LINEAR ACCELERATOR FOR BURNER-REACTOR

G.I.Batskikh, B.P.Murin, A.P.Fedotov
Moscow Radiotechnical Institute
USSR Academy of Sciences, Moscow, USSR

General Consideration

Future development of nuclear power engineering depends on the successful solution of two key problems of safety and utilization of high level radioactive wastes (HLRW) of atomic power plants (APP) .

Modern methods of HLRW treatment involve solidification , preliminary storing for a period of 30 - 50 years necessary for the decay of long-living nuclids and final burial in geological formations several hundred meters below the ground surface. The depth burial of the radioactive wastes requires complicated under ground constructions. It's very expensive and doesn't meet modern ecological requirements.

Alternative modern and more reasonable methods of APP HLRW treatment are under consideration now. One of the methods involves separation of APP waste radionuclids for use in economy with subsequent transmutation of the long-living isotopes into the short-living ones by high-intensity neutron fluxes generated by proton accelerators [1 - 3].

The installation intended for the long-living radionuclides transmutation into the short-living ones is called burner-reactor. It can be based on the continuous regime proton accelerator with 1.5 GeV energy, 0.3 A current and beam mean power of 450 MW. The preferable type of the proton accelerator with the aforementioned parameters is the linear accelerator [4 - 5].

Accelerator layout and parameters

Experience and new ideas in linear proton accelerator design lead to the accelerator scheme presented in Fig. 1.. The following basic concepts were taken into account in burner-reactor linear accelerator (BRLA) design.

- Simultaneous acceleration of H^+ and H^- beams is specified to provide for a number of output beams. Therefore the frequency increase factor (the ratio of the operating frequencies in different parts of accelerator) has to be odd. It was chosen to be equal to 3. Larger values lead to fact that phase spread of the bunch at the output of the first part of accelerator due to space charge effect and accelerator parameters errors surpasses the phase width of the accelerator second part separatrix.

- At the present design stage two pairs of operating frequencies for the accelerator parts are considered : 330 and 990 MHz (990 MHz is the operating frequency of the second part of meson physics facility linear accelerator at the INR of the USSR Academy of Sciences); 200 and 600 MHz. The first frequency pair is preferable. It enables the RF generator size and cost to be decreased. At the same time the beam dynamics still remains favorable with regard to the particle losses.

- Specific acceleration in both accelerator parts was chosen to be equal to 1 MeV/m.

- According to the world achievements in RF high-power generator design the output power of a single generator in both parts of accelerator was chosen to be equal to 5 MW. The numbers of cavities and generators in accelerator parts are equal to 8 and 100 respectively (with due allowance for 10 per cent reserve and feeder losses).

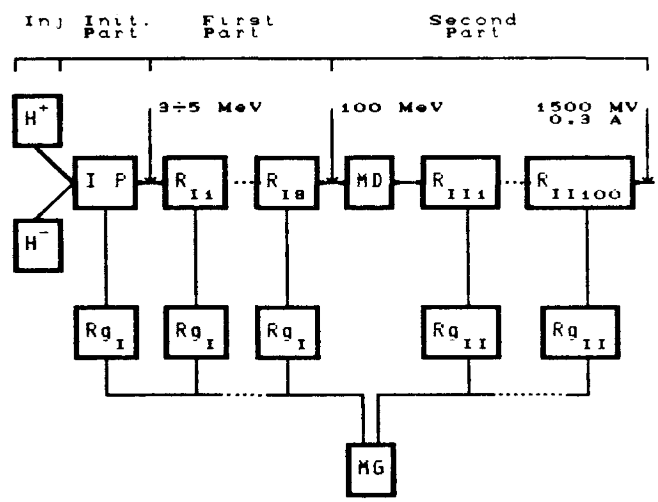

Fig. 1. The diagram of the burner-reactor linear accelerator

Consider the BRLA layout (Fig. 1). The accelerator involves two injectors of H^+ and H^- beams, initial part (IP), first and second parts.

The IP proposed in MRTI is based on the 5 - 8 T superconducting solenoid focusing. The solenoid contains a resonator with opposed vibrators providing for high accelerating wave amplitude E_m. The 1 A value of limiting current corresponds to E_m = 15 kV/cm with equilibrium phase of 70° and injection energy of 200 keV [6,7].

The resonators with drift tubes are used in the first part of the accelerator. Initial energy is 3 - 5 MeV. The main second accelerator part is based on the resonators with washers and diaphragms developed in MRTI for the USSR Academy of Sciences Meson Generator (MEGAN) [8].

An appropriate focusing system for both accelerator parts is that with permanent quadrupole lenses. The option provides for high reliability along with the simplified and unexpensive maintenance. In both accelerator parts a FODO focusing period structure is used which is less sensitive to the magnetic field errors then the FDO structure.

High degree of injected beam current stability (about 1 per cent) is necessary to meet the strict RF field amplitude and phase stability requirements (1 per cent and 1 respectively) of the 500 MW RF power supply system with due allowance for cavity beam loading and desirable system high efficiency.

Regotron - high power RF amplifier

The implementation of RF power supply systems for continuous mode accelerators with total RF power of several hundred MW requires RF generators with at least 5 - 10 MW output power, 70 - 80 per cent efficiency and 20 dB gain. Proposed in MRTI regotron, i.a. a relativistic electron beam generator with distributed RF power extraction system meets the aforementioned requirements [9,10].

One of the generator's peculiar features is the utilization of a certain number N of uncoupled cavities in the power take-off system. The technique provides for the microwave power take-off which is N times that of a single resonator with the given ultimate dielectric strength.

To increase the device efficiency $\eta = 1 - W_f/W_\iota$, where W_ι and W_f are the beam initial and final energies respectively, one has to organize the particle dynamics so as to preserve the bunch configuration and hence the current harmonic at the entrance of the power take-off system through the whole deceleration process till the minimum possible final energy W_f. The well-known principle of the accelerator theory - that of autophasing - is used in the device to solve the problem. The most effective method of the autophasing implementation in a distributed power take-off system is based on the use of cavity pairs. The first cavity of each pair is passive. It is detuned to the higher frequencies with regard to the operating frequency and serves as a beam buncher, whilst the second cavity , which is active, is tuned in to the resonant frequency. It is coupled with the load and takes off the beam power. The typical current first harmonic I_1 variations are plotted in Fig. 2 against the bunch relative energy W/W_o in the power take-off system with (curve 2) and without (curve 1) the autophasing. The autophasing clearly provides for the longer beam energy take-off feasibility and thus for the higher efficiency. Investigations show that regotron is capable of generating 5 - 10 MW HF power in continuous mode with 70 - 80 per cent efficiency.

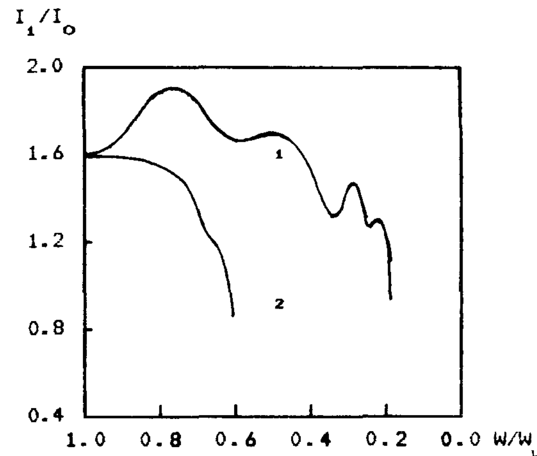

Fig. 2. The dependence of beam current first harmonic on the bunch energy

Initial part of accelerator

The proposal of the radiofrequency quadrupole focusing (RFQ) in the initial part of accelerator is the real basis of the linear proton continuous mode accelerators implementation [11]. However the limiting current of the RFQ initial part of accelerator is less than 1 A.

The next stage of the linear ion accelerators is the development of strong axial magnetic field focusing accelerators with 5 - 8 T superconducting solenoids. In the accelerator the main problem of the initial part - that of focusing - was thus removed. The increase of the synchronous phase in the strong azimuthal magnetic field focusing (SAMFF) accelerators enables the limiting current to be enhanced up to several Amps.

An accelerator based on the SAMFF was proposed in MRTI [6,7]. Experimental proton accelerator with the following parameters was also built.

Output energy	1.5 MeV
Injection energy	100 - 130 keV
Accelerated proton beam current	0.4 A
Operating frequency	196.8 MHz
Beam pulse length	30 - 70 s
Pulse repetition rate	1 pulse/sec
Accelerating-wave amplitude	3.7 MV/m
Focusing magnetic field	7.6 T

The idea of SAMFF was used in the initial part of BRLA. The input and output energies are 100 KeV and 3 - 5 MeV respectively.

Problems

Among the integral problems of accelerator design as a whole name the three main problems - that of economical efficiency, reliability and radiation purity.

<u>Efficiency and reliability problems</u> [12,13]

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 resonator efficiency estimate has a form of

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

where I_b is the beam current, E_a 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. If ZT^2 = 40 MOhm/m, $\varphi_s = 30^\circ$ and I_n = 0.3 A then the resonator efficiency amounts to 0.9.

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

Consider the reliability problem. The reliability of the accelerator can characterized by beam availability, which is equal for LAMPF accelerator - 0.85 and for " I-100 " accelerator - 0.99.

The following problems are crucial for solution of the BRLA reliability problem : creation of reliable high-power regotron type generators with service life of at least 10 thousand hours, provision for the reservation scheme, use of passive elements such as permanent magnets in quadrupole lenses, development of the failure prediction system.

Radiation purity problem.

A linear accelerator is considered to be radiation pure if the induced γ-activity doesn't exceed the occupational radiation dose of 28 μGy/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 [4]

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

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 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

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

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}.

Several methods were proposed and developed in MRTI to solve the radiation purity problem. Some of them were applied, in particular, in MEGAN 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 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.

References

1. S.Schriber,J.Fraser,P.Tunnicliffe, " Future of High Intensity Accelerators in Nuclear Energy ". Proc. X Int. Conf. High Energy Accelerators, v.2, p.408, Protvino, 1977
2. B.Murin,A.Fedotov, "Main Aspects of Proton Linear Accelerators for Nuclear Fuel Breeding". Proc. 6-th All-Union Conf. on Part. Accelerators, v.1, p.241, Dubna, 1978 (in Russian)
3. G.Batskikh, O.Lupandin, B.Murin, A.Fedotov, " On the Way to High Power Linear Accelerators for Long-living Nuclides Transmutation " Preprint 9001, MRTI, Moscow, 1990 (in Russian)
4. B.Murin, B.Bondarev, V.Kushin, A.Fedotov. Ion Linear Accelerators, v.1, Problems and Theory, Moscow, Atomizdat, 1978
5. B.Murin, V.Kulman, L.Lomize, B.Polyakov, A.Fedotov. Ion Linear Accelerators, v.2, Basic Systems, Moscow, Atomizdat, 1978
6. B.Bondarev, A.Kuzmin, B.Murin, V.Pirozhenko, L.Solovyov," The Use of a Superconducting Focusing Solenoid for the Limiting Linear Accelerator Current Enhancement ". Proc. 6-th All-Union Conf. Particle Accelerators, v.1, p.260, Dubna, 1978 (in Russian)
7. B.Bondarev et al. " Experimental RF Proton Accelerator with Superconducting Solenoid Beam Focusing ". Preprint 8901, MRTI, Moscow, 1989, (in Russian)
8. V.Andreev, Zh.Techn.Fiz. ,v.41, No.4, p. 788 , 1971 (in Russian)
9. F.Vodopyanov, B.Murin, " The Method of RF Oscillations Generation with the Use of Relativities Electron Beam ".Proc. RTI, No.22, p. 20, 1975 (in Russian)
10. B.Murin, A.Durkin, O.Shlygin, I.Shumakov, " Superhigh-Power RF Regotron-Type Generator for Linear Accelerators with High Mean Power ", this Conference
11. I.Kapchinsky, B.Teplyakov, Pribory i Tekhnika Eksperimenta, No.2, p.19, 1970 (in Russian)
12. B.Murin, A.Fedotov, " Radiation Purity and Efficiency Problem in Modern Linear Proton and H Ion Accelerators with High Mean Currents ", Atomnaya Energiya, v.38, No.3, p.146, 1975 (in Russian)
13. A.Fedotov, B.Murin," Towards a Radiation-Free Linac of Meson or Neutron Generator ", Proc. 1976 Proton Linear Accelerator Conf., Chalck-River Nucl.Lab., p.377, 1976