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On the Way to High-Power Linear Proton Accelerator for the Long Half-Life Radionuclides Transmutation

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ABSTRACT

The concept of continuous mode high-power linear proton accelerator with 1.5 GeV energy, 0.3 A current for the long half-life nuclides transmutation into the short ones (waste of atomic power plants (APP)) is proposed. The accelerator design main principles, scheme and parameters are presented. The accent is made on the accelerator efficiency, reliability and radiation purity.

One of the methods of APP waste treatment is based on the transmutation of the long half-life nuclides into the short ones by power proton accelerators with 1.5 GeV energy, 0.3 A current, the mean beam power of 450 MW, generating neutron fluxes for burner-reactor [1,2].

The first steps on the way to such accelerators are the linear accelerator in Los-Alamos and the Moscow Meson Facility linear accelerator at the Institute of Nuclear Research of the USSR Academy of Sciences (MMF). The accelerator and its main systems design development was carried out in MRTI [3]. The experience in the creation of the above mentioned installations and other ones designed in USSR [4-9] leads to the accelerator scheme for burner-reactor (BRLA) presented in Fig.1.

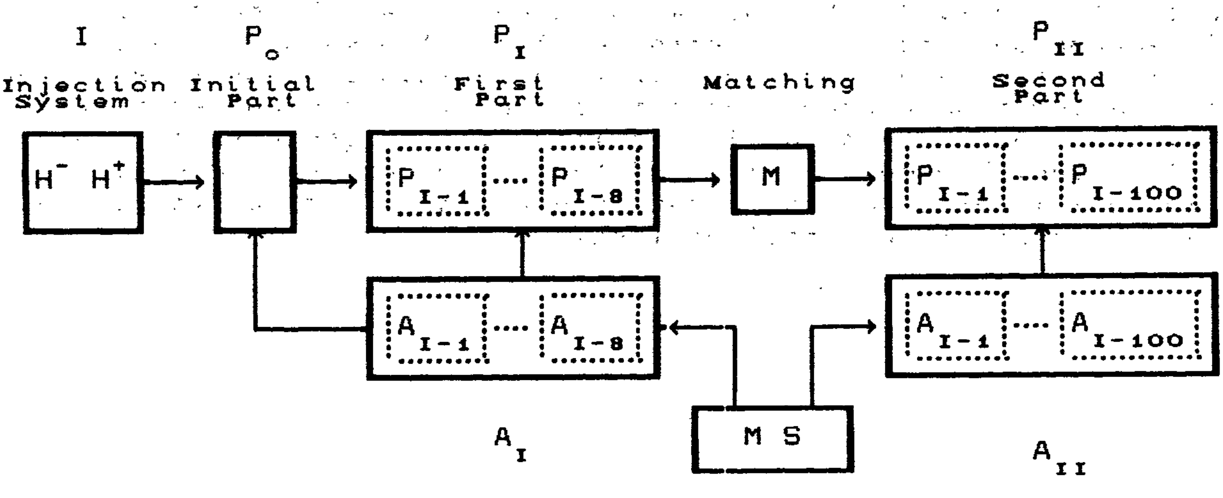


Fig.1. Burner-reactor accelerator installation diagram

The accelerator involves the injector (I), the initial (P_o), the first (P_I) and the second (P_{II}) parts, the matching system between the first and the second accelerator parts (M), amplification channel with the automatic regulation systems (A_I, A_{II}) and the power master system (MS). The following concepts were taken into account in the scheme choice.

1. Simultaneous acceleration of H^+ and H^- beams. In the case the frequency increase factor in the first and the second accelerator parts has to be odd [8]. It was chosen to be equal to 3. With larger values the bunch phase width in the first accelerator part will surpass the second accelerator part separatrix phase width due to space charge effect and accelerating channel parameters errors, and result in the beam losses at the transfer between the first and the second accelerator parts.

2. Transfer energy between the first and the second accelerator parts was chosen to be equal to 100 MeV. It's the optimal energy value as to the shunt impedances of the accelerating structures in the first and the second accelerator parts.

3. The specific acceleration was chosen to be 1 MeV/m. With larger values of specific acceleration the accelerator efficiency decreases while with smaller values the accelerator construction cost and the accelerating channel errors influence increases.

At the present design stage two pairs of operating frequencies for the first and the second accelerator parts are considered : 200 and 600 MHz; 330 and 990 MHz. The accelerating channel has the sufficiently large acceptance and the accelerating resonators are of acceptable size at the frequencies of 200 and 600 MHz. The frequencies of 330 and 990 MHz lead to the acceptance and resonator size decrease. One should note that 990 MHz is the operating frequency of the MMF accelerator second part. So we have considerable experience of the accelerating structure development at this frequency. The ratio of the operating frequencies in the first and the second accelerator parts is equal to 3. It means that the acceleration in the second accelerator part is realizes within one of three consecutive accelerating separatrix. Therefore it is possible to use the scheme presented in Fig.2. [2].

The bunches from three parallel accelerators of the first part are sequentially injecting into each separatrix of the second accelerator part. At the safe mean intensity at the output of BRLA this scheme decreases by a factor of three the mean intensity in parallel accelerators of the first and initial parts and the accelerating beam bunches amplitude in the second accelerator part. In general it will simplify the high-intensity beams acceleration. The complication of the installation as a whole will be insignificant since the first accelerator part provides only seven per cent of the total beam energy.

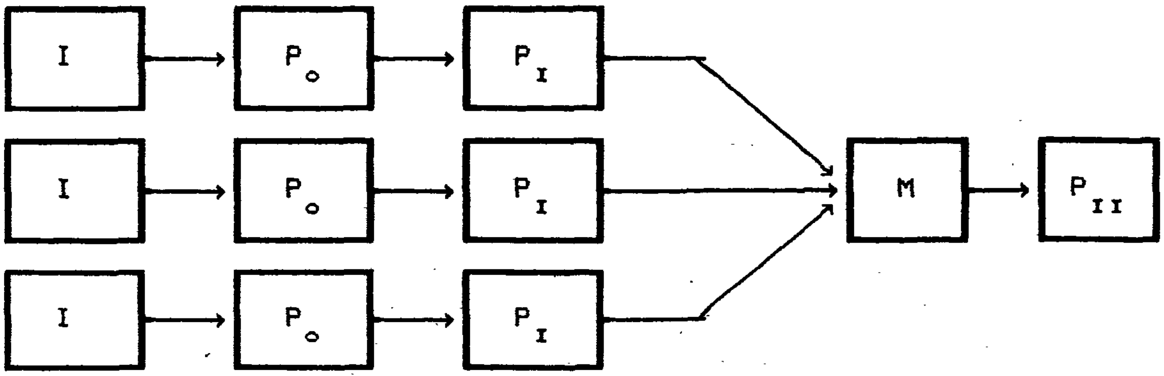


Fig.2.

I - injector system
P_o - initial accelerator part
P_I - first accelerator part
P_{II} - second accelerator part
M - matching system

Consider the accelerator parts.

Injector system (I).

Two parallel $H^+$and H^- beams injectors are usedwith 100-200 keV energy.

Initial accelerator part. (P_o).

The convenient low-energy accelerators use the radio-frequency quadrupole (RFQ) [10] limiting the beam current to 0.3 A. In MRTI a structure was proposed providing for beam current increase. The proposed structure is the accelerating resonator with opposed vibrators and superconducting solenoid focusing [11,12]. The " SIU " experimental accelerator scheme is presented in Fig.3.

The superconducting solenoid with focusing 7 T magnetic field contains a resonator with opposed vibrators. RF power is applied to the resonator output by a coaxial feeder. The beam current value of 0.4 A was achieved in the SIU accelerator with 130 keV injection energy, 1,5 MeV output energy, 200 MHz operating frequency. In principle this scheme allows to accelerate the beam current up to 10 A.

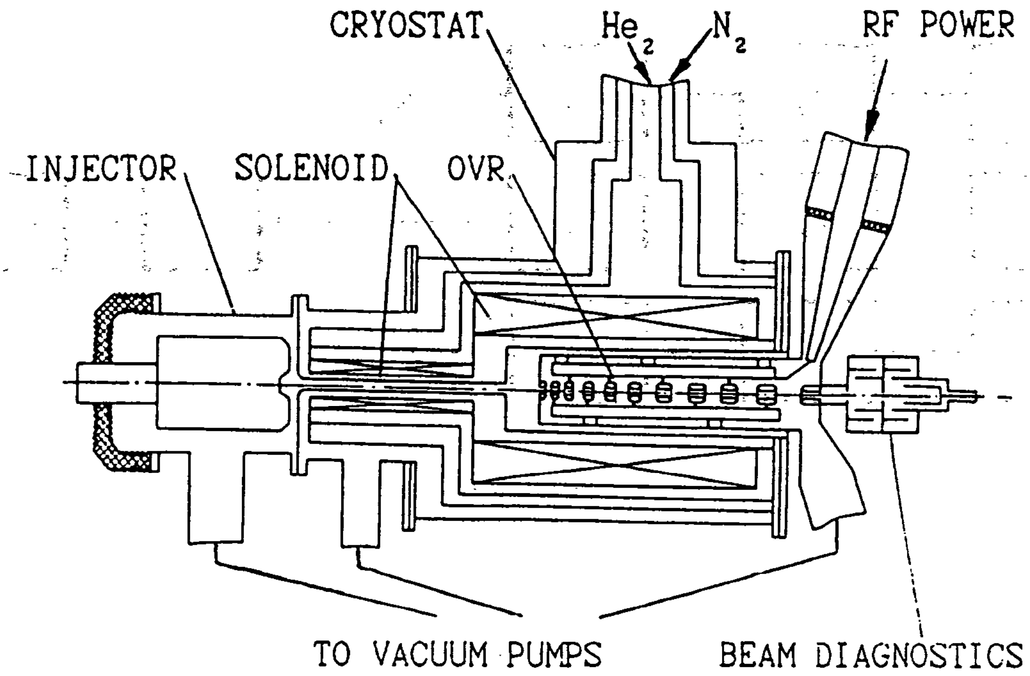


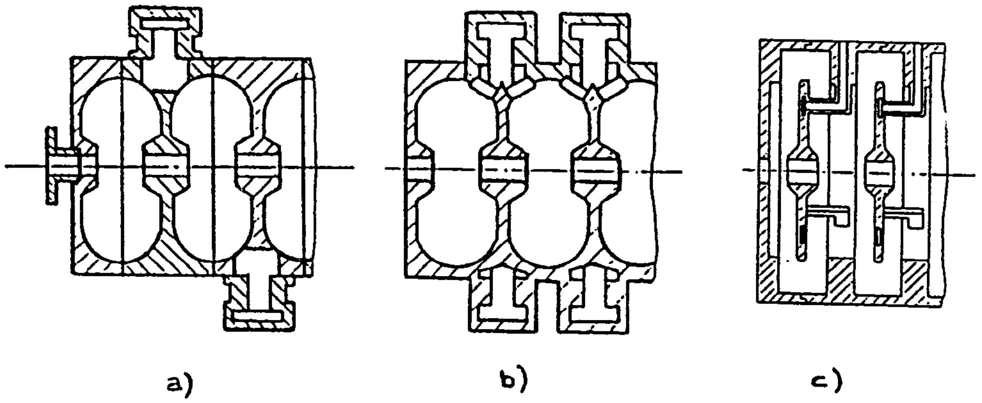
Fig.3. Outline of the SIU-1 experimental RF proton accelerator.

<u>The first accelerator part</u> (P_I)

The resonators with drift tubes are used in the first accelerator part. Initial energy is equal to 2-3 MeV. The field distribution stability along the resonator is realized by resonance rods [13]. This field stability method was successfully used in the MMF accelerator.

<u>The second, main, accelerator part</u> (P_{II})

Consider three structures for the second accelerator part : side-coupled resonator developed in Los-Alamos [14], ring-coupled resonator [15] and resonator with washers and diaphragms developed in MRTI (Fig.4.).



a)　b)　c)

Fig.4.

a) Side-coupled structure
b) Ring-coupled structure
c) Structure with washers and diaphragms

The side-coupled resonators were successfully used for proton and electron accelerators in USA. We proposed the ring-coupled resonator for the MMF accelerator. The above mentioned resonator is equivalent to side-coupled resonator, but it has higher coupling factor. The resonator with washers and diaphragms has significant differences as compared with the above mentioned ones : the high coupling factor (40-50 per cent against 4-7 per cent for the side-coupled and ring-coupled resonators and the high vacuum conductivity. The system drawback consists in the adjacent values of the operating and parasite modes. The fault was removed by means of the T-shaped cuts in diaphragms [17]. The resonator with washers and diaphragms is used in the MMF accelerator and is proposed for BRLA. At present 32 resonators are mounted, tuned and ready to operate. The structure investigations showed its high quality . The focusing system should be based on the quadrupole lenses with permanent magnets [18,19] Such system that increases the reliability, simplifies exploitation and decreases the cost. In the first and the second accelerator parts one should use the FODO focusing structure that is less sensitive to magnetic parameters errors as compared with the FDO structure.

<u>RF system</u>

The new type of RF generator "regotron" is developed in MRTI [20-22]. Regotron is a high-power RF generator based on relativistic electron beam with the distributed RF power takeoffand high efficiency. The scheme of regotron is presented in Fig.5.

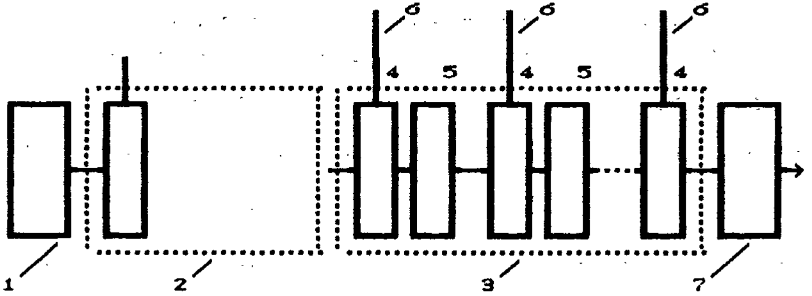


Fig.5. Regotron installation diagram.

1 - high-voltage injector (I) 2 - buncher (B)
3 - distributed power takeoff system (PS)
4 - active cavities of the power takeoff system
5 - bunching cavities of the power takeoff
system 6 - output cavities 7 - beam collector

The device contains four parts :
- the high-energy accelerator generating electron beam with power W_o
- the buncher for the electron beam bunching in accordance with RF signal (B)
- the distributed system of the beam RF power takeoff. The system contains a chain of n resonator pairs (one in a pair is an active load and other is passive)

- collector (C) where the beam residual power W_r is dumped

The regotron efficiency is given by the equation :

$$\eta = 1 - \frac{W_r}{W_o}$$

High efficiency of the device is due to the autophasing mechanism in the power takeoff system [21] preventing from the electron bunches blowup. The distributed power takeoff system with n pairs of resonators allows one to remove the limitation typical for the generators with a single output takeoff resonator with 1 MW limit power [23].

The theoretical estimates and numerical simulation show that regotron is capable of generating 5...10 MW output power in continuous mode with 70-80 per cent efficiency even with low relativistic beam (500 keV energy W_o). The energy recuperation in the collector or its use is considered for the efficiency increase. At present the device development is on the stage of operating model construction.

Use of such high-power RF generators instead of klystron in continuous mode allows to simplify the accelerator RF power supply. The variant with a group of n resonators group is excited by a single regotron with the n energy outputs is possible.

Consider the BRLA design problems.

Efficiency problems

The total accelerator efficiency is basically defined by that of RF resonator energy transformation into the beam kinetic energy (resonator efficiency η_r) and electric power transformation into the RF generator energy (generator efficiency η_g). The total efficiency is equal to the product of the two components $\eta=\eta_r\eta_g$. The power consumption of the focusing, control, measurement, vacuum and subsidiary systems is negligible.

The resonator efficiency estimate has a form of

$$\eta_r = 1/\left[1+(E_y/I_n ZT^2\cos^2\Phi_s)\right]$$

where I_n is the beam current, E_y is the voltage corresponding to the proton energy gain per unit length (its value is equal to the energy gain per 1 m of accelerator), ZT^2 is the effective shunt resistance of resonators per unit length. Accelerated particles current dependence of the resonator efficiency $\eta(I)$ is presented in Fig.6 for three values of the energy gain per unit length. If ZT^2 = 40 MeV/m, φ_s= 30 and I_n = 0.3 A then the resonator efficiency amounts to 0.9.

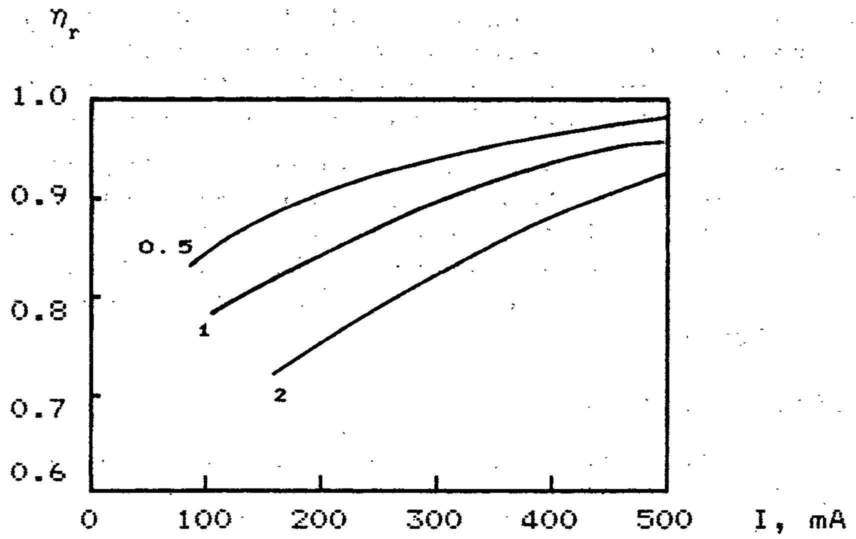


Fig.6. Accelerated particles current dependence of the resonator efficiency for three values of the energy gain per unit length (MeV)

The accelerator efficiency problem should be solved by the construction of regotron with at least 0.8 efficiency. Then $\eta_r \eta_g \approx 0.7$ and the total accelerator efficiency estimate is 0.6. It's quite feasible.

Reliability problem.

The reliability problem is essentially a problem of the installed power utilization factor (K_u) realization. The K_u factor represents the ratio of the accelerator actual operation time with the beam nominal parameters to the year hour sum. According to the nuclear power engineering specifications we present data for linear accelerators in Brookhaven and Los-Alamos to illustrate the reliability of their operation and the contribution of the separate systems.

The linear accelerator in Los-Alamos [14]

K_u=0.85

Injector	- 30 %
RF system	- 25 %
Magnet and their power supply	- 13 %
Vacuum system	- 8 %
Other system	- 34 %

The linear accelerator in Brookhaven National Laboratory

K_u=0.95

Injector	- 29 %
RF system	- 49 %
Vacuum system	- 9 %
Other system	- 18 %

It's obvious that injector and RF systems give maximum contribution to the accelerator operation unreliability.

For devices reliability improvement (first of all RF system and injector) it's necessary to increase K_u factor. For the K_u factor increase should be use the reservation schemes (as in the MMF accelerator for RF system), permanent magnets in quadrupole lenses, development of the failure prediction analysis system through the beam losses measurement. It's necessary to use the recommendation of the paper [23] for the development of RF power system on the regotron base.

Radiation purity problems.

A linear accelerator is considered to be radiation pure if the induced γ-activity doesn't exceed the occupational radiation dose of 28 mGy/hour at the distance of 1 m from the axis of accelerator after 1 hour upon its shut down. The corresponding permissible beam loss in the energy range W = 0.1 - 1 Gev amounts to [24]

$$W\ q \approx 0.05\ \mathrm{GeV\ nA/m} \qquad (1)$$

The problem is essentially that of limiting the beam loss at the level given by the eq.(1). Under the condition the accelerator maintenance does not require manipulators and can be performed manually. Since the time of direct accelerator engineering service (preventive maintenance, malfunction correction) is limited, the manual service is permissible even with the dose power of 0.5 mGy/hour. The corresponding level of beam losses amounts to

$$W\ q \approx 1\ \mathrm{GeV\ nA/m} \qquad (2)$$

Under the condition (2) and with specific acceleration of 1 Mev/m in the second part of accelerator (i.e. 0.1 - 1.5 GeV) the total permissible beam current losses amount to 3 μA. With the beam current of 300 mA it leads to the permissible relative losses of about 10^{-5}, whilst the condition (1) leads to the relative losses of the order of 10^{-6}.

Several methods were proposed and developed in MRTI to solve the radiation purity problem. Some of them were applied, in particular, in MMF accelerator. Among the methods are the following: beam phase volume filtering, suppression of coherent longitudinal and transverse beam oscillations, contactless beam parameters measurement, beam distortion diagnostics through the beam loss measurement, and residual gas pressure limitation in the H^- beam channel.

The phase volume filtration method essence consists in shaping such accelerator input phase volume, that would be less then further accelerator part acceptance and relative particle losses wouldn't exceed $10^{-5}...10^{-6}$ (for BRLA). Transverse phase volume filtering theory principles with space charge and longitudinal-transverse particles oscillations coupling are presented in [8,26,27].

Beam perturbations diagnostic method by beam losses analysis with the help of ionized radiation detectors (see [28-30]) is designed to determine beam perturbations source and location. Beam perturbations diagnostic problems are formulated as follows. One assumes that the phase volume filtration is fulfilled at the beginning of accelerator, tolerances are within the calculated limits, longitudinal and transverse coherent particles oscillations depress system effectively operates. Then beam will be accelerate with possibly small losses. If a single characteristic perturbation will be realized (longitudinal motion perturbation, transverse motion perturbation, H^- ion discharge by residual gas), then a certain loss distribution will result. The reverse problem of one or several (few) perturbations search by measured beam losses distribution is just perturbation diagnostic problem. This problem can be solved. Loss distributions for characteristic beam perturbations are presented in [29-30]. The problem of beam loss distribution function reestablishment by measured neutron field distribution is solved there. Accelerating-focusing channel parameters variation and beam parameters measurement system information are also used by this method.

Current status of radiation purity problems solving as follows. In LAMPF accelerator measured losses at 70...800 MeV, accelerator 1 mA are equal to 10^{-9}. It means that condition (2) is satisfied at 1 mA mean beam current and manual accelerator maintenance problem is solved. Use of the new considered methods permits to hope that this problem will be solved for BRLA.

In conclusion it's possible to make the following inferences.

1. The analysis of linear proton accelerator science and technology development and current status along with the modern problems shows that the design and construction of continuous mode 1.5 GeV - 0.3 A linear proton accelerator is feasible and does not encounter with unsolvable science and technology problems.

2. One of the main BRLA design problems is that of generators with 5 - 10 MW mean power, 200 (300) and 600 (900) MHz operating frequencies, efficiency of order 70...80 % and 10 thousand hours of service life.

3. Further accelerating structures investigations are necessary both for low energies and for high energies.

4. On the way to BRLA implementation it's necessary to solve three important problems to say nothing of the individual linear accelerator systems perfection. The three problems are the efficiency, the reliability and the radiation purity. The basic processes for these problems solution will be simulated at MMF accelerator.

5. Current status of linear proton accelerator science and technology development, experience of the Soviet proton linear accelerator laboratories, including the very powerful MMF linear accelerator, permit to consider the construction of the proton linear accelerator for high level radioactive wastes of atomic power plants transmutation within next 15 years.

6. Since target complex problems are difficult as well, it's necessary to solve accelerator and target complex problems simultaneously. It's worth while to solve a part of target complex problems at MMF linear accelerator.

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