CHOICE OF ACCELERATOR TYPE FOR BORON NEUTRON CAPTURE THERAPY SYSTEM

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Article history:
Received 21.08.2019, Accepted 22.09.2019

Abstract
There are briefly considered physical and medical aspects contemporary development of Boron Neutron Capture Therapy (BNCT) system. Choice of accelerator for neutron produce is discussed. Three of accelerator types are compared: electrostatic accelerator, compact cyclotron and RFQ with working frequency of P-diapason. A few factors determine choice: providing of required neutron flux, compactness of accelerator and whole BNCT system, economical power consumption. Our choice is radio-frequency quadrupole. Two of RFQ variants are considered: compact RFQ and universal one, which has possibility to accelerate two of types particles (proton and deuteron) and to use two of types targets (Lithium and Beryllium) for neutron produce

Key words
Radio-frequency quadrupole, boron-neutron capture, neutron-producing, thermal neutron, epithermal neutron.

1 Introduction

At the present time radiation therapy is the most demanded method, which is used for treatment of 70% patients with malignant tumor [Khmelevsky]. At the same time neutron-capture radiation therapy with ^{10}B substances is the most perspective and challenge but complex method which pierce way to clinical practice during century. Neutron-capture therapy is based on different probabilities of nuclear reactions under interaction thermal and epithermal neutrons with atoms which have different cross-section of capture. Atoms, which have cross-section of capture much more then atoms animal material (^{12}C, ^{2}H, ^{16}O, ^{14}N) are ^{10}B, ^{7}Li, ^{152}Gd. Specialty of neutron-capture reaction ^{10}Be(n,α)^{7}Li is formation high energetic α-particle (^{4}He). Important properties of this particle are high line energy transfer and path length 5-9 mkm that comparable with dimension of cell's core. Hence selective delivery ^{10}B to tumor make possible after reaction with thermal neutrons to have damage local target only. To the present time problem of selective delivery ^{10}B to the target had decided practically. Among chemical joins (mean delivery) of boron had researched good in chemical conditions L-p boronphenilalanin (L-BPA) and sodium borcaptat (BSH). Medico-biological and neutron-physical researches showed that neutron therapy (in depend on tumor and method of treatment) need beams of neutron with energy 0.1–20 MeV and neutron flux density $10^7 \div 10^8$ n/cm^{2}c. For clinical researches and treatment by BNCT method one need beams of epithermal neutron with energy 0.5 eV–10 keV, size 10×10 cm^2 and density flux $\geq 10^9$ n/cm^2c. At the present time in clinical practice, on the whole, nuclear reactor or power cyclotron are used as neutron source. Use of such big constructions in oncological clinics is impossible.

So, creation of compact accelerator as neutron source is urgent problem. Such devices must operate without nuclear danger. Typical reactions for neutron production with help accelerators are: ^{7}Li(p,n)^{7}Be; ^{9}Be(p,n)^{9}Be; ^{9}Be(d,n)^{10}B. Best physical parameters for these purposes can give electrostatic accelerator but his sizes too big. Moreover, output energy of electrostatic accelerator is limited by meaning 2–2.5 MeV.

2 Comparison of linear RF accelerators and cyclotrons for BNCT

M. Yoshioka presented on IPAC'2016 current status planning, designing, ready or having clinical trial accelerators for BNCT [Yoshioka, 2016]. On the whole these include machines of three types: electrostatic tandem with change of charge; two of cyclotrons with output energy 30 MeV and current 1 mA; two of RFQ's and two of tandem RFQ plus DTL with energies from 2.5 up to 8 MeV. Let us to compare linear accelerators and cyclotrons. Cyclotrons have following advantages before linacs:

1. Cyclotron is cheaper then linear accelerator of the same energetic diapason;

2. Cyclotron is more reliable then linac because has usually only RF generator and only amplification line. Linear accelerator of midi and high energy have some or many RF lines of RF system;

3. Energy spectrum accelerated particles is more narrow then the same in linear RF accelerator.

But in cyclotron one can't obtain big current, at least, in the present time. Practically limit is 2 – 2.5 mA. This is connected with small phase capture of particles into acceleration and big losses particles on initial turns by action of space charge forces. Linear RF accelerators have not serious limitations on current value, their beam quality is better (emittance and diameter is smaller).

In paper [Yang et al., 2012] one propose to accelerate molecular ions of hydrogen H_2^+ to decrease influence of space charge forces, on initial turns in cyclotron. Extraction H_2^+ beam will be provided by passing via foil to obtain current two times more, but energy of protons two times less. Such cyclotron may have output energy of H_2^+ beam 6 MeV, current, for example, 2.5 mA. Such cyclotron could be compact and convenient for BNCT. But this idea need serious working out (mathematical and physical modeling, so beam is passing two targets: foil and neutron-producing ones and beam characteristics can change strongly). Item [Yang et al., 2012] is project of high intensity DAEδALUS Cyclotron. The DAEδALUS collaboration is designing advanced cyclotrons that accelerate molecular hydrogen ions to produce decay-at-rest neutrino beams for a novel search for CP violation in the neutrino sector. Cyclotron complex consisting of two cascaded cyclotrons. The injector cyclotron (DIC) is a four-sector compact machine, which accelerate a beam of H_2^+ up to 60 MeV/amu. The beam then extracted by electrostatic deflector and is transported and injected into an eight-sector superconducting ring cyclotron (DSRC) in which the beam is accelerated to 800 MeV/amu by four single gap radio-frequency cavities. Two stripper foils can be used to extract two proton beams at the same time from the ring cyclotron. To the present time dynamic simulations in injector cyclotron and the beam stripping after main cyclotron were produced.

Beam injection to injector cyclotron was researched experimentally at the last time [Winklehner, 2017]. Main beam losses took place in the first cyclotron where space charge is dominated. In the DSRC (main cyclotron) the important beam properties at the stripper are dominated by initial conditions. Space charge and radially neighboring bunches introduce vertical beam halo but the influence is at acceptable levels. The multi-turn stripping scheme relaxes the constraint of the beam losses at extraction. However, with the side effects a large emittance and larger energy spread of the extracted bean. But the proton beam tracking along extraction path shows the beam is well focusing and therefore no significant beam loss is expected. But high energy stripping in DSRC and low energy stripping at compact 6-MeV cyclotron for BNCT are strong different.

Since perspectives of creation of compact cyclotron of H_2^+ ions with following their passing through foil and obtaining of proton beam of energy 3 MeV and current 5 mA are unclear until now, we will consider use of RFQ with frequencies of P-diapason as neutron producer. There are a few variants of RFQ using depend on target type. Positive and negative attributes of Lithium and Beryllium targets are determined diapasons of energies and currents as output parameters of RFQ. On Figure 1 are given total yields of neutrons from different targets depend on proton and deuteron energies [Kononov et al., 2003] (Tritium target we exclude from consideration because high radioactivity).

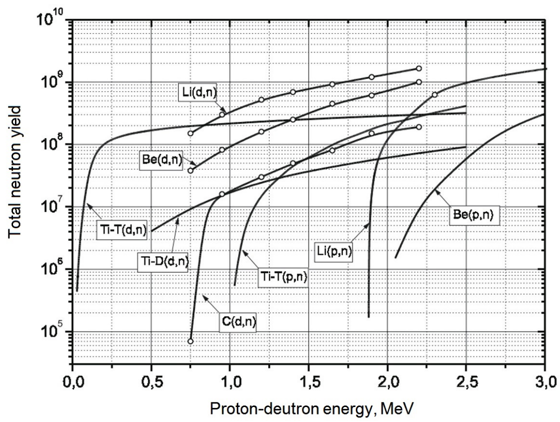

Figure 1. Total neutron yield

Yield of neutron for Lithium target is higher then for Beryllium one (at least under low energies). But Lithium targets (as solid, so liquid) have some inconveniences. Negative attributes of Lithium target:

1) low melting point (180.5° C), so target must be cooled effectively to avoid evaporation;

2) reaction ^{7}Li(p,n)^{7}Be gives ^{7}Be – radioactive nuclide with half-life of 53 days;

3) presence of isotope ^{6}Li lead to generation of tritium ^{6}Li(n,t)^{4}He.

Therefore usually are used energy of bombarding particles (protons and deuteron) 2.5–3 MeV for Lithium target under current 1–3 mA. Reaction ^{9}Be(p,n)^{9}B gives minor yield of neutrons, but yield can increase by bigger current of bombarding protons, and bigger their energy.

According to Yoshioka 13 MeV is critical energy. Neutrons with energy more then 13 MeV produce many kind of active nuclides, that gives residual radiation.

Energy lower then 13 MeV gives minor yield, so one need develop a high current accelerator and avoid target damage by blistering. Special energy for Beryllium target is 8 MeV. Under this energy of bombarding protons they produce neutrons which have energy less then 6 MeV.

In general Beryllium target is used over about 5 MeV proton energies, and the Littium target is used less then about 3 MeV. For the target design, blistering and radioactivity are important components to be considering as well as [Kiyanagi, 2018]. Here is not considered neutron production by accelerated electrons, because photonuclear reactions don't give neutron yield enough for the treatment.

3 RFQ for BNCT

Two variant of RFQ's application will be presented below. It is compact RFQ with output energy 2.5 MeV for Lithium target and universal accelerator, which can use two of type accelerated particles (protons and deuterons) and two type targets: Lithium and Beryllium.

It is possible to combine requirements for Lithium and Beryllium targets in single accelerator. In paper [Ovsyannikov et al., 2016; Altsybeyev et al., 2018] were formulated principles of separated acceleration protons and deuterons in single RFQ structure:

1. Since vanes modulation will be single for acceleration of both types particles, initial velocities protons and deuterons will be equal;
2. Under these conditions initial and final energies of deuteron must be two times more than the same volumes of protons;
3. Matching section for case acceleration of two types particles must be optimized by methods described in papers [Ovsyannikov et al., 2009; Ovsyannikov et al., 2016; Altsybeyev et al., 2018].

Examples of modeling dynamics of ions $H^{\pm}$ and $D^{\pm}$ in single accelerating RFQ structure for different currents are given in [Ovsyannikov et al., 2016]. Working frequency of RFQ is 432 MHz. Diapason of considered currents is 0–25 mA. Here is proposed for using in BNCT system universal RFQ which accelerates deuterons up to 5 MeV (beam is leading out on Beryllium target) and accelerates protons up to 2.5 MeV (beam is leading out of Lithium target). Another data of proposed RFQ are given in Table 1.

This RFQ is not compact (length of vane is 6.5 m) and need special moderator, but permits to change neutron flux volume. This RFQ was calculated on material work [Ovsyannikov et al., 2016]. It can have single ion source, which may use in discharge camera two types gases: hydrogen or deuterium, single accelerating structure and, possible, single special moderator. One may note that vane voltage 50 kV in this RFQ is optimal magnitude as for deuterons so and for protons.

Data of compact RFQ for BNCT system are given in Table 2.

Table 1. Parameters of H–D accelerator (two accelerators in single one)

Parameter	Magnitude
Working frequency	432 MHz
Injection energy of $H^{\pm}$ ions	25 KeV
Injection energy of $D^{\pm}$ ions	50 KeV
Output energy of $H^{\pm}$ ions	2.5 MeV
Output energy of $D^{\pm}$ ions	5 MeV
Average current of $H^{\pm}$ ions in pulse regime	3 mA
Average current of $H^{\pm}$ ions in CW regime	5 mA
Average current of $D^{\pm}$ ions in pulse regime	$\leq$ 5 mA
Average current of $D^{\pm}$ ions in CW regime	$\leq$ 10 mA
Average radius of accelerating channel	1.8 mm
Vane voltage kV	50 kV
Lenght of vane	6.5 m
rms emittance of H, D beams on exit	$\leq$ 0.11 cm·mrad

Table 2. Parameters of compact RFQ for BNCT system

Parameter	Magnitude
Partical's type	proton
Working frequency	432 MHz
Injection energy	50 keV
Output energy	2.5 MeV
Average current	10 mA
Emittance on entry	0.05 cm·mrad
Emittance on exit	0.105 cm·mrad
Average radius of accelerating channel mm	2.7 mm
Vane voltage	50 kV
Vane lenght	3.2 m
Number of accelerating sell	365
Average pulse spread	1.6 %

Optimal emittance on RFQ entry (before matching section) is given on Figure 2.

Dependence of vane modulation on number sells is given on Figure 3.

Separate problem is choice of power amplifier for RF system. The most suitable klystron of 432 MHz for both proposed RFQ variants is device of THALES firm – TH 2120(3). It's parameters are: peak output power – 4 MW; average power – 500 kW; pulse length (max) – 10 ms; efficiency - 65%. It is economical variant for both samples of RFQ, if klystron can work in underloaded regime. If customer wants to use CW regime, then suitable klystron is TH 2167 (firm THALES) with parameters: working frequency – 401 MHz; output power – 300 kW; efficiency – 63%; gain – 37 min dB. In this case one need single device for compact RFQ and two ones for HD RFQ. Under work proposed RFQ with TH 2167 device their geometrical and physical parameters must be recount according to changed frequency ([Ovsyannikov et al., 2006]). Because difference of frequencies is small (∼7%), characteristics of RFQ1 and RFQ2 will change slightly, dimensions will be slightly bigger, but beams parameters it is possibly to maintain the same.

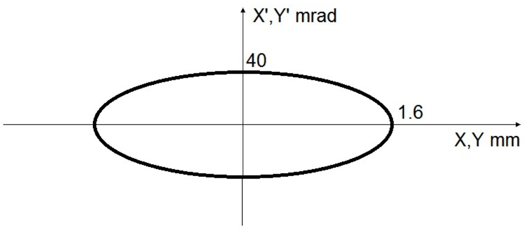

Figure 2. Optimal emittance on RFQ entry

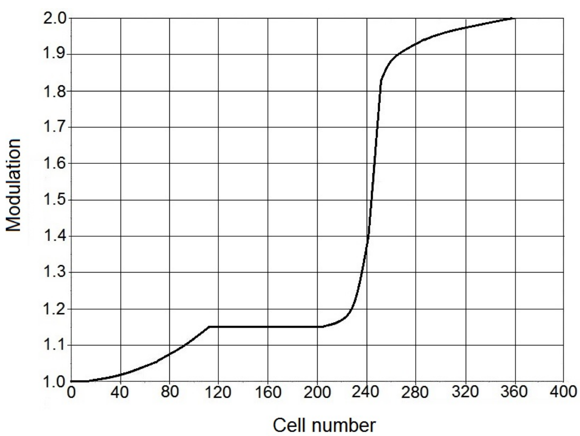

Figure 3. Vane modulation

4 Conclusion

At the present time researches in creation clinical sample of BNCT system are continued in different laboratories of the world. These works is developed most intensive in Japan. Now RFQ is the best candidate as accelerator for BNCT system. But in future it is may be compact cyclotron or some new type of electrostatic accelerator. Choice of accelerator and target is the first step computer technical modeling of BNCT system. Next step is optimization of particle dynamics including neutron beam, that is moderator optimization.

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