THE SPES DIRECT TARGET PROJECT AT LNL*

F. Gramegna[a]

and the SPES Collaboration:

A. Andrighetto[a], C. Antonucci[e], M. Barbui[a], L. Biasetto[c]
G. Bisoffi[a], S. Carturan[a], L. Celona[b], F. Cervellera[a]
S. Cevolani[e], F. Chines[b], M. Cinausero[a], P. Colombo[c]
M. Comunian[a], G. Cuttone[b], A. Dainelli[a], P. Di Bernardo[d]
E. Fagotti[a], M. Giacchini[a], M. Lollo[a], G. Maggioni[a]
M. Manzolaro[c], G. Meneghetti[c], G.E. Messina[b], A. Palmieri[a]
C. Petrovich[e], A. Pisent[a], L. Piga[d], G. Prete[a], M. Re[b], V. Rizzi[a]
D. Rizzo[b], M. Tonezzer[a], D. Zafiropoulos[a], P. Zanonato[d]

[a]Lab. Nazionali di Legnaro, INFN, via dell'Universitá 2, 35020 Legnaro, Italy
[b]Lab. Nazionali del Sud, INFN, via S. Sofia 62, 95125 Catania, Italy
[c]Dip. Ing. Meccanica, Universitá di Padova, via Venezia 1, 35131 Padova, Italy
[d]Dip. Scienze Chimiche, Universitá di Padova, via Marzolo 1, 35131 Padova, Italy
[e]ENEA, Via M.M. Sole 4, 40129 Bologna, Italy

(Received October 30, 2006)

The SPES Direct Target Project at the Laboratori Nazionali di Legnaro (Italy), devoted to the construction of a Radioactive Ion Beam (RIB) Facility within the framework of the new European RIB panorama, is presented. An innovative configuration for the SPES Project, for the production of neutron-rich exotic nuclei, proposes the use of a primary proton beam (40 MeV, 0.2 mA), directly impinging on a large Multi-Slice Uranium Carbide Direct Target. The goal is to reach a high number of fission products (up to 10^{13} fissions/s), still keeping a quite low power deposition inside the target. The description of the overall facility together with details on the Direct Target configuration is presented. Thermo-mechanical calculations, material preparation and characterisation, effusion–diffusion model predictions for the estimation of the release time and total release fraction for different life times and isotopes will be discussed. Finally, a scaled (1:5) prototype of the Target System built to be tested and compared under existing proton beam facilities, will be described.

PACS numbers: 29.25.–t, 29.17.tw, 41.75.–i

* Presented at the Zakopane Conference on Nuclear Physics, September 4–10, 2006, Zakopane, Poland.

1. Introduction

During these last few years the radioactive beam facility panorama has evolved, going towards a better definition on the production techniques for intermediate [1, 2] and third generation facilities [3], which should give important results for the final aim of experimentalists. Among the different requests, in fact, one of the main factors is represented by the final intensities of the produced beams, which are needed to perform the experiments: this is strongly related both to the production technique and to the overall facility efficiencies, as it will be explained in the following paragraphs. The production technique is under study since a number of years and mainly two approaches are followed: one is related to the direct target configuration, where a charged beam is directly impinging on a production target to produce fission fragments at relatively low energy [4] and spallation products at high energy [5]. The second configuration is the so called high power double target configuration, where the charged beam is sent onto a converter (namely C or Be or, at higher power, liquid Hg). This converter, decoupling the high power of the charged beam from the production target, produces a high intensity neutron beam which is effective in the fission production [2]. In this case the production target is very massive (of the order of 600 g up to few kg), while in the direct case only few tens of grams are necessary. However, both solutions have highlights and crucial problems to be considered. Third generation facilities like EURISOL are proposing a coexistence of the two solutions, with up to three direct target installations and one very high power two step target zone [3].

2. The SPES facility

The RIB facility SPES, allowing a frontier program in RIB physics, is being designed and prototyped: the design has been focused on a 40 MeV proton driver, 200 μA current, impinging onto a Multi Slice Direct Target. The idea is an evolution of the facility existing at ORNL [4]. At ORNL, more than 1200 hours of operation were reached and more than 120 different radioactive isotopes have been extracted, using a 42 MeV proton beam ($I_p \simeq 10 \div 12$ μA) from the cyclotron. The beam impinges a uranium carbide 30 mm thick target (400 W total power deposition in the target), giving rise up to 4×10^{11} fissions/s. The evolution of this concept is the target configuration under development at LNL, which will be described in the next paragraph.

As for the development of the SPES accelerators, Fig. 1 shows a 3D pictorial view of the whole facility. The existing heavy ion accelerator complex is shown in the upper left side: a Tandem XTU 15 MV is presently working stand alone or as an injector to the superconducting LINAC ALPI. A second

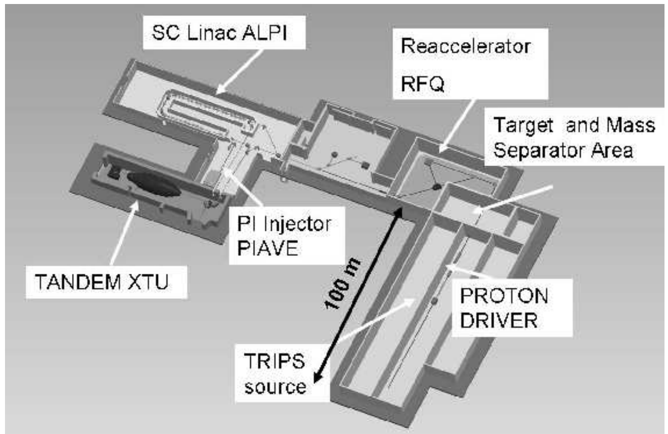

Fig. 1. Artistic view of the RIB facility: on the left side the Tandem XTU, PIAVE and ALPI accelerator complex and the existing experimental Hall III; on the right side the new building for the SPES proton driver and the target and ion separator areas.

injector for ALPI has been installed, based on the PIAVE superconducting RFQs, which can provide, coupled with an ECR source, higher beam masses and intensities. In the right side the 40 MeV proton driver will occupy a relative small part of the building which has been designed for possible future extension of the machine up to 100 MeV. The area dedicated to the target system, comprehensive of the production target itself and the associated sources designed for highly ionised RIB, is followed by the one dedicated to a high resolving power mass separator. The RIB velocity matching to ALPI will be obtained using the PIAVE injector, which have to be relocated in the ALPI building and preceded by a first RFQ that prepares the bunch structure.

As for the driver accelerator, the design has recently been optimised for the direct target requirements, 40 MeV, 200 μA proton beam. A normal conducting and a superconducting linac have been compared taking into account performances, costs and management issues. The selected solution, shown Fig. 2, foresees the use of the source TRIPS [6], developed and built at the Laboratori Nazionali del Sud (LNS), and the TRASCO RFQ [7], which is under construction at LNL; the beam is, therefore, accelerated by a normal conducting Drift Tube Linac (DTL), with permanent quadrupole magnet focusing. All the structures operate at 352.2 MHz, in pulsed mode at 50 Hz and 1.5 % duty cycle. The RFQ has the additional capability of delivering a cw 30 mA proton beam, that will impinge on a beryllium target for neutron production.

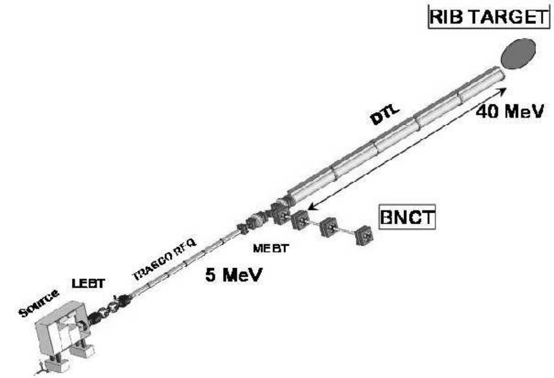

Fig. 2. The Drift Tube (DTL) hypothesis: the Trips source injects in the Trasco RFQ and the modulated beam is accelerated up to 40 MeV from a normal conductive LINAC based on structure DTL.

The TRIPS source has been delivered to LNL in late 2005 and is now operational; two modules for the RFQ are ready out of the total six, the other four are in parallel under construction by industry, whereas klystron and waveguides are being acquired from CERN. Beam dynamics of the DTL structure was successfully carried out: the DTL structure, 12.3 m long, should be built completely by the industry, following the CERN DTL design [8].

3. The SPES direct target configuration

The target configuration has been designed to be highly competitive and to reach the experimental requirements of an high production yield ($\simeq 10^{13}$ fissions/s). The reaction products would cover the mass region $80 \leq A \leq 160$. On the other side a relatively low power deposition (less than 10 kW) in the materials (both window and target) has to be kept, in order to be safely far from critical points (melting point) of the irradiated material. A solution to this drawback has been found considering that only the protons with high fission cross section will be used for fission production, while those with lower energy will be driven toward a passive graphite dump. In this way the main dissipation (which is higher at lower beam energy due to higher energy loss in the material) will be supported by the graphite dump disks, while in the UC_x a relatively small dissipation will be assured. The SPES Direct Target Configuration (SPES DT) is shown in Fig. 3. A thin disk configuration has been chosen in order to optimise the heat dissipation, which is linked to the thermal radiation and, therefore, directly proportional to the body surface. The use of several thin disks increases the total surface and allows for a better cooling. In particular the system which is under development at LNL consists of a target container which is a cylindrical carbon tube, 1 mm thick and 24 cm long; the entrance window is a 0.4 mm thick graphite layer. The active part of the target is composed by seven UC_x disks ($\rho = 2.5$ g/cm^3), with a total mass of 66 g. Calculations have been performed in a larger configuration with the disks having a radius of 3 cm and a smaller geometry with radius 2 cm. The thicknesses of the disks vary from 1.4 to 1.2 mm in order to optimise the power deposition. The passive dump is made by three graphite disks ($\simeq$ 1 mm thick). All disks are 2 cm spaced. The power deposition, the fission rates and the fission fragment distribution have been calculated using the MCNPX code [10] and the ORNL model [11].

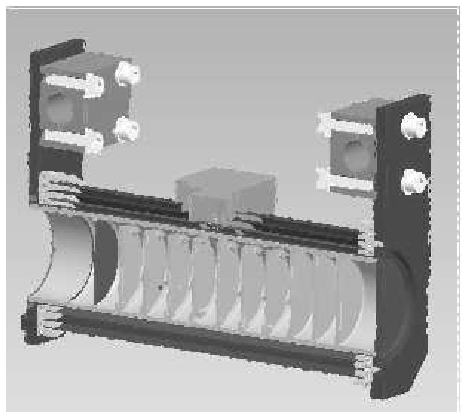

Fig. 3. The SPES Direct Target Configuration.

3.1. Thermo-mechanical calculations

One of the major drawback of a direct target method is surely the energy dissipation of the beam current. There are mainly two heat transfer phenomena to be analysed for the thermal analysis [12]: the first one takes place between the disks and the box inner surface; the second one is acting between the box outer surface and the chamber walls. Moreover, the fact that the graphite cylinder has to be hold at about 2000°C has to be carefully taken into account in both cases. At these temperatures the main phenomenon which induce the cooling of the disks towards the surrounding carbon box is the thermal radiation. A cylindrical shape has been considered in the preliminary calculations. In turn, the box itself will transfer heat by radiation, toward the walls of the chamber hosting the target. A constant and uniform value of 50°C has been considered for the temperature of the chamber walls, close to the room temperature. Numerical calculations suggest that the power deposited by the beam in the production target (about 5 kW) should not represent a critical engineering issue. In fact, a reasonable margin with respect to the material melting point results from the thermal analysis, which shows the capability of the thermal radiation to cool down the disks: the maximum calculated temperature of the disks is about 2200°C, whereas, from literature data, the material melting point ranges between 2315°C and 2540°C. A simulation was also performed for a prediction on the mechanical and thermal stresses: the ANSYS code was used, therefore, to simulate the target behaviour under the influence of the beam hitting power and fixing the temperature of the cylindrical box at $T = 2000$°C. The risk of mechanical failure, under the current assumptions of steady-state operation and elastic behaviour, seems to be avoided (the assumption of elastic behaviour is a very rough approximation and surely needs further refinements).

3.2. Target isotopes release: effusion–diffusion calculation

The delivery of a radioactive beam requires the extraction of the exotic species produced inside the target. They have to be collected in the ion source after the diffusion process in the uranium target material and the effusion in the container. The final beam current depends indeed on several factors: the target production yield, the target efficiency, the ionisation efficiency, the transport efficiency along the accelerator. As we are dealing with radioactive species with a given half-life, a crucial parameter is the release time, which has to be minimised in order to optimise the target efficiency. The release time is given by the sum of the diffusion time in the target material, the effusion time (inter-grain plus free effusion) and the sticking time, that is the time delay after each collision depending on the target and container materials.

To this purpose, some simulations have been performed using the GEANT4 toolkit [13], as well as the RIBO code [14], in order to estimate the effusion time for some neutron-rich nuclei. The details of the simulations and some results are reported in [15] and [16]. The results obtained so far for the ^{132}Sn, ^{90}Kr and ^{81}Ga fission fragments show that the average release time is significantly lower with respect to their half-life. The average total effusion times $t_{\rm eff} = (0.41 \pm 0.02)$ s and $t_{\rm eff} = (0.22 \pm 0.02)$ s were calculated, for Sn and Kr isotopes, respectively. Taking into account that a diffusion time of about 1 s for Sn and 10 s for Kr should be considered, it is clear that the SPES direct target has a very fast average total release time (less than 2 s for Sn isotopes and about 10 s for Kr). Finally, as it is evident from Fig. 4 a total release fraction (TRF) of 90% for ^{132}Sn can be obtained, while a TRF of 40% results for the short living ^{133}Sn. The total release fraction for ^{80}Kr resulted to be 80%.

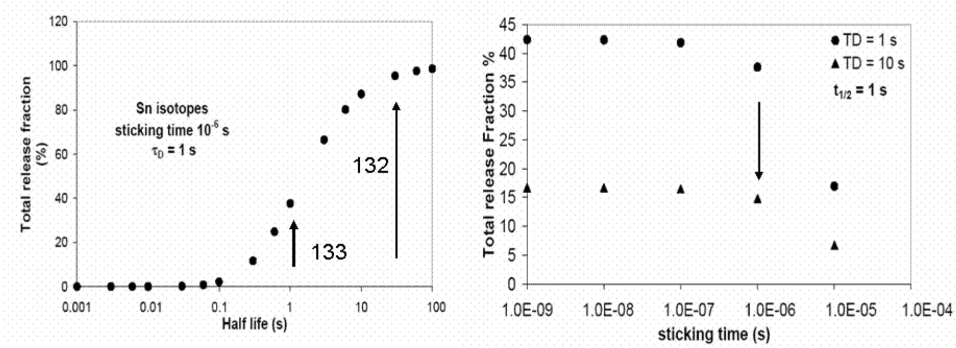

Fig. 4. (a) The total release fraction calculated in the SPES DT configuration for Sn isotopes as a function of the isotope half life; (b) The total release fraction as a function of the sticking time.

3.3. The Pellet production and characterisation

One of the most important issue in order to get an efficient target, is the method followed for the production of target pellets. Therefore, in the SPES project a careful attention has been dedicated to this item. In particular for the target like the one under development for SPES, low-density carbon-dispersed metal carbides (UC_x) are quite promising and uranium dicarbide (UC_2), which has a very high melting-point (2390 °C), seems to be the ideal candidate [17], [18]. It can be produced *in situ* by reaction of a precursor (metal powder, metal oxide, or selected organic salts of the metal: $UO_2(CO_3)$, $UO_2(C_2O_4)$) with a carbon-based matrix (graphite powder or low density carbon foam generators). The formation of ionic uranium dicarbide (acetylide) occurs under high vacuum at temperatures ranging from 1400 to 1700°C [19]. However, in order to obtain durable products, it is necessary to extend thermal treatments up to the extreme target working conditions ($\simeq$ 2000°C), because in this region sintering and changes in the physical/mechanical properties of the pellets occur. The resulting pellets are oxygen and moisture sensitive and, moreover, radioactive. The handling of radioactive material (even when low activity is involved, like in the case of depleted uranium) requires special precautions, authorisations, and dedicated radiologically controlled areas to avoid worker and instrumentation contamination. Because of these facts it could be difficult to obtain results in a short time. For these reasons lanthanum carbides (LaC_x) were used as valuable substitutes of uranium compounds for preliminary bench tests on pellet production and characterisation. In spite of the radiological aspect, in fact, the preparation of pellets of lanthanum carbide dispersed in graphite presents similar challenges as uranium compounds in both synthesis and characterisation. Two production lines were programmed in order to develop the target for SPES: a small target program where the 13 mm diameter pellets are produced, to be compared with existing target systems and the 40 mm diameter pellets which are one of our challenges. At present, the production of 13 mm disks of LaC_2 dispersed in graphite is the most advanced. The pellets are produced in two steps: first, $\simeq 300$ mg of a mixture of lanthanum sesquioxide (Aldrich, 99.99%) or (home synthesised) lanthanum oxalate powders finely dispersed in graphite (Aldrich, 99.99%, -325 mesh) are loaded into a die and pressed (10 tons for 2–3 hours) to get the raw pellets (see Fig. 5); these are then disposed into an oven and heated under vacuum

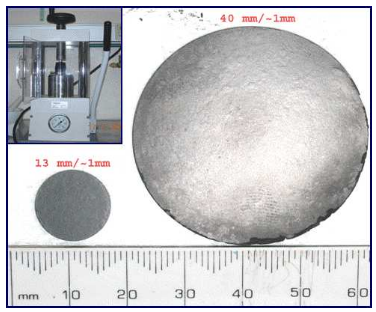

Fig. 5. An example of pellets production: raw La_2O_3/graphite pellets prepared as pressed pellets (left upper corner).

in a graphite crucible for a prefixed time. The temperature ramp is chosen in order to obtain, in sequence and as a function of increasing temperature, dehydration of reagents (if needed), decarbonation (carbonate and oxalate), carburisation and sintering. The whole process lasts between 48 and 96 hours, depending on the recipe for the raw pellet production. A software control system is under development to monitor the relevant parameters during the long period of treatments [20]. Several tests were carried out to optimise the characteristics of the raw pellets. At first, it was clear that

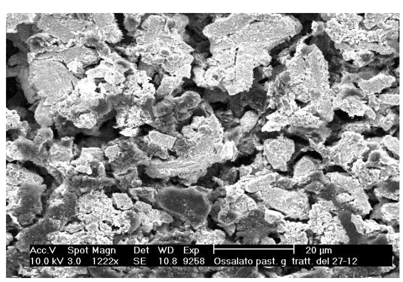

Fig. 6. SEM picture of the LaC_2/graphite pellet obtained after the treatment (in white the carbide, in black the graphite grains).

the applied pressure was inadequate to obtain manageable raw disks without using a binder. Consequently, a small amount (1–2 %) of a polyphenol resin dissolved in acetone was added to the starting mixture before pressing. The carburisation-sintering process is still currently under study. We have performed thermal treatments and characterisation measurements on about 20 lanthanum oxide/graphite or lanthanum oxalate/graphite pellets. Fig. 6 shows a SEM picture of the LaC_2/graphite pellet obtained after the treatment (72 hours, 1500°C in vacuum). At present, pellet complete carburisation and sintering has been achieved as shown in Fig. 7, which gives the results from XRD analysis. The same procedure was applied to obtain several 13 mm raw uranium oxalate/graphite disks, in a glove box: they did not show any difference in quality with respect to the similar lanthanum 13 mm disks. Carburisation and sintering of the radioactive pellets are going to be carried out soon.

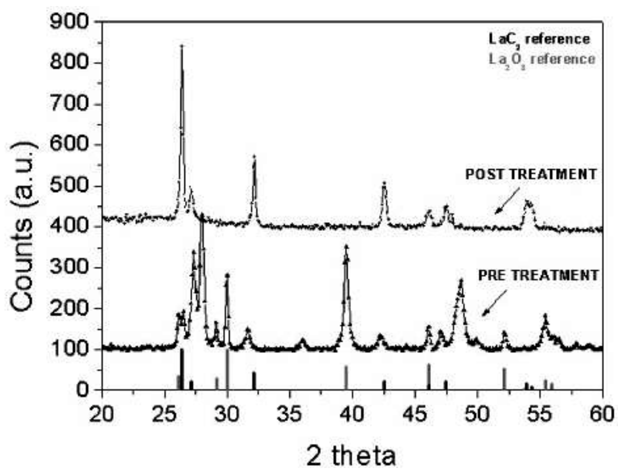

Fig. 7. XRD analysis: the different lines refer to the same pellet before (gray) and after (black) the treatment: in the final pellet no residual oxide is seen, while only LaC_2 is present (no La_2C_3); peaks not labelled belong to graphite.

4. The target prototype

A research program, which will be devoted to test the SPES target configuration with proton beams of proper energy and current, has started: this is considered the first step towards the final SPES Direct Target. HRIBF at ORNL is considered the proper facility to perform part of these tests, because it is indeed based on a primary beam of protons at 40 MeV with currents up to 18μA. The experimental program requires the development of a first target prototype with dimensions scaled to 1:5. This prototype is built to fit the HRIBF target holder. It will allow to test the main ion release characteristics and it will permit to experimentally study, for the first time, the thermal behaviours of the multi slice target configuration in a condition of nominal power density of 600 W per slice for the UCx target. The prototype configuration has been studied for the SiC material (see Fig. 8), which will be the first material under test, to avoid, in the first step, the problems related to the production and manipulation of UCx pellets.

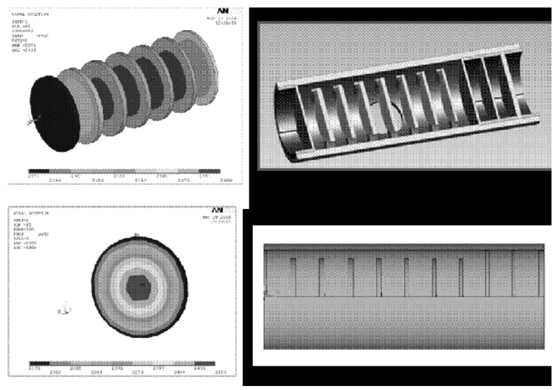

Fig. 8. Left panel: thermal calculation for the prototype in SiC. Right panel: design of the prototype.

The use of SiC target is devoted to the production of exotic aluminium beams ^{25}Al and ^{26}Al, which are of astrophysical interest both at HRIBF and at EXCYT in Catania, the radioactive beam facility of LNS. A comparison of different target configurations and materials will be done, mainly between the standard HRIBF target, made of pressed powder or pills, and the multi-slice target configuration proposed for SPES. Extensive simulations have been performed to evaluate the thermal response and the in-target production, which will be compared to the experimental behaviour. The first test is planned for December 2006 in strict collaboration with the target development group of ORNL.

5. Conclusions

A radioactive beam facility based on a Multi Slice Direct Target configuration is under development at LNL. The calculations performed so far indicate that using a 40 MeV proton beam and a current of about 0.2 mA impinging directly on a multiple UCx disk target, a feasible solution can be reached to produce exotic ions. This solution is still very competitive in the present RIB development framework. In this way, as a matter of facts, about 10^{13} fissions/s can be obtained with appropriate ^{238}U compounds.

REFERENCES

[1] A. Bracco, A. Pisent (Eds.), SPES Techn. Design REP 181/02, LNL-INFN (2002).

[2] SPIRAL2 — the Scient. Objectives of the SPIRAL2 Project, GANIL 2006.

[3] Eurisol Report, European Commission Contract No. HPRI-CT-1999-50001, `www.ganil.fr/eurisol`.

[4] G.D. Alton *et al., Nucl. Instrum. Methods* **A328**, 325 (1993).

[5] P. Bricault, *Rev. Sci. Instrum.* **77**, 03A710 (2006).

[6] G. Ciavola *et al.*, PAC 2001 Conference Proceedings, Chicago, USA, 2406.

[7] A. Pisent *et al.*, LINAC 2004 Conference Proceedings, Lübeck, Germany, 69.

[8] S.V. Plotnikov *et al.*, EPAC 2006 Conference Proceedings, Edinburgh, Scotland.

[9] A. Shor *et al.*, LINAC 2004 Conference Proceedings, Lübeck, Germany, 354.

[10] MCNPX$^{\text{TM}}$ User's Manual, ver. 2.5.0, D.B. Pelowitz Ed., LA-CP-05–369 (2005).

[11] J. Barish *et al.*, HETFIS Code, ORNL-TM-7882, ORNL Report, 1980.

[12] A. Andrighetto, S. Cevolani, C. Petrovich, *Eur. Phys. J.* **A25**, 41 (2005).

[13] S. Agostinelli *et al., Nucl. Instrum. Methods* **A506**, 250 (2003).

[14] M. Santana Leitner, Ph.D. Thesis, UPC-ETSEIB/CERN.

[15] M. Barbui *et al.*, Relative Time Calculation for the SPES Direct UCx Target, RNB7, Cortina d'Ampezzo (Italy), July 3–7, 2006.

[16] V. Rizzi *et al.*, Diff. Calculation with RIBO code for the SPES DT, RNB7, Cortina d'Ampezzo (Italy), July 3–7, 2006.

[17] I.E. Campbell, E.M. Sherwood, Eds., *High Temp. Mat. Techn.*, Wiley (1967).

[18] M. Hansen, *Constitution of Binary Alloys*, McGraw-Hill (1958).

[19] C. Lau, *Target and Ion-Source Work. Group on Fission Target Mat.*, LNL, Dec., 2000.

[20] M. Giacchini, Thin Target Control System, TTCS-GM-02.