An overview for the SPES-BNCT project, proposed some years ago by Legnaro Labs, is given in such a presentation. The project aims at constructing an accelerator-based, high-intensity, thermal neutron beam facility for experimental skin melanoma tumor treatments. The project status-of-art is here reported.
Outline

a. The LNL SPES-BNCT project overview

b. The proton ion source (TRIPS) and the RFQ accelerator (TRASCO)

c. The Be neutron converter

d. LNL experimental activities: Be(p,xn) spectra measurements at the required proton beam energy

e. The Monte Carlo (MC) modeling of the accelerator-based neutron facility

The main items of presentation
The SPES-BNCT project, since its' beginning is based on three main activities:

a. The first one is the construction of an accelerator-based intense thermal neutron beam demonstration facility, aimed at the skin melanoma tumor treatment through a combined *Boron Neutron Capture plus Photodynamic (BNCT+PDT)* therapy approach.

b. The second one is the development of a new dosimetric system based on *microdosimetric detectors* for on-line biological dose monitoring in tumor & health tissues.

c. The development and test of new *boron carriers* having a combined photodynamic effectiveness.

The SPES-BNCT project, since its' beginning is based on three main activities:

a. The first one is the construction of an accelerator-based intense thermal neutron beam for malignant skin melanoma treatments with the BNCT technique;

b. The second one is the development of new miniaturised microdosimetric detectors, which have been already proven to be the best detectors to measure the radiation field quality. A dedicated presentation on that topic will be given in the seminar;

b. The third one concerns the development and test of new boron carriers, in order to couple BNCT and PDT (photodynamic) capabilities. Also to this activity, a dedicated presentation will be given in this seminar.
Different Institutions here enlisted, each one having expertise in the different topics requested for such a multidisciplinary project, have gathered round the SPES-BNCT study group.
The BNCT studies in LNL lab are being carried out since the mid of '90, starting with a preliminary feasibility study for an accelerator-based thermal neutron source. Such investigations led to the construction of a demonstration facility, here shown, installed at the Van de Graaff CN accelerator of LNL labs. It's basically made of an inner heavy water tank as moderator, surrounded by a RG-Graphite structure which acts both as a II neutron moderator stage and reflector.

- **Teflon D₂O tank (moderator stage)**
- Tank enclosed in a Reactor Grade (RG) Graphite structure (moderator-reflector)
- Irradiation position lying on the outer side surface for experimental measurements
- Be-tablet target heat power removal: simple forced air cooling system
A series of experimental measurements were carried out with such a demonstration facility and the main results obtained are here reported. For different proton energies, ranging from 3 to 6 MeV (the TRASCO accelerator output energy is included), the thermal neutron flux component was measured. The scale on the right shows the experimental measurements, while the scale on the left being the proton beam current hitting a Be target needed for a thermal neutron flux level of $10^9$ cm$^{-2}$s$^{-1}$ at least, in order to limit the patient irradiation within one hour. Starting from these basic data, it became clear that, using the high intensity TRASCO accelerator, having 5 MeV output energy and 30 mA proton current, a thermal neutron facility of about $3 \times 10^9$ cm$^{-2}$s$^{-1}$ flux level was therefore feasible.
The general layout of SPES facility complex is here shown. The BNCT project is part of an INFN special project named SPES (Study and Production of Exotic Nuclear Species) which has been recently approved by INFN board and devoted to the new frontier of nuclear physics research of exotic, unstable nuclei.
Other two facilities are under considerations, apart from the BNCT one, based on the same TRASCO high intensity proton driver: the radiation damage facility, and the LENOS facility devoted to nuclear astrophysics research. A dedicated presentation will be given in this workshop.
A 3D sketch of the building showing the high intensity part of the SPES facility complex. Two BNCT neutron sources are here considered, both using the same accelerator and the same neutron converter developed to get:

- a thermal neutron beam for the BNCT treatment of shallow tumors,
- an epithermal neutron beam dedicated to the BNCT treatment of deep-seated tumors.
A schematic sketch of the BNCT irradiation facility:

On the bottom a partial top view of the building layout, in which the accelerator-driven neutron source will be installed. The proton accelerator is made of a proton source (insert in the left corner) and of a RFQ (Radio Frequency Quadrupole) particle accelerator, part of which is shown in the top left corner. The proton beam features after the acceleration are shown on the top right corner. The proton beam will hit a thick beryllium target, to yield an intense fast neutron source (the so-called neutron converter). A multilayer system (the green square in the building layout) will slow the neutron energy down to less than 0.5 eV (thermal neutrons). From the neutron moderator, a collimated thermal neutron beam will come out to treat skin malignant melanomas (see the figure in the bottom right corner). Two green squares, that means two neutron moderators to get a thermal and epithermal neutron beam facility, are taken into account in such a project and visible in the building layout.
The TRIPS proton source here shown, is able to supply a nominal beam current of 40 mA with a good proton fraction and low emittance (see main source data measured). The proton source has been designed and constructed at the INFN south labs in Catania (LNS). It was then moved at LNL and installed with all the required equipments at the end of 2005. After some revisions the first, stable, and high current beams were extracted in Legnaro labs almost three years ago.
The proton accelerator which will be used. Here you see a layout sketch of the RFQ designed in Legnaro labs at the end of '90 for the TRASCO (TRASmutazione Scorie) nuclear waste transmutation program for ADS reactor systems. The accelerator is about 7 meters long and made of six modules mounted together (the RF cavities) resonating at 352 MHz fed by one, high power, RF Klystron. The main technological challenge for such an accelerator type comes from the main constraint to keep beam losses below 1% along the structure, due to the high beam current. This implies the requirement of very severe mechanical tolerances (around 20 μm) in the geometry of the structure, realized in ultra-pure (OFE) copper, while operating with a very high RF power dissipation.
The construction status of main RFQ accelerator components: the first RF high power tests, to assess the accelerator performance which are expected with respect to the specifications, are scheduled to be performed in fiscal year 2010.
The neutron converter (target) developed in the last years, has been designed in collaboration with the Efremov Institute in S. Petersburg (Russia). The target is based on beryllium tiles which are brazed on copper alloy cooling pipes. The peculiar V-shaped like profile has been chosen in order to have a constant power density deposition along the beam direction on the full target surface, while getting a neutron yielding volume as small as possible. Light water is used as coolant.
A full set of coupled thermal-structural-fluid dynamical analyses have been carried out at the design stage, in order to have the basic information on the target response in steady-state operation, using a proton beam power distribution on target similar to the one expected by the RFQ accelerator. The thermal-mechanical-fluid dynamical calculations, here reported from the 3D real model, have shown the hot spot temperature on the Be surface be around 700 °C. On the other hand the mechanical deformations and stresses are within the recommended design limits.
The main steps followed for the real-size target prototype construction:

1. The Be-armored cooling pipes;
2. The machining of the Zr alloy manifold and the collector plates of the cooling system;
3. The cooling pipe elements are welded on the collector plates and the target surface is machined by programmed Electrical Discharge Machining (EDM), in order to remove distortions introduced during brazing and welding to get this way a uniform Beryllium surface profile;
4. The welding of the cooling system manifold with the extension pipes to the collector plates. The half target is now ready for the electron beam power tests.
The Be target reliability and lifetime assessment

1. Thermal-mechanical measurements
   Target response under cycling stresses at operative conditions
   **Design parameters:** 1600 hrs running beam before replacement (200 times/yr, 8 hrs operation)

2. Neutron damage measurements
   bulk damage under neutrons irradiation at the scheduled fluence levels
   **Design parameters:** $\Phi_n \simeq 5 \times 10^{14}$ cm$^{-2}$s$^{-1}$ estimated inside Be bulk during operation
   1600 hrs running beam $\Rightarrow F_n \simeq 3.5 \times 10^{18}$ cm$^{-2}$ neutron fluence
   Radiation damage level expected before replacement: (0.05 - 0.1) dpa

3. Proton damage measurements
   surface damage under protons irradiation at the operative power density and scheduled beam time
   **Design parameters:** $\Phi_p \simeq 5 \times 10^{14}$ cm$^{-2}$s$^{-1}$ averaged over the target hitting surface area during operation
   1600 hrs running beam $\Rightarrow F_p \simeq 2.9 \times 10^{21}$ cm$^{-2}$ proton fluence
   Radiation damage level expected before replacement: $\sim 1$ dpa

A set of tests are needed which are summarized in this slide, to get both the target reliability and lifetime estimation under the operative beam irradiation conditions. First, a series of thermal mechanical tests, in order to assess the cooling system capability and the mechanical deformation and stresses response under the cycling thermal input (the beam on and off per each run). Second, the radiation damage tests, due to the neutron source yielded by target itself and the Be surface damage due to the implantation of protons hitting the surface, being the penetration depth about 300 $\mu$m. The operative parameters scheduled and the radiation damage level expected are also reported.
The half target prototype has then undergone the first electron-beam full power tests on March 2006. The Tsefey electron beam testing facility at Efremov Institute is however able to supply 60 kW of max power, almost the half of 150 kW total heat power each part of target is demanded to remove. The approach followed was therefore to test half of it, at the maximum facility power, using the electron scanning beam “tuned” to arrange a hitting profile similar to what expected by the RFQ proton accelerator.

A proper water-cooled calorimeter, shown in the upper-right picture, was used as a probe to measure the power density distribution in steady-state conditions along the scanning surface. The half target has undergone 2 full tests at 750 W/cm² peak power density, with a total of 1350 thermal cycles. This means an irradiation time longer than 11 hours. As a result the half target positively passed the test: no any visible damage has been observed at the visual inspection.

However to get a more critical thermal-induced stress condition an additional test has been performed, hitting only four out of ten pipes, under 40 kW beam power. That would mean a total power of about 100 kW for the whole surface of half target. Such a test is more severe due to the unloaded pipes, which prevent the thermal expansion of loaded ones. The stresses at the pipe connections with collector plates are, in fact, superior than expected during normal operation, due to both the higher beam power removed by each pipe and an unfavorable, not uniform, beam power loading. In spite of such more severe test conditions, the target has undergone additional 1000 cycles at the maximum reference power density of 750 W/cm². As a result the half target positively passed the test: no any visible damage (cracks) has been observed after the visual inspection.

It may be therefore concluded that, the target design and manufacturing technology adopted meets the design requirements.
The other critical test is related on how the mechanical properties degradation of Be material (mainly hardening and embrittlement) change during the operating condition, under a mixed neutron-proton field. Such a knowledge is, in fact, fundamental for both the target reliability and lifetime estimation. Taking into account the two different processes involved, a radiation damage test has therefore been planned in two basic steps. The first one, based on a series of neutron irradiations at different fluence levels inside Material Testing Reactor (MTR) facilities has already been completed.

The results of a series of neutron irradiation tests, using the same beryllium material which has been used for the construction of target prototype, are here reported.

Both unirradiated and irradiated samples were tensile tested in standard condition at room temperature as well as at the reference temperature of 300 °C. The main results point out that, in the investigated and expected damage range of 0.0005–0.1 dpa, (a parameter proportional to dose released by neutrons into material causing atomic displacements into the crystal lattice) the Be alloy retains its strength and ductile bulk properties within the allowable limit. The hardening effect, i.e. the variations in the yield strength measured, a parameter showing the limit of material elastic behaviour, is better than expected due to comparison with data already available for Cu material tested at the same temperature. The dislocations in the atomic grid, induced by neutron scattering, are thus partly recovered for the relatively high temperature level.
Another important issue is the generation and accumulation of helium inside the bulk material during irradiation, because of some nuclear reaction channels already open having threshold just at few MeV energy. An alpha particle is thus produced, which is trapped inside material causing the creation of small bubbles. In such a way the accumulation and alignment of He bubbles along the original defects inside the material, might likely become the starting points for the brittle fracture propagation. During the tests performed the helium bubbles have been observed (see pictures) only at higher damage levels which are expected at the target operative end-of-life (about 0.08 dpa). Therefore it may be concluded that this appear to be not a concern for the target operation and lifetime.
The second step is the radiation damage investigation of Be material under a proton beam having the same energy (5 MeV) and maximum power density (0.7 kW/cm²) on target surface. Such beam parameters are similar to what is foreseen in the “hottest” part of target surface under TRASCO RFQ irradiation at full beam power. The preparation of test setup, just started, was however interrupted afterwards. Currently, there is no indication about the test restarting for its completion.
The summary of Be material tests planned: the main design parameters and, the final test response. Although the results of the remaining, important proton test is still lacking, there are however indications that the result expected is, as a rule, similar to the estimated one. That means no any critical damage under RFQ proton beam parameters to compromise the target lifetime as well as reliability.
The compact neutron source will be produced via the $^9\text{Be}(p,xn)^9\text{B}$ reactions into a thick beryllium target. However available data at 5 MeV refers to 0° only and a systematic characterization of the double differential distribution was therefore carried out at different emission angles between 0 and 120 degrees. Such measurements are needed for the final stage of Beam Shaping Assembly (BSA) modelling. Measurement of the neutron spectra, performed at the experimental hall of CN accelerator at LNL, were performed using two different spectrometers:

1. Bubble Induced Neutron Spectrometer (BINS) also known as Superheated Drop Detector (SDD)
2. Recoil-proton spectrometer based on a Monolithic Silicon Telescope (MST).
Here are reported two measurements using the monolithic silicon telescope, both at low and maximum energy resolution, about the neutron spectrum at the incoming proton beam direction, downstream the target, compared to the only one available at 5 MeV and measured years ago at MIT, using the standard Time-of-Flight method. As can be seen the matching between the two spectra (in the high energy resolution mode) is quite good taking into account the two different techniques. Right now the detector is not able to count neutrons having energy lower than 0.3 MeV.
The other neutron spectra (in low resolution mode) measured with the Monolithic Silicon Telescope, compared with former measurements at 4 MeV performed at MIT. Starting from this preliminary results, the neutron source level expected with TRASCO, at full beam performance, coupled with the Be target designed, is estimated about $10^{14}$ s$^{-1}$. Such a level is as high as generated inside the core of TAPIRO fast reactor located in ENEA Casaccia Lab. Therefore with such an accelerator we can generate a compact neutron source having relatively low energy, which level is similar to those provided by a low-power nuclear reactor.
Here are shown the preliminary spectra taken with the alternate BINS-based system. Such a detector is not affected by the neutron-gamma discrimination, as the MST is. Moreover it is able to "see" neutrons down to the thermal energy range in higher level neutron fluxes. However, being a few channel spectrometer, the unfolding procedure is basically dependent on \textit{a-priori} information on the spectrum structure expected. A refinement iterative procedure (here not yet accomplished) has therefore to be followed for the final solution. Improvements are in progress.
The neutron source coming out from the Be target has to be slowed down to the thermal energy range. A Beam Shaping Assembly (BSA) system has therefore to be modeled and designed around it. As a general rule, the BSA modeling is closely linked with the target design, which must take into account the geometry of the neutron converter and the effect of the support structure on the neutron and gamma transport. Moreover, the BSA study and final design is strictly related to the knowledge of the energy distribution of fast neutrons emitted by the target in the angular interval of interest. The reference parameters to be fulfilled by a neutron beam, at the so called “beam port” (i.e. the neutron flux level, spectral ratio, as well as contaminant by unwanted beam components) to be properly used for BNCT applications on shallow tumors (skin melanoma) are here reported, based on internationally recognized standards.
A Beam Shaping Assembly (BSA) system had already been modeled with high accuracy in the last years, although referring to a beryllium-proton driven neutron yielding data available at 4 MeV energy. A final modeling step was therefore needed. Here is the current 3D sketch of BSA using the last Be spectral data. The gamma shield in Pb-Bi and the covering panels in LiF strongly limit both the gammas and neutrons that escape from any other direction of BSA, except for the beam port.
The calculation results using the preliminary spectra data at 5 MeV: the main modeling parameters at beam port are within the reference limits.
To give an idea of the effectiveness of the BSA proposed, a 3D as well as 2D distribution of the thermal neutron component of irradiation beam is plotted over the patient facing wall. The collimation provided by the system is quite good.
Conclusions

- **TRIPS source:** in operation at LNL
- **RFQ:** built and ready for RF high power test
- **Be target:** already built and used for lifetime measurements. Additional radiation damage tests (although not completed yet) confirm the design requirements.
- **Infrastructures:** preliminary design available for the SPES building for the high intensity accelerator-driven facilities
Thank You

Legnano National Laboratory aerial view

SPES

New LNL area for RIB’s production and BNCT

PIAVE-ALPI

Exp. Halls