ION LINACS DESIGN WITH SUPERCONDUCTIVITY USE

B.P. Murin, G.I. Batskikh, V.M. Belugin, B.I. Bondarev, A.P. Fedotov, V.A. Konovalov, I.V. Shumakov
Moscow Radiotechnical Institute, Russia
113519, Russia, Moscow, Warshavskoe shosse, 132

Abstract

Two principal schemes of CW high current linac design based on superconductivity use are proposed. Superconducting accelerating structures are suggested to use along the whole linac for acceleration of beams with the currents up to 30 mA. Focusing by longitudinal magnetic field generated by superconducting solenoids are suggested to use for the beams with the currents up to 500 mA. It is shown that in both cases accelerator efficiency is higher than 50% and beam losses is lower than 10^{-5}. Problems of accelerator main system design and its resolution are discussed.

Introduction

Research works on the concepts in designing of high current proton (ion) linear accelerators with the output energy of about 1 GeV for electronuclear purposes are carried out in MRTI for years [1–8]. The works are curried in two aspects: development of CW linac with current of 10–30 mA (first type) for solution of the problems of conversion of weapon-grade plutonium and nuclear-power problems ("power amplifiers") [9]; development of CW linac with current of 100–300 mA for accelerator transmutation (second type). These concepts and technological systems are developed according to the following demands: provision of efficiency more than 50% and high reliability, as well as radiation purity (beam losses - 10^{-5}).

In the first case the problem of high efficiency is brought to the fore. Estimations carried out in MRTI bring out that CW linac version with superconducting accelerating cavities is preferable.

In the second case problems of reliability and efficiency are dictated by solving the problems of superpower HF supply system design and essentially by lossless beam transport along linac. The solving of these problems provide radiation purity as well. As discussed in MRTI papers [1, 6, 8] the problems can be solved by use superpower Regotron-type amplifiers in HF supply system [4] and application the focusing system based on superconducting solenoids.

CW Superconducting Proton Linear Accelerator with the Energy of 1 GeV and current of 10–30 mA

Solution of the problems of conversion of weapon-grade plutonium and of nuclear-power tasks ("power amplifiers" [9]) requires proton beams with the energy of 1 GeV and average current of 10–30 mA. The most expeditious way to obtain such proton beams is CW linear accelerators with superconducting accelerating structures.

CW superconducting linear accelerator of protons [8] possesses a number of decisive advantages in comparison with "room" temperature accelerators in the region of average of beam currents of tens mA: consumed HF power is significantly decreasing and as a consequence the cost of construction and of routine operation are going down, reliability rises and not less than twice the length of the accelerator decreases. Total efficiency of such accelerator under acceleration of beam 10 mA and more will be not lower than 60%. High margin of acceptance in the considered version of linear accelerator allows to expect that losses of the beam in the process of acceleration will not exceed 10^{-5}. Modern level of tectonics and of technology allows to realize the proposed project of linear accelerator.

Proposed scheme of the CW proton linear accelerator is as follows.

The injector produces a beam of protons with energy of 60 keV. Further the protons are accelerated in the initial part of the linear accelerator (IPA) - RFQ-type accelerator. A four-chamber H-resonator excited by the TE_{211} wave of 425 MHz accelerates protons to energy of 3 MeV.

The first part of the linear accelerator consists of short four-gap cavities with drift tubes excited at the frequency of 425 MHz. Energy of protons in this part of the accelerator rises up to 50 MeV. Separation of the accelerating structure to short resonators is dictated by necessity to place between them quadrupole permanent magnets focusing lenses. The structure of the focusing period is FODO.

The second (main) part of the linear accelerator provides acceleration of protons up to the energy of 1 GeV. Accelerating structure consists of 304 nine-cell axially symmetric cavities with elliptical shaped cells excited at the frequency of 1275 MHz. Odd frequencies ratio of the first and the second parts of the linear accelerator is equal 3 and this allows, if necessary, simultaneous acceleration of protons and negative ions of hydrogen. Acceleration rate at the length of the cavities is 5 MeV/m. Averaged acceleration rate along the whole length of the acceleration is 2.5 MeV/m.

The main parameters of the linear accelerator are presented in the Table 1. The parameters of the acceleration will not change for the case of acceleration of hydrogen negative ions beam.

In order to rise reliability and to decrease the costs it is desirable to decrease number of HF channels due to excitation of a group of cavities by one HF generator. In these proposal groups of four cavities are excited by one of generators. Klystrons with output power 500 kW for acceleration of 30 mA beam and about 150 kW for beam current of 10 mA will be needed for excitation of a group of four cavities. In main part of the system of HF power distribution to the cavities of group is constructed with the aid of bridge-type

Table 1

Parameter	Initial Part	First Part	Second Part
Type of accelerator, resonator	RFQ	4-gaps drift tubes	9-cell resonators
Injection energy, MeV	0.06	3	50
Output energy, MeV	3	50	1000
Frequency of accelerating field, MHz	425	425	1275
Number of resonators	1	28	304
Period of focusing, m	0.007–0.056	0.6–2.0	2.0–4.0
Acceptance, specified, π cm·mrad	0.07–0.25	0.2–0.35	0.5–0.7
Effective emittance, specified, π cm·mrad	0.04–0.08	0.08–0.12	0.12–0.2
Equilibrium phase, degree	–(90÷45)	–(45÷30)	–30
Phase width, degree	360÷40	40÷15	45÷40
Pulse spread at output, %	0.4	0.08	0.025
Resonator length, m	3.2	0.25–0.85	0.35–0.93
Diameter of resonator, cm	15.6	49–45	24–21,6
Aperture diameter, mm	3–6	15–20	30–40
Accelerator length, m	3.5	25	380
Power for beam, kW I_b = 10 mA	30	470	9500
I_b = 30 mA	90	1410	28500
Losses removed by helium, W	50	580	3400

devices proposed for decoupling of two loads and division of HF power to equal parts. Split-type of double T-shape bridges may be used as prototypes of such devices. In part 1 four cavities of each group are coupled with the aid of three resonant bridges. Such group is excited by klystron through mean bridge.

In order to provide superconductivity the resonators, its operating surfaces are covered by niobium layer and cooled by liquid helium. Adopted temperature of 2K corresponds to minimum of capital investments and the cost of routine operation. The version of the cryogenic system consisting of typical cryo-modules is chosen in these technical proposals. A cryo-modules consists of a cryostat with several resonators together with adjacent devices inside it..

The following ideology linked with quantitative characteristics of heat removal by helium is adopted. Total power of losses for helium in the cavities of the linear accelerator is approximately 4000 W (see Table 1). Acceptable losses by helium due to losses of the beam in the linear accelerator with hand controlling are 380 W or approximately 10% of the losses in the cavities. The same value is taken for acceptable heat flux from the external space through the cryostat. It defines the requirements to thermal insulation of the cryostat. So the total thermal power (P_{He}) removed by helium is 4700–5000 W.

This approach demand to place in cryo-modules cavities as many as possible. Different versions of cryo-modules are considered. Fragment of cryo-module is shown in Fig. 1. Cryo-system design of accelerator under consideration is the development of RHIC and CEBAF base ideas. One of the main characteristics of particle accelerators for considered nuclear-power utilization is the value of total efficiency of the conversion of electric power into beam power [10].

Full efficiency of a superconducting linear accelerator may be presented by the expression

$$\eta = P_b/(P_e + P_{ec}),$$

where P_b is HF power for acceleration of the proton beam, P_e and P_{ec} - powers of electric feeding of the HF system and of cryogenic system of the accelerator. Let us introduce notations for efficiency of HF and cryogenic system $\eta_{HF} = P_{HF}/P_e$ and $\eta_c = P_{He}/P_{ec}$. Then

$$\eta = P_b/[(P_b + P_{HF})\cdot \eta_{HF}^{-1} + P_{He}\cdot\eta_c^{-1}],$$

Where P_{HF} is power of HF losses in the walls of the cavities. As $P_b >> P_{HF}$ then $\eta = P_b/(P_b\cdot\eta_{HF}^{-1} + P_{He}\cdot\eta_c^{-1})$. Accepting for estimation $\eta_{HF} = 0.7$, $\eta_c = 2\cdot10^{-3}$ and $P_{He} = 5$ kW we shall obtain expression for calculation of efficiency of superconducting accelerator as a function of P_b:

$$\eta = P_b/(1.41\cdot P_b + 2.5\cdot 10^6) \qquad (1)$$

With beam current 10 mA $P_b = 10^7$ efficiency of the accelerator is equal 60%. For beam current 30 mA we have η = 65%. Tectonics of fabrication of the main devices of the accelerator is well experienced in the world though quite similar accelerators were not yet constructed. The accelerator of INR of RAS (protons energy is 600 MeV, average current - 1 mA) developed by MRTI of RAS jointly with invited institutions and superconducting electron accelerator CEBAF may be looked as prototypes. Time necessary for realization of the project is estimated as 7–10 years.

Linear Accelerator With Superconducting Solenoids. With the Energy of 1 Gev and Current of 100–300 mA

The considered concept of the linac with 100–300 mA current is the further outgrowth of the MRTI quests [1–8] for

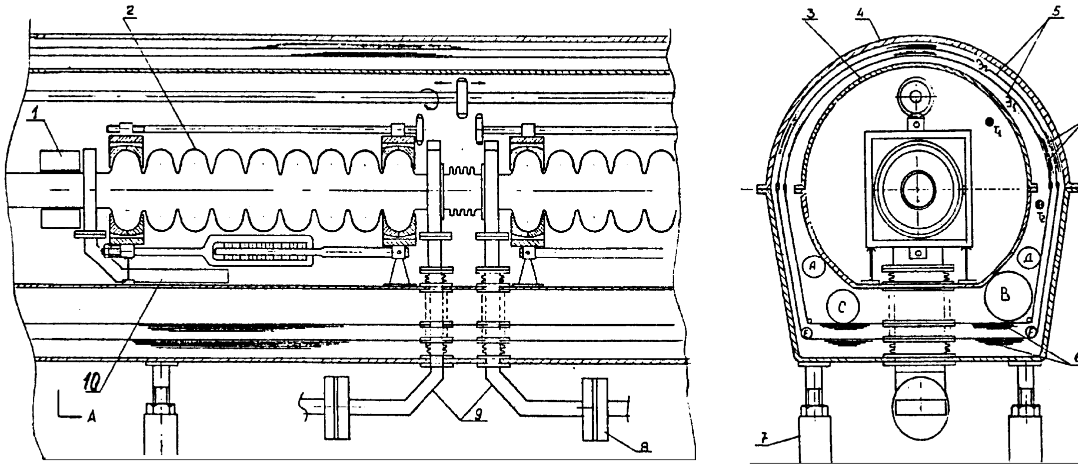

Fig. 1. 1 - quadrupole lens, 2 - accelerating cavity, 3 - helium vessel, 4 - cryo-module enclosure, 5 - heat (Ý$_{2}$) and radiation (Ý$_{1}$) screens enclosure, 6 - superisolation, 7 - supports, 8 - HF window, 9 - HF inputs system, 10 - load for high modes suppression, 11 - cavity adjusting mechanism, A, B, C, D, E, F - system of helium flow.

linac for transmutation of long-living radioactive wastes of nuclear reactors. Novelty of this concept is associated with the use of superconducting solenoid focusing (SSF) in all accelerating parts [8].

Beam transport along the length of accelerator with minimal losses should be closely studied. The most limiting regions are: initial part of acceleration - IPA (up to 3 MeV); matching between focusing channels with different types and structures; high energy part of accelerator (HBL) with high number of focusing elements and accelerating structure.

Single-channel scheme (HILBILAC-DTL-HBL) is used in the linac as before. High acceptance of HILBILAC (IAP) and high current limit (700 mA at a frequency of 350 MHz) make possible to form beam at the IPA output with good transverse characteristics.

Use of focusing by superconducting solenoids at DTL and HBL alleviates the other problems: a) single-type focusing makes possible good matching between different linac part: (HILBILAC-DTL section and DTL-HBL section); b) changing quadruple lenses to solenoids decreases channel sensitivity to random perturbations approximately by a factor of 10; c) use SSF at HBL section makes possible use of "long" cavities (10–13 m in length) based on D&W structure without subdivision on sections. Abandonment of sectionalized HBL cavities structure and coupling bridges between sections make possible essential decrease accelerating field sensitivity to geometrical errors of cavity. Requirements for evenness of "long" cavity excitation thought 7 power input from regotron are reduced as well [4, 6].

Development of such type linac indicates that DTL section realization is not improbable but there are a diversity of difficulties. The main problems are associated with high inductive coupling between solenoids, with strong ponderomotive forces and with scattering fields.

With the beam current higher than 100 mA total efficiency of accelerator will exceed 50%

References

[1] G. Batskikh et al., Linear Accelerator for Burner-Reactor, in *Proceedings of 1990 Linear Accelerator* Conference, Albuquerque, New Mexico, p. 581.

[2] A.P. Fedotov, B.P. Murin, Towards a Radiation-Free Linac of Meson or Neutron Generator Type, in *Proceedings of the 1976 Proton Linear Accelerator Conference*, Chalk-River, Canada, 1976.

[3] V.G. Andreev et al., Basic Principles of Burner-Reactor Linac Design. *Specialist Meeting on Accelerator-Driven Transmutation Technology for Radwaste and Other Applications*, 24–28 June, 1991, Stockholm, Sweden, LA-12205-C, SKN Report No. 54.

[4] B.P. Murin et al., Superhigh-Power RF Regotron-Type Generator For Linear Accelerator with High Mean Current, Ibid.

[5] B.P. Murin, V.M. Pirozhenko, O.V. Plink. High-Current Low-Energy RF Ion Accelerator, in *Proceedings of the 1990 Linear Accelerator Conference*, Albuquerque, New Mexico, p. 707.

[6] B.P. Murin, The Prospects For High-Power Ion Linear Accelerator Construction For Energy Function. Preprint 9210, Moscow Radiotechnical Institute, 1992.

[7] G.I. Batskikh et al., Development of Advanced Technological System for Accelerator-Driven Transmutation Technologies and Applications, July 25–29, 1994, Las Vegas, Nevada, USA.

[8] B.P. Murin et al., The New Concepts in Designing the CW High-Current Linacs, *Proceedings of the 1995 Particle Accelerator Conference*, Volume 2, pp. 1134–1136.

[9] I.V. Chuvilo et al., Weapon Plutonium in Accelerator-Driven Power System. *Second International Conference on Accelerator-Driven Transmutation Technologies and Applications*, 3–7 June 1996, Kalmar, Sweden.

[10] B.P. Murin, A.P. Fedotov, Direction of Development of Powerful Proton Linear Accelerators of Continuous Way of Operation for Nuclear-Power Goals, MRTI Report, No 39–10–95.