CHAPTER XII

SPES NEUTRON BEAM

12.1 The SPES BNCT project: a thermal neutron beam facility for skin melanoma experimental treatment

12.1.1 Introduction

BNCT is a binary radiation therapy. First, a boronated substance is injected in the patient body, secondly the patient is irradiated with thermal or epithermal neutrons. The boronated substance is harmless and designed to be preferably absorbed by tumour cells. Because of the high $^{10}$B thermal neutron capture cross section (3837 barn), the nuclear reaction $^{10}$B(n,α)$^7$Li is likely to occur. The nuclear reaction products ($^4$He of 1.47 MeV and $^7$Li of 0.84 MeV) are densely ionizing charged particles, the ranges of which in soft tissues (~8 µm for the α particle, 5 µm for the lithium ion) are as short as a cell diameter (~10 µm). Therefore, only cells containing $^{10}$B are damaged, remaining the aside cells intact. This peculiar behaviour of energy releasing allows of conceiving a cellular radiation therapy, which is very useful whenever tumour cells infiltrate the healthy tissue extensively. For exploiting this nuclear reaction in radiation therapy, a large research activity is going on in Europe, Japan and United States that aims to find optimal $^{10}$B carriers able to maximise $^{10}$B uptake in tumour cells with respect the healthy cell uptake, as well as the best radiation dosimetry to use.

Up to now two carriers have been used: the boronated phenylalanine (BPA) and the borocaptate (BSH). Both of them have only a limited selectivity for tumour cells. In spite of that, the first patient with malignant skin melanoma (MM) was treated by BNCT on 1987. The tumour was a subcutaneous metastatic lesion of the occipital region. The irradiation was delivered in a single fraction after perilesional administration of BPA, at the Kyoto University [1]. Thanks to the completely positive response and tolerability reported, about 20 patients with MM were treated in Japan with thermal neutrons applying the BNCT technique. In more recent clinical trials, because of the tumour deeper location, epithermal neutrons were used instead of thermal neutrons [2, 3]. Skin MM has been treated also by the Bariloche reactor in Argentina on 2004 with good therapeutic results [4].

However, available reports and retrospective studies show that the method is not standardized [5][6]. Moreover, published reports are not exhaustive. One of the actual limits for the therapeutic plan optimisation is the poor knowledge of the maximum sustainable healthy tissue damage; datum that determines the radiation-field maximum exposition. Such information depends in fact on the knowledge of radiation tissue sensitivity, which changes with radiation changes. Dosimetric measurements nowadays used in BNCT research centres are poorly significant for the biological effectiveness [7]. Intensively research is going on to improve the radiation quality assessment of BNCT and other hadronic beams [8].

The Legnaro BNCT project aims to use the intense proton beam provided in the framework of SPES facility to generate an intense thermal neutron source, which will be used for MM experimental treatments.
12.1.2 The Skin melanoma case

Once a rarity in oncological management, there has been an exponential increase in incidence of MM during the past 20 years. 9000 new MM cases were observed in the United States in 1975 with approximately 5000 expected deaths. The large MM increase is documented by the fact that in 1995 were estimated 34100 new cases with an expected 7200 cancer deaths [9]. In the Veneto region (Northeast of Italy) we have 15 new MM per 100,000 inhabitants a year (about 750 new cases per year). Veneto region has therefore the supremacy for this tumour in Italy [10], where the new cases per year are assessed to be about 5,000. The actual MM therapeutic treatment uses a multi-technique approach: surgery, hyperthermia, chemotherapy, radiation therapy. However, the actual radiation therapy, performed with low-LET radiations, is poorly effective. On the contrary, high-LET tumour-targeted radiations have shown to be highly effective. The 5% of MM tumours develop surface metastases, which can be treated with BNCT. The 40% of patients with MM develop metastases in other parts of the body. Some of these metastases could be successfully treated with BNCT. However it is worthwhile taking into account that MM cannot always be controlled locally without mutilating surgery, there may be a role for high LET radiotherapy in association with conservative surgery as a primary treatment such as in limb sparing and in head and neck tumours.

12.1.3 The SPES-BNCT project

In the framework of SPES project, a high fluence-rate thermal neutron facility will be constructed for treating patients with MM. The facility layout is shown in figure 12.1. The ion source (TRIPS) will supply 50 mA of protons at 80 keV of energy. Protons will be accelerated by a radio frequency cavity (RFQ) up to 5 MeV of energy, bent at 90° and driven by a dedicated high intensity proton beam line onto a high power (150 kW) neutron converter. The neutron converter exploits the reaction 9Be(p,n)9B (Q = -1.85 MeV), which gives rise to a fast neutron spectrum, the average energy of which is of about 1.5 MeV when the beryllium target is thick. In order to moderate the neutron energy down to thermal or epithermal energy, the beryllium target will be put inside a multilayer structure called neutron moderator or energy shifter. In figure 12.1, the moderator is sketched. It has a heavy water core. Nuclear graphite and a lithium layer are designed to obtain a collimated thermal neutron beam, which will be properly used to treat patients affected by MM.

Patients affected by MM have been already treated in Japan and Argentina by using borophenylalanine (BPA) as boron carrier. Although MM have been treated successfully,
dosimetric treatment protocols used will cannot be transferred to the future LNL facility, since its radiation quality, hence the its biological and therapeutic effectiveness, will be certainly different. The only known radiation quality measurement that can be processed to give the biological effectiveness of the radiation field is the microdosimetric spectrum of the field. Therefore, the SPES-BNCT project includes research and development of microdosimetric detectors. The research aims to construct miniaturized tissue-equivalent gas proportional counters (twin TEPC) able to perform fast and reliable microdosimetric measurements in therapeutic BNCT fields.

Since the beginning, the photobiology group of Padova University biological department joined the project to study and to develop new boron carriers for increasing the effectiveness of the BNCT technique. Together with the radiation field flexibility (due to the possibility of changing radiation field just changing neutron moderator) and the microdosimetry technology, the research of new MM-highly-selective boron carriers characterizes the SPES-BNCT project.

12.1.4 High intensity proton-beam transport line (HIPL)

Fig. 12.2: The BNCT beam line (HIPL) is connected with the Medium Energy Beam Transfer (MEBT) line with a 90° bending magnet.

After the RFQ exit, the 5 MeV proton beam (165kW) has to be transported to the BNCT facility with a dedicated transport line, the so-called HIPL (see figure 12.2). Since the same RFQ will inject the proton beam into the high energy linac (DTL) trough a Medium Energy Beam Transfer (MEBT) line, for eventually produce radioactive nuclei, a bending magnet inserted in MEBT centre will turn the beam toward the BNCT facility. The 90° dipole is inserted in between two focusing quadrupoles, which are 600 mm apart. Such a short distance has been chosen to maintain the quality of the beam going to the DTL.

In order to have the designed proton beam intensity of 30 mA on the neutron converter, 33 mA have to be extracted from the RFQ, because the HIPL has 6% of beam loss. The 40 mm proton beam will run inside a 100 mm pipe line. However, in order to arrive at the neutron converter with big enough geometrical cross section for reducing the power density, the last transport line quadrupole focalizes the proton beam at about 5 meter apart the neutron converter. After the focus, the proton beam will run therefore inside a 200 mm pipe line. At the end of the HIPL, proton beam is collimated to properly copy the neutron converter (see paragraph 12.3.2)
projection area. The squared collimator will be cooled in order to dissipate 8 kW (1.6 mA of stopped proton current) of power.

The neutron converter activation after 1600 hours of continuous beam time is very high (see paragraph 12.3.3). Even at two meters of distance from the converter, dose rates due to gamma emitters are very high. In figure 12.3 dose rates of different materials are plotted against the cooling time. Calculations have been performed with a 4 MeV proton beams, because neutron yield data at 5 MeV miss (see paragraph 12.3.4). Dose rate data of figure 12.3 are expected to be more than 3 times higher at 5 MeV of protons. However, data of figure 12.3 have to be considered as well an upper limit, because they are simple analytical calculations based on the point-source approximation and point out the activation dose after the maximum permissible proton fluence (1600 hours of 30 mA protons). Although more precise calculations will be done as soon as neutron yields of 5 MeV protons will be available (see paragraph 12.3.5), it is already rather clear that the last part of HIPL can not be easily serviced. Weeks after the last beam stop, the total dose rate at 2 m will be likely close to 1 mGy/hr. Conversely, it could be the need of quickly substituting the neutron converter for some unexpected failures. Therefore, the HIPL last piece will be equipped with a full-remote target extraction system, the sketch of which is in figure 12.4. The target extraction system will be housed in a 3x4x5 radiation shielded room (see figure 12.5).

![Fig. 12.3: Maximum dose rates, after 1600 hours of 4 MeV 30 mA proton beam, at 2 m of distance from the Be-tile neutron converter due to different target components.](image-url)
12.1.5 The neutron converter

A R&D effort has been carried out in order to select the proper neutron converter type consistent with SPES design specifications. After extensive MCNPX simulation trials on the LNL-CN demonstration facility [11], beryllium has revealed as a whole the best solution, taking into account the neutron yielding performance as well as the related target engineering know-how. As a general rule the target design is closely linked with the design of the neutron beam shaping and filtering assembly (see next paragraph), which must take into account the geometry.
of the neutron converter and the support structure effects on the neutron and gamma transport. Different engineering as well as operative and safety issues, concerning the neutron generator have thus to be carefully assessed, depending on the main SPES project constraints.

Because of the high impinging power (50 kW of thermal power load) the best solution for target cooling has been the most important item under investigation. In order to make use of reliable and already proven target cooling systems, the beam spot area has to be modelled to keep the surface heat load to a level \( \leq 0.7 \text{ kWcm}^{-2} \). After both neutronic as well as technological feasibility studies lasted two years, an original beryllium-based target concept, shown in Figure 12.6, has thus been developed in collaboration with the STC Sintez of Efremov Institute in S. Petersburg [12]. The target main structural component is of 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 of bronze (CuCrZr) alloy onto 0.3 mm thickness SS pipe with the following 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. In order to remove the 150 kW heat load with an almost constant power distribution on the beryllium target surface (along beam axis direction), a V-shaped target profile has been chosen.

**Fig. 12.6:** 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). Be-tile neutron converter and main structural components (right).

**Fig. 12.7:** 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.
The V-shaped profile allows also to satisfy the constrain of having peak-power densities ≤ 0.7 kWcm². Such a target approaches as close as possible the ideal point-like source. Target has been designed to be removable from the BNCT facility, for easy inspection as well as maintenance purposes. Some concerns relating to cooling fluid capability, cooling system simplicity as well as its cost has led light water to be chosen as coolant, for both the target and the related collimator. A detailed thermal-mechanical coupled analysis has also been performed.

**Fig. 12.8:** Neutron converter prototype with beryllium tiles (left) and surface visual inspection after the first electron beam power test performed at the HHF facility (right).

**Fig. 12.9:** Be-bulk neutron converter design (left) and the half-converter constructed prototype (right).
to assess the maximum working temperatures, the related target mechanical stresses and deformations, both under static and cycling loading operating conditions. Target lifetime estimation was performed as well. The steady state thermal analysis results are reported Figure 12.7. The maximum temperature calculated in different components: beryllium (673 °C), bronze (362 °C), SS (344 °C) and Zirconium alloy (21 °C) are well below the correspondingly melting points. The stress intensities calculated at loading stage in all structural parts are well within the design limits.

Several mock-ups have been manufactured and tested at the High Heat Flux (HHF) Tsefey electron-beam facility at the Efremov Institute, with different power density levels, up to 1.1 kWcm\(^{-2}\). All destructive analyses performed on inspected samples revealed good brazing quality, with an uniform brazing layer. The joint between tiles and cooling pipes was not damaged during the tests and no any visible cracks and erosions have eventually been observed inside Be thickness. The first, full-scale target prototype, shown in Figure 12.8, finally constructed at the end of 2004, successfully passed preliminary series of both operative and critical electron-beam power test conditions up to 0.75 kWcm\(^{-2}\) in March-July 2005.

Technology to brazing beryllium layers on bulk CuCrZr supports, although well proven in the framework of ITER project, has the drawback to give rise to relatively high prompt gamma ray yield at the facility beam port. In order to reduce such unwanted gamma component, a technological research has started aiming to a reliable neutron converter made of bulk beryllium only. All target components like manifolds, cooling pipes, neutron converter layers have been designed starting from a full Be block. The main advantage obtained, in addition to a lower gamma yield, is less assembling parts and considerably less brazing joints. Moreover, the same neutron yield would be provided, with a better neutron moderating power than the Be-tile converter. In other words, since the Be bulk partially moderates by itself fast neutrons, neutron moderator dimensions can be smaller.

After a feasibility study by STC Sintez of Efremov Institute (S. Petersburg) lasted four years, a first full-scale prototype (see Figure 12.9) has been assembled on mid 2005. High pressure tests with He gas to find out cracks inside bulk material have passed on late summer 2005. The Be-bulk target works with a slightly larger beam spot area (120x210 mm\(^2\)) in order to lower the peak power density down to 0.5 kWcm\(^{-2}\). That because the Be thermo-mechanical properties are less effective than those ones of copper alloy.
The half target prototype has then undergone a series of both operative and critical power test conditions on fall 2006 at the (HHF) Tsefey electron beam testing facility. The main goal was to assess the target 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 (Figure 12.10), which is close to that one provided by the RFQ proton accelerator. The half target has undergone a series of tests ranging from 0.5 kWcm\(^{-2}\) up to 0.7 kWcm\(^{-2}\) peak power densities. The half target positively passed the test: no any visible damage (cracks) has been observed at the visual inspection on the heated surface. Therefore this second target version may be taken into account as a possible, alternative solution for the BNCT facility. Additional tests concerning radiation damage the target undergoes after 5MeV 30mA irradiation are scheduled on 2007. The radiation damage study will be done by using both proton and high neutron flux beams.

12.1.6 Neutron converter activation

Simple analytical calculations have been performed to assess the maximum neutron converter activation. Calculation have been performed taken into account the Be-tile converter. Activation has been calculated after a single run of 1600 hours, which is assessed to be the mean lifetime of the converter. This assumption is conservative, since the neutron converter unlikely will work for more than 8 hours a day. Therefore, 1600 hours correspond to 6-12 months of continuous daily work. The proton beam energy used for calculating the neutron yield has been of 4 MeV (see next paragraph). The assumed target irradiation conditions are listed in table 12.1.

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>Thermal neutron fluence rate</th>
<th>Total neutron fluence rate</th>
<th>Continuous operation</th>
<th>Total neutron fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.15·10(^{13}) s(^{-1})</td>
<td>5.0·10(^{11}) cm(^{-2}) s(^{-1})</td>
<td>7.0·10(^{11}) cm(^{-2}) s(^{-1})</td>
<td>1600 hours</td>
<td>1.0·10(^{19}) cm(^{-2})</td>
</tr>
</tbody>
</table>

Fig. 12.11: Decay schema of \(^{10}\)Be.

The exact components fraction and the elemental impurities of the 4 industrially-produced structural materials used for constructing the Be-tile neutron converter are listed in table 12.2. Results of post irradiation residual activity and contact dose-rates estimations are reported in figures 12.12 and 12.13. Irradiation conditions are those ones of table 12.1. Copper alloy pipes are responsible for the highest activation and dose contribution. This is mainly due to the short
half lives of $^{64}$Cu and $^{66}$Cu, the decay of which dominates the first 3 weeks of target cooling. Impurities play the biggest role after 1 month, because of their intermediate (mainly $^{64}$Zn $^{54}$Fe, $^{60}$Co) half lives. Impurities with very long lives like $^{93}$Zr ($T_{1/2} = 1.53 \times 10^6$ years) and Nb ($T_{1/2} = 20300$ years) prevent the converter total decay. The activity of beryllium that is due to nuclides created by the direct (p,xn) reaction channels opened at 4 MeV may be considered negligible. Therefore, beryllium activation depends only on $^{10}$Be, which is created by $^9$Be neutron capture. However, $^{10}$Be is a pure beta emitter, as shown in figure 12.11. Therefore, activation of the Be alloy used entirely comes from the impurities included. This conclusions are valid also for a 5 MeV proton beam. However, it is worthwhile to remember that, because of the higher neutron yield at 5 MeV, activation will likely be higher of a factor 3-4.

Table 12.2. Elemental composition weight fraction of the Be-tile converter materials.

<table>
<thead>
<tr>
<th>Be S65 (wt%)</th>
<th>SS316 LN (AISI) (wt%)</th>
<th>CuCrZr alloy (wt%)</th>
<th>Zr-1%Nb alloy (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>98.5</td>
<td>Cu</td>
<td>Zr</td>
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<tr>
<td>O</td>
<td>0.64</td>
<td>Fe</td>
<td>99.01</td>
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<tr>
<td>C</td>
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<td>Cr</td>
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<td>Fe</td>
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<td>Ni</td>
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<td>Mo</td>
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<td>Mg</td>
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<td>Si</td>
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<tr>
<td>Al</td>
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<td>Ti</td>
<td>1.8</td>
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<td>N</td>
<td>0.0225</td>
<td>Cu</td>
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</tr>
<tr>
<td>Ni</td>
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<td>N</td>
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<tr>
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<tr>
<td>Hf</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total mass estimated (gr) | 352.5 | 20.9 | 1597.3 | 2393.5 |
When the neutron converter is hit by 30 mA 5 MeV proton beam becomes an intense fast neutron source with a maximum of energy of about 3 MeV and an average energy of 1.57 MeV in forward direction. In order to treat MM tumours, fast neutrons have to be moderated down to thermal energy, for superficial tumours, or to epithermal energy for deeper tumours. The neutron-moderator design aims to optimise in-air radiation field parameters, called figures of merit (FOM), at the irradiation port of 10x10 cm² nominal area. The BNCT community, has a quick and useful method to assess the design’s FOM for thermal neutron fields (see table 3) [13].

<table>
<thead>
<tr>
<th>BNCT beam port parameters</th>
<th>Required limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{th}$ [cm⁻²s⁻¹]</td>
<td>≥ 1×10⁹</td>
</tr>
<tr>
<td>$\phi_{th}/\phi_{\text{total}}$</td>
<td>&gt; 0.9</td>
</tr>
<tr>
<td>$(\tilde{D}<em>{n,\text{fast}} + \tilde{D}</em>{n,\text{epi}})/\phi_{th}$</td>
<td>≤ ~2×10⁻¹³</td>
</tr>
<tr>
<td>$D_\gamma/\phi_{th}$</td>
<td>≤ ~2×10⁻¹³</td>
</tr>
</tbody>
</table>

Fast energy group $\phi_{\text{fast}}$ E > 10 keV
Epithermal energy group $\phi_{\text{epi}}$ 10 keV ≥ E ≥ 0.5 keV
Thermal energy group $\phi_{\text{th}}$ E < ~0.5 eV
Exploiting the know-how gained in designing the BNCT demonstration facility constructed at the CN 7 MV Van de Graaff laboratory [14, 15], a realistic neutron moderator for MM treatments has been designed. The neutron source is the real Be-tile neutron converter of figure 12.6. However, due to lack of an experimental set of complete double-differential neutron yield data at 5 MeV of proton energy, the experimental data set at 4 MeV [16] has been used in this preliminary design. Such a choice is expected to be conservative with respect the FOM, in spite of the higher mean neutron energy at 5 MeV than at 4 MeV of proton beam, 1.57 MeV and 1.06 MeV respectively [16]. In fact, because of the known resonances between 4.5 and 5.0 MeV, the total neutron-yield production is expected to be much higher at 5 MeV than at 4 MeV of proton [17, 18]. Recent experimental neutron yields at 0° confirm such an expectation. Neutron production at 5 MeV has been in fact measured to be 3.8 times higher than at 4 MeV [16].

Fig. 12.13: Contact doses against cooling time due to activated materials of figure 12.12

Fig. 12.14: MCNPX real-like geometry modeling of the neutron converter inserted inside the neutron moderator (left). Close-up view of the Be neutron converter (centre). Neutrons emission points over the entire source emitting surfaces (right).
In figure 12.14, the neutron converter is sketched, together with the 3D plot of the neutron emission points, all generated within a thin layer of about 300 µm, due to a 4 MeV proton beam and following the profile of the neutron converter surface. More detailed are published elsewhere [14].

After having calculated several moderator models best results have been obtained with the moderator shown in figure 12.15. The facility main features are the heavy-water tank, around the neutron converter and the beryllium oxide (BeO), which reflects neutrons towards the irradiation port with high efficiency thanks to its *albedo* properties. Another important feature is the 2.5 cm thickness of hydrogen-free lithium fluoride (LiF) panels around five out of six walls of the moderator for absorbing thermal neutrons that escape throughout walls. The sixth wall (where the irradiation port is) has a thicker panel of 1 cm.

![Fig. 12.15: The best configuration proposed with the final Be neutron converter: MCNPX geometry](image)

Fig. 12.15: Neutron fluence rate per lethargy unit (left) and neutron kerma rate (right) spectra at beam port irradiation position (dotted line) and averaged all over the rest of the wall (full line) of moderator of figure 15.
Fig. 12.17: Thermal neutron dose rate (Gy/h) 3D profile over the patient-facing wall surface (left). The same plot in 2D view: the square is the irradiation beam port position (right).

Fig. 12.18: Epithermal neutron dose rate (Gy/h) 3D profile over the patient-facing wall surface (left). The same plot in 2D view: the square is the irradiation beam port position (right).

Fig. 12.19: Fast neutron dose rate (Gy/h) 3D profile over the patient-facing wall surface (left). The same plot in 2D view: the square is the irradiation beam port position (right).
Figure 12.16 shows the neutron fluence rate per lethargy unit (cm$^{-2}$s$^{-1}$u$^{-1}$) and the related neutron kerma rate (Gy/min) spectra at irradiation port and averaged all over the rest of the wall. As it can be seen, neutron collimation properties of the moderator are very good (a factor bigger than $10^2$). The FOM values are listed in table 12.4. All the calculated parameters are better than the recommended values listed in table 12.3.

In order to study dosimetric properties in more detailed way, a grid of 2x2 cm$^2$ pixel size has been put in front of the irradiation wall of the moderator of figure 12.15. Figures 12.17-12.19 show kerma values in air at any pixel position for the thermal, epithermal and fast neutrons components of the beam, while figure 12.20 shows kerma values for gamma rays. As it can be seen the thermal neutron beam is confirmed to be very collimated. The ratio of the irradiation port value on the background value (the area were only patient healthy tissues are supposed to be) is of about 100. Fast and epithermal neutron doses are less collimated. However, their absolute values are well less the recommended values, pointing out a possible total body dose of about 3 mGy only. Gamma dose is poorly collimated, because prompt gamma rays are mainly produced by radiative capture of thermal neutrons throughout the moderator. The gamma ray source is widespread over all the neutron moderator volume, because thermal neutrons diffuse stochastically inside it. Nevertheless, the neutron moderator succeeds to concentrate 92 % of the gamma yield at the irradiation port. 1 hour treatment with moderator of figure 12.15 could give to a total body dose of about 100 mGy. However, gamma shields can be easily implemented by simply adding lead layers outside the moderator. More details about the moderator design are in reference [20].

For concluding, we remember that the present computational MCNPX design, based on 4 MeV 30 mA proton beam, provides a high collimated thermal neutron beam (99.7 %), fulfilling

![Figure 12.20: Gamma dose rate (Gy/h) 3D profile over the patient-facing wall surface (left). The same plot in 2D view: the square is the irradiation beam port position (right).](image)

<table>
<thead>
<tr>
<th>Beam port data</th>
<th>$\Phi_{th}$</th>
<th>$\Phi_{th}$</th>
<th>$\Phi_{tot}$</th>
<th>$\hat{D}<em>{n,(epi+fast)}/\Phi</em>{th}$</th>
<th>$\hat{D}<em>{\gamma}/\Phi</em>{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x10$^9$ cm$^{-2}$s$^{-1}$)</td>
<td>(x10$^{-13}$ Gy cm$^{-2}$)</td>
<td>(x10$^{-13}$ Gy cm$^{-2}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.17</td>
<td>0.99</td>
<td>0.008</td>
<td>1.38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
all the established design requirements for a BNCT irradiation facility. Next step will be to measure neutron yield spectra from 0° to 135° for 5 MeV protons by using the CN Van de Graaff accelerator of Legnaro Laboratories (see next paragraph). As soon as 5 MeV data will be available, the final neutron moderator design will start. New design will use both the Be-tile converter and the Be-bulk neutron converter (see figure 12.9), which has neutron moderating capability bigger than that one of the Be-tile neutron converter. Its use is therefore expected to reduce neutron moderator dimensions, as well as the residual activation.

### 12.1.7 Neutron yield measurements

In order to proper design neutron beams for BNCT purposes, source neutrons have to be transported first through the neutron converter and then through the neutron moderator by using Monte Carlo codes like MCNPX. Calculation result accuracy depends mainly on the neutron-source knowledge accuracy. The neutron source is defined by the neutron energy spectrum, which however changes with the neutron angle emission. For our purposes, a good enough neutron-source knowledge means knowing energy spectra down to less than 100 keV for emission angles from 0° to 135°.

Because of the lack of experimental data about neutron yields of the reaction 9Be(p,xn)9B at 5 MeV of protons [16], an experimental campaign has been open to measure neutron yields by using the LNL 7 MV CN accelerator and the superheated drop detectors (SDD). SDDs are superheated gels, which give rise to very small evaporation drops when hit by neutrons. A sonic detection system able to listen drop formation makes SDDs active detectors. The neutron energy detection threshold can be changed by changing SDD temperature. Energy detection thresholds as low as 25 keV are accessible. More details about are published elsewhere [21]. In figure 12.21 a SDD is mounted on a motorized trolley in the CN experimental hall by Legnaro Laboratories.

### 12.1.8 Microdosimetric detectors

BNCT radiation dosimetry is complex because of the co-presence of different radiation components with different biological effectiveness. Living cells experience in fact radiation

![Fig. 12.21: The superheated drop detector (the black vial in the right side picture) and the remote-controlled trolley (left side picture) for neutron yield measurements at different emission angles. The Be target is inserted in the air-cooled holder that is visible in the right side picture. The Be-target-holder end is inclined of 30° with respect the beam line.](image)
events with large LET spreading, ranging from less than one tenth of keV/µm (2.2 MeV gamma rays), to several hundreds of keV/µm (^7Li ions). Moreover, their relative contributes change with the depth and, if the proton beam fluctuates, also with the time possibly. In order to take properly into account radiation field variations for foreseeing resulting biological effect variations, the expression “radiation quality” has been introduced, which points out some radiation-field physical quantities that are somehow significant for the biological effect. In BNCT research centres the ratios of table 3 are supposed to be also good markers of radiation field quality in conjunction with the neutron-gamma dose ratio Dn/Dγ. Such a ratio, which is measurable with the standard twin ionisation chamber method, is in fact expected to be significant for healthy tissue damage. However, a recent radiobiological intercomparison between 7 different BNCT radiation field has pointed out that the biological effectiveness is poorly correlated with the ratio Dn/Dγ [7]. Although doesn’t exist yet a widely accepted radiation action theory, microdosimetric measurements are instead considered significant in radiation therapy [22].

Tissue-equivalent proportional counters (TEPC) are the best detectors for measuring microdosimetric spectra. They have been proved to be able to measure absorbed dose and its quality with high accuracy both for high energy [23] and low energy [24] neutrons, as well as for fast neutron therapeutic beams [25] and BNCT applications [26], [27]. In order to study TEPC performances and precision in BNCT, a first TEPC with an easy tissue equivalent A-150 plastic cathode shell replacement was constructed. The TEPC could be assembled with different cathode walls, the ^10B concentration of which ranged from 0 to 100 ppm in order to measure both the radiation quality experienced by cells with and without ^10B. However, because of its large sensitive volume (2.3 cm³) the counter was able to measure only in relatively weak radiation fields. Measurements were performed inside the irradiation cavity of TAPIRO ENEA fast reactor thermal column only at very low (20 W) power[28].

![Cutaway view of the twin TEPC prototype](image)

**Fig. 12.22:** Cutaway view (right) of the twin TEPC prototype. The red pipeline points out the counting gas circuitry: full red is gas inlet, rose is gas outlet. Real size detector picture is on the left side of the figure. Proportional counter cathodes are the two 1 mm tissue-equivalent black plastic cylinders in the
In order to prevent pile-up event distortions in microdosimetric spectra when radiation field intensity is high, much smaller counters with sensitive volume less than 1 mm$^3$ are necessary [29]. The cathode wall of such a mini TEPC can not be changed. Therefore, a new counter has been designed that is made of two cylindrical TEPCs with two cathode walls, one of them with 50 ppm of $^{10}$B, the other one without $^{10}$B. Such a compact counter, called twin TEPC, could be the main instrument to measure the radiation quality both in air, in phantom and also in vivo, thanks to its millimetric dimensions. To test such a design feasibility, a twin TEPC prototype with two mini TEPCs encapsulated inside the same insulating cylinder (see figure 12.22), which is in turn inserted inside a thin titanium sleeve, has been constructed [30]. The 20 cm long 2.7 mm large titanium sleeve allows for inserting twin TEPC into the irradiation cavity (see figure 12.24) as well as in a phantom and inside the patient body possibly.

Fig. 12.23: Microdosimetric spectra measured inside HYTHOR (see § 12.3.8) cavity by twin TEPC (see text).
First measurements [31] with the twin TEPC prototype are shown in figure 12.23. The microdosimetric spectrum is the TEPC pulse height spectrum that is processed to give the fraction of absorbed dose given by pulses between $y$ and $y + \Delta y$, where $y$ (ratio of the imparted energy on the sensitive-volume mean chord length) is the lineal energy. Measurements of figure 12.23 have been performed with a sensitive volume thickness as big as a chromosome (1 µm). $D$ is the total dose measured by the 50 ppm $^{10}$B TEPC. $D_0$ is the total dose measured by the TEPC without $^{10}$B. Spectra of figure 12.23 are scaled by the ratio $D/D_0$. Therefore, the area under the $^{10}$B curve for a given $\Delta y$ logarithmic interval minus the area under the without-$^{10}$B curve for the same $\Delta y$ logarithmic interval is the percentage increasing of the absorbed dose in that given $\Delta y$ interval, when 50 ppm of $^{10}$B are added. As expected, absorbed dose due to gamma rays (event size < 20 keV/µm) doesn’t increase significantly when $^{10}$B is added in the TEPC wall. On the contrary, absorbed dose due to events of size > 50 keV/µm increases largely because of the events due to He and Li ions. Spectra of figure 12.23 can be processed to give the total field RBE (relative biological effectiveness) [32] or precise evaluation of the different absorbed dose components. More details about are published elsewhere [31, 33].

R&D continues for studying and improving twin TEPC accuracy. The new twin TEPC will use low-gamma and low-beta emitters constructing materials to minimize gamma dose due to counter activation caused by the intense thermal neutron field.

12.1.9 New boron carriers

BNCT optimisation research aims to maximise biological damage in tumour cells without inducing relevant healthy tissue damage. For a given radiation field, it does depend on the ratio of $^{10}$B concentration in tumour tissue with respect the $^{10}$B concentration in healthy tissue as well as on the location of $^{10}$B carrier inside the tumour and healthy cells. In BNCT research centres, the $^{10}$B carriers more used are Borophenylalanine (BPA) and Sodiumdodecaborate (BSH). Both of them can not be easily traced inside the cells. On the contrary, fluorescent $^{10}$B carriers can.

First attempts of using fluorescents carriers have been made with phthalocyanine. A novel $^{10}$B-enriched carboranyl-containing phthalocyanine (B-Pc) has been at the purpose synthesized. In figure 12.25, it can be seen how this molecule can be easy traced inside MM cells. By superimposing the first 3 pictures of figure 12.25, the forth picture is obtained. It shows that the boronated phthalocyanine (B$_4$Pc, red fluorescent stuff) enters inside MM cells passing through
cell membranes, which are pointed out by the green fluorescent light. First irradiation trials were performed, at the Tapiro reactor thermal column in Casaccia, to observe the thermal neutron effect on mice MM tumours after B₄Pc supply. In spite of the small ¹⁰B concentration in tumour tissue (less than 1ppm) a significant delay in tumour growth was observed [34]. Such an expected positive effect could be due to the high efficacy of high-LET He and Li events, as they occur just inside the MM cell. Boronated porphyrines, having similar behaviour, have been synthesised too. Radiobiological research to maximise boronated porphyrines effects is in progress with by the HYTHOR facility (see the following paragraph).

The use of phthalocyanines or porphyrines as ¹⁰B carriers open the way to combined therapies, since such molecules are already used in photodynamic therapy (PDT). Such molecule can be in fact photoactivated by visible or near infrared light with production of cytotoxic species, which lead the tumour to necrosis. Synergic effects between BNCT and PDT will studied.

12.1.10 HYTHOR

HYTHOR (acronym for HYbrid Thermal spectrum shifter TapirO Reactor) is a neutron moderating column designed and constructed by LNL and installed by ENEA Casaccia research centre. HYTHOR can be easily inserted inside the 5 kW TAPIRO reactor (see figure 12.26) and it can as much easily pulled out. HYTHOR irradiation cavity (10X20X25 cm³) can contain up to 6 mice. It is used for microdosimetry and radiobiological studies (see § 12.3.6 and 12.3.7). HYTHOR’s radiation field calculated parameters are in table 5. Hythor’s FOM satisfies the reference parameter condition of a BNCT facility Therefore, experimental studies performed with HYTHOR are significant for a future therapeutic facility. More details about HYTHOR are published in reference [35].

Fig. 12.25: Fluorescence micrographs of cells after 24 h incubation with 7 µM DOPC liposome-incorporated B₄Pc. 1. bright field image 2 fluorescence of phthalocyanine. 3 fluorescence of endosomal probe Lucifer Yellow. 4 overlay of images 2 and 3 (see text).
12.2 The LEgnaro NeutrOn Source (LENOS)

12.2.1 Introduction

In the last years a renewed interest in the low energy neutron physics has triggered the construction of new facilities as well as many experimental apparatus. This process has been mainly boosted by the needs of nuclear data in several fields like nuclear astrophysics, nuclear waste transmutation, generation IV reactors, fusion reactors, decommissioning of first generation fission reactors, radioprotection, dosimetry and by the material science community. For this reasons a great number of facilities have been built or are in preparation all over the world:

![HYTHOR facility layout and picture](image)

**Fig. 12.26:** Layout (left) and picture of HYTHOR facility. HYTHOR is 1x1x2 m³ neutron moderating structure. In the HYTHOR center, the irradiation cavity is visible.

<table>
<thead>
<tr>
<th>Beam port data</th>
<th>$\Phi_{th}$ ($\times 10^{8} \text{cm}^{-2}\text{s}^{-1}$)</th>
<th>$\Phi_{th}/\Phi_{tot}$</th>
<th>$\dot{D}<em>{n,\text{epi+fast}}/\Phi</em>{th}$ ($\times 10^{12} \text{Gy cm}^{-2}$)</th>
<th>$\dot{D}<em>{\gamma}/\Phi</em>{th}$ ($\times 10^{13} \text{Gy cm}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.48</td>
<td>0.92</td>
<td>0.14</td>
<td>0.85</td>
</tr>
</tbody>
</table>

n_TOF (CERN), Frankfurt (Germany), Obninsk and INR-Troitsk (Russia), JPARC (Japan), SNS and LENS (USA) just to cite some of them.

One of the most interesting topic in nuclear astrophysics is related to nucleosynthesis of the elements beyond iron, which are mainly produced via neutron-capture reactions called s (slow) and r (rapid) processes [36]. The main goal of nuclear astrophysics models is to reproduce the observed abundance of the elements in the Universe. In particular, recent data made available by
silicon grains studies, has triggered new hypothesis and has underlined the need of more accurate neutron-capture cross section data.

The neutron-capture cross section data are the fundamental ingredient for the calculation of the stellar reaction rates and thus the possibility of reproducing the observed abundance of the elements in the universe. The s process follows the valley of beta stability and of particular relevance are the branching points, because also the thermodynamic condition of the stellar site can be estimated. The most important quantity needed for the calculation of the stellar reaction rate is the Maxwellian Averaged Cross Section (MACS), defined as

\[
\text{MACS} = \left( \frac{\langle \sigma v \rangle}{v_T} \right)
\]

\[
\langle \sigma v \rangle = \int_0^\infty \int_0^\infty P(v_x) \cdot P(v_y) \cdot \sigma(v) \cdot v \cdot dv_x \cdot dv_y
\]

Where \( P(v) \) is the Maxwellian velocity distribution and \( v_T \) the mean thermal velocity.

Since the relevant quantity is the MACS, measurements of the capture cross section as a function of the energy can be performed with a relative low resolution. The MACS can also be evaluated directly by measuring the total capture cross section having a neutron beam shaped with a Maxwellian spectra with a \( kT \approx 30 \) keV, as obtained by Kaeppeler et al. [50,51]

Despite their importance in the development of stellar nucleosynthesis models, the measurements of neutron-capture cross sections on unstable nuclei are difficult, often technically not feasible [40] due to the induced background, costs and safety related problems. A great effort has been performed by different groups to update and compile the experimental and theoretical nuclear data of interest in astrophysics [37] [38] [39], but have still to be measured some very important isotopes, most of them are unstable.

Beside the important topic of fundamental physics, there is a compelling need for nuclear data also for many field of applied nuclear physics and, in particular, those related to the applications to the new technologies for the production of nuclear energy and to the compilations of evaluated database (ENDF, JEFF, JENDL). The request of nuclear data covers a wide energy range and different processes, as reported in many official documents compiled by the most important agencies, like NEA [41] and IAEA [42].

The evaluated nuclear data libraries are used in many codes, from MCNP to GEANT and, consequently, the accuracy of such programs is strongly dependent from the accuracy of nuclear data collected in the databases.

Because the production of nuclear waste is one of the main problems for a sustainable nuclear energy production, the transmutation of long lived isotopes (mainly actinides and fission fragments) must be pursued. Actinide transmutation is proposed to take place by fission reactions in subcritical reactor like accelerator driven systems (ADS) and in fast spectrum critical reactors such as some proposed Generation IV reactors like the sodium fast cooler reactor (SFR) and gas cooled fast reactors (GFCR), strongly studied by many agencies all over the world. For many isotopes there are no cross section data or the accuracy needed is lower than existing data. Measurement of capture, fission and inelastic cross sections on transuranic elements, fission fragments and specific structural materials are needed. In particular, the capture cross section on some FF, generated during the burn-up of the new proposed fuel can play a fundamental role as a neutron poison, in the same way of \(^{135}\text{Xe}\) and \(^{142}\text{Sm}\) take place in the safety operation of the actual reactors.

Because the spectrum is quite new, if well characterized, the facility can also be used as a benchmark to validate evaluated nuclear data [43].
12.2.2 Main characteristics of the facility

Thanks to the possibility of having in situ the presence of SPES, which produces Radioactive Ion Beams (RIB) by Uranium fission and a high current proton beam which can produce an intense neutron beam, we are investigating the possibility to perform neutron induced cross section measurements for isotopes never or poorly measured before. The name of the future neutron complex is LENOS and could be completed within the time framework of the SPES project.

In LENOS, special targets can be constructed by implanting a selected beam of SPES in a thin baking target, in order to obtain an exotic target to be measured at least, by using the irradiation activation methods. All new generation of RIB facilities have the possibility of performing exotic target, but often the neutron beam is far from the RIB facility, so if the sample is highly radioactive, the possibility to transport it can be limited for safety reasons. The main profit can be obtained having a beam line which transports the low energy exotic beam of SPES directly to the neutron experimental hall. In this way, two lines converges into the same measuring target, the low energy exotic beam and the neutron beam, so the target to be measured can be implanted and consequently irradiated by the neutron beam without moving it.

Beside such characteristic, which is the most important one, measurements with low energy resolution on stable targets can also be performed.

Our purpose is the construction of LENOS within the framework of the SPES project, by using the TRASCO RFQ the neutron production. The already tested BNCT technology will be used for the construction of the Beryllium target, which has an experimentally measured neutron yield at 0 degree of 443 n/pC [44-46] for the reaction $^9$Be(p,xn) at 5 MeV. With a current of 50 mA in CW mode a total flux of about $10^{14}$ n/s on the full solid angle could be achieved. The energy spectra obtained from a thick target shows a peak around 2.6 MeV. Our goal is to have both an activation facility using the proton beam in CW mode and 30mA and a Time of Flight (TOF) facility (which can work at 50 mA CW equivalent), by pulsing the proton beam with a time resolution of about 6 nsec, with a repetition rate from 25 to 250 kHz and a duty cycle from 1% to 0.1% accordingly.

A schematic layout of SPES, with the lines of LENOS, is reported in figure 12.27.
The main characteristics of LENOS facility should be the low background due to the reaction used to generate neutrons and the high neutron flux in a small energy range, which can be especially tailored for the astrophysics measurements (1-300 keV) as well as for the low energy neutron induced reactions for applied nuclear physics (1keV-1MeV). The high flux is obtained using a short flight path, so the energy resolution is expected to be poor, but we consider a value lower than 20% acceptable for our kind of measurements. Preliminary results gives a value of about 10% energy resolution for neutron of 300 keV energy and a significant lower value for slower neutrons.

12.2.3 Primary proton driver

In order to use the synergy with the SPES project, the proton beam used will come out from the TRASCO RFQ (see chapter IV).

The RFQ will work in pulsed mode with an equivalent CW current of 50mA. Such value can be achieved because in pulsed mode operation the real average current will be of 0.5 mA considering a repletion rate of 250 kHz and a duty cycle of 1%. The duty cycle of 1% provide to maintain the power dissipated on target at 2.5 kW which is easy sustainable from the beryllium target.

12.3 The Time Of Flight line

12.3.1 The bunching system

Because of the high current, a bunching system of Mobey type [47] is probably the best choice, in order to have a compact system able to work with a so high spatial charge and low
beam momentum. The dipole magnet should have a size of about 1.5x1.5 m length and should be able to compress 8 pulses of the RFQ microstructure for a total macropulse of about 40 nsec into a single pulse of 6 nsec at the Be target position. The value of 6 nsec has been chosen in order to have a maximum energy resolution of 20% at 70 cm from the target. We have calculated that higher time resolution do not increase significantly the final energy resolution.

12.3.2 The moderator

The neutron spectra generated by the Be(p,n) reaction 5 MeV is peaked around 2.7 MeV, and our goal is to maximize the neutron flux between 1 to 500 keV using a suitable moderator. The best material for our purpose is water, which can work both as a moderator and as a coolant to dissipate the power impinging the target. Heavy water have a capture cross section lower than light water, reduce the thermal tail of the neutron energy distribution but need an higher thickness and give a lower concentration of neutrons in the energy range of interest (1-500keV). Thus, we decided to use light water and a thin layer of neutron absorber at the end. The most desirable energy cut-off should be at 1keV, in order to increase up to 250kHz the repetition rate and so to maximize the average proton current (which could be of 0.5mA).

In order to define the thickness of the moderator, we calculated the quantity \( \frac{N}{N_0} \) as a function of the moderator thickness \( \delta x \), where \( N \) is the number of neutrons which falls in the range of 1-500keV and \( N_0 \) is the number of neutron generated from the Be(p,n) reaction (443 n/pC as taken by EXFOR [48]). The calculation have been performed using MCNPx code, with neutrons emitted at zero degree on the surface of 0.5 cm thick beryllium target with the energy distribution from [45]. The target geometry used for the calculation was a tablet of beryllium surrounded by a sphere of water and an shell of Cd, Gd and Ir for a total of 6 mm thickness to have a low energy cut-off. The value of \( \frac{N}{N_0} \) is calculated as a current outside the absorber shell and the results for different thicknesses of the water sphere is reported in figure 12.28. The thickness which maximizes the number of neutrons which falls in the 1-500keV energy range is from 5 to 7 cm.

![Fig. 12.28: \( \frac{N}{N_0} \) is calculated as a current outside the absorber shell and the results for different thicknesses of the water sphere.](image)

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**Fig. 12.29:** Neutron flux (in unit of N/N₀) obtained in the adopted configuration calculated with MCNPx code on a tally surface of 1 cm².

In figure 12.29 is reported the neutron flux (in unit of N/N₀) obtained in the adopted configuration calculated with MCNPx code on a tally surface of 1 cm². The figure 12.30 reports the energy resolution for neutrons with energy of about 300 keV calculated with the ptrac card on MCNPx.

**Fig. 12.30:** Energy distribution of neutrons arriving on the tally surface at TOF = 96 ± 3 nsec. The tally surface is 1 cm² area and is placed at 70 cm from the beryllium target. The energy resolution is about 10%.
In order to calculate the absolute neutron flux, $N_0$ must be transformed to the total number of neutrons generated in the beryllium target per second. Because the Yield of the 5MeV Be(p,n) reaction is $442 \text{ n/pC}$, to obtain the total number of neutron per second the yield must be multiplied by the average proton current, which essentially depends from the time of flight of the slowest neutron.

![Fig. 12.31: scatter plot of the energy as a function of the flight time.](image)

In Figure 12.31 is reported the scatter plot of the energy as a function of the flight time. The cut of energy is at 2 eV and correspond to a time of flight of 40 $\mu$s. So the repetition rate will be of 25 kHz, while with a value of $T= 40 \mu$s the average current will be of 50 $\mu$A. Table 12.6 gives a comparison of LENOS neutron flux in the region 1-300keV with the flux of other important neutron facilities in the world.

Table 12.6. Comparison between the main neutron facilities. Data for LENOS are calculated with a repetition rate of 25 kHz, an average current of 0.05 mA, a flight path of 70 cm, with 5 cm of light water which works as moderator and as a coolant, and considering the energy range between 1-300 keV. Data from [11]

<table>
<thead>
<tr>
<th>Facility</th>
<th>GELINA (@10 m)</th>
<th>N-TOF (@186 m)</th>
<th>SNS (@20m)</th>
<th>ORELA (@10m)</th>
<th>LANSCE (@20 m)</th>
<th>LENOS (@0.7 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flux (1-300 KeV n/sec/cm²)</td>
<td>$3 \times 10^5$</td>
<td>$3 \times 10^4$</td>
<td>$2.1 \times 10^8$</td>
<td>$2.0 \times 10^6$</td>
<td>$4.6 \times 10^6$</td>
<td>$4.2 \times 10^5$</td>
</tr>
<tr>
<td>Time resolution</td>
<td>1 nsec</td>
<td>6 nsec</td>
<td>350 nsec</td>
<td>24 nsec</td>
<td>125 nsec</td>
<td>6 nsec</td>
</tr>
<tr>
<td>Power dissipated (Kw)</td>
<td>15</td>
<td>45</td>
<td>2000</td>
<td>8-50</td>
<td>64</td>
<td>25</td>
</tr>
</tbody>
</table>
12.3.3 The Lead Slowind Down Spectrometer (LSDL)

In order to cover the energy range down to 1 eV, a construction of a LSDS is also under investigation. It is demonstrated [49] that using a LSDL a time of flight measurements can be achieved in the energy range from 1 eV to 10 keV with an energy resolution of about 30% with a neutron flux which can be $10^4$ times higher than in an equivalent traditional time of flight facility. Using an LSDL, sample with very low mass can be measured, so this kind of instrument will be very useful to measure exotic sample obtained with SPES beam.

12.3.4 The activation/irradiation facility

In nuclear astrophysics measurements, where the most important quantity is the MACS, instead of measuring the cross section in the 1-500 keV energy range and calculate analytically the integral of eq 1, the MACS value can be obtained directly from an irradiation/activation measurements, providing to have a moderator able to shape the energy distribution of the outgoing neutron as much as possible similar to a Maxwellian spectrum with a mean value of $kT\approx 30$ KeV. A very good approximation of the stellar spectrum has been obtained by Kaeppler [50] and Popov [51], using the reaction $^7\text{Li}(p,n)$ at proton energy close to the threshold. The sample to be irradiated is placed close to the target, in order to have a very intense neutron flux. The MACS can be calculated by thought the activated ions by measuring the emission lines with a high resolution gamma detector. This kind of measurements are very accurate, since they don’t take care of isomeric states and thanks to the high flux and the peculiarity of the method, very low mass natural samples can be used. The next step forward in the neutron facility will be the calculations of a moderator able to shape the 5MeV Be(p,n) neutron spectra to a Maxwellian one. In this line, the proton beam will works at 30 mA in CW mode so the power dissipated in the target will be of 150 kW,. In order to sustain so high power, the beryllium target will be the one already developed and tested for BNCT. Our goal is to obtain a neutron flux higher than $10^{10}$ neutrons/s, in order to measure samples with $10^{16}$ atoms/cm$^2$, easy obtainable with 2 weeks of implantation with SPES beam at $10^{10}$ particle/s.

[3] H. Madoc-Jones A phase I dose escalation trial of boron neutron capture therapy for subjects with metastatic subcutaneous melanoma of the extremities. E-mail: gisolares@mit.edu
[27] J. Burmeister et al., Miniature tissue-equivalent proportional counters for BNCT and BNCEFNT. 001 Medical Physics 28, 1911-1925
[41] NEA High Priority Nuclear Data Request List, private communications