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High-power TR-24 cyclotron-based p-n convertor cooled by submerged orifice jet

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Abstract. The TR-24 cyclotron (Advanced Cyclotron Systems Inc., Canada) of the Nuclear Physics Institute in Řež provides protons with variable energies from 18 MeV up to 24 MeV and beam current of 0.3 mA. For such parameters, the p +Be source reaction on thick Be target can produce a white-spectrum neutron field ($E_n \leq 22$ MeV) with the intensity of 5×10^{12} n/s/sr in forward direction. Present paper outlines the development of Be-target cooling system, devoted to remove the heat load of 7 kW (density up to 4 kW/cm^2) from the target. Due to novel "orifice-form" of jet cooling (resulting in the shortest source-to-sample distance of 20 mm) with extremely high cooling efficiency, the TR-24 p-n convertor can achieve neutron-flux up to $2\text{x}10^{12}$n/cm^2/s nearby the target output.

1 Introduction

For accelerator-based neutron irradiation facilities the deuteron break-up on light-nuclei target (^{3}H, D_2O, Li, Be and C) presents most intensive source-reactions tool. However, high-power deuteron accelerators suffer from principal limitations (cyclotrons) and/or by high technical demands (linear accelerators), which result in expensive facilities (SARAF and future projects IFMIF, DONES [1]) – consequently multipurpose and far from dedicated compact solutions.
Commercially available and relatively low-cost high-power proton cyclotrons (mostly of medical purposes) incorporated with suitable proton-neutron convertor (usually with fixed and/or rotating Be discs) are widely proven in the BNCT.

Fig. 1. The TR-24 cyclotron of the Nuclear Physics Institute, Řež.

Present work points at relatively low-cost high-power medical proton cyclotrons, which could provide fast "fusion-like" neutrons at intensity which could not only supply in parallel the future irradiation facilities, but - actually - the material-research fission reactors in particular.
The NPI TR-24 cyclotron, (Advanced Cyclotron Systems Inc.)(Fig. 1) provides protons with variable energies up to 24 MeV and 0.3 mA of external beam current. For such parameters, the p+Be source reaction on thick Be target can produce a white-spectrum neutron field ($E_n \leq 22$ MeV) with an intensity of 5×10^{12} n/s/sr in forward direction (based on MCNPX calculations, experimental activation tests, and standalone investigation of the p+Be source reaction for 24 MeV proton beam using the multi-foil activation technique at the NPI [2]).
Most critical point in the effort to reach desirable high neutron flux density consists in removing a high local heat load from the target by cooling assembly with minimized dimensions in the direction of neutron emission.

2 Cooling assembly of the target

2.1 ANSYS simulations

Due to Gaussian-like profile of a cyclotron beam spot on the target ($\sigma \leq 20$ mm), the heat density up-to 4 kW/cm ^{2} resulting in overall heat load of 7.2 kW needs to be removed from the target of any proton-neutron convertor. Point-like form of accelerator based neutron sources leads to an inverse square dependence of the neutron flux density on source-to-sample distance. Therefore, the dimensions of cooling assembly are to be

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minimized to use high flux density option in a vicinity of the target.

Taking advantages in well appropriate dimensions (small radial length) and commonly known high heat transfer coefficients, various types of orifice nozzles were considered and tested to form a submerged impingement jets in cooling arrangement of static Be target. Nozzles were investigated to form a cooling assembly with water flow of maximum available rate 2 l/s and a system pressure of 1.1 MPa on static Be target.

Special effort was devoted to minimize the distance between the target and output backing side of the cooling chamber.

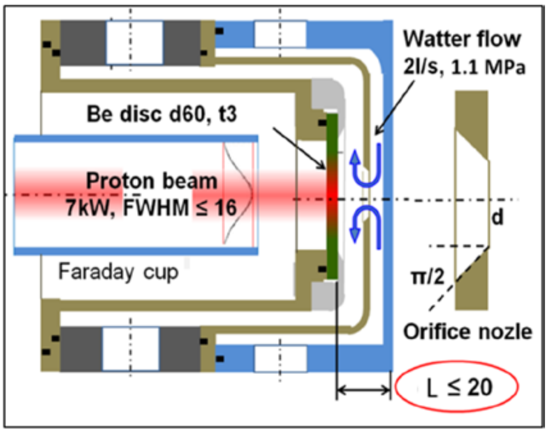

Fig. 2. Schematic arrangement of target chamber with Be disc, Faraday cup and orifice nozzle for ANSYS simulation. Dimensions are in mm.

The simulations were carried out in the forced convection-flow mode ANSYS (Fig. 2) to determine basic characteristics (heat transfer coefficient, fluid velocity at shear layer and pressure in the stagnation one) for different nozzle types (see Fig. 3).

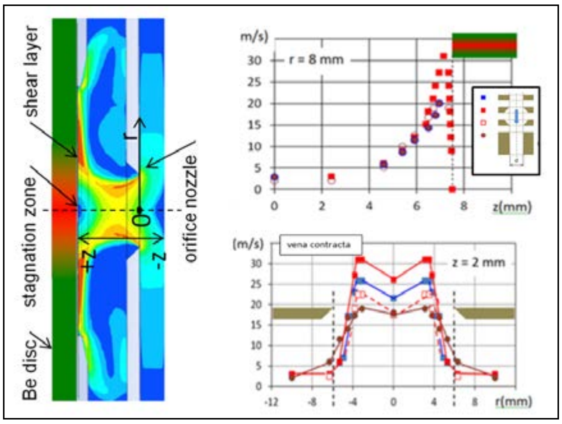

Fig. 3. Resulting velocity distribution of cooling fluid in the shear layer and vena-contracta region for various form of the orifice nozzle. The open sharp-edge orifice was selected as the optimal solution.

2.2 The prototype of Be target chamber

Considering similar empirical data on water wettability (contact angle) of the aluminum and beryllium surfaces, the Al disc (Fig. 4) – instead of Be disc was utilized in the pilot experiments to facilitate a set of three thermocouples inside the target (rather complicate in the case of Be material).

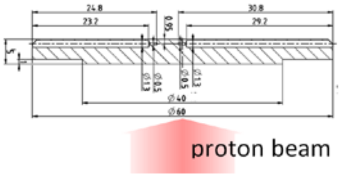

Fig. 4. The aluminum dummy-target for measurement of temperature distribution along beam spot using a set of thermocouples.

The thickness of target discs was determined by full stopping of 24 MeV protons. To take into account an expected hydrogen embrittlement (blistering effects) due to intensive proton beam, backing material with high hydrogen diffusion coefficient is considered instead of usually used not-stopping the protons within the target itself. The reason comes from possible disruption of thermal dynamics in the stagnation zone when part of thermal load is dissipated in the shear layer of cooling water.

2.3 Cooling tests

A mock-up of the target setup (Fig. 5) was manufactured to verify the ANSYS simulation and to determine empirical parameters of boiling mode of cooling.

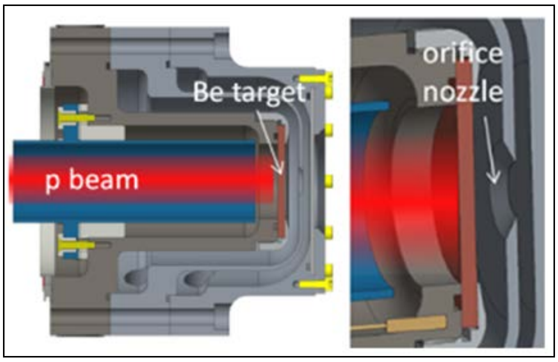

Fig. 5. The target chamber of p-n convertor assembly with orifice-nozzle for the water jet cooling - the prototype construction.

Temperature distribution in the target was measured by the set-up of three thermocouples at water flow rate of 2 l/s, the system pressure of 1.1 MPa, constant water-flow temperature of 20°C (ensured by a cooling unit) at different beam currents and spot dimensions during the irradiation with 24 MeV protons. In the Fig. 6, a typical behavior of measured temperature in various locations across the beam-spot area is given. Here, the linear dependence of temperature on beam current corresponds to heat transfer at convective single-phase mode. Clear evidence is seen for the onset of boiling, the area of nucleate and fully developed nucleate boiling and the presence of local critical heat flux as well.

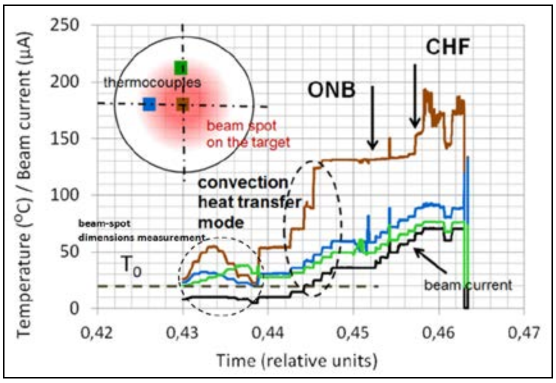

Fig. 6. Typical behavior of temperature in thermocouples located in various positions on the beam spot area during the irradiation by a proton beam.

3 Results and conclusions

Preliminary analysis of experimental data has a) confirmed the ANSYS simulation of transfer characteristics below the onset of boiling point (130°C) and b) provided original data regarding the boiling heat transfer mode and in particular the behavior of critical heat flux regime, see the Fig. 7. Measured steady-state heat fluxes ranged from 2.5 to 4 kW/cm ^{2} exceed several times the typical value of 0.5 kW/cm ^{2} for contemporary p+Be neutron generators usually operating with single-phase flow cooling of fixed Be targets [3,4]

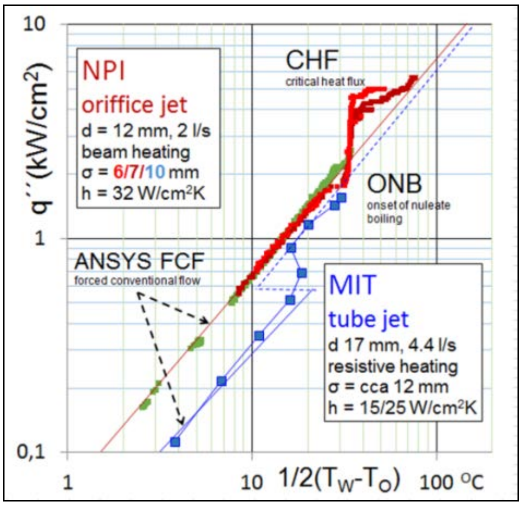

Fig. 7. Preliminary determined heat transfer characteristics of the submerged orifice jet cooling compared to long pipe-nozzle jet, developed at MIT BNCT neutron facility.

Due to novel "orifice-form" of cooling assembly (resulting in the shortest s-to-s distance of 20 mm), the TR-24 p-n convertor can achieve neutron-flux up to $2x10^{12}n/cm^2/s$ nearby the target output, the highest value of flux density for fast-neutron irradiation purposes until now. Target station with the open area at forward direction is developed to provide the irradiation under non-perturbed arrangement of different samples and associated hardware. Remotely controlled manipulators of irradiated components are being developed to ensure basic operation in the large induced activity ranging up to Sv/h. The methods to minimize the blistering efect during operation are under investigation.

Submerged water jet cooling assembly was tested at BNCT neutron facility of the Massachusetts Institute of Technology [5]. Removing of 5 kW heat loaded by resistive heating into fixed steel-dummy target has been reported. However, long pipe-nozzle derogates a possibility to reach high density of the neutron flux in irradiated samples.

Acknowledgements

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