POTENTIALITIES of ELECTRON and ION BEAM ACCELERATORS for LONG-LIVED NUCLEAR WASTE TRANSMUTATION

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Transmutation of nuclear materials can be carried out by thermal neutron capture reactions, by spallation type reactions or via photonuclear reactions caused by high-energy γ-rays generated in the electron linacs. These reactions can complete each other. At the present work two different schemes of proton-electron accelerators utilizing successive or simultaneous acceleration of protons and electrons are proposed. In a case of simultaneous acceleration both the efficiency of acceleration increases and the power loss for the beam focusing decreases. The experimental results on the acceleration and focusing of the mixed electron- proton beams are also presented.

The problem of energy guaranteeing will be one of the most actual tasks in the near future. In parallel with the exhaustion of natural resources it is obvious that modern fuel cycles are very bad for the Nature. But at the same time one predicts that rational solution of the both ecological and fuel problems is practicable in general via utilizing nuclear energy [1]. However it is impossibly without carrying out the following tasks:

- generation of artificial nuclear fuel since the resources of natural nuclear fuel are not sufficient;
- improving the safety of nuclear plants up to the level eliminating the possibilities of Phenix or Chernobil type accidents;
- utilizing the rational methods of the nuclear wastes recovery since the modern methods of wastes burying in the special bunkers or in rocks are not reliable and can lead to the accidents under active geological processes or by acts of diversion.

The nuclear power-engineering at the present time has a grate potential for partial solution of above mentioned problems. This is the transmutation of many nuclides in the neutron flux of the reactor; production of nuclear fuel in breeders; the adoption of the nuclear reactors with a feedback loop around reactivity and so on. But the ideal fuel cycle can not be maintained in reactor-type nuclear plants only in consequence of the following circumstances:

-It is impossible to transmutate Cs^{137} and Sr^{90} which define the residual activity of the nuclear waste in general;

-The most perspective fuel cycles U^{238} - Pu^{239} and Th^{232} - U^{233} are characterized by the very low yield of delayed neutrons and it is impossible to supply nuclear safety of these cycles by standard methods;

-Stabilization of reactivity is maintained by replacing of regulation rods and something can possibly seize.

The problem of the "ideal" fuel cycle can be solved by using the external neutron source and by going to the conception of the subcritical blanket of the reactor. Under Keff~$0.9\div 0.99$ the chain reaction does not take place but the reactor can work as the neutron multiplier with a amplification 1/(1-K) by the neutron flux and $\xi W_f/W_{ng}$ by the energy, where ξ is a fraction of neutrons which share in a fission, W_f is the energy released by one act of the fission, W_{ng} is the cost of the neutron in the units of the energy.

The neutron source can be based on the particle accelerator with a heavy metal target. The specialists of JAERI estimated that the 1.5 GeV 25 mA proton beam could incinerate Np^{237}, Am^{241}, Am^{243}, Am^{244} [2]. The energy released by fission promotes to use higher actinides as the fuel in subcritical blanket. The long-lived izotopes Tc^{99} and I^{129} can be also incinerated into stable or short lived izotopes. But transmutation of Cs^{137} and Sr^{90} needs much higher neutron fluxes and consequently much higher beam power. For reaching equal rates of transmutation and decoy one need the neutron flux of $7.6\cdot10^{16}$ $c^{-1}cm^{-2}$ for Sr^{90} and by an order of magnitude smaller for Sc^{137}. The primary activity of Cs^{137} and Sr^{90} are approximately equal but Sr is 37 times more radiotoxic and the final radiotoxication is determined by Sr. On the other hand the effective way of Sr and Cs incineration may be their irradiation within the giant resonance of (γ,n) reaction. The radiological problems of the task is discussed in [3-5] and according to it the mean beam current should be about several A at the 100 MeV energy. Thus the system based on combined electron-proton beam irradiation makes available to incinerate all types of nuclear wastes.

The possible scheme for realization of this idea is given in fig.1 and the typical parameters of the accelerator are presented in table.

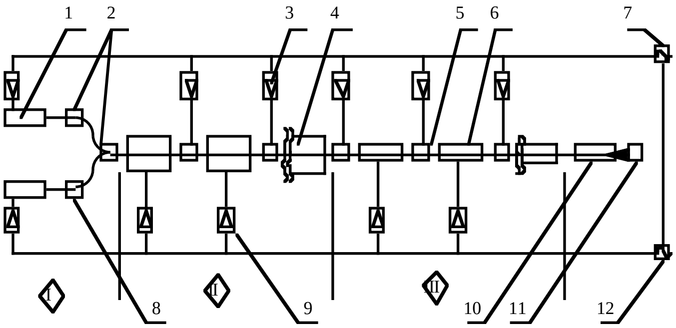

Fig.1 The scheme of the electron-ion beam accelerator for trunsmutation.

In general the accelerating system consists of the low-energy section (I) in which the separate acceleration of electron in the accelerating structure 1 and protons in the structure 8 as well as the following converging two beams in one mixed beam in the magnet system 2 is carrying out; the middle-energy section (II) and the high-energy section (III). The middle-energy section contains the series of the proton

Accelerator section number	Accelerating structure type	Frequency, MHz	Section output energy, MeV	Energy gain, MeV/m	Focusing
I	RFQ	153,7	3÷4	1÷2	-
	Iris loaded waveguide	2766	~15	5÷7	Solenoid
II	Alvarez structure	461	70÷80	~4	Electron beam space charge
	Coupled cavities	2766	30÷40	1,5÷2	Solenoids in drift tubes
III	π-mode side coupled cavities	922	~800	~10	Electron beam space charge
	Coupled cavities	2766	150	1,5÷2	Permanent magnets in drift tubes

accelerating structures 4 with the characteristic length of 1 m, and electron accelerating structures between them with the length of about 10÷15 cm. The RF frequency in the proton accelerating structures should be chosen much less and devisable with the respect to the electron accelerating one for reasons of the particle dynamic [6]. If one chooses the "electron" frequency equal to 2766 MHz the "proton" frequency is 18 times larger at the I section, 6 times larger at the II section, 3 times larger at the III one. The schemes of the section II and III are similar to I one. The basic differences center around the type and the parameters of the structures. It is appropriate to use RFQ at the I section, the drift tube structure at the II section and the π-mode side coupled cavities structure at the III section [7]. The other designation in fig.1 are the following: 3- "electron" frequency power amplifiers; 6- proton accelerating structure at the III section; 7- master oscillator on the "electron" frequency; 9-"proton" frequency power amplifiers; 10- output unit of the mixed beam shaping; 11-target; 12- master oscillator on the "proton" frequency. The coupling of 7 and 12 units represents the phasing between "electron" and "proton" RF fields in the presence of the concrete frequency instability.

Proton focusing at the sections II and III is provided by space charge forces of the electron beam, meanwhile the electron beam is focused by the periodic magnetic field created by solenoids and permanent magnets disposed in the drift tubes. This field simultaneously permits to increase RF electrical field breakdown limit since the lines of magnetic force are perpendicular to the lines of electrical force. It prevents acceleration of secondary and field-emission electrons in the accelerating gap. The calculated trajectories of electrons moving from one drift tube are shown in fig.2.

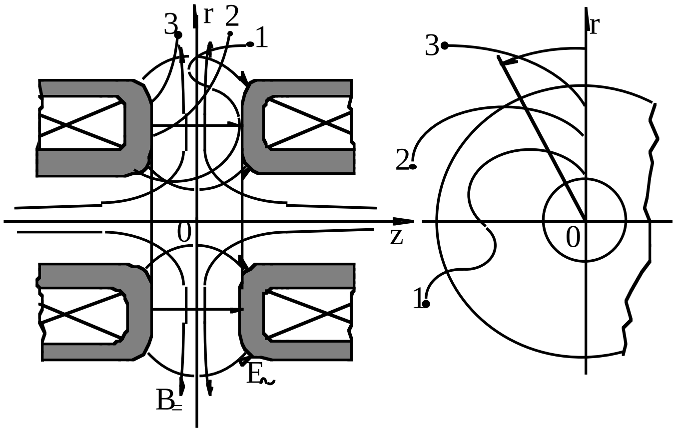

Fig.2. The electron trajectories.

The calculation was carried out for the geometry of the linear accelerator I-101 (Russia) [9]. It is obvious that specific energy liberation, gas and vapour release (and other factors responsible to the electrical breakdown) are much less under magnetic insulation. As the field-emission electrons are not accelerated by the electrical field the likelihood of the electrical breakdown as well as the X-ray intensity is minimized. Moreover the efficiency of harnessing RF power increases that is important in the high power accelerator. The electron beam current can be as much as several A, proton beam current is about several hundred mA. The total length of the accelerating system is 100÷150 m.

At the section III one can recommend permanent ring magnets disposed between accelerating gaps. These magnets can have radial magnetization (fig.3a) or axial magnetization (fig.3b) in the case of the long gaps.

The amplitude of magnetic field is 0.1 T, the electron beam diameter is 4÷6 mm, the aperture diameter is 10÷15 mm. The authors pursued the experiments to study acceleration and transportation of the electron-proton beam at the system in the form of the series of the single-gap accelerators with the ring magnets placed in the drift tubes and also with solenoids. It was determined that radial component of the magnetic field in the area of the axial electric field promotes in successful accelerating cavity feeding. But it requires high vacuum and the absence of ECR conditions. The coefficient K (number of pulses without RF discharge divided by total number of pulses) vs magnetic field amplitude is shown in fig.4. The frequency was 149 MHz, pulse duration was 0.1 ms, the accelerating gap was 8 mm. It was also recognized that delay (5÷10 μs) of ion beam

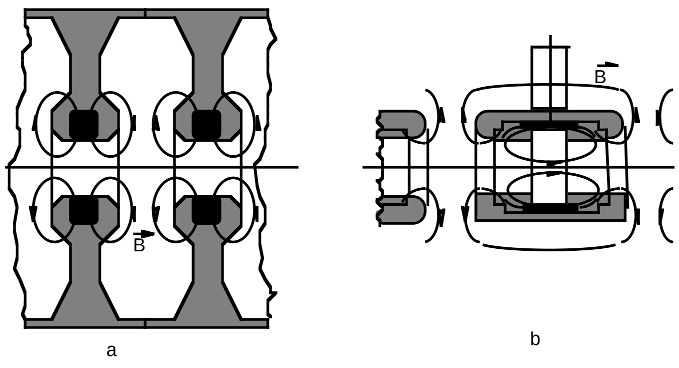

Fig.3. Permanent ring magnets layout in a drift tube: (a)-radial magnetization , (b)- axial magnetization.

pulse respecting RF pulse aided to the coefficient K increase. Furthermore the X-ray emission due to the electron beam bombardment also affected on the stable operation of the device. It was noted that magnetic insulation as well as delay let suppress this phenomena. This can be explained by lower loss of beam and lower secondary particles emission.

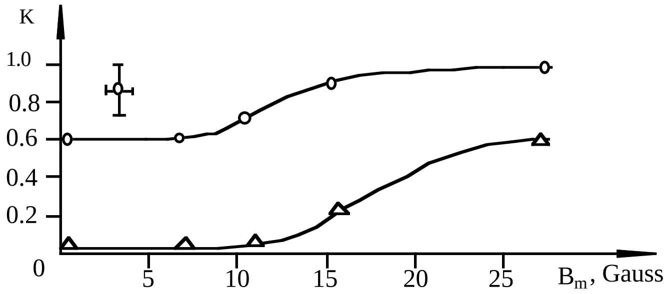

Fig.4. The coefficient K (number of pulses without breakdown divided by total number of pulses) vs magnetic field amplitude: o - with delay of the ion beam pulse; Δ - without delay.

As concerned the mixed beam forming system in the accelerator output (sign 11 on fig.1) the main problem is expected to be tied with the uniformity of the mixed beam intensity within necessary area at the target, in particular with the scanning beam as a whole. This problem can be solved using combined electric and magnetic fields acting to the opposite sides for electrons and ions [9].

Thus, the conducted analysis and the experimental results show the outlook of considered version. The final assessment of this version can be obtained by performing test experiments on electron- proton beam acceleration at the section contains 1 unit for proton and 1 unit for electron acceleration, the total length of the section is about 1m. The proton accelerator focused by electron beam [10] can be used as the injector.

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