tubes and the substrate. Figure 1 shows a radiography of the produced micro-channels target and a good mechanical contact between tubes and fins is achieved. This is, of course, a necessary condition to have an efficient heat transfer. The developed construction method has many advantages with respect to the traditional one, since different material can be used for the substrate (*e.g.* thermal grade diamond) and tubes (*e.g.* steel or niobium for liquid metal cooling or aggressive coolants). Moreover, different shapes can be obtained even after the tube insertion, just by bending and forming the plate. In addition, the fins can have different shapes and can be produced directly onto the pieces to be cooled and the tubes inserted later (*e.g.* application to electronic circuits).

The cylindrical shape of the channels ensures a uniform distribution of fluid velocity inside the tubes which is able to sustain a much higher pressure than squared channels. Figure 2 shows the realized and tested prototype, which consists of 13 copper tubes accommodated in the copper plate, with a centre tube to tube distance of 1 mm. The tubes inserted in the fins have an internal diameter of 0.68 mm and the external one

Fig. 2. – Target used for the tests. The beam impinges on the part where tubes are accommodated in the backing.

of 0.88 mm. The whole target has a thickness of 1.2 mm. All micro-tubes are collected in a large copper tube and soldered, while on the other side a Swagelok connector has been used to couple the target with the water inlet and outlet. The diameter of the tube used has been motivated by the market, since this size is the smallest one we found commercially available at a low price. The target has been designed to be used with a metal cooling medium [1] *e.g.* a eutectic SnInGa alloy commercially available as GALINSTAN. For such a liquid metal, the absence of diffusion of the metal into the copper has been tested for liquid metal temperatures up to 100 °C.

3. – Experimental setup

During the tests, the target has been accommodated into a lithium target assembly (LTA), see fig. 3, in order to keep the target in vacuum during the test and minimize the reflected temperature. The LTA has been produced in carbon fibre (low reflectivity material) and had a Zinc-Selenium window facing the target heated face under an angle of 30°.

Target temperature has been mapped with a thermo camera through the window. A Pt100 thermo resistance probe was also placed inside and attached to the side of the backing plate for a cross check of the temperature measurement. Particular care has

Fig. 3. – Lithium Target Assembly (LTA). Fully constructed in carbon fibre to minimize the background and keep the reflected temperature low. Left: the mounted target is shown together with the PT100 for a cross check of temperature. Right: beam pipe connector.

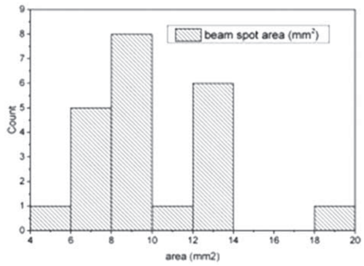

Fig. 4. – Distribution of the beam spot events.

Fig. 5. – Image from the thermo-camera.

been devoted to the calibration of the thermo camera, where a Lambert reflection meter has been used to account for the reflected temperature. The vacuum inside has been kept below 10^{-4} mbar, and an off line calibration has been constructed to account for the real emissivity of the backing surface. The off-line calibration system consists of a heat bath where the water flowing into the target was heated at different temperature. Cross check has been done by using 40, 50 and 70° water temperature by using the PT100 and a sticker with a well-known emissivity of 0.93. From data analysis, we estimated a reflected temperature of 30.7 °C. (in agreement with the room temperature during the tests) and an effective emissivity of 0.22 (which account for the real emissivity and efficiency of the Zn-Se). The test has been performed at Birmingham University using 2.8 MeV protons impinging on the target at different currents, provided by the Dynamitron accelerator [6]. Different beam spot size have been used, ranging from 5 mm^2 to 19 mm^2, see fig. 4), and different beam power (ranging from 100 to 1500 W). Figure 5 shows a typical image from the thermo camera where the beam spot is visible together wit the clamp which keep in position the thermo resistance Pt100.

4. – Data analysis

For each collected point, a contour plot has bee obtained in percentage of the maximum temperature (see fig. 6). As beam spot size, the surface corresponding to the half maximum of the temperature has been chosen. The adopted criteria is the most critical part of data analysis, because of the small beam spot used in the experiment. further investigations are needed to cross check the validity of this criteri. Contour plot and area

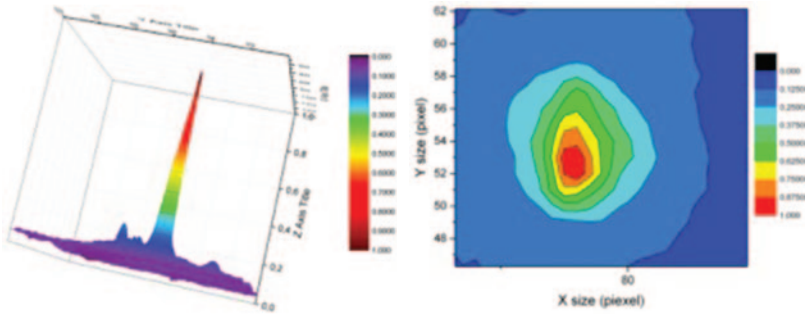

Fig. 6. – Left: 3D temperature distribution normalized. Right: 2D projection. the beam spot area is calculated defining the 50% profile, which correspond to the cross sectional area of the FWHM of left figure.

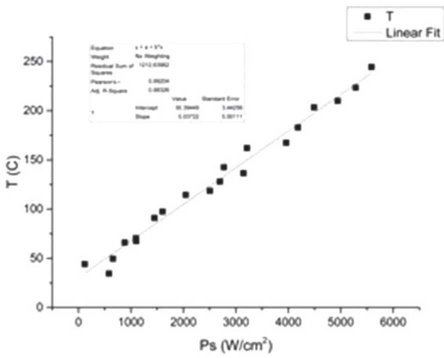

Fig. 7. – Analyzed experimental data. Uncertainties are smaller than the symbols.

calculation have been performed using Origin-lab 9.0 (see fig. 6, right). Temperature is defined as the peak temperature, while the power delivered to the target has been measured by measuring the mass flow and the water temperature difference between inlet and outlet. The beam spot area has been calculated at FWHM of the maximum temperature. A value of the mass flow of 2.8 and 3.8 l/min has been used during the test, with a water pressure of about 8 atm.

Figure 7 shows the obtained results. The linear rise in fig. 7 confirms the expected linear behaviour, with an intercept which well reproduces the reflected temperature and thus the ambient temperature. The spread of points around the linear fit is mostly due to calculations of the beam spot area, apart because of the used criteria to determine the surface, because during the experiment the accelerator was not so stable and often some beam showed two or three peaks. Moreover, the shape of the beam was not always Gaussian, so the uncertainty on the beam spot area was difficult to evaluate, as well as the effect of a two-three peaks distribution. Uncertainty on temperature has been calculated using two different values for emissivity (0.21 and 0.23), but evaluated uncertainties are lower than the symbol size.

Because the range of 2.8 MeV protons on copper is less than 40 μm, the correct quantity to be accounted for is the power per surface unit. Neglecting the Bragg peak energy distribution and assuming a uniform energy distribution along the range of 40 μm, the power per unit volume becomes about 0.75 MW/cm^3, a value much higher than the available high power targets ([7, 8]). The obtained results are better than expected from calculation, and the value of 3 kW/cm^2 already satisfy the needs of the LENOS facility, without the need for implementing the liquid metal cooling. Nevertheless, we expect a calculated improvement of about 40% using metal cooling instead of water, as reported in [1]. The good performance of the target suggests deeper work is required in order to well characterize it, measuring temperature and specific power for different fluids and fluid velocity as well as different channel sizes. The use of metal cooling is also a promising alternative to water and has to be investigated experimentally. In order to define the final target design the blistering effect on copper substrate must be measured, since in the literature discrepant behaviour are reported, probably because the production methods reached temperature and beam concentrations play an important role and the obtained results do not allow a precise characterization of the experimental conditions. The effects of lithium deposition will also be tested in the near future, to verify the thermal contact between Lithium and Copper. We are currently depositing lithium by evaporation in a dedicated evaporator assuring a good thermal contact between metals.

5. – Conclusions

We have applied the micro-channel cooling system to the production of a high specific power target for applications with charged beams. The system has been developed to be used with a lithium target and liquid metal cooling for neutron production in the LENOS project. A new method for the construction, which offers much more degree of freedom and a wider field of applications, has been patented. The realized prototype has been tested with a 2.8 MeV proton beam at Birmingham University and shows that about 4 kW/cm^2 can be dissipated while keeping the maximum surface temperature below 150 °C. The limitation adopted of 150 °C is due to the low melting point of lithium (180 °C) and thus the value of about 3 kW/cm^2 can be much higher whenever the maximum surface temperature can be increased (*e.g.* for beryllium targets).

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