HIGH CURRENT ION LINACS FOR TRANSMUTATION OF LONG-LIVED WASTES

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Introduction

Nuclear power development not once has created the tasks that required the implementation of accelerator technology. Cross-sections and other nuclear constants needed for reactor calculations were determined using accelerators. In view of possible exhaustion of uranium ore deposits the accelerators-breeders were proposed. The present state of fuel resources economics and the aggravation of nuclear safety problems postponed the implementation of electronuclear breeding to future. However, the increasing attention to ecologic problems stimulated the development of the technology for transmutation of long-lived nuclides containing in wastes produced by NPP reactors.

Some actinides and neutron-scarce nuclei can be treated in special nuclear burner reactors. Unfissioning long-lived wastes and especially neutron-redundant nuclei can be transmuted into short-lived and stable nuclei only in accelerator targets. To such wastes along with some fission products as ^{90}Sr and ^{137}Cs one can consider products of neutron activation of reactor constructional elements (^{14}C, ^{59}Ni, etc.). After decomissioning of the reactor the question of reliable disposal of radioactive wastes becomes very important. In case of wide use of nuclear power plants and bearing in mind strict regulations for the disposal of very long-lived wastes ($T_{1/2} \gg 100$ years) the application of accelerators for transmutation becomes very attractive.

In the target of proton linear accelerator transmutations will undergo in hadron cascade. Hadron cascade will spread without significant losses for ionization of the matter at the energy of protons about 1-1.5 GeV. It means that the length of the accelerator will be about one kilometer and the facility will be very expensive. It should be also mentioned that in hadron cascade substantial share of transmutations happens due to forming of residual nuclei (so called "stars"). Secondary evaporated neutrons,in spite of their large number, are not very suitable for transmutations because their mean energy is about 3 MeV that in many cases is not enough for transmutations in (n,2n) type reactions.

In view of above mentioned the concept of intensive neutron generator comprising 50-150 MeV deutron accelerator and lithium target also looks very attractive.

In this case deutron stripping produces neutrons with the energy of several tens of MeV. It is the energy range where (n,xn); (n,p) and other reactions leading to transmutations are comparable with inelastic scattering (n,n'γ). The effectiveness of both transmutation options depends greatly on cross-sections of target nuclei that needs detailed experimental and theoretical studies. That why it is reasonable today to design both types of accelerators.

Intensive neutron generator.

The facility comprising deutron linear accelerator and liquid lithium target for deutron stripping and spallation can provide intensive neutron flux of high energy. The scheme of the facility was suggested in ITEP in 1977[1]. 100% duty factor linac should provide 35 MeV deutrons, beam current being 100 mA. The designed value of 15 MeV neutron flux was (6.6-9) 10^{15} n/sec.

However the present state of ion linac development allows to increase the intensity of neutron flux. The most important achievement in this field was the proposal to use funneling where the beams are combined without increase of phase volume and peak current[2,4]. It is possible to construct a linac with a large number of accelerating beam-lines. In the initial part of the linac each beam is produced by its own ion source that allows to obtain at the linac output the intensive beam and don't enhance requirements to the phase density of the beam at the output of the ion source. Funneling needs to double accelerating field frequency in each subsequent accelerating section. The block-scheme of 100% duty factor, 1A deutron linac is presented in Fig.1. Four parallel line RFQ's[5] can be used for the initial part and drift tube linacs with rare-earth magnet quadrupoles[6,7] for two subsequent parts.

The increase of deutron beam current by the order of ten leads to corresponding increase of integral neutron flux.

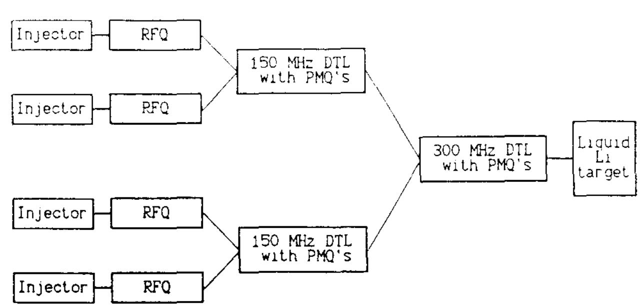


Fig.1. Block-diagram of the 1A deutron linac.

Another way to raise neutron flux intensity is to increase deutron energy. Ionization path is proportional to the square of deutron energy: spallation path in the first aproximation depends only on nucleus and deutron radii. Thus the probability of neutron production in lithium target is growing as the square of deutron energy. The data on emission of neutrons of mean energy E_n vs deutron energy are given in Table I. The size of lithium target area was chosen in the result of heat engineering calculations[1], providing the heat load on the unit area of the target is the same.

TABLE I

Neutron yields estimates

Deutron beam current	Deutron energy	Neutron energy E_n	Neutron yield	Section area of Li target
A	MeV	MeV	neutrons	cm^2
0.1	35	15	$(6.6\text{-}9.0)10^{15}$	10x10
1.0	50	20	$(1.3\text{-}1.8)10^{17}$	40x40
1.0	100	40	$(5.4\text{-}7.3)10^{17}$	55x55
1.0	150	70	$(1.2\text{-}1.6)10^{18}$	65x65

Such parameters as the linac length, RF power and the total power consumed by deutron linac for three energy levels (50,100, and 150 MeV) are given in Table II. Resonators efficiency (electronic) is about 85%. RF generator efficiency can be assumed to be 70%[8]. Thus the total linac efficiency would be about 60%.

TABLE II

Some parameters of deutron linac

Deutron energy	Linac length	RF power	Mains consumptions
MeV	m	MW	MW
50	40	60	100
100	68	115	190
150	96	170	285

Main designed parameters of accelerator sections are given in Table III.

Using of liquid lithium target enables to regenerate power and makes the neutron generator rather economic.

The choice of deutron energy will depend upon the assessments of transmutation efficiency and also on the results of feasibility studies.

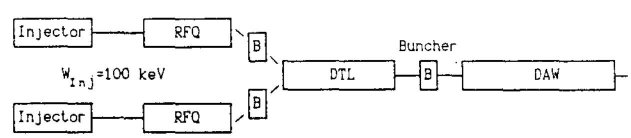
TABLE III

Main design parameters of deutron linac

Parameters	Units	Initial part	Middle part	Main part
Operating frequency	MHz	75	150	300
Number of channels		4	2	1
Deutron energy				
input	MeV	0.1	6	20
output	MeV	6	20	50/100/150
Section length	m	10	12	18/46/72
Acceptance	cm mrad	1.9	5.6	3.0
Emittance (calc.)	cm mrad	0.4-0.6	1.0-1.5	1.5-2.0
Current per channel	mA	250	500	1000
Limit beam current	A	1.28	2.78	4.75
RF losses in Cu	MW	3.6	1.5	3.0/7.7/12.4

Choice of proton linac parameters.

Optimum output parameters of the linac can be chosen on the base of trade off decisions and after the assessment of technological systems capacities (ion source, RF power supply, cooling and so on) and possible beam losses. For this purpose let us assume the output energy of 100% duty factor linac to be 1.5 GeV, beam current - 300 mA. These figures are very close to those that were chosen in 50-70th for electronuclear breeders. However, if to base on modern and advanced developments the linac block-scheme, technical performance of main systems and hence the facility lay-out and the assessments of construction and operating costs would substantially differ from previously made. The block-scheme of the linac (target design is not discussed) is given in Fig.2. The details are discussed in another report[9] submitted to this conference. It is proposed to use two parallel 75 MHz RFQ's where each 150 mA beam is accelerated from 0.1 to 3.5 MeV. Bunched beams are funneled and injected into 150 MeV,150 MHz Alvarez tank and then after additional bunching (to decrease phase length) are accelerated up to the energy of 1.5 GeV in 900 MHz Andreev's (or disk and washer - DAW) structure.



W_{output}	(MeV)	3,5	150	1500
f	(MHz)	75	150	900
I	(mA)	2x150	300	300
P_{Cu}	(MW)	2x0,66	14	58
P_{beam}	(MW)	2x0,525	44	405
P_{Σ}	(MW)	2,5	60	500
V_c	(cm mrad)	6,6-3	5,6-9,4	12,8-23
I_{lim}	(A)	0,93	4,4	42
l	(m)	8	69	550

Fig.2. Block-diagram of high-energy linac.

The parameters of proton linac are given in Table IV. The calculated data are presented in Tables V and VI correspondently.

Conclusion

The increased requirements to nuclear power safety initiated the concept of minimizing the total activity of

TABLE IV

Parameters of the high-energy proton linac

	Parameters	Units	RFQ	DTL	DAW
1	Operating frequency	f (MHz)	75	150	900
2	Number of channels		2	1	1
3	Input energy	W_{in} (MeV)	0.1	3.5	150
4	Output energy	W_{out} (MeV)	3.5	150	1500
5	Length	l (m)	8	70	550
6	Apertures	2a (cm)	4.8-3.32	5	5
7	Current per channel	I (mA)	2x150	300	300
8	Synchronous phase	φ_s (degree)	90°-30°	38°	35°
9	Accelerating structure		modulated vanes	drift tubes	Andreev's structure
10	Focusing		RFQ	PMQ's	PMQ's
11	Voltage between adjacent electrodes	U_L (kV)	255	-	-
12	Averege axis field	E_0 (kV)	-	30	35
13	RF power (losses)	P_{Cu} (MW)	2x0.66	14	58
14	RF power (beam)	P_B (MW)	2x0.55	44	405
15	RF power total)	P_Σ (MW)	2.5	60	500

TABLE V

Initial part (one channel)

	Parameters	Units	Bunching section		Regulary acceleration section	
			Input	Output	Input	Output
1	Average radius	R_0 (cm)	2.5	2.5	2.5	2.5
2	Phase width of separatrix	Φ^o_{sep}	298°	91°	91°	91°
3	Momentum width of separatrix	$(\Delta P/P)_{sep}$	+ 16.6%	+ 5.46%	+ 5.46%	+ 3.17%
4	Phase length	Φ^o	298°	91°	91°	68°
5	Momentum spread	$(\Delta P/P)_a$	-	+ 5.46%	+ 5.46%	+ 2.25%
6	Modulation	m	1.1	2.01	2.01	2.01
7	Transit time factor	T	0.01966	0.4215	0.4215	0.4569
8	Relative velocity	β	0.0146	0.0480	0.0480	0.0862
9	Phase advance of transverse osc. per period	μ	0.696	0.648	0.648	0.693
10	Min. velocity of phase advance	ν_φ	0.470	0.448	0.448	0.487
11	Normalized emittance(adopted value)	ε_t(cm mrad)	0.2	0.4	0.4	0.5
12	Acceptance (calculated value)	A_t(cm mrad)	6.65	3.09	3.09	7.61
13	Relative frequency of longitudinal osc.	Ω/ω	0.08916	0.08916	0.08916	0.05162
14	Current limit	I (mA)	2.64	0.93	0.93	3.37
15	Output energy	W (MeV)	0.1	1.08	1.08	3.50

TABLE VI

Main part of linac

	Parameters	Units	The first part DTL		The second part DAW	
			Input	Output	Input	Output
1	Phase width of separatrix	Φ^o_{sep}	116°	116°	106°	106°
2	Momentum width of separatrix	$(\Delta P/P)_{sep}$	+ 5.86%	2.72%	+ 0.96%	+ 1.15%
3	Phase length	Φ^o	68°	17°	52°	22°
4	Momentum spread	$(\Delta P/P)_a$	+ 4.4%	+ 0.42%	+ 0.84%	+ 0.20%
5	Gap length factor	$g/\beta\lambda$	0.18	0.30	0.30	0.30
6	Transit time factor	T	0.777	0.853	0.698	0.805
7	Relative velocity	β	0.0862	0.5067	0.5067	0.9230
8	Phase advance of transverse osc. per period	μ	1.242	1.09	0.888	0.567
9	Min. velocity of phase advance	ν_Φ	0.562	0.601	0.588	0.465
10	Normalized emittance(adopted value)	E_t (cm mrad)	0.6	0.7	0.8	0.9
11	Acceptance	A_t (cm mrad)	5.62	9.39	12.8	23
12	Length of quadrupoles	l (cm)	10	50	20	20
13	Gradient of magnetic field	G (kGs/cm)	2.71	0.471	2.94	6.0
14	Relative frequency of longitudinal osc	Ω/ω	0.0748	0.0260	0.0100	0.00237
15	Current limit	I (mA)	4.43	3.54	24	48

nuclear fuel cycle radiactive wastes up to the level of the total activity of natural uranium involved. The detailed investigation of transmutation options and designing of the facility comprising high current linac and special target could help to solve one of the most important tasks the mankind being faced - to develop the nuclear power safely without possible ecological consequencies for future generations.

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