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Two Design Options for Compact Linear Accelerators for High Flux Neutron Source

Xiaowen Zhu , Claude Marchand , Olivier Piquet and Michel Desmons

IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France; claudemarchand@cea.fr (C.M.); olivier.piquet@cea.fr (O.P.); michel.desmons@cea.fr (M.D.)

* Correspondence: zhuxw13@pku.edu.cn

Abstract: We describe and compare two optimized design options of RF linear accelerators with different resonant frequencies at 162.5 MHz (f_0) and 325 MHz ($2 \cdot f_0$). The RFQ + DTL linacs have been designed to provide 13 MeV acceleration to a proton beam for achieving a fast neutron yield of not lower than 10^{13} n/s via ${}^9\text{Be}(p, n){}^9\text{B}$ reaction in pulsed-mode operation. Our design studies show that none of the two options is better than the other, but that the choice of operating frequency will mainly be determined by the accelerator length and RF cost consideration. This study can serve as a basis for the design of an initial stage of a new high brilliance Compact Accelerator-driven Neutron Source (CANS), aiming to use neutron scattering techniques for studying material properties in fundamental physics, materials science, nuclear energy, as well as for industries and societal challenges.

Keywords: particle beam transport; RF cavities; power RF sources; medical accelerator technology; accelerators for industry; accelerators for materials science

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1. Introduction

Compact Accelerator-based Neutron Source (CANS) facilities [1–5] create the possibility of an intense source of neutrons with modest capital cost, more flexible than a dedicated fission reactor or a spallation neutron source [6–10] in terms of management of targets and wastes, accelerator-upgrading, safety constraints, decommissioning, etc. They typically operate in pulsed mode with virtually any desired time structure and thus provide optimum neutron fluxes to the neutron scattering instruments. In addition, to operate in pulse mode can make the heat removal issue in the target easier.

Such an Accelerator-based Neutron Source (ABNS) is composed of an ion source (IS), a low energy beam transport line (LEBT), a radio frequency quadrupole (RFQ) to bunch and pre-accelerate the beam, a medium energy beam transport line (MEBT), an accelerating structure like a drift-tube linac (DTL) for example, a high energy beam transport line (HEBT) and a target system, as shown in Figure 1. In this paper, we only study options using RFQ + DTL linacs as accelerating structures, comparing designs at two different frequencies of $f_0 = 162.5$ MHz and $2 \cdot f_0 = 325$ MHz. An example of a new CANS project that may benefit from the studies presented here is the SONATE project, initiated at CEA Paris-Saclay [11].

The main reactions useful for neutron production are $\text{Li}(p, n)$, $\text{Be}(p, n)$, $\text{Be}(d, n)$, $\text{C}(d, n)$, $\text{d}(d, n)$, $\text{t}(d, n)$, respectively [12]. However, the first three reactions are the most favorable ones.

Usually (d, n) reactions are exothermic. Their drawback is a high Q-value, which leads to a harder neutron spectrum and increases difficulty in the moderator design. Furthermore, they will easily induce activation issues in the accelerator parts and make the maintenance more complicated.

The endothermic ${}^7\text{Li}(p, n){}^7\text{Be}$ and ${}^9\text{Be}(p, n){}^9\text{B}$ are more attractive. Compared to (d, n) reactions, the neutron spectrum is relatively soft, which will benefit moderation.

However, beryllium and lithium have different properties. Due to the low melting point (453.65 K) and thermal conductivity ($85 \text{ W m}^{-1}\text{K}^{-1}$) and the high-power density deposited in the target material, it can be difficult to keep the lithium target solid, which leads to the selection of liquid lithium (LiLiT) in the target design [13,14]. Moreover, the residual radioactivity of product nucleus, ^7Be , should be carefully handled in the target system.

In contrast, beryllium is strong, more elastic than steel, does not oxidize in air, and has more favorable thermodynamic properties, which make this material ideal for a water-cooled neutron source [15]. Proton reactions at low energy favor lithium from a consideration of neutron yield alone. However, as the proton beam moves to higher energy, the neutron yield from beryllium is superior to lithium.

Figure 1. Schematic diagram of the ABNS layout: (**Upper**) a 162.5 MHz design option, (**Lower**) a 325 MHz design option.

Considering the requirements of input proton beam current and bombarding energy, the total neutron yields have been collected from the literature for proton energies up to 23 MeV. Figure 2 shows the total neutron yield from $\text{Be}(p, xn)$ across a region of proton energy accessible to the accelerator system [16]. An empirical formula for the total neutron yield, Y_N , as a function of the proton energy, E_p in MeV, is [17],

$$Y_N(E_p) = 3.42 \times 10^8 (E_p - 1.87)^{2.05} [\text{n}/\mu\text{C}] \quad (1)$$

Although the neutron production rate increases monotonically with proton energy, there is a factor of four increase going from 7 MeV to 13 MeV. However, a clear drawback of the ^9Be target at energies above 13 MeV is the production of ^7Be via (p, t) , (p, nd) and $(p, 2np)$ reactions [18,19]. Threshold energies for these reactions are 13.4 MeV, 20.4 MeV and 22.8 MeV, respectively. The half-life of ^7Be is 53 days while it is 12.3 years for tritium.

Since the threshold for the $^9\text{Be}(p, t)^7\text{Be}$ reaction is 13.4 MeV, and if we wish to minimize target activation, the maximum proton energy should not exceed 13.4 MeV. This choice of maximum proton energy is used in the rest of the paper for the design of the presented accelerating structures for ABNS Linacs.

Figure 2. Collected experimental datum on neutron yields from ${}^9\text{Be}(p, xn)$ reactions and the fitting curve is Equation (1).

2. Proton RFQ Accelerator Design

The RFQ accelerator typically outputs a proton beam energy between 2.5 MeV/u and 3.0 MeV/u for the injection to an Alvarez DTL linac. A DTL linac cannot accept low velocity particles as there is a minimum injection energy due to the mechanical constraint for accommodation of quadrupole magnets. Examples include J-PARC RFQ-III [20], CERN L4 RFQ [21] and SNS RFQ [22]. All have frequencies ranging from 324 MHz to 402.5 MHz and utilize 4-Vane type RFQ resonator adopting a constant voltage of about 80 kV and having a tank length of 3~4 m. The advantages of the 4-Vane type RFQ are low dipole field components, high mechanical strength, and easy cooling at high duty cycle operation.

For lower frequency range (150–200 MHz), it is possible to decrease the transition energy (2.5 MeV, for example) to post Alvarez DTL for a longer cell length of $\beta\lambda$ and enable boron neutron capture therapy (BNCT) research using the threshold reaction of ${}^7\text{Li}(p,n){}^7\text{Be}$ [23–26].

2.1. Design Strategy of RFQ Beam Dynamics

To start the RFQ beam dynamics designs, we have to determine some key input parameters, for instance, vane voltage, input energy and output energy. For 162.5 MHz and 325 MHz RFQ designs, the main parameters are listed in Table 1.

Table 1. Design parameters of the proton RFQs.

Parameters	162.5 MHz RFQ	325 MHz RFQ
Beam species	H^+	H^+
Injection energy (keV/u)	35	55
Output energy (MeV/u)	2.5	3.0
Resonant frequency (MHz)	162.5	325
Peak beam current (mA)	20	40
Inter-vane voltage (kV)	65	85
Cavity length (m)	5.18	3.66
Averaged aperture radius r_0 (mm)	5.664	3.575
Vane-tip radius r_t (mm)	4.250	2.680
Ratio $\rho_t = r_0/r_t$	0.75	0.75
Maximum surface field (MV/m)	16.85 (1.24 Kilpatrick)	32.53 (1.82 Kilpatrick)
Input ε_t (norm. rms.) (mm·mrad)	0.200	0.200
Output ε_t (norm. rms.) (mm·mrad)	0.249	0.206
Output ε_l (norm. rms.) (mm·mrad)	0.360	0.296
Transmission (%)	99.6	98.2

2.1.1. Vane Voltage and Kilpatrick Limit

In general, a higher vane voltage will result in a shorter RFQ length. However, a higher voltage will increase the risk of RF breakdown during operation and result in a larger cavity power consumption. Therefore, we use two different strategies for these two RFQs and make a comparison of both designs, namely low voltage (65 kV), low Kilpatrick limit ($K_p = 1.24$) design for 162.5 MHz RFQ and high voltage (85 kV), high Kilpatrick limit ($K_p = 1.82$) design for 325 MHz RFQ.

For normal conducting cavities, the Kilpatrick criterion for sparking as a function of frequency (MHz) is defined as following [27]:

$$f(\text{MHz}) = 1.64E^2e^{-\frac{8.5}{E}} \quad (2)$$

where E in MV/m is the Kilpatrick electric field. At frequencies of 162.5 MHz and 325 MHz, the Kilpatrick electric fields are calculated to be 13.595 MV/m and 17.846 MV/m, respectively. For the highest stability, the peak surface electric field on the vane-tips is usually held below the 1.85 Kilpatrick limit.

The averaged accelerating gradient (MeV/u/m) and Kilpatrick limit of various proton RFQs all over the world is summarized in Figure 3 [28–37]. Thanks to cranking up the peak surface electric field to 1.82 Kilpatrick at the higher frequency of 325 MHz, a shorter RFQ can accelerate a proton beam to desired output energy. Though the 162.5 MHz RFQ has a longer cavity length, it has a lower Kilpatrick factor of 1.24 and thus less risk of electric breakdown and has more potential for future BNCT research. After comparing with the design parameters of other proton RFQs, both designs are considered to be reliable for high duty factor operations.

Figure 3. Energy gain per nucleon and Kilpatrick limit of various proton RFQs in the world.

2.1.2. Injection Energy

The injection energy has a main influence on the space charge effect, which is described by generalized perveance K [38]. It's a dimensionless parameter, defined by

$$K = \frac{qI}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3} \quad (3)$$

where q is the ion charge, I is the beam current, ϵ_0 is the input emittance, c is the speed of light, β is the normalized speed and γ is the Lorentz factor. According to Equation (3), the space charge effect of the 35 keV/u, 20 mA proton beam in the 162.5 MHz RFQ design is

equivalent to that of the 55 keV/u, 40 mA proton beam in the 325 MHz RFQ. In addition, keeping a modest extraction voltage will help to decrease the risk of ion source sparking and is beneficial to its long-term operation.

2.1.3. Output Energy

The RFQ output energy or transition energy to the post Alvarez DTL is primarily determined by the mechanical length of a permanent magnet quadrupole (PMQ). The typical mechanical lengths of PMQs used in the 402.5 MHz SNS DTL [39] and 352.2 MHz CERN L4 DTL [40] are 35 mm and 40 mm, and the corresponding cell lengths ($\beta\lambda$) in the first cells are around 54 mm and 68 mm. Thus, for a 325 MHz DTL design with the first cell length of around 73 mm, the RFQ output energy should be no less than 3.0 MeV, for decreasing the difficulty of housing a PMQ. In contrast, for a 162.5 MHz DTL, the first cell length will be about 147 mm at an output energy of 3 MeV. There is no doubt that a PMQ can be easily housed inside the first drift tube. However, to choose a lower output energy of 2.5 MeV will leave open the possibility for BNCT research with a single RFQ accelerator-based neutron source via the proton-lithium reaction.

2.2. Beam Dynamics Simulations

In the beam dynamics designs, the proton RFQs are optimized with the utilization of the ParmteqM code [41]. The main design parameters of the proton RFQs (162.5 MHz vs. 325 MHz) with constant inter-vane voltages of 65 kV and 85 kV are shown in the Figure 4.

Figure 4. Evolutions of the synchronous phase (Phase in degree), aperture radius (a in mm) and modulation factor (dimensionless m) along RFQs: (a) 162.5 MHz design, (b) 325 MHz design.

Both RFQs hold a Kilpatrick limit lower than 1.85 and a high energy gain per unit length. The cavity lengths are 5.18 m and 3.66 m, with synchronous phases of $-90.0^\circ \sim -27.7^\circ$ and $-90.0^\circ \sim -30.0^\circ$, respectively. For 162.5 MHz RFQ design, the minimum aperture radius is 3.37 mm and the maximum modulation factor m is 2.17. Correspondingly, they are 2.16 mm and a factor of 2.16 in the 325 MHz RFQ design.

The multi-particle tracking simulations are carried out by using the ParmteqM code with an input distribution of 100,000 macro-particles. The transverse phase spaces ($x-x'$) and ($y-y'$) are 4D waterbag, while the longitudinal one ($\phi-W$) is uniform. The transmission efficiency and transverse RMS envelopes as a function of the longitudinal position of the RFQ accelerators are given in Figure 5a–d. Besides, the transverse particle distributions ($x-x'$) at RFQ inputs of both designs (162.5 MHz vs. 325 MHz) are shown in Figure 5e,f. Both RFQs have a high transmission efficiency over 95%. The beam losses mainly concentrate on the sections of the shaper and gentle buncher in the RFQ accelerators. The averaged RMS beam size at the 162.5 MHz RFQ exit is 0.84 mm, while the 325 MHz RFQ has a smaller one of 0.61 mm at the output.

Figure 5. Simulated beam transmission efficiencies, transverse RMS envelopes and input transverse particle distributions ($x-x'$) of beam dynamics in the 162.5 MHz (a,c,e) and 325 MHz (b,d,f) RFQs.

2.3. RF Design Studies

The 2-dimensional cavities, as shown in Figure 6, are designed to satisfy the requirements of the RFQ physics designs and to understand the cavity properties and to estimate the power loss in the cavity, using the CST MWS code [42]. The cross-section, average aperture radius and vane-tip radius of both RFQs are kept constant along the full cavity length for an easy tuning and the possibility of applying a shaper-cutter in the machining. The adoption of a square profile in the 162.5 MHz will benefit from easier openings of holes for tuners, power couplers, vacuum port and so on in the mechanical processing. However, if a similar square profile is used at the frequency of 325 MHz, that will limit the available spaces for tuners and couplers. Thus, an octagonal profile is more favorable to a 325 MHz RFQ.

Figure 6. Simulated cross-section profiles in both RFQs: the square shape in blue represents the 162.5 MHz RFQ design, while the octagonal shape in red shows the 325 MHz RFQ design; X and Y are in the units of mm, and the transverse dimension of 325 MHz RFQ is about 60% of that of the 162.5 MHz RFQ.

To have a better understanding of cavity performances in both designs, a comparison of high-frequency parameters between the square 162.5 MHz RFQ and the octagonal 325 MHz RFQ is presented in Table 2. The half-width of the 325 MHz RFQ inner wall is 101.66 mm, which is about 60% of that in 162.5 MHz RFQ, leaving a slope width of 76.6 mm, which is adequate for tuners and couplers. The mode spacings between the fundamental quadrupole mode (Q_0) and dipole mode (D_0) are 5.0 MHz and 10.6 MHz, respectively, which should guarantee sufficient RF stability during operation. Besides, the square 162.5 MHz RFQ has a larger unloaded quality factor because of its higher area to perimeter ratio. Furthermore, the corresponding specific shunt impedance is about 2.7 times higher, reaching up to 272.1 $k\Omega \cdot m$. Taking account of a factor of 1.3 for power loss scaling to 3-dimensional cavity, the estimated total power in the 162.5 MHz RFQ is evaluated to be one-third of that in the 325 MHz RFQ.

Table 2. Result comparison of 2-dimensional RFQ electrical parameters.

Parameters	162.5 MHz RFQ	325 MHz RFQ
Quadrupole frequency Q_0 (MHz)	162.5	325
Half-width of RFQ inner wall (mm)	176.90	101.66
Dipole mode frequency D_0 (MHz)	157.5	314.4
Vane voltage (kV)	65	85
Quality factor (unloaded)	16,836	11,855
Profile area to perimeter ratio (mm)	41.2	20.6
Specific shunt impedance ($k\Omega \cdot m$)	272.1	101.8
Power loss per unit length (kW/m)	15.5	71.0
Beam power (kW)	50	120
Estimated cavity power (kW)	104.4	337.8
Estimated total power (kW)	154.4	457.8
Max magnetic field (A/m)	2148.1	5268.3

3. Physical Design of DTL Accelerator

The post Alvarez DTL will accelerate the incoming proton beam of RFQ output energy of 2.5~3.0 MeV up to 13 MeV. The TM010 mode is the operating mode in the DTL tank and the phase shift from cell to cell is 0-degree (or 360-degree). Based on the proven

design experiences of SNS DTL [37] and CERN L4 DTL [43], the Permanent Magnet Quadrupoles (PMQs) are chosen to be the DTL focusing elements, which yields a smaller drift tube diameter and higher shunt impedance compared to those drift tubes equipped with electromagnets. Another advantage of the adoption of PMQs is that there is no need for the current supply wires or power converters.

3.1. Design Philosophy and Constraints

The first design priority is to provide an acceleration to the proton beam up to 13 MeV. Later we try to make a compact DTL linac design. There is less stringent requirement on the peak RF power.

Other constraints on the design are:

- (1) Limiting the peak surface electric field on the drift tubes not exceeding 1.6 times the Kilpatrick limit.
- (2) Application of a ramping average E0 field for an easier capture of the proton beam and shortening the tank length to 9.0 m for the 162.5 MHz DTL design. While for the design of 325 MHz DTL, a constant E0 design is applied to maximize the energy acceptance to the proton beam.

3.2. Drift Tube Designs

A series of computations has been carried out using the SUPERFISH code [44] to design drift tubes in the 162.5 MHz and 325 MHz DTLs. The cell length is equal to $\beta\lambda$, where λ is the RF wavelength, and they are 1.845 m for 162.5 MHz and 0.922 m for 325 MHz, respectively. Their corresponding normalized speeds (β_{in}) at DTL entrances are 0.0732 and 0.0800.

The tank (D) and drift tube (d) diameters in a DTL have to satisfy the requirement of $\lambda/4$ post-coupler criteria, which is defined as following [45]:

$$1.03 \geq \frac{[(D - d)/2]}{(\lambda/4)} \geq 0.90 \quad (4)$$

where λ presents the RF wavelength. Both diameters also are constrained to make the cavity resonate at the desired frequency. For these purposes, the tank (D) and drift tube (d) diameters of a conventionally post-coupled DTL operating at 162.5 MHz are determined as ($D = 102$ cm, $d = 15$ cm). Similarly, in the 325 MHz DTL, they are chosen as ($D = 56$ cm, $d = 9$ cm). The frequency in each cell is slightly adjusted by changing some of the other geometrical parameters like the drift tube face angle (α) and gap-to-cell-length ratio ($g/\beta\lambda$) (see Figure 7).

Figure 7. Gap-to-cell-length ratio (a) and face angle (b) variations as a function of cell number required to achieve the designed resonant frequencies (162.5 MHz design in blue and 325 MHz design in yellow).

3.3. Longitudinal Beam Dynamics Considerations

The designed accelerating gradient E_0 is shown in Figure 8a. A ramped average E_0 field ranging from 1.10 MV/m to 1.75 MV/m is adopted to more easily accept the incoming proton beam and to make the 162.5 MHz DTL length compact. The high average electric accelerating field in the 325 MHz DTL tank is held constant at $E_0 = 2.85$ MV/m, maximizing the energy acceptance and energy gain.

Figure 8. Accelerating gradients (a) and synchronous phases (b) of both DTL tanks.

The synchronous phases (ϕ_s), shown in the Figure 8b, are ramped in both DTLs from -30° to -26° and from -30° to -25° . The initial synchronous phase starts at the same value of -30° at the RFQ exit to capture the proton beam in longitudinal phase space, then ramping ϕ_s to increase the accelerating efficiency.

The longitudinal beam dynamics simulated with the TraceWin code [46] are shown in Figure 9. All macro particles are within the stable bunch widths in the whole DTLs, and no beam loss is found in the longitudinal phase space.

Figure 9. Simulated longitudinal beam envelopes inside the DTL cavities: (a) 162.5 MHz design, (b) 325 MHz design.

3.4. Transverse Beam Dynamics Considerations

The transverse focusing scheme in the DTL transverse beam dynamics is selected to be a FODO lattice, which has merits in requiring a smaller number of PMQs and imposing a less stringent requirement on magnetic gradients.

However, for very high intense beams, the strong space charge effect could yield an equipartitioning process, which will lead to emittance growth and increase the risk of beam losses in the downstream parts of the DTL tanks; therefore, the equipartitioning design

method is introduced. The quadrupole gradients of FODO lattices are selected to comply with the following design guidelines [38,47]:

- (1) $\sigma_{0t} < 90^\circ$ /period;
- (2) $\sigma_{0t} \neq n\sigma_{0l}/2$ for $n = 1, 3, \dots$;
- (3) Equipartitioning ratio ≈ 1.0 at full current;
- (4) Avoid known parametric resonances;

The PMQ lengths within one DTL tank are fixed, which are 80 mm (162.5 MHz design) and 40 mm (325 MHz design), respectively. Figure 10 shows the required quadrupole gradients to satisfy these constraints for the FODO lattices in both DTLs. The highest quadrupole gradient in the 162.5 MHz design is about 1/3 to that of the 325 MHz DTL design.

Figure 10. Quadrupole gradients of PMQs inside DTL tanks: 162.5 MHz design in yellow and 325 MHz design in blue.

The beam envelopes along the DTL tanks with FODO lattices are shown in Figure 11. Compared to the 325 MHz design, the transverse beam envelopes in the 162.5 MHz DTL tank have a larger beam size. It should be noted that the beam sizes are all within the aperture radii of drift tubes. As shown in Figure 12, the transverse and longitudinal emittance growths for both designs are within 10%, which presents a low risk of beam losses.

Figure 11. Transverse beam 3 * RMS envelopes (X in blue and Y in red) along both DTL linacs: (a) 162.5 MHz design, (b) 325 MHz design.

Figure 12. Emittance growths along both DTL linacs: (a) 162.5 MHz design, (b) 325 MHz design.

3.5. DTL Cavity Studies

The DTL cavity studies are performed with the SUPERFISH code to calculate the electromagnetic fields and to estimate the required RF consumption. Each DTL tank consists of a cylindrical cavity and 39 drift tubes mounted on the top side of the cavity with a stem diameter of 2.8 cm. The resonant frequency of each tank is tuned to 162.5 MHz and 325 MHz, respectively. Figure 13 shows the on-axis electric-field profiles of the operating mode in both designs and Table 3 summarizes the simulated electromagnetic parameters (for an electrical conductivity of $\sigma = 5.8 \times 10^7$ S/m) of DTL tanks.

Figure 13. Ez-field distributions calculated by the SUPERFISH code (a) 162.5 MHz design, (b) 325 MHz design.

Table 3. General DTL parameters.

Parameters	162.5 MHz DTL	325 MHz DTL
Operating frequency (MHz)	162.5	325
Input energy (MeV)	2.5	3.0
Output energy (MeV)	13.0	13.0
Peak current (mA)	20 mA	40 mA
Accelerating gradient (MV/m)	1.10 $\rightarrow$ 1.75	2.85
Synchronous phase (degree)	$-30^\circ \rightarrow -26^\circ$	$-30^\circ \rightarrow -25^\circ$
Kilpatrick limit	1.6	1.6
Tank length (m)	8.49	4.47
Tank diameter (cm)	102	56

Table 3. Cont.

Parameters	162.5 MHz DTL	325 MHz DTL
Drift tube diameter (cm)	15	9
Bore radius (cm)	1.2	1.0
Focusing lattice	FODO	FODO
PMQ Length (mm)	80	40
Quadrupole gradient (T/m)	18.4 → 14.6	62.8 → 43.7
Cell number	40	40
Copper power (kW)	380.3	520.3
Beam power (kW)	210	400
Averaged ZT^2 (M Ω /m)	44.4	55.5
Quality factor	65598	53102
Estimated total power (kW)	590.3	920.3
Transmission (%)	100	100

4. RF Systems

The RF system is one of the key components in the accelerator system. Figure 14 gives a summary of the power and frequency reach of the various pulsed/CW RF sources [48]. At the frequencies of $f_0 = 162.5$ MHz and $2 \cdot f_0 = 325$ MHz, the RF amplifiers that can possibly drive the RFQ and DTL tanks are based on tetrodes, klystrons and solid-state amplifiers. For tetrode-based amplifier, two Thales tetrodes TH781 [49–53] and TH628 [49,54] can serve this purpose. Specially, the new generation Diacrode (TH628) presents a unique ability in either doubling the output power at a given operating frequency or doubling the frequency at a given power output. When the operation frequency is above 300 MHz, klystrons [49,55,56] are common solutions. However, the drawbacks are the high voltage (HV) needs with oil tank for breakdown protection, expensive modulator, and gain curve saturation at full output power. Another option as RF source for accelerators is to use RF solid-state amplifiers, which is becoming more and more popular in recent years. Solid-state amplifiers promise a relatively cost-effective power conversion from DC to RF. The modularization and standardization of a solid-state system allows relatively easy maintenance and inexpensive restoration. In contrast to a conventional tree combiner, the cavity combiner can combine the output power of all single units in one stage, therefore significantly decreasing the fabrication cost and making the RF source compact [57–59].

Figure 14. Power and frequency of various RF sources for pulsed (a) and CW (b) operations up to 1.3 GHz.

5. Conclusions and Future Research

Two design options of compact linear accelerator systems at the frequencies of $f_0 = 162.5$ MHz and $2 \cdot f_0 = 325$ MHz are studied. Both designs will provide acceleration of a proton beam up to 13 MeV, which then bombards a beryllium target for intense neutron flux generation. The 325 MHz design option would have accelerator sections (RFQ and DTL) of 8.1 m and a total RF power consumption of 1.4 MW. Though the 162.5 MHz design has a longer length of 13.7 m, the total power is only 750 kW, which is one-half of the 325 MHz design requirement. Meanwhile, the overall system efficiencies of both designs are all around 35%. The tolerance analysis of the accelerator physics design and the considerations for RF supply cost, operation cost and total capital costs will be performed in a forthcoming paper.

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