Journal of Nuclear Materials 377 (2008) 290–297

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

An innovative target for the RACE HP experiment

P. Agostini [a], M. Ciotti [b,*], C. Krakowiak [d], C. Petrovich [c], G. Benamati [a], A. Bergeron [e], N. Elmi [a], G. Granget [d], L. Sansone [a], M. Schikorr [f]

[a] ENEA CR Brasimone, 40032 Camugnano, Bologna, Italy
[b] ENEA CR Frascati, Via Enrico Fermi, 40, 00044 Frascati, Roma, Italy
[c] ENEA CR E. Clementel, Via M. M. Sole, 4, 40129 Bologna, Italy
[d] CEA Cadarache, 13108, Saint-Paul-Lez-Durance cedex, France
[e] CEA Saclay, 91191 Gif-sur-Yvette, France
[f] FZK Forschung Zentrum Karlsruhe, Germany

A B S T R A C T

In the RACE (reactor–accelerator coupling experiments) project, a series of ADS (accelerator driven system) experiments are envisaged for the study of the coupling of a neutron source with sub-critical reactors. In these experiments, a continuous electron beam impacts on an actively cooled solid target where it is converted through photonuclear reactions in a neutron flux, able to feed the reactor. In a RACE foreseen 'high power' phase, where the beam power would be enhanced from 1 to about 30 kW, the target would be submitted to very severe conditions both from the mechanical and the thermal points of view. In this paper, the development of a new concept of uranium target is described with detailed neutron production analyses, power deposition distributions, thermo-mechanical simulations and cooling schemes. Two possible solutions are envisaged in order to control the power deposition distribution.

1. Introduction

In the framework of the ECATS activities (experimental activities on the coupling of an accelerator, a spallation target and a sub-critical blanket) of the 6th Framework Program, a series of target designs have been completed for fast neutrons production in sub-critical TRIGA reactors, both through proton spallation process (for the TRADE experiment [1,2]) and photo production process by the impact of an electron beam (25 MeV), carrying an approximate power of 30 kW, onto a target made of high Z-material (RACE experiment [3]). The electron/neutron approach is justified by a considerably lower investment cost for the electron accelerator with respect to the proton accelerator, even if electrons provide a lower conversion efficiency that implies a more complicate target design. The present study deals with a hollow cylindrical target concept through an axial-symmetric geometry for electron–neutron conversion. The goal of the design is to reach the highest neutron production given the fixed electron accelerator. Two possible solutions are hereafter analyzed and compared: the power is spread onto the internal target surface by a diffusion disk or it is distributed by a beam rastering system. The concepts are analyzed in terms of neutron source, cooling performances and fabrication. The cooling circuit, being independent on the target concept, is treated separately. The dimensions of the target and its cooling circuit will be limited by the geometrical constraints of the existing reactor cores.

2. Target concept

The total neutron source depends on the electron beam (power, particle energy, profile), on the target material and on the target geometry. A fully correct evaluation should consider also the core geometry and the coupling with the core. Nevertheless, for a preliminary design, only the in-target neutron yields and the neutrons escaping from the target geometry are here calculated. Approximate photo-neutron evaluations for infinitely thick targets of different materials at different beam energies, are published in literature [4]. Even if these values do not take into account the detailed target geometry, the beam profile, the neutron induced fissions and the neutron absorptions (only a transport code can take into account all these effects), they still provide useful information on how the neutron production changes according to the materials and the beam energy. The accuracy of these data is quoted to be within 20% [4].

The planning constraints come out from the geometrical links due to the possibility to insert the target into the centre of a TRIGA core. Moreover, the target total length has to be limited to 31 cm, while its overall external diameter has to be within 10 cm. The best results can be achieved by the use of pure uranium as target

* Corresponding author.
E-mail address: marco.ciotti@frascati.enea.it (M. Ciotti).

0022-3115/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2008.02.092

material that is the only one that assures, at least theoretically, an acceptable neutron production for the experiments on the ADS dynamic behaviour [5].

The disadvantage of this material is in the necessity to use a cladding to avoid contact with the cooling liquid, for radiation safety. Moreover uranium and cladding impose to consider a simple shape for manufacturing toughness: the concept of distributing the power onto the target by inclining the inner surface, as in the conical solution developed for the TRADE project [6], cannot be further followed. Even the surface optimization [7], leading to a uniform heat flux is no longer achievable, because it would require a too complex surface to be realized. This would be out of the possible machining accuracy for U, too difficult to be clad and with a very delicate beam positioning control, because of the reduced temperature margin.

The easiest shape that can be thought of is a hollow cylinder (.1) that has also the additional advantage to offer an internal surface that is double with respect to a conical shape. At this point, the problem is how to spread the beam onto the internal surface. Two possible solutions have been analyzed: a diffusion window and a rastering system.

3. Diffusion window

The diffusion window has to fulfil two different requirements: assure an acceptable diffusion of the particles and remove the heat released in the material itself. The first requirement addresses towards a significant thickness and a high Z-material. The second one, since the heat production is proportional to the amount of matter, requires a small thickness and low Z-material.

MCNPX scoping calculations have been performed to analyse the possible solutions in a quantitative way.

3.1. Plate type diffuser

Aluminium was initially thought to be a candidate, due to its high thermal conductivity and low Z, which makes it able to be cooled by conduction through its outer circumference, irrespectively of its thickness (Fig. 1). Unfortunately, simulations demonstrated that the diffusing property of Aluminium, even at several millimetres thickness, is very poor, and that the fraction of energetic particles impinging the inner surface of the hollow cylinder, becomes unacceptably low. On another hand, disks of Tantalum, or other high Z-materials, deviate the energetic particles even at low thickness, but can not be efficiently cooled by conduction at their external perimeter. A possible compromise can be represented by a Tungsten-alloy disk of 0.3 mm thickness cooled by thermal radiation only. An important feature of this solution is the avoidance of any conduction cooling, otherwise too intense thermal stresses would set inside the disk material. A further complication is represented by the non uniform profile of the beam which is more intense at its axis and weaker at the periphery, following a Gaussian law. This occurrence produces, in a flat disk, a significant stress concentration between the centre, which tends to expand, and the colder external crown, which prevents the expansion. For this reason, a specific 45° conical shape was proposed (Fig. 2).

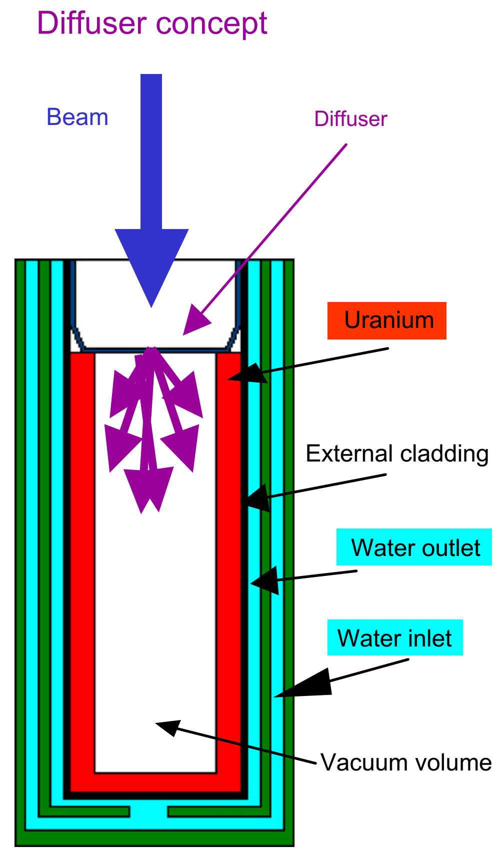

Fig. 1. Overall cylindrical target concept with diffuser.

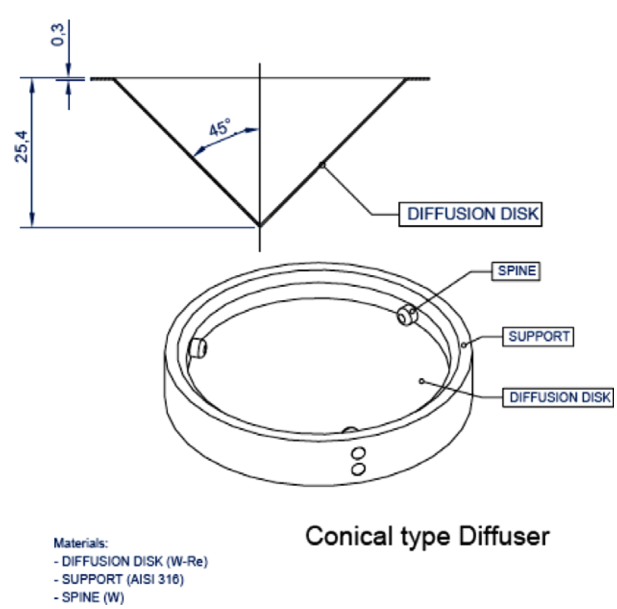

Fig. 2. Conical type diffuser.

3.2. Conical type diffuser

The thermo-mechanical calculations are reported in Figs. 3–5. In order to evaluate the thermo-mechanical results, an acceptability criterion was established: the maximum thermal stress of the structural parts must remain below the extended plasticity conditions.

The local plasticity is allowed, as far as the ratcheting risk is avoided, and as far as the thermal fatigue allows sufficient lifetime for the target.

The pictures show that the maximum stress (55 MPa) is located at about three quarters of the external radius, in a region whose temperature (1470 K) is ordinarily well tolerated by refractory metals. Conversely, the hottest region at the centre of the window

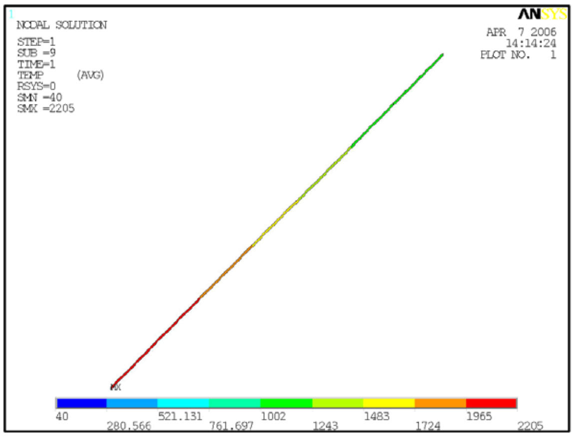

Fig. 3. Temperature distribution of the conical diffuser.

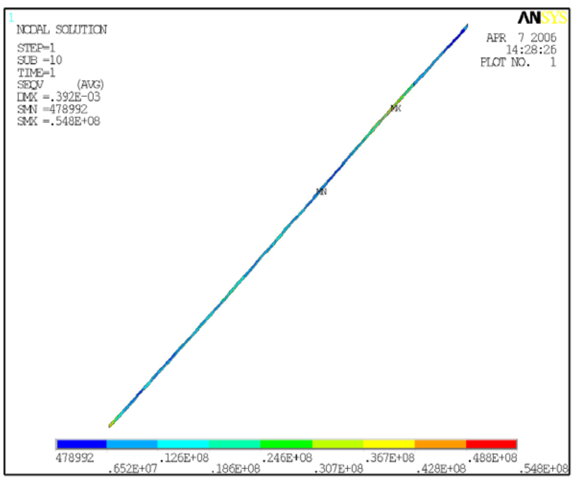

Fig. 4. Von Mises stresses of the conical diffuser.

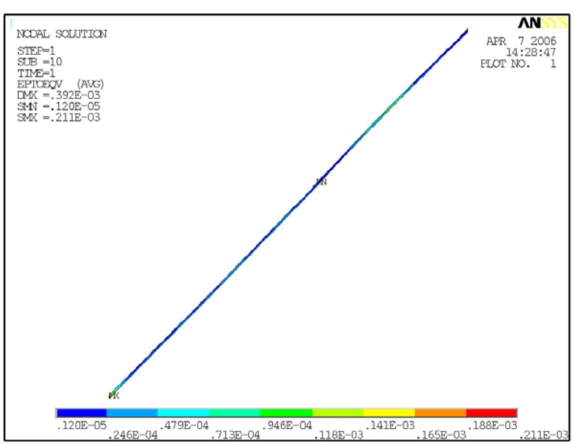

Fig. 5. Thermal deformation of the conical diffuser.

(2470 K) is extensively stressed at a low value (12 MPa) and only locally, at the very centre, at a higher value (36 MPa).

The creep resistance data of the selected W-alloy (W-23.4Re-0.27HfC) [8] allows us to evaluate the life time of the window in this region at approximately two months. Nevertheless, after the initial plastic deformation (only 0.22% according to the calculations), the thermal stress would be reduced and mainly the weight and the pressure forces (primary loads) would affect the creep

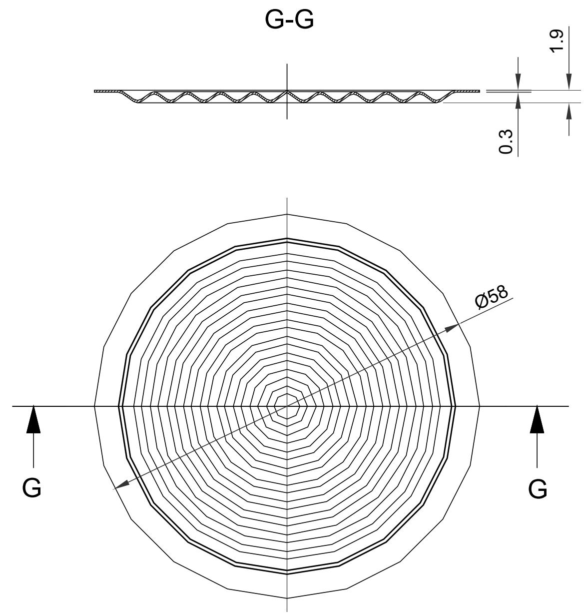

Fig. 6. The bellow-type diffuser. Side and top view.

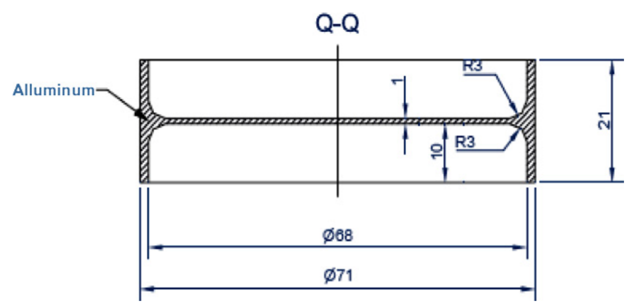

Fig. 7. Aluminium protection window.

resistance. In order to allow an acceptable life span, the volume inside the hollow cylinder has to be evacuated at approximately the same pressure value of the beam line. The encouraging results, from the thermo-mechanical point of view, of the 45° inclined diffusing window, suggested a bellow-type window as an alternative configuration (Fig. 6). In order to avoid any risk to contaminate the accelerator and the beam line by uranium vapors in case of failure of the diffusing window, an aluminum protection window is added (Fig. 7).

4. Target thermo-mechanical evaluations

Full transport calculations have been performed by means of MCNPX [9] together with the data libraries LA150u and BOFOD for the description of the photonuclear reactions (both of them are collected in the IAEA report [10]). All the MCNP simulations are here performed at the beginning of life of the target and without the contribution of the TRIGA neutron flux to the target heating. In a tantalum target, this contribution has been evaluated to be about 3% of the power deposited by a 40 kW proton beam [11]. In a depleted uranium target, this contribution has been checked to be also a second order effect with respect to the power released by the electron beam (the TRIGA reactor has a thermal neutron spectrum and, according to MCNP, the number of fissions of 238U in a critical configuration is about 300 times lower than the number of fissions of 235U). The power deposition results,

Table 1
Sharing of the deposited power for a 30 kW and 20 kW impinging beam

	Power deposited (30 kW, 25 MeV beam)	Power deposited (20 kW, 25 MeV beam)
Ta window	0.73 kW	0.49 kW
U cylinder	21.7 kW	14.5 kW
Bottom U plate	6.0 kW	4.0 kW
Others	0.4 kW	0.3 kW
Total	28.8 kW	19.2 kW

obtained for a fixed Gaussian electron beam ($\sigma_x = \sigma_y = 1$ cm) impinging on a tantalum plate of 0.3 mm in thickness, are shown in Table 1 and Fig. 8. About 20% of the impinging beam power is deposited on the bottom plate.

The power density distribution shown in Fig. 8 was used as input data to evaluate the temperature and thermal stresses fields inside the target uranium body by the means of Cast3M [12], assuming a convection heat exchange coefficient of 15000 W/m^2/K on the outer surface.

This preliminary study shows that both the considerable power fraction towards the bottom plate and the uneven power distribution along the target lateral wall (Fig. 8), result in a non-optimized situation.

First, the power density axial profile induces a high bending stress state in the upper part of the uranium cylindrical wall, as shown in Fig. 9. This result leads to a careful selection of the wall thickness, which could be reduced without affecting too much the neutron production: decreasing the thickness from 15 mm to 10 mm, the neutron source is lowered by only 2%. This is due to the electron-target grazing incidence angle resulting in a quite long path even for small wall thickness.

Second, the power deposition peak in the bottom part (Fig. 8) has two main effects:

- The differential thermal expansion between the cylindrical body and such a massive bottom plate causes strong material deformations at their junction, as shown in Fig. 10. The proposed solution is to disconnect the cylinder from the plate on the one hand, and to optimize the shape of the bottom part on the other hand, in order to improve its cooling.
- The neutrons produced in the target bottom are probably weakly coupled with the reactor core, decreasing de facto the overall conversion efficiency.

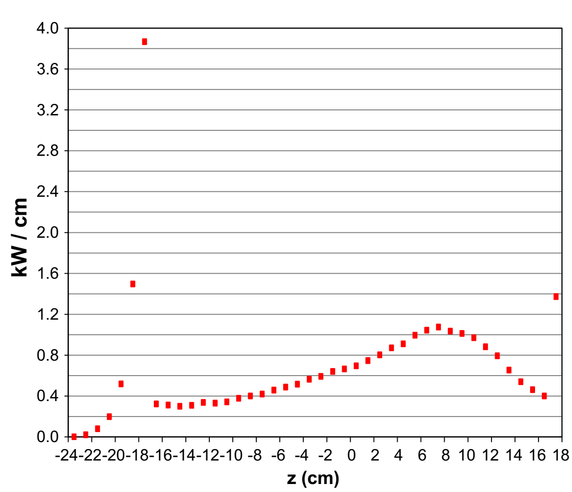

Fig. 8. Power deposition per unit length (30 kW beam) along the cylinder lateral wall. The beam is coming from the right side of the plot at $z = 18$ cm, where the diffuser is located; the bottom plate is at $z = -18$ cm, in correspondence of the power peak.

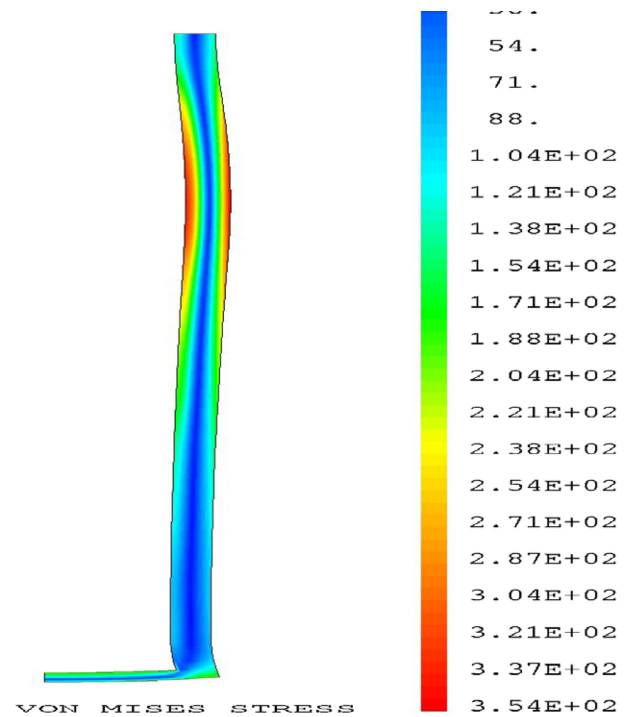

Fig. 9. Von Mises stress for half cylinder.The power density profile will induce high bending thermal stresses in an 8 mm thickness cylindrical wall (about 350 MPa).

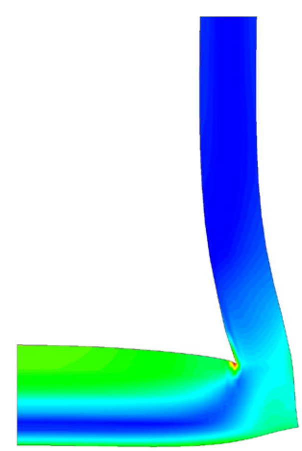

Fig. 10. The junction between the plate (10 mm thickness) and the cylinder (8 mm thickness) will induce very high thermo-mechanical stresses (about 1100 MPa).

All the results obtained in the thermo-mechanical analysis have been taken into account in the target drawings, shown in Figs. 11 and 12. The chosen materials are: U for the target body, tantalum for the container, copper for the bottom plate and stainless steel for the cladding.

In the figures, the cladding that is needed to separate the external uranium surface from the cooling water, is shown. In the internal part, the cladding is not necessary; the diffuser itself acts as a separating surface between the target and the beam line. Further studies are needed to check the mechanical behavior of the cladding, and to select the best uranium-based alloy for neutron performance, fabrication aspects, and thermo-mechanical properties.

For safety reasons also, a thin aluminum separation surface can be added along the line. Due to the very low aluminum absorption coefficient, it is not a critical component.

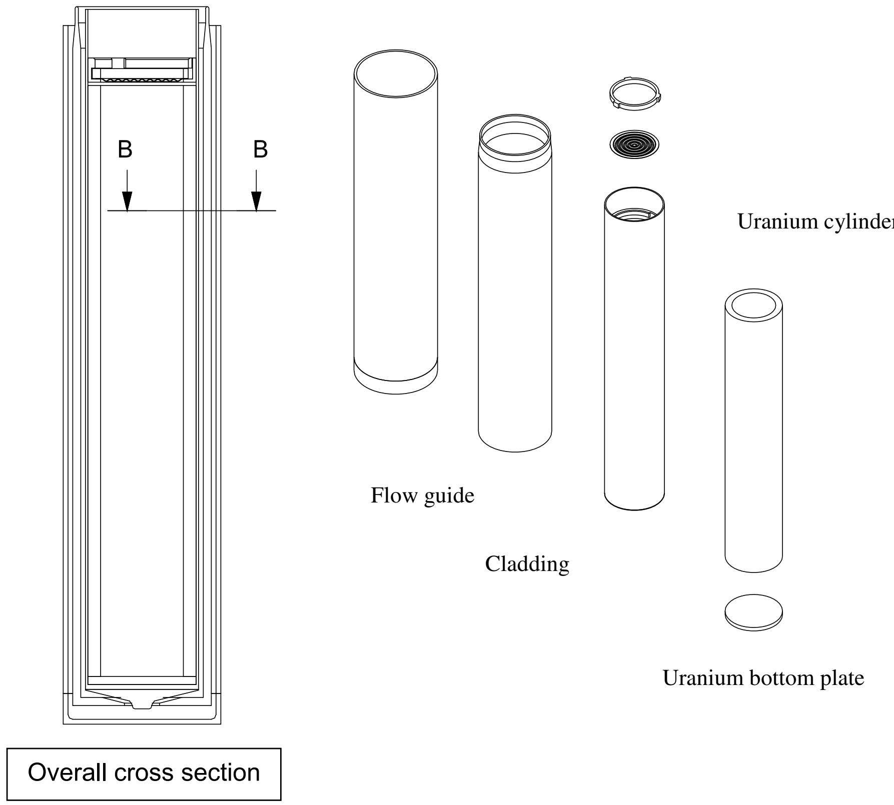

Fig. 11. Cross section and target nested surfaces explosion.

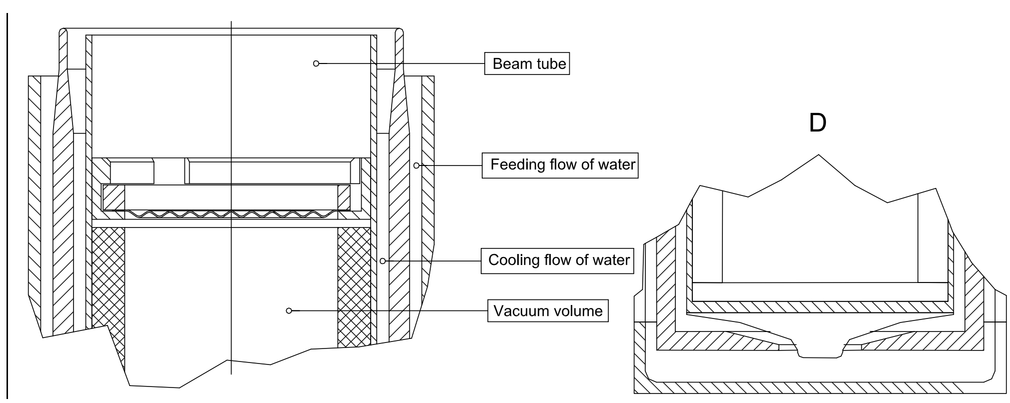

Fig. 12. Details of the target upper and bottom parts. The cooling scheme together with the materials thickness are shown.

5. Rastering system

The diffusion plate concept presents some critical points. The first one is that, even if the solution in its whole appears feasible, the neutrons created in the bottom plate (a beam power fraction of about 20%) are probably weakly coupled with the TRIGA reactor core.

This might lead to a difference between the produced neutrons and the really useful neutrons. The only way to obtain a simple surface with an acceptable heat flow, is to reverse the concept and, instead of optimizing the surface [7], to act on the beam itself and spread it by an active steering system. In this way, the interaction of the beam with the bottom plate can also be avoided.

The active steering system can be composed of two sets of magnets: the first one with the aim of increasing the effective beam size in order to prevent excessive power densities, the second one to drive the enlarged beam in order to cover homogeneously the cylinder internal surface. The first system can be composed of a couple of magnets supplied by a current generator that allows to obtain any beam shape and dimension. A possible configuration could be given by applying the algorithm shown in Figs. 13 and 14 in order to obtain a square beam cross section still centered on the line axis. A high scanning frequency, of the order of tens of kH, can be used. A second rastering mechanism will move the newly shaped beam in order to cover ergodically the target internal surface. Digital algorithms, computer controlled, can be used to prevent power overlapping. A digital scan generator should be used both for the *X* and *Y* axes. A sketch of the configuration is shown in Fig. 13.

The preliminary thermal calculations show that the no-boiling criteria are satisfied: the heat flux is very low, about 38 W/cm^2, and the temperature difference between the cooling water and

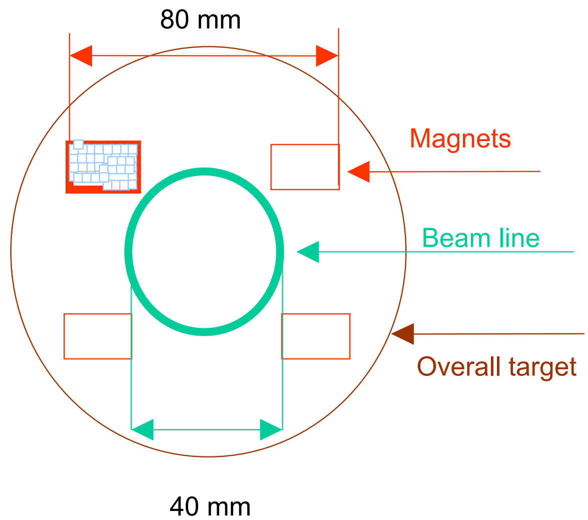

Fig. 13. Cross section from the top of the overall target diameter with the rastering magnets.

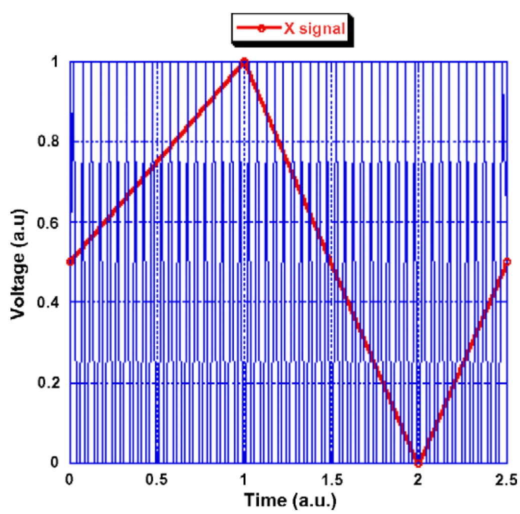

Fig. 14. A typical voltage vs. time voltage output to drive the steering magnets in order to obtain a square beam cross section still centered on the beam line axis.

the external cladding is only 75 K. The maximum temperature in the Uranium meat turns out to be 600 K that is lower than the 1040 K limit assumed in the criterion. No stringent conditions on water flow and/or water pressure are foreseen.

The calculations of neutron production have evidenced 7.8×10^{13} neutrons s^{-1}. The very grazing electron incident angle leads to electron reflections on the target surface, with particles travelling toward the bottom of the target. For this reason, even in this configuration, a certain overloading of the bottom plate occurs.

The magnet dimensioning is not a crucial point leading for a typical geometric configuration and for a beam with $\gamma = 50$, to a few hundreds W power dissipation, an inductance of the order of mH, and a driving voltage – for a frequency ranging in the order of few kHz – only of the order of tens of Volts.

A detailed analysis of the impinging trajectory of the electron beam (Fig. 15) has been performed under the following hypotheses:

- beam impinging at 3/4 of the cylinder height (=35.2 cm), 2.4° angle;

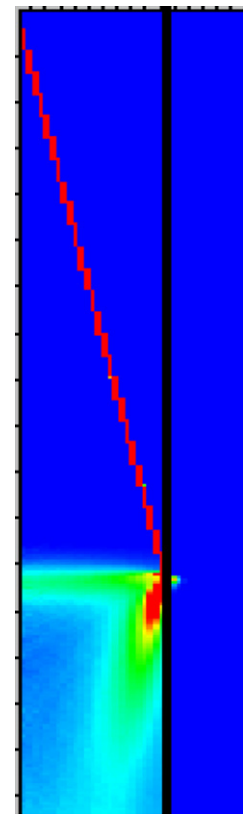

Fig. 15. The picture represents the impinging electron beam largely reflected in the case of small incident angles.

Table 2
Power deposition for different incident angles and beam power

	Power deposited 30 kW, 25 MeV, 2.4° incidence	Power deposited 30 kW, 25 MeV 14.3° incidence
Inner cladding	4.4 kW	2.4 kW
U cylinder	15.1 kW	25.3 kW
Bottom U plate	9.5 kW	0.59 kW
Total	29.2 kW	28.3 kW

- 0.5 mm of Al inner cladding ($r_{int} = 26$ mm);
- 15 mm thickness of U hollow cylinder ($r_{int} = 26.5$ mm; $r_{ext} = 41.5$ mm);
- 0.5 mm of Al external cladding ($r_{ext} = 42$ mm);
- uranium plate at the bottom of the target (thickness and shape to be fixed).

The calculated power deposition (by MCNPX) for different impinging angles is shown in Table 2. From these data we can presumably deduce that an incident angle of the rastering system of about 10° is enough to obtain a low power percentage in the bottom plate. This configuration is feasible and corresponds to a magnet distance from the top of the target of the order of 30 cm.

6. Comparison between the diffusion plate and the rastering system

The two proposed systems present both advantages and disadvantages one compared to the other. The main difference is that the rastering is an active system that can be operated in different configurations, for a uniform power deposition or for a controlled power deposition profile increasing core/target coupling efficiency.

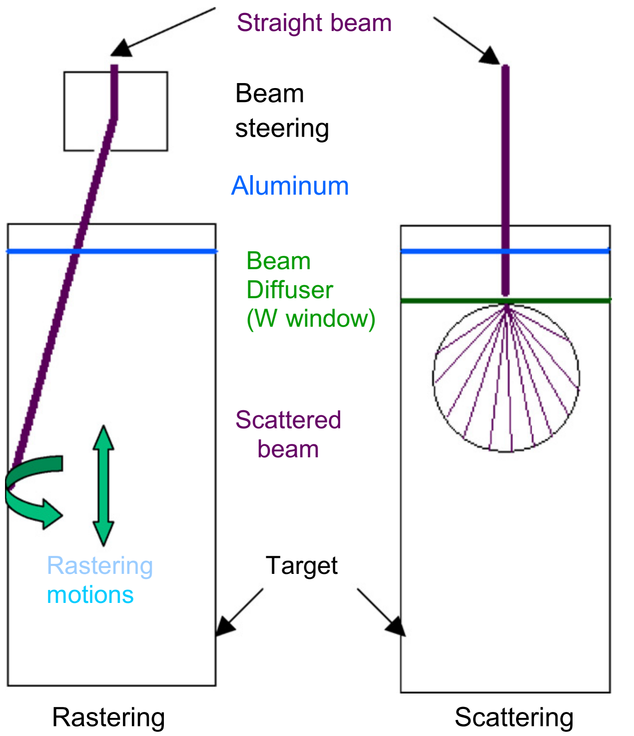

Fig. 16. Comparison between the two proposed schemes.

On the other hand it is more complicated and, even if very reliable, off-normal working conditions are possible and the use of a Uranium target leads to more stringent safety rules. On the other hand four magnets, moving the beam simultaneously, prevent the possibility that a system failure could cause a serious accident. In Fig. 16 a comparison of both the configuration arrangements is shown.

The diffusion disk (when thin enough to allow proper thermo-mechanical behaviour) allows a large beam fraction to reach the bottom plate, where the neutron/core coupling, inferred from simple geometrical considerations, is less efficient. In general, the passive approach reflects on the lack of possibility to control the power deposition pattern. For these reasons, the best configuration could be obtained by coupling the two concepts with a maximum of flexibility and at the same time a higher degree of safety.

7. Safety issues related to the target cooling

The use of a target based on uranium gives rise to safety concerns about the consequences of the hypothetical rupture or blockage of the coolant feeding system. The dispersion of particles of irradiated uranium in the reactor has to be avoided. To prevent this occurrence, at least two barriers must be foreseen. The first barrier consists of the aluminium cladding, which envelops the uranium meat. The second barrier is the container of the target, which separates the cooling water from the reactor water.

To protect the beam line, a gate valve connected with a fast vacuum gauge can be mounted in an upper position.

For the radial target, it is possible to shift the barrier between the target coolant and the beam line, in a lower position, not affected by the beam and with no constraints on its thickness. In this way, it is possible to skip the window, obtaining a higher neutron production rate and a higher safety level. Even in this case, a fast shutter gate has to be positioned along the beam line in order to prevent, in case of accident, the flow of uranium particles along the beam line. The fast gate could be triggered by a residual gas analyzer or a vacuum gauge.

The rastering system will be also electronically monitored in order to switch off the beam in case of off-normal conditions.

Three accidents can be envisaged:

- a local loss of flow, which provokes a hot spot with local burn or breach of the cladding and dispersion of Uranium particles in the coolant;
- a generalised LOFA (loss of flow accident);
- the rupture of the target container.

In the first event, the cooling circuit, which is completely separated from the TRIGA reactor by the second barrier, will prevent the dispersion of uranium particles in the water of the reactor. A set of alarm devices, based on continuous sampling, should be implemented in the circuit to guarantee an early warning when radioactive particles are found in the cooling water. In this circumstance, the beam should be rapidly stopped and the polluted cooling water would remain confined in the feeding system without any consequence for the reactor.

In the second case, it can be shown that, in the multi-plate concept, the upper uranium disk would reach the melting temperature in about 1.3 s. In this case, even the aluminium cladding would be destroyed but the window would prevent the inlet of the cooling water into the beam line. The approximate times of survival of the window in beam-on conditions and without flow are:

- more than 7 s for a tantalum window,
- about 4.4 s for an aluminium window.

These grace times, if accompanied by rapid transducers of pressure and flow-rate, should allow to switch off the electron beam before the window be destroyed.

The rupture of the target container, apart from the window, is in principle very unlikely, because it is not subjected to any significant stress or temperature increase neither in case of LOFA. Nevertheless, in case of container rupture, the cooling water reversed in the reactor would not be polluted, thanks to the effect of the first barrier.

The design of the circuit was carried out trying to insure a very high safety level considering that the target could contain some fission products. For this reason, the circuit has to guarantee that, even if a major accident occurs, the target will not be damaged or, in any case, the possible contamination will be confined inside the primary target loop.

For any U-based target solution, the cooling system must be separated from the TRIGA cooling system and a double barrier is required to protect from dispersions of irradiated uranium in the TRIGA water. The first barrier consists in the cladding and the second barrier is the target container.

The interface between the upper part of the target container and the beam tube is closed by the window. Since after some seconds of exposure to the beam, without cooling, the window could fail, a fast intervention gate valve must be placed to protect the beam line.

8. Conclusions

A new solution for an electron beam target has been analyzed for a power up to 30 kW.

The neutron production results to be almost 8×10^{13} neutrons s^{-1}, that corresponds to a conversion efficiency close to the theoretical limit. The target/core coupling efficiency has not been analyzed in this paper but it can be controlled and maximized using the active rastering system.

Temperatures are well under control in both configurations but can be more cleverly kept under control with the rastering approach.

Mechanical analyses have been extensively performed assuring a configuration reliable with the cylinder-bottom plate separation and optimization of the bottom part design.

Even if the rastering system is highly reliable, safety could be enhanced coupling the active system with the passive diffusion disk concept.

Acknowledgements

The authors appreciate the efforts of all the Scientists and Institutions involved in EUROTRANS, as well as the financial support of the European Commission through the Contract FI6W-CT-2004-516520.

References

[1] C. Rubbia et al., TRADE (Triga Accelerator Driven Experiment): A full Experimental Validation of the ADS concept, AccApp'03 Accelerator Applications in a Nuclear Renaissance, San Diego, California, June 1–5, 2003.
[2] C. Krakowiak et al., The TRADE Solid Target System Design, Global 2003, New Orleans, Louisiana, November, 2003.
[3] D. Beller, Overview of the AFCI reactor accelerator coupling experiments (RACE) project, in: Proceedings of the Eight Information Exchange meeting on Actinide and Fission Product Partitioning and Transmutation, Las Vegas, Nevada, 2004.
[4] W.P. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Technical Report Series No. 188, IAEA, STI/DOC/010/188, 1979a.
[5] M. Carta, N. Burgio, A. D'Angelo, A. Santagata, C. Petrovich, M. Schikorr, D. Beller, L. San Felice, G. Imel, M. Salvatores, Electron versus proton accelerator driven sub-critical system performance using TRIGA reactors at power, in: Proceedings of PHYSOR-2006, Vancouver, BC, Canada, September 10–14, 2006.
[6] P. Agostini et al., The TRADE Target Design and Development, AccApp2003, San Diego, California, June, 2003.
[7] M. Ciotti, Target profile optimization for an ADS experiment, Enea report RT/2006/63/FIM.
[8] S. Sharafat, R.Martinez, N. M. Ghoniem, Design window for tungsten alloys, Apex Study Group Meeting, May 1999.
[9] Denise B. Pelowitz (Ed.), MCNPX^{TM} User's manual, Version 2.5.0, LA-CP-05-0369, April 2005.
[10] Handbook on photonuclear data for applications: Cross sections and spectra, IAEA-TECDOC-1178, October 2000, IAEA Vienna.
[11] P. Agostini, L. Sansone, G. Benamati, C. Petrovich, S. Monti, Nucl. Instrum. and Meth. A 562 (2006) 849.
[12] Cast3M web site: <www-cast3m.cea.fr>.