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ANTHEM PROJECT, CONSTRUCTION OF A RFQ DRIVEN BNCT NEUTRON SOURCE

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Abstract

The project Anthem, funded within the Next Generation EU initiatives, foresees the realization of an innovative accelerator based BNCT (Boron Neutron Capture Therapy) facility in Caserta, Italy.

The INFN (LNL, Pavia, Napoli, Torino) is in charge of the design and construction of the epithermal neutron source, that will assure a flux of 109 s-1 cm-2 with characteristics suited for deep tumors treatment. The driver is a cw RFQ, able to produce proton beam of 30 mA at 5 MeV. impinging on a beryllium target. Specific challenges are related to the medical application of the device. In the paper an overview of the project will be given.

INTRODUCTION

New neutron sources based on compact high intensity linacs have recognized advantages respect to reactors and spallation sources for medical (and many other) applications.

One of the pilots of the project ANTHEM (AdvaNced Technology for Human centEred Medicine) is aiming to the realization of an intense source of epithermal neutrons for Boron Neutron Capture Therapy (BNCT) for deep-seated tumour treatment. Such neutron source is based on a high intensity linear accelerator under realization at INFN (Istituto Nazionale di Fisica Nucleare), Legnaro National Laboratory, Pavia, Napoli and Torino units.

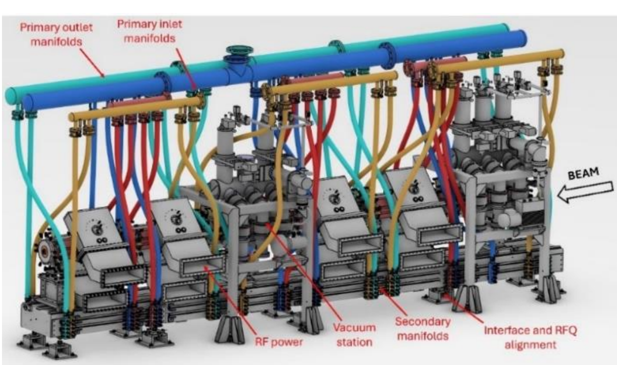

Figure 1: The RFQ integration on the new support.

The accelerator is a Radio Frequency Quadrupole able to accelerate 30 mA of protons up to 5 MeV. The RFQ (Figs. 1 and 2), together with the ion source TRIPS was developed in the last years in the framework of TRASCO project at INFN LNL and LNS respectively.

The proton accelerator is coupled to a high-power beryllium target. For BNCT application this neutron source promises unique performances in terms of neutron flux and spectra (very low gamma and fast neutrons components) as needed for a successful therapy.

Table 1: ANTHEM BNCT Main Parameters

Ion source	MDIS	Proton energy 80 keV
Accelerator	RFQ	352.2 MHz, 7.13 m long
Final energy	5 MeV	
Beam current	30 mA	accelerated
Duty cycle	CW	50% duty cycle possible
p-n Converter	Beryllium	150 kW, 1kW/cm^2
Neutron source intensity	~10^{14} s^{-1}	entire solid angle, Ave. neutron energy 1.2MeV
At BNCT port	~10^9 s^{-1}cm^{-2}	epithermal
RF power	1.0 MW	
Power consumption	~3.5 MVA	

The proposal of a neutrons source based on TRASCO RFQ for BNCT has a quite long history as SPES-BNCT [1] and MUNES projects [2]; for these R&D programs the construction of the facility was not funded, but many technological issues were solved.

Therefore, when in 2022 the group of physicists from INFN, and the group of medical doctors and biologists from Vanvitelli University met with the strong motivation to build a BNCT facility, many elements were clear and a successful proposal could be prepared in short time. Table 1 summarizes the main parameters of ANTHEM BNCT. In this paper we shall concentrate in accelerator and target aspects.

Figure 2: The 3 RFQ segments at INFN-LNL.

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THE ACCELERATOR

In Fig. 3 the schematic lay-out of our system is shown; the accelerator hall (about 16 m long), the RF hall, the beam distribution hall and two irradiation rooms (only one will be equipped for BNCT initially). The construction is being built within a complex in Caserta where many other scientific activities (including the electrostatic accelerator CIRCE) are already active.

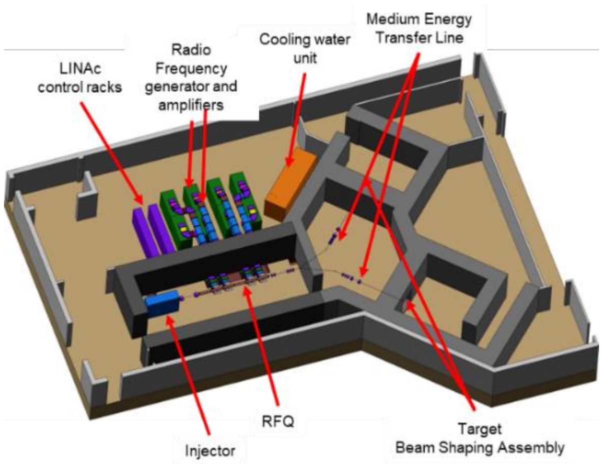

Figure 3: Layout of Anthem BNCT treatment facility.

The ion source (ISRC) TRIPS (TRasco Intense Proton Source) is a high intensity microwave source [3,4], followed by a magnetic Low Energy Beam Transport (LEBT) line, equipped with 2 solenoids and 2 separate steerers to match beam parameters at the RFQ input, with a beam diagnostic box and with a chopper for machine protection system (MPS) purposes and for pulsed beam operations. The ion source, revamped in the last years (mechanics, ancillary systems, controls), is now under test at LNL and has already reached the 30 mA 80 kV with good reliability (Fig. 4). An upgrade to 50 mA is foreseen.

The LEBT is in assembly phase; it will operate with a high degree of beam neutralization (design and commissioning plan follow the long INFN experience with IFMIF and ESS [5]). Particularly challenging is the chopping system, able to chop 50% of a 50-mA beam; the aim of this "green" mode of operation is power saving.

The RFQ, operating at 352.2 MHz, will accelerate with high transmission and small long. emittance the proton beam up to 5 MeV [6-8]. It is a four vanes RFQ, longitudinally divided in three segments, resonantly coupled to reduce sensitivity to transients, thermal instabilities, and mechanical imperfections [9]. The RFQ is designed to operate in CW RF regime, but it can work also in pulsed mode. The total RF power to operate the RFQ is estimated to be $P_{TOT}=(P_{Cu}+P_{Beam})1.15=600$ kW+150 kW1.15=862 kW where P_{Cu} are the ohmic losses on copper surfaces and P_{Beam} is the power delivered to the beam, 15% is the margin for low level RF (LLRF) regulation.

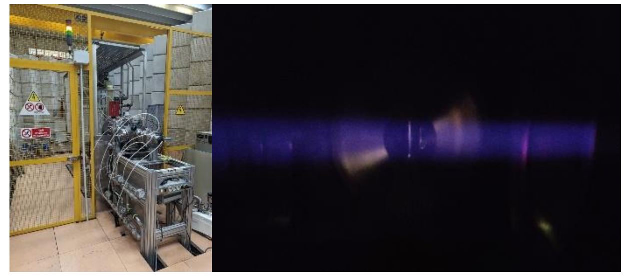

Figure 4: On the left the proton source assembly. On the right, snapshot of the 30 mA 80 keV beam from the ion source.

The cavity will be fed by 8 RF power couplers, each one connected to a solid-state RF power amplifier capable of delivering 125 kW CW for a total available power of 1 MW. The use of 8 independent solid-state amplifiers, in place of a single MW-class klystron/modulator system, requires some design efforts in terms of LLRF and MPS controls, but it promises advantages in terms of redundancy, modularity and maintainability, which are particularly suitable in hospital environment. Figure 3 shows the 8 amplifiers installed in the area adjacent to the accelerator tunnel, with the cooling skid, ISRC HV transformers and the control racks. The first RFQ segment was already tested to nominal field and duty cycle (up to 2.2 E_{kp}, 80 kW/m, 100% duty cycle) [10]. The solid-state amplifiers (Fig. 5) were developed by an Italian company (5/8 tested presently).

The power couplers are under construction, together with a new bridge cavity (bulk copper [11]). The coupler design (cooled copper loop, cylindric RF window, doorknob transition to waveguide) was already demonstrated with full power tests; nonetheless all the couplers will be tested at LNL before being installed on the RFQ, using Fig. 5 shows the test stand principle.

A new mechanical support for RFQ the entire structure has been recently delivered at LNL, and in the next months the RFQ will be assembled and tuned for the transportation to Caserta. The 7,5 m long girder allows the assembly, alignment and commissioning of the RFQ modules at LNL and final integration with cooling water and RF distribution, with the isostatic regulation of the RFQ on the final linac line.

The RFQ is followed by a first Medium Energy Beam Transport (MEBT-1) line up to a dipole switch magnet, which will direct the beam to the neutron target and the treatment room or to the experimental area. The MEBT-2 lines (from the switching magnet to one of the two rooms) will include quadrupoles and 2 octupoles, to properly shape the beam rectangularly on the target (Fig. 6). The beam dynamics in this 14 m long line is quite complex (space charge is not negligible, and the beam bunch structure is gradually lost) and extremely critical (due to the high-power density on the target). Advanced computational methods have been used for the design of this line and will be used for tuning [12].

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The control system is based on the EPICS framework. The use of EPICS will enable the ANTHEM project to effectively manage development timelines and reduce future maintenance time and costs, ensuring a reliable and efficient distributed control system.

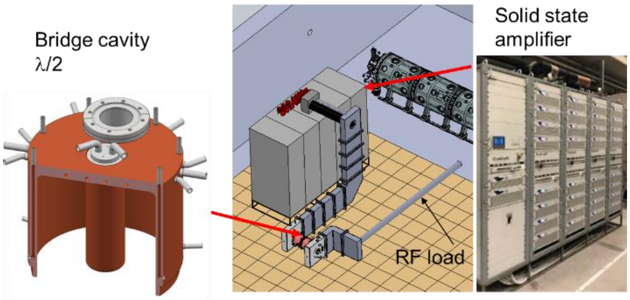

Figure 5: RF tests at LNL (scheme and main elements).

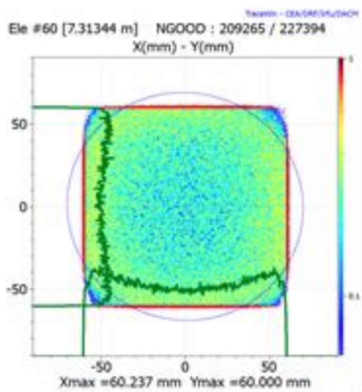

Figure 6: beam spot at the target obtained with proper setting of quadrupoles, octupoles and collimator.

THE TARGET

The 150 kW proton beam will collide perpendicularly with a target designed using a three-layered concept (Fig.7): beryllium for neutron production, palladium for blistering mitigation [13] and copper for efficient heat removal.

With respect to Li-based targets, beryllium is preferable due to its superior mechanical and thermal properties (Melting point: Be=1278°C, Li=~180°C; Thermal conductivity: Be=201 W/mK, Li=85 W/mK). Moreover, proton irradiation of lithium produces tritium and beryllium-7, a radioactive isotope with a half-life of 53 days. The thickness of the 3 layers is optimized to maximise neutron production in beryllium, minimise blistering in beryllium and copper, and ensure efficient heat removal in copper. Since the Bragg-peak depth of 5-MeV protons in beryllium is ~230 µm, the beryllium layer is set to 150 µm. The blistering mitigation metals typically have lower thermal conductivity compared to copper, so this layer is minimised to 400 um. This approach is similar to that used in iBNCT [14,15], but with a single, lower-energy accelerator and approximately twice the beam power (proton energy is 8 MeV for the Japanese facility).

The choice of a relatively low proton beam energy offers the advantages of using a single accelerating structure and a simplified design for the neutron Beam Shape Assembly (BSA) due to reduced contamination from fast neutrons and gammas. However, this also reduces the neutron production efficiency, leading to higher power on the target. To reduce power density, quadrupole and octupole electromagnets shape the proton beam into a square profile over 150 cm². Even with these measures, the neutron converter still faces a challenging power density of 1 kW/cm², requiring an advanced water cooling channel design.

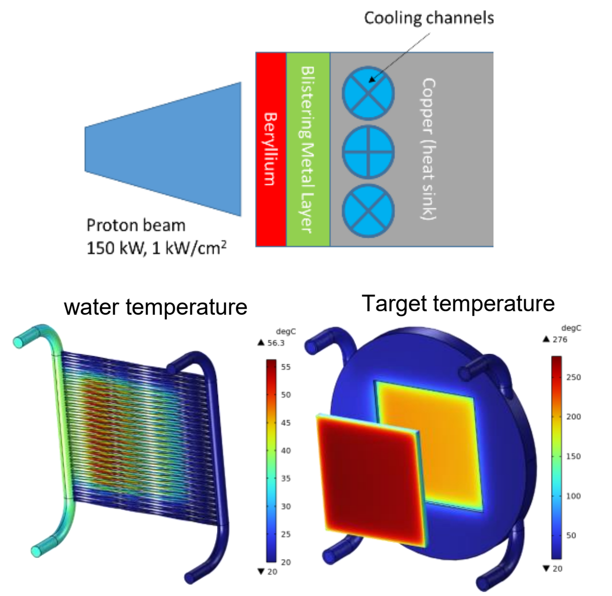

Figure 7: Three-layer target concept and thermal simulations with visible the microchannel cooling system.

The target will be a 150 mm diameter disc with beryllium, palladium and copper layers joined by Hot Isostatic Pressing (HIP). The cooling channels, helicoidal in shape with an approximate diameter of a 1.5 mm are produced by additive manufacturing (AM). The microchannel system is designed to operate with water below 100°C and a pressure drop of approximately 7 bar. Prototypes with AM are being produced, and off line tests of their cooling proprieties will be performed.

CONCLUSION

In the next two years, the infrastructure will be realized in Caserta, the offline tests of the main components will be performed in LNL, comprising a gradual installation and integration of the components at the end of the period. We thank all the colleagues involved in all the aspects of this project. This work was partially funded by the National Plan for NRRP Complementary Investments project n. PNC0000003 (project acronym: ANTHEM).

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