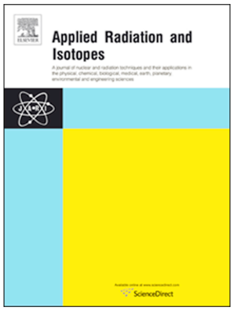

Status of low-energy accelerator-based BNCT worldwide and in Argentina

D.E. Cartelli, M.E. Capoulat, M. Baldo, J.C. Suárez Sandín, M. Igarzabal, M.F. del Grosso, A.A. Valda, N. Canepa, M. Gun, D.M. Minsky, G. Conti, J. Erhardt, H.R. Somacal, A.A. Bertolo, J. Bergueiro, P.A. Gaviola, A.J. Kreiner

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TITLE: Status of low-energy Accelerator-Based BNCT worldwide and in Argentina

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KEYWORDS:
Accelerator-based BNCT; Accelerator-based projects worldwide; Argentine Electrostatic quadrupole accelerator; ^{9}Be(d,n)^{10}B and ^{13}C(d,n)^{14}N reactions.

HIGHLIGHTS

- **The current status of low-energy projects and associated facilities for AB-BNCT worldwide are reviewed.**
- **The recent progress of the Argentine AB-BNCT program is described.**
- **Deuteron induced reactions ^{9}Be(d,n)^{10}B and ^{13}C(d,n)^{14}N at 1.45 MeV deuteron energy as neutron sources.**
- **Machine development status is described.**
- **Neutron production target development status is specified.**

ABSTRACT :

Existing and active low-energy Accelerator-Based BNCT programs worldwide will be reviewed and compared. In particular, the program in Argentina will be discussed which consists of the development of an Electro-Static-Quadrupole (ESQ) Accelerator-Based treatment facility. The facility is conceived to operate with the deuteron-induced reactions ^{9}Be(d,n)^{10}B and ^{13}C(d,n)^{14}N at 1.45 MeV deuteron energy, as neutron sources. Neutron production target development status is specified. The present status of the construction of the new accelerator development laboratory and future BNCT centre is shown.

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MAIN TEXT:

1. Introduction

There is an international consensus that Accelerator-Based BNCT (AB-BNCT) may change the prospects of BNCT due mainly to the possibility of in-hospital siting in contrast to reactor-based facilities. Hence, there is a quest worldwide for finding technical solutions for such a facility. Selection criteria to decide among different technologies may be: simplicity-reliability (e.g., the smallest number of ancillary systems), highest safety (e.g., the lowest activation of facility).
and lowest possible cost (e.g., the lowest energy accelerator), in order to promote the widest possible dissemination.
Right now several accelerator-based facilities for BNCT are being designed, constructed and some already tested at various centers around the world. The aim of these programs is to inaugurate the era of hospital-based facilities, moving progressively away from reactor-based facilities which, according to the prevailing consensus, are more costly and difficult to operate, to license, and, more importantly, are not suitable for installation in hospitals. Progress in recent years will be assessed.
The different options will be compared according to the nuclear reaction employed, beam energy and current, resulting primary neutron spectra features, target design and complexity, resulting epithermal neutron beam characteristics, type of machine, etc. We shall restrict ourselves to facilities based on low energy accelerators (producing proton or deuteron energies of a few MeV), since higher energies are far from ideal in a hospital environment due to activation and the need for heavy shielding.
We shall discuss the different projects according to the neutron-producing nuclear reactions employed. They are on one hand the endoergic ^{7}Li(p,n)^{7}Be and ^{9}Be(p,n)^{9}B and on the other the exoergic ^{9}Be(d,n)^{10}B and ^{13}C(d,n)^{14}N reactions.
^{7}Li(p,n) is best from the neutronic point of view, meaning that the neutron yield is highest and the spectrum rather soft, depending on the bombarding energy, but below 1 MeV for proton beam energies below 2.5 MeV. On the downside, Li has very poor material properties and in addition produces a radioactive end product (^{7}Be), an undesirable feature for a hospital environment. In spite of these facts there are several projects working on this option, in Russia (Aleynik et al., 2011; Taskaev, 2014; Zaidi et al., 2018), in Israel (Halfon et al., 2014 and 2015, Mardor et al., 2018), Japan (Horiike et al., 2015; Tamaki et al., 2015; Tsuchida et al., 2014; Fujii et al., 2014, Nakamura et al.,2017, Uritani et al.,2018, Asano et al., 2019), and China (Xiamen Humanity Hospital in association with TAE Life Sciences, taelifesciences.com), some of them based even on liquid Li targets to circumvent the problem of the solid target melting or deteriorating under the heat load delivered and the radiation damage induced by the powerful beams. These problems can be solved but represent additional non-trivial issues to care about.
An additional and well-advanced project working with this reaction is the one in Finland, at the Helsinki University Central Hospital (in association with Neutron Therapeutics Inc., NTI, www.neutrontherapeutics.com). Their electrostatic accelerator works on the principle published by Kreiner et al., 2007.

Other initiatives are focusing on $^{9}Be(p,n)^{9}B$ (Pisent et al., 2014; Kumada et al., 2014, 2015, 2018). ^{9}Be is a much better material and has no residual radioactivity, but its yield, at energies suitable for $^{7}Li(p,n)^{7}Be$, is quite small, so that higher-energy machines are required. About 5 MeV is probably the lower practical limit for this reaction to be used for AB-BNCT, which is twice as much energy as needed for the Li option.

In particular, the progress of the Argentine Electrostatic Quadrupole accelerator (Kreiner et al., 2007, 2014, 2016; Cartelli et al., 2015) is described. A prototype of 0.72 MV is ready which has been shown to transmit proton beams of up to about 7 mA. Beam diagnostics is performed through fluorescence induced in the residual gas of the high vacuum accelerator tube. Our attention is, at this stage, focused on deuteron-induced reactions and in particular on $^{9}Be(d,n)^{10}B$ and $^{13}C(d,n)^{14}N$, since they allow for the lowest-possible-energy machines. Their suitability for AB-BNCT has been demonstrated. Progress in ^{9}Be- and ^{13}C-based neutron production targets will also be briefly described. A new accelerator development laboratory and future treatment facility is under advanced construction in Argentina and its current status will be mentioned.

2. Active AB-BNCT programs worldwide

Presently there are about 8 countries actively engaged in the development of AB-BNCT. These are Japan, Finland, Russia, Argentina, Israel, Italy, China and more recently the Republic of Korea. France and several other countries are considering starting AB-BNCT projects. Japan is by far the country devoting the largest effort to this endeavor. There are several projects located in Kyoto, Tohoku-Fukushima, Tsukuba, National Cancer Center-Tokyo, Nagoya, Okinawa, etc.

There are two facilities already treating patients, one at KURRI (Kyoto University Research Reactor Institute) and the other at Fukushima South Tohoku Hospital, and a third one under construction at Osaka Medical College, which use a 30MeV-1mA proton cyclotron and Be as a neutron producing target, having to deal with a very hard neutron spectrum and hence with a very high activation (see Kiyanagi, 2018 for a review).

Table I gives the present status and performance of some of the different accelerators of the active projects underway today for AB-BNCT facilities worldwide. Some of these accelerators are already developed and some are under construction. Most of them need still a significant upgrade in terms of beam intensity. We include only low-energy (less than 10 MeV) proton or deuteron machines.

There are various projects included using radiofrequency, RF, systems (Radiofrequency quadrupoles, RFQs, and drift tube LINACs, DTLs) and a number of projects using electrostatic technology in different versions: Vacuum insulated tandem (Russia: Taskaev S, 2014; Zaidi et al, 2018; China: Xiamen Humanity Hospital), Electrostatic Quadrupole (ESQ) single-ended (Argentina: Kreiner et al., 2007, 2014, 2016; Cartelli et al., 2015), Dynamitron (one project in Nagoya, Japan, Tsuchida et al., 2014, Uritani et al., 2018), and single-ended DC (Helsinki-NTI, www.neutrontherapeutics.com).

The machine in Israel (Halfon et al., 2014; Mardor et al., 2018) is an RFQ-DTL already operating on a liquid Li target with still modest currents of about 2 mA. The liquid target has been shown to perform satisfactorily at that power level. There is also another project underway in Japan (Nakamura et al., 2017, Asano et al., 2019) at the National Cancer Center, Tokyo, based on a LINAC and a solid Li target. The liquid Li option has also been studied in Japan (Kobayashi T et al., 2014, Horiike et al., 2015).

The projects based on the ^{9}Be(p,n)^{9}B reaction are located in Italy (Legnaro-Pavia) and Japan (Tsukuba). The Italian project is based on an RFQ, intended to work at about 5 MeV and 30 mA, to produce thermal neutrons to treat superficial tumors (Pisent et al., 2014). An advanced Japanese project, a large interinstitutional project centered around Tsukuba University (Kumada et al., 2014, 2015 and 2018), is based on an RFQ-DTL designed to work at 8 MeV (3MeV RFQ followed by a 5MeV DTL) and a maximum current of 10 mA (not yet achieved).
Turning to the exoergic reactions, ^{9}Be(d,n)^{10}B appears as a promising candidate, especially in connection with a thin target which helps to suppress a good proportion of the harder neutron spectrum (Capoulat et al., 2011a, 2014, 2014a, 2014b, 2019). It has the advantages of the Be target, a stable end product (^{10}B) and already at very low bombarding energies (about 1.45 MeV) has a significant yield. In addition, we have also studied the ^{13}C(d,n)^{14}N reaction which is slightly superior (Capoulat and Kreiner, 2017). Neither of these two reactions have other neutron-emitting channels at these energies. These are the options being currently explored by our group in Argentina, as a first step in the development of accelerator technology, since it requires the smallest possible accelerator. We shall describe the recent progress and the results obtained to date.

Table I: Current status and performance of the different accelerators intended for AB-BNCT facilities worldwide. In addition to Institute and location, machine status and final beam power, target and reaction, beam energy and percentage of the neutron yield at 0^0 with energy less than 1 MeV, also the intensity goal and the actually achieved value, in mA, is given.

Institute Location	Machine Status Final Power	Target reaction	Beam energy (MeV) %Neutron yield at 0^0 of ≤ 1 MeV	Intensity goal Actual (mA)
Tsukuba Japan	RFQ-DTL Under development 80 kW	thick 0.5 mm ^{9}Be(p,n)	8 21% ≤ 1 MeV	10 (>5) 2
Budker Inst. Novosibirsk Russia	Vacuum insulated Tandem Developed 23 kW	Solid ^{7}Li(p,n)	2.0-2.3 100%≤ 1 MeV	10 9
Soreq Israel	RFQ-DTL Upgrade 50 kW	Liquid jet ^{7}Li(p,n)	2.5 100%≤ 1 MeV	20 2
CNEA Buenos Aires Argentina	Single ended Electrostatic Qpole Under development 43 kW	^{9}Be(d,n) thin ^{13}C(d,n) thick	1.45 69%≤ 1 MeV 1.45 70%≤ 1 MeV	30 7

NCCenter Tokyo	RFQ Clinical Trial 50 kW	Solid ^{7}Li(p,n)	2.5 100%≤ 1 MeV	20 12
Nagoya University	Dynamitron DC Commisioning 42 kW	Liquid (static) ^{7}Li(p,n)	2.8 95%≤ 1 MeV	15 2
Helsinki University Hospital-NTI Finland	Single ended DC Developed 78 kW	Solid ^{7}Li(p,n)	2.6 100%≤ 1 MeV	+30 +30
INFN Legnaro Italy	RFQ Under development	^{9}Be(p,n)	5 34%%≤ 1 MeV	20-30 ?
Xiamen Humanity Hospital Xiamen China	Vacuum insulated Tandem Under development	Solid ^{7}Li(p,n)	2.5 MeV 100%≤ 1 MeV	10 ?

Our group is presently working towards the development of a single-ended ElectroStatic-Quadrupole (ESQ) accelerator facility to be installed at the Constituyentes Atomic Center of the Atomic Energy Commission in Buenos Aires (Kreiner et al, 2007, 2011, 2014; Cartelli et al, 2015). The project final goal is a machine capable of delivering 30 mA of 1.45 MeV deuterons to be used in conjunction with a neutron production target based on the ^{9}Be(*d,n*) or ^{13}C(*d,n*) reaction. In the first stage, the accelerator will be able to produce proton and deuteron beams of about 1.45 MeV.

In table II we collect the neutron producing nuclear reactions and the material properties of the targets for the options under consideration today. The main differences between ^{7}Li, neutronically the best material, and ^{9}Be and ^{13}C are the very low melting point of Li, its large chemical reactivity and the fact that Li has a radioactive residue, ^{7}Be. These differences are quite significant if a choice has to be made for a hospital-based facility. The total neutron yields for these reactions at various energies are given in Kreiner, 2012 and Kreiner et al., 2016.

Table II: Different neutron producing nuclear reactions and some material properties of the targets. Reaction, threshold energy, radioactive products, melting temperature and thermal conductivity are given.

Reaction	Threshold energy (MeV)	Radioactive products	Melting Temperature (^{0}C)	Thermal Conductivity (W/m K)
^{7}Li(p,n)^{7}Be	1.88	Yes	180	84.7
^{9}Be(p,n)^{9}B	2.06	No[a]	1287	201
^{9}Be(d,n)^{10}B	0 (exoergic)	No	1287	201

$^{9}Be(d,n)^{10}B^{*}$	~ 1.0[b]	No	1287	201
$^{13}C(d,n)^{14}N$	0	No	3550	230

[a]Very short-lived activity with no gamma emission.

[b]Population of an excited state at ≈ 5.11 MeV in ^{10}B. The reaction for the population of this state has an effective threshold of 0.916 MeV (Capoulat et al.2014) and neutron energies in the 225 to 617 keV range. This reaction on a thin target has been recently measured (Capoulat et al., 2019).

Finally, a remark on the so-called "fusion" reactions d+d and d+t which have already significant yields at very low energies (e.g., 120 keV) but their high Q-values (especially for d+t this value is 17.59 MeV) lead to very high neutron energies and also to near-isotropic emission in the lab frame. The devices used to accelerate the deuterons or tritons, usually in the 100-200 keV energy range, go by the name of neutron generators. They are advantageous from the point of view of the required voltage. Quite sophisticated compact neutron generators are being developed (Custodero et al., 2008) but extremely high currents are necessary to generate fluxes useful for BNCT due to limited yield in the appropriate energy range and inherent inefficiency associated with high-energy and isotropic neutron production. These sources can generate 10^{12} d-d n/s and 10^{14} d-t n/s respectively. The d-t case is disfavored by its very high neutron energies (which demand large moderation and shielding volumes) and by the known difficulties associated with working with tritium, particularly in a hospital environment. In the first case, a 2 ampere deuteron current at 200 keV is designed to produce a source intensity of $2.3x10^{12}$ n/s, which is still, for the d-d reaction, a factor of about 30 too short of the intensity needed for treating a deep-seated tumor with BNCT.

These reactions have been compared in terms of neutron yield with the ones discussed in the present paper, in previous work (Kreiner, 2012).

3. Materials and Methods.

The $^{9}Be(d,n)^{10}B$ reaction

This reaction has been studied for a number of years by a few groups (Guzek et al., 1997; Colonna et al., 1999), and in a particularly detailed way by ours (Capoulat et al., 2014, 2014a, 2014b). In spite of this, the experimental information was somewhat scarce and more data was desirable in the ≈1.45 MeV regime. Still, enough was known to allow an evaluation of this reaction for AB-BNCT. This reaction leads to a neutron production of (0.9 ± 0.1) 10^{13} neutrons/s for a 30 mA deuteron beam. An ≈8 μm thin target maximizes the production of low energy neutrons stemming from the population of a highly excited state in ^{10}B (at 5.11 MeV). This reaction populating this state is effectively endoergic with a threshold of about 1 MeV. The neutron production of the beam with energy less than 1 MeV (the remaining energy after traversing the thin target), leading to high energy neutrons, is eliminated by using a thin target. It is interesting to point out that the maximum neutron energy for the 1.45 MeV deuteron beam is about 5.7 MeV, somewhat smaller than the highest neutron energy (6.1 MeV) produced by the 8 MeV proton beam to be used in the Tsukuba project. Even more significant is that 69% of the neutrons from the $^{9}Be(d,n)^{10}B$ reaction have energies below 1 MeV, while all the neutrons coming from the $^{9}Be(p,n)^{9}B$ reaction have significantly higher energies (Byrd et al., 1983). Those associated with the population of the ground state of ^{9}B have energies in the interval 3.64-

6.14 MeV, while those populating the 2.35 MeV excited state are in the 1.84-3.71 MeV range. Most of the neutron yield is associated with these two states.

The results of the simulations for this reaction were quite promising. Our Monte Carlo simulations have shown that viable brain tumor treatments are feasible by means of low-energy deuteron beams (approximately 1.45 MeV) and simple AlF_3-based beam shaping assemblies (Capoulat et al., 2014). In addition, we measured recently the yield of a thin Be target with a 1.45 MeV deuteron beam and the experimental results confirmed both previous data and our simulations (Capoulat et al., 2019). See Table III.

Table III: Comparison of treatment times, maximum equivalent doses (in tumor, skin and healthy brain), and treatable depths for the nuclear reactions under consideration, $^{13}C(d,n)^{14}N$, $^{9}Be(d,n)^{10}B$, and $^{7}Li(p,n)^{7}Be$ as a reference. In all cases the proton or deuteron beam current considered is of 30mA. The radiobiological weighting factors for the conversion from Gy to Gy-Eq are given in Table 2 of Capoulat and Kreiner, 2017.

Reaction	Treatment time (h)	Maximum dose (Gy-Eq)			Treatable depth (cm)
		Tumor	Skin	Healthy brain	
$^{13}C(d,n)^{14}N$	2:20	57.7	11.9	11.0	5.40
$^{13}C(d,n)^{14}N$	1 (non optimal)	50.0	15.7	11.0	4.61
$^{9}Be(d,n)^{10}B$	2:30	50.9	11.2	11.0	4.80
$^{7}Li(p,n)^{7}Be$	1	56.7	12.4	11.0	5.40

The $^{13}C(d,n)^{14}N$ reaction

This reaction has been repeatedly studied in the past (Colonna et al, 1999, Burlon et al, 2001) and has been recently revisited and thoroughly explored as a neutron source (Capoulat and Kreiner, 2017), demonstrating that it is capable of furnishing a suitable source for BNCT.

The machine

During the last few years we have been devoted to the development of an accelerator for BNCT and all of its subsystems. The principles underlying this machine have been already described (Kreiner et al., 2007, 2014, 2016; Cartelli et al., 2015). We shall concentrate on some of the recently completed aspects.

The final machine is a single-ended ESQ (Electrostatic Quadrupole) accelerator of 1.45MV in the terminal intended to work in air to facilitate the maintenance and minimize the number of ancillary devices (like a pressure vessel and an SF6 system).

The strong transverse electric quadrupole fields help to keep the beam close to the beam axis, counterbalancing the space charge effects and effectively sweeping ions and electrons created along the acceleration column and hence preventing the generation of discharges along the tubes which contributes to a more stable operation.

4. Results and Discussion.

The machine

On the way to achieve the goal of developing an appropriate accelerator for AB-BNCT, we have completely developed a 240 kV accelerator, a single-ended electrostatic quadrupole machine, which is in fact one module of the final machine (which is a stack of similar modules). The accelerator is intended as a test bench for all components like electrostatic and mechanical structures, vacuum chambers, tubes, high voltage power supplies, cooled targets, etc.

Fig. 1. shows the 0.72 MV half-size machine assembled and operational. The 720 kV accelerator is a single-ended machine capable of producing 0.72 MeV proton or deuteron beams.

This machine could be converted into a folded Tandem producing 1.45 MeV beams in conjunction with a 180 deg bending magnet (Kreiner et al., 2007).

This last option may be used as a neutron producing machine in combination with the ^{9}Be(d,n) reaction leading to an approximate neutron production of 0.9×10^{13} neutrons/s for a 30 mA beam. This is in fact a very attractive option for accelerator-based BNCT (Capoulat et al, 2011, 2014, 2014a, 2014b).

The final machine is an ESQ (Electrostatic Quadrupole): a single-ended accelerator, to reach 1.45 MV and hence 1.45 MeV deuteron beams for the ^{9}Be(d,n)^{10}B or ^{13}C(d,n)^{14}N reactions. At present we have completed a half-size prototype which is already running and producing quite intense beams (see Fig. 2). The 1.45 MV machine is under construction.

The accelerator tubes have been completely developed in house. These are 120 kV units made of borosilicate glass insulating rings and stainless steel electrodes. They house the ESQ's, which are carefully centered and aligned to define an optical axis.

The achieved beam transport

Proton beams of up to 7 mA have been transmitted through the machine and into a suppressed Faraday cup. The ion source delivering this beam is of a volume plasma discharge filament driven type.

Fig. 2 shows a proton beam of 6 mA entering into Faraday cup (xz & yz planes) through the fluorescence in the residual hydrogen gas in the high vacuum tube (this method has already been described in Kreiner et al., 2014 and Cartelli et al., 2015).

The observation and beam diagnostics have been performed through the fluorescence induced by the intense beam in the residual gas. Fig. 2 shows two images of the intense proton beam, taken with two CCD cameras located at a right angle of each other through a vacuum window, visible due to the fluorescence induced in the residual hydrogen gas.

The neutron production target

One of the proposed targets is described schematically in Fig. 3. It consists of a thin Be layer onto which the ≈ 1.45 MeV deuteron beam is impinging. After traversing this layer and losing about 400 keV, the beam enters into a layer of a material resistant to radiation and hydrogen damage where it stops. These two layers are attached among themselves and to a Cu (Oxygen-free) backing which is refrigerated efficiently through microchannels (Suarez Anzorena et al., 2013, Capoulat et al., 2014a).

Deposits were performed by CONUAR (Argentine Nuclear Fuels), in facilities with all safety and regulatory requirements, on W, Mo, etc., substrates by means of the Physical Vapor Deposition, PVD, technique. The thickness of deposits was 8-9 μm and prior to the deposition of Be the surface was shot blasted with Al_2O_3. For average rugosities of the backing larger than 0,5 μm we obtained well-adhered deposits (L. Gagetti et al.,2017). Fig. 4 shows SEM images of these deposits. Be deposits with and without thermal treatment are shown on the left-hand side.

They are stable up to 800 °C. On the right-hand side, we show images of irradiated Be layers deposited on W (a) and Mo (b). With fluences up to 10^{19} cm^{-2} no swelling is observed (Gagetti et al., 2017).

In the search for radiation and hydrogen resistant materials, we have explored, characterized and modeled so-called High Entropy Alloys (HEA). These are equiatomic mixtures of Mo, Ta, V, W, and Zr which by themselves are very resistant materials. They were irradiated with proton fluences up to 0.5 x 10^{21} cm^{-2} showing no swelling. Fig 5 shows images of these materials (Suarez Anzorena et al., 2016).

The other option, shown schematically in fig.6 is a “thick” ^{13}C target attached directly to the cooling device (thick meaning that the beam stops in the C layer).

Fig. 7 illustrates a study of the limits in power density. A high power density beam of ~ 650 W/cm² and ~ 0.4 mm radius with insufficient cooling leads to melting of the target. On the other hand, a well-designed microchannel system allows beam power densities of up to 1 kW/cm^2.

Fig. 8 shows an irradiated aluminum microchannel target being able to dissipate up to power densities of 1 kW/cm^2.

Fig. 9 shows the cooled high power target mounted on the 720 kW machine.

The new Accelerator Development Laboratory

Fig. 10 shows the stand as of December 2019 of the Accelerator Development Laboratory and future BNCT treatment Centre at the Constituyentes Atomic Center of CNEA. The tower houses the accelerator and it is surrounded by laboratories, machine shops, offices and facilities for the reception of patients. Both the accelerator room and the patient treatment room are built and well shielded by thick concrete walls complying with the radiation safety and radioprotection requirements and regulations of the Argentine Regulatory Agency.

5. Conclusions

The worldwide situation concerning low-energy AB-BNCT has been briefly reviewed. All projects being presently moved forward around the world, with different degrees of progress, are mentioned. All technological options are on the table and their main features are briefly discussed. They comprise both electrostatic and RF, and all neutron-producing nuclear reactions are being considered.

In particular, the status of the Argentine project is described.

A 720 kV single-ended electrostatic accelerator has been completely mounted and vacuum and high-voltage tested. A 7 mA beam has been transmitted through the machine.

All parts, except high-vacuum equipment, have been developed in house at CNEA laboratories and some are produced by local companies.

The beam diagnostics have been made through the observation with CCD cameras of induced fluorescence in the residual gas.

We concentrate on the $^{9}Be(d,n)^{10}B$ and the $^{13}C(d,n)^{14}N$ reactions since they require the smallest-energy accelerator. This is the option being presently explored in Argentina, as a first step in the development of appropriate accelerator technology.

A treatment room complying with current regulations has been designed and constructed.

Be targets have been developed and deposited on different radiation damage and hydrogen resistant backings. Microchannel-based highly efficient cooling devices have been designed, constructed and tested.

The present stand of a new Accelerator Development Laboratory and future BNCT Centre is shown.

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Status of low-energy Accelerator-Based BNCT worldwide and in Argentina

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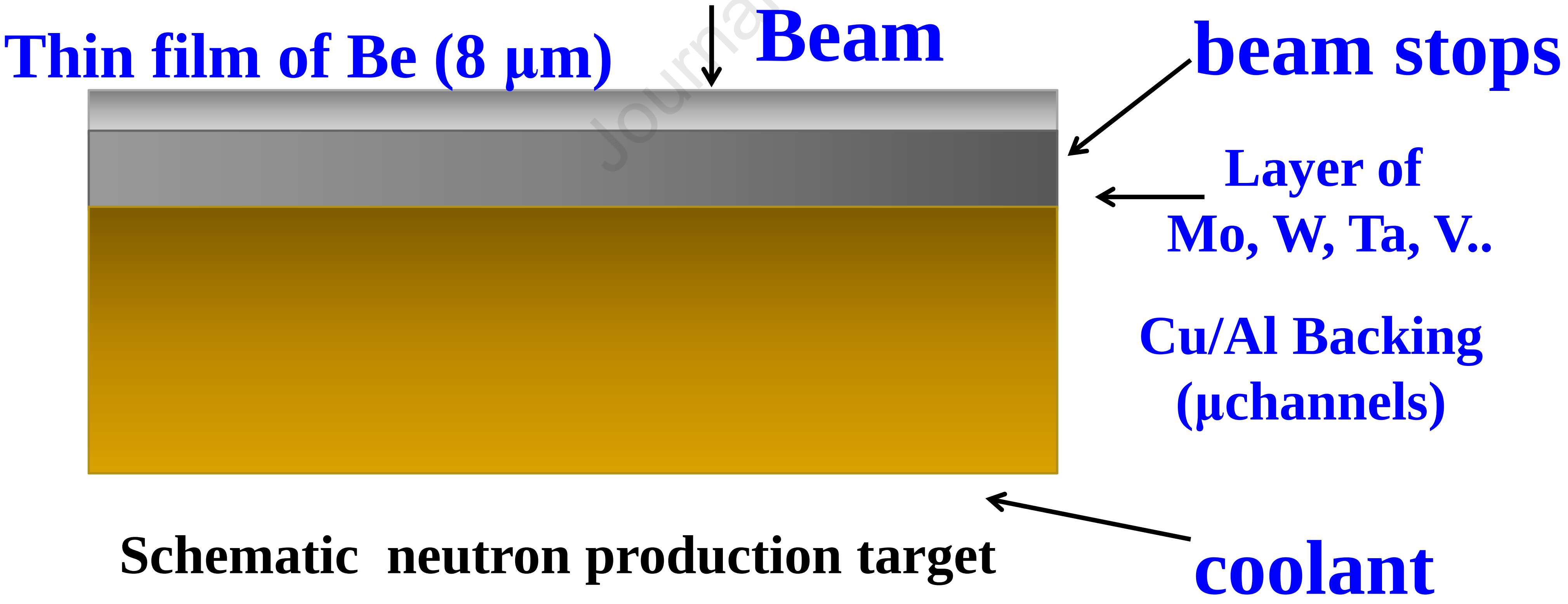
Fig. 1 The 0.72 MV machine assembled and operational.

Fig. 2 Proton beam of 6 mA entering into the Faraday cup (two views in the perpendicular xz & yz planes, z being the beam propagation direction).

Fig. 3 Progress in the design and development of a neutron production target for Accelerator-Based BNCT. Suarez Anzorena et al., 2015.



Thin film of Be (8 µm)

Beam

beam stops

Layer of
Mo, W, Ta, V..

Cu/Al Backing
(µchannels)

coolant

Schematic neutron production target

Fig. 4 Fabrication of Be layers by means of Physical Vapor Deposition (PVD) on substrates of W and Mo. SEM images of Be deposits with and without thermal treatment are shown on the left-hand side. They are stable up to 800 °C. On the right-hand side, we show images of irradiated Be layers deposited on W (a) and Mo ( ). With fluences up to 10^{19} cm^{-2} no swelling is observed. Gagetti et al., 2017.

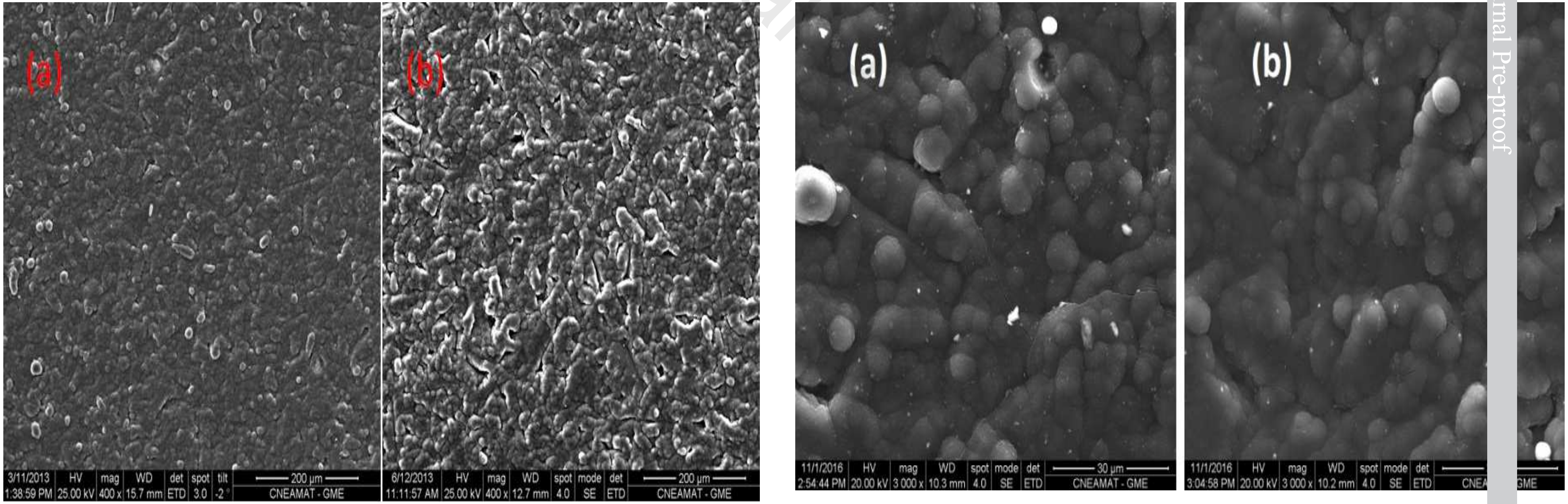


Fig. 5 Images of a MoTaVWZr high entropy alloy (Suarez Anzorena et al., 2016). They resist irradiation up to fluences of 0.5 x 10^{21} cm^{-2} without swelling.

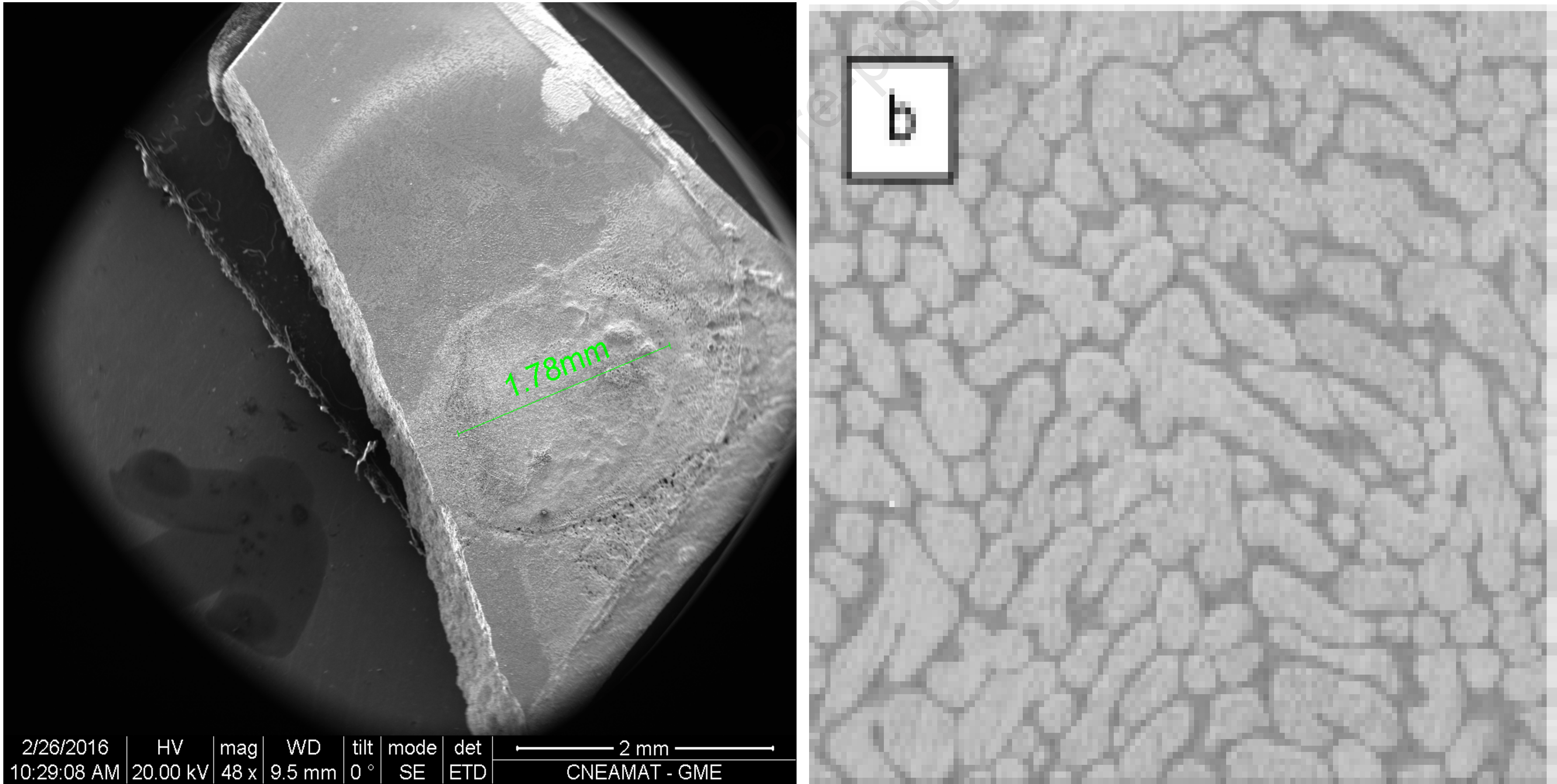
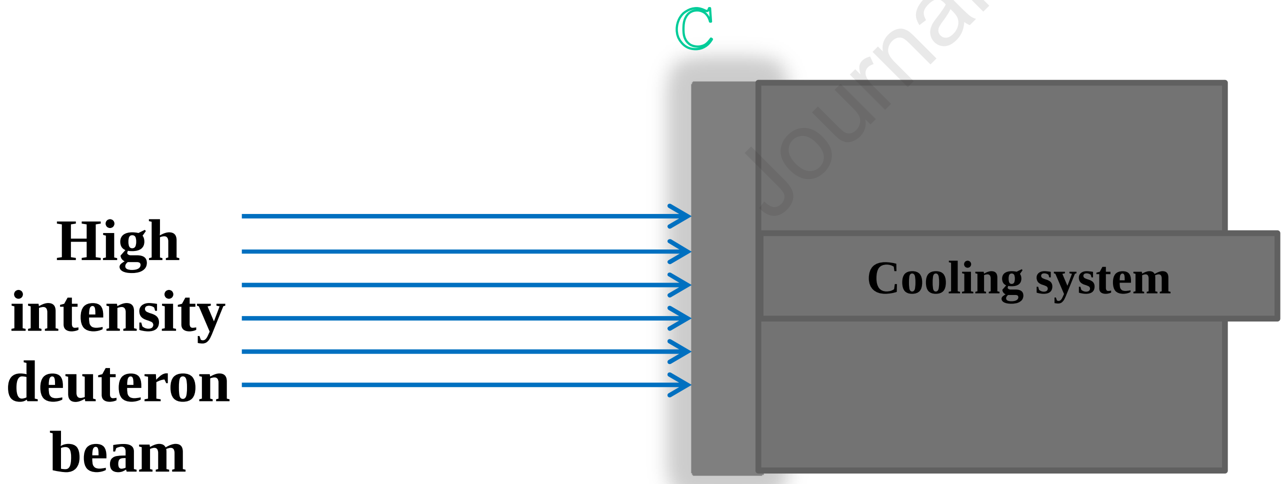


Fig. 6 Conceptual design of Neutron Production Target based on C. The device to generate neutrons through an appropriate nuclear reaction, in this case $^{13}C(d,n)^{14}N$.



The cooling system has to carry away all the heat deposited by beam.

Fig. 7 Study of limits in power density. A high power density beam of ~ 650 W/cm² and ~ 0.4 mm radius with insufficient cooling leads to melting of the target.

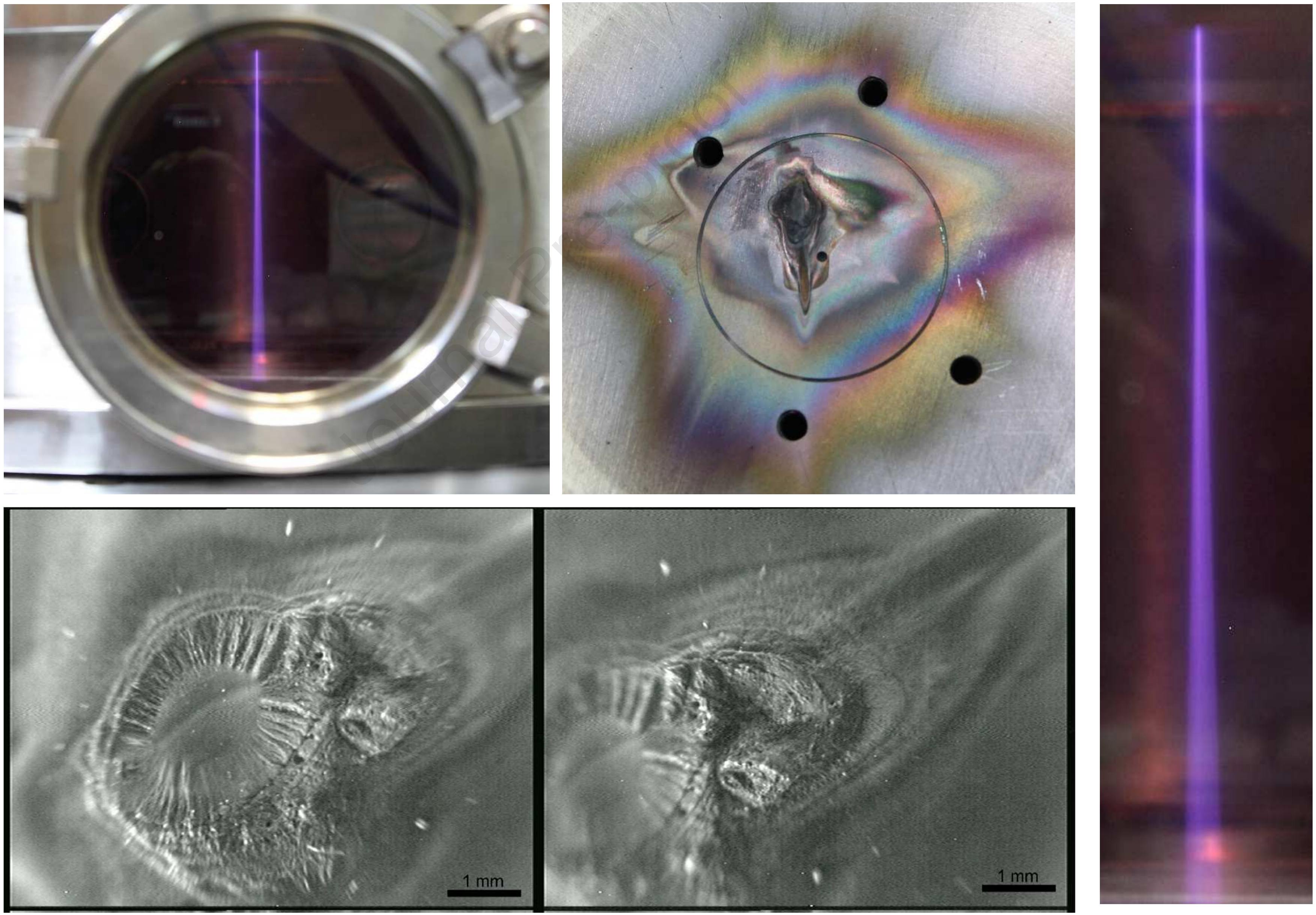


Fig. 8 Irradiated aluminium microchannel target being able to dissipate up to power densities of 1 kW/cm².

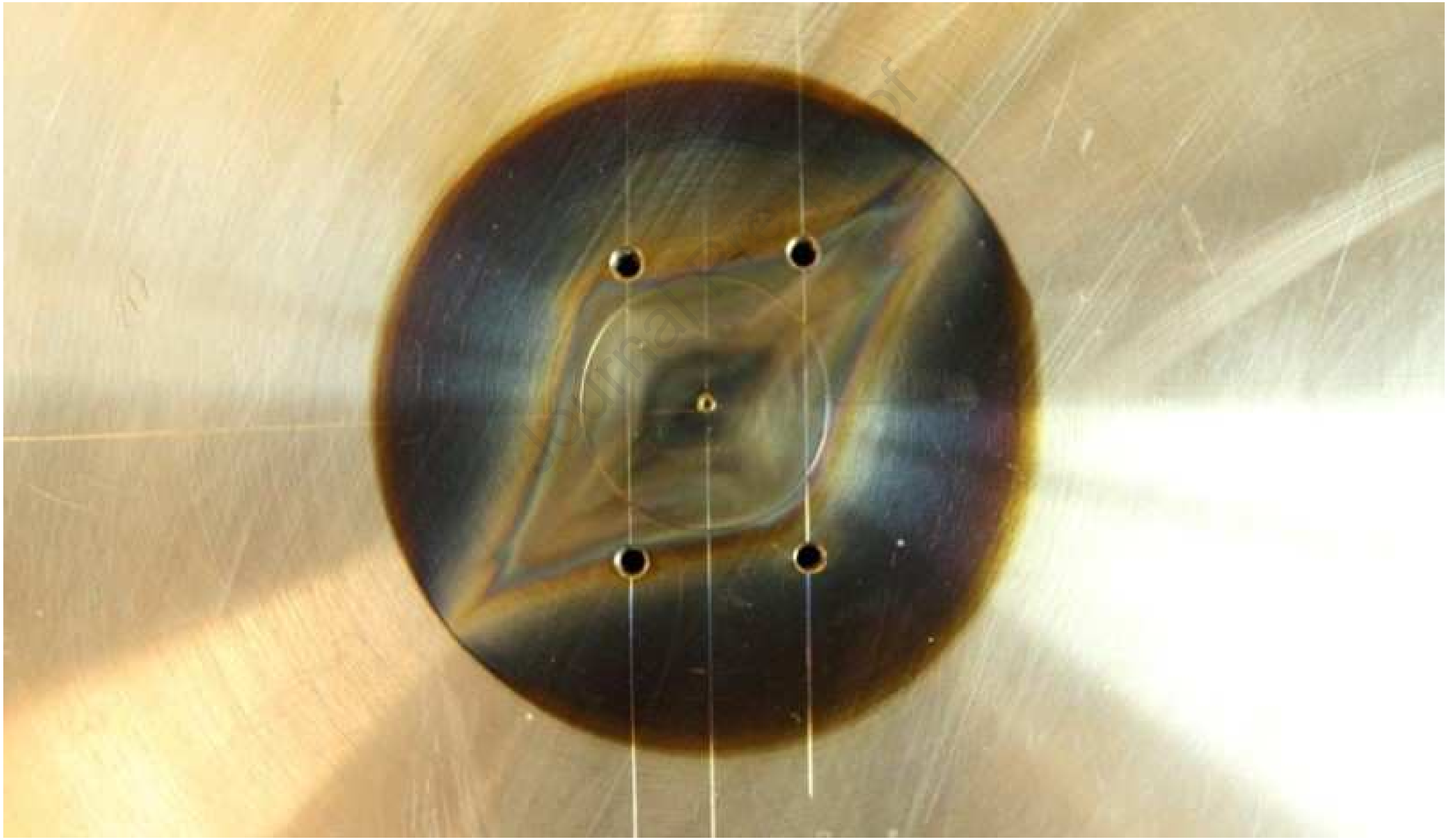


Fig. 9 Cooled high power target mounted on the 720 kW machine.

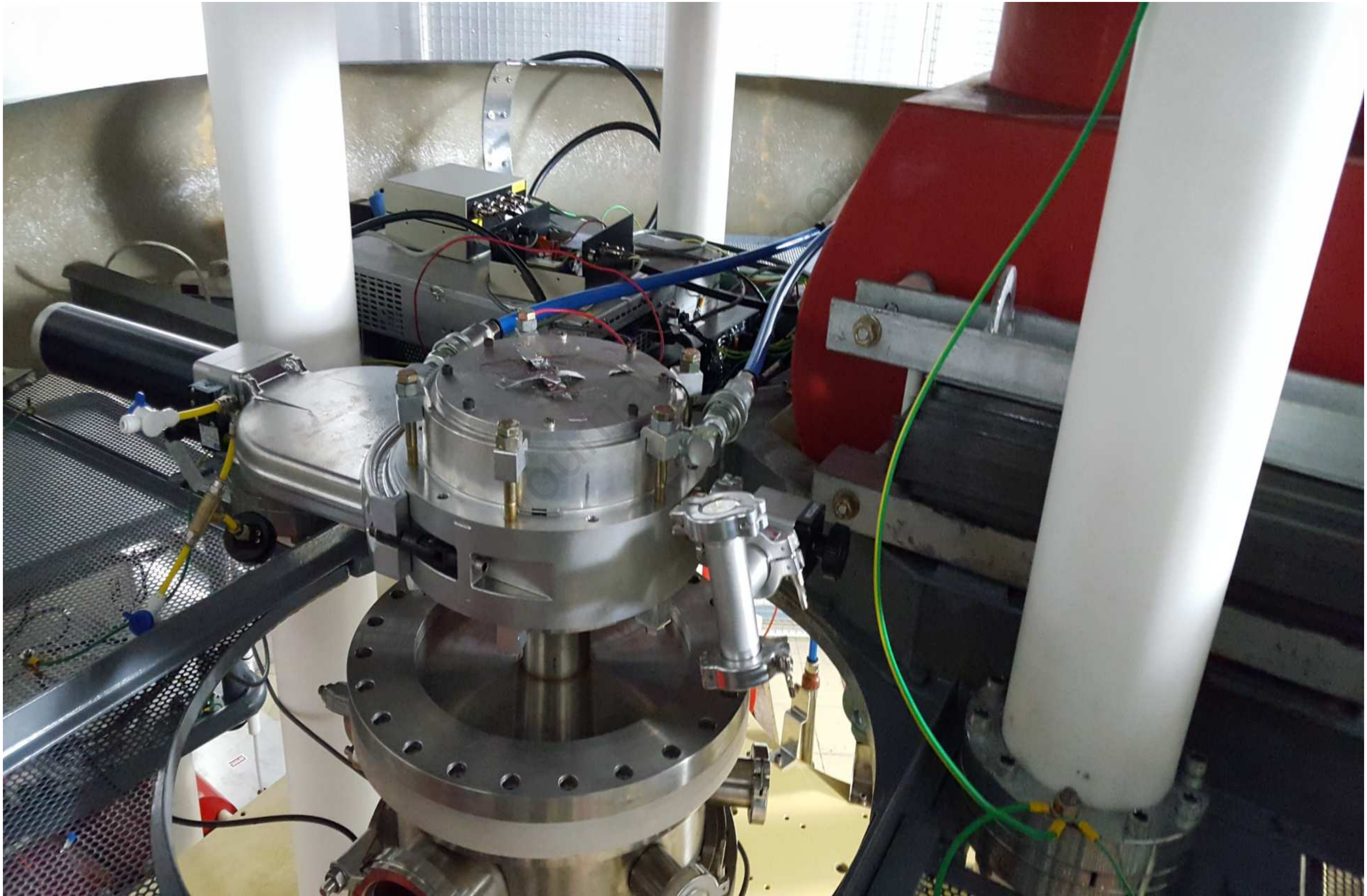


Fig. 10 Stand as of December 2019 of Accelerator development Laboratory and future BNCT treatment Centre.

Declaration of interests

x The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. YES

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: