# AN ACCELERATOR-BASED THERMAL NEUTRON SOURCE FOR BNCT APPLICATION

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*Abstract*

An accelerator-based thermal neutron source, aimed at the Boron Neutron Capture Therapy (BNCT) application on skin melanoma tumour is under construction at the INFN-LNL, in the framework of SPES project. The BNCT facility will exploit the intense proton beam provided by a 5 MeV, 30 mA RFQ that represents the first accelerating step of the SPES exotic nuclei production source. Neutrons are generated by $^{9}Be(p,n)^{9}B$ nuclear reaction in a high power (150 kW) beryllium target. The neutron converter working condition is planned to be close to the Be-armoured components in fusion reactors one, the main difference being in the limitation of target structural materials used in the design in order to fulfil the therapeutic irradiation requirements. Two possible neutron converter designs are being developed: one with saddle block tiles brazed to CuCrZr cooling pipes, while the other one made of a solid Be block. R&D main results of water cooled Be target converter are presented.

## THE NEUTRON TARGET DESIGN

The target device design is closely linked with the design of the neutron beam shaping and filtering assembly, which must take into account the geometry of the neutron converter and the effect of the support structure on the neutron and gamma transport. The beam target design is, in particular, a key point because of the high thermal power load in operating conditions. A target beam spot area, which should keep the surface heat load to a level as low as ~7 $MWm^{-2}$, in order to make use of reliable and already proven target cooling systems, would be required. Moreover one of main design requirements takes into account the need to have a removable target unit from the BNCT facility for easy inspection as well as maintenance purposes. Some concern relating the fluid cooling capability, the cooling system simplicity as well as the economic has led light water to be chosen as cooling fluid for both the target and the collimator. Among different candidate target converters assessed at the preliminary investigation stage with 5 MeV proton beam, [1] beryllium revealed as the most efficient for neutron production. Following detailed specification, a preliminary, high-power, beryllium target prototype has been designed in collaboration with the STC Sintez of Efremov Institute in S. Petersburg [2]. The peculiar target profile shape (parabolic), shown in figure 1, has been selected in order to have an approximately constant power density distribution on the full beryllium target surface along beam axis direction. The target assembly consists of a neutron converter (beryllium tiles) surrounded by a cylindrical tank containing heavy water as first moderator

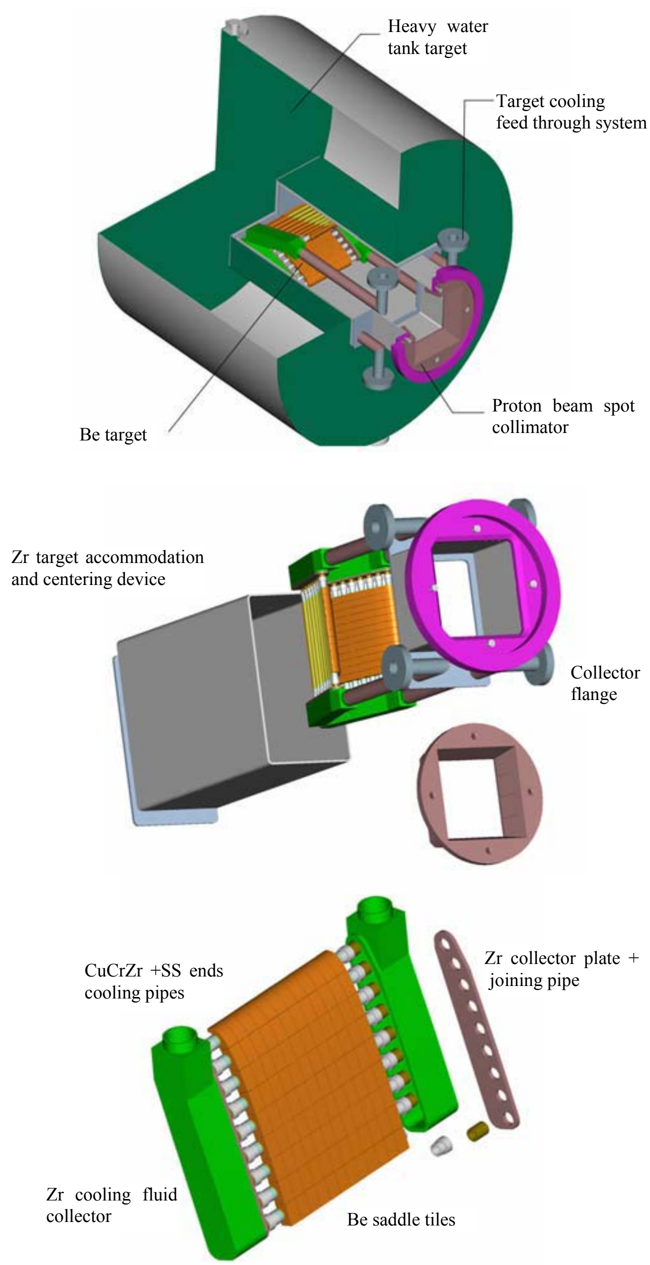


Figure 1: Preliminary design of SPES-BNCT Be target prototype.

stage. The main structure materials selected are zirconium alloy (Zr + 2.5% Nb) and graphite as beam collimator. The neutron converter is based on tile concept, i.e. beryllium tiles which are brazed on the cooling pipes with minimum acceptable gaps among tiles. In order to reduce the amount of heat sink material saddle block geometry is used. Beryllium saddle block are brazed on a 10 mm outer diameter tubes, having a thickness of 1 mm. The pipes are produced by casting of CuCrZr alloy onto 0.3 mm stainless steel tubes with the following quenching and ageing manufacturing process. Such a composite tube structure allows using of well-developed Be-Cu joint technology and avoiding of the corrosion of copper alloy by the coolant. The technology to braze a beryllium layer on a bulk copper support and heat sink material, already proven in the framework of ITER project, has however the drawback of a too high prompt gamma ray contamination at the facility irradiation beam port, which unwanted component needs to be reduced to an extent as low as possible. A further technological effort is therefore under way to develop and test new brazing alloys able to provide a reliable beryllium-aluminum joint target

## THERMAL AND STRESS ANALYSIS

Thermal and stress analysis of neutron converter has been performed by ANSYS code. The work aimed at assessing the maximum working temperatures, the related mechanical stress and deformations both under static and cycling loading operating conditions and at last an estimation of the target lifetime. The main structural target components are shown in figure 2.

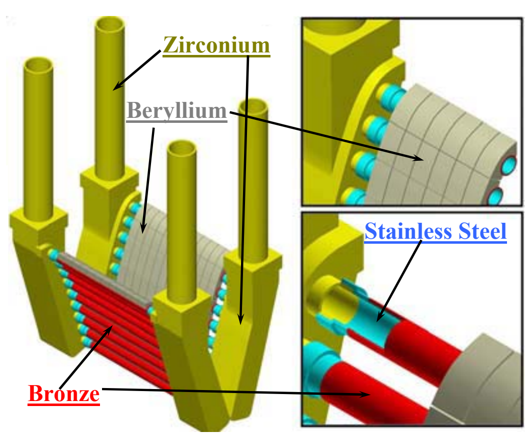


Figure 2: Structural parts of the target.

Thermal and mechanical properties both of beryllium (S65-C type) and stainless steel (316 LN-IG) have been accounted from ITER Material Properties Handbook [3], while CuCrZr properties from ITER Structural Design Criteria [4] have been adopted. Due to both geometry and beam loading symmetry, a quarter of target model needs to be simulated only, the temperatures and stresses distribution being calculated at different steps. The heat flux distribution impinging on the target surfaces has a parabolic profile with a pick power density of 7 $MWm^{-2}$; the fluid heat transfer coefficient has been selected on the proper fluid turbulent flow condition, as shown in figure 3. The coolant fluid is normal deionised water with an inlet pressure of 0.3 MPa and a velocity of 4 m/s.

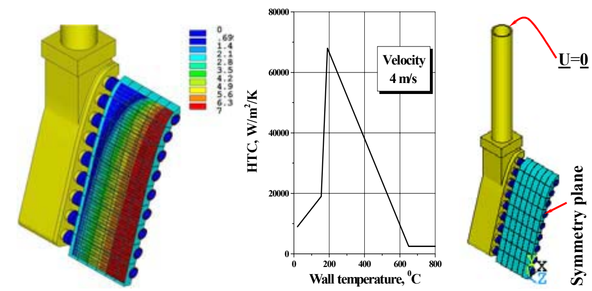


Figure 3: Boundary conditions for stress analysis.

The result of steady state thermal analysis is presented in figure 4. The maximum temperature in single element material is of 673 °C for beryllium, 362 °C for Bronze, 344 °C for Stainless steel and 21 °C for Zirconium.

The stress intensities calculated at loading stage in all structural parts have shown to provide intensities which are all within the allowable design limits as enlisted in table 1.

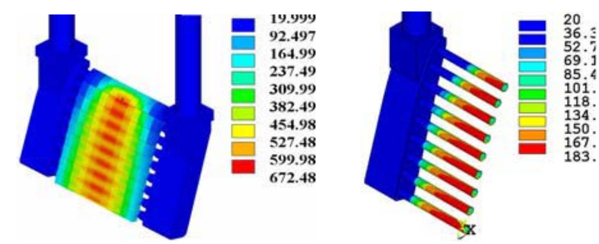


Figure 4: Results of the thermal analysis with ANSYS.

Table 1: Comparison of maximum stress intensities estimated in different target structural parts and the corresponding ultimate design limits.

| | Stress intensity, MPa | | | | |
|---|---|---|---|---|---|
| | loading | | | unloading | |
| | Local temp. °C | Value | Limit: $S_u$ | Value | Limit: $S_u$ |
| Bronze tube | *346* | *172* | *221* | *201* | *307* |
| Steel tube | *182* | *179* | *433* | *251* | *525* |
| Zirconium tube | | *47* | | *15* | |
| Zirconium collector | | *205* | | *144* | |
| Wall of collector with rings | *20* | *147* | *343* | *97* | *343* |
| Zirconium small tubes | | *190* | | *67* | |

Because of thermal expansion some elements of the target have resulted enduring a large displacement at loading stage, the maximum being about 0.83 mm in the X-direction (normal to the cooling channels), while the other about -0.6 mm in Z-direction (along the cooling channels), thus resulting in a contraction of the whole structure. In order to assess the target lifetime the plastic strains have been calculated under cycling load conditions. All plastic strains in the structural parts have been estimated below the design limits. The most critical places are located in bronze and steel pipes, as shown in figure 5.

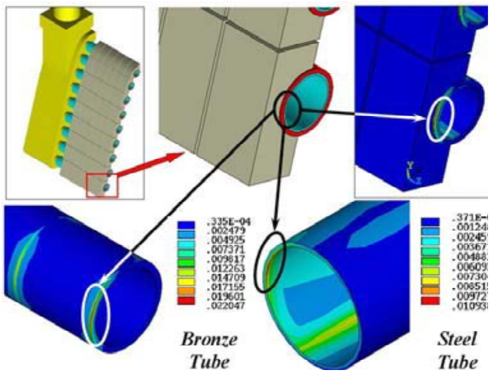


Figure 5: Location of most stressed zones and total strain.

As reference parameter the target lifetime has been defined by the maximum of allowable cycles and is limited, with a safety factor of 10, to about 550 cycles. This result exceeds the 240 cycles required by the technical specifications.

## MOCKUP MANUFACTURING AND TEST

To test the behaviour of the beryllium saddle block under a High Heat Flux (HHF) several mock-ups have been manufactured. Beryllium-saddle tiles were machined and wire-cut from TGP-56 grade. For brazing the beryllium tiles on the CuCrZr tubes a special tool for brazing has been designed and constructed. The mock-ups were brazed by heating with electron beam at the Tsefey

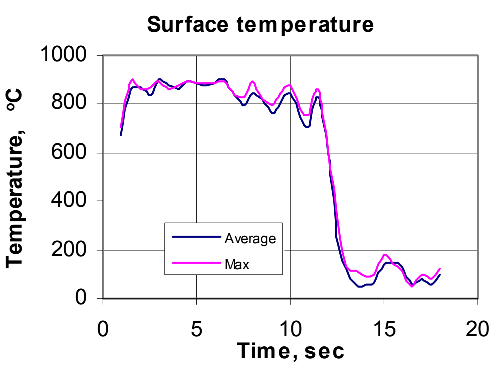


Figure 6: Beryllium surface temperature in HHF screening tests.

facility of the Efremov Institute. The Tsefey facility has also been employed to test the mock-ups at different power density levels, up to 11 $MWm^{-2}$. The measurements were performed in cycling regime the duration of one cycle being fixed to 12 s. Figure 6 shows the mock-up temperature profile vs. time during one cycle at power density of 11 $MWm^{-2}$. A preliminary test was performed at low heat flux, 5 $MWm^{-2}$, and for 1000 thermal cycles, while the second one was performed at the nominal heat flux of 7 $MWm^{-2}$, for again 1000 cycles. The heat flux distribution was found uniform along the mock-up surface, within a tolerance of 10%. By visual inspection, no any damage was detected at the beryllium surface (see figure 7), after a total of 2000 cycles.

Metallographic investigations were performed on the mock-up to check the brazing quality after irradiation. The mock-up was wire-cut and eight samples were

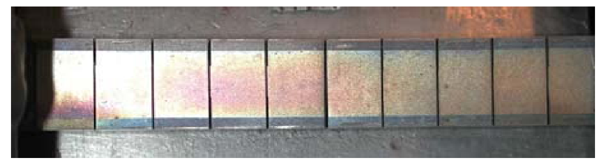

Figure 7: Mock-up after tests at 5 and 7 $MWm^{-2}$, and a total of 2000 cycles.

prepared for the analysis as shown in the following figure 8. All inspected samples have revealed a good brazing quality with a uniform brazing layer. The joint between tiles and cooling tubes has revealed not being damaged

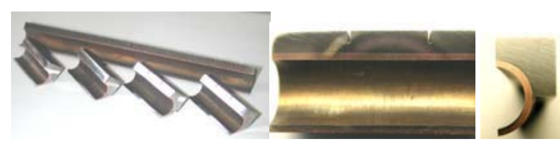

Figure 8: Mock-up cross-sections prepared for metallographic analysis.

during the tests. No any macroscopic cracks and erosions have at last been observed inside the Be saddle tiles thickness.

## CONCLUSIONS

A high power, beryllium neutron converter is being designed in the framework of SPES-BNCT project. Preliminary thermal-mechanical calculations show a stable working regime of armoured beryllium with a heat flux of 7 $MWm^{-2}$. Mock-ups of neutron converter have been tested under an electron beam with a beam power load density up to 11 $MW/m^2$. No any beryllium damage has been observed at the nominal heat flux level. An alterative solution, consisting of a neutron converter made from a solid beryllium block has been investigated. Technological solutions concerning the Be-Zr brazing are under investigation.

## REFERENCES

[1] J. Esposito, Workshop on Neutron and RIB production Targets, Legnaro July 23-27, 2001, P.V. Logatchev and L.B. Tecchio (editors).
[2] Stage II report, STC SINTEZ contract IT/08626377/00058, April 2004.
[3] ITER Material Properties Handbook
[4] ITER Structural Design Criteria