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Abstract

Simulations of the power deposition and target temperature distributions in the SPIRAL ISOL target are presented. These simulations consider different heavy-ion beams with intensities corresponding to 2 and 6 kW on a carbon target. A new solution, which corresponds to the splitting of the production target into two parts, where the first is cooled and the second is heated, allows keeping the overall size of the target ensemble relatively small. An extrapolation of the considered target geometry to primary beam intensities up to 1 MW is also presented.

1 – Introduction.

The SPIRAL project [1, 2] is dedicated to the production and acceleration of radioactive ion beams by the ISOL "Isotope Separation On Line" method. The primary heavy ion beam is delivered by the two Separated Sectors Cyclotron (CSS) of GANIL with intensities corresponding to a power varying from 400W to 6kW (THI project [3]) at a maximum energy of 96.A MeV. As the primary beam varies between C and U, projectile fragmentation is used as production mechanism, thereby allowing the use of the most resilient and efficient production target for most cases. The production target [4] in the first phase of the SPIRAL project is of carbon graphite, which correspond to a relatively easy and general solution for most of the beams requested for the commissioning phase. The target-ion source ensemble is placed in a well-shielded area underground the GANIL accelerator building. In order to have high diffusion efficiency, it is crucial to have uniform high temperature distributions (2400 K) of the target while not destructing it, and a sliced structure [5]. These constraints, together with the strong peaked stopping power distribution of heavy ions in the matter, defined an optimal conical shape of the target, cf. figure 1. The opening angle of the conical part of the target is, in principle, specific to each primary beam, depending on the stopping power function. The radioactive atoms produced by nuclear reactions are released from the target, pass through a transfer tube and are injected into an ECRIS (Electron Cyclotron Resonance Ion Source). The radioactive atoms are then ionised up to charge states corresponding to the ratio q/m from 0.09 to 0.40, corresponding to the accepted range of the cyclotron CIME (Cyclotron for Medium Energy Ions). After extraction from the ECRIS, the low energy RIB are selected by a relatively low-resolution separator R = 250 and injected into the new K=265 compact cyclotron CIME [6].

The aim of this paper is to present few designs of the SPIRAL ISOL target, which allows one to work from 2 to 6 kW primary beam power for a wide primary beam atomic number. We also present some examples of targets dedicated to very high power beam i.e. 100 kW to 1 MW.

2 - The target parameters.

On a previous publication [7], we showed the results of calculated temperature distributions of several targets using a code, which has been specially developed to simulate the temperature distribution inside the SPIRAL target, as well as the dynamic behaviour of the temperature as a function of time. This code is based on the numerical resolution of the temperature diffusion equation, as follows:

$$\rho C \frac{\partial T}{\partial t} - \mathrm{div}\,(k.\mathrm{grad}\,(T)) = q$$

Where ρ is the carbon density, C is the specific heat, T is the target temperature, k is the thermal conductivity and q is the heat source term, corresponding to an external heating system and/or the primary beam and the exchange radiation heating. The finite difference method is used for resolving numerically this equation. The results obtained with several different configurations of target and primary beam has been compared with measurements at GANIL and Louvain-la-Neuve in ref. [7]. The experimental results were in quite good agreement with the simulations and the general geometrical design of the SPIRAL target could be fixed.

The evaporation rate of the target material at high temperature is of paramount importance in considering the life-time of ISOL targets. Although the sublimation temperature of carbon is of the order of 3600K, the evaporation rate at lower temperatures can be very high. Therefore, the maximum temperature allowed to the target limits its life-time. In figure 2 we show the evaporation rate [4] (DASH) and the time to evaporate 0.5 mm of carbon (SOLID), corresponding to one of the slices of the SPIRAL target, as a function of the temperature. It is clear that the fragility of the target is largely enhanced if one of its slices is destructed. Therefore, we assume that the life-time of a target is driven by the time to evaporate one slice completely. Considering that the life time of the target should be of the order of one month, the maximum target temperature allowed at the warmest point of the target would be around 2400K. This maximum temperature constraints all parameters of the target.

In this paper we, first of all, show the behaviour of the SPIRAL target temperature distribution considering four main parameters, which are : The FWHM (Full Width at Half Mean) of the primary beam spot on the target, the beam rotation frequency, the cone half angle and the overall diameter of the target. These parameters are schematically represented in figure 3.

Let us take an example in order to illustrate the effect of these parameters on the target temperature distributions. The parameters in the Table 1 represent selected common conditions, which are used in the following simulations. Only one of these parameters are varied in the following studied cases.

The most stringent observable of the target design is the temperature at warmest point. Therefore, in the following examples we consider the effect of this temperature as a function of the half angle of the conical shape, beam rotation frequency and beam spot size.

Primary Beam		Target	
Ion	^{36}Ar	Half angle	8°
Power (kW)	2	Number of slices	50
E (A MeV)	96	Slice width	0.5 mm
Rotation frequency (Hz)	20	Distance between slices	0.8 mm
Gaussian beam size (FWHM)	7 mm	Diameter	19 mm

Table 1 : Target Parameters for a common case

The first studied parameter is the cone half angle, which is used in order to spread the stopping Bragg peak power over a large volume. The temperature at the warmest point increases with this parameter (Figure 4) until reaching a saturation at a half angle of 60°. If we choose 2400K as the maximum allowed temperature of the warmest point of the target, we should take the half angle value as 8°.

The second studied parameter is the rotation frequency. Figure 4 shows the behaviour of the temperature when the frequency increases from 0.1 Hz to 100 Hz. Three frequency ranges stand out from this picture. The first corresponds to the frequency range between 0.1 Hz up to 1 Hz, where the temperature decreases quickly from •2900 K down to •2500 K. The second range stands between 1 Hz and 10 Hz, where the temperature reduction is slower than in the former case. At frequencies over 10 Hz we observe that the temperature of the warmest point is practically constant. The plotted temperature in figure 5 represents the average value in the steady condition, i.e. after an equivalent infinite time. We should also pay attention to the short temperature fluctuations due to the rotating beam. At 20 Hz, the fluctuations are relatively small (smaller than a few percent) when compared to the target average temperature. These fluctuations correspond to 25 K at the beginning of the heating at low temperature and 66 K when the stability is attained (figure 5). The overall rise time is about 20 s for reaching 90% of the final temperature.

The temperature of the warmest point of the target, as a function of the FWHM size of the beam, is presented for a primary beam with a Gaussian shape in Figure 4. The temperature variation is approximately of 100 K per mm. Indeed, if the beam is too wide, a percentage of the beam power can be outside the diameter of the target and is lost The best size of the beam in these conditions is of the order of 7 mm (diameter).

It is also important to include in the final target design an external heating system of the target, which would furnish auxiliary power. First of all, it is crucial to degas properly the target ensemble before the irradiation, in order to avoid loading of the ion source during the on-line operation. Secondly, the heating system can, eventually, compensate a missing of primary beam power on the target. Therefore, the optimal target temperature, in terms of diffusion, could be guaranteed. For example, if our calculated "2 kW target" of table 1 receives only 1 kW of beam power, the warmest point of the target decreases 300K, which corresponds to a loss of diffusion efficiency from 70% to 40% for the radioactive nucleus ^{35}Ar ($T_{1/2}$ = 1.775 s). If one consider a shorter life time isotope, this efficiency decreasing is even more dramatic. The target design includes an external heating by an Ohmic current through the target axis.

3 - 2 kW and 6 kW target simulations

In a first step, SPIRAL will receive a maximum intensity of the primary beam corresponding to 2 kW. Two simulations of the temperature of targets dedicated to the production of radioactive isotopes of neutron deficient noble gases are presented in the following. The two primary beams used in these calculations are : ^{20}Ne (95 A.MeV) and ^{78}Kr (73 A.MeV) (figure 6). One can note that in a wide range of the target, mainly where the primary beam ions stop, the temperature is homogeneous and around 2450K. It is interesting to note that the difference on the range of neutron deficient isotopes produced by projectile fragmentation compared with the range of the primary beam is small. The homogeneity at high temperature in this zone is important in order to fasten the diffusion time of the radioactive atoms from the target. The parameters of the two targets are almost the same. Both targets have been calculated with 50 slices, and a maximum diameter of 19 mm. The primary rotating beam with a frequency of $f = 20$ Hz has a FWHM size of 7 mm positioned at 4.5 mm from the axis. The only difference between the two targets originates from the cone half angle, which is of 10° for ^{20}Ne and 8° for ^{78}Kr primary beams. The solution with a half cone angle of 8° can also be used for ^{36}Ar primary beam, giving a temperature of the warmest point of the target of 2400K (Table 2).

The optimisation of the geometrical parameters of the SPIRAL target for a primary beam power of 6 kW demands an enhancement of its dimensions. We are limited, however, by a maximum size of the target container, which is defined by 9.5 mm of length and 42 mm of diameter. This maximum dimensions fixes the size of the target-ion-source ensemble, which should fit inside a lead container (dimensions and weight) when removed from the production cave. We have fixed a maximum target diameter of 38 mm and a maximum target length of 9.4 mm. The width of the slices in the case of 6 kW primary beam power has been also slightly changed to 0.7 mm (instead of 0.5 mm) and spaced by 1.3 mm (instead of 0.8 mm) due to machining constraints. A simulation using a ^{20}Ne primary beam with FWHM of 16 mm, placed at 8.5 mm from the axis is shown in figure 7. In this simulation, we assumed an « effective » sublimation temperature of 2400K for the carbon. The effect of this assumption is to simulate the picture of the target after approximately one month of functioning. This is equivalent to consider a very long evaporation time of the carbon, which would induce the formation of a hole in the centre of the target. This hole is observed in this simulation and corresponds to the black zone around $z = 60$ mm. In this case, 18 carbon slices have been evaporated in the target. Concerning the simulation, the situation shown in this picture is stable, i.e. the hole does not increases any more, since the maximum temperature in the target is smaller than the effective sublimation temperature, fixed at 2400K. On the other hand, the target can be considered as destructed. As a matter of fact, the highest temperature inside the target before the hole formation was very high ($T > 2600$K). This assumption, allows us to estimate the evolution of the « hole formation » inside the target as a function of time. From calculations, we deduced that the hole appears approximately after 8 hours of irradiation. As a matter of fact, no solution could be found in order to avoid a hole in the target within the geometrical constraints.

Primary beam	Primary beam power (kW)	Cone half angle (°)	Highest temperature (K)
^{20}Ne	2	10	2353
^{36}Ar	2	8	2400
^{78}Kr	2	8	2400

Table 2 : The highest temperature inside the 2 kW Ne, Ar and Kr targets.

One simple solution of the problem is the use of a system with two separated targets. This "trick" is possible in the case where the main nuclear process for radioactive nuclei production is projectile fragmentation. Within this production picture, the quasi-projectile fragments are ejected from the first production target and stopped on the second one. Therefore, we can dissipate part of the primary beam power in a first target, which can be cooled. The production process takes place in both targets, but only the second one acts as a diffusing matrix for the radioactive releasing. We found, in our case, an optimum sharing of the overall power dissipating 1.5 kW in the first target and 4.5 kW in the second one. The angular straggling due to the first target is of the order of some milliradians at these energies (95.A MeV), which means that if we would keep a short distance between targets (of around 130 mm in the SPIRAL case), no significant loss would be observed.

The radial temperature distributions of a first Pyrolitic carbon target cooled by an external water system are shown in figure 8 for ^{20}Ne and ^{36}Ar primary beams. The warmest point on this target is 1000K and 1800K for each case. The temperature distribution on the second target is shown in the figure 9 for the ^{20}Ne case. We adopted the same « effective » sublimation temperature as on the latter case, i.e. 2400K. We can see that a very small hole appears after one month of irradiation.

There are many interesting features of this solution. The first one is its flexibility, because one can choose the nature of the first production target independently of the diffusion characteristics of the second one. An example is to use Pyrolitic Carbon, which has good thermal conductivity in one axis, and, consequently, can be well cooled. This material can be used in the production target and not in the diffusing one [9]. Another possibility is to use Be targets or Liquid-Li in order to optimise the production of the radioactive quasi-projectile. It should be noted that the power-sharing ratio could be defined almost freely, only respecting that the interesting radioactive nucleus should be stopped on the second optimised diffusion target. This kind of solution can easily be used on second generations RIB projects, if a Heavy-Ion driver is used.

4 – High power primary beams.

Following the scheme presented on the preceding session, one could imagine to extend the technique of splitting targets for higher power primary beams. It is clear that this solution is only useful in the case where a Heavy Ion Driver is used. The goal of these calculations is only to show the size of a hypothetical second target, used for diffusing the radioactive produced elements, in such a case.

It is important to note that if one would be looking for the production of lighter atomic number radioactive fragment, the ideal solution would be to stop completely the primary beam on the first cooled target and use the second one exclusively as diffusion matrix. This case is not considered in this paper.

We concentrate our simulations in the case of a ^{20}Ne – 95A MeV primary beam with 300 kW and 1 MW power. In both cases we adopted that 60% of the power is dissipated in the first cooled target and 40% in the second one. This power sharing has been conditioned by the range of all neutron deficient Ne radioactive atoms, produced inside the first target and stopped in the second one. This is the most stringent condition for this configuration. In all other cases, i.e. for residues with lighter atomic number, the range of the corresponding fragments would be larger than the one of ^{20}Ne.

After several different test calculations, we converged to the conclusion that the better target configuration, which matches the requested constraints, corresponds to a parabolic surface shape bombarded by a flat beam profile. In figure 10 we show the temperature profile of a diffusion target which receives 40% of a total beam power of 300 kW and 1 MW. We would like to point out that the temperature distribution around 50 mm of the Bragg peak spreads between 2000 and 2435 K. The diameter of the target is 260 mm and 500 mm for the 300 kW and 1 MW beam power, respectively.

A possible implementation of such large target inside a container is proposed in figure 11 The opened container around the target should ensure an excellent conductivity for the radioactive species. A funnel-shaped structure conducts the radioactive atoms to the ion source directly.

6 - Conclusion

The temperature distribution of ISOL production target has been studied in the framework of the SPIRAL project. A compromise between target life-time and radioactive atom diffusion constrained the optimal operating temperature. The warmest point target temperature should be around 2400 K in order to allow a target life-time greater tan 2 weeks. Within this condition, two kind of targets have been presented. The first one for 2 kW total power of the beam, consisting of a single target with a conical shape. This kind of target is well suited for any primary beam and its temperature distribution is quite homogeneous. The second solution presented concerns the 6 kW primary beam power. In this case and due to the limited volume fixed for the target, a splitting of the production target into two parts has been proposed. This new configuration allows one to cool the first target while heating the second. It is a well suited solution if one consider the projectile fragmentation process as the most important in this energy range.

An extrapolation for the next generation ISOL based radioactive beam facilities is presented for 300 kW and 1 MW total beam power. It is shown that a double target configuration with a parabolic diffusion target shape (second one) can be used in both cases. It is clear that, due to the size of the target, a study should be performed in order to optimise the transport of the radioactive atoms to the ion source.

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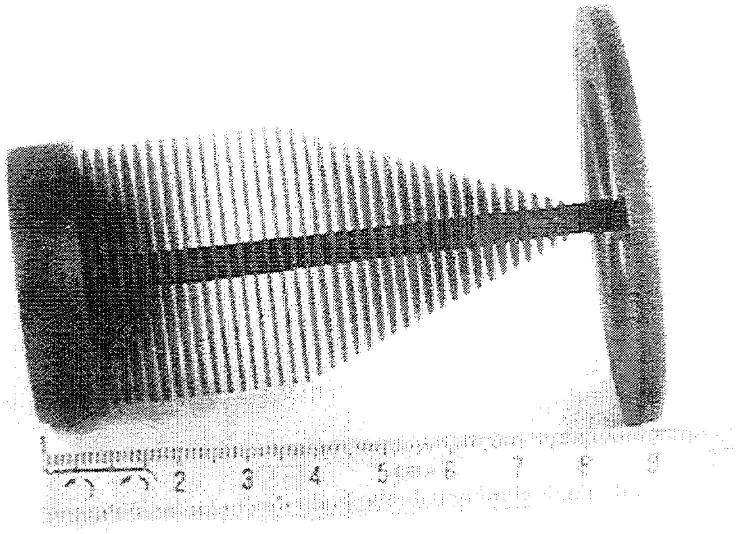

Figure 1 : Photo of the target

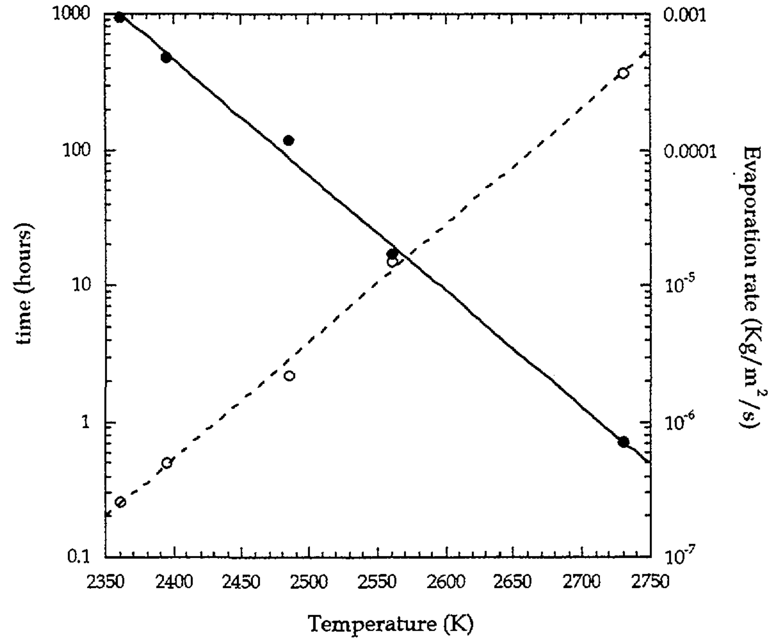

Figure 2 : Destruction time of a carbon slice of 0.5mm and evaporation rate of the carbon as a function of the temperature.

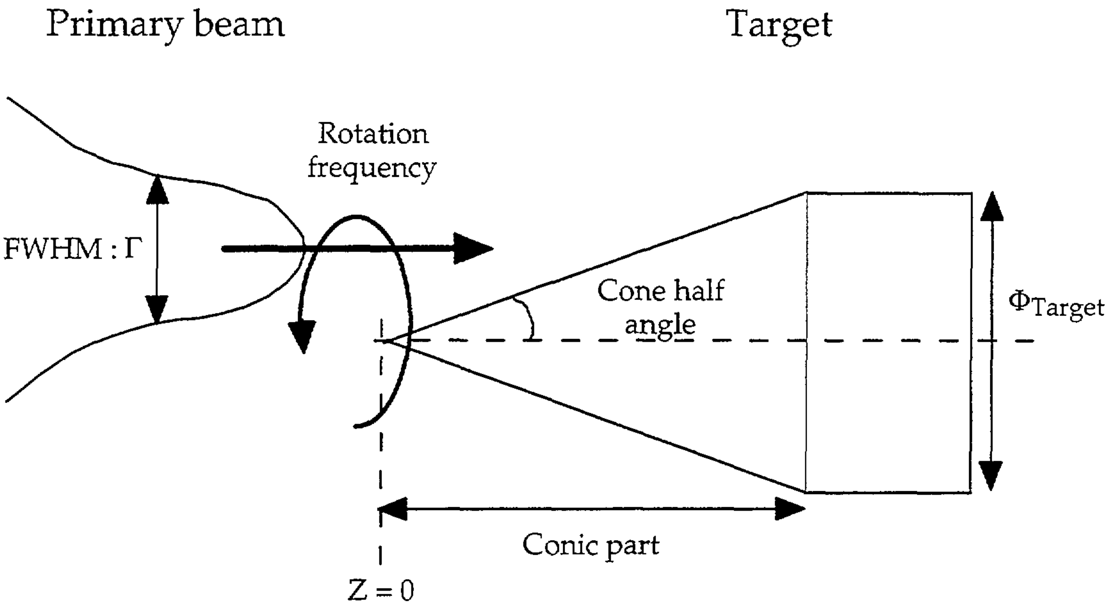

Figure 3 : Parameters of the couple Target/Primary beam

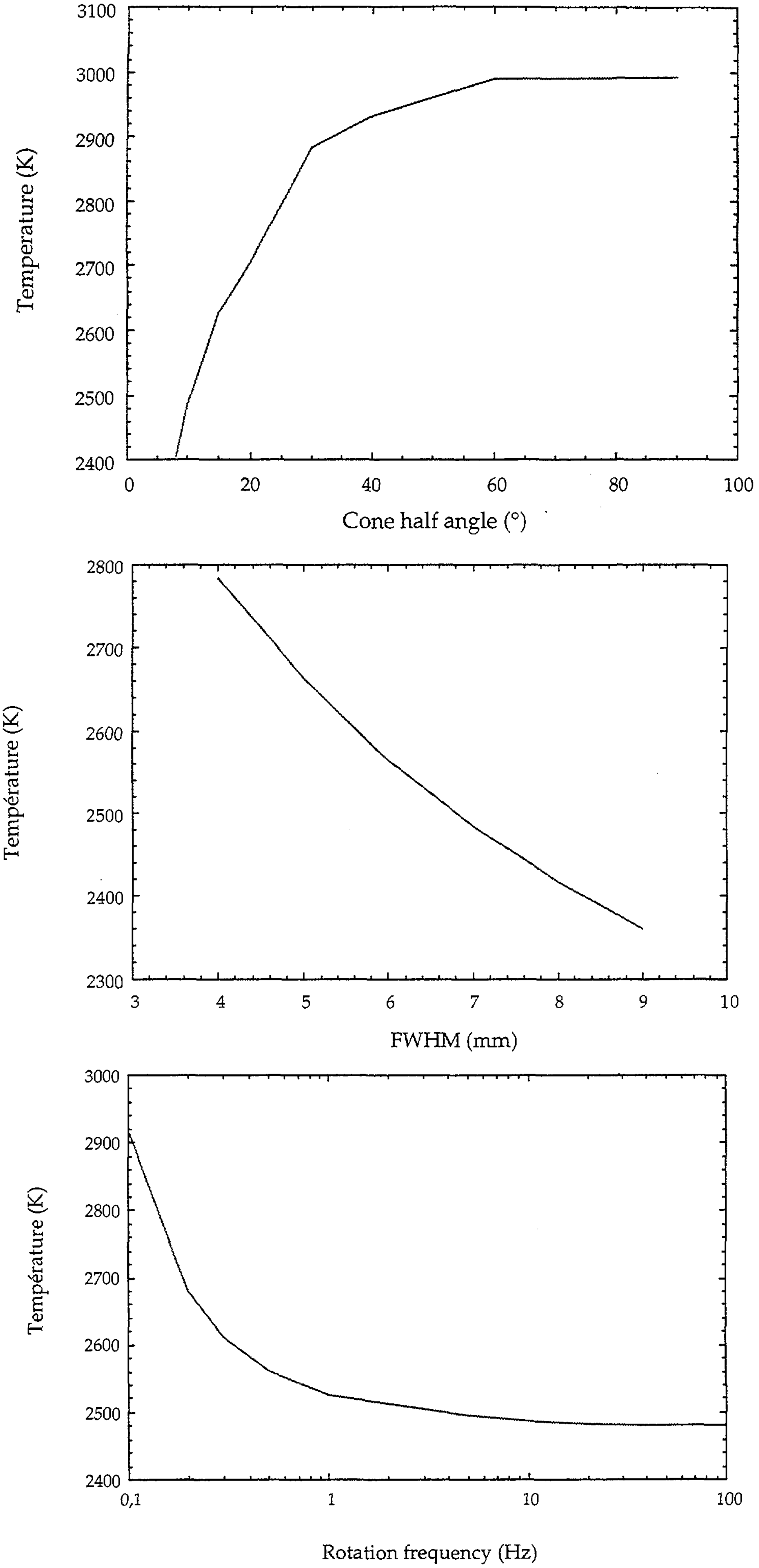

Figure 4 : Temperature of the warmest point of the target as a function of half angle, rotation frequency and FWHM of the primary beam

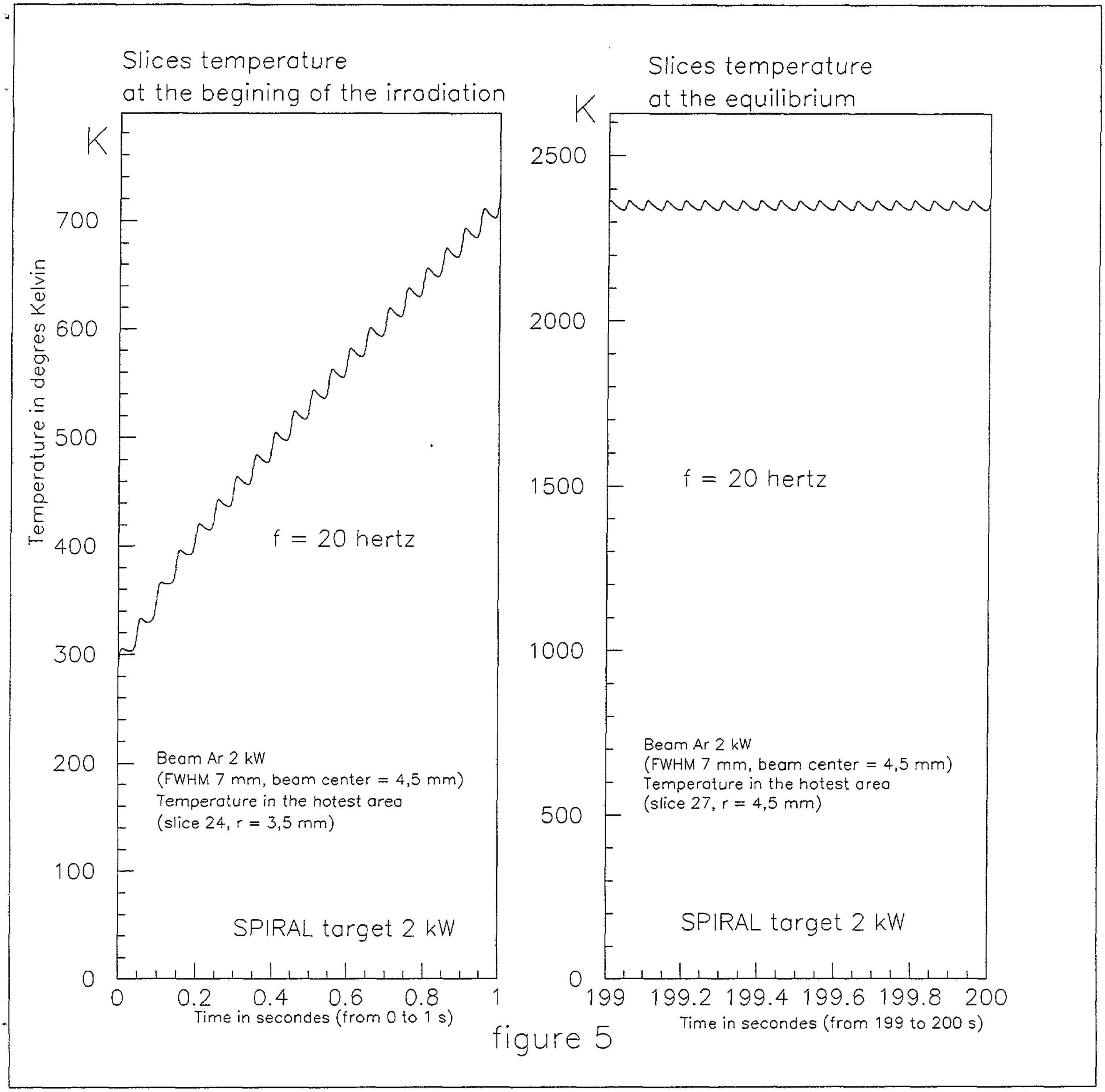

Figure 5 : Temperature fluctuation around the average [6]

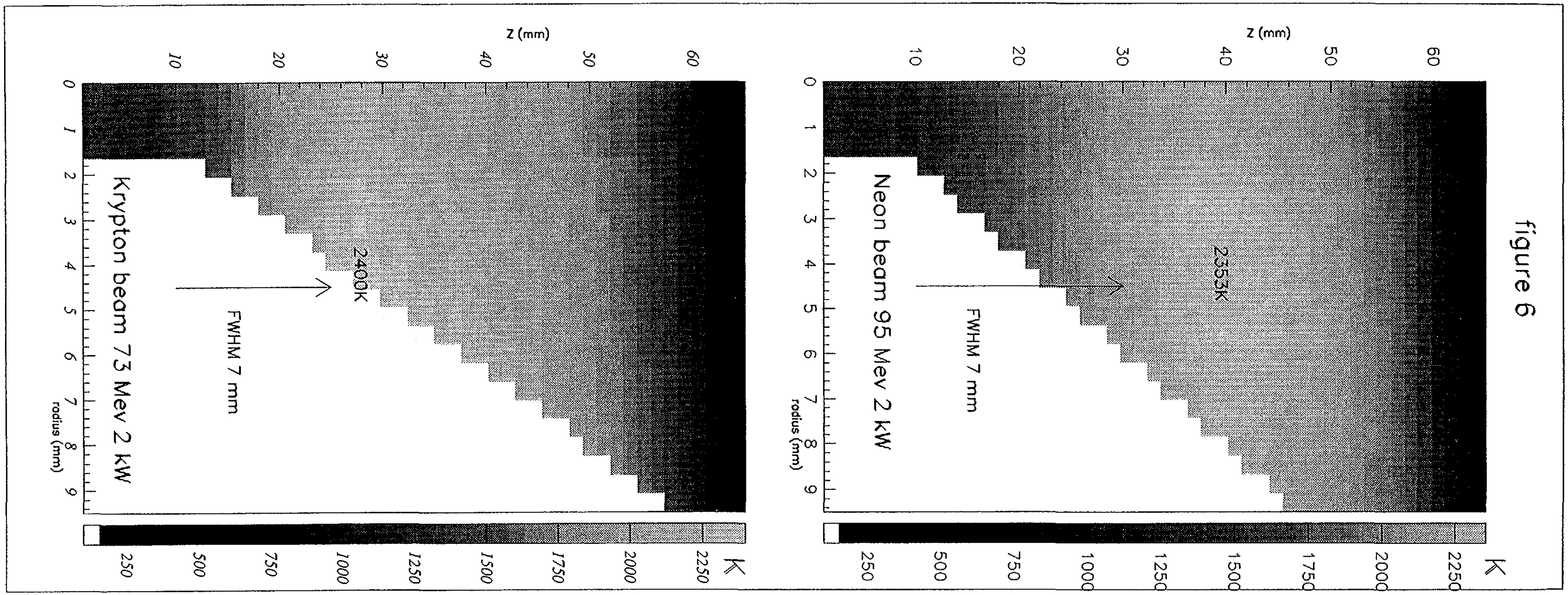

Figure 6 : Temperature distribution for the target dedicated to the Ne and Kr rich-proton isotopes production (2 kW case)

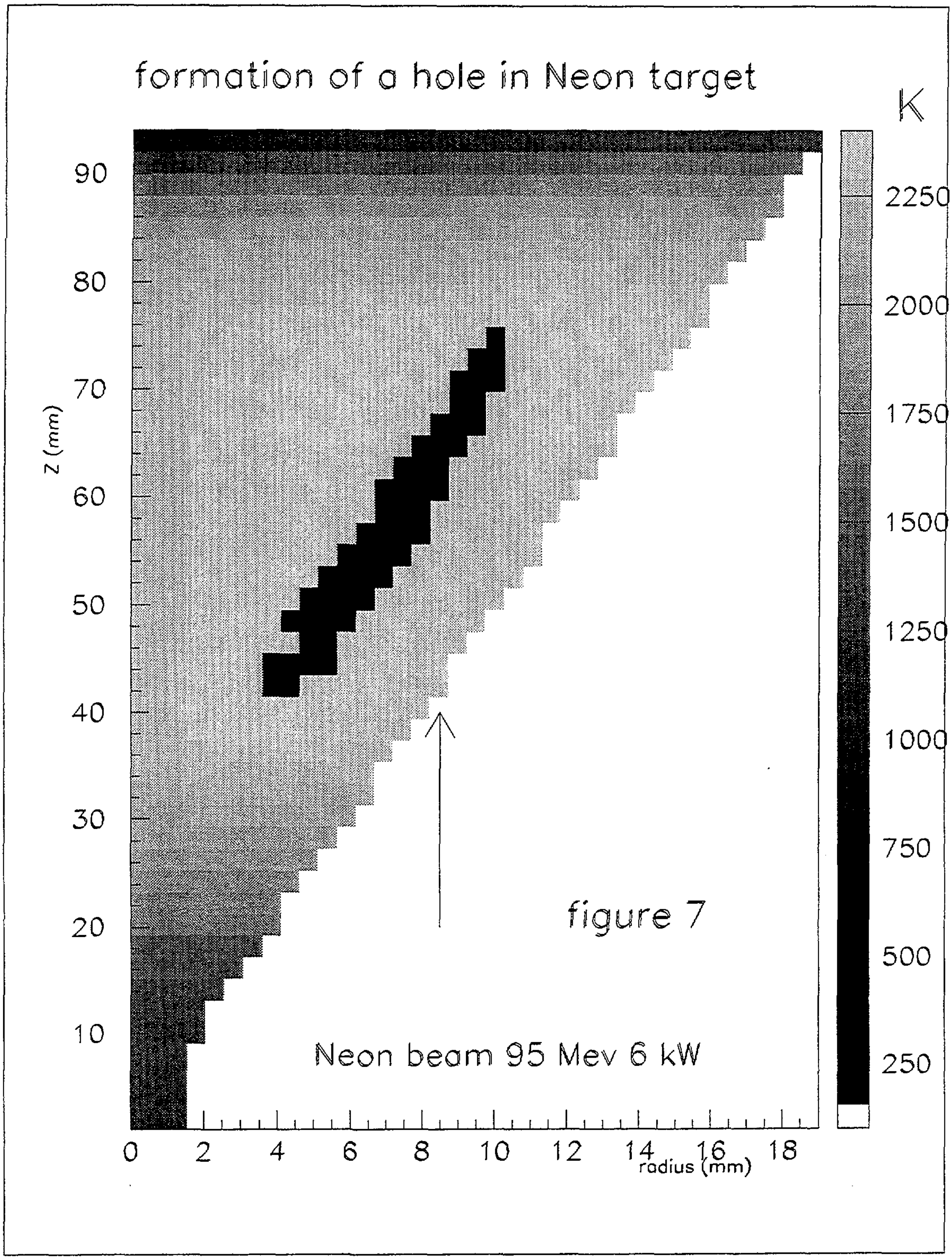

Figure 7 : Hole inside the target dedicated to the Ne rich-proton isotope production (6 kW case)

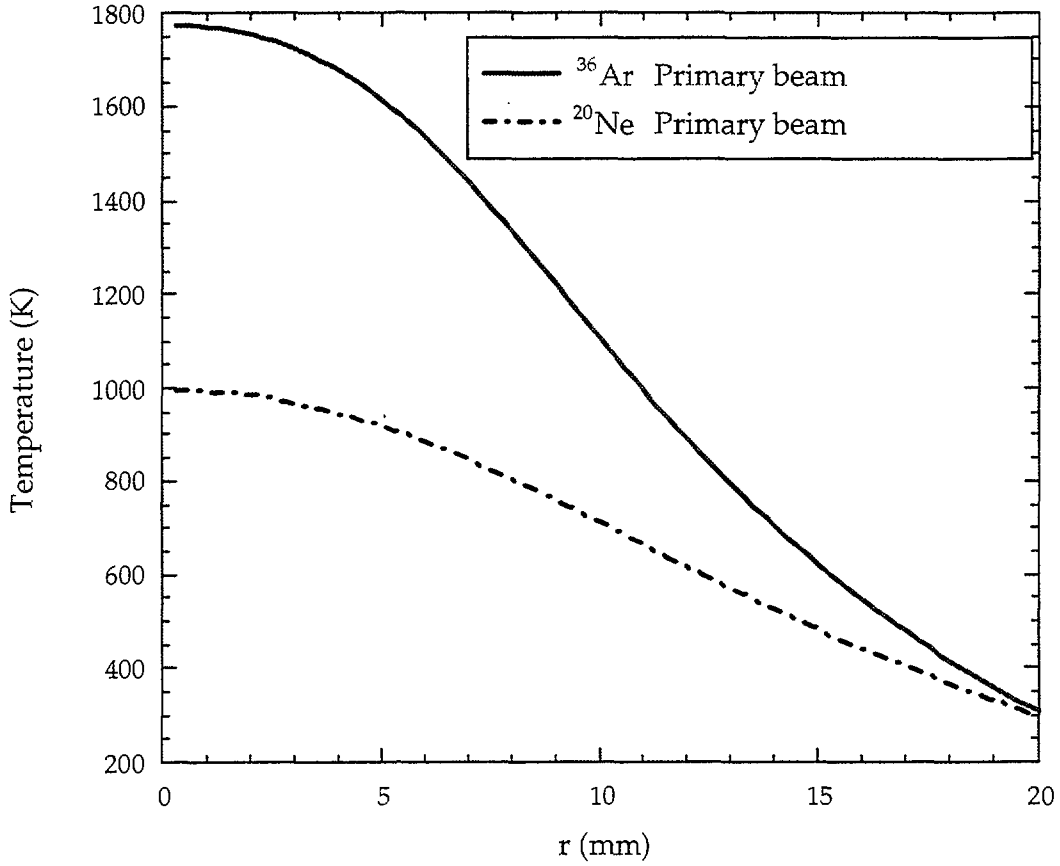

Figure 8 : Temperature distributions in the first targets

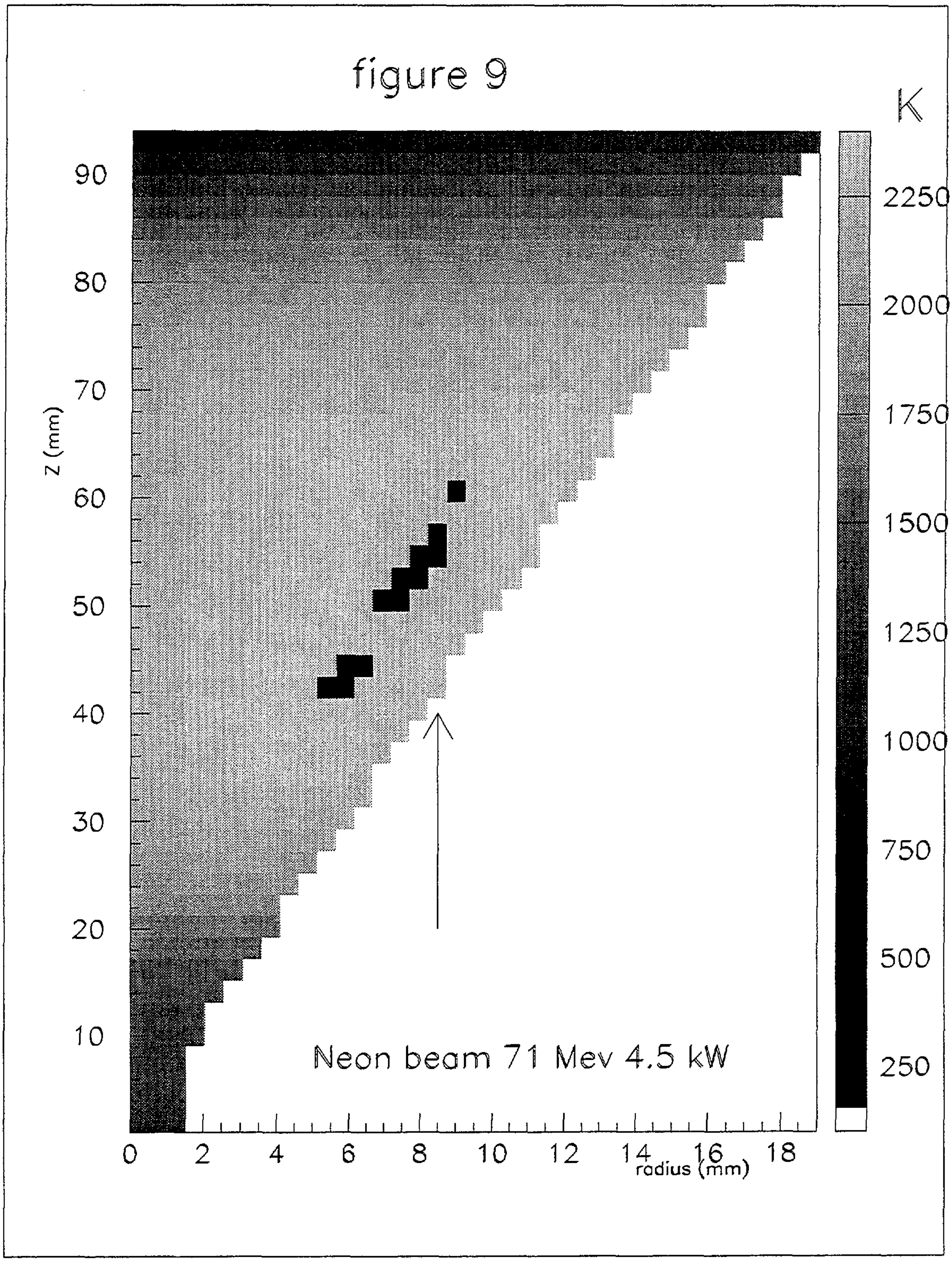

Figure 9 : Temperature distribution in the second target the target dedicated to the Ne rich-proton isotope production (4.5 kW case)

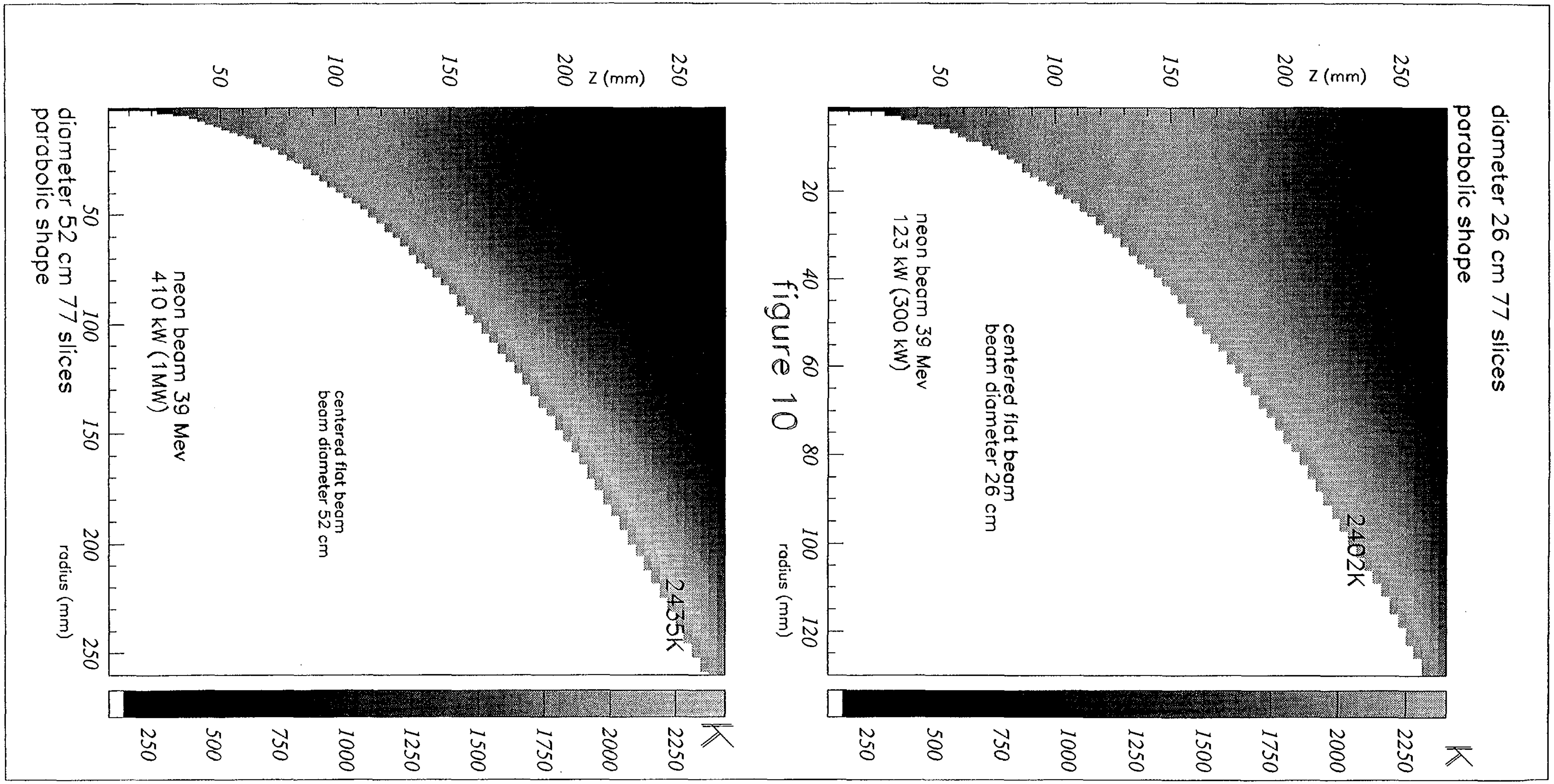

Figure 10 : Temperature distribution for the target dedicated to the Ne rich-proton isotope production (300 kW case and 1000 MW case)

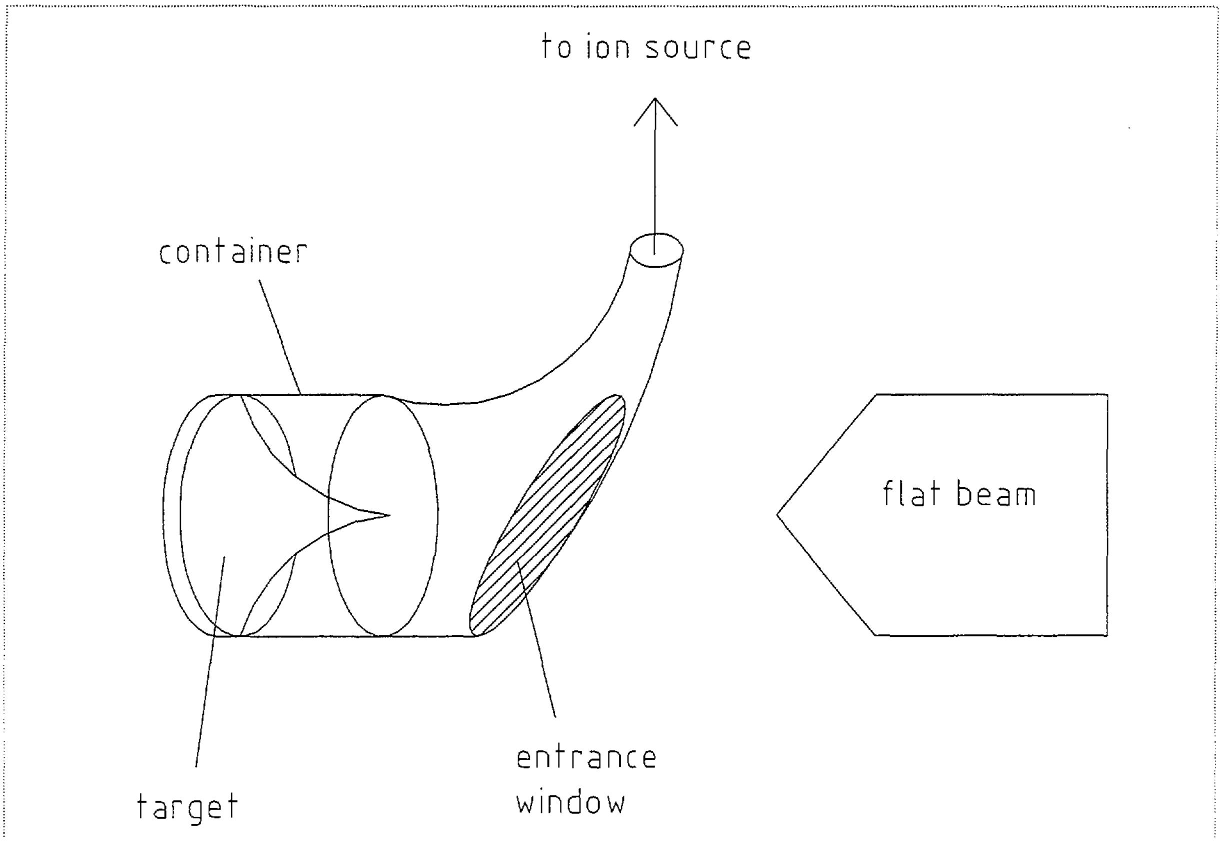

Figure 11 : Picture of the high power target container