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Investigation of the Thermal Performance of Solid Targets for Radioisotope Production

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Abstract

The large-scale production of various radioisotopes is often carried out with a target system in which solid target material is plated onto a water-cooled backing. A detailed thermal analysis of such a solid target system under different bombardment conditions was made by means of a finite element analysis program. Results of a parameter study are presented and are discussed with the objective of maximizing the beam current limit of the solid target design employed at TRIUMF. Predicted surface temperatures are also compared with direct measurements.

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1. Introduction

Low-energy cyclotrons ($E_p \leq 30$ MeV) are often employed in the production of radioisotopes. Since extremely large quantities are involved in the commercial production of some of these radioisotopes the proton beam intensities are pushed as high as possible to maximize production rates. Despite this, in the past production has been limited by the cyclotron in most cases. However, with the introduction of the new generation of negative-ion cyclotrons, capable of delivering several hundred µA of beam, the maximum rate at which radioisotopes can be produced is now limited by the (thermal) performance of the targets.

At TRIUMF, for example, two low-energy negative-ion cyclotrons (CP42 and TR30) are operated full time for the production of radioisotopes. While the 12-year-old CP42 is operated mostly at maximum capacity (160 - 200 µA), production runs on the recently-installed TR30 are carried out with much lower beam currents (200 - 250 µA on each beamline) than what this machine is capable of (presently ~500 µA total, single or dual beam). This practice came about as a result of our experiences with occasional catastrophic thermal failure of targets in the past. Like several other solid target designs, the one employed at TRIUMF [1] for the production of radioisotopes, such as ^{57}Co, ^{67}Ga, ^{111}In and ^{201}Tl, is based on a system in which enriched solid target material is plated onto a water-cooled backing plate. Therefore a target failure is not only associated with radiation safety hazards and production losses, but it usually also results in the loss of substantial amounts of expensive target material. Hence, the beam current limit chosen for a particular target design in practice tends to be rather conservative in order to eliminate such failures.

In this work, a parameter study of the target under bombardment was conducted with the aim of finding ways to increase the beam current limit associated with the present target design and to optimize future designs. Finite element analyses (FEA) were made of the heat flux and temperature distributions in the target under different operational conditions by means of a FEA code. The existing cooling configuration [2] and operational parameters were taken as a departure point and temperature distributions were calculated in a large number of FEA runs where the different parameters were varied. The results of the parameter study are presented and are discussed in terms of maximizing the beam current limit on the target. The surface temperature of a target under bombardment was also measured directly by means of thermocouples and corresponding predicted temperatures are compared with the measurements.

2. Target design and cooling configuration

The present solid target configuration is shown schematically in Fig. 1. It comprises a copper or copper-plated aluminum body with cooling-water ports and a silver backing plate onto which a thin layer (~100 µm thick) of target material (enriched ^{58}Ni, ^{68}Zn, ^{112}Cd or ^{203}Tl) is plated. A series of grooves is machined into the 3.5 mm thick silver plate to form cooling fins. When the plate is soldered onto the target body these grooves form 16 rectangular channels (0.8 mm × 2.5 mm), through which the cooling water is forced at a high velocity. The proton beam, which hits the target surface at a glancing angle of 7°, is stopped in a relatively thin layer (~200 µm thick) where it deposits all its energy. The heat generated in this layer close to the target surface is then conducted to the water-cooled back of the target plate and into the cooling fins. From there the heat is transferred to the cooling water and removed.

Since the plated target material is irradiated in vacuum it is crucial to achieve the lowest possible surface temperature for a given beam power and focus in order to prevent the loss of target material and/or radioactive products through evaporation.

3. Calculation of temperature distributions

Heat flow problems in complex geometries, such as cyclotron targets, cannot be solved analytically and so numerical methods [3] based on finite difference techniques have to be used. In this work such methods were employed to calculate the temperature distributions in targets by means of the FEA code, ♦ALGOR® [4].

A model of the target, or a part thereof, is divided into a number of small elements. In a two-dimensional problem an element is usually triangular or rectangular in shape with each of its corners defined as a so-called node, whereas in three-dimensions an element is usually brick shaped, also with the corners defined as nodes. The temperature at each node is then calculated, taking into account the thermal conductivity of the material and the thermal boundary conditions (heated regions and cooled surfaces) imposed on the target. A high level of accuracy in the calculations is achieved by choosing a large enough number of elements to model the target configuration. The overall accuracy of analysis results ultimately depends on how well the input parameters can be determined.

Several parameters dictate the temperature distribution in the target plate during bombardment: the cooling configuration itself, the thermal conductivity of the plate material, the cooling water temperature, the beam power density distribution and the heat transfer coefficient between the water and the cooling-channel wall. An accurate representation of particularly the latter two is crucial.

3.1 Beam profile

The power density (or intensity) of a non-circular cyclotron beam is best represented by a 2-dimensional Gaussian distribution. Since radioisotope production beams are usually collimated in order to protect sensitive components of the target, truncated distributions have to be used to model the heat load on a radioisotope production target.

At TRIUMF carbon collimators with rectangular apertures are used to trim the beam edges. For a high-current bombardment the beam typically fills the aperture with a certain amount of spill on the collimators so that the beam focus condition is usually defined in terms of the amount of beam spill. Due to the 7° glancing angle the beam power is distributed over an area of approximately

25 mm × 75 mm of the target surface. Hence, as illustrated in Fig. 2, the power density P of the proton beam is represented in this work by a truncated two-dimensional Gaussian distribution

$$\begin{aligned} P &= P_0\, e^{-\frac{x^2}{2\sigma_x^2}}\, e^{-\frac{y^2}{2\sigma_y^2}} && \text{for } |x| \le 12.5 \text{ and } |y| \le 37.5 \\ &= 0 && \text{for } |x| > 12.5 \text{ or } |y| > 37.5, \end{aligned}$$

where P_0 is the total beam power and

σ_x and σ_y are the standard deviations for the x and y distributions respectively.

Calculated beam profiles at y=0 for different beam focus conditions are presented in Fig. 3. In each case the amount of beam spill on the four collimator sections is assumed to be equal.

3.2 Heat transfer coefficient

For use in thermal analysis problems the heat transfer coefficient h for a smooth cooling tube is calculated from the expression [3]

$$h = \frac{k}{d}\,\mathrm{Nu},$$

where k is the thermal conductivity of the cooling fluid,

d is the so-called hydraulic diameter of the rectangular channel and

Nu is the dimensionless Nusselt number.

The Sieder and Tate correlation [5] was used to calculate h in this work:

$$\mathrm{Nu} = 0.27\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14},$$

where

$\mathrm{Re} = \dfrac{\rho d v}{k}$ is the Reynolds number,

$\mathrm{Pr} = \dfrac{c_p \mu}{k}$ is the Prandtl number,

ρ is the density of the water,

v is the free-stream water-velocity,

c_p is the specific heat and

μ and μ_w are the dynamic-viscosity values evaluated at the bulk temperature and cooling-cannel wall temperature, respectively.

Since ♦ALGOR® does not allow the use of a temperature-dependent heat transfer coefficient the value of the wall temperature of the cooling channel was fixed at 100°C for the calculations.

4. Measurement of target surface temperatures

Two production targets (a 25 mm × 75 mm target capable of handling 7.5 kW and a larger 40 mm × 100 mm target capable of withstanding 15 kW) were specially modified to measure directly the surface temperature during bombardment. The silver face of the target was coated with liquid kapton which was then cured to produce a solid film. Certain spots where temperatures were to be measured were masked off during the coating process. A thin nickel layer, masked as strips which terminate at the measurement spots, was plated on top to produce a series of Ag/Ni thermal junctions. These junctions were used to measure the temperature directly on the surface. As a control measure another 0.8 mm diameter thermocouple (type-K) was embedded just below the surface of the target plate at the central Ag/Ni junction location as shown in Fig. 4. Beam intensities of up to 460 μA were directed onto these targets using the TR30 cyclotron system and direct surface temperature measurements were obtained during the irradiation process.

5. Results and discussion

Three FEA investigations were pursued in which input parameters were varied individually in order to see their effect on the thermal performance of the solid target. In the first two exercises the water flow rate through the target (which affects *h*) and the beam focus (which affects the peak power density) were varied. In the third exercise a large number of FEA runs were made on the central section of the target in order to see the effect of changes in the cooling geometry on the thermal performance of the target.

5.1 Effect of beam focus and water flow rate

Figure 5 shows the results of runs for a 200 μA (6 kW) proton beam with various beam-focus and water-flow conditions. The maximum surface temperature of the target (i.e. in the central region of the beam strike area) is plotted as a function of total cooling-water flow rate through the target for different beam-spill values. It is apparent that the surface temperature is highly dependent on both these parameters, thereby underlining the importance of having the ability to control them accurately during bombardment.

At TRIUMF the water flow rate through targets vary presently between 8 L/min and 20 L/min, depending on the target station, while beam-focus conditions vary between 5% and 15% beam spill. Due to thermal failure of some targets in the past production beam currents have been limited to 200 μA, translating to an average of approximately 180 μA on target. Assuming a maximum surface temperature of 140°C it can be concluded from Fig. 6 that it should be possible to increase this limit by almost a factor of two provided that the water flow rate and beam spill are maintained at 20 L/min and 15%, respectively.

5.2 Effect of changes in geometry

In Fig. 7 the results are shown of a large number of FEA runs on the central section of the target in which the dimensions, *a*, *b*, *c* and *d*, were varied one by one, keeping all other parameters fixed at

the values of the existing (standard) target. In each case the maximum surface temperature is plotted as a function of the dimension value. For the cases *a* and *d* variation of the relevant dimension is straight forward. However, variation of the cooling channel dimensions, *b* and *c*, influences the water flow and, consequently, the heat transfer coefficient at the channel wall. In order to maintain a realistic approach to the parameter study in these two cases the pressure drop across the cooling channels was kept constant and the flow rate re-determined in each case, making use of friction factors for smooth tubes [3]. Hence, a different heat transfer coefficient was used in each FEA run.

For the beam parameters used in the calculations (200 μA, 10% beam spill) a maximum surface temperature of 109°C is predicted for the standard cooling geometry, which had been optimized previously [2] for a copper target plate. Re-optimizing the geometry for a silver target would require reducing this temperature significantly by changing one or more of the dimensions. However, it is clear from Fig. 7 that the present cooling configuration leaves little room for improvement in the thermal performance of the target. On the other hand the figure also shows that the plate thickness *a*, for example, can be significantly increased, causing only a slight deterioration in thermal performance. It is therefore possible to increase the strength of the target plate in this way so that it can be operated at significantly higher pressures (and consequently higher water flow rates) resulting in a net improvement in thermal performance.

5.3 Comparison with measurements

A comparison of predicted and measured temperatures for the higher-power target is shown in Fig. 8. In general there is good agreement between the predictions and the measurements. Some variation at the high-current end can probably be ascribed to peeling of the surface thermocouples.

6. Conclusions

A detailed parameter study of the present solid target design by means of the FEA program ♦ALGOR® demonstrated that the maximum surface temperature during bombardment is most sensitive to the proton beam focus and the cooling water flow rate. Optimizing these two parameters may result in an almost doubling of the present production beam current limit of 200 μA associated with the existing design.

The study also shows that the thermal performance of the design is relatively insensitive to variations in the dimensions of the present cooling geometry. This fact can be exploited in a new target design to remove the present pressure limitation on the targets, allowing still higher water flow rates and a further increase in the beam currents. Furthermore, the present solid target stations at TRIUMF allow for targets to be irradiated over a much larger surface area, which can also be exploited in a future high-current target [6].

Comparison of predicted surface temperatures during bombardment of such a high-current target with direct measurements confirmed that the maximum temperatures we anticipate are within the operating parameters of our solid target system. Specifically, we see that our goal of not exceeding 150°C at maximum intensities (500 μ) is easily achievable.

Acknowledgments

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FIGURE CAPTIONS

Fig 1. Target design and cooling configuration.

Fig 2. Example of a two-dimensional Gaussian distribution used in the calculations to represent the power density on the target.

Fig 3. Power-density profiles at y=0 for various beam focus conditions. A focus condition is defined in terms of the total amount of beam spill, which is assumed to be equally divided among the four collimators.

Fig 4. Cross-section through a target assembly showing the construction of thermocouples used to make temperature measurements during irradiation.

Fig 5. Maximum surface temperature of the target (i.e. in the beam center) as a function of total cooling-water flow rate through the target for various focus conditions of a 200 μA, 30 MeV (6 kW) proton beam.

Fig 6. Beam-on-target as a function of total cooling-water flow rate through the target for a maximum surface temperature of 140°C.

Fig 7. Variation of maximum surface temperature of the target (in the beam center) with changes in the dimensions of a target section for beam-current and beam-spill values of 200 μA and 10%, respectively. For each curve only one dimension is varied, keeping the others fixed at the values of the standard geometry. A fixed pressure drop (22920 Pa) across the cooling channel is assumed for the cases *b* and *c*.

Fig 8. Comparison of predicted and measured temperatures at the center of the high-current target surface.

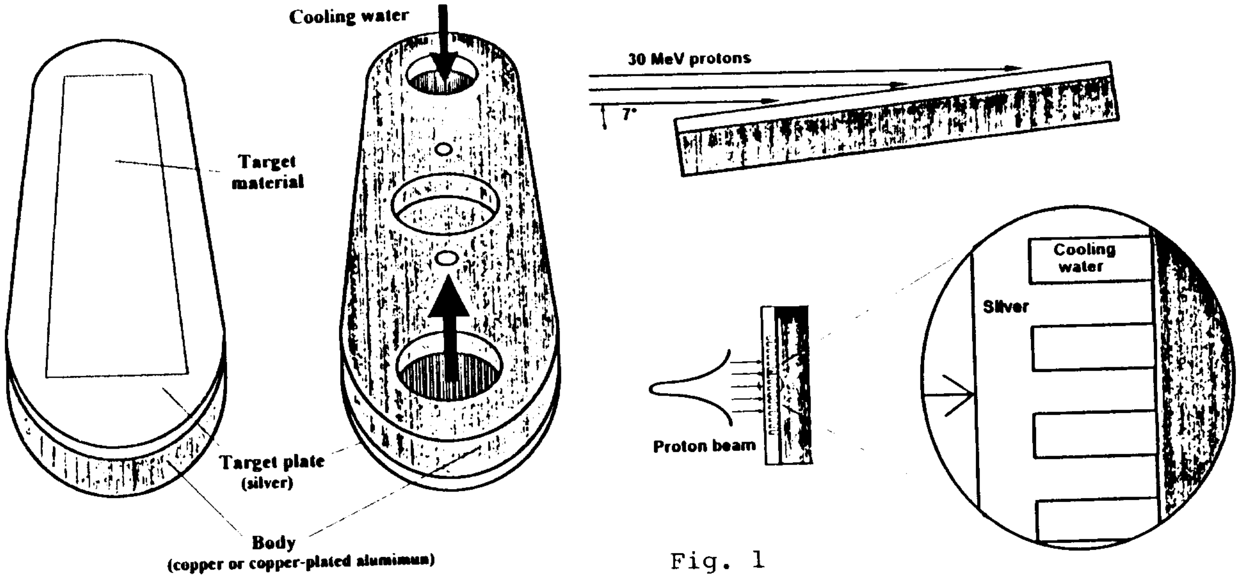

Fig. 1

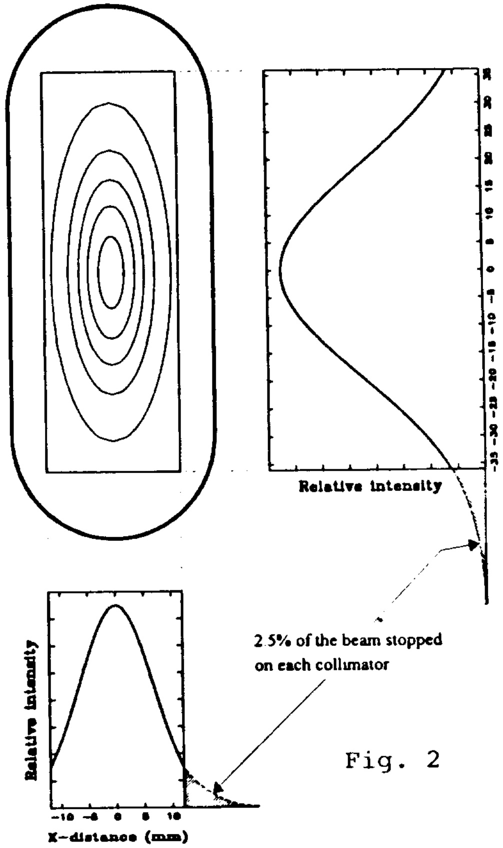

Fig. 2

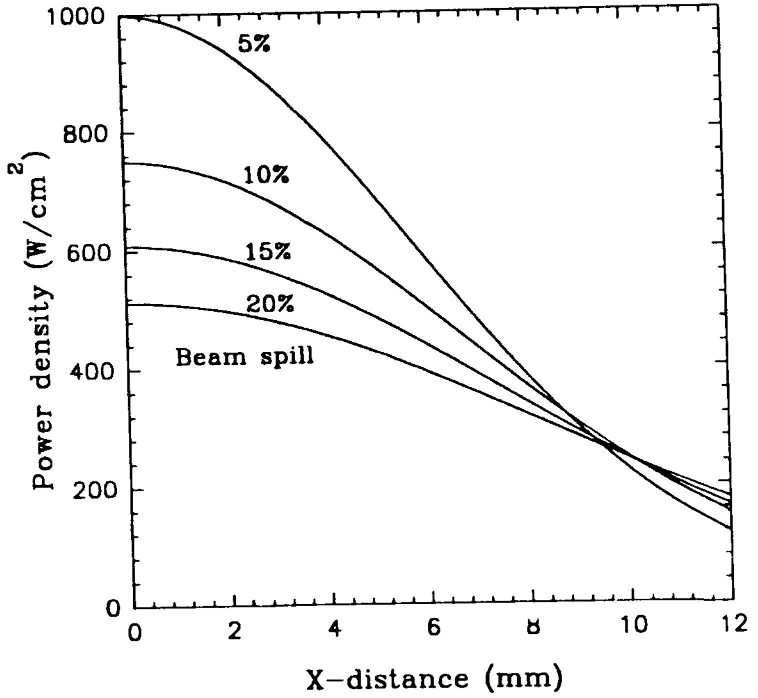

Fig. 3

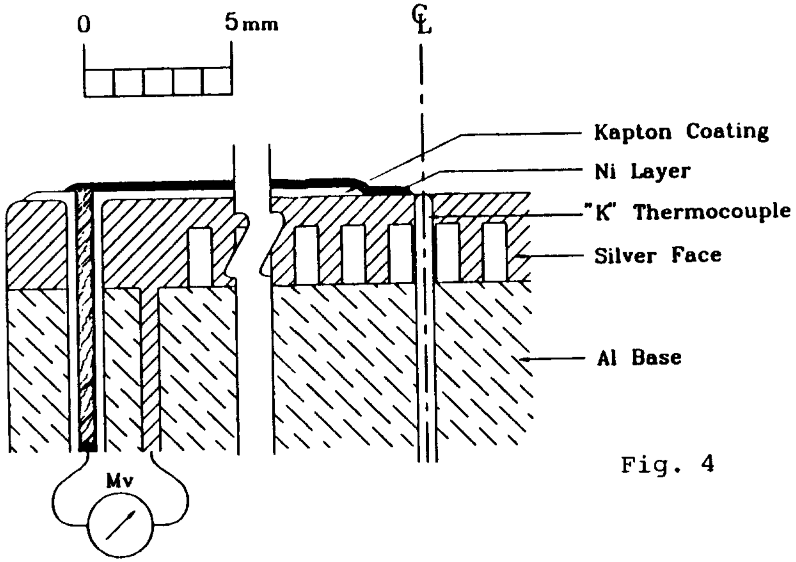

Fig. 4

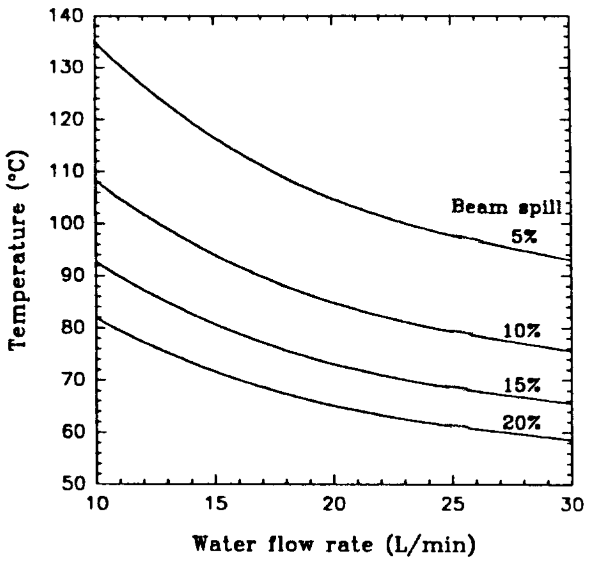

Fig. 5

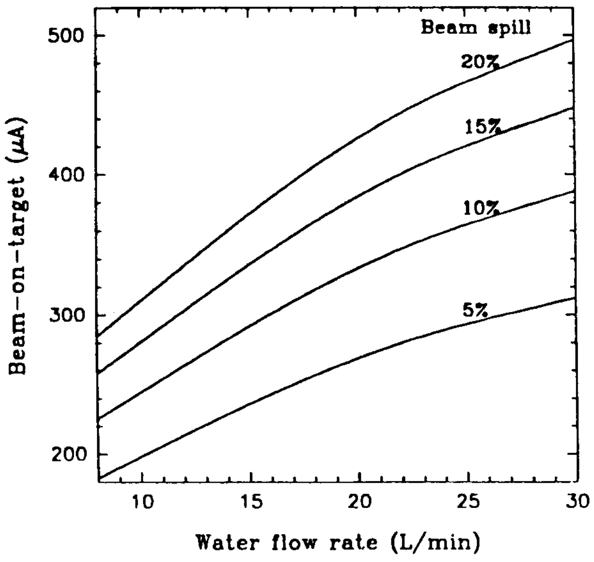

Fig. 6

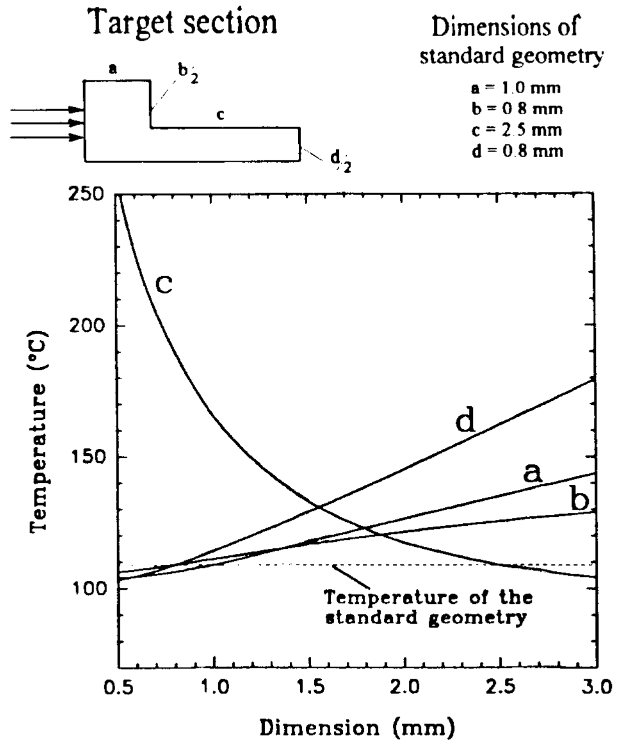

Fig. 7

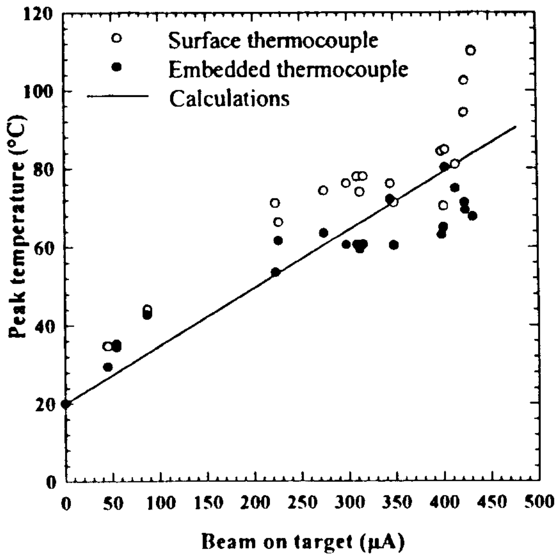

Fig. 8