THE RFQ AS A NEUTRON SOURCE BOTH FOR HIGH INTENSITY AND MICROPULSES

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The capability of the RFQ to accelerate extraordinary high beam currents in the low β range is considered with respect to neutron production. At present available beam intensities rather appear limited by sources than linacs. However, since the ions are injected into the RFQ on ground potential, one still can expect considerable improvements here. The following discussion takes into account such ion energies that are easily obtainable with the RFQ. It turns out that, even on the basis of a 1 MeV/amu limit, this must not necessarily be demanded.

Neutron Reactions

For the neutron production by means of more or less energetic primary particles we first consider the exothermic deuteron and α particle reactions.

1. H^2 (d,n) He^3
2. Li^7(d,n) $\left\{ \begin{array}{l} He^4 + He^4 \\ Be^8 \end{array} \right.$
3. Be^9(d,n)B^{10}
4. H^3(d,n)He^4
5. Be^9(α,n)C^{12}

Since reactions induced by low energy protons are mostly endothermic, rather high thresholds exist. E.g. for H^3(p,n)He^3 the threshold comes up to 1.019 MeV, so this hardly pays[1]. All the more for Li^7(p,n)Be^7 1.88 MeVmust be surpassed[1]. In [1] a summary of possible proton reactions is listed. Here reactions, which use radioactive isotopes with a surplus of neutrons seem more promising, such as C^{14}(p,n)N^{14} (threshold 0.664 MeV) or Be^{10}(p,n)B^{10} (threshold 0.2 MeV), however, not much is known about cross sections resp. neutron yields, so these reactions will not be discussed in this paper.
For deuterons reactions 1. - 4. are of interest, the only radioactive target material being that with tritium. Again not much is known about isotopes with surplus neutrons, when bombarded with low energy deuterons, however, one can expect higher neutron yields as well here. But this demands further detailed investigations.
α-induced reactions with heavier target nuclei again usually are endothermic and require high energies. As an exothermic target nuclide Be^9 is outstanding and has been frequently used for neutron sources in combination with α emitters such as radium^{226}, plutonium^{239} or polonium^{210}. More candidates are according to [1] B^{11} or O^{18} with neutron yields of about 1/3 of those for Be^9. Obtainable yields for the reaction 5 with respect to RFQ capabilities will be discussed and compared to 1.-4. in the following section.

Neutron Yields

We can get a good impression of obtainable thick target yields, when we view table I. Each entry marked with * is taken from the fundamental article[2]. These mean equivalent source strengths in millicurie of a Rn-Be-source to give the same total neutron amount as is produced by 1 μamp of deuterons. With a total yield of 25000 neutrons per second from one millicurie Rn-Be corresponding neutron numbers per second and μamp are written below marked entries.
Since reaction 1. is not discussed in [2] for the heavy ice target (only with P_2O_5 solution in heavy water) we utilize fig. 1. Here yields gained from the Be^9(d,n) reaction 3. agree with corresponding values of table I. Yields for reactions 1 in a heavy ice target as well as for reaction 4 are added to table I. To discuss the reaction 5. we proceed in the same way as was done in [3]. In case of Ra^{226} together with its daughter substances four groups of α particles are emitted with a mean energy of about 5.98 MeV, of which due to slowing down effects in the Ra-Be-mixture only the energy of about 4.2 MeV carries the neutron production by way of reaction 5. For this energy we find a cross section of 0.3 barn (fig. 2) then as a matter of fact according to [3] a yield of 10^{-4} neutrons per α particle corresponds to this cross section. From Po^{210} α particles come out with uniform energy of 5.3 MeV, in the mixture are slowed down to mean 3.7 MeV, for which we find the cross section 0.18 barn in fig. 2, corresponding to a neutron yield of $0.7 \cdot 10^{-4}$.
When we assume the same energy factor 0.7 with respect to slowing down for energies, which are available within the RFQ, we arrive at neutron yields as listed in table II. (It should be mentioned that this assumption seems a bit optimistic, since stopping powers increase with decreasing energy.)
Summarizing all the estimated yields of tables I and II table III comprehends neutron source strenghts

obtainable with yet comfortable RFQs. Included are the Q values with respect to the considered reaction. Qs determine endothermic (< 0) or exothermic (> 0) conversions and roughly inform on the neutron energies. Thus for a 100 mA beam we expect 10^{12} - 10^{13} neutrons per second. Beam powers (last column of table III) might cause problems for thick targets, however. An interesting aspect could be the facility of accelerating deuterons as well as α's in the same machine, where voltages have to be doubled in case of α's with respect to deuterons..

Table IV demonstrates feasible examples of realization. Current limits and phase advances are determined according to [4]. For 45 MHz not much experience exists concerning shunt resistances respectively required rf power in order to excite proper electrode voltages. In [6] R_p = 300 kΩ was measured for a 68 cm long resonator at 16.9 MHz, [7] gives R_p = 62 kΩ for 118 cm at 202 MHz and [8] R_p = 110 kΩ for 83 cm with 108 MHz, so R_p = 150 kΩ·m seems reasonable for 45 MHz. On these R_p values rf powers of last column in table IV are based. For further examples of very high current RFQs see [10]. Beam currents should not surpass 84% of I_{max} of table IV. Tables III and IV thus inform on apparative expenditure and yields of typical neutron generators.

A Final Remark about Micropulses

Utilizing a method, which was proposed in[5] , single neutron pulses can be generated by installing an asynchronous combination of two (or more) RFQs. For an example a sequence of a 45 MHz and a 50 MHz sample delivers deuteron- (resp. neutron-) pulses with a time structure of fig. 3. In this way from the original 100 mA dc deuteron beam one filled bucket resp. micropulse still contains $2 \cdot 10^{-9}$ Cb or ≈ 10^{10} deuterons.

References

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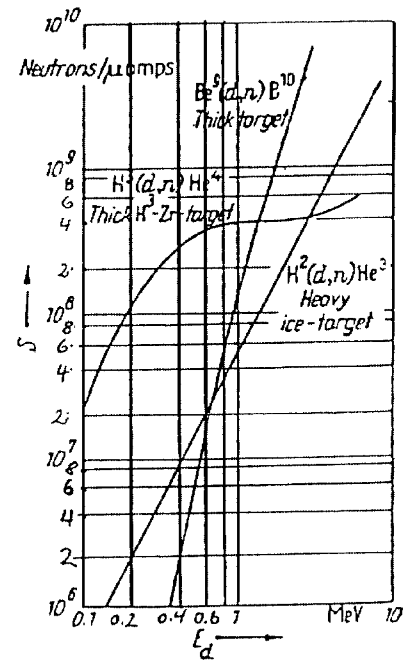

Fig. 1 The thick target neutron yield from various (d, n) reactions (from Bulletin "H" of the High Voltage Engineering Corporation Burlington) from [3]

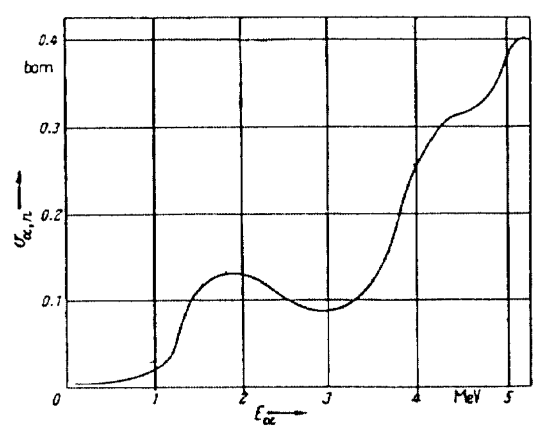

Fig. 2 The cross section of the Be^9 (α,n) C^{12} reaction as a function of the -particle energy (from [3])

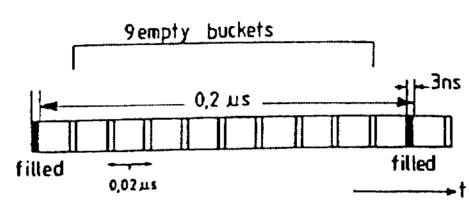

Fig. 3 Micropulses of asynchronous RFQs with f_1 = 45 MHz, f_2 = 50 MHz

Table I
Thick target yields
particles ^2H

H^2 energy [ke] →		300	400	600	800	1000
1. H^2+H^2	with P_2O_5 solution	40* $1\cdot10^6$	140* $3.5\cdot10^6$	250* $6.3\cdot10^6$	550* $1.4\cdot10^7$	860* $2.1\cdot10^7$
	with heavy ice	$4\cdot10^6$	$9\cdot10^6$	$2\cdot10^7$	$3.5\cdot10^7$	$6\cdot10^7$
2. H^2+Li^7		40* $1\cdot10^6$	160* $4\cdot10^6$	800* $2\cdot10^7$	4200* 10^8	-
3. H^2+Be^9		9* $2\cdot10^5$	100* $2\cdot10^6$	700* $2\cdot10^7$	2400* $6\cdot10^7$	6800* $2\cdot10^8$
4. H^2+H^3	with tritium ice	$2\cdot10^8$	$3\cdot10^8$	$3.5\cdot10^8$	$4\cdot10^8$	$4\cdot10^8$

Table II
Yields for ^4He

α energy [MeV]	1.2	1.6	2.4
α energy [keV/amu]	300	400	600
Slowed down energy [MeV]	0.8	1.1	1.7
WQ [barn]	0.02	0.04	0.12
Scaled yields n/α	$7\cdot10^{-6}$	$1.3\cdot10^{-5}$	$4\cdot10^{-5}$
Yields per μAmp. α	$4\cdot10^7$	$8\cdot10^7$	$2.5\cdot10^8$

Table III
RFQ neutron yields

Reaction	RFQ energy per amu [keV]	neutrons per s and μAmp	Q [MeV]	target	beam power p·100 mAmps [kW]
1	300 500	$2\cdot10^7$ $6\cdot10^7$	3.2	heavy ice	60 100
2	300 500	$2\cdot10^7$ $> 10^8$	15	problematic acc. to [1, p. 70]	60 100
3	300 500	$1.7\cdot10^7$ $1.7\cdot10^8$	4.4	metallic Be-plates or powder on Cu-plates	60 100
4	200 300 500	$3\cdot10^8$ $3.5\cdot10^8$ $3.5\cdot10^8$	17.6	tritium ice	40 60 100
5	300 500	$4\cdot10^7$ $1.6\cdot10^8$	13.1	s. reaction 3	120 200

Table IV
RFQ samples
shaper omitted
particles $^2H^+$

f [MHz]	input energy [keV]	V [kV]	R_1 [mm]	σ [°]	I_{max} [mA]	total power without beam load [kW]	acc. length [cm]
45	19 27	55 120	10 10	35 59	45 120	53 109	262 114
108	18	50	3	50	38	25	93
202	50	85	3.5	25	100	85	86