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Promising applications and technologies for neutron production targets; workshop highlights, tentative summary and conclusions; guidelines for documentation of results.

The neutron production target strongly depends from the energy of the incoming beam and whether this beam is stopped inside the production target (with all issues related to Bragg peak) or in a layer underneath the production target or is dumped elsewhere.

For a general orientation, we can parametrize stresses of the targets with
1) P_{D2} the power density for unit surface and the total power deposited in target P_{D0};
2) P_{D3} the (maximum) power density for unit volume (or mass, clearly maximum at Bragg and low beam energies;
3) the converter material and the maximum temperature allowed for its physical status (for example for solid Li is about 450 K, for liquid Li about 1000 K, for solid Be 1551 K) and possible activation issues;
4) the gas produced by beam stoppage (gas occlusion may cause embrittlement and swelling or blistering, depending on beam intensity, material permeability, porosity and duty cycle).

When neutron flux intensity is the main concern, neutron production efficiency may be conveniently measured by P_{n1} the number of MeV (of particle kinetic energy) needed on average to extract one neutron from the target , taking in account all relevant nuclear reactions and beam slowing down; for example, in spallation sources, P_{n1}=30 MeV using proton over 600 MeV as primary beam and W solid targets [see Pisent slides]. If a particular spectra of neutron is of interest, a different beam energy optimization is taken; for example: 40 MeV deuterons against a liquid Li target are used in the IFMIF project to optimize the 14 MeV content of neutron spectra; then P_{n1}=600 MeV [Pisent]

For Boron Neutron Capture Theraphy (BNCT) epithermal neutrons (0.5 eV to 10 keV) are preferred, and other irradiation are strictly limited (see for example IAEA guidelines IAEA-Tecdoc-1223, [see Kobayashi slides]), which requires some neutron moderator and shielding. The choice of primary beam energy is then dictated by two opposing considerations: a) the higher the energy, the longer the range of ions (protons or deuterons) inside matter, the easier the target design; b) the lower the ion energy, the lower the maximum neutron energy, the easier the moderator design. This opens way to a variety of designs, also in consideration of existing equipment (or construction capabilities) at interested institution.
Several interesting target design (Li, and solid Be) were discussed at the meeting [see slides of Taskaev, Kreiner, Pisent, Kobayashi, Green, Phoenix], at ion energies of 1.4, 2.8, 8 and 30 MeV, and will be summarized later.

For spallation sources, typical targets are: 1) liquid Mercury; 2) solid W, in rapid rotation to favour cooling [Weissend]; 3) liquid Pb-Bi. Liquid targets may have regulatory problem, but are the obvious solution to gas occlusion. Solid targets may avoid gas occlusion, by leaving the beam to pass and be dumped elsewhere; also they can manage this problem by proper choice of materials, subdivision, working temperature.

A 1st example of BNCT target (Kyoto-Sumitomo) employs a 5.5 mm thick Be target and 30 MeV, whose range is 5.8 mm in Be; so protons stop in the cooling water [see Kobayashi slides]. A 2nd example of BNCT target uses 8 MeV protons (0.7 mm range) and a 0.5 mm Be target, followed by backing layer (mitigating gas occlusion) and heat removal layer [i-BNCT, Kobayashi]. A 3rd example of BNCT target uses 5 MeV protons (available from a high intensity RFQ built at INFN-LNL) on a thin Be foil target, solidly bond to a copper alloy block, where beam stops; block is cooled by water and $P_{D2} = 0.7$ kW/cm^2 [Pisent]. In all these targets, reaction is

$$\mathrm{p + Be \;\rightarrow\; n + {}^{9}Be - 2\ MeV}$$

and neutron needs to be moderated (and may be used for other tasks), Be is far its melting point (1551 K); since Be has very low permeability to gas (and to H in particular), beam needs to be stopped elsewhere
A 4th example of BCNT system uses a removable 0.7 mm thick solid Li target, over a copper cooling plate, with 2.8 MeV protons, which have a 0.3 mm range; in this case the Li target protect copper from blistering. [Green, Phoenix slides]. Reaction is

$$\mathrm{p + {}^{7}Li \;\rightarrow\; n + {}^{7}Be - 1.64\ MeV}$$

and a orthogonal and flat mounting is used: a) to reduce maximum neutron energy to 0.7 MeV; b) to confine Li in case of accidental Li melting. In liquid Li target for SARAF proton energy can be reduced 1.91 MeV or 2 MeV only (achieving $P_{D2} = 4$ kW/cm^2 and $P_{D3} > 1$ MW/cm^3) and very low energy neutrons. Other examples uses a 0.05 mm thick solid Li with a Pd stopper [Fuiji] and proton energy regulated to 2.5 MeV, with an RFQ accelerator and conical assembly (Pd stopper protect copper from blistering).
Another example uses a very thin Be target, with deuterons beam optimized [Kreiner] to drive the chain of reactions

$$\mathrm{d + {}^{9}Be \;\rightarrow\; n + {}^{10}Be^{*} - 1\ MeV}$$

$$\mathrm{{}^{10}Be^{*} \rightarrow\; {}^{10}Be^{*}} + \gamma$$

This allows directly producing low energy neutrons (also with Be target). Solid Li target with improved cooling systems [Taskaev, Mastinu] are also used used in VITA and LENOS system; in the latter, neutron distribution may have a quasi Maxwellian distribution (with temperature up to 30 keV and 90 keV), which is obtained by shaping the proton beam energy distribution with a degrader (a rotating 70 micron thick carbon target).
Considering that total power of BNCT accelerator based facility is still limited $P_{D0} < 4$ kW for reason described, treatment in the order of one or two hours seem still necessary, which is still consistent with upgrade of the existing clinical database [Evangelista slides]. At the state of discussion, it is difficult to say whether an overwhelming best solution for BNCT accelerator exists or if design should start from existing facilities to reduce costs. Areas of active collaboration among workshop participants are evident.

Technical issues of targets for radiopharmaceuticals production seem similar, and market perspectives are excellent.

Another important application of proton, deutron and neutron beams is the production of radioactiove ion beams (RIB), as in facility SPES being built in Legnaro [see Prete slides], and of radioisotopes. Target made of porous UC_6 for RIB were described [see Stracener slides]. Just as as example, neutron beams (produced by spallation with GeV protons on a heavily cooled static W target) may used via

$$n + {}^9\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^6\mathrm{He}$$

(max cross section 0.1 barn at 3 MeV) to produce the RIB specie ^{6}He, which may accelerated and stored in racetrack ring to produce neutrino beams [see Stora slides]

Measurement of cross section

$$p + \mathrm{Be} \rightarrow n + \{X\}$$

where {X} is any other product were carefully described [Osipenko], and important for the precise understanding of previously described targets, and update of cross section databases of neutron transport codes (MNCP, Fluka, Geant4 to name a few). Tools for precise neutron spectroscopy were also described [see Hawkes, Bedogni slides]; study of single neutron event are possible both with dedicated channel from spallation source [Milocco] and with specialized target for the SPES beam [see Silvestrin slides].

Concerning coolant, most used fluid for solid target is water. Several data on heat transfer in various regimes were reported in the slides. In most regimes, it is important to provide maximum turbulence of the fluid near the cooled surface, to improve heat transfer.

In practice this means increasing the fluid speed at the localized surfaces where stronger cooling is needed, for example by reducing channel cross section at those surfaces, even at the price of a large pressure drop. Computational fluid dynamic studies are therefore worthwhile, but considering complexity of these simulations, simple test on models with heat provided by several concentrate sources (electron beams, welding torches, and so on) are very useful; both approaches were reported in the slides.

Some experiment with Gallium show the importance of corrosion effects [Taskaev] and the use of Gallium alloys is being studied [Mastinu].

Concerning accelerator, under 3 MeV electrostatic ion accelerator can be very compact; several example appeared in the slides [Kreiner, Taskaev, Smick]. Another advantages of electrostatic accelerators is energy efficiency, while rf accelerators have advantages of modularity, and their reliability does not decrease with increase of ion energy (moreover, they reach higher energies [Gammino, Pisent, Weissend]). Cyclotron projects up to 70 MeV were presented [Prete, Calabretta], with use also of molecular ions (H_2^+).

Concerning ion sources, use of Penning ion sources and Electron Cyclotron Ion Sources were presented [Taskaev, Gammino]; reliability of rf accelerators is naturally complemented by improved reliability of ion sources and accurate simulation of ion transport [Gammino, Pisent].

Other remarks (made in the discussion by several participants) included:
1) there is a need for extensive databases of gas occlusion (and related damages, blistering) on target structural materials, (Li, Be, graphite, diamond, palladium, Mo, W, iron and nearby elements, and most of all, Copper);
2) investigation of porous materials and nanostructured target materials may be worthwhile (the physical compromise being between thermal conductivity and gas permeability); also micromachining may help to a solution;
3) anyway, BNCT targets should be inexpensive, for rapid substitution;
4) target manufacturing techniques (bonding, film deposition, simple assembling) are worth discussing;
5) list of working machines and targets presented in this workshop should be checked and organized;
6) liquid metal coolants are promising, even if corrosion should be studied with great caution (considered alloys lead-bismuth where permitted, gallium-indium-tin) and activation should be also studied;
7) even using water, careful design of coolant system is worthwhile;
8) computational methods to test technology versus treatment plans may be useful;
9) development of neutron monitoring is very important.

At the end of workshop, it was agreed to publish slides of the presentation, discussion summaries and abstract book on the web workshop site.

To summarize, applications of neutron production with accelerators discussed in the presented slides includes:
a) nuclear physics and neutrino physics; b) application to astrophysics; c) BNCT; d)isotope production; e) single event damage in microelectronics; f) study of material damages.