THE ACCELERATOR DRIVEN SPES-BNCT PROJECT AT INFN LEGNARO LABS

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An attractive, accelerator-driven, high flux thermal neutron beam facility is currently under construction at the INFN Legnaro National Laboratory (LNL), in the framework of the SPES research program. The experimental treatment of extended skin melanoma tumor, with a combined Boron Neutron Capture plus Photodynamic therapy approach (BNCT+PDT), is being investigated. The intense beam delivered by the 5 MeV, 30 mA (150 kW) cw RFQ which is the SPES proton driver, will be employed. One of the main elements of the BNCT facility is the construction of a reliable neutron producing target, based on the $^{9}Be(p,n)^{9}B$ reaction. Two, original, beryllium-based neutron converter concepts have been developed and constructed for that purpose. Both full-scale prototypes already passed a series of thermo mechanical electron beam tests at operative and critical power conditions. The additional radiation damage tests are in progress. The Accelerator-Based Beam Shaping Assembly (AB-BSA) modeling is currently underway. The BNCT neutron irradiation facility, which main features are here reported, based on the saddle-type beryllium neutron converter, has reached an advanced design status.

I. INTRODUCTION

The investigation of exotic, not stable nuclei has been recognized in the last years as a new frontier in nuclear physics research. The aim of SPES (Study and Production of Exotic Species) project at LNL is the construction of an advanced Radioactive Ion Beams (RIB's) facility, having an intermediate size between the existing, first generation, GANIL-SPIRAL and CERN-ISOLDE ones and the next generation, large scale, EURISOL. The Radioactive Ion Beams (RIB's) are generated via fission reactions induced in ^{238}U by an intense fast neutron source. The exotic nuclei of interest will be then injected in the existing superconducting linac PIAVE-ALPI complex as post accelerator. A first feasibility study report on SPES project, taking into account a proposal for a 100 MeV, 1 mA superconducting linac, was published in 1999 (Ref. 1). A first Technical Design Report (TDR) was instead issued in 2002 (Ref. 2), where a general description of the facility can be found. The first part of the original project, named SPES-1, including the linac up to 20 MeV and the R&D on fission fragments production in UCx targets, was approved and funded by the INFN board in 2004. In the last years, however, some significant modifications have arisen with respect to the original project. A new detailed TDR is therefore soon to be issued[3]. The first major difference is related to the exotic beam production system. It has been modified into a Direct-Target, working with a proton beam of 40 MeV energy and 0.2 mA average current, with respect to the original Two-Step concept. In such a way the same nominal 10^{13} s^{-1} fission rate is estimated. The second major difference introduced deals with the high energy part of the accelerator system. A 40 MeV Drift Tube Linac (DTL), operating at 352 MHz, pulsed at repetition rate of 50 Hz, is now being taken into account. This last structure replaces the superconducting linac which was originally foreseen in the former TDR.

The r.f. source and the RFQ driver were formerly developed within the TRASCO (TRAsmutazione SCOrie) research program, aimed at the construction of a high intensity linac for ADS reactors dedicated to nuclear waste transmutation. The source TRIPS[4] (TRasco Intense Proton Source) able to supply 30 mA beam at 80 keV, was built and commissioned at LNS. It has then been transferred to LNL in fall 2005 and began to produce the first beam in mid 2006 (Ref. 5). The RFQ is a 7.13 m long, continuous wave (c.w.), accelerating structure composed by six modules fed by a single 352 MHz, 1.3 MW klystron. It has been designed to raise the proton beam energy up to 5 MeV. The construction of this high

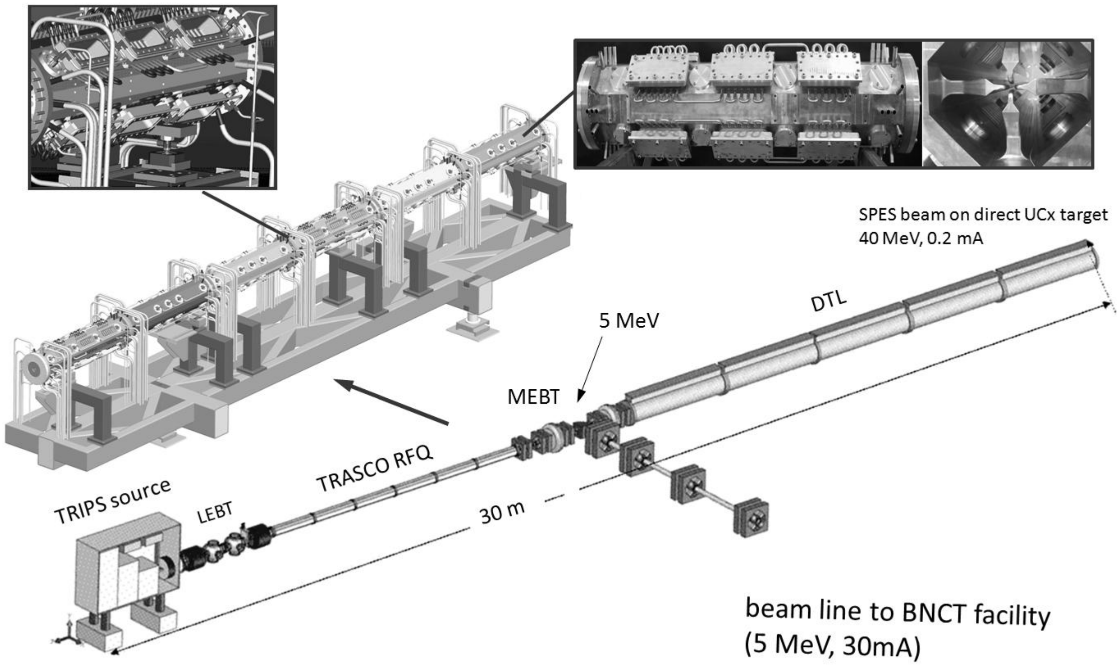

Fig. 1. Schematic layout of SPES-1 facility with the beam line for the interdisciplinary application. TRIPS (TRasco Intense Proton Source), RFQ (Radio Frequency Quadrupole) is the first accelerating stage, the MEBT (Medium Energy Beam Transfer) is the connecting beam line to DTL (Drift Tube Linac), or to the dedicated line to the thermal neutron facility for BNCT application.

intensity accelerator has led to many technological challenges. Two out of six modules of RFQ[6] have already been completed, while the remaining four modules are currently under an advanced construction stage. A sketch of the new SPES-1 accelerating layout, including the RFQ, the DTL linac, and the first module of RFQ completed ready for RF measurements after brazing treatment, is shown in Figure 1.

II. THE SPES-BNCT PROJECT

The TRIPS ion source and the RFQ installed at LNL will represent a unique facility, able to deliver 30 mA, 5 MeV beam, which may be also used as a standalone system. The availability of an additional accelerator-driven neutron source was recognized as a useful tool since the beginnings of SPES project. Therefore a thermal neutron beam facility, devoted to Boron Neutron Capture Therapy (BNCT) experimental treatments on skin melanoma tumors was, in fact, proposed in the framework of SPES project. The neutron source spectrum, provided through (p,xn) reactions by a suitable neutron converter, is then slowed down to the thermal energy range (i.e. $E_n \leq 0.5$ eV) by a proper spectrum shifter device. The *in-air* thermal neutron flux level, at least of $1 \cdot 10^9 cm^{-2}s^{-1}$ at beam port is in fact requested. A proof-of-principle layout sketch of the final beam shaping assembly and the RFQ driver is reported in Figure 2. Accelerator based neutron sources having such a characteristics are not currently available worldwide and the patient BNCT trails performed are so far based on the use of nuclear reactors.

Even if other experimental applications may use the relatively intense neutron source, the BNCT application will be the main interdisciplinary user of the SPES-1 facility. The SPES-BNCT project will therefore represent a challenge to explore the treatment of extended skin melanoma with such a therapeutic modality. Furthermore it will be a fundamental test bench for an operative, accelerator based BNCT facility concept, which could provide in perspective a possible spin-off for a hospital-based system.

An overview on the items of the research program, mainly focused on the neutron converter prototypes developed and tested, as well as the status on irradiation facility design, is here summarized. Additional information on the BNCT project relying on the in-vivo tests with the new boron carriers which are being developed and tested are reported in (Ref. 7). The new, mini Tissue Equivalent Proportional Counter (mini-TEPC) developed and constructed at LNL, for on-line biological dose monitoring in both tumor and healthy tissues, are reported elsewhere[8].

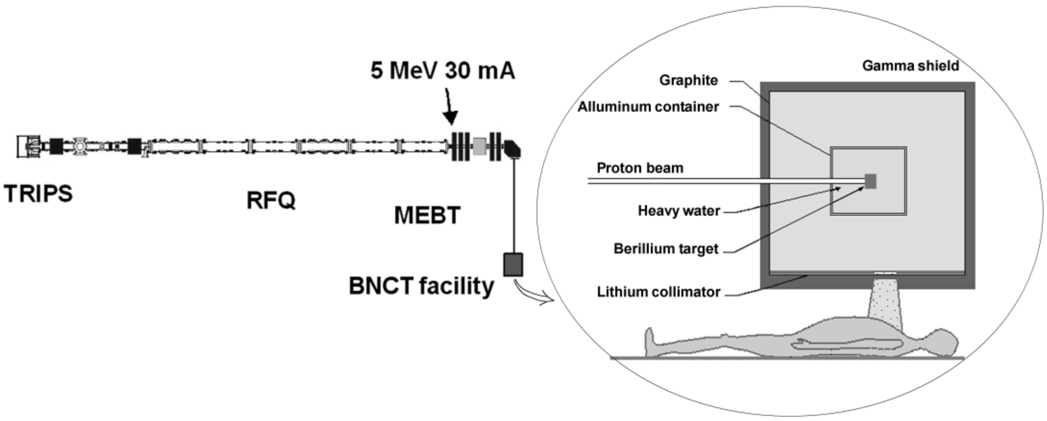

Fig. 2. The accelerator-driven SPES-BNCT irradiation facility layout proposed

III. THE NEUTRON CONVERTER DESIGN

A R&D effort has been carried out in order to select the proper neutron converter type consistent with the SPES design specifications. The main low energy, proton-induced nuclear reactions considered for an accelerator based BNCT facility to yield a neutron source: $^{7}Li(p,n)^{7}Be$, $^{9}Be(p,n)^{9}B$ and $^{13}C(p,n)^{13}N$, have been taken into account at the design stage. A summary of neutron yielding, as well as material main bulk and thermal properties may be found elsewhere[9]. A full set of detailed MCNPX simulation trials, based on the LNL-CN demonstration facility[10] modeling, were preliminary performed to assess the neutron beam performance[11]. Beryllium revealed at last the best solution, due to both the neutron yielding at the fixed RFQ output energy and the related design requirements for a reliable solid target.

Different engineering solutions have been compared to get a good balance between the primary need of a compact neutron source design and the use of simple, reliable solutions for target cooling. Preliminary thermal feasibility studies[12] performed on simple, water-cooled beryllium targets, revealed that critical conditions for heat transfer to cooling system are achieved at beam power densities of about 1 $kWcm^{-2}$. Such an extreme working condition has to be avoided, if fairly large engineering safety margins have to be fulfilled for a reliable neutron converter. A maximum surface heat load level lying in the range 0.5-0.7 $kWcm^{-2}$ would instead be required, in order to make use of reliable and already tested target cooling systems.

After both neutronic as well as technological feasibility studies lasted two years in collaboration with the STC Sintez of Efremov Institute in S. Petersburg, the design of an original, beryllium-based target, shown in Figure 3 and Figure 4, has thus been produced[13]. The target main structural components are based on a zirconium alloy (Zr + 2.5% Nb), while the neutron converter exploits the tile concept, i.e. beryllium tiles which are brazed on a 10 mm outer diameter, 1 mm thickness, cooling pipes. These latter are produced by casting bronze (CuCrZr) alloy onto 0.3 mm thickness SS pipe followed by a quenching and ageing manufacturing process. Such a composite pipe structure allows for the application of the well-developed Be-Cu joint technology, thus avoiding the corrosion of copper alloy by the coolant.

Moreover a peculiar V-shaped profile has been chosen for the target geometry. The advantage of such an approach is to meet the design criteria of a neutron yielding volume as close as possible to the ideal point-like source. Another important advantage is that the parabolic power profile of RFQ beam (Figure 4) is changed in a uniform distribution on the beryllium target surface along the beam axis direction. The maximum surface power density lies in the target center, while reducing at the extremities, as shown in Figure 5. The surface area is limited at 130x170 mm^2 on each target half which fulfills the main requirement of a peak-power density as low as ~0.7 $kWcm^{-2}$. Some concern relating the cooling fluid capability, the cooling system simplicity as well as the economics led to light water being chosen as coolant, for both the target and the related collimator. Due to the given geometry of the cooling system full turbulent flow conditions are achieved (Re ~40000) with a water velocity of 4 m/s. In such a way the required high heat transfer coefficient of about $6 \cdot 10^4\, Wm^{-2}K^{-1}$ is gained, with a flow rate of about 180 L/min, able to remove the total impinging heat load (150 kW). The main hydraulic parameters are a coolant inlet pressure being fixed at 0.3 MPa, while, the pressure drop in the whole circuit being of 0.02 MPa.

A detailed thermal-mechanical coupled analysis has also been performed to assess the maximum working temperatures and the related target mechanical stresses and deformations under static and cycling loading operating conditions. The steady state thermal analysis

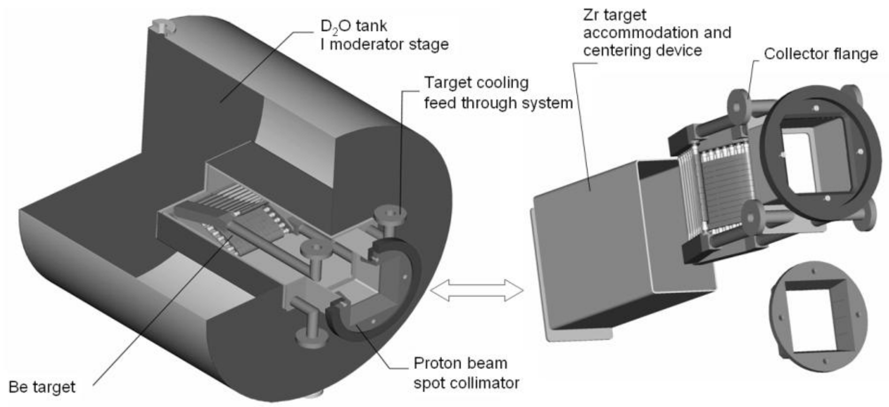

Fig. 3. Final design of Be neutron converter for SPES-BNCT facility: the target assembly with the first moderator stage arranged in cylindrical form (left), the target plug system (right).

main results are also reported in Figure 5. The maximum temperatures calculated in the different components: beryllium hitting surface (673 °C), Cu-alloy pipes (362 °C), SS pipe liners, (344 °C) and Zirconium alloy cooling feed system (21 °C) are well below the correspondingly melting points. Moreover the stress intensities calculated at loading (beam on) and unloading (beam off) stages in all structural parts have turned out to be within the allowable design limits. The target also fulfills the other critical design requirement to pass the limit of 2000 hrs lifetime, under 200 thermal cycles (the beam is on and off per each run).

Several mock-ups have been manufactured and tested at the High Heat Flux (HHF) Tsefey electron beam facility at the Efremov Institute, under different power density levels, up to 1.1 kWcm^{-2}. All destructive analyses performed on inspected samples revealed good brazing quality, with a uniform brazing layer. The joint between tiles and cooling pipes was not damaged during the tests and no visible cracks and erosions have been observed through the Be thickness. The first, full-scale half-target prototype, shown in Figure 6, was finally constructed by the end of 2004. It successfully passed the preliminary series of both operative and critical e-beam power test conditions up to 0.75 kWcm^{-2} in March-July 2005.

The technology to braze a beryllium layer on a CuCrZr support and heat sink material, although well proven in the framework of ITER project, has however the drawback of a relatively high prompt capture gamma source level at the facility beam port. In order to meet the LNL requirements and reduce such unwanted gamma component, a new technological research has therefore started, aiming at constructing a reliable neutron converter made of bulk beryllium only. All the target system: manifolds, cooling pipes, and the neutron converter layer have, therefore, to be manufactured starting from a full Be block. The main advantage with respect to the former target version is less assembly parts and considerably less brazing. Moreover, the same neutron yielding of Be-tile converter would be provided, with an improvement in the

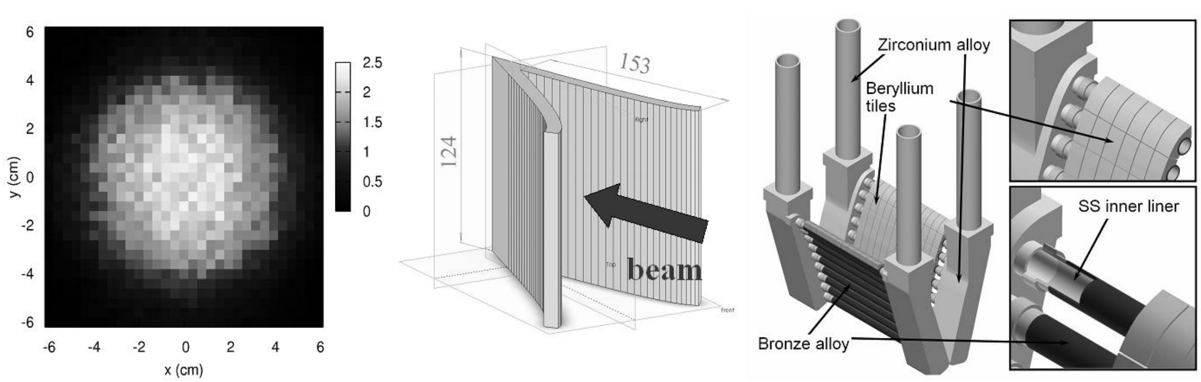

Fig. 4. Cross sectional view of TRASCO RFQ proton beam power density distribution (kW/cm^2) at the target collimator on a plane normal to the beam line (left). The neutron converter profile with main sizes given in mm (center). Target main structural components (right).

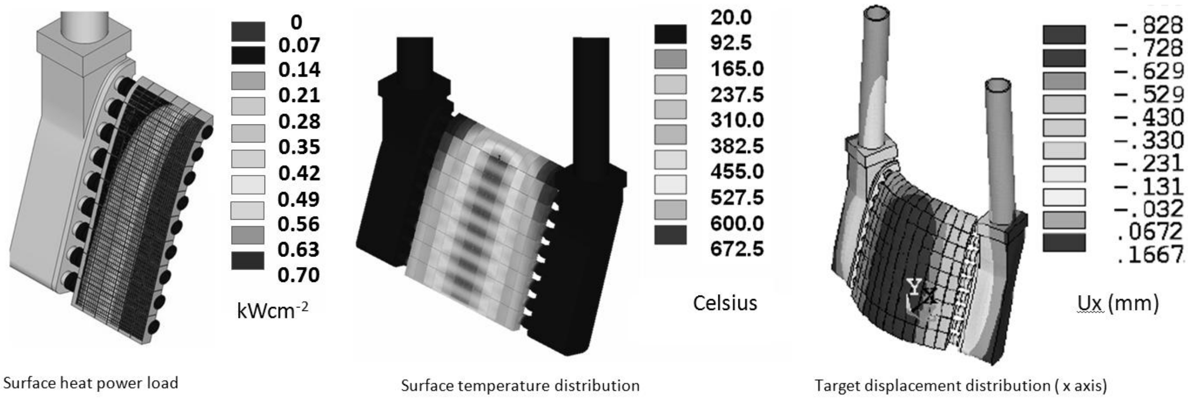

Fig. 5. Target surface heat power load distribution from SPES RFQ parabolic beam shape (left). Corresponding surface temperature distribution in steady state operation (center). Target deformation (displacements along beam normal direction) under thermal stress condition (right). ANSYS® code.

neutron moderating power because of better neutron slowing down properties for beryllium. In such a way a higher neutron flux per unit accelerator current at the patient position may be provided.

After a feasibility study by STC Sintez of Efremov Institute (S. Petersburg) lasted four years, a first full-scale prototype, shown in Figure 7, has been assembled on mid 2005. The new target positively passed the preliminary He leakage tests in late summer 2005, thus proving the proper manufacturing process was adopted. The Be-bulk neutron converter works with a slightly larger beam spot area (120x210 mm^2) on each target half, in order to lower the peak power density down to 0.5 $kWcm^{-2}$, thus providing a larger engineering safety margins

The half target prototype has then undergone a series of both operative and critical power test conditions in fall 2006 at the (HHF) Tsefey electron beam testing facility. The main goal was to assess both the target design criteria and the prototype reliability under heat loading condition as close as possible to the real ones. The electron scanning beam was tuned to heat the target surface with a power deposition parabolic profile, quite close to the one provided by the RFQ proton accelerator. The half target has undergone a series of test ranging from the designed 0.5 $kWcm^{-2}$ up to 0.7 $kWcm^{-2}$ peak power density. As a result the half target positively passed the test: no visible damage (cracks) has been observed by the visual inspection on the heated surface. Therefore this second target version may be considered as a possible alternative solution for the BNCT facility. The additional investigation concerning radiation damage tests the target undergoes after 5 MeV 30 mA irradiation are scheduled on 2007. The radiation damage study will be done by using both proton and high neutron flux beams in condition as close as possible to the real ones.

IV. PRESENT STATUS OF THE IRRADIATION FACILITY MODELING

As a general rule the neutron beam shaping and filtering assembly design is closely linked with the target

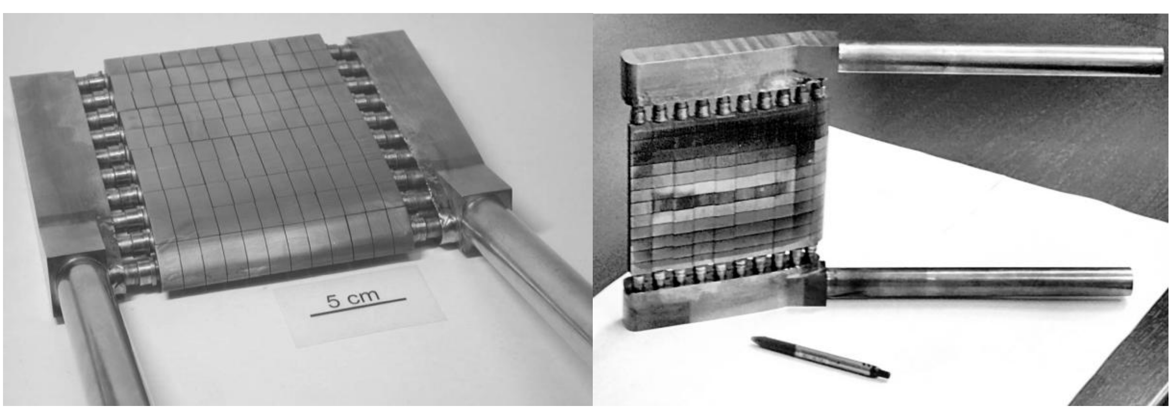

Fig. 6. Target prototype final assembly (left) and surface visual inspection after the first electron beam power test performed at the HHF facility (right).

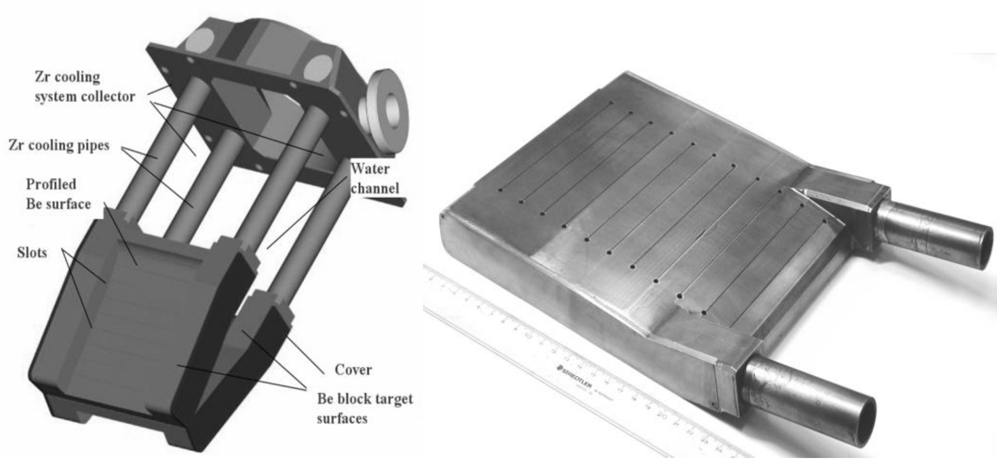

Fig. 7. The Be-bulk type neutron converter developed: final target layout (left). First, real scale, half target prototype constructed (right)

design, which must take into account the real-scale geometry of the neutron converter and the support structure effects on the neutron and gamma transport.

The experience gained in the last years at LNL labs with the 5 MeV, 1μA demonstration facility[14], driven by the CN Van de Graaff accelerator, revealed quite useful for the next Monte Carlo facility design stage. Different, realistic, Be neutron converter concepts were, in fact, tested during the preliminary feasibility study[15]. Extensive MCNPX simulation trials were performed, taking into account the CN demonstration facility as geometry reference. Basic beam parameters, calculated at the irradiation port, lying on the side surface, have then been compared, in order to get the basic knowledge on the beam shaping assembly layout useful to the final facility design. The treatment of shallow tumors with BNCT technique requires an eminently thermal neutron beam, with a limited non-thermal and gamma doses contaminations. A set of *in-air Figure Of Merit (in-air FOM)* beam reference parameters, given at the irradiation port, having a fixed standard area of 10x10 cm^2, have at this purpose been developed in the BNCT community, as a quick and useful method to compare the calculated parameters. The more stringent and widely accepted recommended goals, here used to make a useful comparison among neutron spectra calculated at beam port, supplied by the different facility configurations investigated, as well as related energy group ranges, are listed in Table I (Ref. 16). On the other hand, a detailed depth-dose distribution calculation only, inside tissues of a simulated phantom, would be a further, more reliable step, to characterize the neutron beam quality. However, due to the lack of a full set of experimental double-differential neutron yielding spectra at 5 MeV proton energy, the experimental data set at 4 MeV[17] have been used instead in the preliminary BSA design. Starting from the original demonstration facility configuration, new simulation trials were performed, all housing the final,

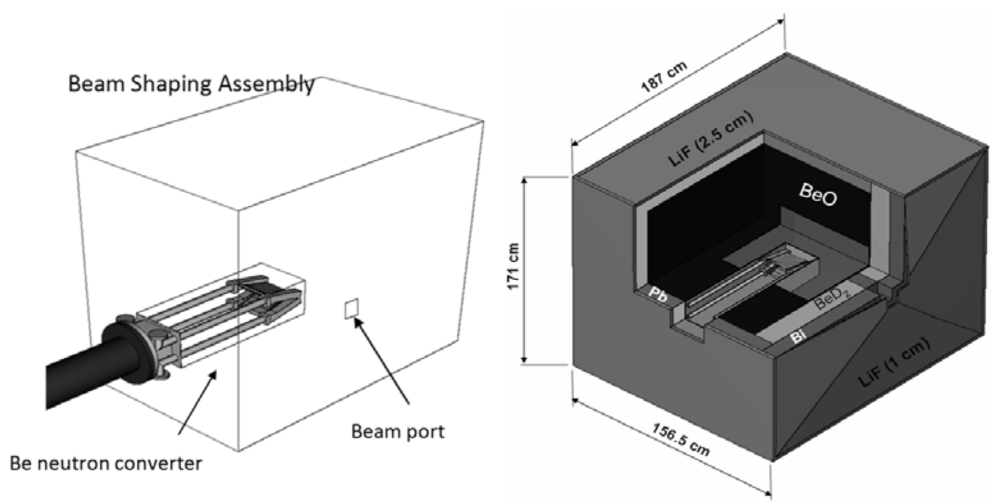

Fig. 8. 3D view of real-like geometry modelling for the irradiation facility (left). The current configuration proposed with the final Be neutron converter: MCNPX geometry

full-scale, saddle-type, Be neutron converter modelling. After having assessed different moderator models, the best results have been obtained with the irradiation facility shown in Figure 8, which beam port parameters calculated are listed in Table II.

The irradiation facility is basically made of a large (70x70x50 cm^3), Teflon (CF_2)-made, heavy water tank, which surrounds the neutron converter mainly towards the irradiation port. The tank is then inside a beryllium oxide (BeO) structure instead of the former RG-Graphite. This latter choice is to exploit its remarkable albedo property for better confining and moderating of the neutrons inside the BSA volume. Another important improvement is a 2.5 cm thickness of, hydrogen-free, lithium fluoride (LiF) panels around five out of six walls of the BSA (1 cm covering the beam port wall), for absorbing the thermal neutrons that escape throughout walls. A grid of 2x2 cm^2 pixel size was put in front of the wall for mapping the neutrons and gamma dose rate distribution over the beam port facility wall. Figure 9 show the results for the thermal neutron component of the beam. Additional data are published elsewhere[18]. The square on the 2D images represent the 10x10 cm^2 irradiation port position. Table III reports the average dose rate on the beam port and over the rest of the wall for each component of the beam, along with the fraction of the total dose rate that

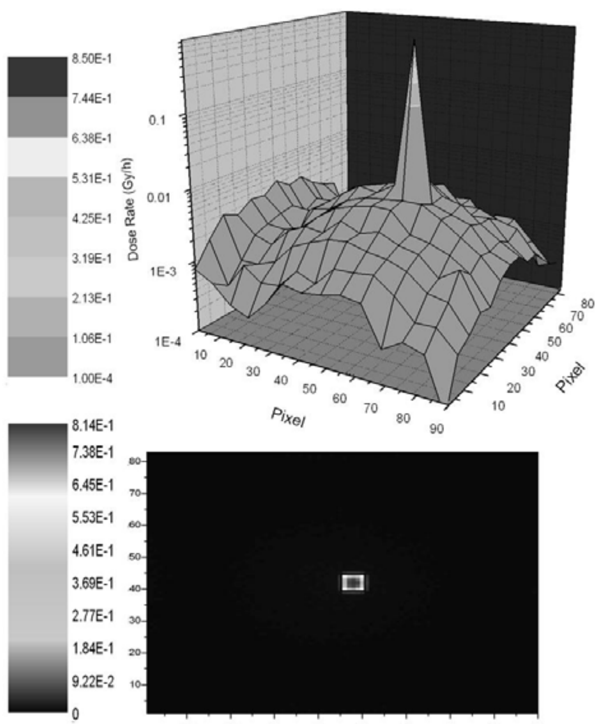

Fig. 9. Thermal neutron dose rate (Gy/hr) 3D profile over the beam port wall surface (top). The same plot in 2D view: the square represents the irradiation beam port position (bottom). The pixel size in the plot scales is 2x2 cm^2. MCNPX calculation

TABLE.I: BNCT in-air neutron beam port recommended limits. (Ref. 16)

BNCT beam port parameters		Required limits
Φ_{th}	$[cm^{-2}s^{-1}]$	$\geq 1 \cdot 10^9$
Φ_{th} / Φ_{total}		> 0.9
$\dot{K}_{n\ epi\text{-}fast} / \Phi_{th}$	$[Gycm^2]$	$\leq \sim 2 \cdot 10^{-13}$
$\dot{K}_{\gamma} / \Phi_{th}$	$[Gycm^2]$	$\leq \sim 2 \cdot 10^{-13}$
Fast energy group	$E > 10$ keV	
Epithermal energy group	10 keV $\geq E \geq$ 0.5 eV	
Thermal energy group	$E < \sim 0.5$ eV	

corresponds to the beam port area.

As can be seen from both the table data and the related figure, the neutron beam is very well collimated on the irradiation port for the proposed configuration. The less collimated component of the beam is due to the prompt gamma radiation, because those gammas are mainly produced by radiative capture of thermal neutrons inside the BSA volume since thermal neutrons diffuse stochastically inside the BSA. Nevertheless 92 % of the gammas come out through the irradiation port.

V. CONCLUSION

An accelerator-based source of thermal neutrons, for treating skin melanoma with BNCT technique, is foreseen in the framework of the SPES project, proposing a facility for exotic nuclei production at LNL in Italy. An extensive technological development has been performed on two different Be-based neutron converters. The prototypes constructed successfully passed the electron beam test at heat loading conditions quite close to that provided by the RFQ, which is the SPES proton driver. The present computational MCNPX design study of the proposed irradiation facility, based on a 4 MeV proton-driven Be neutron source, would already be able to provide a high collimated thermal neutron beam (99.7 %), fulfilling all the established design requirements for a BNCT irradiation facility. Further improvements are in progress for better shielding the gamma radiation. An experimental project is planned by LNL to measure neutron yield spectra from the $^9Be(p,xn)^9B$ reaction, using a thick target and 5 MeV proton beam. When the whole set of Be neutron data will be available, the actual model will be implemented and minor facility modifications are expected to be made. Because the total neutron yield at 5 MeV is expected to be at least a factor of three higher than those at 4 MeV[9,17], the final thermal neutron irradiation facility performance is expected to be better than results here presented.

TABLE.II: Summary of data calculated at beam port for the proposed irradiation facility for 4 MeV 30 mA proton beam. MCNPX calculations.

Beam Port data	
$\Phi_{th\ (E\leq 0.5\ eV)}$ $(cm^{-2}s^{-1})$	$(1.17 \pm 0.003) \times 10^{9}$
Φ_{th} / Φ_{total}	0.99
$\dot{K}_{n\ epi\text{-}fast}$ $(Gy{\cdot}h^{-1})$	$(3.00 \pm 0.70) \times 10^{-3}$
$\dot{K}_{n\ epi\text{-}fast} / \dot{K}_{n\ tot}$	4.27×10^{-3}
$\dot{K}_{\gamma}$ $(Gy{\cdot}h^{-1})$	0.58 ± 0.01
$\dot{K}_{\gamma} / \dot{K}_{n\ tot}$	8.2×10^{-1}
$\dot{K}_{epi\text{-}fast} / \Phi_{th}$ $(Gy{\cdot}cm^{2})$	$7.93{\times}10^{-16}$
$\dot{K}_{\gamma} / \Phi_{th}$ $(Gy{\cdot}cm^{2})$	$1.38{\times}10^{-13}$

TABLE.III: Summary of data calculated at beam port and at rest of wall for the current BSA proposed.

Beam component	Beam Port (Gy/h)	Rest of Wall (Gy/h)	Beam port fraction vs. total (%)
Thermal neutrons	$7.0{\cdot}10^{-1}$	$1.9{\cdot}10^{-3}$	99.7
Epithermal neutrons	$6.8{\cdot}10^{-4}$	$1.4{\cdot}10^{-5}$	98
Fast neutrons	$2.6{\cdot}10^{-3}$	$8.3{\cdot}10^{-5}$	97
Gamma	$5.8{\cdot}10^{-1}$	$5.3{\cdot}10^{-2}$	92

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